EARTHQUAKE STRONG GROUND MOTION STUDIES AT THE IDAHO NATIONAL ENGINEERING LABORATORY

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ABSTRACT

Site-specific strong earthquake ground motions have been estimated for the Idaho National Engineering Laboratory assuming that an event similar to the 1983 M_s 7.3 Borah Peak earthquake occurs at epicentral distances of 10 to 28 km. The strong ground motion parameters have been estimated based on a methodology incorporating the Band-Limited-White-Noise ground motion model coupled with Random Vibration Theory. A 16-station seismic attenuation and site response survey utilizing three-component portable digital seismographs was also performed for a five-month period in 1989. Based on the recordings of regional earthquakes, the effects of seismic attenuation in the shallow crust and along the propagation path and local site response were evaluated. This data combined with a detailed geologic profile developed for each site based principally on borehole data, was used in the estimation of the strong ground motion parameters. The preliminary peak horizontal ground accelerations for individual sites range from approximately 0.15 to 0.35 g. Based on our analysis, the thick sedimentary interbeds (greater than 20 m) in the basalt section attenuate ground motions as speculated upon in a number of previous studies.

INTRODUCTION

On 28 October 1983, a surface wave magnitude M_s 7.3 (moment magnitude M 6.9) earthquake occurred in the vicinity of Borah Peak along the Lost River Range approximately 90 km northwest of the Idaho National Engineering Laboratory (INEL) which is located within the eastern Snake River Plain (Figure 1). Previous geologic studies of the Arco and Howe scarps along the southern segments of the northwest-trending Lost River and Lemhi faults respectively (both Basin and Range normal faults), have uncovered evidence for multiple earthquakes. The most recent events are characterized by offsets of more than 3 m that possibly occurred approximately 15,000 to 30,000 years ago [1]. These data suggest that there exists a potential for future earthquakes similar to the 1983 Borah

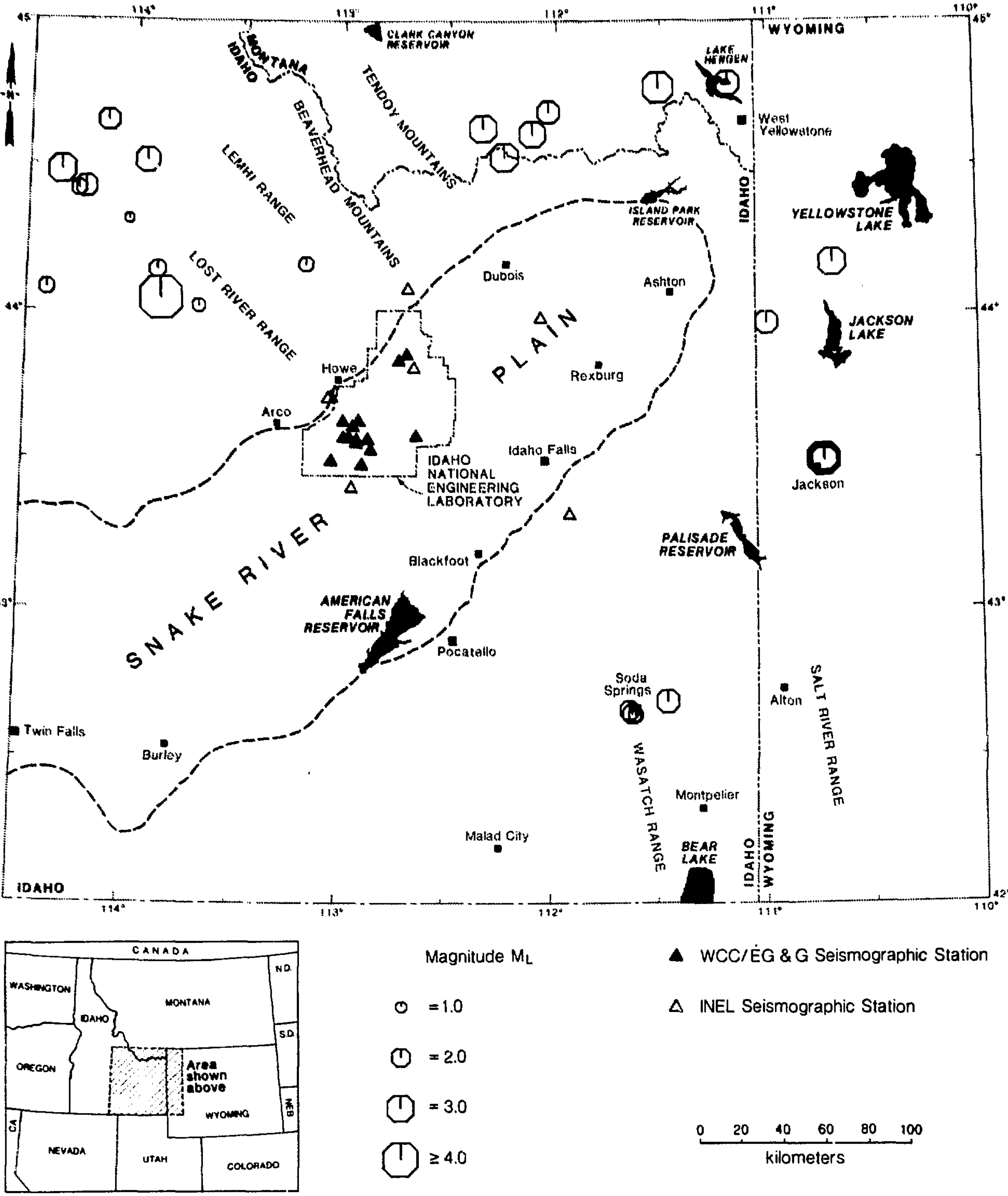

Figure 1. Regional setting of the INEL and locations of earthquakes recorded by the seismic survey. Also shown are the permanent stations of the INEL seismographic network.

Peak event which may occur at close distances to facilities at the INEL. In the past, empirical studies of ground motion have been performed for the INEL based on data from earthquakes occurring in other regions worldwide. This is due to the lack of recorded strong ground motion data for 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, site-specific strong ground motion parameters for the INEL are required for input into seismic safety analyses. This paper describes (1) the studies being jointly performed by Woodward-Clyde Consultants (WCC) and EG&G Idaho, Inc. to assess potential earthquake strong ground motions at the INEL and (2) the preliminary estimates of strong ground motion that might be experienced during a hypothetical earthquake, similar to the 1983 Borah Peak event, occurring along the southern segment of the Lemhi fault.

Scope of Work

Specific objectives of this study are: 1) provide site-specific estimates of peak horizontal ground acceleration and response spectra for selected sites located on soil or bedrock; 2) develop a peak acceleration-attenuation relationship for earthquakes in the range M 6 to 8 that is specific to the INEL; 3) perform a seismic survey of selected sites using portable digital seismographs; and 4) 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 this study, the strong ground motion parameters will be estimated based on a methodology incorporating the Band-Limited-White-Noise (BLWN) ground motion model coupled with Random Vibration Theory (RVT). The BLWN model incorporates the general characteristics of the source and wave propagation as well as propagation path and 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.

An additional important aspect of the BLWN model employing a simple source model is that the site- and region-dependent parameters can be evaluated by observations of local or regional earthquakes. Thus, results from the seismic survey will provide data for input into the strong motion predictions in addition to providing site-specific ground-motion recordings to calibrate the BLWN-RVT model.

Previous Studies

In previous evaluations of potential strong-ground motions at the INEL dating back to the early 1970's, the sources of the design earthquakes have been the southern segments of the Lost River fault (near Arco) and the Lehmi fault (near Howe) (Figures 1 and 2). The magnitudes of the events have generally ranged from 6 3/4 to 7 3/4 with resulting peak horizontal ground accelerations of 0.15 to 0.45 g at the ground surface [2]. (For other pertinent discussions, see Harris [2] and Dahlke and Secondo [3] in this volume.)

In 1977, Agbabian Associates [4] reviewed the evidence for two factors that had been speculated upon as possibly diminishing the levels of earthquake ground motions within the Snake River Plain: (1) "decoupling" of the Plain by perimeter faulting and (2) attenuation due to the interbedded alluvial layers within the basalts. It was concluded that there was no evidence at that time to indicate the existence of either process. The latter was considered unlikely because the seismic waves would not be affected by the interbeds due to the differences between their much larger wavelengths and the thinness of the interbeds.

In 1983, the Borah Peak earthquake occurred providing the first strong motion records at the INEL although at distances exceeding 90 km. Thirteen accelerographs which were the closest instruments to the event were triggered, recording peak horizontal accelerations ranging from 0.022 to 0.078 g at

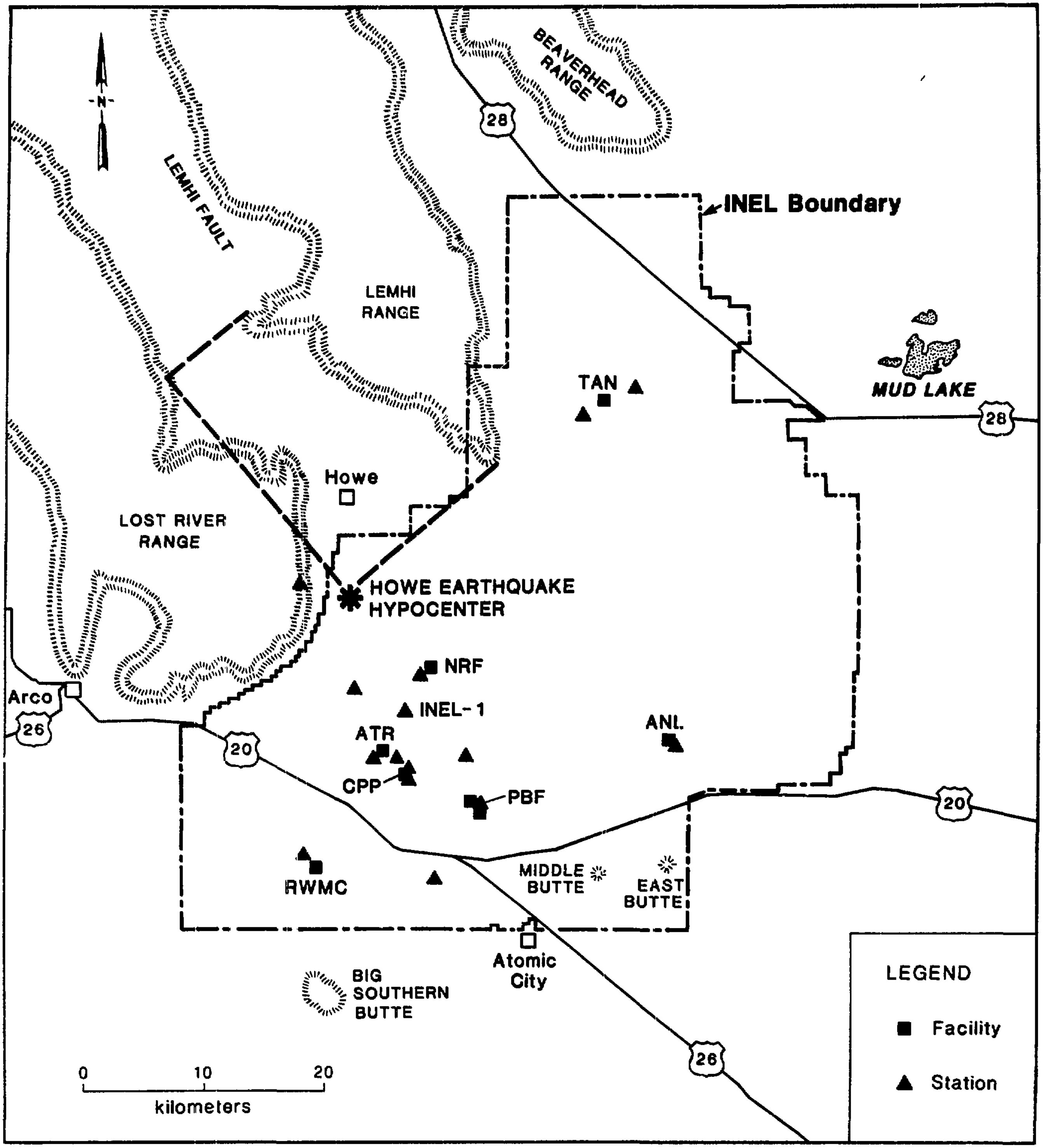

Figure 2. Locations of seismic stations and major facilities at the INEL. Also shown is the surface projection of the hypothetical "Howe" earthquake rupture plane on the southern segment of the Lemhi fault.

basement or free-field sites at the facilities ANL, ATR, CPP and PBF [5] (Figure 2). In an attempt to estimate near-field accelerations for the 1983 earthquake, Jackson and Boatwright [6] calculated values of 0.21 to 0.54 g for distances of 18 to 11 km, respectively, based on the observed attenuation of the largest aftershock. These estimates, however, may only be appropriate for a site located within the Basin and Range province and probably not for the Snake River Plain province.

APPROACH

Band-Limited-White-Noise Point Source Model

The BLWN ground motion model first developed by Hanks and McGuire [7] (sometimes referred to as the stochastic model) 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 [7,8,9]. The ground motion model uses an ω-square Brune source model with a single corner frequency and a constant-stress parameter [8]. RVT is used to relate rms (root-mean-square) values to peak values of acceleration [8], and oscillator response [10,11] computed from the power spectra to expected peak time domain values. Details of the methodology are described in Silva et al. [12] and Silva and Darragh [13].

The shape of the acceleration spectral density a(f) is given by

$$a(f)=C\,\frac{f^2}{1+(f/f_c)^2}\,\frac{M_o}{R}\,P(f)A(f)e^{-\frac{\pi f R}{\beta_o Q(f)}} \quad (1)$$

where M_o is the seismic moment, R the hypocentral distance, β_o the shear wave velocity at the source, Q(f) the frequency dependent quality factor, A(f) the near-surface amplification factors, P(f) the high-frequency truncation filter, f_c the source corner frequency, and C a constant.

Source scaling is provided by specifying two independent parameters, the seismic moment (M_o) and the high-frequency stress parameter ($\Delta\sigma$). $\Delta\sigma$ relates f_c to M_o. The spectral shape of the source model is then described by the two free parameters M_o and $\Delta\sigma$. f_c increases with the shear-wave velocity and with increasing stress parameter, both of which are region dependent.

Amplification by near-surface velocity gradients is accounted for in the detailed site-specific velocity models.

The P(f) filter is an attempt to model the observation that acceleration spectral density falls off rapidly beyond some region-dependent maximum frequency. This observed phenomenon truncates the high frequency portion of the spectrum and is responsible for the band-limited nature of the stochastic model. Following the Anderson and Hough [14] attenuation model, the form of the P(f) filter is taken as

$$P(f) = e^{-\pi\kappa(r)f} \quad (2)$$

where r is epicentral distance and κ(r) is a distance-dependent damping factor that represents the loss in energy of the seismic waves as they propagate. At zero epicentral distance, κ represents energy attenuation in the shallow crust beneath the site [15].

As r increases, the rays penetrate deeper into the crust where the mechanism of attenuation contributes a frequency dependence to the damping. This part of the path attenuation is generally modeled with a frequency dependent Q of the form

$$Q(f) = Q_o\left(\frac{f}{f_o}\right)^{\eta} \quad (3)$$

where Q_o is the reference Q at frequency f_o.

To summarize, the parameters that are required for the ground motion estimates are the source parameters of the earthquake (seismic moment or moment magnitude, stress parameter, and source depth), shortest distance to the rupture plane, propagation path parameters (Q(f), shear wave velocity [V_s], and density [ρ]) and the detailed geology beneath each site as characterized by V_s, ρ and Q_s for each layer. Modulus and damping curves modified from Seed and Idriss [16] are used to characterize the response of the soils in the geologic profiles having V_s less than 0.75 km/sec.

Seismic Attenuation and Site Response Survey

In early February 1989, the first of 16 stations in the seismic survey were installed either at or near facilities of interest at the INEL or as part of an array aligned approximately with the trend of active earthquake sources within the region (Figure 2). A desire to have stations located on a variety of subsurface geology was also considered in the site selection. Finally, the need to avoid high levels of ground noise due to activities associated with the operations at the INEL and to be near a borehole in which detailed information on the subsurface geology was available, governed the exact station locations.

Each site was equipped with a Sprengnether DR-100 digital event recorder and an orthogonal three-component set of Mark Products L-4C or Teledyne-Geotech S-13 1.0 Hz seismometers. Data were recorded at 100 sps per channel and bandpass-filtered between 0.2 and 30 Hz. The seismometers were generally buried to a depth of 1 m to minimize wind noise. Power was provided by external batteries recharged by solar panels. Digital cassette tapes were generally changed every two days and the internal clocks of the DR-100's calibrated with a portable reference clock. Station locations were determined using a portable Satellite Navigation System. Calibrations of the digital seismographs were performed at the beginning, middle and end of the survey in mid-July.

Approximately 40 regional earthquakes of sufficient magnitude (local magnitude $M_L \geq 2.5$) were well-recorded on 200 seismograms during the seismic survey (Figures 1 and 3). All events were processed from the data cassettes and the largest are being used in the analysis of κ and Q. Hypocentral locations and magnitudes for most of the earthquakes were provided by the University of Utah Seismograph Stations (UUSS), the Montana Bureau of Mines and Geology (MBMG), and the U.S. Bureau of Reclamation (USBR). These agencies

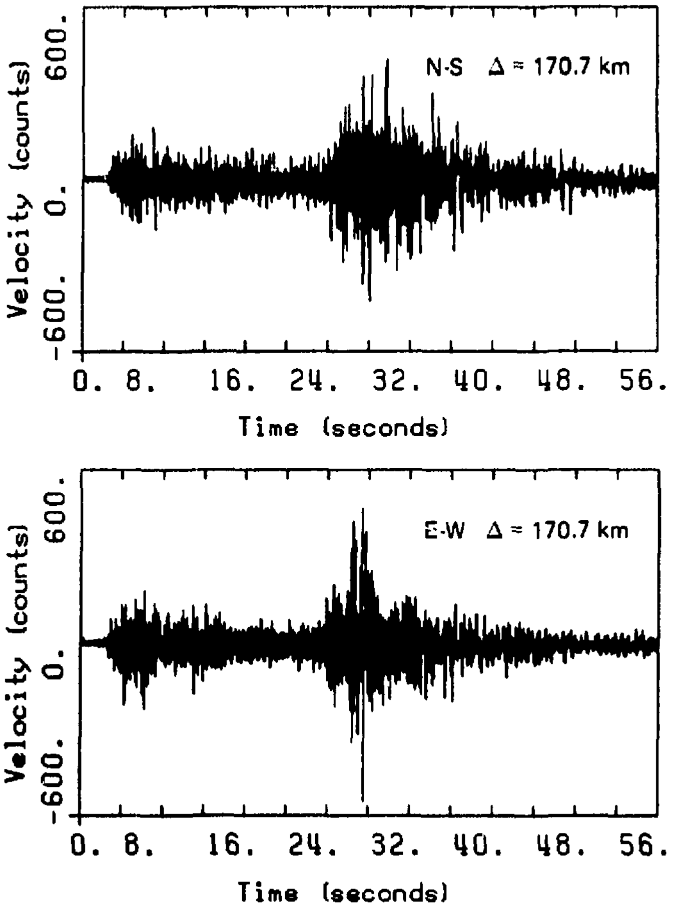

Figure 3. Typical regional earthquake as recorded by the seismic survey. This event (M_L 3.5) occurred near Hebgen Lake (Figure 1) on 6 June 1989.

operate the Utah regional network, the Montana network and the Teton network, respectively. A few events, principally in the Borah Peak area, were located by the INEL eastern Snake River Plain network (Figure 1). The best recorded earthquakes were two events of $M_L > 4$ which occurred at the Utah-Idaho border in early July and two $M_L > 3.5$ events near Jackson, Wyoming in late June (Figure 1).

INPUT PARAMETERS

Earthquake Source Parameters

An earthquake similar to the 1983 Borah Peak earthquake but occurring along the southern segment of the Lemhi fault near the town of Howe was assumed as the maximum earthquake pertinent to seismic safety (Figure 2). The following source parameters were assumed based on the 1983 earthquake [17]:

moment magnitude	M 6.9
seismic moment	M_o 2.1 x 10^{26} dyne-cm
stress parameter	75 bars
source depth	16 km

The stress parameter is probably an upper bound value based on the estimates of the static stress drop for the 1983 event [17]. Turko [18] has estimated a maximum earthquake of M_s 6.9 for the southern segment of the Lemhi fault based on its estimated rupture length. A conservative assumption of a maximum magnitude of M 6.9 (M_s 7.3) incorporates the estimated uncertainty in the definition of this segment and the assumption that only this segment will rupture in a maximum event.

A hypothetical rupture plane for the "Howe" earthquake is assumed to be a 45° southwest-dipping normal fault with an initial point of rupture at 16 km depth at the southwestern corner of the rupture plane identical to the 1983 Borah Peak event [17] (Figure 2). Closest distances to the plane of rupture are conservative and range from 10 to 28 km for the various facilities.

Propagation Path Parameters

For the propagation path between the closest point of the rupture plane of the Howe earthquake and the sites, a half-space model characterized by a V_s of 3.55 km/sec and a ρ of 2.7 g/cm^3 was assumed based on Sparlin et al. [19]. Based on an analysis of L_g waves, Singh and Herrmann [20] determined a regional crustal coda Q_o of 450 and a η of 0.2 for Q(f) (see equation 3). In contrast, Braile et al. [21] observed high attenuation in a seismic refraction experiment within the eastern Snake River Plain and they attribute it to low Q values in the volcanic rocks (Q_p 20 to 200) and throughout the crust (Q_p 160 to 300) where Q_p is the P-wave quality factor. Thus for preliminary modeling of the 1983 Borah Peak earthquake, a Q_o of 450 and η of 0.2 were assumed because most of the propagation path was within the Basin and Range province. For the Howe earthquake along the southern Lemhi fault at the edge of the Snake River Plain, a Q_o of 200 and η of 0.55 may be more appropriate (Q_p was assumed to be equal to Q_s). A technique which fits the non-linear model in Equation 1 to observed spectra from selected regional earthquakes using the Levenberg-Marquardt method is presently being performed to further refine the values of Q_o and η.

Site Parameters

Three site parameters need to be specified as a function of depth for the BLWN-RVT model: V_s, Q_s and ρ. Thus geologic profiles were developed for the individual sites. Stratigraphic data for the upper 200-300 m at each site were extracted from the nearest available well or borehole. The remainder of the 3-km geologic profiles were characterized based upon data from a 3159 m deep exploratory well (INEL-1).

Much of what is known about the subsurface geology beneath the INEL is based on INEL-1. The lithologic log of INEL-1 shows that at least 52 distinctive layers were encountered [22]. The upper section above a depth of 745 m consists of basaltic lava flows with interbedded sediments of alluvial, lacustrine and volcanic origin. The lower section consists principally of rhyolitic welded ash-flow tuffs interbedded with devitrified rhyolites. A thick (87 m) tuffaceous layer separates the basalt and welded tuff sections. At a depth below approximately 2460 m, a rhyodacite porphyry was encountered [22].

Values of V_s and ρ for each layer in the geologic profiles were estimated from (1) sonic (V_p) and density logs performed in INEL-1 and INEL 2-2A, a 915-m deep hole and (2) laboratory measurements of core samples from the two holes under in-situ conditions of temperature and pressure. Uncertainties in V_s values are greatest for the sedimentary interbeds and devitrified rhyolite compared to the volcanic rocks.

For the soil sites, we have assumed a V_s of 0.41 km/sec and a ρ of 2.00 g/cm^3 for the Lost River flood-plain sands, silts, and gravels overlying the basalt. From approximately 3 km (the bottom of INEL-1) to a depth of 5 km, a V_s of 3.05 km/sec and ρ of 2.54 g/cm^3 were assumed based on Sparlin et al. [19].

Preliminary values of Q_s were estimated based on V_s for each layer. The resulting Q_s profiles contained average values over the 5 km depth in the range 100 to 150, which is conservative when compared with the average Q structure beneath the Snake River Plain to this depth as proposed by Braile et al. [21].

κ and its standard error at each site are being estimated by least-squares fits to the distance-corrected spectra of selected regional events with $M_L \geq 3.0$. These events were chosen because they have the largest signal-to-noise ratios at high frequencies. In addition, several events were large enough to be recorded on many stations in the seismic survey. These recordings are presently being used in spectral-ratio analyses to define the differences in κ between the various stations. These two procedures will help constrain the site-specific attenuation in our final models.

RESULTS AND DISCUSSION

Model Predictions of the 1983 Borah Peak Mainshock Ground Motions

Of the eight lowest structural level or free-field strong motion sites at the INEL, five sites were founded on basalt or in the basements of structures with piers embedded in basalt and three were soil sites. Employing the BLWN-RVT methodology, absolute acceleration response spectra (5% damping) for the 1983 earthquake for several of the strong motion sites were estimated to compare with averaged response spectra from the actual recordings. The predicted spectra for the INEL-1 rock site and a rock and soil site at ATR are shown in Figures 4 and 5.

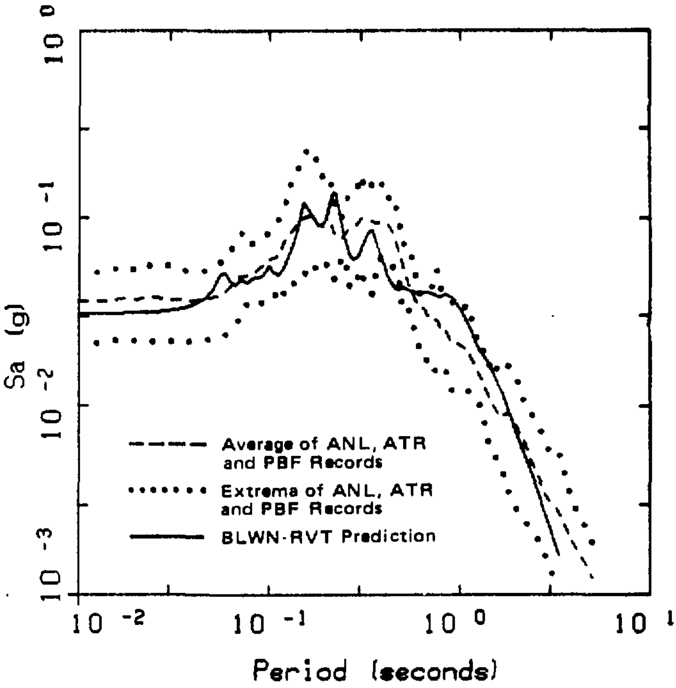

Figure 4. Absolute acceleration response spectra (5% damping) comparing the average of 10 INEL horizontal strong motion records on rock of the 1983 Borah Peak earthquake and the BLWN-RVT model prediction at INEL-1.

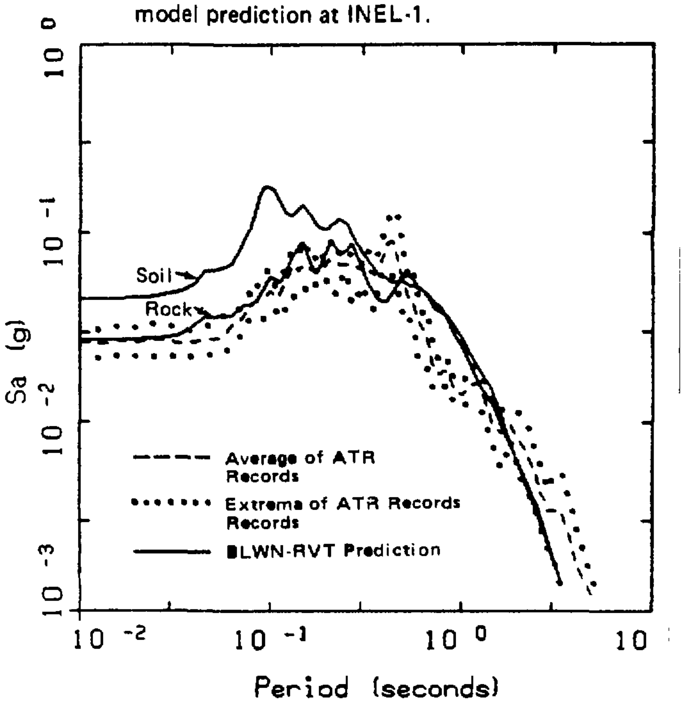

Figure 5. Absolute acceleration response spectra (5% damping) comparing the average of four horizontal records of the 1983 Borah Peak earthquake as recorded at ATR (see Figure 2) and BLWN-RVT model predictions for a soil and rock site at ATR.

In general, the spectra predicted from the ground motion model lie within the extrema of the data (Figures 4 and 5) and are a good representation of the averages of the data. The observed peak accelerations, however, tend to be slightly higher than those predicted by the preliminary modeling.

For the ATR site, the model predictions for rock closely match the observed spectra over the displayed range of periods compared to the predictions for soil (Figure 5). This may be due to the fact that the strong motion sites are located in the basement of a building supported by piers or columns that are embedded in the basalt layer. The inference is that the soil layer does not have a large effect on the response of this structure due to its support in the basalt.

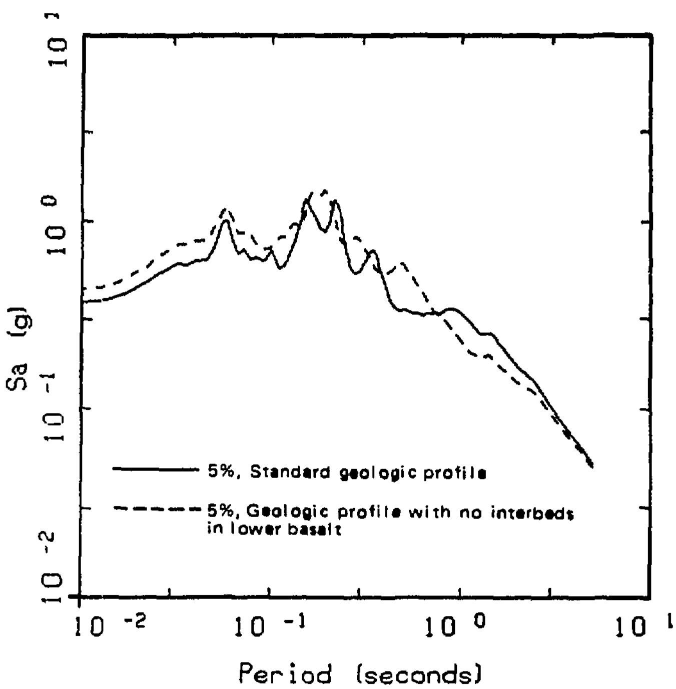

Figure 6. Predicted acceleration response spectra of the Howe earthquake at the INEL-1 rock site with and without sedimentary interbeds in the lower basalt section.

<u>Site-Specific Ground Motion Estimates</u>

For the site-specific estimates of strong ground motion from the Howe earthquake, values of peak horizontal ground acceleration and response spectra (5% damped) have been computed. <u>Preliminary</u> peak accelerations for the various sites range from approximately 0.15 to 0.35 g.

The <u>preliminary</u> peak horizontal acceleration predicted for the INEL-1 site (rock) from the Howe earthquake is 0.36 g at a distance of 16.9 km. The acceleration response spectrum for the INEL-1 site exhibits substantial detail, i.e. resonant peaks, as might be expected for a site-specific spectrum (Figure 6). These peaks are the result of large velocity contrasts at geologic contacts which are numerous in the complex INEL-1 geologic profile. The preliminary estimation of ground motions for a shallow soil site (approximately 12 m of alluvial soil overlying basalt) shows substantial amplification resulting in an approximate 1.5 increase in peak horizontal ground acceleration compared to a corresponding rock site.

A comparison of 5% damped absolute acceleration response spectra based on the INEL-1 geologic profile and the profile with the detailed basalt section from 207 to 660 m replaced with a homogeneous basalt layer is also shown in Figure 6. As expected, the response spectrum of the altered INEL-1 profile shows fewer resonant peaks, some shifting in the frequency of resonant peaks, and generally a higher level of ground motions. The peak horizontal acceleration based on the detailed model is 0.36 g compared to 0.43 g for the profile with the homogeneous lower basalt section. This 19% difference in peak values reflects the attenuation of the seismic waves by the thicker sedimentary interbeds (> 20 m?) in the lower basalt section as the waves propagate up through the near-surface geology. This effect of the thicker interbeds, which has been speculated upon in a number of previous studies [4], appears to be a significant factor in lowering potential strong ground motions at the INEL.

For the purposes of comparison, peak horizontal ground accelerations for the INEL-1 site were computed based on the empirical acceleration-attenuation relationships of Seed and Idriss [23] (probably the most widely used relationship in the earthquake engineering community), Idriss [24], Joyner and Boore [25] and Campbell [26] (unconstrained) and are shown in Table 1 with the preliminary estimate obtained in this study. The relationship by Seed and Idriss is based on rock site recordings. The Idriss, Joyner and Boore, and Campbell relationships incorporate data from selected soil sites. However, according to Joyner and Boore [25], a statistical evaluation of their data suggests that their relationship is also directly applicable to rock sites. All the relationships provide estimates of free-field surface ground motion. The preliminary peak acceleration for the INEL-1 site estimated in this study is in general agreement with the values computed from the empirical relationships (Table 1). Differences are not unexpected, however, given the site-specific nature of our preliminary estimate compared to the empirically-based estimates which are generally dominated by California strong ground motion data.

Table 1

Comparison of Median Peak Horizontal Accelerations at the INEL-1 Rock Site for the Howe Earthquake

Relationship	Magnitude	Distance (km)	PGA (g)
Seed and Idriss	M_s 7.3	10.6*	0.45
Joyner and Boore	M 6.9	10.6*	0.30
Campbell	M_s 7.3	16.9**	0.23
Idriss	M_s 7.3	16.9**	0.29
This study	M 6.9	16.9**	0.36

* Shortest horizontal distance to surface projection of rupture plane.

** Shortest distance to rupture plane.

SUMMARY

Site-specific strong ground motion estimates in terms of peak horizontal ground acceleration and absolute acceleration response spectra are presently being determined for various facilities at the INEL based on the BLWN-RVT methodology. A normal faulting earthquake of M 6.9 (M_s 7.3) similar to the 1983 Borah Peak earthquake but occurring along the southern segment of the Lemhi fault is considered as the maximum event for seismic safety analyses. Such an earthquake would occur at closest rupture distances of 10 to 28 km from various facilities. Detailed geologic profiles based principally on borehole data have been developed for each site and used in the ground motion estimates. Estimates of κ and Q(f) are being obtained from an analysis of the regional earthquakes recorded during the seismic survey.

The near-surface geology, specifically the shear wave velocity contrasts between the basalt layers and the sedimentary interbeds and the Q_s assigned to each layer, have a major effect on the ground motion estimates. The stress parameter also significantly influences the level of ground motions. The preliminary peak horizontal ground accelerations for various sites at the INEL range from approximately 0.15 to 0.35 g depending principally upon the distance to the rupture plane of the hypothetical Howe earthquake, and the details of the geologic profiles. The thicker sedimentary interbeds in the basalt section and the tuffaceous interbed separating the basalt and welded tuff sections attenuate ground motions according to the BLWN-RVT methodology as speculated upon in a number of previous investigations. Currently, the effects of a finite earthquake source on the ground motion estimates, e.g., radiation pattern and rupture directivity, are being evaluated for sites at the INEL.

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