An Energy Approach in Defining Soil Liquefaction

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SYNOPSIS:The concept of energy to define liquefaction has been recognized by several authors. This approach has the advantage over other known methods to define liquefaction of considering a fundamental concept (energy), and of offering the potential of more closely considering random motion effects such as those introduced by earthquake loading.

This paper presents the development of relationships between normalized pore pressure and unit energy required to induce liquefaction from testing hollow cylinder sand specimens prepared at different relative densities, and subjected to different confining pressures and shear strain amplitudes. Specimens were tested under constant maximum strain using a sinusoidal torsional shear device. These relationships are useful in determining the required amount of energy to induce liquefaction which coupled with a time series record of the design ground motion would allow the determination of the liquefaction potential of a soil deposit.

INTRODUCTION

Liquefaction has been recognized, for over a century, as a potential form of failure when loose and saturated granular soils are subjected to dynamic loads. The granular soil essentially behaves as a dense liquid when the pore pressure buildup equates the existing effective stress. This also implies that the soil is unable to develop any shear strength, thus affecting the stability of any structures supported on it.

Liquefaction-related research has been extensive in recent decades. The development of more advanced testing and monitoring equipment has certainly contributed to increased studies in this aspect of geotechnical engineering. Laboratory testing of granular soils thus can be conducted under conditions resembling actual field situations.

Researchers have properly identified the parameters affecting the liquefaction potential of granular soils including soil type, void ratio, confining pressure as well as intensity and duration of dynamic loading. In addition liquefaction studies have been extended to field applications in an effort to determine the liquefaction potential of a soil deposit.

The concept of histeretic damping of soils subjected to cyclic shearing is well known by researchers and practitioners alike. This implies a certain level of energy needs to be imparted to undrained and saturated soils to induce liquefaction. The concept of energy to define liquefaction has been recognized by several authors including Nemat-Nasser et al.(1976), Hoshiya et al. (1986), and Figueroa (1990). This approach has the advantage over other known methods to define liquefaction of considering a fundamental concept (energy), and of offering the potential of more closely considering random motion effects such as those introduced by earthquake loading.

This paper presents the results of the liquefaction testing of hollow cylinder sand specimens prepared at different relative densities, and subjected to different confining pressures and shear strain amplitudes. Specimens were tested under constant maximum strain using a sinusoidal torsional shear device. Relationships between normalized pore pressure and unit energy required to induce liquefaction were developed from test results. These relationships are useful in determining the required amount of energy to induce liquefaction which coupled with a time series record of the design ground motion would allow the determination of the liquefaction potential of a soil deposit.

SPECIMEN PREPARATION AND TEST PROCEDURE

All hollow cylinder specimens used in the liquefaction study were prepared using a uniform (Reid Bedford) sand classified as SP according to USCS. Specimens were dry-compacted by vibration at relative densities of 50, 60 or 70%. The test plan included conducting torsional shear tests with specimens subjected at nominal confining pressures of 10, 20 or 30 psi, and at three levels of maximum shear strain including 0.0102, 0.056, and 0.0045, thus requiring a total of 27 tests to determine the levels of energy for liquefaction. All test were conducted with a backpressure of 20 psi.

Hollow cylinders (2"i.d. x 2.8"o.d. x 5.08"h) were selected because of the smaller radial change in the shear stress occurring between the inside and the outside wall of the cylinder, as compared to the significant change in the stress in a solid cylinder between zero at the center and a maximum at its perimeter. Specimens were subjected to periodic sinusoidal torsional shear strains applied at a frequency of 0.1 Hz, until liquefaction developed.

Carbon dioxide was circulated through the water pressure lines and the specimen before saturation. This promotes its complete saturation. Pore water pressure, torque, angular and vertical displacements were monitored every 0.1 sec with an A/D converter residing in a microcomputer, as well as continuously with a strip chart recorder. Unprocessed data (voltage readings) from the displacement, pressure and torsional transducers were stored for further analysis.

The calculation of the shear stress from the torque and the shear strain from the angular displacement at each data point permitted the definition of the histeresis loops up to the point of liquefaction. The accumulated energy per unit volume for liquefaction (W) is calculated by the expression:

$$W = 0.5\ \Sigma\ [\tau_0(\gamma_{i-1} - \gamma_i) + \tau_{i-1}(\gamma_i - \gamma_0) + \tau_i(\gamma_0 - \gamma_{i-1})] \quad (1)$$

with:

τ = Shear stress in psi

γ = Shear strain

This equation is valid for i=2 to the number of data points, and with initial shear stress and strain equal to zero.

TEST RESULTS AND ANALYSIS

Typical cyclic torsional shear test results leading to the liquefaction of a sand specimen are presented in Figures 1 to 4. The test parameters included a relative density of 70%, a nominal confining pressure of 30 psi, and a shear strain amplitude of 0.0102.

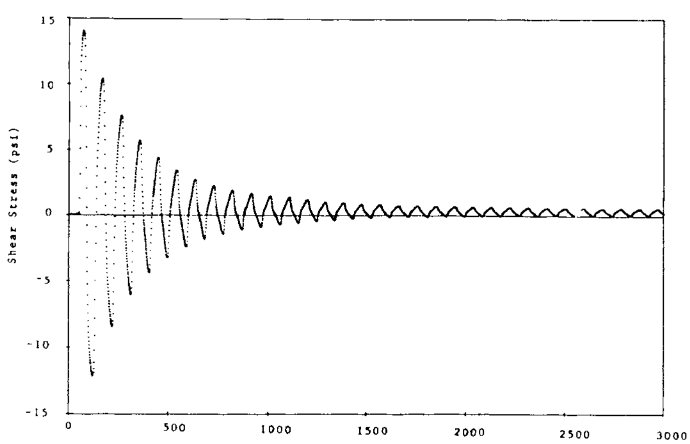

Figure 1. Typical Shear Stress Decay During a Liquefaction Test

Figure 1 shows the characteristic decay in shear stress with time (each point was obtained at 0.1 sec intervals). Once liquefaction occurs (after about 130 sec) there is no further decrease in the shear stress. The remaining shear stress may be associated with the inherent test system friction.

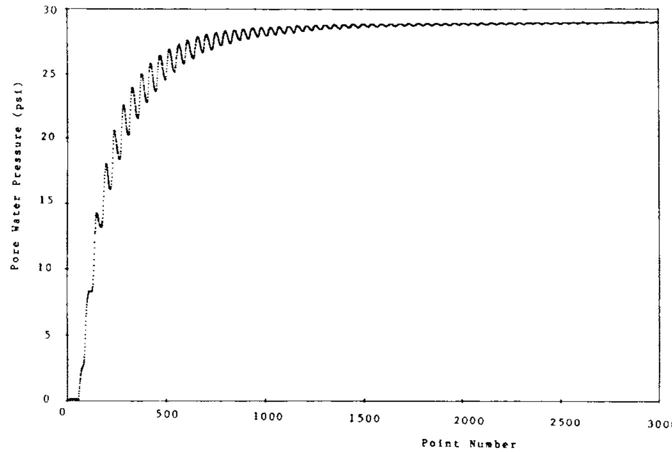

Figure 2. Pore Pressure Increase Leading to Soil Liquefaction

Rapid increases in the pore pressure develop during the first few cycles as indicated in Figure 2. Pore pressure continues to increase at a decreasing rate up to the point of liquefaction where it remains approximately constant. Even though the test was conducted at a nominal confining pressure of 30 psi, liquefaction developed at a pressure nearing 29 psi, as indicated by the horizontal portion of the curve shown in Figure 2.

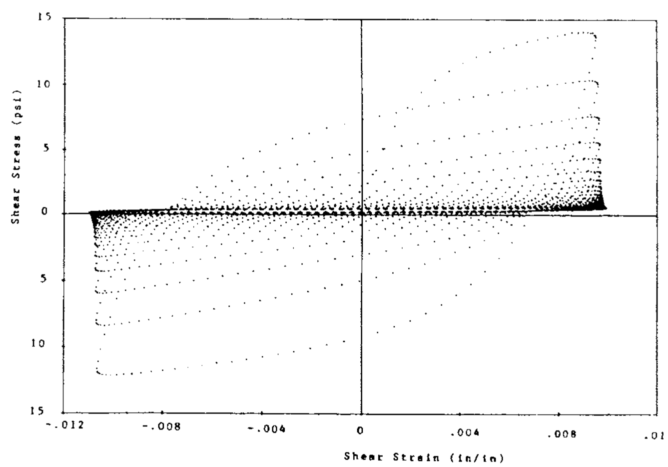

Figure 3. Characteristic Histeresis Loops During a Liquefaction Test

Characteristic shear stress-shear strain cycles leading to the complete degradation of the specimen after liquefaction are presented in Figure 3. As expected, the shear stress approaches zero after liquefaction, and no additional energy is imparted to the soil beyond this point. Any additional work shown is associated with inherent losses of the testing system. In addition, the shear modulus approaches zero when liquefaction develops as shown if Figure 4.

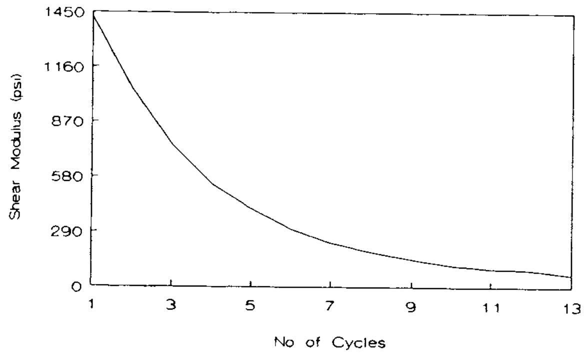

Figure 4. Shear Modulus Variation per Cycle before Liquefaction

The concept of energy in defining liquefaction is evident in Figure 5, where the normalized pore water pressure vs. energy per unit volume is depicted for the same test. The pore pressure has been normalized by the effective confining stress, which would then approach to a value of one when liquefaction develops. A least squares polynomial regression between the normalized pore pressure (u/σ_3) as the dependent variable and the energy per volume (W in lb-in/in^3) as the independent variable yields a highly significant expression of the form:

$$u/\sigma_3 = 0.0067 + 1.756\ W - 0.801\ W^2 \qquad (2)$$

with:

R = 0.9969 Regression coefficient

R^2 = 0.9939 Coefficient of Determination

Sx = $1.466\text{x}10^{-2}$ Standard error of estimate

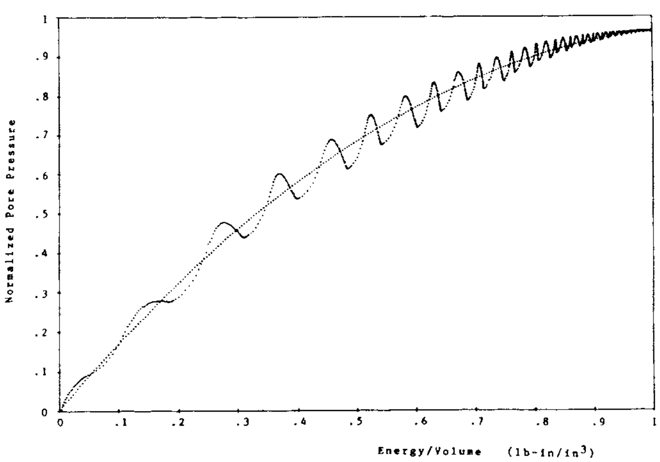

Figure 5. Normalized Pore Pressure as a Function of Unit Energy up to Liquefaction

A reversed relationship between the energy/volume as the dependent variable and the normalized pore pressure as the independent variable is also best fitted with a polynomial function of the form:

$$W = 0.0182 + 0.2284\ (u/\sigma_3) + 0.7291\ (u/\sigma_3)^2 \qquad (3)$$

with:

R = 0.9919

R2 = 0.9839

Sx = $3.35\text{x}10^{-2}$

The same data is also fitted with a power function which also yields a high coefficient of determination, with the form:

$$u/\sigma_3 = 1.036\ W^{0.69} \qquad (4)$$

with:

R^2 = 0.983

However, it is noted that although the coefficient of determination is high for the power function, the polynomial function best represents the relationship between the normalized pore pressure and the energy/volume when approaching liquefaction.

Similar relationships have been developed by Dahisaria (1990) for tests conducted under different conditions according to the detail previously indicated. Figure 6 shows the regression lines between normalized pore water pressure and energy/ volume determined for identical test conditions except for different confining stresses as indicated in the figure. All regression equations yield a coefficient of determination nearing one indicating a strong interrelation between these two parameters, and consequently between the development of liquefaction and the required level of energy. The effect of confining stress in the development of liquefaction is evident, as more stress cycles and consequently more energy is required for testing at higher confining stresses.

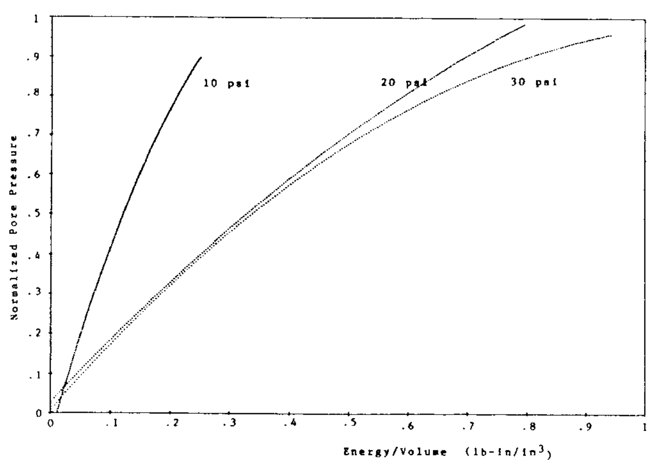

Figure 6. Effect of Confining Stress on the Normalized Pore Pressure vs. Unit Energy Relationship (Values Given Indicate Confining Stress)

A normalized pore pressure approaching unity is indicative of imminent liquefaction.

Engineering practice would greatly benefit if relationships between the level of energy required for liquefaction, and factors identified to affect the liquefaction potential of soil deposits could be developed. Efforts are currently underway in this regard, and preliminary results indicate that significant relationships do exist. Results of the complete research effort will be presented in ensuing publications.

SUMMARY AND CONCLUSIONS

Significant and unique relationships between the normalized pore water pressure and the energy per volume imparted to the soil to produce liquefaction were developed. These relationships, based on more accurate torsional shear test results, offer the potential for application in geotechnical engineering practice, as a certain level of unit energy is required to develop liquefaction for characteristic test conditions.

The energy approach offers the potential for application in the evaluation of the liquefaction potential of a soil deposit by calculating the unit energy level imparted to the soil during the non-uniform dynamic motion, from a time series record of the design earthquake. This level is then compared with the required unit energy for liquefaction for the existing field conditions to determine whether or not liquefaction will occur at the site.

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