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An Efficient Three-Dimensional Soil-Structure Interaction Analysis for Incident Plane Waves

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Abstract

An efficient method is proposed for transient response analysis of three-dimensional structures resting on viscoelastic half-space for incident plane waves. The formulation consists of two parts: (a) the time domain formulation of the unbounded soil which is modeled by lumped-mass explicit finite element and transmitting boundary condition and (b) the coupling algorithm between the soil and structure through foundation. It is an implicit-explicit method, in which the soil is analyzed by explicit procedure avoiding equation solving, and the structure is analyzed by implicit procedure. The time step of explicit and implicit procedure can be different. Examples are given to demonstrate the feasibility of this method, and the influence of incident angle on the structure response is investigated. The results obtained indicate the possible importance of the effects introduced by nonvertically incident SH wave.

Keywords: Soil-structure dynamic interaction; transmitting boundary; explicit-implicit integration scheme;

1. Introduction

On a deformable soil, structural response is governed by the interplay between the characteristics of the soil, the structure and the input motion[1]. Therefore, soil-structure interaction problems require combined soil and structure models. While structure models are very well established in the literature, soil models involve complicated analysis due to their unbounded nature. The standard way of analyzing problems of this type is to truncate the unbounded medium in order to render the computational domain finite and apply absorbing boundary conditions at the computational boundary.

When the artificial boundary is imposed, the finite computational region can be analyzed by domain discretization technique. Finite element method is a popular domain discretization technique as it can accommodate easily for heterogeneity in the soil or structure medium and for nonlinearity in the materials, as well as in the geometry. Finite element transient algorithms could be classified into two distinct categories: implicit algorithms, in which a matrix system is solved, one or more times per step, to advance the solution; and explicit algorithms, in which the solution may be advanced without storing a matrix, or solving a system of equations. Implicit algorithms generally have the advantage with respect to numerical stability. In fact, in many cases, “unconditioned stability” may be attained (i.e. no time step restriction engendered by stability considerations). Explicit algorithms, on the other hand, generally require that small time steps be taken to insure numerical stability. Often the step-size restriction is more stringent than accuracy considerations require. However, the computational cost per step is generally much less for explicit algorithms than for implicit algorithms due to the avoidance of equation solving[2] .It is by now concluded that neither approach is optimal for all cases. Although the local boundary conditions can reduce the computational cost, the total computational cost for the analysis of large-scale soil-structure system is still very large using either implicit or explicit algorithms only, which prevents the present methods to analyze the practical 3D large-scale soil-structure interaction. Thus, we require that the dynamic interaction analysis be performed not only accurately but also efficiently. In dynamic soil-structure interaction analysis, it is effective to treat the soil and the structure by explicit and implicit algorithms respectively, which is due to the following two considerations: (1) Structure is relatively stiff, and therefore impose stringent time step restrictions if dealt with explicitly. So, it is sensible to analyze the structure by implicit procedures. (2) Degree-of -freedom of the soil is large in direct method for soil-structure interaction analysis, and the soil is always not very stiff, therefore it is efficient to analyze the soil using explicit algorithm.

Most of the presently available methods to evaluate the soil-structure interaction effects are based on the assumption that the seismic excitation can be represented by plane vertically incident compressional or shear waves. The experimental evidence as well as theoretical analyses indicate that nonvertically incident seismic waves may have important effects on the response of structures. Trifunac [3] and Wong[4]have studied the two-dimensional response of a shear wall excited by nonvertically incident antiplane SH waves and found that the angle of incident has a marked effect on the structural response if the vertical cross section of the embedded foundation is not semi-circular. For three-dimensional structures, Iguchi [5]studied the response of one-story structure to nonvertically incident SH excitation including the effects of soil-structure interaction. The response of nuclear power plant structures to obliquely incident SH waves including the effects of soil-structure interaction has been studied by Lee and Welsey[6] by using an approximate expression for the torsional input. Kobori and Shinozaki[7] have analyzed the torsional response of a one-story structure to obliquely incident SH waves. Luco [8]studied the torsional response of continuous elastic and symmetrical structures supported on a flat circular foundation and an embedded hemispherical foundation[9] when excited by obliquely incident SH waves. Luco[10] has studied the earthquake response of three-dimensional structures to nonvertically incident waves including the effects of soil-structure interaction.

Studies of the response of three-dimensional real structures subjected to obliquely incident waves have been limited by the low efficiency of the method. In this paper attempts are made to develop an efficient direct method for analyzing three-dimensional soil-structure interaction subjected to obliquely incident waves. The soil is analyzed by explicit algorithm, and the structure is analyzed by implicit algorithm. The unbounded nature of the soil is simulated by the transmitting boundary condition proposed by Liao and his co-works[11,12]. This boundary condition is local and easy to implement. To account for general, three-dimensional soil-structure interaction, the developed soil algorithm is coupled with the Finite Element Code ANSYS. The displacements and stresses at any point in soil-foundation-structure system can be calculated simultaneously. In section 2 the equations for calculating the responses of the overall soil-structure system are given, and the procedure for analysis of soil- structure interaction is presented in detail. In section 3 we present three examples to validate the feasibility and effectiveness of the proposed method. Conclusions and suggestions for further research are presented in section 4.

2. System model and equations of motion

The soil-structure system consists of soil subsystem, rigid foundation and structure subsystem in this study. The soil subsystem and the structure subsystem are connected by the rigid foundation. The transmitting boundary conditions is used along the five boundary sections for three-dimensional case (four side sections and one bottom section) in order to model the far field conditions and allow for outgoing wave propagation.

2.1 Soil subsystem

The soil is modeled using eight-node hexahedral elements. Each node has three translational degrees of freedom along x,y and z coordinates. Having discretized the region bounded by the artificial boundary using FEM, the discrete nodes of soil subsystem are divided into three groups: the boundary nodes which are on the artificial boundary, the nodes which are connected with the rigid foundation, and the interior nodes which include all the others. The motions of the interior nodes and the boundary nodes are addressed in this section, and those of the nodes connecting with the foundation will be discussed in the later section.

2.1.1 Motions of the interior nodes

The governing equations of the interior nodes may be set up using the standard finite element technique. What should be noted is that the lumped-mass formulation is suggested for the spatial discretization in this study. This is because the lumped-mass formulation combined with explicit time integration scheme is efficient for large-scale computations. The governing equations of the interior nodes are written in the following form:

$$\mathbf{M}_I \ddot{\mathbf{u}}_I + \sum_L^N \mathbf{C}_{IL} \dot{\mathbf{u}}_L + \sum_L^N \mathbf{K}_{IL} \mathbf{u}_L = \mathbf{F}_I \tag{1}$$

where, $\mathbf{M}_I$ is a 3×3 diagonal mass matrix of node I for the lumped-mass formulation, N is the number of nodes surrounding node I (including node I), $\ddot{\mathbf{u}}_I, \dot{\mathbf{u}}_I, \mathbf{u}_I$ are 3×1 vectors of acceleration, velocity and displacement of the node I . $\mathbf{C}_{IL}$ and $\mathbf{K}_{IL}$ are 3×3 matrices of damping and stiffness between node I and node L. The material damping $\mathbf{C}_{IL}$ is assumed to be a linear combination of the mass and the stiffness matrix. $\mathbf{F}_I$ is 3×1 vector of external force exerted on node I . The diagonal mass matrix of node I can be expressed as

$$\mathbf{M}_I = \begin{bmatrix} M_I & 0 & 0 \\ 0 & M_I & 0 \\ 0 & 0 & M_I \end{bmatrix} \tag{2}$$

Where, M_I is the lumped mass of node I .

The acceleration and velocity at time $p\Delta t$ can be expressed in terms of the displacements at time $(p-1)\Delta t$, $p\Delta t$ and $(p+1)\Delta t$ by the following difference method

$$\ddot{\mathbf{u}}^p = \frac{\mathbf{u}^{p+1} - 2\mathbf{u}^p + \mathbf{u}^{p-1}}{\Delta t^2} \tag{3}$$

$$\dot{\mathbf{u}}^p = \frac{\mathbf{u}^p - \mathbf{u}^{p-1}}{\Delta t} \tag{4}$$

where , $\ddot{\mathbf{u}}^p$, $\dot{\mathbf{u}}^p$ and $\mathbf{u}^p$ are the vectors of acceleration, velocity and displacement at time $p\Delta t$ respectively, Δt is time step.

Using the above difference approximation, the equations of interior nodes at time $(p+1)\Delta t$ can be written as

$$\mathbf{u}_I^{p+1} = 2\mathbf{u}_I^p - \mathbf{u}_I^{p-1} - \frac{\Delta t^2}{M_I}\left[\frac{1}{\Delta t}\sum_L^N \mathbf{C}_{IL}(\mathbf{u}_L^p - \mathbf{u}_L^{p-1}) + \sum_L^N \mathbf{K}_{IL}\mathbf{u}_L^p - \mathbf{F}_I^p\right] \tag{5}$$

where, $\ddot{\mathbf{u}}_I^p$ 、 $\dot{\mathbf{u}}_I^p$ and $\mathbf{u}_I^p$ are the vectors of acceleration, velocity and displacement of node I at time $p\Delta t$ respectively. $\mathbf{F}_I^p$ is the vector of external force exerted on node I at time $p\Delta t$. The character of Eq. (5) is local in space and time, which is the local feature of wave motion. In other words, the motions of a specific spatial point at the next moment are determined completely by the motions of its neighboring points at the present and past times within a short time window. In addition, the assembly of mass and stiffness matrices is not really needed. So, the computational and storage requirements can be reduced greatly.

2.1.2 Motions of the boundary nodes (artificial boundary conditions)

We assume that the soil in boundary regions is linear. Thus, the governing equations of the boundary nodes can be written as Multi-Transmitting Formula (MTF) (Liao, 1996)

$$u^s((p+1)\Delta t, 0) = \sum_{j=1}^N (-1)^{j+1} C_j^N u^s((p+1-j)\Delta t, -jc_a\Delta t) \tag{6}$$

where $u^s(t,x)$ is displacement of outgoing wave (or scatter wave), which is a function of time $t = p\Delta t$ and $x = -jc_a\Delta t$, Δt is the time step, p is an integer. The coordinates $x = -jc_a\Delta t$ indicate the sampling points on the x-axis, which is perpendicular to the artificial boundary at a boundary point 0 under consideration. C_j^N are the binomial coefficients, c_a is the artificial speed, N is the approximation order of MTF.

For the source problem in which the external loads are exerted on the structure or soil interior nodes, the total displacements are equal to displacements of outgoing waves and can be calculated through Eq.(6) directly. For the scattering problem in which the input wave impinges on the artificial boundary, the wave field decomposition is needed to obtain the total displacements through Eq. (6). In this study, the total displacement is decomposed into the free field displacement and the scattering displacement in the side boundary region, that means

$$\mathbf{u} = \mathbf{u}^s + \mathbf{u}^f \tag{7}$$

Where, $\mathbf{u}^f$ is the free field displacement and can be calculated by Thomson-Haskell propagator matrix method [13, 14]. $\mathbf{u}^s$ is the scattering displacement. The scattering displacement $\mathbf{u}^s$ of the boundary node at time level p+1 can be calculated through MTF Eq. (6). Thus, the total displacements of the boundary nodes at the time level p+1 can be obtained by Eq. (7).

2.2 Structure subsystem

The governing equations of motion of a multi-degree of freedom system as derived in a semi-discrete FEM approach is expressed in matrix form as

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F} \tag{8}$$

where, $\mathbf{M}$, $\mathbf{C}$,and $\mathbf{K}$ being the mass, damping and stiffness matrices of the structure, respectively. Vector **u** represents the displacement field at nodal points of the system, **F** represents the external excitation vector and dots indicate derivatives with respect to time. The Rayleigh-type damping is adopted and may be written as follows:

$$\mathbf{C} = a\mathbf{M} + b\mathbf{K} \tag{9}$$

a and b are the coefficients related to the properties of the structure and can be determined by the following equations.

$$a = \frac{2\xi\omega_i\omega_j}{\omega_i + \omega_j} \tag{10}$$

$$b = \frac{2\xi}{\omega_i + \omega_j} \tag{11}$$

where ξ is a specified damping ratio; ω_i is the first natural frequency; ω_j is the highest frequency that contributes significantly to the response.

Applying Newmark's integration scheme, the governing equation of motion can be cast in a form of algebraic equation system:

$$(b_1\mathbf{M} + b_4\mathbf{C} + \mathbf{K})\mathbf{u}^{p+1} = \mathbf{F}^{p+1} + \mathbf{M}(b_1\mathbf{u}^p - b_2\dot{\mathbf{u}}^p - b_3\ddot{\mathbf{u}}^p) + \mathbf{C}(b_4\mathbf{u}^p - b_5\dot{\mathbf{u}}^p - b_6\ddot{\mathbf{u}}^p) \tag{12}$$

where,

$$b_1 = 1/(\beta\Delta t^2) \quad b_2 = 1/(\beta\Delta t) \quad b_3 = 1 - 1/(2\beta) \tag{13}$$

$$b_4 = \gamma\Delta t b_1 \quad b_5 = 1 + \gamma\Delta t b_2 \quad b_6 = \Delta t(1 + \gamma b_3 - \gamma) \tag{14}$$

β and γ are constants associated with Newmark's method.

2.3 Foundation subsystem

The foundation connects the soil and structure, and transfer the interaction force between soil and structure. It is assumed that the foundation is rigid and the soil and foundation is perfectly bonded. The motion of the rigid foundation is described by six degrees of freedom: three translations (u_x, u_y, u_z) and three rotations ($\theta_x, \theta_y, \theta_z$).

2.3.1 Forces exerted on foundation from soil

Assuming node k is a soil element node on soil-foundation interface, the force exerted on the foundation by the soil at node k can be expressed as

$$\mathbf{F}_k = \left\{F_{kx}, F_{ky}, F_{kz}, M_{kx}, M_{ky}, M_{kz}\right\}^T \tag{15}$$

where, F_{kx}, F_{ky} and F_{kz} are the forces at node k along x,y and z direction respectively. M_{kx}, M_{ky} and M_{kz} are the torques about x,y and z axis respectively, and here, $M_{kx} = M_{ky} = M_{kz} = 0$. $\mathbf{F}_k$ is equal to the force exerted on node k by the soil nodes surrounding it. Thus, according to finite element procedure, the force $\mathbf{F}_k$ at time $p\Delta t$ can be expressed as

$$\mathbf{F}_k^p = \begin{Bmatrix} F_{kx}^p \\ F_{ky}^p \\ F_{kz}^p \end{Bmatrix} = \frac{1}{\Delta t}\sum_L^N \mathbf{C}_{kL}(\mathbf{u}_L^p - \mathbf{u}_L^{p-1}) + \sum_L^N \mathbf{K}_{kL}\mathbf{u}_L^p \tag{16}$$

where, F_{kx}^p, F_{ky}^p and F_{kz}^p are the force at node k exerted by soil at time $p\Delta t$; N is the number of nodes surrounding node k (including node k).

The total force exerted on foundation by soil at time $p\Delta t$ can be written as

$$\mathbf{F}_D^p = \sum_{k=1}^m \mathbf{A}_k^T \mathbf{F}_k^p \tag{17}$$

$$\mathbf{F}_D^p = \left\{F_{Dx}^p, F_{Dy}^p, F_{Dz}^p, M_{Dx}^p, M_{Dy}^p, M_{Dz}^p\right\} \tag{18}$$

$$\mathbf{A}_k = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta z_k & -\Delta y_k \\ 0 & 1 & 0 & -\Delta z_k & 0 & \Delta x_k \\ 0 & 0 & 1 & \Delta y_k & -\Delta x_k & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{19}$$

where， m is the number of soil nodes connecting with the foundation. F_{Dx}^p， F_{Dy}^p and F_{Dz}^p are forces acted on foundation through soil at time $p\Delta t$ along x,y and z direction respectively. M_{Dx}^p， M_{Dy}^p and M_{Dz}^p are torques exerted on foundation by soil at time $p\Delta t$ about x,y and z axis respectively. $\mathbf{A}_k$ is a transformation matrix, and Δx_k， Δy_k and Δz_k are the coordinates of node k with respect to center of mass of the foundation.

2.3.2 Forces exerted on foundation from structure

Assuming that node i is a structure point connecting with foundation, similarly, we can obtain the force extered on foundation by structure at node i at time $p\Delta t$

$$\mathbf{F}_i^p = \left\{F_{ix}^p, F_{iy}^p, F_{iz}^p, M_{ix}^p, M_{iy}^p, M_{iz}^p\right\}^T \tag{20}$$

where， F_{ix}^p， F_{iy}^p and F_{iz}^p are the forces on node i along x,y and z direction respectively. M_{ix}^p， M_{iy}^p and M_{iz}^p are the torques about x,y and z axis respectively. Thus, the total force acting on the foundation through structure can be written as

$$\mathbf{F}_S^p = \sum_{i=1}^n \mathbf{A}_i^T \mathbf{F}_i^p \tag{21}$$

$$\mathbf{F}_S^p = \left\{F_{Sx}^p, F_{Sy}^p, F_{Sz}^p, M_{Sx}^p, M_{Sy}^p, M_{Sz}^p\right\} \tag{22}$$

$$\mathbf{A}_i = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta z_i & -\Delta y_i \\ 0 & 1 & 0 & -\Delta z_i & 0 & \Delta x_i \\ 0 & 0 & 1 & \Delta y_i & -\Delta x_i & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{23}$$

where， n is number of structure element nodes connecting with foundation, $\mathbf{A}_i$ is a transformation matrix, and Δx_i， Δy_i and Δz_i are the coordinates of node i with respect to center of mass of the foundation.

2.3.3 Motions of the foundation

The total force exerted on foundation can be obtained from Eq. (17) and Eq. (21), that is

$$\mathbf{F}^p = \mathbf{F}_D^p + \mathbf{F}_S^p = \sum_{k=1}^{m} \mathbf{A}_k^T \mathbf{F}_k^p + \sum_{i=1}^{n} \mathbf{A}_i^T \mathbf{F}_i^p \tag{24}$$

The equilibrium equation of the foundation can be written as

$$\mathbf{M}_F \ddot{\mathbf{u}}_F^p = \mathbf{F}^p \tag{25}$$

$$\ddot{\mathbf{u}}_F^p = \left\{ \ddot{u}_{Fx}^p, \ddot{u}_{Fy}^p, \ddot{u}_{Fz}^p, \ddot{\theta}_{Fx}^p, \ddot{\theta}_{Fy}^p, \ddot{\theta}_{Fz}^p \right\}^T \tag{26}$$

$$\mathbf{M}_F = \begin{bmatrix} M_{Fx} & 0 & 0 & 0 & 0 & 0 \\ 0 & M_{Fy} & 0 & 0 & 0 & 0 \\ 0 & 0 & M_{Fz} & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{Fx} & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{Fy} & 0 \\ 0 & 0 & 0 & 0 & 0 & I_{Fz} \end{bmatrix} \tag{27}$$

where， $\ddot{\mathbf{u}}_F^p$ is the acceleration vector of the foundation at time $p\Delta t$. $\mathbf{M}_F$ is the inertial matrix of the foundation, M_{Fx} (M_{Fy} , M_{Fz}) is the mass of the foundation, I_{Fx} ， I_{Fy} and I_{Fz} are moments of inertial of foundation about x, y and z axis respectively.

Applying the central difference time integration (Eq. (3)) to Eq. (25), the motions of foundation at time $(p+1)\Delta t$ can be written as

$$\mathbf{u}_F^{p+1} = 2\mathbf{u}_F^p - \mathbf{u}_F^{p-1} + \Delta t^2 \mathbf{M}_F^{-1} \mathbf{F}^p \tag{28}$$

On the assumption that the connection between structure (soil) and foundation is bonded perfectly, the motions of node connecting structure (soil) with foundation can be decided by foundation motion, that is

$$\mathbf{u}_i^{p+1} = \mathbf{A}_i \mathbf{u}_F^{p+1} \tag{29}$$

For soil node, Eq. (29) can be written in details as

$$\mathbf{u}_k^{p+1} = \begin{Bmatrix} u_{kx}^{p+1} \\ u_{ky}^{p+1} \\ u_{kz}^{p+1} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta z_k & -\Delta y_k \\ 0 & 1 & 0 & -\Delta z_k & 0 & \Delta x_k \\ 0 & 0 & 1 & \Delta y_k & -\Delta x_k & 0 \end{bmatrix} \begin{Bmatrix} u_{Fx}^{p+1} \\ u_{Fy}^{p+1} \\ u_{Fz}^{p+1} \\ \theta_{Fx}^{p+1} \\ \theta_{Fy}^{p+1} \\ \theta_{Fz}^{p+1} \end{Bmatrix} \quad (30)$$

For structure node, Eq. (29) can be written in details as

$$\mathbf{u}_i^{p+1} = \begin{Bmatrix} u_{ix}^{p+1} \\ u_{iy}^{p+1} \\ u_{iz}^{p+1} \\ \theta_{ix}^{p+1} \\ \theta_{ix}^{p+1} \\ \theta_{ix}^{p+1} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta z_i & -\Delta y_i \\ 0 & 1 & 0 & -\Delta z_i & 0 & \Delta x_i \\ 0 & 0 & 1 & \Delta y_i & -\Delta x_i & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} u_{Fx}^{p+1} \\ u_{Fy}^{p+1} \\ u_{Fz}^{p+1} \\ \theta_{Fx}^{p+1} \\ \theta_{Fy}^{p+1} \\ \theta_{Fz}^{p+1} \end{Bmatrix} \quad (31)$$

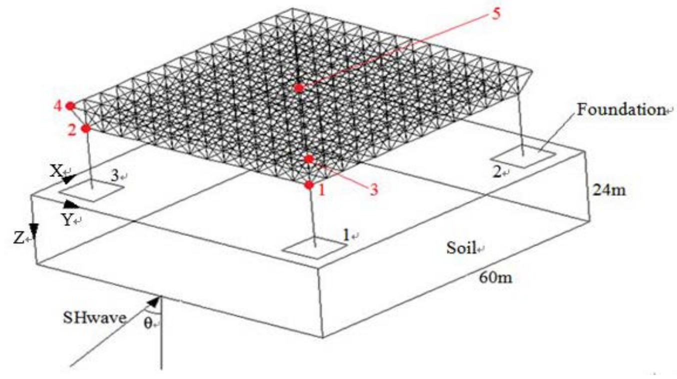
3. Numerical examples

A comprehensive FORTRAN program has been developed to implement the proposed three-dimensional analysis of soil-foundation-structure interaction under earthquake. The program consists of more than 30 fundamental subroutines which can be grouped as several major functional modules such as data acquisition, structure subsystem module, soil subsystem module, foundation subsystem module, transmitting boundary module, free field module, etc. These modules can be modified or changed as desired. Therefore, it is possible to update the program with progression of the research.

The example is a multi-functional hall, which is a four-point-supported square pyramid space grid structure (shown in Fig.1). The number of lattices is 14×14 (each a $3m$ square) and the height of roof is $3.2m$. The column network dimension is $39m\times39m$ and the height of the steel tube columns ($\phi600\times20$) is $9m$. The chords and the web members are steel tubes of $\phi168\times6$ and $\phi152\times5$ respectively. Four independent reinforced concrete foundations under columns are considered on half-space. The dimension of each independent foundation is $3m\times3m\times0.5m$. Eight-node hexahedral elements are employed to model the soil media. The dimension of the calculated soil is $60m\times60m\times24m$. The dimension of the soil element is $1.5m\times1.5m\times2m$ and the total number of soil elements is 19200. The parameters of soil layer are shown in Table 1. The time steps for soil and structure are $0.0002s$ and $0.002s$ respectively. The default Newmark parameters $\beta=1/4$ and $\gamma=1/2$ are used. The transmitting boundaries are imposed on five soil boundary surfaces (four side boundaries and one bottom boundary). Live loads and dead loads are considered according to Chinese load code for the design of the building structures. The input seismic displacement is shown in Fig.2.

Table 1 – Material properties of soil layers

Number of soil layer	Shear wave speed(m/s)	Mass density (10^3kg/m^3)	Poisson ratio	Damping ratio	Thickness (m)
1	165	1.83	0.40	0.07	2
2	184	1.92	0.45	0.07	4
3	232	2.06	0.45	0.07	6
4	324	2.24	0.47	0.07	12



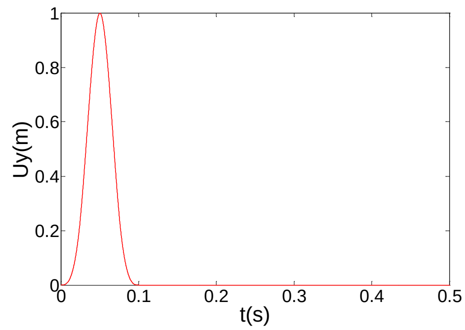


Fig. 1 – Description of the model

Fig. 2 – Input displacement in x direction

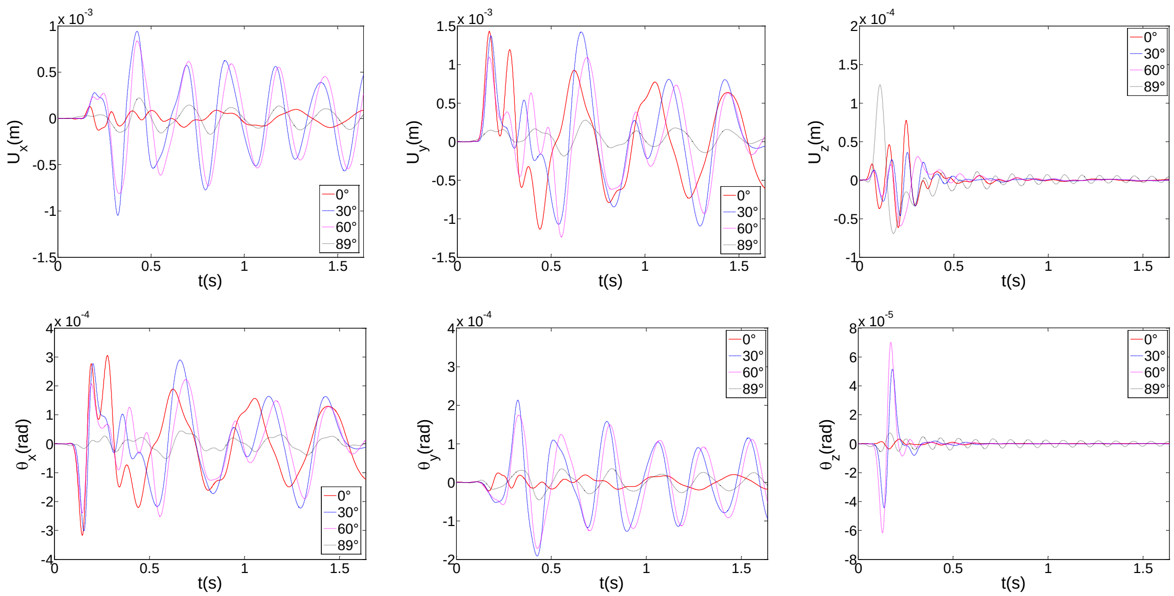


Fig. 3 – Response of the point 1 on structure for different incident angle

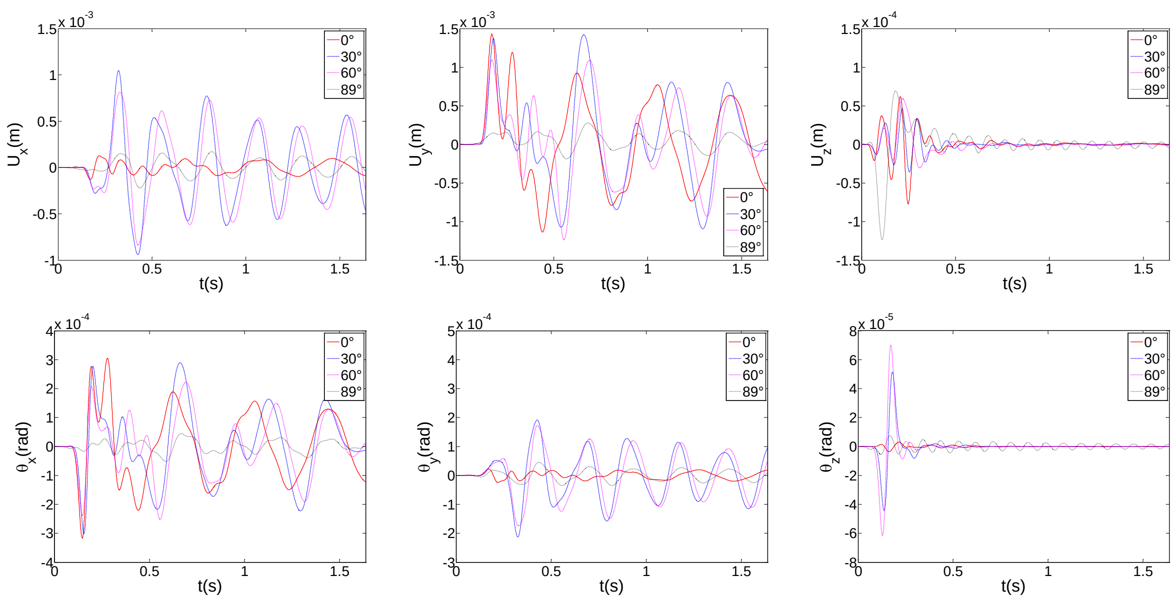


Fig. 4 – Response of the point 2 on structure for different incident angle

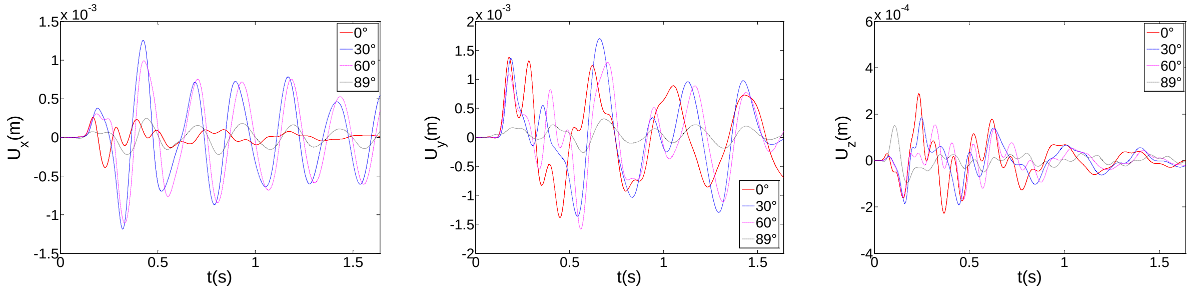


Fig. 5 – Response of the point 3 on structure for different incident angle

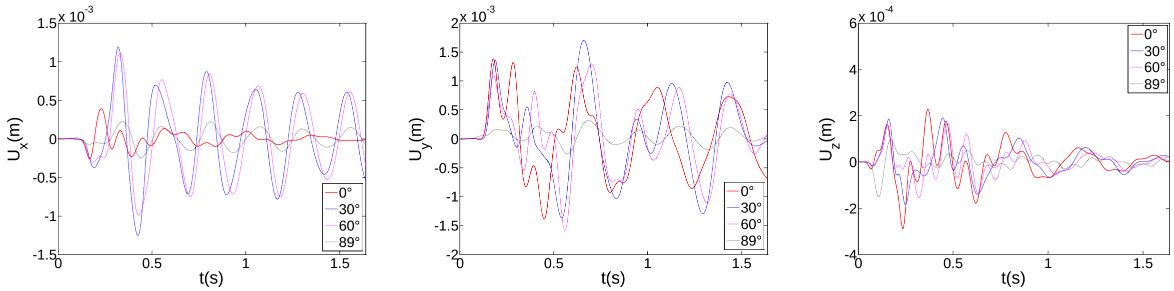


Fig. 6 – Response of the point 4 on structure for different incident angle

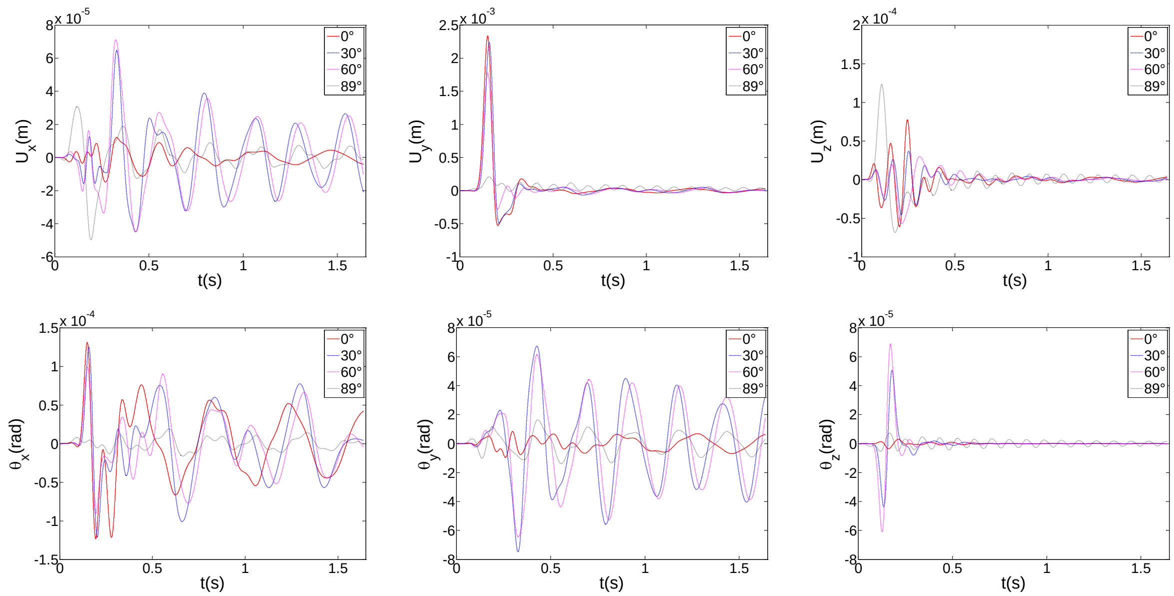
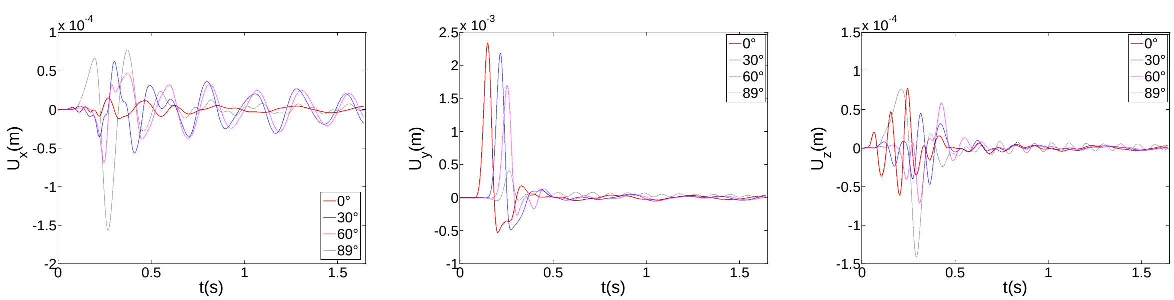


Fig. 7 – Response of the foundation 1 for different incident angle



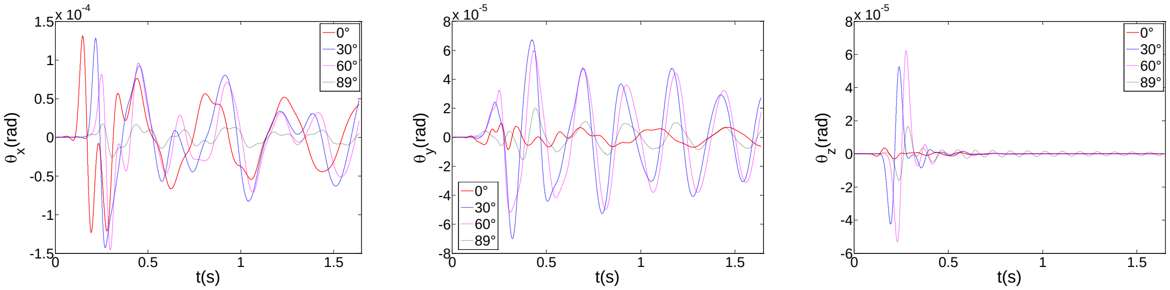


Fig. 8 – Response of the foundation 2 for different incident angle

The response of the selected points on grid structure (shown in Fig.1) and foundations are given in Fig.3 through Fig.8. As expected, the response along x axis, the rocking around y-axis and rotation for obliquely incident SH wave are significantly higher than the corresponding response for vertically incident case (Fig.3 and Fig.4). The response of the foundation 1 and foundation 2 have different phase for nonvertically incident SH wave, but the same phase for vertically incident case (Fig.7 and Fig.8). The results obtained indicate the possible importance of the effects introduced by nonvertically incident SH wave.

4. Conclusions

In this paper we have described a method for analyzing three-dimensional dynamic soil-structure interaction for incident plane wave. The proposed method may be used as an auxiliary approach for the seismic capacity evaluation of interactive soil-foundation-structure systems. The algorithm developed is found to be quite efficient and economical. The characteristics of this method are:

（1）The seismic responses of the structure, foundation and soil can be analyzed at the same level of detail, so that the results of the analysis will be meaningful for both structure and foundation designs.

（2）It is an implicit-explicit method, in which the soil is analyzed by explicit procedure avoiding equation solving, and the structure is analyzed by implicit procedure. The time step of explicit and implicit can be different. This technique can result in substantial cost reduction.

（3）The influence of the unbounded soil is considered by imposing local transmitting boundary.

The results obtained in this paper indicate the response of structure and foundation are greatly different between vertically incident SH wave and nonvertically incident case.

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6. References

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