NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
State University of New York at Buffalo

Study of Site Response at a Selected Memphis Site

by

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Technical Report NCEER-90-0023

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PREFACE

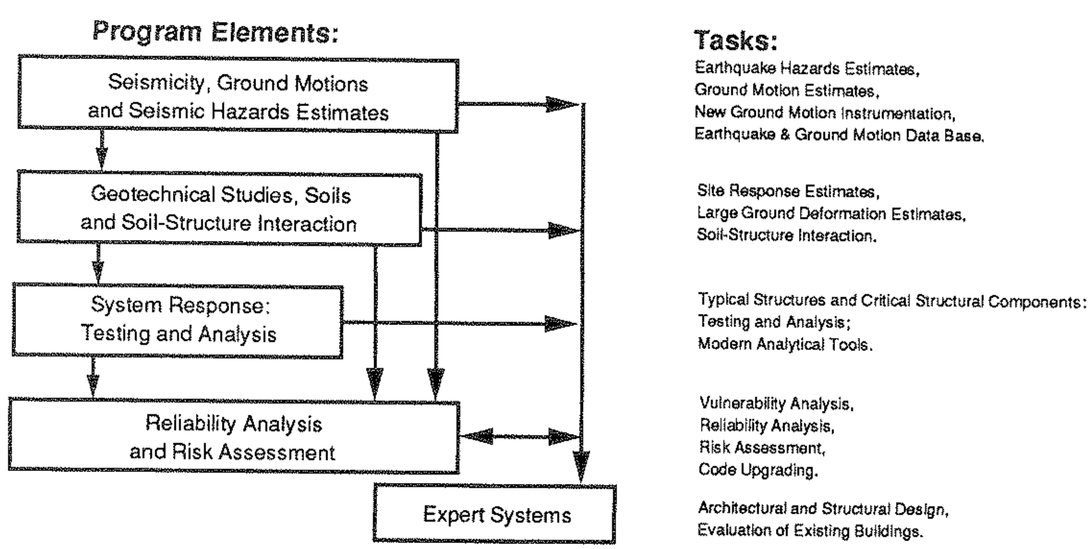
The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis 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 1, Existing and New Structures, and more specifically to geotechnical studies.

The long term goal of research in Existing and New Structures is to develop seismic hazard mitigation procedures through rational probabilistic risk assessment for damage or collapse of structures, mainly existing buildings, in regions of moderate to high seismicity. The work relies on improved definitions of seismicity and site response, experimental and analytical evaluations of systems response, and more accurate assessment of risk factors. This technology will be incorporated in expert systems tools and improved code formats for existing and new structures. Methods of retrofit will also be developed. When this work is completed, it should be possible to characterize and quantify societal impact of seismic risk in various geographical regions and large municipalities. Toward this goal, the program has been divided into five components, as shown in the figure below:



Geotechnical studies constitute one of the important areas of research in Existing and New Structures. Current research activities include the following:

1. Development of linear and nonlinear site response estimates.
2. Development of liquefaction and large ground deformation estimates.
3. Investigation of soil-structure interaction phenomena.
4. Development of computational methods.
5. Incorporation of local soil effects and soil-structure interaction into existing codes.

The ultimate goal of projects concerned with geotechnical studies is to develop methods of engineering estimation of large soil deformations, soil-structure interaction, and site response.

This report describes site amplification studies conducted at a typical Memphis site for a New Madrid earthquake of magnitude M_w*=7.0 having a source at a distance of 65km from Memphis, Tennessee. A seismologically-based stochastic model is used to generate bedrock motions which, after being modified for soft-rock, are used an input motion for the near surface site profile. The typical site is analyzed by using state-of-the-art techniques and the results are finally presented as design spectrum.*

ABSTRACT

The influence of geological and geotechnical factors on potential ground motions in Memphis due to a 65km distant hypothetical M_w=7 New Madrid earthquake has been investigated. From the study of the seismotectonic environment and the seismicity of the region, the characteristics of the "design earthquake" are selected. A seismological model of the radiation/attenuation of the earthquake source and of the generated waves is used to generate synthetic bedrock ("hard rock") accelerograms, which are then propagated through a deep deposit of "soft-rock" to obtain input base excitations for the near-surface soil profiles. A representative soil profile for Memphis is selected from a large number of borelog data. Propagation of the generated seismic waves through this soil profile is modeled with state-of-the-art formulations to obtain the seismic motions at the ground surface. Effects of nonlinear inelastic versus equivalent-linear analysis has also been investigated. Results are presented in the form of site-specific response spectra and a proposed design spectrum.

ACKNOWLEDGEMENT

This report is a part of an ongoing investigation of site response in Memphis area due to the New Madrid Earthquakes, sponsored by the National Center for Earthquake Engineering Research (Grant No. 89-1508). The support of the NCEER for this work is gratefully acknowledged. The writers are also indebted Prof. A.S. Papageorgiou of R.P.I. and Dr. Klaus Jacob of Lamont-Doherty Geological Observatory for many valuable suggestions, and Professor J.H. Prevost of Princeton Unviersity for providing the nonlinear dynamic analysis computer program DYNA1D.

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SECTION 1

INTRODUCTION

The city of Memphis, Tennessee is located about 65km away from the southern segment of the New Madrid seismic zone (Fig. 1-1). The New Madrid seismic zone is regarded by seismologists and disaster response planners as the most hazardous zone east of the Rocky Mountains [8]. In the winter of 1811-1812, this zone produced three of the largest earthquakes known to have occurred in North America (M_s=8.5, 8.4 and 8.8; [8 & 11]). The zone is still, quite seismically active, and a major geological structure--an ancient crustal rift--has been identified [4] to exist beneath the shallow sediments of the Mississippi embankment (Fig. 1-2). This rift is of such character and dimension that it could generate major earthquakes. Thus, the city of Memphis is currently regarded as an area of potential seismic hazard.

The effect of local soil conditions on the amplitude and frequency content of ground motions at the surface of soil deposits at Memphis due to a potential New Madrid earthquake has been the subject of considerable interest and research in recent years. In this report, an effort is made to investigate the effects of geological and geotechnical conditions on ground surface motions at a representative site of Memphis (with a typical Upland Memphis soil profile) due to a hypothetical M_w=7.0 New Madrid earthquake. First, from the study of the seismotectonic environment and the seismicity of the region, the characteristics of the "design earthquake" are selected. Second, a stochastic seismological model ([2], [6] & [9]) of the radiation/attenuation of the earthquake source and of the generated waves is used to generate synthetic seismic bedrock motions. The influence of the model parameters, such as stress parameter, $\Delta\sigma$, and cut-off frequency, f_{max}, on the ground surface response spectra is also investigated. The actual bedrock ("hard rock") in the Memphis area is very deep, located at a depth of about 2500 to 3000 ft. below the ground surface level. Therefore, response spectra defined for "hard-rock" must not be used to prescribe input motions to the base of the near-surface soil profiles unless the velocity contrast between soil profile and underlying earth, and the amplifying effect of the "softer rock" between the hard-rock and the soil profile are taken into account. Thus, the "hard-rock" motions obtained with the seismological model are multiplied by the square-root of impedance ratio to obtain the input base excitations (i.e., "soft-rock" motion) for the near-surface soil profiles. A representative soil profile for Memphis is selected from a large number of borelog data reported by Ng et al [10]. The selected soil profile represents about 70% of the Memphis borelogs and 90% of the Upland Memphis borelogs. Propagation of seismic waves through the selected near-surface soil profile is modeled with state-of-the-art formulations (SHAKE and DYNA1D) to obtain the ground surface motions. Results are presented in the form of response spectra with 5% damping. Effects of linear-elastic, equivalent-linear (SHAKE) and nonlinear-inelastic (DYNA1D) analyses on the ground response spectrum is also investigated.

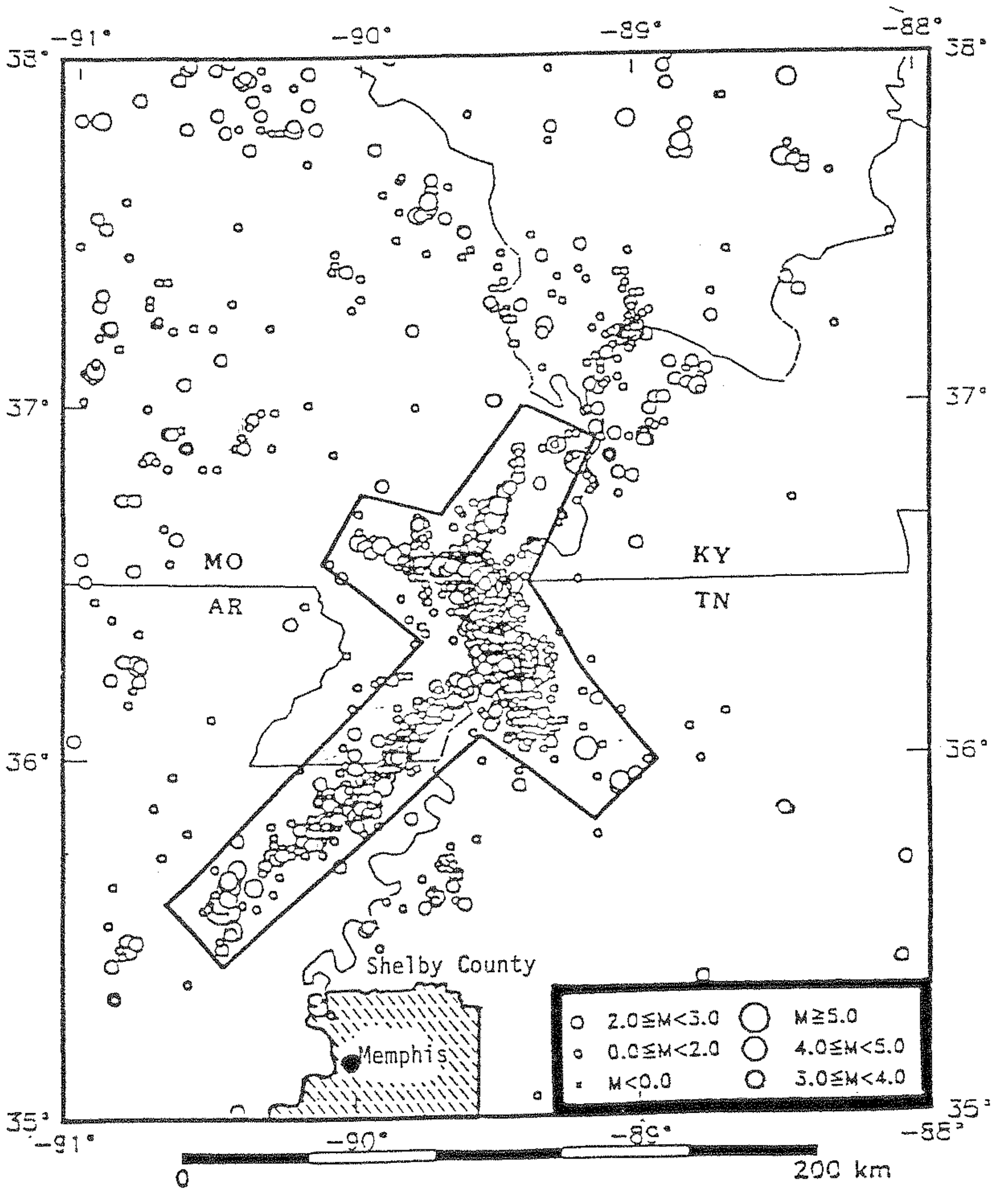

Fig. 1-1 New Madrid Seismic Zone (after Hwang et al, [7])

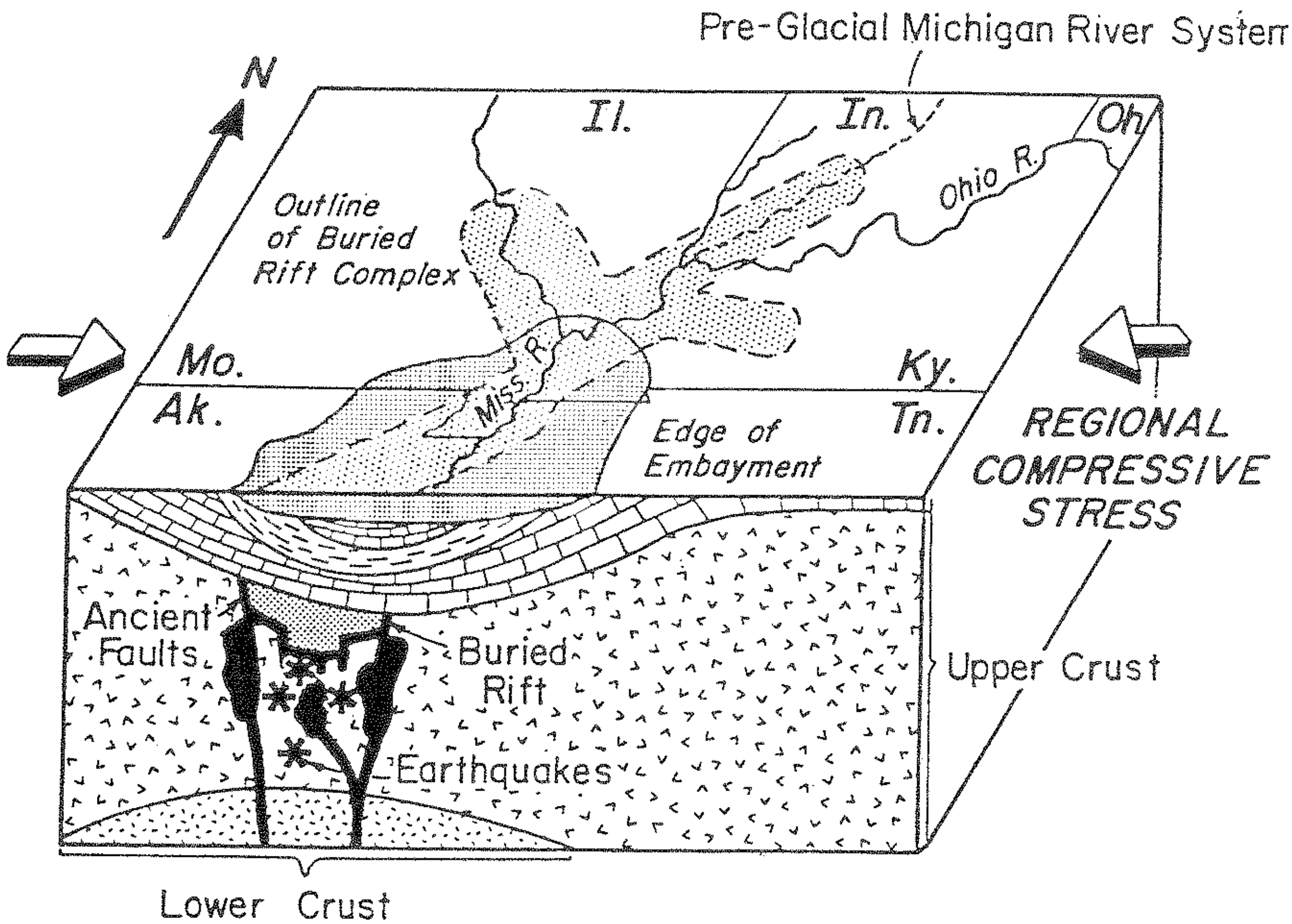

Fig. 1-2 Block Diagram of Buried Reelfoot Rift Complex
(after Braile et al, [4])

SECTION 2

DESIGN EARTHQUAKE

In this study, based on the work of Johnston [8], a New Madrid earthquake of moment magnitude M_w=7.0, having a 20% probability of exceedence in 50 years and 40% probability of exceedence in 100 years as depicted in Fig. 2-1, is assumed to occur near Marked Tree, Arkansas. The epicentral distance of the selected site in Memphis from the seismic source is about 65km.

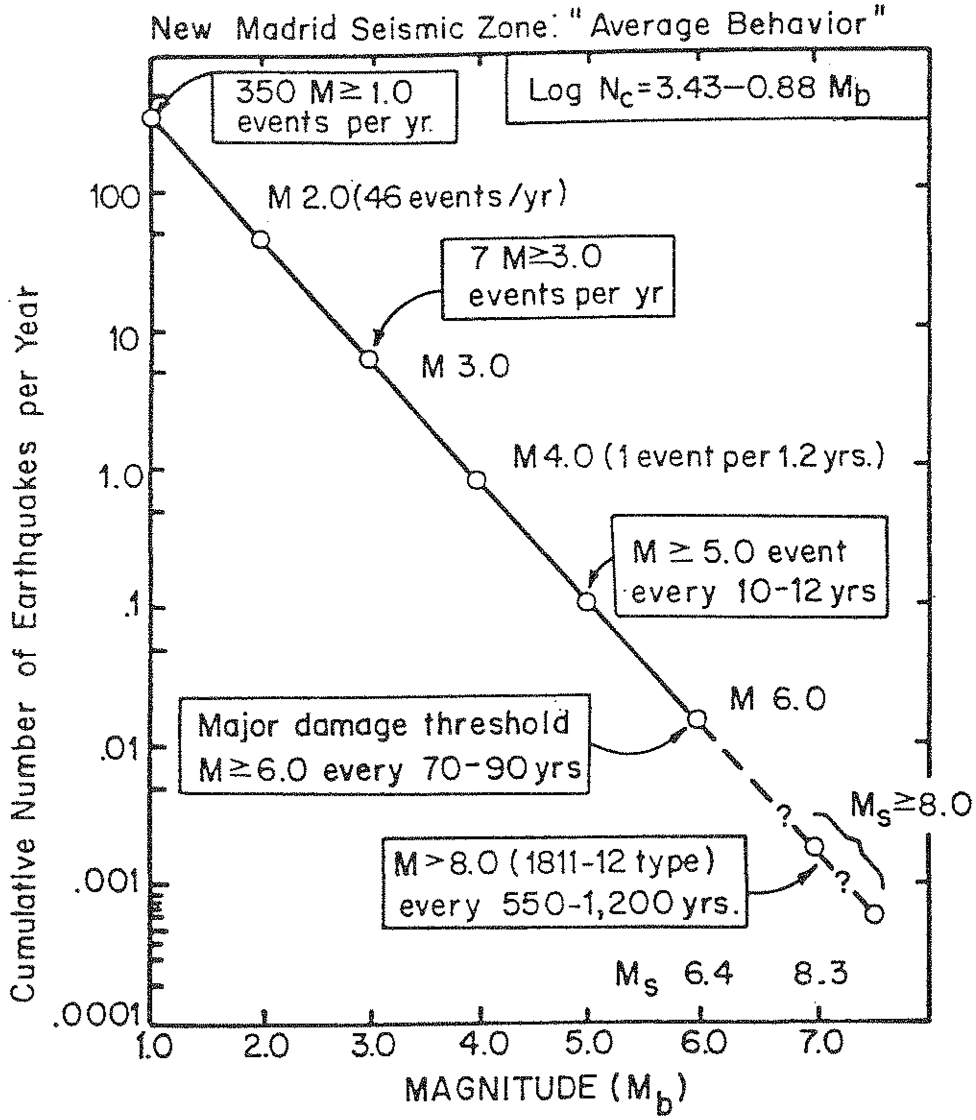

Fig. 2-1 - Frequency-Magnitude Curve for New Madrid Earthquake Zone (after Johnston, [8])

SECTION 3

PREDICTION OF BEDROCK MOTION

3.1 Seismological Parameters

The paucity of strong motion recordings from intraplate earthquake events makes prediction of strong motion in Central and Eastern United States a difficult problem. The scaling of earthquake source parameters of intraplate events is not well understood yet. However, there appears to be a consensus ([3] & [12]) that intraplate seismic sources scale roughly with a constant stress drop.

Based on the work of [3], [12] and [1] the following seismological parameters applicable to the Eastern North America (ENA) are used with the Hanks-McGuire-Boore stochastic model ([2] & [6]) to obtain synthetic bedrock earthquake motions:

Moment magnitude	$M_w = 7.0$
Epicentral distance	$R = 65km$
Focal depth	$h = 10km$
Stress scaling parameter	$\Delta\sigma$ =100,150 & 200 bars
Cut-off frequency	f_{max} = 20, 30 & 40 Hz
Quality factor	$Q(f) = 1000\ f^{0.4}$ (an average of the various Q models proposed for ENA, as reviewed by McGuire & Toro [9]).
Bedrock shearwave velocity	V_r = 3.5 km/sec
Source rock density	ρ_r = 2.7 gm/cm^3

Geometrical attenuation $G(R) = 1/R$

Seismic moment (in dyn-cm) $\log M_o = 1.5M_w + 16$

Corner frequency (in Hz) $f_c = 4.9x10^6 \; V_r \; (\frac{\Delta\sigma}{M_o})^{1/3}$

Source duration (in seconds) $T_d = 1/fc$

Radiation pattern $<R_{\theta\phi}> = 0.55$

Horizontal component $V = 0.71$

3.2 Fourier Amplitude Spectrum of Bedrock Motion

The fourier amplitude spectrum generated from the seismological model is expressed as follows [3]

$$A(f) = C \; S(f) \; D(f) \; I(f) \tag{1}$$

where, C is a scaling factor (accounting for the shear wave radiation pattern) defined by the expression

$$C = \frac{<R_{\theta\phi}> \; V}{4\pi \; R \; \rho_r \; V_r^{\;3}} \tag{2}$$

S(f) is a source spectral function defined by the expression

$$S(f) = \frac{M_0}{1 + (\frac{f}{f_c})^2} \tag{3}$$

D(f) is a diminution function for frequency-dependent attenuation defined by the expression

$$D(f) = \exp\left[\frac{-\pi . f . R}{Q(f) . V_r}\right] \left[1 + (f/f_{max})^8\right]^{-0.5} \qquad (4)$$

and I(f) is a function which translates spectral displacement into acceleration spectra and is defined by the expression

$$I(f) = (2\pi f)^2 \qquad (5)$$

3.3 Synthetic Bedrock Accelerograms

As already mentioned, the semi-theoretical method, based on the work of [2] and [9], is used to generate **synthetic** time histories of bedrock acceleration. The method assumes a simple **source acceleration spectrum** [5] exhibiting two characteristic frequencies, f_c and f_{max}, and attaining a constant value proportional to the seismic moment M_o at frequencies $f_c < f < f_{max}$. Having assessed the source spectrum, simple wave propagation physics are invoked to obtain the modulus of the **acceleration spectral density function** at a R-distant point on the surface of the earth. Then, Random Vibration theory is used to obtain rms and peak values of acceleration and velocity, and acceleration response spectrum. Furthermore, synthetic acceleration histories are generated in a semi-empirical way, by using the previously predicted **modulus** while extracting the **phases** from an actual accelerogram (recorded under "similar" conditions; Imperial valley earthquake, 1979, R=57 kM, M_w=7.0). The advantage of this technique is that the non-stationarity, randomness, and change in frequency with time are incorporated naturally in the synthetic motion. The basic assumption is that the source and wave propagation parameters are reflected primarily in the spectral modulus, while multipath effects and surface wave contributions affect the phase spectrum.

Based on the above mentioned methodology a synthetic bedrock accelerogram generated for Memphis area along with several acceleration response spectra (with 5% damping) are portrayed in Figs. (3-1 to 3-4). The predominant periods are seen to be about 0.12s. Although this seems to be somewhat low for an M_w7 event, recorded evidence can be cited in support of a $T_p \simeq 0.10$s. Specifically, at least two significant accelerograms have been found with similar T_p values:

(i) The record at Karakyr Point, USSR, in the M_s7 Gazli 1976 Earthquake. The acceleration response spectrum (with peak ground acceleration, pga ≈ 0.70g) exhibits a dominant period, T_p ≈ 0.08s.

(ii) The record at Tabas, Iran in the M_s7.5 Tabas Earthquake. The acceleration response spectrum (with pga ≈ 0.81g) exhibits a dominant period, T_p ≈ 0.19s.

The uncertainties in model parameters $\Delta\sigma$ and f_{max} are investigated by considering three values of both $\Delta\sigma$ and f_{max}. Fig. 3-1 shows the synthetic bedrock spectral acceleration for the three values of $\Delta\sigma$. The spectral acceleration curves for all three value of $\Delta\sigma$ show fundamental periods approximately at 0.05 sec and 0.13 sec. The low values of dominant periods are due to a very slow attenuation with distance of high frequencies in the eastern U.S. It should be noticed that an increase in the value of $\Delta\sigma$ results in an increased spectral acceleration peak. For example, the peak values of bedrock spectrum SA(g) at T≈0.13 sec. are 0.29, 0.4 and 0.51 for $\Delta\sigma$ = 100, 150 and 200 bars, respectively. For central and eastern North America, the value of $\Delta\sigma$ suggested by various researcher [3], [9], [12] & [11] varies from 100 to 200 bars. Thus, for results presented hereafter $\Delta\sigma$ = 150 bars is used throughout.

The cutoff-frequency f_{max} is a parameter to model decay of the Fourier amplitude spectrum beyond a certain frequency (a property of near surface attenuation, dependent on geology). As depicted in Fig. 3-2, the influence of the f_{max} values (within the range of 20 to 40 Hz) on the spectral acceleration is negligible. Thus, a f_{max} value of 30 Hz is used hereafter.

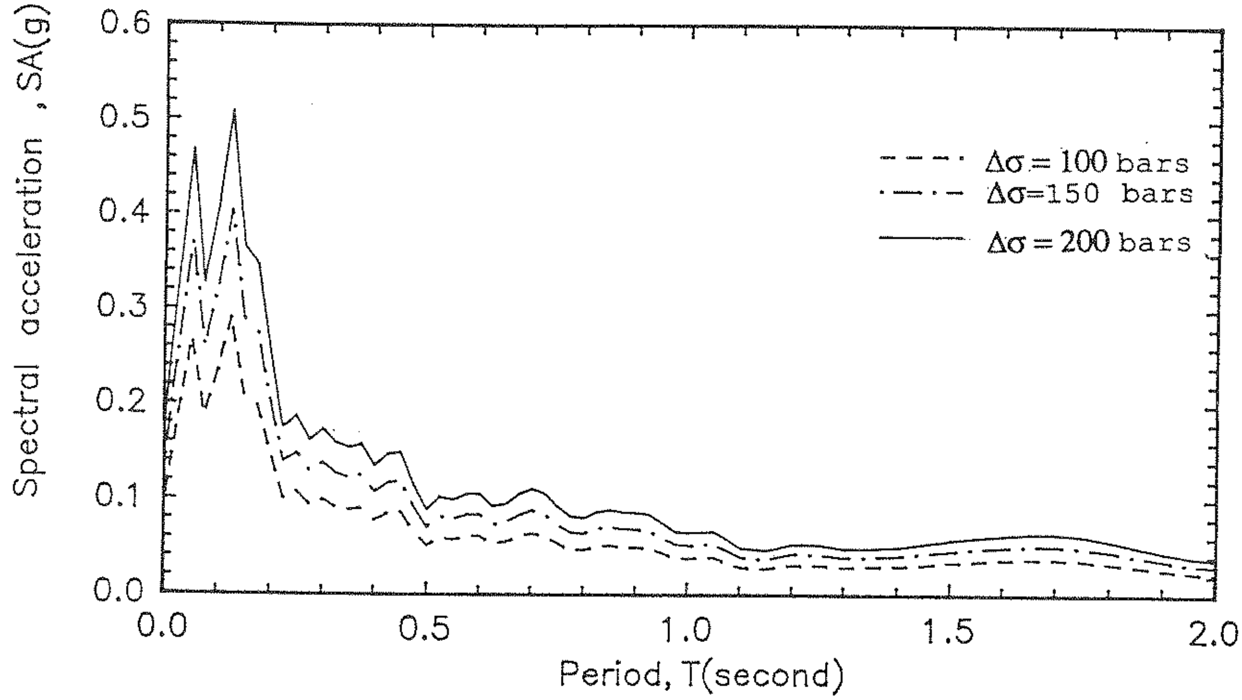

Fig. 3-1 - Effect of $\Delta\sigma$ on Bedrock Spectral Acceleration

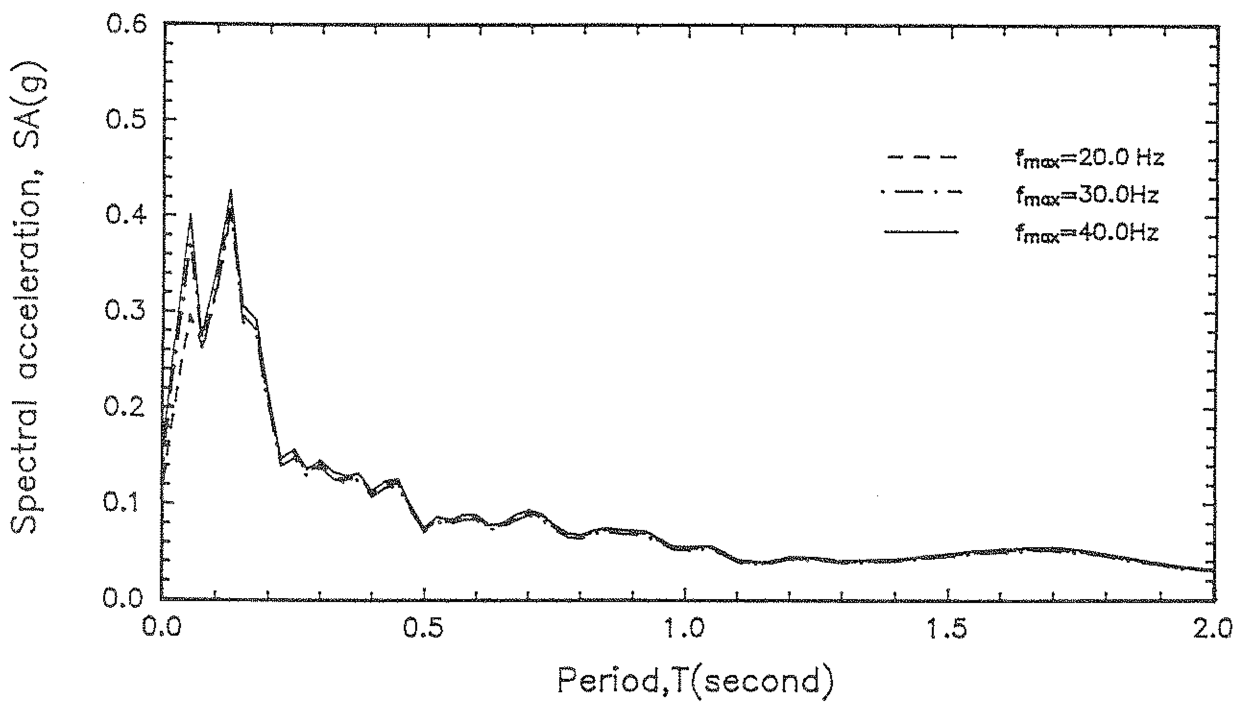

Fig. 3-2 - Effect of f_{max} on Bedrock Spectral Acceleration

The synthetic bedrock accelerogram and its response spectra, generated using the model with $\Delta\sigma$ = 150 bars and f_{max} = 30Hz, are shown in Figs. 3-3 and 3-4, respectively. The peak value of bedrock acceleration is 0.146g, and its response spectrum has a peak value of 0.41g at T ≈ 0.13 sec.

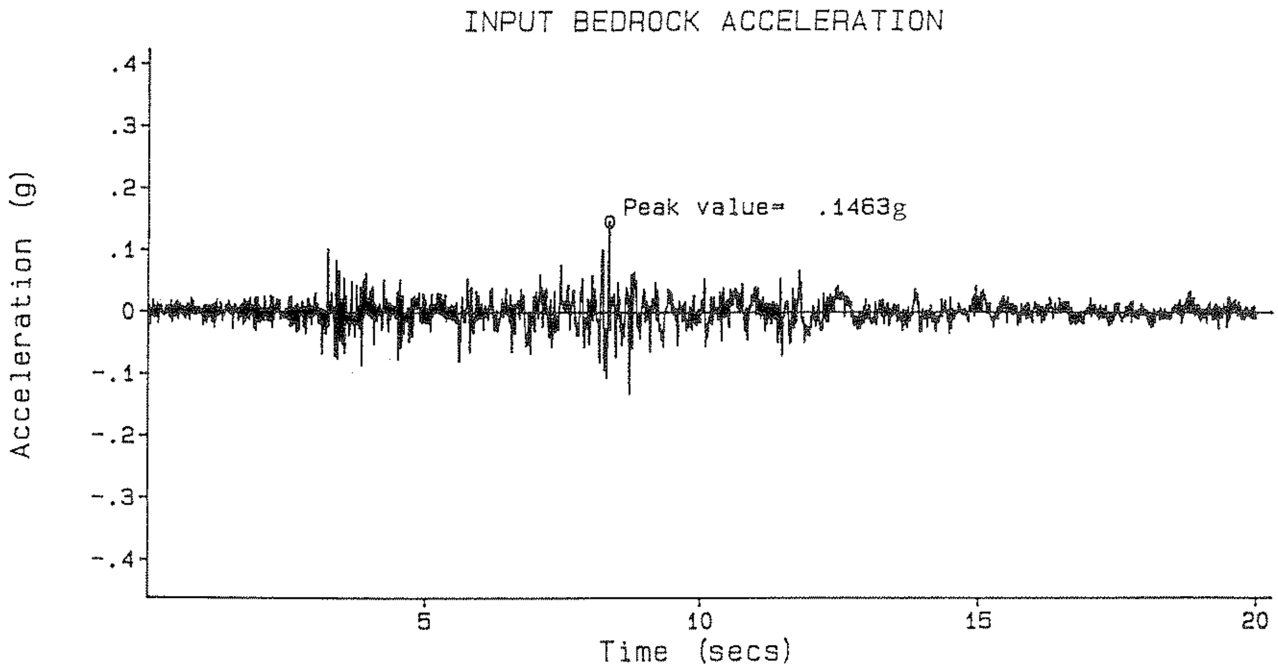

Fig. 3-3 - Time History of Bedrock Acceleration

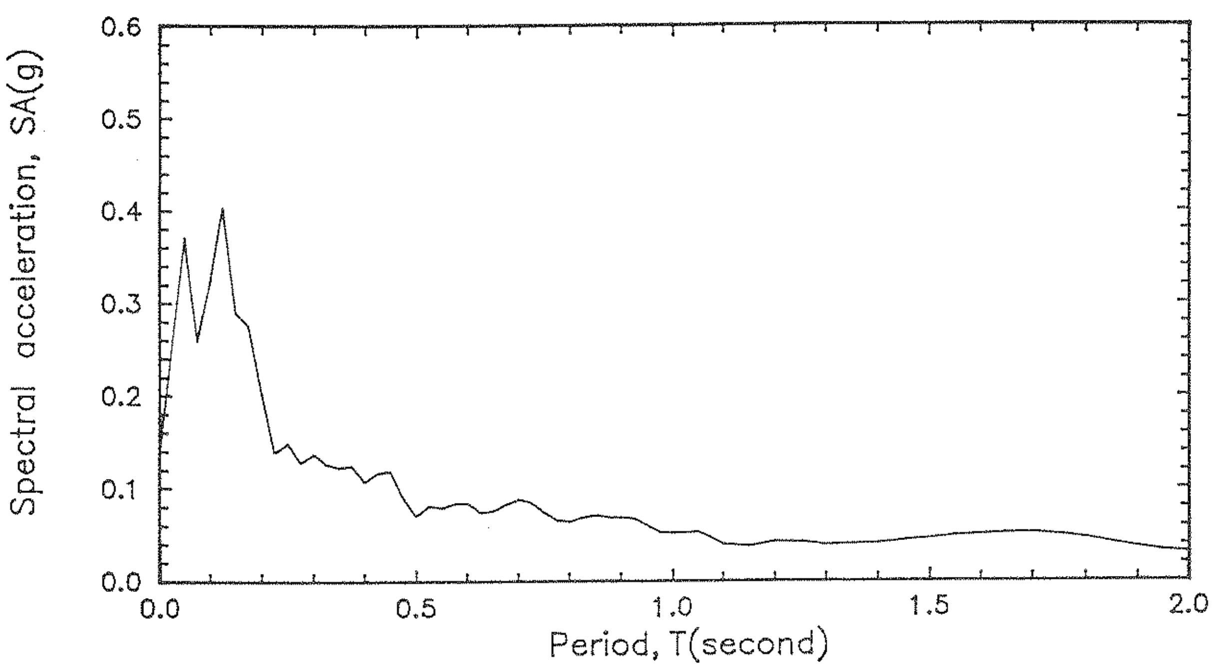

Fig. 3-4 - Bedrock Spectral Acceleration

SECTION 4

SOFT-ROCK ACCELEROGRAM

The actual bedrock ("hard-rock") in Memphis area is very (approx. 3000 feet) deep. Therefore, a response spectrum defined for bedrock must not be used to prescribe input motion to the base of the near-surface soil profile unless the velocity contrast between soil profile and underlaying earth, and the amplifying effect of the "softer-rock" between the "hard-rock" and the soil profile are taken into account. Thus, for Memphis, the synthetic bedrock motion obtained with the seismological model is propagated through a very deep ($z \rightarrow \alpha$) representative "soft-rock" layer having a shear wave velocity $V_{sr} \approx 600$ m/sec. and density $\rho_{sr}=2.5$ gm/cm^3. The incident wave is transmitted through the hardrock-softrock interface with an amplitude (A_{sr}) which exceeds the incoming-wave amplitude (A_r) by a factor is equal to the square-root of the impedance ratio; i.e.,

$$A_{sr} \approx A_r \sqrt{\frac{\rho_r \quad V_r}{\rho_{sr} \quad V_{sr}}} \tag{6}$$

This expression suggested by Joyner & Boore [17] is based on Aki & Richards [18] and is believed to approximately account for transmission of incoming non-vertical waves, non-plane-layered laterally heterogeneous soil conditions and "corrugated" soil-rock interface(s) (Jacob [19]).

The resulting soft-rock accelerogram and its response spectrum are displayed in Figs. 4-1 and 4-2, respectively. The peak acceleration for "soft-rock" is 0.366g compared to 0.146g of the "hard-rock". Similarly, the peak value of the soft-rock response spectrum is 1.0g compared to 0.4 g of the hard-rock. Thus, the bedrock seismic motion is being amplified by the soft-rock deposit.

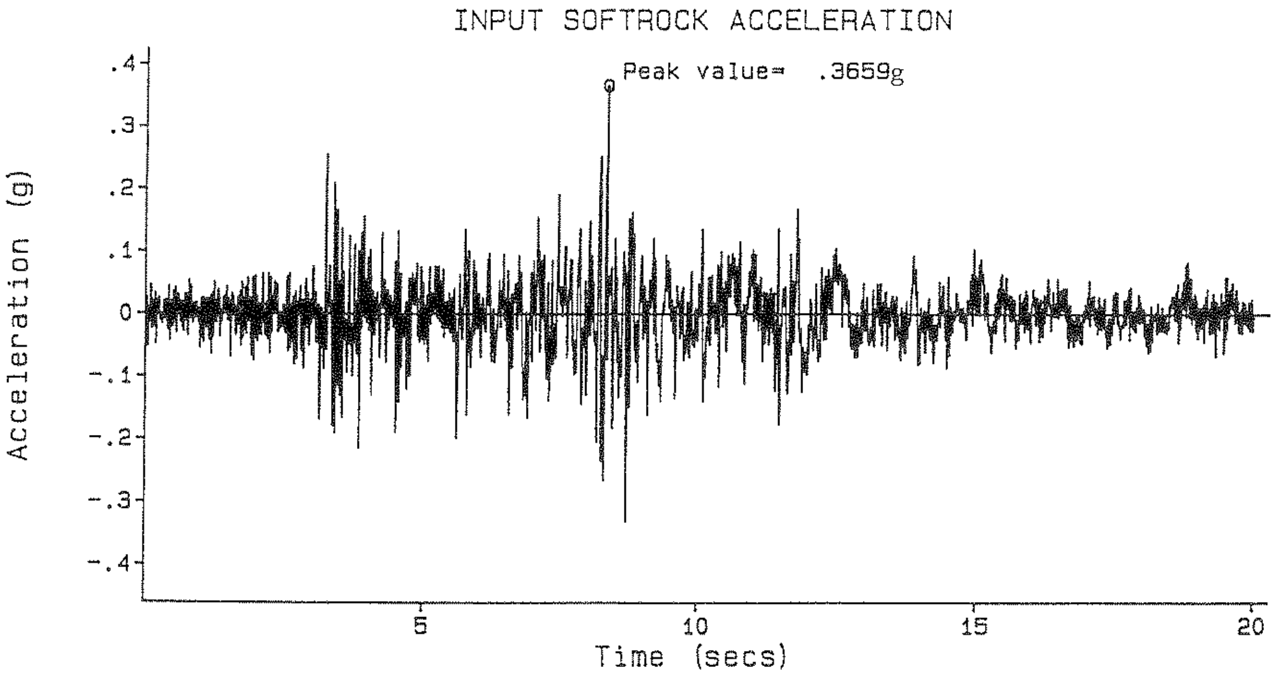

Fig. 4-1 - Time History of Soft-rock Acceleration

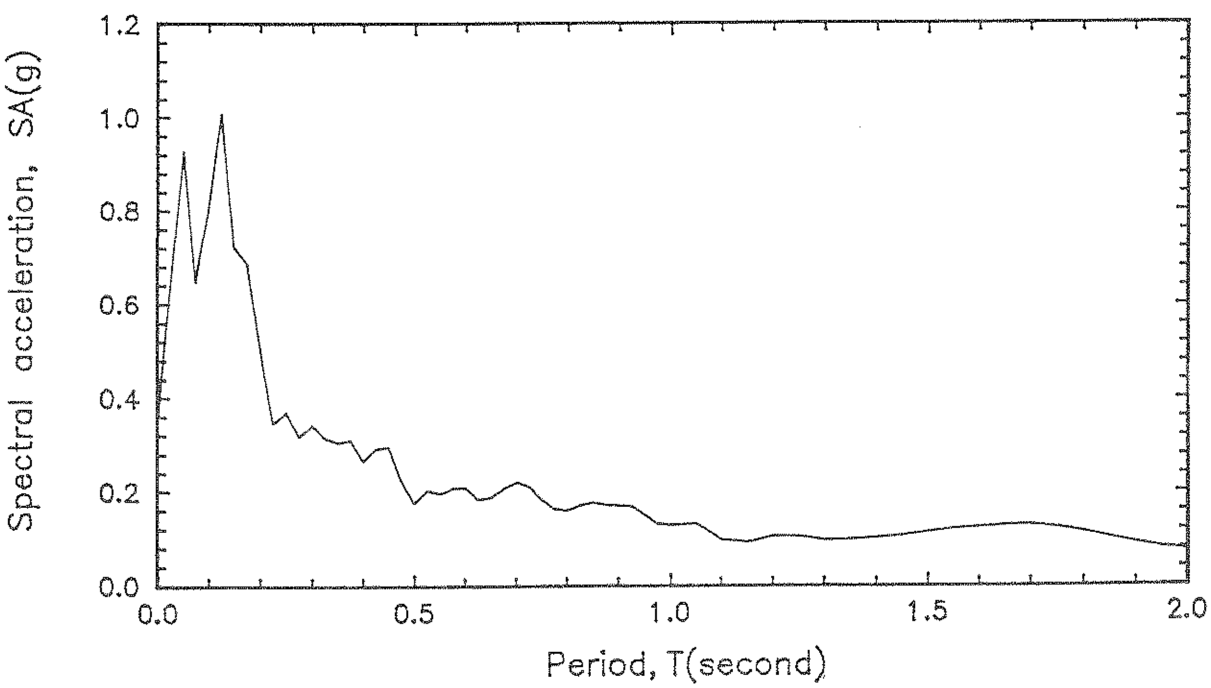

Fig. 4-2 - Soft-rock Spectral Acceleration

SECTION 5

MODELING OF MEMPHIS SOIL PROFILE

A representative soil profile of Memphis, illustrated in Fig. 5-1, is obtained from a data analysis of the extensive borelog data of Memphis provided by Ng et al [10]. The selected soil profile represents about 70% of the Memphis borelogs and 90% of the Upland Memphis borelogs. The water table is located at 10 feet depth. As depicted in Fig. 5-1, the borelog terminates at 100 feet depth. Thus, the soil profile below 100 feet is constructed based on the geological stratification beneath the Memphis area reported by Whittenberg et al [16]. The soil deposit directly overlying the "soft-rock" is a stiff clay (CL) deposit known as "Jackson Formation".

Utilizing the SPT N-values and other available borelog data, the geotechnical properties of each soil layer are estimated with the help of existing empirical relationships between the N-values and the respective parameter. The low strain shear velocity and damping factors for soil layers are estimated based on the information provided by Seed et al [14] and Sun et al [15]. The estimated geotechnical properties for the representative soil profile are displayed in Table 5-1.

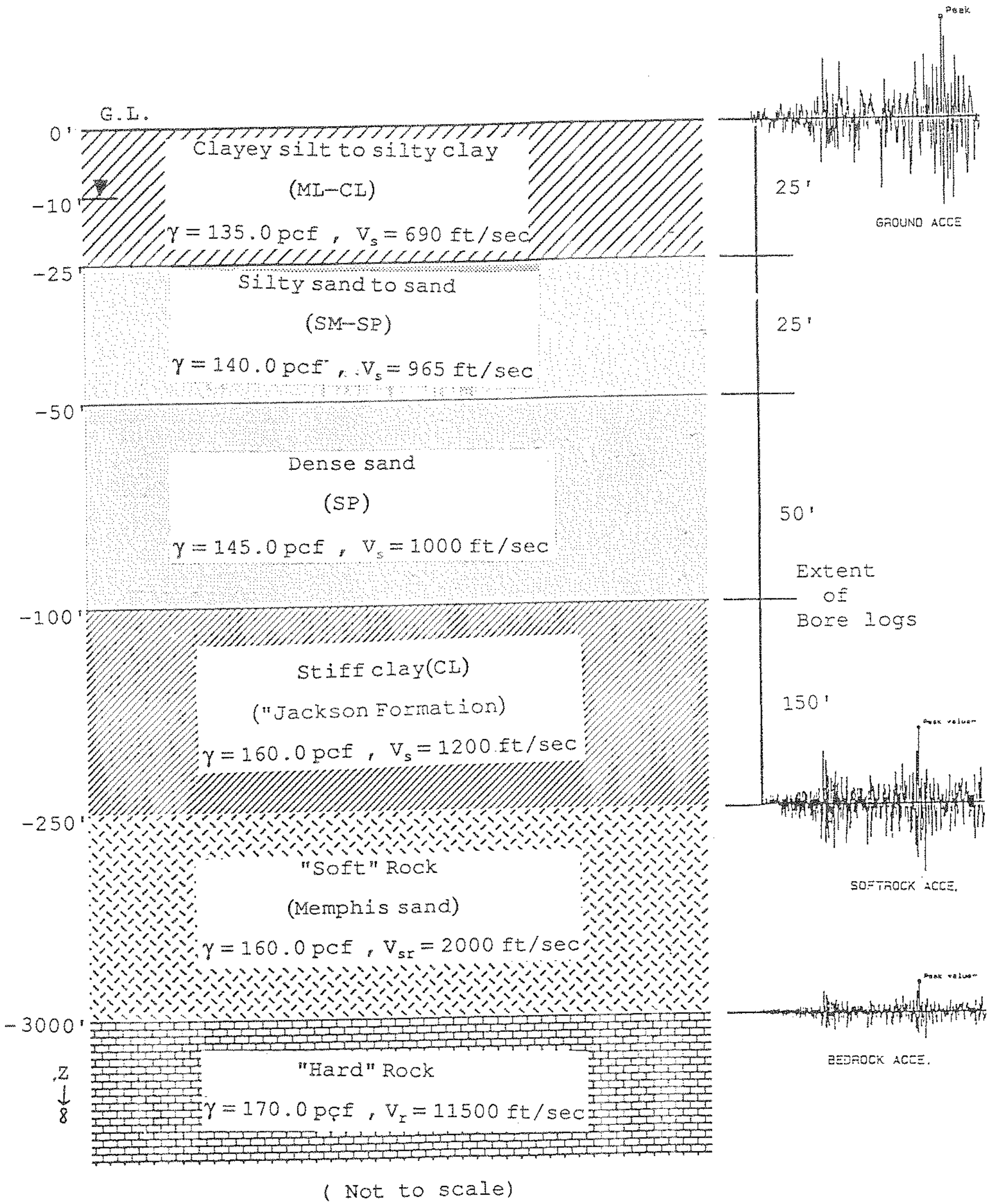

Fig. 5-1 - Representative Soil Profile for Upland Memphis

TABLE 5-1 - Geotechnical Properties for the Memphis Soil Profile

Depth 'z' (in ft.)	Description	N	γ (pcf)	D(%)	ϕ'	G_o (psf)	V_s (ft/sec)	γ_{max}	τ_{max} (N/m^2)
0 - 25'	Clayey silt to silty clay (ML-CL)	10	135	45%	26°	$2.0x10^6$	690.0	0.05	$1.05x10^6$
- 50'	Silty sand to sand (SM - SP)	30	140	65%	35°	$4.1x10^6$	965.0	0.03	$1.20x10^6$
-100'	Dense sand (SP)	50	145	80%	35°	$4.5x10^6$	1000.0	0.03	$1.25x10^6$
-250'	Stiff clay (CL) "Jackson Formation"	80	160	100%	36°	$6.9x10^6$	1200.0	0.03	$2.87x10^6$
	"Soft-Rock"								

Notations

N = SPT (blow count) value for soil

γ = Unit weight of soil

D = Relative density of soil

ϕ' = Effective friction angle of soil

G_o = Small-strain shear modulus of soil

V_s = Shear wave velocity in soil

τ_{max} = Shear strength of soil

γ_{max} = Shear strain related to τ_{max}

SECTION 6

SITE RESPONSE

The top soil layers (overlaying the soft-rock) of the representative Memphis soil profile (Fig. 5-1) is modelled using the computer programs SHAKE (Equivalent-linear analysis) and DYNA1D (Nonlinear inelastic analysis) to perform a one-dimensional dynamic site response analysis based on vertical propagation of shear waves. The "soft-rock" accelerogram is used as the input seismic motion at the base (z=-250 ft) of the near-surface soil layers.

The program SHAKE is based on the elastic wave propagation theory and it uses the "equivalent-linear" method to model the nonlinear dynamic shear moduli and damping as a function of shear strain. Nonlinear soil properties for the soil layers are modelled using the dynamic modulus degredation vs. shear strain (G vs. τ) and damping ratio vs. shear strain (β vs. τ) relationships reported by Seed et al [14] and Sun et al [15]. On the other hand, the DYNA1D code is a finite element based program (Prevost [13]) which uses nonlinear-inelastic constitutive models to incorporate the nonlinear inelastic stress-strain behavior of the soil materials.

The acceleration time history at the ground level obtained from the site response analysis with the SHAKE program is shown in Fig. 6-1. The peak value of the ground acceleration is 0.286g, compared to 0.146g of bedrock and 0.366g of "soft-rock".

Fig. 6-2 shows the normalized spectral accelerations at the ground level obtained with linear-elastic (SHAKE), equivalent-linear (SHAKE) and nonlinear-inelastic (DYNA1D) modelling of the soil materials. The normalized spectral accelerations are the spectral accelerations normalized w.r.t. to the peak ground acceleration. The largest value of the normalized spectrum for linear analysis is 2.4 (at $T \approx 0.13$ sec.), for equivalent-linear 3.0 (at $T \approx 0.13$ sec.), and for nonlinear 2.4 (at $T \approx 0.18$ sec.). Those peaks are close to the fundamental period of the top soil layer (T=0.14 sec.) and the soft-rock

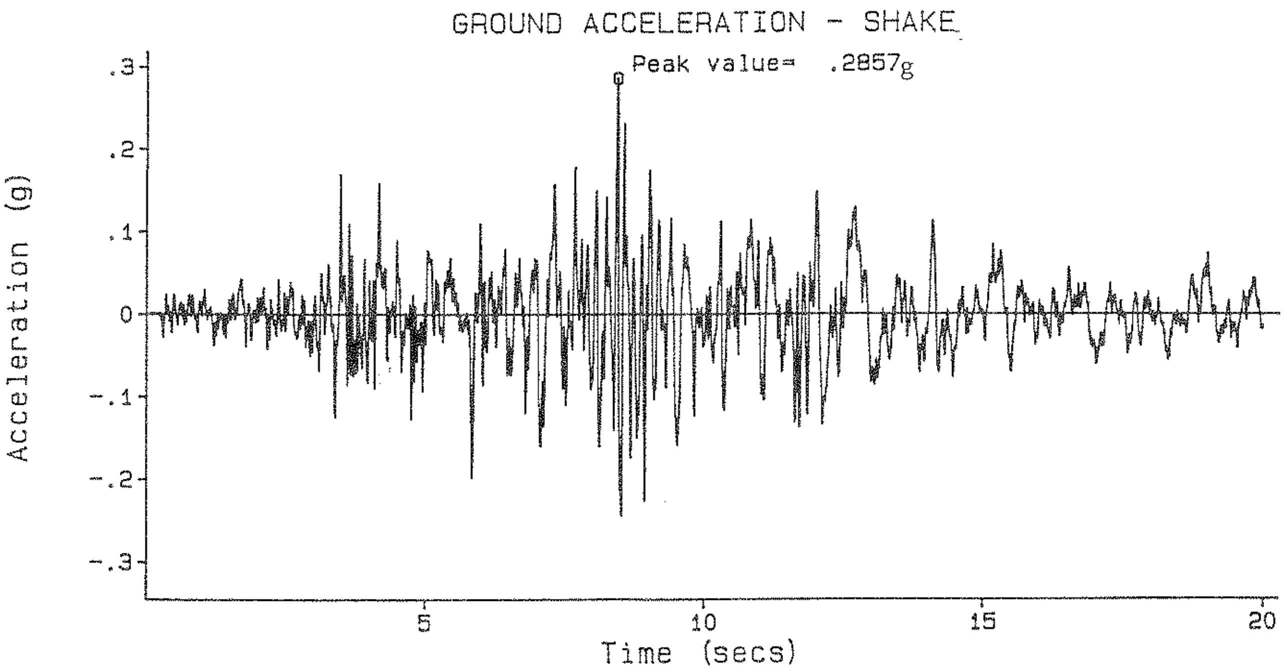

Fig. 6-1 - Time History of Ground Acceleration (SHAKE)

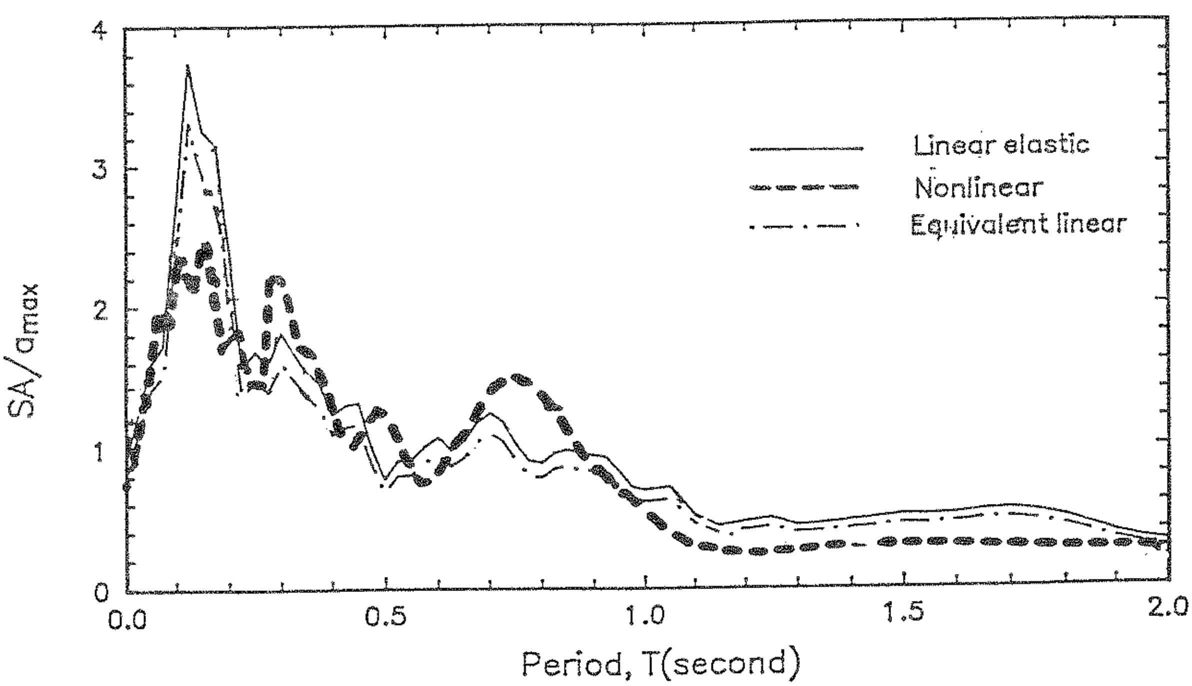

Fig. 6-2 - Normalized Ground Spectral Acceleration spectral acceleration peaks. Additional peaks in ground acceleration spectra appear at T=0.3 sec. and T=0.7-0.9 sec., with T=0.8 being the fundamental period of the near-surface soil profile. Furthermore, it is evident from Fig. 6-2 that a nonlinear inelastic analysis shifts the maximum value of the spectrum to a higher period (i.e.to a lower frequency), and the 2nd & 3rd spectral peaks have higher values than the corresponding linear and equivalent-linear peaks.

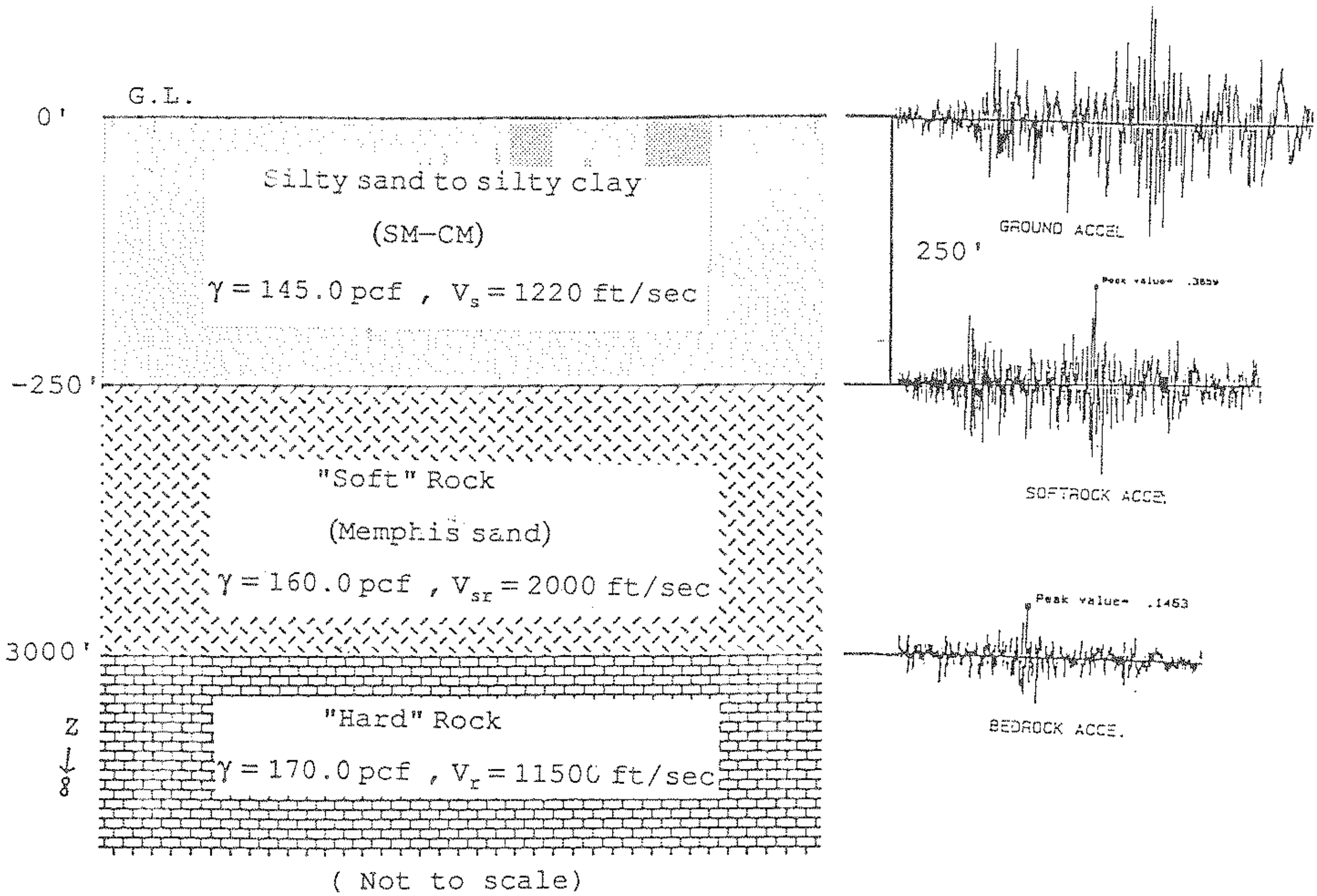

Fig. 6-3 - Simplified Soil Profile for Upland Memphis

Fig. 6-4 shows the normalized ground spectral accelerations obtained using the "equivalent-linear" model (SHAKE), for two soil profiles (Figs. 5-1 & 6-3). The simplified soil profile, shown in Fig. 6-2, is constructed by replacing the actual near-surface soil layers of Fig. 5-1 by an equivalent layer having the same fundamental period as the actual profile. As can be seen from Fig. 6-4, the simplified profile has higher spectral peaks compared to those of the actual profile. However, the pattern of the spectral curves are almost identical.

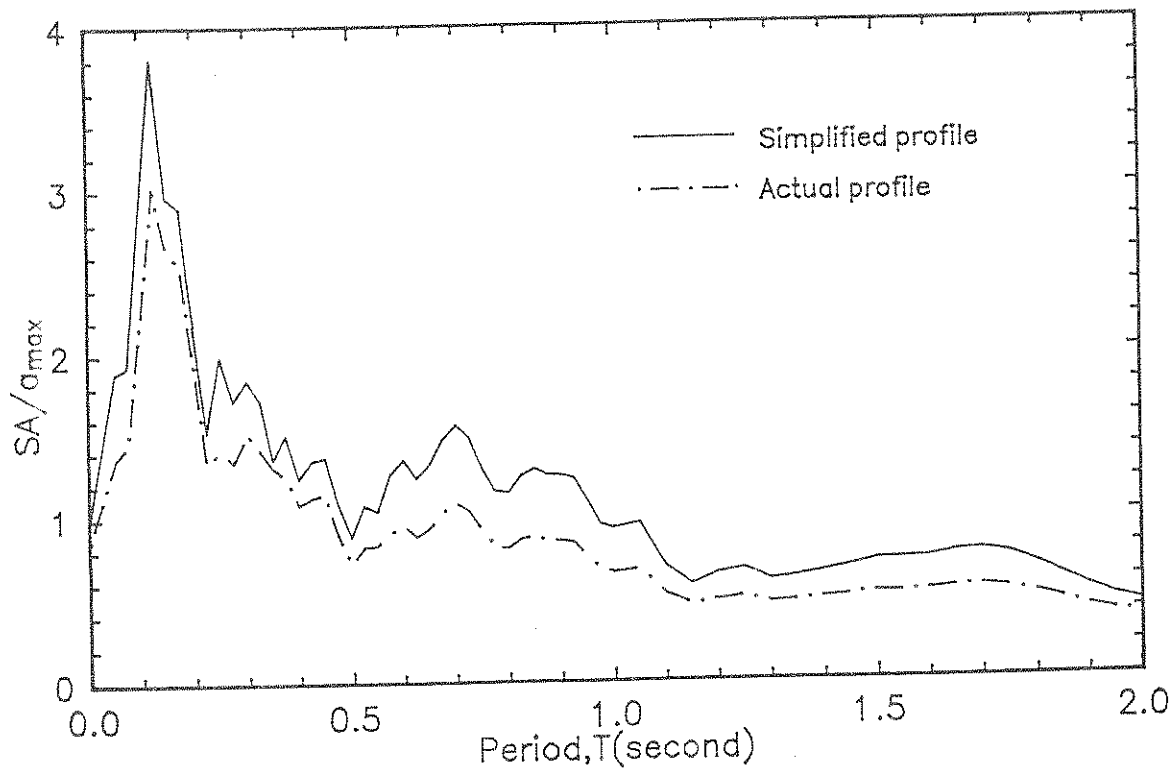

Fig. 6-4 - Ground Spectral Acceleration Simplified vs. Actual Profile

Based on the results of the present study, a design spectrum proposed for the city of Memphis is shown in Fig. 6-5, along with the existing UBC code spectrum.

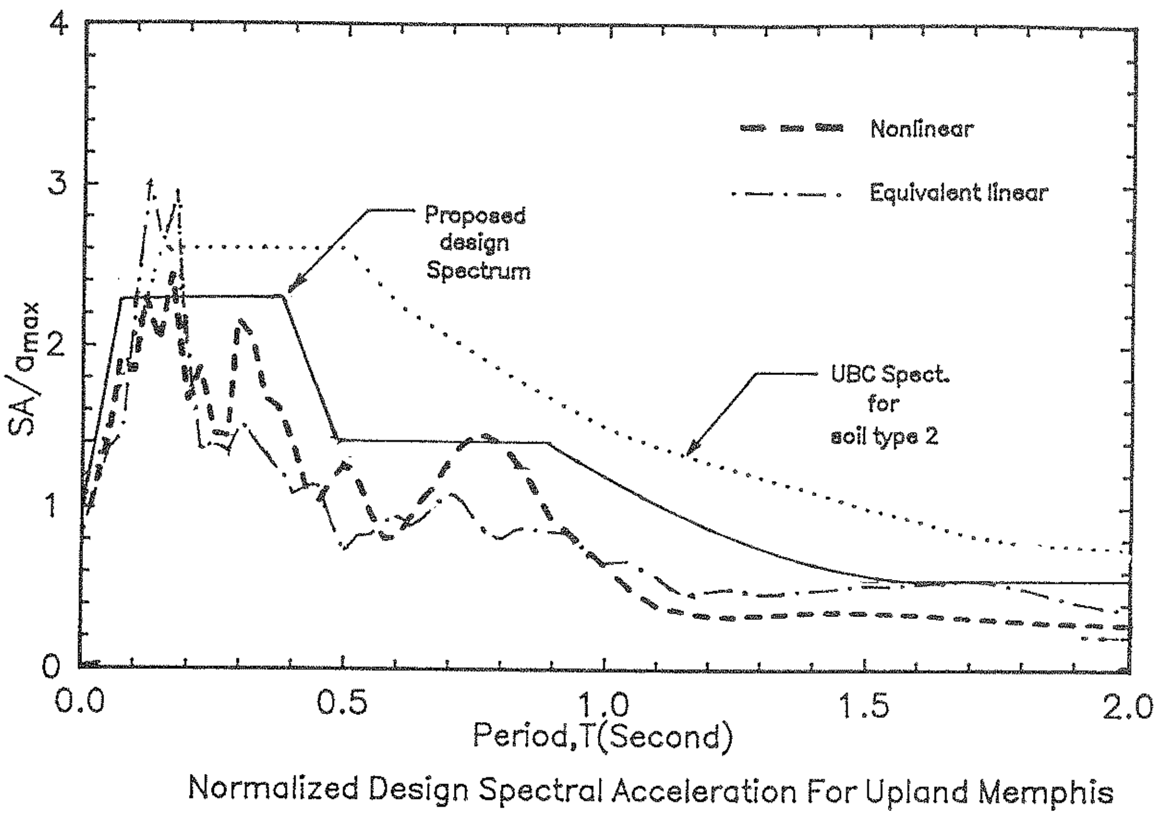

Fig. 6-5 - Design Spectrum for Upland Memphis

SECTION 7

CONCLUSION

Site response spectra for a representative soil deposit of Memphis are presented by utilizing the Hanks-McGuire-Boore seismological model to generate synthetic bedrock motions and state-of-the-art formulations SHAKE & DYNA1D to perform the seismic site response analyses. Influence of the underlaying "soft-rock" deposit on the site response at Memphis is found to be of primary importance.

SECTION 8

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