SEISMIC HAZARD ALONG A CRUDE OIL PIPELINE IN THE EVENT OF AN 1811-1812 TYPE NEW MADRID EARTHQUAKE

by

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PREFACE

The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

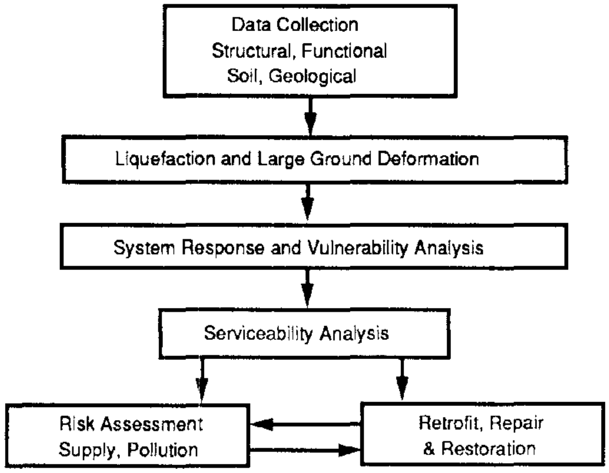
- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

This technical report pertains to Program 3, Lifeline Systems, and more specifically to crude oil transmission systems.

The safe and serviceable operation of lifeline systems such as gas, electricity, oil, water, communication and transportation networks, immediately after a severe earthquake, is of crucial importance to the welfare of the general public, and to the mitigation of seismic hazards upon society at large. The long-term goals of the lifeline study are to evaluate the seismic performance of lifeline systems in general, and to recommend measures for mitigating the societal risk arising from their failures.

From this point of view, Center researchers are concentrating on the study of specific existing lifeline systems, such as water delivery and crude oil transmission systems. A seismic performance analysis of crude oil transmission systems in the New Madrid area is underway. The study focuses on the vulnerability of these systems to seismic events. Technical and societal issues arising from disruption of the supply of crude oil from the south to the northeast following an earthquake are addressed, as is potential environmental pollution due to seismically induced failure of pipelines.

The research activities comprising the crude oil transmission system study are shown in the accompanying figure.



This report provides an assessment of the seismic hazard that exists along a major crude oil pipeline traversing the New Madrid seismic zone. An 1811-1812 type New Madrid earthquake with moment magnitude 8.2 is assumed to occur at three locations where large historical earthquakes have occurred. Six pipeline crossings of the major rivers in West Tennessee are chosen as the sites for hazard evaluation because of the liquefaction potential at these sites. A seismologically-based model is used to predict the bedrock accelerations. Uncertainties in three model parameters, i.e., stress parameter, cutoff frequency, and strong-motion duration are included in the analysis. Each parameter is represented by three typical values. From the combination of these typical values, a total of 27 earthquake time histories are generated for each selected site due to an 1811-1812 type New Madrid earthquake occurring at a postulated seismic source.

ABSTRACT

An assessment of the seismic hazard that exists along the major crude oil pipeline (pipeline 22) is presented in this report. An 1811-1812 type New Madrid earthquake with moment magnitude 8.2 is assumed to occur at three locations where large historical earthquakes have occurred. Six pipeline crossings of the major rivers in West Tennessee are chosen as the sites for hazard evaluation because of the liquefaction potential at these sites. A seismologically-based model is used to predict the bedrock accelerations. Uncertainties in three model parameters, i.e., stress parameter, cutoff frequency, and strong-motion duration are included in the analysis. Each parameter is represented by three typical values. From the combination of these typical values, a total of 27 earthquake time histories can be generated for each selected site due to an 1811-1812 type New Madrid earthquake occurring at a postulated seismic source.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION 1

INTRODUCTION

A major crude oil pipeline, Capline (pipeline 22), passes through the recharge area of underground water supplies in the West Tennessee region (figure 1-1). Because of the age of this pipeline, it is doubtful that any seismic design was included in the pipeline design. The vulnerability of the pipeline subject to an 1811-1812 type New Madrid earthquake is a major concern. In a pilot study conducted by the NCEER lifeline group [1], the buried pipeline was considered to fail due to soil liquefaction induced by earthquakes. The areas of high probability of liquefaction in Tennessee include most of the stream beds in West Tennessee (figure 1-1). If a pipeline were ruptured during an earthquake, the spilled material could contaminate the recharge area, thus impacting the water supply of almost all West Tennessee. Such an impact would be enormous since there is no immediately alternative source of water supply in this region. In this study, the seismic hazards along pipeline 22 is assessed, assuming that a scenario earthquake with magnitude similar to the 1811-1812 New Madrid earthquakes will occur at a postulated source in the New Madrid seismic zone.

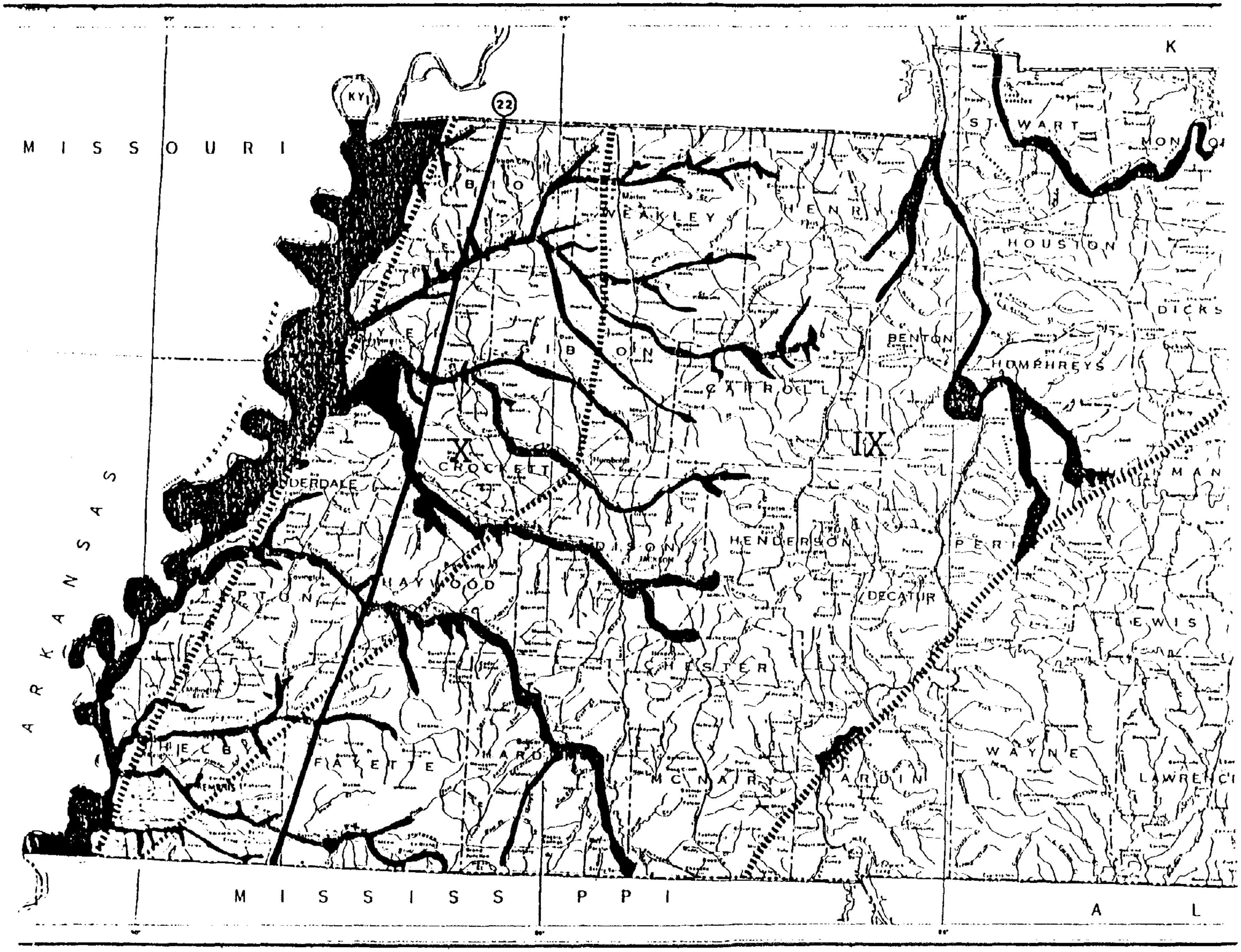


FIGURE 1-1 Pipeline 22 and Liquefiable Soil Areas in Tennessee

SECTION 2

PIPELINE AND SEISMIC SOURCES

The Capline system is a 40-inch pipeline operated by Shell Pipeline Corporation of Houston, Texas. The pipeline transports crude oil from southeastern Louisiana to Patoka, Illinois [1], traveling through soft sediments of the Mississippi Valley and crossing major rivers in West Tennessee: Wolf River, Loosahatchie River, Hatchie River, Forked Deer-South Fork, Forked Deer-North Fork, and Obion River. These river crossings are the potential locations of soil liquefaction during a large earthquake, and therefore are selected as the sites for seismic hazard evaluation. The locations of these six river crossings are listed in table 2-I and also shown in figure 2-1.

The New Madrid seismic zone (NMSZ) is clearly delineated by the concentration of epicenters (figure 2-2). From the pattern of epicenters, at least three distinct linear trends suggesting the orientations of three subsurface fault segments in the New Madrid region are observed [2,3]. These three fault segments are (1) a southern segment extending from Marked Tree, Arkansas, to Caruthersville, Missouri, roughly along the axis of the Reelfoot rift complex; (2) a middle segment trending northwest and extending from Ridgely, Tennessee, to west of New Madrid, Missouri; and (3) a relatively shorter northern segment extending from west of New Madrid, Missouri, to southern Illinois. From the focal mechanism studies [3,4], both the northern and southern segments exhibit a predominantly right-lateral strike-slip fault-plane motion. The middle segment, on the other hand, exhibits a thrust-faulting mechanism.

During the winter of 1811-1812, three great earthquakes occurred in the Mississippi Valley. Because of low attenuation in the eastern and central United States, the intensity of the 1811-1812 New Madrid earthquakes (according to Nuttli [5]) produced far greater damage than that produced by any other historical earthquake in the North American continent. The shocks were felt over a wide area of the central and eastern United States. Nuttli constructed a generalized isoseismal map of the first principal shock that occurred on December 16, 1811 (figure 2-3). The area estimated to be 600,000 km^2, experienced damaging earth motions (modified Mercalli intensity $\geq$ VII). Figure 2-4 illustrates the ground disruptions such as

TABLE 2-I Site Locations

Site	River	Latitude	Longitude
1	Wolf River	35.07°	89.63°
2	Loosahatchie River	35.28°	89.56°
3	Hatchie River	35.55°	89.44°
4	Forked Deer-South Fork	35.80°	89.36°
5	Forked Deer-North Fork	35.96°	89.32°
6	Obion River	36.25°	89.17°

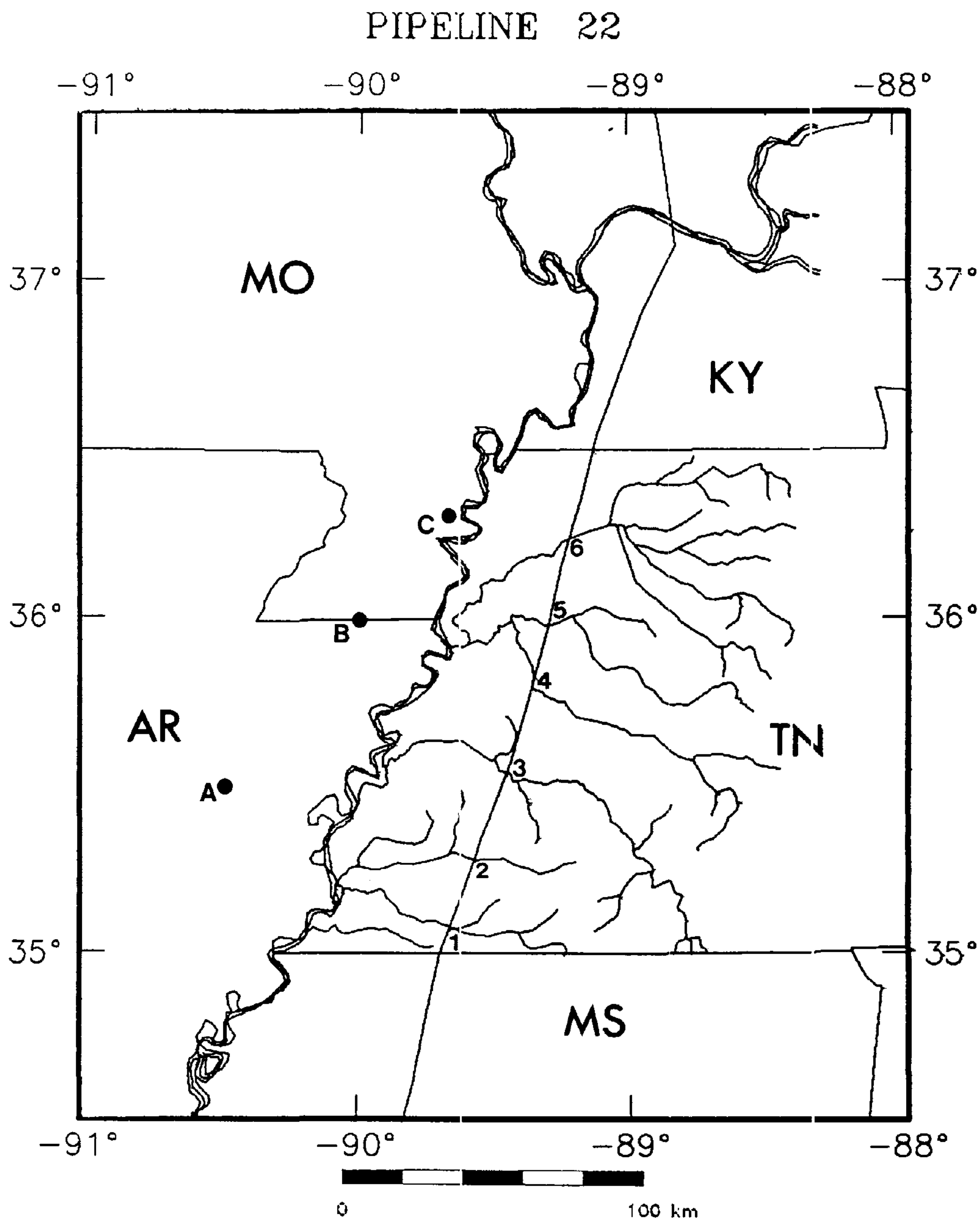


FIGURE 2-1 **Source and Site Locations**

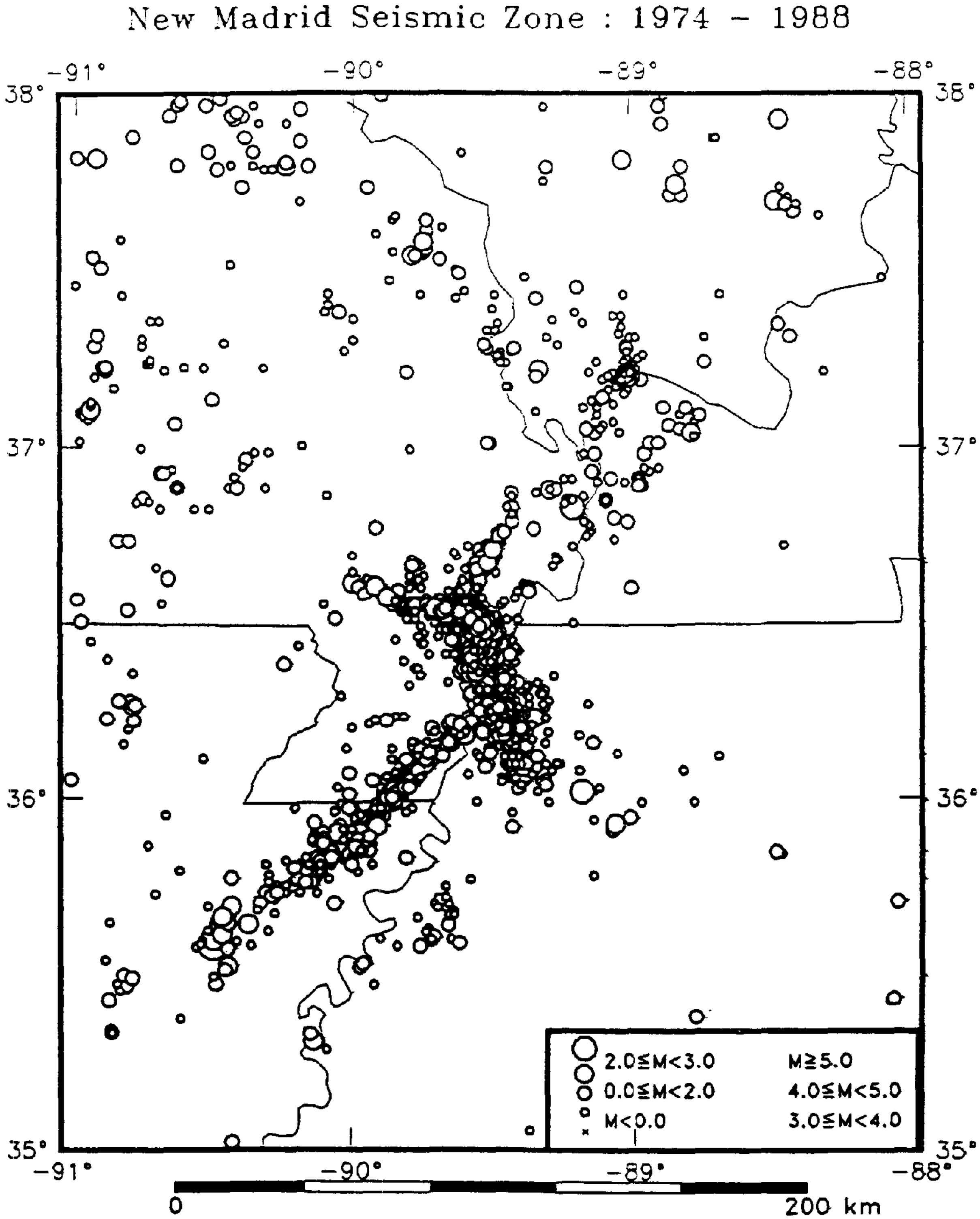


FIGURE 2-2 **Epicenters of New Madrid Earthquakes**

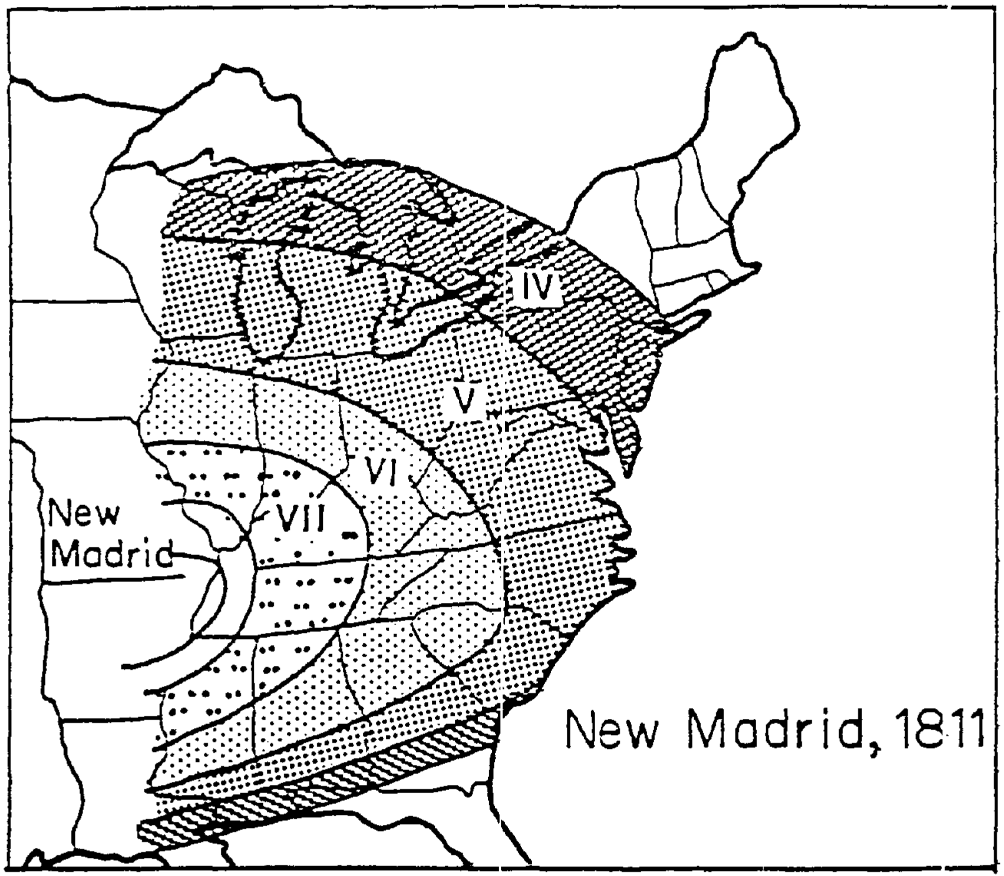


FIGURE 2-3 Isoseismal Map of the 1811 New Madrid Earthquake (after Nuttli, O. W., 1973)

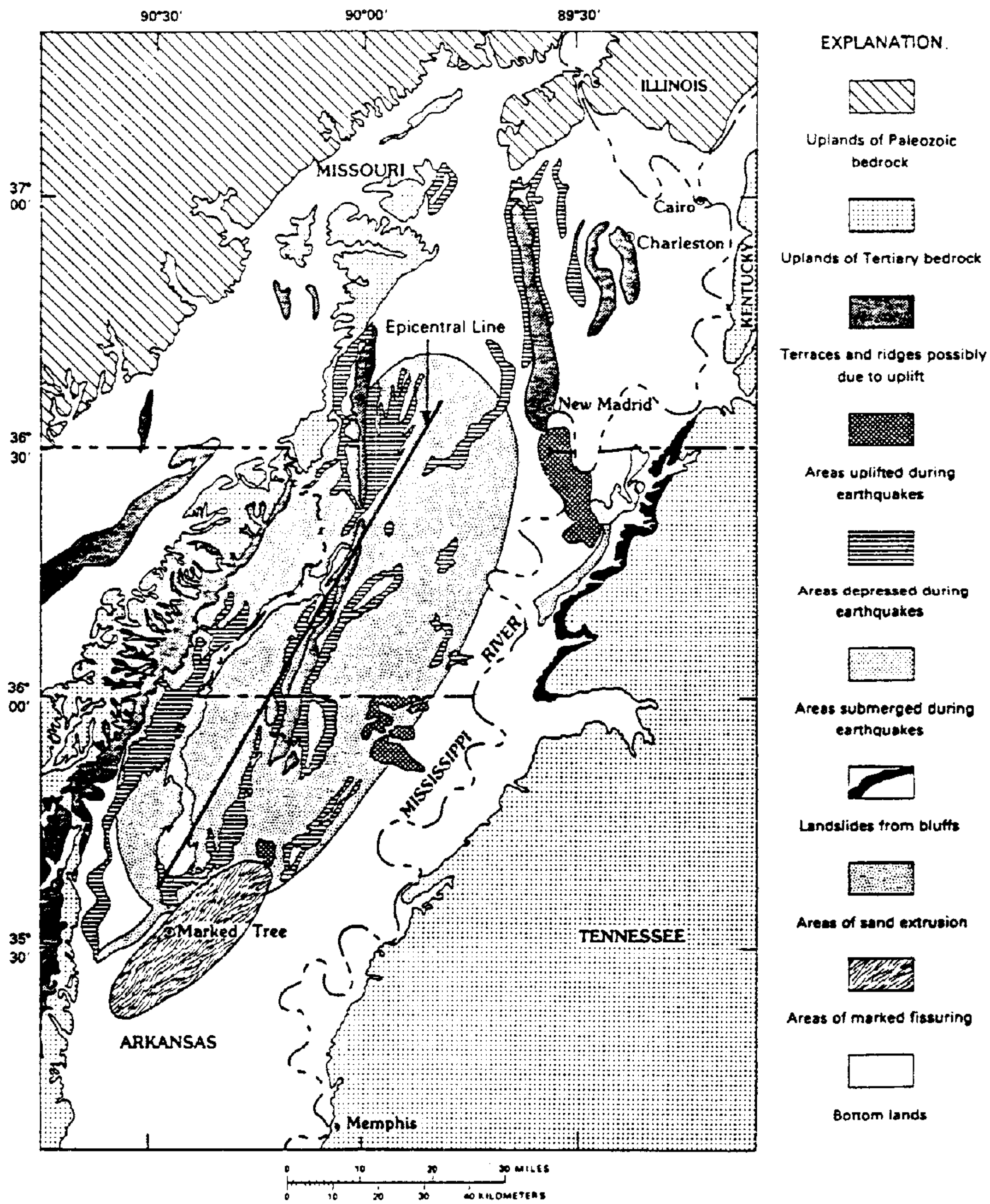


FIGURE 2-4 Map of Ground Effects of the 1811-12 New Madrid Earthquakes (adapted from Fuller, 1912; taken from Jibson and Keefer, 1988)

uplift and sand extrusion due to the 1811-1812 New Madrid earthquakes [6].

In addition to the three 1811-1812 New Madrid earthquakes, there were two other damaging earthquakes that occurred in the NMSZ (figure 2-5). One occurred in 1843 near Marked Tree, Arkansas, and the other occurred in 1895 near Charleston, Missouri. Table 2-II lists the locations and moment magnitudes **M** of these five historical events [7].

In this study, a scenario earthquake similar to an 1811-1812 type New Madrid earthquake is postulated to occur in the NMSZ. Considering the concentration of instrumental epicenters, the historical events, and the site locations selected for this study, three earthquake sources (A, B, and C) are selected as shown in table 2-III. Since the scenario earthquake is assumed to have a magnitude similar to the 1811-1812 New Madrid earthquakes (**M** = 8.2, 8.09, and 8.3), the moment magnitude **M** = 8.2 is assigned to the postulated scenario earthquake. The epicentral distances from these three seismic sources to six selected sites are listed in table 2-IV.

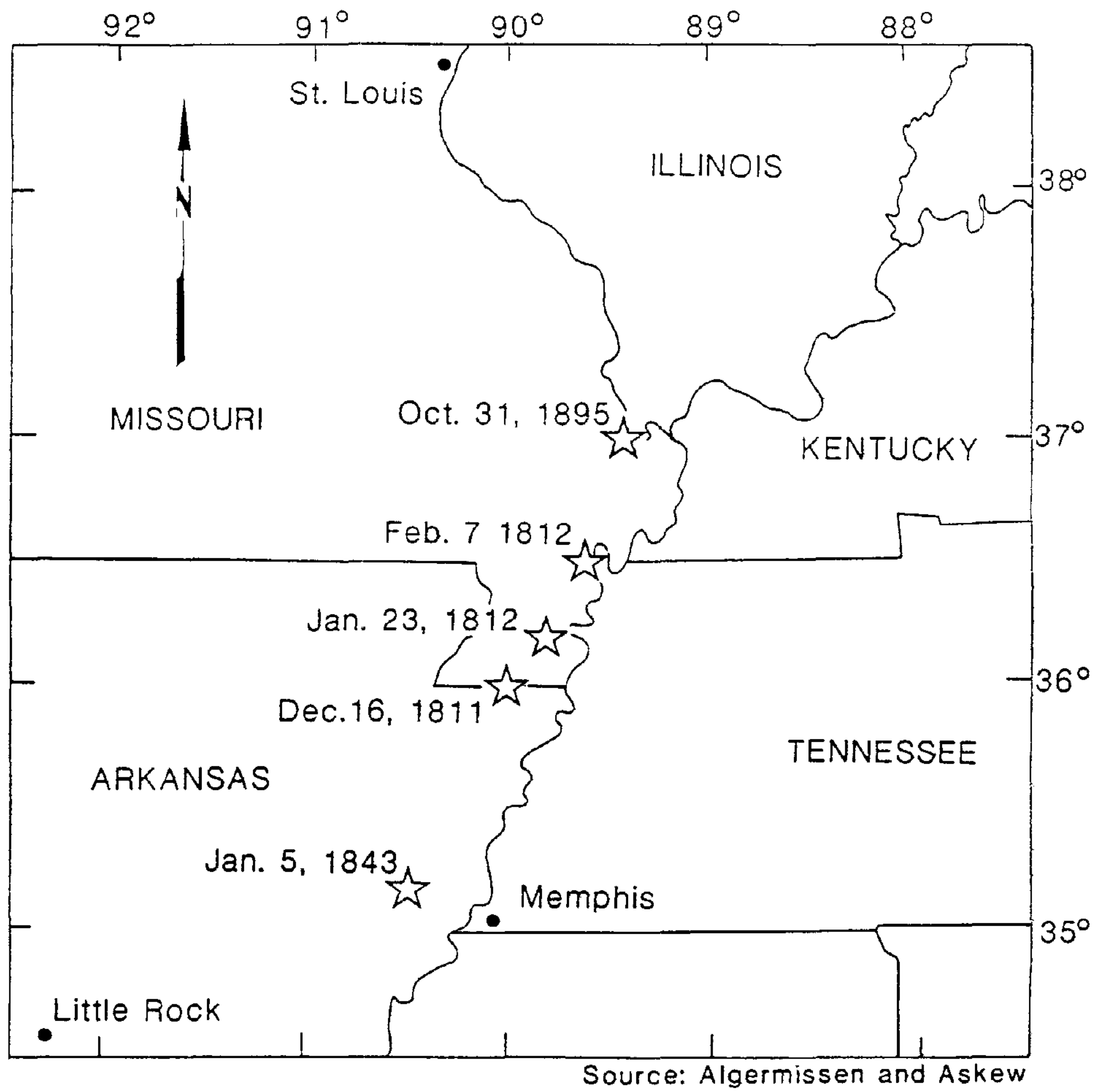


FIGURE 2-5 **Epicenters of Five Historical New Madrid Earthquakes**

TABLE 2-II Historical New Madrid Earthquakes

Event	Epicenter		M
	Latitude	Longitude	
1811 Dec 16	36.0N	90.0W	8.20
1812 Jan 23	36.3N	89.6W	8.09
1812 Feb 07	36.5N	89.6W	8.30
1843 Jan 05	35.5N	90.5W	6.47
1895 Oct 31	37.0N	89.4W	6.81

TABLE 2-III Source Locations

Source	Latitude	Longitude	Historical Reference
A	35.5N	90.5W	1843 0105 Marked Tree event
B	36.0N	90.0W	1811 1216 New Madrid event
C	36.3N	89.6W	1812 0123 New Madrid event

TABLE 2-IV Epicentral Distances

Source	Site	R(km)
A	1	84.62
	2	89.13
	3	96.35
	4	108.30
	5	118.63
	6	145.81
B	1	95.79
	2	92.36
	3	67.10
	4	48.63
	5	42.94
	6	56.48
C	1	118.25
	2	113.73
	3	84.68
	4	59.25
	5	45.08
	6	38.91

SECTION 3

SEISMIC HAZARD ESTIMATION

Estimating the characteristics of ground motions induced by a large New Madrid earthquake is quite challenging because of the lack of strong-motion data in the New Madrid region. In this study, a seismologically-based model is used to predict the horizontal bedrock motions primarily due to shear waves generated from a seismic source [8]. The model is centered on a power spectrum which in turn is developed from a Fourier amplitude spectrum. The Fourier amplitude spectrum is constructed based on the physical characteristics of an earthquake including source mechanism and path attenuation. From the power spectrum, earthquake time histories and probability-based response spectra can be generated directly. The power spectrum can also be used to estimate the peak earthquake accelerations.

3.1 Fourier Amplitude Spectrum

The Fourier amplitude spectrum used in this study essentially follows the Boore and Atkinson approach [9].

$$A(f) = C \times S(f) \times D(f) \times I(f) \qquad (3.1)$$

where C is a scaling factor; $S(f)$ is a source spectral function; $D(f)$ is a diminution function; and $I(f)$ is a shape filter.

The source spectral function $S(f)$ is a frequency-domain representation of the seismic energy released by an earthquake. In this study, we use an ω^2 source spectrum proposed by Brune [10]. This source spectrum is a function of a single corner frequency f_0 and a seismic moment M_0:

$$S(f) = \frac{M_0}{1 + (\frac{f}{f_0})^2} \qquad (3.2)$$

The corner frequency f_0 is determined by the seismic moment M_0, crustal shear wave velocity β, and stress parameter $\Delta\sigma$:

$$f_0 = 4.9 \times 10^6 \beta(\frac{\Delta\sigma}{M_0})^{1/3} \tag{3.3}$$

The seismic moment M_0 is related to average fault displacement $\tilde{D}$, fault rupture area A, and modulus of rigidity μ in the source zone:

$$M_0 = \mu A \tilde{D} \tag{3.4}$$

Stress parameter $\Delta\sigma$ describes the level of the source spectral function above the corner frequency f_0. The stress parameter $\Delta\sigma$ proposed by Atkinson [11], Boore and Atkinson [9], Brune [10], and Joyner [12] is a constant and is independent of earthquake magnitude, while the stress parameter suggested by Nuttli [13] increases with magnitude. In this study, a constant $\Delta\sigma$ is used.

According to the scaling law suggested by Boore [14] and Joyner [12], the scaling factor C is

$$C = \frac{<R_{\theta\phi}> F V}{4 \pi \rho \beta^3} \cdot \frac{1}{r} \tag{3.5}$$

where:

- $<R_{\theta\phi}>$ = radiation pattern
- F = free-surface effect
- V = partition of a vector into horizontal components
- ρ = crustal density
- r = hypocentral distance

$<R_{\theta\phi}>$ is the radiation pattern corresponding to different types of seismic waves over a range of azimuths (θ) and takeoff angles (ϕ). For ϕ and θ averaged over the whole focal sphere, the shear-wave radiation pattern $<R_{\theta\phi}>$ is 0.55 [15]. F accounts for the amplification due to the free surface and is taken as 2 [14]. V is the factor that accounts for the partition of a vector into horizontal components and is chosen as $1/\sqrt{2}$. Based on the hypocentral locations of instrumentally recorded microearthquakes in the NMSZ, the focal depths normally range from 5 to 20 km below the surface where the granitic basement rock of the upper and middle continental crusts are found. In this study, an average focal depth is taken as 10 km. The density ρ of continental crust at this focal depth is taken as 2.7 gm/cm^3, and the shear-wave velocity β is 3.5 km/sec. The hypocentral distance r is the distance measured from the focus of an earthquake to the site. The term 1/r in equation (3.5) accounts for the diminishing of source spectrum as a result of body-wave geometric spreading.

The diminution function $D(f)$ represents the anelastic attenuation that accounts for the damping of the earth's crust and a sharp decrease of acceleration spectra above a cutoff frequency f_m.

$$D(f) = \exp\left[\frac{-\pi f r}{Q(f)\,\beta}\right] P(f,f_m) \qquad (3.6)$$

where:

$Q(f)$ = frequency-dependent quality factor
$P(f,f_m)$ = high-cut filter

The exponential term in equation (3.6) accounts for path attenuation. The quality factor $Q(f)$ describes the attenuation of seismic waves and is frequency dependent. The great distance at which the 1811-1812 New Madrid earthquakes were felt has been attributed to the low attenuation of seismic waves in central and eastern United States [5]. Several frequency-dependent quality factors $Q(f)$ have been proposed [16-18]. Based on the attenuation study conducted by Dwyer and others [16] in central United States, the quality factor of shear and Lg waves is

$$Q(f) = 1500\, f^{\,0.40} \qquad (3.7)$$

Since this study is related to the NMSZ, we feel that the quality factor proposed by Dwyer and others is more appropriate and so is used in this study.

The high-cut filter $P(f,f_m)$ accounts for the observation that the acceleration spectra often show a sharp decrease above a cutoff frequency f_m. In this study, a Butterworth filter is used as the high-cut filter:

$$P(f,f_m) = \left[1 + \left(\frac{f}{f_m}\right)^8\right]^{-1/2} \tag{3.8}$$

The shape filter $I(f)$ is to shape the source spectral function for a particular type of earthquake motion of interest. For acceleration, the shape filter is given as

$$I(f) = (2\pi f)^2 \tag{3.9}$$

3.2 Power Spectral Density Function

An earthquake accelerogram generally shows a build-up segment followed by a strong-motion segment which is in turn followed by a decay segment. The frequency content of earthquake accelerograms is approximately constant during the strong-motion segment. Thus, the strong-motion segment of an acceleration time history is considered as a stationary random process. The one-sided power spectral density function (power spectrum) $S_a(f)$ can be derived from the Fourier amplitude spectrum.

$$S_a(f) = \frac{2}{T} |A(f)|^2 \tag{3.10}$$

where $A(f)$ is the Fourier amplitude spectrum as in equation (3.1), and T is the strong-motion duration.

3.3 Acceleration Time Histories

In this study, synthetic earthquake time histories are generated using the method proposed by Shinozuka [19]. Given the power spectrum, the stationary acceleration time histories $a_s(t)$ can be generated as follows:

$$a_s(t) = \sqrt{2} \sum_{k=1}^{N} \sqrt{S_a(\omega_k)\Delta\omega} \ \cos(2\pi\omega_k t + \phi_k) \qquad (3.11)$$

where:

$S_a(\omega_k)$ = one-sided earthquake power spectrum
N = number of frequency intervals
$\Delta\omega$ = frequency increment
ω_k = $k \, \Delta\omega$
ϕ_k = random phase angles uniformly distributed between 0 and 2π

The nonstationary acceleration time histories a(t) can be obtained from the multiplication of an envelope function w(t):

$$a(t)=a_s(t) \ w(t) \qquad (3.12)$$

The envelope function w(t) proposed by Hwang et al. [2] and used in this study is comprised of three segments: (1) a parabolically increased segment simulating the initial rise part of the accelerogram and its duration is chosen as one fifth of T, (2) a constant segment representing the strong-motion portion of an earthquake excitation and has a duration equal to T, and (3) a linearly decayed segment extending four fifths of T. Thus, the total duration is 2T. It is noted that real seismograms are commonly observed with long coda durations; however, the coda durations are considered unimportant in most engineering applications.

3.4 Peak Values of Earthquake Motions

The peak value A_p of an acceleration time history a(t) over a duration T is defined as

$$A_p = \max | a(t) | \qquad (3.13)$$

The statistical distribution of A_p can be approximated by the asymptotic distribution function of the extreme values [20]. In this study, the cumulative distribution function of A_p proposed by Vanmarcke [21] is used.

$$F_{A_p}(r) = [1-\exp(-\frac{\alpha^2}{2})] \exp\left[-\nu_0 T \frac{1-\exp(-\sqrt{\pi/2}\ \alpha\delta_e)}{\exp(\alpha^2/2)-1}\right]; \ r > 0 \qquad (3.14)$$

in which ν_0 is the mean zero-crossing rate of the displacement response; $\delta_e = \delta^{1.2}$ in which δ is a shape factor [21]; and $\alpha = r/\sigma_a$ is a normalized barrier level. The standard deviation σ_a can be computed from the power spectrum $S_a(\omega)$.

The mean and standard deviation of A_p are particularly useful for engineering applications. The mean value $\bar{A}_p$ and standard deviation σ_{Ap} can be expressed as

$$\bar{A}_p = p_m \sigma_a \qquad (3.15)$$

$$\sigma_{Ap} = q \sigma_a \qquad (3.16)$$

From equation (3.14), Der Kiureghian [22] obtained the following empirical equations for p_m and q:

$$p_m = \sqrt{2 \ln(\nu_e T)} + 0.5772 / \sqrt{2 \ln(\nu_e T)} \qquad (3.17)$$

$$q = 1.2 / \sqrt{2 \ln(\nu_e T)} - 5.4 / (13 + [2 \ln(\nu_c T)]^{3.2}) \qquad (3.18)$$

in which

$$\nu_e T = \begin{cases} \max(2.1, 2\delta\nu_0 T); & 0.00 < \delta \le 0.10 \\ (1.63\ \delta^{0.45}-0.38)\nu_0 T; & 0.10 < \delta < 0.69 \\ \nu_0 T & 0.69 \le \delta < 1.00 \end{cases} \qquad (3.19)$$

3.5 Parameter Uncertainties

The seismologically-based model for the horizontal bedrock accelerations is defined by several parameters as summarized in table 3-I. In this study, the moment magnitude **M** is chosen as 8.2 to simulate the 1811-1812 type New Madrid earthquake. The epicentral distance R is dependent on the site locations. Some parameters such as the radiation pattern is determined from the consideration of earthquake seismology. The focal depth and the corresponding crustal density ρ and shear-wave velocity β are chosen from the data related to the New Madrid region. Since these parameters appear to have less influence on the resulting bedrock accelerations, a deterministic value is assigned to each of these parameters. A deterministic quality factor $Q(f)$ is also used in this study due to the lack of pertinent information to quantify the variation. On the other hand, the stress parameter $\Delta\sigma$, cutoff frequency f_m, and strong-motion duration T have significant effects on the resulting bedrock accelerations. Thus, the uncertainties in these parameters are included in the analysis.

In this study, a constant stress parameter is used to predict the horizontal bedrock time histories. Boore and Atkinson [9], McGuire and others [23], and Somerville and others [24] suggested an average $\Delta\sigma$ around 100 bars for central and eastern North America. Using the 1988 Saguenay earthquake, Atkinson and Boore [25] determined that the stress parameter is about 200 bars. Thus, three values, $\Delta\sigma$ = 100, 150, and 200 bars, are selected for this study.

The cutoff frequency f_m is a parameter to model the decay of the Fourier amplitude spectrum beyond certain frequency. The selection of f_m also affects the peak value of an earthquake. According to Boore and Atkinson [9], f_m is uncertain in eastern North America. McGuire and others [23] suggested f_m = 40 bars for rock sites in this region. From the study of the 1988 Saguenay earthquake, Chen and Hwang [26] found that the value of f_m seems to decrease as the epicentral distance increases and fm = 20 to 30 Hz are obtained for rock sites at epicentral distances less than 100 km. In this study, we select 20, 30, and 40 Hz to cover the uncertainty in cutoff frequencies.

The strong-motion duration T is another important factor that affects the outcome of the time histories. Hanks [27] suggested that strong

TABLE 3-I Earthquake Parameters

Parameters	Symbol	Value
Moment Magnitude	**M**	8.2
Epicentral Distance	R	Table 2-IV
Focal Depth	h	10.0 km
Radiation Pattern	$<R_{\theta\phi}>$	0.55
Horizontal Component	V	0.71
Shear Wave Velocity	β	3.5 km/sec
Crustal Density	ρ	2.7 gm/cm^3
Quality Factor	$Q(f)$	$1500f^{0.4}$
Stress Parameter	$\Delta\sigma$	Variable
Cutoff Frequency	f_m	Variable
Strong-Motion Duration	T	Variable

motion duration T is equal to the source duration, which is the reciprocal of the corner frequency f_0:

$$T = \frac{1}{f_0} \tag{3.20}$$

On the basis of this equation, the strong-motion duration T for an **M** = 8.2 earthquake with a stress parameter of 150 bars is about 32 sec. According to studies conducted by Johnston [28], Krinitzsky and others [29], Lai [30], and Sues and others [31], strong-motion duration has significant variation. Thus, the coefficient of variation is taken as 50%. Based on this consideration, three values of 16, 32, and 48 sec are chosen for an earthquake with **M** of 8.2 and $\Delta\sigma$ of 150 bars. For earthquakes with different stress parameters, the strong-motion durations are computed according to the same procedure.

3.6 Numerical Results

In this study, the uncertainties in model parameters $\Delta\sigma$, f_m, and T are represented by three values. From the combination of these typical values, a total of 27 samples of earthquakes can be generated and are listed in table 3-II. For the purpose of illustration, the seismic source is assumed at Marked Tree, Arkansas (source A) and the site is taken as the Wolf River crossing (Site 1). $\Delta\sigma$, f_m, and T are selected as 150 bars, 30 Hz and 32 sec, respectively. These parameters, together with those listed in table 3-I, are used to generate synthetic earthquakes. The Fourier amplitude spectrum, power spectrum and a synthetic time history corresponding to these parameters are shown in figures 3-1, 3-2, and 3-3, respectively. The 27 peak bedrock accelerations (PBA) computed directly from the power spectrum are listed in table 3-III. Appendix A shows the peak bedrock accelerations of all six sites from three different seismic sources. A statistical analysis is carried out to determine the maximum value A_{max}, minimum value A_{min}, mean value A_{mean}, and coefficient of variation (COV). Table 3-IV shows these statistics for all six sites from three seismic sources. Notice that the COV for all cases are about 0.33 and the mean value is very close to the so-called best-estimate value, i.e. the peak value determined using the mean parameter values.

TABLE 3-II Samples of Earthquake

Sample	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)
1	100.00	20.00	18.00
2	100.00	20.00	36.00
3	100.00	20.00	54.00
4	100.00	30.00	18.00
5	100.00	30.00	36.00
6	100.00	30.00	54.00
7	100.00	40.00	18.00
8	100.00	40.00	36.00
9	100.00	40.00	54.00
10	150.00	20.00	16.00
11	150.00	20.00	32.00
12	150.00	20.00	48.00
13	150.00	30.00	16.00
14	150.00	30.00	32.00
15	150.00	30.00	48.00
16	150.00	40.00	16.00
17	150.00	40.00	32.00
18	150.00	40.00	48.00
19	200.00	20.00	15.00
20	200.00	20.00	30.00
21	200.00	20.00	45.00
22	200.00	30.00	15.00
23	200.00	30.00	30.00
24	200.00	30.00	45.00
25	200.00	40.00	15.00
26	200.00	40.00	30.00
27	200.00	40.00	45.00

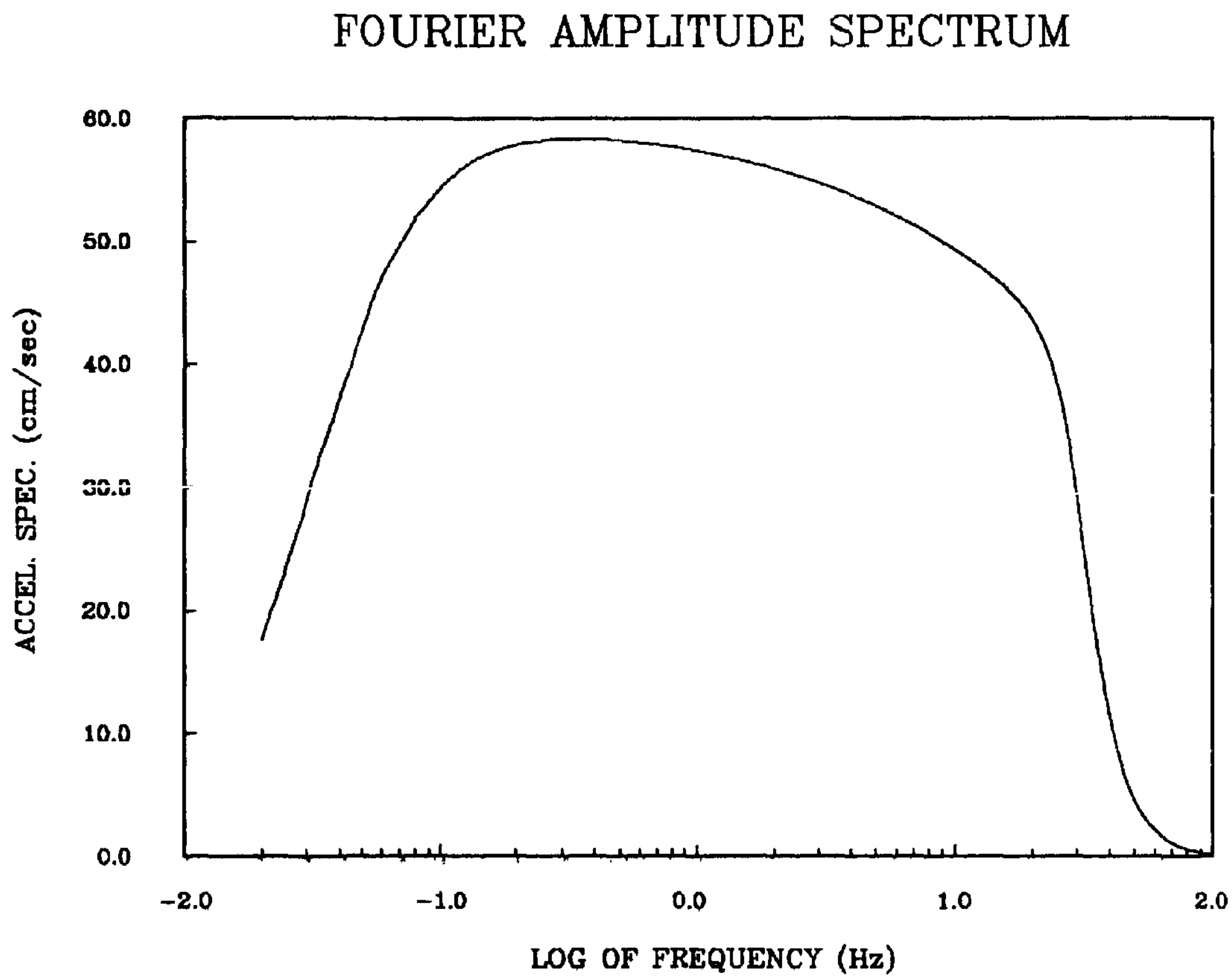


FIGURE 3-1 Fourier Amplitude Spectrum (M=8.2, R=85 km)

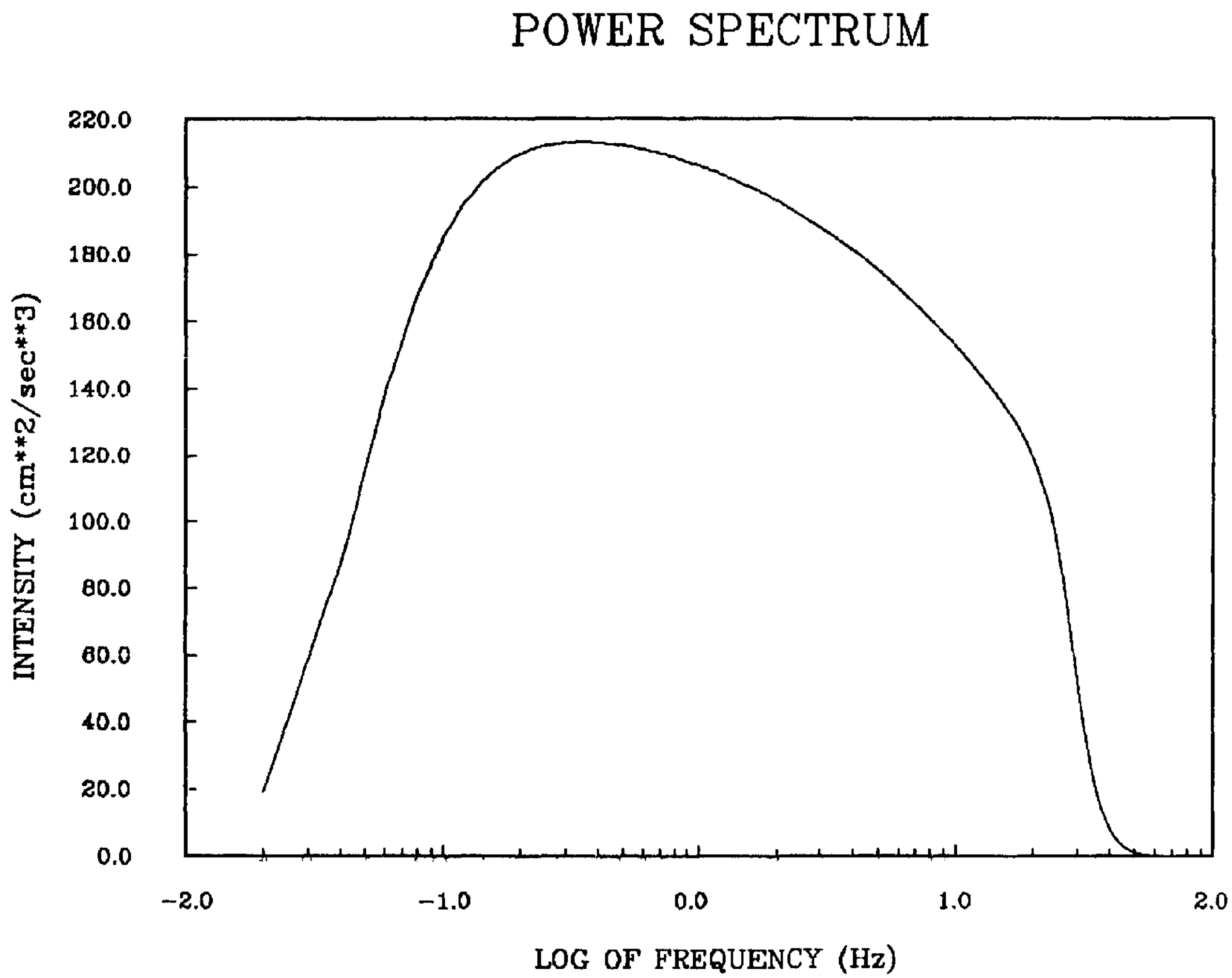


FIGURE 3-2 Power Spectrum (M=8.2, R=85 km)

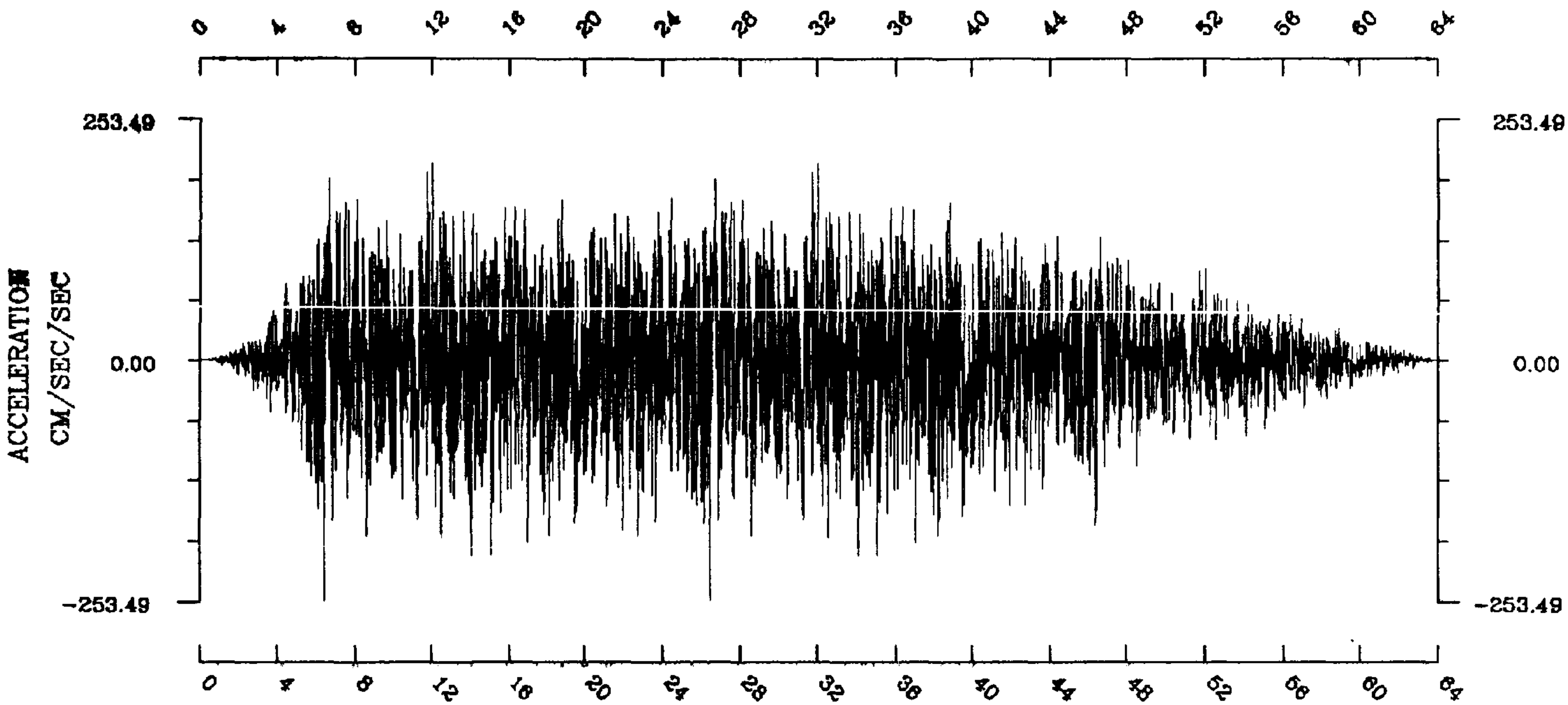


FIGURE 3-3 A Sample of Synthetic Earthquake (M=8.2, R=85 km)

TABLE 3-III Peak Accelerations at Wolf River Crossing due to Seismic Source at Marked Tree

Sample	Δσ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.21
2	100.00	20.00	36.00	0.16
3	100.00	20.00	54.00	0.13
4	100.00	30.00	18.00	0.25
5	100.00	30.00	36.00	0.19
6	100.00	30.00	54.00	0.16
7	100.00	40.00	18.00	0.29
8	100.00	40.00	36.00	0.21
9	100.00	40.00	54.00	0.18
10	150.00	20.00	16.00	0.29
11	150.00	20.00	32.00	0.22
12	150.00	20.00	48.00	0.18
13	150.00	30.00	16.00	0.35
14	150.00	30.00	32.00	0.26
15	150.00	30.00	48.00	0.22
16	150.00	40.00	16.00	0.39
17	150.00	40.00	32.00	0.29
18	150.00	40.00	48.00	0.24
19	200.00	20.00	15.00	0.36
20	200.00	20.00	30.00	0.27
21	200.00	20.00	45.00	0.23
22	200.00	30.00	15.00	0.43
23	200.00	30.00	30.00	0.32
24	200.00	30.00	45.00	0.27
25	200.00	40.00	15.00	0.49
26	200.00	40.00	30.00	0.36
27	200.00	40.00	45.00	0.30

TABLE 3-IV Statistics of Peak Bedrock Accelerations

Source	Site	A_{max} (g)	A_{min} (g)	A_{mean} (g)	COV
	1	0.49	0.13	0.27	0.33
	2	0.46	0.12	0.25	0.33
A	3	0.42	0.11	0.23	0.33
	4	0.38	0.10	0.21	0.33
	5	0.36	0.10	0.20	0.32
	6	0.31	0.09	0.17	0.32
	1	0.42	0.11	0.23	0.33
	2	0.44	0.12	0.24	0.33
B	3	0.65	0.17	0.36	0.33
	4	0.95	0.25	0.51	0.33
	5	1.09	0.28	0.59	0.34
	6	0.80	0.21	0.43	0.33
	1	0.36	0.10	0.20	0.32
	2	0.37	0.10	0.20	0.32
C	3	0.49	0.13	0.27	0.33
	4	0.76	0.20	0.41	0.33
	5	1.03	0.27	0.56	0.34
	6	1.21	0.31	0.65	0.34

SECTION 4

SUMMARY AND CONCLUSIONS

Estimation of seismic hazard is an essential task in carrying out seismic risk assessment studies. In this study, we present the seismic hazard assessment along pipeline 22 (Capline). An 1811-1812 type New Madrid earthquake with **M** = 8.2 is assumed to occur at three locations, where large historical earthquakes have occurred. Six pipeline crossings of major rivers in West Tennessee are chosen as the sites for hazard evaluation because of the liquefaction potential at these locations. A seismologically-based model is used to predict the bedrock accelerations. Uncertainties in three model parameters, i.e., stress parameter $\Delta\sigma$, cutoff frequency f_m, and strong-motion duration T are included in the analysis. Each parameter is represented by three values. From the combination of these parameters, 27 samples of earthquake are generated for each pair of seismic sources and selected sites. The results of the seismic hazard analysis can be used to evaluate the liquefaction potential at these sites, assess the vulnerability of pipeline facilities, investigate the risk from a postulated pipeline break, and prepare an emergency response plan.

SECTION 5

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Appendix A Peak Bedrock Accelerations

SOURCE: A   SITE: 1   R = 84.62 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.21134
2	100.00	20.00	36.00	0.15717
3	100.00	20.00	54.00	0.13188
4	100.00	30.00	18.00	0.25347
5	100.00	30.00	36.00	0.18800
6	100.00	30.00	54.00	0.15753
7	100.00	40.00	18.00	0.28591
8	100.00	40.00	36.00	0.21169
9	100.00	40.00	54.00	0.17723
10	150.00	20.00	16.00	0.29097
11	150.00	20.00	32.00	0.21658
12	150.00	20.00	48.00	0.18181
13	150.00	30.00	16.00	0.34920
14	150.00	30.00	32.00	0.25920
15	150.00	30.00	48.00	0.21728
16	150.00	40.00	16.00	0.39403
17	150.00	40.00	32.00	0.29195
18	150.00	40.00	48.00	0.24452
19	200.00	20.00	15.00	0.36212
20	200.00	20.00	30.00	0.26967
21	200.00	20.00	45.00	0.22643
22	200.00	30.00	15.00	0.43474
23	200.00	30.00	30.00	0.32283
24	200.00	30.00	45.00	0.27069
25	200.00	40.00	15.00	0.49065
26	200.00	40.00	30.00	0.36369
27	200.00	40.00	45.00	0.30467

SOURCE: A SITE: 2 R = 89.13 km

EQ	Δσ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.19876
2	100.00	20.00	36.00	0.14782
3	100.00	20.00	54.00	0.12403
4	100.00	30.00	18.00	0.23780
5	100.00	30.00	36.00	0.17638
6	100.00	30.00	54.00	0.14780
7	100.00	40.00	18.00	0.26768
8	100.00	40.00	36.00	0.19820
9	100.00	40.00	54.00	0.16594
10	150.00	20.00	16.00	0.27365
13	150.00	30.00	16.00	0.32761
14	150.00	30.00	32.00	0.24318
15	150.00	30.00	48.00	0.20386
16	150.00	40.00	16.00	0.36891
17	150.00	40.00	32.00	0.27335
18	150.00	40.00	48.00	0.22894
19	200.00	20.00	15.00	0.34056
20	200.00	20.00	30.00	0.25362
21	200.00	20.00	45.00	0.21296
22	200.00	30.00	15.00	0.40786
23	200.00	30.00	30.00	0.30288
24	200.00	30.00	45.00	0.25396
25	200.00	40.00	15.00	0.45937
26	200.00	40.00	30.00	0.34052
27	200.00	40.00	45.00	0.28526

SOURCE: A SITE: 3 R = 96.35 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	8.00	0.18113
2	100.00	20.00	36.00	0.13471
3	100.00	20.00	54.00	0.11304
4	100.00	30.00	18.00	0.21588
5	100.00	30.00	36.00	0.16012
6	100.00	30.00	54.00	0.13418
7	100.00	40.00	18.00	0.24222
8	100.00	40.00	36.00	0.17936
9	100.00	40.00	54.00	0.15017
10	150.00	20.00	16.00	0.24938
11	150.00	20.00	32.00	0.18563
12	150.00	20.00	48.00	0.15584
13	150.00	30.00	16.00	0.29740
14	150.00	30.00	32.00	0.22076
15	150.00	30.00	48.00	0.18507
16	150.00	40.00	16.00	0.33382
17	150.00	40.00	32.00	0.24736
18	150.00	40.00	48.00	0.20718
19	200.00	20.00	15.00	0.31035
20	200.00	20.00	30.00	0.23113
21	200.00	20.00	45.00	0.19408
22	200.00	30.00	15.00	0.37024
23	200.00	30.00	30.00	0.27495
24	200.00	30.00	45.00	0.23055
25	200.00	40.00	15.00	0.41567
26	200.00	40.00	30.00	0.30814
27	200.00	40.00	45.00	0.25814

SOURCE: A SITE: 4 R = 108.30 km

EQ	Δσ (bars)	*f*m (Hz)	T (sec)	FBA (g)
1	100.00	20.00	18.00	0.16551
2	100.00	20.00	36.00	0.12309
3	100.00	20.00	54.00	0.10329
4	100.00	30.00	18.00	0.19648
5	100.00	30.00	36.00	0.14574
6	100.00	30.00	54.00	0.12213
7	100.00	40.00	18.00	0.21974
8	100.00	40.00	36.00	0.16272
9	100.00	40.00	54.00	0.13624
10	150.00	20.00	16.00	0.22786
11	150.00	20.00	32.00	0.16962
12	150.00	20.00	48.00	0.14240
13	150.00	30.00	16.00	0.27067
14	150.00	30.00	32.00	0.20093
15	150.00	30.00	48.00	0.16845
16	150.00	40.00	16.00	0.30283
17	150.00	40.00	32.00	0.22441
18	150.00	40.00	48.00	0.18796
19	200.00	20.00	15.00	0.28357
20	200.00	20.00	30.00	0.21119
21	200.00	20.00	45.00	0.17734
22	200.00	30.00	15.00	0.33696
23	200.00	30.00	30.00	0.25025
24	200.00	30.00	45.00	0.20984
25	200.00	40.00	15.00	0.37708
26	200.00	40.00	30.00	0.27954
27	200.00	40.00	45.00	0.23420

SOURCE: A SITE: 5 R = 118.63 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.15653
2	100.00	20.00	36.00	0.11642
3	100.00	20.00	54.00	0.09770
4	100.00	30.00	18.00	0.18536
5	100.00	30.00	36.00	0.13749
6	100.00	30.00	54.00	0.11522
7	100.00	40.00	18.00	0.20687
8	100.00	40.00	36.00	0.15319
9	100.00	40.00	54.00	0.12827
10	150.00	20.00	16.00	0.21550
11	150.00	20.00	32.00	0.16042
12	150.00	20.00	48.00	0.13468
13	150.00	30.00	16.00	0.25534
14	150.00	30.00	32.00	0.18956
15	150.00	30.00	48.00	0.15892
16	150.00	40.00	16.00	0.28509
17	150.00	40.00	32.00	0.21127
18	150.00	40.00	48.00	0.17696
19	200.00	20.00	15.00	0.26818
20	200.00	20.00	30.00	0.19974
21	200.00	20.00	45.00	0.16773
22	200.00	30.00	15.00	0.31788
23	200.00	30.00	30.00	0.23609
24	200.00	30.00	45.00	0.19797
25	200.00	40.00	15.00	0.35498
26	200.00	40.00	30.00	0.26318
27	200.00	40.00	45.00	0.22049

SOURCE: A SITE: 6 R = 145.81 km

EQ	Δσ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.13770
2	100.00	20.00	36.00	0.10242
3	100.00	20.00	54.00	0.08595
4	100.00	30.00	18.00	0.16207
5	100.00	30.00	36.00	0.12023
6	100.00	30.00	54.00	0.10076
7	100.00	40.00	18.00	0.18000
8	100.00	40.00	36.00	0.13330
9	100.00	40.00	54.00	0.11162
10	150.00	20.00	16.00	0.18957
11	150.00	20.00	32.00	0.14113
12	150.00	20.00	48.00	0.11848
13	150.00	30.00	16.00	0.22326
14	150.00	30.00	32.00	0.16576
15	150.00	30.00	48.00	0.13897
16	150.00	40.00	16.00	0.24804
17	150.00	40.00	32.00	0.18383
18	150.00	40.00	48.00	0.15399
19	200.00	20.00	15.00	0.23591
20	200.00	20.00	30.00	0.17571
21	200.00	20.00	45.00	0.14756
22	200.00	30.00	15.00	0.27794
23	200.00	30.00	30.00	0.20644
24	200.00	30.00	45.00	0.17312
25	200.00	40.00	15.00	0.30885
26	200.00	40.00	30.00	0.22900
27	200.00	40.00	45.00	0.19186

SOURCE: B SITE: 1 R = 95.79 km

EQ	Δσ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.18241
2	100.00	20.00	36.00	0.13566
3	100.00	20.00	54.00	0.11384
4	100.00	30.00	18.00	0.21747
5	100.00	30.00	36.00	0.16130
6	100.00	30.00	54.00	0.13517
7	100.00	40.00	18.00	0.24407
8	100.00	40.00	36.00	0.18072
9	100.00	40.00	54.00	0.15131
10	150.00	20.00	16.00	0.25114
11	150.00	20.00	32.00	0.18694
12	150.00	20.00	48.00	0.15694
13	150.00	30.00	16.00	0.29959
14	150.00	30.00	32.00	0.22239
15	150.00	30.00	48.00	0.18643
16	150.00	40.00	16.00	0.33636
17	150.00	40.00	32.00	0.24924
18	150.00	40.00	48.00	0.20876
19	200.00	20.00	15.00	0.31254
20	200.00	20.00	30.00	0.23276
21	200.00	20.00	45.00	0.19545
22	200.00	30.00	15.00	0.37297
23	200.00	30.00	30.00	0.27698
24	200.00	30.00	45.00	0.23225
25	200.00	40.00	15.00	0.41884
26	200.00	40.00	30.00	0.31049
27	200.00	40.00	45.00	0.26011

SOURCE: B   SITE: 2   R = 92.36 km

EQ	Δσ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.19054
2	100.00	20.00	36.00	0.14171
3	100.00	20.00	54.00	0.11891
4	100.00	30.00	18.00	0.22758
5	100.00	30.00	36.00	0.16880
6	100.00	30.00	54.00	0.14145
7	100.00	40.00	18.00	0.25581
8	100.00	40.00	36.00	0.18941
9	100.00	40.00	54.00	0.15858
10	150.00	20.00	16.00	0.26234
11	150.00	20.00	32.00	0.19527
12	150.00	20.00	48.00	0.16393
13	150.00	30.00	16.00	0.31352
14	150.00	30.00	32.00	0.23272
15	150.00	30.00	48.00	0.19510
16	150.00	40.00	16.00	0.35253
17	150.00	40.00	32.00	0.26122
18	150.00	40.00	48.00	0.21879
19	200.00	20.00	15.00	0.32648
20	200.00	20.00	30.00	0.24314
21	200.00	20.00	45.00	0.20416
22	200.00	30.00	15.00	0.39031
23	200.00	30.00	30.00	0.28985
24	200.00	30.00	45.00	0.24304
25	200.00	40.00	15.00	0.43898
26	200.00	40.00	30.00	0.32541
27	200.00	40.00	45.00	0.27261

SOURCE: B SITE: 3 R = 67.10 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.27601
2	100.00	20.00	36.00	0.20524
3	100.00	20.00	54.00	0.17221
4	100.00	30.00	18.00	0.33427
5	100.00	30.00	36.00	0.24790
6	100.00	30.00	54.00	0.20772
7	100.00	40.00	18.00	0.38013
8	100.00	40.00	36.00	0.28141
9	100.00	40.00	54.00	0.23559
10	150.00	20.00	16.00	0.38003
11	150.00	20.00	32.00	0.28284
12	150.00	20.00	48.00	0.23742
13	150.00	30.00	16.00	0.46053
14	150.00	30.00	32.00	0.34179
15	150.00	30.00	48.00	0.28651
16	150.00	40.00	16.00	0.52390
17	150.00	40.00	32.00	0.38813
18	150.00	40.00	48.00	0.32506
19	200.00	20.00	15.00	0.47296
20	200.00	20.00	30.00	0.35218
21	200.00	20.00	45.00	0.29570
22	200.00	30.00	15.00	0.57335
23	200.00	30.00	30.00	0.42572
24	200.00	30.00	45.00	0.35694
25	200.00	40.00	15.00	0.65239
26	200.00	40.00	30.00	0.48352
27	200.00	40.00	45.00	0.40503

SOURCE: B SITE: 4 R = 48.63 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.39318
2	100.00	20.00	36.00	0.29235
3	100.00	20.00	54.00	0.24529
4	100.00	30.00	18.00	0.48125
5	100.00	30.00	36.00	0.35686
6	100.00	30.00	54.00	0.29900
7	100.00	40.00	18.00	0.55220
8	100.00	40.00	36.00	0.40875
9	100.00	40.00	54.00	0.34218
10	150.00	20.00	16.00	0.54137
11	150.00	20.00	32.00	0.40289
12	150.00	20.00	48.00	0.33818
13	150.00	30.00	16.00	0.66304
14	150.00	30.00	32.00	0.49204
15	150.00	30.00	48.00	0.41243
16	150.00	40.00	16.00	0.76108
17	150.00	40.00	32.00	0.56378
18	150.00	40.00	48.00	0.47213
19	200.00	20.00	15.00	0.67378
20	200.00	20.00	30.00	0.50167
21	200.00	20.00	45.00	0.42120
22	200.00	30.00	15.00	0.82550
23	200.00	30.00	30.00	0.61287
24	200.00	30.00	45.00	0.51383
25	200.00	40.00	15.00	0.94776
26	200.00	40.00	30.00	0.70235
27	200.00	40.00	45.00	0.58830

SOURCE: B SITE: 5 R = 42.94 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.44846
2	100.00	20.00	36.00	0.33344
3	100.00	20.00	54.00	0.27977
4	100.00	30.00	18.00	0.55074
5	100.00	30.00	36.00	0.40837
6	100.00	30.00	54.00	0.34216
7	100.00	40.00	18.00	0.63373
8	100.00	40.00	36.00	0.46908
9	100.00	40.00	54.00	0.39268
10	150.00	20.00	16.00	0.61751
11	150.00	20.00	32.00	0.45953
12	150.00	20.00	48.00	0.38572
13	150.00	30.00	16.00	0.75879
14	150.00	30.00	32.00	0.56308
15	150.00	30.00	48.00	0.47197
16	150.00	40.00	16.00	0.87346
17	150.00	40.00	32.00	0.64700
18	150.00	40.00	48.00	0.54181
19	200.00	20.00	15.00	0.76854
20	200.00	20.00	30.00	0.57221
21	200.00	20.00	45.00	0.48042
22	200.00	30.00	15.00	0.94472
23	200.00	30.00	30.00	0.70136
24	200.00	30.00	45.00	0.58801
25	200.00	40.00	15.00	1.08772
26	200.00	40.00	30.00	0.80604
27	200.00	40.00	45.00	0.67514

SOURCE: B SITE: 6 R = 56.48 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.33432
2	100.00	20.00	36.00	0.24859
3	100.00	20.00	54.00	0.20858
4	100.00	30.00	18.00	0.40736
5	100.00	30.00	36.00	0.30208
6	100.00	30.00	54.00	0.25311
7	100.00	40.00	18.00	0.46561
8	100.00	40.00	36.00	0.34468
9	100.00	40.00	54.00	0.28855
10	150.00	20.00	16.00	0.46033
11	150.00	20.00	32.00	0.34259
12	150.00	20.00	48.00	0.28757
13	150.00	30.00	16.00	0.56123
14	150.00	30.00	32.00	0.41651
15	150.00	30.00	48.00	0.34913
16	150.00	40.00	16.00	0.64173
17	150.00	40.00	32.00	0.47539
18	150.00	40.00	48.00	0.39812
19	200.00	20.00	15.00	0.57291
20	200.00	20.00	30.00	0.42658
21	200.00	20.00	45.00	0.35817
22	200.00	30.00	15.00	0.69874
23	200.00	30.00	30.00	0.51878
24	200.00	30.00	45.00	0.43495
25	200.00	40.00	15.00	0.79914
26	200.00	40.00	30.00	0.59224
27	200.00	40.00	45.00	0.49608

SOURCE: C SITE: 1 R = 118.25 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.15684
2	100.00	20.00	36.00	0.11665
3	100.00	20.00	54.00	0.09789
4	100.00	30.00	18.00	0.18574
5	100.00	30.00	36.00	0.13778
6	100.00	30.00	54.00	0.11546
7	100.00	40.00	18.00	0.20732
8	100.00	40.00	36.00	0.15352
9	100.00	40.00	54.00	0.12855
10	150.00	20.00	16.00	0.21593
11	150.00	20.00	32.00	0.16074
12	150.00	20.00	48.00	0.13495
13	150.00	30.00	16.00	0.25587
14	150.00	30.00	32.00	0.18995
15	150.00	30.00	48.00	0.15925
16	150.00	40.00	16.00	0.28570
17	150.00	40.00	32.00	0.21172
18	150.00	40.00	48.00	0.17734
19	200.00	20.00	15.00	0.26872
20	200.00	20.00	30.00	0.20014
21	200.00	20.00	45.00	0.16806
22	200.00	30.00	15.00	0.31854
23	200.00	30.00	30.00	0.23658
24	200.00	30.00	45.00	0.19838
25	200.00	40.00	15.00	0.35575
26	200.00	40.00	30.00	0.26374
27	200.00	40.00	45.00	0.22096

SOURCE: C SITE: 2 R = 113.73 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.16064
2	100.00	20.00	36.00	0.11948
3	100.00	20.00	54.00	0.10026
4	100.00	30.00	18.00	0.19045
5	100.00	30.00	36.00	0.14127
6	100.00	30.00	54.00	0.11839
7	100.00	40.00	18.00	0.21276
8	100.00	40.00	36.00	0.15755
9	100.00	40.00	54.00	0.13192
10	150.00	20.00	16.00	0.22116
11	150.00	20.00	32.00	0.16463
12	150.00	20.00	48.00	0.13821
13	150.00	30.00	16.00	0.26236
14	150.00	30.00	32.00	0.19476
15	150.00	30.00	48.00	0.16328
16	150.00	40.00	16.00	0.29320
17	150.00	40.00	32.00	0.21728
18	150.00	40.00	48.00	0.18200
19	200.00	20.00	15.00	0.27523
20	200.00	20.00	30.00	0.20498
21	200.00	20.00	45.00	0.17213
22	200.00	30.00	15.00	0.32661
23	200.00	30.00	30.00	0.24257
24	200.00	30.00	45.00	0.20340
25	200.00	40.00	15.00	0.36509
26	200.00	40.00	30.00	0.27066
27	200.00	40.00	45.00	0.22676

SOURCE: C SITE: 3 R = 84.68 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.21115
2	100.00	20.00	36.00	0.15702
3	100.00	20.00	54.00	0.13176
4	100.00	30.00	18.00	0.25324
5	100.00	30.00	36.00	0.18782
6	100.00	30.00	54.00	0.15739
7	100.00	40.00	18.00	0.28563
8	100.00	40.00	36.00	0.21148
9	100.00	40.00	54.00	0.17706
10	150.00	20.00	16.00	0.29071
11	150.00	20.00	32.00	0.21638
12	150.00	20.00	48.00	0.18165
13	150.00	30.00	16.00	0.34887
14	150.00	30.00	32.00	0.25895
15	150.00	30.00	48.00	0.21708
16	150.00	40.00	16.00	0.39364
17	150.00	40.00	32.00	0.29167
18	150.00	40.00	48.00	0.24428
19	200.00	20.00	15.00	0.36179
20	200.00	20.00	30.00	0.26942
21	200.00	20.00	45.00	0.22623
22	200.00	30.00	15.00	0.43433
23	200.00	30.00	30.00	0.32253
24	200.00	30.00	45.00	0.27043
25	200.00	40.00	15.00	0.49018
26	200.00	40.00	30.00	0.36334
27	200.00	40.00	45.00	0.30438

SOURCE: C SITE: 4 R = 59.25 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.31716
2	100.00	20.00	36.00	0.23584
3	100.00	20.00	54.00	0.19788
4	100.00	30.00	18.00	0.38583
5	100.00	30.00	36.00	0.28612
6	100.00	30.00	54.00	0.23974
7	100.00	40.00	18.00	0.44042
8	100.00	40.00	36.00	0.32603
9	100.00	40.00	54.00	0.27294
10	150.00	20.00	16.00	0.43670
11	150.00	20.00	32.00	0.32500
12	150.00	20.00	48.00	0.27281
13	150.00	30.00	16.00	0.53157
14	150.00	30.00	32.00	0.39450
15	150.00	30.00	48.00	0.33068
16	150.00	40.00	16.00	0.60700
17	150.00	40.00	32.00	0.44967
18	150.00	40.00	48.00	0.37659
19	200.00	20.00	15.00	0.54349
20	200.00	20.00	30.00	0.40468
21	200.00	20.00	45.00	0.33978
22	200.00	30.00	15.00	0.66181
23	200.00	30.00	30.00	0.49137
24	200.00	30.00	45.00	0.41197
25	200.00	40.00	15.00	0.75588
26	200.00	40.00	30.00	0.56020
27	200.00	40.00	45.00	0.46924

SOURCE: C SITE: 5 R = 45.08 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	PBA (g)
1	100.00	20.00	18.00	0.42612
2	100.00	20.00	36.00	0.31684
3	100.00	20.00	54.00	0.26583
4	100.00	30.00	18.00	0.52265
5	100.00	30.00	36.00	0.38755
6	100.00	30.00	54.00	0.32472
7	100.00	40.00	18.00	0.60076
8	100.00	40.00	36.00	0.44469
9	100.00	40.00	54.00	0.37226
10	150.00	20.00	16.00	0.58674
11	150.00	20.00	32.00	0.43664
12	150.00	20.00	48.00	0.36651
13	150.00	30.00	16.00	0.72009
14	150.00	30.00	32.00	0.53437
15	150.00	30.00	48.00	0.44791
16	150.00	40.00	16.00	0.82802
17	150.00	40.00	32.00	0.61335
18	150.00	40.00	48.00	0.51364
19	200.00	20.00	15.00	0.73025
20	200.00	20.00	30.00	0.54370
21	200.00	20.00	45.00	0.45649
22	200.00	30.00	15.00	0.89653
23	200.00	30.00	30.00	0.66559
24	200.00	30.00	45.00	0.55802
25	200.00	40.00	15.00	1.03113
26	200.00	40.00	30.00	0.76411
27	200.00	40.00	45.00	0.64002

SOURCE: C SITE: 6 R = 38.91 km

EQ	$\Delta\sigma$ (bars)	f_m (Hz)	T (sec)	FBA (g)
1	100.00	20.00	18.00	0.49670
2	100.00	20.00	36.00	0.36930
3	100.00	20.00	54.00	0.30985
4	100.00	30.00	18.00	0.61142
5	100.00	30.00	36.00	0.45336
6	100.00	30.00	54.00	0.37985
7	100.00	40.00	18.00	0.70497
8	100.00	40.00	36.00	0.52181
9	100.00	40.00	54.00	0.43681
10	150.00	20.00	16.00	0.68393
11	150.00	20.00	32.00	0.50895
12	150.00	20.00	48.00	0.42720
13	150.00	30.00	16.00	0.84241
14	150.00	30.00	32.00	0.62512
15	150.00	30.00	48.00	0.52396
16	150.00	40.00	16.00	0.97166
17	150.00	40.00	32.00	0.71973
18	150.00	40.00	48.00	0.60271
19	200.00	20.00	15.00	0.85121
20	200.00	20.00	30.00	0.63375
21	200.00	20.00	45.00	0.53208
22	200.00	30.00	15.00	1.04883
23	200.00	30.00	30.00	0.77863
24	200.00	30.00	45.00	0.65278
25	200.00	40.00	15.00	1.21002
26	200.00	40.00	30.00	0.89665
27	200.00	40.00	45.00	0.75102

NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
LIST OF TECHNICAL REPORTS

The National Center for Earthquake Engineering Research (NCEER) publishes technical reports on a variety of subjects related to earthquake engineering written by authors funded through NCEER. These reports are available from both NCEER's Publications Department and the National Technical Information Service (NTIS). Requests for reports should be directed to the Publications Department, National Center for Earthquake Engineering Research, State University of New York at Buffalo, Red Jacket Quadrangle, Buffalo, New York 14261. Reports can also be requested through NTIS, 5285 Port Royal Road, Springfield, Virginia 22161. NTIS accession numbers are shown in parenthesis, if available.

NCEER-87-0001 "First-Year Program in Research, Education and Technology Transfer," 3/5/87, (PB88-134275/AS).

NCEER-87-0002 "Experimental Evaluation of Instantaneous Optimal Algorithms for Structural Control," by R.C. Lin, T.T. Soong and A.M. Reinhorn, 4/20/87, (PB88-134341/AS).

NCEER-87-0003 "Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, to be published.

NCEER-87-0004 "The System Characteristics and Performance of a Shaking Table," by J.S. Hwang, K.C. Chang and G.C. Lee, 6/1/87, (PB88-134259/AS). This report is available only through NTIS (see address given above).

NCEER-87-0005 "A Finite Element Formulation for Nonlinear Viscoplastic Material Using a Q Model," by O. Gyebi and G. Dasgupta, 11/2/87, (PB88-213764/AS).

NCEER-87-0006 "Symbolic Manipulation Program (SMP) - Algebraic Codes for Two and Three Dimensional Finite Element Formulations," by X. Lee and G. Dasgupta, 11/9/87, (PB88-219522/AS).

NCEER-87-0007 "Instantaneous Optimal Control Laws for Tall Buildings Under Seismic Excitations," by J.N. Yang, A. Akbarpour and P. Ghaemmaghami, 6/10/87, (PB88-134333/AS).

NCEER-87-0008 "IDARC: Inelastic Damage Analysis of Reinforced Concrete Frame - Shear-Wall Structures," by Y.J. Park, A.M. Reinhorn and S.K. Kunnath, 7/20/87, (PB88-134325/AS).

NCEER-87-0009 "Liquefaction Potential for New York State: A Preliminary Report on Sites in Manhattan and Buffalo," by M. Budhu, V. Vijayakumar, R.F. Giese and L. Baumgras, 8/31/87, (PB88-163704/AS). This report is available only through NTIS (see address given above).

NCEER-87-0010 "Vertical and Torsional Vibration of Foundations in Inhomogeneous Media," by A.S. Veletsos and K.W. Dotson, 6/1/87, (PB88-134291/AS).

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NCEER-87-0012 "Parametric Studies of Frequency Response of Secondary Systems Under Ground-Acceleration Excitations," by Y. Yong and Y.K. Lin, 6/10/87, (PB88-134309/AS).

NCEER-87-0013 "Frequency Response of Secondary Systems Under Seismic Excitation," by J.A. HoLung, J. Cai and Y.K. Lin, 7/31/87, (PB88-134317/AS).

NCEER-87-0014 "Modelling Earthquake Ground Motions in Seismically Active Regions Using Parametric Time Series Methods," by G.W. Ellis and A.S. Cakmak, 8/25/87, (PB88-134283/AS).

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NCEER-87-0017 "Digital Simulation of Seismic Ground Motion," by M. Shinozuka, G. Deodatis and T. Harada, 8/31/87, (PB88-155197/AS). This report is available only through NTIS (see address given above).

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NCEER-87-0024 Vertical and Torsional Impedances for Radially Inhomogeneous Viscoelastic Soil Layers," by K.W. Dotson and A.S. Veletsos, 12/87, (PB88-187786/AS).

NCEER-87-0025 "Proceedings from the Symposium on Seismic Hazards, Ground Motions, Soil-Liquefaction and Engineering Practice in Eastern North America," October 20-22, 1987, edited by K.H. Jacob, 12/87, (PB88-188115/AS).

NCEER-87-0026 "Report on the Whittier-Narrows, California, Earthquake of October 1, 1987," by J. Pantelic and A. Reinhorn, 11/87, (PB88-187752/AS). This report is available only through NTIS (see address given above).

NCEER-87-0027 "Design of a Modular Program for Transient Nonlinear Analysis of Large 3-D Building Structures," by S. Srivastav and J.F. Abel, 12/30/87, (PB88-187950/AS).

NCEER-87-0028 "Second-Year Program in Research, Education and Technology Transfer," 3/8/88, (PB88-219480/AS).

NCEER-88-0001 "Workshop on Seismic Computer Analysis and Design of Buildings With Interactive Graphics," by W. McGuire, J.F. Abel and C.H. Conley, 1/18/88, (PB88-187760/AS).

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