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DYNAMIC PROPERTIES OF MEMPHIS SOILS AND THEIR APPLICATIONS IN SEISMIC HAZARDS ASSESSMENTS

TZYY-SHIOU CHANG

Center for Earthquake Research and Information, Memphis State University, Memphis, TN 38152

ABSTRACT--The most critical and essential information for seismic studies is the accurate low- and high-strain dynamic properties of soils involved. According to current geotechnical techniques, high-strain nonlinear behavior and damping, which are important characteristics of soils for strong ground motion and liquefaction studies, can only be determined in the laboratory. Test results show that the two typical Memphis soils tested exhibit significantly lower elastic shear modulus G_0 (about 10 to 40% less than estimated by commonly used empirical equations) under confining pressure <15 psi. Beyond 15 psi, a significant increase of shear modulus reduces the differences. Test results also show that high-strain nonlinear characteristics of Memphis soils are significantly different from those of soils elsewhere. The clayey silt (loess) behaves more like cohesionless soil rather than cohesive soil. On the basis of test results and the knowledge of general subsurface conditions in the Memphis area, the seismic site response and liquefaction potential in the event of major New Madrid seismic zone earthquakes can be evaluated.

The seismic hazards of the northern Mississippi embayment that are caused by earthquakes in the New Madrid seismic zone (NMSZ) have been studied and recognized. Seismic records show that the NMSZ, located in the northern edge of the Mississippi embayment, is still a seismically active zone where earthquakes occur almost every other day, most of which are below the threshold of feeling (M&H Engineering and Memphis State University, 1974; Johnston and Nava, 1985). However, there looms the possibility of major earthquakes such as those of an estimated magnitude 8 that occurred in the winter of 1811-1812 (Johnston and Nava, 1985). Recently, especially after the Loma Prieta earthquake in California on 17 October 1989, research on structural and geotechnical earthquake engineering in the major seismic zones of the eastern United States has been brought to public attention. Such research also is essential for providing important technical information to local government agencies and civilians for regional earthquake hazard evaluation and for developing appropriate earthquake plans.

One of the most important lessons we have learned from the consequences of previous earthquakes is that the seismic characteristics of in situ soils play a critical role in causing damage to structures at particular locations during earthquake shaking (M&H Engineering and Memphis State University, 1974; Seed, 1976; Astaneh et al., 1989). An understanding of local site conditions, such as liquefaction resistance, and the dynamic properties of in situ soils during strong ground motion is essential for obtaining accurate results for regional seismic studies and for overall earthquake engineering hazard evaluation.

In this study, geotechnical properties of eight Memphis soils (NMSZ sediments) are investigated to provide important information for the current seismic studies at the Center for Earthquake Research and Information (CERI), Memphis State University, and to provide guidelines for a future complete sutdy of NMSZ sediments. In addition, the regional seismic hazards assessment in the Memphis area, formed by means of the test results, is also presented and discussed.

GENERAL TESTING PROGRAM

Eight soil specimens were collected from the local geotechnical consulting companies listed in Table 1. Locations of the individual soil samples are shown in Fig. 1, and the general testing program is presented in Table 2. All the fundamental static properties of the collected Memphis soils were determined in general accordance with American Society for Testing and Materials standard procedure. The dynamic properties of two typical NMSZ soils (specimens 6 and 7) were determined in the laboratory using combined resonant column test (low-strain amplitude) and cyclic torsional test (high-strain amplitude; Chang and Woods, 1987, and Chang et al., 1990*a*).

FUNDAMENTAL STATIC PROPERTIES

Grain-size Distribution--Grain-size analyses were performed for specimens 1, 2, 5, and 6 (Fig. 2). Test results reveal that both specimens 1 and 2 are composed of about 75% silt and 25% clay, which can be classified as silt to clayey silt (ML-CL). This soil, called "loess," is a common surficial soil in the Mississippi embayment (M&H Engineering and Memphis State University, 1974; Chang et al., 1990*b*). Results also show that speciment 5 is a poorly-graded fine to medium sand (SP), while specimen 6 is a well-graded gravelly sand (with about 25% weight of gravel, SP-SW-GP). These two granular soils are two typical alluvial sand deposits in the Mississippi embayment region.

Specific Gravity--Test results show that the sediments in the study area have specific gravities in the normal range of natural sediments. Specific gravity of specimens 1, 5, and 6 were determined, and the average result of five tests for each specimen is 2.77, 2.64, and 2.65, respectively.

Relative Density--Maximum and minimum void ratios of the cohesionless soil specimens 5 and 6 were determined. A significant difference in these values is observed between the two granular soils

TABLE 1. Number, soil type, and location of the specimens.

Specimen	Location	Soil type
1	Collierville	Clayey silt to silt (ML-CL)
2	Collierville	Clayey silt to silt (ML-CL)
3	Defense Depot	Clayey silt to silt (ML-CL)
4	Park and Airways	Clayey silt to silt (ML-CL)
5	St. Jude Hospital	Sand (SP)
6	Collierville	Coarse sand (SP-SW-GP)
7	Belvedere and Peabody	Clayey silt to silt (ML-CL)
8	Dupont Plant, Fite Road	Clayey silt to silt (ML-CL)

tested. The average values of e_{max} and e_{min}, which are important index properties of granular soils, are 0.739 and 0.469 for specimen 5 and 0.931 and 0.605 for specimen 6.

Moisture Content--The results of moisture content tests on specimens 1, 2, 3, 4, 7, and 8 (test results for 7 and 8 provided by the specimen supplier) are 25.6, 16.0, 19.3, 23.1, 27.0, and 29.0%, respectively. It can be concluded that the normal moisture content of the loess soils in this region may be in the range of 15 to 30%. Moisture content is an important factor controlling the strength and other in situ properties of loess soil in the Mississippi embayment (M&H Engineering and Memphis State University, 1974; Chang et al., 1990*b*).

Dry Density and Unconfined Compressive Strength--Dry density, in situ blow count, and unconfined compressive strength (which is theorectically twice that of undrained shearing strength of cohesive soils) are 95.6 pcf, 12, and 1.57 ksf for specimen 7 and 92.0 pcf, 4, and 1.89 ksf for specimen 8. The data do not provide adequate information for developing a meaningful relationship among dry density, blow count, and undrained shearing strength.

DYNAMIC PROPERTIES OF TYPICAL MEMPHIS SOILS

The earthquake-induced shear strain of soils can be much higher than the elastic range; i.e., shear strain is much greater than the limit of elastic range (for soils, about 10^{-3}%). The nonlinear strain-stress behavior should be determined for accurate evaluation of stress of soil layers under a particular earthquake shaking.

Low-strain Dynamic Properties--The elastic shear modulus of the specimens (i.e., strain level $<10^{-3}$%) is determined by resonant column test. The resonant frequency of the specimen with known dimensions and density under various confining pressure levels is determined, and then the shear modulus can be determined (Richart et al., 1970; Chang et al., 1990*a*). Specimen 7 (Belvedere and Peabody silt) was tested at e = 0.83, and specimen 6 (Collierville sand) was tested at e = 0.70 (relative density 70%). The confining pressure series used in the tests is 5, 10, 20, and 40 psi.

The low-strain shear modulus is expected to increase with increasing confining pressure (Figs. 3 and 4). At confining pressure <15 psi, shear modulus of the two tested Memphis soils is significantly lower than estimated by commonly used empirical equations. However, beyond about 15 psi, significant increase of shear modulus due to increasing confining pressure reduces the differences and, in some cases, test results are higher than empirical equation estimations. Test results show that the differences are as high as 60% (in general, about 10 to 40%).

Another remarkable finding from the test results is the effect of confining pressure on low-strain shear modulus (G_0). Most of the commonly used empirical equations reveal that shear modulus is increased in proportion to $(\sigma_0)^{1/2}$, which was concluded on the basis of averaged laboratory test results. The tests on the two Memphis soils show that under confining pressure <15 psi, shear modulus is generally propertional to $(\sigma_0)^{1/2}$, but, beyond 15 psi up to 40 psi, G_0 is generally proportional to $(\sigma_0)^{0.6}$. This indicates that a more significant increase of G_0 at $\sigma_0 > 15$ psi is observed for the two typical Memphis soils that were tested. This may be an important seismic characteristic of sediments in the Mississippi embayment region; however, more tests are required to confirm this observation.

High-strain Dynamic Properties--The substantial decrease of shear modulus and the increase of damping ratio, D, of soils (nonlinear behavior) as a result of increasing strain level beyond the elastic range (about 10^{-3}%) are significant in seismic studies of liquefaction potential

TABLE 2. General testing program.

Test item	1	2	3	4	5	6	7	8
Low-strain dynamic property						X	X	
High-strain dynamic property						X	X	
Grain-size analysis	X	X			X	X		
Specific gravity	X				X	X		
Relative density					X	X		
Moisture content	X	X	X	X			X[1]	X[1]
Shear strength							X[1]	X[1]
Dry density							X[1]	X[1]

[1] Test conducted by the specimen supplier.

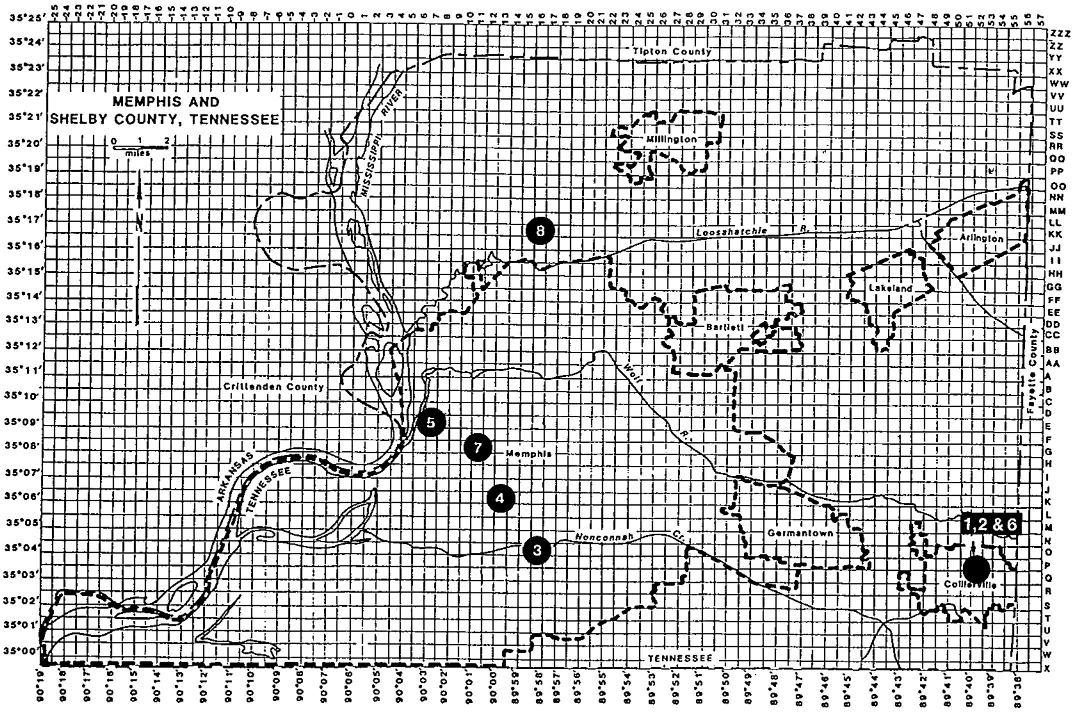

FIG. 1. Sampling locations of soil specimens.

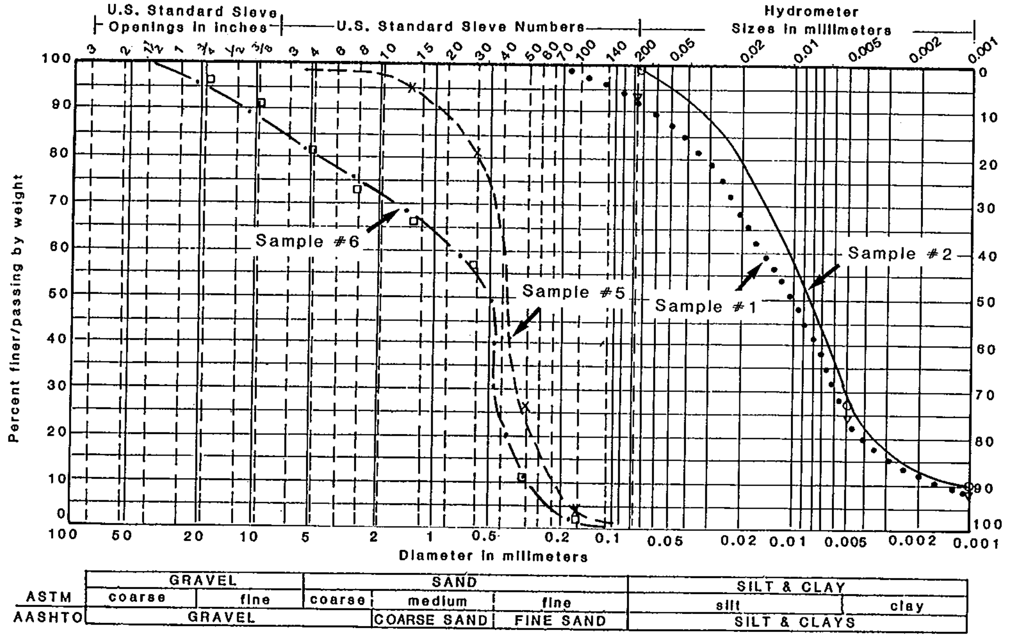

FIG. 2. Grain-size distribution curve for specimens 1, 2, 5, and 6.

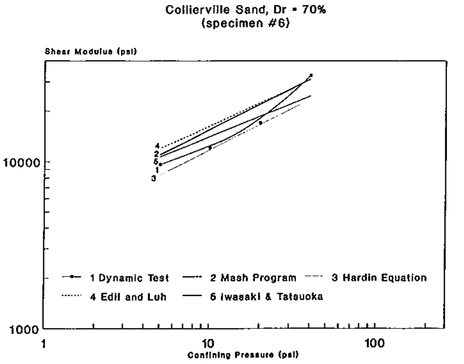

FIG. 3. Shear modulus versus confining pressure for Collierville sand.

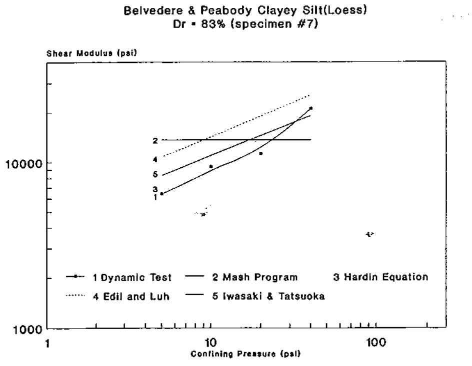

FIG. 4. Shear modulus versus confining pressure for Peabody clayey silt.

and strong ground motion studies (Martin, 1976; Seed, 1976). This nonlinear behavior is defined for specimens 6 and 7 based on the high-strain dynamic test results (Fig. 5). Results clearly show a significant decrease in G and an increase in D when shear strain is $>10^{-2}$%, and the shear modulus is only about 10% of the low-strain shear modulus G_0 at 1% strain.

The Martin-Davidenkov mathematic model is commonly used for interpreting such a nonlinear modulus-strain degradation of soils and has been proven to be sufficient in both theoretical and practical applications. This model shows that shear modulus of soils at high-strain levels can be determined by a fraction of the low-strain elastic modulus (Martin, 1976). The fraction is presented in terms of strain level and parameters that represent the nonlinear behavior of the soils:

$$G(\gamma) = G_0[1-H(\gamma)] \qquad (1)$$

$$H(\gamma) = [(\gamma/\gamma_0)^{2B}/1+(\gamma/\gamma_0)^{2B}]^A \qquad (2)$$

in which G_0 = low-strain elastic shear modulus, $G(\gamma)$ = shear modulus at strain level , $H(\gamma)$ = stiffness degrading function, γ_0 = reference strain level, and A,B = parameters that reflect the nonlinear characteristic of soil.

The values of A and B parameters for the tested Memphis soils are shown in Table 3. Comparisons of the nonlinear behavior between the Memphis soils and soils elsewhere are also presented in Fig. 6 for both cohesive and cohesionless soils. Clearly significant differences are observed between soils at different locations, which implies that the nonlinear behavior of the Memphis soils (NMSZ sediments) should be thoroughly studied since this important seismic characteristic cannot be accurately estimated by the current available empirical equations or the available model parameters based on test results at other locations. By applying values of developed parameters based on soils elsewhere, the seismic studies of Memphis sites would never produce results with accuracy and high confidence.

Another remarkable finding from the test results is that the nonlinear behavior of the tested clayey silt (loess, granular cohesive soil) is similar to that of cohesionless granular soil rather than to cohesive soil. Because loess is a common and dominant surficial soil in the NMSZ, a detailed study of this silty material (including low-strain elastic and high-strain nonlinear characteristics) is essential for seismic and earthquake engineering studies of the NMSZ region.

TABLE 3. Nonlinear A and B parameters for soils.

Soil	A	B	γ_0
Collierville sand[1] (e = 0.70)			
3-variable	1.46	0.38	1.06×10^{-4}
2-variable	0.51	0.61	6.60×10^{-4}
Dense Ottawa sand[1] (e = 0.54)	0.85	0.67	9.83×10^{-4}
Loose Ottawa sand[1] (e = 0.68)	0.92	0.52	9.45×10^{-4}
Peabody clayey silt[1]			
3-variable	0.92	0.41	5.67×10^{-4}
2-variable	1.10	0.31	4.00×10^{-4}
Silty clay			
PI = 5-10%	1.01	0.46	4.08×10^{-4}
PI = 10-20%	1.22	0.46	5.39×10^{-4}
PI = 20-40%	1.32	0.41	7.37×10^{-4}

[1] $\sigma_0 = 40$ psi.

REGIONAL SEISMIC HAZARDS ASSESSMENTS

The subsurface conditions in the Memphis area were studied by CERI on the basis of data from >8,500 engineering bore holes throughout the study area (Ng et al., 1989; Chang et al., 1991). The subsurface conditions were presented in a series of representative boring logs in accordance with a grid system applied to the target area as shown in Fig. 7. The number shown in each cell indicates the actual boring logs available from which the final representative soil log was developed. These logs, which contain necessary engineering data such as soil type and stratification, in situ strength, and ground water level, are used for regional seismic hazards assessments. The dynamic properties of soils in the study area are estimated based on both general empirical equations and the results of this study. The preliminary evaluation of seismic site response and liquefaction potential in the event of major NMSZ earthquakes, M = 6.5 and M = 7.5, are performed at CERI (Chang et al., 1990*b*; Hwang et al., 1990). The liquefaction potential of Memphis and Shelby County in the event of an M = 6.5 earthquake is shown in Fig. 8 (Chang et al., 1990*b*). Another result in the study area is the site average shear velocity (ranging from 289.6 to 451.1 m/sec) and seismic site period (0.63 to 1.00 sec; Hwang et al., 1990). An example site response spectrum, which is very important for structural earthquake-resistant design, is shown in Fig. 9.

CONCLUSIONS AND FURTHER STUDIES

The preliminary conclusions of the dynamic properties of typical Memphis soils and seismic hazards assessment are addressed based on the test results in this study; however, more tests on NMSZ sediments are required to confirm these conclusions. At confining pressure <15 psi, the low-strain properties of Memphis soils are remarkably lower

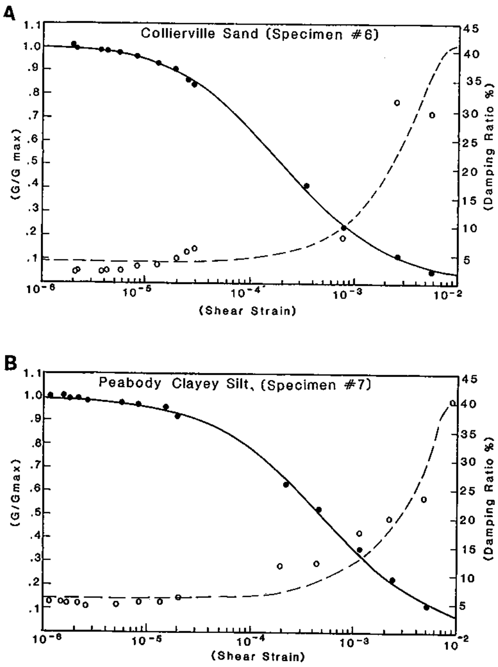

FIG. 5. (G/G_{max}) versus strain and damping ratio versus strain for (A) Collierville sand and (B) Peabody clayey silt.

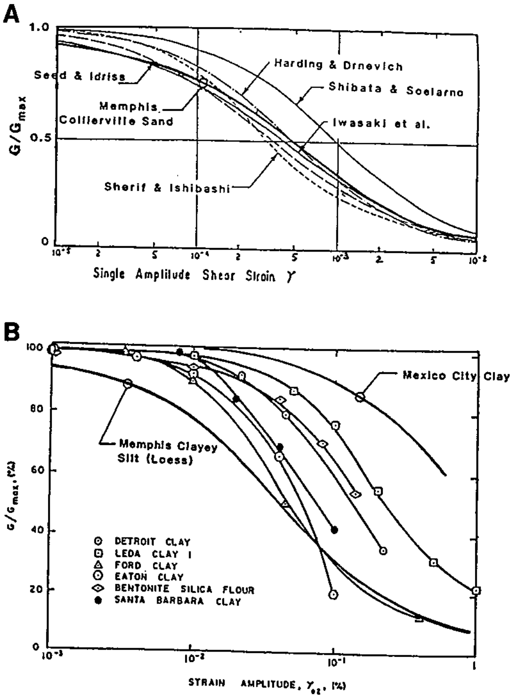

FIG. 6. Comparison of normalized modulus reduction relationships for (A) sands and (B) clays.

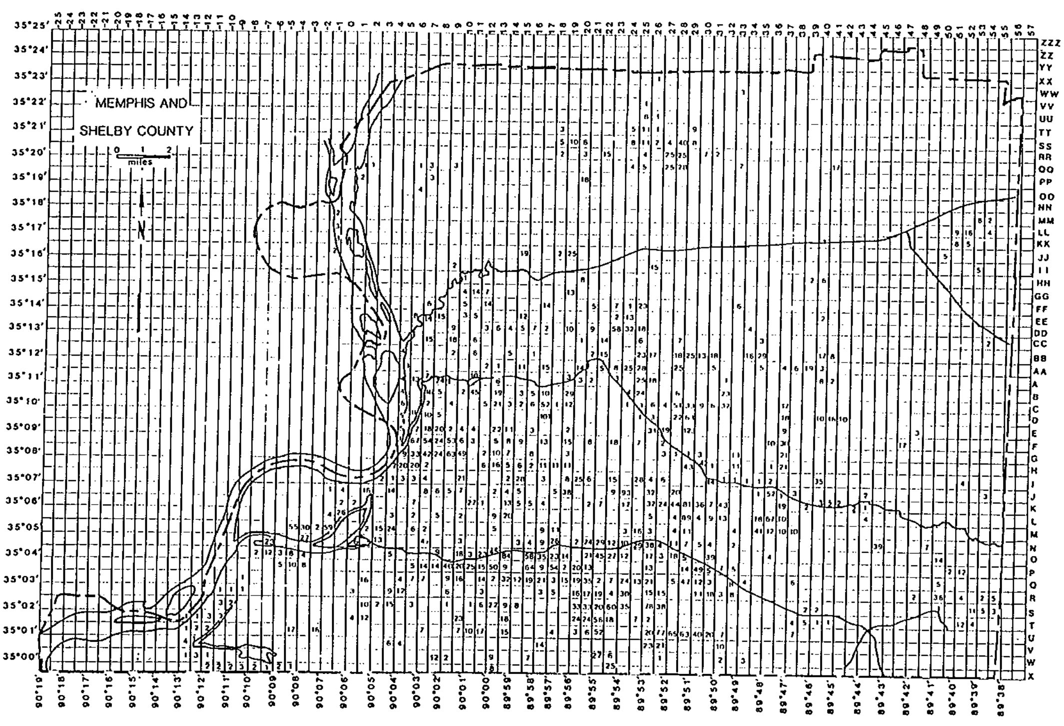

FIG. 7. Boring data distribution map of Memphis and Shelby County, Tennessee.

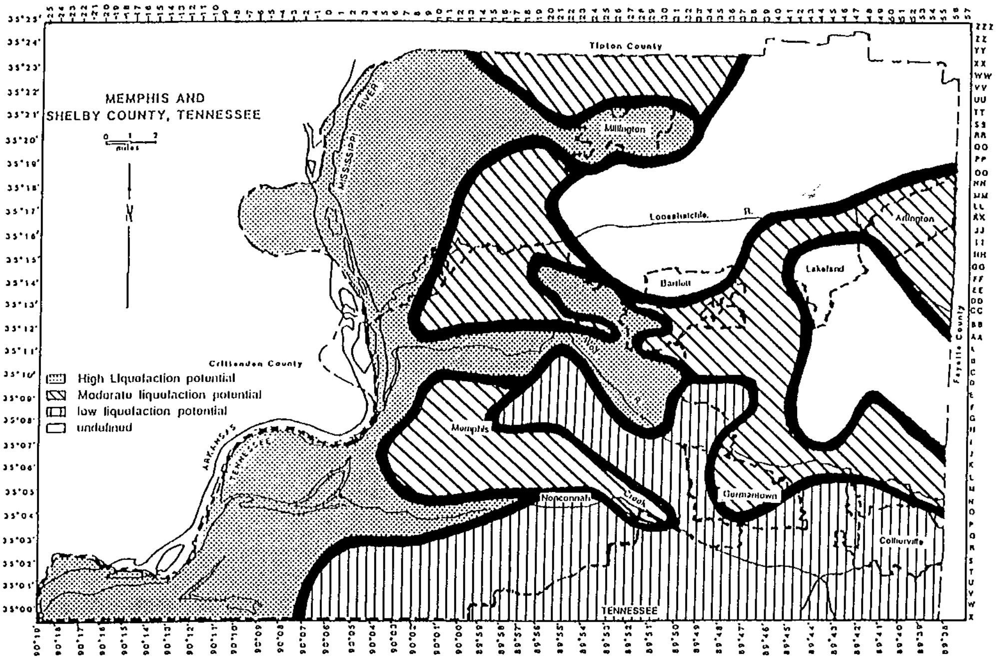

FIG. 8. Liquefaction potential map of Memphis and Shelby County based on CERI criteria (M = 7.5, southern NMSZ; after Chang et al., 1990*b*).

(about 10 to 40%) than estimated by available empirical equations. Beyond 15 psi up to 40 psi, significant increase of shear modulus reduces the differences, and, in some cases, the test results are higher than empirical equation estimations. No simple relationship between low-strain shear modulus and confining pressure is defined for Memphis soils as indicated in some empirical equations. The nonlinear behavior of Memphis soils is significantly different from those of soils elsewhere. Clayey silt (loess) in this region behaves more like cohesionless granular soil than cohesive soil. The dynamic properties of in situ soils are essential for obtaining reliable results of seismic studies. These dynamic properties can be accurately determined in the laboratory for the soils present in the study area.

Further studies will include a complete regional seismic study of general sediments in the NMSZ, including low-strain and high-strain nonlinear dynamic properties and liquefaction resistance. A detailed study of geotechnical properties of loess in the NMSZ region will also be undertaken, because loess is a unique soil and data regarding its engineering properties (fundamental and dynamic) are rare. Such information is essential for regional seismic studies in the NMSZ region.

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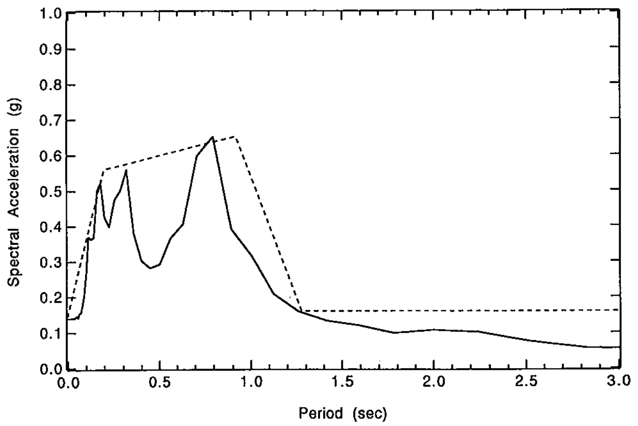

FIG. 9. Approximate response spectrum for site J2 (after Hwang et al., 1990).

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