An Effective Substructure Analysis for Soil-Structure Interaction

Chaojiang Fu

College of Civil Engineering, Fujian University of Technology, Fuzhou, 350108, China

email: cjfu@163.com

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Abstract. A 2-dimensional plain strain finite element seismic soil-structure interaction (SSI) analysis based on the substructure method is presented. A complete SSI analysis is performed. Namely, linear and non-linear SSI analysis is considered; and analysis without the consideration of SSI is performed; and non-linear material behavior is considered.

Introduction

In the civil engineering field, the large number of buildings built in the complex soil, analysis of soil structure interaction is a very important and difficult topic [1]. It is important how to establish the reasonable and practical soil model to study effect the complex characteristics of the heterogeneity, nonlinear and infinite domain of the soil on the structures in the theory and engineering [2,3].

In dealing with the analysis of dynamic soil-structure interaction, one of the most difficult tasks is the modeling of unbounded media. Many numerical methods or techniques have been developed to solve this problem, such as transmitting boundaries of different kinds, boundary elements, and infinite elements and their coupling procedures [4,5]. In the substructure method, the soil-structure system is divided into two parts: the structure and the unbounded soil. These substructures are connected by a soil-structure interface, also called near-field/far-field interface. The unbounded soil is assumed to behave linear but in the near-field non-linarites can be included. So not only non-linear effects of the building itself can be included in the analysis, but also non-linear material behaviour of the soil adjacent to the structure (near-field).

In this paper, a substructure method is used as well where the near-field is analyzed with the FEM, while the unbounded soil is modelled by special finite elements, based on a similarity transformation, referred as cloning algorithm[6] Linear and non-linear SSI analysis are considered; and analysis without the consideration of SSI is performed; and non-linear material behavior is considered.

Equations of motion of the structure

If the soil-structure interaction is not considered, the equation of the motion for the structure under the seismic excitation in the time domain can be expressed as follow [7].

$$\boldsymbol{M}\ddot{\boldsymbol{r}}(t)+\boldsymbol{C}\dot{\boldsymbol{r}}(t)+\boldsymbol{K}\boldsymbol{r}(t)=-\boldsymbol{M}\ddot{\boldsymbol{r}}_g(t) \qquad (1)$$

in which $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are $n\times n$ mass, damping and stiffness matrices, respectively, n is the number of degrees of freedom of the structure, $\boldsymbol{r}$ is the total displacement vector of the system, and $\ddot{\boldsymbol{r}}_g$ is the acceleration vector of the free-field ground motion.

A systematic formulation and discussion of nonlinear soil structure interaction is presented by Aydinoglu[8] The basic equations of the soil-structure system can be expressed in the time domain as.

$$\begin{bmatrix} \boldsymbol{M}_{ii} & \boldsymbol{M}_{ih} \\ \boldsymbol{M}_{hi} & \boldsymbol{M}_{hh} \end{bmatrix}\begin{bmatrix} \ddot{\boldsymbol{r}}_i^t(t) \\ \ddot{\boldsymbol{r}}_h^t(t) \end{bmatrix}+\begin{bmatrix} \boldsymbol{Q}_i(t) \\ \boldsymbol{Q}_h^i(t) \end{bmatrix}+\begin{bmatrix} 0 \\ \boldsymbol{R}_h^r(t) \end{bmatrix}=\begin{bmatrix} 0 \\ \boldsymbol{P}_h^i(t) \end{bmatrix} \qquad (2)$$

where $\boldsymbol{M}$,$\boldsymbol{Q}$,$\boldsymbol{R}$ and $\boldsymbol{P}$ are mass matrix, nonlinear internal forces, interaction forces and effective force vector, respectively. The response vector, $\boldsymbol{r}$ of Eq. (2) is represented by total displacement indicated by superscript t. The first term on the left-hand side represents the inertial forces in respective parts of the system with the last component, $\boldsymbol{Q}_h^i(t)$ being the nonlinear internal forces acting on the inner face of the interaction horizon.

For the substructure method, the interaction force-displacement relationships in the time domain can be expressed in terms of the relative interaction displacements calculated along the interaction horizon, which is formulated as

$$\boldsymbol{R}_h^r(t) = \int_0^t S_{hh}^r(t-t)r_h^t(t)dt - \boldsymbol{P}_h^r(t) \tag{3}$$

with $S_{hh}^r(t)$ representing the far-field dynamic stiffness matrix in the time domain. The second term on the right-hand side is time effective forces, and can be expressed as

$$\boldsymbol{P}_h^r(t) = \int_0^t S_{hh}^r(t-t)v_h^f(t)dt \tag{4}$$

where $v_h^f(t)$ is obtained from nonlinear analysis of the unexcavated free-field.

The interaction forces of the soil medium at the soil-structure interface given by Eq. (3) are discretized at time station *n* for a piecewise constant acceleration unit impulse response matrix as

$$\boldsymbol{R}_{hn}^r = g\Delta t\boldsymbol{M}^{\infty}{}_1\ddot{\boldsymbol{u}}_{hn}^t - g\Delta t\boldsymbol{M}^{\infty}{}_1\ddot{\boldsymbol{u}}_{hn}^f + (1-g)\Delta t\boldsymbol{M}^{\infty}{}_1\ddot{\boldsymbol{u}}_{hn-1}^{\Delta} + \sum_{j=1}^{n-1}\boldsymbol{M}^{\infty}{}_{n-j+1}(\dot{\boldsymbol{u}}_{hj}^{\Delta} - \dot{\boldsymbol{u}}_{hj-1}^{\Delta}) \tag{5}$$

Substituting Eq. (5) in Eq. (2) leads to the nonlinear seismic soil-structure interaction formulation in the time domain which is expressed as

$$\begin{bmatrix} \boldsymbol{M}_{ii} & \boldsymbol{M}_{ih} \\ \boldsymbol{M}_{hi} & \boldsymbol{M}_{hh}^i + g\Delta t\boldsymbol{M}^{\infty}{}_1 \end{bmatrix}_n \begin{bmatrix} \ddot{\boldsymbol{u}}_i^t(t) \\ \ddot{\boldsymbol{u}}_h^t(t) \end{bmatrix}_n + \begin{bmatrix} \boldsymbol{Q}_i(t) \\ \boldsymbol{Q}_h^i(t) \end{bmatrix}_n + \begin{bmatrix} 0 \\ \boldsymbol{R}_h^r(t) \end{bmatrix}_n = \begin{bmatrix} 0 \\ \boldsymbol{P}_h^i(t) - \tilde{\boldsymbol{R}}_h^r \end{bmatrix}_n \tag{6}$$

With this formulation, the nonlinearity of soil can be consistently taken into account within the near field by properly defined constitutive models [5]. To solve Eq. (6), Wilson-*q* method is applied to treat the time variable, and the initial stiffness method is used to treat material plasticity.

Material nonlinearity

In SSI analysis, The material nonlinearity of both soil and structure is considered in this paper, i.e., the nonlinear characteristics of the near field is considered. The Von Mises model is employed to model the failure of the materials. For the plain strain application the failure surface of the model is expressed as $F = \bar{s} - s_y = 0$,where s_y is yield stress and $\bar{s}$ is deviator stress.

Numerical example

The calculation model is10-layer cast-in-place framework structure, as shown in Fig.1. The soil parameters are given in Table 1. Its height is 3.0m, and total height H=30.0m. The base is slab foundation on natural ground. Its width B=15.0m, and thickness is 1.5m. Considering soil field with b_z = 75.0m, and depth h_z = 15.0m. The column section size is 500mm × 500mm, and beam section size is 250mm × 250mm. The Concrete is C25. Its elastic modulus is 2.8×10^{10}Mpa, Poisson's ratio is 0.15, and gravity density is 25KN/m^3. The EL Clentro wave acceleration time curve is used as seismic time history curves. The time length is 10s, as shown in Fig.2. The acceleration response spectrum is shown in Fig.3. To investigate the effects of soil-structure interaction, the following cases are studied:(1) neglecting the effect of soil-structure interaction, i.e. assuming the structure being fixed at its base, the soil is assumed to be completely rigid and only the superstructure is considered for analysis, (2) linear soil-structure interaction analysis, (3) nonlinear soil-structure interaction analysis.

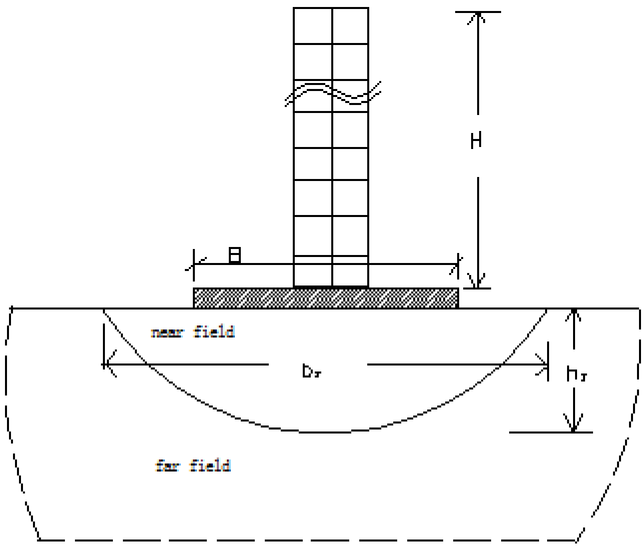

Fig. 1 Model for computational example

Table 1 Soil profile properties

Layer No	Soil type	Thickness/m	Unit weight/(KN/m^3)	Young modulus/Mpa	Poisson's ratio	Shear wave velocity/(m/s)
1	Silty clay	3	18.7	7.0	0.36	160
2	Silty sand	4	17.9	7.2	0.35	180
3	Silty clay	6	18.4	6.8	0.38	180
4	Clay	4	18.0	6.6	0.40	180
5	Silty clay	3	17.7	6.8	0.38	200
6	Clay	40	19.0	6.9	0.37	300
7	Rock		24.0	20	0.22	1600

The response of soil-structure interaction is shown in Fig.4. From these figures, it can be seen that fixed base analysis gives somewhat greater displacements. The displacement response curve shape of linear and nonlinear analysis is coincident. But the nonlinear displacement response is more obvious, its value of displacement is slightly larger. Comparing seismic response curve of top displacement of the structure of hypothesis rigid base with considering soil-structure interaction, it can be found that its maximum displacement is amplified. Duing to the considering soil-structure interaction, the basic cycle of system became longer than not considering soil-structure interaction. According to the theory of response spectrum, it is known that seismic action becomes less. Corresponding to the rigid base, seismic action becomes large. Most element stress of the superstructure is greater than the yield stress and becomes plastic, thus its deformation increases, and the displacement of the structure is slightly larger.

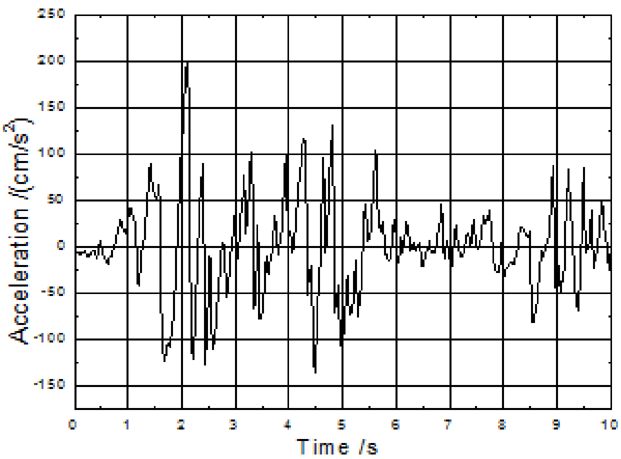

Fig. 2 Acceleration time history at the ground surface

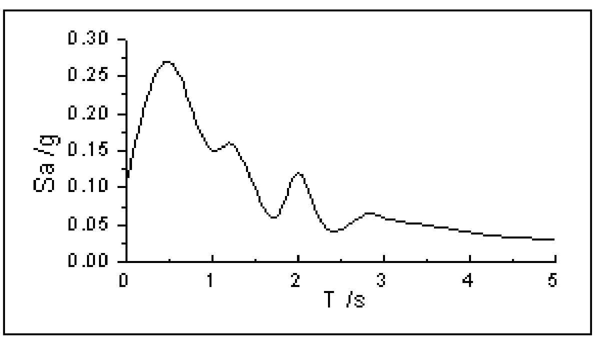

Fig. 3 Acceleration response spectrum

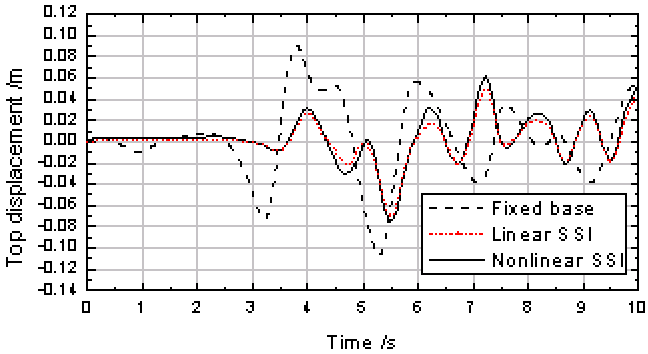

Fig. 4 Response history of top displacement of the structure

Conclusions

The linear and nonlinear soil-structure interaction is analyzed based on the substructure method. It is shown that the procedure works well and it can be used for the seismic structure analysis. The method can be expanded to three-dimensional problem.

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