REVIEW OF ENERGY-BASED LIQUEFACTION RESEARCH AT CASE WESTERN RESERVE UNIVERSITY

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ABSTRACT

The development of pore pressure leading to liquefaction of soils subjected to earthquake loadings has been associated by several researchers in recent years to the amount energy imparted to the soil during the dynamic motion. More recently, exploratory laboratory work conducted at Case Western Reserve University indicated that regardless of the mode of stress application, sinusoidal or random, the unit energy needed to initiate liquefaction is nearly constant for a given effective confining stress and a specific relative density. This work also demonstrated that the unit energy imparted to the soil to induce liquefaction is independent of the shear strain amplitude. Data obtained during torsional shear tests made possible the development of relationships between the unit energy required for liquefaction (as the dependent variable) and the effective confining pressure and the relative density (as the independent variables). This paper summarizes these significant developments, and includes preliminary results of tests conducted on soils that liquefied during the recent Northridge Earthquake (Lower San Fernando Valley Dam). The fundamentals of an energy-based method to determine the liquefaction potential of a soil deposit are also presented.

INTRODUCTION

Liquefaction of saturated sandy soils is a common problem in earthquake-prone zones, leading to major damage to buildings, dams and other civil engineering structures. Extensive liquefaction research over the past few decades has helped determine some of the parameters influencing the liquefaction potential of a soil deposit, and procedures to identify these deposits have been developed, combining field and laboratory tests.

After the original introduction of the energy concept in the analysis of the densification and liquefaction of cohesionless soils by Nemat-Nasser and Shokooh (1979), a number of experimental studies conducted by Davis and Berrill (1982), Simcock et al (1983), Berrill and Davis (1985), Law et al (1990), Figueroa (1990) and Figueroa and Dahisaria (1991), Figueroa et al. (1994), and Liang et al (1995) have been aimed at establishing relationships between pore water pressure increases during the dynamic motion and the dissipated energy; and to explore the validity of using the energy concept in the evaluation of the liquefaction potential of a soil deposit.

Using hollow cylindrical specimens of Reid Bedford Sand subjected to sinusoidal torsional loading Figueroa et al (1994) developed a relationship between the dissipated energy per unit volume to reach liquefaction and the effective confining pressure, the relative density and the shear strain amplitude. They found that the dissipated energy per unit volume could conceivably replace both the amplitude of the shear strain and the number of cycles to predict the onset of liquefaction. Later, Liang et al (1995) presented the results of torsional shear tests conducted at different relative densities and confining pressures, using an earthquake-type time series of loading, demonstrating that the energy per unit volume needed to induce liquefaction was independent of the dynamic loading form, and could be used to evaluate the liquefaction potential of soils subjected to earthquakes Figueroa et al (1995) also tested silty sands that liquefied during the recent Northridge Earthquake (Lower San Fernando Valley Dam), and compared the amount of energy per unit volume required for the liquefaction of these soils with that for the Reid Bedford sand, to determine the influence of the grain size distribution

The following sections summarize liquefaction-related research conducted at Case Western Reserve University, its goal being the development of an energy-based practical procedure to determine the liquefaction potential of a soil deposit

LABORATORY TESTING

The soils selected for study were Reid Bedford Sand, obtained from the Reid Bedford Bend, located south of Vicksburg, Mississippi, and Lower San Fernando Dam (LSFD) silty sand, obtained from the Lower San Fernando Dam, in the Los Angeles, California area. Classification tests to determine the properties of these soils included sieve analysis, specific gravity and relative density. Their results are shown in Table 1

The long, thin, hollow cylindrical specimens used in the torsional shear liquefaction testing had the following dimensions.

Outside diameter	=	7.1 cm
Inside diameter	=	5.1 cm
Height	=	12.9 cm
Volume	=	247.2 cm^3

Sample preparation is described in detail in Figueroa et al. (1994).

Test Program

Tests were conducted on specimens at nominal relative densities of 50, 60 and 70 percent for the Reid Bedford Sand, and at relative densities ranging between 57 and 92 percent for the LSFD Silty Sand. Three initial effective confining pressures were used, namely 41.4 kPa, 82.7 kPa and 124.1 kPa; for each relative density

Some of the Reid Bedford Sand tests were conducted using a controlled-strain type device which applies a sinusoidal torsional deformation, through and eccentric mechanical drive The remaining tests on this soil, as well as all tests on the LSFD Silty Sand were conducted with a controlled-stress type device applying a random torsional loading.

Torsional Loading Control

The magnitude of shear strain in the controlled-strain device is a function of the eccentricity in the mechanical drive. While the shear strain is maintained constant throughout the test, the shear stress decreases as the soil begins to liquefy.

A synthetic earthquake time series generation computer package was used to generate a random torsional loading proportional to the time history of the ground acceleration (Seed and Idriss, 1971; Ishihara and Yasuda, 1972 and 1975). Input parameters to this package include: the duration of the earthquake, maximum ground acceleration, intensity envelope function, target response spectrum, and damping ratio. A typical synthetically generated time history of ground acceleration is shown in Figure 1 The controlled-stress torsional shear device is computer-controlled The digital signal from the synthetic time series of acceleration is converted to an analog form and sent to an Electric-to-Pneumatic Transducer to provide the needed actuating forces.

RESULTS AND ANALYSIS

Liquefaction is considered to occur when the developed pore water pressure becomes equal to the applied effective confining pressure at all stages of loading. Torsional shear testing of granular soils permits the determination of hysteresis loops showing the variation of the shear stress with the shear strain up to liquefaction. Figure 2 shows an example of the characteristic decay in the shearing resistance of a Reid Bedford Sand specimen before the development of liquefaction; and the progressive flattening of the loops, indicating the softening of the soil as the pore water pressure increases. The specimen was prepared at a nominal relative density of 60%, and was subjected to sinusoidally varying torsional loading, at an effective confining pressure of 124.1 kPa and a shear strain amplitude of 0 47%.

Results of a series of sinusoidal torsional tests on this sand showed that the accumulated unit energy to liquefaction is constant for a certain combination of parameters affecting the development of liquefaction. The accumulated energy per unit volume (δW) absorbed by the specimen up to liquefaction can be calculated from the hysteresis loops (Figueroa et al , 1994)·

$$\delta W = \sum_{i=1}^{n-1} \frac{1}{2}(\tau_i + \tau_{i+1})(\gamma_{i+1} - \gamma_i) \qquad (1)$$

where:

τ = shear stress;
γ = shear strain;
n = number of points recorded to liquefaction.

Generalized relationships were obtained by Figueroa et al (1994), after conducting 27 liquefaction tests, by performing regression analyses between the energy per unit volume dissipated in generating liquefaction as the dependent variable and the relative density, confining pressure and amplitude of the applied shear strain as the independent variables. Following are the most significant relationships (those with the highest coefficient of determination R^2) which were developed.

$$\delta W = -2124.23 + 14\,05\,\sigma_c' + 37.16\,Dr + 174.66\,\Gamma; \qquad R^2 = 0\,934; \qquad (2a)$$

$$\delta W = -2028.13 + 14\,05\,\sigma_c' + 37\,15\,Dr; \qquad R^2 = 0.922; \qquad (2b)$$

where.

δW = Energy per unit volume (J/m^3);
σ_c' = Initial effective confining pressure acting on the sample (kPa);
D_r = Relative density of the sample (%),
Γ = Amplitude of the applied shear strain (%);
R^2= Coefficient of determination,

$$\text{Log}_{10}(\delta W) = 1.982 + 0.00477\,\sigma_c' + 0.0116\,Dr + 0.0376\,\Gamma, \qquad R^2=0.942; \qquad (3a)$$

$$\text{Log}_{10}(\delta W) = 2.002 + 0.00477\,\sigma_c' + 0.0116\,Dr; \qquad R^2=0.937; \qquad (3b)$$

Equations 2a and 3a use all of the parameters in the regression while equations 2b and 3b use two of the three parameters, which are relative density and effective confining pressure. By comparing equation 2a with equation 2b and 3a with 3b, it can be seen that including the effect of the amplitude of shear strain (Γ) only improves the coefficient of determination by 0.012 for equation 2a and 0.005 for equation 3a. Inclusion of the shear strain changes the constants by less than 5%; and barely changes the coefficients corresponding to other parameters. It can be concluded that for the tests conducted in this program, the effect of the shear strain amplitude (Γ) can be ignored in establishing the relationship between the energy per unit volume for liquefaction and the influence parameters. Because of the high Coefficient of Determination which is obtained for Equation 3b, it is also concluded that this equation provides the best fit for the data. However, the linear fit expressed by equation 2b also yields a very high coefficient of determination and may be preferred because of its simplicity. These equations show that.

1. For the same initial effective confining pressure, the energy per unit volume increases with the relative density of the soil. Thus a higher amount of energy is required to liquefy a sand with a higher relative density.

2. For the same relative density, more energy per unit volume is dissipated with increased applied effective confining pressure.

3 There is very little difference between the energy per unit volume needed for the onset of liquefaction under sinusoidal and under random loading. Regression analysis will now be used to judge the significance of these differences.

Figure 3 shows characteristic hysteresis loops obtained after testing Reid Bedford Sand using a non-uniform shear stress As in the sinusoidal torsional loading (constant strain) tests, the loops tend to become progressively flatter as the sample begins to liquefy; and after liquefaction the stress-strain relationships are almost horizontal. The area of the hysteresis loops also nears zero at liquefaction. The specimen was prepared at a relative density of 59.9% (nominal 60%) and was subjected to an initial effective hydrostatic pressure of 124.1 kPa.

At the beginning of the test, the specimen is stiff and the shearing resistance can build up without large displacements However as the stiffness (shear modulus) decreases, larger deformations take place with decreasing shearing resistance. This resistance is almost negligible when the sample liquefies. Similar observations were made by other researchers using stress controlled hydraulic or pneumatic loading systems (Ishihara and Yasuda, 1972).

The response time history of the resisting shear stress and the corresponding power spectrum show a frequency band width similar to that of the excitation (Liang et al., 1995) However, specimens prepared at a higher relative density and subjected to a higher initial effective confining pressure develop a shear stress power spectrum closer to the excitation spectrum than the spectrum of specimens prepared at a lower relative density and subjected to a lower initial effective confining pressure.

As in the sinusoidal torsional tests, relationships were obtained by performing regression analyses between the energy per unit volume at the onset of liquefaction as the dependent variable and the relative density and the initial effective confining pressure as the independent variables. Several relationships such as linear, second order polynomials and logarithmic were examined; however, the following equation provided the best fit to the data obtained from nine non-uniform torsional loading tests, conducted at combinations of three relative densities and three effective confining pressures:

$$\text{Log}_{10}(\delta W) = 2\ 062 + 0.0039\ \sigma_c' + 0.0124\ Dr; \qquad R^2 = 0\ 925; \qquad (4)$$

The similarity of Equations. 3b and 4 is striking, and it may be stated that they are equivalent. A statistical F-test, as described by Sen and Srivastava (1990), was used to test this hypothesis. Results of the F-test, presented by Liang et al. (1995) strongly support the validity of the hypothesis.

The influence of grain size on the amount of energy per volume at the onset of liquefaction was examined by conducting random-loading torsional shear tests on soils that liquefied during the recent Northridge Earthquake (Lower San Fernando Valley Dam). Index properties and classification of these finer soils were already shown in Table 1. The LSFD Silty Sand contains up to 28% of silt, as compared to a negligible amount in the Reid Bedford Sand. Testing was conducted using the same time series of non-uniform torsional stress as in the Reid Bedford Sand with combinations of four nominal relative densities and three effective confining pressure for a total of twelve tests (Figueroa et al , 1995)

Figure 4 compares the amount of energy per unit volume to the onset of liquefaction for the Reid Bedford Sand and for the LSFD silty sand. The finer LSFD soil requires lower unit energy for liquefaction, within the ranges tested, than the coarser Reid Bedford Sand at the same effective confining pressure. The influence of relative density on the energy per volume is practically eliminated with increased silt content, regardless of the value of the effective confining pressure, as can be seen in the following equations

$$\text{Log}_{10}(\delta W) = 2\ 484 + 0\ 00471\ \sigma_c' + 0.00052\ Dr; \qquad R^2 = 0.995, \qquad (5)$$

$$\text{Log}_{10}(\delta W) = 2.529 + 0.00474\ \sigma_c', \qquad R^2 = 0.994; \qquad (6)$$

The elimination of the relative density from the regression (Equation 6) barely affects the constant, the coefficient for σ_c' and the coefficient of determination, as compared with Equation 5. This may be the result of modifying the kinematics of the granular soil by the significant presence of silt in the inter granular spaces

SUMMARY AND CONCLUSIONS

The use of the energy concept to define the liquefaction potential of a soil has been examined through a series of laboratory tests conducted on Reid Bedford sand and Lower San Fernando Dam Silty Sand. Results of nine torsional shear tests conducted at different relative densities and confining pressures, using an earthquake type time series of torsional loading, were compared to those obtained from tests conducted under sinusoidally applied strains. This comparison, supported by regression analysis, confirms the conclusion that the energy per unit volume needed to induce liquefaction is independent of the dynamic loading form and can be used to evaluate the liquefaction potential of a soil under earthquake excitation.

Similarly, the influence of relative density on the energy per volume was examined by comparing the results of liquefaction testing of Lower San Fernando Dam Silty Sand , with similar tests using Reid Bedford Sand. Its influence is practically eliminated with increased silt content, regardless of the value of the effective confining pressure. This may be the result of modifying the kinematics of the granular soil by the significant presence of silt in the inter granular spaces

All these findings provide a link between laboratory and field behavior and provide the basis for the development of an energy-based method to evaluate the liquefaction potential of a soil deposit. In simple terms, the energy per unit volume needed for liquefaction and determined in the laboratory through the torsional shear testing of undisturbed (if possible) or reconstructed soil specimens from a specific deposit would be compared to the energy per unit volume induced by the random excitation of an earthquake. If the latter, determined with the aid of advanced soil response models to earthquake loadings, is higher than the former, the deposit would experience liquefaction

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REFERENCES

Berrill, J.B. and Davis, R.O., "Energy Dissipation and Seismic Liquefaction of Sands: Revised Model," Soils and Foundations, Vol. 25, No. 2, pp 106-118, 1985

Davis, R. O. and Berrill, J. B., "Energy Dissipation and Seismic Liquefaction in Sands," Earthquake Engineering and Structural Dynamics, Vol. 19, pp. 59-68, 1982.

Figueroa, J.L., "A Method for Evaluating Soil Liquefaction by Energy Principles," Proceedings, Fourth U.S. National Conference on Earthquake Engineering, Palm Springs, CA - May 1990.

Figueroa, J.L., Dahisaria, M.N., "An Energy Approach In Defining Soil Liquefaction," Proceedings, Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics - University of Missouri-Rolla - March 1991.

Figueroa, J.L., Saada, A.S., Liang, L. and Dahisaria, M.N., "Evaluation Of Soil Liquefaction By Energy Principles," Journal of the Geotechnical Engineering Division, ASCE, Vol. 120, No. 9, Proc. Paper 1841, pp. 1554-1569, 1994

Figueroa, J L., Saada, A.S., and Liang, L "Effect of Grain Size on the Energy per Unit Volume at the Onset of Liquefaction" Accepted for Presentation and Publication, Proceedings, Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics - University of Missouri-Rolla - April, 1995

Ishihara, K. and Yasuda, S , "Sand Liquefaction In Hollow Cylinder Torsion under Irregular Excitation," Soils and Foundations, Vol. 15, No. 1, pp 45-59, 1975.

Ishihara, K and Yasuda, S., "Sand Liquefaction Due To Irregular Excitation," Soils and Foundations, Vol. 12, No. 4, pp. 65-77, 1972.

Law, K.T., Cao, Y L., and He, G N., "An Energy Approach for Assessing Seismic Liquefaction Potential," Canadian Geotechnical Journal, Vol. 27, pp 320-329, 1990.

Liang, L., Figueroa, J.L., and Saada, A.S. "Liquefaction Under Random Loading: A Unit Energy Approach," Accepted for Publication Journal of the Geotechnical Engineering Division, ASCE, 1995

Nemat-Nasser, S., Shakooh, A., "A Unified Approach to Densification and Liquefaction of Cohesionless Sand in Cyclic Shearing," Canadian Geotechnical Journal, Vol. 16, pp. 659-678, 1979.

Seed, H.B and Idriss, I.M., "Simplified Procedure for Evaluating Soil Liquefaction Potential," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol.97, No.SM9, September, pp.1249-1274, 1971.

Sen, A. and Srivastava, M., "Regression Analysis: Theory, Methods and Applications," Springer-Verlage, New York Inc., 1990.

Simcock, J., Davis, R.O., Berrill, J.B. and Mallenger, G., "Cyclic Triaxial Tests with Continuous Measurement of Dissipated Energy," Geotechnical Testing Journal, GTJODJ, Vol. 6, No. 1, pp. 35-39, 1983.

Table 1. - Index Properties and Classification (Figueroa et al., 1995)

Property	Reid Bedford Sand	LSFD Silty Sand
USCS Group	SP	SM
Specific Gravity	2.65	2.67
Max. Void Ratio	0.85	1.22
Min. Void Ratio	0.58	0.71
D_{50}	0.26 mm	0 13 mm

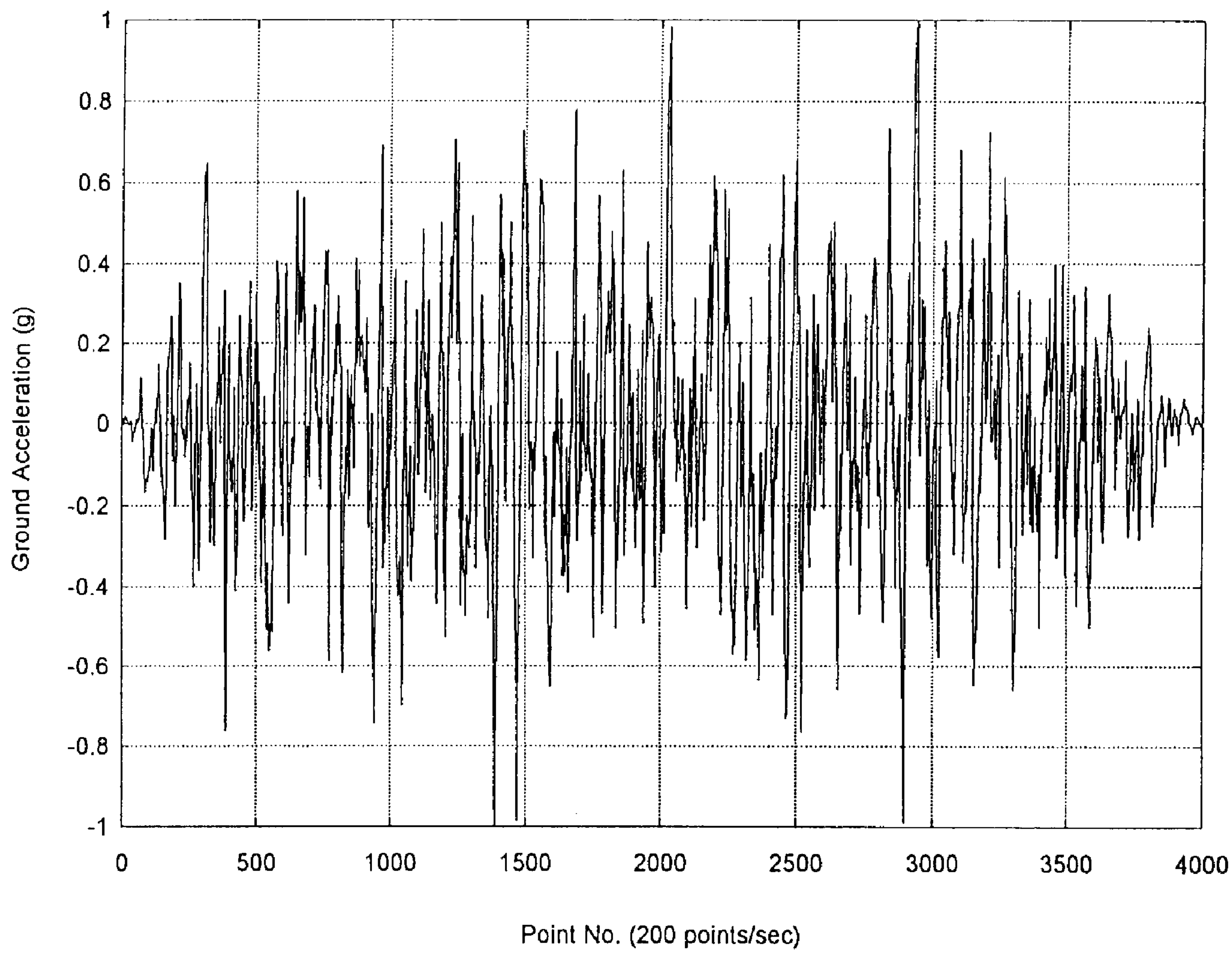

Figure 1. Simulated Ground Acceleration (Liang et al., 1995)

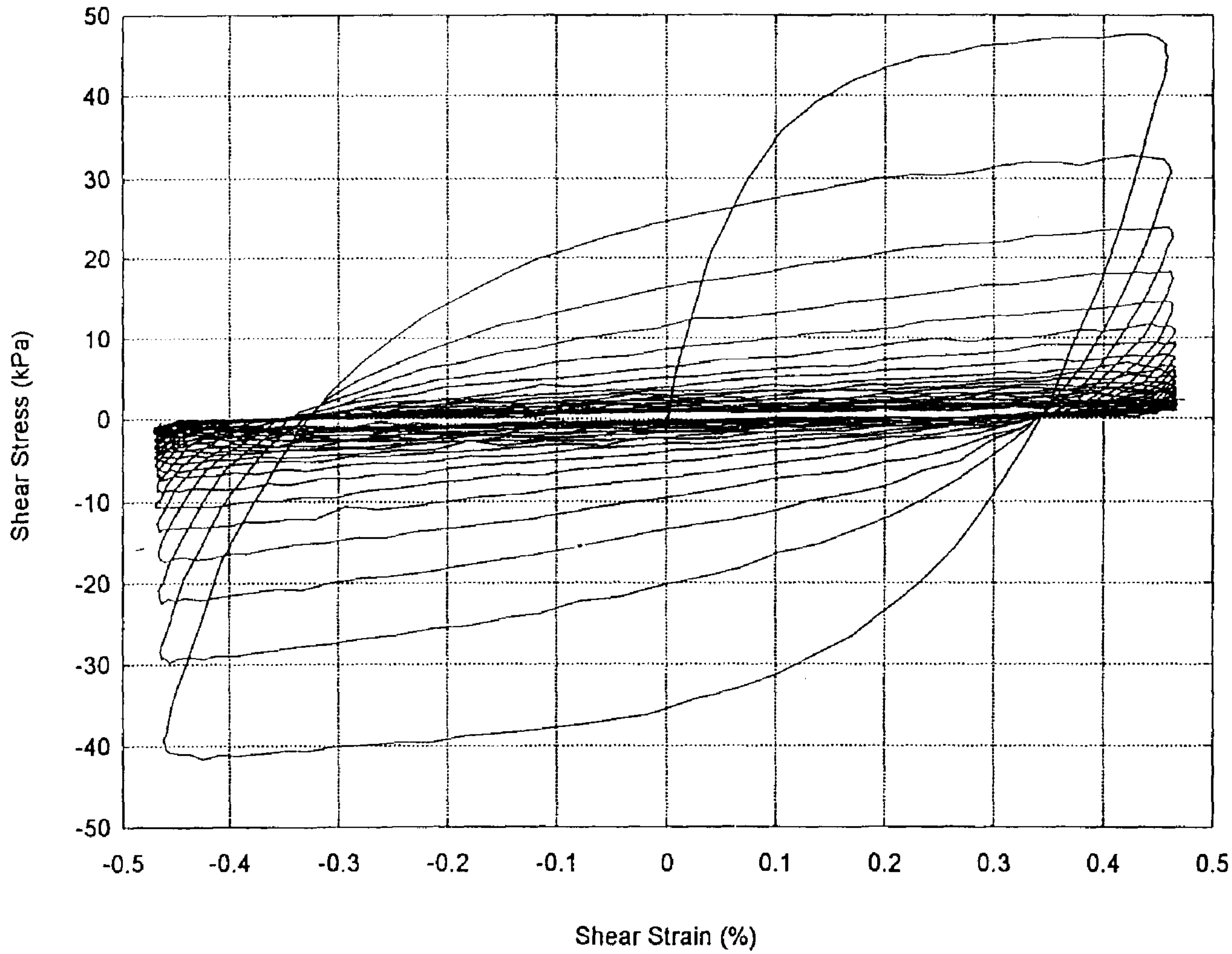

Figure 2. Shear Stress-Strain Relationships During Sinusoidal (Strain Controlled) Torsional Shear Testing (Figueroa et al., 1994)

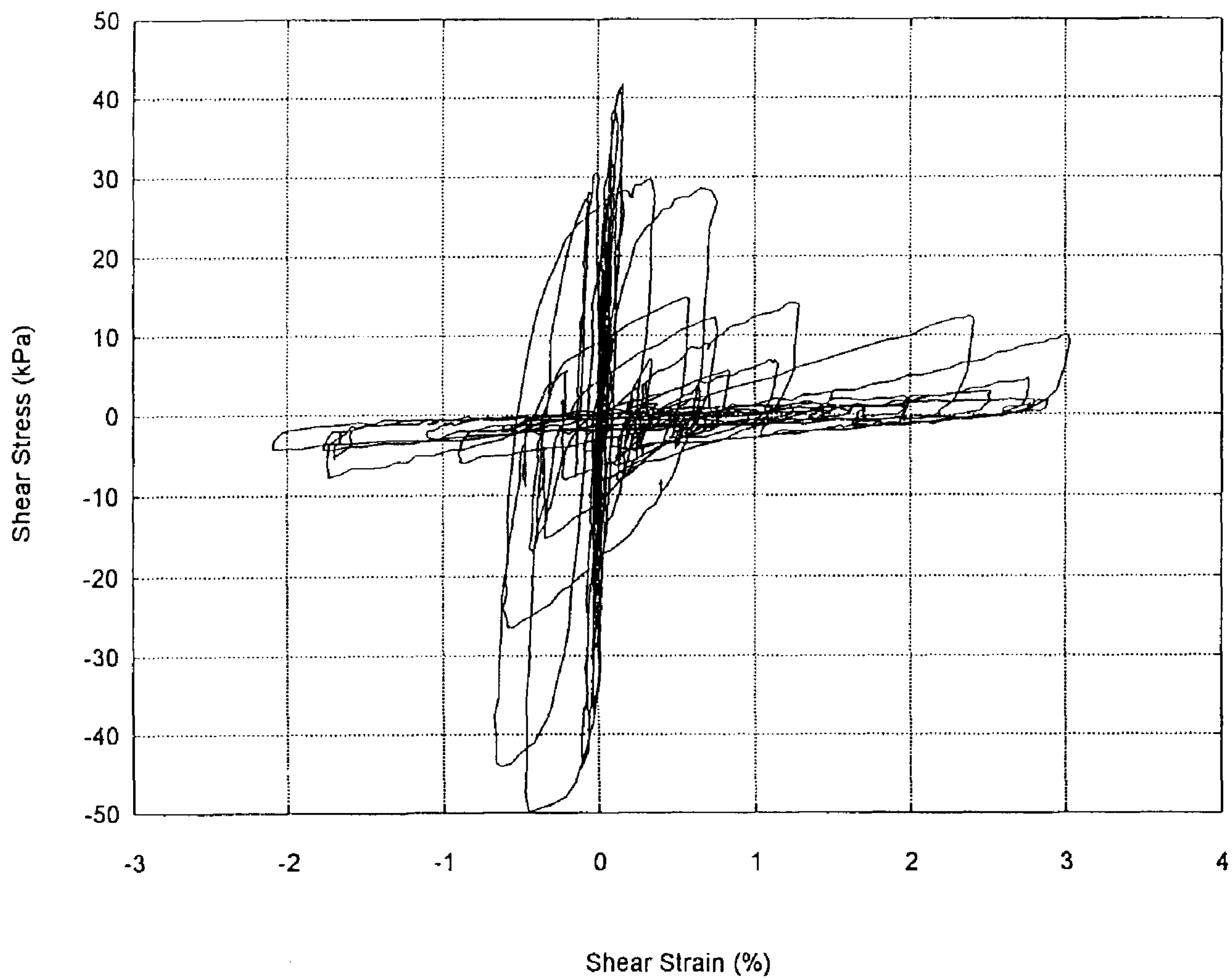

Figure 3. Shear Stress-Strain Relationships During Random (Stress Controlled) Torsional Shear Testing (Liang et al., 1995)

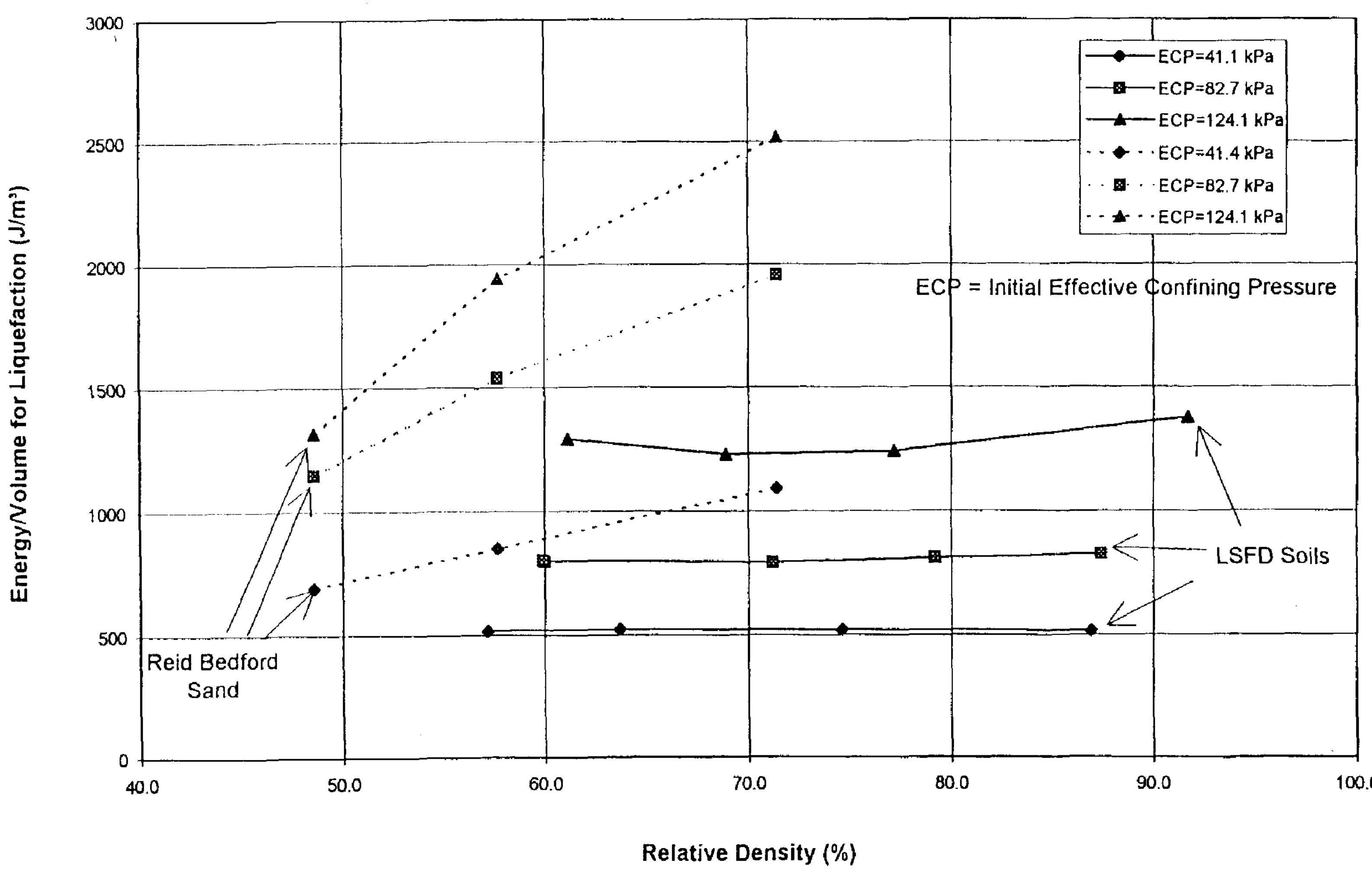

Figure 4. Effect of Grain Size on the Energy/Volume for Liquefaction (Figueroa et al., 1995)