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ABSTRACT

In this paper, Shanghai saturated soft soil is modeled as a two-phase porous media system consisting of solid and fluid phases. On the basis of resonant column test and dynamic triaxial test data of Shanghai saturated soft soil, the dynamic calculation model including a set of relationships of stress, strain, pore water pressure and earthquake subsidence is developed to compute the seismic response of soil. The procedure to identify soil constants for the dynamic calculation model is also reported in detail. Subsequently, a dynamic effective stress analysis with the finite element method has been recommended to predict the seismic response of soil. Finally, the developed dynamic calculation model together with the dynamic effective stress analysis is utilized to predict the seismic response of Shanghai soil strata through the finite element method and some valuable conclusions are obtained from the results.

INTRODUCTION

Shanghai is located on the East Coast of China at the mouth of the Yangtze River at the Donghai Sea. The alluvial soil deposit of Shanghai is 150-400m deep with an about 100m thick saturated soft soil, which has a large water content and a high compressibility. Although Shanghai is not a seismic area, there are several seismic sources within a range of 200-300 km. The earthquake influencing Shanghai was firstly recorded in 288. Several moderate earthquakes have affected Shanghai in the past twenty years, such as Liyang Earthquake in 1979 (M = 6.0), South Huanghai Sea Earthquake in 1984 (M = 6.2), Changshu-Taicang earthquake in 1990 (M = 5.1) and South Huanghai Sea Earthquake in 1996 (M = 6.1). It has a great meaning to predict the earthquake response of Shanghai saturated soft soil.

The equivalent linear approach has been widely used to compute the approximate nonlinear response of soil approximately. Martin and Seed (1982) reviewed the equivalent linear method and the nonlinear methods. From the study of an extensive experimental data, a dynamic computation model is proposed in this paper, which is an equivalent viscoelastic model including a set of relationships of stress, strain, pore water pressure and earthquake subsidence. Compared with elastoplastic models, the model simulates the soil dynamic behavior in a cycle of loading as a whole, not in detail.

Biot (1955, 1962) established the basic dynamic equations for porous media. Later, Zienkiewicz et al. (1982, 1984) introduced the numerical solution of these equations. Based on these theories the dynamic effective analysis method is conducted with the dynamic calculation model in this paper.

CALCULATION MODEL

Shear modulus

The proposed expression of the secant shear modulus G at a strain amplitude γ is

$$\frac{G}{G_{\max}} = 1 - H(\gamma) \tag{1}$$

In the model, the function $H(\gamma)$ is

$$H(\gamma) = \left[\frac{(|\gamma|/\gamma_r)^{2B}}{1 + (|\gamma|/\gamma_r)^{2B}}\right]^A \tag{2}$$

where γ_r = a reference or yield strain; and A and B = two dimensionless parameters.

It is suggested that values of γ_r for Shanghai saturated soft soil could be determined by the empirical relationship

$$\gamma_r = C \cdot \sqrt[3]{\sigma_0'} \tag{3}$$

where σ_0' = the effective mean principal stress in kPa, and C = an empirical parameter. Table 1 shows a summary of the experimental numerical values for the three parameters A, B, and C obtained for Shanghai saturated soft soil.

Table 1. Reference value of parameters: A, B, and C

Soil type	*A*	*B*	C
Clay	1.62	0.42	0.00013
Silt	1.12	0.44	0.00017
Sand	1.10	0.48	0.00022

The following relationship between G_{max}, the void ratio e, the over consolidation ratio OCR, and the confining pressure σ_0' has been widely used:

$$G_{\max} = D\frac{OCR^k}{0.3+0.7e^2}p_a\left(\frac{\sigma_0'}{p_a}\right)^{0.5} \tag{4}$$

where P_a = atmospheric pressure, and k = a coefficient which relates to plasticity index of soil. Shanghai saturated soft soil may be treated as normally consolidated soil except surface crust and dark green stiff clay of about 3m thickness in the depth of 25m. Based on the above relationship and experimental data, an acceptable fit for Shanghai saturated soft soil is obtained, as follows: D = 353 for clay, D = 451 for silt, and D = 485 for sand.

The curve of shear modulus ratio $G/G_{\max}$ of Shanghai clay with γ is compared with the experimental data in Fig. 1.

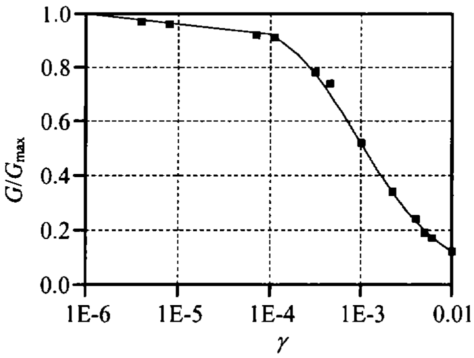

Fig. 1. The relationship between shear modulus ratio and shear strain of Shanghai clay

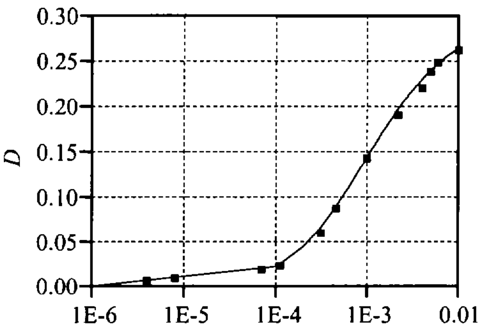

Fig. 2. The relationship between damping ratio and shear strain of Shanghai clay

Damping

For Shanghai saturated soft soil, the variation of the damping ratio, D, with strain level is

$$\frac{D}{D_{\max}} = \left(1-\frac{G}{G_{\max}}\right)^{\beta} \tag{5}$$

where $D_{\max}$ = 0.30 for clay, $D_{\max}$ = 0.25 for silt and sand; and β = 1.0. A comparison between the proposed model and experimental data is shown in Fig. 2.

Pore water pressure generation

On the basis of the results from undrained cyclic triaxial test data, the pore water pressure buildup of Shanghai clay and silt may be expressed as

$$\frac{p}{\sigma_0'} = aN^b \tag{6}$$

where p = the pore water pressure; N = the number of uniform stress cycles; and a and b = two experimental parameters which are determined by the ratio of the dynamic shear stress to the effective confining pressure. Table 2 shows the reference value of a and b for Shanghai clay and silt. The curve of pore water pressure ratio p/σ_0' and N of Shanghai mucky clay is compared with the experimental data in Fig. 3.

Table 2. Reference value of a and b for Shanghai clay

Soil type	a	b
Clay	$0.274\, r_\tau^{0.767}$	$0.375\, r_\tau^{0.431}$
Silt	$0.273\, r_\tau^{0.711}$	$0.348\, r_\tau^{0.394}$

$r_\tau = \tau_d / \sigma_0'$; τ_d = dynamic shear stress.

For Shanghai sand, the development of pore water pressure in laboratory cyclic loading tests is of the form

$$\frac{p}{\sigma_0'} = (1-ms_l)\frac{2}{\pi}\arcsin\left(\frac{N}{N_f}\right)^{\frac{1}{2\theta}} \tag{7}$$

where s_l = static stress level; m and θ = experimental parameters, for Shanghai sand m = 1.1 and θ =0.7; and N_f = the accumulative number of cycles at the same stress level required to produce a peak cyclic pore water pressure ratio of 100% under undrained conditions.

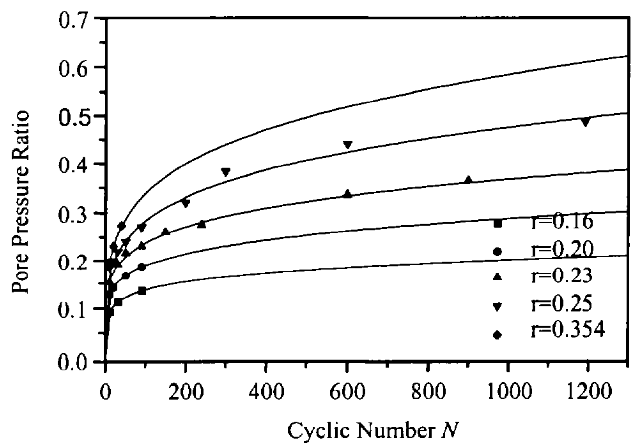

Fig. 3. Variation of pore water pressure ratio and N of Shanghai mucky clay

Earthquake subsidence

The earthquake subsidence can be divided into the volumetric and deviatoric components, ε^p and γ^p. The volume change, ε^p, comes from dissipation of seismic pore water pressure and can be calculated through consolidation equation. For Shanghai saturated soft soil (Zhou Jian and Hu xiaoyan, 1998), γ^p is formulated according to the undrained cyclic triaxial tests as follow

$$\gamma^p = \frac{r^*}{d - (d - 20)r^*} \tag{8}$$

where d = an experimental parameter, d = 8 for Shanghai sand, d = 3 for Shanghai clay. $r*$ is

$$r^* = \frac{r - r_s}{r_f - r_s} \tag{9}$$

where r_s = initial dynamic stress ratio; r_f = failure dynamic stress ratio.

DYNAMIC ANALYSIS METHOD

If the pore water acceleration has been neglected, the formulation of Biot governing equations is represented as the following

$$\sigma_{ij,j} + \rho g_i = \rho \ddot{u}_i, \; \left(k_{ij} p_{,j}\right)_{,i} - \dot{\varepsilon}_{ii} - \left(k_{ij} \rho_f g_j\right)_{,i} = 0 \tag{10}$$

where σ_{ij} = the total Cauchy stress in the combined solid and fluid mix at any instant, u_i = the displacement, p = the pore water pressure, ρ and ρ_f are the density of the mixed soil and fluid itself respectively. The equations can be solved numerically under given boundary and initial conditions by the finite element method. In this the displacements **u** are described in terms of the nodal values $\overline{\mathbf{u}}$ as

$$\mathbf{u} = \mathbf{N}\overline{\mathbf{u}} \tag{11}$$

with a similar discretization for the pressures,

$$\mathbf{p} = \overline{\mathbf{N}}\overline{\mathbf{p}} \tag{12}$$

where $\overline{\mathbf{p}}$ is the vector of nodal pressure values. In the above $\mathbf{N}$ and $\overline{\mathbf{N}}$ are appropriate shape functions. Performing spatial discretization, the finite element formulation are derived as

$$\int_\Omega \mathbf{B}^T \sigma' d\Omega + \mathbf{M}\ddot{\overline{\mathbf{u}}} - \mathbf{Q}\overline{\mathbf{p}} = \mathbf{f}, \; \mathbf{H}\overline{\mathbf{p}} + \mathbf{Q}^\mathrm{T}\dot{\overline{\mathbf{u}}} = \overline{\mathbf{f}} \tag{13}$$

where $\mathbf{M}$ = mass matrix, $\mathbf{Q}$ = couple matrix, $\mathbf{H}$ = permeability matrix, $\mathbf{f}$ = nodal earthquake load vector, $\overline{\mathbf{f}}$ = nodal seepage discharge vector.

The main analysis procedures are as fellows:

1. Calculate initial static state of soil.
2. Determine parameters of the dynamic calculation model.
3. Calculate dynamic state of soil.
4. Calculate seismic pore water pressure increment and undrained residual strain.
5. Repeat step 2-4 until the earthquake motion ends.
6. Continue post-earthquake static analysis until the dissipation of pore water pressure completes.

APPLICATION

The formulation presented allows any problem of earthquake response to be studied quantitatively. In the example the Shanghai horizontal soil layer of depth 280m, which is subjected to a base motion of the first 10s N-S component of the El Centro Earthquake (May, 1940) with the maximum acceleration scaled to 0.1g, is studied in terms of the dynamic calculation model. The base motion input for analysis is shown in Fig. 4.

The ground acceleration history and the distribution of maximum accelerations are shown in Figs. 5 and 6 respectively. It is interesting that the surface maximum acceleration is only 0.92 m/s^2. Why is the surface maximum acceleration less than the base? The main reason is probably that the buildup of pore water pressures causes a decrease in stiffness of Shanghai soil. The ground and bedrock response spectra with 5 percent damping ratio are shown in Fig. 7. The spectral values of the ground acceleration are less than those of the bedrock accelerations between the period of 0.1 and 1.2 seconds. The soil deposit acts as a filter when the bedrock earthquake acceleration is transmitted through it. The soil deposit filters out a significant portion of the high frequency content of the bedrock acceleration.

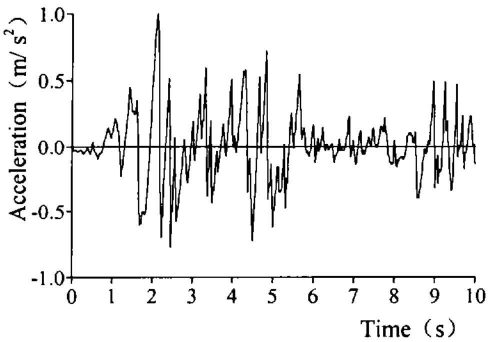

Fig. 4. Input earthquake wave

During the earthquake, the pore water pressure of deep soil is very small. But the pore water pressures from the depth less than 20m to the ground is gradually increasing. The maximum pore water pressure ratio equals 0.35 in the depth of 9m. The calculated maximum earthquake subsidence is about 15mm until the dissipation of pore water pressure completes.

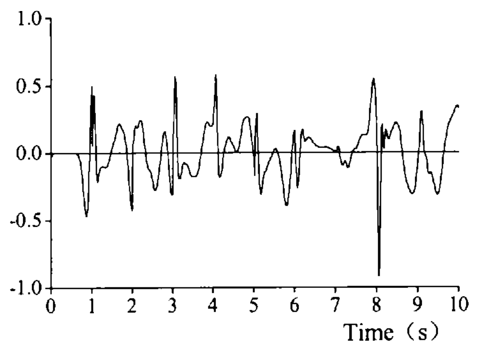

Fig. 5. Predicted acceleration time history of ground

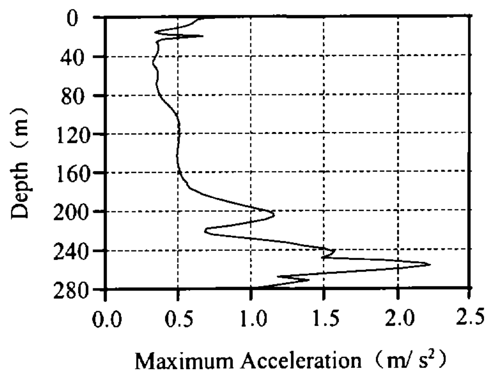

Fig. 6. Predicted variation of the maximum acceleration with depth

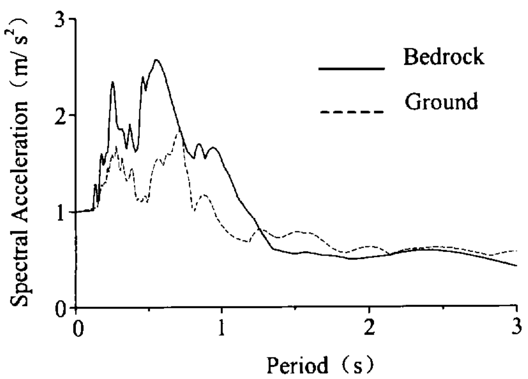

Fig. 7. Predicted response spectra of ground and bedrock

CONCLUSION

An equivalent viscoelastic dynamic model for Shanghai soil is presented. It contains four formulas for calculating the shear modulus, the damping ratio, pore water pressure and earthquake subsidence.
An approach of dynamic effective stress analysis in the fluid-saturated porous solid is summarized in terms of Biot governing equations and finite element formulation. The seismic response of Shanghai soil strata of 280m depth is also investigated by FEM with the Biot dynamic consolidation formulation and presented model. Some valuable conclusions are obtained from the results.

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