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Nevada Nuclear Waste Storage Investigations Project

Ground Motion Evaluations at Yucca Mountain, Nevada With Applications to Repository Conceptual Design and Siting

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by
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Under Sandia Contract: 58-8701

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ABSTRACT

The ground motion at Yucca Mountain, Nevada, was evaluated, and its effect on siting and conceptual design of a prospective nuclear waste repository was considered. Two levels of ground motion are proposed in this report for seismic design, the higher level for design of facilities classified as important for off-site radiological safety, the lower level for on-site safety. It is recommended that a probabilistic approach be used to define ground motions with a 2,000-year return period for the higher level and a 500-year return period for the lower level. Probabilistic seismic hazard models were developed both for earthquakes and for underground nuclear explosions (UNEs). Probabilistic analyses yielded horizontal peak ground acceleration (PGA) values of 0.25 g and 0.40 g for the 500-year and the 2,000-year earthquake ground motions, respectively. Similar analyses for UNEs yielded horizontal PGA values of 0.125 g and 0.15 g for the two levels. Although the PGA levels for design UNEs are less than those for design earthquakes, the UNE horizontal response spectrum exceeds that for earthquakes for periods greater than about 1 sec at the higher level (2,000-year) and for periods greater than about 0.4 sec at the lower level (500-year). This report also presents results on the dynamic response of candidate sites for surface facilities and the type of data required in the seismic design of underground facilities.

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EXECUTIVE SUMMARY

The objective of this work was to evaluate the potential seismic ground motion at Yucca Mountain, Nevada, for the purpose of siting and conceptual design of a prospective nuclear waste repository. The principal focus of the evaluation was to develop preliminary ground motion characterizations in terms of peak ground acceleration and response spectra for use in conceptual design. The seismic environment at this site consists of ground motion generated by both earthquakes and underground nuclear explosions (UNEs).

Several engineering issues were also considered. One of these issues involves the possibility that the wedge-shaped alluvial deposits underlying the candidate sites for the surface facilities might enhance motion, causing unfavorable effects for siting. Another issue is to know clearly what information and data are required for seismic analysis and design of underground facilities.

Subsurface Geology of Surface Facility Sites

Relevant geologic maps, borehole data, and reflection/refraction surveys were reviewed. Four geologic cross sections were prepared for use in evaluating the possible effects of wedge-shaped alluvial deposits on the seismic responses of the candidate sites for the surface facilities. Dynamic properties of the subsurface materials are not available because the necessary laboratory and in situ measurements have not been made for the candidate sites. Only qualitative comments about the dynamic properties are possible.

Seismic Response of Surface Facility Sites

The geologic cross sections show that the alluvial wedges at fan margins have angles of about 10°. Seismic refraction data indicate modest seismic acoustic impedance contrast with the underlying Paintbrush Tuff. Analysis of surface and downhole recordings of a UNE event at one candidate site, which was underlain by 115 ft of alluvium, did not reveal pronounced response characteristics of the alluvial layer. Possible reasons for this include strong seismic absorption in the alluvium, which would attenuate layer resonance, and weak acoustic impedance contrast, which would limit dynamic amplification effects. Additional evidence in support of the conclusion that alluvial response effects may not be particularly pronounced is the observation that surface recordings at nearby alluvial and rock sites are reasonably comparable. Available evidence does not provide strong grounds for discriminating among the various candidate sites on the basis of site response or for preferring foundations on rock to those on alluvium.

Data Needed in Seismic Design of Underground Facilities

The evaluation of data needs focused on the appropriateness of various procedures for conceptual design and the different types of components within the underground facility. The types of data needed for seismic design of underground facilities depend on the types and sophistication of the analytical procedures. Seismic evaluations will require response spectra at the depth of the repository horizon and peak ground motion parameters (acceleration, particle velocity, and displacement) at the ground surface, the bedrock surface, and the repository horizon. Shear wave and Rayleigh wave velocities are also needed.

Proposed Terminology for Seismic Design Criteria

In order to specify ground motion characteristics, it was first necessary to develop terminology that would be unique for a geologic repository. Proposals for the classification of repository facilities recommend distinctions between Classifications 1, 2, and 3. The primary distinction concerns radiological safety during and after an earthquake or accident. Classification 1 facilities are essential for maintaining off-site radiological safety whereas Classification 2 facilities are necessary for maintaining only on-site radiological safety. In general, facilities with no radiological safety function fall into Classification 3. Two design earthquake levels are proposed, labeled DE-1 and DE-2. An annual exceedance rate of 5×10^{-4} (i.e., a return period of 2,000 years) is recommended for DE-1 and a rate of 2×10^{-3} (i.e., a return period of 500 years) for DE-2. Two design UNE levels are proposed, called DUNE-1 and DUNE-2 and defined by the same annual exceedance rates as DE-1 and DE-2, respectively.

A postclosure earthquake (PCE) with an annual exceedance rate of 10^{-4} (a return period of 10,000 years) is proposed for the purpose of evaluating long-term repository performance.

Method of Specifying Design Ground Motions

Parallel probabilistic calculations were performed to assess earthquake and UNE ground motion hazard. The basic sets of information used in the calculations are descriptions of the rate and distribution of events with respect to geography and size and of ground motion amplitude as a function of event size and distance. Earthquake and UNE occurrences are assumed to be uniformly distributed in identified seismogenic zones and prescribed test areas, respectively. Earthquake ground motion is modeled using regression results from California strong-motion accelerograph data. UNE ground motion is modeled using regression results obtained from NTS data by Sandia National Laboratories, with site-specific adjustments derived from analysis of UNE signals recorded at Yucca Mountain. The probabilistic calculations involve transforming information on the rate and distribution of event occurrence in the site region into information on rate of exceedance as a function of site ground motion level.

Earthquake Ground Motion

A seismogenic zonation of the site region was established on the basis of historic seismicity, late Quaternary strain rates, and style of Late Cenozoic deformation. Earthquake recurrence rates estimated from historic moderate-magnitude seismicity are generally compatible with paleoseismic data on the occurrence rate of major earthquakes producing detectable scarps. Ground motion was modeled using regression results for accelerograph data recorded principally in California. There is conflicting evidence as to whether seismic attenuation in the site region is greater or less than in California, and there is speculation that seismic sources in the two regions might differ systematically, reflecting differences in state of stress. These issues remain to be resolved.

Peak horizontal ground accelerations determined for DE-2, DE-1, and the PCE are 0.25 g, 0.40 g, and 0.65 g, respectively. Uniform-hazard spectra are given for these three design levels. Vertical-component response spectra are taken to be two-thirds the horizontals for DE-2 and DE-1, modeled as near-regional events, and equal to the horizontal for the PCE, modeled as a near-field event. Subsurface amplitudes at repository depth are provisionally taken to be half those at the surface.

UNE Ground Motion

A UNE occurrence model was established from historic NTS testing prior to the Threshold Test Ban Treaty and the foregoing accelerated test schedule. Testing was assumed to occur in the Buckboard Mesa area located north of the site, an area as yet unused for UNE detonations. Assumed yield limits were those established on the basis of off-site damage potential. While current testing under the Threshold Test Ban Treaty produces negligible ground motion hazard at the site, significant hazard is calculated for the hypothetical occurrence model, based on an expansion of testing in terms of geography and yield. The principal hazard stems from postulated testing in the Buckboard Mesa area, which has a yield limit of 700 kt. Yucca Mountain recordings of Pahute Mesa UNE events were analyzed to determine site-specific adjustments to attenuation functions obtained by Vortman (1984a).

Peak horizontal accelerations for DUNE-2 and DUNE-1 were determined to be 0.125 g and 0.15 g, respectively, and accelerations for the vertical component were 0.15 g and 0.18 g. It is the nature of UNE-generated ground motion that peak vertical accelerations are greater than peak horizontal accelerations at the distances being considered here. UNE response spectral shapes were obtained from statistical analysis of Yucca Mountain recordings of Pahute Mesa UNE events scaled to a yield of 700 kt. The 700-kt spectral shapes were developed in lieu of UNE uniform-hazard spectra, for which requisite attenuation functions are not available. Both horizontal and vertical components of subsurface ground motions recorded at repository depth at Yucca Mountain are significantly less than surface motions for frequencies from 1 Hz to the data band limit of 25 Hz. In the case of horizontal components, the subsurface ground motions are also less for frequencies less than 1 Hz. Pending the development of a satisfactory model for the surface and downhole data, it is recommended that subsurface motions be taken as half those at the surface for interim design purposes.

Ultimately, subsurface response spectra should be based directly on analysis of subsurface UNE recordings when sufficient data are available.

Comparison of Earthquake and UNE Ground Motion

Probabilistic analyses for earthquakes yield horizontal PGA levels of 0.25 g, 0.40 g, and 0.65 g for DE-2, DE-1, and the PCE, respectively. Corresponding vertical PGA levels are 0.17 g, 0.27 g, and 0.65 g. Analyses for UNEs yield horizontal (radial) PGA levels of 0.125 g and 0.15 g for DUNE-2 and DUNE-1, respectively, with corresponding vertical PGA levels of 0.15 g and 0.18 g. Although the PGA levels for design UNEs are less than those for design earthquakes, the horizontal-component response spectrum for DUNE-1 exceeds that for DE-1 for periods greater than about 1 sec, and the DUNE-2 spectrum exceeds the DE-2 spectrum for periods greater than about 0.4 sec. Similar results are observed for vertical-component spectra.

ACKNOWLEDGMENTS

The authors of this report are A. B. Cunningham, R. W. Greensfelder, R. C. Lee, G. N. Owen, and M. R. Somerville. Owen was project manager and project engineer and Somerville was project seismologist. D. P. Jhaveri provided overall technical direction for the project.

After work on this contract had commenced, Somerville and Lee left the employment of URS/Blume and joined several other professionals in establishing QEST Consultants. In order to preserve continuity in the project, a portion of the work was subcontrated to them. Chapter 3 and Chapters 6 through 9 of this report were prepared by Somerville with assistance from Greensfelder and Lee.

The cooperation and assistance of H. R. MacDougall, J. T. Neal, C. V. Subramanian, L. J. Vortman, and K. D. Young of Sandia National Laboratories is greatly appreciated.

1. INTRODUCTION

Sandia National Laboratories (SNL), as a participant in the Nevada Nuclear Waste Storage Investigations (NNWSI) project, is responsible for the conceptual design of a prospective nuclear waste repository to be located in tuff in the southwestern portion of the Nevada Test Site (NTS) at Yucca Mountain. The NNWSI project is under the direction of the U.S. Department of Energy (DOE). URS/John A. Blume & Associates, Engineers (URS/Blume), under contract to SNL, has evaluated the potential seismic ground motion at Yucca Mountain and considered some of the engineering issues that ground motion raises regarding siting and conceptual design of the repository. The seismic environment at this site consists of ground motion generated by both natural seismicity (earthquakes) and underground nuclear explosions (UNEs).

The scope of work was divided into six tasks (SNL, 1984), as follows:

1. Information Review and Siting Recommendations
    a. Seismic Reflection/Refraction and Borehole Data
    b. Subsurface Material Properties
    c. Recommendations for Siting of Surface Facilities
    d. Information and Seismic Data Needed for Underground Facility Design
    e. Ground Motion from Natural Seismicity versus UNEs
2. Terminology Development and Methodology Specification
3. Natural Seismic Design Information
    a. Design Earthquakes and Return Periods
    b. Ground Motion Parameters
    c. Site-Specific Design Response Spectra
4. UNE Seismic Design Information
    a. Ground Motion Parameters
    b. Site-Specific Design Response Spectra
5. Overview Assessment of Surface and Underground A/E Work
6. Report

One of the engineering issues posed by the scope of work (Subtask 1c) involves the possibility of enhanced ground motion at candidate sites for the surface facilities, or portions of those sites, and possible unfavorable effects of that ground motion for siting of the surface facilities. It is known that surficial soils can affect surface ground motions and that these effects are dependent upon thickness, geometry, and dynamic characteristics of the soils and underlying rock. Since the candidate sites are underlain by wedge-shaped alluvial deposits, it is desirable to know if the deposits under one site would enhance motion more than those under another site or if the motion at the margin of a deposit is less favorable for design of facilities than motion away from the margin. In order to evaluate these possibilities, we reviewed the site-specific data, assessed the dynamic properties and geology of subsurface soils, and considered results of other theoretical and field studies. In Chapter 2 of this report, the lateral and vertical distribution of soil and rock and their dynamic properties at the candidate sites are presented. Chapter 3 continues with a further discussion of some of the site data and discusses theoretical considerations and field evidence for enhanced ground motion. In this manner, Subtasks 1a and 1b of the scope of work are addressed in Chapters 2 and 3, and Subtask 1c in Chapter 3.

Another issue raised by SNL in the scope of work concerns the information and data required for seismic analysis and design of underground facilities (Subtask 1d). Although the analysis and design of surface facilities for seismic loads is commonplace, seismic analysis and design of underground facilities is not. Thus, SNL sought advice on the seismic information and data needed for analyzing and designing underground facilities in the context of conceptual design. This information is identified in Chapter 4.

Task 2 of the scope of work directs URS/Blume to develop proposed terminology for use in seismic design that would be unique for a geologic repository and to specify methods to determine the ground motion criteria at Yucca Mountain. The terminology is presented in Chapter 5 and the methodology for determining ground motion in Chapter 6.

Earthquake ground motion parameters and response spectra, as required by Task 3 of the scope of work, are presented in Chapter 7. Ground motion criteria for UNEs, required by Task 4, are presented in Chapter 8. These criteria are specific to Yucca Mountain and are intended for use in conceptual design of repository facilities, both surface and underground.

After developing the ground motion criteria for earthquakes and UNEs in Chapters 7 and 8, respectively, the two sets of criteria are compared in Chapter 9. Task le of the scope of work requested this comparison in order to determine which criteria should be used for conceptual design.

Activities under Task 5 of the scope of work involved communications and meetings with personnel in two architect-engineer organizations (Bechtel National, Inc., and Parsons Brinckerhoff Quade & Douglas, Inc.) and in Science Applications International Corporation. The purpose of these contacts was to provide information regarding developments within the NNWSI project and to discuss appropriate approaches for seismic design of both surface and underground facilities. These activities were carried out at the direction of SNL and are documented in SNL project files. They are not discussed further in this report.

Data in this report are presented in U.S. customary units (e.g., feet) in some places and in metric units (e.g., meters) in others. This is because data were obtained from various published sources, and conversion to one consistent system would make the data difficult to trace and would produce potentially confusing decimals and fractions.

2. SUBSURFACE GEOLOGY OF SURFACE FACILITY SITES

In order to evaluate the seismic response characteristics of the candidate surface facility sites, relevant geologic maps, borehole data, and reflection/refraction surveys were reviewed. In this chapter, we present our findings on subsurface geology and dynamic properties of the candidate sites.

Geologic Cross Sections

Four geologic cross sections were prepared through six candidate surface facility site locations (2, 3, 4, 5, 7, and 8). The locations of the sections are shown in Figure 2.1. The four sections, shown in Figure 2.2, are based on exploratory drilling directed by SNL (Neal, 1985) and on a surface geologic map prepared by the U.S. Geological Survey (USGS, 1984). These sections have been prepared for use in appraising the effects of surficial alluvial materials on earthquake and UNE ground motions at the candidate surface facility sites and are not intended for any other purpose. Detailed geologic information is not required for such appraisal; the most important feature of the sections is the line of demarcation between alluvium and bedrock.

Dynamic Properties

In general, dynamic properties are derived from laboratory tests and from in situ measurement of shear wave velocity. Given the soil or rock density and the compressional and shear wave velocities, dynamic shear modulus and other elastic constants that are appropriate for low strain levels can be calculated directly. Laboratory tests of relatively undisturbed samples can be performed to obtain measurements at higher strains. However, the necessary laboratory and in situ measurements have not been made at the candidate sites; consequently, dynamic properties are not currently available. Only qualitative comments about the dynamic properties are possible.

The tuffs and welded tuffs making up bedrock in this portion of the NTS comprise a highly heterogeneous assemblage, insofar as their dynamic properties are concerned. The nonwelded tuffs, which may have been deposited by air or, to a lesser extent, by water transport, are very low-density, high-porosity materials. The average specific gravity of the nonwelded tuff is 1.95 and the average porosity is 32% (Tillerson and Nimick, 1984). Such materials would be expected to exhibit very high attenuation of seismic motion, probably higher in the lowest density materials than typical desert alluvium. To the extent that the alluvium contains reworked tuff particles, it would also exhibit higher attenuation. Compressional-wave seismic measurements performed by the USGS (1982) indicate that the earth materials at the candidate sites are, in general, highly absorptive for seismic motion.

At the opposite extreme, the thoroughly welded tuff is very brittle and rigid, having an average specific gravity of 2.3 and porosity of 17% (Tillerson and Nimick, 1984). Such material probably has very low attenuation. Bedrock properties, therefore, could be expected to vary through a wide range, depending on the degree of welding. It is not possible to distinguish such variety in physical properties of materials in the cross sections, nor is it possible to calculate representative values for dynamic properties of bedrock or alluvium from available data.

3. SEISMIC RESPONSE OF SURFACE FACILITY SITES

Seismic Refraction and Borehole Data

Geophysical data pertinent to seismic response considerations for siting of repository surface facilities consist of several refraction lines run and interpreted by the USGS over the last several years and numerous well logs in the vicinity of Exile Hill. In addition, other geophysical data, such as gravity, resistivity, and magnetics, have been introduced to shed light on the complex structure of Yucca Mountain. For the locations of Exile Hill and Yucca Mountain with respect to the candidate surface facility sites, see Figure 2.1.

Three seismic refraction lines were reported by the USGS (1982). Two of the lines ran approximately parallel from northwest to southeast; Yucca C ran to the east of Exile Hill, and Yucca 2B ran to the south of Exile Hill. The third line, Yucca A, ran approximately east-west, crossing the southern portion of Yucca Mountain. Each of the "spreads" was 2.76 km long and used a 120-m geophone spacing and shot point spacing of 1,270 m. Yucca 2B ran adjacent to facility sites 4 and 8 and terminated to the southeast in facility site 5. This run was interpreted with a laterally varying three-layer velocity model with a total thickness of 700 to 800 m. On the northwest end of this run, velocity control was provided by two holes: UE25a-1 and UE25a-7. The northwest end of the Yucca C run started at the boundary of facility site 2 and passed within 365 m of facility site 3. Its velocity model was interpreted with a laterally varying four-layer model approximately 500 m in thickness. Yucca A crossed the northernmost area of site 4 and crossed the southern tip of Exile Hill. Yucca A could not be interpreted because of poor signal quality.

The velocity structure from lines 2B and C was found to be extremely complex, presumably a result of faulting both parallel and perpendicular to the alluvial valley. Additionally, no correlation was evident between the well log velocities and the refraction data. The results of Yucca C indicated a strong discontinuity in velocity approximately 500 m from the southeast end, starting at approximately 50 m in depth. This discontinuity is approximately 1 km/sec in magnitude and was interpreted to be a major fault boundary (Paintbrush fault). No assignment of unit labels to seismic velocities was attempted.

The USGS subsequently undertook a more thorough geophysical approach to the area between Exile Hill and Fran Ridge (Ackermann, 1984). A new refraction line was run about 100 m south of Yucca A. This new line was 2.3 km in length and named SFAC123. SFAC123 used geophone spacings of 15 m and shot points approximately 225 m apart. The interpreted model was a laterally varying three-layer model. Control along this line was provided by borehole cuttings from holes UE25WT-5 and UE25WT-14.

Several problems were noted from the lines processed: (1) there is an inconsistency in the modeled depth to welded tuff at the crossing of spreads Yucca 2B and SFAC123, (2) the structural feature associated with the Paintbrush fault is indicated on the western edge of Fran Ridge from SFAC123 and centered on Fran Ridge from Yucca C, and (3) velocities in the shallow Paintbrush Tuff differ by more than 25% between SFAC123 and Yucca C. Differences in the velocity models have been attributed to: (1) uncertainty or errors in the models Yucca 2B and Yucca A that could make these models suspect, and (2) velocity anisotropy that would require azimuthal adjustments for comparison of these refraction lines.

Because of the complex structure evident in the USGS interpretation of Yucca Mountain, it is difficult to abstract a velocity profile for the facility sites with any certainty. Until detailed downhole velocity measurements can be performed at the facility site, only broad generalizations can be made regarding velocity structure.

Information on surficial layering at candidate site 3 (the reference conceptual site) has been deduced primarily from the geologic observations along line B-B' that runs in the east-west direction through Exile Hill (see Figure 2.2). Information on shallow subsurface geological units is provided by data from boreholes RF-3 and RF-8, which penetrate to depths of 45.7 m and 39 m, respectively (Neal, 1985). This information does not, unfortunately, include material dynamic properties.

Additional constraints on layer thickness and seismic velocities can be abstracted from the USGS refraction line SFAC123 (Ackermann, 1984). This line lies approximately 900 m south of line B-B' and along line C-C' (see Figure 2.1). The data from the SFAC123 line were used to determine seismic velocities, which, in turn, provided a rough relationship between the geologic units observed in the RF holes and the dynamic elastic moduli observed from both refraction measurements and material velocity measurements.

A simple model for velocity structure, suitable for analyzing facility site response, was abstracted from the above data for the interim, until site-specific observations become available. The first layer is alluvium and of thickness 90 ft at borehole RF-3. Since velocity values were not obtained in RF-3, the seismic velocity (V_p) in this layer was taken to be 2,500 ft/sec on the basis of the alluvial velocities found in the uppermost 100 ft of hole UE25WT-14 (Ackermann, 1984). The second layer is tuffaceous sediment and is found between depths of 90 ft and 150 ft and extends, presumably, to the Paintbrush Tuff (PT). The seismic velocity of the second layer has not been measured but was taken to have a value in the lower range of those found for the PT. This velocity was taken to be 7,000 ft/sec on the basis of the velocities across the extension of Exile Hill in refraction line SFAC123, between elevations of approximately 3,300 and 3,700 ft (Ackermann, 1984). The dip of the second layer was taken to be approximately 6° on the basis of the distance to the Paintbrush outcrop (see Figure 2.2). Facility site 3 then can be modeled as a thin alluvial wedge overlying much faster tuff. With an assumed Poisson's ratio of 0.22 for the alluvial layer (Olsen, 1970) and 0.33 for the tuffaceous sediment layer (Guzowski et al., 1982), the seismic shear velocities are 1,500 and 3,500 ft/sec, respectively. Densities for the alluvium and tuff were taken from Olsen (1970) and are 1.8 and 1.9 g/cm^3, respectively. These densities are consistent with seismic velocity-density correlations the USGS has determined from Yucca Mountain sites USWG-4 and USWG-3. Near-surface attenuation parameters (Q_p and Q_s) are not available for Yucca Mountain; however, highly absorptive material has been found to be present in the weathered Yucca Mountain surface layers (USGS, 1982).

Evaluation of Alluvial Wedge Propagation Effects

All of the candidate sites considered for location of the repository surface facilities are alluvial fans, as indicated in the geologic cross sections of Figure 2.2. The investigations reported here were undertaken to evaluate the potential effects of the geometry of the alluvial fans on their seismic response, particularly at their margins, and to compare bedrock and alluvial seismic motions. The investigations were intended to provide a basis for discriminating among the candidate sites in terms of seismic response and for recommending siting of the repository surface facilities on the alluvial fans, on bedrock at their margins, or both.

The evaluation was approached by analyzing the results of published field and numerical experiments in terms of the primary parameters of the problem and drawing inferences from these results with regard to expected seismic response effects at the candidate sites. Recordings of a Pahute Mesa UNE event at recently established seismic stations in two candidate site areas were analyzed for evidence of effects attributable to the alluvial wedge.

The primary parameters that determine the seismic response of an alluvial wedge are the angle between the bedrock-alluvium interface and the surface of the alluvium, the seismic impedance contrast between bedrock and alluvium, and the seismic absorptivity of the alluvium (Harmsen and Harding, 1981; Ohtsuke and Harumi, 1983; King and Tucker, 1984). The seismic impedance is defined as the product of seismic wave velocity and density, and the seismic impedance contrast is the ratio of bedrock to alluvial seismic impedance. Existing data for the Yucca Mountain site do not provide good resolution of the values of these three parameters. Bedrock dip angles are typically first-order estimates obtained from two control points. Shear wave velocities have not been measured and, for present purposes, were estimated from measured compressional wave velocities and assumed values of Poisson's ratio. There are no measurements of seismic attenuation whereby the importance of reverberations in the alluvial wedge could be assessed.

With respect to alluvial wedge angle and seismic impedance contrast between bedrock and alluvium, all of the candidate sites are roughly comparable as far as can be distinguished from available data. The cross sections shown in Figure 2.2 indicate that angles between the Paintbrush Tuff and the alluvial surface are typically 10°. At sites 7 and 8, a second bedrock-alluvium interface, dipping approximately 60° to the west, is formed by the Bow Ridge fault, which bounds the west side of Exile Hill. The acoustic impedance contrast between bedrock and alluvium, calculated from the velocity estimates given above, is approximately 3.0 for compressional waves and 2.5 for shear waves.

The effect of the wedge angle has been investigated by Harmsen and Harding (1981) using finite-difference calculations for vertically propagating P and SV waves. For small wedge angles, the dominant nondirect motion is due to multiple reflection in the wedge. As the angle increases, less reflected energy returns to nearby surface points. For an angle of 26.5°, the dominant nondirect motion is due to Rayleigh waves generated at the wedge corner, and these sometimes produce the strongest short-period ground motion. The importance of multiple reflections relative to Rayleigh wave generation increases with the acoustic impedance contrast.

Finite-difference calculations similar to those of Harmsen and Harding (1981) were reported by Ohtsuke and Harumi (1983) for vertically incident SV waves and wedge angles of 26.5° and 63.5°, with an acoustic impedance contrast of 2. For a 26.5° wedge angle, both studies show a 25% amplification effect due to Rayleigh wave generation at the inclined surface. Stronger local amplification was found by Ohtsuke and Harumi (1983) for the larger wedge angle. In both studies, amplitude peaks were found to move to lower frequencies with increasing distance from the wedge corner or edge. Amplitudes generally increase with distance, but there is a tendency for amplification of high frequencies near the edge. For an acoustic impedance contrast of 2, both studies show maximum spectral ratios of about 2 between horizontal-component alluvial surface and rock surface motions.

The applicability of the numerical calculations to wave-propagation effects at the site is limited in several respects. The amplification effects are calculated assuming plane wave incidence, whereas it has been observed that seismic motion at NTS is incoherent for frequencies above a few hertz (McLaughlin et al., 1983). The calculations do not account for seismic absorption and will therefore tend to overestimate alluvial surface motions, particularly in the case of multiple reflections. Finally, no results are available for wedge angles as small as 10°, which are typical at the candidate sites. It can be inferred for small wedge angles that Rayleigh wave generation would be a small effect and that the principal wedge effect would be due to multiple reflections in the alluvium. However, the effect due to multiple reflections may also be small if the alluvium is strongly absorptive. For large wedge angles of about 60°, such as those formed by the Bow Ridge fault at the eastern margins of sites 7 and 8, it is inferred that Rayleigh wave generation would be the principal wedge effect, producing modestly enhanced seismic response.

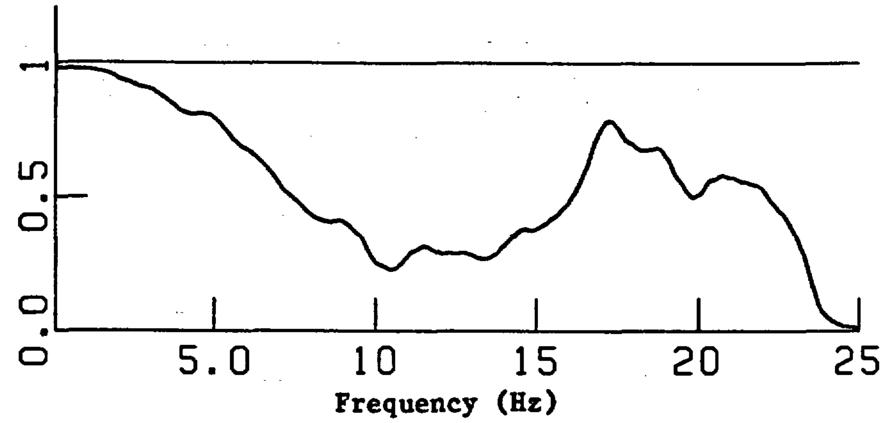
Seismic array measurements at alluvial margins are few, and none is directly applicable to the Yucca Mountain site. Field observations of seismic motion recorded by instrument arrays crossing the margins of three sediment-filled valleys were reported by King and Tucker (1984) and Tucker and King (1984). Wedge angles at the margins of the valleys, located in the Garm region of the USSR, are approximately 20°. Amplifications as high as a factor of 5, in certain frequency bands, were observed for horizontal motion in two valleys with shear wave acoustic impedance contrasts of 5 and 6. For the third valley, with an acoustic impedance contrast of 3, amplifications of alluvial response relative to rock were as high as 2. This case differed from the others in that the largest amplification occurred at the edge of the valley rather than at its center. Amplifications were found to be generally higher for horizontal motion parallel to the valley sides than for motion in the perpendicular direction. The amplification effects were found to be relatively insensitive to the azimuth of the earthquake sources and were similar for shear and coda waves. Durations of band-passed signals were similar at rock and alluvial sites, implying that the observed amplification was not due to high-Q resonance within the valleys. The lowest frequencies at which amplification occurred were not related in a simple manner to the local sediment thickness.

King and Tucker inferred that multiple reflections in the sediments at these sites were not primarily responsible for motion amplification. The opposite may apply at Yucca Mountain, where the geometry of the smaller wedge angle would be expected to enhance the effect of multiple reflections. In either case, however, the seismic attenuation is not known.

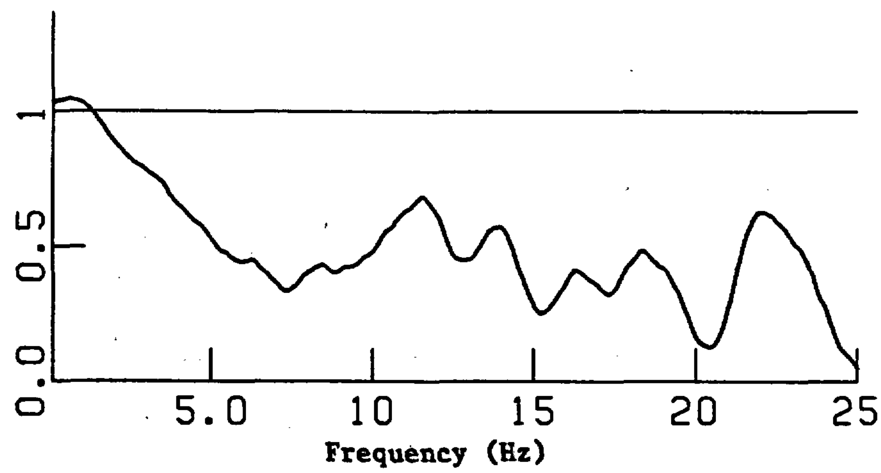
King and Tucker (1984) noted the engineering significance of the spatial variability of the observed motions. In one case, for the valley with the shear wave acoustic impedance contrast of 6, amplitudes varied by as much as a factor of 5 over a distance of less than 100 m. Smaller amplifications and spatial variation were observed for the valley with an acoustic impedance contrast of 3, similar to that estimated for the Yucca Mountain site.

Recordings of a UNE event on Pahute Mesa at stations in two candidate site areas were analyzed in this study for effects due to the seismic response of the alluvial wedges. The data were recorded at Stations 26 and 27, located in candidate site areas 3 and 4, respectively. (A description of the processing and analysis of the Yucca Mountain data is given in Chapter 8, and station locations are shown in Figure 8.1.)

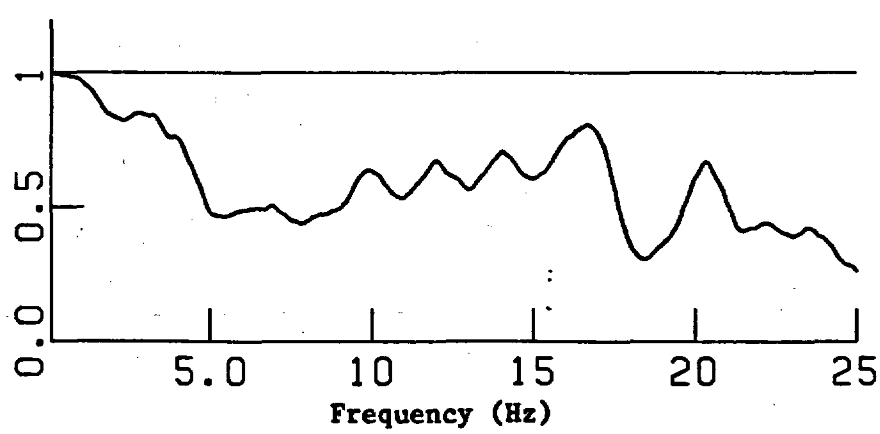
Station 27 is a surface-downhole pair, with the subsurface instruments located at a depth of 115 ft at the interface of the alluvium and Tiva Canyon Tuff. Downhole/surface spectral modulus ratios at this station are shown in Figures 3.1 and 3.2 for the whole record and for a 10-sec window of body waves arriving prior to the surface waves, respectively. (The spectral modulus is another term for the Fourier amplitude spectrum.) The spectral ratios decrease with frequency from values close to 1 at low frequency to about 1/2 at 7 Hz for the vertical component and 5 Hz for the horizontal component; they remain near 1/2 at higher frequencies. This frequency dependence is identical to that expected from the free-surface reflection of body waves in a halfspace, with the frequency at which the factor-of-two reduction is attained corresponding to a wavelength 4 times the subsurface depth. At lower frequencies (longer wavelengths), there is constructive interference of incident and reflected waves. Frequencies corresponding to a quarter wavelength for P and S waves in the 115-ft alluvial thickness were computed, using the estimated velocities, to be 5.4 and 3.3 Hz, similar to those for a factor-of-two reduction in the vertical and horizontal spectral modulus ratios. These frequencies also apply to the lowest-order resonances of the alluvial column, but pronounced resonances at these and higher frequencies are not apparent in the observed spectral ratios. To first order, the observed ratios can be accounted for in terms of the free-surface reflection effect, with little apparent effect due to



a. Vertical Component

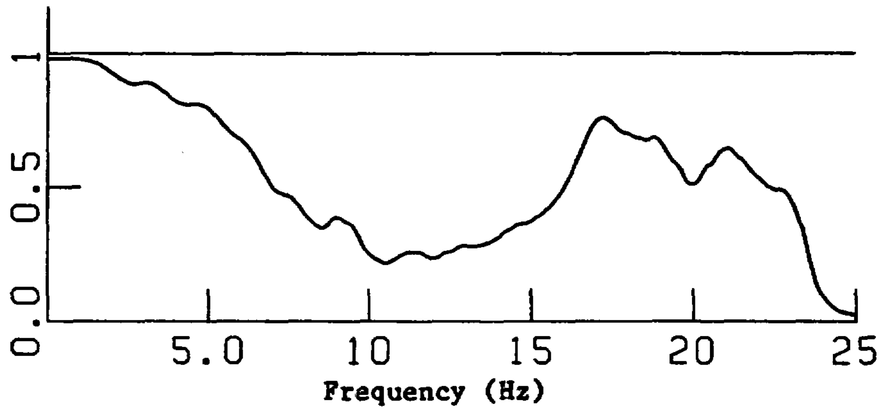


b. Radial Component

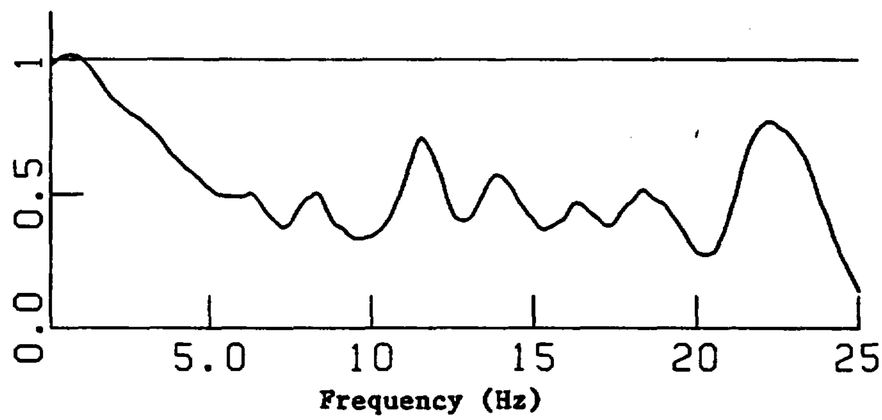


c. Transverse Component

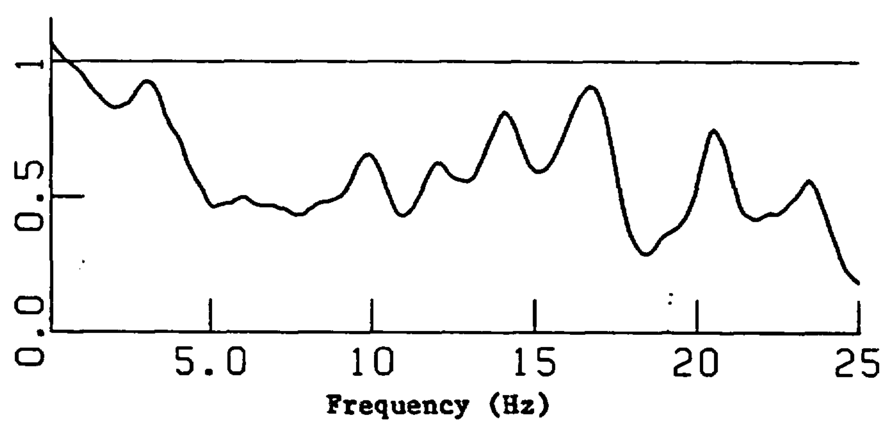
FIGURE 3.1 DOWNHOLE/SURFACE SPECTRAL MODULUS RATIOS FOR WHOLE RECORDS, STATION 27, EVENT KAPPELI



a. Vertical Component



b. Radial Component



c. Transverse Component

FIGURE 3.2 DOWNHOLE/SURFACE SPECTRAL MODULUS RATIOS FOR BODY WAVES, STATION 27, EVENT KAPPELI the bedrock interface, and no resolution regarding the effect of its dip. It is likely that seismic absorption is responsible for the absence of pronounced modal effects in the observed spectral ratios.

Additional information on seismic response was obtained by comparison of surface spectra at Station 27 with those at Station 26, situated on alluvium 1 km to the north in the reference conceptual site area, and at Station 14, situated on rock 2 km to the northwest (see Chapter 8, Figures 8.2 and 8.3). The observation that the surface spectra at these three sites are not greatly dissimilar suggests that the net effect of the alluvial wedge on seismic amplitudes is relatively small. However, these results for one event recorded at three widely spaced stations are not definitive. Analysis of signals recorded at these stations for other events at Pahute Mesa and Yucca Flat would be informative, but an array of smaller aperture is required to resolve wave-propagation effects in the alluvial wedge.

Available evidence does not provide strong grounds for discriminating among candidate sites in terms of seismic response. The theoretical studies using finite-difference calculations indicate that Rayleigh wave generation could be significant at the steeply dipping alluvium-bedrock interface formed by the Bow Ridge fault, affecting the eastern margins of candidate sites 7 and 8. However, Rayleigh wave generation would not be significant at the gently dipping alluvium-bedrock interfaces characteristic of the candidate sites. For small angles, the principal wedge effect expected from the theoretical results is multiple reflection of body waves, but this effect will be ameliorated by seismic absorption, not considered in the calculations. The absence of pronounced modal effects in UNE data recorded by the Station 27 downhole array suggests that the alluvium has significant seismic absorptivity. Seismic absorption could also account for the observed similarity of UNE motion amplitudes at rock and alluvial sites, in that seismic absorption will counteract the effect of dynamic amplification of motion in the alluvium. In summary, available evidence does not provide strong grounds for preferring one candidate site over the others or for preferring foundations in bedrock over those in alluvium. If large structures are to be sited on deep alluvium, it is advisable to consider the effects of possible differential motion over the foundation dimensions.

4. DATA NEEDED IN THE SEISMIC DESIGN OF UNDERGROUND FACILITIES

The various types of data needed in the seismic design of underground facilities are presented in this chapter. While seismic analysis and design procedures, and the data needed to conduct those procedures, are well established for surface facilities, such is not the case for underground facilities. The reason for this is partly that underground facilities are generally regarded as less vulnerable to vibratory ground motion and, therefore, are not generally designed for seismic loads. Moreover, very few critical facilities have been designed for locations with strong seismic environments, and no deep facilities similar to a nuclear waste repository have undergone the kind of licensing scrutiny that a repository will be subjected to. Hence, SNL requested that special attention be placed on the information needed for seismic design of underground facilities.

Since the types of data needed depend upon the types and sophistication of the analytic procedures, the discussion includes comments on the appropriateness of various procedures to the design of different types of components within the underground facilities, with emphasis on conceptual design. Some of the additional types of data needed for final design are indicated and discussed.

Seismic inputs to the underground facilities will result from both earthquakes and UNEs; therefore, ground motion generated by both types of sources must be considered in design. References to ground motion parameters (acceleration, particle velocity, displacement) and response spectra in this chapter imply both types of sources.

Components of the underground facility important for radiological safety of the public or of operating personnel must be designed to mitigate the consequences of an accident caused by vibratory ground motion. Radiological safety criteria are established by the U.S. Nuclear Regulatory Commission (NRC) in 10 CFR Parts 20 and 60 (NRC, 1983a, 1983b). In addition to radiological safety requirements, DOE may wish to require seismic design of certain portions of the underground facilities to reduce potential economic loss and possible hazards to operating personnel that might be hypothesized apart from radiological concerns. (Possible hazards to operating personnel need not be hypothesized for UNE ground motion because personnel can be evacuated before an event.)

It should be noted that building codes, such as the Uniform Building Code (UBC), presently (1985) do not address seismic design of tunnels, shafts, and other types of underground structures. Such codes would apply only to equipment and other freestanding components attached to tunnel walls, floors, or roofs or attached to shaft walls. Thus, most components in the underground facilities would not be designed for seismic loads unless assigned radiological or special importance. This is consistent with the practice for most other underground facilities. Mines are not, in general, designed for earthquakes; however, attention is commonly given to mitigating the effects of rock burst where that is a problem. Important civil projects, such as powerhouse chambers and subways, usually are evaluated for seismic motion when located in areas of high seismic activity.

Analytical and design procedures have been summarized by Owen and Scholl (1981). Specific details of how these procedures should be applied to the potential nuclear waste repository at Yucca Mountain for conceptual design are presented below in order to indicate the data needed for seismic design of underground facilities.

Underground Openings

The term "underground openings" is used here to refer to tunnels, shafts, chambers, and equipment alcoves excavated from rock. Support requirements may be nil or may consist of rock bolts, shotcrete, or steel sets. These support systems are sufficiently flexible that the underground opening will deform in conformance with the free-field vibratory ground deformations. Openings in alluvium, if any, will most likely be cut-and-cover concrete box structures. Since such structures are fairly rigid with respect to the soil, they are discussed later as cut-and-cover tunnels and are not included in this discussion of underground openings.

If underground openings need to be stabilized to resist ground motions (whether due to earthquakes or UNEs), simple analytical design procedures will certainly suffice for conceptual design. In these procedures, free-field strains are calculated on the basis of the one-dimensional wave equation. The largest value for free-field axial strain due to earthquakes is usually obtained by assuming that all of the energy is propagating in the shear wave. The Committee on Seismic Analysis of the Nuclear Structures and Materials Committee, American Society of Civil Engineers (ASCE, 1983), gives the axial strain due to the shear wave as $v_{max}/2V_s$, where v_{max} is the maximum particle velocity and V_s is the shear wave velocity in the surrounding rock mass. The surface wave will also create an axial strain given by v_{max}/V_r, where V_r is the Rayleigh wave velocity (ASCE, 1983). The question of which expression to use depends on whether the maximum particle velocity is associated more with the shear wave or the surface wave. The ASCE (1983) comments that this depends on the distance from the source and adds that "there is no hard rule for what the distance should be, but it is generally thought that the shear wave would control if the site is within one fault (rupture) dimension." It seems reasonable to assume for purposes of conceptual design for earthquake motion that the shear wave controls the calculation of strain in the alluvium and in the bedrock. However, Rayleigh waves may be more significant than shear waves in UNE motion. The Rayleigh wave becomes prominent at horizontal distances from an explosion of about five times the burst depth (Vortman, 1982). Since Yucca Mountain is located at distances from the various test areas that are greater than five burst depths, the Rayleigh wave will be fully developed by the time the ground motion arrives. Therefore, it is probably more appropriate to assume that the maximum particle velocity in the UNE motion is associated with the surface wave for both repository depth and shallow depths. These assumptions should be verified for final design.

The maximum axial strain parallel to the longitudinal axis of the opening is equal to the maximum free-field axial strain. The maximum axial strain circumferential to the opening is the maximum free-field axial strain multiplied by the dynamic strain concentration factor. We are not aware of any published derivation of this factor for a shear wave incident upon a cylindrical cavity. However, it can be shown that the static strain concentration factor for pure shear is $4(1 - \nu)$, where ν is Poisson's ratio.

Furthermore, Mow and Pao (1971) show that the dynamic stress concentration factor increases 10% to 15% over the static stress concentration factor as values of ν increase from 0.15 to 0.25. Thus, a conservative value for the dynamic stress concentration factor would be 4, a value used by Hendron and Fernandez (1983).

Dynamic strains (or stresses) computed using these simple procedures, together with strains (or stresses) due to in situ pressures and heat sources, are then compared with damaging threshold values of strains (or stresses) for the rock mass, the liner, or both. Given the simplicity of the dynamic model and uncertainties in calculated strains (or stresses), be they dynamic, static, or thermal, it is difficult to predict damage conclusively, let alone design to mitigate predicted damage. One way to approach this problem is to assess the rock support capacity using the strain (or stress) values in a qualitative rather than a quantitative sense and to redesign the rock support on the basis of geologic engineering principles. Such a procedure is described by Owen, Scholl, and Brekke (1979).

Hendron and Fernandez (1983) present a quantitative approach that uses the dynamic force from local wedges of rock at the boundary of the opening. Assuming that the rock mass at the opening moves with the rock mass surrounding the opening, local wedges will experience the free-field acceleration. Thus, the dynamic pressure on the support can be conservatively estimated as the weight of wedge in the side walls or the weight of the loose rock in the crown times the maximum acceleration expressed in percent of gravity.

In summary, the seismic data needed to evaluate the stability of underground openings at repository depth for earthquake or UNE motion in conceptual design consist of peak acceleration and peak particle velocity at that depth and the shear wave and Rayleigh wave velocities of the surrounding rock mass. In situ and thermal stresses, rock mass strength, and weights of potential rock wedges are also required; however, it is assumed that this information is already available for static design considerations.

In final design of the waste repository, more rigorous analytical procedures would be desirable, particularly for openings considered important for radiological safety. Computer models using time histories for the input motion and not just peak parameters of acceleration and particle velocity should be employed. These models will require such rock mass properties as density, seismic wave velocities (shear and compressional), Poisson's ratio (determined from seismic wave velocities), damping, and joint properties. Such models are available (for example, Dowding et al., 1982), but, in spite of their apparent sophistication, they are limited. To our knowledge, no computer program for predicting dynamic motions around a rock opening has been verified using field records of both the incident wave and the response of the opening. Furthermore, incident waves are highly complex, consisting of different wave types propagating in different directions. Thus, the representation of incident waves is simplified in the models, often as a single wave type, which is the same assumption used in the simplified procedures described above. Also, rock mass jointing around the opening cannot be completely known and, hence, cannot be accurately modeled. For these reasons, computer models must be regarded as being more useful for advanced parametric studies of opening response than for determining accurate predictions of stresses to use in design.

Finally, it is interesting to note that dynamic instability of rock openings is a problem in low-cycle fatigue. Thus, duration of the vibratory motion, in particular the duration of frequency components with significant strain amplitudes, may affect the potential for damage to openings. However, at this time, there is no theoretical or empirical basis for evaluation of dynamic stability using the expected value of the duration of the design earthquake or UNE motion. Duration is not useful in conceptual design except as a relative measure for comparing potential damage due to the two different ground motions. The use of a time history with a computer model in final design would automatically incorporate duration into the evaluation.

Underground Equipment

Underground equipment that may need to be evaluated for resistance to seismic motion may consist of alarm systems for safety and security, monitoring systems for radioactivity and air quality, power systems, and computers for controlling these systems. The procedures for analysis and design are the same as those for equipment located in surface facilities. Input motions need to be specified at support points. In conceptual design, it is sufficient to specify these input motions by response spectra; however, time histories may be necessary for final design. Since these components will be attached to the walls, floors, and roofs of the underground openings, they will be subjected to input motions that are essentially the free-field motions. Thus, the input motions for equipment in the underground repository should be expressed by response spectra at the appropriate depth.

In the present conceptual design of the repository, hoist systems will not be used to transport waste. Although these systems are not expected to be important to radiological safety, concerns about personnel safety and economic loss may dictate an evaluation of hoist systems for seismic motion. The dynamic behavior of the hoisting cable, suspended cage, and guides is linear in the vertical direction but may be nonlinear in the horizontal direction. An appropriate analysis would be to subject a finite element model to a time history input. However, for conceptual design, it may be satisfactory to determine bounds on hoist behavior by applying forces based on peak motion parameters or response spectra values to approximate support points of a simplified model.

Cut-and-Cover Tunnels

A portion of the waste-handling ramp may extend through alluvium. If it does, it is assumed that it will be a concrete box constructed by cut-and-cover methods. If this tunnel needs to be evaluated for seismic motion, simple analytical procedures will suffice for conceptual design. Assuming that tunnel deformations conform to the free-field motion (which is a conservative assumption), maximum axial strains along the longitudinal axis of the tunnel will be either the maximum free-field axial strain in the soil or the maximum bending strain. The former is given by the same expression presented above for underground openings: $v_{max}/2V_s$ or v_{max}/V_r. The latter, due to a shear wave propagating along the longitudinal axis, is given by Ra_{max}/V_s^2, where R is the maximum dimension of the tunnel and a_{max} is the peak ground acceleration (ASCE, 1983). Although values for v_{max} and a_{max} should correspond to the depth of the structure and may be smaller than surface values, surface values will suffice.

Buried reinforced concrete box structures should be evaluated for effects due to racking by the seismic wave. The shear distortion in the soil varies vertically from the surface of the alluvium to the top of the bedrock. For conceptual design, the distribution can be assumed to be linear, using the horizontal peak ground displacement in the alluvium at the surface and the horizontal peak displacement in the bedrock at the bottom of the soil column. The walls of the buried box structure should also be evaluated for dynamic soil pressure. Although not entirely applicable from a theoretical standpoint, the dynamic pressure is usually determined by the Mononobe-Okabe theory and applied at mid-height. Procedures outlined in ATC-6 (Applied Technology Council, 1981) should be used. Values of the peak acceleration are required for both the horizontal and vertical directions. Although the values should correspond to the depth of the structure, values at the ground surface should be sufficient.

In final design, computer models might be used to obtain reduction in axial strains for soil-structure interaction, vertical distribution of shear distortion in the soil, and dynamic soil pressures. The additional data needed will be a time history of the free-field motion and soil damping.

Other Considerations for Underground Structures

The above discussion indicates the seismic data needed for analysis of underground structures located in rock at repository depth and in alluvium at the ground surface. Since ramps and shafts penetrate the ground from the surface to repository depth, it may be necessary to analyze strains around these openings at intermediate depths in the bedrock. For conceptual design, it would be sufficient to conduct analyses at repository depth and at the bedrock surface. Therefore, peak accelerations and particle velocities are needed in the bedrock at its surface as well as at repository depth.

If a tunnel or shaft is excavated through an abrupt transition zone between large soil and rock masses, there may be a large differential vibratory displacement between the two masses concentrated over a short distance. A heavy concrete lining or box structure may have difficulty accommodating itself to the differential displacement. If it is determined that the structure will be damaged by this motion, a seismic joint should be incorporated into the design. Engineering judgment will have to be used in making this determination, which will require peak ground displacements in the bedrock and the soil adjacent to the soil-rock interface.

The stability of retaining walls and slopes adjacent to tunnel portals may also be of concern. Retaining walls can be evaluated using the Mononobe-Okabe formula as outlined by the ATC (1981). This requires values of the peak ground acceleration in both the horizontal and the vertical directions. Standard procedures are available for evaluating slope stability under vibratory motion. They also require vertical and horizontal values of peak ground acceleration.

Summary

Seismic evaluations of the underground facilities in the conceptual repository require various information about the design seismic motion. The need for response spectra and values of the peak parameters--acceleration, particle velocity, and displacement--have been identified at various depths in the underground repository. The needed quantities and their locations are indicated by check marks in Table 4.1. Dynamic analysis also requires shear wave velocities in the host rock and the surface alluvium and the Rayleigh wave velocity.

Design response spectra and design values for some of the desired peak ground motion parameters for earthquakes and UNEs are given in this report. Peak accelerations, peak particle velocities, and design response spectra for surface motion due to earthquakes are in Chapter 7 and for UNEs in Chapter 8. Peak ground displacements for UNEs are given in Chapter 8. Peak ground displacements for earthquakes can be estimated from the design accelerations using published studies on the relationships among the ground motion parameters; for example, see Mohraz (1976).

It is tentatively recommended that response spectra and peak motion parameters at repository depth be one-half the values at the ground surface. This is a first-order engineering approximation that should be adequate for conceptual design. This assumption has not been verified for earthquake

TABLE 4.1

ELEMENTS OF THE DESIGN SEISMIC MOTION REQUIRED FOR CONCEPTUAL DESIGN OF UNDERGROUND FACILITIES

Element	Location		
	Alluvium Surface	Bedrock Surface	Repository Horizon
Peak Acceleration	✓	✓	✓
Peak Particle Velocity	✓	✓	✓
Peak Displacement	✓	✓	
Response Spectra			✓

✓ = needed data

ground motion at the site and has been supported for UNE ground motion by analysis of only a small data set. Motion at depth is discussed in more detail in Chapters 7 and 8.

5. PROPOSED TERMINOLOGY FOR SEISMIC DESIGN CRITERIA

It is desirable to develop seismic design terminology that is unique for nuclear waste repositories. In order to develop rational definitions, the general classification of structures, systems, and components and their desired performance under various conditions must be considered. Therefore, in this chapter, we first propose definitions for the classification of facilities in terms of radiological safety and general performance objectives. Next, we recommend definitions for various levels of design ground motions. We conclude with a discussion of performance objectives in seismic design.

Definitions for the Classification of Facilities

Required performance for radiological safety is the primary means of classifying facilities. Structures, systems, and components that are "important to safety" during preclosure are defined by 10 CFR Part 60.2(a) as those engineered structures, systems, and components essential to the prevention or mitigation of an accident that could result in a radiation dose to the whole body, or any organ, of 0.5 rem or greater at or beyond the nearest boundary of the unrestricted area. (To facilitate further discussion, the word "facilities" shall be used to mean structures, systems, and components.) This criterion applies only to off-site exposure. At this time, neither NRC rules (10 CFR Part 60 and 10 CFR Part 20; 1983a and 1983b) nor proposed EPA rules (40 CFR Part 191; 1982) specify applicable limits for exposure on the repository site following an accident. DOE has established occupationally related exposure limits for operation of its nuclear facilities (DOE, 1981). These limits are probably appropriate for use in accident-scenario analyses of the conceptual design of a nuclear waste repository.

During the preclosure (operational) period of the repository, seismic events might cause accidental releases of radiation. Thus, facilities that are "important to safety" must be designed to meet radiological performance objectives for earthquake and UNE ground motions. The experience of nonnuclear facilities in recent earthquakes has demonstrated that the application of current seismic design requirements, such as the Uniform Building

Code (UBC; International Conference of Building Officials, 1982), does not necessarily insure functionality of important facilities after a major earthquake. The use of a larger value, say 1.5, for the importance factor I in the UBC lateral-force equations would appear to reduce the risk; however, major earthquakes have resulted in demands several times larger than the design capacity, not just 50% larger (URS/Blume, 1984). Thus, important nuclear facilities require special considerations for seismic design that go beyond normal code requirements. To achieve maximum safety for the general public, repository facilities necessary to mitigate off-site releases of radiation should be designed for a seismic design level that has a very high probability of not being exceeded during the operating period. Such a design level would represent severe earthquake ground motion for the moderately active region in which the proposed waste repository is located.

It seems reasonable that facilities that only affect on-site radiological safety need not be designed to resist a very high design level because administrative controls and personnel training can limit on-site, postaccident exposure. However, facilities necessary to mitigate on-site releases of radiation should be designed for a seismic design level that has a high probability of not being exceeded during the operational period. Such a design level would represent a moderate earthquake ground motion.

Some useful distinctions for classifying facilities are provided by Seismic Design Guidelines for Essential Buildings (URS/Blume, 1984). This guideline is a supplement to TM 5-809-10, which is referenced in DOE's General Design Criteria Manual as an applicable code for seismic lateral-force design (DOE, 1983). The supplement furnishes guidance for the design of "essential" and "high-risk" buildings that may require analytical procedures beyond the scope of TM 5-809-10. Essential facilities are defined as those "that are necessary for [postaccident] recovery and require continuous operation during and after an earthquake." These must remain functional in severe ground motion; whether or not they must remain undamaged depends on their functional requirements. High-risk facilities are those "where primary occupancy is for assembly of a large number of people," and, "where services are provided to a large area or large number of other buildings." Facilities in this classification may be permitted to suffer limited damage in severe ground motion, but they need to remain functional for moderate ground motion.

Both categories require analytical procedures and seismic loads beyond the scope of typical building codes, and one requires more attention than the other. In applying the distinction to waste repository facilities, it is clear that more attention should be placed on facilities necessary to mitigate off-site releases of radiation than on those necessary for on-site radiological hazard mitigation. Firefighting facilities, radioactive monitoring systems, and emergency power systems might be classified in the category requiring greater attention if they are needed to mitigate releases to the off-site environment. (The facilities mentioned above are only illustrative examples. Classification can only be properly performed through careful accident-scenario analysis of the entire repository facility.)

Nonradiological performance criteria should be considered in classifying facilities needing special design attention. The primary needs are the protection of personnel safety and the maintenance of important services (i.e., fire protection and emergency power) to a large area of the facilities. Such needs seem to be as important as maintaining on-site radiological safety and should be considered in that category.

Economic considerations may also provide a basis for classifying facilities. Damage to a facility may result in a direct loss for repairs or replacement and in an indirect loss for operational disruption.

These various considerations were used to define three classifications for repository facilities. Classification 1 facilities require special design considerations for severe ground motion. Classification 2 facilities need special design considerations for moderate ground motion. Facilities in the third category do not require special attention and may be designed by the lateral-force requirements in the UBC or TM 5-809-10, as necessary. For the purpose of seismic design, the three classifications are defined as follows:

1. Classification 1 Facilities

Those facilities that are "important to safety" as defined by 10 CFR Part 60.2(a) and therefore essential for maintaining off-site radiological safety during and following accidents. (It seems reasonable to expect that these facilities are also essential for maintaining off-site and on-site radiological safety during normal operations; however, that is not an issue in seismic design.)

2. Classification 2 Facilities

   a. Those facilities that are necessary for maintaining on-site radiological safety during and following accidents but that have no impact on off-site safety. (These facilities are probably also necessary for maintaining on-site radiological safety during normal operations.)

   b. Those facilities used for the assembly of a large number of people or for providing important services to a large area or a large number of other buildings.

   c. Those facilities whose loss would result in an unacceptable economic loss in physical property or in operational dysfunction.

3. Classification 3 Facilities

All other surface and underground facilities not included in Classifications 1 and 2.

During the process of classifying each facility, it may happen that a facility will fall into more than one classification. In that case, the lower numbered (i.e., more restrictive) classification must obviously apply.

This classification system applies only to preclosure facilities and is not intended for use with postclosure facilities. Some components of the postclosure facilities will be important to waste isolation and should be considered separately.

Definitions for the Design Ground Motions

The above discussion of classification of facilities indicates that two earthquake design levels--one representing severe ground motion, the other moderate ground motion--are needed in the design of critical preclosure facilities. It is proposed that these two levels be labeled the Design Earthquake 1 (DE-1) and the Design Earthquake 2 (DE-2), for the severe and moderate ground motions, respectively.

Since the preclosure facilities will also be subjected to ground vibrations created by the weapons testing program, the design of critical facilities should also consider two UNE design levels, designated as Design UNE 1 (DUNE-1) and Design UNE 2 (DUNE-2). In order to compare UNE design levels with earthquake design levels, the hazard levels need to be the same, and the methodologies should be comparable. The methodologies for assessing hazards from both earthquakes and UNEs are based on a probabilistic analysis using occurrence models as described in Chapter 6. The UNE ground motion hazard at Yucca Mountain due to current testing is negligible for design purposes. Although UNE occurrence is determined by human decision-making processes rather than natural processes, testing might assume the appearance of a random process if the historical testing program were repeated indefinitely into the future. Therefore, the UNE occurrence model is based on testing from a certain period of time hypothetically extended into the future with certain assumptions about the distribution of yields among test areas. By using a probabilistic approach, the value of the peak ground acceleration (or another peak ground motion parameter or spectral amplitude) can be obtained for both earthquakes and UNEs corresponding to the same hazard level.

The hazard level is best specified by the annual probability of exceedance, that is, the probability that a specific level of ground motion (usually peak ground acceleration) will be exceeded at a site or in a region in one year. The term "return period" is also used to specify the hazard level. The return period is regarded as the average time between occurrences of ground motion of a specific level or higher. Regarding earthquakes from a deterministic standpoint, the return period is also thought of as the average time between occurrences of a specific earthquake (specific magnitude and specific fault). However, this latter view is not applicable to UNEs because intermediate and high-yield detonations have occurred many times during fairly short periods of time. While it would be less confusing to discuss UNE motion levels only in terms of the annual probability of exceedance, return period will be used for convenience.

The repository facilities remaining after closure need to be evaluated for possible effects due to earthquake vibrations that may occur over an extremely long period of time, say 10,000 years. When considering release rates from the decommissioned repository, the only possible facility components that vibratory motion might affect would be the rock mass and seals. It does not seem likely that the passage of seismic waves through the repository will disturb either of these unless the seismic source is practically within the repository. Nevertheless, possible effects on the rock mass and seals should be considered. Since the rock mass cannot be "designed" (although seals can be), this ground motion will not be referred to as a design earthquake for the decommissioned period. We suggest naming it simply the Postclosure Earthquake (PCE).

Since these five ground motion levels (DE-1 and -2, DUNE-1 and -2, and PCE) are to be defined probabilistically, an acceptable level of risk must be specified in the form of an annual recurrence rate. Ideally, this level should be established by beginning with acceptable levels of risk to health from a major release of radioactive material and then working backward through structural fragilities and consequence analysis to arrive at the acceptable risk level for the causative ground motion. Although attempts have been made to formulate quantitative safety goals for nuclear power plants (NRC, 1980), such goals have not yet been accepted by society and its decision makers. Thus, guidance was sought instead from current thinking on risk levels associated with the Safe Shutdown Earthquake (SSE) and the Operating Basis Earthquake (OBE) for nuclear power plants.

Reiter (1984) notes that several studies appear to support the assumption that the chance of exceeding the SSE peak acceleration in the eastern U.S.

is on the order of 10^{-3} or 10^{-4} per year. Using this to define the level of risk for the OBE leads to a conflict. The OBE is defined, in Appendix A to 10 CFR Part 100, as "that earthquake which . . . could be reasonably expected to affect the plant site during the operating life of the plant." The regulation also indicates that the OBE acceleration should be at least one-half that of the SSE acceleration. Reiter comments on the conflict then created by the application of SSE risk levels:

> A reduction in peak acceleration by a factor of 2 in the eastern U.S. typically leads to an increase in probability of occurrence by a factor of 4 or 5. Taking into account the observation that the SSE may have an annual probability of exceedance on the order of 10^{-3} or 10^{-4} per year implies that the OBE could have an annual probability of exceedance on the order 5×10^{-3} or 5×10^{-4} per year. Assuming a Poisson distribution, these annual probabilities translate to exceedance probabilities of only 19% or 2% during the 40-year lifetime of a nuclear power plant. In other words, adhering to the one-half SSE criterion would appear to assure there was not a reasonable chance of the OBE being exceeded during the lifetime of a nuclear plant.

For this reason, Reiter notes, the NRC staff has at times accepted OBE levels that have roughly calculated annual probabilities of exceedance between 10^{-2} and 10^{-3} per year. Generally, within the earthquake engineering community, one will hear the SSE described as a level of ground motion with a 1,000-year return period (i.e., 10^{-3} per year) and the OBE as a level of ground motion with a 500-year return period (i.e., 2×10^{-3} per year). These risk levels fall within the ranges suggested by Reiter.

The DE-1 and DUNE-1 represent severe ground motions for their respective sources; therefore, they are similar in definition to the SSE for nuclear power plants. However, nuclear waste repository facilities will be fairly passive and will operate without radioactive water or steam and without the potential of core meltdown associated with power reactors. Assuming a Poisson distribution, the 1,000-year return period associated with an SSE corresponds to a probability of exceedance of 4% during the 40-year lifetime of a nuclear power reactor. Since the lifetime of the operating repository is assumed to be approximately 100 years, a 1,000-year-return-period event has a probability of exceedance of 10% in that lifetime. This seems a little high to permit recommendation of 1,000-year return period for severe ground motion to be used in licensing a waste repository; therefore, it seems prudent to increase the return period. This rationale supports the acceptability of a 2,000-year return period for the DE-1 and DUNE-1, with a probability of exceedance of 5% in 100 years.

The DE-2 and DUNE-2 are similar in definition to the OBE only because all are defined as ground motions with moderate risk and their primary orientation in radiological safety is on-site rather than off-site. An event with a 500-year return period has a probability of exceedance of 8% in 40 years and 18% in 100 years. Regardless of the greatly increased probability of exceedance in the longer lifetime, the passive nature of the repository operating facilities and the emphasis on on-site radiological safety, rather than off-site safety, allow the probability of exceedance higher than that for a nuclear power plant. Thus, a 500-year return period for the DE-2 and DUNE-2 appears acceptable.

The PCE is applicable for repository evaluations over a 10,000-year period; thus, this event should have a very long return period, comparable to that time period. At this time, data permit estimation of return periods to about 10,000 years. Therefore, the PCE should be established by a 10,000-year return period.

The five ground motion levels are defined as follows:

- <u>Design Earthquake 1 (DE-1)</u>
  This design level represents a severe earthquake motion for use in evaluating and designing Classification 1 facilities. It is determined from an appropriate probabilistic model of the seismicity of the site region. We recommend that the return period of the DE-1 level be 2,000 years. This corresponds to an annual exceedance rate of 5×10^{-4} and a probability of exceedance in 100 years of 5%.

- Design Earthquake 2 (DE-2)

  This design level represents a moderate earthquake motion for use in evaluating and designing Classification 2 facilities. It is determined from the same probabilistic model used to establish the DE-1. We recommend that the return period of the DE-2 level be 500 years. This corresponds to an annual exceedance rate of 2×10^{-3} and a probability of exceedance in 100 years of 18%.

- Design UNE 1 (DUNE-1)

  This design level represents a severe UNE motion for use in evaluating and designing Classification 1 facilities. In order to compare the DUNE-1 demand with the DE-1 demand, the annual exceedance rate is set at 5×10^{-4}.

- Design UNE 2 (DUNE-2)

  This design level represents a moderate UNE motion for use in evaluating and designing Classification 2 facilities. The annual exceedance rate should be 2×10^{-3} so that its risk level is comparable to the DE-2 risk level.

- Postclosure Earthquake (PCE)

  This ground motion level represents reasonable earthquake motions for evaluating postclosure facilities. We recommend that the return period of the PCE level be 10,000 years. This corresponds to an annual exceedance rate of 10^{-4} and a probability of exceedance in 10,000 years of 63%.

Performance Objectives in Seismic Design

The classifications refer to general performance objectives only and do not in any way imply specific engineering performance criteria. Such criteria should be generated from the process that leads to the designation of a facility in one category or another and from accident scenario analyses. For example, engineering performance criteria must specify whether structures, in general or specifically, are to respond in the elastic range or in the postyield range. The acceptable behavior is dictated by the functional requirements of the structure during and after the seismic event. The specification of engineering performance criteria is outside the scope of this project; however, some general guidelines regarding the development of performance objectives for the various classifications are in order.

- <u>Classification 1 Facilities</u>

  Facilities that fall under Classification 1 must be designed to resist severe ground motion (the larger of DE-1 and DUNE-1) with their essential functions remaining intact. This does not mean that all of these facilities must remain undamaged by the severe motion. Some of these facilities, or portions of them, may be allowed to sustain repairable damage; that is, they may be designed for limited postyield behavior. However, it may be necessary to require some facilities to remain undamaged; that is, they must remain elastic. An analysis of the functional requirements of the facility will lead to establishing desired behavior during severe ground motion.

- <u>Classification 2 Facilities</u>

  Facilities that fall under Classification 2 must be designed to resist moderate ground motion (that is, the larger of DE-2 and DUNE-2) in a manner consistent with their function. The functional requirements of these facilities necessary for maintaining on-site radiological safety (Classification 2a) may be established through accident-scenario analysis. It may be possible to reduce on-site exposure by administrative controls of postaccident procedures (evacuation procedures, use of protective clothing, etc.), thus reducing performance demands on the facilities. The functional requirements of these facilities without radiological safety functions are based on reducing potential threats to life or potential economic loss that might occur if the facilities were damaged.

- Classification 3 Facilities

  Facilities that do not fall into the above two classifications may be designed for the lateral force requirements in the UBC or TM 5-809-10. Facilities designed to these seismic design requirements are expected to resist minor earthquakes without damage; resist moderate earthquakes without significant structural damage, but with some nonstructural damage; and resist severe earthquakes without major failure. Design to these standards does not imply continued functionality of the facility following a severe earthquake; however, loss of functionality is acceptable for these facilities.

Classification 1 facilities, which are designed to resist severe ground motion, would be expected to resist moderate motion (that is, the larger of DE-2 and DUNE-2) with equal or better performance. However, it is common practice to combine the demands of severe ground motion with the demands of the unfactored dead load and a realistic estimate of the actual live load and also to combine the demands of moderate ground motion with the demands of the factored (i.e., increased) dead load and the design live load. This practice has, on occasion, resulted in a combined demand using the moderate ground motion that is greater than the one using the severe ground motion. However, the need to design Classification 1 facilities for both demand combinations cannot be established a priori; both the manner in which the demands are combined and the functional requirements of the facilities must be considered. These comments are intended only as a caution and do not imply that facilities in Classification 1 must be evaluated for the level 2 as well as the level 1 ground motions.

6. METHOD OF SPECIFYING DESIGN GROUND MOTIONS

Criteria for defining design ground motions are proposed in Chapter 5. Criteria are given for repository facilities of three classifications, based on radiological safety and general performance objectives. For the operating phase of the repository, criteria are given in probabilistic terms for facilities of Classifications 1 and 2. The criterion for the postclosure phase is also given in probabilistic terms. The purpose of this chapter is to outline how the probabilistic criteria are implemented to obtain design ground motions.

The Probabilistic Approach

Probabilistic specification of design ground motions is one element of a full probabilistic risk analysis that will be needed to evaluate risk in quantitative terms. This analysis will be performed when specific performance criteria and accident scenarios are developed. At present, the risk consequences of the given design levels are not known. Design levels 2 and 1 were formulated as having "high" and "very high" probabilities of not being exceeded during the operating phase, and the probabilities were quantified as 82% and 95%, on an ad hoc basis.

In addition to its role in overall risk assessment, probabilistic analysis of ground motion at the repository serves the need for a single parameter--exceedance rate--whereby hazards of different origins (earthquakes and UNE events) can be compared on a common basis and whereby criteria for performance over different time spans (operational and postclosure) can be quantified.

Initially, probabilistic analysis of UNE ground motion appears awkward, and "deterministic" analysis seems natural. Deterministic information on the location and maximum yield of possible future UNE events is well established, while the rate of future UNE occurrence, needed for probabilistic analysis, cannot be ascertained. However, standard deterministic analysis as practiced for earthquake ground motion assessment cannot be applied in the case of UNE ground motion because multiple, rather than single, event occurrences must be considered. This requires that both the number of occurrences of the deterministic event and the standard deviation of the ground motion attenuation function are needed in order to quantify the level of confidence that the design ground motion will not be exceeded during the operational phase of the repository. The method adopted for probabilistic analysis of UNE ground motion is to model UNE occurrence as distributed over prescribed testing areas and yield ranges, in a manner analogous to that for earthquake hazard analysis. Occurrence rates for the UNE model are based on past testing at NTS.

Probabilistic response spectra, defined in terms of exceedance rate (or its inverse, recurrence expectancy or "return period") are known as uniform-hazard spectra because they have a uniform likelihood of exceedance at all frequencies. They are obtained by performing hazard calculations for a spectrum of frequencies, using an attenuation relation that gives response spectral amplitude as a function of event size, distance, and spectral frequency. Suitable attenuation functions are available for earthquakes but not for UNE ground motion, and so uniform-hazard spectra have not been obtained for UNE events. Instead, spectral shapes for design UNE motions were obtained from statistical analysis of Yucca Mountain recordings of Pahute Mesa UNE events scaled to a common yield of 700 kt. The chosen yield of 700 kt is the limit established for possible future testing in the Buckboard Mesa area, the principal potential source of UNE ground motion hazard at the repository site. Probabilistic analysis of UNE peak ground acceleration, velocity, and displacement indicates that UNE uniform-hazard spectra would be similar in shape to those obtained for 700-kt events.

The two basic sets of information that are needed for probabilistic ground motion assessment are a description of ground motion amplitude as a function of event size and distance and a description of the rate of occurrence and distribution of events with respect to geography and size. The method of specifying these sets of information is discussed below.

Ground Motion Attenuation

Seismic ground motion criteria are conditioned by the kind of ground motion information that is available. In the case of UNE ground motion, site-specific data were available from Yucca Mountain recordings of Pahute Mesa events. These data were analyzed to determine site-specific adjustments to regression equations for peak ground motion obtained by Vortman (1984a) for Pahute Mesa events. The analysis yielded a significant positive amplitude anomaly for Pahute Mesa events recorded at Yucca Mountain, with the site-specific geometric standard deviation significantly lower than that for a site chosen at random, as determined by the statistics of Vortman (1984a). The details of this analysis are presented in Chapter 8. For present purposes, the amplitude anomaly is treated as a "site" effect that would apply for UNE events at all testing areas, although current investigations indicate some azimuthal and therefore "path" dependence (Vortman, 1984b). Probabilistic calculations were performed for both site-specific and random-site attenuation functions for component peak ground acceleration, velocity, and displacement. The standard deviation determined from the random-site statistics grossly overestimates the actual dispersion of signal amplitudes at a given site. For this reason, the site-specific results, while preliminary, were preferred and were used to determine peak vertical and horizontal (radial-component) ground accelerations for design levels 1 and 2.

The Yucca Mountain recordings are for relatively recent UNE events post-dating the 150-kt Threshold Test Ban Treaty. In order to obtain site-specific ground motion statistics, recordings for all of the events were scaled to a common yield. Yield scaling, using the algorithm of Mueller and Murphy (1971), also served the purpose of estimating spectra for events of higher yield than have been recorded at Yucca Mountain.

In the case of earthquake ground motion, there is as yet no site-specific information comparable to that for UNE events. Earthquake ground motion criteria were obtained from regression results given by Joyner and Boore (1982) for peak ground acceleration, velocity, and response spectral amplitude for the larger of two horizontal components. These results were obtained for shallow earthquakes recorded in the western U.S., principally in California, and are of uncertain applicability to the Yucca Mountain site region in terms of seismic source characteristics and seismic attenuation. Attenuation model-dependence of the probabilistic results was examined by performing parallel calculations for peak horizontal ground acceleration using attenuation models given by Campbell (1982) for California and for Utah. Very similar hazard results were obtained, albeit fortuitously, for the Joyner and Boore (1982) and Campbell (1982) Utah attenuation models when evaluated with the same coefficient of variation. The Joyner and Boore (1982) results were adopted for determining earthquake ground motion criteria because they provide a consistent basis for calculating response spectral amplitudes as well as peak ground motion amplitudes. For the vertical component, not considered by Joyner and Boore (1982), response spectral amplitudes were taken to be two-thirds those for the horizontal component for DE-1 and DE-2, modeled as near-regional events, and equal to the horizontal-component amplitudes for the PCE, modeled as a near-field event.

Event Occurrence Models

Both earthquake and UNE occurrence were modeled as Poisson point processes of constant rate and uniform distribution in prescribed seismogenic zones and testing areas, respectively. The Poisson model specifies the long-term rate of event occurrence and the distribution of interevent time intervals, but not the individual event times, i.e., the events are unpredictable. The UNE occurrence model was not based on current testing, which causes relatively insignificant ground motion hazard at Yucca Mountain, but rather on a hypothetical expansion of testing in terms of geography and yield. Testing was assumed to take place in the Buckboard Mesa area (see Chapter 8, Figure 8.11), which has not been used to date for UNE detonations. The closest distance from the Buckboard Mesa area to the reference surface facility site is 21.3 km. UNE occurrence was assumed to be distributed among the testing areas by yield according to established yield limits and in a manner that concentrates intermediate-yield events of the hypothetical testing model in the Buckboard Mesa area. Event yields were assumed to range up to 250 kt at Yucca Flat, from 250 to 700 kt at Buckboard Mesa, and from 700 to 1,500 kt at Pahute Mesa. The rate of UNE occurrence was based on the historic rate of testing at NTS during the period of intermediate- and low-megaton-yield detonations from mid-1963 to mid-1973. UNE recurrence rates were represented by a logarithmic relation between event frequency and yield, analogous to the earthquake frequency-magnitude relation

$$\log N = a - bM$$

where N is the annual number of events of magnitude M or greater. In the UNE analog, magnitude is replaced by the logarithm of the yield.

For earthquake hazard calculations, the optimal strategy for modeling the seismicity of the site region is a function of the quantity and quality of information on seismicity and tectonism of the region. Investigations initiated in support of the NNWSI project are rapidly enhancing the data base, particularly in regard to microseismicity and paleoseismicity (USGS, 1984). Yet to be assembled is a specific seismotectonic model that interrelates historic low-magnitude seismicity and earthquake focal mechanisms with paleoseismicity evidenced from fault scarp morphology and slip-rate data. For the present study, it was considered untimely to attempt assignment of seismicity on a fault-specific basis. Instead, seismogenic zones were delineated from regionalization of the southern Great Basin on the basis of historic seismicity, late Quaternary strain rates, and style of Late Cenozoic deformation, in a manner similar to that of Greensfelder et al. (1980). This approach relies on broad spatial averaging to determine historic and paleoseismic activity rates at magnitude thresholds of 4 and 7, respectively. It was found that the activity rates at these thresholds are generally consistent with a frequency-magnitude b-value of about 0.9, similar to that determined for a large catalog of historic western Nevada earthquakes (Douglas and Ryall, 1977). Historic seismicity data alone do not provide good resolution of the b-value for the seismogenic zones in the site region. The apparent compatibility of historic and paleoseismic activity rates established in this seismicity model is the key element of meaningful resolution of the seismic hazard, and model-dependent analysis without this element was not pursued. The adopted seismogenic zonation is considered satisfactory in representing spatially averaged long-term seismicity of the site region, although it is not based on a specific seismotectonic model.

Subsurface Ground Motion

Spectral modulus ratios of UNE recordings at repository depth and on the surface at the Yucca Mountain site were computed to examine near-surface propagation effects. The results, presented in Chapter 8, bear out the conclusion of Vortman and Long (1982a) that ratios of subsurface and surface motion are strongly site-dependent. Subsurface spectral amplitudes for both horizontal and vertical components were found to be significantly lower than those at the surface for all frequencies from 1 Hz up to the band limit of about 25 Hz. In the case of the horizontal components, subsurface spectral amplitudes were also significantly lower at frequencies less than 1 Hz, where a spectral ratio approaching 1 is expected. Spectral ratios for body-wave windows were similar to those for whole records, and a satisfactory explanation of the results was not found. To a fair approximation, the observed subsurface/surface spectral modulus ratios for Pahute Mesa UNE events can be represented by the value 1/2 over the entire frequency band of interest for vertical and horizontal components.

Similar results were obtained by King (1982) for earthquakes recorded at the surface and at a depth of 1,090 ft in the Paleozoic Eleana formation at Calico Hills, 12 km east of Yucca Mountain. Subsurface/surface response spectral ratios were found to be nearly independent of frequency over the recording band of 0.2 to 20 Hz, with a value of 2/3. This frequency behavior is similar to that observed for UNE motion at Yucca Mountain. The difference in spectral ratios for the two cases may be attributable to differences in geologic structure, constitution, and topography at the sites.

Pending the formulation of a physical model to explain these observations, the approximation adopted for present purposes is that subsurface/surface spectral ratios are frequency-independent for both earthquake and UNE motion. Subsurface/surface spectral ratios are taken to be 1/2 for both earthquake and UNE motion for interim design.

This assumption has not been verified for earthquake ground motion at the site and has been supported for UNE ground motion by analysis of only a limited data set; therefore, further investigations are recommended. Wide-band, high-dynamic-range recording at surface and subsurface locations is recommended for investigating earthquake motions at the repository site. Further analysis of Pahute Mesa and Yucca Flat events recorded at the Yucca Mountain array is recommended to investigate the spectral characteristics of subsurface and surface signals.

7. EARTHQUAKE GROUND MOTION

Seismicity, Seismotectonics, and Paleoseismicity

Ground motion criteria that are established on a probabilistic basis depend on the rate of earthquake occurrence and its distribution with respect to geography and magnitude. Rates of seismic activity in the site region can be measured from available data for two very different magnitude thresholds and time spans. Earthquake recording over the past several decades provides occurrence rates at a magnitude threshold of about 4, while geologic evidence on fault scarp morphology and displacement chronology provides occurrence rate estimates at a magnitude threshold of about 7 over the past several tens of millennia. In both cases, occurrence rate estimates require averaging over areas of thousands of square kilometers, as discussed subsequently. In addition to a large gap in the magnitude threshold of these occurrence rate estimates, there is a significant gap in understanding, from a seismotectonic standpoint, the relationship between historic low-magnitude seismicity and potential high-magnitude seismicity. Of particular importance is the question of the relationship between and relative importance of strike-slip and normal faulting in the site region.

Current information on the seismicity, seismotectonics, and geologic structure of the site region is discussed in a report by the USGS (1984). Epicenters and focal mechanisms of small earthquakes occurring in the NTS region from August 1978 to December 1982 are shown in Figure 7.1 (USGS, 1984, Figure 46). Focal plane solutions determined for three events all show strike-slip mechanisms, but in no case is the fault plane identified or associated with mapped faults. Events A and C are located near the northeast-striking Mine Mountain fault, but in neither case are the nodal planes consistent with displacement on this fault. Event A may be associated with right-lateral strike-slip on one of several north-striking faults that are mapped to the south of the Mine Mountain fault. Event B, located in the Yucca-Frenchman shear zone, is not clearly associable with any mapped fault. For the magnitude 4 Massachusetts Mountain earthquake of 1971, located 4 km north of event B, Carr (1974) determined a strike-slip mechanism with the preferred fault plane striking east-northeast.

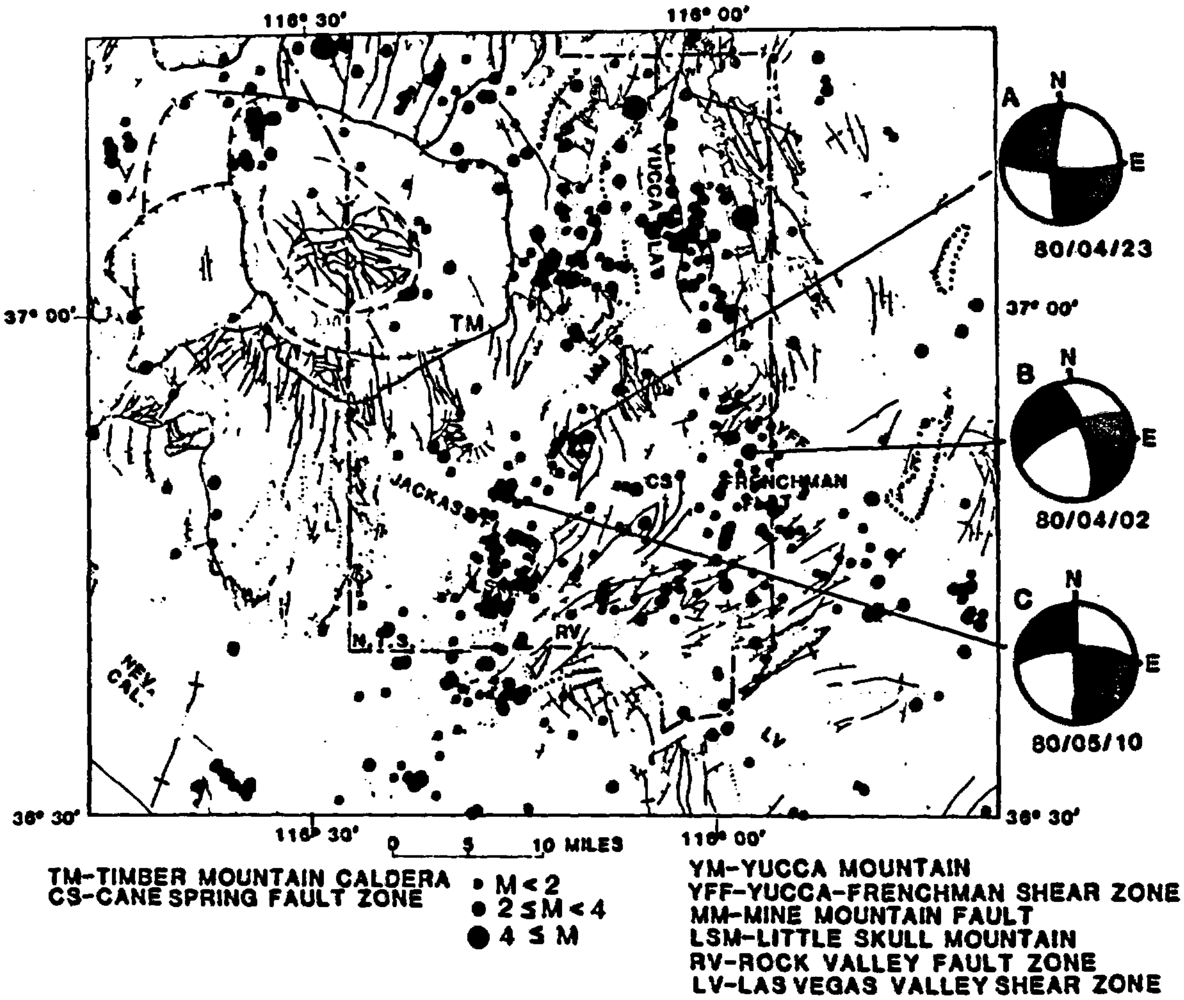


FIGURE 7.1 EARTHQUAKE EPICENTERS AND FOCAL MECHANISMS IN THE NTS AREA FROM AUGUST 1978 THROUGH DECEMBER 1982 (From USGS, 1984)

The USGS (1984), summarizing results for the NTS and adjacent parts of the southern Nevada seismic belt (Smith, 1978), concludes that "earthquakes occur principally as right-lateral strike-slip events on north-trending faults" (p. 76). While this appears to be the case for recent low-magnitude events in the NTS region and for the magnitude 6.1 event of 1966 located near the Utah border, it may not be generally true of large-magnitude seismicity in the site region. Conjugate left-lateral and right-lateral strike-slip on east- and north-trending faults and normal slip on northeast-trending faults are all consistent with the northwesterly least principal stress direction (Carr, 1974).

The historic and paleoseismic activity of the eastern front of the Sierra Nevada north of Bishop, California, may provide an instructive parallel with that of the southern Nevada seismic belt. Both are elongate zones of relatively high seismicity compared with adjacent regions on either side, and both exhibit substantial differences in crustal thickness across their widths. In both cases, normal faulting is clearly evident from paleoseismic evidence, and yet, in both cases, historic earthquakes primarily have strike-slip mechanisms. The seismic activity rate of the northeastern Sierra front is about an order of magnitude higher than that of the southern Nevada seismic belt, there having been some 35 events of magnitude 5 or greater and 5 events of magnitude 6 or greater in the interval 1910 to 1979 (excluding the 1980 and later sequences). Focal mechanisms determined for these events are most often right- or left-lateral strike-slip on northwest- or northeast-striking planes, and the events cluster where the major rangefront normal faults are offset in a left-lateral sense (Van Wormer and Ryall, 1980; Somerville et al., 1980). Just as it would be mistaken to consider that twentieth-century seismicity of the northeastern Sierra front is fully representative of long-term seismicity, given evidence of repeated Holocene displacement of major rangefront faults (Bell, 1981), it may be misleading to evaluate the seismic potential of faults in the southern Nevada seismic belt in a literal manner from historic seismicity and focal mechanisms. For this reason, no attempt was made in this study to assign seismicity on a fault-specific basis.

The strategy adopted for portraying the seismicity of the site region for seismic hazard analysis was to regionalize the southern Great Basin on the basis of historic seismicity, relative Late Quaternary strain rates, and style of Late Cenozoic deformation. This approach relies on broad spatial averaging to determine historic and paleoseismic activity rates at magnitude thresholds of 4 and 7, respectively. Seismic activity rates in the Great Basin are characteristically of the order 0.01 event of magnitude 4 or greater per year per 1,000 km^2 (Greensfelder et al., 1980). The spatial frequency of identified Holocene scarps, indicative of major (magnitude 7+) earthquake occurrence over the past 10,000 years, is characteristically of the order 1 per 10,000 km^2 (Bucknam and Algermissen, 1982). Measurement of historic and paleoseismic activity rates, therefore, involves averaging over areas of thousands of square kilometers. This approach has the potential disadvantage of "smoothing out" significant local variation of the seismic hazard.

An alternative strategy for representing the seismicity of the site region for seismic hazard analysis is to assign seismicity to identified faults on the basis of slip-rate estimates. This approach was used by Campbell (1980, 1984) for northeastern and southeastern NTS sites in close proximity to the Yucca and Cane Spring faults, respectively. This approach was not adopted for the present study because of incomplete information on recency and rate of displacement of faults in the Yucca Mountain vicinity. As information on faulting and seismotectonics in the site region develops, the fault-specific method will permit seismic hazard estimation with improved spatial resolution.

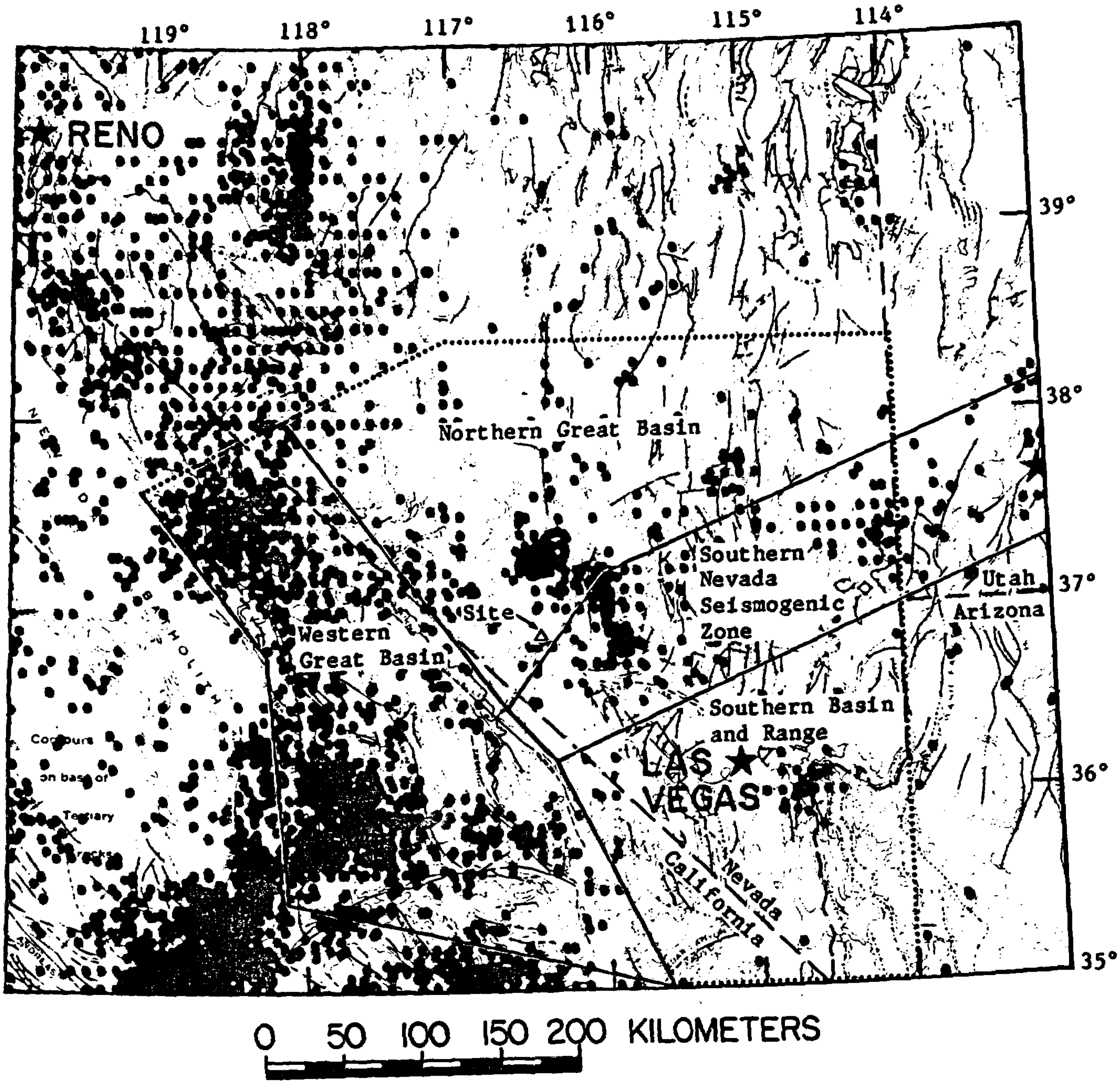
Seismogenic Zonation

In order to make a satisfactory probabilistic assessment of earthquake hazard at the Yucca Mountain site, it was decided to define extensive zones of long-term seismicity whose nearest approach to the site is less than or equal to about 100 km. The zoning presented here is based on data on historic seismicity and Pliocene-to-Quaternary-aged fault patterns. The result is termed a seismogenic zonation rather than a seismotectonic zonation because it falls short of identifying which faults are active and the style of current deformation.

The procedure undertaken for this study involved the following three steps: (1) a review of published literature on historic seismicity and Late Cenozoic tectonics of the southern Great Basin and southern Basin and Range provinces; (2a) delineation of two key seismogenic zones based principally on a concentration of seismicity along two prominent belts of Late Cenozoic faulting; (2b) definition of two additional zones flanking the key zones just noted; and (3) assignment of seismicity and maximum magnitude to all four zones. The first two steps are discussed below. Discussion of step 3 is left for the next section of this chapter. The four zones are shown in Figure 7.2, superimposed on the epicenter map of Smith (1978, Plate 6-1). Note that the concentration of epicenters approximately 50 km north and east of the site is due to UNE afterevents rather than natural seismicity.

Among the most comprehensive syntheses of seismotectonics for the entire study region is that by Greensfelder et al. (1980). In that study, the Great Basin was divided into five major subprovinces on the basis of the distribution and relative activity of Late Cenozoic (Late Pliocene and Quaternary) faults, as well as historic seismicity. One of the more important results of the research was further elucidation of the Southern Nevada Seismogenic Zone (SNSZ), which had been identified in the literature earlier. Smith (1978) refers to this zone as the southern Nevada East—West Seismic Belt. Significant characteristics of this zone include a well-documented concentration of historic seismicity, an apparent concentration of Late Quaternary normal faults, and an alignment of mapped left-lateral faults near or on a lineament, the "Garlock—Caliente lineament," detected on ERTS satellite photography (scale of 1:5M). Motion on these left-slip faults appears to be principally of Pliocene age but may extend into the Quaternary.

The SNSZ abuts an extremely active zone of seismicity and Quaternary faulting at its west end--the well-known Sierra Nevada frontal zone that includes Owens Valley, site of the great earthquake of 1872. This zone is herein widened eastward (i.e., its eastern boundary is shifted eastward) and is named the Western Great Basin (WGB). Together, the WGB and SNSZ dominate the seismotectonic activity of the southern Great Basin; they form a recumbent T pattern whose leg is the SNSZ. This pattern is quite evident in most published seismicity maps of the region, such as that by Smith,



Note: Seismogenic zone boundaries are shown by solid lines; limits of seismogenic zones as represented in earthquake hazard calculations are shown by dotted lines. The epicenter map is from Smith (1978, Plate 6-1). The concentration of epicenters approximately 50 km north and east of the site represents UNE afterevent activity, rather than natural seismicity.

shown in Figure 7.2. Seismicity rates of these zones were estimated by Greensfelder et al. (1980), and the further analysis conducted for the present investigation essentially confirms their results.

To the north and south, the SNSZ is flanked by the Northern Great Basin (NGB) and the Southern Basin and Range (SBR) zones, as defined herein. Lying entirely to the east of the prominent 118th meridian seismic zone of northwestern Nevada, the NGB exhibits considerably less seismicity than does the SNSZ or WGB. The SBR has almost negligible seismicity and Quaternary faulting in Nevada and Arizona (DuBois et al., 1982; C. Menges, personal communication, 1984). The fifth Great Basin subprovince recognized by Greensfelder et al. is the Colorado Plateau—Rocky Mountain Marginal Zone, which is not considered here because of its great distance from the site.

The accuracy of the zone boundaries within about 150 km of the site is estimated to vary from 10 km to 25 km. The best-defined boundary is that forming the east side of the WGB. It runs just a few kilometers to the east of the Death Valley—Furnace Creek fault system and extends northerly along this trend as far as Fish Lake Valley, Nevada. Although historic seismicity has been relatively weak between Owens and Death valleys, Quaternary faulting is not. East of the WGB, Quaternary faulting and seismicity are comparatively weak; the eastern boundary of this zone appears to correspond to the eastern limit of major right-slip faulting of Quaternary age. The southern boundary of the WGB lies along the Garlock fault, which separates the WGB from the very much less active Mojave block. The northern boundary of the WGB was drawn arbitrarily, but seismicity there is so distant from the site as to be inconsequential.

The boundaries of the SNSZ are more approximate than those of the WGB. They were drawn to enclose the east-northeasterly-trending belt of seismicity and pronounced Quaternary faulting that extends across southern Nevada. The information available on Quaternary faulting in this region is quite limited. The maps presented by Slemmons (1967) are still of a preliminary nature since they are based on ordinary high-sun-angle aerial photography (produced by the U.S. Department of Agriculture at a scale of 1:60,000). Other published geologic maps do not address the problem of Quaternary faulting. A report by the U.S. Geological Survey (1984) describes and maps Late Pliocene-to-Quaternary faults within about 160 km of the Yucca Mountain site. Except in a few instances, the report does not distinguish older from younger faults and therefore does not provide a basis for assessing rates of geologic seismicity in the study region. In drawing the boundaries of the SNSZ, we have relied heavily upon the fault maps of Slemmons (1967) and other fault data discussed by Greensfelder et al. (1980). The eastern boundary of the SNSZ is arbitrary but inconsequential by reason of its great distance from the site.

The location of the SNSZ—NGB boundary where it crosses NTS is important to hazard assessment of the site because of its proximity and the seismic contrast across it. Assessing the distribution of natural seismicity within NTS is problematical because, even with an event catalog with UNE events and identified afterevents deleted, we cannot know what natural events would have occurred in the absence of UNE testing. Therefore, delineation of the SNSZ—NGB boundary near and through NTS rested chiefly on the distribution and style of Pliocene-to-Quaternary faulting. The boundary is positioned along the most northerly of the left-lateral faults (trending north-northeasterly) that appear to characterize the northern edge of the SNSZ along most of its length. This trend is marked by the Cane Spring fault on the NTS and continues eastward along the Arrowhead Mine fault and Pahranagat shear system, correlatives of which are mapped as far east as Caliente, Nevada. Although motion on these faults appears to be principally of Pliocene age, they are herein considered to represent the northern edge of the SNSZ, whose interior contains a number of faults with similar trends. The SNSZ includes the southern half of the group of faults in and near Yucca Flat, which is believed to manifest undisputed Holocene displacements (USGS, 1984).

In order to investigate the paleoseismicity of the site vicinity, direct geomorphic evidence of faults was obtained by examining two sets of aerial photographs of the southern NTS area. One comprised 54 false-color infrared prints of the NHAP-83 series produced by the U.S. Department of Agriculture, Agriculture Soil Conservation Service, at a scale of 1:58,000. These prints cover a roughly square area extending east from Bare Mountain to Frenchman Flat and north from Mercury Valley to Shoshone Mountain.

Although no fault scarps were observed in alluvium, the small-scale, high-sun-angle, and low-contrast nature of these photos is not well suited to the task of detecting subtle fault traces. However, many fault-line scarps were evident, and most of them appeared to be highly dissected (thus a pre-Late Quaternary age is probable). Some of these scarps looked fresh and may represent Late Quaternary movements. The strong east-northeasterly trend of scarps and topography in this region is in marked contrast to that of the NGB. Also examined was a set of black-and-white aerial photos of the Bare Mountain and Yucca Mountain areas taken by the USGS in 1978 at a scale of 1:12,000. These revealed the well-known youthful bedrock scarp along the east side of Bare Mountain and also numerous fault-line scarps on and around Yucca Mountain; no scarps in alluvium could be seen.

Seismicity Models

The procedure used in establishing seismicity rates for the seismogenic zones consisted of (1) enumerating the activity rate at a magnitude threshold of 4; (2) assuming a trial frequency-magnitude b-value of 0.9, representative of large catalogs of Great Basin earthquakes; and (3) calculating the rate of major earthquakes ($M > 7$) and the crustal strain rate and comparing these with paleoseismic data on the spatial frequency of Holocene and Late Quaternary scarps and with geodetically measured strain rates. Lower- and upper-bound variants of earthquake recurrence consistent with estimated historic and paleoseismic activity were established for the SNSZ and NGB, which dominate the seismic hazard at the site.

It was found that, with a b-value of 0.9, there was general compatibility among historic seismicity, paleoseismicity, and geodetic data. This finding is important in justifying the probabilistic approach as providing meaningful resolution of the seismic hazard. With a b-value of 0.9, the historic seismicity of the SNSZ is higher than indicated by Holocene faulting and is more consistent with that represented by the concentration of Late Quaternary faults.

Primary evidence supporting a b-value near 0.9 is provided by the large catalog of western Nevada earthquakes described by Douglas and Ryall (1975), for which $b = 0.91$ for events of magnitude 4 to 7.5. For a much smaller catalog of events recorded by the USGS southern Nevada network, a b-value of 0.91 ± 0.04 was determined for events of magnitude 2.5 to 4.5 over a three-year interval (USGS, 1984).

The recurrence relation used in the probabilistic calculations is given by the density function:

$$-dN(M)/dM = a - bM$$

truncated at a specified maximum magnitude. N(M) is the cumulative distribution function giving the time- and area-normalized number of events with magnitude M or greater. Note that the density function, not the cumulative distribution function, is truncated at the maximum magnitude, a distinction that is important in assessing strain rate from seismicity rate (Anderson and Luco, 1983).

The seismic moment rate is computed from the magnitude-recurrence relation as in Anderson (1979), using the moment-magnitude relation of Thatcher and Hanks (1973):

$$\log M_0 = 16.0 + 1.5M_L$$

where M_0 and M_L are seismic moment and Richter local magnitude. This is practically the same as the relation between moment and moment-magnitude (M_W) given by Hanks and Kanamori (1979):

$$\log M_0 = 16.05 + 1.5M_W$$

Crustal strain rate ($\dot{e}$), measured in the direction of crustal extension, is calculated from the moment rate ($\dot{M}_0$) using the formula of Anderson (1979):

$$\dot{M}_0 = (2\mu V\dot{e})/0.75$$

where μ is the crustal rigidity, taken to be 3×10^{11} dyne/cm^2, and V is the volume of crust undergoing seismogenic deformation and is calculated for a seimogenic zone of depth 15 km (Smith and Bruhn, 1984).

Parameters of the seismicity models used in the hazard calculations are listed in Table 7.1. Lower- and upper-bound variants are given for the SNSZ and NGB, and these are referred to as the lower and higher seismicity models, respectively. The unit of measurement of historic activity rate, N4, is the number of events of magnitude 4 or greater per year per 1,000 km^2, as in Ryall et al. (1966) and Greensfelder et al. (1980). Calculated activity rates at a magnitude threshold of 7, N7, are expressed as the number of events with magnitude 7 or greater per 10,000 years per 10,000 km^2, for comparison with paleoseismicity rates evaluated by Bucknam and Algermissen (1982) in terms of the number of scarps per 10,000 years per 10,000 km^2. Strain rates in the direction of maximum extension are expressed in units of microstrain per year.

For the SNSZ, the lower-bound historic seismicity rate, N4 = 0.015, is as measured by Greensfelder et al. (1980) from California Institute of Technology (CIT) and University of Nevada, Reno (UNR), catalog data for an interval 1932-1962 preceding UNE testing at NTS. The combined CIT and UNR catalog approaches, but may not attain, complete reporting in this region for magnitude 4. A much higher rate, N4 = 0.11, was measured for the same 34,000-km^2 area from the National Oceanographic and Atmospheric Administration (NOAA) catalog for the interval 1963-1973. This measurement is contaminated by UNE events and afterevents at NTS and also by inclusion of the 1966-1967 sequence near the Utah border, which, while belonging to the SNSZ, does not appear to represent the seismicity of an average decade. For the present study, measurements were made for a smaller area of 21,000 km^2 from a catalog compiled by SNL from various sources, with UNE events and identified afterevents deleted. A rate N4 = 0.045, determined for the interval 1960-1980, was adopted for the higher seismicity model.

Strain rates and rates of magnitude 7+ seismicity in the SNSZ were computed from the historic seismicity rates assuming a maximum magnitude of 7.5. For an event of this magnitude on a normal fault, an expected rupture length of about 50 km is indicated by the western U.S. data in the set compiled by Bonilla et al. (1984). While this length is large in comparison with the mapped lengths of faults in the SNSZ, the possibility of multiple ruptures totaling this length cannot be ruled out. For the lower estimate of historic activity rate, N4 = 0.015, a b-value of 1.0 yields a calculated

TABLE 7.1

SEISMICITY MODELS USED FOR EARTHQUAKE HAZARD ANALYSIS

Seismogenic Zone		b-value	M_{max}	N_4*	N_7†	$\dot{e}$ (microstrain/year)
Western Great Basin		0.9	8.0	0.15	26.0	0.047
Northern Great Basin	A	0.9	7.5	0.015	1.9	0.0024
	B	1.0	7.5	0.0075	0.5	0.0007
Southern Nevada Seismogenic Zone	A	0.9	7.5	0.045	5.8	0.0071
	B	1.0	7.5	0.015	1.0	0.0014
Southern Basin and Range		0.9	7.0	0.0015	--	0.0001

* Measured number of earthquakes of magnitude 4 or greater per year per 1,000 km^2

† Calculated number of earthquakes of magnitude 7 or greater per 10,000 years per 10,000 km^2

A Higher seismicity model

B Lower seismicity model

N7 of 1.0 (Table 7.1). This is compatible with the paleoseismic zonation of Bucknam and Algermissen (1982), in which the zone containing the SNSZ has N7 = 0.7. This broad zonation does not distinguish the SNSZ from adjacent regions to the north and south. Bucknam and Algermissen (1982) estimate that their mapping method records not less than 80% of earthquakes with magnitude 7 and greater that have occurred in the past 15,000 years. For the higher estimate of historic activity rate and the preferred b-value of 0.9, the calculated N7 is 5.8. This exceeds the largest value, 3.4, determined by Bucknam and Algermissen (1982) for a zone in north-central Nevada where mapping is most complete. Slemmons (1967) shows comparable densities of Late Quaternary faulting in the SNSZ and in north-central Nevada but a much lower density of Holocene faults in the SNSZ relative to north-central Nevada. Thus, the higher seismicity model is compatible with Late Quaternary fault data, while the lower seismicity model is more compatible with Holocene fault data.

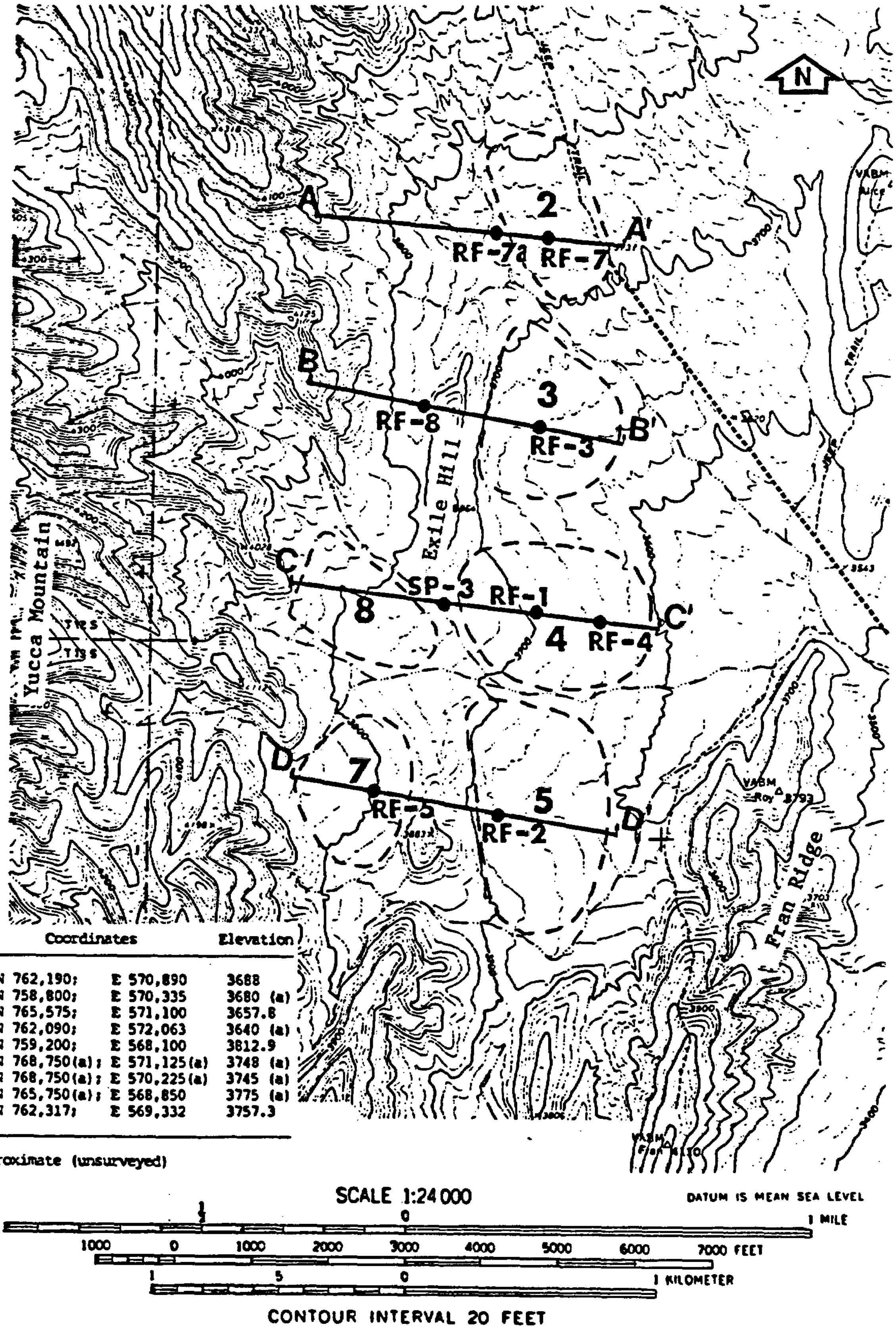
Extensional strain rates of 0.0014 and 0.0071 microstrain/year are predicted for the lower and higher seismicity models for the SNSZ. Geodetic data obtained from a trilateral network in Yucca Flat are indicative of nearly pure shear strain, with maximum principal strains oriented north-south and east-west (Prescott, 1985). Strain rates determined over the interval 1971-1983 are -0.10 and 0.08 microstrain/year for the north-south and east-west directions, with uncertainties of 0.02. Such strain rates cannot be accommodated by the present seismicity models and are assumed to represent an anomalous response, perhaps related to UNE testing at Yucca Flat.

Recurrence rates of earthquakes with magnitude 6 or greater in the 30,000-km^2 area of the SNSZ considered here are approximately 0.5 and 2 events per century for the lower and higher seismicity models. The only such event in the historic record of the past century is the magnitude 6.1 earthquake of 1966 that occurred near the Nevada-Utah border (von Hake and Cloud, 1966). Thus, there is no example of a recurrence interval for magnitude 6 in this zone, unless one includes the earthquake of 1908 reported in Death Valley, whose magnitude was estimated to be 6-1/2 (Richter, 1958). Inclusion of this event, whose location is uncertain, would give a rate consistent with the higher seismicity model.

For the NGB, the lower-bound historic seismicity rate given in Table 7.1, N4 = 0.0075, was obtained from Model B of Rogers et al. (1977). This rate was evaluated from the historic seismicity of the Great Basin exclusive of the 118th meridian zone of historic ruptures. The upper bound, N4 = 0.015, was obtained for the interval 1940-1980 from the catalog furnished by SNL. With b-values of 1.0 and 0.9, respectively, for the lower and higher seismicity models, and for a maximum magnitude of 7.5, recurrence rates of major earthquakes, N7, were calculated to be 0.5 and 1.9 (Table 7.1). By comparison, N7 values in the paleoseismic zonation of Bucknam and Anderson (1982) are 0.7 in the region to the north of the site, zero in a region immediately to the northwest, and 1.7 further to the northwest. No representative geodetic data are available for comparison with the calculated strain rates. A trilateration network has recently been installed by the USGS at the Yucca Mountain site to obtain strain measurements.

For the WGB, the adopted historic seismicity rate, N4 = 0.15, is that determined by Greensfelder et al. (1980) from a composite of sources for the interval 1932-1973. In the present study, the eastern margin of the WGB is drawn further to the east, as noted above, incorporating a region of relatively low historic seismicity. However, a downward adjustment of the above seismicity rate is not warranted in view of the evidence cited above for substantial paleoseismicity of the Death Valley—Furnace Creek fault system. The calculated strain rate, assuming a maximum magnitude of 8, is 0.047 microstrain/year. This strain rate is comparable in amplitude with principal strain rates of 0.08 and -0.07 microstrain/year, oriented west-northwest and north-northeast, determined from trilateration surveys in Owens Valley in the interval 1974-1979 (Savage, 1983).

In the SBR, the historic seismic activity rate is approximately an order of magnitude lower than that to the north. The most significant activity to date has been that induced by the impoundment of Lake Mead in 1935; this seismicity contaminates the N4 estimates of Greensfelder et al. (1980). For the present study, the historic seismicity rate adopted for the SBR was obtained from analysis of the Arizona earthquake catalog of DuBois et al. (1982). For instrumentally determined epicenters in the interval 1950-1980, N4 values of 0.0033 and 0.0002 were determined for zones 1 and 3 as defined by DuBois et al.; an average value of 0.0015 for these two zones,



	Coordinates		Elevation
RF-1	N 762,190;	E 570,890	3688
RF-2	N 758,800;	E 570,335	3680 (a)
RF-3	N 765,575;	E 571,100	3657.8
RF-4	N 762,090;	E 572,063	3640 (a)
RF-5	N 759,200;	E 568,100	3812.9
RF-7	N 768,750(a);	E 571,125(a)	3748 (a)
RF-7A	N 768,750(a);	E 570,225(a)	3745 (a)
RF-8	N 765,750(a);	E 568,850	3775 (a)
SP-3	N 762,317;	E 569,332	3757.3

(a) Approximate (unsurveyed)

FIGURE 2.1 LOCATIONS OF CANDIDATE SURFACE FACILITY SITES (Modified from Neal, 1985) which together occupy most of Arizona, was adopted for this study. A maximum magnitude of 7 was assumed for the SBR.

Ground Motion Attenuation

The second basic element of seismic hazard assessment, in addition to an earthquake occurrence model, is a description of strength of shaking as a function of earthquake magnitude and distance. Such a description is called a ground motion attenuation function. Ground motion attenuation functions from the regression results of Joyner and Boore (1982) and Campbell (1982) were used in the probabilistic calculations. Both are based on accelerograph data principally from California earthquakes, but Campbell (1982) provides for explicit adjustment according to the crustal anelastic attenuation.

Joyner and Boore give attenuation functions for 5%-damped response spectral velocity, in addition to peak ground acceleration and velocity, and these are used to compute uniform-hazard spectra. The data analyzed by Joyner and Boore were for shallow earthquakes in western North America in the magnitude range 5.0 to 7.7. Magnitudes are determined on the moment-magnitude scale (Hanks and Kanamori, 1979). Distance is defined in terms of the closest distance between the recording site and the vertical projection of the earthquake rupture surface. Results for peak horizontal ground acceleration and velocity are given only for the larger of two horizontal components. The larger of two horizontal acceleration components is on the average 13% higher than the mean (Campbell, 1981).

Seismic hazard calculations were also performed using the Campbell (1982) attenuation function, which explicitly incorporates anelastic attenuation as a parameter. This permits evaluation of the effect of different estimates of crustal attenuation in the site region. Campbell analyzed data for shallow earthquakes, mostly in California, with magnitudes in the range 5.0-7.7. The magnitude scale is defined as M_S for magnitudes 6.0 or greater, and M_L for magnitudes less than 6.0. This scale is generally consistent with the moment-magnitude scale. Distance is defined as the closest distance from the site to the earthquake rupture surface. In the present calculations, depth to the rupture surface was assumed to be 5 km for magnitudes less than 5.5 and 0 for magnitudes greater than 6.5. For magnitudes between 5.5 and 6.5, taken as the lower threshold for surface rupture and the upper threshold for no surface rupture, rupture depth (Z) was modeled as:

$$Z = 2.5 + 2.5 \cos [\pi (M - 5.5)] \text{ km}$$

The Campbell regression results are for the mean of two horizontal components of peak acceleration.

The Campbell equation explicitly incorporates the coefficient of anelastic attenuation, which is inversely related to the seismic quality factor (Q). Calculations were performed for both the California and Utah Q models of Campbell (1982). While Campbell (1984) used a Q model for NTS that has higher attenuation (lower Q) than his Utah model, the Utah model was used in this study because it is more consistent with Q estimates based on measurements at NTS (Rogers, 1984). Q values for the Campbell models and for the NTS model preferred by Rogers are listed below.

	Frequency (Hz)		
	1	5	10
Campbell (1982), California	150	363	532
Campbell (1982), Utah	500	690	792
Rogers (1984), NTS	600	705	755

The Campbell (1982) equation yields attenuation curves whose shapes are magnitude-dependent, while those of Joyner and Boore (1982) do not. In spite of this and other differences indicated above, differences in predicted mean PGA are small compared to the statistical uncertainty. The most important difference between the equations, for purposes of probabilistic hazard assessment, is in their standard deviations. The Joyner and Boore regression for PGA has a much higher geometric standard deviation, 1.9, than that determined by Campbell, 1.5. Direct evidence is lacking as to the dispersion of earthquake ground motion amplitudes in the site region. However, there is a large volume of information on the statistics of UNE ground motion recorded in the site region. This information is of uncertain applicability to earthquake ground motion because of differences in source mechanism and degree of heterogeneity and anisotropy in the source region, as well as in the composition of ground motion by wave type. For Pahute Mesa UNE events, Vortman (1984a) determined geometric standard deviations of about 2 for component peak acceleration, velocity, and displacement. Much lower geometric standard deviations, less than 1.5, have been reported at specific sites (Vortman, 1980). At Station 14 on the Yucca Mountain site, standard deviations of 1.46 were determined for vertical and radial PGA for eight yield-scaled Pahute Mesa UNE events, as reported in Chapter 8.

In order to illustrate the importance of the standard deviation in hazard estimation, and to compare results for the Campbell (1982) and Joyner and Boore (1982) equations, hazard calculations were performed with standard deviations of both 1.5 and 1.9 in each case. The larger value is preferred because it is closer to the Vortman (1984a) results, although a sound basis for comparison is lacking, as noted above. The smaller value is closer to site-specific results for NTS events, and its use is considered inappropriate pending the outcome of investigations of the nature of seismic amplitude anomalies observed at Yucca Mountain for UNE events, discussed in Chapter 8.

Lacking in both the Campbell (1982) and Joyner and Boore (1982) regressions are results for the vertical component.

A potentially important limitation of the present results arises from applying the above attenuation functions to earthquakes represented as point sources, i.e., fault distance is equated with epicentral distance. This will underrepresent the area affected by motion of a given level for earthquakes of significant rupture length and, therefore, may underestimate the hazard due to large events, depending on their distribution relative to the site. This effect will be less important for high frequencies and PGA, where the contribution of smaller events is dominant, than for lower frequencies, where larger events dominate the hazard. Thus, the uniform-hazard spectra may tend to be underestimated at the longer periods.

The attenuation functions adopted for the earthquake ground motion criteria given herein are those of Joyner and Boore (1982). Their applicability to the site region is evaluated as follows. There is conflicting evidence as to whether there are significant differences in seismic attenuation between southern Nevada and California. King and Hays (1977) compare distance exponents of response spectral amplitude from recordings, predominantly on alluvium, of NTS events in southern Nevada and earthquakes in California. The distance exponents are practically identical over the full band width of the data, from 0.05 sec to 2.5 sec. For aftershocks of the 1975 Pocatello Valley, Idaho, earthquake recorded on alluvium in northern Utah (King and Hays, 1977), distance exponents were significantly larger (indicating stronger attenuation) than for the California and southern Nevada data. This result is opposite to that obtained by Campbell (1982) based on Q estimates for north-central Utah.

Additional evidence on seismic attenuation in the Great Basin is provided by Chavez and Priestley (1985), who report synthetic Richter magnitude determinations of earthquakes of the 1980 Mammoth Lakes, California, sequence. Seismograms recorded in the Great Basin in the distance range 100 to 600 km show more attenuation (about 0.3 magnitude units) than predicted by Richter's attenuation curve for the California local magnitude scale. Synthetic Richter magnitudes determined at near distances exhibit the same form as observed for earthquakes in southern California and Baja California.

In summary, there is conflicting evidence as to whether seismic attenuation in the Great Basin is greater or less than in California. The use of California data, such as Joyner and Boore's (1982), will not lead to known bias in the hazard estimation.

Another issue concerning the applicability of California strong motion results to the site region is the possibility of systematic differences in strong motion related to differences in the state of stress and earthquake mechanism. This possibility has been suggested by McGarr (1984), who finds that near-field accelerations for earthquakes in compressional tectonic regimes may be three times higher than in extensional tectonic regimes, with intermediate accelerations indicated for strike-slip earthquakes. If so, attenuation relations based on data principally from California earthquakes would tend to overestimate earthquake accelerations in the site region. This is because a significant fraction of thrust events, in addition to strike-slip events, are represented in the California accelerograph data, while earthquakes in the site region are expected to have normal faulting and strike-slip mechanisms. The data considered by McGarr (1984) are for a wide range of magnitudes, from mine tremors to large earthquakes, and are therefore of considerable relevance to repository design. However, the effects of seismic absorption on the data and on their interpretation have not been evaluated. Thus, it is considered premature to apply the preliminary results on the effect of state of stress to the present ground motion criteria.

Probabilistic Calculations

Probabilistic calculations were performed using a computational algorithm that transforms information on the recurrence rates of earthquakes in the site region into information on the recurrence rate as a function of motion amplitude at the site. The basic element of the calculation is evaluation of the probability of exceeding a given site motion level, given the occurrence of an earthquake of specified magnitude and location. This evaluation is obtained from the attenuation function and its standard deviation and is repeated for closely spaced locations within the seismogenic zone. The results are integrated over the seismogenic zone, assuming uniform likelihood of occurrence throughout, to obtain the probability of exceeding the given site motion level when an earthquake of the specified magnitude occurs somewhere in the seismogenic zone. The probability obtained from the spatial integration is then multiplied by the rate of occurrence of earthquakes of the specified magnitude, as given by the seismicity model. These calculations are repeated at closely spaced magnitude intervals, and the results are then integrated to obtain the rate of exceedance of the given site motion level due to earthquakes of all magnitudes up to the maximum magnitude for the seismogenic zone. (A lower magnitude limit of 4.0 was used in the present calculations.) Results for all seismogenic zones are summed to give the total rate of exceedance of the given site motion level. Parallel calculations are performed for motions of different level and kind.

PGA Parameter Study Results. PGA hazard calculations were performed with variations in seismicity, crustal attenuation using the Campbell (1982) models for California and Utah, and PGA standard deviation. In addition, results were obtained for the preferred seismicity model using the Joyner and Boore (1982) PGA attenuation model. Variations in seismogenic zonation were not considered.

Figure 7.3 shows results obtained using a PGA geometric standard deviation of 1.5, as determined by Campbell (1982). This value is similar to the site-specific coefficient of variation observed at Yucca Mountain for Pahute Mesa UNE events and is not considered appropriate for earthquake hazard analysis in the absence of site-specific information on seismic response at Yucca Mountain during earthquakes. The four hazard curves (solid lines) obtained using the Campbell attenuation functions are for lower and higher seismicity models and for California and Utah attenuation. The Utah attenuation model yields exceedance rates about 50% to 100% higher than the California model. Results for the higher seismicity model and the Joyner and Boore (1982) attenuation model (dashed line) give PGA values about 15% higher than for Campbell's Utah model. Allowing for a 13% difference between the larger and the average of horizontal PGA components (Campbell, 1981), the results are nearly identical.

Figure 7.4 shows results obtained using a PGA geometric standard deviation of 1.9, as determined by Joyner and Boore (1982). This value is considered appropriate for hazard estimation in the absence of site-specific information on earthquake ground motion at Yucca Mountain. Results obtained using the Campbell attenuation functions (solid lines) again are for low and high seismicity models and California and Utah attenuation models. The hazard curve for the higher seismicity model and the Joyner and Boore (1982) attenuation function (dashed line) is nearly identical to that for Campbell's Utah attenuation model, allowing for a 13% difference between the larger and the average of horizontal PGA components.

Acceleration exceedance rates for the high-seismicity models are approximately two to five times greater than for the low-seismicity models, in proportion to the difference in seismicity rates for the two models. For a given exceedance rate, peak accelerations are typically one-third greater

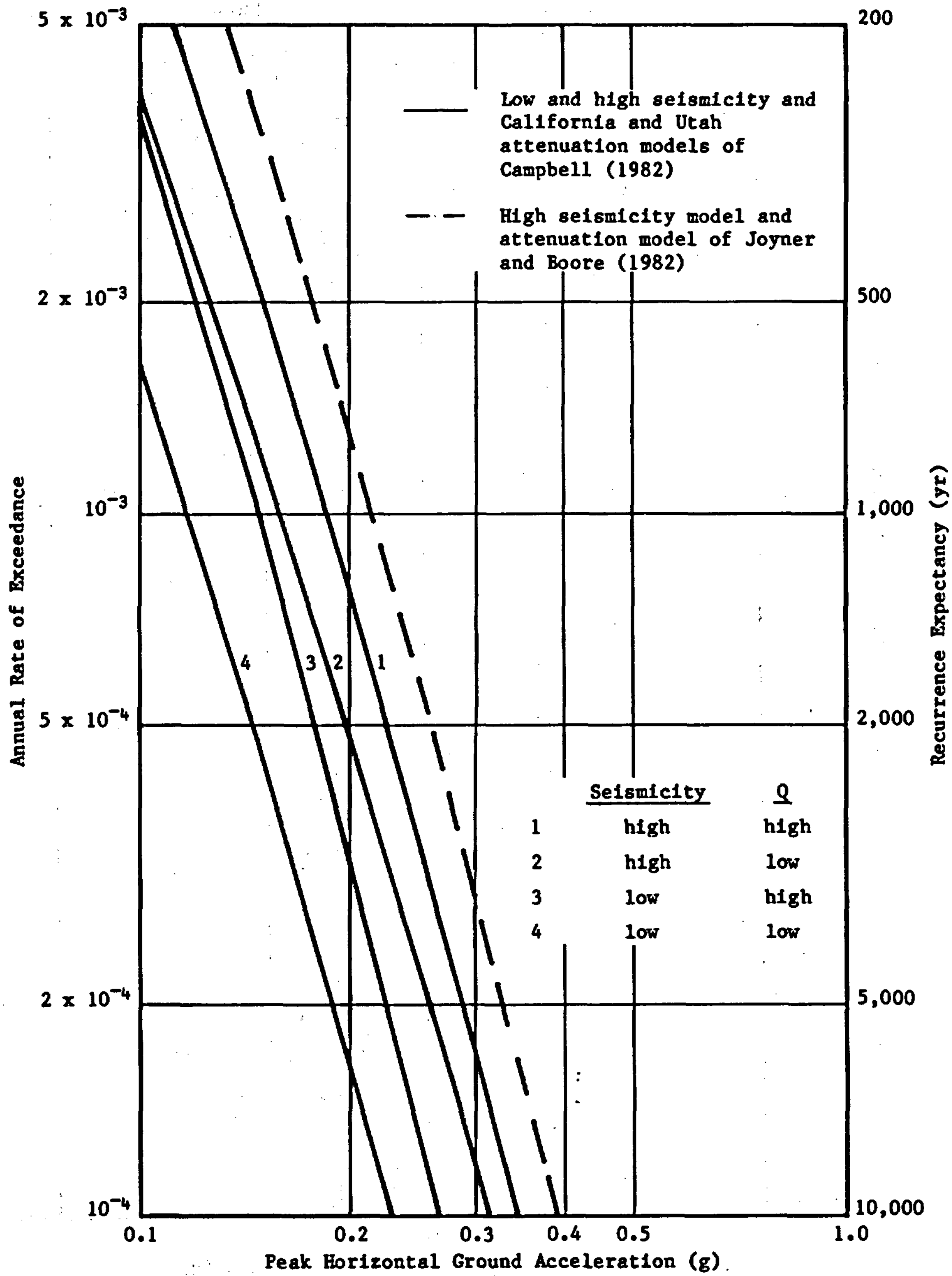


FIGURE 7.3 EARTHQUAKE HAZARD RESULTS FOR PEAK HORIZONTAL GROUND ACCELERATION EVALUATED WITH A GEOMETRIC STANDARD DEVIATION OF 1.5

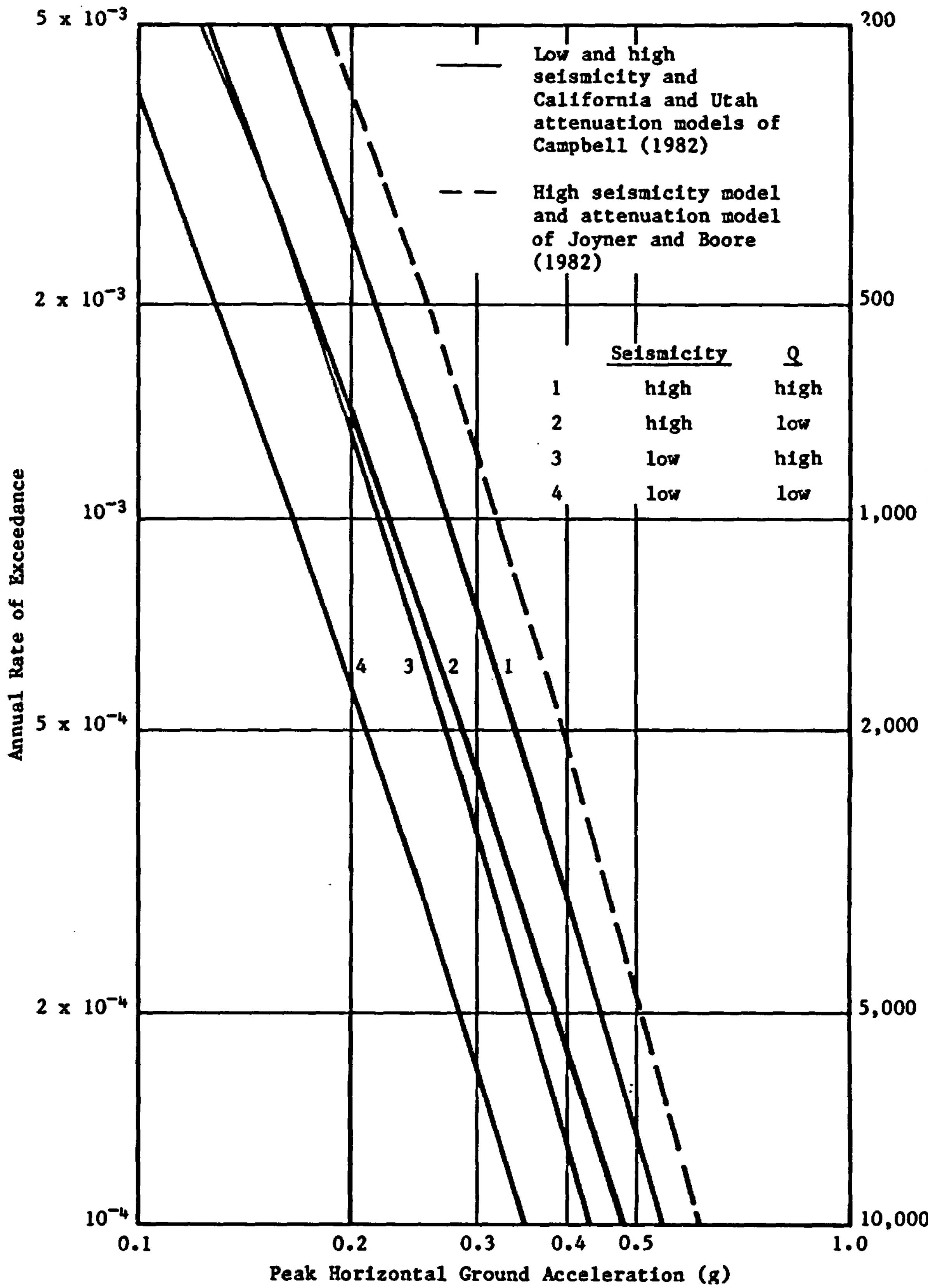


FIGURE 7.4 EARTHQUAKE HAZARD RESULTS FOR PEAK HORIZONTAL GROUND ACCELERATION EVALUATED WITH A GEOMETRIC STANDARD DEVIATION OF 1.9

for the high-seismicity models. These results provide a first-order estimate of the effect of uncertainty in the seismicity on the calculated hazard. As discussed previously, the higher and lower seismicity models were constructed as approximate bounds on estimates of moderate-magnitude historic seismicity and large-magnitude paleoseismicity rates. The uncertainty in earthquake recurrence is probably not much greater than represented by these bounds because, if it were greater, there would be difficulty in reconciling historic and paleoseismic activity rates with reasonable b-values. A further uncertainty in the calculated seismic hazard arises from the uncertainty in seismogenic zonation. The seismicity contrast between the SNSZ and the NGB is 3 for the high-seismicity model and 2 for the low-seismicity model. The adopted zonation places the site in the NGB at a distance of about 10 km from the SNSZ boundary, and these two zones have nearly equal contributions to the hazard at the site. Moving the SNSZ-NGB boundary by 10 or 20 km could reduce or increase the calculated exceedance rates by a fraction of the seismicity contrast. The overall range of uncertainty in the exceedance rates, stemming from uncertainties in recurrence rates and zonation, is estimated to be a factor of 4, i.e., the upper limit is approximately four times the lower limit. For a given exceedance rate, the PGA for the upper limit is about 50% greater than that for the lower limit. The preferred results, i.e., those for the higher seismicity model and the given zonation, lie near the upper limit of this range.

The similarity of the results for the Joyner and Boore and Campbell Utah models is fortuitous. Results for the Joyner and Boore model would be expected to be closer to those for the California model rather than the Utah model of Campbell. However, intermediate results in the hazard calculations show significant differences in the magnitude composition of the hazard. For a given ground motion level, calculated probability densities are used to identify the magnitude of events most likely to produce ground motion exceeding that level (see Douglas and Ryall, 1975). For the Joyner and Boore calculation shown in Figure 7.4, probability density maxima for PGA levels of 0.25 g, 0.4 g, and 0.5 g occur for magnitudes of 4.0, 4.8, and 5.4, respectively. The corresponding magnitudes are 5.7, 6.2, and 6.6, respectively, in the case of Campbell's Utah attenuation model and the same seismicity model. The latter results are considered more realistic as a description of potentially damaging ground motion. The difference is due in part to differences in formulation of the Campbell and Joyner and Boore models. The former allows for magnitude dependence of the shape of the attenuation curve, while the latter does not and therefore tends to exaggerate the importance of small earthquakes. This tendency is exacerbated in the present calculations by extrapolation of the attenuation regression results beyond the magnitude 5 data-set threshold to magnitude 4.

As indicated in the previous discussion of ground motion attenuation, a second question concerning the magnitude composition of the calculated hazard arises from the point-source representation used in seismicity modeling. An alternative to the point-source model is to assume that earthquake ruptures will be distributed randomly with respect to location and orientation, and with lengths given by a rupture length—magnitude correlation (Douglas and Ryall, 1975). Douglas and Ryall report a calculation for western Nevada using the Schnabel and Seed (1973) attenuation curves, a maximum magnitude of 7.6, and a b-slope of 0.91. Earthquakes most likely to produce accelerations exceeding 0.25 g, 0.4 g, and 0.5 g were found to be of magnitudes 5.7, 5.9, and 6.1, respectively. These magnitudes are similar to those reported above for the calculation using Campbell's attenuation model. While this comparison is not diagnostic, because of differences in assumptions and methods, it lends support to the magnitude composition of the hazard determined from the Campbell attenuation model.

Despite differences in magnitude composition, overall hazard results are nearly identical for the Joyner and Boore and Campbell Utah attenuation functions, with the latter modified by use of the geometric standard deviation of 1.9 determined by Joyner and Boore. It is immaterial numerically which calculation is adopted to determine PGA design levels. The calculation using the Joyner and Boore attenuation functions was chosen for determining the PGA levels so as to be consistent with the response spectra determined from the same set of regression results. Note that these results apply to the larger of two horizontal components. This is convenient for comparison with results for UNE hazard calculations, which are obtained from attenuation functions for individual vertical, radial, and transverse components. The radial component of UNE ground motion is generally larger than the transverse component and is therefore roughly comparable with the larger of two randomly oriented components as used by Joyner and Boore. In many engineering applications, it is preferable to use the average of the two horizontal components, but for present purposes, this adjustment is not made.

Design Earthquake Accelerations. Peak ground accelerations for DE-2, DE-1, and the PCE are defined as having recurrence expectancies of 500, 2,000, and 10,000 years, respectively. From the hazard curve in Figure 7.4 obtained using the Joyner and Boore (1982) attenuation function, peak horizontal ground accelerations were determined to be 0.25 g, 0.40 g, and 0.65 g (rounded up from 0.62 g) for DE-2, DE-1, and PCE, respectively.

No calculations for the vertical component of earthquake ground motion were performed in this investigation because of the absence of suitable attenuation functions. It has been standard practice to assume that vertical-component peak accelerations and response spectral amplitudes are two-thirds those determined for the horizontal component (Newmark and Hall, 1969). However, more recent data reported by Campbell (1982b) indicate that the ratio of peak vertical to peak horizontal acceleration depends appreciably on fault distance for large-magnitude earthquakes (magnitude 6 and greater). The ratio of peak vertical to peak horizontal acceleration was found to exceed a value of two-thirds for fault distances less than 10 to 25 km and to exceed unity at higher magnitudes (7 and greater) for distances less than about 5 km. Ratios as small as one-half were found to be representative of distances approaching 50 km. Causative earthquake magnitudes and distances are not uniquely specified for the design earthquakes, but intermediate results in the probabilistic calculations indicate that DE-2 and DE-1 acceleration levels would most likely be caused by large earthquakes occurring within a few tens of kilometers of the site. For these earthquakes, a two-thirds ratio of vertical to horizontal PGA is appropriate and is recommended for design purposes. For the postclosure acceleration level, the most likely causative earthquake is slightly larger and considerably closer than for the likely causative earthquakes for DE-2 and DE-1. Therefore, it is recommended that vertical-component PGA be taken as equal to horizontal-component PGA for the PCE. Horizontal and vertical components of PGA for the various earthquakes are summarized below.

	Recurrence Expectancy (yr)	Horizontal PGA (g)	Vertical PGA (g)
Design Earthquake 2	500	0.25	0.17
Design Earthquake 1	2,000	0.40	0.27
Postclosure Earthquake	10,000	0.65	0.65

Response Spectra

The Joyner and Boore (1982) response spectra are defined for 12 periods in the band 0.1 to 4.0 sec, and for 5% critical damping. For periods less than 0.1 sec, the response spectra are not defined except in terms of the high-frequency asymptote as given by the peak acceleration. For present purposes, it was assumed that the response varies linearly on a tripartite plot between the value at 0.1 sec and the value determined by the peak acceleration at a nominal period of 0.025 sec.

Response spectra with recurrence expectancies, at all frequencies, of 500, 2,000, and 10,000 years are shown in Figure 7.5. These are the uniform-hazard spectra for DE-2, DE-1, and the PCE and were computed using the Joyner and Boore (1982) regression results for the larger of two horizontal components recorded at rock sites.

Subsurface Motion

Seismic motion of repository depth at the Yucca Mountain site has been recorded for UNE events, as described in Chapter 8, but not for earthquakes. Spectral modulus ratios given in Chapter 8 show that spectral amplitudes at repository depth in Yucca Mountain are significantly lower than those recorded at the surface for all frequencies from 1 Hz up to the data band limit of about 20 Hz. For horizontal components, the ratios do not converge to 1, as expected, in the low-frequency limit. The behavior expected for reflection of body waves at the surface of an elastic half-space is that the subsurface/surface spectral ratio should diminish by a factor of 2 in the band from 0.0 Hz to a frequency that corresponds to a quarter-wavelength equal to the subsurface depth. Frequencies of S and P waves of quarter-wavelength 1,200 ft in the Paintbrush Tuff are approximately 1 and 2 Hz, respectively. However, the observed horizontal-component spectral ratios for UNE events are significantly less than 1 for frequencies less than 1 Hz. To a fair approximation, the spectral ratios are bounded by the value 1/2 at all frequencies.

King (1982) has analyzed signals for eight earthquakes recorded using Mark Products L-1 seismometers (4.5 Hz) at the surface and at a depth of 1,090 ft at Calico Hills, approximately 12 km east of Yucca Mountain. The measurements were made in Paleozoic sedimentary rocks of the Eleana formation. The compressional wave velocity increases gradually from 2.0 km/sec at the surface to 3.2 km/sec at the depth of the downhole installation. The recorded earthquakes, all of magnitude 2 or less, occurred at depths from 1.5 to 10 km and at epicentral distances from 10 to 34 km. King found that the subsurface motions had frequency characteristics similar to those of the surface motions over the entire frequency band of the recordings, from 0.2 to 20 Hz, and characterized the subsurface response spectral amplitudes as being a factor of 1.5 less than those at the surface. In terms of frequency dependence (or lack thereof), the spectral ratios obtained by King from earthquakes recorded at Calico Hills are similar to those reported in Chapter 8 for UNE events recorded at Yucca Mountain. This suggests that, to first order, spectral characteristics of subsurface motion relative to surface motion are the same for earthquakes and UNE events. Note that, although the events analyzed by King were selected on the basis of signal-to-noise ratio, the signal-to-noise levels were not reported, and the effect of noise on the spectral ratios, particularly near the band limits, has not been evaluated.

Pending the development of a physical model for the observed behavior of subsurface and surface spectra, a first-order approximation adopted for present purposes is that subsurface/surface spectral ratios are frequency-independent for both earthquake and UNE motion. The difference in spectral ratios for the two sets of observations is assumed to be attributable to differences in geologic structure, constitution, and topography. This assumption is consistent with the observation of Vortman and Long (1982a, 1982b) that subsurface/surface signal amplitude ratios observed for UNE events are strongly site-dependent. On this basis, it is assumed that subsurface/surface spectral ratios for earthquake motion at Yucca Mountain would be essentially the same as those observed for UNE events. As a first approximation, motion amplitudes at repository depth are taken to be 1/2 those at the surface for both earthquake and UNE events.

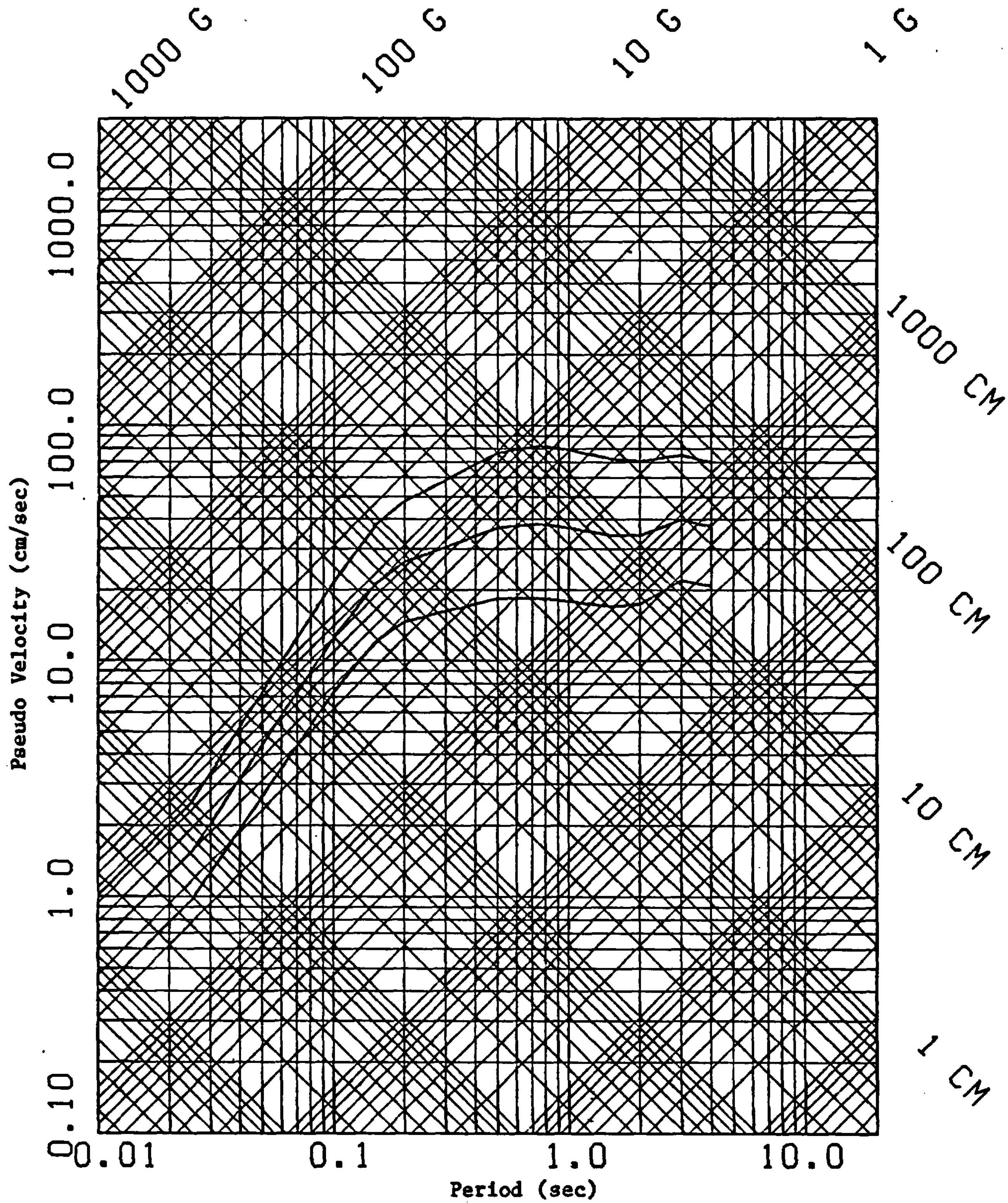


FIGURE 7.5 5%-DAMPED UNIFORM-HAZARD RESPONSE SPECTRA FOR ROCK SITES, HORIZONTAL COMPONENT, FOR RECURRENCE RATES OF 500, 2,000, AND 10,000 YEARS (DE-2, DE-1, and PCE, bottom to top)

8. UNE GROUND MOTION

The investigations reported in this chapter include analysis of surface and subsurface signals recorded at Yucca Mountain for UNE events, development of a site-specific adjustment to UNE ground motion attenuation functions, and probabilistic calculation of UNE ground motion hazard using a UNE occurrence model based on past testing at NTS.

The following dual objectives of evaluating UNE ground motion in relation to the NNWSI were stated by Vortman (1979): to ensure that the repository will not be damaged by UNE ground motion and to ensure that the repository will not be located where vulnerability to UNE ground motion would inhibit the Weapon Test Program's ability to conduct tests. The latter condition requires an evaluation based on the geographic and yield limits of future testing, as described by Vortman (1979). With regard to geographic limits, testing is assumed to occur in the Buckboard Mesa area north of Yucca Mountain, as yet unused for UNE events. Yield limits are assumed to be those established on the basis of off-site damage potential rather than the current 150-kt yield limit set by the Threshold Test Ban Treaty. The yield limit set for the Buckboard Mesa area is 700 kt (Vortman, 1979).

The testing limits precisely determine the size and location of the UNE event that has the maximum potential in terms of ground motion at the Yucca Mountain site, namely a 700-kt event located in the Buckboard Mesa area at its closest approach, a distance of 21.3 km, to the reference conceptual site for repository surface facilities. Because the maximum UNE potential is precisely defined, it would seem most appropriate to adopt a "deterministic" approach to UNE ground motion criteria. However, while the maximum UNE event can be described deterministically, the site ground motion cannot. Rather, the level of confidence that the event will not cause site ground motion exceeding any given amplitude can be given from the statistics of the ground motion attenuation function. In the case of multiple occurrences of the event, the level of confidence cannot be specified without specifying the number of events. Thus, quantitative assessment of UNE ground motion hazard requires a probabilistic evaluation that involves the rate of UNE testing.

The probabilistic calculations reported in this chapter model UNE occurrence as distributed throughout prescribed testing areas with prescribed yield ranges, rather than as repetitions of events of yield 700 kt at the same location. They are analogous to those obtained for earthquake ground motion in the previous chapter and can be compared directly in terms of a common parameter, exceedance rate. In characterizing UNE ground motion hazard, it is preferable to refer to "exceedance rate" rather than "return period" because the latter term may be incorrectly construed to imply that the ground motion hazard can be determined only if the hazard persists over a time span exceeding the return period. Although exceedance rate is preferred, we will use return period or recurrence expectancy in order to parallel our discussion of earthquake hazard.

Probabilistic hazard results are given in this chapter for UNE peak ground acceleration, velocity, and displacement. Because of the absence of attenuation functions for response spectral amplitude, however, it was not possible to determine uniform-hazard response spectra (i.e., spectra with uniform exceedance rate at all frequencies). In place of uniform-hazard spectra, response spectra shapes are given for a yield of 700 kt. Spectral shapes are determined from statistics of Yucca Mountain recordings of Pahute Mesa events scaled to a common yield of 700 kt. As discussed subsequently, it is inferred that UNE uniform-hazard spectra would be very similar in shape to those determined for the 700-kt event.

Yucca Mountain Recordings of Pahute Mesa UNE Events

A program of surface and subsurface recording at NTS sites for UNE events has been undertaken by Sandia National Laboratories (Vortman and Long, 1982a, 1982b) in support of the NNWSI program. The instrumentation and data processing for this program are described by Vortman (1979) and Vortman and Long (1982a). See Figure 8.1 for the locations of recording stations at the Yucca Mountain site. Stations 12, 25, and 28 are surface-downhole pairs, with subsurface instruments at repository depth (1,155, 1,175, and 1,230 ft, respectively, in boreholes USW G-3, USW G-1, and USW G-2). An earlier installation at borehole USW G-1, Station 24, with subsurface instruments at a depth of 1,850 ft, was replaced by Station 25 in mid-1983. Stations 26 and 27 are located in candidate areas for repository

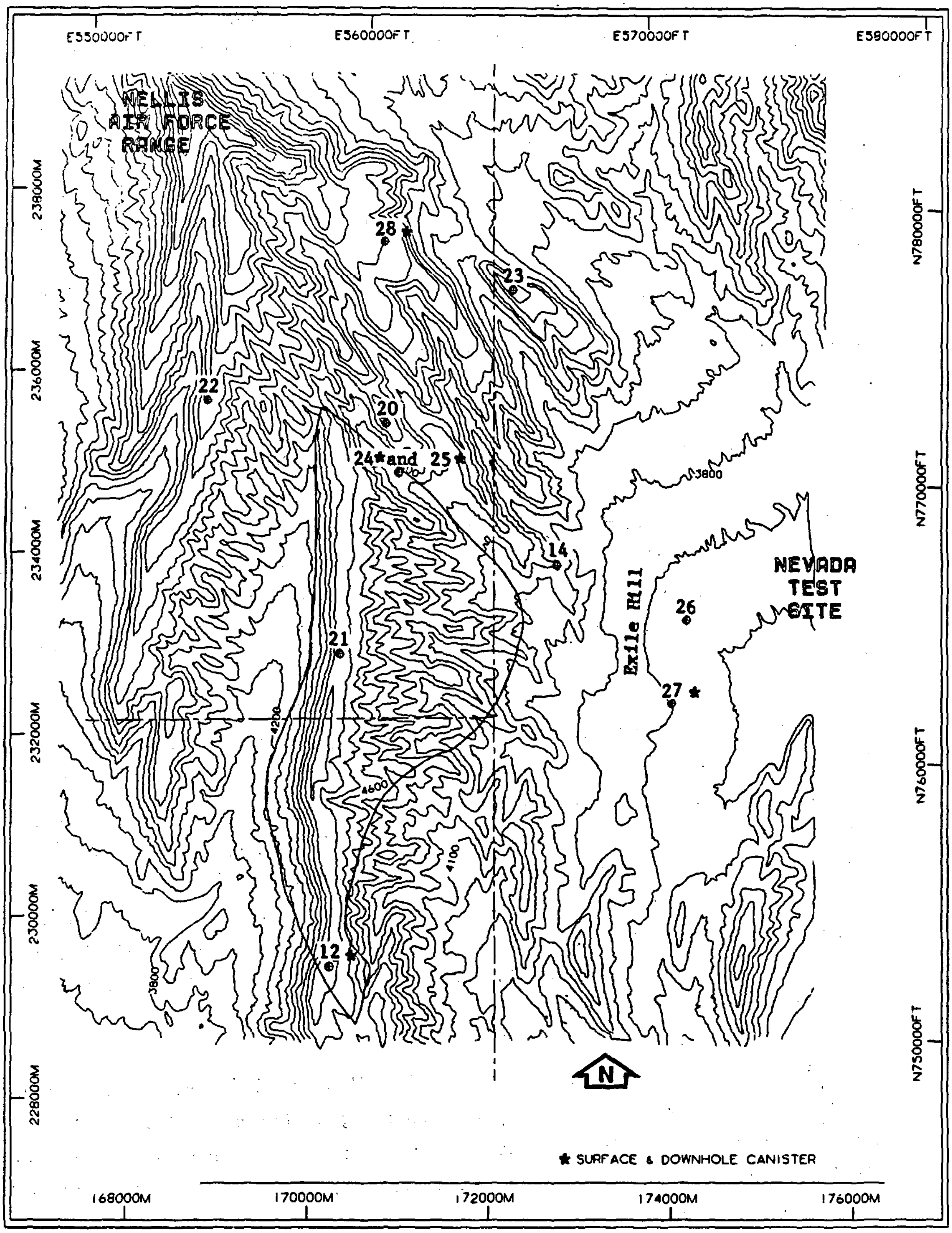


FIGURE 8.1 LOCATIONS OF SNL'S SEISMOGRAPHIC STATIONS AT YUCCA MOUNTAIN

surface facility siting. Station 27 is a surface-downhole pair, with the subsurface instruments situated at the alluvium—Tiva Canyon Tuff interface at a depth of 115 ft.

Yucca Mountain recordings of UNE events in the Pahute Mesa area, centered approximately 50 km north of the site, were selected for this study because of similarity to the Buckboard Mesa area in terms of azimuth and geology at UNE emplacement depths. The signals used in these analyses were scaled from the original recordings to a yield of 700 kt, using the Mueller and Murphy (1971) UNE spectrum model with physical parameter values given by Murphy (1977) as representative for Pahute Mesa detonations in saturated tuff and rhyolite media.

Results obtained in this study from analysis of the Yucca Mountain recordings include site-specific PGA statistics, spectral modulus ratios of signals from surface-downhole and surface-surface pairs, and statistics of surface and subsurface response spectra. The results were used to determine site-specific adjustments to attenuation functions obtained by Vortman (1984a) for Pahute Mesa UNE events and to provide site-specific response spectra.

The present investigations were limited in scope and in the size of the data sample. A more rigorous and extensive analysis of a larger event sample will be needed to evaluate seismic wave-propagation effects at the site for design purposes. Specifically, analysis of the path-dependence of the recordings of Pahute Mesa events is needed to assess their applicability as models for Buckboard Mesa events. Data for Yucca Flat events should also be analyzed. Recordings of only one Pahute Mesa event were available for the newly installed Stations 26 and 27 located in candidate areas for repository surface facilities.

The following analysis illustrates the significance of site-specific ground motion statistics for UNE events in evaluating design criteria. Amplitude anomalies apparent at Yucca Mountain for Pahute Mesa events were, for simplicity, evaluated in terms of a "site" effect, although there is evidence for significant azimuthal dependence (Vortman, 1984b). As will be seen subsequently, probabilistic PGA values determined for the preclosure design levels, using statistics for a site chosen at random, exceed those obtained using site-specific statistics, even though the latter incorporate a "site" amplification factor of 2.

Yield Scaling. The yield-scaling algorithm of Murphy (1977), using the UNE source model of Mueller and Murphy (1971), was implemented in a Fortran code supplied to SNL for processing Yucca Mountain recordings of Pahute Mesa events. The basic element of the calculation was evaluation of the far-field spectrum (Murphy, 1977, equation 1) expressed as a function of event yield, depth of burial, and elasticity and density of the emplacement medium. Depth of burial was assumed to obey the cube-root scaling law, and physical parameters representative of Pahute Mesa emplacement media, as given by Murphy (1977), were used in the calculations. The event-specific scaling method described by Murphy (1977) was not used in the present analysis but is recommended for future investigations.

A characteristic that distinguishes the far-field displacement spectra of UNE events from those of earthquakes is a maximum in the spectral displacement that occurs at a period proportional to the elastic radius, which is a function of event yield and depth. The spectral displacement maximum occurs at periods greater than 1 sec for yields above 100 kt. As will be seen below, UNE events govern the ground motion criteria at long periods (T >1 sec).

PGA Statistics. Component PGA statistics were computed for the yield-scaled Yucca Mountain accelerograms and were compared with regression results obtained by Vortman (1984a) for Pahute Mesa events with yields greater than 90 kt. The regression results adopted as a reference standard are those for both rock and alluvial recording sites in Group III of Vortman (1984a), which excludes data from Yucca Mountain sites. Table 8.1 lists ratios of PGA from the yield-scaled records to PGA evaluated from the Vortman functions for 700 kt and for average shot-point distances, as indicated, for five surface and two subsurface stations. Lognormal distribution of PGA was assumed, and geometric standard deviations are given in the table.

TABLE 8.1

PEAK ACCELERATION AMPLITUDE FACTORS AND GEOMETRIC STANDARD DEVIATIONS FOR YIELD-SCALED YUCCA MOUNTAIN RECORDS OF PAHUTE MESA UNE EVENTS

Station	Δ* (km)	Number of Events	Amplitude Factor†			Geometric Standard Deviation		
			Vertical	Radial	Transverse	Vertical	Radial	Transverse
Surface								
23	45	4	2.07	1.83	1.78	2.01	1.69	1.53
24,25	47	4	2.19	1.68	1.89	1.47	1.62	1.30
14	48	8	1.59	1.59	1.69	1.46	1.46	1.35
21	49	5	1.88	1.30	1.29	1.67	1.66	1.84
12	53	3	0.90	0.69	0.81	1.28	1.15	1.28
Subsurface								
25	47	2	0.44	0.47	0.39	—	—	—
12	53	3	0.57	0.53	0.41	1.11	1.15	1.38

* Mean shot-point distance

† Evaluated relative to the Vortman (1984a) mean attenuation functions - Group III, alluvium and rock

Significant aspects of these results include large positive amplitude anomalies at several Yucca Mountain surface sites, subsurface amplitudes substantially lower than observed and expected at the surface, and site-specific standard deviations (best resolved for Station 14) much smaller than for the Vortman (1984a) regressions (2.04, 2.13, and 2.33, respectively, for vertical, radial, and transverse components for a randomly chosen site).

The amplitude factors listed in Table 8.1 are similar to results obtained by Vortman (1984b) from analysis of unscaled signals. The present results are subject to a slight bias in that the yield-scaling exponent at high frequencies, 0.53, employed in the Murphy (1977) algorithm, exceeds the values obtained by Vortman (0.518, 0.454, and 0.426, respectively, for peak vertical, radial, and transverse acceleration). The results are indicative of a broad area affected by anomalously high amplitudes for Pahute Mesa events, with maximum amplitude factors near 2 at the northern limit of the repository site. At Station 12, near the southern limit of the repository site, peak accelerations were slightly below average, and near-average accelerations were recorded at Stations 15 and 16, located approximately 20 km to the north-northeast of Station 12 (Vortman, 1984b). These observations limit the extent of the anomaly in the radial (approximately north-south) direction. Current investigations to determine the cause of the amplitude anomalies observed at Yucca Mountain, and to the east at Calico Hills, indicate a significant azimuthal dependence, with distinct differences in amplitude for events in the eastern and western parts of Pahute Mesa (Vortman, 1984b). These observations suggest that propagation phenomena near the source region are responsible in part for the observed amplitude anomalies and leave open the question of expected amplitudes for events at Buckboard Mesa.

For present purposes, the amplitude anomalies were treated as site-related, i.e., independent of event azimuth and distance. Accordingly, site-specific adjustments to the Vortman (1984a) attenuation functions were formulated from the foregoing results for use in the probabilistic calculations described below. Calculations were performed for site amplification factors of 1.5 and 2.0 for surface motion. The site-specific geometric standard deviation was taken to be 1.46, as determined for vertical and radial components at Station 14.

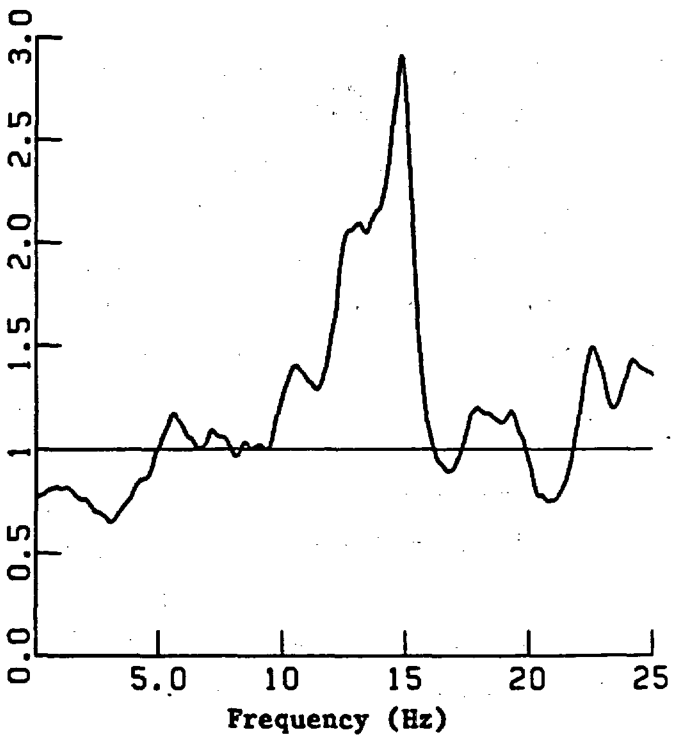
Subsurface amplitudes at Stations 12 and 25, unlike the surface amplitudes, are similar to expected levels, allowing for a factor of 2 for the free-surface reflection effect. Spectral comparisons of surface and subsurface signals are given in the next section.

Spatial Variation of Surface Motions. Spectral modulus ratios for surface station pairs were computed to investigate local variability of UNE ground motion at the site. The investigation was motivated by the need to determine spectra for repository surface facilities. At Station 26, located within the reference conceptual site, data for only one Pahute Mesa event, KAPPELI, were available for analysis. Spectral comparisons were made between Station 26 and other surface stations, with the aim to identify a station with similar spectral amplitudes that has recorded a sufficient sample of Pahute Mesa events for statistical purposes.

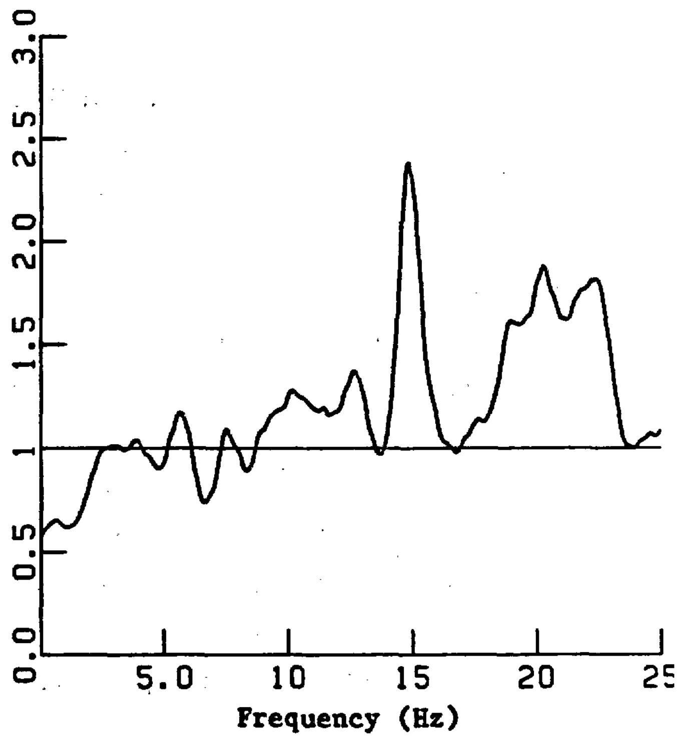
In computing spectral modulus ratios, adjustment for noise was effected by power-spectral subtraction, using pre-event noise samples. Note that, as a part of routine signal processing, SNL applies a low-pass filter with the corner set at the frequency at which the signal-to-noise ratio approaches 1. Filter corner frequencies are not necessarily the same for all records. In some cases, the corner frequency is as low as 24 Hz, so that the spectral modulus ratios computed here, while valid up to 20 Hz, are in some cases invalid beyond 20 Hz.

In terms of surface spectra for event KAPPELI, Stations 27 and 14 were found to be the most similar to Station 26, while Station 25 was the most dissimilar. Station 27 is underlain by 115 ft of alluvium and is located 1 km south of Station 26, where the alluvial thickness is 35 ft.

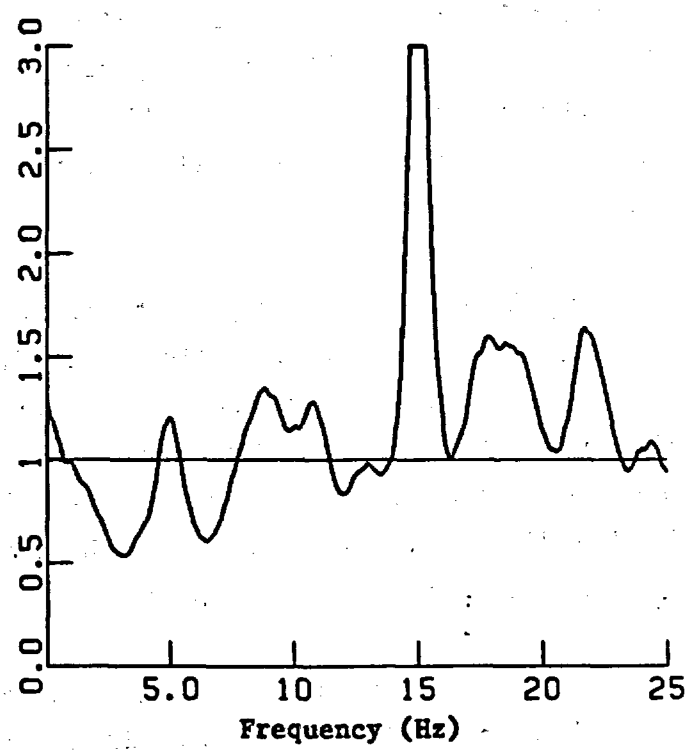
Whole-record spectral modulus ratios between Stations 27 (surface) and 26 are shown in Figure 8.2. Spectral ratios are close to 1 for all components, except for a pronounced peak near 15 Hz. Downhole/surface spectral ratios for Station 27 are reported in Chapter 3 (see Figures 3.1 and 3.2). These show spectral amplitudes at the alluvium-tuff interface that are approximately half the surface amplitudes at frequencies above 5 and 7 Hz for horizontal and vertical components, respectively.



a. Vertical Component



b. Radial Component



c. Transverse Component

FIGURE 8.2 SPECTRAL MODULUS RATIOS FOR WHOLE RECORDS, SURFACE STATION 27/ STATION 26, EVENT KAPPELI

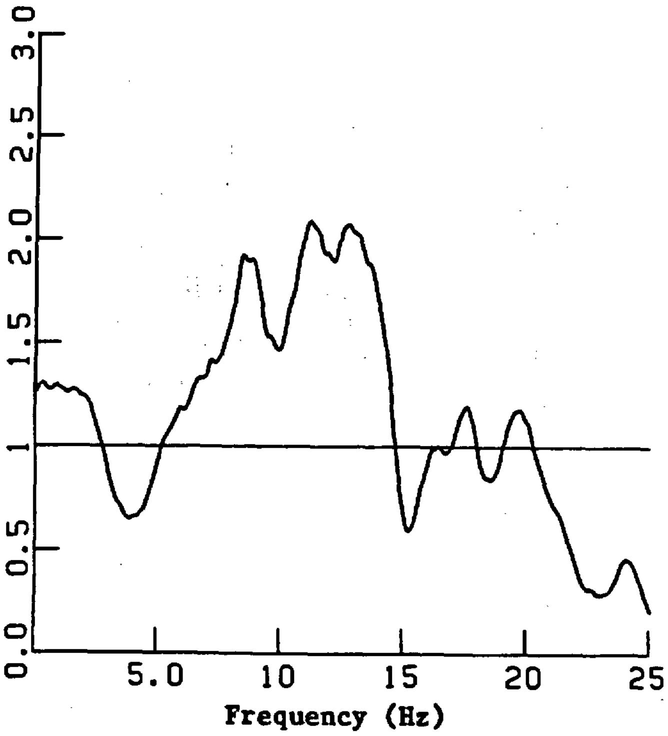
Of the stations with several recordings of Pahute Mesa events, Station 14 exhibited spectra most similar to Station 26 spectra for event KAPPELI. Station 14 is located on rock 1.5 km west-northwest of Station 26. Figure 8.3 shows spectral modulus ratios between Stations 14 and 26 for event KAPPELI. Pronounced effects due to the alluvium at Station 26 are not evident in the spectral ratios. Station 14 has higher spectral amplitudes than Station 26 at frequencies below 2 Hz and generally lower spectral amplitudes at frequencies above 15 Hz.

As an example of extreme dissimilarity of surface spectra, modulus ratios between Stations 25 (surface) and 26 are shown in Figure 8.4. Station 25 is located on rock 3.5 km northwest of Station 26. The spectral ratios are characterized by values of about 2.5 for frequencies above 5 Hz. As indicated above, consistently high peak accelerations were recorded at Station 25 (surface) for Pahute Mesa events.

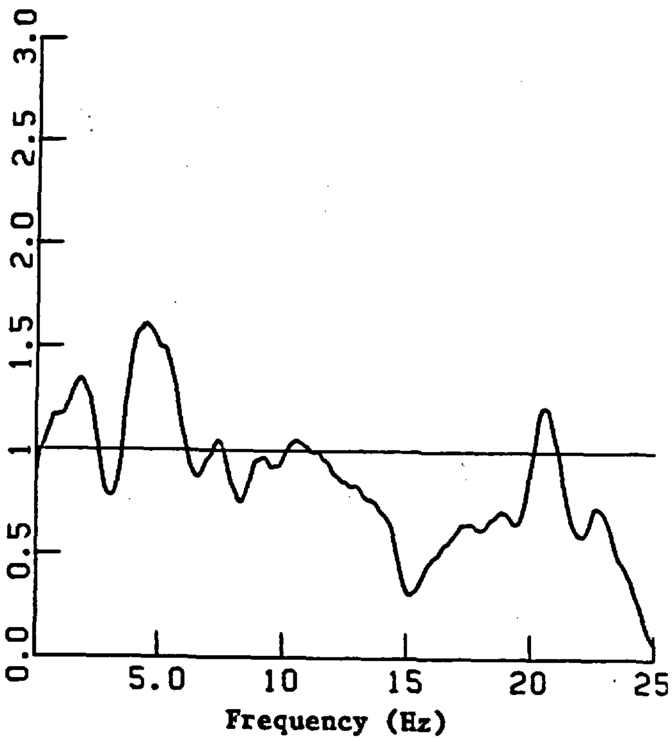
The conclusion reached from comparison of surface spectra was to adopt Station 14 as an interim reference station for defining surface spectra. This choice was based on the general similarity of spectra at Stations 14 and 26 for event KAPPELI and was motivated by the availability of data for a sufficient number of Pahute Mesa events recorded at Station 14 to obtain meaningful statistics.

Downhole/Surface Spectral Modulus Ratios. Instruments for recording signals at repository depth are located at Stations 12, 25, and 28, at depths of 1,155, 1,175, and 1,230 ft, respectively. Downhole and surface signal pairs were available for three Pahute Mesa events recorded at Station 12 and for two events at Station 25. In addition, data for two events were available for Station 24, which was coincident with Station 25 except that downhole instrumentation was at a depth of 1,850 ft.

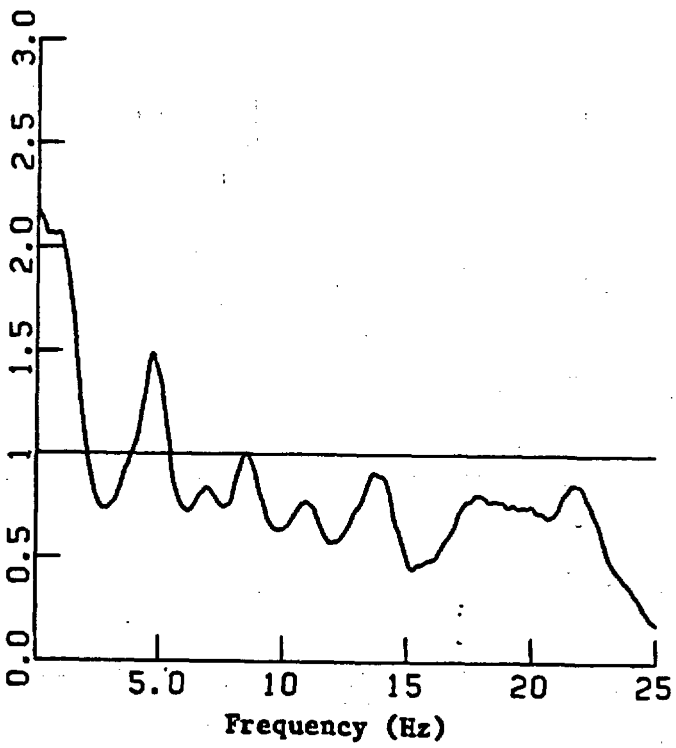
Spectral modulus ratios were computed as before, with power-spectral noise subtraction. Note that spectral ratios above 20 Hz are invalid in some cases because of the effect of low-pass filtering during routine processing at corner frequencies as low as 24 Hz.



a. Vertical Component

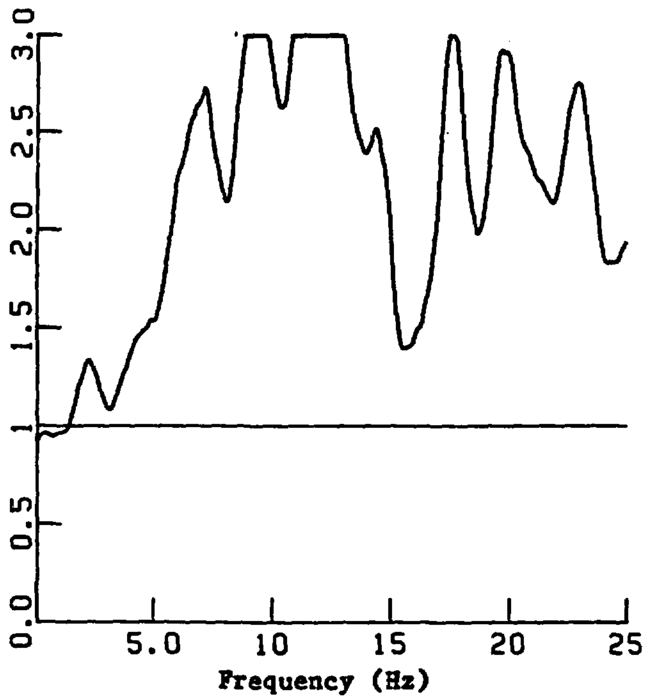


b. Radial Component

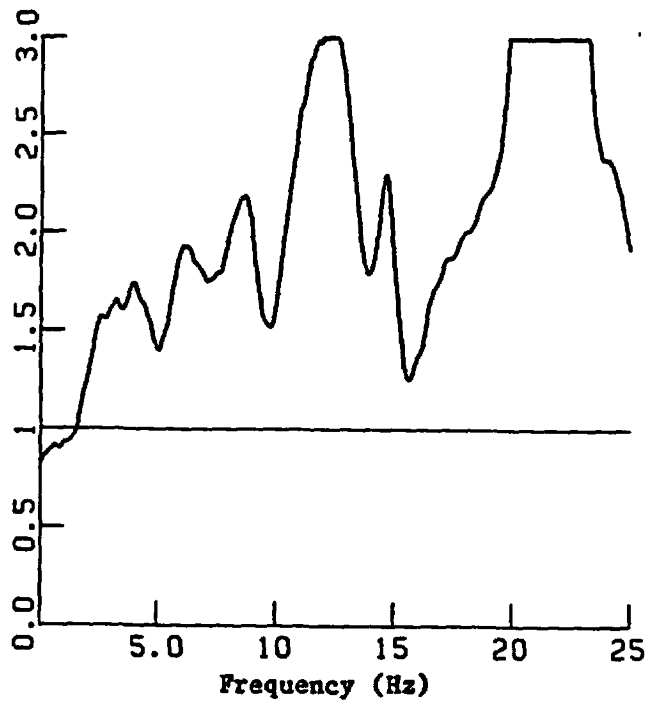


c. Transverse Component

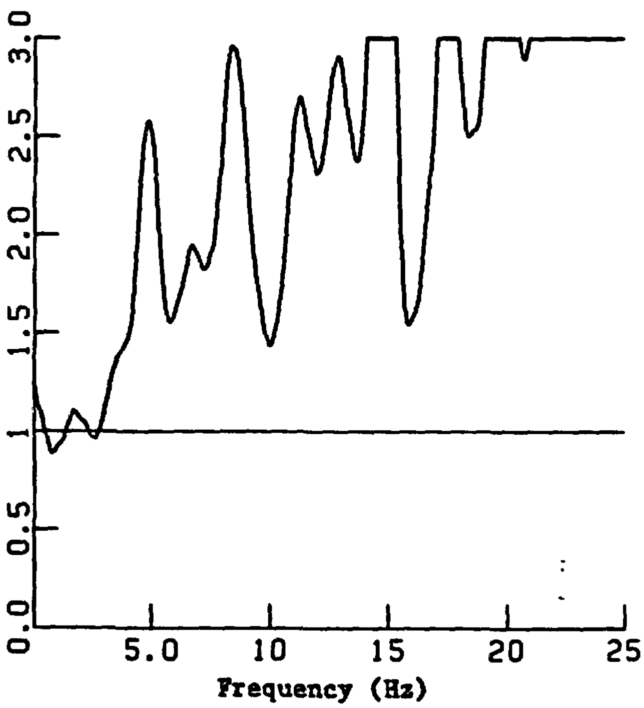
FIGURE 8.3 SPECTRAL MODULUS RATIOS FOR WHOLE RECORDS, STATION 14/STATION 26, EVENT KAPPELI



a. Vertical Component



b. Radial Component



c. Transverse Component

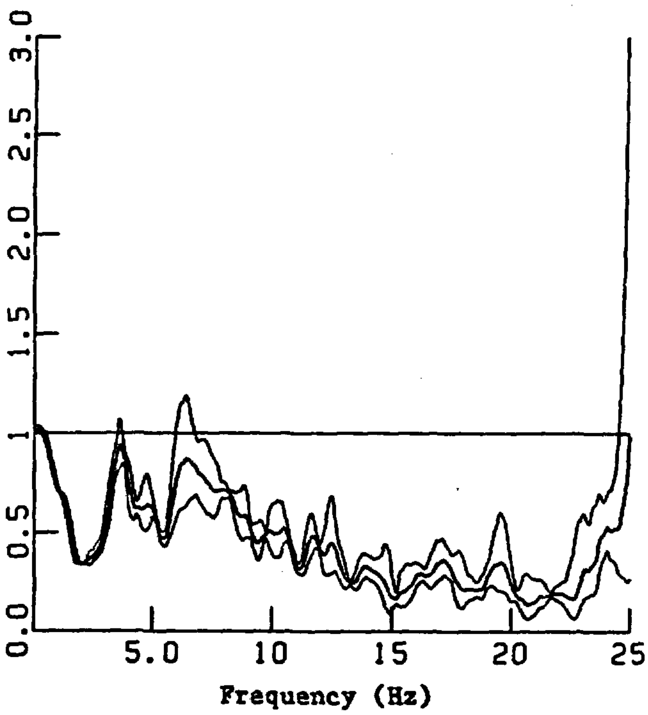
FIGURE 8.4 SPECTRAL MODULUS RATIOS FOR WHOLE RECORDS, SURFACE STATION 25/ STATION 26, EVENT KAPPELI

Downhole/surface spectral modulus ratios for Stations 12 and 25 are shown in Figures 8.5 and 8.6. Comparison of the results for these stations exemplifies the conclusion of Vortman and Long (1982a) that ratios of surface and downhole motion are strongly site-dependent. The disparity in downhole/surface spectral ratios for these stations is principally attributable to differences in surface rather than subsurface motion. As noted above in the discussion of PGA statistics, surface Stations 12 and 25 are characterized respectively by small negative and large positive amplitude anomalies for Pahute Mesa events. By comparison, subsurface Stations 12 and 25 have similar PGA levels that, assuming a free-surface amplification factor of 2, are close to the mean of the Vortman (1984a) regression results.

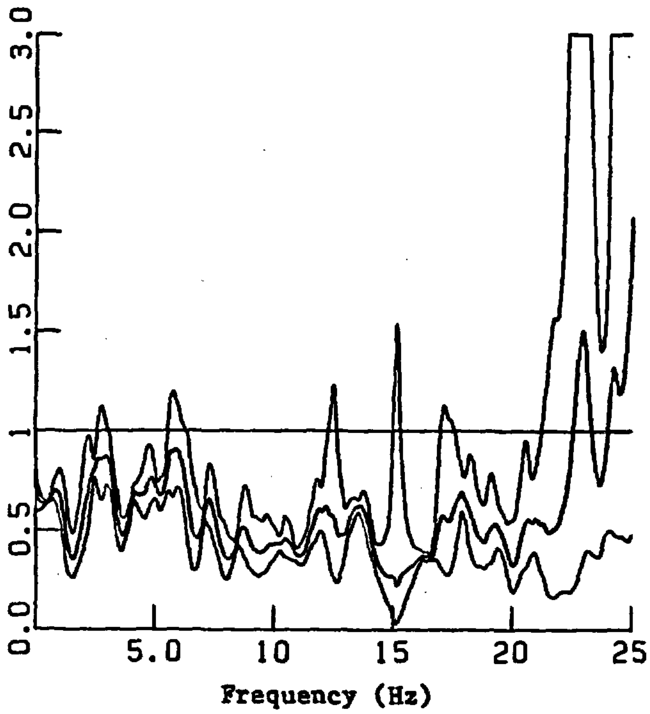
Figure 8.7 shows downhole/surface spectral ratios for Station 24, coincident with Station 25 except for subsurface instrumentation at a greater depth, 1,850 ft. These ratios are slightly higher than for Station 25 for frequencies above 1 Hz.

A notable aspect common to all results for horizontal components is that the spectral ratio does not converge to 1 as expected in the low-frequency limit. A satisfactory explanation for this phenomenon has not been found. At Stations 24 and 25, there is a rapid diminution in spectral ratios in the band from 0 to 1 or 2 Hz and relatively small variation in spectral ratios at higher frequencies. This behavior is indicative of the free-surface reflection effect, in that the downhole/surface spectral ratio is expected statistically to diminish by a factor of 2 in the band from 0.0 Hz to a frequency that corresponds to a quarter-wavelength equal to the subsurface depth. Frequencies of S and P waves of quarter-wavelength 1,200 ft are approximately 1 and 2 Hz, respectively. Thus, the frequency dependence of the spectral ratios is as expected, but their amplitudes are not.

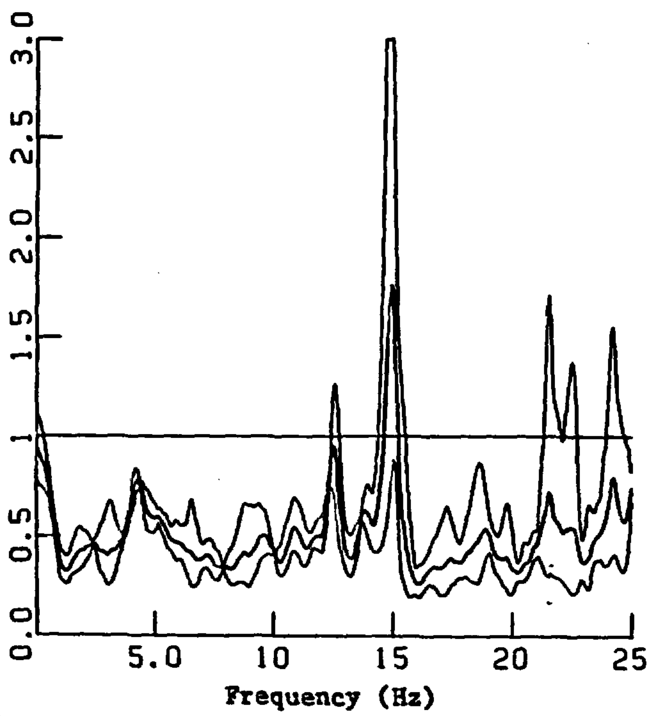
Downhole/surface spectral ratios computed for 10-sec windows of body waves arriving prior to the surface waves are shown in Figures 8.8 and 8.9 for Stations 12 and 25. These spectral ratios are practically the same as the whole-record ratios reported above. As before, the relatively low spectral ratios for horizontal components at low frequencies are unexplained.



a. Vertical Component

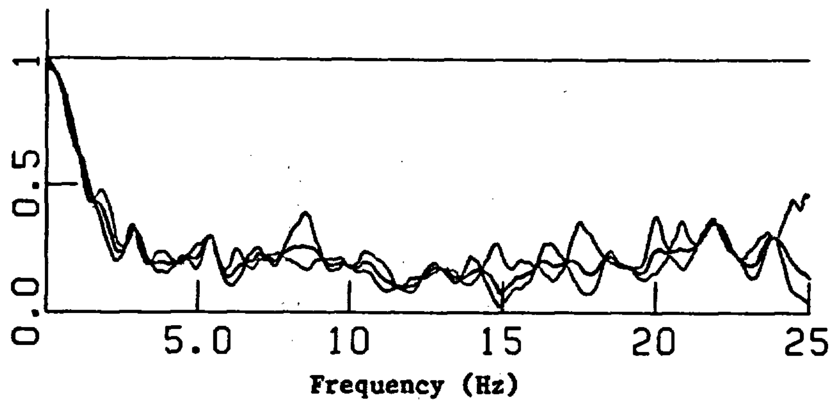


b. Radial Component

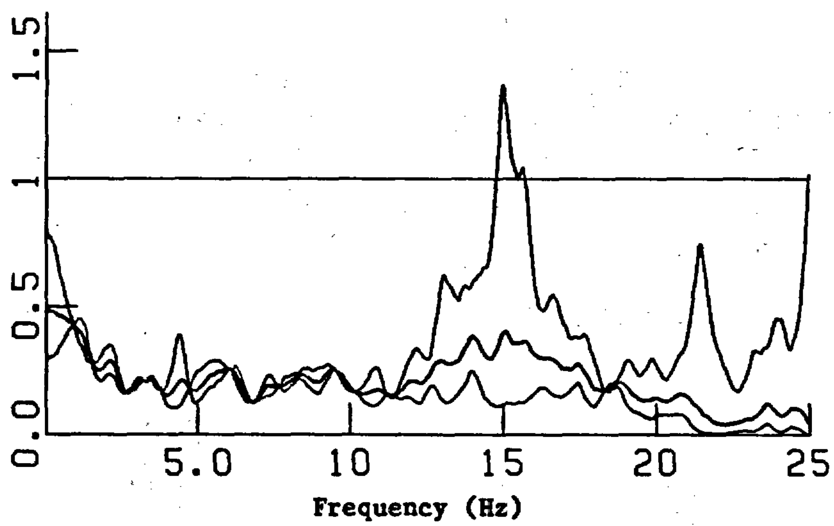


c. Transverse Component

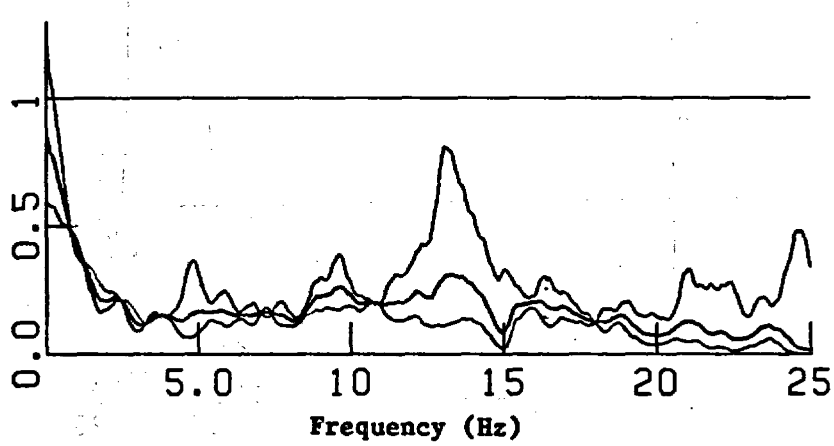
FIGURE 8.5 DOWNHOLE/SURFACE SPECTRAL MODULUS RATIOS FOR WHOLE RECORDS, GEOMETRIC MEAN AND ±1 STANDARD DEVIATION, STATION 12, EVENTS KAPPELI, CHANCELLOR, AND CABRA



a. Vertical Component



b. Radial Component



c. Transverse Component

FIGURE 8.6 DOWNHOLE/SURFACE SPECTRAL MODULUS RATIOS FOR WHOLE RECORDS, GEOMETRIC MEAN AND ±1 STANDARD DEVIATION, STATION 25, EVENTS KAPPELI AND CHANCELLOR

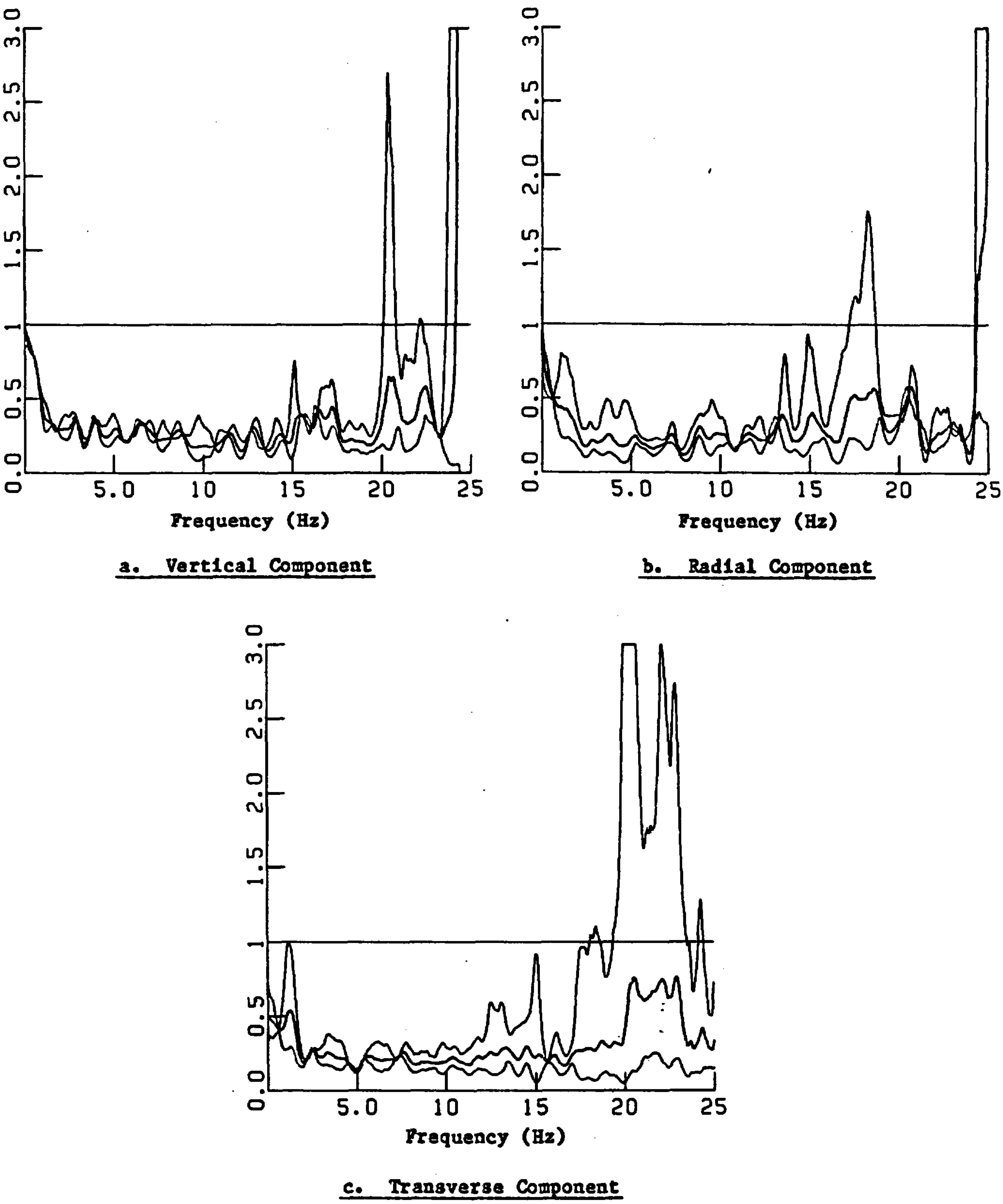
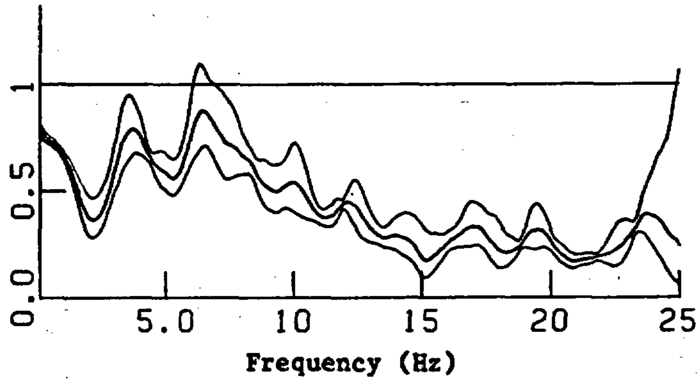
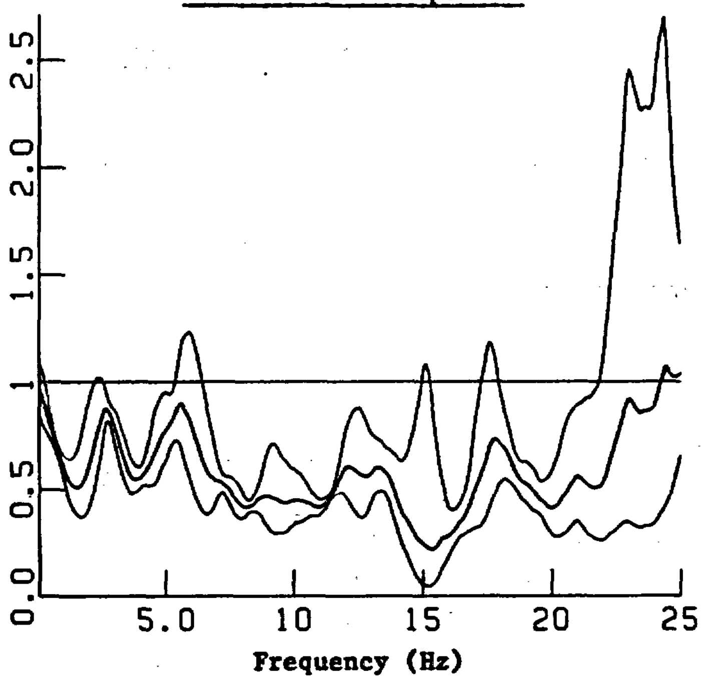


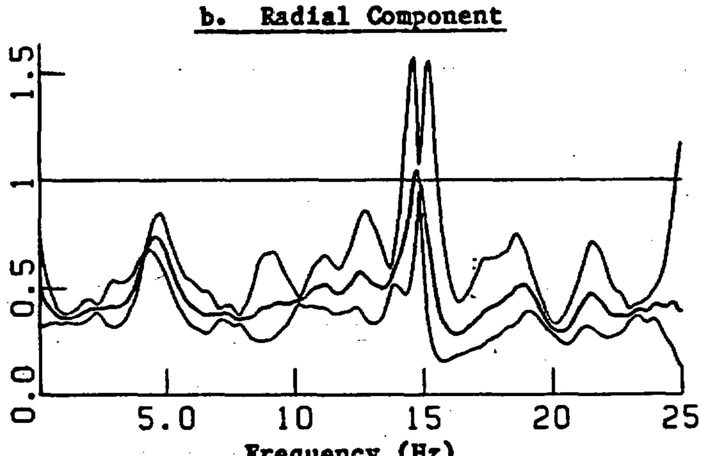
FIGURE 8.7 DOWNHOLE/SURFACE SPECTRAL MODULUS RATIOS FOR WHOLE RECORDS, GEOMETRIC MEAN AND ±1 STANDARD DEVIATION, STATION 24, EVENTS CABRA AND GIBNE



a. Vertical Component

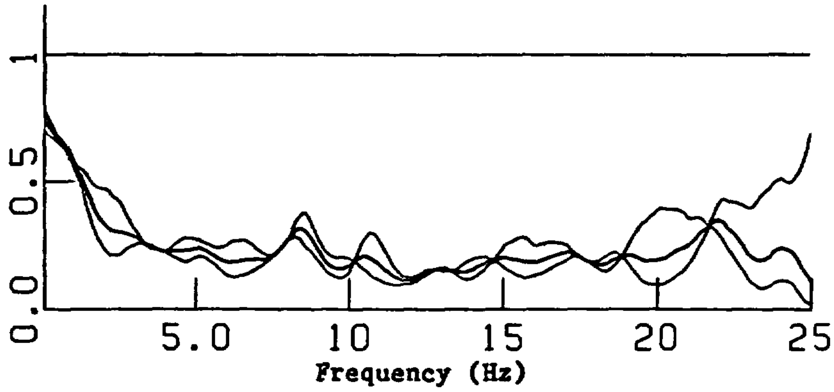


b. Radial Component

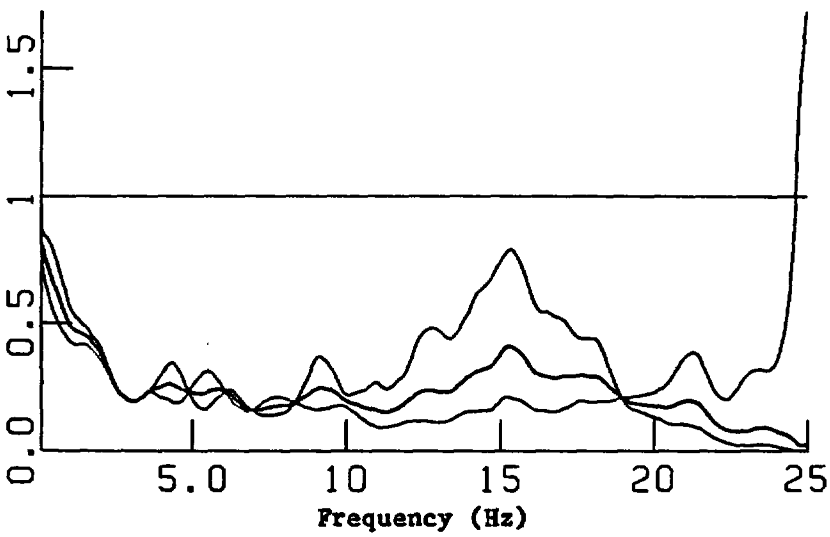


c. Transverse Component

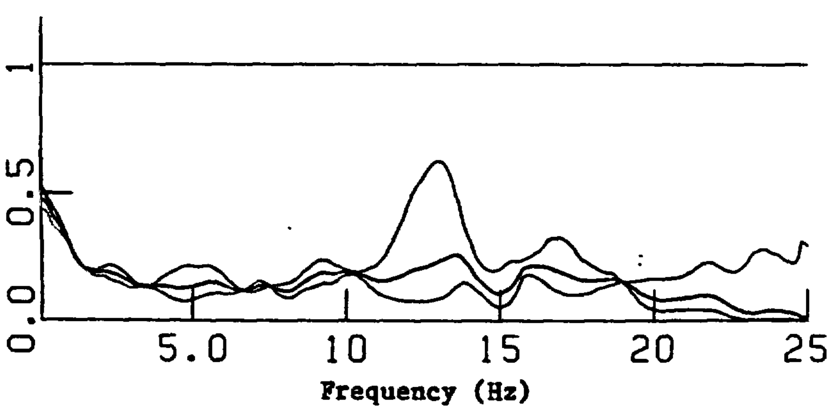
FIGURE 8.8 DOWNHOLE/SURFACE SPECTRAL MODULUS RATIOS FOR BODY WAVES, GEOMETRIC MEAN AND ±1 STANDARD DEVIATION, STATION 12, EVENTS KAPPELI, CHANCELLOR, AND CABRA



a. Vertical Component



b. Radial Component



c. Transverse Component

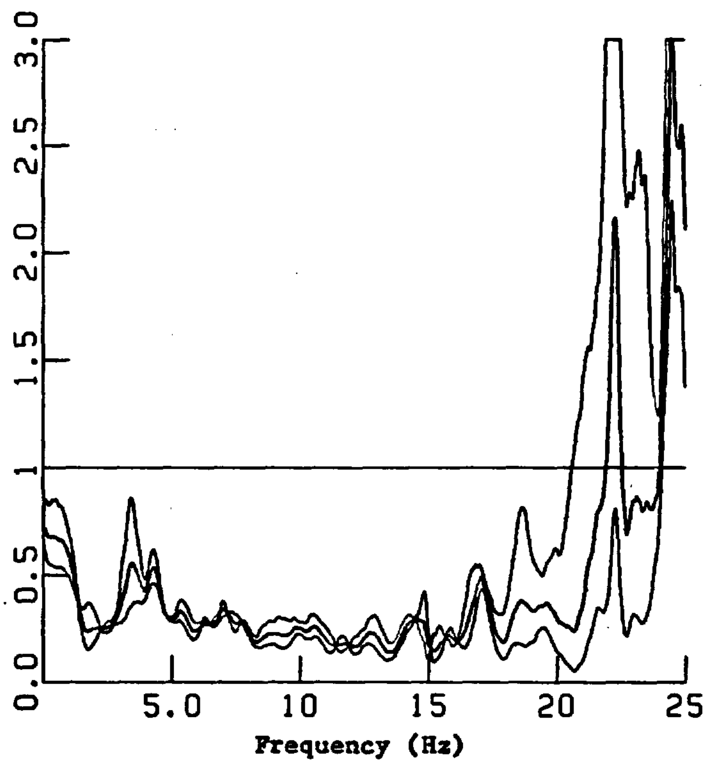
FIGURE 8.9 DOWNHOLE/SURFACE SPECTRAL MODULUS RATIOS FOR BODY WAVES, GEOMETRIC MEAN AND ±1 STANDARD DEVIATION, STATION 25, EVENTS KAPPELI AND CHANCELLOR

For comparison with Station 14, adopted as the reference station for repository surface facility ground motion, spectral ratios of Stations 12 and 25 (subsurface) relative to Station 14 are shown in Figure 8.10 for event KAPPELI. To a fair approximation, these spectral ratios are bounded by the value 1/2 at all frequencies up to the band limit of 20 Hz. In the interim, this approximation was adopted for specifying subsurface motion in terms of surface motion at Station 14, pending further analysis of the data. Response spectra of subsurface and surface motion are compared at the end of this chapter.

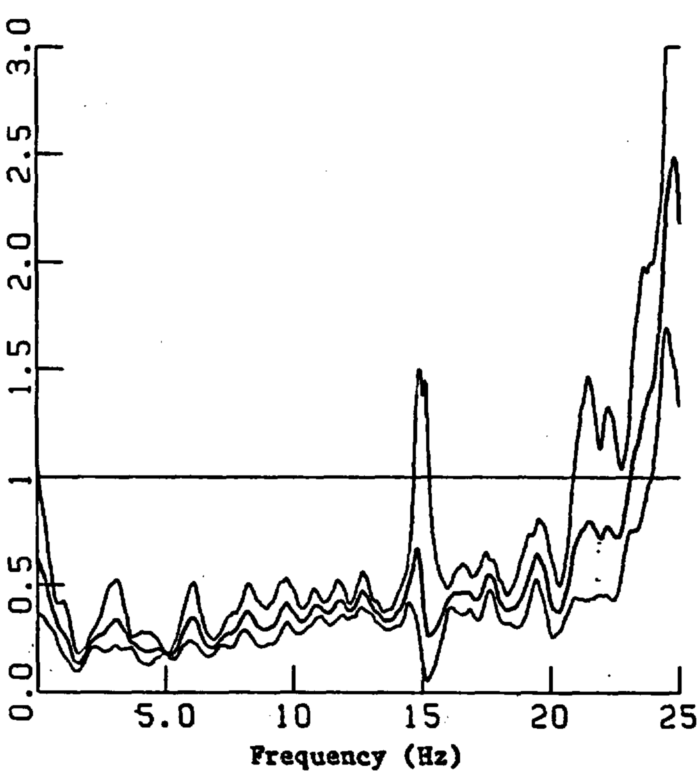
Probabilistic Calculations Using the Poisson Model

UNE Occurrence Model. Probabilistic calculations using a Poisson model of UNE occurrence were performed to establish the potential ground motion hazard due to underground testing. These calculations were analogous to the earthquake hazard calculations reported in the previous chapter and are compared with them in the following chapter. UNE occurrence was modeled as a Poisson point process of constant rate and uniform distribution in prescribed testing areas.

Current underground testing at NTS, conducted primarily in the Pahute Mesa and Yucca Flat testing areas (Figure 8.11), is limited by the Threshold Test Ban Treaty to yields up to 150 kt. The ground motion hazard at the Yucca Mountain site due to current testing is negligible for design purposes. Thus, the UNE occurrence model used to evaluate the potential ground motion hazard was not based on current testing but rather on a hypothetical expansion of testing in terms of geography and yield. Testing of UNEs was assumed to occur in the Buckboard Mesa area (Figure 8.11), which has not been used to date. The closest distances from the Buckboard Mesa area to the Yucca Mountain shaft and surface facility reference conceptual site locations are 22.8 and 21.3 km, respectively. UNE occurrence was assumed to be distributed among the testing areas by yield as follows: up to 250 kt at Yucca Flat; 250 to 700 kt at Buckboard Mesa; and 700 to 1,500 kt at Pahute Mesa. Uniform spatial distribution of shot points is assumed in each area.



a. Vertical Component



b. Radial and Transverse Components for Four Ratios

FIGURE 8.10 SPECTRAL MODULUS RATIOS FOR WHOLE RECORDS, DOWNHOLE STATIONS 12 AND 25/STATION 14, GEOMETRIC MEAN AND ±1 STANDARD DEVIATION, EVENT KAPPELI

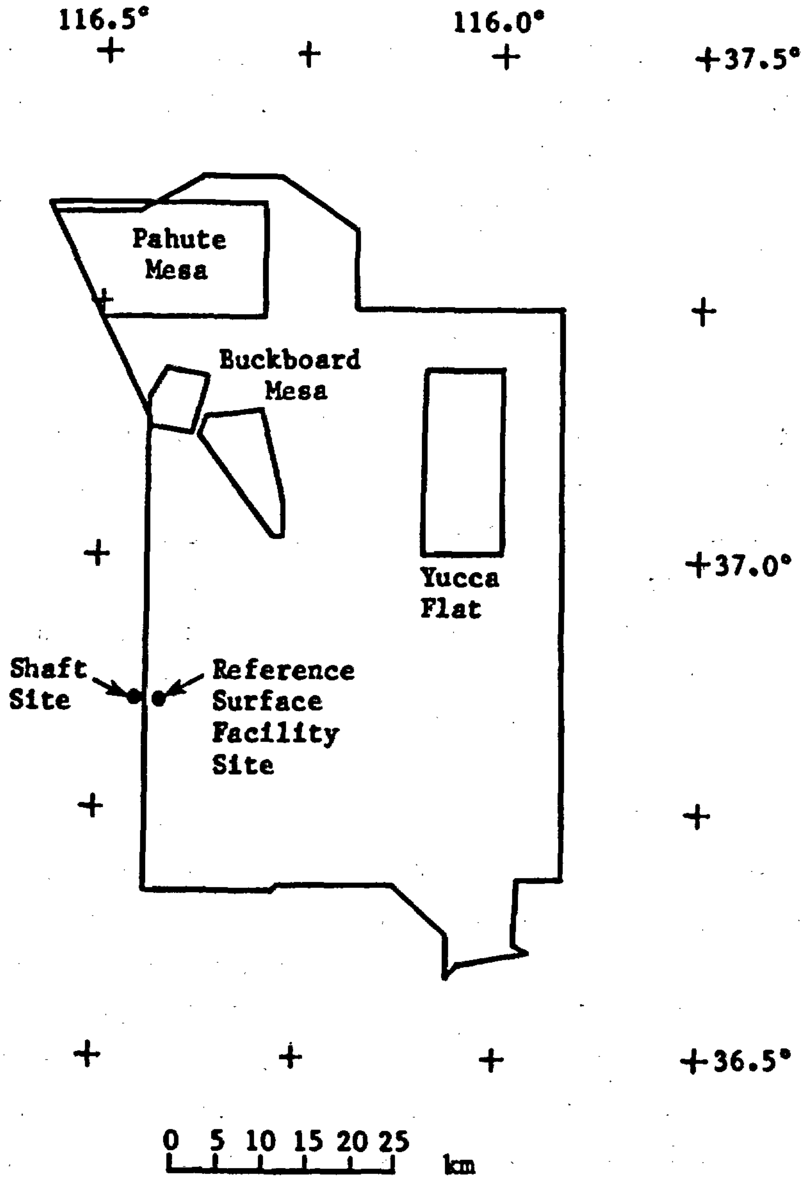


FIGURE 8.11 REPOSITORY SHAFT AND REFERENCE SURFACE FACILITY SITES IN RELATION TO UNE TESTING AREAS AS REPRESENTED BY POLYGONS IN GROUND MOTION HAZARD CALCULATIONS

The rate of UNE occurrence adopted for the hazard calculations was based on the historic rate of testing at NTS during the period of intermediate- and low-megaton-yield detonations for mid-1963 to mid-1973. In the 10-year interval from June 1963 to June 1973, there were 84 events of low-to-intermediate yield (20 to 200 kt), 8 events of intermediate yield (200 to 1,000 kt), and 4 events of low-megaton yield (Springer and Kinnaman, 1971, 1975). The cumulative frequency-yield relation obtained from the data for events with yields of 20 kt and greater (96 events), and 200 kt and greater (12 events) is:

$$\log N = 2.15 - 0.9 \log W$$

where N is the annual number of events of yield W kt or greater. This relation gives approximately nine intermediate-yield events per decade, closely matching the 1963-1973 occurrence rate. This yield range is the most critical for estimating ground motion hazard at the Yucca Mountain site because it encompasses the hypothetical testing in the Buckboard Mesa area. According to this model, six events per decade in the yield range 250 to 700 kt will occur at Buckboard Mesa.

A second period of intermediate-yield testing at NTS took place from May 1975 to March 1976, during the accelerated test schedule leading up to the Threshold Test Ban Treaty. Because the accelerated test schedule is unrepresentative of long-term testing, it was not included in the event sample used to derive the UNE occurrence model. Twelve intermediate-yield events were detonated in the 10-month interval from May 1975 to March 1976. This rate of intermediate-yield testing is an order of magnitude greater than that during the interval 1963-1973. If intermediate-yield testing is averaged over the interval 1963-1984, including the accelerated test schedule, the average rate is one event per year, nearly the same as for the interval 1963-1973.

Ground motion exceedance rates obtained from the probabilistic calculations are directly proportional to the rate constant in the recurrence relation. Thus, ground motion hazard results are readily obtainable for any fraction or multiple of the adopted occurrence rates.

Ground Motion Attenuation. Vortman (1984a) obtained regression results for vertical, radial, and transverse component peak ground acceleration, velocity, and displacement as functions of epicentral distance and yield for Pahute Mesa UNE events with yields greater than 90 kt. Separate regression results were obtained for alluvial, rock, and both alluvial and rock recording sites, and for three data set selections. The regressions used for the UNE hazard calculations were for Group III alluvial and rock recordings, as preferred by Vortman (1984a). Less than 20% of this data set was from alluvial recording sites. Attenuation functions for alluvial sites are poorly constrained (Vortman 1984a) and do not permit meaningful comparisons with results for rock sites.

The regression equations for peak vertical and radial acceleration for Group III alluvial and rock recordings are:

$$\ln PGA_v = -0.909 + 0.518 \ln W - 1.78 \ln R, \ \sigma = 2.04$$

$$\ln PGA_r = -1.911 + 0.454 \ln W - 1.40 \ln R, \ \sigma = 2.13$$

where PGA is expressed as a multiple of the acceleration of gravity, W is yield in kilotons, R is epicentral distance in kilometers, and σ is the geometric standard deviation. These results were obtained from data sets of 338 and 292 records for the vertical and radial components, respectively. The given standard deviations apply to the estimation of peak acceleration at a site chosen at random. In the absence of specific information, it was assumed that these attenuation functions apply to UNE events in the Yucca Flat and Buckboard Mesa testing areas as well as to those at Pahute Mesa. This assumption is most critical for Buckboard Mesa, which is, at least geologically, similar to Pahute Mesa. It is likely that, while there may be systematic differences in mean attenuation functions for different testing areas, the dispersion would be similar. Regression analysis for Yucca Flat events is in progress (Vortman, 1984b).

In addition to the above results for a site chosen at random, site-specific attenuation functions were also considered in the hazard calculations reported below. Site-specific results were obtained from the statistics of peak accelerations recorded at Station 14 for eight yield-scaled Pahute

Mesa events, reported above. For both vertical and radial components, peak accelerations exceeded the means of the above regressions by factors of about 1.6 and had geometric standard deviations of 1.46. Treating the amplitude anomaly as a site effect, site-specific attenuation functions were formulated by adding the logarithm of the site factor to the Vortman (1984a) equations and replacing the geometric standard deviations by the site-specific value of 1.46. As before, it was assumed that the attenuation functions apply to Buckboard Mesa and Yucca Flat as well as to Pahute Mesa events.

Station 14 was chosen as the reference site for computing site-specific ground motion statistics because of general similarities to Station 26 and because of statistical resolution, more UNE events having been recorded there than at other stations in the site vicinity. At Station 26, located within the reference conceptual surface facility site area, recordings of only event KAPPELI were available for this study. As reported above, signal amplitudes at Stations 14 and 26 were similar for this event, but more data are needed to resolve the amplitude characteristics of Station 26. Given this uncertainty, hazard calculations were performed for site factors of 1.5 (representative of Station 14) and 2.0 (representative of stations with greater amplitude anomalies, e.g., Stations 23 and 25). The latter was adopted as a conservative estimate of the site factor for the reference conceptual site. It was assumed that the PGA standard deviation determined from the Station 14 data is applicable elsewhere in the site vicinity.

Probabilistic Results and Design UNE Accelerations. Site coordinates used in the hazard calculations were, as before, those of borehole RF-3 (36.853° N, 116.25° W), located within the reference conceptual site for repository surface facilities. Figures 8.12 and 8.13 show rate of exceedance as a function of peak vertical and radial acceleration. For recurrence expectancies greater than about 100 years, site-specific results obtained for a site amplification factor of 2 show lower ground motion hazard than for a site chosen at random. This demonstrates the importance of the standard deviation parameter in determining the results at low hazard levels. The preferred results are those obtained using a site-specific geometric standard deviation of 1.46 and a surface facility site amplification factor conservatively estimated to be 2.0.

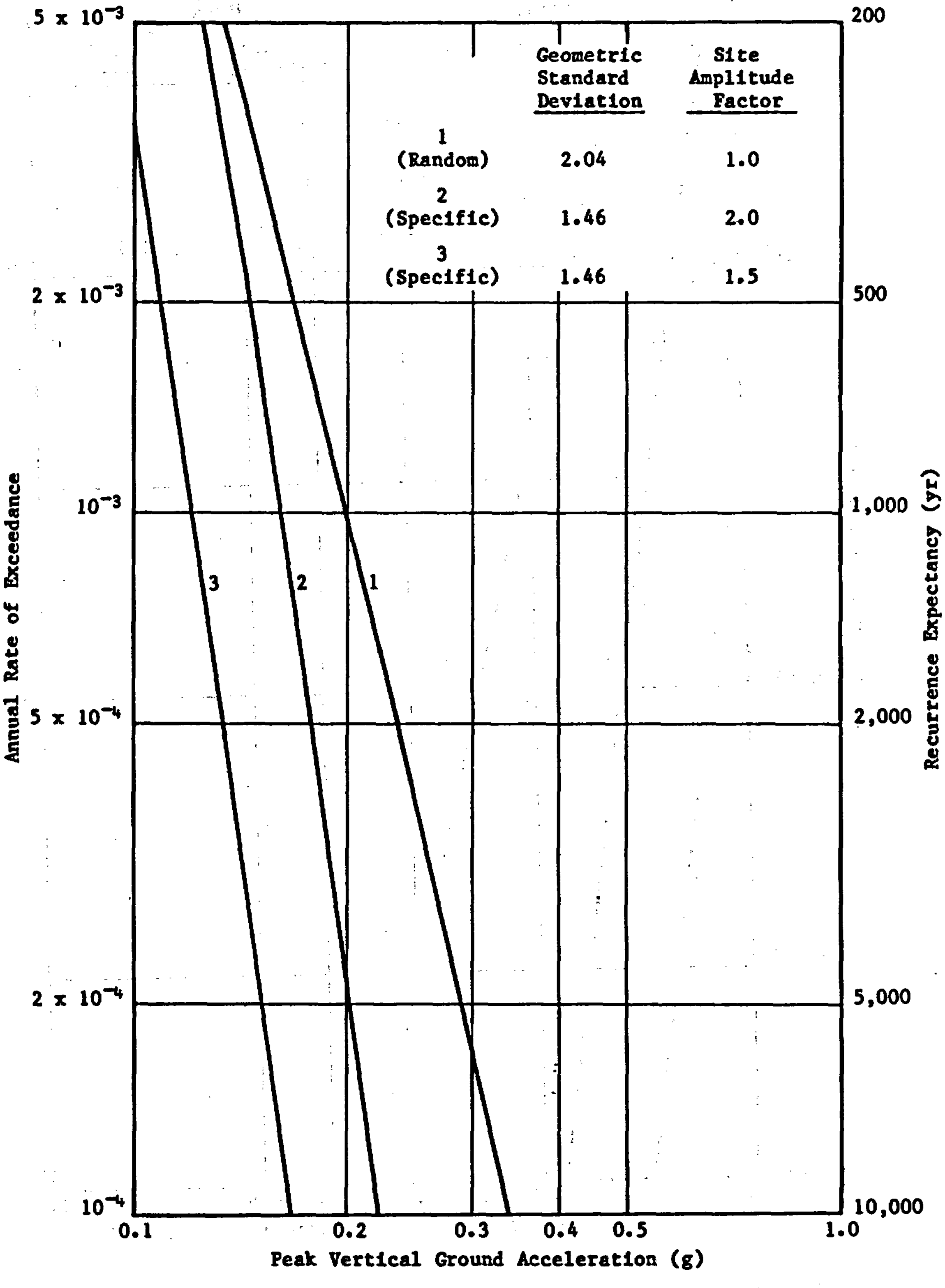


FIGURE 8.12 UNE HAZARD RESULTS FOR PEAK VERTICAL GROUND ACCELERATION, EVALUATED FOR RANDOM-SITE AND SITE-SPECIFIC MODELS

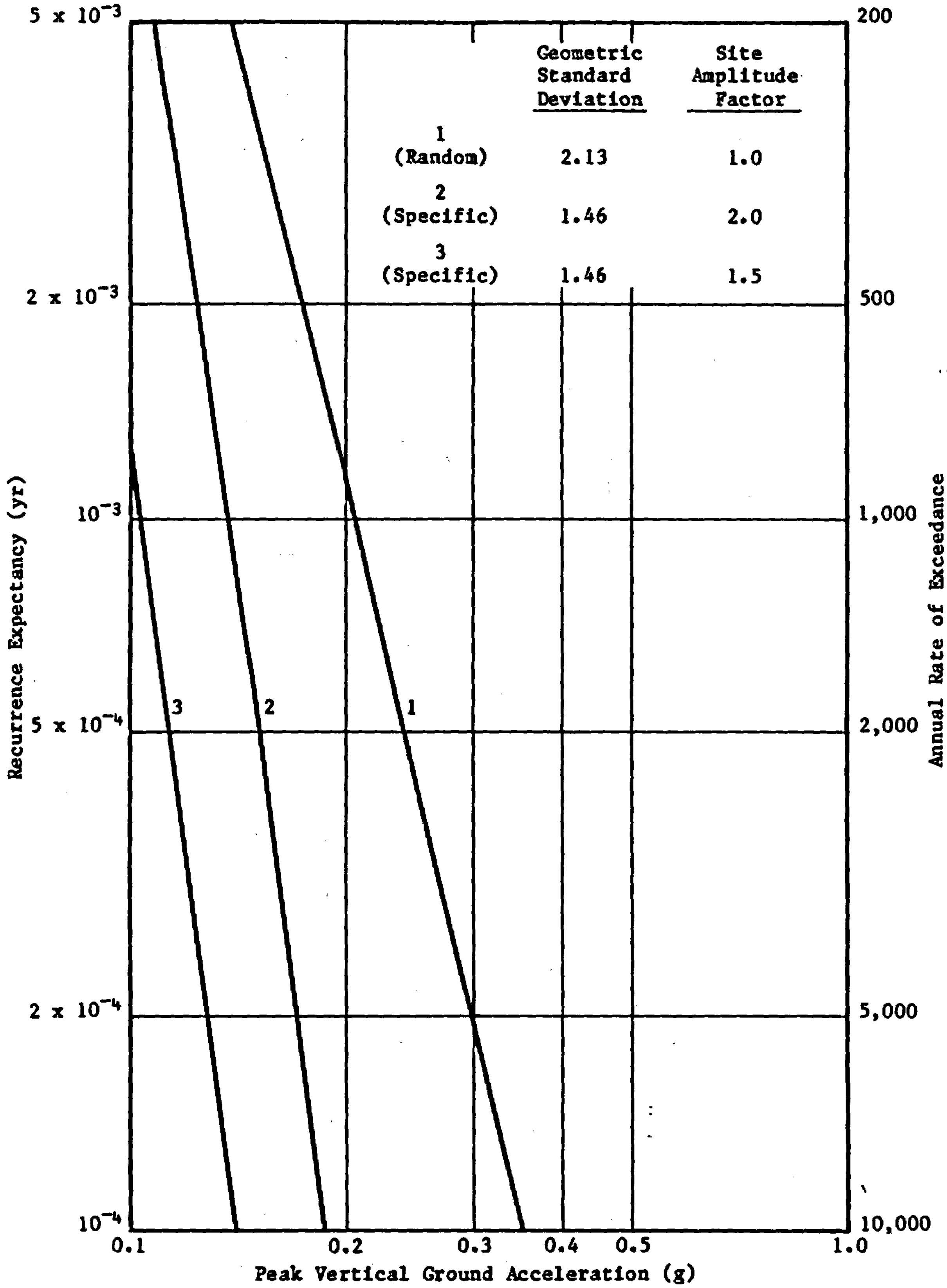


FIGURE 8.13 UNE HAZARD RESULTS FOR PEAK RADIAL GROUND ACCELERATION, EVALUATED FOR RANDOM-SITE AND SITE-SPECIFIC MODELS

For recurrence expectancies of 500 years and 2,000 years, as defined for design levels 2 and 1, respectively, the peak vertical accelerations are 0.15 g and 0.18 g. Peak horizontal (radial) accelerations are 0.125 g and 0.15 g, respectively.

UNE Response Spectra

While the adopted methodology for specifying ground motion calls for uniform-hazard spectra, such spectra have not been obtained for UNE events because of the absence of attenuation functions for response spectral amplitude. In place of uniform-hazard spectra, the response spectra shapes given here are for an event yield of 700 kt. These response spectra were obtained by determining mean response spectral shapes from the yield-scaled Yucca Mountain recordings and then scaling these shapes to the probabilistic design UNE accelerations determined above. These spectra therefore have the design-level exceedance rates at high frequencies but not necessarily at intermediate and low frequencies. To investigate this issue, probabilistic calculations, reported at the end of this chapter, were performed using attenuation functions for peak ground velocity and displacement in place of intermediate- and low-frequency spectral response. It was concluded that uniform-hazard spectra for UNE events would be very similar in shape to those given below for a 700-kt event.

Statistics of response spectra for Station 14, representing surface motion, were computed for 5% critical damping. This value of damping was selected because it is a standard value for specifying response spectra and is the value used in the Joyner and Boore (1982) attenuation relations for earthquake spectra. Figure 8.14 shows mean and mean-plus-one-standard-deviation response spectra for vertical-component surface motion, obtained by processing yield-scaled signals for Pahute Mesa events recorded at Station 14. No distance scaling was done, so these results are representative of 700-kt events at Pahute Mesa, at an average distance of 48 km. The standard deviation of the response spectrum is relatively uniform with respect to frequency. Parallel comparisons for radial and transverse components are shown in Figures 8.15 and 8.16, respectively. Note that, if these spectra were scaled to a distance of 21.3 km, the closest approach to the Buckboard Mesa area, the spectral amplitudes would be higher by a factor of about 3.75.

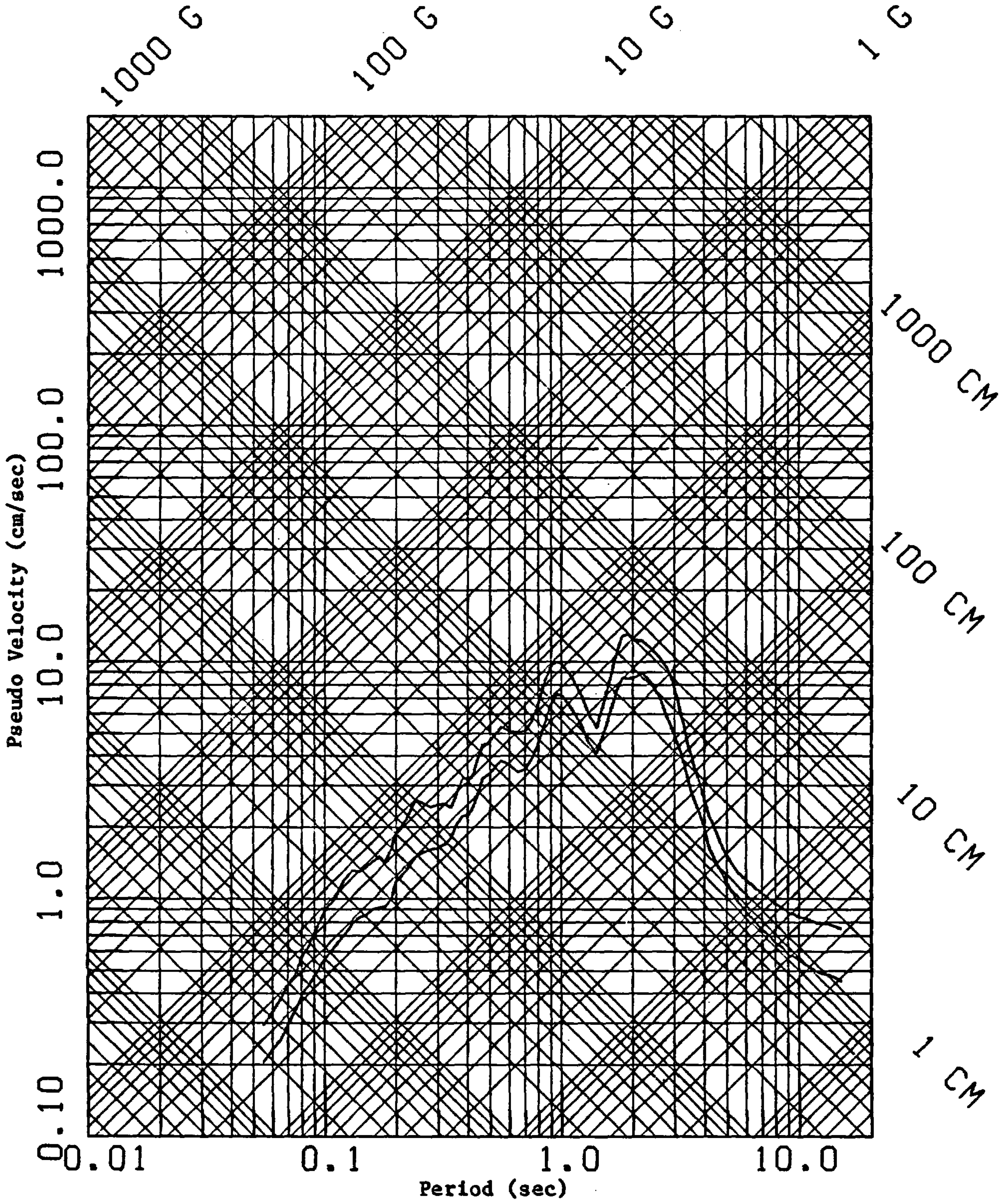


FIGURE 8.14 5%-DAMPED SURFACE RESPONSE SPECTRA FOR PAHUTE MESA UNE EVENTS RECORDED AT STATION 14, MEAN AND MEAN PLUS ONE STANDARD DEVIATION, VERTICAL COMPONENT

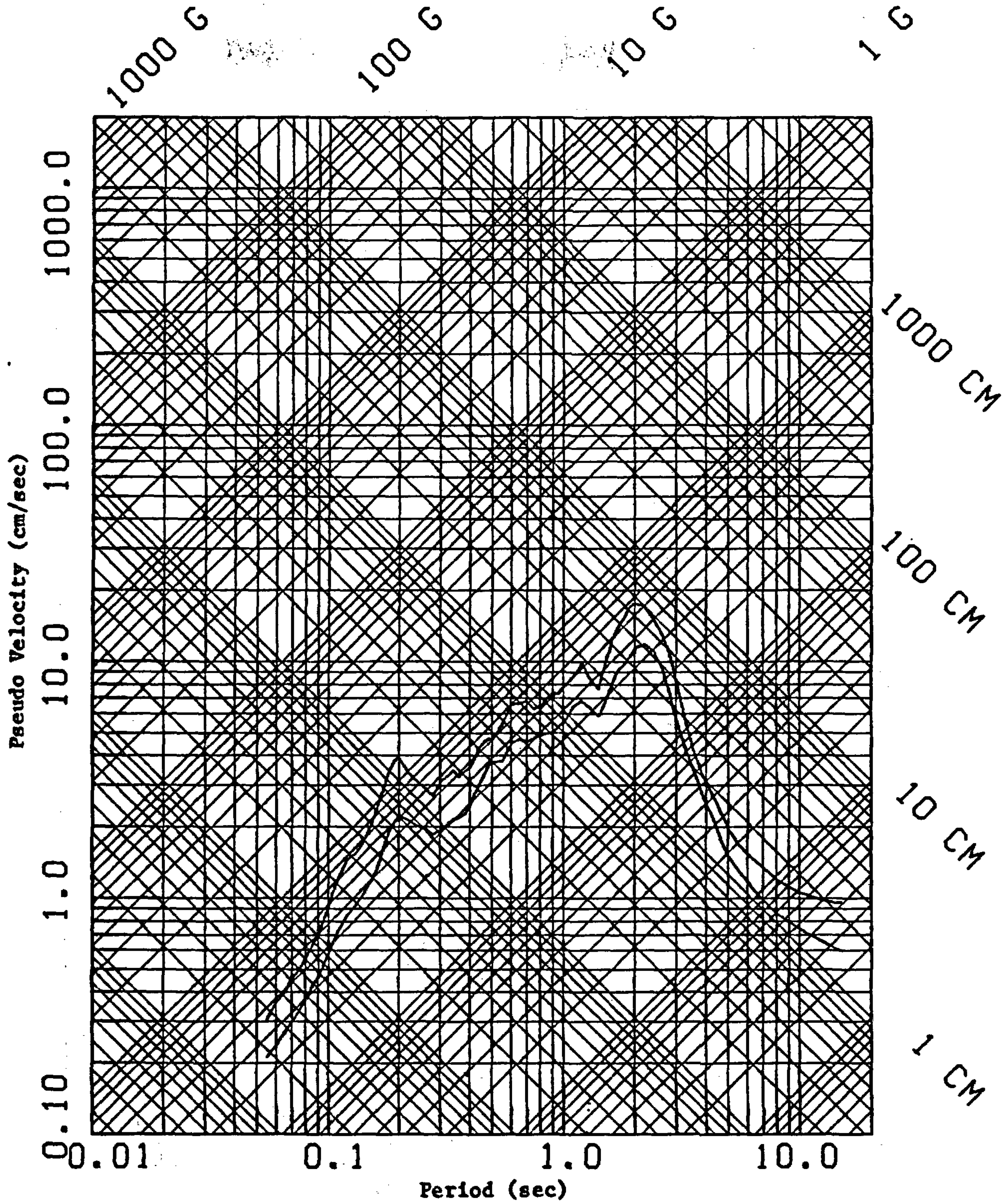


FIGURE 8.15 5%-DAMPED SURFACE RESPONSE SPECTRA FOR PAHUTE MESA UNE EVENTS RECORDED AT STATIONS 12 AND 25, MEAN AND MEAN PLUS ONE STANDARD DEVIATION, RADIAL COMPONENT

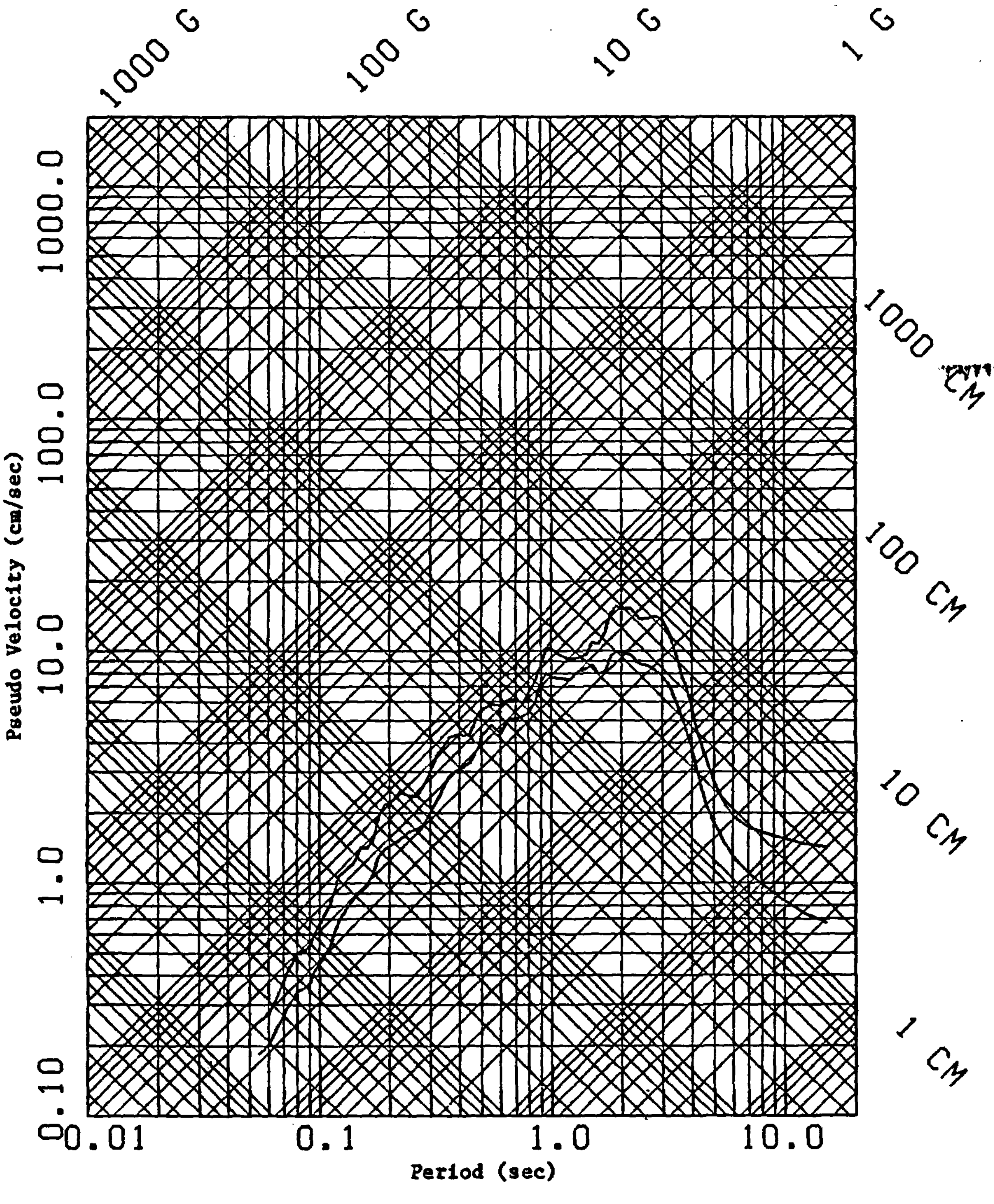


FIGURE 8.16 5%-DAMPED SURFACE RESPONSE SPECTRA FOR PAHUTE MESA UNE EVENTS RECORDED AT STATION 14, MEAN AND MEAN PLUS ONE STANDARD DEVIATION, TRANSVERSE COMPONENT

Statistics of response spectra were also computed for subsurface Stations 12 and 25, representing motion at repository depth, for 5% critical damping. Figure 8.17 shows vertical-component spectra for motion at repository depth, obtained by computing statistics for the combined data for Stations 12 and 25. Even though data for two different stations were included, the standard deviation is similar to that at Station 14. Parallel comparisons for radial and transverse components are shown in Figures 8.18 and 8.19, respectively. Note, as before, that scaling to a distance of 21.3 km would increase the spectral amplitudes by a factor of about 3.75.

Figure 8.20 compares the mean vertical component spectra for surface and subsurface. Response spectral amplitudes are about three times higher at the surface for periods up to 1 sec and not quite twice as high for periods greater than 2 sec. Parallel comparisons for radial and transverse components are shown in Figures 8.21 and 8.22, respectively. Surface response is three to four times higher than subsurface response in the band 0.1 to 1.5 sec and about twice as high for periods greater than 3 sec. In summary, surface response exceeds subsurface response by factors of 2 or more in all cases except in the vertical component for periods longer than 2 sec. These results are similar to the spectral modulus ratios shown in Figure 8.10.

Vertical-component surface spectra for Design UNE-2 and Design UNE-1 motion are shown in Figure 8.23. These were obtained by scaling the mean Station 14 spectrum to peak accelerations of 0.15 g and 0.18 g, determined to have recurrence expectancies of 500 and 2,000 years. The horizontal-component DUNE-2 and DUNE-1 spectra, shown in Figure 8.24, were scaled from the mean radial-component spectrum for Station 14 to peak accelerations of 0.125 g and 0.15 g.

It is recommended that, for present purposes, subsurface response spectra be taken as half the corresponding surface spectra, pending further investigations concerning the frequency dependence (or lack thereof) of subsurface/surface spectral ratios. The same recommendation was made above in the case of earthquake ground motion. Ultimately, subsurface UNE ground motion criteria should be based directly on the statistics of UNE recordings at repository depth, in the same manner as for surface motion.

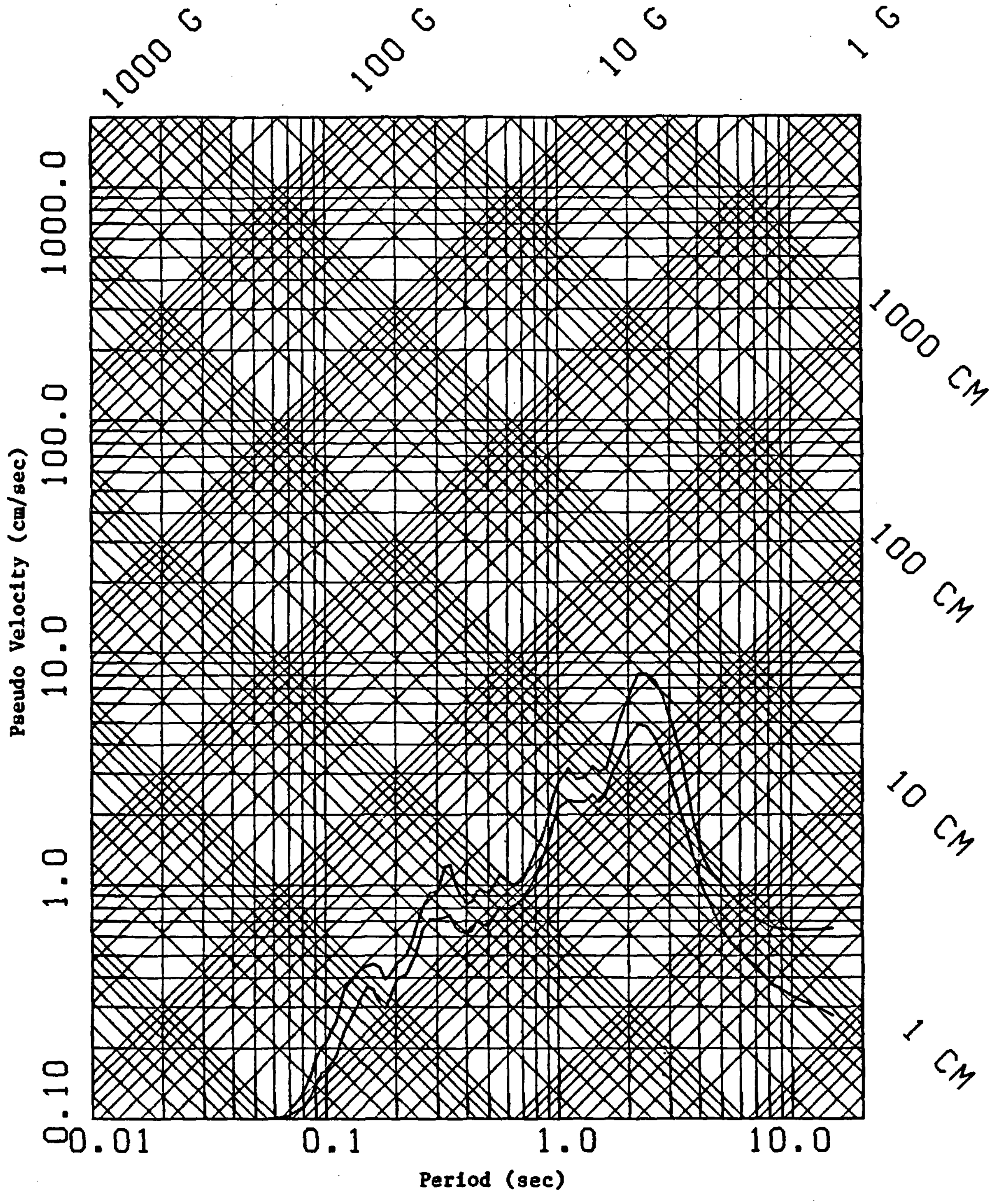


FIGURE 8.17 5%-DAMPED SUBSURFACE RESPONSE SPECTRA FOR PAHUTE MESA UNE EVENTS RECORDED AT STATIONS 12 AND 25, MEAN AND MEAN PLUS ONE STANDARD DEVIATION, VERTICAL COMPONENT

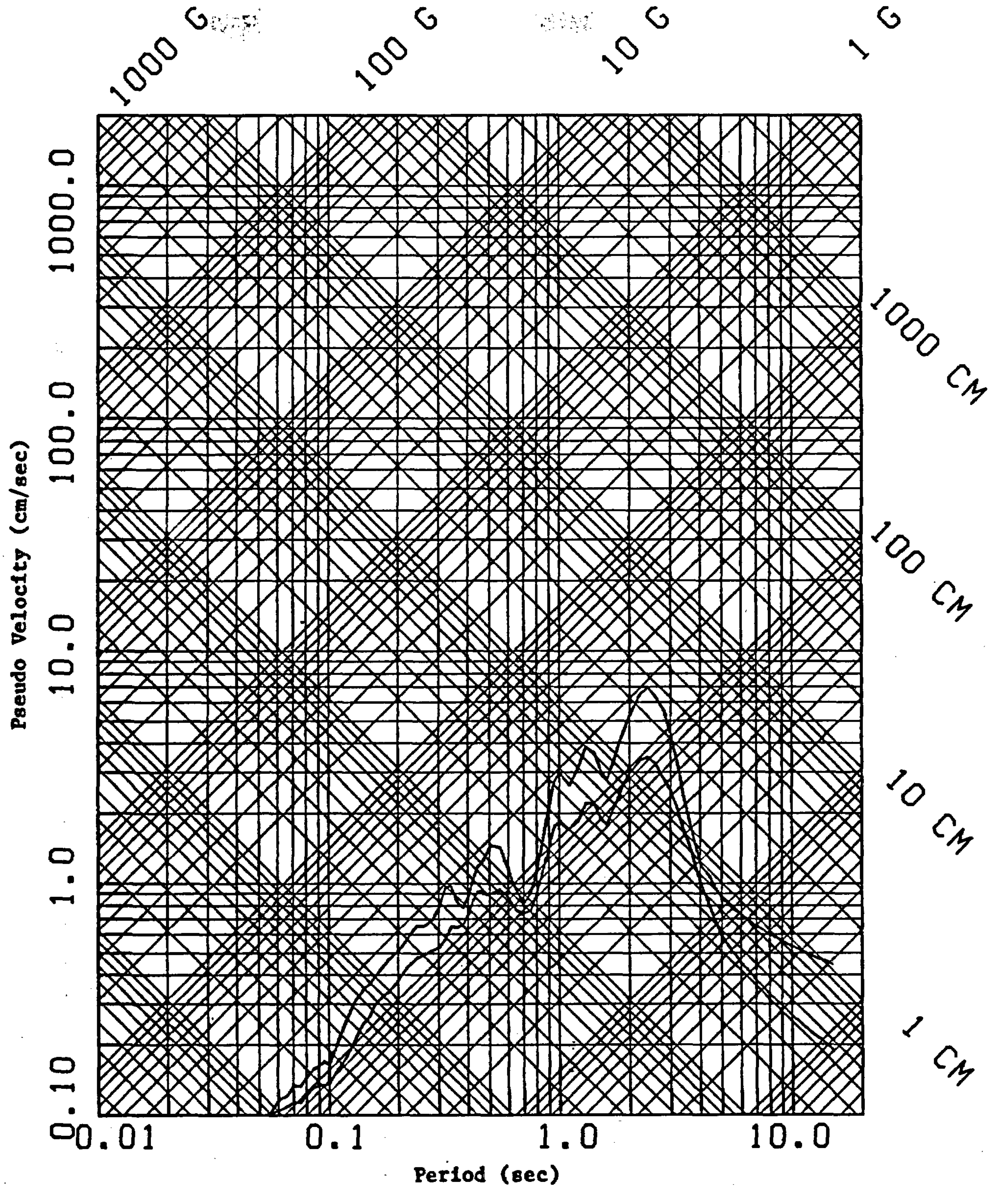


FIGURE 8.18 5%-DAMPED SUBSURFACE RESPONSE SPECTRA FOR PAHUTE MESA UNE EVENTS RECORDED AT STATIONS 12 AND 25, MEAN AND MEAN PLUS ONE STANDARD DEVIATION, RADIAL COMPONENT

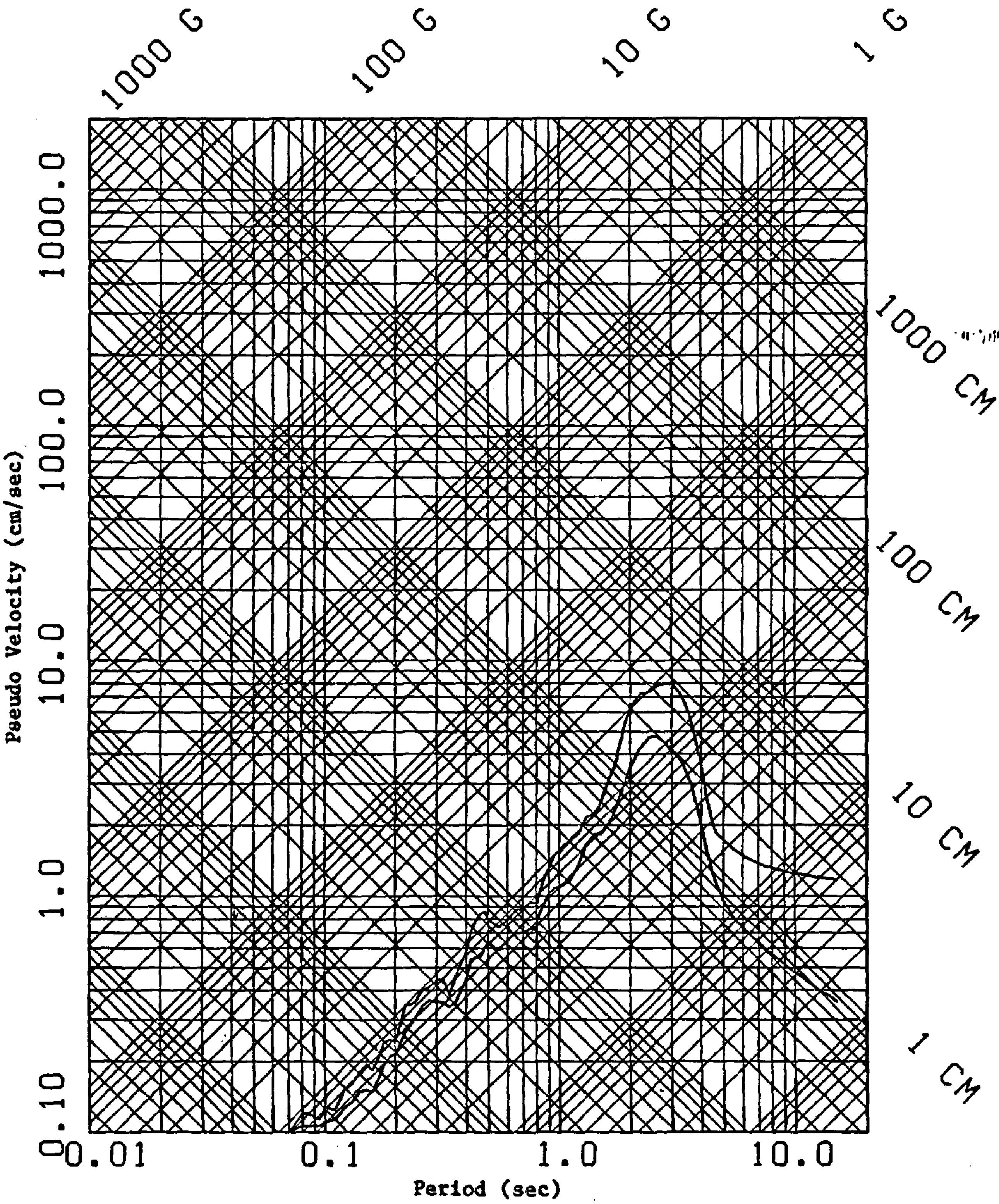


FIGURE 8.19 5%-DAMPED SUBSURFACE RESPONSE SPECTRA FOR PAHUTE MESA UNE EVENTS RECORDED AT STATIONS 12 AND 25, MEAN AND MEAN PLUS ONE STANDARD DEVIATION, TRANSVERSE COMPONENT

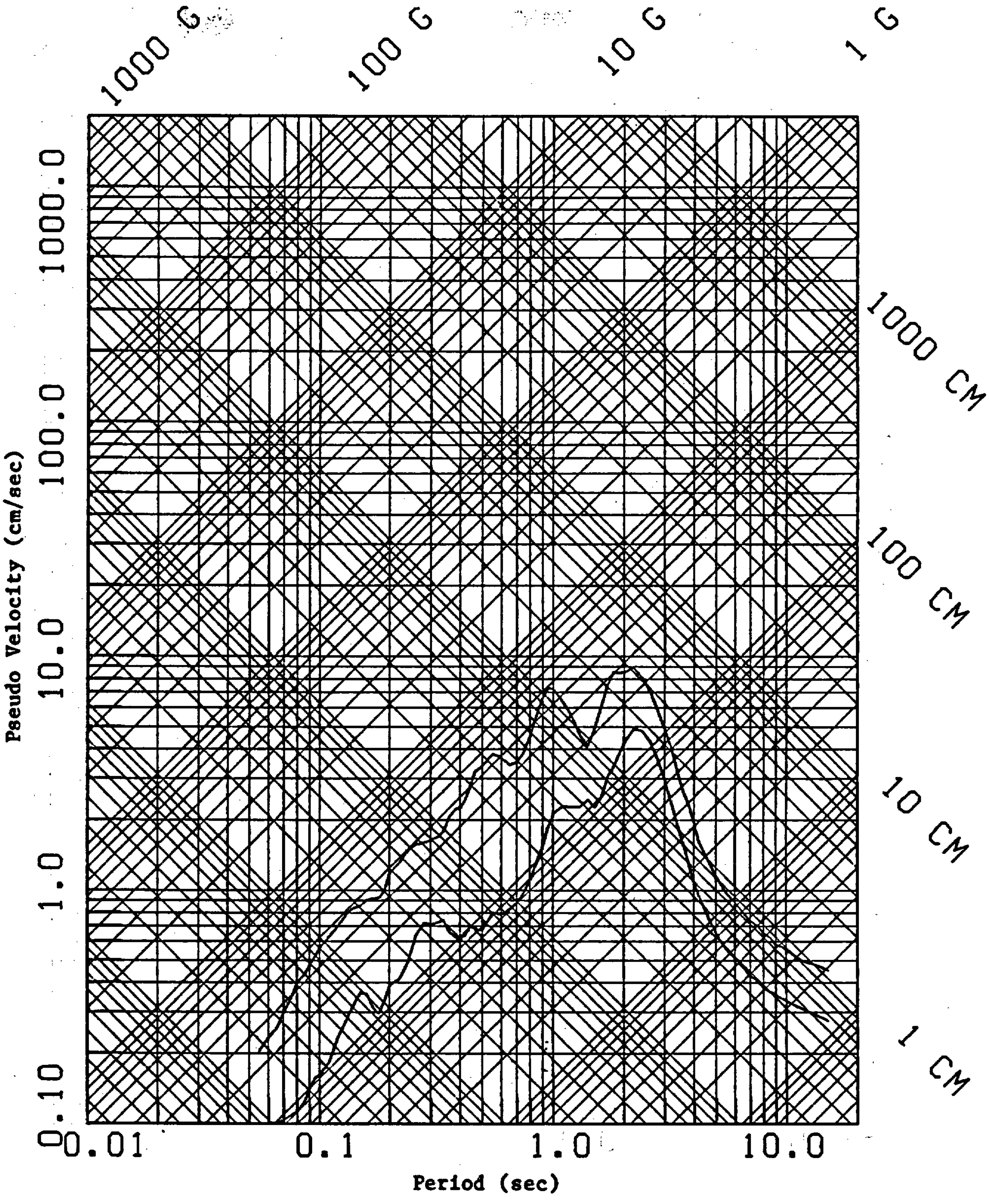


FIGURE 8.20 COMPARISON OF MEAN SURFACE AND SUBSURFACE RESPONSE SPECTRA FOR PAHUTE MESA UNE EVENTS RECORDED AT STATION 14 (SURFACE) AND STATIONS 12 AND 25 (SUBSURFACE), 5% DAMPING, VERTICAL COMPONENT

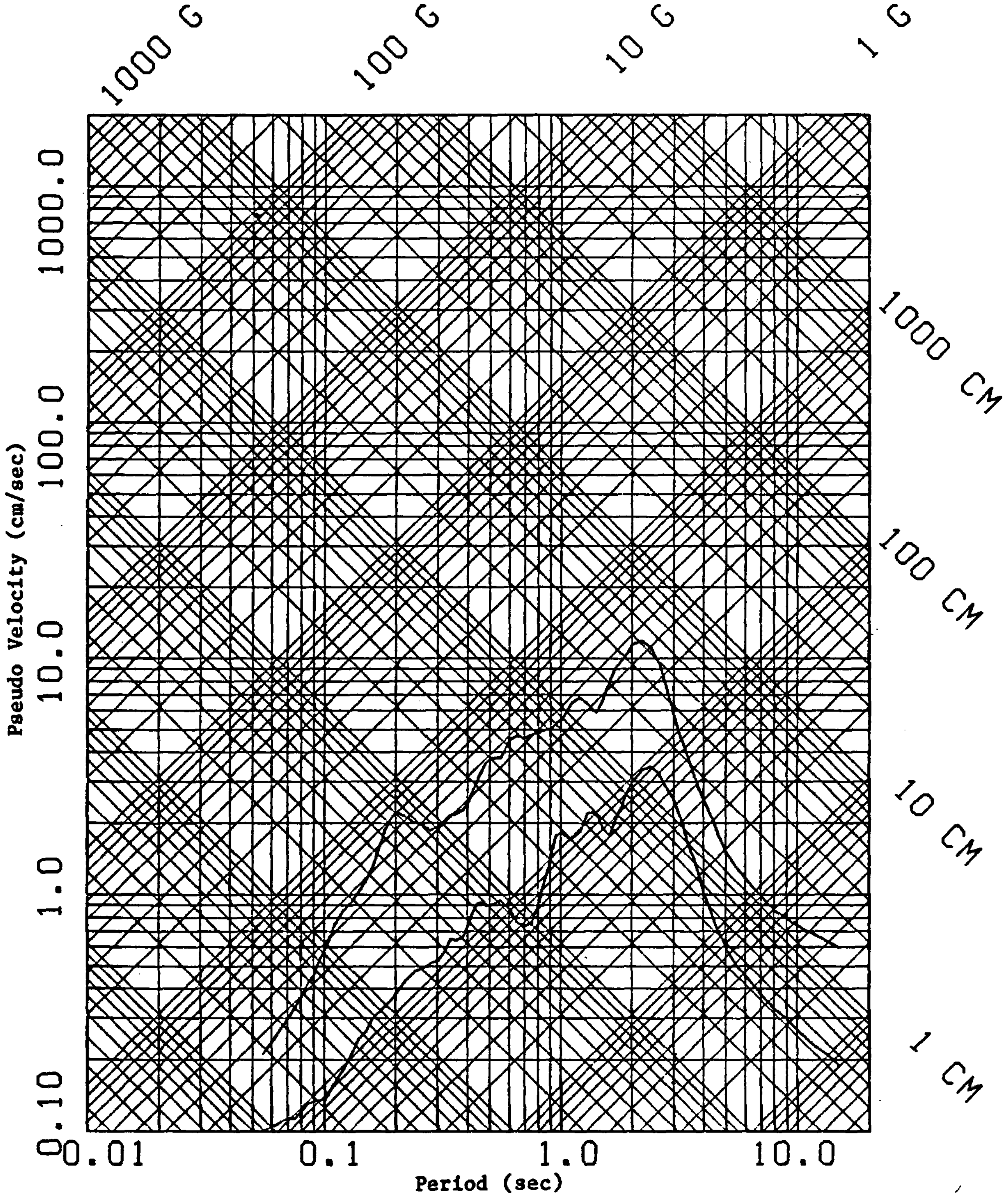


FIGURE 8.21 COMPARISON OF MEAN SURFACE AND SUBSURFACE RESPONSE SPECTRA FOR PAHUTE MESA UNE EVENTS RECORDED AT STATION 14 (SURFACE) AND STATIONS 12 AND 25 (SUBSURFACE), 5% DAMPING, RADIAL COMPONENT

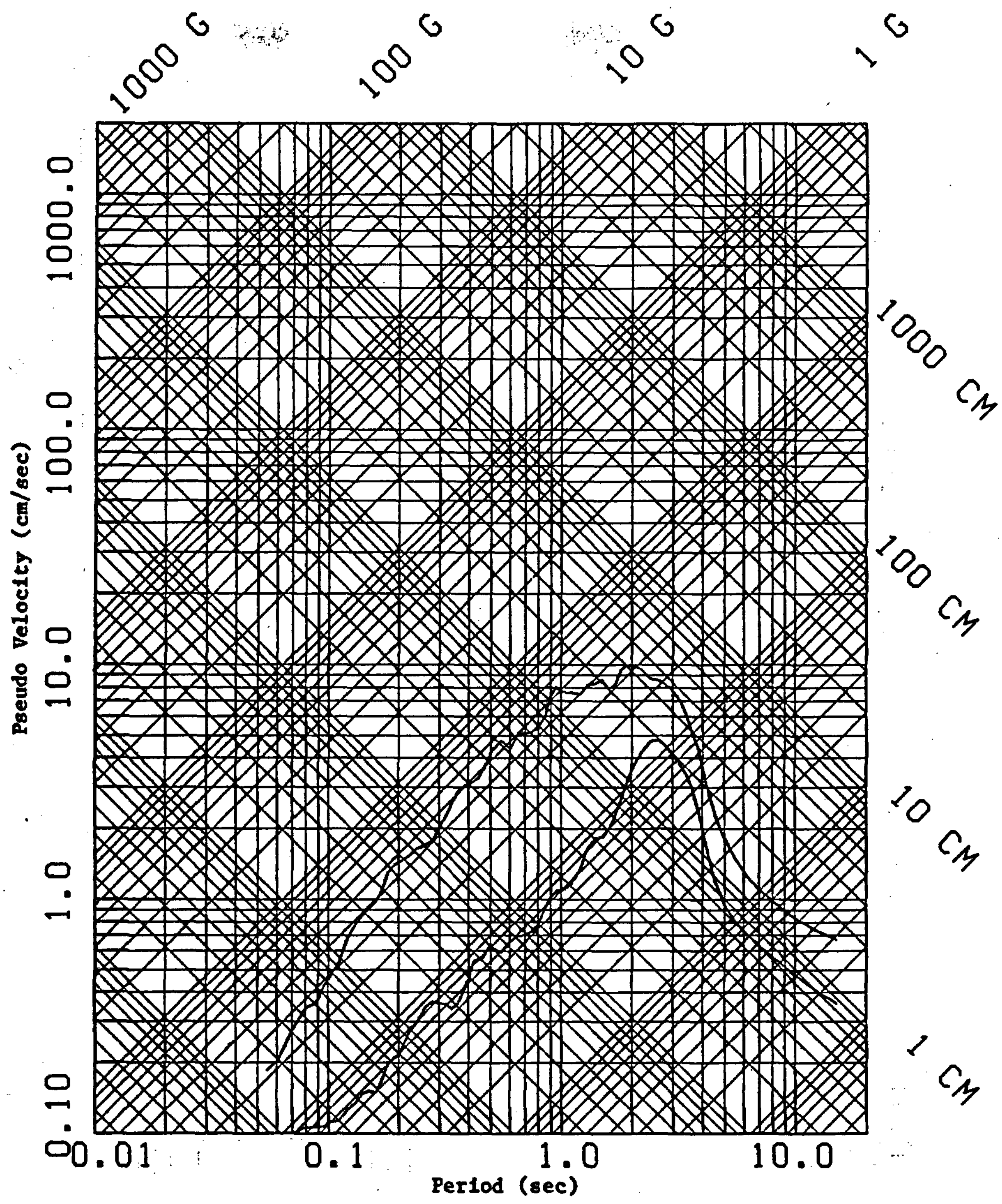


FIGURE 8.22 COMPARISON OF MEAN SURFACE AND SUBSURFACE RESPONSE SPECTRA FOR PAHUTE MESA UNE EVENTS RECORDED AT STATION 14 (SURFACE) AND STATIONS 12 AND 25 (SUBSURFACE), 5% DAMPING, TRANSVERSE COMPONENT

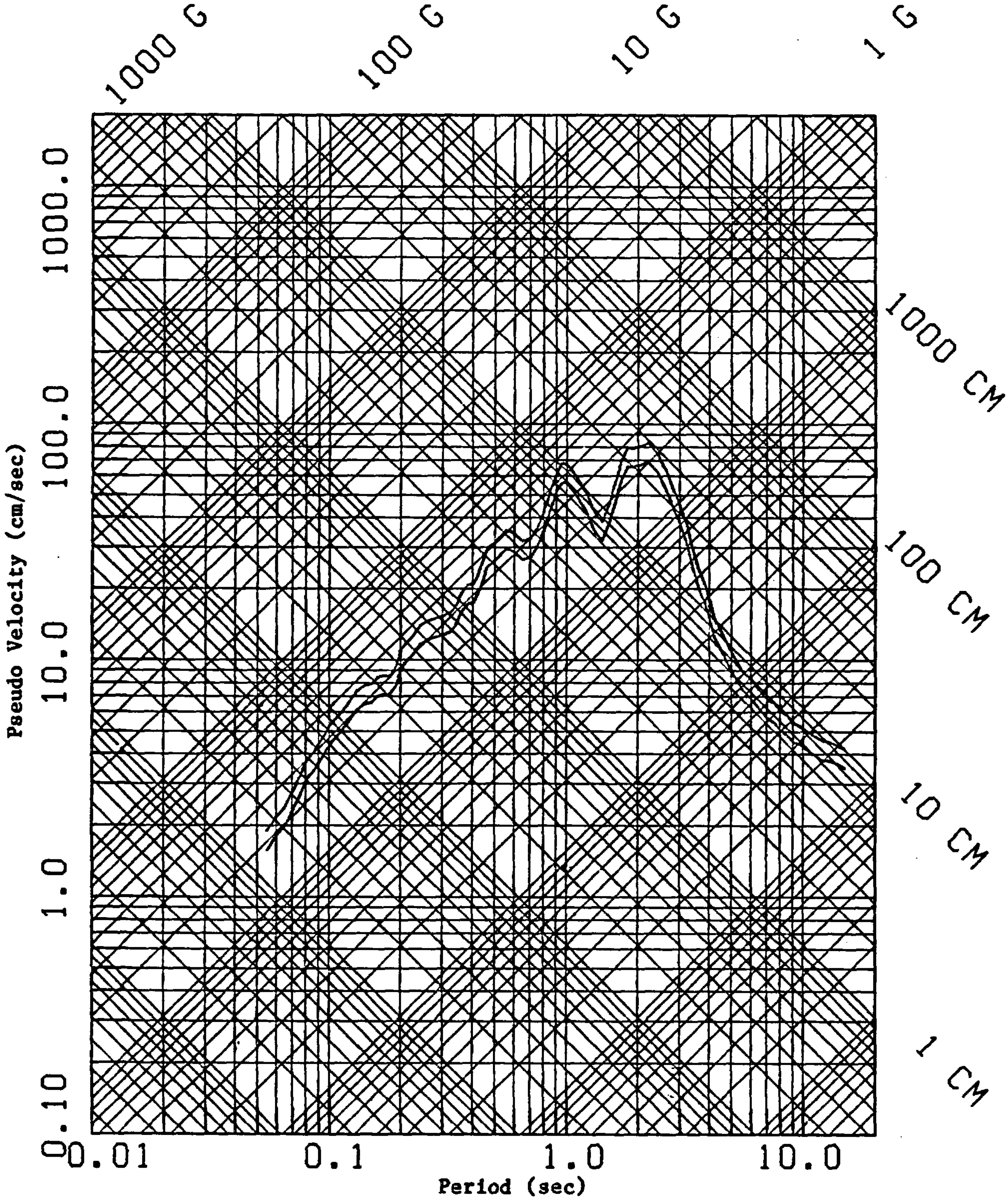


FIGURE 8.23 5%-DAMPED SURFACE VERTICAL-COMPONENT RESPONSE SPECTRA RECORDED AT STATION 14, SCALED TO PGAs OF 0.15g AND 0.18g, WITH RECURRENCE EXPECTANCIES OF 500 AND 2,000 YEARS (DUNE-2 AND DUNE-1)

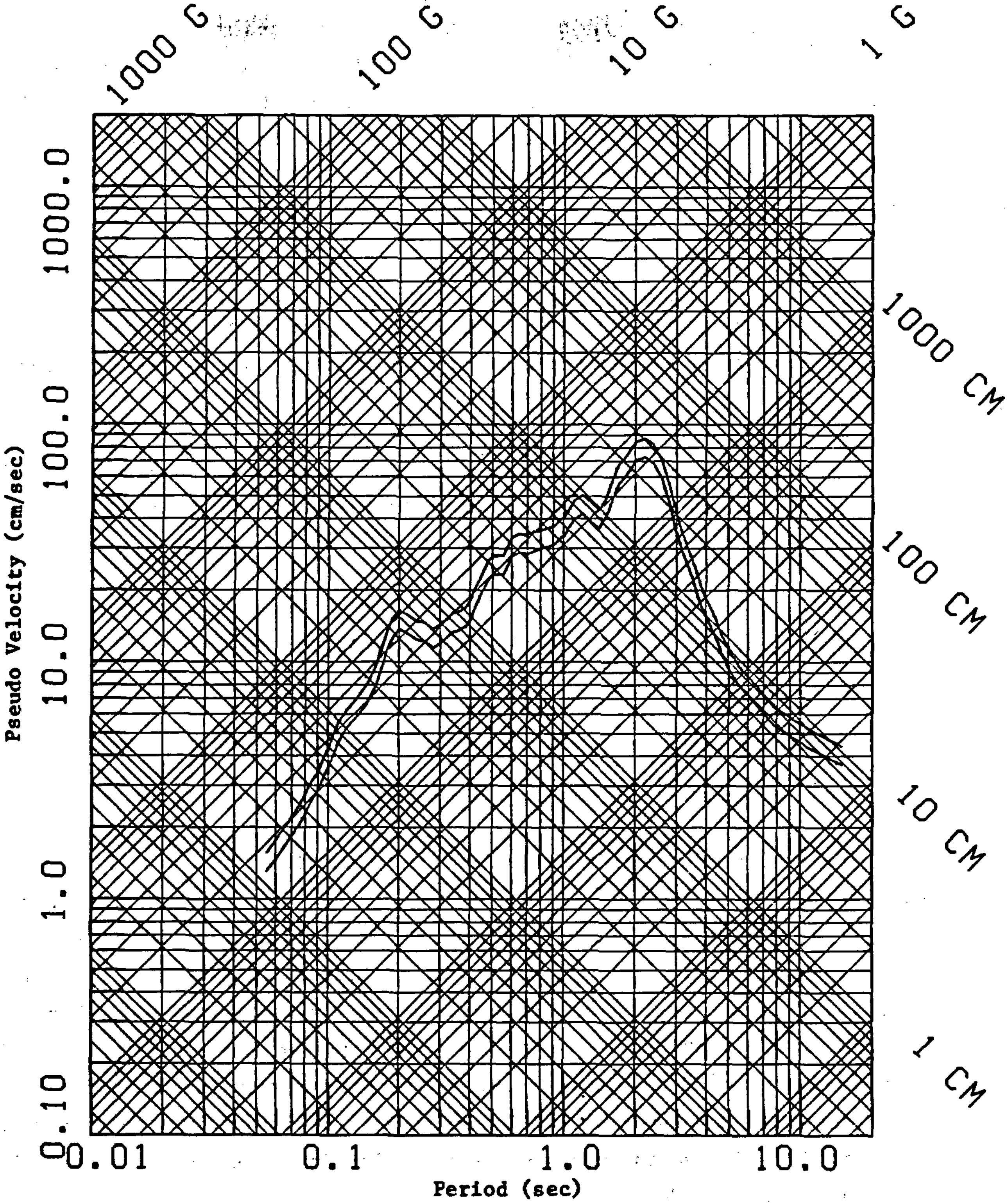


FIGURE 8.24 5%-DAMPED SURFACE HORIZONTAL-COMPONENT RESPONSE SPECTRA RECORDED AT STATION 14, SCALED TO PGAs OF 0.125g AND 0.15g, WITH RECURRENCE EXPECTANCIES OF 500 AND 2,000 YEARS (DUNE-2 AND DUNE-1)

As mentioned previously, no uniform-hazard spectra for UNE events were obtained because of the absence of attenuation functions for response spectral amplitude. However, probabilistic calculations were performed for peak ground velocity and displacement, and these were compared with values obtained for the 700-kt event, scaled to the DUNE-2 and DUNE-1 PGA levels. The latter values were obtained by first evaluating the Vortman (1984a) regression equations to obtain peak acceleration, velocity, and displacement for an event of 700 kt at a distance of 21.3 km. The velocity and displacement values were then multiplied by the ratio of the design UNE acceleration to the acceleration for 700 kt at 21.3 km. Results for the radial component are shown below.

	DUNE-2 (0.125 g)	DUNE-1 (0.15 g)
Radial-Component Peak Ground Velocity (cm/sec)		
700-kt Event	12.5	15.0
Probabilistic	12.2	14.9
Radial-Component Peak Ground Displacement (cm)		
700-kt Event	3.9	4.7
Probabilistic	3.6	4.4

The probabilistic calculation gives peak velocities for design levels 1 and 2 that are almost identical to those obtained "deterministically" for the 700-kt event scaled to the appropriate PGA levels. In the case of peak ground displacement, probabilistic values are about 10% lower than those for the design event. The results are similar because the UNE hazard is dominated by events near the yield limit and near the southern geographic limit of the Buckboard Mesa area. While these results are not directly applicable to response spectral amplitude, we infer that uniform-hazard spectra for UNE events would be very similar in shape to those given here for an event of yield 700 kt.

It is relevant to evaluate the design UNE spectra in terms of their likelihood of being exceeded as a result of single and multiple occurrences of the maximum potential UNE event, a 700-kt detonation at 21.3 km. Spectra for such an event would resemble the design UNE spectra in shape, except for slight effects due to the greater distance, 48 km, of the Yucca Mountain recordings of Pahute Mesa events that were yield-scaled to 700 kt. We obtained design spectra by simply shifting the empirical spectra upward to match the probabilistic PGA levels of the design UNEs. To evaluate confidence levels that the design spectra would not be exceeded in the event of a 700-kt detonation at 21.3 km, we used the Vortman (1984a) attenuation results for distance scaling, and site-specific statistics. For simplicity, we used PGA as the parameter for evaluating confidence levels.

The expected peak radial acceleration at Yucca Mountain for a 700-kt event at 21.3 km is 0.080 g, allowing for the site amplification factor of 2. The mean + σ and mean + 2σ radial accelerations are 0.117 g and 0.17 g, again using site-specific statistics. The DUNE-1 peak radial acceleration of 0.15g is close to the 95th percentile, given the occurrence of a single event. It would be expected that this level would be exceeded once in every 20 detonations of 700-kt events at 21.3 km. If we interpret the DUNE-1 in terms of the deterministic 700-kt event, it is equivalent to the occurrence of 20 such events during the 100-year operational phase of the repository. Parallel evaluation of the DUNE-2 level yields 88% confidence that it would not be exceeded given the occurrence of a 700-kt event at 21.3 km, with the expectation that it would be exceeded once in eight such occurrences.

The design levels appear more conservative if we refer specifically to Station 14, which has a site amplification factor of 1.6 rather than 2, as used in all of the foregoing analysis. In this case, the expected peak radial acceleration for a 700-kt event at 21.3 km is 0.064 g, and the DUNE-2 and DUNE-1 PGA levels are near the 96th and 99th percentiles, respectively.

Parallel evaluations based on response spectral amplitude rather than PGA would yield essentially the same results because standard deviations of response spectral amplitude, illustrated in Figures 8.14 to 8.16, are relatively uniform across the spectrum and are similar to those for PGA.

9. COMPARISON OF EARTHQUAKE AND UNE GROUND MOTION

Earthquake and UNE ground motion are compared below in terms of recurrence of peak ground acceleration and velocity and in terms of design response spectra. The relative importance of earthquake and UNE ground motion is a function of recurrence expectancy (return period) and spectral frequency. Without reference to these parameters, no useful generalization can be made. Earthquakes are of increasing importance, relative to UNE events, with increasing recurrence expectancy and with increasing spectral frequency.

Peak Ground Motion

Figure 9.1 compares horizontal PGA hazard curves for earthquakes and UNE events. UNE results are given for two cases: for a randomly chosen site, as for the earthquake hazard results, and for a site-specific adjustment to the Vortman (1984a) regression results based on analysis of Yucca Mountain data. For horizontal PGA, earthquakes become more important than UNE events for recurrence expectancies longer than 20 years or for horizontal PGAs above 0.07 g.

Results for horizontal peak ground velocity (PGV) are shown in Figure 9.2. In this case, earthquakes become more important than UNE events for recurrence expectancies longer than 400 years or for horizontal PGVs greater than 12 cm/sec.

Since horizontal PGV is greater for earthquakes than for UNEs for recurrence expectancies greater than 400 years, one might be tempted to conclude that earthquakes will govern at design levels 2 and 1, where recurrence expectancies are 500 and 2,000 years, respectively. However, as will be seen below, long-period response-spectral velocity for UNE motion exceeds that for earthquake motion at both design levels.

Design Response Spectra

For earthquake ground motion, uniform-hazard spectra were computed for levels 2 and 1 with recurrence expectancies of 500 and 2,000 years, respec-

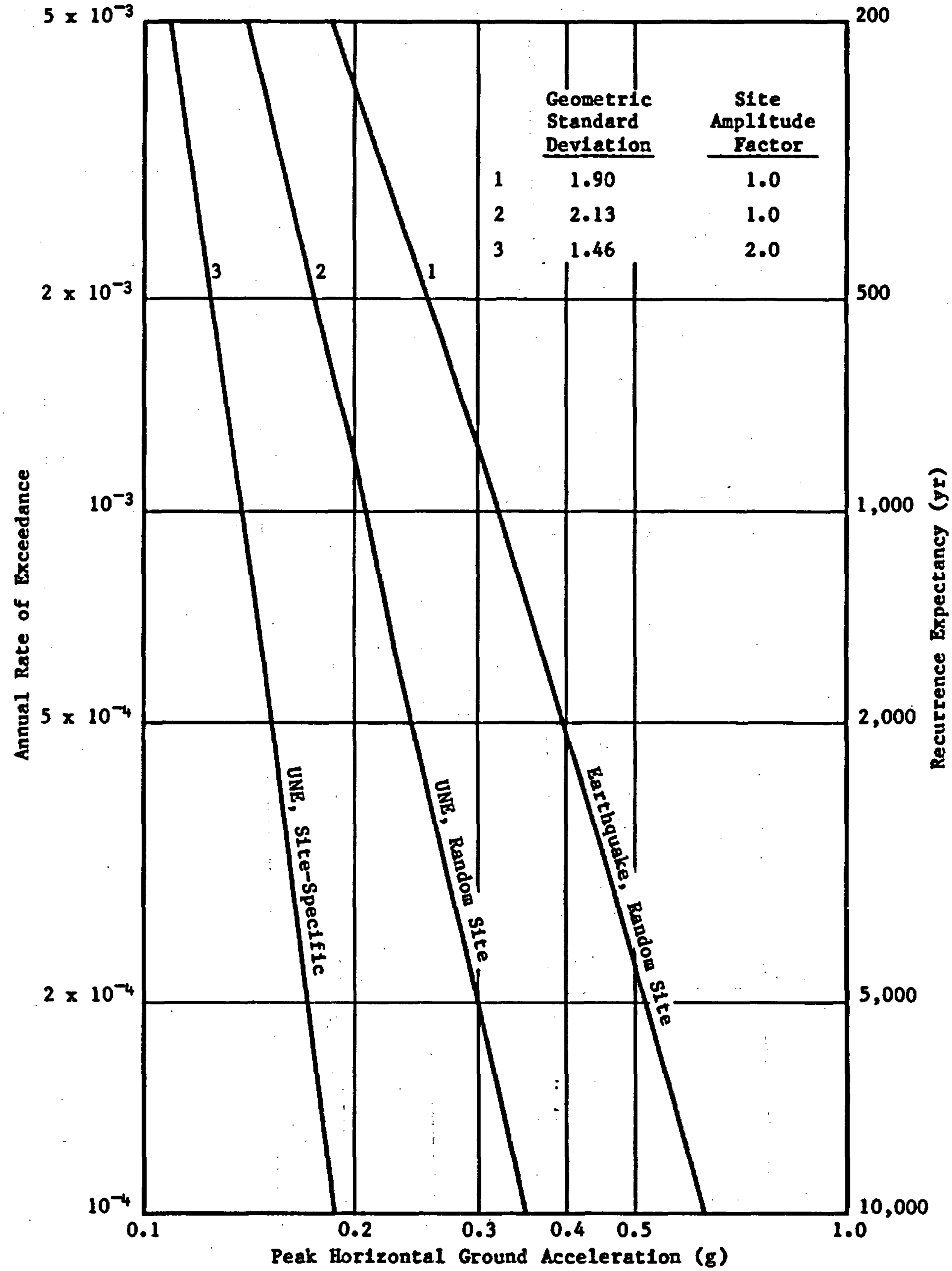


FIGURE 9.1 COMPARISON OF EARTHQUAKE AND UNE HAZARD RESULTS FOR PEAK HORIZONTAL GROUND ACCELERATION

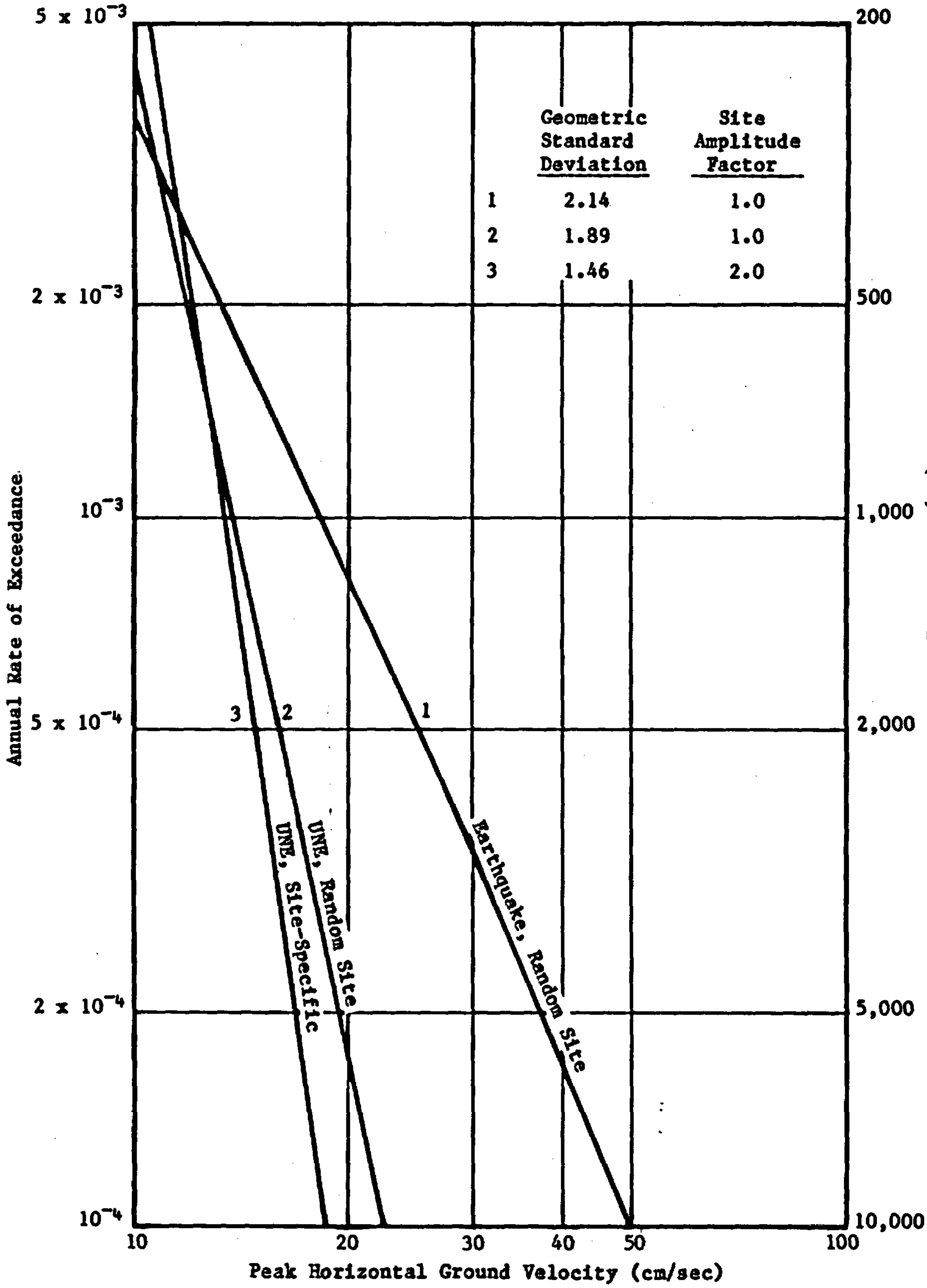


FIGURE 9.2 COMPARISON OF EARTHQUAKE AND UNE HAZARD RESULTS FOR PEAK HORIZONTAL GROUND VELOCITY

tively. For the vertical component, not considered in the Joyner and Boore (1982) regressions, spectra for DE-2 and DE-1 were taken to be two-thirds those for the horizontal component.

In the case of UNE ground motion, peak horizontal and vertical ground accelerations for levels 1 and 2 were obtained from probabilistic calculations, using site-specific statistics obtained from the Yucca Mountain recordings of Pahute Mesa UNE events. Site-specific response spectral shapes were obtained for an event of yield 700 kt and were scaled to the probabilistically determined PGA levels. UNE uniform-hazard spectra are expected to be very similar to those for the 700-kt event, on the basis of hazard calculations for peak ground velocity and displacement as described at the end of Chapter 8. No uniform-hazard spectra were obtained because of the absence of attenuation functions for UNE response spectral amplitudes.

Figures 9.3 and 9.4 compare level 2 earthquake and UNE response spectra for horizontal and vertical components, respectively. Comparisons for level 1 are shown in Figures 9.5 and 9.6.

Results for level 2 horizontal spectra (Figure 9.3) show that the UNE spectrum exceeds the earthquake spectrum for periods above 0.4 sec. For level 2 vertical spectra (Figure 9.4), the importance of UNE relative to earthquake motion is greater than in all other cases. Here, the UNE spectrum exceeds the earthquake spectrum for periods above 0.2 sec.

Horizontal response spectra for level 1 (Figure 9.5) show that the UNE spectrum exceeds the earthquake spectrum for periods beyond 1 sec. Vertical response spectra for level 1 (Figure 9.6) again illustrate the importance of UNE ground motion at the longer periods. The UNE spectrum exceeds the earthquake spectrum for periods above 0.4 sec.

The principal conclusion to be drawn from this comparison of earthquake and UNE ground motion hazard is that both must be considered for seismic design. Earthquakes and UNE events produce hazards of distinctly different frequency content, as observed by Vortman (1982). The probabilistic results show that earthquakes will govern at high frequencies, while UNE

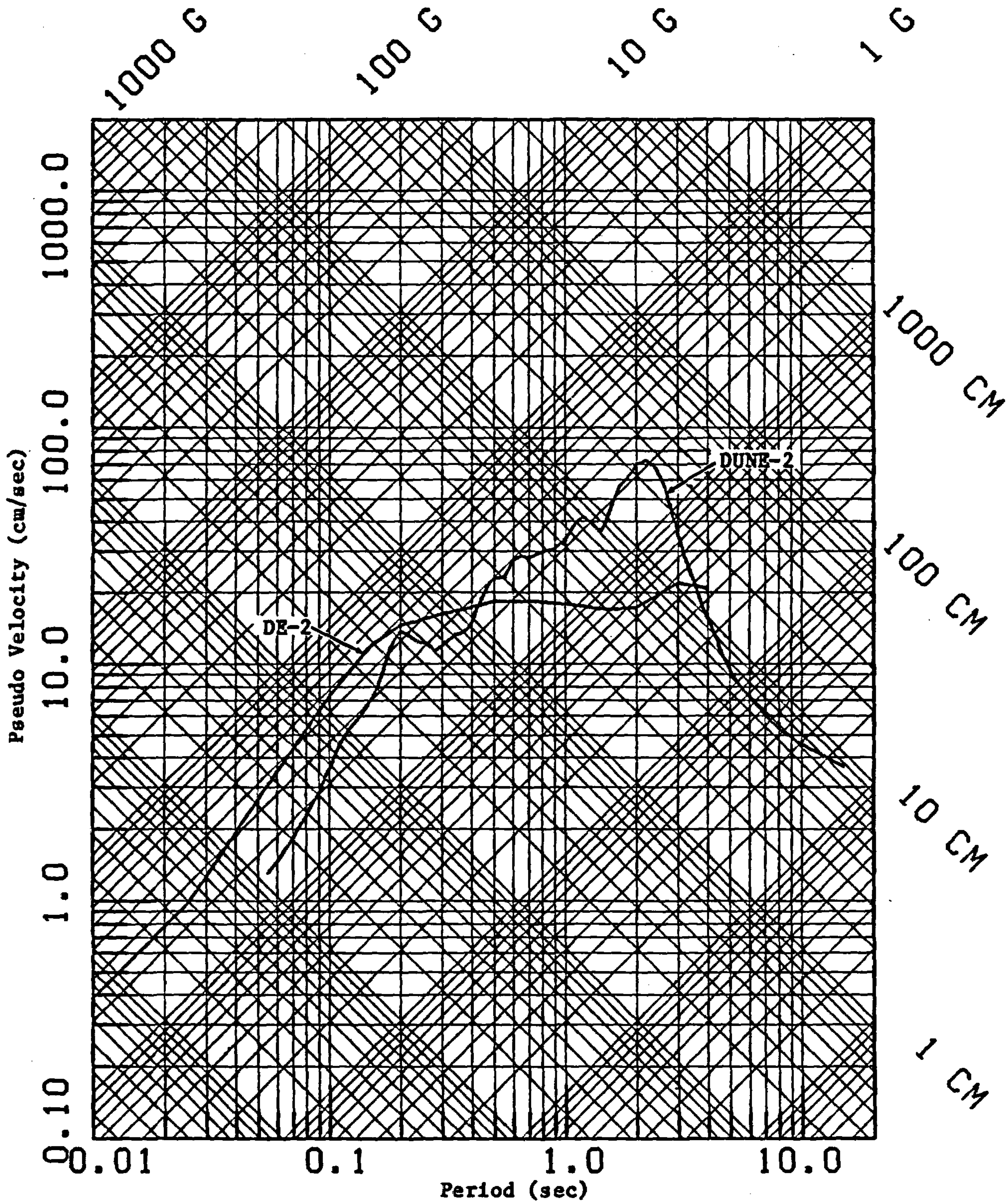


FIGURE 9.3 COMPARISON OF 5%-DAMPED HORIZONTAL-COMPONENT RESPONSE SPECTRA FOR LEVEL 2 PGA (500-YEAR RECURRENCE EXPECTANCY)

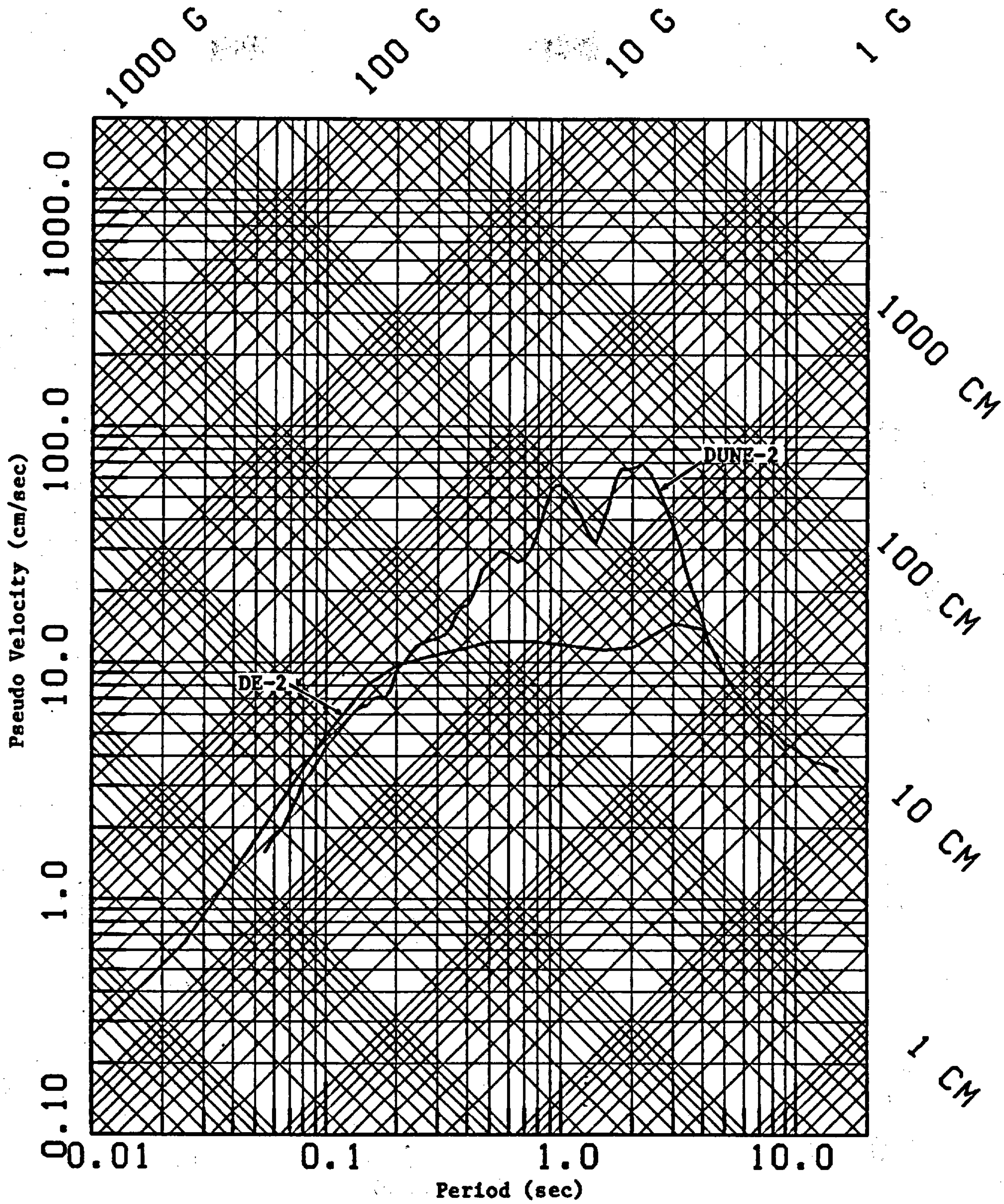


FIGURE 9.4 COMPARISON OF 5%-DAMPED VERTICAL-COMPONENT RESPONSE SPECTRA FOR LEVEL 2 PGA (500-YEAR RECURRENCE EXPECTANCY)

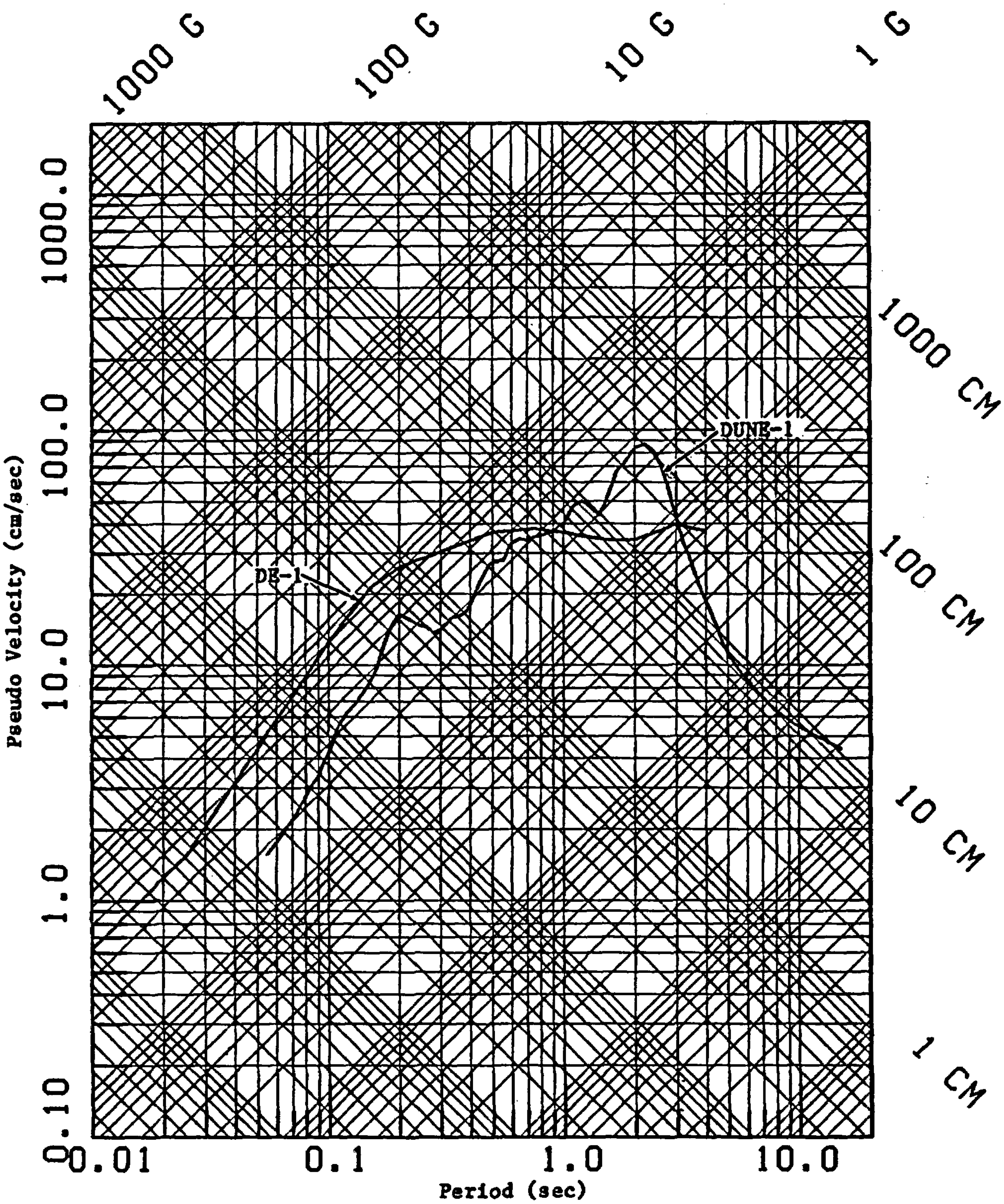


FIGURE 9.5 COMPARISON OF 5%-DAMPED HORIZONTAL-COMPONENT RESPONSE SPECTRA FOR LEVEL 1 PGA (2,000-YEAR RECURRENCE EXPECTANCY)

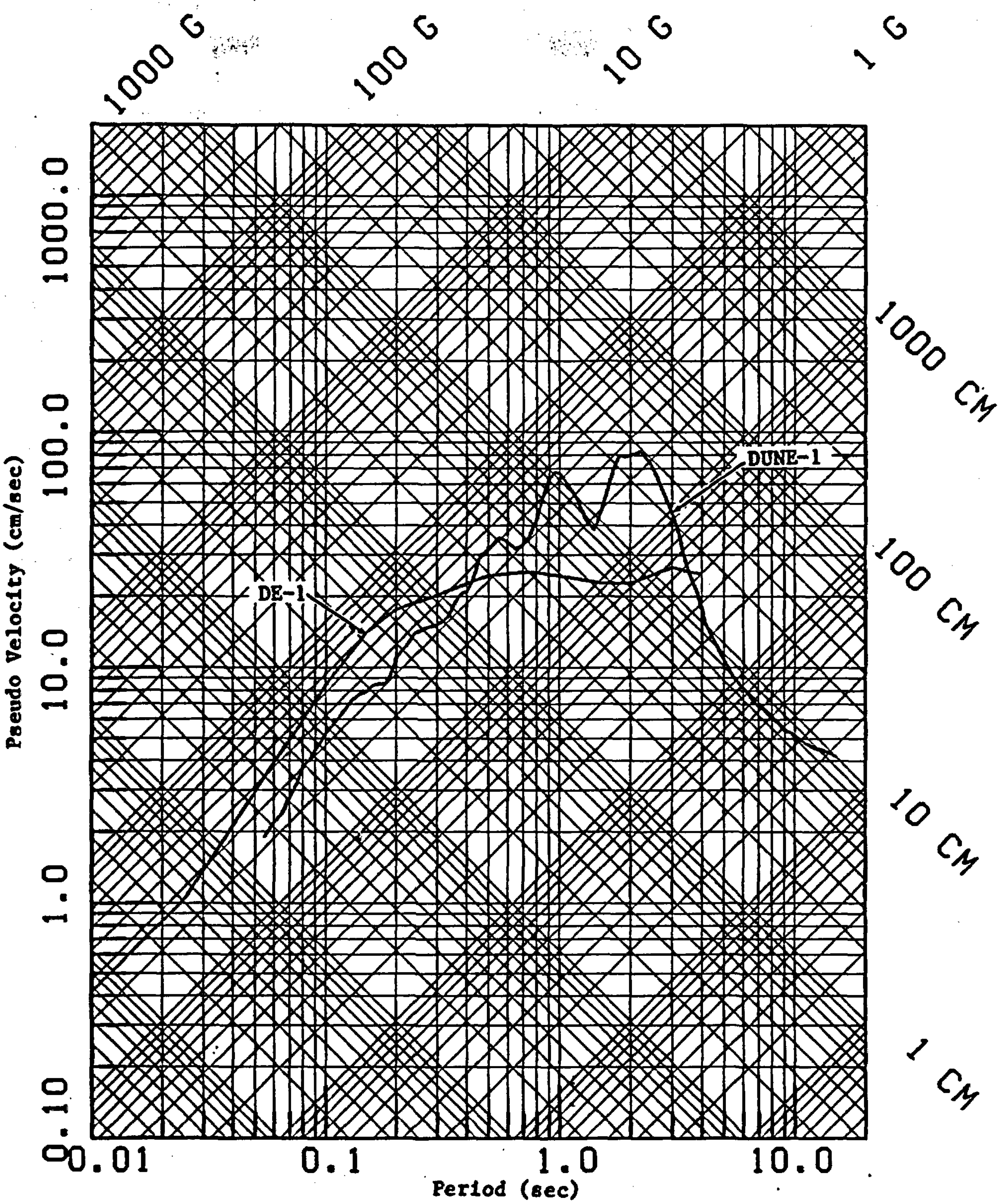


FIGURE 9.6 COMPARISON OF 5%-DAMPED VERTICAL-COMPONENT RESPONSE SPECTRA FOR LEVEL 1 PGA (2,000-YEAR RECURRENCE EXPECTANCY)

events will govern at low frequencies. At intermediate frequencies, the earthquake and UNE spectra are very similar.

Both earthquake and UNE response spectral levels are, of course, subject to uncertainty, and each could be increased or decreased on the basis of different but equally acceptable assumptions in the probabilistic analyses. Earthquake ground motion levels, because of uncertainties in recurrence rates and zonation, could vary in a 50% range for a given exceedance rate, that is, the upper limit could be as much as 50% higher than the lower limit (see Chapter 7). The uncertainty in the potential UNE ground motion hazard is difficult to estimate with confidence. If, for the sake of argument, we assume that the UNE ground motion levels also have a 50% range in uncertainty, the earthquake and UNE design response spectra compared in Figures 9.3 to 9.6 could be shifted relative to each other by a factor of about 2 at most. However, earthquakes would still tend to be important for high frequencies and potential UNE events important for low frequencies. Thus, the basic conclusion that both earthquakes and UNE ground motion must be considered for seismic design would not be altered.

10. CONCLUSIONS AND RECOMMENDATIONS

The significant conclusions and recommendations reached in the course of this study are summarized in this chapter.

Subsurface Geology of Surface Facility Sites

The necessary laboratory and in situ measurements have not been made at the reference conceptual site; consequently, dynamic properties are not available. A preliminary geotechnical investigation is required to obtain the engineering properties of the subsurface materials for use in conceptual design. In the process, shear and compressional wave velocities should be obtained from appropriate field tests. Laboratory tests of relatively undisturbed samples should be made to determine shear moduli and damping at strain levels higher than those generated for seismic velocity measurements. The laboratory and field data should be integrated to derive dynamic properties over a range of strain levels.

Attenuation can also be obtained, at some additional expense, by in situ measurements at the same time that seismic velocities are measured; however, the procedures are not standard practice. If it becomes necessary to predict the behavior of the alluvial wedges more thoroughly for final design, in situ measurements of attenuation are recommended.

Seismic Response of Surface Facility Sites

The available data do not provide a basis for strongly favoring one candidate site over another in terms of seismic response. The eastern margins of sites 7 and 8 may experience enhanced amplification due to possible Rayleigh wave motion generated at the alluvium-bedrock interface formed by the Bow Ridge fault. At all sites, it is possible that multiple reflections of body waves in the alluvial wedges may produce amplification at certain frequencies. Although such effects were not evident in recordings of a UNE event at Stations 26 and 27, results based on one event cannot be considered definitive. Analysis of signals recorded at these stations for other events at Pahute Mesa and Yucca Flat would be informative, and an array of smaller aperture is required to resolve wave-propagation effects in the alluvial wedges.

Available evidence does not provide strong grounds for discriminating among the various candidate sites on the basis of their seismic response. Nor is there a basis for preferring foundations on rock to those on alluvium.

Data Needed in Seismic Design of Underground Facilities

For conceptual design of the underground facilities, peak acceleration and peak particle velocity are needed at the alluvial surface and in the repository horizon. In addition, peak displacements are needed in the alluvium and bedrock at the interface of these two materials in order to estimate the distortion created in shafts or tunnels that penetrate the interface. Response spectra in the repository horizon are needed for seismic evaluation of subsurface freestanding structures or equipment.

Proposed Terminology for Seismic Design Criteria

Proposals for the classification of repository facilities recommend distinctions between Classifications 1, 2, and 3. The primary distinction concerns radiological safety during and after an earthquake or accident. Classification 1 facilities are essential for maintaining off-site radiological safety whereas Classification 2 facilities are necessary for maintaining only on-site radiological safety. In general, facilities with no radiological safety function fall into Classification 3. Secondary distinctions between Classification 1 and 2 facilities include needs for continuous operation, protection of large assemblies of people, and economic impact.

Two design earthquake levels are proposed, labeled DE-1 and DE-2. An annual exceedance rate of 5×10^{-4} (i.e., a return period of 2,000 years) is recommended for DE-1 and a rate of 2×10^{-3} (i.e., a return period of 500 years) for DE-2. Two design UNE levels are proposed, called DUNE-1 and DUNE-2 and defined by the same annual exceedance rates as DE-1 and DE-2, respectively. A postclosure earthquake (PCE) with an annual exceedance rate of 10^{-4} (a return period of 10,000 years) is proposed for the purpose of evaluating long-term repository performance.

Earthquake Ground Motion

Ground motion criteria for earthquakes were obtained using the Joyner and Boore (1982) attenuation functions based on data recorded predominantly in California. Available data do not resolve a consistent difference in seismic attenuation between the Great Basin and California. A question remains about the effect of the tectonic stress regime on seismic source processes (McGarr, 1984) and therefore about the applicability of strong motion observed for strike-slip and thrust earthquakes in California to normal faulting events in the extensional stress regime of the site region.

Of most immediate benefit to earthquake hazard assessment at the Yucca Mountain site would be wide-band, high-dynamic-range seismic monitoring at surface and subsurface sites of the existing Yucca Mountain array. Without earthquake recordings at the site, it is extremely difficult to resolve questions as to the implication of observed UNE amplitude anomalies for earthquake ground motion, the spectral characteristics of earthquake motion at the site, and the relationship between subsurface and surface spectra. All of these questions render the given earthquake ground motion criteria tenuous, particularly in the case of motion at repository depth. Therefore, it is essential that wide-band recording of earthquake motions, both surface and subsurface, commence as soon as possible. This might be accomplished by continuous recording at the SNL stations already in place at Yucca Mountain.

UNE Ground Motion

The recommended ground motion criteria for UNE events are based on site-specific data recorded at Yucca Mountain for Pahute Mesa detonations. Amplitude anomalies observed at Yucca Mountain for these events were, for simplicity, treated in terms of a "site" effect. Further analysis of the Yucca Mountain array recordings of UNE events at Pahute Mesa and Yucca Flat is needed to determine the nature of the observed amplitude anomalies.

The UNE ground motion criteria are relatively well resolved, given the selected UNE occurrence model. The given UNE criteria, based on site-specific ground motion statistics incorporating a site amplification factor of 2, are lower than criteria obtained for random-site ground motion statistics (see Figures 8.12 and 8.13).

It is recommended that, for conceptual design purposes, subsurface response spectra be taken as half the corresponding surface spectra, pending further investigations concerning the frequency dependence (or lack thereof) of subsurface/surface spectral ratios. Ultimately, subsurface UNE ground motion criteria should be based directly on the statistics of UNE recordings at repository depth, in the same manner as for surface motion, given a sufficient population of recordings.

No data are available for evaluating the applicability of the Pahute Mesa event data to possible UNE testing in the Buckboard Mesa area, which, according to the selected UNE occurrence model, dominates the UNE seismic hazard at Yucca Mountain. This should be investigated by Yucca Mountain array recordings of conventional explosive detonations at Buckboard Mesa.

Comparison of Earthquake and UNE Ground Motion

Probabilistic analyses for earthquakes yield horizontal PGA levels of 0.25 g, 0.40 g, and 0.65 g for DE-2, DE-1, and PCE, respectively. Corresponding vertical PGA levels are 0.17 g, 0.27 g, and 0.65 g. Analyses for UNEs yield horizontal (radial) PGA levels of 0.125 g and 0.15 g for DUNE-2 and DUNE-1, respectively, with corresponding vertical PGA levels of 0.15 g and 0.18 g. Although the PGA levels for design UNEs are less than those for design earthquakes, UNE response spectra for horizontal components exceed those for earthquakes for periods greater than about 1 sec for level 1 (see Figure 9.5) and for periods greater than about 0.4 sec for level 2 (see Figure 9.3). Similar results are observed for vertical spectra.

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