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Y. S. Chae
Rutgers University, Piscataway, NJ

W. C. Au
Rutgers University, Piscataway, NJ

Y. C. Chiang
Rutgers University, Piscataway, NJ

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Determination of Dynamic Shear Modulus of Soils from Static Strength

Y. S. Chae, W. C. Au and Y. C. Chiang

Department of Civil and Environmental Engineering, Rutgers University, Piscataway, N.J.

SYNOPSIS A correlation study between the dynamic shear modulus obtained from the resonant column technique and the static strength obtained from the undrained triaxial compression test is described. The materials studied were a uniform sand, a non-active fine silty clay and a highly-active bentonite clay treated with additives to increase the range for static and dynamic shear strength of the soils. It is noted that a linear relationship exists between the dynamic shear modulus, except for those soil specimens having very low strength, independent of test parameters. Using linear regression analysis, empirical equations for predicting the maximum dynamic shear modulus from the static strength have been obtained for the three different soils.

INTRODUCTION

Presently, dynamic shear moduli are determined in the field by such geophysical methods as seismic refraction, steady-state vibration, up-hole and/or cross-hole surveys. These methods are utilized for obtaining moduli at very small strain levels and do not permit evaluation of shear moduli at shear strain levels produced by strong earthquake motions. Thus, field data are not directly usable for modeling earthquake response. Laboratory tests, such as resonant column, cyclic simple shear, and cyclic triaxial shear tests, permit determination of shear moduli of small specimens at various strain levels. However, laboratory tests are complicated by problems of sample disturbances, possible change in soil structure, boundary effects and stress history.

The values of stress-strain modulus obtained from the conventional triaxial compression test tend to be quite low compared with dynamic stress-strain moduli from low amplitude strain tests. There is some evidence that at a comparable level of strain amplitude the dynamic properties obtained by either the in-situ or the laboratory tests are fairly comparable. The dynamic properties obtained at any given level of strain amplitude may, by means of an established empirical procedure, be used to determine the same at other levels of strain amplitude. It may also be possible that the dynamic properties may be correlated to, and obtained from the standard static test. If that is true, then the ability to predict the dynamic properties from the conventional simple static test, such as triaxial compression test, which is routinely done, would be greatly beneficial and advantageous in many situations especially for use in preliminary analysis. This paper reports the results of an experimental study correlate the dynamic shear modulus with the static strength for three different types of soils.

EXPERIMENTAL PROGRAM

Materials

The materials used for this study were a uniform sand, a silty clay (non active) and a bentonite clay (highly active). In order to increase the range of static and dynamic strength of the soils, the sand and silty clay specimens were treated either with cement, lime or a lime-fly ash combination. The bentonite clay was treated either with lime, salt or a lime-salt combination. The sand particles ranged from 2 mm to 0.074 mm in diameter and had a uniformity coefficient of 3.43 and a specific gravity of 2.63. The silty clay had a specific gravity of 2.65, liquid limit of 30.1% and plasticity index of 9.8%. An x-ray diffraction analysis showed the main clay minerals to be chlorite. For the additives, a regular grade hydrated calcitic lime, $Ca(OH)_2$ and an activated fly ash with 85% passing No. 325 sieve (U.S. Standard) were used. The bentonite clay consisted of 90% montmorillonite and 10% other minerals. The specific gravity was 2.7. The untreated soil had the optimum moisture content of 24.3% and the maximum dry density of 80 pcf (12.6 kN/m^3). It had a liquid limit of 593% and the plasticity index of 544%. The treated soils showed a wide variance of optimum moisture content and maximum dry density depending on the type of treatment and the treatment level. The salt used was a chemically pure sodium chloride crystal. Based on a preliminary investigation, a 3% (by dry weight of clay) salt solution was used for all salt and lime-salt treatment.

Specimen Preparation

Tests were performed on remolded specimens prepared by a modified Harvard miniature compactor. A hammer weighing 0.82 lb (3.65 N), was dropped 6 in (15.24 cm) to compact the specimen in five layers with ten drops on each layer. A portion of soil and additives were first dry-mixed and then a predetermined amount of distilled or salt water was added to bring about a desired moisture content. The mixture was again mixed thoroughly. The entire mixing process was done in a sealed plastic bag so that evaluation and carbonation were kept at a minimum. Molding of specimen was done immediatley after mixing. After the specimen was extruded from the mold, it was wrapped in a plastic sheet and placed in a capped glass bottle, again to prevent evaporation and carbonation. The bottle was then stored in a water bath where a 70 ± 2°F (21 ± 1°C) temperature and approximately 95% humidity were maintained at all times. All treated soil specimens were cured for 28 days before testing.

Test Setup and Procedure

The dynamic shear modulus of untreated and treated soils was determined by means of the resonant column technique under torsional mode of vibration. A detailed description of the oscillator, the theory of vibration and test procedure for this technique is given elsewhere, and will not be repeated herein. Test parameters and program are summarized in Table 1.

TABLE I. Parameters and Program

Soil	Solution	Additives	Moist. Content	Confining Pressure Psi (kPa)	Strain x 10^{-5}	No. Specimen Tested
Sand	H_2O	Cement: 0% 2 4 6 Lime: LFA 0% 0% 1 10 3 5	Optimum Moisture Content ± 6%	3 (21) 10 (69) 20 (138) 35 (241)	27.96 14.82 7.45 4.65 2.80	44
Silty Clay	H_2O	Cement: 0% 2 4 6 Lime:LFA 0% 1 3 5	Optimum Moisture Content ± 6%	3 (21) 10 (69) 20 (138) 35 (241)	27.96 14.82 7.45 4.65 2.80	44
Bentonite Clay	H_2O	Lime: 0% 4 6 8 10	Optimum Moisture ± 6%	3 (21) 10 (69) 20 (138) 35 (241)	27.96 14.82 7.45 4.65 2.80	74

The independent test variables were moisture content and treatment level for the specimen, and confining pressure and shear-strain amplitude for the testing apparatus. The specimens were tested at four levels of confining pressures. At a given confining pressure application, the dynamic shear modulus was determined in sequence at five shear strain amplitudes. Moisture content was varied over a wide range on both sides of the optimum. A total of 162 specimens were analysed. Immediately following the resonant column test, the specimens were tested in a triaxial compression (undrained) test for the evaluation of statis properties of the soils. The deviatoric stress at the strain of 1% was chosen as the static strength of the soils for the purpose of correlating with the dynamic shear modulus.

ANALYSIS AND DISCUSSION OF TEST RESULTS

There are many parameters affecting the dynamic shear modulus and the static strength of a soil. The parameters considered to be most important are confining pressure, strain amplitude, moisture content and soil structure. Evaluation of the effect of each of these parameters on the dynamic shear modulus has been reported previously by Au (1980), Chae (1978) and Chiang (1972). For the additive-treated soils in the present investigation, the additional major parameter to be considered is the treatment level (content of cement, lime or lime-fly ash). In all of the tests conducted, a striking similarity in pattern was noted between the gain of static strength and the gain of dynamic shear modulus with increasing level of treatment, and, therefore, a correlation between the two could be derived.

Gain in Dynamic Shear Modulus

Gains in dynamic shear modulus with treatment level for the sand, silty clay and the bentonite clay are shown in Figs. 1, 2 and 3, respectively, in which the ratio of the modulus between the treated and untreated soils is plotted against treatment level. It is seen that the modulus increases with the treatment level. The increase is more significant with the cohesionless soil than the cohesive soils. The figures clearly demonstrate that cement, lime or LFA stabilization can be used effectively in weak soils because it increases strength of soils subjected to dynamic loading. It is noted in these figures that the modulus ratio is greatly affected by confining pressure for sand. The confining pressure, however, appears to have no effect on the ratio for clay soils.

The different behavior of cohesive and cohesionless soils may be attributed to the combined contribution of cohesion and internal friction to the shearing resistance of the soils. It has been shown by Barkan (1962) that under static loading conditions an increase in internal friction due to the addition of cement or lime is very small regardless of the soil type, while cohesion of both fine and granular soils increases markedly. Since there is a fairly parallel increase in the static and dynamic strength, as will be seen later, the amount of

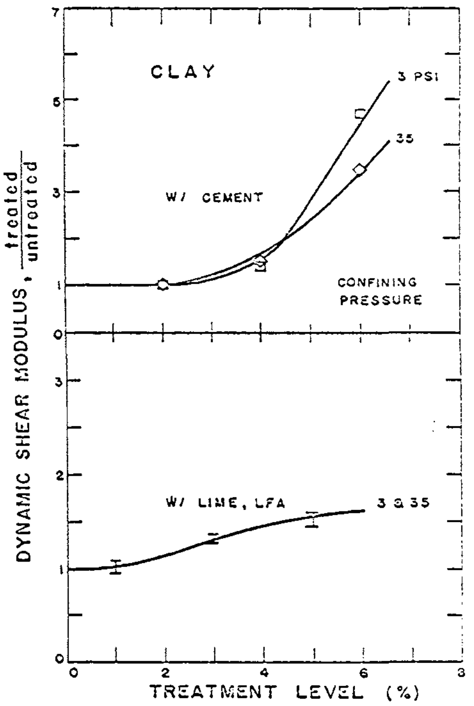

Fig. 2. Dynamic Shear Modulus Ratio vs Treatment Level (Silty Clay)

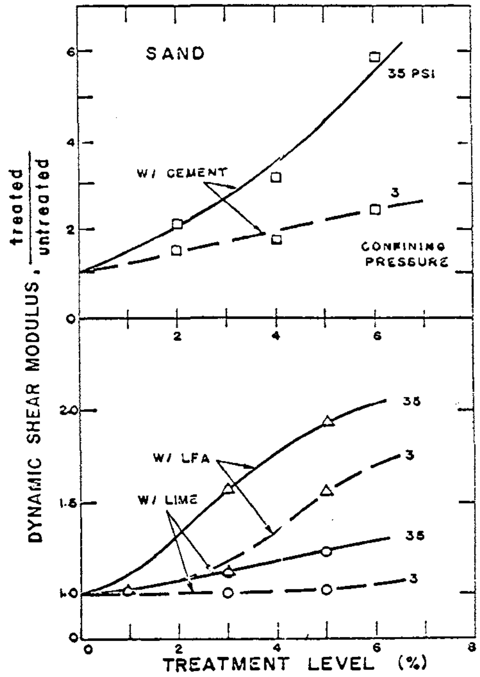

Fig. 1. Dynamic Shear Modulus Ratio vs Treatment Level (Sand)

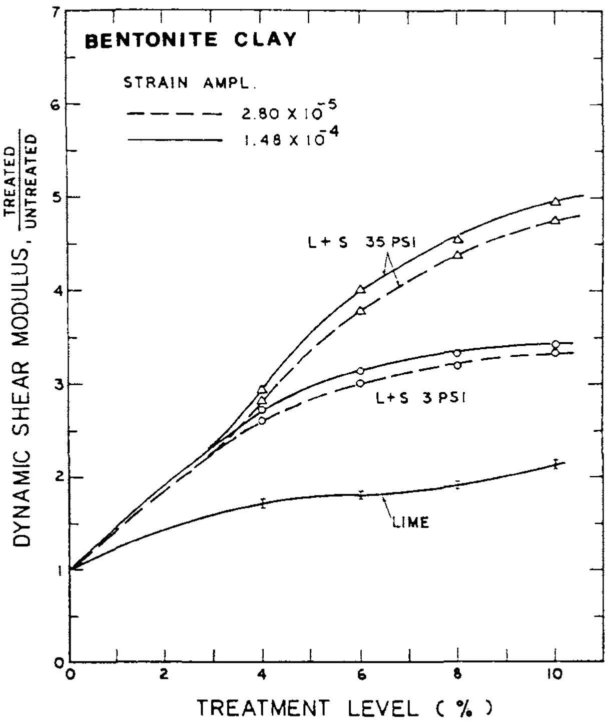

Fig. 3 Dynamic Shear Modulus Ratio vs Treatment Level (Bentonite Clay)

increase in dynamic shear modulus at a given confining pressure resulting from cement or lime treatment of cohesive soils is probably due, in a large extent, to the increased value of cohesion resulting from treatment. For cohesionless soils, the internal friction remains more or less unaffected by treatment level and the increase of cohesion is relatively small. It seems reasonable, therefore, to speculate that at a given confining pressure, the amount of increase in dynamic shear modulus of sand at different treatment levels is attributed, to a large degree, to the characteristics of dynamic loading itself which is more influential at greater confining pressure.

Gain in Static Strength

Gains in static strength resulting from cement, lime, LFA or lime-salt treatment for the three types of soils are shown in Figs. 4, 5 and 6. The static strength was determined from the triaxial compression (undrained) tests using the same specimen and the confining pressure as in the dynamic tests. The ratio of static strength, defined as the deviatoric stress at 1% strain, of treated specimens to untreated ones is plotted as a function of treatment level. The choice of 1% strain is for the purpose of comparison, and in most cases it falls within the "elastic range" of soils.

Comparing the gain of static strength as depicted in Figs. 4, 5 and 6 with the gain of dynamic shear modulus as shown in Figs. 1, 2 and 3 indicates a striking similarity in pattern of increase with the level of treatment. The

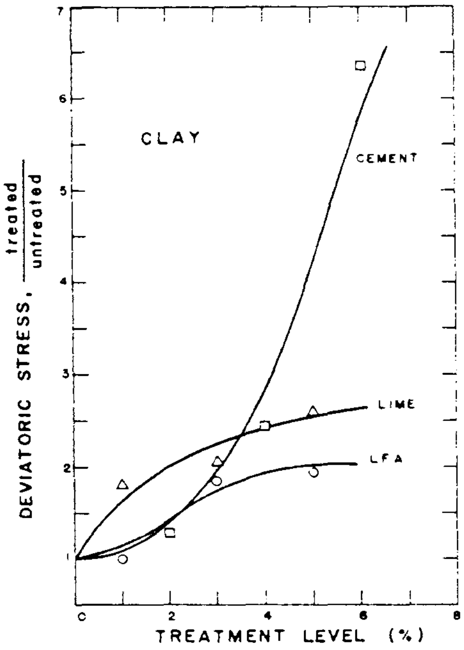

Fig. 5 Deviatoric Stress Ratio vs Treatment Level (Silty Clay)

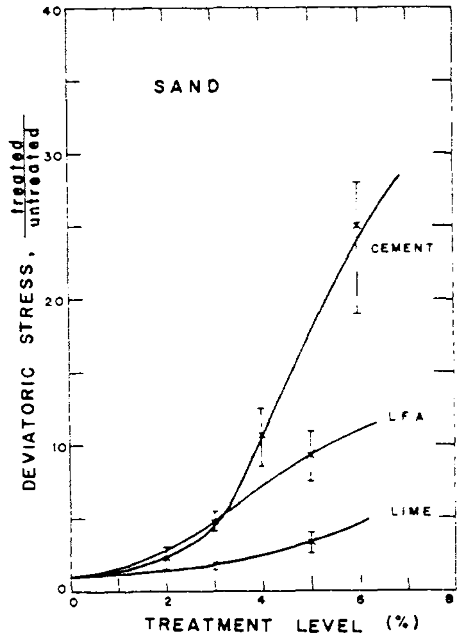

Fig. 4 Deviatoric Stress Ratio vs. Treatment Level (Sand)

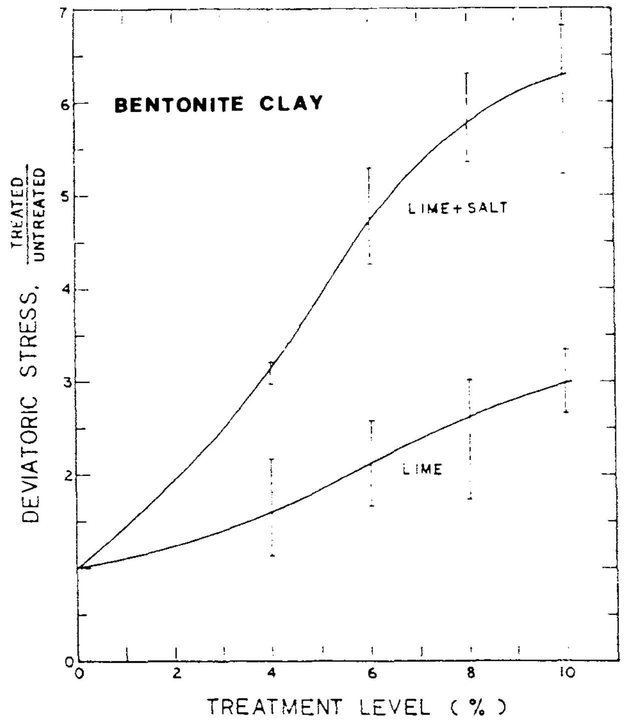

Fig. 6 Deviatoric Stress Ratio vs Treatment Level (Bentonite Clay)

parallel increase in static and dynamic strength is understandable in view of the combined contribution of cohesion and internal friction resulting from treatment to the shearing resistance of the soils as explained previously. It may seem feasible, therefore, to correlate the dynamic shear modulus with the static strength.

<u>Correlation Between Dynamic Shear Modulus and Static Strength</u>

Figs. 7, 8 and 9 are plots of the maximum dynamic shear modulus vs. the static strength for all specimens tested for the sand, silty clay and bentonite clay. It is apparent from these figures that a linear relationship exists between the static strength and the dynamic modulus, except for those soils having very low strength, regardless of the type of additives, treatment level and moisture content. Using linear regression analysis, the following empirical expressions for predicting the maximum dynamic shear modulus, G in ksi, from the static strength, $\bar{\sigma}_d$ in ksi, are obtained for the three types of soils:

For sand $\quad G = 420\ \bar{\sigma}_d + 14 \quad$ (1)

For silty clay $\quad G = 600\ \bar{\sigma}_d + 8 \quad$ (2)

For bentonite clay $\quad G = 130\ \bar{\sigma}_d + 14 \quad$ (3)

It is observed that the relationship between the maximum dynamic shear modulus and the static strength is independent of test parameters, and is a function only of the type of soil. Thus, the maximum dynamic shear modulus

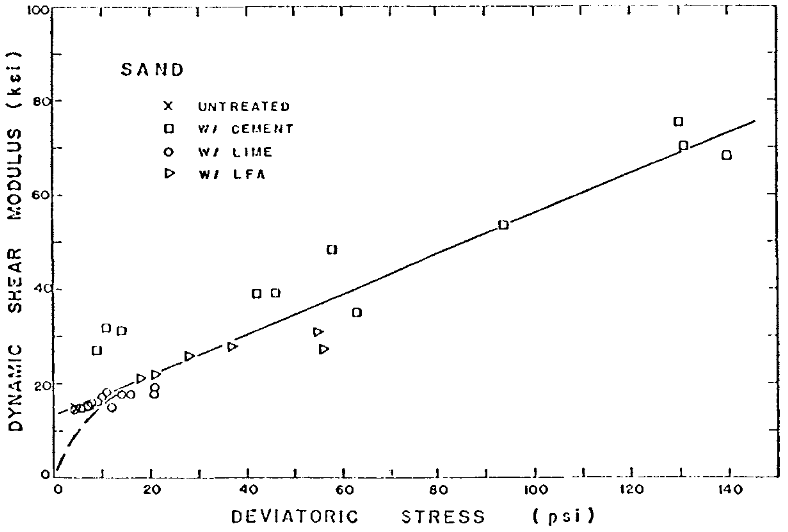

Fig. 7 Dynamic Shear Modulus vs. Static Strength (Sand)

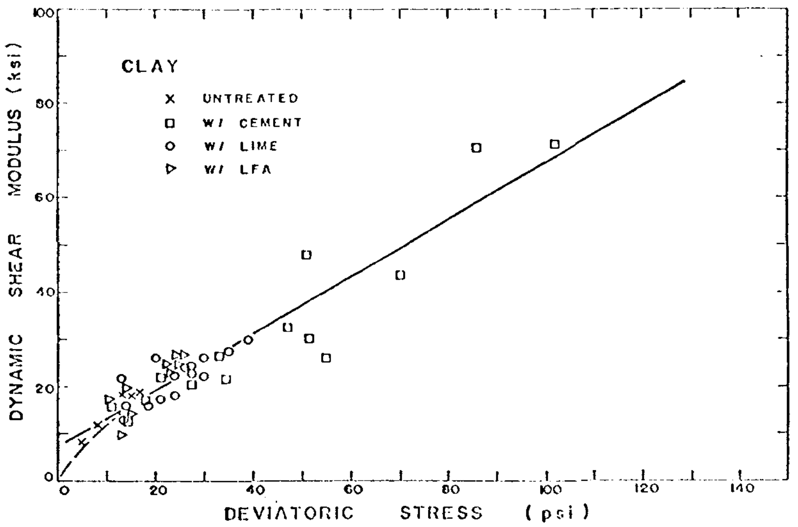

Fig. 8 Dynamic Shear Modulus vs Static Strength (Silty Clay)

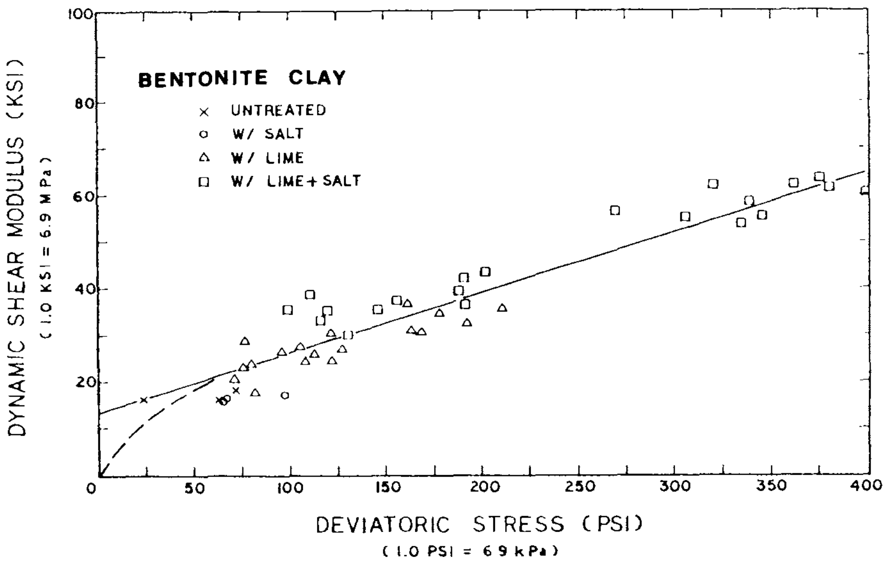

Fig. 9 Dynamic Shear Modulus vs Static Strength (Bentonite Clay)

of any soil may be obtained from the static strength based on a simple relationship

$$G = m\,\bar{\sigma}_d + n \qquad (4)$$

where m and n are the constants for a given type of soil. This correlation has been obtained for high-strength soils, and a further study is needed to evaluate the correlation, if any, for low-strength soils.

CONCLUSION

The dynamic shear modulus of high-strength soils may be determined from the static shear strength. Empirical equations correlating the maximum dynamic shear modulus and the static strength for three types of soils (sand, silty clay, and bentonite clay) have been obtained. The relationship between the dynamic modulus and static strength is essentially linear and is independent of test parameters.

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