DYNAMIC SHEAR MODULUS AND DAMPING IN ADDITIVE-TREATED EXPANSIVE SOILS

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SUMMARY

Dynamic shear modulus and damping in expansive soils treated with lime, salt and lime-salt combination has been determined by the resonant column technique to study the parametric effects of confining pressure, shear strain amplitude, moisture content, treatment level, type of additives and soil structure. The effect of each of these parameters is found to be significant, and can be explained in terms of the change in macrostructure and corresponding change in the physicochemical properties of the soil. The study shows that the use of additives for stabilizing expansive soils not only improves their static properties by reducing swelling and increasing the shear strength, but also improves their dynamic properties. The dynamic shear modulus is related to, and predicted from the static strength of the soil.

INTRODUCTION

Determination of the dynamic properties of soils, such as shear modulus and damping, is of fundamental importance in the analysis of dynamically loaded foundations, earthquake-induced ground motions and soil-structure interaction as analytical techniques now available require the input of well-defined dynamic properties of soils. Problems associated with expansive soils have been recognized world wide including such regions as Africa, Australia, India, South America, Europe and Canada as well as the United States. Annually, expansive soils inflict billions of dollars in damages all over the world; in the United States alone, the cost of these damages amounts to some $2.3 billion annually. Because expansive soils cover some of the earthquake prone areas, especially the western part of the U.S., and numerous facilities on expansive soils are subjected to dynamic loading due to machinery operation and blasting, an understanding of expansive soil behavior under dynamic loading is of essential necessity.

Of the number of remedial measures which can be utilized to minimize or eliminate damage associated with expansive soils, the use of an additive such as lime and/or sodium chloride, has proven to be an effective and economical way of stabilization under static loads. However, knowledge of the dynamic behavior of soils treated with additives is quite limited. Application of chemical soil stabilization techniques for foundations subjected to vibratory loads has been suggested in the past; however, advantages of using soils treated with additives have not been

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fully utilized due mainly to lack of knowledge and understanding of the behavior of chemically treated soils under dynamic loading. An extensive laboratory testing program has been undertaken at Rutgers in the last several years to provide information on the dynamic properties (shear modulus and damping) of many types of soils treated with additives. The results of earlier investigations concerned with common sands and clays were reported previously by Chiang and Chae (3,4). This paper presents the results of the latest study concerned with the dynamic properties of expansive soils.

EXPERIMENTAL PROGRAM

The soil used for this study was a commercial western bentonite clay mined at Black Hill, South Dakota. Montmorillonite constitutes 90% of bentonite substance and the other 10% consists of minute fragments of other minerals, the most abundant being feldspar. The particle size distribution, when dispersed in water, showed 96-97% finer than 44 microns; 93-94% finer than 5 microns; 87-89% finer than 0.5 microns; and 60-65% finer than 0.1 microns. 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). 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. The lime used was a Fisher certified A.C.S. hydrated calcitic lime, $Ca(OH)_2$.

The major independent test parameters considered were moisture content and treatment level of additives for the soil, and confining pressure and shear strain amplitude for the testing apparatus. The soil was treated either with salt, lime, or a lime-salt combination. Treatment levels were chosen at 4, 6, 8 and 10%. Moisture contents were varied over a wide range on both sides of the optimum. The specimens were tested at confining pressures ranging up to 35 psi (241 kPa). At a given confining pressure, the dynamic shear modulus and damping were determined at five different shear strain levels ranging to 2.80×10^{-4}. Altogether, a total of 74 specimens were tested. With various combinations of the test parameters considered, a total of approximately 1500 tests were conducted.

The dynamic shear modulus and damping were determined by means of "resonant column" technique in torsion on remolded specimens prepared by a miniature compactor designed specially for this study. A detailed discussion of the test apparatus, test procedure and the theoretical concept of torsional resonant column technique used in this study may be found in the reference by Au (1). Immediately following a dynamic test, the specimen was tested in a static triaxial compression apparatus to evaluate the static properties of the soil for the purpose of correlating with dynamic properties.

It should be noted that the untreated soil possessed a very high swelling potential. In fact, when fully saturated, it could expand to 15 times it's original dry volume. With the addition of salt (up to 3%), the swelling potential decreased due to the reduction of interparticle repulse forces. Addition of lime also drastically reduced the plasticity index and swelling potential. The effect of a combined lime-salt treatment on swelling potential was even more pronounced. It is of interest to note that the swelling potential was essentially the same irrespective of treatment level beyond 4% lime content. It should be pointed out, therefore, that the 4% lime-3% salt combination produced the most effective treatment with regard to reducing the swelling potential of the expansive clay tested.

ANALYSIS AND DISCUSSION OF TEST RESULTS

As previously stated, the major parameters considered in the present study were confining pressure, strain amplitude, moisture content, soil structure, type of additives and treatment level. A detailed analysis, discussion of the test results and findings therefrom are presented in the reference by Au (1). The typical results and essential findings are summarized herein.

Effect of Confining Pressure. - Variations of dynamic shear modulus with confining pressure are presented in Fig. 1. Each curve in this figure represents the response of a specimen cured for 28 days at its optimum moisture content. It is observed that the dynamic shear modulus increases with increasing confining pressure and their relationship can be plotted as a straight line in a log-log scale at all levels of treatment and strain amplitude. The treatment of soil results in an increase in dynamic shear modulus with lime-salt combination being the most effective of the three additives. Salt treatment changes the soil structure and decreases the swelling potential, but increases the shear modulus only slightly. The slopes of shear modulus-confining pressure (G-$\bar{\sigma}$) lines for both the untreated and lime-treated soils are approximately 1/10, while for the lime-salt treatment the slope varies from 1/8 to 1/4. These values are much lower than 1/2 which has been reported by many investigators for cohesive soils with low surface activity. For instance, the dynamic shear modulus versus confining pressure relationship predicted by Hardin's equation (5) is plotted in Fig. 1 for the corresponding void ratio of 1.103. It is seen that the highly active Na-bentonite used in the present study has a higher dynamic shear modulus, but a low rate of increase at the same confining pressure than non-active clay. The increase in the shear modulus of active clay above that for less-active clay with the similar void ratio and the state of stress may be attributed to the special soil structure of highly active clays as is discussed in detail by Au (1).

The effect of confining pressure on damping expressed as logarithmic decrement is shown in Fig. 2 for the lime-salt treated soils. Since the moisture content and treatment level do not affect the damping, as will be discussed later, the relationship shown in the figure represents the average values obtained at various moisture contents and treatment levels. In general, the logarithmic decrement values are significantly greater at lower confining pressure, and decreases with increasing confining pressure. Furthermore, logarithmic decrement for all soils tested appears to decrease in an approximately straight line when plotted on a log-log scale with 1/4 to 1/3 power of confining pressure at a strain amplitude of

2.8×10^{-5}. However, the rate of decrease is much greater with higher confining pressure.

Effect of Strain Amplitude. - Due to the apparatus limitation it was able to vary the strain amplitude over a small range (an order of magnitude). It was found in general that at a given treatment level and confining pressure the dynamic shear modulus decreases with shear-strain amplitude for both the treated and untreated soils. The results confirm the general findings by others for different types of soils. Cohesive soils including expansive soils are less sensitive to change in strain amplitude than cohesionless soils. Since the dynamic shear modulus is shear-strain dependent, comparison of dynamic shear modulus determined from different testing apparati or techniques should be made at a comparable strain amplitude such as the maximum dynamic shear modulus.

It is generally known that the shape of the stress-strain curve for a particular soil can be adequately represented by a hyperbolic curve, and the maximum shear modulus can be defined as the shear modulus at zero shear strain. In order to illustrate this point, the rate of change in dynamic shear modulus with strain amplitude is plotted in Fig. 3 in which the maximum shear modulus was obtained at zero strain amplitude. It is observed that the rate of change is affected by the type of treatment, treatment level and confining pressure. In general, the treated soils are significantly less affected by the change in shear strain amplitude than untreated soils, which may be attributed to the cementing reaction of lime and clay. At a given treatment level, the effect of higher confining pressure is to retard the decrease of shear modulus with increasing shear strain amplitude.

Logarithmic decrement appears in general to decrease continuously with decreasing strain amplitude. Presumably, the logarithmic decrement approaches zero as strain amplitude reaches zero. The influence of confining pressure on damping is again very profound as the rate of increase in damping with increasing strain amplitude is much greater under low confining pressure.

Effect of Moisture Content. - The test results show that the dynamic shear modulus of lime-treated soils is significantly affected by moisture content or degree of saturation. At a given confining pressure, strain amplitude and treatment level, the dynamic shear modulus increases with moisture content up to a value slightly beyond the optimum moisture content, then decreases with further increase in moisture. Theoretically, the effect of water in the soil is to reduce the velocity of wave propagation. This reduction is brought about by the presence of an "apparent mass" which couples the solid and fluid masses. It seems that for clay the lack of this apparent mass is the case when the degree of saturation is low, up to the optimum content. Beyond the optimum, the density-moisture curve runs closely in parallel to the zero air-void curve, and, therefore, that the apparent mass is evidently present in this region of high degree of saturation, thereby reducing the shear wave velocity and thus, dynamic shear modulus.

The dynamic shear modulus of the soil treated with salt alone decreases slightly with increasing moisture content. This behavior may be explained by the relationship between salt concentration and Bingham yield stress (1). For the soil treated with lime-salt combination, the effect of moisture on the dynamic shear modulus is relatively insignificant, and for practical purposes, the shear modulus may be assumed to be unaffected by the change in moisture content.

Fig. 4 shows the effect of moisture content on the logarithmic decrement for lime-salt treatment at the strain amplitude of 2.8×10^{-5} at two extreme confining pressures. It is of interest to observe that the logarithmic decrement remains practically unchanged, within the range of moisture content studied, at a given confining pressure, irrespective of lime-treatment level.

Effect of Treatment Level. - Observations regarding the effect of treatment level (lime content) on the dynamic properties have been made previously in connection with other parameters studied. Increase in dynamic shear modulus with treatment level is shown in Fig. 5 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 lime-salt treated soil than with the lime treated soil. The figure clearly demonstrates that lime-salt stabilization can be used effectively in expansive soils because it increases rigidity of soils subjected to dynamic loading.

The effect of treatment may be explained in terms of combined contribution of cohesion and internal friction to the shearing resistance of the soils. Barkan (2) has shown that under static loading conditions an increase in internal friction due to the addition of 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 increase in dynamic shear modulus at a given confining pressure resulting from lime treatment of cohesive soils is probably due, to a large extent, to the increased value of cohesion resulting from treatment.

The effect of treatment level on damping is shown in Fig. 6 for lime-treated soils, in which the ratios of the logarithmic decrement of treated to untreated soils are plotted against treatment level. It clearly shows the increase in damping capacity with the presence of lime. However, it is noted that although the damping capacity of soils increases rapidly with the strain amplitude, the logarithmic decrement ratio does not seem to be affected by the strain amplitude except at low confining pressure and high amplitude. It was also observed that the effect of treatment level appears to be very little for the lime-salt treated soils.

Correlation between Dynamic Properties and Static Strength. - Evaluation of the parameters required to describe the dynamic behavior of soils involve sophisticated and often expensive laboratory tests. The ability to predict the results of a dynamic test, such as the resonant column technique, from a static test would be beneficial, especially in the preliminary analysis of soil dynamics problems. In order to possibly correlate the maximum dynamic shear modulus with the static strength, a number of triaxial compression (undrained) tests were performed.

Fig. 7 is a plot of the maximum dynamic shear modulus against the static strength (deviatoric stress) of all specimens tested. It is noted in this figure that a linear relationship apparently 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 the method of least square, an empirical equation for obtaining the maximum dynamic shear modulus, G in MPa, from the static strength, $\overline{\sigma}_d$ in kPa, was derived for the soil as:

$$G = 0.13\,\overline{\sigma}_d + 91.0 \qquad (1)$$

The relationship between logarithmic decrement and static strength is plotted in Fig. 8. It is seen that the logarithmic decrement increases over the low-strength range, but remains practically constant beyond a certain deviatoric stress value. This may be attributed mainly to the moisture content in the soils. No direct relationship can be obtained between damping and static strength.

CONCLUSION

The study has shown that the use of additives to stabilize expansive soils not only improve their static properties by reducing swelling and increasing the shear strength, but also improves their dynamic properties. It has been shown that the treatment with lime-salt combination is the most effective. The effects of various parameters are very significant on the dynamic properties of treated expansive soils. There is a good indication that the dynamic properties can be correlated to, and predicted from the static strength of soils.

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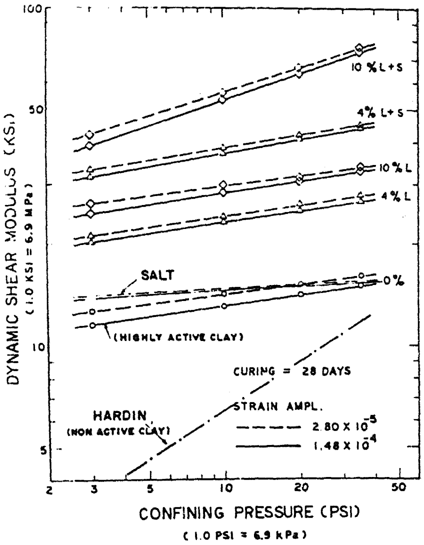

FIG. 1 EFFECT OF CONFINING PRESSURE ON DYNAMIC SHEAR MODULUS

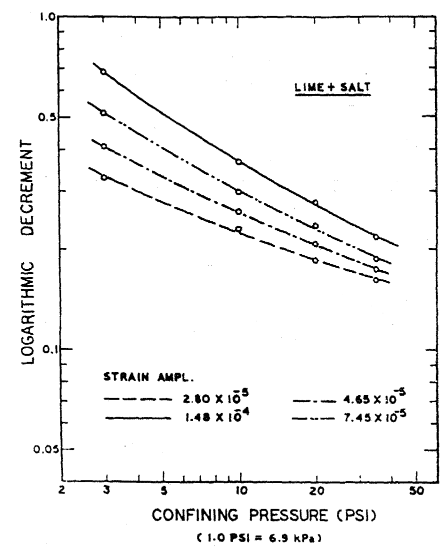

FIG. 2 EFFECT OF CONFINING PRESSURE ON DYNAMIC SHEAR MODULUS

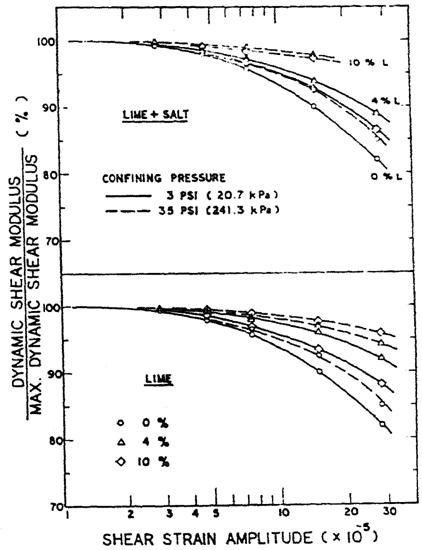

FIG. 3 EFFECT OF SHEAR STRAIN AMPLITUDE ON DYNAMIC SHEAR MODULUS

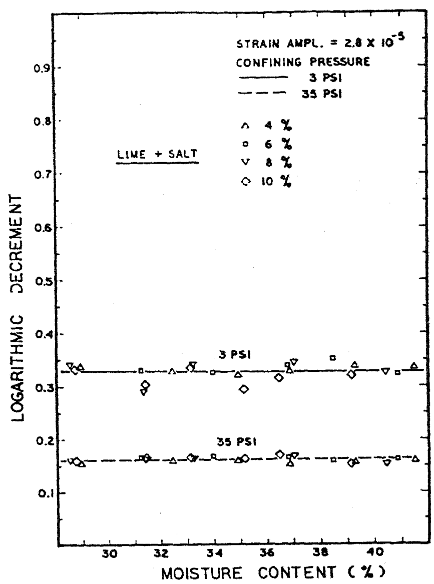

FIG. 4 EFFECT OF MOISTURE CONTENT ON DAMPING

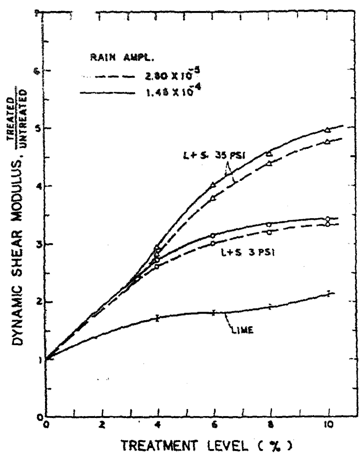

Fig. 5 Effect of Treatment Level on Dynamic Shear Modulus

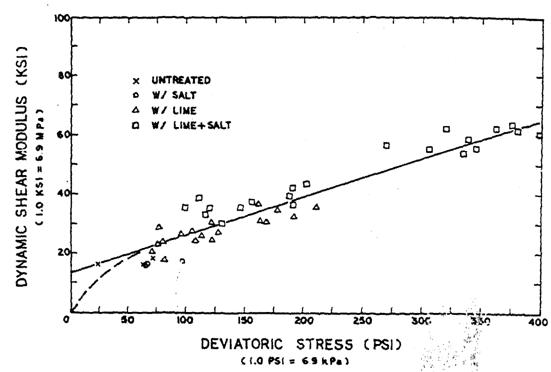

Fig. 7 Correlation Between Dynamic Shear Modulus and Static Strength

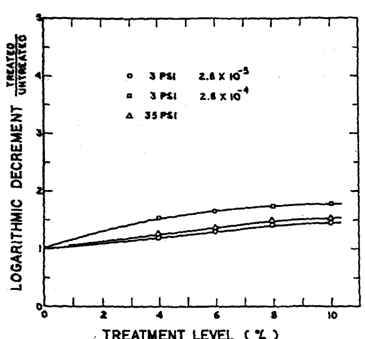

Fig. 6 Effect of Treatment Level on Damping

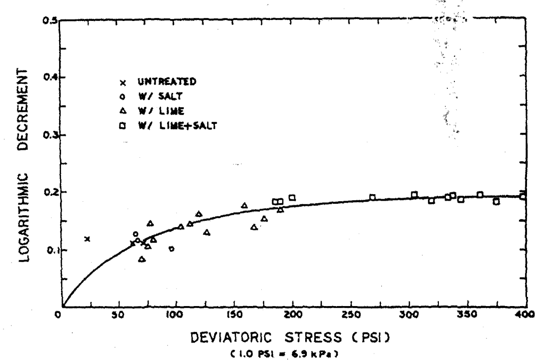

Fig. 8 Correlation Between Damping and Static Strength