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BOUNDARY EFFECTS IN SIMULATION OF SOIL-STRUCTURE INTERACTION PROBLEMS

K. Edip, M. Garevski, V. Sheshov, and J. Bojadjieva
Institute of Earthquake Engineering and Engineering Seismology,
"Ss. Cyril and Methodius" University, Skopje, Republic of Macedonia.

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This paper presents the influence of boundary conditions in numerical simulation of soil-structure interaction problems. It discusses aspects related to a seismic load influencing a soil medium and a frame structure resting on the soil. The soil conditions are represented by 30 m soft, medium, and dense soil deposits with four layers resting on bedrock. The side boundaries of the finite element model are simulated as fixed, viscous boundaries and newly developed infinite elements. The results from the performed analysis show that, in addition to the structural properties and soil characteristics, the choice of side boundaries also plays an important role in seismic response of RC frame structures.

Introduction

Past earthquakes have shown that seismic response of structures is considerably influenced by soil-structure interaction. The main difficulty in solving soil-structure interaction problems is correct numerical simulation of soil media and their interaction with structures resting on these media. In recent years, the development of computers has enabled the use of sophisticated computer programs for numerical simulation of soil media. In this work, three types of soil are taken into consideration, namely, hard, medium dense, and soft soils as stated in Eurocode 8, Part 1. In order to examine the SSI effects on structural rigidity, RC models of one, three, and five storey frames are modelled and time history analysis is performed. In the analysis, soil medium is subjected to the acceleration time history of Imperial Valley EQ, El Centro record, 1940-May-18 (El Centro) earthquake. A coupled soil-structure system is subjected to the above acceleration time history, and the results of structural response are compared accordingly. The dynamic analysis is done by using the general finite element program ANSYS that enables modelling of both soil and structure and taking into consideration the soil-structure interaction. The variation of structural response to acceleration, displacements, and internal forces is presented in a tabular form and comparisons are made accordingly.

Soil Modeling

The soil medium is presented as a two-dimensional model composed of four layers resting on bedrock. In Table 1, the soil layer properties are tabulated in a way that the bottom layers are characterized by better soil characteristics.

The soil is assumed to represent a linear-elastic material and is discretized by using four noded plane strain elements PLANE42. The dynamic analysis is performed by transient analysis and using the "step by step" method. The proportional viscous damping matrix is taken to be proportion-

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TABLE 1

Soil medium	Layer number	Thickness, m	Unit weigh, kN/m^3	Shear velocity, m/s
Hard	1	3	16	330
	2	7	17	420
	3	6	17.5	510
	4	14	18	690
Medium	1	3	16	160
	2	7	17	210
	3	6	17.5	250
	4	14	18	340
Soft	1	3	16	90
	2	7	17	100
	3	6	17.5	120
	4	14	18	160

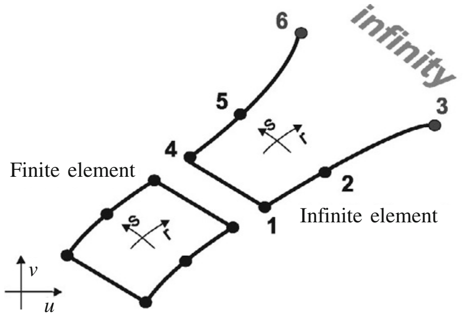

Fig. 1. Coupling of finite and infinite elements.

al to the mass and stiffness matrix (Rayleigh damping). The Rayleigh damping factors (α and β) are calculated such that the critical damping is 5% for the first two modes (α = 1.2907, β = 0.001405). The bottom boundary of the soil model is fixed, while the side boundaries are simulated as fixed, viscous, and infinite element boundaries. In order to prevent reflection of waves, viscous and infinite element boundaries are analyzed.

The radiation damping at the side boundaries as given in Cohen [1] is simulated by dashpots in which the radiation coefficient is obtained from the relation

$$c = A\rho V, \tag{1}$$

where A is the area between the nodes along the side, ρ is the soil density, and V is the shear and/or compression wave velocity depending on the direction of action.

The formulation of infinite elements is the same as that of finite elements in addition to mapping of the domain. Infinite elements were first developed by Zienkiewicz et al. [2] and since then have been developed in both frequency and time domain. In [3] infinite elements with absorbing properties that can be used in time domain are proposed. An infinite element is developed by similar techniques, where the infinite element is obtained from a six noded finite element as shown in Fig. 1.

The element displacement in u and v direction is interpolated with the usual shape functions N_1, N_2, N_4, and N_5:

$$\begin{aligned} u &= [N_1\ N_2\ 0\ N_4\ N_5\ 0]\mathrm{u}; \\ v &= [N_1\ N_2\ 0\ N_4\ N_5\ 0]\mathrm{v}, \end{aligned} \tag{2}$$

where u and v are vectors with nodal point displacements in global coordinates:

$$\begin{aligned} N_1 &= -(1-s)r(1-r)/4;\ N_2 = (1-s)r\,(1-r^2)/2; \\ N_3 &= -(1+s)r(1-r)/4;\ N_4 = (1+s)r\,(1-r^2)/2. \end{aligned} \tag{3}$$

For coordinate interpolation in the *r–s* coordinate system, a unidimensional mapping is applied:

$$r=[M_1\ M_2\ 0\ M_4\ M_5\ 0]\mathrm{r};$$
$$s=[N_1\ N_2\ 0\ N_4\ M_5\ 0]\mathrm{s}, \tag{4}$$

where the mapping functions are

$$\begin{aligned} M_1 &= -(1-s)r(1-r); \\ M_2 &= -\frac{1}{2}(1-s)(1+r)/(1-r); \\ M_4 &= -(1+s)r(1-r); \\ M_5 &= -\frac{1}{2}(1+s)(1+r)/(1-r), \end{aligned} \tag{5}$$

where r and s are vectors of nodal point displacements in local coordinates. It should be mentioned that, on the side of infinity (r = 1), no mappings are assigned to the nodes as it is taken that no displacement is possible at infinity. Construction of element matrices is done by using the usual procedures [4]. The new coordinate interpolation functions are taken into consideration in the Jacobian matrix [5]. The approximation for the element integrals is done by Gauss qaudrature formulas. For the absorbing layer of the infinite element, the Lysmer-Kuhlmeyer approach [6] is used. In all instances, a plane strain two-dimensional case is studied. For impact of plane waves on the element sides, normal and tangential stresses are derived as

$$\begin{bmatrix} \sigma_n \\ \tau \end{bmatrix} = \begin{bmatrix} a\rho c_p & 0 \\ 0 & b\rho c_s \end{bmatrix} \begin{bmatrix} \dot{u}_n \\ \dot{u}_t \end{bmatrix}, \tag{6}$$

where c_p and c_s indicate compression and shear waves, while ρ is the density of the soil medium. In order to take into account the directions of the incident waves, coefficients a and b (as suggested in [7]) are used as multipliers for better numerical results. Transformation from local to global coordinates is done automatically by the ANSYS software so that there is no need for defining transformation matrices. By bringing together the contributions from each element, the governing incremental equations for equilibrium in dynamic analysis are obtained. The time derivatives are approximated by Newmark's method, and equilibrium iterations are used in each step as given in the Theory References of the ANSYS software.

Coupled Soil-Structure System Response

In order to show the influence of the soil boundaries on the structure, a comparison of boundary cases has been performed. First, the soil side boundary is simulated as a fixed support, which is usually done in many applicative projects. Then, the same soil medium is bounded by viscous boundaries, which are included into the ANSYS software. Finally, the soil is surrounded by the newly programmed infinite elements. The frame structural elements are idealized as two-dimensional elastic beam elements BEAM3 having three degrees of freedom at each node, translations in the nodal x and y directions, and rotation about the nodal z axis. The behavior of the frame structure is supposed as elastic and is modeled by using two parameters, the elasticity modulus $E = 3.15\times10^7$ kPa and the Poisson's ratio $n = 0.2$. The bay length of the frame is taken to be 4.0 m and the storey height is considered to be 3.0 m. The cross-section of the beams is 40×50 cm, while the column cross-section is 50×50 cm. A mass of 11 tons is assigned to each node to simulate the real structural behavior (a total of 44 tons per floor). There are four different frames that are taken into consideration. For all RC frames, the beam and column cross-sections, the floor masses, and the number of bays are kept constant in all cases. The only parameter that is altered is the storey number. The structures are modeled as one-, three-, and five-storey RC frames.

Finite element modelling of the coupled soil-structure system is performed by the ANSYS software, as shown in Fig. 2. The effect of the soil-structure interaction is explored by using the accelera-

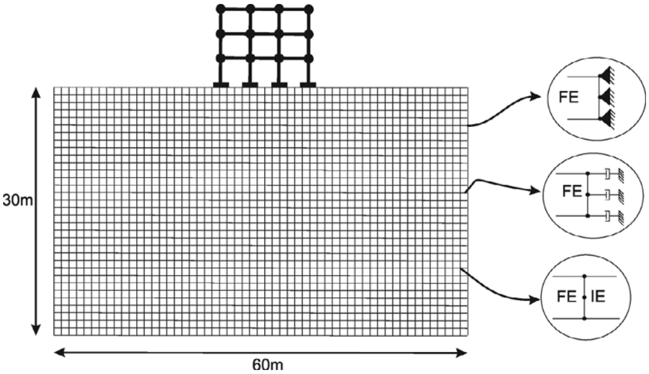

Fig. 2. Coupled soil-structure system of a three-storey frame.

TABLE 2

No. of storey	Soil medium	Boundary	Acceleration at top of structure, m/s^2		Maximum displacement at top of structure, cm	Maximum moment at top of structure, kNm
			maximum	amplification		
1	Hard	Fixed	11.2	4.57	0.447	152.1
		Viscous	5.72	2.33	0.220	58.7
		Infinite element	4.17	1.70	0.171	48.6
	Medium	Fixed	13.5	5.51	0.624	223.2
		Viscous	5.13	2.09	0.319	83.5
		Infinite element	4.91	2.00	0.191	67.8
	Soft	Fixed	11.1	4.53	1.11	222.2
		Viscous	4.61	1.88	0.527	85.3
		Infinite element	3.29	1.34	0.257	63.2
3	Hard	Fixed	8.95	3.65	1.87	155.1
		Viscous	8.68	3.54	1.93	145.5
		Infinite element	6.08	2.48	1.45	115.1
	Medium	Fixed	10.5	4.28	3.45	182.2
		Viscous	7.88	3.21	2.96	118.1
		Infinite element	5.55	2.26	2.09	99.9
	Soft	Fixed	10.3	4.20	8.22	175.1
		Viscous	7.12	2.91	3.65	108.3
		Infinite element	4.50	1.83	2.93	92.3
5	Hard	Fixed	9.74	3.98	5.56	153.1
		Viscous	9.15	3.73	4.78	145.3
		Infinite element	7.83	3.19	4.22	126.3
	Medium	Fixed	8.51	3.47	6.48	158.3
		Viscous	8.04	3.28	5.86	149.1
		Infinite element	6.39	2.61	4.08	114.1
	Soft	Fixed	8.80	3.59	11.1	131.2
		Viscous	5.85	2.39	7.58	81.9
		Infinite element	4.78	1.95	4.83	56.2

tion time history of the El Centro earthquake with a scaled peak ground acceleration of $0.25g$. The foundation where the structure is supported is taken to be a 4 noded plane element with two degrees of freedom at each node and translations in the nodal x and y directions. The moment transfer capability between the column and the footing is created by using a constraint equation where the rotation of the beam is transferred as force couples to the plane element.

In Fig. 2 the side boundaries are presented as fixed, viscous, and infinite element boundaries. In Table 2, the results on the structural response are given.

According to the acceleration values shown in Table 2, the maximum acceleration at the top of the structure is considerably decreased when using the viscous boundaries of the commercial software. Moreover, when using infinite elements, the acceleration values are even more decreased showing that, in the case of infinite elements, the wave reflection at the boundaries is even more minimized. This is due to the fact that the infinite elements use indices *a* and *b* (as given in [7]) that have a considerable influence on the results. Moreover, the use of infinite elements absorbs the waves, not letting them propagate back to the soil domain. Thus, the effect of earthquake forces upon structural elements is real without wave reflections from the boundaries [8].

On the other hand, the difference in the soil medium stiffness plays an important role on the results. As is observed from the results, the soil-structure interaction phenomenon plays an important role when the soil is soft and the number of stories is five, meaning that the mass of the structure is big. It is to be mentioned that the use of infinite elements for different soil types gives accurate results as long as the simulation of soil elements is in the linear elastic domain.

Conclusion

The use of side boundaries alters the results greatly. Using fixed boundaries at the far end of the side boundaries increases the amount of computation. Moreover, on the other side, the values of internal forces obtained in using fixed boundaries increase the internal forces due to wave reflection from the boundaries. On the other hand, the use of viscous and infinite elements influences the internal forces of the structural response in such a way that the wave propagation is absorbed at the side boundaries. In this work, the infinite elements with absorbing properties are shown to be a promising substitute for the viscous boundaries offered by commercial softwares.

REFERENCES

1. M. Cohen, *Silent Boundary Methods for Transient Wave Analysis*, California Institute of Technology, California (1980).
2. O.C. Zienkiewicz, C. Emson, and P. Bettess, "A novel boundary infinite element," *Int. J. Numer. Methods Eng.*, **19**, 393-404 (1983).
3. B. Häggblad and G. Nordgren, "Modelling nonlinear soil-structure interaction using interface elements, elastic-plastic soil elements and absorbing infinite elements," *Comp. Struct.*, **26**, 307-324 (1987).
4. K.J. Bathe, *Finite Element Procedures in Engineering Analysis*, Prentice-Hall, Englewood Cliffs. NJ (1982).
5. P. Bettess, *Infinite Elements*, Penshaw Press, New Castle, England (1992).
6. J. Lysmer and R.L. Kuhlmeyer, "Finite dynamic model for infinite media," *J. Eng. Mech. Div.*, ASCE, **95**, 859-877 (1969).
7. W. White, S. Valliappan, and I.K. Lee, "Unified Boundary for Finite Dynamic Models," *J. Eng. Mech. Div.*, ASCE, **103**, 949-964 (1977).
8. K. Edip, *Development of Three Phase Model with Finite and Infinite Elements for Dynamic Analysis of Soil Media*, UKIM-IZIIS, Skopje (2013).