USGS National Seismic Hazard Maps


The U.S. Geological Survey (USGS) recently completed new probabilistic seismic hazard maps for the United States, including Alaska and Hawaii. These hazard maps form the basis of the probabilistic component of the design maps used in the 1997 edition of the NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, prepared by the Building Seismic Safety Council and published by FEMA. The hazard maps depict peak horizontal ground acceleration and spectral response at 0.2, 0.3, and 1.0 sec periods, with 10%, 5%, and 2% probabilities of exceedance in 50 years, corresponding to return times of about 500, 1000, and 2500 years, respectively. In this paper we outline the methodology used to construct the hazard maps. There are three basic components to the maps. First, we use spatially smoothed historic seismicity as one portion of the hazard calculation. In this model, we apply the general observation that moderate and large earthquakes tend to occur near areas of previous small or moderate events, with some notable exceptions. Second, we consider large background source zones based on broad geologic criteria to quantify hazard in areas with little or no historic seismicity, but with the potential for generating large events. Third, we include the hazard from specific fault sources. We use about 450 faults in the western United States (WUS) and derive recurrence times from either geologic slip rates or the dating of pre-historic earthquakes from trenching of faults or other paleoseismic methods. Recurrence estimates for large earthquakes in New Madrid and Charleston, South Carolina, were taken from recent paleoearthquake studies. We used logic trees to incorporate different seismicity models, fault recurrence models, Cascadia great earthquake scenarios, and ground-motion attenuation relations. We present disaggregation plots showing the contribution to hazard at four cities from potential earthquakes with various magnitudes and distances.

INTRODUCTION

In June 1996 we completed new national seismic hazard maps for the contiguous United States. These maps were placed on our Internet web site (http://geohazards.cr.usgs.gov/eq/) and subsequently published as large-format maps (Frankel et al. 1997a, b). We recently produced new hazard maps for Alaska (Wesson et al. 1999a, b) and Hawaii (Klein et al. 1999a, b). The USGS has a long history of publishing probabilistic national seismic hazard maps, starting with Algermissen and Perkins (1976) and including
Alternative Models of Seismic Hazard
For Central and Eastern U.S.

$$M_{max} = 6.5 \text{ in crotan}$$
$$M_{max} = 7.5 \text{ outboard of crotan}$$
$$M_{max} = 7.5 \text{ Wabash Valley}$$
$$m_{bg} = m_{bg} - 5.0 \text{ for hazard calculation}$$

1. M3+ Since 1924, smoothed spatially
2. M4+ Since 1880, smoothed spatially
3. M5+ Since 1700, smoothed spatially
4. Background Source Zones

M \approx 7.0

Figure 4. Methodology used for the central and eastern United States.

et al. 1990, Johnston and Schweig 1996) and the magnitude estimated for the largest 1811-
1812 quakes based on intensity data (Johnston 1966). We used M7.3 events in Charleston,
South Carolina, with a recurrence time of 650 years based on paleoquakes (see Amick and
Gelin 1991) and the intensity-based magnitude of the 1868 shock (Johnston, 1996). We also added the hazard from the Meers Fault in southwest Oklahoma and the
Cheraw Fault in southeastern Colorado, based on geological information from trenching.

WESTERN UNITED STATES

The California portion of the hazard maps was produced jointly by the California
Division of Mines and Geology and the USGS (see Petersen et al. 1996). The values plotted
in the CDMG and USGS seismic hazard maps for California are identical.

The scheme for mapping hazard in the WUS is shown in Figure 5. On the left side we
consider hazard from earthquakes with magnitudes less than or equal to moment magnitude
7.0. For most of the WUS, we used two alternative models: 1) smoothed historical seismicity
(weight of 0.67) and 2) large background zones (weight 0.33) based on broad geologic
criteria and input from workshop participants (weights were discussed at a regional
workshop). Again, a spatially varying weighting scheme was used so that including the
background zones did not lower the hazard estimates for areas with relatively high seismicity.
We also added the hazard from a shear zone extending from the northern end of the Death
Valley fault (California) through the Tahoe-Reno Nevada area through northeastern
California ending at the latitude of Klamath Falls, Oregon (Frankel et al. 1996). The shearing
rate for this zone was partially constrained by space-geodetic measurements. No large
background source zones were applied for California and the West Coast. Deep earthquakes
(d>35 km) were treated with separate runs with the appropriate attenuation relations (see
below). Most of these deep events occurred in the Puget Sound region.

5.0 \leq M \leq 7.0

M \geq 6.5

Figure 5. Methodology used for the western United States.

We then added the hazard from about 450 Quaternary faults or fault segments (Figure 2).
We considered faults where geologic slip rates have been determined or estimates of
recurrence rates have been made from trenching studies. For California, a consensus process
of experts was employed to develop fault parameters for the hazard maps (Petersen et al.
1996, Working Group on Northern California Earthquake Potential 1996; McCrory 1996,
Working Group on California Earthquake Probabilities 1995, and references therein). The
hazard from blind thrust faults in the Los Angeles area, the Santa Barbara Channel, and along
the western edge of the Great Valley was included in the maps. The sources of the parameters
used for the other faults are given in Frankel et al. (1996) and the fault-parameter table on our
web site.

For faults with known segmentation (e.g., San Andreas, Wasatch faults), we used a
characteristic model where the recurrence times are determined for single-segment rupture.
For the San Andreas and Hayward faults we also used multiple segment rupture scenarios.
Most of the faults in Figure 2 have not been sufficiently studied to know their rupture
segmentation. For these faults, we used two alternative models to calculate recurrence times
and magnitudes: 1) characteristic model where the slip on the fault is released by large
earthquakes that rupture the entire fault and 2) Gutenberg-Richter recurrence relation, which
has an exponential distribution of recurrence times. For the Gutenberg-Richter recurrence
model we applied a minimum magnitude of 6.5 and a maximum magnitude corresponding to
rupture of the entire fault or fault segment (Petersen et al. 1996). The recurrence times for
both models were determined from the geologic slip rates. The estimation of earthquake
recurrence rates from fault slip rates is a major source of uncertainty in the hazard
calculations (see Cramer et al. 1996).
We considered two scenarios for great earthquakes on the Cascadia subduction zone. For the first scenario we assumed that the recurrence time of rupture at any point along the subduction zone was 500 years. This time is in or near most of the average intervals estimated from coastal and offshore evidence (see, e.g., Atwater and Hennihill-Halley 1996). The second scenario (weight 0.67) is for the rupture zones of M8.3 earthquakes to fill the entire subduction zone every 500 years. The second scenario (weight 0.33) we used is a M9.0 earthquake rupturing the entire Cascadia subduction zone every 500 years, on average. Evidence for such a large event is found in tsunami records in Japan for a January 1700 earthquake (Satake et al. 1996).

ALASKA AND HAWAII

The procedure for the Alaska maps was similar to that of the western United States, except with alternative segmentation models of the Aleutian-Alaskan megathrust (Figure 6a, b; Wesson et al. 1999a, b). The recurrence rate for large earthquakes along the megathrust is determined from historical seismicity. The hazard from deep earthquakes (d=50-120 km) is also included.

For the Hawaii maps, areal source zones were used for the major sources of earthquakes on the flanks of active volcanoes on the Big Island (Figure 6b; see Klein et al. 1999a, b). Near source zones were combined with smoothed seismicity for shallow and deep earthquakes. For the islands west of the Big Island a combination of the spatially smoothed historical seismicity and a source zone with a seismicity rate decreasing to the west was used to quantify the hazard.

ATTENUATION RELATIONS AND REFERENCE SITE CONDITION

Whenever possible we used more than one ground-motion attenuation relation in the hazard maps. Figure 7 lists the various relations used in the maps. Different attenuation relations were applied in the CEUS than the WUS, reflecting the observation that ground motions decay more slowly with distance in the CEUS. Special attenuation relations were required for Cascadia subduction zone earthquakes and deep, intra-lith events beneath Puget Sound. When multiple relationships were used, they were assigned equal weights. The WUS relations were determined empirically from strong-motion data, while the CEUS relations are derived from stochastic simulations and random vibration theory, using path and source properties determined from small earthquakes. The western U.S. relations included higher ground motions for thrust earthquakes compared to strike-slip and normal earthquakes. For Hawaii, the Munson and Thurber (1997) attenuation relations were also used.

The reference site condition for the maps was a firm-rock site with an average shear-wave velocity of 760 m/sec in the top 30m. This corresponds to the boundary between NEHRP B and C sites (see Martin and Dobry 1994). This is a typical rock site for the western United States. The Toro et al. (1997) attenuation relations for hard-rock sites in the CEUS were adjusted to the B-C site by using amplification factors derived from a hypothesized velocity profile (see Frankel et al. 1996). The variability of ground motion is included in the hazard calculation.

SAMPLE MAPS

Figure 8 shows the two seismic hazard maps for the contiguous United States used in the '97 NEHRP Provisions: spectral accelerations at 0.2 and 1.0 sec periods with 2% PE in 50

<table>
<thead>
<tr>
<th>Hazard Model for Alaska</th>
</tr>
</thead>
<tbody>
<tr>
<td>M = 7.0</td>
</tr>
<tr>
<td><strong>Spatially Smoothed Seismicity</strong></td>
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<tr>
<td>Shallow Earthquakes (0-50 km)</td>
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<tr>
<td>5.0 = M = 7.3</td>
</tr>
<tr>
<td>Deeper Earthquakes (50-80 km)</td>
</tr>
<tr>
<td>5.0 = M = 7.0</td>
</tr>
<tr>
<td>Deepest Earthquakes (80-120 km)</td>
</tr>
<tr>
<td>5.0 = M = 7.0</td>
</tr>
<tr>
<td>Megathrust source zones</td>
</tr>
<tr>
<td>5.0 = M = 7.0</td>
</tr>
</tbody>
</table>

*An upper limit of magnitude 7.3 was adopted for the shallow earthquakes to accommodate the possible occurrence of a background earthquake of that magnitude.*

(a) Components of Hawaii Seismic-Hazard Maps

1. Area source zones on the flanks of active volcanoes (Big Island)  
   - southeast: SFL, KAO, HLE  
   - Kona: KON, HUA  
   - Finite rupture zones for M = 6.5  
   - M5.0-6.2 southeast zones  
   - M5.0-7.0 Kona zones

2. Area source zones for Kilauea caldera and rift zones  
   - CAL, KHZ, ERZ  
   - M5.0-6.5

3. Spatially smoothed shallow seismicity with variable b-value  
   (area in and around Big Island not in 1 and 2)  
   - M5.0-7.0

4. Spatially smoothed deeper seismicity with variable b-value  
   - M5.0-6.5

5. (a) NW source zone with ramped a-value (0.5 weight)  
   (b) Spatially smoothed seismicity NW of Big Island with ramped a-value zone west of Kauai (0.5 weight)  
   - M5.0-7.0

Figure 6. Methodology used for (a) Alaska hazard maps and (b) Hawaii maps.
Attenuation Relations

Firm-Rock Site Condition (Vs 30m = 760 m/sec; NEHRP BC)

Western United States

Crustal EQ's
2. Sadigh et al. (1997)
3. Campbell (1997) (just for PGA)

Subduction Zone EQ's
1. Youngs et al. (1997)

Deep, intra-slab EQ's
1. Youngs et al. (1997)

Central and Eastern United States

1. Toro et al. (1997)
2. Frankel et al. (1996)

Figure 7. Attenuation relations used in the national maps.

years. Areas of high hazard reflect regions with high historic or pre-historic seismicity and/or areas with active faulting. The highest hazard in the conterminous United States is along the San Andreas Fault-plate boundary region of California. High hazard areas include the coast of the Pacific Northwest, the Puget Sound lowlands, eastern California, western Nevada, and the intermountain seismic belt extending from southern Nevada, through Utah and the Salt Lake City area, and continuing through western Nevada into the Yellowstone area and western Montana and central Idaho. In the central and eastern United States, the highest hazard areas are New Madrid, and Charleston, South Carolina, which have a record of historic and pre-historic large earthquakes. Areas of moderate hazard in the CEUS include eastern Tennessee and the northeastern United States. The smoothed appearance of the 1.0 sec maps in the CEUS is the result of the very low attenuation in the CEUS for 1.0 sec period. Earthquakes at hundreds of kilometers distance have significant contributions to the long-period (1.0 sec) hazard for a site in the CEUS. This is not the case for the WUS, where the attenuation of seismic waves with distance is much more severe. Distant earthquakes can dominate the hazard at long period in the CEUS for areas of low seismicity.

The highest hazard in Alaska (Figure 9) is along the Aleutian-Alaska megathrust, although high hazard is also found along the crustal faults in the interior of Alaska and along the southeast portion of the state (see also Wesson et al. 1999 a, b).

The highest hazard in the state of Hawaii (Figure 10) is along the southeastern coast of the Big Island, which has repeated large earthquakes, high seismicity levels, and high deformation rates. The seismic hazard generally decreases as one proceeds westward to the other islands (see also Klein et al. 1999a, b).
Figure 9. Seismic hazard maps for Alaska for spectral accelerations at 0.2 and 1.0 sec for 2% PE in 50 years (from Wesson et al., 1998).

Figure 8 (continued). Seismic hazard map of the continental United States for 1.0 sec spectral acceleration and 2% PE in 50 years.

Firm Rock - 76% increase shear wave velocity with 5% probability of exceedance in 50 years.

Horizontal spectral response acceleration (g/g) for 1.0 sec period (5% of critical damping).

2 IUGS CREPS February 1996
1 IUGS CREPS October 1989
U.S. Geological Survey
Earthquake Hazards Mapping Project
Estimates of uncertainties for CEUS cities were published in Frankel et al. (1997c). Cramer et al. (1996) conducted an uncertainty analysis for their earlier CDMG hazard maps for southern California.

**DISAGGREGATION OF HAZARD**

Since the probabilistic hazard is the sum of hazard from a variety of source locations, it is often difficult to associate the hazard to specific potential earthquakes. Following McGuire (1996), we have disaggregated the hazard to examine the contribution to the hazard as a function of magnitude and distance. These plots can be useful for specifying design earthquakes from a probabilistic analysis. We show some disaggregation plots for New York City and Chicago in Figure 11. The height of each bar on these plots represents the percent contribution of that magnitude and distance bin to the annual rate of exceeding the ground motion corresponding to the specified probability level (e.g., 10% PE in 50 years). The total probabilistic hazard (annual frequency of exceedance) is the sum of the hazard over all of these magnitude-distance bins.

The disaggregation plot for New York City (Figure 11) for 0.2 sec SA shows that most of the hazard is from close-in (<100 km distance) smaller earthquakes (M< 6.5). For 1.0 sec SA, more distant and larger events are important to the hazard estimate. In general, as the period of the SA is increased, larger, more distant earthquakes have more contribution to the hazard at a site. The disaggregation plots for Chicago (Figure 11) show two overall peaks: one for nearby smaller earthquakes and one for M8.0 earthquakes in New Madrid at about 550 km distance. The New Madrid events clearly dominate the hazard at 1.0 sec SA for Chicago. For 0.2 sec SA (2% PE in 50 years), the hazard at Chicago is dominated by close-in smaller earthquakes, with the New Madrid events having a smaller relative contribution than at 1.0 sec.

Figure 12 displays the disaggregation plots for Los Angeles and Seattle for 1.0 sec spectral acceleration with 10% PE in 50 years. For Los Angeles (near City Hall), the hazard is dominated by close-in faults such as the Elysian Park blind thrust, the Newport-Inglewood fault, the Hollywood fault, the Palos Verdes fault, and the Sierra Madre fault. The San Andreas fault (M7.8) at a nearest distance of 55 km is a smaller, but still significant contributor to the hazard at this period and PE. For Seattle, much of the hazard is from the nearby Seattle fault. The intra-slab seismicity constitutes about 18% of the hazard. The disaggregation plot also shows that the great Cascadia subduction earthquakes (M8.3 and 9.0) are a significant portion of the hazard for 1.0 sec SA to Seattle. Tables and maps of the disaggregation results for 100 cities are available on our website. Further discussion of the method and results for the CEUS disaggregation can be found in Harmsen et al. (1999).

**CONCLUSIONS**

The new national seismic hazard maps are scientifically defensible characterizations of the hazard from earthquake ground shaking that have undergone extensive review and scrutiny. Therefore, these maps are suitable as the basis of design maps for building codes as well as for other applications such as loss estimation and emergency planning. The availability of the new national seismic hazard maps and associated products presents a unique opportunity to better understand the regional factors that control the seismic hazard in the United States.
Figure 11. Disaggregation plots for New York City and Chicago, for various periods and PE. Height of bars represents percent contribution to hazard (annual rate of exceedance) for that magnitude-distance bin. Magnitude is given as moment magnitude. Shading on bars indicates contribution to hazard as function of the standard deviation of ground motion above or below the median value for that magnitude and distance. Lightest shade (at top of bars) is greater than two standard deviations above the median value, next darkest shade is 1 to 2 standard deviations, then 0 to 1 standard deviation.

Figure 12. Disaggregation plots for Los Angeles and Seattle.

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REFERENCES CITED


