NUREG/CR-3839
UCID-20083

An Empirical Assessment of Near-Source Strong Ground Motion for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

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Prepared for
U.S. Nuclear Regulatory Commission

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Laboratory

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Manuscript Completed: May 1984
Date Published: June 1984

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NRC FIN No. A0406

ABSTRACT

To help assess the impact of the current U.S. Geological Survey position on the seismic safety of nuclear power plants in the Eastern United States (EUS), several techniques for estimating near-source strong ground motion for a Charleston size earthquake were evaluated. The techniques for estimating the near-source strong ground motion for a 6.6 m_b (7.5 M_s) in the Eastern United States which were assessed are methods based on site specific analyses, semi-theoretical scaling techniques, and intensity-based estimates. The first involves the statistical analysis of ground motion records from earthquakes and recording stations having the same general characteristics (earthquakes with magnitudes of 7.5 M_s or larger, epicentral distances of 25 km or less, and sites of either soil or rock). Some recommendations for source and characterization scaling of the bias resulting primarily from an inadequate sample of near-source recordings from earthquakes of large magnitude are discussed. The second technique evaluated requires that semi-theoretical estimates of peak ground motion parameters for a 6.6 m_b (7.5 M_s) earthquake be obtained from scaling relations. Each relation uses a theoretical expression between peak acceleration magnitude and distance together with available strong motion data (majority coming from California) to develop a scaling relation appropriate for the Eastern United States. None of the existing ground motion models for the EUS include the potential effects of source or site characteristics. Adjustments to account for fault mechanisms, site topography, site geology, and the size and embedment of buildings are discussed. The final approach used relations between strong ground motion parameters and Modified Mercalli Intensity in conjunction with two methods to estimate peak parameters for a 6.6 m_s (7.5 M_s) earthquake. As with other techniques, adjustment of peak acceleration estimates are discussed. Each method differently approaches the problem of estimating near-source strong ground motions. The results and limitations of each technique are discussed and recommendations for future work are presented.

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AN EMPIRICAL ASSESSMENT OF NEAR-SOURCE STRONG GROUND MOTION FOR A 6.6 m_b (7.5 M_s) EARTHQUAKE IN THE EASTERN UNITED STATES

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1.0 INTRODUCTION

In a letter to the Nuclear Regulatory Commission, the U.S. Geological Survey (USGS, 1982) has stated:

> "Because the geologic and tectonic features of the Charleston region are similar to those in other regions of the eastern seaboard, we conclude that although there is no recent or historical evidence that other regions have experienced strong earthquakes, the historical record is not, of itself, sufficient grounds for ruling out the occurrence in these other regions of strong seismic ground motions similar to those experienced near Charleston in 1886."

Most nuclear power plants on the east coast of the United States have been designed based on the hypothesis that an earthquake as large as the Charleston event could not occur outside the Charleston region. To help assess the impact of the current U.S. Geological position on the seismic safety of these nuclear power plants, this report presents an empirical evaluation of strong ground motion for a Charleston size earthquake occurring near a site in the Eastern United States.

The Charleston earthquake occurred in the late night hours of August 31, 1886. It was centered approximately 25 km northwest of Charleston, South Carolina near the town of Summerville. The strongly shaken area included cities as far as 150 km from the epicenter and the effects of the earthquake were reported as far away as 1300 km. "Earthquake History of the United States" (Coffman and von Hake, 1973) reports the epicentral intensity of this event to be IX-X on the Modified Mercalli Intensity Scale of 1931. Bollinger (1977) believes the distribution of shaking effects is more consistent with an intensity X earthquake. The body-wave magnitude of this earthquake has been estimated to be 6.6 m_b, representing a surface-wave magnitude of 7.5 M_s (Nuttli, 1983). From the known seismicity and tectonics of the South Carolina seismic zone, the Charleston earthquake is believed to have been relatively shallow. There is, however, still controversy as to the fault mechanism of this event.

In order to obtain as broad a basis as possible for the empirical prediction of strong ground motion from an earthquake of this magnitude, several methods have been used in this study. These include predictions based on site-specific analyses, semi-theoretical scaling relations, and Modified Mercalli Intensity. A description of each technique, a presentation and discussion of results, and recommendations for future work will be presented in the remainder of this report.

2.0 SITE-SPECIFIC ESTIMATES

This technique involves the statistical analysis of ground motion records from earthquakes and recording stations having the same general characteristics as those proposed for the site of interest. For the current study, strong-motion records are selected to represent near-source distances consistent with the selection of a Safe Shutdown Earthquake (SSE) in the Eastern United States. The criteria for selecting strong-motion records for the site-specific analysis are as follows: (1) magnitudes of 6.5 M_S or larger, (2) epicentral or fault distances of 25 km or less, and (3) sites located on either rock or soil.

2.1 Rock Spectra

Table 1 lists the 18 available digitized rock records meeting the selection criteria. Two of these records (Cerro Prieto, 800 W. First) have not been used in the present analysis because of difficulties in retrieving the records from tape. Inspection of Table 1 indicates several significant biases associated with these records. The most obvious bias is the dominance of records from large embedded structures of the San Fernando earthquake. Other significant biases involve the magnitudes of the events which range from 6.5-6.9 M_S, considerably below the target magnitude of 7.5 M_S, and the distances associated with the records which are predominantly greater than 15 km.

The 16 rock records listed in Table 1 for which digitized accelerograms were available were used to generate site-specific spectra for 5%-damped pseudo-relative velocity (S_V). To test the sensitivity of the spectra to various recording site characteristics, five subsets of the record set were investigated. These subsets represent (1) the 14 rock records excluding the Pacoima Dam and Koyna Dam recordings, (2) the 6 free-field and small building sites, where small buildings are those of one or two stories in height, (3) the 6 hard rock sites, (4) the 5 hard rock sites excluding the Pacoima Dam recordings, and (5) the 10 soft rock sites.

Spectra from three of these record sets are presented in Figs. 1-6. Figure 1 displays the spectra from both horizontal components for the 6 hard rock recordings and Fig. 2 displays the median, 84th-percentile and envelope spectra of these records. Figures 3 and 4 display the same plots for the 5 hard rock records excluding the Pacoima Dam recording, and Figs. 5 and 6 display the same plots for the 10 soft rock records. The spectra from the remaining three record sets were found to be bounded by the spectra displayed in Figs. 1-6 and are, therefore, not presented in this report.

Table 2 summarizes the median and 84th-percentile estimates of peak ground-motion parameters obtained for each of the site-specific record sets. The median values of peak horizontal acceleration (PGA) are found to range from 0.17g for the set excluding the Pacoima Dam and Koyna Dam records to 0.29g for the hard rock records. The corresponding range in the 84th-percentile values is 0.23 to 0.66g. Site-specific predictions based on all 16 rock records fall in the middle of this range having values of 0.21g (median) and 0.40g (84th-percentile). The large values of peak acceleration associated with the hard rock records are due primarily to the inclusion of the Pacoima Dam record which dominates this small record set. If this record is excluded from the set then the median estimate for hard rock sites reduces to 0.22g, consistent with the set containing all rock records. A similar result is found for the site-specific spectra (see Figs. 2 an 4).

Because of the relatively long wavelengths associated with ground velocities, shallow soil sites, whose soil depths are 10m or less, were considered rock sites for the site-specific analysis of peak horizontal velocity (PGV). This added one hard rock record (Lake Hughes No. 9) and four soft rock records (Lake Hughes No. 12, Castaic, 222 Figueroa, and 234 Figueroa) to the rock record set (see Table 3). These records were subsequently removed from the soil record set for the analysis of peak velocity.

The median values of peak horizontal velocity are found to range from 9.3 cm/sec for hard rock sites excluding the Pocoima Dam recording to 20.5 cm/sec for soft rock sites. The corresponding range in the 84th-percentile values is 17.6 to 29.2 cm/sec. These results indicate a greater sensitivity of peak velocity to site characteristics than was found for peak acceleration. This sensitivity results primarily from differences in rock type. For example, separation of the records into hard and soft rock sites reduces the standard deviation of the estimates and indicates that soft rock sites have velocities roughly a factor of two larger than hard rock sites.

A comparison of PGV to PGA ratios for rock sites with those found for soil sites in Table 4 indicates that this ratio for soft rock sites is very similar to that obtained for soil sites, but that hard rock sites have ratios substantially lower than soil sites. These results, when contrasted with the relative uniformity of peak acceleration with respect to site characteristics, indicate that spectral shapes are substantially different for hard rock sites as compared to either soft rock or soil sites. This is confirmed by the median site-specific spectra of Figs. 4, 6 and 8. These differences should be accounted for when predicting strong ground motion in the Eastern United States.

2.2 Soil Spectra

Table 3 lists the 74 available digitized soil records meeting the site-specific selection criteria. Eight of these records have not been used in the current analysis because of problems with the data tapes. These include the free-field record from the Imperial County Services Center and the 7 Mexican records, all from the 1979 Imperial Valley earthquake. While the distribution of soil records with respect to magnitude and distance is an improvement over the corresponding distribution of rock records, there remains a clear bias towards earthquakes of M_S less than 7.5 and distances greater than 15 km. The data are dominated by two earthquakes, the San Fernando earthquake, whose records primarily come from large embedded buildings, and the 1979 Imperial Valley earthquake, whose records come from small ground-level structures.

The 66 soil records listed in Table 3 for which digitized accelerograms were available were used to generate site-specific spectra for 5%-damped S_v. The results are displayed in Figs. 7-8. Figure 7 displays the spectra from both horizontal components for all 66 records and Figure 6 displays the median, 84th-percentile, and envelope spectra. Three subsets of these records were used to test the sensitivity of soil spectra to differences in site characteristics. These subsets include (1) the 61 soil records excluding the shallow soil sites, (2) the 41 soil records excluding large embedded buildings, and (3) the 31 free-field and small building sites.

Table 4 summarizes the median and 84th-percentile estimates obtained for each of the site-specific record sets. The median values of peak horizontal acceleration are found to range from 0.19 g for the set including all records to 0.26 g for the free-field and small building set. The corresponding range in the 84th-percentile values is 0.35 to 0.52 g. Excluding the 5 shallow soil records was found to have no effect on these estimates.

The range in peak horizontal velocity among the four record sets is found to be 22.6 to 31.4 cm/sec for the median values and 43.0 to 66.4 cm/sec for the 84th-percentile values. The results for both acceleration and velocity indicate some sensitivity to building size and embedment, more so than was observed for rock sites. These biases have been accounted for through the application of appropriate scaling variables as discussed in the following section.

A comparison of Tables 2 and 4 indicates very little difference between site-specific estimates of peak horizontal acceleration for soil and rock when all available records are used. This is consistent with the near-source analyses of Campbell (1981a, 1983). A comparison of peak velocity estimates and Figs. 4 and 8, however, due indicate a difference in response spectra for hard rock sites at the longer periods. For periods less than about 0.3 sec the median and 84th-percentile hard rock spectra are found to be very similar to the soil spectra. However, for periods greater than 0.3 sec the soil spectra are found to exceed the hard rock spectra, this exceedance becoming larger the longer the period. This is generally consistent with the results of Joyner and Boore (1982). The comparison between soft rock and soil spectra, Figs. 6 and 8, show that these spectra are similar at all periods of interest.

2.3 Adjusted Estimates

Some of the biases in the selected record sets could be mitigated by the addition of records from recent foreign events, some of which are listed in Table 5. However these records are not easily available. Note also that all but one of these additional events have magnitudes less than the 7.5 M_S magnitude of interest in this study. It would seem, then, that the only realistic solution to the severe bias in the selected data set is to use all available records meeting the magnitude and distance criteria set forth above, then scale each to obtain the desired earthquake and site characteristics before developing site-specific estimates. While a marked departure from current practice, we feel that such an approach is necessary in order to obtain realistic ground motion estimates for a 6.6 m_b earthquake in the Eastern United States.

The near-source analyses of peak horizontal acceleration presented by Campbell (1983) have been used to scale the site-specific accelerations for site characteristics. He used a comprehensive set of near-source peak acceleration data and weighted nonlinear regression analyses to develop scaling variables for such characteristics as fault mechanism, building size, and instrument embedment. He found that reverse and reverse-oblique faults are associated with peak accelerations approximately 40% higher than strike-slip and normal faults and that large embedded buildings (buildings of 3 stories in height or greater with instruments in basements) are associated with peak accelerations approximately 24% smaller than small non-embedded buildings and free-field installations. He also found that small embedded buildings have peak accelerations about 11% smaller than small non-embedded buildings.

Campbell also reports the results of an analysis of records obtained from adjacent buildings during the same earthquake which indicates that the size of the building also effects the recorded peak acceleration. An analysis of data obtained primarily from the San Fernando earthquake indicated that peak horizontal acceleration decreases with increasing difference in number of stories between two buildings by the relationship $R(\%) = 1.2\ \Delta s$, where R is the reduction in peak acceleration in percent and Δs is the difference in the number of stories. Therefore, peak accelerations decrease approximately 12% for every 10-story difference in height.

Scaling for magnitude and distance was accomplished through a scaling relationship developed by TERA Corp. (1982). They used 84 free-field and small building recordings obtained within 50 km of 21 earthquakes of magnitude 5.0-7.7 to develop the following relationship for peak horizontal acceleration:

$$\ln PGA = -2.829 + 0.827M - 1.39 \ln[R + 0.177 \exp(0.595M)] + 0.34F - 0.12E \qquad (1)$$

where PGA is the mean of the peak values of the two horizontal components in g (hereafter referred to as mean peak horizontal acceleration), M is magnitude, R is closest distance to the fault rupture surface in km, F is a scaling variable for fault mechanism, and E is a scaling variable for embedment. Magnitude M is defined as local magnitude (M_L) if both M_L and surface-wave magnitude (M_S) are less than 6.0 and defined as M_S if both magnitudes are 6.0 or larger. The scaling variables are defined as follows: F = 1 for reverse and reverse-oblique faults, F = 0 for strike-slip and normal faults, E = 1 for embedded instruments, and E = 0 for ground-level instruments. The standard error of the regression was 0.378 and the r^2 value was 0.82.

Campbell (1983) presented a preliminary analysis of peak horizontal velocity that was used to adjust site-specific estimates of this parameter. He used essentially the same data base as was used to develop Eq. (1) except that large structures and shallow soil sites were included. This increased the data set to 114 recordings. His regression analysis resulted in the following relationship:

$$\ln PHV = -1.262 + 1.01\,M - 0.919 \ln[R + 0.00681 \exp(0.88M)] \qquad (2)$$

where PHV is mean peak horizontal velocity in cm/sec and the other parameters are as defined in Eq. (1). The standard error of the regression was 0.522 and the r^2 value was 0.74.

Campbell used an analysis of residuals to identify significant differences in peak velocity between various site characteristics. His analysis indicated that large buildings, whether embedded or not, are associated with peak velocities approximately 20% higher than small buildings and that hard rock recordings are approximately 50% lower than those on soil. While soft rock recordings were found to be somewhat less than those on soil, this reduction was not found to be statistically significant. Recordings from reverse faults were found to be significantly higher than those from strike-slip faults, however, the size of this difference was not as great as that observed for peak acceleration. This latter result is complicated somewhat by the presence of large structures in the data set. All things being considered, reverse and reverse-oblique faults are estimated to increase peak horizontal velocity by approximately 20%, about one-half as much as was found for peak acceleration.

Since the scaling variables F and E have no effect on the scaling of PGA with magnitude and distance, they were arbitarily set equal to zero in the analysis that follows. The appropriate adjustment factor for magnitude and distance for each of the records in Tables 1 and 3 was estimated by evaluating Eqs. (1) and (2) for the magnitude and distance associated with a near-source Charleston-type earthquake and taking the ratio of these computed values of PGA and PGV to ones estimated from Eqs. (1) and (2) using the actual magnitude and distance of the recording. For this purpose the Charleston-type earthquake was assigned a magnitude of 7.5 M_S and a fault distance of 15 km. The distance was selected to be consistent with the development of an SSE in the Eastern United States.

The scaling variables for magnitude, distance, fault type, and site characteristics discussed above were used to adjust the peak accelerations and velocities of the selected records to represent as closely as possible characteristics of a free-field recording approximately 15 km from an earthquake of magnitude 6.6 m_b (7.5 M_S). The median and 84th-percentile values of the adjusted peak parameters are presented in Table 6 for two types of fault mechanisms -- reverse/reverse-oblique mechanisms and strike-slip/normal mechanisms. Based on the results presented in Tables 2 and 4, two subsets of the selected data were analyzed. The similarity in estimated values of peak parameters for soil and soft rock records suggested that these records could be combined into one subset for the purpose of presenting statistics for the adjusted records. However, the substantial difference in PGV to PGA ratios between hard rock records and other records suggested that these records should be analyzed separately. In this case the Pacoima Dam recording was excluded because of its dominance of this small record set.

The results of Table 6 indicate as before that peak horizontal accelerations are similar for soil and rock sites at the near-source distances of interest in this study. These values are sensitive to fault mechanisms, however, with median values ranging from 0.36 to 0.38 g for reverse and reverse-oblique faults and from 0.26 to 0.27 g for strike-slip and normal faults. Eighty-fourth percentile values are approximately 30 to 50% larger than these median values. Peak horizontal velocities for either fault type are found to be approximately 45% smaller for hard rock records as compared to soft rock and soil records. This compares favorably with the 50% reduction for hard rock sites found by Campbell (1983) in his analysis of near-source recordings of peak horizontal velocity.

The ratios of PGV to PGA presented in Table 6 are found to range from 110 to 133 cm/sec/g for soil and soft rock records. These values may be compared with a ratio of 122 cm/sec/g (48 in/sec/g) for soil sites as suggested by Newmark and Hall (1982) and ratios of 110 to 135 cm/sec/g for stiff and deep stiff soils as suggested by Seed and Idriss (1982) for the development of design response spectra. The PGV to PGA ratios for hard rock sites in Table 6 are found to range from 58 to 81 cm/sec/g, which may be compared with ratios of 91 cm/sec/g (36 in/sec/g) as suggested by Newmark and Hall (1982) and 55 cm/sec/g as suggested by Seed and Idriss (1982) for rock sites.

Comparing the adjusted estimates in Table 6 with the original estimates in Tables 2 and 4 indicates that scaling of the records for appropriate source and site characteristics has resulted in increasing median estimates of peak horizontal acceleration by 70 to 100% and 84th-percentile estimates by 30 to 50% for reverse fault mechanisms and increasing median estimates of PGA by 20 to 40% and 84th-percentile estimates by 0 to 5% for strike-slip fault mechanisms. Similarly high adjustments are observed for PGV. This confirms the severe bias that was associated with the selected record sets. Scaling has also substantially increased the uniformity of the record sets, decreasing the standard deviations of these sets by as much as 50%.

We conclude that scaling for appropriate source and site characteristics has proven to be an effective means of reducing the bias associated with the site-specific selection of records representing near-source ground motion from a 6.6 m_b (7.5M_S) earthquake in the Eastern United States. This bias results primarily from an inadequate sample of near-source recordings from earthquakes of this large magnitude. Unfortunately, similar scaling variables have not yet been developed for response spectra, so an adjustment of site-specific spectra are not possible at this time. The results for peak acceleration and peak velocity suggests that substantial adjustments to these spectra are anticipated.

3.0 SEMI-THEORETICAL ESTIMATES

Semi-theoretical estimates of peak ground motion parameters for a 6.6 m_b earthquake have been obtained from scaling relations proposed by Campbell (1981b, 1982), LLNL (1984), and Nuttli and Herrmann (1983). Each relation uses a theoretical expression between peak acceleration, magnitude and distance together with available strong-motion data (the majority of which comes from California) to develop a scaling relation appropriate for the Eastern United States. A brief description of each model is presented below.

3.1 Scaling Relations

3.1.1 Campbell (1981b) Model

Campbell (1981b) used the near-source data base compiled by Campbell (1981a) to develop two peak acceleration scaling relations for the Central United States: one for fault distance and another for epicentral distance. The data base consisted of 116 recordings from 27 worldwide earthquakes of $M \geq 5.0$, where M is magnitude as defined in Eq. (1). Distances were restricted to be no further than 30 km from the fault rupture plane for $5.0 < M < 6.25$ and no further than 50 km from the fault for $M \geq 6.25$. Peak acceleration was assumed to be regionally invariant at the source (i.e., at $R = 0$) and coefficients of anelastic attenuation for the Western United States were adopted from Nuttli (1979).

Weighted nonlinear regression analyses were used to develop the following scaling relationship for PGA in terms of fault distance:

$$\ln PGA = -4.255 + 0.79M - 0.862 \ln [R + 0.0286 \exp(0.778M)] - \gamma R \qquad (3)$$

where PGA, M and R are defined as in Eq. (1) and γ is the coefficient of anelastic attenuation in km^{-1}. The standard error for the regression was reported to be 0.409. A similar analysis for epicentral distance resulted in the following scaling relationship:

$$\ln PGA = -2.497 + 0.922M - 1.27 \ln [R + 25.7] - \gamma R \qquad (4)$$

The standard error of the regression for Eq. (4) was found to be 0.548, significantly larger than that resulting from the use of fault distance. This clearly demonstrates the inappropriateness of using epicentral distance to scale PGA at near-source distances.

Since the standard measure for earthquake size in the Central United States is m_b, Campbell suggested the following algorithm for converting from m_b to M based on the relationships among magnitude scales suggested by Nuttli (1979):

$$M = \begin{cases} 1.64\, m_b - 3.16 & (m_b \geq 5.59) \\ 1.02\, m_b + 0.30 & (m_b < 5.59) \end{cases} \qquad (5)$$

Appropriate values of γ for the Central United States were also obtained from Nuttli (1979), from which the following expression was developed:

$$\gamma_{CUS} = 0.023 - 0.0048M + 0.00028M^2 \tag{6}$$

Application of Eq. (5) for a magnitude of 6.6 m_b appropriate for a Charleston-type earthquake would yield a value for M of 7.7. This value is inconsistent with the 7.5 M_S value suggested by Nuttli (1983) for the Charleston earthquake. For the purpose of this study, M = 7.5 was used in the evaluation of Eqs. (3) and (4) to be consistent with Nuttli's most recent estimate. Using this magnitude in Eq. (6) yields $\gamma_{CUS} = 0.0028$.

3.1.2 Campbell (1982) Model

Equation (3) was later revised by Campbell (1982) using a frequency dependent expression for γ of the form

$$\gamma = \frac{\pi T^{\eta}}{Q_o T_o^{\eta} TU} \tag{7}$$

where T is period, U is group velocity, Q_o is a reference value for the quality factor Q, T_o is a reference value for period, and η is defined by the expression

$$Q = Q_o \left(\frac{T_o}{T}\right)^{\eta} \tag{8}$$

The predominant period of PGA for sites located on rock in the Western United States was modified from a plot given by Seed et. al. (1969), resulting in the relation

$$T = \begin{cases} -0.229 + 0.0650M + (0.000556M - 0.00172)R & (M \geq 7.0) \\ -0.043 + 0.0382M + (0.000556M - 0.00172)R & (M < 7.0) \end{cases} \tag{9}$$

Campbell obtained an expression for γ appropriate for California by substituting $Q_o = 150$, $\eta = 0.55$, U = 3.5 km/sec and $T_o = 1$ sec (Singh and Herrmann, 1983) into Eq. (7). Using this expression for γ and the relation for period given by Eq. (9), the analysis of Campbell (1981b) based on fault distance was revised to give the following relationship:

$$\ln PGA = -4.290 + 0.777M - 0.797 \ln [R + 0.012 \exp(0.898M)] - \gamma R \tag{10}$$

where the parameters are defined as in Eqs. (1) and (3). The standard error of the regression resulting from this analysis was 0.405.

For the purposes of this study, Eq. (10) was evaluated using M = 7.5. A value for the coefficient of anelastic attenuation was taken to represent in general the Atlantic Coastal Plain and Piedmont Provinces of the Eastern

United States. It was estimated from Eq. (7) using $Q_o = 850$, $\eta = 0.3$, $U = 3.5$ km/sec and $T_o = 1$ sec (Singh and Herrmann, 1983). The perdominant period of PGA was taken to be 0.25 sec as suggested by Nuttli (1979). The resulting value for γ was 0.0028.

3.1.3 LLNL (1984) Model

LLNL (1984) developed a scaling relationship for peak horizontal acceleration, which they consider to be appropriate for the Central United States, by revising the analysis of Joyner and Boore (1981). Their data set consisted of 182 recordings from 23 North American earthquakes of $M \geq 5.0$, including some recordings as far as several hundred kilometers from the source of the earthquake. Several assumptions were used in the analysis. First, as suggested by Nuttli (1979), it was assumed that the differences between Western and Central United States earthquake effects could be solely attributed to differences in regional attenuation properties. Second, the coefficient of geometrical attenuation was taken to be -5/6, not -1 as originally proposed by Joyner and Boore, to be consistent with the value used by Nutti (1979) and Dwyer et al. (1983) in determining regional values for γ. Finally, a value of m_b appropriate for the Central United States (Chung and Bernreuter, 1981; Nuttli and Herrmann, 1982) was used in place of moment magnitude as the measure of earthquake size. Based on these assumptions, a reanalysis of the Joyner and Boore data led to the following relationship:

$$\ln PGA = 3.99 + 0.59\, m_b - 0.833 \ln R - \gamma R \qquad (11)$$

where,

$$R = [d^2 + (5.3)^2]^{1/2}$$

In these expressions PGA is the peak acceleration of the maximum horizontal component (hereafter referred to as the maximum peak horizontal acceleration) in cm/sec^2 and d is the shortest distance between the site and the surface projection of the fault rupture plane in km.

The reanalysis of the Joyner and Boore data set resulted in $\gamma = 0.007$, a value relatively consistent with the range 0.006 to 0.010 determined by Nuttli (1979) for Western United States earthquakes of $m_b = 5.0 - 7.0$. LLNL (1984) adopted a value of 0.003 for γ in the Central United States from Dwyer et al. (1983) in applying Eq. (11) to that region. This value has also been adopted for the purposes of this study.

3.1.4 Nuttli and Herrmann (1983) Model

The final models considered for this study are the peak acceleration and peak velocity scaling relationships proposed by Nuttli and Herrmann (1983). These relationships were developed from spectral scaling relations based on empirical studies of mid-plate magnitudes and moments and frequency dependent attenuation properties of Central United States earthquakes. The form of the relationships represent point-source geometrical attenuation of Lg waves and were calibrated from existing Central United States strong-motion data.

For peak horizontal acceleration, they proposed the expression

$$\ln PGA = 1.313 + 1.15\ m_b - 0.833\ \ln\ (R^2 + h^2)^{1/2} - 0.0037(R-1) \qquad (12)$$

where PGA is mean peak horizontal acceleration in cm/sec^2, m_b is body-wave magnitude, h is focal depth in km, and R is epicentral distance in km.

For mean peak horizontal velocity they proposed the expression

$$\ln PGV = -8.29 + 2.30\ m_b - 0.833\ \ln(R^2 + h^2)^{1/2} - 0.0018(R-1) \qquad (13)$$

Equations (12) and (13) are valid for $4.4 < m_b \leq 7.4$ and, as proposed, should be used with minimum values of focal depth (km) estimated from the expression

$$\ln h_{min} = -3.98 + 1.05\ m_b \qquad (14)$$

3.2 Results

Estimates of peak acceleration and velocity based on the above referenced scaling relations for distances of 0 to 200 km appear in Tables 7 and 8. The estimates for peak acceleration have been divided into two groups based on the definition of distance used in the relations. The distance listed in Table 7 is either epicentral distance or distance to the surface projection of the fault depending on the type of model used. The application of the fault-distance models of Campbell (1981b, 1982) required an estimate of the distance to the fault rupture plane. For this purpose the assumed fault rupture was confined to a depth of 10 km to be consistent with the known tectonics of the Eastern United States. Estimates from LLNL (1984) have been reduced by 12% (Campbell, 1981a) to represent the mean peak acceleration of the two horizontal components.

Table 7 indicates a discrepancy between estimates based on the epicentral-distance models and those based on the fault-distance models, with the former being systematically larger. This is apparently the result of the increased amount of magnitude scaling exhibited by the epicentral-distance models and results from the inappropriateness of epicentral distance in characterizing the near-source attenuation of strong ground motion. Results from Table 7 indicate that on the average peak horizontal accelerations range from 0.23g at a distance of 20 km to 0.33g at a distance of 10 km for the fault-distance models. The similar range for the epicentral distance models is 0.53 to 0.71g. The fault-distance estimates are found to be relatively insensitive to the assumption of a 10-km depth for the fault rupture. For example, assuming fault rupture at the surface increases these values by only 10% or less.

The peak horizontal velocities for distances of 10 to 20 km given by the Nuttli and Herrmann (1983) model (Table 8) are found to range from 60 to 75 cm/sec and represent a PGV to PGA ratio of approximately 135 cm/sec/g. This ratio is consistent with both the site-specific results for soil and soft rock given in Table 6 and the 110 to 135 cm/sec/g range suggested by Newmark and Hall (1982) and Seed and Idriss (1982) for soil.

3.3 Adjusted Estimates

None of the existing ground motion models for the Eastern United States include the potential effects of source or site characteristics. Campbell (1983) has found various characteristics such as fault mechanism, site topography, site geology, and the size and embedment of buildings to have a significant effect on the amplitude of recorded strong ground motion.

An estimate of the effect of these characteristics on the prediction of peak horizontal acceleration can be obtained from Eq. (1) and a similar unpublished relationship developed as part of the study by TERA Corp. (1982). The unpublished relationship was based on the same data base used to develop Eq. (1), except that large buildings were included. This increased the number of recordings to 124. In addition, it was developed without the use of scaling variables to represent the effects of fault mechanism and instrument embedment. These features put it on a consistent basis with the relationships developed by Campbell (1981b, 1982) for the Eastern United States. This unpublished relationship is given by the expression

$$\ln PGA = -3.093 + 0.822M - 1.30 \ln[R + 0.176 \exp(0.568M)] \qquad (15)$$

where the parameters are defined as in Eq. (1). The standard error of estimate for the above regression was 0.422.

An estimate of the factor required to adjust the predictions of Campbell (1981b, 1982) to represent free-field motions from a reverse/reverse-oblique earthquake may simply be obtained by taking the ratio of PGA estimated from Eq. (1), with $F = 1$ and $E = 0$, to that estimated from Eq. (15). This ratio for a fault distance of 10 to 20 km and $M = 7.5$ indicates that these predictions should be increased approximately 23% to account for these characteristics. This same analysis for strike-slip and normal faults ($F = 0$) indicates that these same predictions should be decreased by 12% to account for these characteristics. Since the data base used to develop the LLNL (1984) fault-distance model is similar to that used by Campbell (1981b, 1982), we will assume that these same factors may be used to adjust the LLNL (1984) estimates as well.

Applying these adjustments to the fault distance predictions appearing in Table 7 and averaging the values so obtained for distances of 10 and 20 km results in the estimates appearing in Table 9. Estimates of the 84th-percentile values are based on a standard error of 0.38 adopted from Eq. (1), a value believed to be appropriate for near-source estimates when scaling by fault mechanism and instrument embedment are included. The average adjusted estimates based on all three fault-distance models are found to be quite similar to the adjusted site-specific estimates appearing in Table 6.

The epicentral and fault-distance models of Campbell (1981b) may be used to determine the adjustment required to modify the Nuttli and Herrmann (1983) results to represent fault-distance estimates. From Table 7 we find for distances of 10 and 20 km that estimates of peak horizontal acceleration based on Campbell's fault-distance model are approximately 60% lower than those based on his epicentral-distance model. Since the estimates of Nuttli and Herrmann (1983) in Table 7 include a depth term, estimates based on epicentral distance only (i.e., h_{min} = 0 km) must be computed in order to apply the above adjustment factor to their results. Performing this computation, Eq. (12) yields estimates of 1.07 and 0.58g for epicentral distances of 10 and 20 km, respectively. Averaging these values and applying a reduction factor of 60% gives an adjusted value of 0.33g. This value is consistent with the average fault-distance estimate for reverse/reverse-oblique fault mechanisms in Table 9. Considering the compressional stress regime in the Central and Eastern United States, the agreement between these estimates is appropriate and demonstrates compatability between the two approaches.

4.0 INTENSITY-BASED ESTIMATES

Relations between strong ground motion parameters and Modified Mercalli Intensity (I_S) may be used in conjunction with two methods to estimate peak parameters for a 6.6 m_b earthquake. The most direct way is to use the observed epicentral intensity of the 1886 Charleston earthquake together with relationships between peak parameters and I_S (e.g., Trifunac and Brady, 1975) to estimate the strong ground motion expected to occur within the epicentral region (i.e., within 10 to 20 km) of the earthquake. The second approach is to combine relations between peak parameters and I_S with an intensity attenuation model for the Eastern United States. The assumptions required to apply these methods to the Eastern United States are discussed in LLNL (1984).

4.1 Epicentral-Intensity Models

The method based on epicentral intensity requires an estimate of I_0 for the Charleston earthquake. "Earthquake History of the United States" (Coffman and von Hake, 1973) reports an epicentral intensity of IX-X for this event. Bollinger (1977), on the other hand, believes that the shaking effects of this earthquake are more consistent with an I_0 of X, although he admits that there is some controversy concerning this estimate (Bollinger, personal communication). The controversy concerns the effects of ground failures on the assigned intensities. Some investigators believe that the ground effects associated with liquefaction and landsliding have been responsible for assigning too high an intensity to this event. Considering shaking effects on firm ground, it has been suggested that the epicentral intensity could be as little as IX for the 1886 event.

An independent empirical assessment of the epicentral intensity for this earthquake may be gained through the recent study of Nuttli et al. (1983). They have developed relationships between epicentral itensity and body-wave magnitude for three regions -- South Carolina, the Central United States, and the Eastern United States. The relationship for South Carolina depends solely on the estimated magnitude and intensity for the Charleston earthquake for magnitudes greater than 4.0 and, therefore, cannot be used to estimate an I_0 for this event. The other relations are given by the following expressions: for the Central United States,

$$I_0 = 2.07\ m_b - 3.97 \tag{16a}$$

and for the Eastern United States,

$$I_0 = 1.98\ m_b - 3.41 \tag{16b}$$

Based on a magnitude of 6.6 m_b for the Charleston earthquake (Nuttli, 1983), these relationships give epicentral intensities numerically equal to 9.69 $\pm$ 0.27 and 9.66 $\pm$ 0.16, for Eqs. (16a) and (16b) respectively, indicating an I_0 = IX$^+$ for this event.

Nuttli et al. (1983) also developed intensity attenuation relationships for South Carolina and the Eastern United States. These are: for South Carolina,

$$I_s = 0.86 + 1.81\ m_b - 2.30\ \log_{10}R - 0.0085\ R \qquad (17a)$$

and for the Eastern United States,

$$I_s = 0.085 + 1.98\ m_b - 2.49\ \log_{10}R - 0.00091\ R \qquad (17b)$$

where R is hypocentral distance in km. These relatioships may be used to estimate an I_0 for the 6.6 m_b Charleston earthquake if we assume (1) a hypocentral depth of 19 km based on the relationship between minimum focal depth and body-wave magnitude for the Central United States given by Eq. (14) and (2) an epicentral area whose radius is 10 to 15 km. Under these assumptions Eq. (17a) gives values of I_0 numerically equal to 9.42 to 9.56 $\pm$ 0.61 and Eq. (17b) gives values of 9.68 to 9.82 $\pm$ 0.87. These estimates are also consistent with an I_0 of IX^+ for this event.

While the estimates based on Eqs. (16) and (17) suggest an intensity of IX^+ for the Charleston earthquake, the epicentral intensities used to develop these correlations, especially for the larger values of interest in this study, can be expected to suffer from the same bias towards higher intensities as has been suggested for the Charleston earthquake. Taking this into consideration, a more realistic interpretation of these results would suggest that they are consistent with an I_0 of IX.

The 1952 Kern County, California earthquake serves as an excellent example of the bias that exists in assigning epicentral intensities. This 7.7 M_S event is similar in size to the Charleston earthquake. "Earthquake History of the United States" (Coffman and Von Hake, 1973) reports an epicentral intensity of XI for this event. However, the description of damage presented in "United States Earthquakes, 1952" (Murphy and Cloud, 1954) indicates that this intensity assignment is based on a single location where a Southern Pacific Railroad tunnel crossed the fault rupture zone. In fact, all intensity IX to X reports were assigned on the basis of ground failure observations such as fault rupture, landsliding, slumping, and ground fissures. On the other hand, the towns of Arvin, Caliente and Bealville, all located within several miles of the fault, were assigned intensities of VII to VIII. Even accounting for the firm site conditions associated with these locations, it would be extremely difficult to justify an epicentral intensity greater than IX for this earthquake once ground failure effects are discounted.

From the above discussion it would appear that while X represents a conservative estimate for the epicentral intensity of the Charleston earthquake, a more reasonable estimate would be IX. The sensitivity of the predicted ground motion parameters to these intensity values will be demonstrated later in this section.

Another concern in estimating ground motion from epicentral intensity is the potential effect of site geology on the assigned value of intensity. The intensity reported for a given location, such as a town, generally represents the maximum intensity observed at that location. In addition, when intensity maps are drawn the largest prevailing intensities in the region are used to determine the isoseismal contour lines. Therefore, it is reasonable to assume that the larger intensities associated with sites located on alluvium, either on alluvial plains or river valleys, control the assignment of epicentral intensity for a specific earthquake.

Assuming this is also true for the Charleston earthquake, we have used the studies of Neumann (1954), Richter (1959) and Medvedev (1965) to estimate epicentral intensities associated with site geologies other than alluvium. These studies indicate that sedimentary rock sites are associated with intensities approximately one unit less than firm alluvium sites and that basement or crystalline rock sites are associated with intensities approximately two units less than firm alluvium sites. Saturated alluvium and artificial fill can have intensities as much as one unit greater than firm alluvium.

A list of the ground motion-intensity relations used to predict peak parameters from epicentral intensity appears in Table 10. The models were compiled by LLNL (1984). Estimates of peak parameters for epicentral intensities of VII, VIII, IX and X are given in Tables 11 and 12. This is the range of intensities expected in the epicentral region of a 6.6 m_b earthquake for a variety of site geologies. The lowest two intensities represent the level of shaking expected on basement rock for assigned epicentral intensities of IX and X. The highest two intensities are those expected on alluvium for the same epicentral intensities, while the intermediate intensities are those expected on sedimentary rock. The M_L-based models of Bernreuter (1981) were evaluated for $M_L = 6.6$, consistent with an m_b of 6.6 in the Eastern United States (Chung and Bernreuter, 1981; Nuttli and Herrmann, 1982). The R-based models of Bernreuter (1981) and McGuire (1977) were evaluated using an epicentral distance of 15 km.

The appropriate estimates of the peak parameters for each model appear as the underlined values in Tables 11 and 12. The value associated with the higher intensity represents an assumed epicentral intensity of X for the Charleston earthquake while the value associated with the lower intensity represents I_0 = IX. Relationships based on a combined soil and rock data set were evaluated as if they represented alluvial sites. This decision was based on a comparison of the peak acceleration models of Trifunac and Brady (1975) and Trifunac (1976). Both studies used the same data base, but Trifunac included a variable representing the geology of the site. In addition, Trifunac treated the peak parameters as lognormal variables, whereas Trifunac and Brady treated them as if they were normally distributed. Murphy and O'Brien (1977) found that the assumption of a normal distribution by Trifunac and Brady resulted in a mean value of PGA for I_s = VI that was 60% larger than the mean value of the logarithm of PGA. When this factor is applied to the Trifunac and Brady estimates for soil and rock in Table 11 they are found to closely match the Trifunac estimates for alluvial sites at all intensity levels investigated.

The results of a statistical (lognormal) analysis of estimates in Tables 11 and 12 for assumed epicentral intensities of IX, IX-X, and X are summarized in Table 13. The intensity IX-X estimates represent a logarithmic average of the I_0 = IX and I_0 = X estimates appearing in Table 13. The estimates based on I_0 = X are found to be a factor of two larger than those based on I_0 = IX, demonstrating an extreme sensitivity to this parameter. Predictions for I_0 = IX are generally consistent with reverse/reverse-oblique estimates based on the site-specific and semi-theoretical approaches (Tables 6 and 9) and lends support to the hypothesis that this is a more reasonable estimate of epicentral intensity for the Charleston earthquake than the I_0 = X value proposed by some investigators. The 81-88 cm/sec/g range of PGV to PGA ratios are similar to the 91 cm/sec/g value suggested for rock by Newmark and Hall (1982) and fall within the range 55-110 cm/sec/g reported by Seed and Idriss (1982) for rock and stiff soils. This range is midway between the ratios for hard rock and soil/soft rock sites determined from the site-specific record sets.

4.2 Intensity-Attenuation Models

Intensity-based estimates of ground motion parameters based on intensity-attenuation relations have been obtained from scaling relations proposed by Nuttli and Herrmann (1978), Battis (1981), LLNL (1984), Nuttli et al. (1983), and Klimkiewicz and Pulli (1983). Each relation combines an intensity-attenuation model for the Eastern United States with a relationship between ground-motion parameters and intensity developed primarily from Western United States data. A brief description of each model is presented below.

4.2.1 Nuttli and Herrmann (1978) Model

Nuttli and Herrmann (1978) combined an intensity-attenuation relationship for the Central United States modified from Gupta and Nuttli (1976),

$$I_S = 3.1 + I_0 - 1.07 \ln R \quad (R \geq 20 \text{ km}) \tag{18}$$

with the Murphy and O'Brien (1977) relationship between PGA, I_S, M_L and R (their model C from Table 10) to develop a scaling relation for peak horizontal acceleration. Equation (18) was developed by dropping the anelastic attenuation term and adjusting the remaining coefficients so that it approximated the original expression for epicentral distances of 300 km or less. Magnitude was introduced through the expression (Nuttli, 1974)

$$I_0 = 2\, m_b - 3.5 \tag{19}$$

The combined relationship was scaled to match existing strong-motion recordings in the Central United States, resulting in the expression

$$\ln PGA = 1.47 + 1.20\, m_b - 1.02 \ln R \tag{20}$$

In this expression PGA represents the mean peak horizontal acceleration in cm/sec^2 and R is epicentral distance in km. For R<15 km PGA is assumed to be equal to the value obtained at 15 km.

4.2.2 Battis (1981) Model

Battis (1981) used two assumptions to develop a scaling relationship for the Central United States from Modified Mercalli intensity. He assumed that in the "near field" (i.e., at $R = 10$ km) peak acceleration is the same for the same epicentral intensity, independent of the tectonic regime. In the "far field", defined as the limit of the felt area, he assumed that peak horizontal acceleration is similar for all regions and sizes of earthquakes, adopting a value of 6 cm/sec^2. Near-field values of PGA for both the Western and Central United States were estimated from the scaling relationship of McGuire (1974). Relations developed by Brazee (1976) were used to relate M_L to both m_b and I_0 for the Western United States, then McGuire's relationship in terms of I_0 was used to express PGA in terms of m_b for the Central United States based on a regional relationship proposed by Nuttli (1973).

Relationships between the radius of felt area (R_f) and m_b were used to relate magnitude, distance and PGA in the far field by assuming that PGA = 6 cm/sec^2 at these distances. The R_f-m_b relationship for the Central United States was developed from data presented by Nuttli and Zollweg (1974). Synthetic data were generated in the near and far field from the above relationships at 0.5 - magnitude unit intervals between 4.0 and 6.5 m_b. These data were used in conjunction with standard least-squares procedures to produce the expression

$$\ln PGA = 3.155 + 1.24\, m_b - 1.24 \ln(R + 25) \qquad (21)$$

Because of the way that PGA data were generated, this parameter represents mean peak horizontal acceleration in cm/sec^2 and R is epicentral distance in km. The constant R+25 was not fit in the regression, rather it was adopted from McGuire (1974). The largest residual for the synthetic data of $m_b >$ 5.0 was found to be 0.3. Much larger residuals were characteristic of the fit for smaller magnitudes. No similar relationship was developed for peak velocity.

4.2.3 LLNL (1984) Models

Four scaling relationships were adopted from LLNL (1984). All are based on the Gupta and Nuttli (1976) intensity-attenuation relationship for the Central United States, modified to represent the average distance to the specified intensity. This modification, representing a reduction of 0.5-intensity units for a given epicentral intensity and distance, resulted in the expression

$$I_s = 3.2 + I_0 - 1.17 \ln R - 0.0011\, R \qquad (22)$$

Epicentral intensity was converted to m_b using the expression developed by Nuttli (1974) for the Central United States, Eq. (19).

The above expressions were combined with two types of expressions relating peak ground motion parameters to site intensity. The first expression includes epicentral distance as an independent variable and the second includes M_L as an independent variable. These expressions appear in Table 10 as Bernreuter (1981) models A and B, respectively. The resulting scaling relationships for peak horizontal acceleration are

$$\ln PGA = 1.61 + 1.14\, m_b - 0.99 \ln R - 0.00063\, R \qquad (23)$$

for the model including distance, and

$$\ln PGA = 0.77 + 1.13\, m_b - 0.74 \ln R - 0.00069\, R \qquad (24)$$

for the model including magnitude. In this latter equation, M_L is assumed to be equivalent to m_b for earthquakes occuring in the Eastern United States (Chung and Bernreuter, 1981; Nuttli and Herrmann, 1982). In these expressions PGA is mean peak horizontal acceleration in cm/sec^2 and R is epicentral distance in km.

Similar relations for peak horizontal velocity are, for the model including distance,

$$\ln PGV = -3.17 + 1.52\, m_b - 0.95 \ln R - 0.00084\, R \qquad (25)$$

and, for the model including magnitude,

$$\ln PGV = -2.78 + 1.19\, m_b - 0.60 \ln R - 0.00056\, R \qquad (26)$$

where PGV is mean peak horizontal velocity in cm/sec. The assumed standard error for application of Eqs. (23) through (26) by Bernreuter (1981) was 0.7. Peak ground motion parameters were considered to be constant for epicentral distances of 20 km or less.

4.2.4 Nuttli et al. (1983) Models

While several intensity attenuation-based ground motion models were proposed and tested by Nuttli et al. (1983), the two models found to have the best agreement with the available strong-motion data in the Eastern United States are used to estimate peak horizontal acceleration for the present study. The first model combines the Gupta and Nuttli (1976) intensity attenuation relationship,

$$I_s = 3.7 + I_o - 1.17 \ln R - 0.0011\, R \qquad (27)$$

with Eq. (19) and the Murphy and O'Brien (1977) relationship (Table 10, Model C) to establish the following scaling relation:

$$\ln PGA = 1.45 + 1.19\, m_b - 1.05 \ln R - 0.00035\, R \qquad (28)$$

In this expression PGA is the maximum peak horizontal acceleration in cm/sec^2 and R is epicentral distance in km. Peak aceleration is considered independent of distance for $R \leq 20$ km.

A second model used as its basis an intensity-attenuation relationship for South Carolina developed from isoseismal maps of 24 earthquakes of m_b = 1.6-6.6. The attenuation relation was combined with a relationship between m_b and I_0 appropriate for South Carolina (Nuttli et al., 1979) to produce the expression

$$I_s = 0.19 + 1.18\ m_b - 0.84\ \ln R - 0.0014\ R \tag{29}$$

where R is epicentral distance in km. The standard error for the regression was 0.36. Equation (29) was then combined with the relationship of Murphy and O'Brien (1977) (Table 9, Model C) to produce the scaling relation

$$\ln PGA = 1.45 + 1.13\ m_b - 0.95\ \ln R - 0.00046\ R \tag{30}$$

where PGA and R are defined as in Eq. (28). Peak acceleration is considered to be independent of distance for $R \leq 10$ km.

Nuttli et al. (1983) presented additional intensity attenuation relationships for South Carolina and the Eastern United States based on hypocentral distance. But because of their incompatability with the use of epicentral distance by Murphy and O'Brien (1977), they were not used in the present study. Nuttli et al. (1983) did not present any intensity-based models for peak velocity.

4.2.5 Klimkiewicz and Pulli (1983) Model

Klimkiewicz and Pulli (1983) have proposed a scaling relationship for peak horizontal velocity for New England. They developed an intensity-attenuation relationship from six New England earthquakes ranging in magnitude from 3.0 to 5.7 m_b. They used the relationship of McGuire (1977) (Table 10, Model B) to express intensity in terms of PGV for sedimentary rock resulting in the expression

$$\ln PGV = -5.39 + 1.70\ m_b - 0.756\ \ln R - 0.0017\ R \tag{31}$$

We have developed a similar relationship for peak acceleration by combining their intensity-attenuation relation with McGuire's (1977) relationship (Table 10, Model B),

$$\ln PGA = -2.05 + 1.52\ m_b - 0.676\ \ln R - 0.0015\ R \tag{32}$$

In these expressions PGA and PGV are the mean peak horizontal components of acceleration in cm/sec^2 and velocity in cm/sec, respectively, and R is epicentral distance in km.

4.2.6 Results

Results of the intensity-attenuation approach are given in Tables 14 and 15 for epicentral distances of 5 to 400 km. Predictions were not arbitrarily truncated at small distances, as suggested by most investigators, so that an adjustment factor could be applied to the estimates to make them compatible with fault-distance estimates. Average values of the peak acceleration estimates of Table 14 are found to range from 0.49g at a distance of 20 km to 0.87g at a distance of 10 km. The corresponding peak velocity estimates of Table 15 are found to range from 38.2 to 68.2 cm/sec. Comparing these peak velocity values to estimates of peak acceleration by the same investigators gives PGV to PGA ratios of 90 cm/sec/g at both distances. These ratios are somewhat low with respect to ratios determined by the site-specific approach and, together with the epicentral-intensity results in the previous section, indicate that the intensity-based approaches tend to underestimate peak velocity.

4.2.7 Adjusted Estimates

The ratio of fault-distance to epicentral-distance estimates based on the semi-theoretical models of Campbell (1981b) can be used to adjust the peak acceleration estimates of Table 14 to approximate those expected from fault-distance models. Applying this 60% reduction (see Section 3.3) to the average of the 10 and 20 km predictions of Table 14 results in a peak horizontal acceleration of 0.27g. This value is similar to the semi-theoretical and site-specific estimates for strike-slip and normal fault mechanisms appearing in Tables 6 and 9 and, when averaged with the epicentral intensity estimate for I_0 = IX in Table 13, results in an intensity-based estimate for peak horizontal acceleration of 0.32g.

5.0 DISCUSSION

A summary of the adjusted median estimates of peak horizontal acceleration for all three empirical methods is given in Table 16. Adjustments were made so that these estimates would represent as closely as possible the peak horizontal acceleration expected in the near-source region of a Charleston-type earthquake in the Eastern United States. The desired characteristics of such a prediction were that it represent (1) an earthquake of magnitude 6.6 m_b (7.5 M_s), (2) a distance of approximately 15 km from the surface projection of fault rupture, and (3) a free-field instrumental recording on soil or rock.

The site-specific estimates of Table 16 are taken from Table 6 and represent an average of the values obtained for the soil/soft rock and hard rock record sets. The semi-theoretical estimates were taken from Table 9 and represent the average of the estimates obtained from the three fault-distance models. The intensity-based estimate represents the average of the values obtained from the epicentral-intensity approach, as found in Table 13 for I_o = IX, and the intensity-attenuation approach. All three methods are found to give similar estimates and indicate remarkable consisteny among the various methods. However, as discussed in the previous sections of this report, this consistency is realized only after the application of significant adjustments -- adjustments required to put these estimates on a consistent basis.

A summary of the adjusted estimates of the standard deviations of the peak ground motion parameters based on all three methods appears in Table 17. The site-specific estimates, taken from Table 6, represent the standard deviations associated with the soil/soft rock record set. The hard rock record set contains so few records that its standard deviation is not considered reliable. The semi-theoretical estimates are taken from Table 9. The 0.38 value represents the standard error of estimate associated with a regression analysis on a near-source set of free-field peak acceleration recordings where fault type and embedment are included as scaling variables and distance is measured from the fault (i.e., Eq. 1). The 0.42 value represents the standard error associated with a similar analysis where fault type is not included as a variable (i.e., Eq. 15). The intensity-based estimates come from Table 13 and represent the analysis for which an epicentral intensity of IX was assumed for the Charleston earthquake. They represent the scatter associated with the various models used to estimate the peak ground motion parameters from epicentral intensity.

The values of standard deviation obtained from the various methods are found to be quite consistent. The average value of 0.38 represents an 84th-percentile to median ratio of 1.46. This ratio is representative of the scatter associated with the prediction of near-source ground-motion parameters determined for moderate-to-large earthquakes throughout the world (Campbell, 1981a) and falls in the range 1.4 to 1.5 recommended by Seed and Idriss (1982) for the design of critical facilities.

A summary of the adjusted peak velocity to peak acceleration ratios obtained from all three methods is given in Table 18. The site specific estimates are taken from Table 6 and represent an average of the median and 84th-percentile values for each fault classification. The semi-theoretical estimate is taken from Table 8 and represents the average results of Nuttli and Herrmann (1983) for distances of 10 and 20 km. The intensity-based estimate is taken from Table 13 (for I_0 = IX) and Section 4.2.6 and represents an average of the 84th-percentile and median estimates of this ratio.

The ratios from all three methods are relatively consistent once site geology effects are considered. For example, Seed and Idriss (1982) have recommended PGV to PGA ratios that are highly dependent on site classification. For distances less than about 50 km from the source, they recommend ratios of 55, 110 and 135 cm/sec/g for rock, stiff soil and deep soil, respectively. Newmark and Hall (1982) also recommend ratios that are dependent on site geology, suggesting ratios of 91 cm/sec/g for rock and 122 cm/sec/g for soil. The ratios for soil and soft rock based on the site-specific and semi-theoretical methods both fall within the range 110 to 135 cm/sec/g suggested by these investigators. The site-specific estimate for hard rock also falls within their recommended 55 to 91 cm/sec/g range for rock. The intensity-based estimate for soil and rock also falls within the upper portion of the recommended range of ratios for rock. This suggests that the intensity-based method tends to underestimate this ratio and its results should be discounted for estimating peak velocities.

6.0 RECOMMENDATIONS

The peak ground motion parameters considered to be representative of free-field recordings within the near-source region of a 6.6 m_b (7.5 M_s) earthquake in the Eastern United States are given in Table 19. These values are recommended as a result of careful consideration of the results of this study and represent a concensus from three widely used empirical procedures.

The reliance by all methods on strong-motion data recorded in the Western United States creates some concern regarding the reliability of these estimates. This concern is mitigated to some extent, however, by two factors. The first factor is the segregation of the estimates by fault mechanism. Reverse and Reverse-Oblique fault mechanisms represent a compressional stress regime, a regime common to the Eastern United States. The second factor is the similarity between the semi-theoretical estimates of Nuttli and Herrmann (1983) and those determined from all three methods. Nuttli and Herrmann's models were calibrated using Eastern United States strong-motion data, yet when adjusted to represent fault distance rather than epicentral distance, their model gives a peak horizontal acceleration of approximately 0.33g at a distance of about 15 km. This value is consistent with those recommended in Table 19. Added verification will have to await the results of earthquake modeling studies for the region.

Appropriate scaling studies were not available with which to adjust the site-specific spectra presented in Figs. 1-8. Therefore, it is not known at present how these spectral shapes may be affected by the various source and site characteristics that were found to significantly influence the estimates of peak ground motion parameters. No semi-theoretical methods for predicting response spectra in the Eastern United States are currently available and only a few intensity-based models exist. For these reasons it is recommended at present that response spectra be developed from the peak parameters presented in Table 19 using the procedures suggested by Newmark and Hall (1982).

The following research is recommended as a means of enhancing the reliability of the stong-motion predictions developed in this report.

(1) For the site-specific method, procedures should be developed for adjusting the response spectra for various source and site characteristics. This would require spectral dependent scaling variables for magnitude, distance, fault mechanism, building size, site geology, and instrument embedment.

(2) The semi-theoretical methods should be extended to include peak horizontal velocity and response spectra as well as scaling variables for the characteristics listed in (1) above. These scaling relations would serve both as a means of adjusting site-specific estimates of peak velocity and response spectra and as an independent means of estimating these parameters.

(3) Additional strong-motion records, such as those listed in Table 5, should be obtained and used to augment the limited number of records currently used to develop site-specific estimates of strong ground motion parameters for a 6.6 m_b (7.5 M_s) earthquake.

(4) Recent near-source strong-motion data should be used to establish relationships between site intensity and ground motion parameters for the large intensities and ground motions observed at these close distances. This would establish the appropriate form of this relationship for these critical design conditions.

(5) Earthquake modeling studies should be used to independently predict strong ground motion parameters for a 6.6 m_b (7.5 M_s) earthquake in the Eastern United States. These studies could be used to verify the empirical procedures currently adopted. Once properly calibrated these models would also serve as a means of including fault geometry and rupture mechanics in the prediction of strong ground motion in the Eastern United States as well as forming a theoretical basis for extending the prdictions to larger earthquakes if required.

7.0 REFERENCES

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TABLE 1

Strong-Motion Records Used to Develop Site-Specific Spectra for Rock

Earthquake	Date	Fault Type*	Magnitude		Station	Distance (km)	Geology	Structure Size***
			M_s	m_b				
Koyna, India	12-10-67	S	6.5	6.1	Koyna Dam, Gallery	3.2	Hard Rock	Large
San Fernando, California	2-09-71	R	6.6	6.2	Pacoima Dam, Abut.	3.2	Hard Rock	Large
					3838 Lankersheim, Bsmt.	15.4	Soft Rock	Large
					Griffith Park Obs.	16.9	Hard Rock	Large
					CIT Seismological Lab.	18.4	Hard Rock	Small
					4867 Sunset, Bsmt.	19.1	Soft Rock	Large
					3435 Wilshire, Bsmt.	23.5	Soft Rock	Large
					2500 Wilshire, Bsmt.	23.6	Soft Rock	Large
					L.A. Wtr. & Pwr, Bsmt.	24.1	Soft Rock	Large
					800 W. First, Bsmt.**	24.1	Soft Rock	Large
					445 Figueroa, Bsmt.	24.9	Soft Rock	Large
					Lake Hughes No. 4	24.9	Hard Rock	Small
Friuli, Italy	5-06-76	R	6.5		Tolmezzo, Abut.	10.0	Soft Rock	Large
Imperial Valley, California	10-15-79	S	6.9	5.7	Cerro Prieto, Mex.**	15.7	Hard Rock	Small
					Superstition Mt.	24.5	Hard Rock	Small
Campania-Lucania, Italy	11-23-80	N	6.7		Bagnoli I.	12.0	Soft Rock	Small
					Sturno	18.0	Soft Rock	Small
					Calitri	19.0	Soft Rock	Small

*Fault Type Code: Strike-Slip (S), Reverse or Reverse-Oblique (R), and Normal (N).

**These records are not currently used to develop site-specific spectra.

***Structure Size Code: Free field or buildings of two stories in height or less (small) and dams and buildings of three stories in height or greater (large).

TABLE 2

Site-Specific Estimates of Peak Ground Motion Parameters on Rock for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Record Set	Peak Horizontal Acceleration (g)				Peak Horizontal Velocity (cm/sec)				PGV/PGA	
	No.	$\sigma_{\ln PGA}$	Median	84%	No.	$\sigma_{\ln PGV}$	Median	84%	Median	84%
All Rock Records	16	0.63	0.21	0.40	21	0.67	17.5	34.2	83	86
All Rock Records w/o Koyna & Pacoima	14	0.31	0.17	0.23	19	0.59	15.9	28.7	94	125
Free-Field and Small Building Records	6	0.23	0.18	0.23	9	0.81	13.6	30.6	59	133
Hard Rock Records	6	0.83	0.29	0.66	7	0.99	12.7	34.1	44	52
Hard Rock Records w/o Pacoima	5	0.52	0.22	0.37	6	0.64	9.3	17.6	42	48
Soft Rock Records	10	0.36	0.17	0.24	14	0.35	20.5	29.2	120	122

TABLE 3

Strong-Motion Records Used to Develop Site-Specific Spectra for Soil

Earthquake	Date	Fault Type	Magnitude M_S	Magnitude m_b	Station	Distance (km)	Soil Depth***	Structure Size
El Centro, California	5-19-40	S	7.1	-	El Centro No. 9, Bsmt.	6.2	Deep	Large
Puget Sound, Washington	4-13-49	R	7.1	-	Olympia, Grnd.	17.0*	Deep	Small
Eureka, California	12-21-54	-	6.5	-	Eureka Fed. Bldg., Bsmt.	24.0*	Deep	Large
Puget Sound, Washington	4-29-65	N	6.5	-	Seattle Fed. Bldg., Bsmt.	23.0*	Deep	Large
San Fernando, California	2-09-71	R	6.6	6.2	8244 Orion, Grnd.	7.5	Deep	Large
					15107 Van Owen, Bsmt.	9.7	Deep	Large
					15910 Ventura, Bsmt.	14.3	Deep	Large
					Jet Prop. Lab., Bsmt.	14.8	Deep	Large
					15250 Ventura, Bsmt.	15.4	Deep	Large
					14724 Ventura, Grnd.	15.4	Deep	Large
					Lake Hughes No. 12	18.7	Shallow	Small
					6430 Sunset, Grnd.	19.2	Deep	Large
					6464 Sunset, Bsmt.	19.2	Deep	Large
					7080 Hollywood, Bsmt.	19.3	Deep	Large
					1760 Orchid, Grnd.	19.3	Deep	Large
					Hollywd. Str. Bldg., Bsmt.	20.5	Deep	Large
					Hollywd. P.E. Lot	20.5	Deep	Small
					CIT Millikan Lib., Bsmt.	21.8	Deep	Large
					120 Robertson, Bsmt.	22.4	Deep	Large
					435 Oakhurst, Bsmt.	22.5	Deep	Large
					CIT Athenaeum, Bsmt.	22.5	Deep	Small

TABLE 3 (continued)

Earthquake	Date	Fault Type	Magnitude M_S	m_b	Station	Distance (km)	Soil Depth***	Structure Size
					Lake Hughes No. 9	22.6	Shallow	Small
					Castaic	22.8	Shallow	Small
					450 Roxbury, Grnd.	22.9	Deep	Large
					3407 Sixth, Bsmt.	23.5	Deep	Large
					3470 Wilshire, Bsmt.	23.5	Deep	Large
					3550 Wilshire, Bsmt.	23.5	Deep	Large
					3710 Wilshire, Bsmt.	23.5	Deep	Large
					4680 Wilshire, Bsmt.	23.5	Deep	Large
					616 Normandie, Bsmt.	23.5	Deep	Large
					9100 Wilshire, Bsmt.	23.7	Deep	Large
					6200 Wilshire, Grnd.	24.0	Deep	Large
					222 Figueroa, Grnd.	24.1	Shallow	Large
					234 Figueroa, Grnd.	24.1	Shallow	Large
					1625 Olympic, Grnd.	24.8	Deep	Large
					900 Fremont, Bsmt.	24.8	Deep	Large
					1177 Beverly, Bsmt.	24.9	Deep	Large
					U.C.L.A., Grnd.	24.9	Deep	Large
					533 Fremont, Bsmt.	24.9	Deep	Large
					808 Olive, Grnd.	24.9	Deep	Large
					1800 Cent. Prk., Bsmt.	25.0	Deep	Large
					1808 Cent. Prk., Bsmt.	25.0	Deep	Large
Gazli, USSR	5-17-76	R	7.0	6.3	Karakyr	3.5	Deep	Small
Tabas, Iran	9-16-78	R	7.4	6.5	Tabas	3.0	Deep	Small
Imperial Valley California	10-15-79	S	6.9	5.7	Meloland Freefield	0.5	Deep	Small
					El Centro No. 7	0.6	Deep	Small
					El Centro No. 6	1.0	Deep	Small
					El Centro No. 5	1.0	Deep	Small
					Brawley	3.6	Deep	Small
					El Centro No. 8	3.8	Deep	Small
					Bonds Corner	4.0	Deep	Small
					El Centro No. 4	4.1	Deep	Small

TABLE 3 (continued)

Earthquake	Date	Fault Type	Magnitude		Station	Distance (km)	Soil Depth***	Structure Size
			M_S	m_b				
					Aueropuerto, Mex.**	5.0	Deep	Small
					Cucapah, Mex.**	5.0	Deep	Small
					Agarias, Mex.**	5.0	Deep	Small
					Diff. Array	5.1	Deep	Small
					Chihuahua, Mex.**	7.3	Deep	Small
					Holtville	7.5	Deep	Small
					Imp. Co. Center**	7.6	Deep	Small
					El Centro No. 10	8.5	Deep	Small
					El Centro No. 3	9.4	Deep	Small
					Mexicali, Mex.**	10.4	Deep	Small
					Calexico	10.6	Deep	Small
					El Centro No. 2	11.0	Deep	Small
					El Centro No. 11	12.6	Deep	Small
					Par. Test Site	14.0	Deep	Small
					Compuertas, Mex.**	14.6	Deep	Small
					El Centro No. 1	15.0	Deep	Small
					Westmoreland	15.0	Deep	Small
					El Centro No. 12	18.0	Deep	Small
					Delta, Mex.**	21.7	Deep	Small
					El Centro No. 13	22.0	Deep	Small
					Calapatria	23.0	Deep	Small
Campania-Lucania, Italy	11-23-80		6.7	--	Auletta	25.0	Deep	Small

*Epicentral distance

**These records are not currently used to develop site-specific spectra.

***Soil Depth Code: Soil depths $\leq$ 10 m (Shallow) or soil depths > 10 m (Deep).

TABLE 4

Site-Specific Estimates of Peak Ground Motion Parameters on Soil for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Record Set	Peak Horizontal Acceleration (g)				Peak Horizontal Velocity (cm/sec)				PGV/PGA	
	No.	$\sigma_{\ln PGA}$	Median	84%	No.	$\sigma_{\ln PGV}$	Median	84%	Median	84%
All Soil Records	66	0.61	0.19	0.35	--	--	--	--	--	--
All Soil Records w/o Shallow Soil Sites	61	0.62	0.19	0.35	61	0.64	22.6	43.0	119	122
All Soil Records w/o Large Embedded Buildings	41	0.64	0.23	0.44	36	0.70	28.2	56.9	123	129
Free-Field & Small Building Records	31	0.69	0.26	0.52	28	0.75	31.4	66.4	121	128

TABLE 5

Additional Foreign Records Not Readily Available

Earthquake	Date	Fault Type	Magnitude	Station	Geology
Lice, Turkey	9-06-75	R	6.7	Lice	--
Guerrero, Mexico	3-14-79	R	7.8	La Villita Dam	Rock
				El Infiernillo Dam	Rock
Montenegro, Yugoslavia	4-15-79	R	6.9	Ulcinj, Albatros Hotel	Rock
				Ulcinj, Olympic Hotel	Soil
				Herceg Novi	Rock
				Bar	Soil
				Petrovac	Soil
Gulf of Corinth, Greece	2-24-81	N	6.7	Corinth	Soil

TABLE 6

Adjusted Site-Specific Estimates of Peak Ground Motion Parameters for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Record Set	Peak Horizontal Acceleration (g)				Peak Horizontal Velocity (cm/sec)				PGV/PGA	
	No.	$\sigma_{\ln PGA}$	Median	84%	No.	$\sigma_{\ln PGV}$	Median	84%	Median	84%
Reverse and Reverse-Oblique Faults										
Soil & Soft Rock Records	71	0.38	0.36	0.53	71	0.35	41.0	58.1	114	110
Hard Rock Records w/o Pacoima	5	0.25	0.38	0.49	5	0.42	22.1	33.6	58	69
Strike-Slip and Normal Faults										
Soil & Soft Rock Records	71	0.38	0.26	0.38	71	0.35	34.2	48.4	133	128
Hard Rock Records w/o Pacoima	5	0.25	0.27	0.35	5	0.42	18.4	28.0	68	81

TABLE 7

Semi-Theoretical Estimates of Peak Horizontal Acceleration for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Distance (km)	Peak Horizontal Acceleration (g)				
	Epicentral-Distance Models		Fault-Distance Models		
	Campbell (1981b)	Nuttli and Herrmann (1983)	Campbell (1981b)	Campbell (1982)	LLNL (1983)*
0	1.34	0.64	0.39	0.41	0.59
5	1.06	0.62	0.37	0.39	0.45
10	0.86	0.56	0.33	0.35	0.31
20	0.61	0.44	0.25	0.27	0.18
30	0.46	0.34	0.20	0.22	0.13
50	0.30	0.23	0.13	0.15	0.08
70	0.21	0.16	0.10	0.11	0.06
100	0.13	0.11	0.07	0.08	0.04
150	0.08	0.07	0.04	0.05	0.02
200	0.05	0.04	0.03	0.04	0.02

*These estimates have been reduced by 12% to represent the mean of the two peak horizontal components.

TABLE 8

Semi-Theoretical Estimates of Peak Horizontal Velocity for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Epicentral Distance (km)	Peak Horzontal Acceleration (g)	Peak Horizontal Velocity (cm/sec)	PGV/PGA (cm/sec/g)
	Nuttli and Herrmann (1983)	Nuttli and Herrmann (1983)	
0	0.64	84.3	132
5	0.62	81.5	132
10	0.56	75.0	134
20	0.44	59.7	136
30	0.34	47.5	140
50	0.23	32.5	141
70	0.16	24.3	152
100	0.11	17.3	157
150	0.07	11.3	161
200	0.04	8.1	203

TABLE 9

Adjusted Semi-Theoretical Estimates of Peak Horizontal Acceleration for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States (Fault-Distance Models)

Model	$\sigma_{\ln PGA}$	Peak Horizontal Acceleration (g)*	
		Median	84th-Percentile
	Reverse and Reverse-Oblique Faults		
Campbell (1981b)	0.38	0.36	0.53
Campbell (1982)	0.38	0.38	0.56
LLNL (1983)	0.38	0.31	0.45
All Models	0.38	0.35	0.51
	Strike-Slip and Normal Faults		
Campbell (1981b)	0.38	0.26	0.38
Campbell (1982)	0.38	0.27	0.40
LLNL (1983)	0.38	0.22	0.32
All Models	0.38	0.25	0.36

*These values represent an average of the predictions obtained at distances of 10 and 20 km.

TABLE 10

Ground Motion - Intensity Relations Used to Estimate Peak Ground Motion Parameters from Epicentral Intensity

Reference	Code	Model		Site Geology
		Peak Accelerations (cm/sec^2)	Peak Velocity (cm/sec)	
Trifunac and Brady (1975)	A	$\mathrm{lnPGA}= 0.032+0.69I_S$	$\mathrm{lnPGV}=-1.45+0.58I_S$	Soil & Rock
Trifunac (1976)	A	$\mathrm{lnPGA}=-0.19+0.67I_S$	$\mathrm{lnPGV}=-2.25+0.67I_S$	Alluvium
	B	$\mathrm{lnPGA}= 0.14+0.67I_S$	$\mathrm{lnPGV}=-2.22+0.67I_S$	Sedimentary Rock
	C	$\mathrm{lnPGA}= 0.47+0.67I_S$	$\mathrm{lnPGV}=-2.19+0.67I_S$	Basement Rock
McGuire (1977)	A	$\mathrm{lnPGA}= 0.27+0.60I_S$	$\mathrm{lnPGV}=-1.51+0.54I_S$	Alluvium
	B	$\mathrm{lnPGA}=-0.83+0.85I_S$	$\mathrm{lnPGV}=-4.02+0.95I_S$	Sedimentary Rock
	C	$\mathrm{lnPGA}= 2.01+0.51I_S-0.31\ \mathrm{lnR}$	$\mathrm{lnPGV}=-1.11+0.52I_S-0.072\ \mathrm{lnR}$	Alluvium
	D	$\mathrm{lnPGA}= 1.45+0.68I_S-0.36\ \mathrm{lnR}$	$\mathrm{lnPGV}=-3.61+0.92I_S-0.064\ \mathrm{lnR}$	Sedimentary Rock
Murphy and O'Brien (1977)	A	$\mathrm{lnPGA}= 0.58+0.58I_S$	Not Available	Soil & Rock
	B	$\mathrm{lnPGA}=-1.29+0.88I_S$	Not Available	Soil & Rock (R 25km)
	C	$\mathrm{lnPGA}= 1.38+0.32I_S-0.68\ \mathrm{lnR} +0.55M_L$	Not Available	Soil & Rock
Bernreuter (1961)	A	$\mathrm{lnPGA}= 1.79+0.57I_S-0.32\ \mathrm{lnR}$	$\mathrm{lnPGV}=-2.94+0.76I_S-0.06\ \mathrm{lnR}$	Soil & Rock
	B	$\mathrm{lnPGA}= 0.96+0.63I_S-0.13M_L$	$\mathrm{lnPGV}=-2.62+0.51I_S+0.17M_L$	Soil & Rock
LLNL (1983)	A	$\mathrm{lnPGA}=-1.69+0.86I_S$	Not Available	Soil & Rock (I_S=IV-X)
	B	$\mathrm{lnPGA}=-2.32+0.96I_S$	Not Available	Soil & Rock (I_S=V-X)

TABLE 11

Intensity-Based Estimates of Peak Horizontal Acceleration for Epicentral Intensities Ranging from VII to X

Reference	Model	Remarks	Site Geology	Peak Horizontal Acceleration (g)			
				I_0=VII	I_0=VIII	I_0=IX	I_0=X
Trifunac and Brady (1975)	A		Soil & Rock	0.13	0.26	0.52	1.05
Trifunac (1976)*	A		Alluvium	0.09	0.16	0.31	0.61
	B		Sedimentary Rock	0.13	0.22	0.43	0.84
	C		Basement Rock	0.16	0.31	0.60	1.18
McGuire (1977)	A		Alluvium	0.09	0.16	0.30	0.54
	B		Sedimentary Rock	0.17	0.40	0.93	2.18
	C	R=15 km	Alluvium	0.12	0.19	0.32	0.54
	D	R=15 km	Sedimentary Rock	0.19	0.38	0.75	1.48
Murphy and O'Brien (1977)*	A		Soil & Rock	0.09	0.17	0.30	0.53
	B	R 25km	Soil & Rock	0.12	0.28	0.68	1.65
	C	R=15km,M_L=6.6	Soil & Rock	0.20	0.28	0.38	0.53
Bernreuter (1981)	A	R=15 km	Soil & Rock	0.14	0.25	0.43	0.76
	B	M_L=6.6	Soil & Rock	0.09	0.17	0.33	0.62
LLNL (1983)*	A	I_S=IV-X	Soil & Rock	0.08	0.16	0.38	0.90
	B	I_S=V-X	Soil & Rock	0.08	0.19	0.50	1.31

*These estimates have been reduced by 12% to represent the mean of the two peak horizontal components.

TABLE 12

Intensity-Based Estimates of Peak Horizontal Velocity for Epicentral Intensities Ranging from VII to X

Reference	Model	Remarks	Site Geology	Peak Horizontal Velocity (cm/sec) I_0=VII	I_0=VIII	I_0=IX	I_0=X
Trifunac and Brady (1975)	A		Soil & Rock	13.6	24.3	43.4	77.5
Trifunac (1976)*	A		Alluvium	10.2	19.8	38.8	75.8
	B		Sedimentary Rock	10.5	20.4	40.0	78.1
	C		Basement Rock	10.8	21.1	41.2	80.5
McGuire (1977)	A		Alluvium	9.7	16.6	28.5	48.9
	B		Sedimentary Rock	13.9	35.9	92.8	239.8
	C	R=15 km	Alluvium	10.3	17.4	29.2	49.2
	D	R=15 km	Sedimentary Rock	14.2	35.8	89.7	225.1
Bernreuter (1981)	A	R=15 km	Soil & Rock	9.2	19.6	42.0	89.8
	B	M_L=6.6	Soil & Rock	7.9	13.2	22.0	36.7

*These estimates have been reduced by 12% to represent the mean of the two peak horizontal components.

TABLE 13

Epicentral-Intensity Estimates of Peak Ground Motion Parameters for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Epicentral Intensity	Peak Horizontal Acceleration (g)				Peak Horizontal Velocity (cm/sec)				PGV/PGA	
	No.	$\sigma_{\ln PGA}$	Median	84%	No.	$\sigma_{\ln PGV}$	Median	84%	Median	84%
IX	15	0.35	0.35	0.50	10	0.43	28.6	44.0	82	88
IX-X	30	0.40	0.49	0.74	20	0.46	40.2	63.6	82	86
X	15	0.44	0.70	1.08	10	0.49	56.4	92.2	81	85

TABLE 14

Intensity-Attenuation Based Estimates of Peak Horizontal Acceleration for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Epicentral Distance (km)	Peak Horizontal Acceleration (g)						
	Nuttli & Herrmann (1978)	Battis (1981)	LLNL (1983) M_L-Based	LLNL (1983) R-Based	Nuttli et al. (1983)* C.U.S.	S.C.	K&P** (1983)
5	2.36	1.26	1.16	1.92	1.83	1.44	1.00
10	1.17	1.04	0.69	0.96	0.88	0.74	0.62
20	0.57	0.76	0.41	0.48	0.42	0.38	0.38
30	0.38	0.59	0.30	0.32	0.28	0.26	0.29
50	0.22	0.40	0.20	0.19	0.16	0.16	0.20
70	0.16	0.30	0.16	0.13	0.11	0.11	0.15
100	0.11	0.21	0.12	0.09	0.08	0.08	0.11
150	0.07	0.14	0.08	0.06	0.05	0.05	0.08
200	0.05	0.10	0.06	0.04	0.03	0.04	0.06
300	0.04	0.06	0.04	0.03	0.02	0.03	0.04
400	0.03	0.05	0.03	0.02	0.02	0.02	0.03

*These estimates have been reduced by 12% to represent the mean of the two peak horizontal components for the Central United States (C.U.S.) and South Carolina (S.C.).

**Klimkiewicz and Pulli (1983).

TABLE 15

Intensity-Attenuation Based Estimates of Peak Horizontal Velocity for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Epicentral Distance (km)	Peak Horizontal Velocity (cm/sec)		
	LLNL (1983) M_L-Based	LLNL (1983) R-Based	K&P* (1983)
5	60.6	206.1	99.9
10	39.9	106.2	58.6
20	26.1	54.5	34.1
30	20.4	36.7	24.6
50	14.8	22.2	16.2
70	11.9	15.8	12.1
100	9.4	11.0	8.8
150	7.2	7.1	5.9
200	5.8	5.2	4.3
300	4.3	3.2	2.7
400	3.4	2.2	1.8

*Klimkiewicz and Pulli (1983).

TABLE 16

Summary of Adjusted Median Estimates of Peak Horizontal Acceleration for the Near-Source Region of a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Method	Peak Horizontal Accelerations (g)		
	Strike-Slip/Normal Faults	Reverse/Reverse-Oblique Faults	All Faults
Site-Specific	0.27	0.37	0.32
Semi-Theoretical	0.25	0.35	0.30
Intensity-Based	--	--	0.32

TABLE 17

Summary of Adjusted Standard Deviations of Peak Ground Motion Parameters for the Near-Source Region of a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Method	Remarks	Standard Deviation	
		$\sigma_{\ln PGA}$	$\sigma_{\ln PGV}$
Site-Specific		0.38	0.35
Semi-Theoretical	Segregated by Fault Type	0.38	--
	All Faults	0.42	--
Intensity-Based		0.35	0.43

TABLE 18

Summary of Velocity-Acceleration Ratios for the Near-Source Region of a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Method	Geology	PGV/PGA (cm/sec/g)
Site-Specific	Soil & Soft Rock	121
	Hard Rock	69
Semi-Theoretical	Soil	135
Intensity-Based	Soil & Rock	82

TABLE 19

Recommended Estimates of Peak Ground Motion Parameters for the Near-Source Region of a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

Fault Mechanism	σ ($\log_e$)	Peak Horizontal Acceleration (g)		Peak Horiztonal Velocity (cm/sec)		PGV/PGA (cm/sec/g)
		Median	84th-Percentile	Median	84th-Percentile	
Soil and Soft Rock Sites						
Strike-Slip/Normal	0.38	0.26	0.38	33	48	125
Reverse/Reverse-Oblique	0.38	0.36	0.53	45	66	125
All Faults	0.42	0.31	0.47	39	59	125
Hard Rock Sites						
Strike-Slip/Normal	0.38	0.26	0.38	18	27	70
Reverse/Reverse-Oblique	0.38	0.36	0.53	25	37	70
All Faults	0.42	0.31	0.47	22	33	70

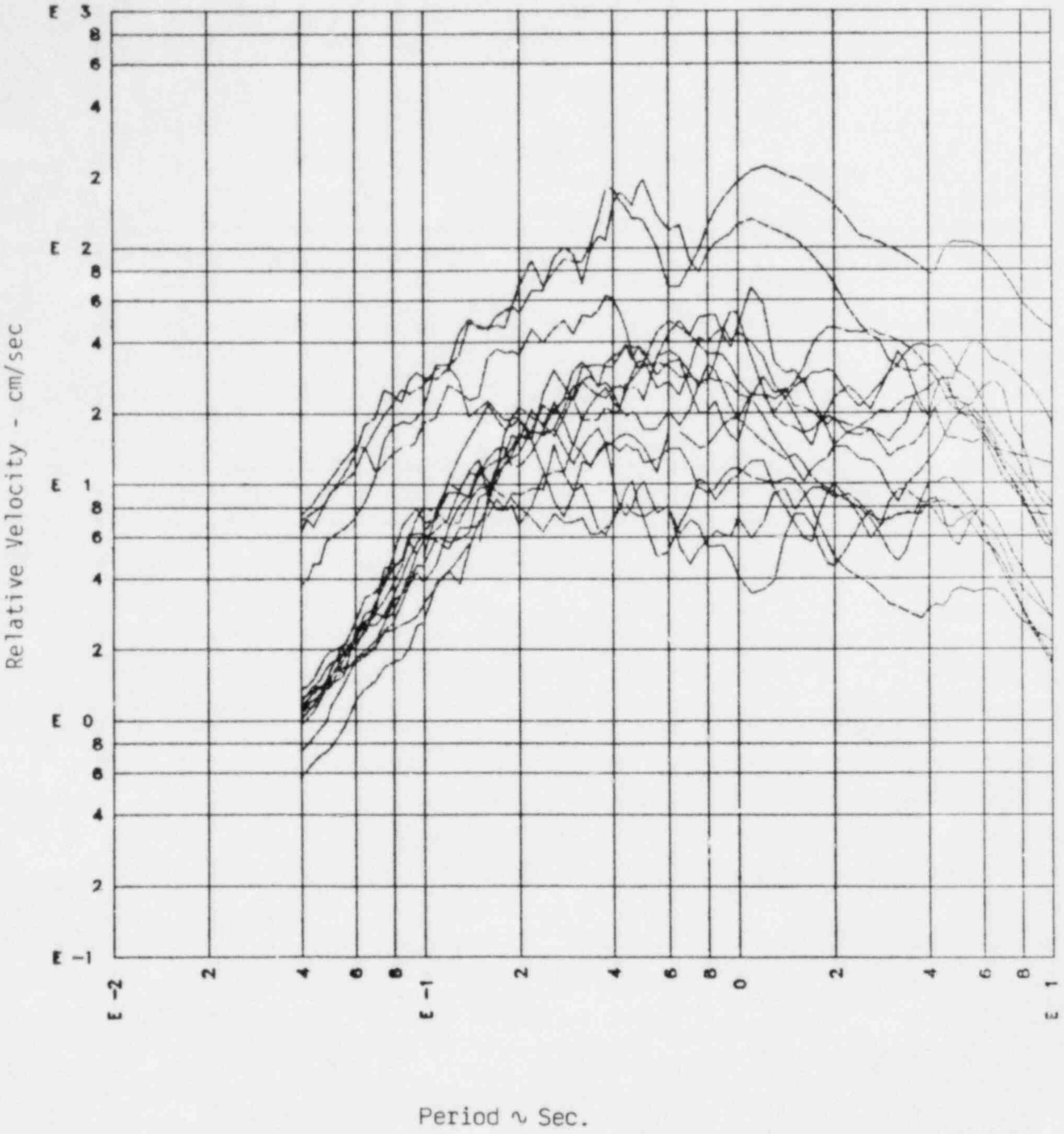

Figure 1. Overlay of Spectra from Hard Rock Sites

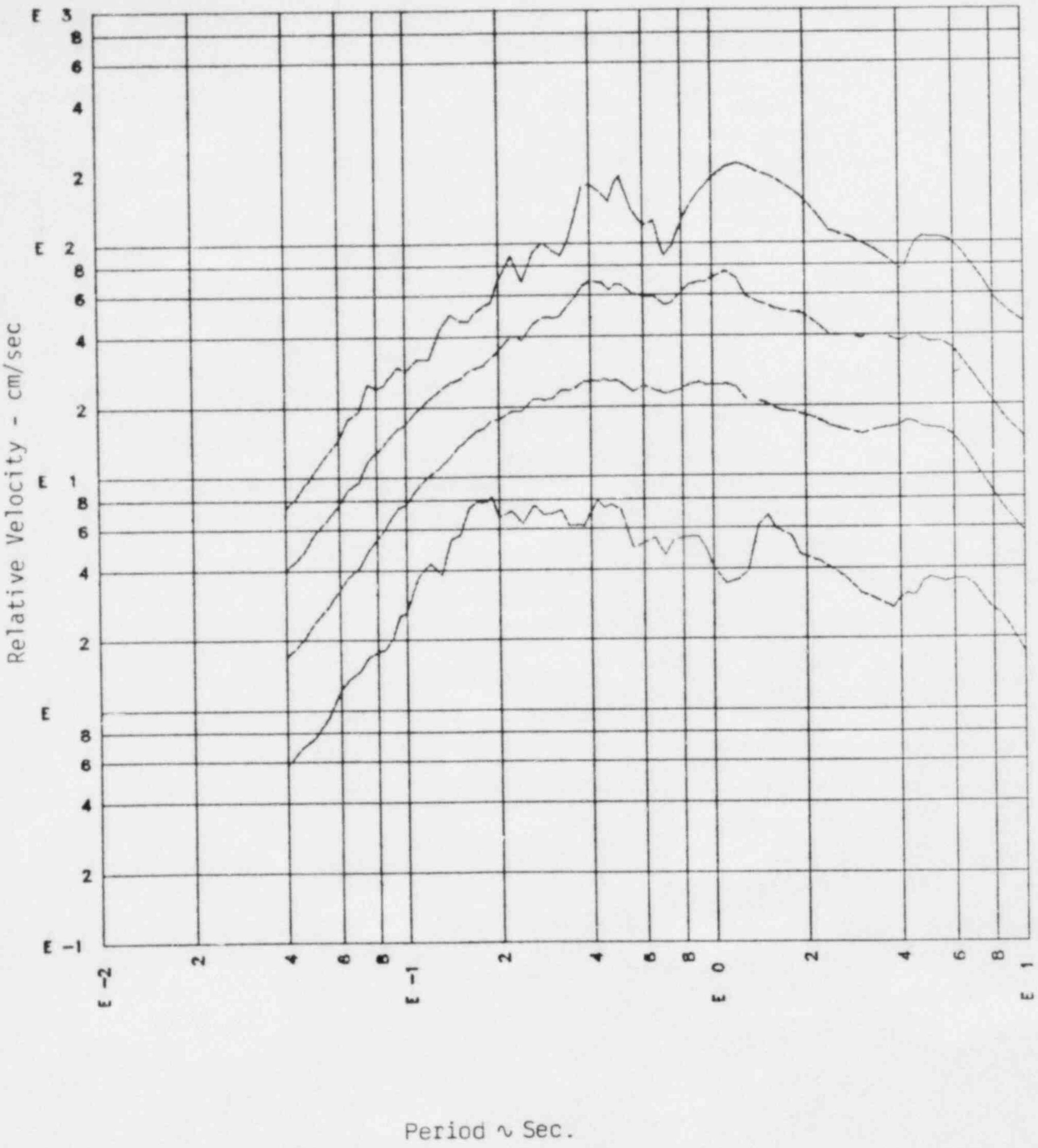

Figure 2. Median, 84th Percentile, and Envelope of Spectra Plotted on Figure 1

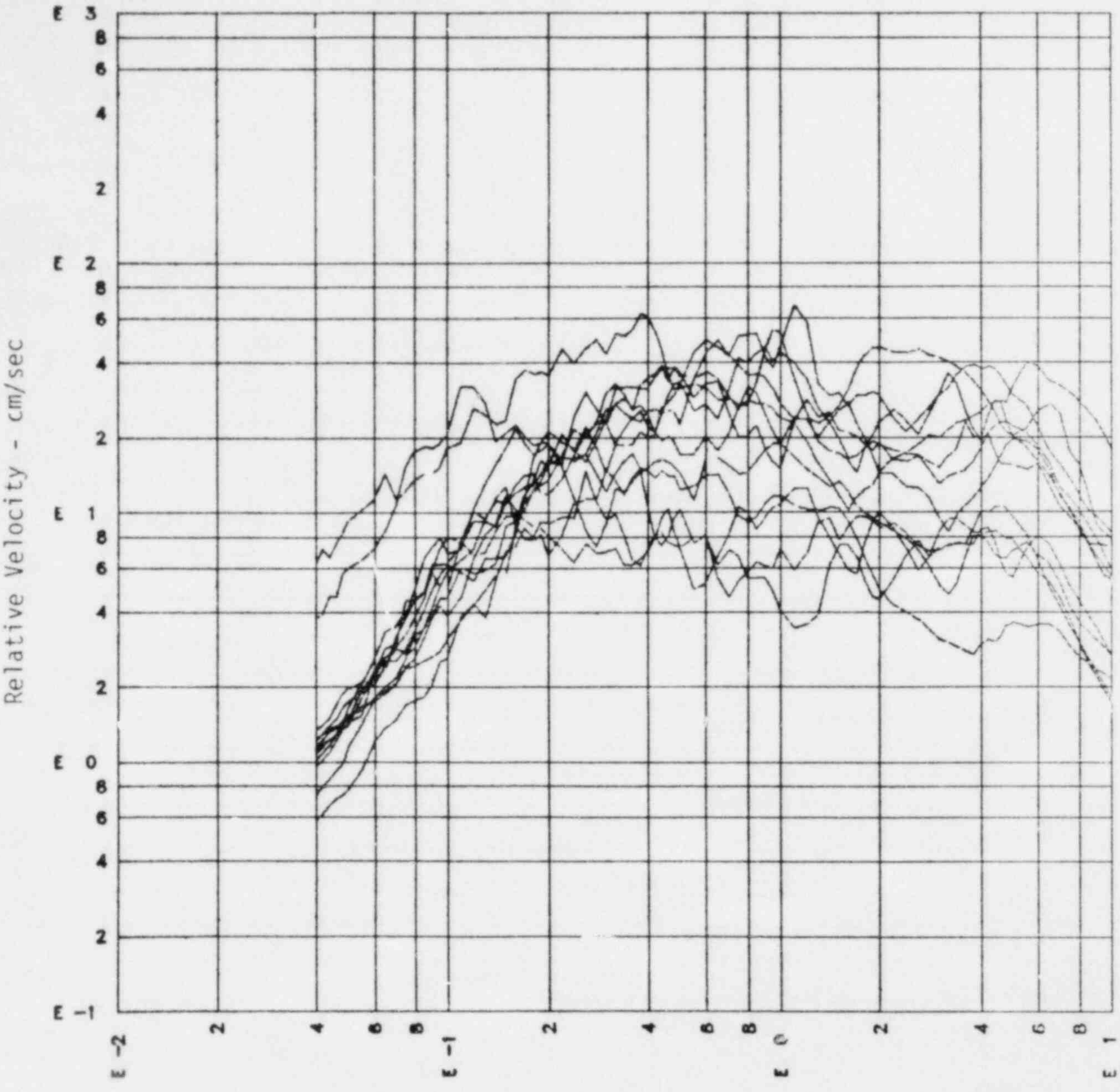

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Figure 3. Same Records as Figure 1 Excluding the Pacoima Dam Record

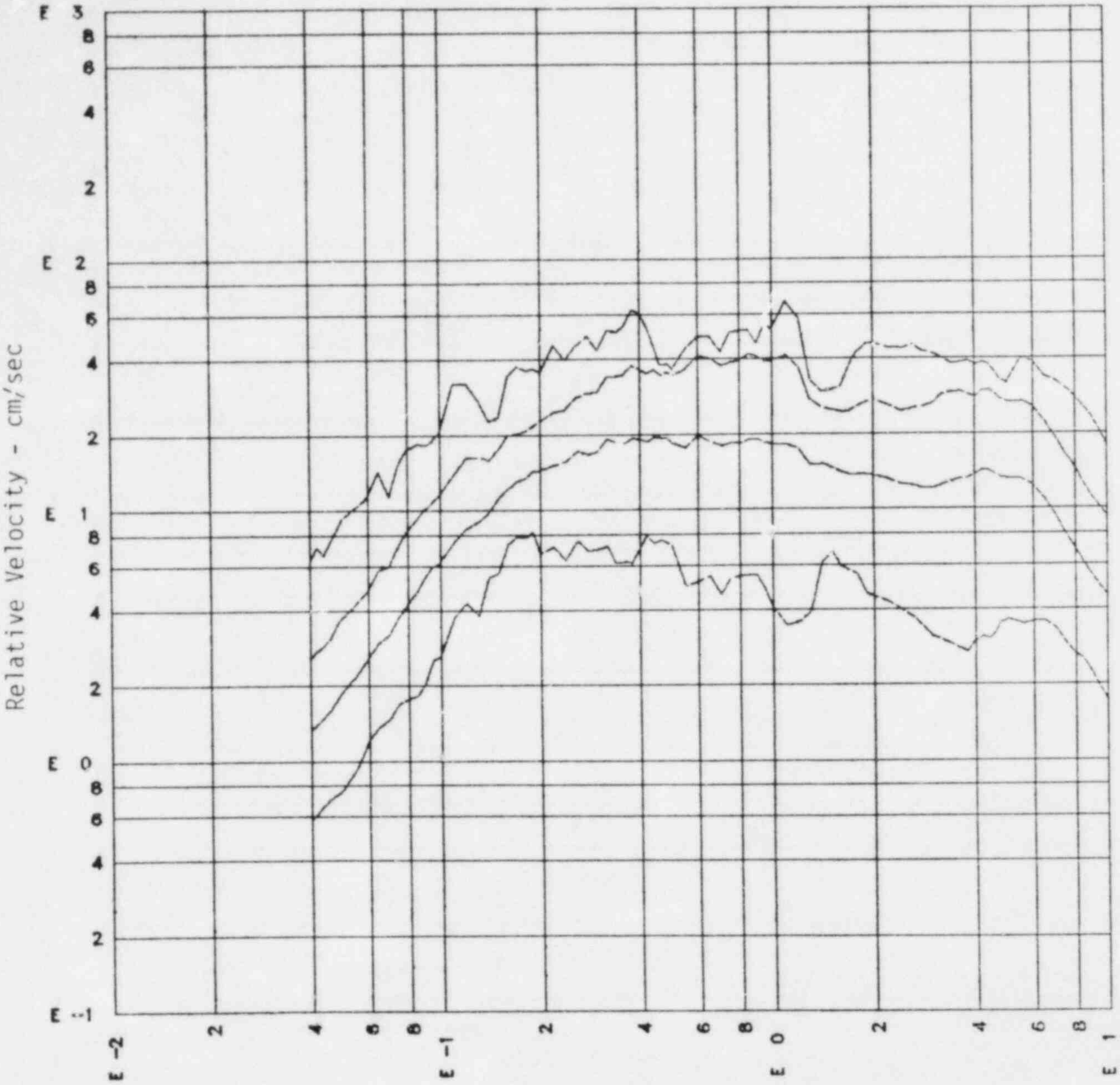

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Figure 4. Median, 84th Percentile, and Envelope of Spectra Plotted on Figure 3

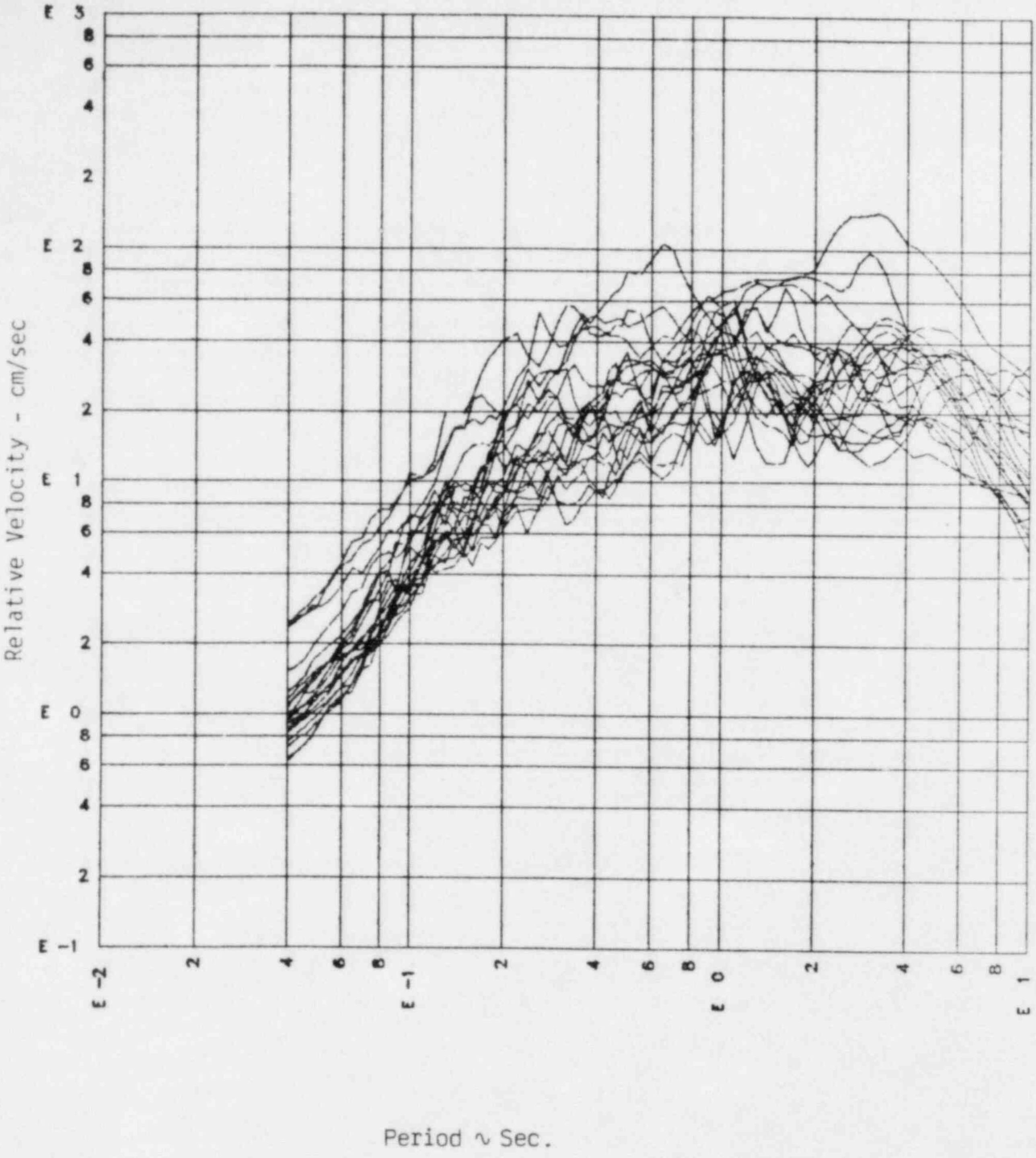
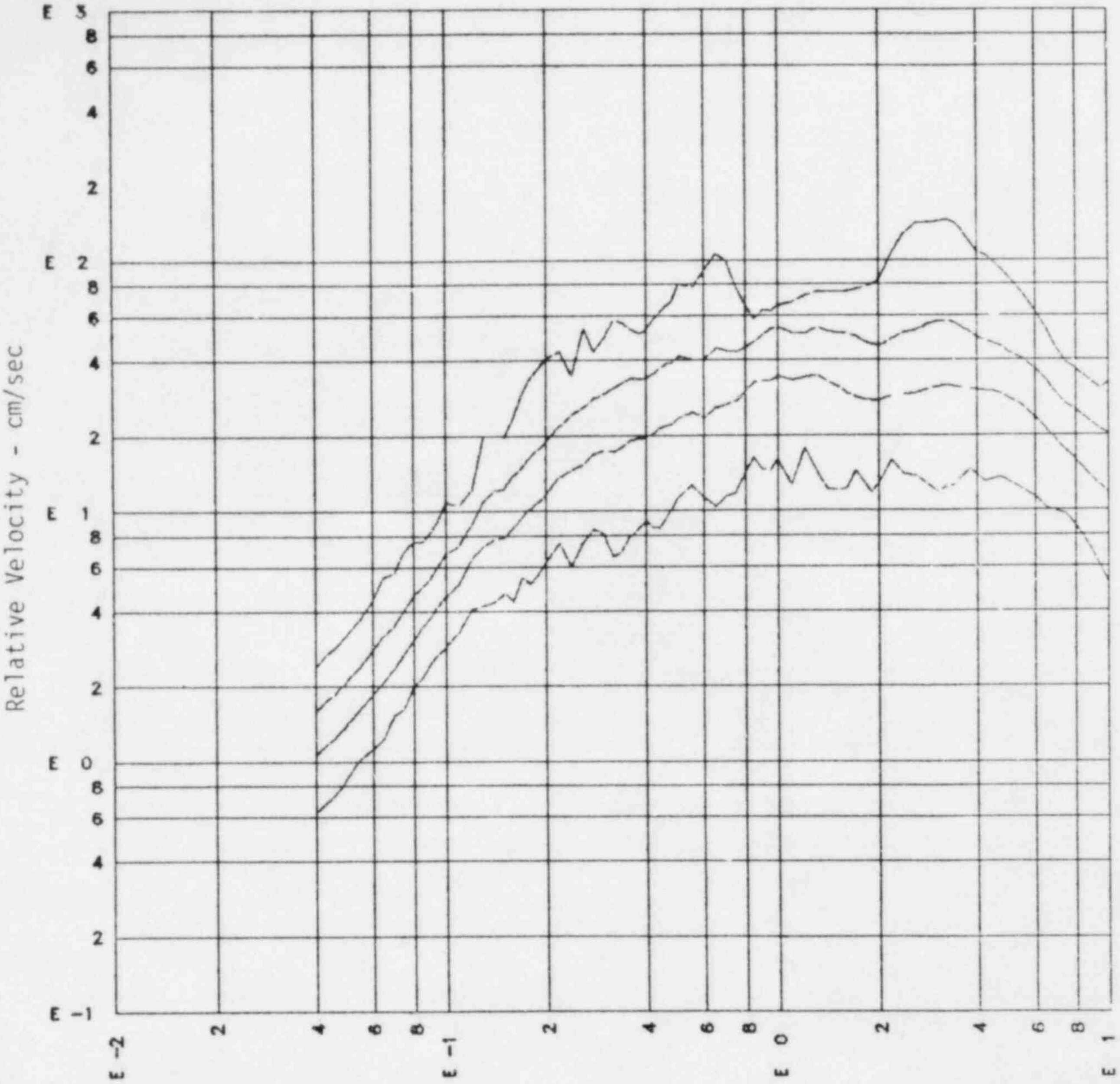


Figure 5. Overlay of Spectra from Soft Rock Sites



Period ∿ Sec.

Figure 6. Median, 84th Percentile, and Envelope of Spectra Plotted on Figure 5

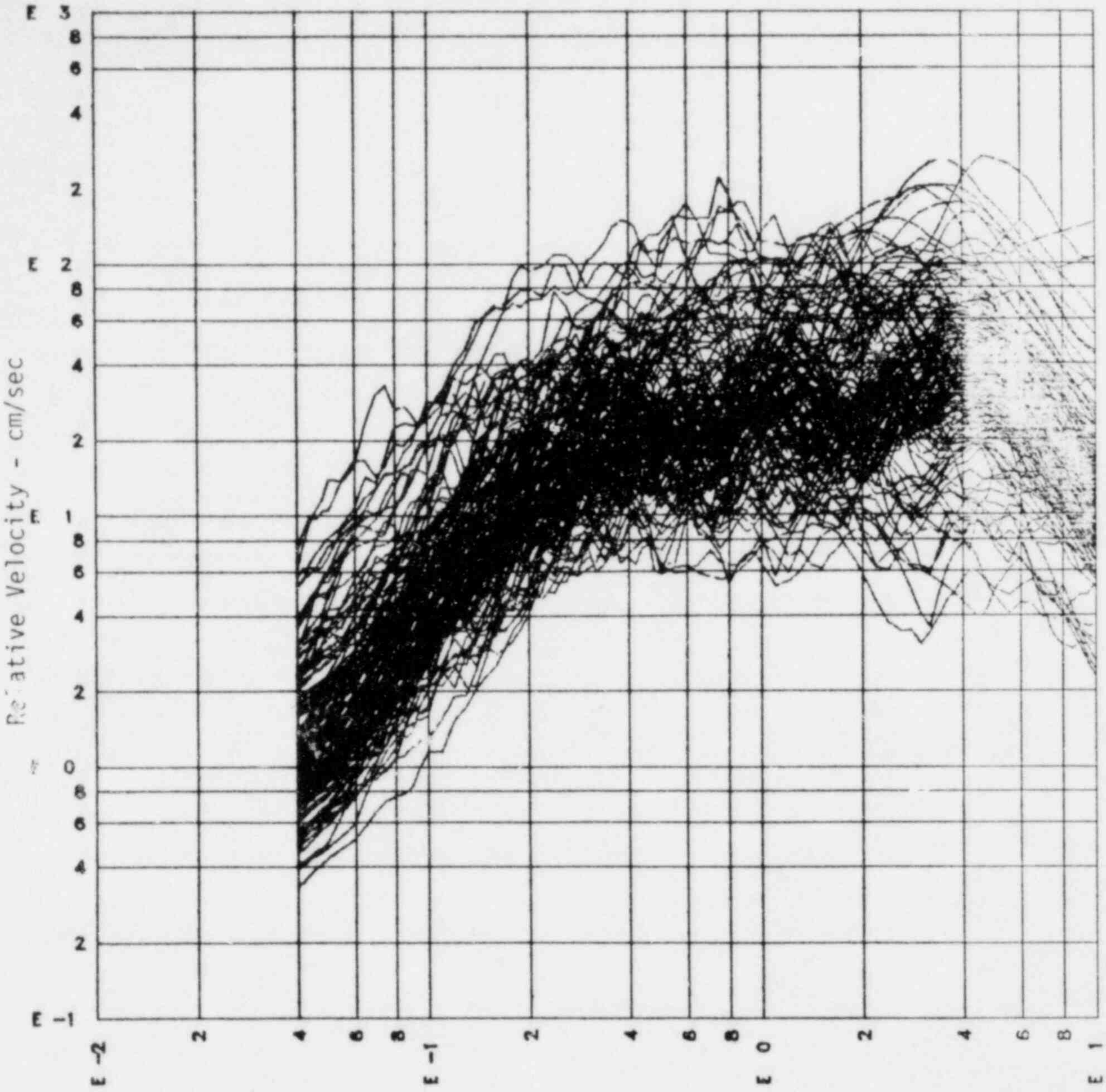


Figure 7. Overlay of Spectra from Soil Sites

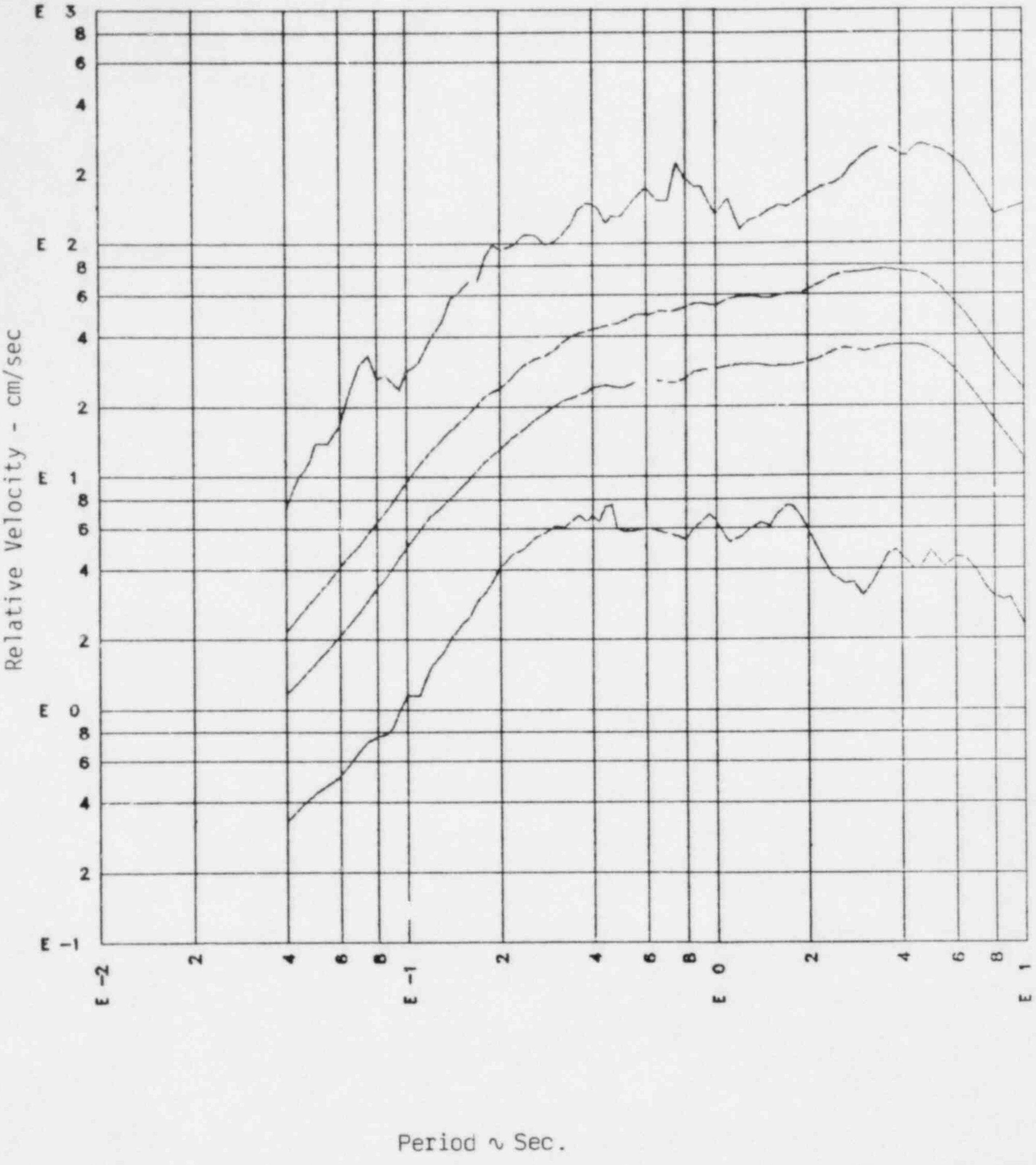


Figure 8. Median, 84th Percentile, and Envelope of Spectra Plotted on Figure 7

NRC FORM 335
(7-77)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER (Assigned by DDC)
NUREG/CR-3839
UCID-20083

4. TITLE AND SUBTITLE (Add Volume No., if appropriate)
An Empirical Assessment of Near-Source Strong Ground Motion for a 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States

2. (Leave blank)

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
Kenneth W. Campbell

5. DATE REPORT COMPLETED

MONTH	YEAR
May	1984

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Lawrence Livermore National Laboratory
P.O. Box 808, L-95
Livermore, California 94550

DATE REPORT ISSUED

MONTH	YEAR
June	1984

6. (Leave blank)

8. (Leave blank)

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Engineering
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. PROJECT/TASK/WORK UNIT NO.
Task 10 & 11 B&R No.20-19-04-11

11. CONTRACT NO.
FIN A0406

13. TYPE OF REPORT
Technical

PERIOD COVERED (Inclusive dates)

15. SUPPLEMENTARY NOTES

14. (Leave blank)

16. ABSTRACT (200 words or less)

To help assess the impact of the current U.S. Geological Survey position on the seismic safety of nuclear power plants in the Eastern United States (EUS), several techniques for estimating near-source strong ground motion for a Charleston size earthquake were evaluated. The techniques for estimating the near-source strong ground motion for a 6.6 m_b (7.5 M_s) in the Eastern United States which were assessed are methods based on (1) site specific analyses, (2) semi-theoretical scaling techniques, and (3) intensity-based estimates. Each method differently approaches the problem of estimating near-source strong ground motions. The results and limitations of each technique are discussed and recommendations made to correct for bias in the methods. Suggestions for future work are also presented.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

Earthquakes
Strong Ground Motion
Attentuation

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS (This report)
UNCLASSIFIED

20. SECURITY CLASS (This page)
Unclassified

21. NO. OF PAGES

22. PRICE
$

NRC FORM 335 (7-77)

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

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WASHINGTON DC 20555

NUREG/CR-3839

FOR A 6.6 m_b (7.5 M_s) EARTHQUAKE IN THE EASTERN UNITED STATES