ADDRESSING EARTHQUAKE STRONG GROUND MOTION ISSUES AT THE IDAHO NATIONAL ENGINEERING LABORATORY

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ABSTRACT

In the course of reassessing seismic hazards at the Idaho National Engineering Laboratory (INEL), several key issues have been raised concerning the effects of the earthquake source and site geology on potential strong ground motions that might be generated by a large earthquake. The design earthquake for the INEL is an approximate moment magnitude (M_w) 7 event that may occur on the southern portion of the Lemhi fault, a Basin and Range normal fault that is located on the northwestern boundary of the eastern Snake River Plain and the INEL, within 10 to 27 km of several major facilities. Because the locations of these facilities place them at close distances to a large earthquake and generally along strike of the causative fault, the effects of source rupture dynamics (e.g., directivity) could be critical in enhancing potential ground shaking at the INEL. An additional source issue that has been addressed is the value of stress drop to use in ground motion predictions. In terms of site geology, it has been questioned whether the interbedded volcanic stratigraphy beneath the ESRP and the INEL attenuates ground motions to a greater degree than a typical rock site in the western U.S. These three issues have been investigated employing a stochastic ground motion methodology which incorporates the Band-Limited-White-Noise source model for both a point source and finite fault, random vibration theory and an equivalent linear approach to model soil response.

INTRODUCTION

Since 1988, efforts have been underway to reexamine the seismic safety of existing facilities at the Idaho National Engineering Laboratory (INEL). In large part, this increased attention to seismic hazards is due to the occurrence of the 1983 surface wave magnitude M_s 7.3 (moment magnitude M_w 6.8) Borah Peak earthquake which occurred approximately 100 km away. The INEL is located along the northwestern margin of the eastern Snake River Plain (ESRP) adjacent to three major Basin-and-Range normal faults including the Lost River fault which was the source of the 1983 earthquake (Figure 1). The fault of most significance to the INEL is the Lemhi fault which appears to have ruptured along its two southernmost segments two to three times in the interval 15,000 to 25,000 years B.P. [1, 2]. Because most of the facilities at the INEL are within 10 to 25 km of the southern end of the fault, an accurate assessment of potential strong ground shaking is imperative.

Deterministic strong ground motion modeling of a potential M_w 6.9 southern Lemhi fault earthquake has been recently performed employing a stochastic methodology which incorporates the Band-Limited-White-Noise (BLWN) source model for both a point source and a finite fault, random vibration theory (RVT) and an equivalent linear approach to model soil response [3, 4]. In the course of these studies, three key issues have been raised concerning the effects of the earthquake source and site geology on strong ground motions. The effects of propagation path on the seismic waves (e.g. attenuation), the third of the three categories of ground motion factors (source, path and site; Figure 2) are not significant at the INEL when considering the design earthquake because of the short source-to-site distances.

The first issue focuses on the effects of rupture dynamics on ground motions. Because most of the facilities at the INEL are in the near-field of a potential southern Lemhi fault earthquake and generally along strike of the fault, rupture directivity may be significant. Enhanced ground motions due to directivity have been observed in several California earthquakes.

An additional source issue is the appropriate value of the stress parameter (as defined by Boore [5]) to use in modeling a potential Lemhi earthquake and the relationship between the stress parameter and the measurable quantity, stress drop. (Ground motions increase with increasing stress parameter or stress drop.) Stress drops for earthquakes occurring within the extensional western U.S. appear to have generally smaller values than for earthquakes in the compressional regimes along the plate boundary in California and in the eastern U.S. In fact, this difference may account for the possible observation that earthquake ground motions in extensional regimes, such as the Basin and Range Province, are smaller than in compressional regimes (e.g., [6]) possibly because the stress drops of normal-faulting earthquakes are smaller.

In terms of the site geology, it has been suggested that the interbedded basalts and welded tuffs beneath the ESRP and the INEL attenuate ground motions compared to a typical rock site in the western U.S. The effects of damping within the unconsolidated to weakly consolidated sedimentary interbeds and scattering may be factors unique to the ESRP. How these three issues were addressed and evaluated is discussed in the following paper.

SCOPE OF WORK

A program of strong ground motion studies for the INEL was initiated in late-1988 [3, 7, 8]. The specific objectives of these studies were to: 1) provide site-specific estimates of peak horizontal ground acceleration and response spectra for nine existing or proposed facility sites located on soil and/or bedrock; 2) record local and regional earthquakes at selected sites using portable digital seismographs; and 3) process and analyze the data recorded by the survey to evaluate local site response and seismic attenuation along the propagation path and in the very shallow crust.

In the past, ground motion evaluations for the INEL have been empirical in nature, restricted to the use of data from earthquakes occurring in other regions worldwide. This was due to the lack of recorded strong ground motion data for large magnitude events at distances less than 90 km at the INEL, or for that matter, the intermountain U.S. For this reason and because of the uncertainties regarding propagation path and site response effects on ground motions (Figure 2), site-specific strong ground motion modeling was performed and parameters for the INEL were estimated for seismic safety analyses.

APPROACH

The BLWN ground motion model first developed by Hanks and McGuire [9] in which the energy is distributed randomly over the duration of the source has proven remarkably effective in correlating with a wide range of ground motion observations [9, 5, 10, 11, 12]. The BLWN model incorporates the general characteristics of the source and wave propagation as well as site effects. The model is appropriate for an engineering characterization of ground motion since it captures the general features of strong ground motion in terms of peak acceleration and spectral composition with a minimum of free parameters.

The ground motion model assumes an ω^{-2} Brune

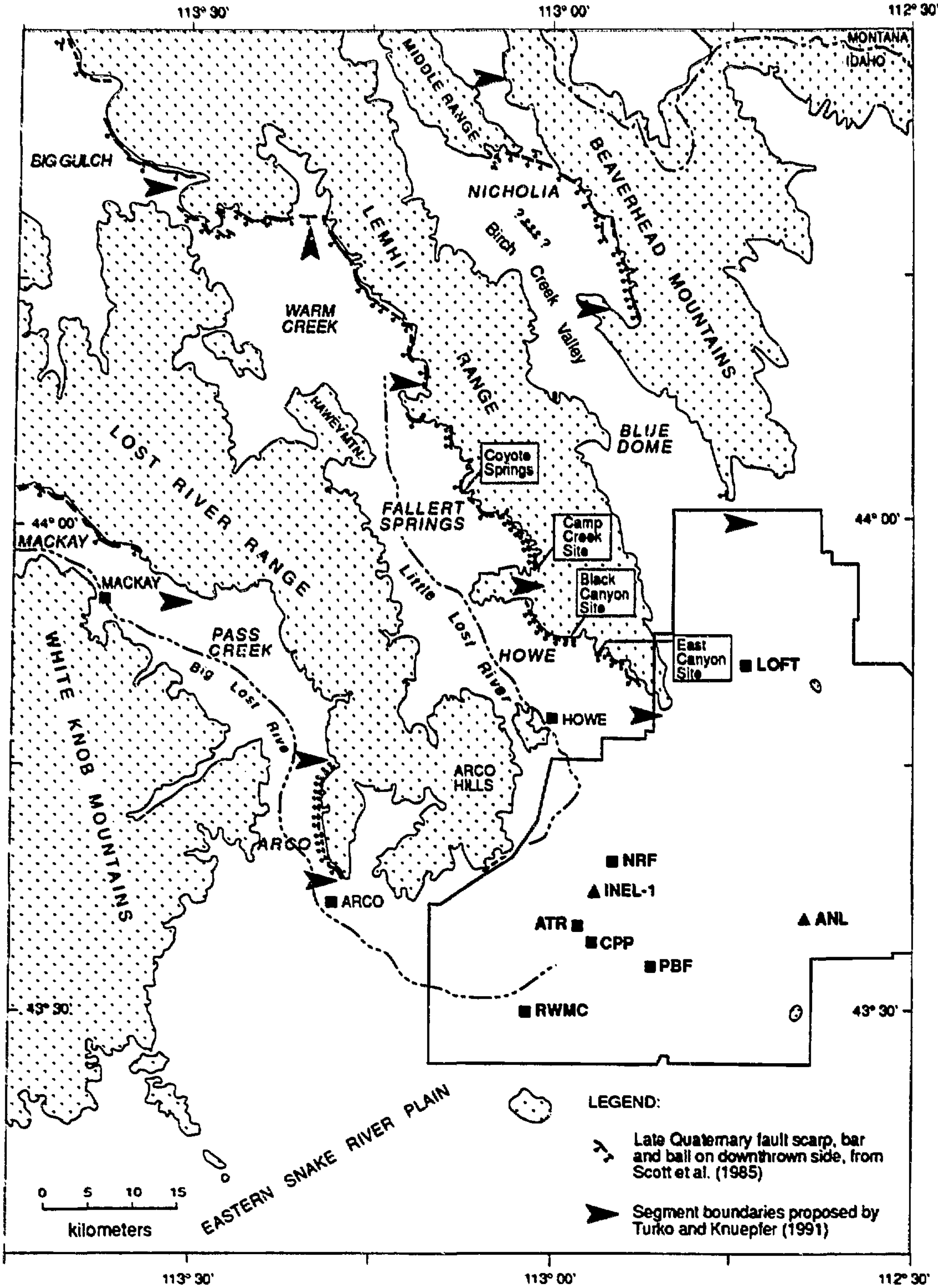

Figure 1. LOST RIVER, LEMHI AND BEAVERHEAD FAULTS ADJACENT TO THE INEL. ALSO SHOWN ARE PALEOSEISMIC TRENCH SITES INVESTIGATED ALONG THE SOUTHERN LEMHI FAULT [1, 2].

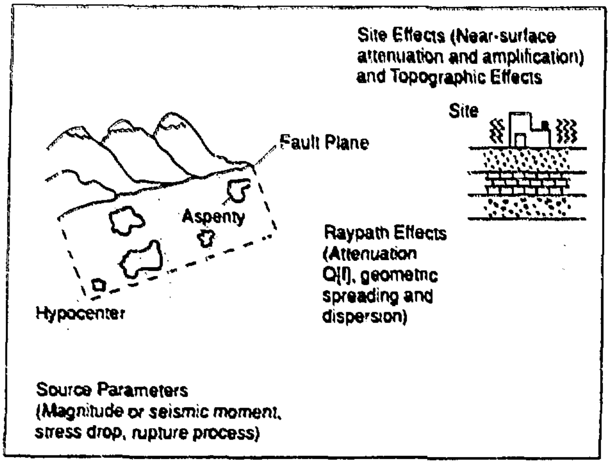

Figure 2. SOURCE, RAY PATH, AND SITE EFFECTS ON GROUND MOTIONS.

source model with a single-corner frequency and a constant-stress parameter [5]. RVT is used to relate rms (root-mean-square) values of acceleration and oscillator response computed from the power spectra to expected peak time domain values. Details of the methodology are described in WCC [3]. The observation that acceleration spectral density falls off rapidly beyond some region-dependent maximum frequency is incorporated in the form of $e^{-\pi\kappa(r)f}$ where r is the epicentral distance and $\kappa(r)$ is a distance-dependent damping factor following the Anderson and Hough [13] attenuation model. This observed phenomenon truncates the high frequency portion of the spectrum and is responsible for the band-limited nature of the stochastic model. At $r = 0$, κ represents the intrinsic energy attenuation in the shallow crust beneath the site [14]. Q(f), the frequency-dependent portion of the attenuation along the raypath, is also incorporated into the model. It takes the form of $Q(f) = Q_0(f/f_0)^{\eta}$ where Q_0 is the reference value at frequency f_0.

The original stochastic methodology assumed a point source (e.g., [11]). Recently, the modeling of a finite fault has been combined with the BLWN-RVT methodology [15]. The BLWN source model is used to generate ω^{-2} sources in lieu of spectra from small earthquakes (or Green's functions) in the summation of the finite source.

ISSUES AND RESULTS

The stochastic ground motion approach was used to model a potential M_w 6.9 earthquake occurring on the southern portion of the Lemhi fault (Figure 1). The magnitude of the design earthquake is consistent with the possibility that the two southern segments of the fault, the Howe and Fallerts Springs segments, could rupture in a single event. A stress parameter of 50 bars was assumed reasonable for such an event [3] (see following discussion). The Lemhi fault was depicted as a 45° southwest-dipping normal fault whose closest approach to facility sites at the INEL ranged from 10 to 27 km. A point source was assumed in the ground motion modeling with the source constrained to the point on the rupture plane closest to each site. It was expected that such a model would provide conservative ground motion values.

Crustal attenuation was described as $Q(f) = 450^{0.2}$ [3]. Site-specific geologic and velocity profiles were developed for each of the sites based on available well data and a 3-km deep exploratory borehole called INEL-1 (Figure 3). Site-specific values of the near-surface attenuation as described by the factor κ were estimated through an analysis of the regional earthquakes recorded by the temporary network [3].

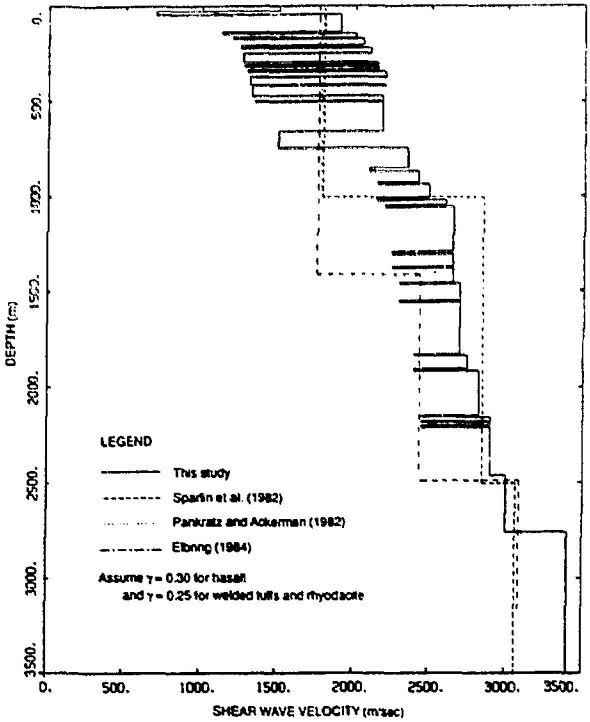

Figure 3. SHEAR-WAVE VELOCITY PROFILE AT THE INEL-1 DRILLHOLE.

Based on these input parameters, acceleration response spectra were computed for each site. Peak horizontal accelerations ranged from 0.09 to 0.40 g at distances of 27 to 10 km, respectively for both rock and soil sites [3]. As a result of this study, three significant issues have been raised concerning the estimated ground motions at the INEL (also in a broader sense, two of the factors affect ground motion predictions for the Intermountain U.S.), and they are discussed in the following.

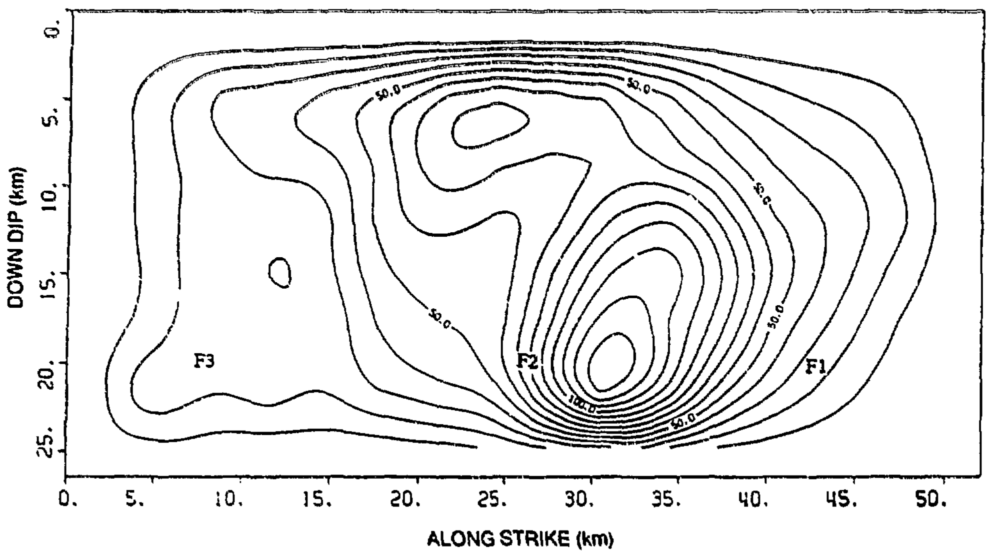

Figure 4. 1983 BORAH PEAK EARTHQUAKE SLIP DISTRIBUTION [19] USED IN FINITE FAULT MODELING FOR THE SOUTHERN LEMHI FAULT EARTHQUAKE. SLIP IS IN CM.

Rupture Directivity

The existence of strong directivity effects in ground motions for frequencies of engineering significance has been controversial. The observation and quantification of directivity is complicated by other competing effects such as the heterogeneous nature of coseismic slip along rupture planes, site response and attenuation [16]. Although directivity has been predominately observed in California strike-slip earthquakes (e.g., 1979 Coyote Lake, 1979 Imperial Valley and 1980 Livermore earthquakes), some recorded ground motions from the 1971 San Fernando earthquake, which was the result of thrust faulting, are also believed to have contained directivity effects.

In the 1983 Borah Peak earthquake, rupture initiated at a depth of 16 km at the southern end of the Lost River fault and proceeded northwestward [17, 18]. Because such unilateral rupture has been observed to result in enhanced ground shaking due to effects of directivity, albeit infrequently, the possibility of directed rupture towards the INEL from an earthquake on the southern Lemhi fault was investigated.

To test this possibility, ground motion modeling of a southern Lemhi fault earthquake using a finite fault rupture model was performed based on the approach of Silva et al. [15]. The slip distribution along the segment of the Lost River fault that ruptured in 1983 as modeled by Mendoza and Hartzell [19] was used (Figure 4). Three rupture initiation points (F1, F2, F3) were assumed to evaluate possible directivity effects. They were located near the southern edge, center and northern edge of the rupture plane, all at depths of 16 km.

Acceleration response spectra were computed for each of the three nucleation points for a site 5 km east of CPP (Figure 1). Figure 5 shows the resulting spectra and peak accelerations [4]. As expected, the ground motions computed for the southern focus (F1) are the lowest, characterized by a peak acceleration of 0.17 g. Interestingly, the center focus (F2), which would result in a bilateral rupture, produces a nearly equivalent peak horizontal acceleration of 0.24 g at the site as unilateral rupture towards the site (F3) (Figure 5). This is probably due to the updip effect of directivity being much more significant for a focus located near the large asperity (areas of relatively larger slip) rather than at the northern end of the fault (Figure 4). For this fault geometry and site location, the directivity amounts to about 40 percent increase in peak acceleration. These results suggest that although directivity can in some situations enhance ground motions from a normal-faulting earthquake, the slip distribution or, more specifically, the locations of asperities may be equally or more significant in controlling the level and spectral content of near-field ground motions.

In most cases, it is doubtful, however, that an a priori knowledge of the slip distribution of most future earthquakes will be available including events near the INEL. Thus the use

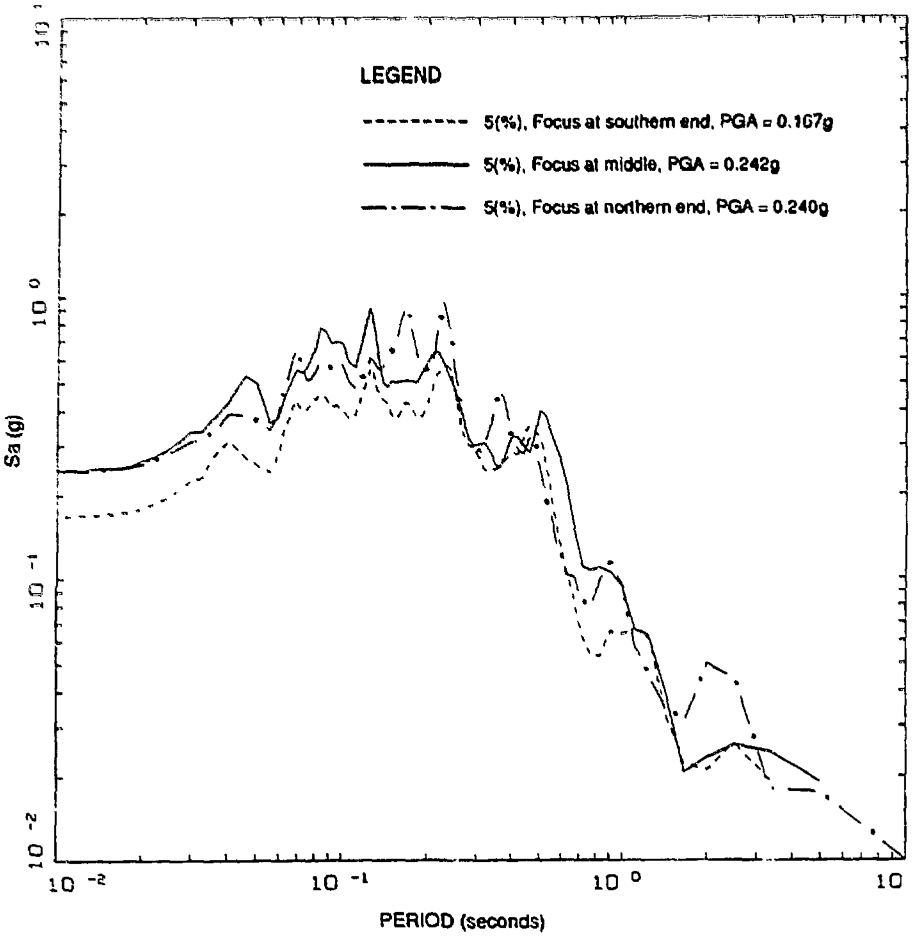

Figure 5. ACCELERATION RESPONSE SPECTRA FROM FINITE FAULT MODELING.

of a randomized slip distribution in ground motion predictions may be more reasonable in a probabilistic sense. The use of conservative slip distributions and rupture scenarios is a reasonable approach for critical facilities.

Earthquake Stress Drops

As has been observed in many studies, the value of the stress parameter used in stochastic modeling is critical in estimating ground motions. Complicating this selection is the uncertainty in what the stress parameter actually is in terms of a physical parameter of the earthquake source (i.e., is the stress parameter simply a scaling factor or is it somehow related to stress drop?).

Boore [5, 20] and Boore and Atkinson [10] have previously found that a stress parameter of 50 bars gives a good predictive fit to a number of strong motion records of western U.S. earthquakes in the range of M_w 5.0 to 7.7 and even subduction zone earthquakes as large as M_w 9.5. According to Boore (USGS, personal communication, 1991), the stress parameter is identical to the stress drop for earthquakes which have a source spectrum consistent with a single-corner-frequency-ω^{-2} model. In this case, the stress drop may be computed by determining the seismic moment, M_0, and corner frequency, f_c, $[\Delta\sigma = 8.44\ M_0\ (f_c/\beta_0)^3]$ and is generally referred to as the Brune stress drop or static stress drop. The root-mean-square (rms) stress drop was introduced by Hanks [21] and is defined as the stress drop required in the single-corner-frequency-ω^2 Brune model to predict observed rms accelerations. Thus a convenient way of assessing the appropriateness of the BLWN source model is to compare Brune stress drops with rms stress drops, both computed from data recorded in the region of interest. The assumption of equivalency between the stress parameter of the stochastic model and Brune or rms stress drops is correct if both the rms and Brune stress drops are equivalent.

Brune and/or rms stress drops were computed for 28 Basin and Range earthquakes including 18 aftershocks [4] and several regional earthquakes recorded by a temporary digital seismographic network installed at the INEL in 1989 [3] (Table 1). The Brune stress drops were calculated using a nonlinear least-squares simultaneous inversion of the Fourier spectra which inverts for six BLWN parameters: $\Delta\sigma$, M_0, $\kappa(0)$, Q_0, η, and A, the frequency-independent site amplification [4]. The rms stress drops were computed utilizing a modified version of the Hanks and McGuire [9] technique which incorporates the BLWN parameters resulting from the inversions [4]. (See Boatwright [22] for an excellent discussion of the various stress drops.)

As has been observed in numerous other studies, stress drops for earthquakes appear to be generally independent of magnitude (Table 1). The log-normal average Brune stress drop for all 28 events is 35 bars. The log-normal average rms stress drop of 21 events is 30 bars. The fact that the Brune and rms stress drops are similar indicates that these events can be modeled as single corner-frequency-ω^{-2} sources. Currently, the 1983 mainshock records are being reprocessed and both Brune and rms stress drops will be computed.

Table 1
BASIN AND RANGE EARTHQUAKE STRESS DROPS

Date	Time (GMT)	Origin Location	Magnitude	Stress Drop (bars) Brune	rms
29 May 89	0349	Centennial Mtns, MT	M_L 3.0	18.2 ± 2.6	--
6 Jun 89	2002	Hebgen Lake, MT	M_L 3.5	19.6 ± 3.2	--
24 Jun 89	0924	Jackson, WY	M_L 3.7	12.8 ± 3.0	--
24 Jun 89	1025	Jackson, WY	M_C 3.6	18.3 ± 3.7	--
27 Jun 89	1551	Hansel Valley, UT	M_L 3.0	45.5 ± 7.4	--
27 Jun 89	1628	Hansel Valley, UT	M_L 2.9	47.6 ± 7.9	--
28 Jun 89	0316	Centennial Valley, MT	M_L 3.1	7.6 ± 1.3	--
29 Oct 83	2329	Borah Peak, ID	M_L 5.8	30.1 ± 54.7	57.2
29 Oct 83	2339	Borah Peak, ID	M_L 5.4	25.7 ± 28.7	32.7
30 Oct 83	0124	Borah Peak, ID	M_L 4.8	61.7 ± 26.6	31.0
30 Oct 83	0159	Borah Peak, ID	M_L 4.7	31.4 ± 14.5	14.9
2 Nov 83	2343	Borah Peak, ID	M_L 4.2	27.4 ± 8.7	52.4
6 Nov 83	2104	Borah Peak, ID	M_L 4.6	43.5 ± 12.6	22.0
29 Oct 83	2113	Borah Peak, ID	M_L 3.3	76.5 ± 13.3	39.4
29 Oct 83	1737	Borah Peak, ID	M_L 3.3	66.2 ± 11.8	22.3
30 Oct 83	0116	Borah Peak, ID	M_L 3.3	57.7 ± 8.8	20.8
30 Oct 83	0254	Borah Peak, ID	M_L 4.0	60.1 ± 13.9	14.0
30 Oct 83	1749	Borah Peak, ID	M_L 3.5	58.4 ± 3.0	29.0
3 Nov 83	0150	Borah Peak, ID	M_L 4.2	66.3 ± 14.9	84.1
4 Nov 83	0500	Borah Peak, ID	M_L 3.5	49.3 ± 7.2	22.6
4 Nov 83	0708	Borah Peak, ID	M_L 3.7	35.2 ± 5.7	15.5
5 Nov 83	0537	Borah Peak, ID	M_L 3.5	55.8 ± 8.5	29.1
5 Nov 83	1736	Borah Peak, ID	M_L 3.8	27.1 ± 5.0	17.5
5 Nov 83	2256	Borah Peak, ID	M_L 3.6	52.8 ± 7.0	18.3
6 Nov 83	2111	Borah Peak, ID	M_L 3.8	42.5 ± 7.1	13.0
30 Sept 62	1335	Cache Valley, UT	M_L 5.6	25.2 ± 5.2	45.4
31 Oct 35	1837	Helena, MT	M_L 6.0	49.3 ± 76.5	62.9
28 Nov 35	1441	Helena, MT	M_L 5.5	101.8 ± 51.6	95.4

Although, in practice, average static stress drops calculated from the fault rupture dimensions and seismic moment ($\Delta\sigma = 8 M_o/3\pi w^2 L$) are often uncorrelatable with Brune stress drops due to the uncertainties in estimating rupture dimensions [22], it is instructive to examine static stress drops for other Basin and Range earthquakes. A static stress drop of 17 bars has been determined by Boatwright and Choy [23] for the 1983 Borah Peak earthquake based on the maximum fault displacement ($\bar{u}$) of 2 m and a total length of faulting of 35 km. Doser and Smith [17] estimated static stress drops of 12 and 17 bars based on average displacement, rupture dimension, and either geologic or seismologic estimates of the seismic moment, respectively. Doser and Smith [17] state that even considering possible errors in stress drop estimates, the 1983 earthquake was probably a low stress drop event compared to other normal-faulting earthquakes and that the stress drop did not exceed 75 bars. Shemeta and Pechmann [24] computed static stress drops for 53 aftershocks in the Richter magnitude (M_L) range 2.5-5.6; the average value was 9 bars and all stress drops were less than 50 bars. The 28 March 1975 M_s 6.0 Pocatello Valley earthquake in southeastern Idaho had an estimated dynamic stress drop of 50 bars and a static stress drop of 20 bars [25].

As a comparison with other Basin and Range earthquakes, Doser [26] estimated a static stress drop of 115 bars for the 18 August 1959 M_s 7.5 Hebgen Lake earthquake. However, the mainshock was a complex double-event possibly involving rupture on one or more faults. Doser [26] also estimated stress drops of 17 and 4 bars for two of the largest aftershocks, M_s 6.3 and 5.9 on 18 and 19 August 1959, respectively.

Based on these analyses and a review of other studies, the data suggests that a stress parameter of 50 bars is a reasonable value to use in the estimation of strong motions for a southern Lemhi fault earthquake as well as most other Basin and Range normal faulting events.

Site Effects

In an early evaluation of seismic design criteria for INEL facilities in 1977, it was suggested that ground motions would be smaller in the ESRP due to attenuation within the alluvial interbeds within the basalt stratigraphy. At that time, it was concluded that there was no evidence to indicate that such a process would occur and that it was unlikely due to the thinness of the interbeds relative to the wavelengths of seismic waves that are of engineering significance.

However, results of this recent site-specific analysis indicate that the interbeds are probably significant in terms of attenuating ground motions especially since such interbeds are dramatically thicker than previously believed [3]. (Another contribution is the absence of a strong shear-wave velocity gradient in the volcanic section in the uppermost crust which tends to lower ground motions relative to a typical western U.S. rock site [3]). Site κ's which reflect the near-surface attenuation, were computed based upon the recorded regional earthquakes and a template technique described in WCC [3]. The value of κ is inversely proportional to the shear wave velocities and Q_s beneath each site.

κ values ranged from 0.002 sec at ANL to 0.026 sec at ATR, with an average of 0.015 sec in the ESRP. Typical values of κ for western North America (WNA) rock sites range from approximately 0.02 to 0.06 sec and for eastern North America, approximately 0.006 sec. This suggests that attenuation in the shallow crust beneath the ESRP may be slightly lower on average than the WNA, but can vary considerably locally.

The ESRP κ values generally correlate with our assessments of the subsurface geology beneath each site. Preliminary analysis of INEL borehole data shows the percentage of interbeds to decrease with distance away from the Big Lost River floodplain. Sites such as ATR, PBF, and the INEL-1 drillhole (Figure 1) have relatively high values because they lie within the floodplain and probably have the greatest number and total thickness of interbeds within the basalt section. Hence, the greater the total thickness of the interbeds, the lower the average Q_s, the higher the κ value and the greater the attenuation in the geologic profile. Not surprisingly, station BLM situated on the fairly dense and strong limestone of the Lost River Range outside the ESRP has the lowest observed κ of 0.002 sec.

A sensitivity analysis was performed using the INEL-1 geologic profile (Figure 3) to assess the attenuating properties of the basalt interbeds. As the number of thicker interbeds (>30 m) increased, hence increasing kappa, the peak horizontal accelerations decreased [3]. Thinner interbeds did not appreciably effect the peak accelerations in terms of increased damping, although some additional attenuation occurs from scattering. Thus the presence of the sedimentary interbeds in the basalts beneath the ESRP appears to attenuate high-frequency ground motions to a greater degree than for rock sites with very few interbeds or for sites located off the plain.

SUMMARY

Site-specific ground motions have been estimated for facility sites at the INEL assuming a M_w 6.9 design earthquake occurring on the southern Lemhi fault at source-to-site distances of 27 to 10 km. Acceleration response spectra have been computed at both rock and soil sites with peak horizontal accelerations ranging from 0.09 to 0.40 g, respectively. Although earlier modeling assumed a point source for the design earthquake, which results in conservative ground motion values, the phenomenon of rupture directivity was investigated. Surprisingly, for the assumed 1983 Borah Peak earthquake slip distribution model, a rupture initiation point at the lower center of the rupture plane (bilateral rupture) gave similar ground motions as unilateral rupture towards the INEL. In this case, this is due to the favorable locations of asperities and their subsequent rupture which appear to be quite significant in specifying the level and spectral content of ground motions. A stress drop of 50 bars was found to be a reasonable value for an earthquake on the southern Lemhi fault based on an analysis of other normal-faulting earthquakes in the Basin and Range. Finally, the sedimentary interbedded volcanic stratigraphy beneath the INEL attenuates ground motions relative to a typical western U.S. rock site based on site-specific stochastic modeling.

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