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Estimating Dynamic Properties from Static Tests

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SYNOPSIS The applicability of various types of constitutive models to estimating dynamic material properties for soils from the results of static shear tests is briefly reviewed. The primary obstacle to making such predictions is the limiting resolution of conventional static tests. A simple procedure using empirical relationships to interpolate beyond the limit of the static shear tests is suggested for use in preliminary analysis and in cases where cyclic test data is not available.

INTRODUCTION

At the present time, the only reliable methods for directly determining the material property relationships required for dynamic response analysis are geophysical exploration and cyclic laboratory testing. Only through laboratory testing can properties in the intermediate to large shear strain range (shear strain, γ, greater than 10^{-3} percent) be determined. For preliminary analysis it is often difficult to justify the time and money necessary to perform such tests. Furthermore, in many parts of the world the sophisticated equipment required to perform these laboratory tests is not available.

The only alternative to laboratory testing currently available is the use of empirical correlations such as those proposed by Hardin and Drnevich (1970) and Seed and Idriss (1970). For certain classes of soils it may be possible to use the results of static shear tests to improve the accuracy of these correlations. A simple and reliable procedure for using static shear test results to estimate dynamic material properties would significantly improve the reliability of dynamic response analysis in cases where it is not possible to perform sophisticated cyclic shear tests. The results of static tests are often available for preliminary design even when cyclic test results are not, and static testing equipment is much more widely available than cyclic equipment.

DYNAMIC MATERIAL PROPERTIES

At the present time, most dynamic response analyses are elastic or visco-elastic wave propagation analysis which use strain-dependent equivalent linear soil properties. The equivalent linear shear modulus is defined as the slope of the line connecting the tips of the stress-strain hysteresis loop, while the fraction of critical damping is proportional to the area of the hysteresis loop. Typically, input to response analysis consists of plots of equivalent linear shear modulus (G) and fraction of critical damping (β) versus shear strain. Results from uniform cyclic shear tests are used to develop these plots. Seed and Idriss (1970) have presented typical shapes of these plots as a function of soil type.

Figure 1 shows the idealized strain (or stress) dependent uniform cyclic shear hysteretic stress-strain behavior of soil assumed for this study. The dashed line connecting the tips of the hysteresis loops is known as the backbone curve. This curve completely defines the modulus shear strain relationship. The significant aspects of Figure 1 are the decrease in stiffness (modulus) and the increase in damping with increasing stress or strain level. This idealized representation assumes isotropic rate independent non-progressive soil behavior.

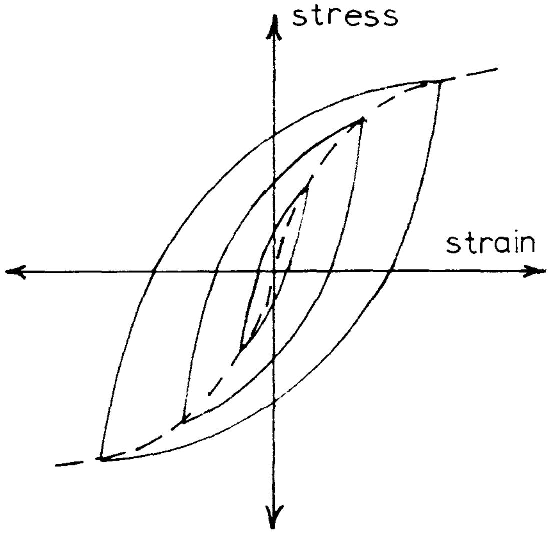

Fig. 1. Idealized Cyclic Shear Behavior

The assumptions of rate independence and nonprogressive behavior are generally valid for dry cohesionless soils and stiff and low plasticity clays. Saturated cohesionless soils may show progressively increasing shear strains (decreasing modulus) under constant stress level conditions due to pore pressure generation. Soft clays may show rate dependent behavior as well as progressively increasing shear strains.

CONSTITUTIVE MODELS FOR SOILS

Since the advent of numerical methods for the solution of boundary value problems in geomechanics, a wide variety of constitutive stress-strain models have been developed for soils. Several of these models are general enough to allow predictions of cyclic shear behavior using parameters derived from static shear tests.

The first class of constitutive models developed for numerical modeling was the pseudo-elastic models. This class of models employs empirical descriptions of stress-strain curves to evaluate secant or tangent moduli for use in elasticity solutions. The most common of these models use Kondner's (1963) assumption of a hyperbolic shaped stress-strain curve. The Ramberg-Osgood model (Ramberg and Osgood, 1943) uses a higher order curve than a hyperbola to describe stress-strain behavior. By making certain assumptions about soil behavior during unloading, reloading, and stress reversal, any of these psuedo-elastic models can be used to estimate dynamic soil properties from static shear tests.

Elasto-plastic constitutive models such as Critical State Soil Mechanics (Schofield and Wroth, 1968) and the Lade-Duncan model (Lade and Duncan, 1975) can provide accurate representations of the primary loading curve. However, most of these models use isotropic hardening rules that result in strictly elastic unload-reload behavior with no hysteresis. Therefore, these models are unsuitable for predicting cyclic soil behavior.

Prevost (1977) has recently developed an elasto-plastic model using a combination of isotropic and kinematic hardening rules. Prevost has used his model to describe both static and cyclic shear behavior.

Endochronic theory (Cuellar et al., 1977) is a recently developed constitutive model which uses intrinsic time variables, or damage variables, to characterize the accumulation of inelastic strains. Originally developed for concrete, endochronic models have been applied to describe both static and cyclic behavior of soils.

ESTIMATING CYCLIC BEHAVIOR FROM STATIC TESTS

Both Prevost' elasto-plastic model and endochronic theory are general enough to allow for prediction of cyclic shear behavior for static test results. However, both of the models require computer analysis to evaluate the requisite parameters.

The Ramberg-Osgood model used in conjunction with the Masing criterion for unloading and reloading offers a straightforward method for predicting dynamic material properties from static shear tests if one assumes that the static stress-strain curve is identical to the backbone curve. The Masing criterion stipulates that the unload/reload portion of a cyclic stress-strain curve has the same shape as the backbone curve but with both stress and strain scales expanded by a factor of two. The assumption that the backbone curve and static stress-strain curve are identical follows logically from the previously stated assumption of non-progressive rate-independent behavior.

The Ramberg-Osgood model has been used for time-domain dynamic response analyses of structural systems for some time (Jennings, 1963). Idriss, Dobry and Singh (1978) have recently applied it to soils.

The main problem that arises in using the Ramberg-Osgood model to estimate dynamic material properties from static shear tests is the poor resolution of static tests in the small shear strain range ($\gamma < 10^{-1}\%$). The resolution of even the highest quality triaxial compression test is generally insufficient to permit definition of the stress-strain curve in this range. In order to completely define the input parameters required for dynamic response analysis moduli values in the small strain range must be known.

If the infinitesimal shear modulus is known from geophysical data, moduli in the small strain range can be determined by using the Seed and Idriss shape curves to interpolate over the unknown region. If geophysical data is not available, there are several other options for evaluating the maximum modulus, G_{max}. The maximum shear modulus can be estimated using empirical correlations such as the equation developed by Hardin and Drnevich (1970), or it can be estimated as twice the initial unload/reload modulus (or twice the initial tangent modulus if no unload/reload cycle was performed). This latter suggestion is based on Lade's (1980) recommendation for evaluating the elastic modulus for his elasto-plastic model. This recommendation is supported by the observation that the value of $G/G_{max} = 0.5$ on the Seed and Idriss shape curves correspond to shear strains between $10^{-1}\%$ and $10^{-2}\%$, the limit of resolution of conventional triaxial compression tests.

SIMPLIFIED METHOD

Based on the above discussion, the following simple method for estimating dynamic material properties from static shear tests is suggested. The moduli for $\gamma > 10^{-1}\%$ can be calculated as the secant moduli to the static stress-strain curve. The maximum moduli ($\gamma = 10^{-4}\%$) can be calculated as twice the initial slope of the unload/reload curve, if available, or else as twice the initial tangent moduli to the static stress-strain curve. The Seed and

Idriss typical shape curves can be used to interpolate between the maximum modulus and the limit of the static shear test data. Damping can be calculated using the Masing criterion and a static stress-strain curve reconstructed from the dynamic shear strain-modulus relationship.

This simple method was used to predict dynamic properties for two soils, #20 Crystal Silica sand and San Francisco Bay mud. Predictions for the sand were made from static tests performed in the Stanford soils laboratory. These predictions were compared to results from cyclic triaxial tests reported by Silver and Park (1975) and from resonant column tests performed at Stanford. Cyclic triaxial tests were also performed at Stanford and compared to Silver and Park's results to confirm that the sample preparation procedures used at Stanford were correct. Figures 2 and 3 show the comparisons for the sand.

Static properties of San Francisco Bay mud were taken from Bonaparte and Mitchell (1979). Predictions were compared to dynamic test results reported by Stokoe and Lodde (1978). Comparisons between predictions and measured results is shown in Figures 4 and 5.

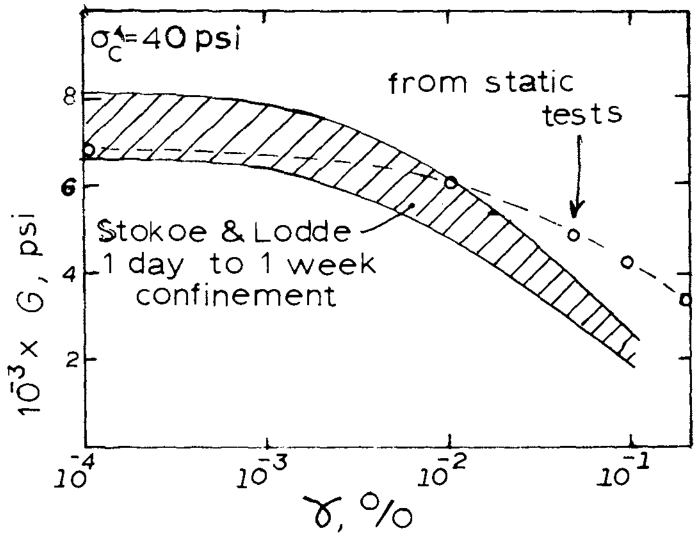

Fig. 2 Modulus of San Francisco Bay Mud

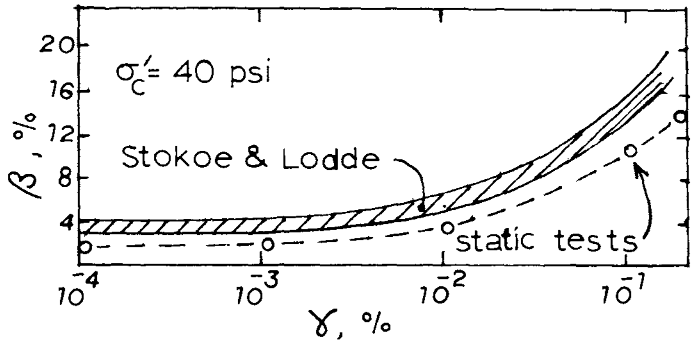

Fig. 3 Damping of San Francisco Bay Mud

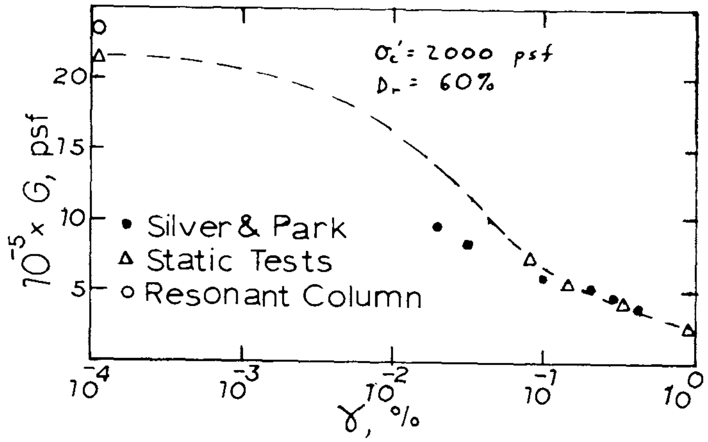

Fig. 4. Modulus of #20 Crystal Silica Sand

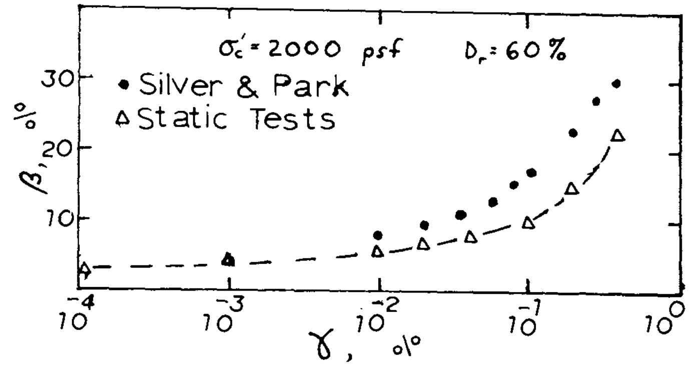

Fig. 5. Damping of #20 Crystal Silica Sand

CONCLUSIONS

If the static stress-strain curve of a rate-insensitive non-progressive soil could be completely defined by a laboratory test, then the dynamic material properties could be estimated from that test. However, the limit of resolution of most laboratory static shear test prohibits definition of the static stress-strain curve below shear strains of $10^{-1}\%$ to $10^{-2}\%$. To estimate the complete property relationships required for dynamic analysis from static tests, the maximum shear modulus must be estimated using empirical methods and the Seed and Idriss shape curves must be used to interpolate between G_{max} and the limit of resolution of the static tests.

ACKNOWLEDGEMENTS

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