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Effect of Fines Content on the Cyclic Undrained Behavior of Sand

Paper No. 1.31

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SYNOPSIS The influence of fines on the liquefaction potential of sandy soils has been studied by conducting isotropically consolidated stress controlled triaxial tests. Experimental results are compared with predictions using the theory developed by Nasser and Shokooh which is based on energy considerations. The theory determines the excess pore water pressure in terms of the number of cycles N, the dimensionless shear stress amplitude , and the initial and minimum values of the void ratio. The comparisons show good agreement between experimental data and model predictions for the pore water generation under cyclic loading for both loose and medium sands and medium silty soils.

INTRODUCTION

There are controversial results on liquefaction of silty sands and the effect of silt content on liquefaction potential. Investigations on liquefaction potential of silty soils are limited, though there is an extensive amount of research done on liquefaction of pure sand. In this paper, effect of fines content on pore pressure buildup during stress controlled tests are predicted by a model formulated by Nemat-Nasser and Shokooh. Testing data is obtained from undrained normally consolidated stress controlled tests (Erten, 1994). The undrained behavior of silty sands were also investigated based on strain controlled tests and results showed the same trend with stress controlled tests (Erten & Maher, 1994).

Theory is based on the fact that densification and liquefaction of the soils involve rearrangement of the grains, requiring a release of certain amount of energy which is related to changes in void ratio and pore water pressure. This energy increases as the void ratio approaches its minimum value depending on the confining pressure, shape distribution of sand particles and the size of the particles. A simple differential equation is proposed which relates the energy loss in cyclic loading to the consequent increase in the pore pressure in the saturated undrained case. The theory is then applied in its simplest form to predict some of the existing experimental results for liquefaction phenomena (Nasser and Shokooh, 1979).

THEORY

The theory, as proposed by Nasser and Shokooh involves two parameters, one of which is fixed by the densification consideration and the other one is expressed explicitly as a function of initial void ratio, e_0 the minimum void ratio, e_m and other relevant parameters. During cyclic shearing, to change void ratio from e to $e+de$, a certain amount of energy is expended. This energy is an increasing function of $e-e_m$ and a decreasing function of the excess pore pressure, p. Here, e is the void ratio and it can not be decreased below its minimum , without the expenditure of an infinite amount of energy. When the test is run under undrained conditions, as e decreases, pore water pressure, increases. Since, the particles rearrange themselves more easily, this causes further increase in the pore pressure. The above observations can be quantified as:

$$hN\tau_0^{\alpha+1} = \frac{\nu e_0}{\eta_w g(e_0-e_m)}\int_0^p \frac{dp'}{f(1+p')} \qquad (1)$$

where the left hand side is the work performed and the right hand side is the work required during cyclic shearing. The parameters h and α are parameters which, depend on the history of the deformation, confining pressure and the initial value of the relative density. It is reasonable to expect that, h should increase with increasing confining pressure and with increasing density. Here η_w is bulk modulus of water, $dp = d\bar{p} / \sigma_c$ and ν is a positive parameter. $\hat{\tau}_0$ which is the maximum shear stress amplitude for a cyclic shearing, is normalized by dividing it by the confining pressure, $\tau_0 = \hat{\tau}_0 / \sigma_c$. N is the number of cycles to liquefaction. The simplest theory corresponds to the following elementary forms for the functions f and g in equation 1 are as follows:

$$f(1+p) \equiv (1+p)^r, \qquad r>0 \qquad (2)$$

$$g(e_o - e_m) \equiv (e_o - e_m)^n, \quad n > 1 \qquad (3)$$

Substitution of these functions into 1 and integration, equation 4 is obtained,

$$hN\tau_0^{\alpha+1} = \frac{\hat{\nu}e_0}{(e-e_0)^n}\left[1-(1+p)\right]^{1-r} \qquad (4)$$

where, $\hat{\nu} = \nu/(r-1)\eta_w$.

Here, η and $\hat{\hat{\nu}} = \hat{\nu}/h$ can be introduced as follows:

$$\eta \equiv N_l \tau_0^{\alpha+1} \frac{(e-e_0)^n}{e_0} = \hat{\nu}(1-2^{1-r}) \qquad (5)$$

For a given sand with grain size and shape distribution known, $\hat{\hat{\nu}} = \hat{\nu}/h$ depends on the relative density and confining pressure. Here, N_l is the number of cycles to initial liquefaction which is the state where pore pressure equals the confining pressure. Since for silty soils, the definition of failure is changed, N_l is no more used for this research. Instead, number of cycles to cause 10% strain is used. The test results on silty sands indicated values of p smaller than 1, depending on the type of soil. So, the equation is modified for each test. From the densification analysis made by the above writers, n is set to 3.5 and from liquefaction analysis α is set to 4.

Equation 6 gives the excess pore water pressure in terms of the number of cycles N, the dimensionless shear stress amplitude τ_o, and the initial and minimum values of the void ratio.

$$p_M = \left\{1 - N\tau_o^{\alpha+1}(e_o - e_m)^n / \hat{\hat{\nu}}e_o\right\}^{1/1-r} - 1 \qquad (6)$$

The results of this equation have been compared by several sets of experimental data. The Ottowa sand used in this research has a minimum void ratio of 0.5 and maximum void ratio of 0.78. Fines used are the crushed silica and for each silt content, the specimen has different e_{max} and e_{max} values. The experiments performed on sand samples with 50% and 70% relative densities for a confining pressure of 98 kPa. and for various fixed shear stress amplitudes. The excess pore water pressure and the shear strain amplitude have been reported in terms of the number of cycles for the above stated values of the initial relative density. The values of calculated η for all soil types are given in Table 1.

In Nasser's work, the value of r is chosen to fit the experimental data. Similarly, the value of r best representing the experimental results of this research is determined. However this is not a straightforward task since equation 6 does not involve r in a simple manner. In addition to the exponent $1/(1-r)$, $\hat{\hat{\nu}} = \hat{\nu}/h$ with $\hat{\nu} = \nu/(r-1)\eta_w$ is a function of r. Hence, an iterative scheme is used to obtain a value of r that best fits the data for a particular experiment. The values of r and η for each soil type is given in Table 1.

Calculations reveal that r must be greater than 1 and from the iterations, it must range between 2 and 6 for clean sand. r is taken as 3.7 for clean sand in this research. For a given sand with a given grain size and shape distribution, $\hat{\hat{\nu}} = \hat{\nu}/h$ depends on the confining pressure and on the initial value of the relative density. From the test results it can be concluded that the value of η is a constant for relative densities 50% and 70%. Indeed, as Nasser and Shookoh showed, here η is accepted as a constant (within experimental error) for relative densities 50% and 70%. So, η can be set to 0.3 x 10^{-6} for the clean sand with relative densities smaller than 70%.

The pore pressure buildup predictions from the model results, show excellent agreement with the results of the tests. Figures 1 through 5 represent comparisons for soils, where the solid lines correspond to the theoretical results and marks correspond to the experimental results.

When one experimental point is chosen in order to fix the parameter η, one can plot the variation of cyclic stress ratio with number of cycles for the indicated confining pressure. Since η is a material parameter, for each silt content it is different. From Table 1, values of η can be placed in equation $N_l\tau_o^5$ =constant, for each soil type. And for different shear stresses, number of cycles to liquefaction is calculated. As an example, the case of 30% is taken below. When the value of η is placed in liquefaction equation , it becomes:

$$N\tau_0^5 = 7.4 * 10^{-7} e_o / (e_o - e_m)^{3.5} * \left[1-(1+p)^{-1.5}\right] \qquad (7)$$

which relates the number of cycles for a given τ_o to the corresponding pore water pressure. There are no free constants in this equation. Its validity against experimental results are tested and presented in Figure 6.

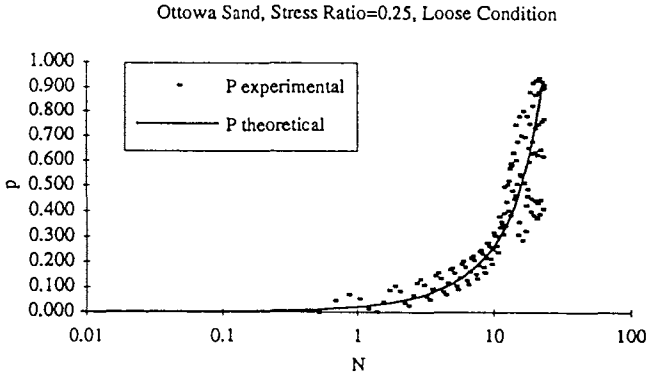

Figure 1 Normalized Excess Pore Pressure vs. Number of Cycles in Cyclic Shearing of Loose Sand

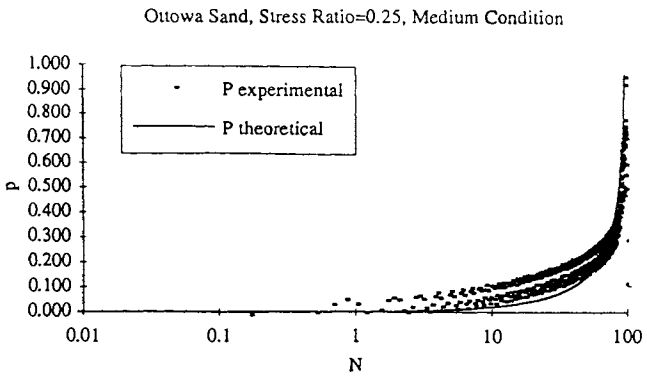

Figure 2 Normalized Excess Pore Pressure vs. Number of Cycles in Cyclic Shearing of Medium Sand

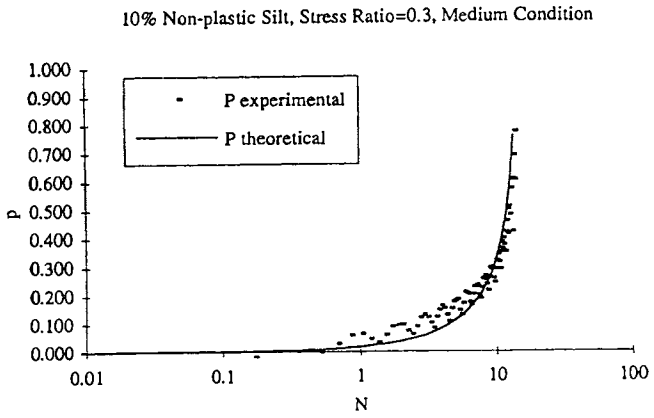

Figure 3 Normalized Excess Pore Pressure vs. Number of Cycles in Cyclic Shearing of Silty Sand (10% Silt)

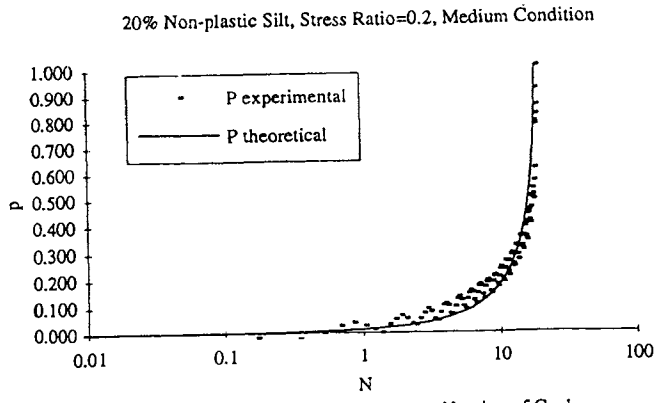

Figure 4 Normalized Excess Pore Pressure vs. Number of Cycles in Cyclic Shearing of Silty Sand (20% Silt)

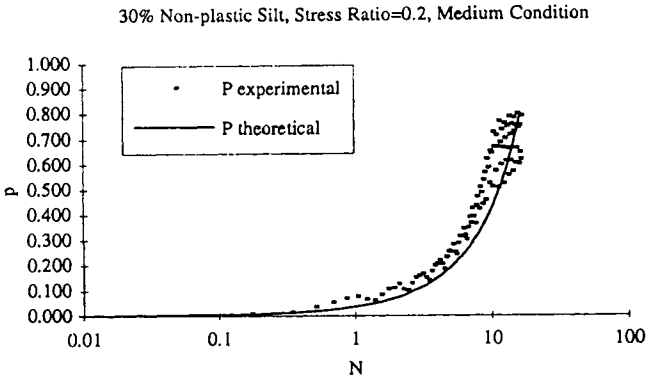

Figure 5 Normalized Excess Pore Pressure vs. Number of Cycles in Cyclic Shearing of Silty Sand (30% Silt)

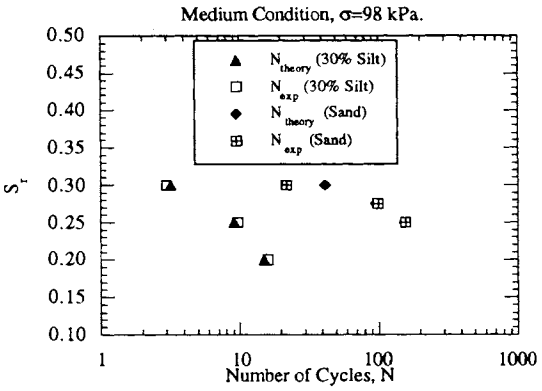

Figure 6 Stress Ratio vs. Number of Cycles to Liquefaction

TABLE 1 Values Of r and η

	Sand	10% silt	20% silt	30% silt
Range	2<r<6	4.2<r<4.8	3.5<r<5.4	1.02<r<3.6
r	3.7	4.5	4.7	2
η*	$3.8*10^{-5}$	$1.62*10^{-6}$	$6.65*10^{-6}$	$7.4*10^{-7}$

TABLE 2 Value Of η For Different for Ottowa Sand

D_r (%)	σ_c(kPa)	N_l	τ_o	$\eta * 10^{6(*)}$
50	98	4	0.35	0.337
	98	11	0.30	0.428
	98	17	0.25	0.333
	98	76	0.20	0.390
70	98	26	0.30	0.125
	98	365	0.25	0.336
	98	393	0.20	0.210

$$*\eta = \frac{(e_o - e_m)^{3.5}}{e_o} N_l \tau^5 \text{ with } e_m = 0.5$$

CONCLUSIONS

The following conclusions can be made based on the results:

1) It is believed that the energy based model provides an adequate basis for predicting the pore pressure generation for clean sand and silty sand. The verification of the proposed model is shown by comparison of results predicted by this model and experimental results on clean sand and silty sand.

2) The difference between the experimental and analytical curves is overcome by iterating the value of r, to find the best fit. After, a better agreement between the measured and calculated pore water pressures are obtained, the value of η, is used to predict the test results.

3) The energy model shows that fines significantly affect the liquefaction behavior of the soil. η as expected, decreased as the resistance of soil to liquefaction decreased. So, adding fines up to a critical value of 30% by dry weight, accelerated the pore pressure buildup.

4) The model parameters were originally set by the results from simple shear tests. And the model successfully predicted the results from triaxial tests. So, it can be concluded that this is a satisfactory model.

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