GROUND MOTION MAPS THAT ACCOUNT FOR SITE EFFECTS, BASIN EFFECTS, DURATION OF SHAKING AND RUPTURE DIRECTIVITY IN THE SAN FRANCISCO BAY AREA

Award Number 1434-HQ-98-GR-0026

Investigators: Paul G. Somerville, Arben Pitarka, Nancy Collins
URS Greiner Woodward-Clyde
566 El Dorado Street
Pasadena, CA 91101
Tel: (626) 449-7650
Fax: (626) 449-3536
Email: paul_somerville@urscorp.com

Program Element: I. Products for Earthquake Loss Estimation

Key Words: Strong ground motion, amplification, site effects, seismic zonation

Investigations Undertaken

This report describes ground motion maps for the scenario earthquakes listed in Table 1. These ground motion maps include rupture directivity, site effects, and the effects of basin structure. The maps are for the five earthquake scenarios listed in Table 1. The parameters of the earthquake scenarios are listed in Table 2.

Table 1. List of San Francisco Bay Area Earthquake Scenarios

FAULT SYSTEM	FAULT SEGMENT
San Andreas	San Francisco Peninsula, central epicenter San Francisco Peninsula, southern epicenter
Hayward	Northern East Bay, northern epicenter Northern East Bay, southern epicenter Southern East Bay, southern epicenter

Our approach to making the maps was to use a basic ground motion model, and then apply adjustments to the ground motion model to incorporate rupture directivity effects and basin effects. The effect of shallow geological site conditions is represented through different site categories in the basic ground motion model. The site categories included in the maps are rock, soil, and soft soil, as defined in the 3D seismic velocity model of Brocher et al. (1997). The attenuation relations of Abrahamson and Silva (1997) were used to calculate the ground motions for rock and soil sites. The attenuation relations of Idriss (1991, with subsequent revisions) were used to calculate the ground motions for soft soil sites. The shallow geological site conditions were defined using shear wave velocity ranges, listed in Table 3, that are compatible with the site categories used in the Abrahamson and Silva (1997) and Idriss (1991) attenuation relations. Rupture directivity effects were represented using an empirical model derived by Somerville et al. (1997). This model is applied as a modification to the attenuation relations.

Table 2. Source Parameters of San Francisco Bay Area Earthquake Scenarios

Parameter	San Andreas, San Francisco Peninsula	Hayward, Northern Segment	Hayward, Southern Segment
Length (km)	78	50	40
Width (km)	12	12	12
Depth Range (km)	0 - 12	0 - 12	0 - 12
Seismic Moment (dyne.cm)	2.7×10^{26}	1.5×10^{26}	1.0×10^{26}
Mw	6.92	6.75	6.64
Northern end point (Lat., Long.)	37.793, 122.576	38.102, 122.433	37.771, 122.170
Southern end point (Lat., Long.)	37.224, 122.052	37.720, 122.117	37.472, 121.908
Hypocenter - north	35 km from N end	2 km from N end	
Hypocenter - south	18 km from S end	5 km from S end	5 km from S end
Hypocentral depth	9.2 km	9.3 km	9.2 km
Strike (E of N)	144	146	146
Dip	90	90	90
Rake	180	180	180
Rise Time (sec)	1.3	1.2	1.2

Table 3. Definition of Site Categories using Shear Wave Velocities

Site Category	Shear Wave Velocity (averaged over the top 30 meters) (meters/sec)	Corresponding NEHRP Site Category	Attenuation Model
Rock	> 360	S_B, S_C	Abrahamson and Silva, 1997
Soil	150 - 360	S_D	Abrahamson and Silva, 1997
Soft Soil	< 150	S_E	Idriss, 1991

The effects of deep sedimentary structure were estimated from calculations of the ground motions using the 3D seismic velocity model described above. The calculations were done using a 3D finite difference code described by Pitarka (1999). The grid spacing was chosen to be 150 meters at the surface, producing results that are reliable for periods of 1.5 second and longer. The calculations were done for the respective earthquake scenarios, but were not used to directly estimate the ground motions, because the 3D calculations are not broadband and do not contain the nonlinear effects of shallow soils. Instead, the calculations were used to derive a modification factor to account for 3D effects. This modification factor was derived by taking the ratio of the 3D calculation to a calculation done for one of two 1D reference models. The ratio of these calculations represents an adjustment factor that is applied to the ground motions obtained from the empirical model. The shallow reference model was used when the depth to the layer with a shear wave velocity of 2.0 km/sec is between 0.5 and 2.2 km, and the deep reference model was used when the depth to the layer with a shear wave velocity of 2.0 km/sec is greater that 2.2 km. For the San Andreas fault scenarios, only the shallow basin model was used because the effect of the deep basin was negligible in the area covered by the maps.

Results

The predominant influences on the ground motions in the densely urbanized regions are the site conditions and, at longer periods, rupture directivity effects and basin effects. Soft soil conditions amplify the ground motions at low ground motion levels, but the high ground motion levels in the near fault regions are reduced by soft soil conditions at the shorter periods. Rupture directivity effects depend on the location of the hypocenter, with long period ground motions building up away from the hypocenter and reaching a saturation level at a distance along the fault equal to 40% of the fault rupture length.

The predominantly strike-slip mode of faulting in the San Francisco Bay area has not generated a large degree of subsidence and basin filling in this region. Along the eastern shore of San Francisco Bay, the only large basin structure is a basin that lies mostly beneath the central part of the east bay but which also underlies a narrow strip of the shoreline extending from Oakland Airport to south of the San Mateo bridge in Hayward. The deepest basin lies east of the Hayward fault, so the strongest basin effects are in the Coast Ranges. For earthquakes on the Hayward fault, the main effect of the sedimentary basins on ground motions is to increase the ground motions at periods of 1.5 second and longer along the southeastern shore of San Francisco Bay between the Oakland Airport and the San Mateo Bridge, and to the east of the Hayward fault in the Coast Ranges. Along the San Andreas fault, the main basin structures lie west of the fault in Daly City, and east of the fault between Redwood City and Portola Valley. For earthquakes on the San Andreas fault, the main effect of the sedimentary basins is to increase the intermediate and long period ground motions in these two regions.

In the scenario ground motions in Figures 1 and 2, the top left panel shows the average horizontal ground motion including basin effects but excluding directivity effects. The top right panel incorporates rupture directivity effects for the average horizontal, while the lower two panels shown the fault normal and fault parallel components. The combined effects of site conditions, basin effects and rupture directivity produce complex patterns of ground motions. As for the case of rupture directivity, the basin effects depend on the location of the epicenter, and tend to become largest at distances beyond about 20 km of the epicenter. In many cases, the basin effects in the fault parallel direction are larger than those in the fault normal direction, offsetting the effects of rupture directivity which produce large fault normal motions. The most severe ground motion conditions in the East Bay occur for southerly rupture from a northern hypocenter in San Pablo Bay on the North Hayward fault (Figure 1). In this scenario, basin effects and rupture directivity effects reinforce each other along the southeastern shore of San Francisco Bay between the Oakland Airport and the San Mateo Bridge. In contrast, northerly rupture from a southern epicenter near southeastern Oakland on the North Hayward fault produces neither strong directivity effects nor strong basin effects along this stretch of shoreline, because of the proximity of the hypocenter to this region. At intermediate and long periods, the most severe ground motion conditions along the San Andreas fault occur west of the fault in Daly City and east of the fault in Palo Alto, due to basin effects, and in the San Francisco Airport region, due to the combination of near fault and soft soil conditions. (Figure 2).

The conditions that gave rise to extremely large basin edge effects in the Kobe earthquake (Pitarka et al., 1998) and in Santa Monica during the 1994 Northridge earthquake (Graves et al., 1998), which are rapid lateral variations in seismic velocity across basin-bounding faults, may not be prevalent in the Bay area. Further, most of the densely urbanized locations within the Bay area are no more than 10 km from a major strike-slip fault. Consequently, at most locations in the Bay area, the most critical ground motion phenomenon associated with the major strike-slip faults at intermediate and long periods is that due to rupture directivity. These ground motions are further increased in localized areas underlain by soft soils or basins.

Non-Technical Summary

This report describes ground motion maps in the San Francisco Bay area for scenario earthquakes on the San Andreas and Hayward faults. The combined effects of site conditions, basin effects and rupture directivity produce complex patterns of ground motions. The most severe ground motion conditions for intermediate and long periods in the East Bay occur for southerly rupture from a northern hypocenter in San Pablo Bay on the North Hayward fault. In this scenario, basin effects and rupture directivity effects reinforce each other along the southeastern shore of San Francisco Bay between the Oakland Airport and the San Mateo Bridge. At intermediate and long periods, the most severe ground motion conditions along the San Andreas fault occur west of the fault in Daly City and east of the fault in Palo Alto, due to basin effects, and in the San Francisco Airport region, due to the combination of near fault and soft soil conditions.

References

Abrahamson, N.A. and W.J. Silva (1997). Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismological Research Letters* 68, 94-127.

Idriss, I.M. (1991). Earthquake ground motions at soft soil sites. Proceedings of the Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, March 11-15, 1991.

Pitarka, A. (1999) 3D elastic finite-difference modelling of seismic wave propagation using staggered grids with nonuniform spacing, *Bull. Seism. Soc. Am.* 89, 54-68.

Somerville, P.G., N.F. Smith, R.W. Graves, and N.A. Abrahamson (1997). Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity, *Seismological Research Letters* 68, 180-203.

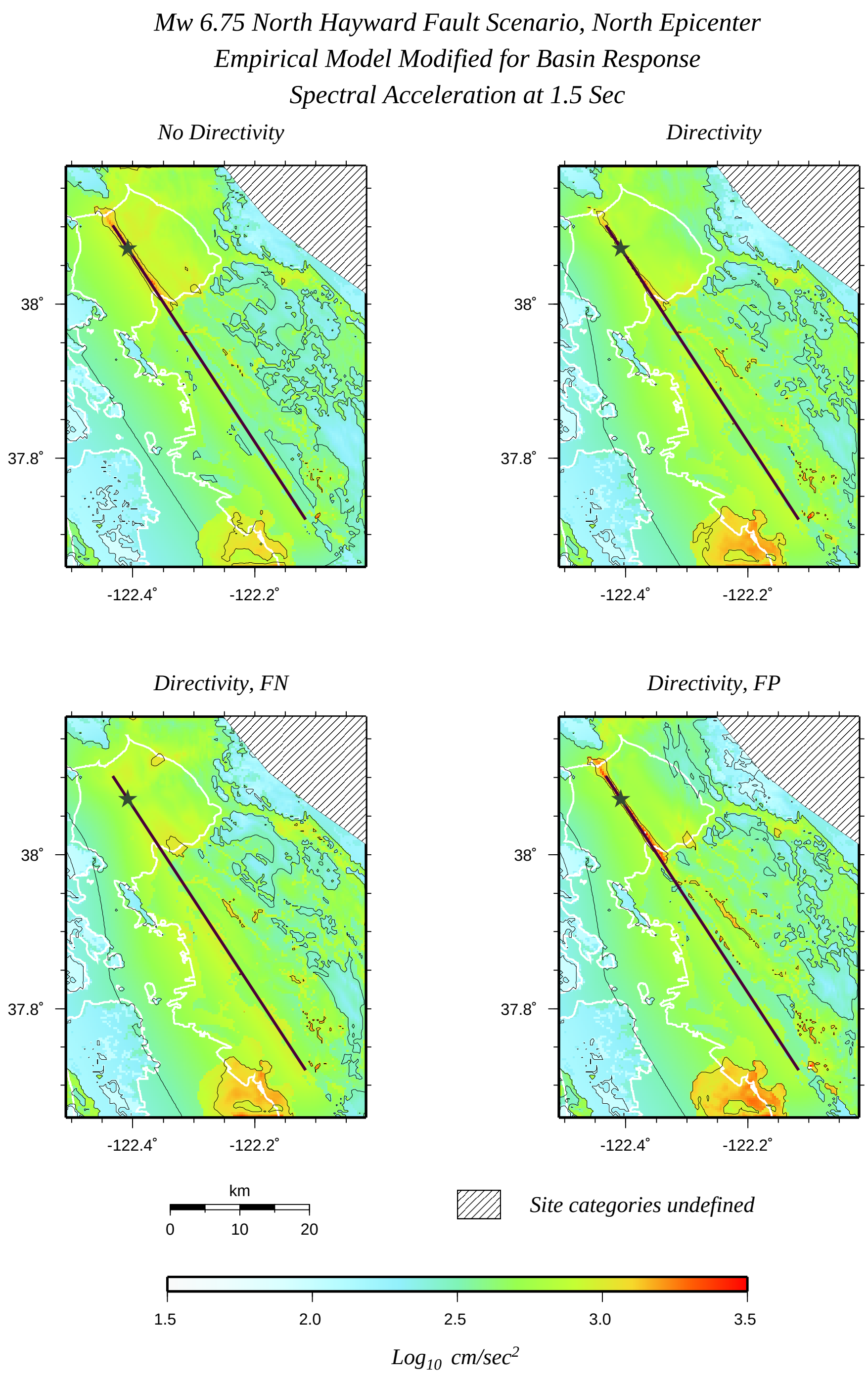

Figure 1. Ground motions for a North Hayward scenario earthquake.

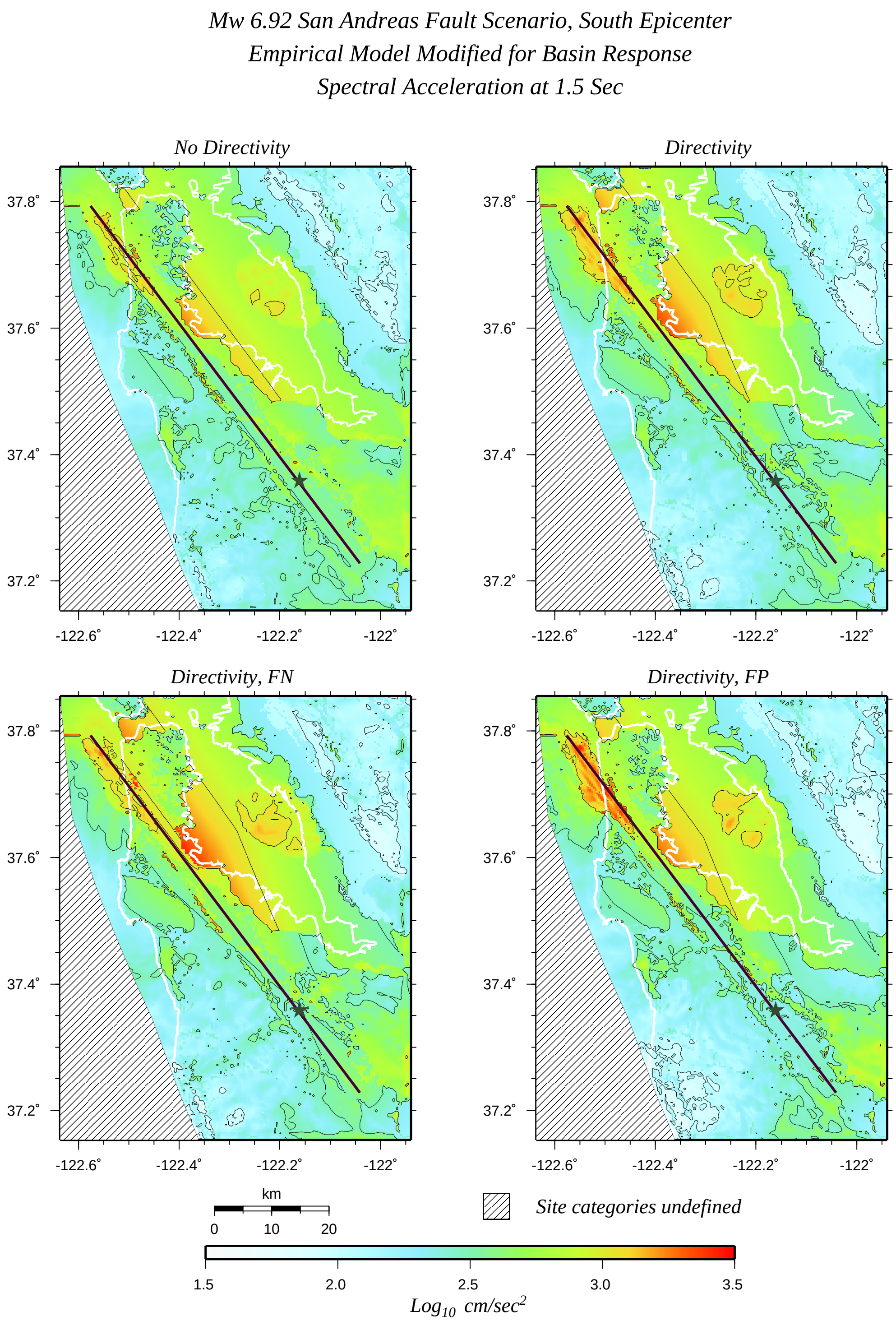

Figure 2. Ground motions for a San Andreas scenario earthquake.