PROGRESS REPORT ON GEOTECHNICAL EARTHQUAKE STUDIES
AT UNIVERSITY OF MISSOURI-ROLLA, ROLLA, MISSOURI

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SUMMARY

There is growing awareness among the profession today (1980) regarding the earthquake hazard in the midcontinent region of the United States. The New Madrid fault zone is believed to have produced an earthquake of the greatest magnitude experienced in the U.S. in 1811-1812. The soils encountered are loessial and modified loessial soils which are believed to have a characteristically unique structure.

University of Missouri-Rolla has embarked upon an ambitious program of enlarging the present program on microzonation studies in the St. Louis, Missouri area to include determination of dynamic properties and liquefaction characteristics of loess.

Also studies on soil-structure interaction of piles and retaining walls have been planned.

INTRODUCTION

The greater St. Louis area of Missouri and Illinois in the U.S., one of the largest population centers in the Midwest, is located within 200 miles of one of the most seismically active regions in the United States. This seismic region encompasses a portion of southeastern Missouri, southwestern Illinois, western Kentucky and northwestern Tennessee and was the location of the greatest sequence of earthquakes in North American history --the New Madrid earthquakes of 1811 and 1812. The earthquakes caused topographic changes over 50,000 square miles, were felt over two-thirds of the United States, and structural damage was reported as far away as Ohio, South Carolina, and Georgia (Fuller, 1912). Since the events of 1811 and 1812, at least 85 earthquakes of Modified Mercalli Intensity (MMI) V or greater (13 earthquakes of MMI VII or greater) have been recorded within 200 miles of the New Madrid area, Figure 1.

In addition to the proximity of the St. Louis area to an active seismic region, other geologic factors exist to add to the potential for damage from earthquakes. First, one of the distinguishing features of Central United States earthquakes is their large area of perceptibility of ground motion (more widespread and of greater duration and amplitude) as compared to those in the West (Nuttli, 1972). Secondly, the urban expansion has extended onto thick lucustrine and alluvial deposits along the Mississippi and Missouri Rivers and their tributaries, as well as over thick loess deposits on the uplands. Deep deposits of unconsolidated materials tend to amplify earthquake-induced ground motion, resulting in greater intensities and damage at the surface. As an example of the urban expansion, a large

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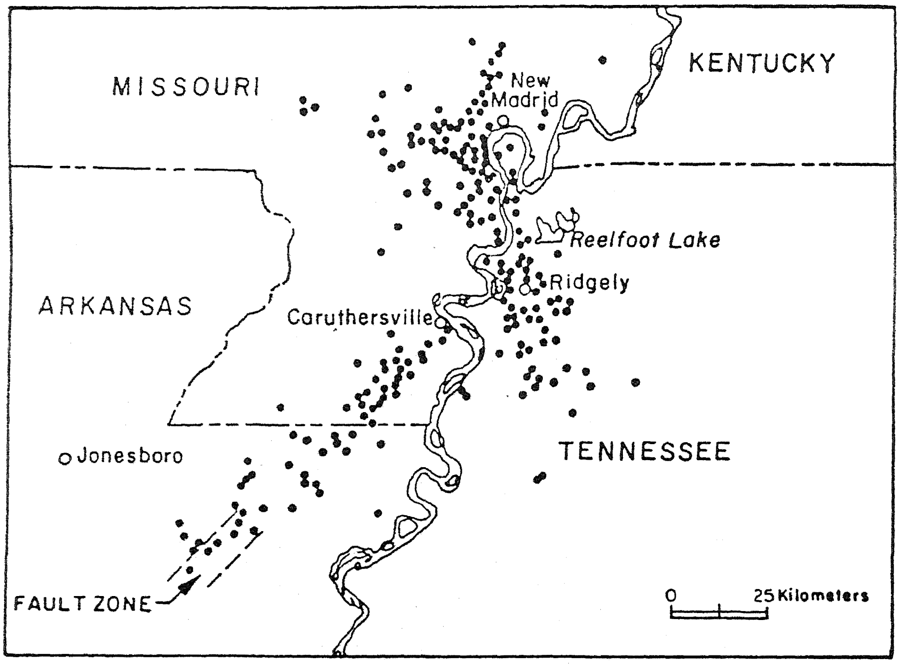

Figure 1. A portion of the New Madrid Fault Zone and Associated Earthquake Epicenters (after U.S. Geological Survey, 1979)

commercial development has been proposed on the Missouri River flood plain in the area of Creve Coeur Lake, St. Louis County. Planned for this area is a large outdoor sports stadium, large industrial parks, commercial hotels, and manufacturing warehousing. The flood-plain deposits of the area consist of over 100 feet of sandy sediment with the water table within 10 feet of the surface. This type of deposit tends not only to amplify the ground motion from earthquakes, but also to be subject to serious ground failure and subsidence due to liquefaction.

As a result, if a large earthquake were to occur with today's population distribution, there would be far more damage than with the 1811 and 1812 events. A recent study of potential earthquake damage for the maximum New Madrid event (Liu and Hsieh, 1979) estimates, for a nighttime occurrence, that the death rate could exceed 370 and the total monetary damages could reach 3.2 billion dollars in the St. Louis area alone.

There is, fortunately a growing awareness among the profession today (1980) regarding the earthquake hazard in the midcontinent region of the United States. The soils encountered in this area are loessial and modified loessial soils which are believed to have a characteristically unique structure. Practically no information is available on the dynamic behavior of such soils.

University of Missouri-Rolla has embarked upon an ambitious program of enlarging the present program being carried out on microzonation studies in the St. Louis, Missouri area and include several new programs to their list.

DYNAMIC PROPERTIES OF LOESSIAL SOILS

Loess is a naturally occurring, predominantly silt-sized aeolian soil, which is to be found in many areas of the central United States and elsewhere. Deposits of depths greater than 100 feet are present in the valleys of the Mississippi and Missouri Rivers.

Although loess is considered to be a fine-grained soil with an average particle diameter of less than 0.074 mm, in its purest form it is cohesionless and consists primarily of particles of one size. Its structure is relatively loose and yields low unit weights (80-90 pcf). It has been known to collapse under loading.

Although some investigations of the engineering properties of loess have been made, very little research has been done in the area of dynamic property evaluation. This is unfortunate, because extensive loessial deposits occur in large urban population centers, such as Memphis, Tennessee, and St. Louis, Missouri. The lack of dynamic response properties is significant, because these centers lie in the proximity of the New Madrid fault zone, along which occurred in 1811-1812 what is believed to be the earthquake of greatest magnitude experienced in the United States. Because of this fact and the increased concern over the lack of earthquake resistant design, it is imperative that data be accumulated on the dynamic characteristics of this material.

Although it is believed by many researchers that silty soils do not liquify as readily as sandy soils, the fact that loessial soils are uniform, cohesionless, and relatively loose could indicate a potential for liquefaction. This is even more possible under the relatively long periods of strong motion believed by many to be characteristics of midcontinent earthquakes.

The major difficulty of conducting laboratory research on loessial soils is that they are easily disturbed during sampling, transportation, and handling. Techniques have been developed at the University of Missouri-Rolla to reduce this factor to a minimum, but further refinement is needed.

The objective of the research is to evaluate by laboratory tests the effect of physical properties of Mississippi Valley loessial soils on the dynamic response properties and to study the influence of the dynamic test parameters (stress magnitude, frequency, and number of cycles) on the dynamic moduli, damping and liquefaction.

Influence of Strain Level on Dynamic Soil Properties. It is well known that the level of induced strain has a profound influence upon the static and dynamic parameter (E, G, and μ) of a soil. Such knowledge has resulted in the development of a variety of tests for evaluating these parameters at various strain levels. However, no single test technique has evolved that allows testing throughout a wide range of strain levels. This is unfortunate because the difficulty of correlating the results of one test type to that of another are compounded by the difficulties of variations in soil types, sampling and handling disturbance effects and other similar problems. These drawbacks have severely hampered the development of constitutive relationships for strain level dependent moduli, Poisson's ratio and damping values.

The measurement of elastic moduli, Poisson's ratio and damping using ultrasonic wave propagation techniques has been done extensively for rock, concrete and other rigid materials. However only a relatively small amount of research has been conducted on unconsolidated materials (soils). Recent research by Stephenson (1978) has indicated possibly useful advantages of this technique for low strain (10^{-4}-10^{-5} %), nondestructive applications. If this equipment could be placed in triaxial test setup having dynamic loading capabilities, then tests could be conducted on a single soil sample to evaluate the parameters in question through a very wide range of strain amplitude. The nondestructive ultrasonic wave propagation tests would yield results in the low strain (10^{-4}-10^{-5} %) range. Dynamic triaxial shear tests would produce results in the intermediate strain (10^{-2}-1%) range. Static triaxial shear tests then would yield the desired parameters in the high strain (10-15%) ranges. Since the entire test sequence could be conducted on a single test specimen, the major obstacle of test sample nonhomogeneity would be eliminated. The results could then be more clearly analyzed for the influence of strain level.

The specific research objectives for this study are:

a. Evaluate the influence of strain level on the E and G moduli, Poisson's ratio and damping for loessial soils.

b. Develop testing equipment to measure the influencing parameters at different levels of strain.

MICROSEISMIC ZONING

In 1978 the United States Geological Survey awarded a research grant to the University of Missouri-Rolla for the purpose of conducting a pilot study to analyze the potential of earthquake-induced geologic hazards in a portion of the Creve Coeur Quadrangle in St. Louis County, Missouri. The primary objectives of the research were to provide an appraisal of the relative levels of individual seismic hazards in the form of zoning maps at detailed scales, and to assess the significant seismic hazards for the study area. The format of the zoning maps was to be useful to engineers and architects, as well as government officials, planners and others involved in land-use planning.

For this study, the appraisal of the relative levles of individual seismic hazards was accomplished by inputting the selected design earthquakes and the static and dynamic properties of the soil deposits into the SHAKE computer analysis to determine the modifications of the ground response from the various soil deposits at the study site. The resulting ground response data, combined with the static and dynamic material properties and data on thickness, topography, and ground-water levels were used to determine the susceptibility of the unconsolidated units to seismic-induced geologic hazards. The relative potential for failure of these units was evaluated on the basis of computed factors of safety for the different levels of ground motion. A schematic outline illustrating the production of the earthquake hazards maps is included in Figure 2.

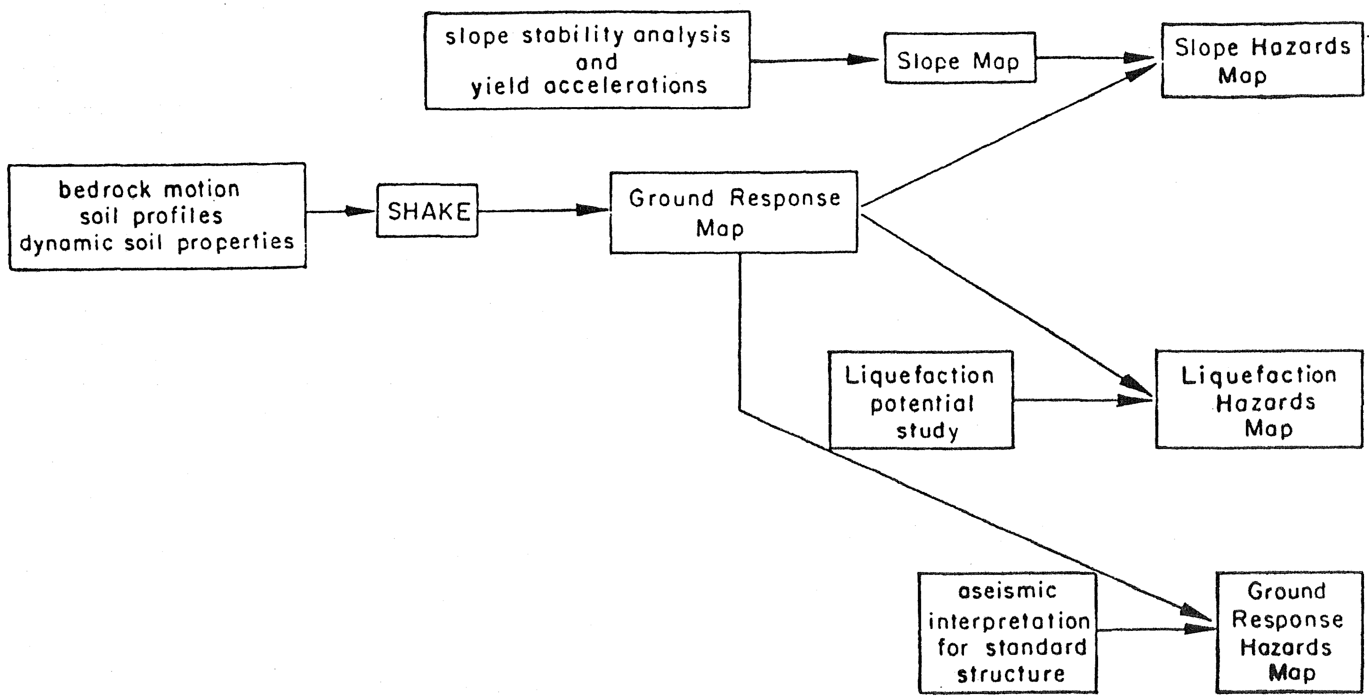

Figure 2. Schematic Outline Illustrating Production of Earthquake Hazards Map.

The result of this study was the development of a set of maps which show the potential for slope failure, liquefaction, and damage to structures from ground motion in the event the maximum expected earthquake were to occur. Since the maps are based on state-of-the-art analytical methods and engineering hazard evaluations, they should be useful in the planning, development, and design of new structures in the rapidly growing Creve Coeur area. In addition, the research has led to the development of systematic techniques for appraisal of individual seismic hazards. This method of seismic hazard analysis is believed to be an improvement over existing procedures since it incorporates both quantitative engineering data and qualitative geologic data. Also, these procedures have a wide range of applicability for seismic zoning studies other than in the St. Louis area.

LIQUEFACTION STUDIES

Liquefaction studies have been performed in the laboratory with the following different types of tests (Yoshimi, 1977):

1. Triaxial tests with completely reversible cyclic shear stresses
2. Triaxial tests with partially reversed or unreversed cyclic shear stresses
3. Cyclic simple shear tests
4. Cyclic torsion tests on hollow cylinders
5. Vibration table tests

Details of all these test set-ups and methods of tests have been described and reviewed adequately in the literature (Seed, 1976).

Vibration table tests have the following advantages over other tests (Yoshimi, 1977; Prakash, 1981). 1) A vibration table test is a full scale test. 2) Simulation of stress conditions has a greater resemblance to field conditions.

Recent vibration table studies reported by Finn (1972), Seed and Silver (1972), Kubo, et al., (1975), De Alba, et al., (1976), Seed, et al., (1978), and Gupta and Prakash (1978), indicate that vibration tables of sizes up to 20' x 13.3' have been used. Table 1 summarizes the salient data of the different types of shake tables. It has been learnt that the larger the size of the table, the larger the difficulties in testing. Pyke, et al., (1975) used 4-ft diameter cylindrical samples covered with steel caps to study settlement on a 4-ft square vibration table. They reported that the stresses were essentially uniform over more than 70% of the area under the caps. It is therefore proposed that a 7' x 3'.6" table be employed for investigations at UMR. This size should provide enough area with uniform stress conditions so that instruments can be placed to monitor the pore pressure in the sample and displacement of small sized footings.

National Science Foundation have made a grant for fabrication and installation of this slip table in the Soil Dynamics Laboratory at UMR. The programmed motion will be imparted through a servo-controlled drive. The equipment for inducing a programmed motion will be improvised by using the drive mechanism of the MTS system already available and interfacing it to an existing minicomputer capable of generating the programmed excitation signal. The response will be digitally recorded by using analog to digital

Table 1

INVENTORY OF SHAKE TABLES

Serial	Size of Table	Self Weight (lb)	Sample Size	Frequency H_z	Amp. inch	Maximum Acc^n (g)	Maximum Vel. in/sec	Surcharge psi	Reference
1	2	3	4	5	6	7	8	9	10
1	9'x6'	1000	6'x1.5'x7"	2	± 2		17	50^2	Finn (1972)
2	10'x7'	--	10'x7'x12"	4	--	0.3	--	2.43^2	Seed & Marshall (1972)
3	30'x13.3'x5'	--	--	--	--	--	--	--	Kubo (1975) Yoshimi (1977)
4	7.5'x3.7'	--	(2'2"x1'2"x4")[1]	--	--	--	--	8^2	De Alba, et al., (1976)
5	4'4'	--	4'φx3"(8.79 ft^2)[1]	4,6	--	--	--	2.56	Pyke, et al, (1976)[3]
6	3'3"x2'x2'1"	--	3'3"x2'x2'1"	5	--	0.6	--	5.5	Gupta & Prakash (1978)

[1]Effective zone of free field stress

[2]Noninertial surcharge

[3]Report on settlement of sand

conversion equipment. The computer is equipped with an on-line plotter and printer.

The proposed slip table will have the following specifications:

1.	Maximum superimposed load of sample and surcharge	66 kips
2.	Frequency	4-6 hz
3.	Maximum amplitude	$\pm$ 5 mm
4.	Maximum acceleration	.1 g

The following instruments will be embedded inside the samples to monitor their response during shaking:

1. Pore pressure transducers
2. LVDT displacement transducers to monitor horizontal and vertical displacement of small sized footings.

The signals from the transducers will be amplified and fed directly into a NOVA Model 3/12 computer. Soil samples will also be tested on the dynamic triaxial equipment and results correlated with shake table data.

The soils in the midwest are predominently silt and modified loess as described earlier. Therefore, the data on liquefaction characteristics of this special material is proposed to be obtained.

STUDIES ON SOIL-PILE INTERACTION

Piles are an obvious choice for supporting engineered structures if the soils close to the ground surface have low strength or high compressibility. The ability of the piles to perform adequately as a foundation is governed by the capacity of the piles themselves as well as their ability to interact with the surrounding soil to transmit the loads to the soil without causing the soil or the piles to fail. Currently, research is being conducted on the nature of the interaction between piles and soil that are subjected to static loading conditions; however, when these structures are subjected to time-dependent loadings, such as those caused by earthquakes, winds water waves, and machine vibrations, dynamic soil-pile-structure interaction becomes important.

Prakash and Chandrasekaran (1973, 1977, 1980), Chandersekaran and Prakash (1980) and Prakash (1981) have studied the problem of soil-pile interaction in detail by using a simple discrete model. In this model, the soil-pile interaction effects are accounted for by including in the model linear springs that are connected to the mass points at one end and to an immovable support at the other. The concept of subgrade modulus has been utilized in finding the values of the spring constants. The problem of finding the natural frequencies of free vibrations of the system was solved by using the transfer matrix method, Tse, et al., (1978). By using this approach, information has been obtained for piles embedded in a soil whose modulus can be considered either to remain constant or vary linearly with the depth. In both the above soil types, solutions have been obtained for conditions of pile top free to rotate as well as for pile top fixed against rotation. In each of the above cases, the influence of the following factors has been analyzed: 1) soil stiffness, 2) flexural stiffness

(EI) of the pile, 3) sustained vertical load assumed as a point load, and 4) pile length.

The question which needs further study is:

The load of a multistoried building is not a concentrated load. The interaction of the superstructure with the piles and the soil needs to be studied to determine response of the system as a whole.

The objective of the research work proposed at UMR is to study the soil-pile-structure interaction for a structure that is a typical residential or industrial building. The system will be idealized by a discrete model with a sufficient number of degrees of freedom.

The natural frequencies of the normal modes of vibration of the combined systems will be compared with those cases in which either the structure is replaced by a point mass at the pile top or the foundation is regarded as being rigid. This comparison will reveal the importance of considering the interaction effects between the structure and the soil-pile foundation.

The response of the combined system to seismic disturbances will be studied by spectral analysis and dynamic analysis of the equations of motion subject to appropriate initial and boundary conditions and actual horizontal earthquake accelerations along one direction. In each case, the response of the combined system will be compared with that of the modified system in which either the structure is replaced by a point mass at the pile top or the foundation is regarded as being rigid.

A parametric study will be undertaken to clarify the role of various parameters involved and to illustrate the influence of various parameters on the soil-pile-superstructure interaction and on the stiffness properties of the soil-pile system. Charts will be presented for use in practical applications.

The findings will be examined and recommendations will be made for decision making in conventional design and for possible inclusion in the future codes to be written in the USA for earthquake resistant design of structures.

STUDIES ON RETAINING WALLS

There are two questions associated with satisfactory performance of a retaining wall namely 1) the dynamic increment in earth pressure and 2) displacement during an earthquake. For rigid walls, the dynamic increment increment in earth pressure is computed and stability of the wall in (1) sliding, (2) overturning and (3) bearing capacity are determined. Most of the methods of determination of dynamic increment in earth pressure depend upon the limiting equilibrium of soil and modification of the Coulomb's theory (Mononobe and Matsuo, 1929 and Prakash and Saran, 1966). The dynamic increment in earthpressure has been shown to be a function of peak ground velocity (Prakash and Nandkumaran, 1979).

There are basically two methods to obtain displacements of rigid retaining walls due to ground motion.

Method 1. In this method, the soil is assumed rigid plastic, i.e., there is no deformation in the soil and hence no displacement in the wall until the factor of safety equals unity.(Newmark, 1965 and Richards and Elms, 1979).

Method 2. In this method, realistic load-deformation characteristics of the wall, both towards and away from the fill and at the base are evaluated. In the simplified model, only translation of the wall has been considered. Effective soil mass from the backfill participating in the vibrations of the wall was evaluated from a laboratory study (Nandkumaran, 1974, Prakash, et al., 1981).

However, this model may not predict the realistic movements of the walls, since the walls do not always undergoe displacements in translation. Therefore, there is a need to develop a realistic model which may consider both rotation and/or translation of the wall.

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