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LA-UR -89-2613

SEP - 1989

CONF-8910192--3

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TITLE

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LA-UR--89-2613

DE89 016606

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SUBMITTED TO

Second DOE Natural Hazards Phenomena Mitigation Conference
October 3-5, 1989, Knoxville TN

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VARIABILITY OF RELATIVE SEISMIC SITE RESPONSE AT LOS ALAMOS, NM

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ABSTRACT

To estimate the range of seismic response at low strain of sites within Los Alamos National Laboratory, ground motion recordings were obtained at 13 sites from nuclear tests carried out in Nevada. The sites are distributed within a 10 X 10 km area. The ground motions recorded at each site were conceptually modelled as the result of source, path, and site contributions. Because almost all of the paths are in common, the variations seen for each source can be attributed to site response.

The sites were monitored in various combinations with seven nuclear tests; each site recorded only a few of the tests. Because horizontal ground motion is more important for structural engineering and was larger than the vertical, we focussed on horizontal site response. The range of relative site response seen is about a factor of 5 to 6 at 1.5 Hz. Topography has a strong effect on response, with sites in canyons being a factor of 3 to 4 lower than nearby sites on mesas. Increased depth to seismic basement beneath some stations also correlates with higher relative site response. Relative site response does not obviously correlate with variation of seismic velocities in the near surface (e.g. upper few meters).

INTRODUCTION

As part of a geologic and seismologic investigation of earthquake hazards in the area of Los Alamos National Laboratory, we sought to estimate the range of relative site response at several locations within the Laboratory. In addition, we wanted to test whether response spectra for a single site are representative for the entire Laboratory. We used an empirical approach, in which we recorded several sources at a number of different sites. This approach did not require that we know the details of the geologic structure beneath the sites, since all wave propagation effects are contained in the recorded data. The empirical approach was well suited to this study because the seismic velocity structure beneath the sites is not known in detail.

We conceptually decomposed the ground motion records for each site into source, path, and receiver effects. Because the source to station distances were all much larger than the differences between the source locations and between the station locations, we could simplify the analysis by removing the common path effects.

The sources for the ground motion recordings were nuclear tests conducted at the Nevada Test Site. The usable frequency band of these recordings, about .3 to 3 Hz, is narrower than was hoped for. Moreover, it is narrower than would be expected to occur during any possible nearby earthquake. Nevertheless, the relative site responses found by this study should be representative of the relative site responses resulting from any possible nearby earthquake. A study by Rogers, et al, [1] found that in the Los Angeles Basin the relative site response seen in recordings of nuclear tests correlated with the relative site response seen from the nearby San Fernando earthquake of 1971. The source to station distances studied by Rogers, et al, [1] are shorter than those used in this study, the frequency band used by Rogers, et al, is not dramatically wider than the frequency band used in this study.

METHOD

Three-component ground motion data were digitally recorded at 13 different sites. Various combinations of the sites recorded ground motion from seven different nuclear tests; no site recorded all of the nuclear tests. A total of 35 3-component data recordings were used in the analysis. The magnitudes of the nuclear tests ranged from 5.0 to 5.8.

Digital data were recorded at a sample rate of 100 samples/sec, with the anti-alias filter set at 12.5 Hz. Recordings were first corrected for instrumental gains, then were windowed according to the wavetype of the arrival. The direct arrivals, P_g and L_g, comprised two data windows, with the remaining five taken from successively later times in the L_g coda. Figure 1 shows an example event recording, with the start of the data windows noted. Data windows were 20.48 sec long (comprising 2048 samples). The earliest arrival, P_n, was too small to use in the analysis, and is marked on the trace only for reference.

By using multiple data windows that provide possibly redundant but independent information, we hoped to obtain more stable estimates of the relative site responses. Three different wave types were analyzed: P_g, L_g, and L_g coda. Because they consist of quite different propagation modes, we analysed data from the different types separately. The L_g coda was analyzed in five separate time windows (C1 to C5 in Figure 1), with results from individual windows averaged to provide the results discussed here.

A window of the seismic noise was taken ahead of the P_n arrival to estimate the signal to noise ratio in each of the data windows. Only data windows with signal to noise ratio greater than 2 were used. Data from each window were then band-pass filtered into several octave-width frequency bands, centered at frequencies of 0.375, 0.75, 1.5, and 3.0 Hz.

Figure 1 also shows the spectrum of the L_g arrival, and the noise spectrum for comparison. The spectral plots make the band-limitation of the data clear; usable signal extends from about 0.3 to 3.0 Hz. The relatively narrow data bandwidth largely results from the effects of distance from the sources, but the relatively high cultural noise level in the area and the highly attenuating near surface volcanics also contributed.

Following Phillips and Aki [1], the observed ground motion recordings were conceptually represented by:

$$A_{ijkl} = \log_{10} (S_{ikl} \cdot P_{kl} \cdot R_{jkl}) \quad (1)$$

where the indices i, j, k, l refer to source, site, wavetype (window), and frequency band, respectively; A is the observed ground motion; S is the source effect; P is the effect of the path; and R is the receiver (site) effect. The path effect has been written as depending only on the wavetype and frequency, since the seismic wave paths were nearly the same for all combinations of sources and sites.

We neglect any possible azimuthal effects in the source and site terms. The direction of the seismic rays from the sources to all stations was nearly identical. Similarly, the directions of the rays arriving at the stations were nearly identical for all sources.

By removing the mean amplitude for a given source and wavetype (data window) from the ground motion recordings, we can rewrite equation (1) as:

$$A_{ijk} - A_{ave}^{(ik)} = r_{ijk} - r_{ave}^{(ik)} \quad (2)$$

where $r = \log_{10} R$, and the individual indices for the frequency have been dropped since different bands will be analyzed individually. The (ik) superscript stands for the mean value holding source and wavetype indices fixed.

The source and path terms have been removed from consideration in equation (2). We have assumed the sources to be isotropic, and take the effects of the different sources to be simply differences in recorded amplitudes. Removing the path term is justified because the path effect is in common for all the ground motion recordings.

From the formulation of equation (2), we used standard inverse methods to solve for the individual site responses relative to the average for all sites. The variance reduction is 90% for the 1.5 Hz data band, supporting the use of our conceptual model.

RESULTS

The relative responses for the three wavetypes analyzed have similar shapes when combined in array averages (Figure 2). Relative response values plotted in Figure 2 are array averages for each wavetype and frequency band. The most important features in the figure are the relative response of the different components. The correlation coefficients of individual site measurements of P_g and L_g are 0.83, 0.91, and 0.90 for the Z, N, and E components, respectively. Because of the higher relative excitation of horizontal component ground motion the we report here the results of analysis of the L_g and L_g coda arrivals.

The most fundamental result of this study is the relatively large variation in response at different sites. From the 13 sites occupied, which span a distance of about 10 km, the relative horizontal response varies by about a factor of 5 to 6 at 1.5 Hz (Figure 3). The values plotted in Figure 3 are Log_{10} of the response in the 1.5 Hz band at each site relative to the average for all sites. The highest relative response at 1.5 Hz (+0.45) is at Site 7, the lowest (-0.35) is at site PSS; a difference of 0.8 in Log_{10} response which corresponds to about a factor of 6 difference in the relative response between the sites. A similar study of site response at microearthquake monitoring stations in central California [2] found site responses that differed by factors of 5 or more at 1.5 Hz. Thus, the range of relative response seen in our study is not unreasonable.

Some sites that are only a few km apart, and whose overall surface and near surface geological character are very similar, show a factor of 2 or more difference in response. Note the differences in Figure 3 between response at sites 7 and 8 (+0.45 and +0.40 relative response) and the nearby sites 4 (+0.05), 6 (+0.15), and TA-55 (+0.05). Sites 7 and 8 are on mesas separated by intervening canyons. Sites 4 and 6 are on the same mesa; TA-55 and Site 8 are both on an adjacent mesa. and yet show a large difference in relative response. With standard errors (1 sigma, in units of Log_{10}) of the relative responses of less than 0.05, the differences discussed here are significant.

A strong topographic effect can be seen in the quite different relative responses of nearby canyon (sites 5 and LAC) and mesa sites (sites 4, TA-55, 6, 7, and 8). Responses at the canyon sites are as much as a factor of 2 to 3 lower than at nearby mesa sites.

In addition to investigating the site responses at a single frequency, we can also compare the response as a function of frequency for individual sites. In Figure 4 we compare the response at site 7 with that at site PSS. Figure 4 shows the response at the two sites compared to the average of all sites at each frequency band. We see the two extremes of behavior - increasing response with increasing frequency (site 7) and decreasing response with increasing frequency (PSS).

DISCUSSION

All of the sites studied are situated on Bandelier Tuff, which is a 1.1 MY old variably welded ignimbrite deposit. Seismic velocities at or near the sites studied range from about 3,000 (site PHP) to 15,000 (near site PSS) feet per second [3]. The thickness of the tuff beneath the mesa top sites ranges from about 200 feet at sites in the SE (PHP, AMS) to about 800 feet at sites in the central and western portion of the area (PSS) [4].

We do not fully understand the causes of the large differences seen in the relative response of sites. Several effects may be influencing the site response. Resonance of the mesas may partly explain the relatively larger response seen at mesa sites compared to those in canyons. Differences in the near surface (upper several meters) velocity alone may not be a major factor, since the near surface velocities probably do not vary substantially between nearby sites. Another factor that may influence relative response of different sites may be the formations beneath the Bandelier Tuff. Underlying the Bandelier Tuff in the western portion of the Laboratory is the Tschicoma Dacite, in the central portion is the Puye Formation, an alluvial fan deposit, and in the east is the Cerros del Rio basalt [4].

Site PSS, which shows the lowest response of all the sites, is situated on tuffs that are densely welded [3]. The underlying dacite at site PSS may have a low seismic Q as a result of fracturing as seen in nearby outcrop (c.f. [3]). Nevertheless, to explain the deficiency in high frequency response seen at PSS solely by attenuation, the Q in the dacite would probably have to be unreasonably low.

Interestingly, the contours of site response seen in Figure 3 correlate with the pattern of Bouguer gravity over the study area [5]. Sites 7 and 8, which have the highest relative response, fall within a gravity low that is interpreted as a graben [4,5]. The anomalously high response at those sites may result from the greater thickness of sub-Bandelier tuff sediments in the graben. Thus, the observed variations in site response may result from geologic structures that are a kilometer or more below sites.

CONCLUSIONS

The factor of 5 to 6 difference in the seismic responses at sites situated within 10 km of each other implies that it would be unreliable to use the response of a single site to characterize the response of all sites throughout the Laboratory. From the basis of site response alone, sites in the western portion of the Laboratory would appear to be preferable for structures. Counteracting the favorable site response seen there is proximity to a possible source zone for local earthquakes, the Pajarito Fault Zone, which passes within a kilometer of site PSS. The recurrence interval for earthquakes along the Pajarito Fault Zone is not well known, but may be several thousands of years. The magnitudes of the largest earthquakes attributable to the Pajarito Fault Zone are also not well known, but may be as large as 6 to 7 [3].

The work reported here is a part of a geologic and seismologic study of earthquake hazards in the area of Los Alamos National Laboratory. We plan to calculate response spectra for selected sites from recordings of local earthquakes. Because of the widely variable geologic and seismic structure beneath the Laboratory, those response spectra may be more reliable for use in structural design than response spectra calculated from models of the structure.

ACKNOWLEDGEMENTS

This work was done under the auspices of the U.S. Department of Energy.

FIGURE CAPTIONS

Figure 1. Vertical component seismogram recorded at site PHP (top), and the corresponding spectra from the L_g arrival and a time window of noise from before the P_n arrival (bottom). Vertical bars on the seismogram mark the start of 20.48 sec time windows used in the analysis of site response. The usable signal bandwidth is between about 0.3 and 3 Hz.

Figure 2. Plots of relative response averaged from all sites studied. Traces labelled 1 and 2 are the north, and east components, respectively; traces labelled Z are the vertical components. Top: results from the P_g window; middle: for the L_g window; bottom: for the five L_g coda windows. Note that the vertical component is lower than the horizontals for the L_g and L_g coda windows.

Figure 3. Map view showing the locations of the sites studied and the relative horizontal response at 1.5 Hz. Relative response is shown as Log_{10} of the response at the site compared to the average for all sites. Note the large range of relative response, from -0.3 at PSS to +0.45 at site 7 (A Log_{10} range of 0.75 is a factor of 5 to 6).

Figure 4. Relative site response with frequency for sites 7 (top) and PSS (bottom). Traces labelled 1, 2, and 3 are the vertical, north, and east components, respectively. Note the different response as a function of frequency, with Site 7 showing increased response, and PSS showing decreased response.

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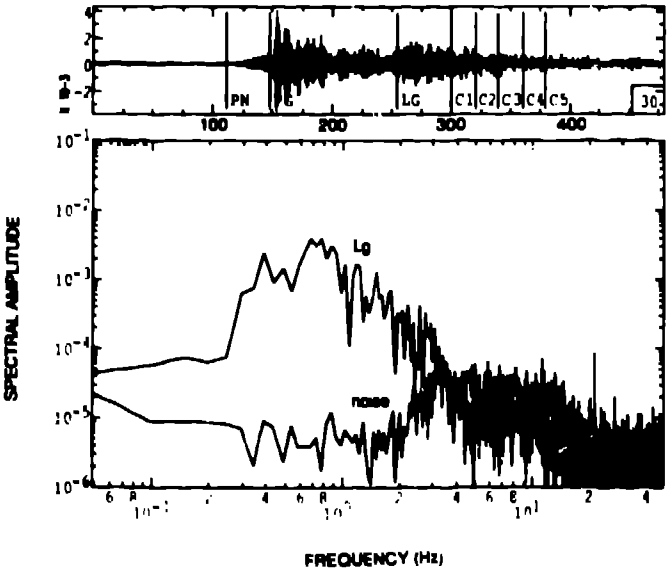
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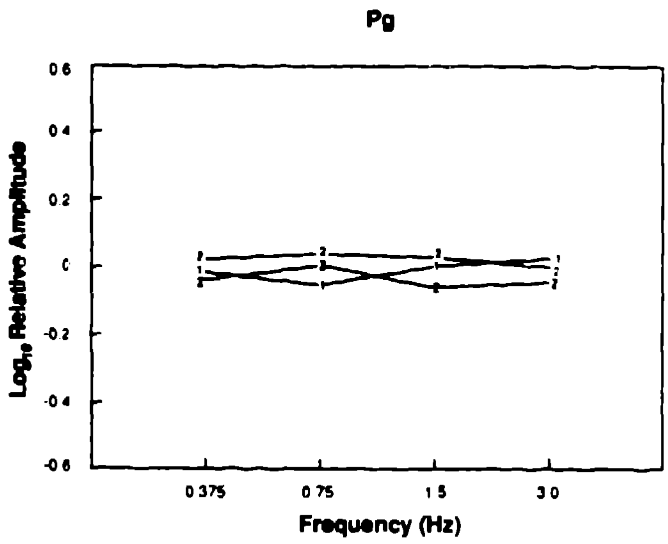
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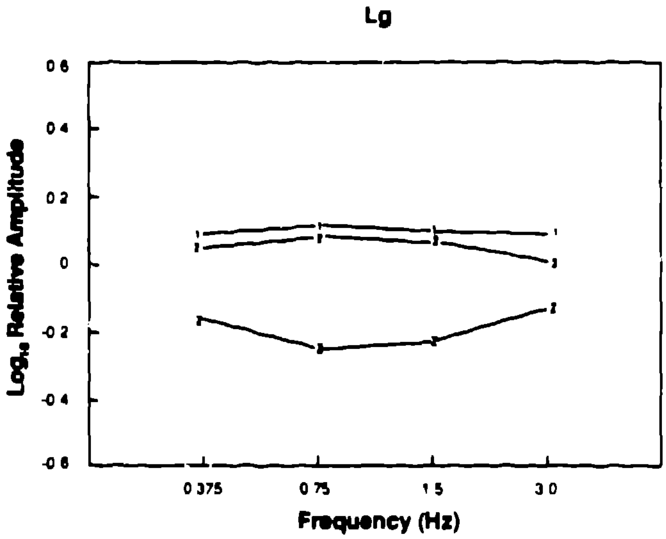
Frequency (Hz)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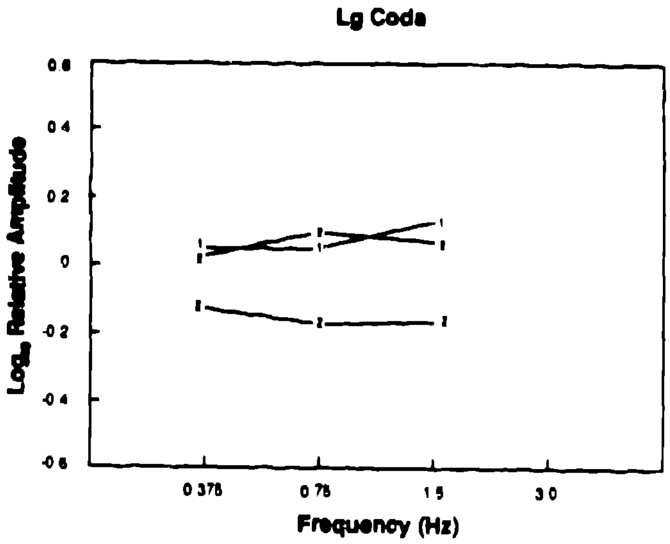
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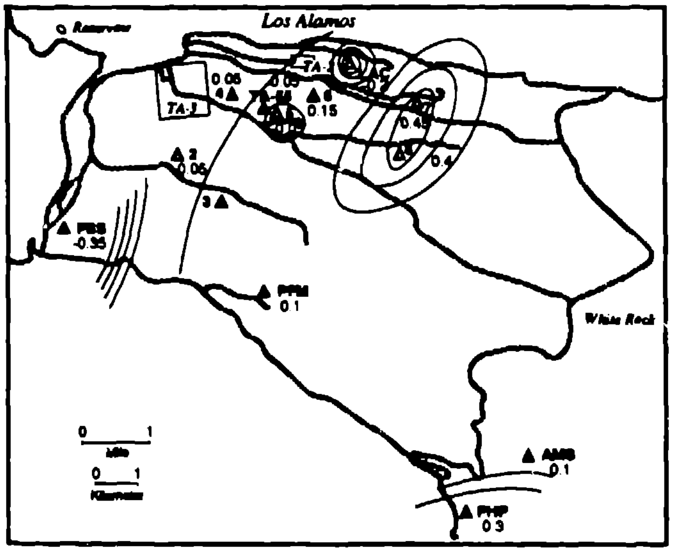
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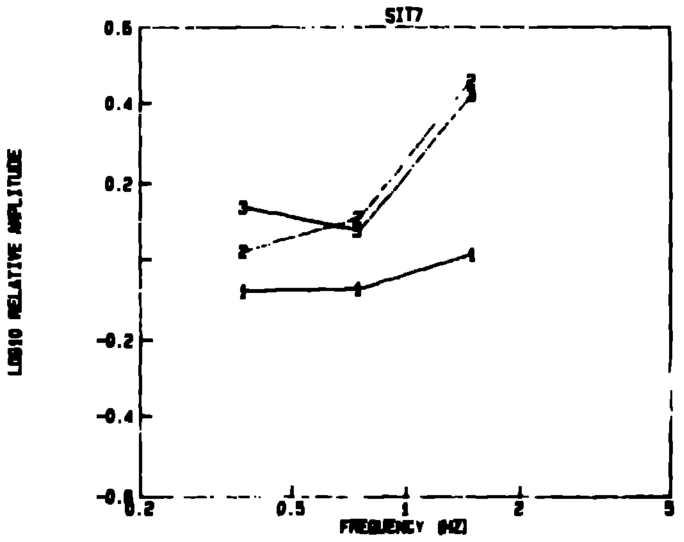
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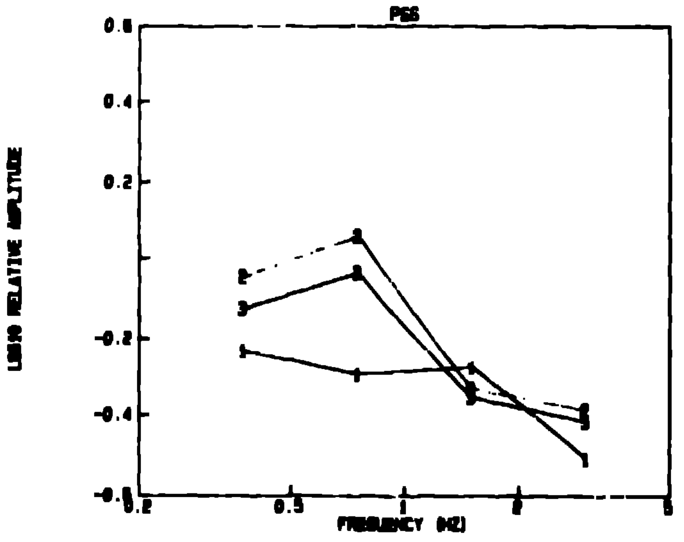
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FREQUENCY (HZ)
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