International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1995 - Third International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

04 Apr 1995, 10:30 am - 12:00 pm

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## Recommended Citation

Rodriguez-Roa, F. and Palma, G., "Dynamic Properties of a Granular Soil" (1995). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 23.
https://scholarsmine.mst.edu/icrageesd/03icrageesd/session01/23

**Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics,**
**April 2–7, 1995, Volume I, St. Louis, Missouri**

# Dynamic Properties of a Granular Soil

**Paper No. 1.52**

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SYNOPSIS The variation of the Dynamic Shear Modulus, G, and Damping Ratio, D, in a coarse grained alluvial soil from the Santiago area, Chile, is analyzed when changes occur in its grain size distribution, degree of compaction, confining pressure, magnitude of the cyclic deviator stress, and number of applied loading loops. Using statistical techniques it was possible to determine the degree of influence of each one of such factors in the magnitude of G and D. Further, the experimental error derived from laboratory tests measurements could be evaluated.
The Hyperbolic Model shows a better performance than the Ramber-Osgood Model when theoretical results are adjusted to experimental shear stress-strain laws.

## INTRODUCTION

This paper analyzes the variation of the dynamic shear modulus and damping ratio in a coarse grained alluvial soil from the Santiago area, Chile, when changes occur in the following factors: grain size distribution, degree of compaction, confining pressure, magnitude of the cyclic deviator stress and number of applied loading loops. The research was based on the results obtained in tests carried out in the load controlled, cyclic triaxial test equipment existing at the National Road Laboratory. The research included two stages. The purpose of each stage and the results obtained are commented herein.

## FIRST STAGE OF THE RESEARCH

General considerations During this stage, two different values were used for each of the selected factors, as this is the minimum amount required in order to apply the statistical technique known as "Factorial Analysis of Experiments". The purpose of this stage was to evaluate the significance of each factor in the values of G and D. Four identical specimens were prepared and tested for each combination of the factors analyzed. The four fold repetition of tests served the purpose of obtaining a statistical evaluation of the inevitable experimental error associated to the measurement of the Dynamic Shear Modulus and Damping Ratio with the cyclic triaxial equipment.

Experimental work Using a certain borrow material from the Santiago area, two different coarse grained soils with the grain size distribution curves shown in Figure 1, were prepared in the laboratory. The first soil corresponds to a silty and clayey sand, SM-SC, with 30% gravel and 17% fine grained soil of low plasticity. The second soil corresponds to a well graded sandy gravel, GW, with 4% fine grained soil of low plasticity. Both soils were mainly made up of subrounded particles.

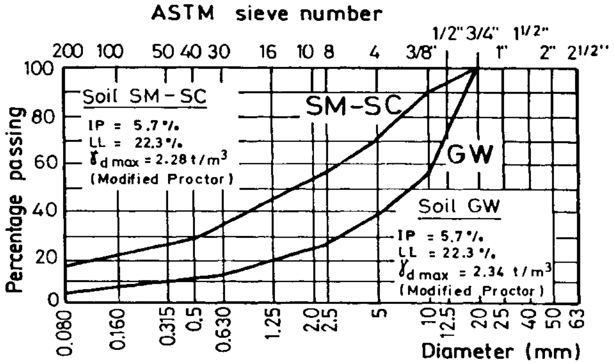

FIG. 1 INDEX PROPERTIES OF THE SOILS TESTED

All the test specimens were 4 in-diameter samples compacted with 4% moisture content at either 85% or 98% of the maximum Modified Proctor dry density.

All the tests were carried out maintaining constant the preparation water content and with the drainage valves fully opened. The confining pressure was set at either 0.2 or 1.0 kg/cm$^2$.

The cyclic deviator stress was applied, as a sinusoid of frequency 3Hz with the same amplitude in compression as in extension. A digital data acquisition system was used in order to monitor the vertical load, the vertical deformation and the radial deformation of the samples.

During this first stage of the research, the amplitude of the cyclic deviator stress, $\sigma_d$, was selected as either 50% (lower level) or 90% (upper level) of the confining pressure. This means that the cyclic stress ratio defined as $R = \sigma_d/2\sigma'_0$ varied from 0.25 to 0.45 in the assumption that the induced pore pressures were not significative ($\sigma'_0$ = effective confining pressure). Concerning the number of cycles, during this stage the lower level was 10 cycles and the upper level 10,000 cycles respectively.

Results Figure 2 shows typical shear stress-strain loops corresponding to cycles 10 and 10,000. This figure shows that, for the samples prepared at a high compaction degree (Dry density = 98% of the maximum dry density in the Modified Proctor test) the inclination of the hysteresis loops for cycles 10 and 10,000 are not significantly different. Thus, within the range of maximum shear strains tested, approximately between $2.5 \times 10^{-2}$ and $10^{-1}$ %, and in the absence of significative pore pressures, the reuse of samples of dense coarse granular soils in the cyclic triaxial test would not alter significantly the Dynamic Shear Modulus with respect to the value which would be obtained from virgin samples. But a reduction of some significance in the value of the Damping Ratio was often noticed as the number of cycles increased.

Given the complexity of the method of Factorial Analysis of Experiments, it is not possible to formulate the method within the limited space available herein. The interested reader can find in the references a publication with detailed explanations of this interesting and valuable statistical procedure.

By applying the above technique to the laboratory tests carried out in this first stage, it was concluded that the confining pressure was the most relevant factor affecting the value of the Shear Modulus. Other important factors were the degree of compaction and the magnitude of the cyclic deviator stress. The grain size distribution was not a relevant factor for the soils tested.

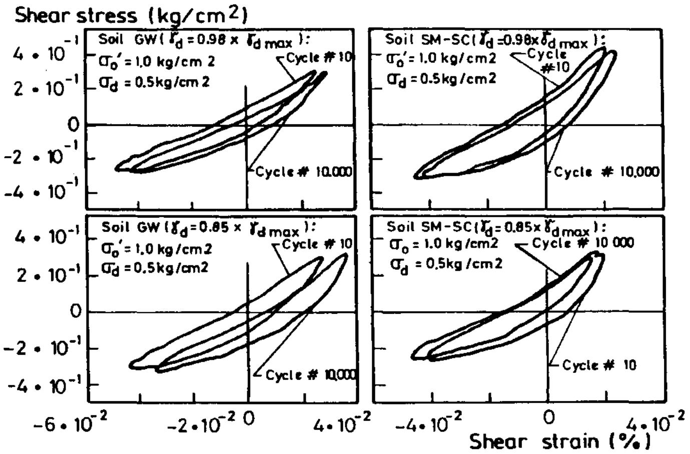

FIG. 2 TYPICAL STRESS-STRAIN LOOPS

Concerning the Damping Ratio, it varied mainly with the number of applied loading loops. The cyclic deviator stress, $\sigma_d$, did not have a major influence because, during this first stage of the research, a rather small variation of the stress ratio R was used and, consequently, the same happened with the induced strains. Moreover, it is worthy to note that the variations in the value of the Damping Ratio might be hidden by the experimental error. In fact, the experimental error in the value of the Dynamic Shear Modulus ranged between 7% and 30% of its mean value, and it ranged between 6% and 40% for the Damping Ratio.

## SECOND STAGE OF THE RESEARCH

General considerations The purpose of the second stage was to completely define the "Basic Curve" or dynamic stress-strain behavior of the soil within the range of strains allowable in the cyclic triaxial shear test equipment.

The experimental results were compared with the results of both the Hyperbolic Model and the Ramberg-Osgood (R-O) model, in order to determine which one of them would represent in a better way the physical evidence.

Basic Curve and Masing's Rule The application of a cyclic, symmetrical load over an element of an isotropic soil, results in a non linear stress-strain behavior of the nature indicated in Figure 3. The locus of the extreme points of the hysteretic loop corresponding to different magnitudes of distortion, is defined as the "Basic Curve" of the soil. As Figure 3 shows, the value of the secant Shear Modulus, G, associated to each loop, decreases as the maximum shear strain increases. The slope of the tangent to the Basic Curve at the origin, defines $G_0$, the maximum value of the Shear Modulus in a soil, corresponding to a small magnitude of strain. The abscissa of the point where the tangent through the origin intercepts the maximum shear strength of the soil, $\tau_f$, is known as the reference shear strain, $\gamma_r$ (see Fig. 3). The loss of energy in each loop or Hysteretic Damping, D, is computed from the expression (Seed and Idriss, 1970):

$$D = \frac{\text{Area within the loop}}{4\pi \times \text{Area}\,\Delta\,\text{OAB}} \qquad \text{(Eq. 1)}$$

If the analytical expression of the Basic Curve is known, then it is possible to obtain a theoretical description of the upper and lower limits of the loop by using the associated equations to Masing's Rule, as it is shown in Figure 4 (Ishihara, 1986). Thus, once the hysteretic loop of a cycle is defined, it is also possible to estimate its Damping Ratio.

Hyperbolic Model and R-O Model The Hyperbolic Model assumes that the Basic Curve can be approximated by the hyperbola (Ishihara, 1986):

$$\tau = \frac{\gamma G_0}{1 + \frac{\gamma}{\gamma_r}} \qquad \text{(Eq. 2)}$$

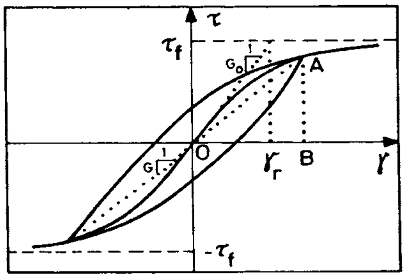

FIG. 3 BASIC CURVE OF A SOIL

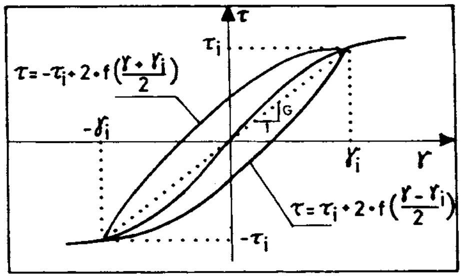

FIG. 4 DEFINITION OF THE LOOP USING MASING'S RULE

Since, in particular, this equation is valid in any of the extreme points of the loop, with coordinates $(\gamma,\tau)$, the equivalent Shear Modulus, or Secant Modulus, $G = \tau/\gamma$, satisfies the relationship:

$$\frac{G}{G_0} = \frac{1}{1+\dfrac{\gamma}{\gamma_r}} \qquad \text{(Eq. 3)}$$

Using Masing's Rule, from (Eq. 2) the Damping Ratio is obtained as:

$$D = (4/\pi)(1+\gamma_r/\gamma)(1-(\gamma_r/\gamma)\cdot\ln(1+\gamma/\gamma_r))-2/\pi \qquad \text{(Eq. 4)}$$

According to the R-0 model, the Basic Curve can be expressed as (Ishihara, 1986):

$$\tau = \frac{\gamma G_0}{1+\alpha\left|\dfrac{\tau}{\tau_f}\right|^{(r-1)}} \qquad \text{(Eq. 5)}$$

Again, considering that at any point of the Basic Curve the Secant Shear Modulus, G, is equal to $\tau/\gamma$, it is obtained:

$$\frac{G}{G_0} = \frac{1}{1+\alpha\left|\dfrac{G\gamma}{G_0\gamma_r}\right|^{(r-1)}} \qquad \text{(Eq. 6)}$$

Using Masing's Rule in (Eq. 5) the following expression for the Damping Ratio is obtained:

$$D = \frac{2(r-1)\left(1-\dfrac{G}{G_0}\right)}{\pi(r+1)} \qquad \text{(Eq. 7)}$$

The value of the constants "$\alpha$" and "r" appearing in Eqs. (6) and (7) can be obtained by curve fitting to the experimental results.

Experimental work The general characteristics of the cyclic triaxial tests were maintained during the second stage of the research, as well as the grain size distribution of the two soils, the degree of compaction of the samples and the values of confining pressure. This stage was carried out with reused samples, gradually increasing the magnitude of the cyclic deviator stress so as to cover all the development of the curves G vs. $\gamma$ and D vs. $\gamma$, within the strain capabilities of the testing equipment, approximately $5 \times 10^{-3}$ to $5 \times 10^{-1}$ %. For each value of the cyclic deviator stress, the parameters G and D were evaluated for the last cycle of loading application, which was always the cycle # 10.

Results The analytical fitting to the experimental results yielded better correlation coefficients for the Hyperbolic Model than for the R-0 Model. Figure 5 shows some typical results obtained with the Hyperbolic Model. The curves of Figure 5 show that the analytical approximation of G vs. $\gamma$ tends to underestimate the value of G0, and hence it is convenient to estimate this parameter by geophysical methods.

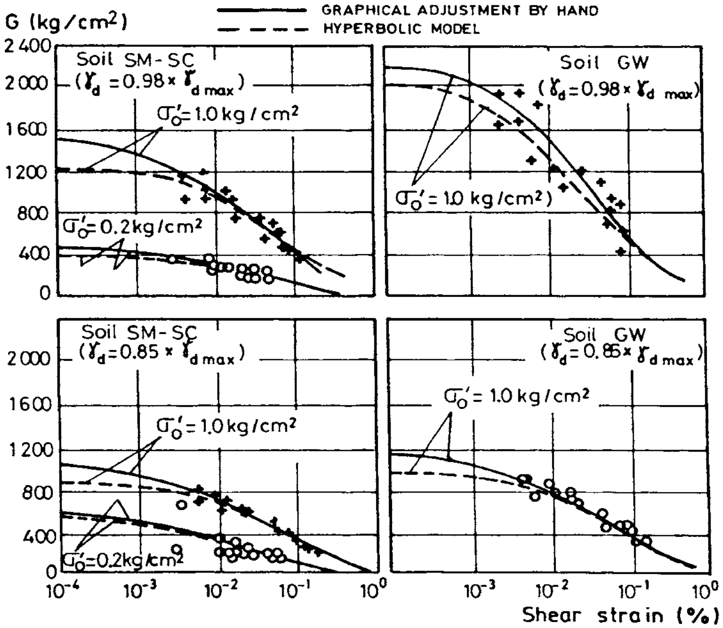

FIG. 5 CURVES FITTED TO THE EXPERIMENTAL RESULTS

The experimental changes of the curves G vs. $\gamma$ and D vs. $\gamma$ with the values assigned to the different factors considered, are shown in Figures 6 and 7. These figures also show the range of values proposed by Seed et al. (1986) for the Dynamic Shear Modulus and Damping Ratio in sands and gravels, which allow to confirm the adequacy of the results obtained herein.

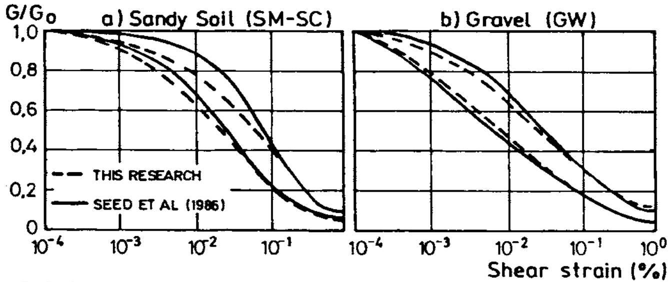

FIG. 6 VARIATION OF THE SHEAR MODULUS IN COARSE GRAINED SOILS FROM THE SANTIAGO AREA: a) Sandy soil (SM-SC) b) Gravel (GW)

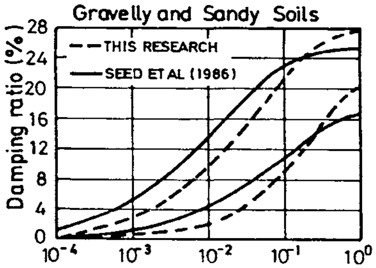

FIG. 7 VARIATION OF THE DAMPING RATIO IN COARSE GRAINED SOILS FROM THE SANTIAGO AREA

## CONCLUSIONS

This work has shown the enormous practical usefulness that the Factorial Analysis of Experiments can present during the planning of soil mechanics tests, either in the laboratory or in the field, and during the interpretation of the test results.

The experimental error associated to cyclic triaxial tests of recompacted samples ranged from 7% to 30% in the evaluation of the Dynamic Shear Modulus and from 6% to 40% in the evaluation of the Damping Ratio.

From the sensitivity analysis carried out during the first and second stages of the research, it is concluded that the most significant factors which influence the magnitude of the Dynamic Shear Modulus in a non saturated granular soil, besides to the strain level, are the confining pressure and the degree of compaction. The grain size distribution is a secondary factor and the number of cycles is the least important one. The previous result is valid whenever there are no significant pore pressures during loading application.

Concerning the Damping Ratio, it depends on the same factors that influence the Dynamic Shear Modulus. The order of their relative significance is not clear, however, due to the dispersion of the experimental results. Nevertheless, in this case the number of cycles was more significant than the grain size of the soil.

The analytical curve-fitting to the experimental dynamic relationship of "Shear Stress" versus "Shear Strain", demonstrated that the Hyperbolic Model yields less dispersion than the Ramberg-Osgood one. However, the use of such model to obtain an indirect estimate of the $G_0$ Shear Modulus, corresponding to small angular distortions (on the order of $10^{-4}$ %) is not advisable as long as the cyclic triaxial tests do not allow to work with shear strains smaller than $5 \times 10^{-3}$ %. It is preferable to estimate that parameter by extrapolating the experimental curve by hand, and if possible, with some kind of geophysical support.

## ACKNOWLEDGMENTS

The authors would like to express their gratitude to the National Road Laboratory for the authorization to use their cyclic triaxial test equipment and to FONDECYT, Project N° 1930704, for the financial support given to this research.

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