Evaluation of Granular Soil Properties in Seismic Analysis of Nuclear Structures

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Abstract

The seismic analysis of nuclear power plant structures founded on soils, as well as related soil-structure interaction studies, are often made by means of "equivalent" linear models of soil behavior, represented by effective values of damping and of Young's modulus. Such approach requires resorting to iteration on the material properties, thus leading to a "multilinear" analysis which can be justified in practice on account of the scarce knowledge of constitutive equations applicable to soils under a general three-dimensional stress state. It is therefore important to establish bounds on the applicability of the multilinear solutions, and to develop reliable procedures for the evaluation of the soil properties to be used in seismic analyses. The paper focuses attention on the dynamic properties of sandy soils.

To that effect, an extensive program was conducted using a triaxial dynamic testing apparatus developed at the UFRGS, and the results compared with existing experimental evidence, including data from resonant-column testing.

Linear and nonlinear regression techniques applied to the experimental data led to new equations relating damping and soil stiffness to the dependent variables, and permitted as well the determination of the expected error of the estimated parameters. It was found that an increasing frequency, slightly increases both Young's modulus and the effective damping ratio. In addition, the influence of the content of fines was found to be significant. This variable does not appear in several available empirical equations, which only consider the confining pressure, the void ratio and the amplitude of the cyclic shear deformations as relevant variables.
1. **Introduction**

The dynamic analysis of soils, foundations and soil-structure systems is often performed on the basis of models in which the soil behavior is described by means of two parameters: an equivalent shear modulus $G_{eq}$ or, alternatively, an equivalent Young modulus $E_{eq}$, and an effective damping ratio. Such approach, in this paper denoted as multi-linear analysis because the modulae varies with the strain level, can be justified in practice by the difficulties that are still encountered in the analysis of large nonlinear systems, and by the insufficient knowledge of constitutive equations applicable to soils under three-dimensional stress conditions. In fact, reliable non-linear solutions for unidimensional problems, such as the method of characteristics, implemented, among others, by Streeter, Wylie and Richart [1] and by Brito [2] are widely available. However, generalizations to bi- and three-dimensional problems have met with difficulties. This as well as other alternatives still constitute areas of research and development and do not seem ready for practical use.

The multilinear solution is applicable when both the excitation and the response are stationary, that is, when the statistical parameters that define the excitation, such as its mean value, rms value, frequency content, etc, do not vary with time and simultaneously, the system is stable. The hypothesis of stationarity of the excitation, valid in case of vibrations induced by rotating machinery, turbines, etc., may under certain conditions, be also applicable to seismic or wind excitation.

Brito 'et al' [3] discuss difficulties related to the convergence of multilinear solutions by comparing results obtained for a horizontal soil system subjected to seismic loading with the Programs SHAKE, FLUSH and INFLUSOLO. Satisfactory convergence was observed in case of weakly non-linear systems, defined as those in which the equivalent shear modulus does not decrease below 30% of its initial value for any point of the system or any step of the iterative procedure. In strongly non-linear systems, the multilinear approach must be used with extreme caution, if at all.

In connection with solutions based on stress-strain relations, such as the method of characteristics, in which the resultant damping is of the hysteretic type, the presence of spurious peaks in the high frequency range of the calculated surface response spectra, indicated that viscous damping also plays a role in energy dissipation. In fact, the addition of a small amount of viscous damping to the soil system - about 1% of critical - solves the problem by eliminating the peaks in the high frequency range (above 20 Hz) without significantly affecting the rest of the spectrum [2, 3].

This report is concerned with the properties of granular soils needed to determine their response to dynamic excitation, in relation to the multilinear approach as well as in connection with solutions based on a unidimensional stress-strain relationship.

Taking into consideration that previous papers on the dynamic properties of granular soils cannot be regarded as conclusive with respect to the
independence of the stress-strain diagram on the excitation frequency \( f_0 \), one of the objectives of this work was to evaluate its influence. In addition, since preliminary results had shown that the content of fines may also be a relevant variable, factor hitherto not explicitly considered by other authors, an effort was made to assess its significance in a more general formulation.

Thus, an extensive experimental program was undertaken at the CPGE de la Universidade Federal do Rio Grande do Sul, UFRGS, Porto Alegre, Brasil, on Guaiba sand by means of a triaxial dynamic testing equipment developed at the UFRGS. Results of this program are reported in this paper.

2. Choice of relevant variables

2.1 Multilinear analysis

The hysteretic cycle resulting when the soil is subjected to a harmonic excitation with frequency \( f_0 \) and constant amplitude is schematically shown in Fig. (1). For excitation amplitudes below a critical value the response is stationary and the closed curve is repeated in successive cycles of vibrations. Under such circumstances, the slope of the straight line OA, denoted herein as \( E_{eq} \) (or \( G_{eq} \)) can be used to evaluate the stiffness matrix of the soil system in an equivalent linear analysis. The energy spent in an oscillation cycle is proportional to the area enclosed by the hysteresis diagram, and is the basis for the determination of the equivalent damping ratio \( \lambda \).

In general, in granular soils, it is admitted that \( E_{eq} \) (or \( G_{eq} \)) depend on the confining pressure \( p' \), the deformation amplitude \( \varepsilon_a \) (or \( \gamma_a \)), and the compacity (void ratio) \( e \). In this report the dependence of \( E_{eq} \) on the excitation frequency \( f_0 \) and on the content of fines will be likewise investigated.

In previous studies concerning granular soils, it was considered that the damping ratio \( \lambda \) depends only on the deformation amplitude \( \varepsilon_a \) (or \( \gamma_a \)). It will be admitted herein that \( \lambda \) is a function of both \( f_0 \) and \( \varepsilon_a \).

2.2 Ramberg-Osgood stress-strain relations

The so-called Ramberg-Osgood skeleton curve is given by:

\[
\varepsilon = \frac{\sigma}{E_0} \left( 1 + \alpha \left| \frac{\sigma - \sigma_y}{R} \right|^{R-1} \right)
\]

(1)

and

\[
\varepsilon - \varepsilon_i = \frac{\sigma - \sigma_i}{E_0} \left( 1 + \alpha \left| \frac{\sigma - \sigma_i}{R} \right|^{R-1} \right)
\]

(2)

for the unloading and reloading branches. In eqs. (1-2), \( \sigma \) denotes the axial (or shear) stress, \( \varepsilon \) the axial (or shear) deformation, \( \sigma_y \) and \( \varepsilon_y \) the "characteristic" stress and strain, respectively, while \( \alpha \) and \( R \) are parameters that, with \( \sigma_y \) and \( \varepsilon_y \), define the material behavior. The pair \((\varepsilon_i, \sigma_i)\) are the coordinates of the last point in which the stress rate changes sign. When the
material is subjected to harmonic excitation, it describes the hysteretic cycle shown in Fig. (2) in which:

$$E_{eq} = \frac{E_0}{1 + \alpha \left( \frac{\sigma_{\max}}{\sigma_{\min}} \right)^{R-1}}$$

(3)

and the damping ratio \( \lambda \) defined by the area of the hysteretic cycle divided by twice the area of the triangle OAB times \( 2\pi \), is given by:

$$\lambda = \frac{2(R-1)}{\pi(R+1)} \left(1 - \frac{E_{eq}}{E_0} \right)$$

(4)

In granular soils it is generally accepted that the material parameters depend on the same variables that influence the equivalent modulus.

3. Description of preliminary results

3.1 Methodology

In order to assess the influence of the parameters described in the preceding section on the equivalent modulus and on the damping ratio, a multiple linear regression analysis was performed on data obtained by means of triaxial cyclic compression tests on Guaiaba sand, without fines and with a fine content of 5% in weight. The test and soil descriptions are given in Appendix A. The dependent variables \( \lambda \) and \( E_{eq} \) were expressed in terms of a multiplicative model of the form

$$y_1 = \lambda = a_0 x_1^{a_1} x_2^{a_2} x_3^{a_3} e_1$$

(5)

$$y_2 = E_{eq} = b_0 x_1^{b_1} x_2^{b_2} x_3^{b_3} e_2$$

(6)

where \( x_1 = p' \), \( x_2 = f \), \( x_3 = e \) and \( e_1 \), \( e_2 \) being the error terms.

Given a set of observations \((\lambda_i, E_i, x_{1i}, x_{2i}, x_{3i})\) \( i = 1, n \), and using the method of non-linear multiple regression estimates can be found of the parameters \( a_i \), or \( b_i \), by minimizing the sum of the squares of the deviations: \( S = \sum (\text{observed } y_i - \text{estimated } y_i)^2 \).

Alternatively, equations (5) and (6) can be linearized by applying a logarithmic transformation to obtain:

$$y_1 = \ln y_1 = \ln a_0 + \sum a_i \ln x_i + \ln e_1$$

(7)

$$y_2 = \ln y_2 = \ln b_0 + \sum b_i \ln x_i + \ln e_2$$

(8)

and then use the method of linear multiple regression to find the estimates of the parameters.

Under the usual assumption made in regression analysis that the errors are normally and independently distributed with a constant variance, the
estimates given by the least square success are linear, unbiased and with a minimum variance. This minimum variance refers to the transformed equations and not to the original ones.

3.2 Results

Available data for soils A and B were analyzed using a non-linear multiple regression (NLRP) for the untransformed variables and a linear regression program (LRP) for the logarithmically transformed variables. The standard error of estimate given by the NLRP was about 10% less than the corresponding value given by the LRP with comparable degree of significance for the estimated parameters. In what follows, only the results given by the LRP will be given.

By comparing the computed t-values with the corresponding table values one finds that the coefficients $a_1$, $a_3$, $b_1$ and $b_3$ are highly significant in all cases, and that $a_2$ is not significant for $\lambda$ in soil A but has some significance in the other cases. (See Tables 1 and 2)

The value of the coefficient of determination $R^2$ shows that about 90% the variability of the equivalent modulus and about 65% of the variability of the damping ratio are explained by the respective models. There seems to be some question about the assumption of normality for the modulus data which may be due to the presence of some outlying observations.

The resulting equations are

Soil A

$$E_{eq} = 614.6 \rho^{0.68} f^{0.04} \varepsilon_a^{-0.28}$$  \hspace{1cm} (9)

$$\lambda = 693.6 \rho^{0.35} f^{0.02} \varepsilon_a^{0.31}$$  \hspace{1cm} (10)

Soil B

$$E_{eq} = 206.5 \rho^{0.71} f^{0.03} \varepsilon_a^{-0.41}$$  \hspace{1cm} (11)

$$\lambda = 415.6 \rho^{0.35} f^{0.02} \varepsilon_a^{0.31}$$  \hspace{1cm} (12)

where $E_{eq}$ and $\rho'$ are in KN/m$^2$ (see Figs. 3-4).

The expression for $E_{eq}$ are applicable for deformations greater than $5 \times 10^{-5}$. For smaller values of $\varepsilon_a$ reasonable approximations can be obtained using this limit. Predicted individual values of $E_{eq}$ have coefficients of variation between 16% and 25% with a mean value of about 20%.

4. Critique of results and conclusions

The influence of the confining pressure and of the axial strain amplitude on Young's modulus and damping ratio are shown in Figs. (3) and (4) for both soils A and B. These trends are similar to previous results published by Hardin 'et al'[4], Iwaski 'et al'[5] and others.

However, although soils A and B had essentially the same void ratio and
were submitted to the same range of confining pressures and axial strain amplitudes, their Young's moduli and damping ratios were very different (see Figs. 3 and 4). These surely reflect the influence of the different content of fines in the samples and, at least for Young's modulus, they show a similarity to a phenomena first revealed by Iwasaki 'et al'[5].

The influence of frequency is not readily apparent from the experimental data, but the regression analysis described in Section 3 indicated that both Young's modulus and the damping ratio for soils A and B increase with the excitation frequency. This suggests that even dry sands present some amount of viscous damping - besides the more important parcel of hysteretic damping - and justifies the addition of a small percentage of viscous damping to the Ramberg-Osgood soil model, in order to eliminate high frequency peaks in the response spectra.

After processing the data it was found that the experimental error could be reduced by improving the system for attaching the LVDTs to the soil specimen. A new series of tests was then planned using the modified equipment. The experimental program was designed to quantify the influence of the content of fines on the soil properties, and includes the development of expressions to obtain the Ramberg-Osgood parameters, as well as Eeq and λ. Preliminary results indicate that, for axial strain amplitudes between 5x10^{-5} and 5x10^{-4}, damping ratios are lower than previously found.

APPENDIX A

Description of soil and experimental set up

Soil A, that was used in a research by Bica [6], consisted of a quartz sand, from the Guaiaba river, having its grain sizes limited by the #30 and #60 sieves, but having 5% in weight of fines added to its constitution. This soil showed a specific gravity of 2.655, a mean grain size of 0.46 mm and a uniformity coefficient of 1.50, according to Brazilian standards. The mean void ratio of all the specimens was 0.69 and the water content was less than 3%.

Soil B, which was used in a research by Rocha [7], consisted of the same sand as described above, but without the addition of fines. This soil showed a specific gravity of 2.69, a mean grain size of 0.49 mm and a uniformity coefficient of 1.51, according to the same standards. The main void ratio of all the specimens was 0.66 and all were tested air dried.

Essentially the same equipment was used in both experiments. It consisted of a conventional triaxial chamber with a force transducer placed inside it. Displacements were measured with LVDTs attached to the piston rod, in the case of soil A, or to the top cap, for soil B. Cyclic axial forces were generated by a pneumatic system, with solenoid valves that were driven by an electronic actuator.
More details of the experimental techniques are thoroughly described by references [6] and [7].

References


<table>
<thead>
<tr>
<th>Table 1 - Damping ratio</th>
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| \begin{tabular}{|c|c|c|c|c|c|c|c|}
| Soil A & Parameters & $R^2$ & Se & Analysis of Residuals & Possible \[\text{CV}\] & Variance & Outliers \\
| $n_1 = 38$ & t-values & \begin{tabular}{c}
$a_0$
\end{tabular} & \begin{tabular}{c}
$a_1$
\end{tabular} & \begin{tabular}{c}
$a_2$
\end{tabular} & \begin{tabular}{c}
$a_3$
\end{tabular} & \begin{tabular}{c}
Normality
\end{tabular} & \begin{tabular}{c}
Constant
\end{tabular} & \begin{tabular}{c}
None
\end{tabular} \\
| 693.6 & -0.347 & 0.017 & 0.311 & 69.6 & 16.5 & Normal & Constant & None \\
| 3.8 & 0.06 & 7.8 & & & & & & \\
| Soil B & Parameters & $R^2$ & Se & Analysis of Residuals & Possible \[\text{CV}\] & Variance & Outliers \\
| $n_2 = 102$ & t-values & \begin{tabular}{c}
$b_0$
\end{tabular} & \begin{tabular}{c}
$b_1$
\end{tabular} & \begin{tabular}{c}
$b_2$
\end{tabular} & \begin{tabular}{c}
$b_3$
\end{tabular} & \begin{tabular}{c}
Normality
\end{tabular} & \begin{tabular}{c}
Constant
\end{tabular} & \begin{tabular}{c}
One
\end{tabular} \\
| 415.6 & -0.235 & 0.355 & 0.268 & 63.0 & 20.1 & Normal & Constant & One \\
| 6.4 & 3.1 & 10.3 & & & & & & \\
| \end{tabular} | \end{tabular} |

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<tr>
<th>Table 2 - Equivalent modulus</th>
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| \begin{tabular}{|c|c|c|c|c|c|c|c|}
| Soil A & Parameters & $R^2$ & Se & Analysis of Residuals & Possible \[\text{CV}\] & Variance & Outliers \\
| $t\text{-values}$ & \begin{tabular}{c}
b_0
\end{tabular} & \begin{tabular}{c}
b_1
\end{tabular} & \begin{tabular}{c}
b_2
\end{tabular} & \begin{tabular}{c}
b_3
\end{tabular} & \begin{tabular}{c}
Small departure
\end{tabular} & \begin{tabular}{c}
Constant
\end{tabular} & \begin{tabular}{c}
Two
\end{tabular} \\
| 614.6 & 0.677 & 0.042 & -0.284 & 87.0 & 11.5 & Small departure & Constant & Two \\
| 12.7 & 2.9 & 13.6 & & & & & & \\
| Soil B & Parameters & $R^2$ & Se & Analysis of Residuals & Possible \[\text{CV}\] & Variance & Outliers \\
| $t\text{-values}$ & \begin{tabular}{c}
206.5
\end{tabular} & \begin{tabular}{c}
22.3
\end{tabular} & \begin{tabular}{c}
1.96
\end{tabular} & \begin{tabular}{c}
25.4
\end{tabular} & \begin{tabular}{c}
Small departure
\end{tabular} & \begin{tabular}{c}
Constant
\end{tabular} & \begin{tabular}{c}
Two
\end{tabular} \\
| 0.71 & 0.02 & 0.413 & & & & & & \\
| 22.3 & & & & & & & & \\
| |
Fig. 1 - Hysteretic loop, for harmonic excitation.

Fig. 2 - Ramberg-Osgood equations.

Fig. 3 - Experimental data: equivalent Young's modulus, $E_{eq}$ ($f = 1 \text{Hz}$)

Fig. 4 - Experimental data: damping ratio, $\lambda$ ($f = 1 \text{Hz}$)