EFFECTS ON SITE RESPONSE OF METHODS OF ESTIMATING IN SITU NONLINEAR SOIL BEHAVIOR

by

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SUMMARY

Five currently available methods for estimating in situ backbone curves of soil are discussed and compared. All methods incorporate field low-amplitude shear moduli, but most do not incorporate a second important parameter, rate-adjusted field maximum shearing stresses. Nonlinear seismic response analyses with shallow and deep sites of soft clay subjected to low- and high-level excitation illustrate the importance of using these parameters. Surface response spectra and maximum ground motions are directly affected by the in situ backbone curve used.

INTRODUCTION

Realistic seismic response analyses must consider the nonlinear behavior of soil (Joyner and Chen, 1975; Streeter et. al., 1974; and Taylor and Larkin, 1978). This nonlinear behavior is typically characterized by an initial loading curve which is composed of an initial tangent modulus, G_{max}, a failure shear stress, τ_{max}, and a curve linking G_{max} and τ_{max} as shown in Fig. 1. The initial loading curve, also called the backbone curve, represents the nonlinear behavior of the soil subjected to monotonic loading to failure. When combined with various hypotheses for hysteretic behavior, this curve forms the basis for defining the shape and location of hysteresis loops generated during subsequent cyclic loading.

A combination of field and laboratory tests is generally employed to determine different parts of the backbone curve. These parts are then combined by various methods to estimate the complete in situ curve. The initial tangent modulus is one part of the backbone curve which is determined in both the field and laboratory. In the field, seismic tests such as crosshole and downhole are used to evaluate G_{max} at shearing strains less than about 0.001 percent. Cyclic tests such as triaxial, simple shear, and resonant column are used to determine laboratory G_{max} values. However, values of G_{max} determined in the field consistently range from 20 percent to more than 100 percent above laboratory G_{max} values. Some type of reconciliation between G_{max} values must therefore be made to estimate the initial slope of the backbone curve. Consideration must be given to the effect on G_{max} of the testing methods, especially in terms of the effects of anisotropy, strain rate, and wave length.

Maximum shearing stress is the other part of the backbone curve which is determined in both the field and laboratory. Pressuremeter, static cone and vane tests are used in the field to determine τ_{max} while static triaxial and simple shear tests are usually used in the laboratory. These field and

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laboratory values are normally in much closer agreement than field and laboratory values of G_{max} so that little reconciliation is required. However, these values of τ_{max} do not incorporate any strain rate effect which is more pronounced on τ_{max} than on G_{max} and which should be considered when modeling the backbone curve for earthquake loading.

The part of the initial loading curve connecting G_{max} and τ_{max} is normally determined only in the laboratory and normally only a portion of this curve in the low- to intermediate-strain range is determined. Several field methods for determining this part of the backbone curve are in various states of development, but their use is extremely limited. Therefore, considerable judgment is required in adjusting this part of the laboratory curve to estimate the shape of the field curve.

Given the differences between measured field and laboratory parts of the initial loading curve, the lack of measurements on other parts of the curve, and the need for proper modeling of the various parameters affecting the curve for earthquake excitation, it is not surprising that several methods have been proposed for estimating the in situ backbone curve from field and laboratory results. These methods have been directed towards predicting the shear modulus-shearing strain curve at the start of cyclic loading, and some of them present quite divergent (and sometimes unrealistic) patterns in the high-strain range of the stress-strain plane. The methods, commonly referred to as adjustment methods, are reviewed herein, and their similarities and differences are shown by applying them to a soft clay at a shallow site (20 m) and a deep site (100 m). The importance to nonlinear site response analyses of estimating the in situ backbone curve is then illustrated by using an unadjusted and an adjusted backbone curve in the analyses of the shallow and deep sites subjected to low-level and high-level earthquake excitation.

SOIL SITES

Two soil sites composed of normally consolidated clay overlying bedrock were studied. The only difference between the two sites is the thickness of the clay layer. At the first site, the layer is 20 m thick while at the second site it is 100 m thick.

The properties of the clay at each site are patterned after field and laboratory measurements performed on San Francisco Bay Mud at Hamilton Air Force Base near San Francisco, California. Field tests and laboratory samples from depths of 9 to 15 m were used to determine properties in this depth range, and these values were then extrapolated to estimate values throughout the remainder of the soil profile. The clay is assumed to have the following properties: bulk density, void ratio, and degree of saturation equal to 1.46 gm/cm^3, 2.50, and 100 percent, respectively. The water table is assumed to be at the ground surface.

Initial tangent moduli based on crosshole tests in the field and resonant column tests in the laboratory are shown in Fig. 2. Field moduli, $G_{max\ field}$, exceeded laboratory moduli, $G_{max\ lab}$, by 70 percent for laboratory measurements performed after one day of drained confinement. Maximum shearing stresses in the field, $\tau_{max\ field}$, were determined from pressuremeter tests (Clough and Denby, 1980) which showed an undrained shear strength to vertical effective stress ratio (c/p) of 0.37. For brevity in this work, $\tau_{max\ lab}$ was assumed equal to $\tau_{max\ field}$. However, these values of maximum shearing stress are not adjusted for the effect of a higher rate of loading which would occur during earthquake excitation. Therefore, an adjustment factor of 1.4 was assumed, and the rate-adjusted τ_{max} in the field is denoted as $\tau^*_{max\ field}$. Profiles of the laboratory and rate-adjusted field maximum shearing stresses are shown in Fig. 3.

High-amplitude resonant column tests were used to determine the shape of the initial loading curve in the laboratory. Secant shear moduli versus shearing strain amplitude were determined in the strain range from 0.0002 to 0.3 percent. These results are presented in a normalized form in Fig. 4. The strain axis was normalized by dividing the shearing strain by reference strain, γ_r, where γ_r equals τ_{max} divided by G_{max}. Laboratory τ_{max} was used with $G_{max\ lab}$ to determined laboratory reference strain, $\gamma_{r\ lab}$. Since $\tau_{max\ lab}$ was not adjusted for rate of loading, $\gamma_{r\ lab}$ is not rate adjusted. Figure 4 also shows the hyperbolic curve used to approximate the laboratory results as well as to extend them into the high-strain range. This hyperbolic curve was used in the site response analyses as the laboratory curve.

ADJUSTMENT METHODS

Five methods have been proposed for estimating the in situ initial loading curve from field and laboratory measurements. These methods are: percentage increase (Seed and Idriss, 1970), arithmetic increase (Richart et. al., 1977), linear decrease (Taylor and Larkin, 1978), reference strain (Drnevich and Massarsch, 1979), and strain adjustment (Makdisi et. al., 1978). All of these methods have two points in common. First, the initial tangent modulus determined in the field by seismic methods is used as the initial modulus of the field initial loading curve. Second, the effect of rate of loading on τ_{max} is not explicitly taken into account in any of these methods, although several methods advocate proper testing procedures to determine τ_{max}. Proper testing would require times to failure on the order of a few tenths of a second which would thus determine a rate-adjusted τ_{max}. This rate adjustment factor can be quite significant. Whitman (1970) reported that for undrained loading the factor ranged from about 1.1 to 1.4 for sands and from about 1.4 to 2.0 for clays.

Percentage Increase Method. The percentage increase method simply involves adjusting the laboratory modulus-strain curve upward by the ratio of the low-amplitude field modulus to the low-amplitude laboratory modulus. This adjustment method can be described mathematically by:

$$G_{field} = G_{lab} *(G_{max\ field}/G_{max\ lab}) \tag{1}$$

where G_{field} is the adjusted field modulus at any strain level and G_{lab} is the laboratory modulus at the same strain level. This adjustment is the same at all levels of shearing strain. Hence, τ_{max} is not corrected independently, and if determined by testing in the proper frequency range, it is incorrectly adjusted twice.

Arithmetic Increase Method. The arithmetic increase method involves an upward translation of the laboratory modulus-strain curve by an amount equal to the difference between the low-amplitude field and laboratory moduli. This adjustment method can be expressed as:

$$G_{\text{field}} = G_{\text{lab}} + (G_{\text{max field}} - G_{\text{max lab}}) \qquad (2)$$

This method was proposed for shearing strains equal to or less than about 0.1 percent. Application of the method at higher strains can lead to significant overestimations of moduli. In addition, no means of incorporating τ_{max} in the method was proposed.

Linear Decrease Method. This method divides the laboratory modulus-strain curve into three parts and adjusts each part separately. For shearing strains below about 0.001 percent, an adjustment factor equal to the ratio between low-amplitude field and laboratory moduli is used. At shearing strains exceeding 1.0 percent, the laboratory curve is assumed to be equal to the field curve, and hence, no adjustment is made. For shearing strains in the range of about 0.001 percent to 1.0 percent, the adjustment factor is assumed to decrease linearly with the logarithmic increase in strain amplitude from the small-strain value at about 0.001 percent to one at 1.0 percent.

Reference Strain Method. This method uses the concept of normalizing the strain axis with the reference strain and further postulates that the shape of the normalized field and laboratory curves are the same. Hence, the shape of the laboratory curve of $G/G_{\text{max lab}}$ versus $\gamma/\gamma_{r\text{ lab}}$ is the same as that of the field curve of $G/G_{\text{max field}}$ versus $\gamma/\gamma_{r\text{ field}}$. Therefore, if $G_{\text{max field}}$, $\tau_{\text{max field}}$, and the laboratory backbone curve are determined, the complete backbone curve in the field can be determined from the laboratory curve. This approach applies equally well to stress-strain and modulus-strain backbone curves and easily incorporates $\tau^{*}_{\text{max field}}$.

Strain Adjustment Method. The strain adjustment method involves correcting moduli obtained from cyclic triaxial tests for nonuniform strains within the test specimen. Measured platen-to-platen strains are decreased as a result of measurements which indicate that strains within the middle third of the specimen are considerably smaller than those measured platen-to-platen. This adjustment effectively shifts the laboratory modulus-strain curve upward. The in situ G_{max} is used as the upper bound in the low-amplitude strain range to which a smoothened, adjusted laboratory curve is fit. The net result is similar to the results of the other four methods.

Methods Applied to Soil Sites. To demonstrate the results of using these adjustment methods, the first four methods were used to calculate field backbone curves from the field and laboratory results shown in Figs. 2, 3, and 4 for the clay comprising the two sites. (The strain adjustment method was not studied because no cyclic triaxial tests were performed.) The results are presented in terms of normalized curves in the modulus-strain and stress-strain planes in Figs. 5 and 6, respectively. By normalizing the curves, the results then apply to the soil at all depths within the sites.

All four adjustment procedures give similar trends on the modulus-strain plane as shown in Fig. 5. The adjusted curves are bracketed by the linear decrease method as the lower bound and by the arithmetic increase method as the upper bound. The curve denoted as "field curve" is predicted with the reference strain method by using $G_{max\ field}$ and $\tau^*_{max\ field}$. This curve represents the best estimate of the field backbone curve under these conditions. However, the exact shape is still in question because no in situ measurement of the field curve exists with which to compare.

The adjusted backbone curves on the stress-strain plane are shown in Fig. 6. This semi-logarithmic plot emphasizes the shape of the curve in the intermediate- to high-strain range, where variations between the adjustment methods become apparent. Curves from the arithmetic increase and percentage increase methods overestimate the field backbone curve in the intermediate- to high-strain range and should not be used in this range without modification to account for $\tau^*_{max\ field}$. (The exact result of the percentage increase method depends on the ratio of $G_{max\ field}$ to $G_{max\ lab}$ compared with the rate adjustment factor.) Curves from the linear decrease and reference strain methods underestimate the field backbone curve in the high strain range when a rate-adjusted τ_{max} is not used.

SITE RESPONSE COMPUTATIONS

Nonlinear site response analyses were conducted for the two soil sites to show the difference resulting from the use of a properly adjusted and an unadjusted initial loading curve. The hyperbolic stress-strain relation is used to represent the laboratory (unadjusted) curve and the reference strain method with $G_{max\ field}$ and $\tau^*_{max\ field}$ is used to represent the field adjusted curve. The computer program used for the site response analyses is MULAP (Chen, 1975).

Each site is subjected to two intensities of input bedrock motion, low-level and high-level excitation. The input bedrock motion is based on the first 10 seconds of the N21E component of the Taft recording of the 1952 Kern County earthquake. For use as high-level input motion, the Taft strong-motion record was multiplied by a factor of four, giving a peak acceleration of 0.7g and a peak velocity of 67 cm/sec. The low-level input motion, shown in Fig. 7, was obtained by scaling the high-level input motion by a factor of one-tenth. The response spectrum of input bedrock motion for low-level excitation is shown in Fig. 8.

TABLE I - SUMMARY OF MAXIMUM GROUND MOTIONS

Excitation	Low Level				High Level			
Site	Shallow		Deep		Shallow		Deep	
Stress-Strain Curve	Lab	Field	Lab	Field	Lab	Field	Lab	Field
Max. Surf. Accel. (g)	0.086	0.117	0.086	0.110	0.115	0.161	0.112	0.154
Max. Surf. Vel. (cm/sec)	15.96	14.88	15.59	15.98	73.50	78.99	78.86	93.95
Max. Surf. Displ. (cm)	6.11	5.55	9.28	8.26	61.29	63.86	72.96	80.99
Max. Strain[1] (%)	0.26	0.21	0.24	0.16	3.62	3.50	1.94	1.46

[1] Note: Maximum strain does not occur at the surface.

Results - The results of the response analyses of free-field ground motion are presented in Figs. 9 through 12 in terms of surface response spectra and in *Table I in terms of* maximum ground motions. Response spectra are significantly altered when the adjusted field curve is used in place of the laboratory curve. In each case, a general upward shifting of the spectrum occurs for periods less than 1.5 sec.

In terms of maximum ground motions, selection of the appropriate initial loading curve is clearly important. For low-level excitations where little yielding occurs and where the G_{max} adjustment has a strong effect, higher maximum accelerations, lower maximum displacements, and lower maximum strains occur when the field rather than the laboratory curve is used. For high-level excitation, considerable yielding occurs which causes plastic behavior to be an important factor, and maximum surface accelerations directly reflect the value of τ_{max}. As shown in Table I, the ratio of maximum surface accelerations is roughly in the ratio of 1:1.4 which is the ratio of laboratory to rate-adjusted field τ_{max} values.

CONCLUSIONS

1. In situ low-amplitude shear moduli and rate-adjusted maximum shearing stresses should be included in any method of developing a field initial loading curve for use in nonlinear site response analyses. The reference strain method conveniently incorporates each of these parameters.

2. The importance of estimating the field initial loading curve on surface response spectra and maximum ground motions is clearly shown, especially *the adjustment of* G_{max} *values for low-level excitation* and the adjustment of τ_{max} values for high-level excitation.

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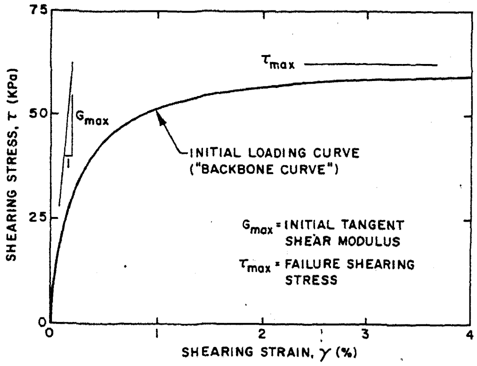

FIG. 1-CHARACTERIZATION OF NONLINEAR SOIL BEHAVIOR BY INITIAL LOADING CURVE

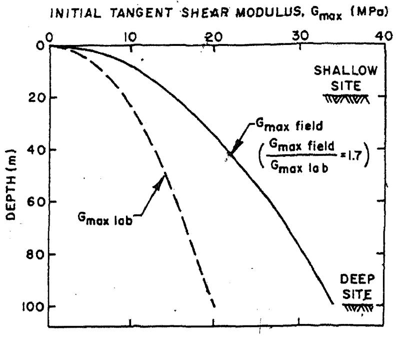

FIG. 2-PROFILES OF FIELD AND LABORATORY INITIAL TANGENT MODULI

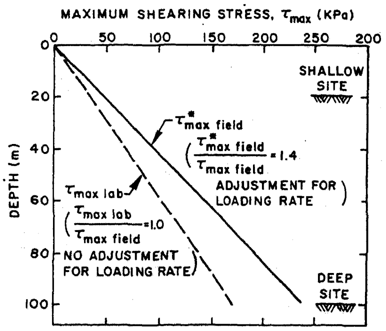

FIG. 3-PROFILES OF FIELD AND LABORATORY MAXIMUM SHEARING STRESSES

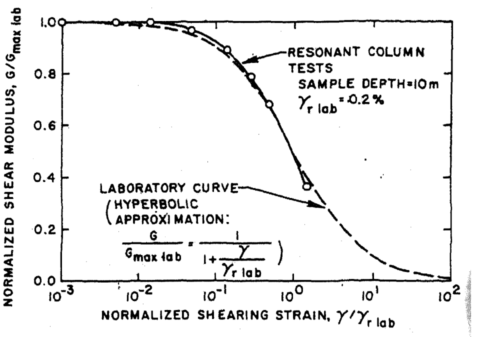

FIG. 4-NORMALIZED LABORATORY SECANT SHEAR MODULUS-SHEARING STRAIN CURVE

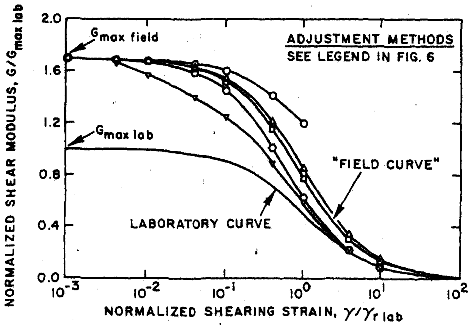

FIG. 5-NORMALIZED MODULUS-STRAIN CURVES CALCULATED BY ADJUSTMENT METHODS

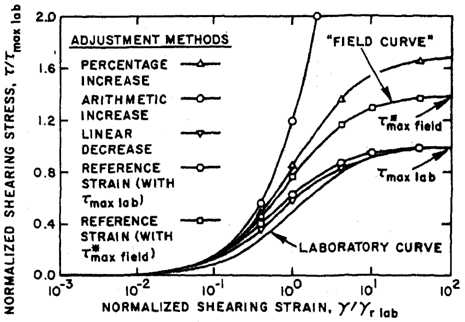

FIG. 6-NORMALIZED STRESS-STRAIN CURVES CALCULATED BY ADJUSTMENT METHODS

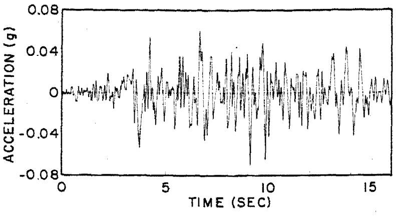

FIG. 7-ACCELERATION-TIME HISTORY USED FOR LOW-LEVEL INPUT BEDROCK MOTION

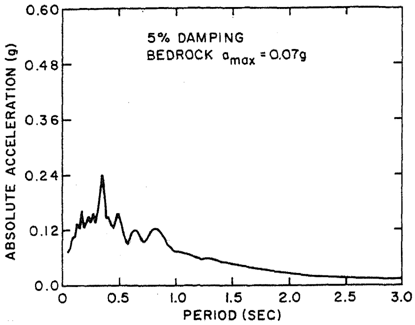

FIG. 8-RESPONSE SPECTRUM OF BEDROCK INPUT MOTION FOR LOW-LEVEL EXCITATION

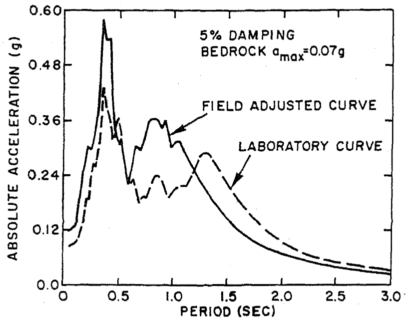

FIG. 9-SURFACE RESPONSE SPECTRA FOR SHALLOW SITE SUBJECTED TO LOW-LEVEL EXCITATION

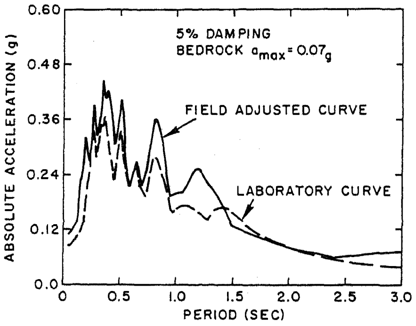

FIG. 10-SURFACE RESPONSE SPECTRA FOR DEEP SITE SUBJECTED TO LOW-LEVEL EXCITATION

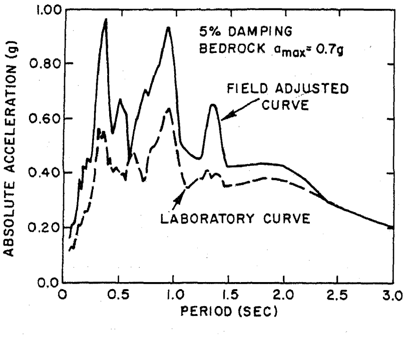

FIG. 11-SURFACE RESPONSE SPECTRA FOR SHALLOW SITE SUBJECTED TO HIGH-LEVEL EXCITATION

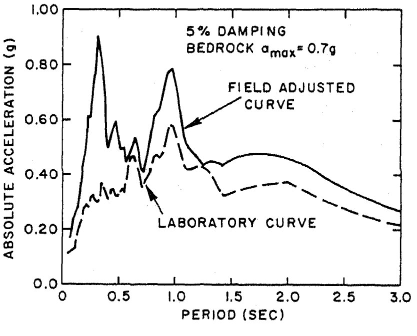

FIG. 12-SURFACE RESPONSE SPECTRA FOR DEEP SITE SUBJECTED TO HIGH-LEVEL EXCITATION