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NUMERICAL EARTHQUAKE GROUND MOTION MODELING AND ITS USE IN MICROZONATION

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ABSTRACT

Numerical modeling increasingly has been used in the United States to estimate strong ground motions in seismic hazard evaluations and in developing seismic design criteria for critical facilities. This approach has been motivated by the need to incorporate region- and site-specific seismic source, path, and site effects into ground motion predictions, particularly in regions where there is an absence or paucity of strong motion data. Recently, we have developed and used in seismic hazard analyses, attenuation relationships based on a stochastic numerical ground motion modeling technique. The methodology utilizes the Band-Limited-White-Noise seismic source model coupled with random vibration theory and an equivalent-linear site response approach. Combining these stochastic relationships with empirical attenuation relationships, we have developed microzonation maps to depict probabilistic peak ground motions. A case history, that of the Idaho National Engineering Laboratory in eastern Idaho, is presented to illustrate our approach and the unique issues which can be addressed in developing truly region- and area-specific microzonation maps.

KEYWORDS

Earthquakes; ground motions; numerical modeling; microzonation; attenuation.

INTRODUCTION

Within the past decade in the United States, numerical modeling increasingly has been used to estimate strong ground motions for engineering applications. Specifically, since 1988 we have used a stochastic ground motion methodology to aid in developing seismic design criteria for several large facility complexes for the U.S. Department of Energy (DOE) including the Los Alamos National Laboratory in northern New Mexico (Wong *et al.*, 1995a), the Idaho National Engineering Laboratory (INEL) in eastern Idaho (Wong *et al.*, 1993), the Savannah River Laboratory in South Carolina (Youngs *et al.*, 1991) and the proposed underground high-level nuclear waste repository at Yucca Mountain, Nevada (TRW, 1994). This approach has been particularly valuable at these facilities because they are located in areas where strong motion data are lacking.

The traditional approach of estimating ground motions relies on empirically-based attenuation relationships which are strongly anchored to California where the vast majority of strong motion records have their origin. Numerical ground motion modeling, when calibrated against available strong motion data, provides a powerful tool allowing for the incorporation of seismic source, path, and site parameters which may be unique to the specific region and site of interest. Because concerted efforts are underway in many parts of the U.S. to evaluate and mitigate for seismic hazards where strong motion data are not available, the need for numerical modeling will become increasingly more important.

In this paper, we describe the use of numerical modeling in the development of probabilistically-based seismic hazard maps. The application described herein, that of the Idaho National Engineering Laboratory, is at a local scale and thus the resulting maps can be considered microzonation maps. Deterministic seismic hazard maps can also be developed but probabilistic maps have been the preferred basis for hazard assessment in the U.S. since the mid-1970's and for use in building codes such as the Uniform Building Code

APPROACH

Stochastic Ground Motion Methodology

The stochastic ground motion methodology used in our studies is based on the Band-Limited-White-Noise (BLWN) source model coupled with random vibration theory (RVT). This model, first developed by Hanks and McGuire (1981), assumes a point source with energy distributed randomly over the duration of the source. The model uses an ω^{-2} Brune source model with a single corner frequency and a constant-stress parameter (Boore, 1983) (Figure 1). Source scaling is provided by specifying two independent parameters, M_0 and the high-frequency stress parameter ($\Delta\sigma$). The stress parameter, which has a source spectrum consistent with a single-corner-frequency ω^{-2} model, is the stress drop of the earthquake. The parameter kappa (κ), which is contained in P(f) is attributed to attenuation in the very shallow crust beneath the site (Figure 1). For a typical western North American rock site, values range from 0.02 to 0.06 sec (Silva and Darragh, 1995). In order to compute peak time-domain values, i.e., peak acceleration, peak particle velocity, and peak oscillator response, RVT is used to relate rms calculations to peak value estimates. A complete description of the BLWN-RVT methodology can be found in Silva (1993) and Schneider *et al.* (1993).

Based on the BLWN-RVT approach, attenuation relationships for peak horizontal acceleration (or other peak motions) can be developed (Silva and Wong, 1994). Incorporating various source, path, and site parameters, site-specific relationships can be developed for use in hazard analyses. Point-source ground motions are simulated for a range of magnitudes and source-to-site distances. The simulations are performed using a magnitude-dependent distribution of point-source depth and a distribution of stress drops to represent the randomness in ground motions from earthquake to earthquake.

The parameters Q_0 and κ can be treated as uncertain variables in the seismic hazard model and hence, attenuation relationships are developed for a given site for the alternative Q_0 and κ values. Because a single value of Q_0 should be appropriate for estimating ground motions in the region, the choice of Q_0 is treated explicitly in the hazard model logic tree (see following discussion). Similarly, it is believed that a single value of κ is appropriate for a given site. Uncertainty in κ for a site can be modeled by considering a best estimate value and values that are ± a factor of two. Thus, nine different stochastic relationships can be developed for a given site.

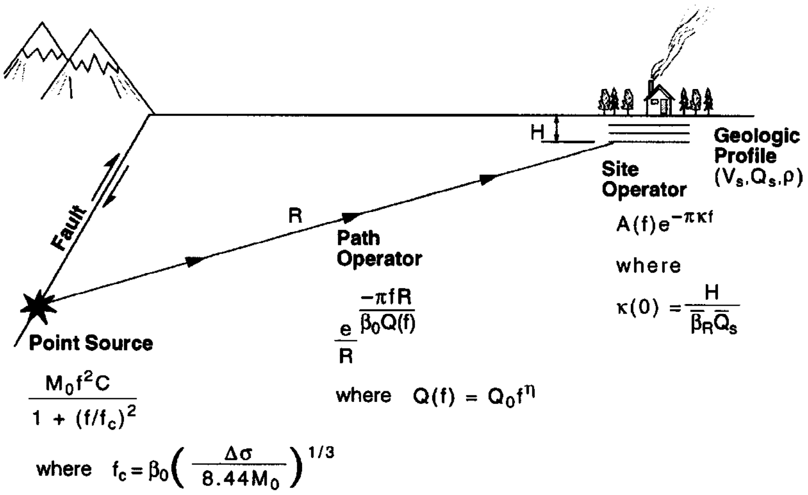

Figure 1. Schematic of the Point-Source BLWN-RVT Ground Motion Methodology.

Attenuation relationships for peak ground acceleration and peak spectral accelerations are obtained by fitting the point source simulations with the functional form

$$\ln(Y) = C_1 + C_2(M-6) + C_3(M-6)^2 + C_4\ln(R') + C_6R \qquad \text{for } R' \leq 90 \text{ km}$$
$$\ln(Y) = C_1 + C_2(M-6) + C_3(M-6)^2 + C_4\ln(90) + C_5\ln(R'/90) + C_6R \quad \text{for } R' > 90 \text{ km}$$
$$R' = R + \exp(C_7 + C_8M)$$

where Y is the peak ground motion parameter, M is moment magnitude (M_w), R is the shortest distance to the surface projection of rupture (similar to the Joyner and Boore [1982] empirical attenuation model), and C_1 through C_8 are parameters fit to the data.

The standard error associated with each attenuation relationship is specified by combining the standard error generated by the random depths and stress drops with the modeling uncertainty. The standard error is computed for distances less than 10 km, where the effect of random depth is the largest, and for distances greater than 10 km. As with any numerical modeling approach, a proper statistical estimate of the modeling uncertainty should be made. The modeling error associated with the BLWN-RVT approach has been computed based on the 1989 Loma Prieta earthquake (Schneider *et al.*, 1993) and was used in this analysis.

Probabilistic Seismic Hazard Analysis

The methodology used to compute the probabilistic peak accelerations follows the approach developed by Cornell (1968). Seismic hazard is a function of the location and geometry of potential sources of future earthquakes, the frequency of occurrence of various size earthquakes on these sources, and the characteristics of seismic wave propagation in the region. The seismic hazard model consists of two basic components: a model of the sources of potential future earthquakes and a model of the effects of future earthquakes at specific sites. The methodology provides for the explicit inclusion of the range of possible interpretations in components of the model including seismic source characterization and ground motion estimation. Uncertainties in models and parameters are incorporated into the hazard analysis though the use of logic trees.

CASE HISTORY - INEL

The INEL is located near the northwestern margin of the Eastern Snake River Plain (ESRP) in southeastern Idaho (Figure 2). The ESRP is a northeast-trending, topographically-subdued physiographic province that is bordered on the northwest and southeast by the Basin and Range province and on the northeast by the Yellowstone Plateau. The Intermountain seismic belt (ISB), a major zone of seismicity in the western United States, and the Centennial Tectonic Belt, an east-west-trending seismic zone, which may be part of the ISB, wrap around the southeastern, eastern, northern and northwestern sides of the ESRP. Portions of the ISB exhibit geologic evidence for repeated episodes of late-Quaternary surface rupture associated with predominantly normal-faulting earthquakes of M_w 7 and greater (Smith and Arabasz, 1991). The largest historical earthquake within the ISB was the 1959 M_w 7.3 Hebgen Lake, Montana earthquake. The Centennial Tectonic Belt includes the epicentral area of the 1983 M_w 6.8 Borah Peak, Idaho earthquake.

As part of an ongoing seismic hazards program, a series of probabilistic seismic hazard maps were developed for the INEL (Wong *et al.*, 1995b). These maps display peak horizontal accelerations on rock for four annual exceedance probabilities (or return periods) corresponding to four DOE Performance Categories: (1) General Use - $2x10^{-3}$(500 years); (2) Low Hazard - $1x10^{-3}$ (1,000 years); (3) Moderate Hazard - $5x10^{-4}$(2,000 years); and (4) High Hazard - $1x10^{-4}$ (10,000 years).

Seismic Sources

Seismic sources that contribute to the probabilistic seismic hazard at the INEL include fault sources, volcanic rift zones, and regional seismic source zones (Wong *et al.*, 1995b). The fault sources are the three closest Basin and Range faults to the INEL: the Lemhi, Lost River, and Beaverhead faults (Figure 2). Each fault is modeled by parameters that define its three-dimensional geometry, maximum earthquake magnitude, and earthquake recurrence rate. Recent studies of the southern Lemhi and Lost River faults were used to develop interpretations of the location of the southern termination of each fault, fault dip, timing and extent of prehistoric ruptures, fault segmentation, maximum magnitude, slip rate, earthquake recurrence intervals, and temporal clustering of earthquake activity (Wong *et al.*, 1995b). All three faults are composed of six segments. The Thousand Springs and part of the Warm Spring segments, in the central part of the Lost River fault zone, ruptured during the 1983 Borah Peak earthquake. The magnitude of the maximum earthquake for each fault segment was determined using the empirical relations of Wells and Coppersmith (1994) for rupture length, area, and displacement, where data on the latter were available. Preferred values ranged from M_w 6 3/4 to 7 for all three faults. Slip rates ranged from 0.02 to 1 mm/yr. Based on paleoseismic evidence for temporal clustering of events, recurrence intervals ranged widely from 500 to 40,000 years for the Lost River fault and 2,000 to 35,000 years for the Lemhi fault.

Volcanic rift zones were modeled as seismic source zones that incorporate potential seismicity associated with dike emplacement (Wong *et al.*, 1993). Earthquake recurrence rates were estimated based on the frequency of eruptive episodes within each of the rift zones. Their geometries and maximum magnitude estimates incorporate worldwide observations of volcanic rift zones, as well as site-specific observations within the ESRP. The maximum magnitude assigned to the volcanic rift zones was M_w 5 ± 1/2 .

Several regional seismic source zones are also included in the probabilistic analysis, the most important of which are the ESRP and the northern Basin and Range province. Source zones are areal source regions and earthquakes are assumed to occur randomly within them. Because more distant faults are less significant to the INEL seismic hazard, they are incorporated into the areal source zones rather than modeled as discrete faults. The areal source zones are characterized by their maximum magnitude, earthquake depth distribution, and recurrence. The

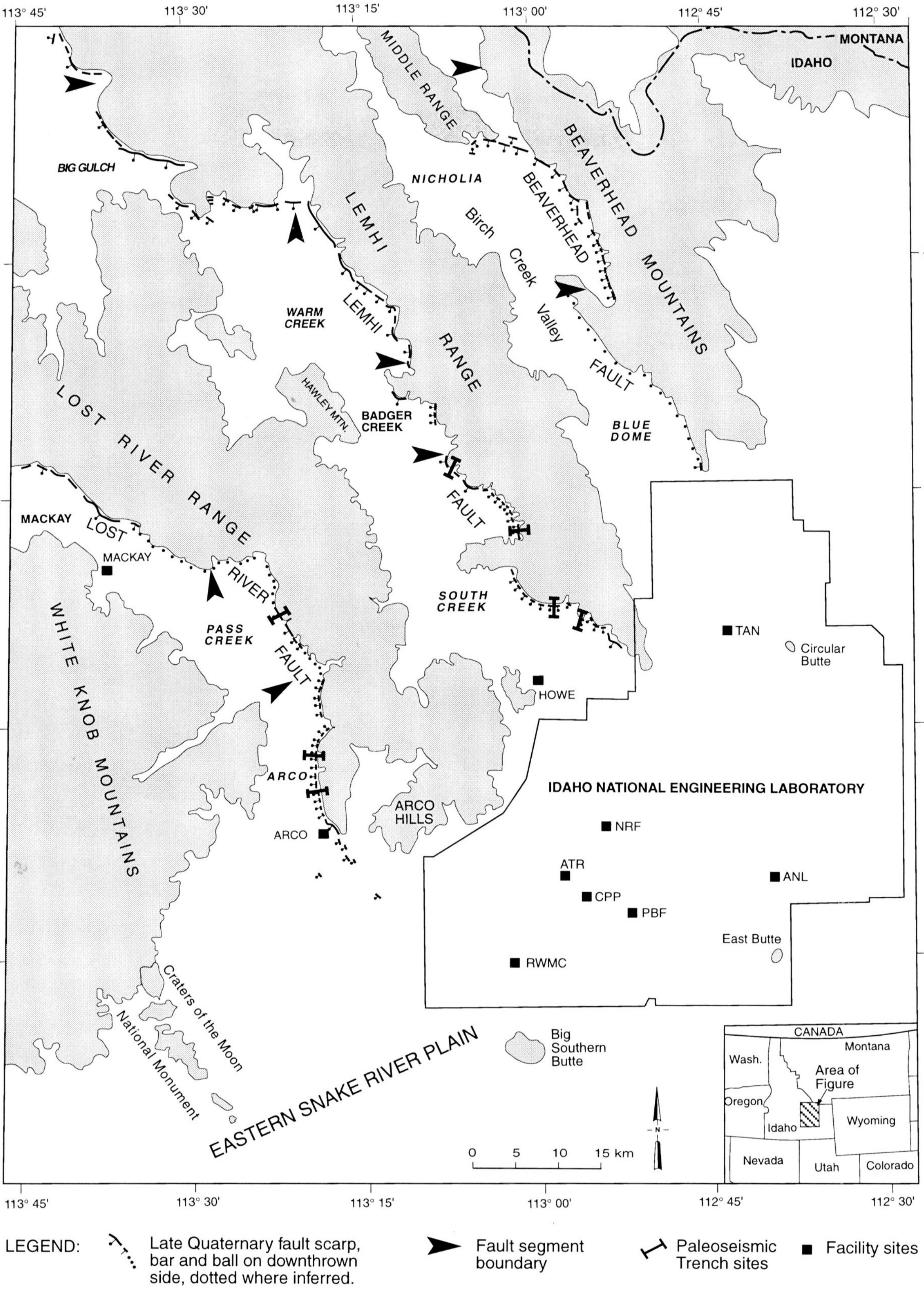

Figure 2. Late Quaternary Faults and Facility Sites at the INEL.

historical earthquake catalogue, with dependent events removed and corrected for incompleteness, provides the basis for estimating recurrence rates within these source zones.

Path Effects

The seismic attenuation along the path from source to site is parameterized in the model by Q_o and η. Based on an inversion of regional earthquakes and Borah Peak aftershocks, a Q(f) of $220f^{046}$ was calculated and used in our analysis (Wong *et al.*, 1995b). Lower and upper-bound values of 100 and 670, respectively, were also considered to incorporate the uncertainty in Q_0. A half-space shear wave velocity of 3.55 km/sec and density of 2.7 g/cm^3 were assumed appropriate for the path between the bottom of the site profiles and the earthquake source based on the available data on crustal structure.

Site Effects

The subsurface geology at a site influences the ground motions in two ways. A gradient of increasing velocity with depth amplifies motions, while material damping reduces the motions. INEL was subdivided into nine areas based primarily on the known surface geology and available borehole data (Wong *et al.*, 1995b) (Figure 3). The volcanic stratigraphy beneath the INEL, which consists of alternating basalt and sedimentary interbeds in the top approximately 1 km over welded and unwelded tuffs, appears to be capable of strongly affecting ground motions. For each area, a generalized geologic and shear-wave velocity profile was developed using available borehole data and a limited amount of *in situ* geophysical and velocity measurements. In our model, the near-surface damping is parameterized by κ and the amplification is modeled by propagation through a site-specific velocity profile. The inversion of regional earthquakes and Borah Peak aftershocks discussed above also provided estimates of κ for each of the nine areas. They ranged from 0.01 to 0.03 sec.

Attenuation Relationships

Based on the previously described parameters, nine stochastically-based, area-specific attenuation relationships were developed. Point-source estimates of ground motions were calculated for a range of relevant magnitudes and distances upon which the stochastic site-specific attenuation relationships were derived. Ground motions were calculated for M_w 5, 6, 7, and 7 1/2 and for each area-specific velocity profile varying stress drop, κ, Q_0, and point-source focal depth in a total of 50 runs each. For other magnitudes, peak values can be interpolated from these four equations. The range of stress drops considered in the analysis was 25 to 150 bars. Our preferred value of about 75 bars is based on an analysis of stress drops for Basin and Range normal faulting earthquakes (Stark *et al.*, 1992). The magnitude-dependent focal depth distributions were based on instrumental observations of contemporary seismicity in the Basin and Range province. The epicentral distances considered in developing the stochastic attenuation relationships ranged from 0 to 200 km. Ground shaking from seismic sources beyond 200 km is generally insignificant to any site in the western U.S.

In addition to the nine stochastic attenuation relationships, three empirical rock relationships based on western U.S. strong motion data were utilized including Joyner and Boore (1988), Idriss (1991) and Sadigh *et al.* (1993). The empirical and stochastic relationships were weighted 0.40 and 0.60, respectively, and used together in the hazard analysis. Comparison of the stochastic and empirical relationships indicates that the near-surface geology at the INEL, as incorporated in the former, generally attenuates ground motions at frequencies of about 1 to 20 Hz.

A grid of approximately 400 nodes at approximately 2.5 x 2.5 km spacing was defined to produce the hazard maps for the INEL. Each node was assigned to one of the nine geologic areas with its associated stochastic attenuation relationship. For each node, peak horizontal acceleration values were calculated based on the probabilistic seismic hazard analysis and the values were contoured and smoothed. The hazard map for an approximate 500-year return period (10% exceedance in 50 years) shows the contours of peak acceleration increasing in value from the southeast to the northwest (Figure 4). This increase is due to the hazard at the INEL being dominated by the Basin and Range faults on its northwestern boundary and the northern Basin and Range seismic source zone. Thus, the hazard is lowest in the southeastern corner of the INEL along the axis of the generally aseismic ESRP and highest in areas adjacent to the faults.

SUMMARY

Based on the BLWN-RVT numerical ground motion modeling technique, microzonation maps can now be developed which truly incorporate region- and site-specific information on earthquake sources and path and site effects. These parameters can be directly accounted for in stochastic attenuation relationships which are used in probabilistic (or deterministic) seismic hazard analysis. As in site-specific seismic hazard analyses, numerical techniques are most useful in areas where strong motion data are sparse or absent. In our applications, we have been able to incorporate: (1) crustal attenuation Q(f); (2) regionally-appropriate earthquake focal depths and stress drops; (3) crustal velocity structure; and (4) near-surface geology characterized by detailed seismic velocity profiles, near-surface attenuation (κ), and dynamic soil properties. Future applications of our approach include development of microzonation maps for the Portland, Oregon, metropolitan area and the Albuquerque-Santa Fe, New Mexico urban corridor.

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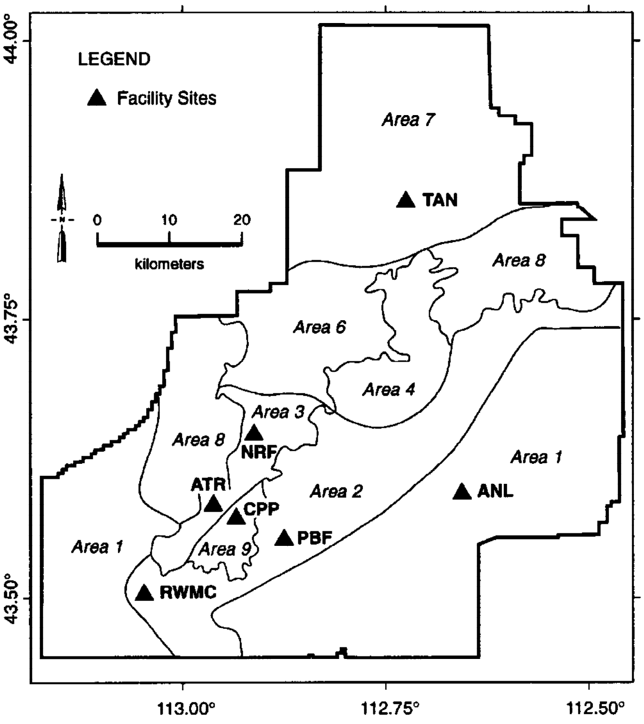

Figure 3. Location Map of the INEL Facility Sites and Geologic Areas.

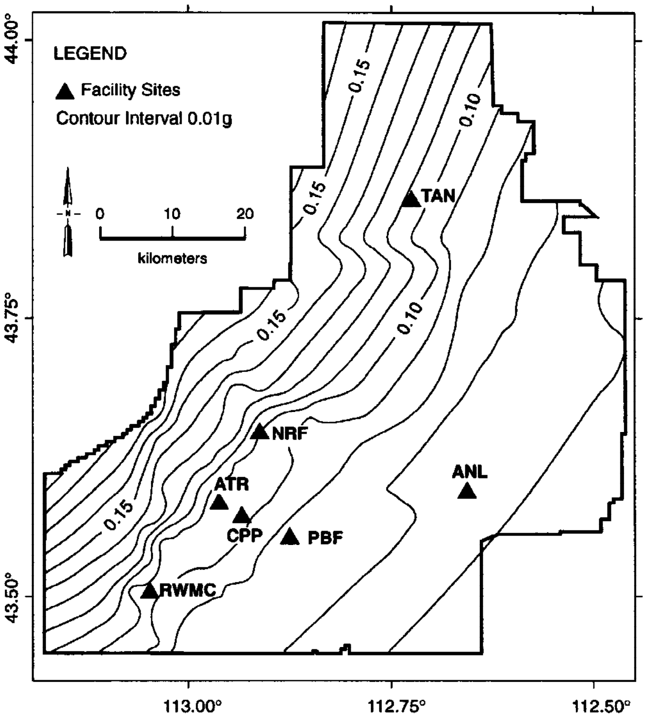

Figure 4. Probabilistic Seismic Hazard Map for the INEL – Peak Horizontal Acceleration at a Return Period of 500 years.

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