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STOCHASTIC SEISMIC RESPONSE ANALYSIS OF SOFT SOIL SITES

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ABSTRACT

The Bouc-Wen smooth hysteretic model is modified to better represent the nonlinear shearing stress-strain behavior of soils observed under cyclic and random dynamic loading. As is, the Bouc-Wen model overestimates the hysteretic damping in the soils at large strains, and does not properly account for small hysteretic loading reversals at large strains that may occur under random dynamic loading. It is proposed to use the modified Bouc-Wen model to compute the response of horizontally layered soil deposits under random seismic loadings by extending a well-known stochastic equivalent linearization technique used with the Bouc-Wen model to the modified Bouc-Wen smooth hysteretic model.

1.0 INTRODUCTION

Variations of recorded ground motions from the Loma Prieta earthquake with local site conditions clearly show the need for appropriate ground response analysis to predict levels of shaking at soft soil sites. Typically, ground response analyses are conducted in the frequency domain and use one dimensional shear wave propagation theory together with an empirical equivalent linear response analysis in the frequency domain[1] which, nevertheless, has been shown to offer a reasonably accurate means for estimating the peak horizontal ground accelerations recorded at some soft soil sites during the Loma Prieta earthquake[2], i.e., sites without significant deterioration of the mechanical properties of the soil under the earthquake loading. However, for large input bedrock accelerations and for short duration earthquake loadings the frequency-domain analysis procedure may not be sufficiently accurate as a result of stronger nonlinearities, degradation of the soil properties and the transient nature of seismic earthquake loadings. Under those circunstances, nonlinear site response analysis in the time-domain should be performed.

The Bouc-Wen smooth hysteretic model is capable of representing strongly nonlinear and hysteretic behavior as well as strength and stiffness degradation under both cyclic and random loading. While many other models have been proposed for time-domain nonlinear ground response analysis, the mathematical description of the Bouc-Wen model in terms of differential equations allows for a simple stochastic equivalent linearization technique in the time-domain to obtain the response statistics of nonlinear-hysteretic dynamic systems under random seismic loadings. Nevertheless, the Bouc-Wen model overestimates the hysteretic damping in the soil under cyclic loadings at very large strain levels[3], i.e., it predicts hysteresis loops which are fatter than those actually observed in laboratory tests. Furthermore, the model does not properly account for small hysteretic load reversals at large strain levels. Here, the Bouc-Wen smooth hysteretic model is modified to better reproduce the shearing stress-strain behavior of soils observed under cyclic and random loading. It is also proposed to use the modified Bouc-Wen model for the ground response analysis of horizontally layered soil deposits under random earthquake loadings together with a one-dimensional lumped mass model for the soil deposit that includes an appropriate transmitting boundary[4].

2.0 EQUATIONS OF MOTION FOR THE LUMPED MASS-MODEL

The effect of soft soil layers on the severity of shaking for horizontally layered soil sites is to be evaluated with a one-dimensional ground response analysis which idealizes the site amplification as the result of vertically propagating shear waves. This approach has been shown to offer a reasonably accurate means for estimating site amplification effects for horizontal ground accelerations[2] which are the accelerations of interest in this study. Accordingly, a lumped mass model for the soil deposit (see Fig. 1) is constructed as follows[3,4]: the soil deposit is divided into a number of elements (layers); the lumped masses, m_i, $i = 1, 2, ..., n+1$, are obtained by lumping one-half the mass of each layer at the layer boundaries and, at the interface between the lowest element and the base only one-half of the mass of the lowest layer is lumped. The motion of the system is described by the total displacements x_i, $i = 1, 2, ..., n+1$, of the layer boundaries. Nonlinear springs with stress-strain properties representing the nonlinear, strain-dependent and hysteretic behavior of the soil connect the massess as shown in Fig. 1. The total shear strain at each layer is defined by $\gamma_i = (x_{i+1} - x_i)/\Delta h_i$.

With the Bouc-Wen model the hysteretic component, z, of the shear strain is described by

$$\frac{\partial z}{\partial \gamma} = A - \beta \frac{|\gamma|}{\dot{\gamma}} |z|^{r-1} z - \delta |z|^r \tag{1}$$

where γ is the total shear strain, A, β, δ and r are parameters that describe the shape of the hysteresis loops. The shear stress is given by

$$\tau = \alpha G_m \gamma + (1 - \alpha) G_m z \tag{2}$$

where G_m is the (small strains) shear modulus and αG_m is the residual stiffness. The maximum hysteretic shear stress is given by

$$\tau_m = (1 - \alpha) G_m [A/(\beta + \delta)]^{1/r} \tag{3}$$

The following values have been recommended for the parameters of the smooth hysteretic model[3]: $A = 1.0$, $\delta = \beta$, $r = 0.5$, $\alpha = 0.05$ with β and γ calculated from Eq. 3 for a specified value of τ_m.

Dynamic equilibrium of each lumped-mass requires that, for $i = 1, 2, ..., n$,

$$\begin{aligned} & m_i \ddot{x}_i + (1 - \delta_{i1})[\alpha_{i-1} K_{i-1}(x_i - x_{i-1}) + (1 - \alpha_{i-1}) K_{i-1}(\zeta_i - \zeta_{i-1})] \\ & -[\alpha_i K_i (x_{i+1} - x_i) + (1 - \alpha_i) K_i (\zeta_{i+1} - \zeta_i)] = 0 \end{aligned} \tag{4}$$

where $\delta_{i1} = 0$ if $i \neq 1$ and $\delta_{i1} = 1$ if $i = 1$, $K_i = G_{mi}/\Delta h_i$, $i = 1, 2, ..., n$ and $(\zeta_{i+1} - \zeta_i)/\Delta h_i = z_i$ for $i = 1, 2, ..., n$.

For the $n+1$st mass the equation of equilibrium is

$$m_{n+1}\ddot{x}_{n+1} + \alpha_n K_n(x_{n+1} - x_n) + \\ +(1-\alpha_n)K_n(\zeta_{n+1} - \zeta_n) = \rho_R V_R(2U - \dot{x}_{n+1}) \quad (5)$$

The term $\rho_R V_R(2U - x_{n+1})$ represents the shear stress that is applied to the bottom of the soil deposit from the underlying stiffer soil or rock base, where ρ_R and V_R are the unit mass and velocity of the shear wave propagation in the underlying base. The term U denotes the input motion in terms of particle velocity from the incident wave[4].

The earthquake ground motion accelerations can be represented by an amplitude and frequency modulated nonstationary random process, with an instantaneous power spectral density function, $S(\omega)$, an amplitude modulating function, $I(t)$, and a frequency modulating function, $\Phi(t)$[5]. With this model, the instantaneous power spectral density function of the earthquake ground acceleration is characterized by the so-called Clough-Penzien spectrum[6] as follows:

$$S(\omega) = S_0 \frac{1 + 4\zeta_B^2(\omega/\omega_B)^2}{[1 - (\omega/\omega_B)^2]^2 + 4\zeta_B^2(\omega/\omega_B)^2} x \frac{(\omega/\omega_G)^4}{[1 - (\omega/\omega_G)^2]^2 + 4\zeta_G^2(\omega/\omega_G)^2} \quad (6)$$

The parameters of the model, i.e., the parameters in the analytical expressions for $S(\omega)$, $I(t)$ and $\Phi(t)$ are obtained from recorded accelerograms. As an example, the mean response spectrum for 2 percent damping obtained using the stochastic ground motion model with its parameters derived on the basis of one horizontal component of the Anderson Dam records (downstream) for the 1989 Loma Prieta earthquake, is shown in Fig. 2 together with the response spectrum, for 2 percent damping, for the same horizontal component of the Anderson Dam records (downstream).

3.0 MODIFIED BOUC-WEN MODEL

The differential equation relating the shear strain γ to the variable z is modified as follows:

$$\frac{dz}{du} = A - \beta\frac{|\dot{u}|}{\dot{u}}\left|\frac{z - z_i}{1 + c_i}\right|^{r-1}\left(\frac{z - z_i}{1 + c_i}\right) - \delta\left|\frac{z - z_0}{1 + c_i}\right|^r \quad (7)$$

where z_i is the value of z at the last load reversal and c_i is given by

$$c_i = -\frac{|\dot{u}|}{\dot{u}}\frac{z_i}{z_{max}} \quad (8)$$

and,

$$z_{max} = \left(\frac{A}{\beta + \delta}\right)^{1/r} \quad (9)$$

Two cases need to be considered as shown in Fig. 2: (i) the ascending branch for $\dot{u} > 0$ and $(z - z_i)/(1 + c_i) > 0$ and the descending branch for $\dot{u} < 0$ and $(z - z_i)/(1 + c_i) < 0$. With the proposed modification, the model can better represent small load reversals at large strains, such as those shown in Fig. 3, which are for a sandy soil tested in torsional simple shear[7].

Also, the area enclosed by the shearing stress-strain hysteresis loops is smaller than that for the original Bouc-Wen model which results into less hysteretic damping at high strains.

With the proposed modification, the stochastic equivalent linearization technique proposed by Wen[8] cannot be used without modification as it cannot "memorize" the most recent load reversals. It is proposed to modify that equivalent linearization technique by computing the equivalent linear coefficients on the basis of Eq. 9 rather than on the basis of Eq. 1 and using the probability distribution function of the peaks of z for the load reversal points z_i. Note that, for positive values of z, load reversals occur either when z reaches a local maximum, i.e., when $\dot{u}$ goes from positive to negative, or when z reaches a local minimum, i.e., when $\dot{u}$ goes from negative to positive. A similar argument applies for load reversals at negative values of z. This implies that when the velocity is positive the quantity z_i corresponds either to a negative local minimum (a peak) or a positive local minimum (a valley), while when the velocity is negative, z_i is either a positive local maximum or negative local maximum. The accuracy of the proposed extension to the stochastic equivalent linearization is being compared with Monte Carlo simulation results.

4.0 CONCLUSIONS

A modification of the Bouc-Wen smooth hysteretic model is proposed to better represent the shearing stress-strain behavior of soils under cyclic and random loadings observed in laboratory tests. In particular, the modified model addresses the characterization of small load reversals at large strains, that may occur under random dynamic loadings. It is proposed to use the modified model for ground response analysis of horizontally layered soil sites under random dynamic loadings by extending the equivalent linearization technique used with the Bouc-Wen's smooth hysteretic model. The accuracy of the proposed method of analysis is currently under investigation.

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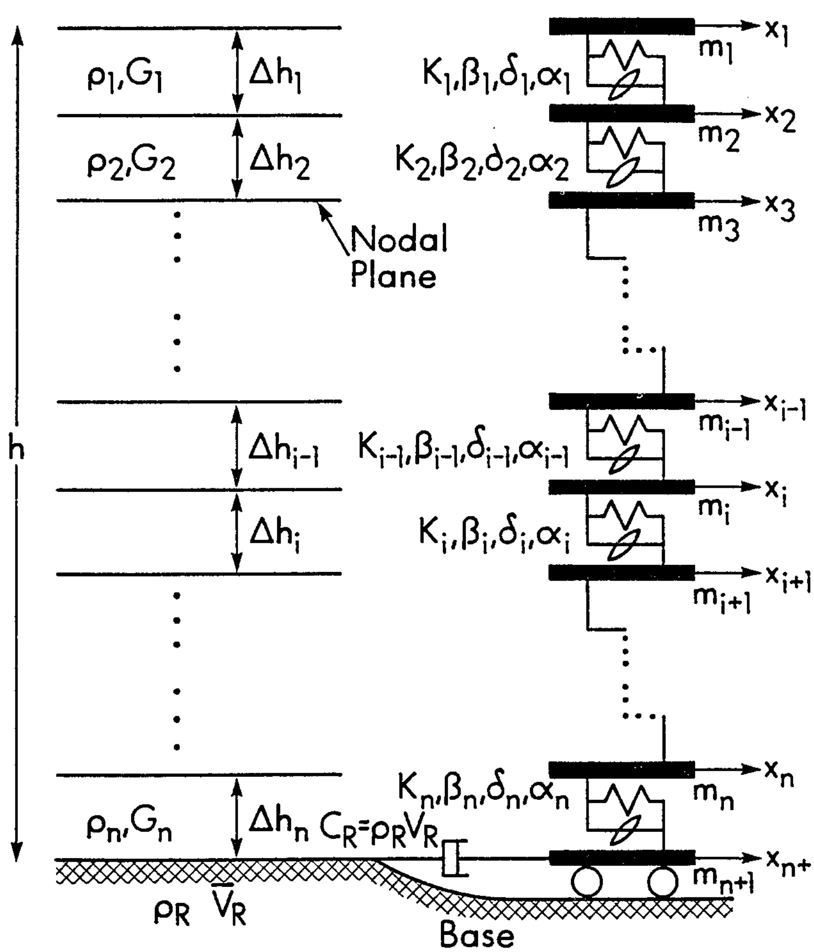

Figure 1. Lumped mass model for the soil deposit

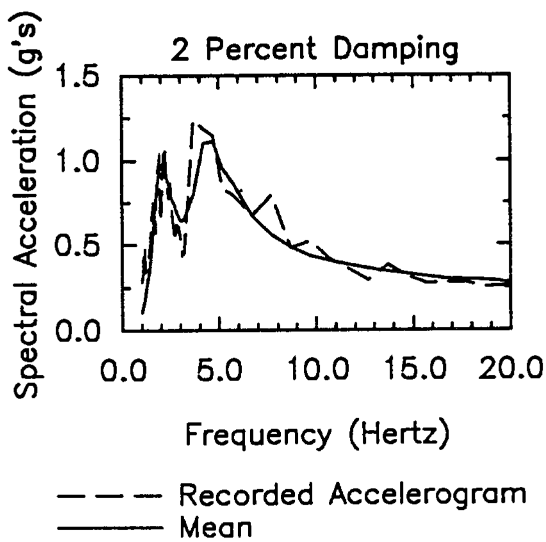

Figure 2. Response Spectrum for Recorded Ground Motion and Stochastic Ground Motion Model

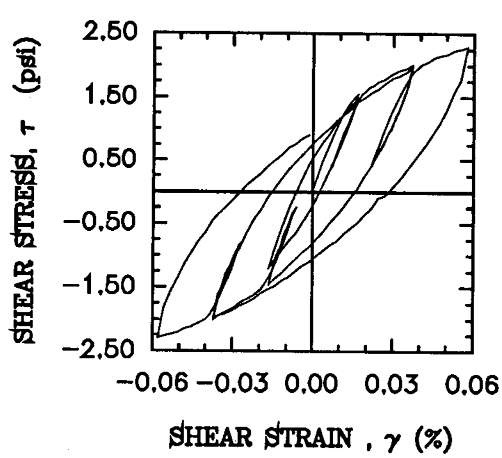

Figure 3. Shearing Stress-Strain Hysteresis Loops from Simple Trosional Shear