INFLUENCE OF INTERFACE BEHAVIOR IN DYNAMIC SOIL-STRUCTURE INTERACTION

C. S. Desai (I)
M. M. Zaman (II)
Presenting Author: C. S. Desai

SUMMARY

A simplified procedure called thin-layer element is proposed for simulating no slip, slip debonding and rebonding modes of deformation at interfaces in dynamic soil-structure interaction. The constitutive model is expressed in terms of normal and shear responses of the interface and the material parameters can be found from laboratory tests with a special device. Typical examples are presented to analyze the effect of interface behavior on dynamic response of structures and foundations.

INTRODUCTION

Response of a structure-foundation system subjected to dynamic loadings such as due to earthquakes can be influenced significantly by the characteristics of the interfaces or junction between the structure and foundation. Although the interface behavior in dynamic soil-structure interaction has been recognized for a long time, development of appropriate models for simulation of such behavior has been undertaken only very recently. The purpose of this paper is to present use of a simple thin-layer interface element with appropriate constitutive description of its normal and shear behavior and application to typical problems involving dynamic soil-structure interaction.

Review

The subject of dynamic soil-structure interaction is wide in scope and it is not intended to present a detailed review herein. Hence, only those publications relevant directly to this study will be included; detailed reviews are available elsewhere (Refs. 1-5). In dynamic analysis, consideration to interface behavior and application of various models for this behavior have been presented by various investigators (Refs. 1-9).

MODELLING OF INTERFACE BEHAVIOR

The interface model used here is called thin-layer element, Fig. 1 (Ref. 10). It has been used successfully for a number of static soil-structure interaction problems; here it is modified and used for dynamic soil-structure interaction. In this approach, it is assumed that the behavior near the interface involves a thin finite zone, rather than zero thickness as often assumed in previous investigations (Refs. 7 and 11).

(I) Prof., Dept. of Civil Eng. & Eng. Mech., Univ. of Arizona, Tucson, AZ, USA

(II) Asst. Prof., Dept. of Civil Eng., Univ. of Oklahoma, Norman, OK, USA

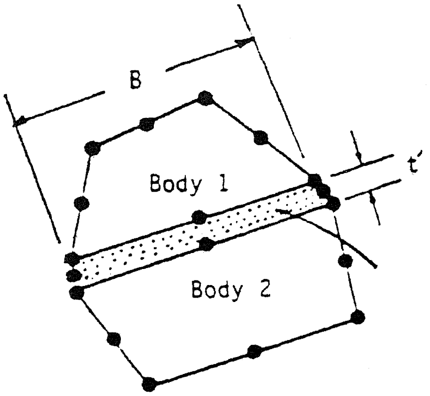

Figure 1. Schematic of Thin Layer Element

In the proposed approach, the thin interface element is treated essentially like any other solid finite element except for the constitutive behavior which is expressed in the incremental form as

$$\{d\sigma\} = [C]_i \{d\varepsilon\} \tag{1}$$

where $\{d\sigma\}$ and $\{d\varepsilon\}$ = vectors of incremental stresses and strains, respectively, and $[C]_i$ is given by

$$[C]_i = \begin{matrix} [C_{nn}]_i & [C_{ns}]_i \\ [C_{sn}]_i & [C_{ss}]_i \end{matrix} \tag{2}$$

in which $[C_{nn}]$ = normal component, and $[C_{ss}]$ = shear component; $[C_{ns}]$, $[C_{sn}]$ represent coupling effects which is not considered at this time. In the analysis proposed herein, the normal component is expressed in terms of the states of stress in the thin zone and the surrounding geological and structural elements. For simplicity, it is often appropriate to assume the normal behavior of the interface zone to be the same as that of the geological material. The shear behavior is expressed by defining a shear modulus G_i as

$$G_i = F\,(\sigma_{nn}, \tau, u_r, N, t') \tag{3}$$

where σ_{nn} = normal stress, τ = shear stress, u_r = relative displacement, N = number of loading cycles and t' = thickness of the element. It is obtained from a polynomial representation of shear stress-relative displacement relation as

$$G_i = \left.\frac{\partial\tau}{\partial u_r}\right|_{\sigma_{nn},\, N\,=\,\text{constant}} \times t' \tag{4}$$

The relation between τ and u_r is expressed as

$$\tau = \alpha_1 + \alpha_2\, u_r + \alpha_3\, u_r^2 \tag{5}$$

Here α_i are expressed as functions of σ_{nn} and N.

Modes of Deformation

The interface formulation allows for various modes of deformation such as no slip, slip, debonding or separation and rebonding. The element is assumed to remain in the no slip mode as long as the state of stress satisfies the following criterion:

$$F_s < 0 \text{ and } \sigma_{nn} \text{ is compressive} \qquad (6)$$

where the slip function, F_s, is expressed as

$$F_s = (\text{sgn}) \{(\tau)^t + \Delta\tau\} - [c_a + \{\sigma_{nn}\}^t + \Delta\sigma_{nn}\} \tan \delta \qquad (7)$$

c_a = activated cohesion, δ = activated friction angle and (sgn) = 1 if $\{(\tau)^t + \Delta\tau\}>0$ and (sgn) = -1 if $\{(\tau)^t + \Delta\tau\}<0$, Δ denotes increment, and t = time level. The element is assumed to experience slip if the normal stress is compressive and

$$F_s \geq 0 \qquad (8)$$

Depending upon the applied stress increments, it may be necessary to perform iterations in order to satisfy the criterion in Eq. (8).

The element is assumed to experience debonding or separation if the normal stress is tensile. Then the difference between the tensile stress and tensile strength of the interface is converted into equivalent correction or residual loads which are distributed to the surrounding material elements. Rebonding is assumed to occur when the normal stress becomes compressive in an element that has experienced tensile condition.

If computations indicate penetration of nodes of the thin element, it is controlled by always maintaining a small thickness equal to $\varepsilon x t'$, where ε is a small number; this value is often adopted as 0.1. The excess forces induced due to this enforcement are distributed in the surrounding material elements.

Laboratory Testing

The shear behavior of the interface can be obtained by using the cyclic multi-degree-of-freedom shear device that allows translational, torsional and rocking modes (Ref. 12). For instance, the parameters in Eq. (5) were determined from a series of tests for Ottawa sand-concrete interfaces with the translational device under different normal stresses, initial relative density and amplitudes and frequency of loading. Details of evaluation of the parameters for Ottawa sand-concrete interface are given in Ref. 5.

The finite element equations of dynamic equilibrium were solved in the time domain by using Newmark's Beta method. The behavior of the structural material is usually assumed to be linearly elastic. The behavior of the geological materials can be idealized as linear elastic or elastic-plastic hardening through Cap models (Ref. 3). The interface behavior is assumed to be nonlinear elastic with the normal behavior the same as that for the soil whereas the shear behavior is defined by using Eqs. 4 and 5. The unloading is assumed to be elastic.

APPLICATIONS

A number of problems involving closed-form, other finite element solutions and field observations such as SIMQUAKE II (Refs. 3 and 8), are solved and the results using the proposed element are evaluated. Two typical problems are described briefly.

Example 1: Comparison with Zero-Thickness Element

Toki et al. (Ref. 7) used the zero-thickness interface element proposed in Ref. 11 to obtain finite element solutions for response of a pier foundation of a long span bridge subjected to dynamic loading.

Figure 2 shows a finite element mesh for the pier embedded in a linear soil medium. The linear elastic properties for the structural concrete and two soil layers are given below:

	Young's Modulus	Poisson's Ratio	Unit Weight	Damping Ratio
Concrete	1.31×10^6 t/m^2	0.167	2.4 t/m^3	0.05
Layer 1	1.66×10^4	0.400	1.8	0.2
Layer 2	6.66×10^4	0.400	1.8	0.2

The properties of the interface assumed are

Young's modulus = 1.66×10^4 t/m^2; Poisson's ratio = 0.4
Unit weight = 1.8 t/m^3 Damping ratio = 0.2

It may be noted that the properties used by Toki et al., particularly the damping ratio, and adopted herein may not be realistic. This problem is used herein simply to compare some of the predictions from the thin-layer element with those from the zero-thickness element for given properties and conditions.

Sinusoidal (horizontal) displacement excitation was applied at all nodes located at the bed rock level; it is given by

$$u_B(t) = A_o \sin \Omega t \tag{10}$$

where $u_B(t)$ = bed rock displacement at time t, Ω = frequency of input excitation and A_o = amplitude of excitation.

Figure 3 shows comparison of predicted vertical displacements at points A and C (Fig. 2) for Ω = 2 Hz. For this case, the predicted displacements, with the interface (WIN case) at the top of the structure, are higher than those without interface (NIN case). On the other hand, the trend is reversed, particularly after t = 0.25 secs for the point C on the ground level adjacent to the structure. Figure 4 shows a comparison between predictions of the thin-layer element and those from the zero-thickness element (Ref. 8) for maximum horizontal displacement at Point A of the structure for various frequencies. For this point the provision of interface appears to overpredict the response.

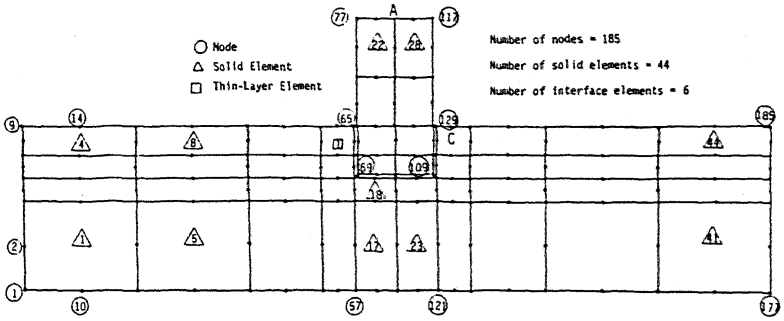

Figure 2. Finite Element Mesh for Pier Foundation Problem

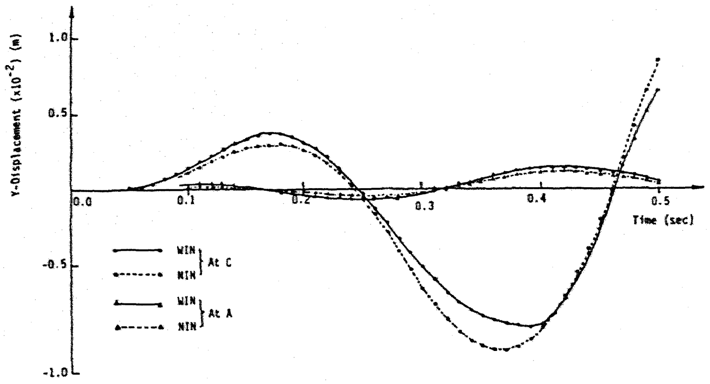

Figure 3. Computed Vertical Displacements; $\ddot{u}_B$ = 0.3g, Ω = 2 Hz

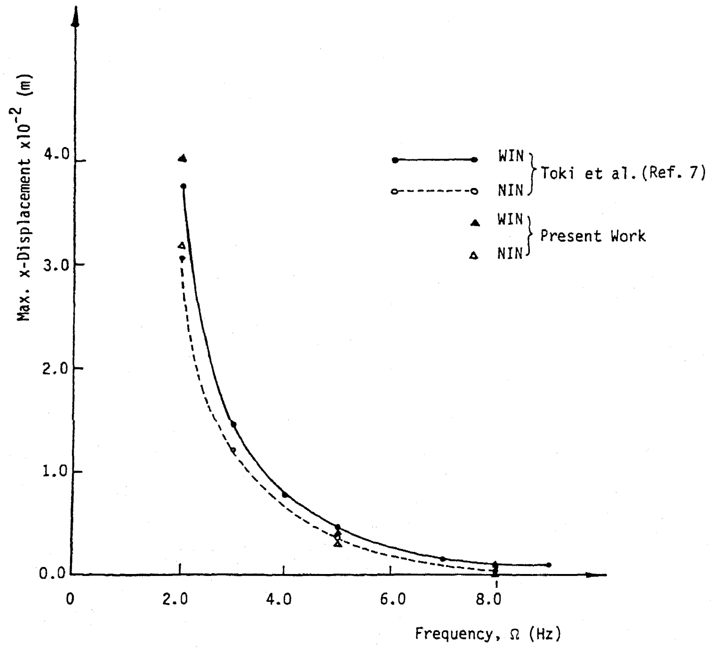

Figure 4. Comparison of Maximum Horizontal Displacements at Point A With Results by Toki et al. (Ref. 7); $\ddot{u}_B = 0.3g$

Example 2: Structure in Nonlinear Soil Medium

Figure 5 shows comparison for predicted horizontal velocities at point D for the two cases, for a system similar to that in Fig. 2. Here the soil is assumed to be elastic-plastic hardening material simulated by using the Cap model (Refs. 3, 5 and 8), and the interface by using the model in Eq. (5). Details of the material parameters are given in Ref. 5.

Comment

The above results indicate that the effect of provision of interface may increase or decrease the response (displacement, velocity, acceleration) depending upon factors such as geometrical properties, location, frequency, time level and material behavior. Similar observations have also been reported previously by Wolf (Ref. 9).

CONCLUSION

The proposed thin-layer element can simulate various modes of deformation at the interfaces and can enable evaluation of the effects of interface behavior on dynamic response of structures and foundations.

ACKNOWLEDGMENT

The research results were obtained under Grant No. CEE 8116843 from the National Science Foundation, Washington, D. C.

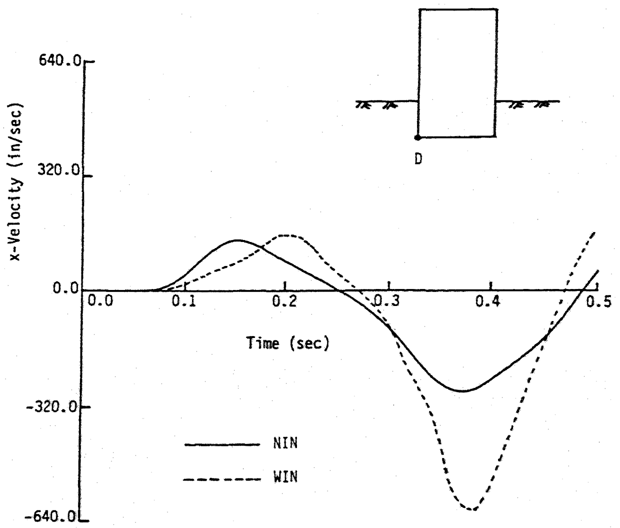

Figure 5. Computed Horizontal Velocities for Nonlinear Soil

REFERENCES

1. Wolf, J. P., "Soil-Structure Interaction With Separation of Base Mat From Soil," Nucl. Eng. & Design, Vol. 38, 1976, pp. 357-384.
2. Desai, C. S., "Behavior of Interfaces Between Structural and Geological Media," Proc., Int. Conf. on Recent Adv. in Geotech. Earthquake Eng., St. Louis, MO, 1981.
3. Vaughan, D. K. and Isenberg, J., "Nonlinear Soil-Structure Analysis of SIMQUAKE II, Report, No. 810-2, to EERI, Weidlinger Associates, Menlo Park, CA, 1982.
4. Heuze, F. E. and Barbour, T. G., "New Models for Rock Joints and Interfaces," J. of Geotech. Eng. Div., ASCE, Vol. 108, GT5, 1982, pp. 757-776.
5. Zaman, M. M., "Influence of Interface Behavior in Dynamic Soil-Structure Interaction Problems," Ph.D. Dissertation, Univ. of Arizona, Tucson, AZ, 1982.
6. Kausel, E. et al., "Seismically Induced Sliding of Massive Structures," J. of Geotech. Eng. Div., ASCE, Vol. 105, GT12, 1979, pp. 1471-1488.
7. Toki T. et al., "Separation and Sliding Between Soil and Structure During Strong Ground Motion," Earth. Eng. & Struct. Dyn., Vol. 9, 1981, pp. 263-277.
8. Vaughan, D. K. and Isenberg, J., "Nonlinear Rocking Response of Model Containment Structures," Earthquake Eng. & Struct. Dyn., Vol. 11, 1983, pp. 275-296.
9. Wolf, J. P., "Response of Structures Permitting Lift-off to Rotational Input Motion From Horizontally Propagating Waves," Proc., 2nd ASCE Conf. in Civil Eng. & Nuclear Power, Vol. VI, Knoxville, Tenn., 1980.
10. Desai, C. S. et al., "Thin-Layer Elements for Interfaces and Joints," Int. J. Num. Analyt. Meth. Geomech., in press.
11. Goodman, R. E. et al., "A Model for the Mechanics of Jointed Rock," J. of Soil Mech. & Found. Div., ASCE, Vol. 94, SM3, 1968, pp. 637-659.
12. Desai, C. S., "A Dynamic Multi-Degree-of-Freedom Shear Device," Report No. 80-36, Dept. of Civil Eng., VA Tech., Blacksburg, VA, 1981.