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THE SOIL STRUCTURE INTERACTION ANALYSIS BASED ON SUBSTRUCTURE METHOD IN TIME DOMAIN

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SUMMARY

In this paper, a variation of the FEM which is so-called general substructure method is carried out for analysis of response of structures to earthquake ground motion. The interaction force-displacement relationship is calculated by using the consistent infinitesimal finite element cell method. Assembling the interaction force-displacement relationship of the unbounded soil medium with the equation of motion of the structure leads to the basic equations of the total dynamic system. To solve these equations in time domain, a fortran code is developed. As a result, irregular bounded medium material inhomogeneities can be processed and nonlinearity of soil can be consistently taken into account. To verify the studies, a two dimensional, plain strain, soil structure interaction system is solved in time domain. At the end, set of numerical results are presented and discussed.

INTRODUCTION

Dynamic soil-structure interaction analysis have significant effect on the response of the structure to earthquake excitation. Due to the complexity of this phenomenon and its practical importance, considerable amount of work has been done over the last quarter of the 20th century. The modeling and analysis of SSI involves a good knowledge of structural dynamics, wave mechanics and soil dynamics. Therefore it has a challenging nature among researchers and engineers. Its complexity includes uncertainties such as wave composition, spatial variation of ground motion, geometrical and material nonlinearities of soil medium and mathematical modeling of SSI. Among various methods, the development of modeling and analysis of SSI has followed two different methods, namely Direct Method and Substructure Method. These methods are evidenced and well documented in two textbooks published [Wolf 1985], [Wolf 1988]. In recent years, both methods are still being developed to achieve the desired results. Among them, a common formulation equally applicable to both methods is presented by Aydınoğlu [Aydınoğlu 1993a],[Aydınoğlu 1993b]. This is achieved by changing the size of irregular soil zone and definition of dynamic boundary conditions along the interaction horizon. In determination of the interaction force-displacement relationships of the degrees of freedom in the nodes on the soil-structure interface for use in the consistent formulation of direct and substructure method, the rigorous formulation based on similarity and finite element method, which is originally developed by Wolf and Song [Wolf and Song 1996], has been proven to be very effective.

The aim of this paper is perform an numerical dynamic soil-structure interaction analysis in time domain by using the computer program ENLAS, which is originally developed by Kutanis. In order to compute unit-impulse response matrix for time domain analysis of unbounded medium, another computer program called SIMILAR, provided by Wolf and Song, is incorporated into ENLAS.

FUNDAMENTAL EQUATIONS

A systematic formulation and discussion of nonlinear soil structure interaction is presented in the article by Aydınoğlu [Aydınoğlu 1993a].

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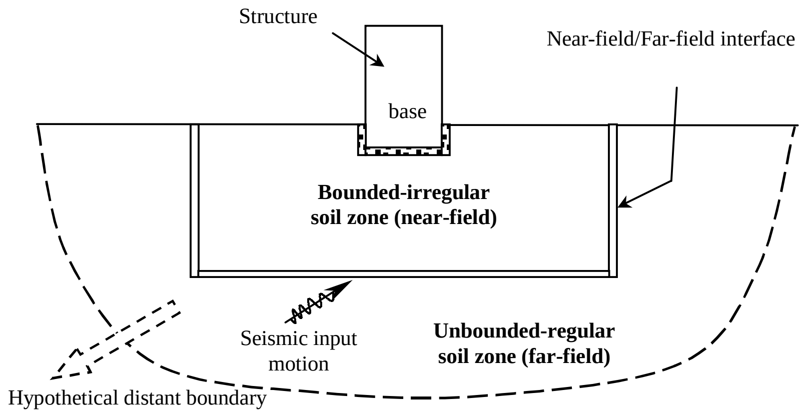

Fig. 1. Common model for direct and generalized substructure methods.

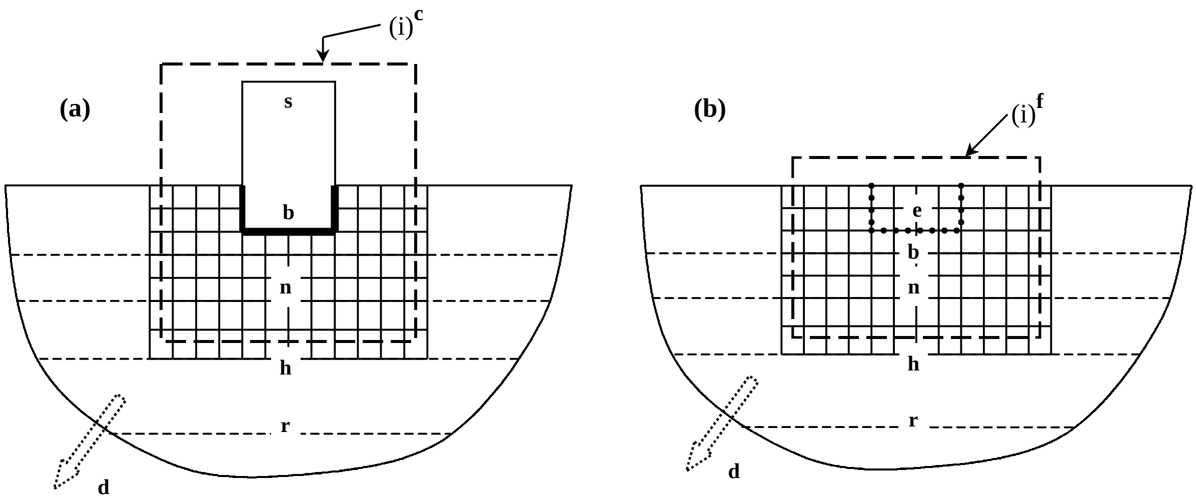

Fig. 2. Identification of (a) soil structure system, (b) unexcavated free field

Referring to the soil structure model given in Fig.1 together with corresponding indices shown in Fig. 2, the basic equations of the soil-structure system can be expressed in time domain as [Aydınoğlu 1993a]:

$$\begin{bmatrix} M_{ii}^{(c)} & M_{ih} \\ M_{hi} & M_{hh}^{i} \end{bmatrix} \begin{Bmatrix} \ddot{r}_i^t(t) \\ \ddot{r}_h^t(t) \end{Bmatrix} + \begin{Bmatrix} Q_i(t) \\ Q_h^i(t) \end{Bmatrix} + \begin{Bmatrix} 0 \\ R_h^r(t) \end{Bmatrix} = \begin{Bmatrix} 0 \\ P_h^i(t) \end{Bmatrix} \qquad (1)$$

where **M, Q, R, P** are mass matrix, nonlinear internal forces, effective force vector and interaction forces, respectively. The response vector, **r** of eqn. (1) is represented by total displacement which are 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, $Q_h^i(t)$, being the nonlinear internal forces acting on the inner face of interaction horizon.

For the generalized 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, namely, the difference between the total and the free-field displacements, which is formulated as:

$$R_h^r(t) = \int_0^t S_{hh}^r(t-\tau) r_h^t(\tau) d\tau - P_h^r(t) \qquad (2)$$

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

$$P_h^r(t) = \int_0^t S_{hh}^r(t-\tau) v_h^f(\tau) d\tau \tag{3}$$

where $v_h^f(\tau)$ is obtained from nonlinear analysis of the unexcavated free-field. The relative interaction displacements which are defined as:

$$r_h^{\Delta}(t) = r_h^t(t) - v_h^f(t) \tag{4}$$

Thus from eqns (2)-(4):

$$R_h^r(t) = \int_0^t S_{hh}^r(t-\tau) r_h^{\Delta}(\tau) d\tau \tag{5}$$

Finally, the non-zero effective force vector component of eqn (1) can be expressed as:

$$P_h^i(t) = \begin{bmatrix} M_{hi} & M_{hi} \end{bmatrix} \begin{Bmatrix} \ddot{v}_i^f \\ \ddot{v}_h^f \end{Bmatrix} + \bar{P}_h^i(t) \tag{6}$$

where the second term represents the internal forces acting on the inner face of the interaction horizon as obtained from one- or two-dimensional nonlinear analysis of unexcavated free-field system incident seismic waves.

To overcome the numerical difficulties and to simplify the formulation and the derivation, the interaction forces is expressed as a convolution integral of the accelerations [Song and Wolf 1996]:

$$R_h^r(t) = \int_0^t M^{\infty}(t-\tau) \ddot{r}_h^{\Delta}(\tau) d\tau \tag{7}$$

where $M^{\infty}(t)$ is the acceleration unit impulse response matrix in the time domain. It can be determined directly with the consistent infinitesimal finite element cell method which is addressed in Wolf & Song 1995.

The interaction forces of the soil medium at the soil-structure interface eqn (7) are discretized at time station n for a piecewise constant acceleration unit impulse response matrix [Wolf and Song 1995] as:

$$\{R_h^r\}_n = \gamma\Delta t[M^{\infty}]\{\dot{r}_h^t\}_n - \gamma\Delta t[M^{\infty}]\{\dot{v}_h^f\}_n + (1-\gamma)\Delta t[M^{\infty}]\{\dot{r}_h^{\Delta}\}_{n-1} + \sum_{j=1}^{n-1}[M^{\infty}]_{n-j+1}\left(\{\dot{r}_h^{\Delta}\}_j - \{\dot{r}_h^{\Delta}\}_{j-1}\right) \tag{8}$$

NUMERICAL IMPLEMENTATION

The procedures presented in the previous sections are now used to solve the interaction problems in time domain. As an example, using the data given in Fig. 3 and Table 1, first, seismic free-field input motion along the interaction horizon is determined. This is achieved by the analysis of unexcavated virgin soil in the absence of the structure. For this purpose, a well-known computer program, SHAKE, is used. Then, assuming the far-field to be linear, dynamic boundary conditions along the interaction horizon is defined by calculating the unit-impulse response matrix of the far-field in time domain (Fig 4). In the third step, the analysis of the soil structure system under the action of free-field input motion determined in the first step, subject to the dynamic boundary conditions determined in the second step, is carried out. At the first stage of the analysis, once, the time history acceleration of free-field input motion at the surface is also obtained (Fig. 5), using the Fourier transform techniques spectral acceleration (g) versus period (sec) is plotted (Fig.6). In order to illustrate the effects of seismic soil structure interaction, a simple strategy has been followed: First, by modifying the stiffness of the structure the fixed base period of the structure is varied from T1=0.08 sec to T1=2.5 sec. Then, at the same periods, the structure is re-analyzed by taking into consideration of the SSI effects. The results are obtained in terms of total base shear (N) versus time history (sec). To carry out the SSI analysis, a simple two dimensional structure with rigid foundation is considered. The structure and near-field soil medium is modeled by using the plain strain finite element meshes. As a input motion Erzincan (1992) E-W component is used to be a vertically incident shear wave.

CONCLUSIONS

In this study, although the formulation [Aydınoğlu 1993a] is derived for nonlinear analysis of SSI, for the sake of simplicity and better understanding, the analysis is carried out in linear procedure. The conclusion can be summarized as follows:

Under the relatively soft soil conditions (that is, shear wave velocity is less than 300 m/s)

1. If the first mode period of the fixed base structure is considered to be the left of point **a** (Fig. 6), that is the structure is extremely stiff, it is observed that the SSI effects plays an important role rather than fixed base system (Fig.7).
2. As the period of the structure increases from the left of point **a** to the right of point **b** (Fig.6), the SSI effects is diminishing. That is, the fixed base system becomes dominant.
3. Then, it is demonstrated that the effects of SSI is particularly important, if the structure is extremely stiff and the soil medium is relatively soft.

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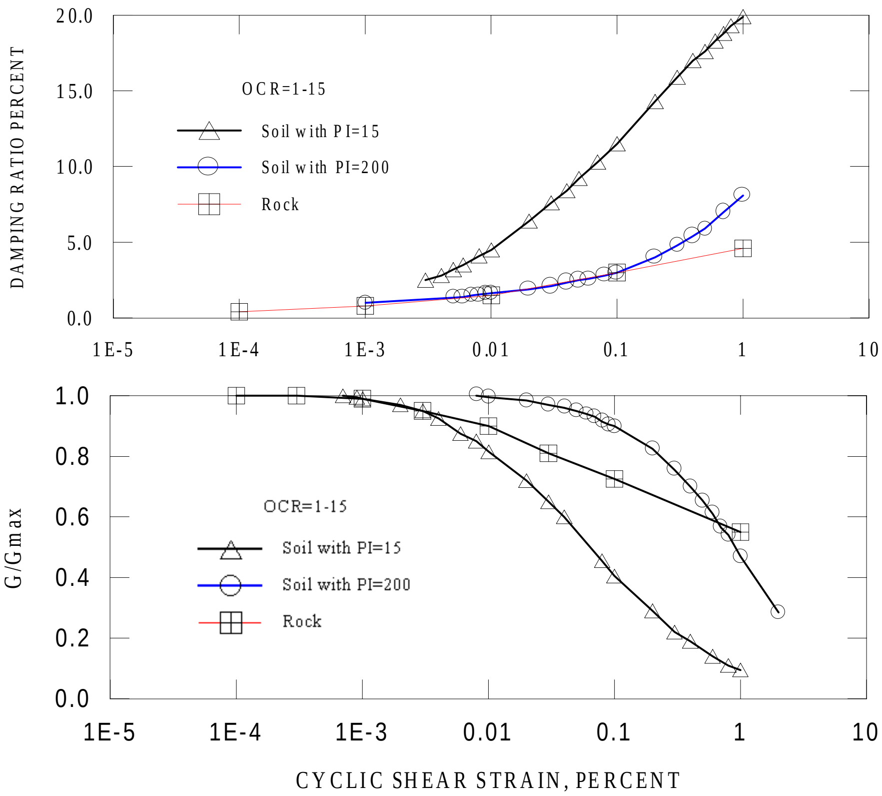

Fig. 3. Modulus reduction curves and damping ratio with cyclic shear strain (After Vucetic & Dobry, 1991)

Table 1. Soil profile data

Layer No	Soil Type	Thickness (ft)	Damping (%)	Unit Weight (kcf)	Shear Wave (fps)
1	PI=15	10	0.05	0.106	500
2	PI=200	15	0.05	0.112	600
3	PI=200	21	0.05	0.112	600
4	PI=200	14	0.05	0.112	600
5	PI=200	10	0.05	0.112	700
6	PI=200	130	0.05	0.118	900
7	Rock	-	0.01	0.160	5000

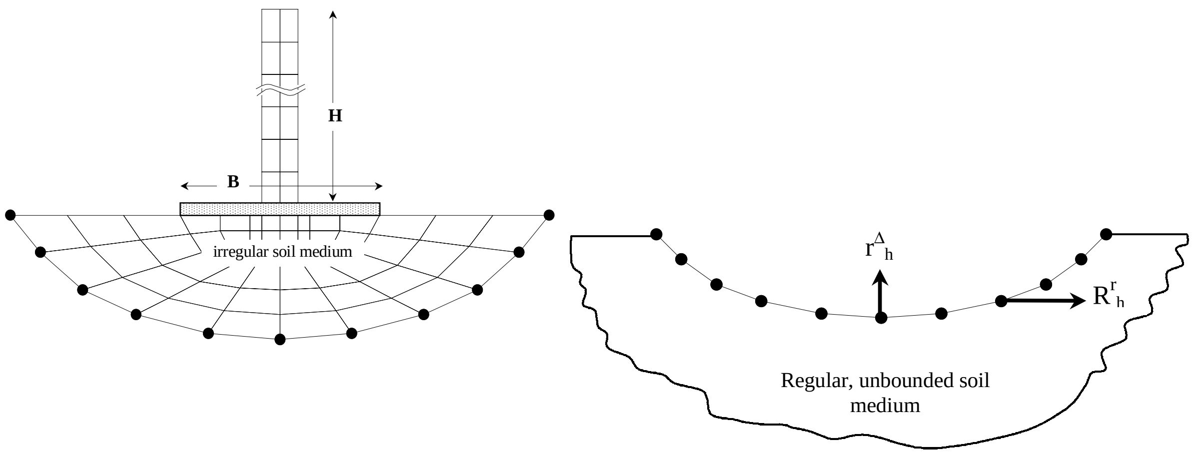

Fig 4. Geometry and discretization of the SSI system

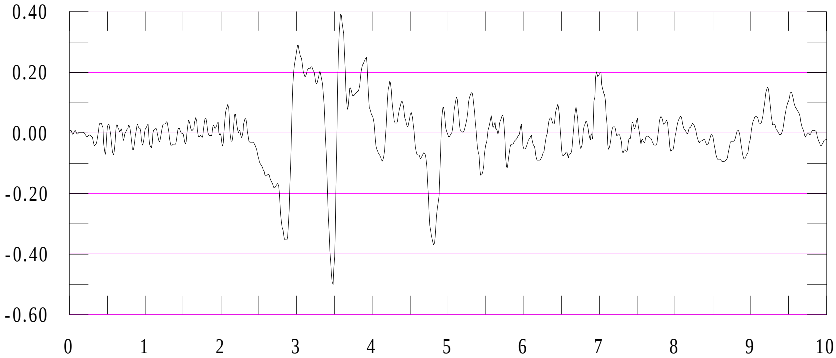

Fig. 5. Time history acceleration of free-field input motion at the surface. (Erzincan, E-W 1992)

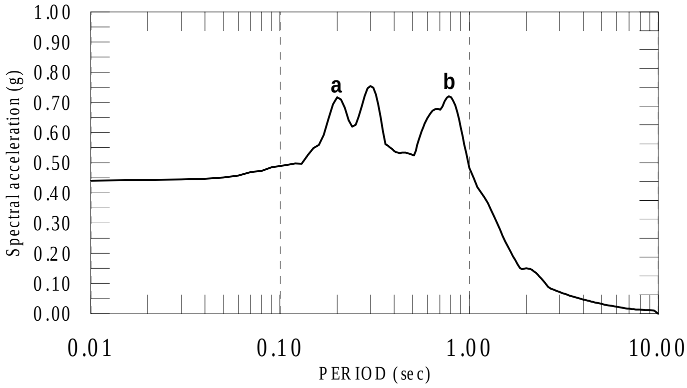

Fig. 6. Free-field spectral acceleration at the free surface.

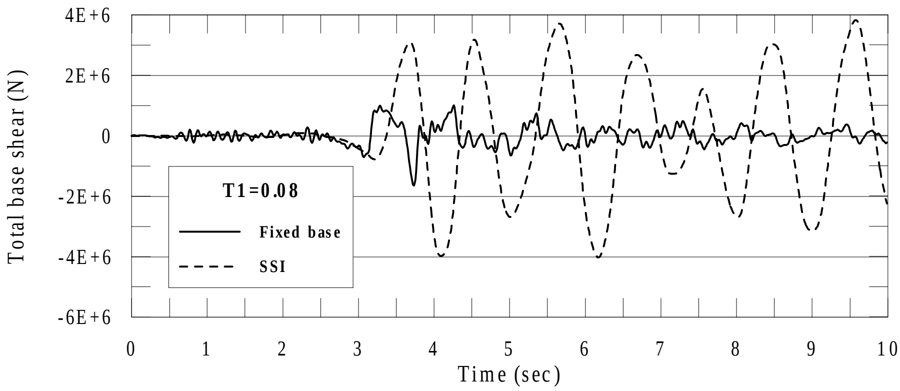

Fig. 7. The effects of SSI at small-period range