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Equivalent dynamic infinite element for soil–structure interaction

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ABSTRACT

In this paper, equivalent dynamic infinite element is proposed. The idea of the method is based on the elastic recovery of general infinite element and the energy absorption of viscous boundary. The equivalent dynamic infinite element is not required for wave functions, since the waves on the interfaces with adjacent finite and infinite elements are absorbed by the equivalent damping. And the role of the far field medium in the elastic recovery has also been considered in the equivalent dynamic element. Such an element can be used directly as general finite element and appropriates for dynamic soil–structure interaction problems. Numerical analyses involving comparisons with known analytical or numerical solutions are presented. The results obtained show the effectiveness of the proposed equivalent dynamic infinite element.

1. Introduction

The problem of soil–structure interaction (SSI) in the dynamic analysis and design has become increasingly important with the rapid development of major construction such as nuclear facilities, dam structure, high-rise buildings, large span bridges and marine engineering. It is well recognized that SSI could play a significant role on structural response. However, common practice usually does not account for the effects of SSI on the dynamic behavior of structures. It is the reason that soil–structure dynamic interaction problems involving massive structures and infinite soil medium are very complex. In the past, most works on SSI were made to apply the finite element method (FEM) directly to dynamic problems by truncating the near-field region for analysis. The application of the domain type techniques to the solution of the soil–structure system will involve the reflection of waves from the truncated boundaries to the domain of interest. Suitable boundary conditions are applied at the truncated boundaries to prevent the reflection of the waves, such as viscous boundary [1], FE cloning method [2], boundary element [3] and infinite element method [4].

The viscous boundaries have been widely used for various wave propagation problems. But the number of finite elements required can still be large, as such boundaries are usually capable of transmitting plane or cylindrical waves only, and therefore they must be placed far from the initially disturbed region [5]. FE cloning method for nonlinear dynamic problems involves the inverse of Fast Fourier Transform to obtain the time domain results. The boundary element method does not require domain discretization and allows a reduction in the spatial dimensionality, but the matrix is non-symmetric, non-positive definite and fully populated for single domains and block banded for multi-domains.

Infinite element can be regarded as the natural extension of the finite element to treat unbounded domain. In the infinite element method, the near field is modeled by finite elements and the far field is modeled by infinite elements (Fig. 1). From the algorithmic point of view, the infinite element is treated as a standard finite element except for the infinite approximation in the infinite direction. So the accuracy of the numerical solution depends only on the finite element method. The development of the infinite element has been receiving increased attention. The infinite element is very successful in elastostatics, consolidation analysis, seepage flow, hydrodynamics, acoustics and other fields [6–16]. Medina and Penzien [17], Medina and Taylor [18], Chow and Smith [19] used different infinite elements for analyzing two-dimensional (2D) or axisymmetrical wave problems, which differ in the selection of wave propagation functions. However, there were limitations to deal with structures having complex geometries and to solve the multiple wave components in layered soil media. Yun et al. developed more effective infinite elements for layered media [20,21]. Zhao and Valliappan [22] and Park and Watanabe [23] proposed and developed three dimensional (3D) infinite elements of mapped type, respectively. However, only frequency domain elements have been developed for solving dynamic problems. Recently, the elastodynamic infinite elements have been developed by using wave functions containing various wave components [24,25]. One of the major drawbacks of the method is the necessity of a fundamental solution to exist. Such an analytical solution is difficult to derive.

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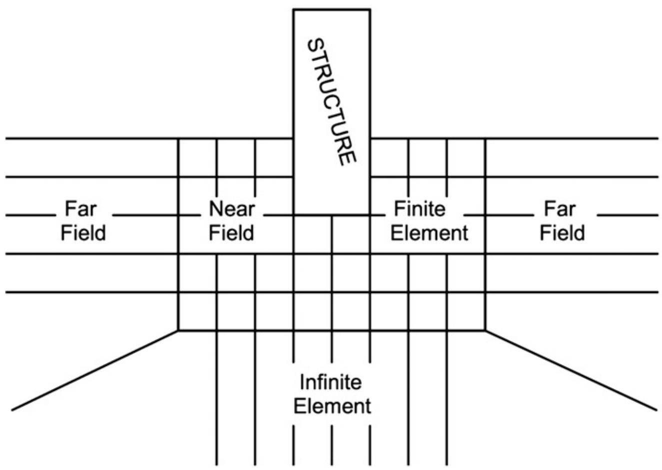

Fig. 1. Soil–structure system.

In short, infinite element as the extension of the general finite element is dominant in dynamic soil–structure interaction. Its advantages are as follows: it does not involve analytical solution and can be given a unified solving format; it can be effectively coupled with finite element; the accuracy of the numerical solution depends only on the finite element method.

Therefore, the purpose of this paper is the application of infinite element to analyze the time-domain. In this paper, a time domain approach is developed for analyzing soil–structure dynamic interaction. In order to simulate soil–structure dynamic interaction, the advantages of infinite element and viscous boundary are coupled. Such a method can be called equivalent dynamic infinite element method (EDIEM), which based on general infinite element and to add equivalent damping matrix. In contrast to elastodynamic infinite element, the equivalent dynamic infinite element has no necessity for wave functions, since the waves on the interfaces with adjacent finite and infinite elements are absorbed by the equivalent damping. The role of the far field medium in the elastic recovery is considered by the static infinite element in the equivalent dynamic element. Therefore, it can be used for dynamic soil–structure interaction in time domain.

The secondary development tools UPFs and data interface have been used to add the equivalent dynamic infinite element to standard ANSYS procedure. Numerical example analyses are presented for verification and applications of the equivalent dynamic infinite element.

2. Mapping functions of EDIEM

Conceptually, the infinite element is the extension of the finite element to infinite direction. Geometrically, it tends to infinite. Namely, the domain represented by infinite element is infinite. Therefore, the mapping between global (x,y) and local (ε,η) coordinates (Fig. 2) which can be generally expressed as

$$x=\sum_{i=1}^{n} M_i x_i \tag{1}$$

$$y=\sum_{i=1}^{n} M_i y_i \tag{2}$$

is necessary to satisfy the condition that x and y tend to infinite as ε equals 1. x and y are the global coordinates of the element; M_i is the mapping function; n is the number of nodes for each infinite element; x_i and y_i are the global coordinates at node i.

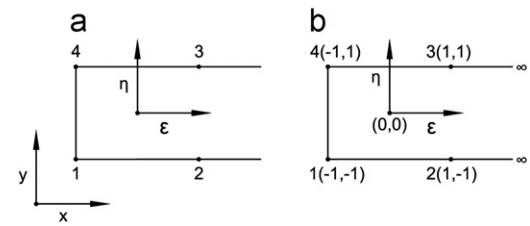

Fig. 2. Four-node infinite element. (a) Global Cartesian coordinates. (b) Local Cartesian coordinates.

The mapping functions of four-node element can be written as [12]

$$M_1=-\frac{2\varepsilon}{1-\varepsilon}\frac{1-\eta}{2} \tag{3}$$

$$M_2=\frac{1+\varepsilon}{1-\varepsilon}\frac{1-\eta}{2} \tag{4}$$

$$M_3=\frac{1+\varepsilon}{1-\varepsilon}\frac{1+\eta}{2} \tag{5}$$

$$M_4=-\frac{2\varepsilon}{1-\varepsilon}\frac{1+\eta}{2} \tag{6}$$

The ranges of the local coordinates are $\varepsilon\in[-1,1]$, $\eta\in[-1,1]$.

The mapping functions meet the following conditions:

(1) $\sum_{i=1}^{4} M_i=1$;
(2) when $M_i=1$, on node i, other nodes, $M_j=0$;
(3) when $\varepsilon=1$, $(x,y)\to(\infty,\infty)$.

3. Displacement functions of EDIEM

In addition, the displacement at infinity is zero in soil–structure interaction problems. The displacement field in infinite element can be described in the standard form of the shape functions based on decay function as

$$u=\sum_{i=1}^{n} f(r)N_i u_i=\sum_{i=1}^{n} Q_i u_i \tag{7}$$

$$v=\sum_{i=1}^{n} f(r)N_i v_i=\sum_{i=1}^{n} Q_i v_i \tag{8}$$

where u and v are the displacements of the element; N_i are the shape functions of the standard finite element; Q_i are the displacement functions; n is the number of nodes for each infinite element; u_i and v_i are the displacements at node i; $f(r)$ is the decay function.

The shape functions of four-node element are as follows:

$$N_1=\frac{(1-\varepsilon)(1-\eta)}{4} \tag{9}$$

$$N_2=\frac{(1+\varepsilon)(1-\eta)}{4} \tag{10}$$

$$N_3=\frac{(1+\varepsilon)(1+\eta)}{4} \tag{11}$$

$$N_4=\frac{(1-\varepsilon)(1+\eta)}{4} \tag{12}$$