

# Formulation of Elastodynamic Infinite Elements for Dynamic Soil-Structure Interaction

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*Abstract:* - The paper is devoted to formulations of decay and mapped elastodynamic infinite elements, based on modified Bessel shape functions. These elements are for Soil-Structure Interaction problems, solved in time or frequency domain and can be treated as a new form of the recently proposed Elastodynamic Infinite Elements with United Shape Functions (EIEUSF) infinite elements. The formulation of 2D horizontal type infinite elements (HIE) is demonstrated here, but by similar techniques 2D vertical (VIE) and 2D corner (CIE) infinite elements can also be formulated. Using elastodynamic infinite elements is the easier and appropriate way to achieve an adequate simulation including basic aspects of Soil-Structure Interaction. Continuity along the artificial boundary (the line between finite and infinite elements) is discussed as well and the application of the proposed elastodynamical infinite elements in the Finite Element Method is explained in brief. Finally, a numerical example shows the computational efficiency of the proposed infinite elements.

*Key-Words:* - Soil-Structure Interaction, Wave propagation, Infinite Elements, Finite Element Method, Bessel functions

## 1 Introduction

In static Soil-Structure Interaction (SSI) analysis, the simple truncation of the far field with setting of appropriate boundary conditions gives very often good results. However, in dynamic cases, an artificial boundary made by truncation makes results to be erroneous because of reflection waves. In last decades, much works has been done on unbounded domain problems and several kinds of modeling techniques have been developed to avoid these effects. Such techniques are viscous boundary, transmitting boundary, boundary elements, infinite elements and system identification method. At the same time several numerical methods for these types of problems were suggested. The basic idea of these approaches is to divide domain  $\Omega$  into two parts the bounded part  $\Omega_c$  and unbounded part  $\Omega_\infty$ , where for the first one is valid  $x_i \leq c_i$ . For appropriate simulations we need to set the assumption that function  $u(x_i) = 0$  on  $\Omega_\infty$ .

Among these approaches, using infinite elements is good way to solve Soil-Structure Interaction problems since its concept and formulation are similar to those of Finite element method except for the infinite extent of the element region and shape function in one direction and there is no loss of

symmetry of the element matrices. The domain  $\Omega_\infty$  is partitioned into a finite number of infinite elements directly incorporated with the meshes on the bounded domain  $\Omega_c$ . In the numerical models these domains very often have called near ( $\Omega_c$ ) and far ( $\Omega_\infty$ ) fields. Infinite elements are classified into five types: classical, decay, mapped, elastodynamical and envelope infinite elements [7].

## 2 Backgrounds for Infinite Elements

Infinite elements are widely used in the numerical simulations when unbounded domain exists. The origin of these elements is the works of Bettess [4] and Ungless [19]. Classification of the infinite elements is proposed in [7]. During the last three decades much element formulations have been suggested [1, 6, 11, 22, 23, 23].

Soil-Structure Interaction is a typical civil engineering problem [2, 3, 5, 13-18]. The infinite elements can be integrated in the Finite element method codes [8, 14, 20, 21] adequately dynamic SSI simulations to be obtained. The infinite elements as a computational technique is one of the often used since their concepts and formulations are much closed to those of the finite elements. These

elements are very effective for models of structures containing a near field discretized by finite elements and a far field discretized by infinite elements. In the last two decades a lot of dynamic infinite elements were developed. Yum [22] proposes one of the most effective elastodynamical elements.

### 3 Elastodynamical infinite element with united shape functions (EIEUSF)

The displacement field in the elastodynamical infinite element can be described in the standard form of the shape functions based on wave propagation functions [10, 12] as

$$\mathbf{u}(x, z, \omega) = \sum_{i=1}^n \sum_{q=1}^m N_{iq}(x, z, \omega) \mathbf{p}_{iq}(\omega)$$

or

$$\mathbf{u}(x, z, \omega) = N_p(x, z, \omega) \mathbf{p}(\omega) \quad (1)$$

where  $N_{iq}(x, z, \omega)$  are the standard shape displacement functions,  $\mathbf{p}_{iq}(\omega)$  is the generalized coordinates associated with  $N_{iq}(x, z, \omega)$ ,  $n$  is the number of nodes for the element and  $m$  is the number of wave functions included in the formulation of the infinite element. For horizontal wave propagation basic shape functions for the HIE infinite element, the local coordinate system of which is given in Fig. 1, can be expressed as:

$$N_{iq}(x, z, \omega) = T(x, z, \eta, \xi) N_{iq}(\eta, \xi, \omega) \quad (2)$$

$$N_{iq}(x, z, \omega) = T(x, z, \eta, \xi) L_i(\eta) W_q(\xi, \omega)$$

where  $W_q(\xi, \omega)$  are horizontal wave functions and  $L_i(\eta)$  are Lagrange interpolation polynomial which has unit value at  $i$  th node while zeros at the other nodes. For HIE infinite element the ranges of the local coordinates are:  $\eta \in [-1, 1]$  and  $\xi \in [0, \infty)$ . Here  $T(x, z, \eta, \xi)$  assures the geometrical transformations of local to global coordinates.

Taking into account only real parts of the wave functions the equations of the wave propagation can be written as

$$\text{Re } W_q(\xi, \omega) = \cos\left(\frac{\omega}{c_s} \xi\right) e^{-\alpha \xi}$$

or

$$\text{Re } W_q(\xi, \omega) = \cos\left(\frac{\omega}{c_p} \xi\right) e^{-\alpha \xi} \quad (3)$$

where  $c_s, c_p$  are the wave velocities for *S-waves* and *P-waves* respectively, and  $\alpha$  is appropriate constant, called attenuation factor.

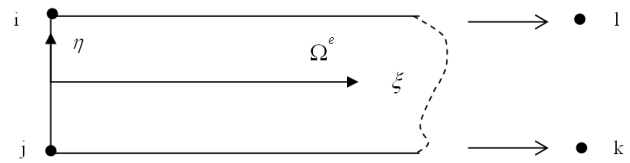


Fig. 1 Local coordinate system of horizontal infinite elements (HIE).

Expanding this functions in a Fourier-like series for all wave functions included in the formulation of the infinite element the shape functions for HIE can be written as

$$\text{Re } W(\xi) = \frac{1}{m} \sum_{q=1}^m A_q \cos\left(\frac{\omega_q}{c_s} \xi\right) e^{-\alpha \xi}$$

or

$$\text{Re } W(\xi) = \frac{1}{m} \sum_{q=1}^m A_q \cos\left(\frac{\omega_q}{c_p} \xi\right) e^{-\alpha \xi} \quad (4)$$

The coefficients  $A_q$  can be written as:

$$A_q = \int_0^{T_x} \text{Re } W(\xi, t) \cos\left(\frac{\omega_q}{c_s} \xi\right) dt$$

or in the form

$$A_q = \frac{1}{\Omega_e} \int_0^{\Omega_e} \text{Re } W(\xi) \cos\left(\frac{\omega_q}{c_s} \xi\right) dt \quad (5)$$

Because,  $m$  is a finite number and  $A_q$  can be treated as weight coefficients, so that  $\sum_{q=1}^m A_q = 1$  for shape functions than (4) can be expressed as

$$\text{Re } W(\xi) = \frac{1}{m} \sum_{q=1}^m \sum_{n=1}^{\infty} 1 \cos\left(\frac{\omega_q}{c_s} \xi\right) e^{-\alpha \xi},$$

$$\text{Re } W(\xi) = \frac{1}{m} \sum_{q=1}^m \sum_{n=1}^{\infty} 1 \cos\left(\frac{\omega_q}{c_p} \xi\right) e^{-\alpha \xi} \quad (6)$$

Using this approach can be written

$$N_i(x, z) = \sum_{q=1}^m N_{iq}(x, z, \omega) \quad (7)$$

$$N_i(x, z) = T(x, z, \eta, \xi) L_i(\eta) \text{Re } W(\xi)$$

and

$$\sum_{q=1}^m N_{iq}(x, z, \omega) \mathbf{p}_{iq}(\omega) \quad (8)$$

$$N_i(x, z) \mathbf{p}_i = T(x, z, \eta, \xi) L_i(\eta) \text{Re } W(\xi) \mathbf{p}_i$$

Then equation (1) can be expressed as

$$\mathbf{u}(x, z) = N_p(x, z)\mathbf{p} \quad (9)$$

The procedure described by the above equations can be treated as a superposing procedure based on a finite number of terms, where real components of the wave functions  $\text{Re}W_q(\xi, \omega)$  are preliminary shape functions or basis functions from mathematical point of view, and coefficients  $A_q$  are generalized coordinates with only one component, corresponding to the node  $i$  or weight coefficients from mathematical point of view.

#### 4 Element shape functions, based on Bessel functions

The idea and concept of the **EIEUSF** class infinite elements are presented in [10, 11, 12]. Several **EIEUSF** formulations are discussed and have been demonstrated that the shape functions, related to nodes  $k$  and  $l$  (the nodes, situated in infinity, *Fig.1*) are not necessary to be constructed, because corresponding to these shape functions generalized coordinates or weights, see eq. (1), are zeros. The displacements in infinity are vanished, and these shape functions must be omitted.

For horizontal wave propagation the basic shape functions for the *HIE* infinite element can be expressed using Bessel functions as follows:

$$N_{iq}(\eta, \xi, \omega) = L_i(\eta)\tilde{J}_0^q(\psi\xi) \quad (10)$$

where  $\tilde{J}_0^q(\psi\xi)$  are modified Bessel functions of first kind. These functions can be written as

$$\tilde{J}_0^q(\psi\xi) = J_0^q(\psi\xi)\exp(-\beta\xi) \quad (11)$$

where  $J_0^q(\psi\xi)$  are standard Bessel functions of first kind. In eq. (11)  $\psi$  and  $\beta$  are constants, chosen in such a way that the length of the wave and the attenuation of the wave respectively, are identical with those, if eq. (2) is used. This means that the following two relations are valid:

$$\psi = \frac{\omega}{\varpi} \quad (12)$$

or

$$\psi = \frac{L_w}{\bar{L}_w} \quad (13)$$

where  $\varpi$  is the wave frequency corresponding to  $\omega$  if Bessel functions are used to approximate the displacements in the infinite element domain, and:

$$\exp(-\beta\xi) = \frac{1}{\sqrt{\xi}}\exp(-\alpha\xi) \quad (14)$$

because the Bessel functions of first kind decay proportionally to  $1/\sqrt{\xi}$ . Although the roots of Bessel functions are not generally periodic, except asymptotically for large  $\xi$ , such functions give acceptable results. And what is more, using Bessel functions one can approximate change of the wave length in the far field region.

If the element has four nodes and eight DOF only four shape functions can be used to approximate the displacements, related to one frequency. These functions can be written as:

$$N_{1q}(\eta, \xi, \omega) = N_{iq}^u(\eta, \xi, \omega) = L_i(\eta)J_0^q(\psi\xi)\exp(-\beta\xi) \quad (15a)$$

$$N_{2q}(\eta, \xi, \omega) = N_{iq}^v(\eta, \xi, \omega) = L_i(\eta)J_0^q(\psi\xi)\exp(-\beta\xi) \quad (15b)$$

and

$$N_{3q}(\eta, \xi, \omega) = N_{jq}^u(\eta, \xi, \omega) = L_j(\eta)J_0^q(\psi\xi)\exp(-\beta\xi) \quad (16a)$$

$$N_{4q}(\eta, \xi, \omega) = N_{jq}^v(\eta, \xi, \omega) = L_j(\eta)J_0^q(\psi\xi)\exp(-\beta\xi) \quad (16b)$$

In the above equations, eq. (15.a) is identical to eq. (15.b) and eq. (16.a) is identical to eq. (16.b). If rotational DOF are used then the element has four nodes and ten DOF. Two additional shape functions must be used, written as:

$$N_{5q}(\eta, \xi, \omega) = N_{iq}^\varphi(\eta, \xi, \omega) = L_i(\eta)[J_1^q(\psi\xi)\exp(-\beta\xi) - \beta J_0^q(\psi\xi)\exp(-\beta\xi)] \quad (17a)$$

and

$$N_{6q}(\eta, \xi, \omega) = N_{jq}^\varphi(\eta, \xi, \omega) = L_j(\eta)[J_1^q(\psi\xi)\exp(-\beta\xi) - \beta J_0^q(\psi\xi)\exp(-\beta\xi)] \quad (17b)$$

Here  $J_0^q(\psi\xi)$  and  $J_1^q(\psi\xi)$  are Bessel functions of first kind. The Taylor series indicates that  $J_1^q(\psi\xi)$  is the derivative of  $J_0^q(\psi\xi)$ .

The function  $L_i(\eta)$  is linear if no mid-nodes. Finally, if mid-node on the side  $i$ - $j$  is used, then the Lagrange interpolation polynomials must be quadratic. Modified Bessel functions of first kind, in accordance with eq. (11) ( $\tilde{J}_0^q(\psi\xi)$  and  $\tilde{J}_1^q(\psi\xi)$ ), are illustrated in *Fig. 2*.

The continuity along the artificial boundary (the line between finite and infinite elements, see *Fig. 3* line  $-x_b$  and line  $x_b$ ) is assured in the same way as between two plane finite elements [9]. The

application of the proposed infinite elements in the Finite element method is discussed below.

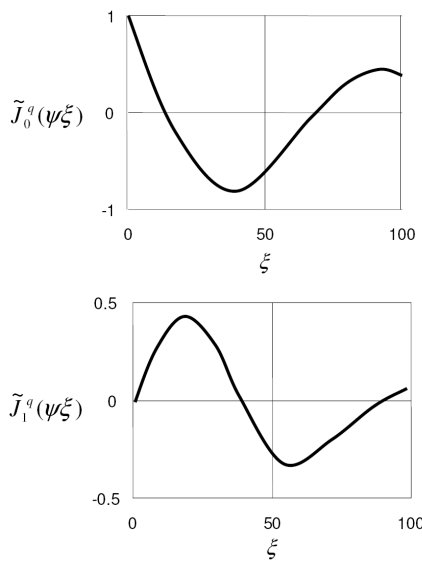


Fig. 2  $\tilde{J}_0^q(\psi\xi)$  and  $\tilde{J}_1^q(\psi\xi)$  modified Bessel functions.

Using the procedure, given in details in [10] and briefly described here, mapped **EIEUSF** finite elements, based on modified Bessel functions, can be formulated, based on eq. (18)

$$\begin{aligned}
 N_i(x, z) &= \sum_{q=1}^m N_{iq}(x, z, \omega) = \\
 &= \sum_{q=1}^m T(x, z, \eta, \xi) N_{iq}(\eta, \xi, \omega) = \\
 &= \sum_{q=1}^m T(x, z, \eta, \xi) L_i(\eta) \tilde{J}_0^q(\psi\xi)
 \end{aligned} \tag{18}$$

where  $\tilde{J}_0^q(\psi\xi) = J_0^q(\psi\xi) \exp(-\beta\xi)$ .

### 5 Stiffness and mass matrices of the element

By analogy with **EIEUSF** [12] and since each shape function  $N_{iq}(x, z, \omega)$  is associated with only one frequency,  $\mathbf{p}_{iq}(\omega)$  is a generalized coordinate involving a single wave component only. Then the component matrices  $k_{iq}$  and  $m_{iq}$  can be written as

$$k_{iq} = \int_{\Omega_e} \bar{B}_i^T D \bar{B}_q d\Omega_e \tag{19}$$

and

$$m_{iq} = \left( \int_{\Omega_e} \bar{N}_i^T N_q d\Omega_e \right) I \tag{20}$$

where  $\bar{B}_i = [\partial](\bar{N}_i) = [\partial](L_i W)$ ;  $[\partial]$  is a linear differential operator matrix. If Bessel functions are used, the first derivative of  $J_0^q(\psi\xi)$  is  $J_1^q(\psi\xi)$  (The Taylor series indicate that  $J_1^q(\psi\xi)$  is derivative of  $J_0^q(\psi\xi)$ ) and can be expressed as

$$\frac{d}{d\xi} J_0^q(\psi\xi) = (J_{-1}^q(\psi\xi) + J_1^q(\psi\xi)) / 2 .$$

The equation of motion for the entire SSI system including the far field soil region can be written as

$$\begin{bmatrix} S_{ss}(\omega) & S_{sb}(\omega) \\ S_{bs}(\omega) & S_{bb}(\omega) + S_{bb}^g(\omega) \end{bmatrix} \begin{Bmatrix} U_s(\omega) \\ U_b(\omega) \end{Bmatrix} = \begin{Bmatrix} F_s(\omega) \\ F_b(\omega) \end{Bmatrix} \tag{21}$$

where  $U(\omega)$ ,  $F(\omega)$  and  $S(\omega)$  are respectively displacement vector, force vector and dynamic stiffness matrix in frequency domain. Subscripts  $s$  and  $b$  stand for the nodes along the artificial boundary between the near and the far field soil region and for those of the structure and near field soil region respectively. This equation can be transformed into time domain by inverse Fourier transformation as

$$\begin{aligned}
 &\begin{bmatrix} M_{ss} & M_{sb} \\ M_{bs} & M_{ss} \end{bmatrix} \begin{Bmatrix} \ddot{u}_s(t) \\ \ddot{u}_b(t) \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & S_1^g \end{bmatrix} \begin{Bmatrix} \dot{u}_s(t) \\ \dot{u}_b(t) \end{Bmatrix} + \\
 &+ \begin{bmatrix} K_{ss} & K_{sb} \\ K_{bs} & K_{bb} + S_0^g \end{bmatrix} \begin{Bmatrix} u_s(t) \\ u_b(t) \end{Bmatrix} = \\
 &= \begin{Bmatrix} f_s(t) \\ f_b(t) - \int_0^t \{ S_2^g + (t-\tau) S_3^g \exp(-a(t-\tau)) u_b(\tau) d\tau \} \end{Bmatrix}
 \end{aligned} \tag{22}$$

where  $u(t)$  and  $f(t)$  are respectively displacement and force vectors, and  $S_j^g$  are mechanical characteristics of the far field soil region.

### 6 Numerical example

Structure with rigid strip foundation on a homogeneous half-space is modeled as shown in Fig.3. Four models of the far field are used, briefly described as:

- *model 1* - elastic springs with stiffness  $k_b^2$ , calculated using the Gorbunov-Possadov relation [7], modified in accordance with the mesh as  $k_b^2 = E_b J_\eta (1-\nu) / d.(1+\nu)(1-2\nu)$ ;
- *model 2* - elastic springs with stiffness  $k_b^1$ , calculated using the Tsitovich relation [7], modified in accordance with the mesh as

$k_b^1 = E_b \cdot l_\eta / 0.87 \cdot d \cdot (1 - \nu^2)$ , where  $l_\eta$  is the element size and  $b = 1$  - thickness of the element;  
 - *model 3* - the far field is discretized by massless **EIEUSF** infinite elements with only one frequency (single wave component);  
 - *model 4* - the far field is discretized by massless infinite elements with Bessel shape functions.

The stiffness matrices of the infinite elements, used in models *model 3* and *model 4* are calculated by **EIEUSF matrix module**. Horizontal harmonic displacements with period  $T_\theta = 0.8s$  and amplitude  $u_b^{max} = 0.1m$  are applied on the nodes as shown in Fig.3. The geometry of the model and the material parameters are given in [10].

The results for the first 10 natural periods, corresponding to the models and max displacement of node *S*, are given in Table 1. The time history of the displacements of node *S*, see Fig.3, between 8.4s and 8.5s are illustrated in Fig.4.

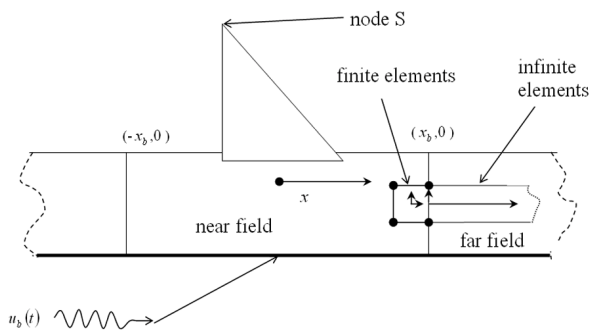


Fig. 3 Computational model

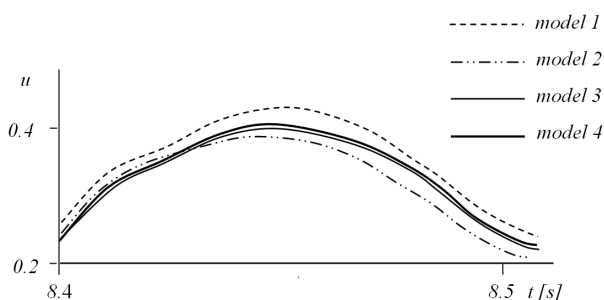


Fig. 4 Time history of the displacements of node S

Table 1

Models	model 1	model 2	model 3	model 4
	1.2608	1.2598	1.2606	1.2606
	0.7215	0.7215	0.7215	0.7215
	0.6105	0.5946	0.6052	0.6068
natural periods	0.5680	0.4359	0.5514	0.5523
of vibration	0.5448	0.4185	0.5152	0.5171
	0.3774	0.3515	0.3716	0.3722
	0.3635	0.3514	0.3575	0.3586
	0.3521	0.3402	0.3511	0.3514
	0.3521	0.3394	0.3506	0.3509
	0.3348	0.3123	0.3338	0.3329
max displacement [m]	0.4679	0.4359	0.4518	0.4522

## 7 Conclusion

In this paper a formulation of elastodynamical infinite element, based on Bessel shape functions appropriate for Soil-Structure Interaction problems is presented. This element is a new form of the infinite element, given in [10]. The base of the development is new shape functions, obtained by modification of the standard Bessel functions of first kind. The stiffness matrices of the examined infinite elements are calculated by **EIEUSF matrix module**, developed by the same author.

The numerical example shows the computational efficiency of the proposed infinite elements. Such elements can be directly used in the FEM code. The results are in a good agreement with the results, obtained by **EIEUSF** infinite elements.

The formulation of 2D horizontal type infinite elements (*HIE*) is demonstrated, but by similar techniques 2D vertical (*VIE*) and 2D corner (*CIE*) infinite elements can also be formulated. It was demonstrated that the application of the elastodynamical infinite elements is the easier and appropriate way to achieve an adequate simulation (2D elastic media) including basic aspects of Soil-Structure Interaction. Continuity along the artificial boundary (the line between finite and infinite elements) is discussed as well and the application of the proposed elastodynamical infinite elements in the Finite element method is explained in brief.

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