Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.III)

4-1-7

DYNAMIC BEHAVIOR OF ARTIFICIALLY CEMENTED SANDS

Surendra K. SAXENA[1] Krishna R. REDDY[1]
Anestis S. AVRAMIDIS[2]

[1]Department of Civil Engineering, Illinois Institute of Technology, Chicago, Illinois, USA
2Black and Veatch, Chicago, Illinois, USA

SUMMARY

This paper presents the results obtained from resonant column, and cyclic triaxial tests using artificially cemented sand specimens. Important parameters affecting dynamic properties are identified. New nondimensional relationships are developed for low strain properties. Existance of correlation between cyclic strength and dynamic moduli is confirmed. Overall study results show that strengthening of poor sand deposits by cementation is an efficient method of mitigating earthquake effects.

INTRODUCTION

This paper reports the results of an extensive experimental research program performed at the Illinois Institute of Technology, (I.I.T.) with the aim of creating a broad data base to understand the dynamic behavior of uncemented and artificially cemented sands. Because soil is nonlinear material, its properties vary with strain magnitude. There is no single laboratory or field test to determine properties throughout the entire strain range applicable to geotechnical engineering practice. Therefore, resonant column tests, undrained cyclic triaxial tests, and static triaxial consolidated drained tests are conducted to evaluate cemented sand properties over the entire range of strains of interest. Testing procedures and equipment are in complete accord with well established standards. The soil used to prepare all specimens was Monterey No.0 sand and the cementing agent utilized was Portland cement Type I (Ref.1). Artificial cemented soil was chosen because the parameters affecting the behavior of such soils are better controlled and thus the behavior is better understood. All specimen were prepared using the method of undercompaction (Ref.2) and this makes the created data base unique in the sense that conclusions may be drawn by correlating the results obtained from three testing methods without accounting for sample preparation effects. Using the test results, the beneficial effects of cementation are expressed in the form of equations by statistical methods to be useful for practicing engineers. This paper presents and discusses the typical results obtained from these tests, and the developed equations quantifying the beneficial effects of cementation.

RESONANT COLUMN TESTING

Resonant column test results yield values of dynamic longitudinal and torsional moduli and damping ratios (internal damping) of soils at strain levels usually less than 0.01%. The commonly used Drnevich Resonant Column device had to be modified to test strongly cemented sand because of presence of more than one resonance frequency during testing thereby deviating from the basic assumption that it resembles a single degree freedom system. Consequently it was modified and overall stiffness of the apparatus increased considerably (Ref.3). The modified apparatus yields lower dynamic modulus and damping values as compared to original apparatus at a given strain amplitude and is deemed more accurate, because the modified apparatus behaves almost rigidly. The testing procedure essentially consists of inducing vibrations of controlled frequency and amplitude to the top end of the specimen while the bottom end being fixed, and monitoring the response using accelerometers which vibrate with the soil specimen. By varying the induced frequency, the state of resonance is established. At this state, the amplitude of applied force, the induced displacements and the resonance frequency are measured and used to deduce the dynamic properties of the soil specimen using the analogy of the vibration response of a cylindrical rod.

Strain amplitude (0.00001 to 0.01%), effective confining pressure (49 to 588 kPa), relative density (25 to 80%), cement content (0 to 8%), and curing period (15 to 60 days) are the main variables examined in this study. Test results clearly indicate that dynamic moduli decrease and damping ratios increase with increase in strain amplitude. The decrease in moduli is mainly due to nonlinearity of soils and the increase in damping ratios is caused by energy absorption due to particle rearrangement. Although the increase in effective confining pressure, relative density, and curing period causes an increase in dynamic soil properties, the strongest effect on the properties was that of cement content. As cement content increases moduli are increased. Damping ratios, however, initially increase as cement content increases and then decreases with continuing increase in cement content. This behavior was explained by a new postulate by the authors (Ref.4). The beneficial effect of small amount of cementation to increase simultaneously both moduli and damping ratios makes the stabilization of sand by Portland cement a useful concept in the geotechnical engineering practice.

Regression analysis was performed using the test results to develop simple and sufficiently accurate nondimensional relationships for dynamic moduli and damping ratios. Following are the equations based on results with uncemented sand:

$$G_m = \frac{428.2}{(0.3 + 0.7e^2)} (P_a)^{0.426} (\bar{\sigma}_o)^{0.574} \qquad (1)$$

$$E_m = \frac{1703.57}{(0.3 + 0.7e^2)} (P_a)^{0.61} (\bar{\sigma}_o)^{0.39} \qquad (2)$$

$$D_s = 9.22 \left(\frac{\bar{\sigma}_o}{P_a}\right)^{-0.38} (\gamma)^{0.33} \qquad (3)$$

$$D_1 = \left(\frac{\bar{\sigma}_o}{P_a}\right)^{-0.13} (\varepsilon)^{0.33} \qquad (4)$$

where P_a, G_m, E_m, D_s, D_1, $\bar{\sigma}_o$, γ and ε are atmospheric pressure, maximum dynamic shear modulus, maximum dynamic Young's modulus, dynamic shear damping, dynamic longitudinal damping, effective confining pressure, dynamic shear strain and dynamic longitudinal strain respectively.

The beneficial effects of cementation obtained from results with cemented sand are expressed in the following form:

For low cementation (CC<2%)

$$\frac{\Delta G_m}{P_a} = \frac{172}{(e - 0.5168)} (CC)^{0.88} \left(\frac{\bar{\sigma}_o}{P_a}\right)^{(0.515e-0.3CC+0.285)} \qquad (5)$$

$$\frac{\Delta E_m}{P_a} = \frac{2193.4}{(e - 0.2262)} (CC)^{(2.03-1.739e)} \qquad (6)$$

For high cementation (2% < CC < 8%)

$$\frac{\Delta G_m}{P_a} = \frac{773}{e} (CC)^{1.2} \left(\frac{\bar{\sigma}_o}{P_a}\right)^{(0.698e-0.04CC-0.2)} \qquad (7)$$

$$\frac{\Delta E_m}{P_a} = \frac{2930.5}{(e - 0.4921)} (CC)^{(2.692e-1.44)} \qquad (8)$$

where ΔG_m and ΔE_m are the increase in maximum dynamic shear and Young's moduli respectively due to cementation. Similarly the increase in dynamic shear and longitudinal damping ratios (ΔD_s and ΔD_1) at low cementation (CC<2%) are developed for specific strain levels.

$$\Delta D_s = 0.49(CC)^{1.07} \left(\frac{\bar{\sigma}_o}{P_a}\right)^{-0.36} \qquad \ldots\text{for } \gamma = 10^{-3}\% \quad (9)$$

$$\Delta D_1 = 1.17(CC)^{0.75} \left(\frac{\bar{\sigma}_o}{P_a}\right)^{-0.1} \qquad \ldots\text{for } \varepsilon = 10^{-4}\% \quad (10)$$

Chiang and Chae (Ref.5) and Acar and Tahir (Ref.6) have previously proposed such relations, however the difference between the newly proposed relation and the two previously reported relations is shown in Fig.1. The deviation can be attributed to differences in stiffness of the testing device, *soil type, sample preparation, range of parameters, and others as* discussed in detail by the authors (Ref.4).

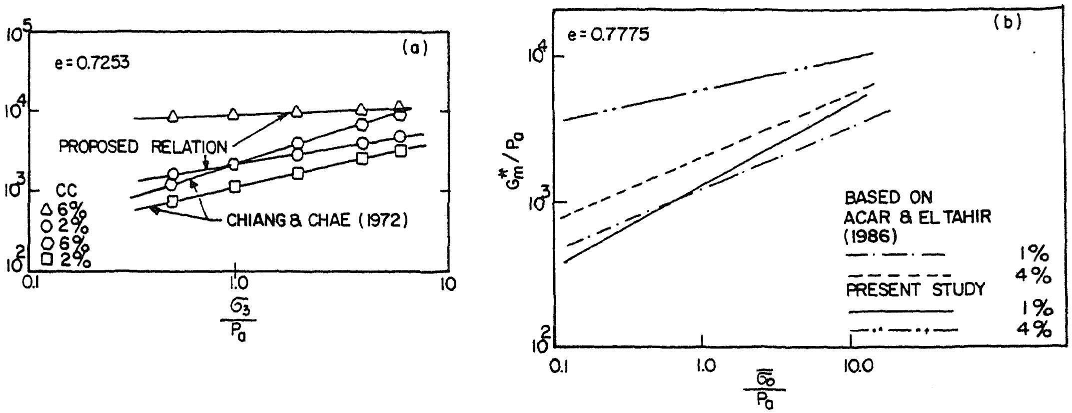

Fig. 1 Comparison of proposed relation with reported relations for dynamic shear modulus

CYCLIC TRIAXIAL TESTING

The equipment and devices used for the tests in this study satisfy all the requirements set by Nuclear Regulatory Commission of the United States. Specimen prepared with different relative density (25 to 80%), cement content (1 to 8%), and curing period (15 to 60 days) are tested under cyclic triaxial loading conditions in this investigation. The procedure of testing essentially consists of specimen saturation followed by isotropic consolidation under effective confining pressure of 98 kPa, and finally application of a sinusoidal type of loading with preset amplitude starting from a compression half-cycle at the constant frequency of 1 Hz until initial liquefaction (i.e. excess pore water pressure is equal to effective confining pressure) occurs.

Results indicate that specimen with cement content of 5%, and 8% are not at all susceptible to liquefaction (Fig.2). Fig.2 also shows the rapid development of excess pore water pressure at early stage for uncemented sand, and after considerable number of cycles for cemented sands depending on the level of cementation. Fig.2 indicates that the maximum increase in the excess pore water pressure during loading is inversely proportional to the cement content thus emphasizes significance of stabilization of loose sand by cement. Typical results in Fig.3 show the increase in cyclic strength with cement content. Results not presented for space limitation, but presented elsewhere (Ref.7) also show definite increase in cyclic strength with the increase in density, and curing period.

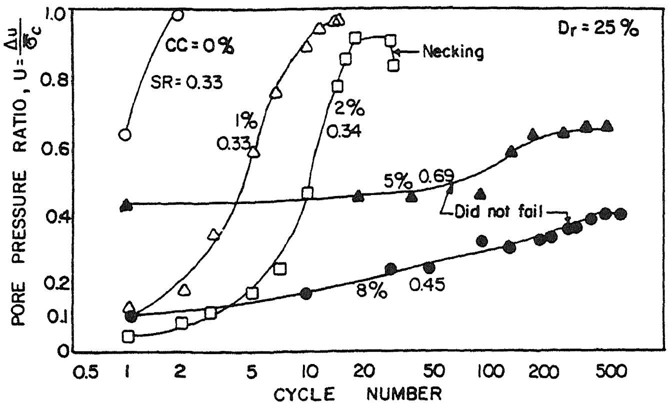

Fig. 2 Pore pressure development in cyclic triaxial test

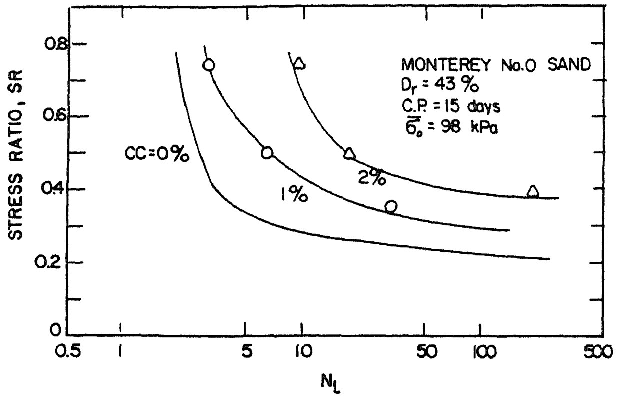

Fig. 3 Effect of cementation on liquefaction resistance

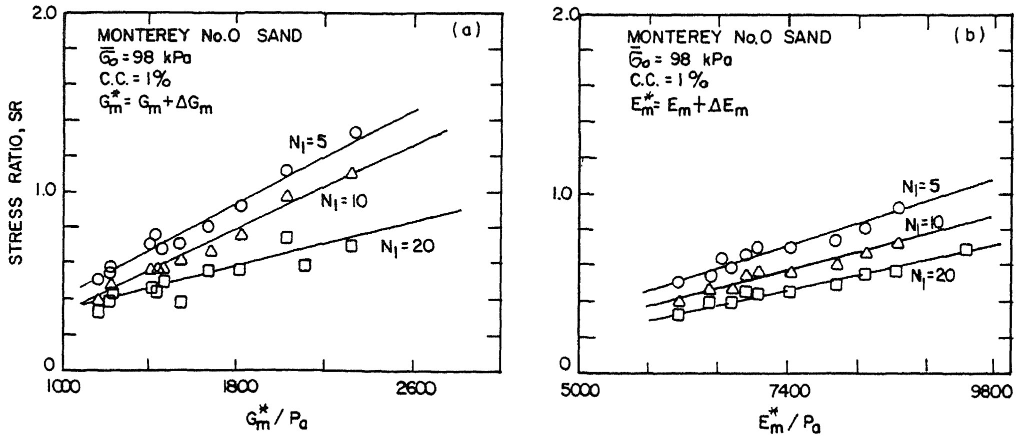

Fig. 4 Correlation between moduli and cyclic strength

A one-to-one correspondence between cement content, relative density, and curing period for cyclic triaxial and resonant column tests was maintained, so that a G^*_m or E^*_m value could be directly assigned to the corresponding cyclic triaxial test. Fig.4 shows the typical results obtained by adopting this procedure, and confirms the existence of good correlation between dynamic moduli and cyclic strength determined in the laboratory for any specific N_1. Existence of such correlation is also confirmed for other levels of cementation. Though the correlations are dependent on type of sand, level of cementation and effective confining pressure, they provide laboratory estimates of cyclic strength of artificially cemented sands and possibly naturally cemented sands from measured moduli or wave velocities.

CONCLUSIONS

The investigation concludes that a small amount of cementation increases low strain dynamic properties (dynamic moduli and damping ratios) and liquefaction resistance of uncemented sands. The proposed nondimensional equations for dynamic moduli and damping ratios are useful to quantify the beneficial effects of cementation.

REFERENCES

(1) Saxena, S.K., and Reddy, R.K., "Mechanical Behavior of Cemented Sands," Report to the National Science Foundation, Report No.IIT-CE-8701, Department of Civil Engineering, Illinois Institute of Technology, June, 1987.

(2) Ladd, R.S., "Preparing Test Specimen Using Undercompaction," Geotechnical Testing Journal, GTJODT, Vol.1, No.1, March, 1978,pp.16-23.

(3) Avramidis, A.S., "Behavior of Cemented Sand Under Static and Dynamic Loads," Ph.D. Thesis, Department of Civil Engineering, Illinois Institute of Technolgy, August, 1985.

(4) Saxena, S.K., Avramidis, A.S., and Reddy, R.K., "Dynamic Moduli and Damping Ratios for Cemented Sands at Low Strains," Canadian Geotechnical Journal, Vol.25, No.2, May, 1988.

(5) Chiang, Y.C., and Chae, Y.S., "Dynamic Properties of Cement Treated Soils," Highway Research Record No.379, 1972, pp.39-51.

(6) Acar, Y.B., and El-Tahir, E.A., "Low Strain Dynamic Properties of Artificially Cemented Sand," Journal of Geotechnical Engineering, ASCE, Vol.112, No.11, November, 1986, pp.1001-1015.

(7) Saxena, S.K., Reddy, R.K., and Avramidis,A.S., "Liquefaction Resistance of Artificially Cemented Sand," Journal of Geotechnical Engineering, ASCE, accepted for publication.