SEISMIC RESPONSE OF SUBSTRUCTURES NONLINEARLY COUPLED WITH SOIL

by

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SUMMARY

This paper deals with the numerical evaluations of the dynamic stiffness and the seismic response of rigid and flexural substructures which are supported by a semi-infinite soil stratum. The soil stratum resting on the hard bedrock is represented by assembling the elements of the rigid bodies and the shear-compression springs (RBS model) which easily make it possible to express the cracks or slips at the elemental interfaces. For a steady harmonic vibration the stress-strain relationships are assumed to have bilinear hysteretic characteristics subjecting to Mohr-Coulomb rule and linearized for the quasi-linear computations.

INTRODUCTION

Soil behavior shows nonlinearity during earthquakes or other strong excitations and has been mostly of concern for aseismic design and analysis. So far the finite elements have been widely used to analyze the linear or nonlinear behavior of soil and given much useful results [1,2]. Since the finite element method is mainly available under small strain, however, it cannot follow the extremely nonlinear behavior of soil, that is, cracks or slips during earthquakes or other strong excitations. To represent soil failure in this paper RBS model is used in which the nodal points are separated from the stress-strain field [3]. This new discrete model also simulate the effect of the far field using the transmitting boundary matrix [1].

The dynamic stiffness of substructures is evaluated at first in the form of the complex stiffness coefficients which are obtained by applying the periodical lateral or rocking loads at the top. The computational results of the substructures resting on the ground surface are compared with Veletsos's continuous solutions [4]. Then the frequency responses of the substructures for the bedrock excitations are investigated. It is shown that the frequency response functions considerably depend upon the intensity of earthquakes and the embedment.

ANALYTICAL PROCEDURES

The equations of motions of discretized system in Fig. 1 are written by

$$[M]\{\ddot{X}\} + [K]\{X\} = \{F\} + \{F\}_B \quad \cdots\cdots (1)$$

where [M], [K] are the mass and the stiffness matrices, $\{X\}$ is the horizontal, vertical and rotational displacements vector, $\{F\}$ is the corresponding excitation vector and $\{F\}_B$ is the boundary force vector to express the transmitting boundaries.

From Eq. 1 the response displacements to a unit horizontal force and a unit rocking moment applied at the top of the substructures provide the flex-

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ibility coefficients. Therefore inverting the flexibility matrix the stiffness matrix of the substructures is obtained in the form [2]

$$[K] = \begin{bmatrix} K_{XX} & K_{X\phi} \\ K_{\phi X} & K_{\phi\phi} \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Alternatively the reduced stiffness coefficients are defined by

$$K_X = K_{XX} - K_{X\phi}K_{\phi X}/K_{\phi\phi} \quad ; \quad K_\phi = K_{\phi\phi} - K_{X\phi}K_{\phi X}/K_{XX} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

NUMERICAL RESULTS

It is often shown that the discrete model gives the wavy dynamic stiffness of substructures in frequency domains [2]. Hence to eliminate such wavy paterns in this RBS model analysis 10 % viscous damping is commonly used for soil. The steady response of soil-substructure system is obtained iteratively linearizing the bilinear hysteretic stress-strain relationships with Mohr-Coulomb criterion. The shear wave velocity of soil varies linearly with the depth.

For the sake of convenience the reduced stiffness coefficients K_X and K_ϕ in Eq. 3 are expressed in the form

$$K_X = k_1 + ia_0c_1 \; ; \; K_\phi = k_2 + ia_0c_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where k_1, k_2 and c_1, c_2 are the stiffness and the damping coefficients, respectively and a_0 is the nondimensional frequency.

Fig. 2 is the illustrations of the cracks or slips of a softer ground for relatively strong excitations at a_0=0 and a_0=0.25 in which the fundamental frequency of the soil deposit is a_0=0.20.

Fig. 3 shows that critical force levels and embedment for no failure of soil are approximately linearly correlated. The static case (a_0=0) has the broad transition zone between no failure and failure, whereas the dynamic case (a_0=0.25) which is close to the deposit resonance has narrow transition zone which means the catastrophically decreasing stiffness of the substructures.

*Fig. 4 presents the dynamic effect of K_X and K_ϕ under the linear stress-*strain relationships. Less embedment makes the real part of K_X close to the static stiffness which is close to Veletsos's half space solutions and K_ϕ decreases with increasing a_0.

Fig. 5 shows the effect of the input level on the stiffness of substructures. Linear stiffness falls to about the half for ten times input level increment due to the destructed soil.

Fig. 6 shows the frequency response functions of substructures. The resonance peaks of the substructures move to lower frequency range and the effect of the soil deposit decreases as the intensity of earthquakes increases. Thus the failure of soil produces the huge displacement response because the viscous damping of soil is less effective in lower frequency range.

CONCLUDING REMARKS

Using the new discrete model in this paper the dynamic stiffness and the frequency response functions of substructures are investigated mainly in terms of input levels and embedment under a proper assumptions of failure criterion of soil. A part of the results are compared with the existing solutions. To prevent the partial failure before the total failure of soil around substructures during strong earthquakes some available and sufficient anchorages are suggested for shallowly embedded structures.

The results obtained will be affected by the variation of geological properties and structural parameters. Therefore the practical aseismic evaluation of substructures should be based on more proper selections of the associated parameters to reflect the in-situ characteristics of soil.

ACKNOWLEDGMENT

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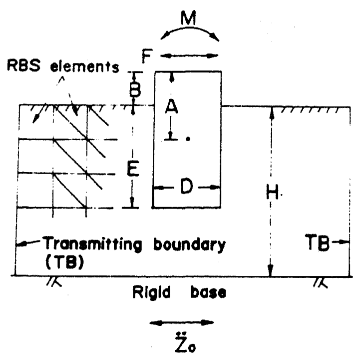

Fig. 1 Soil Stratum and Substructure Model

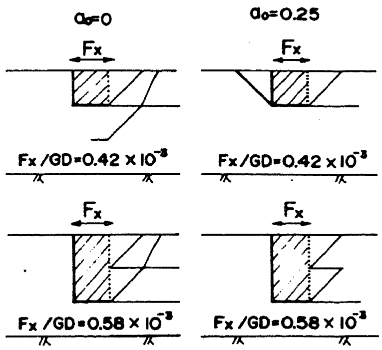

Fig. 2 Illustrations of Cracks or Slips for Lateral Excitations

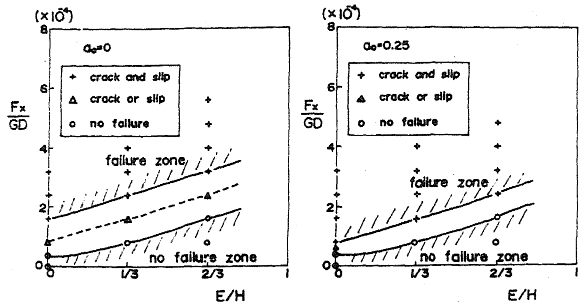

Fig. 3 Failure of Ground Depending on Input Levels and Embedment

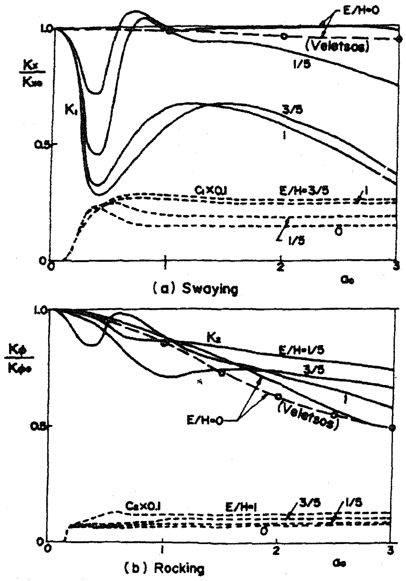

Fig. 4 Dynamic Effect of Stiffness Coefficients (H/D = 2.5)

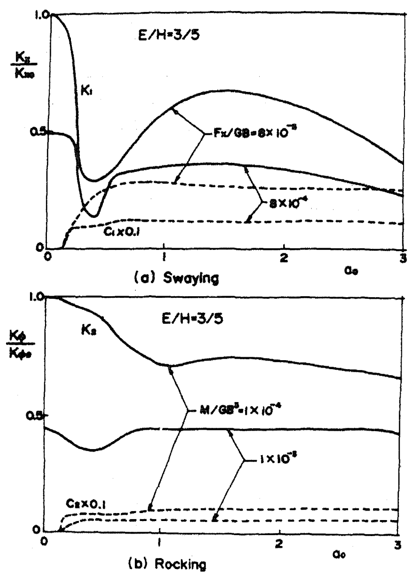

Fig. 5 Decreasing Stiffness with Increasing Input Levels

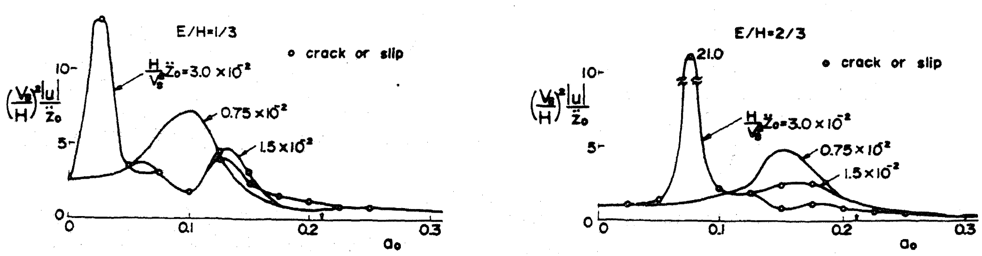

Fig. 6 Frequency Response Functions of Substructures Depending on Input Levels