Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 1168-1183

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

TIME-DOMAIN SOIL-STRUCTURE INTERACTION ANALYSIS OF NUCLEAR FACILITIES

S. L. Chen and J.Q. Wang

Department of Civil Engineering, Nanjing University of Aeronautics and Astronautics,
Nanjing, 210016, China; email: iemcsl@nuaa.edu.cn

Keywords: Soil-Structure Interaction, Nuclear Plant, Absorbing Boundary, Parallel Finite Element Method.

Abstract. *A computationally efficient explicit-implicit FEM in parallel manner to analyze the response of three-dimensional soil-structure system subjected to inclined plane wave is presented. The unbounded soil is modelled by lumped-mass explicit parallel finite element method and absorbing boundary condition, the structure is analysed through implicit finite element method, and response of the rigid foundation is calculated through explicit time integration scheme. The different time steps can be chosen for the explicit and implicit integration scheme, which can greatly improve the efficiency. The codes for this method are programmed. The method is applied to a detailed nuclear plant model.*

doi: 10.7712/120117.5483.17011

1 INTRODUCTION

When a structure is subjected to an earthquake, the dynamic interaction between soil, foundation, and structure influences the structure's response. The soil-structure interaction (SSI) is more pronounced in stiff and massive structures, such as nuclear power facilities, than lighter and more flexible ones. In the nuclear industry, the SSI analysis of safety-related structures has been typically conducted using the frequency domain analysis method[1] in which the nonlinear behavior of the soil–structure system is considered by assuming equivalent shear moduli and damping ratios. The frequency domain analysis method is computationally efficient and requires only a few parameters to model the dynamic soil properties. However, the frequency domain analysis method may provide misleading results for high intensity seismic input, such as an earthquake that is beyond the design level. The assumption of equivalent linear behavior does not explicitly consider the nonlinear behavior of soil–structure systems such as the hysteretic behavior of soil. In the time domain analysis method[2-6], the dynamic analysis is carried out by solving the equation of motion at each time step using a direct numerical integration scheme. In this approach, a large soil domain and a structural system is modeled as a single numerical model such that the inertial and kinematic interactions are inherently considered in the analysis. In addition, because this method satisfies equilibrium at each time step, it is possible to model the inelastic hysteretic behavior of materials or structural elements. 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[7], 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.

In this paper attempts are made to develop an efficient direct method for analyzing three-dimensional soil-structure interaction subjected to incident waves. The soil is analyzed by explicit parallel algorithm with communication between different processes through message passing interface (MPI) protocol, 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[8]. 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 an nuclear power structure for example 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), $\ddot{\mathrm{u}}_I, \dot{\mathrm{u}}_I, \mathrm{u}_I$ 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 3×1vector 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, $\mathbf{M}_I$ 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) [8]

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

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. The most practical form of the local ABC is the second-order MTF, which is written as

$$u^s((p+1)\Delta t, 0) = 2u^s(p\Delta t, -c_a\Delta t) - u^s((p-1)\Delta t, -2c_a\Delta t) \tag{7}$$

Since $u^s(t,x)$ in Eq.(6) are sampled at points $x = -jc_a\Delta t$, which do not generally coincide with the discrete nodes $x = -n\Delta x$, Δx being the space step, in order to implement Eq.(6), an interpolation scheme is required to express $u^s(t, -jc_a\Delta t)$ in terms of $u(t, -n\Delta x)$. The interpolation may be realized in a number of ways. Here, we adopted the following way.

The displacements of scatter wave at the nodal points are denoted by

$$u_n^{sp} = u^s(p\Delta t, -n\Delta x) \tag{8}$$

Suppose that a quadratic interpolation is used, the displacements at the computational points may be written as:

$$u^s(p\Delta t, -jc_a\Delta t) = \sum_{n=0}^{2j} t_{j,n} u_n^{sp} \qquad (j=1,2) \tag{9}$$

$$t_{1,0} = T_1,\ t_{1,1} = T_2,\ t_{1,2} = T_3 \tag{10}$$

$$t_{2,0} = T_1^2,\ t_{2,1} = 2T_1T_2,\ t_{2,2} = 2T_1T_3 + T_2^2,\ t_{2,3} = 2T_2T_3,\ t_{2,4} = T_3^2 \tag{11}$$

$$T_1 = \frac{1}{2}(2-S)(1-S), T_2 = S(2-S), T_3 = \frac{1}{2}S(S-1) \tag{12}$$

where, $S = \dfrac{c_a\Delta t}{\Delta x}$.

Substituting Eq.(9) into Eq.(7), the second-order MTF can be written as

$$u_0^{s(p+1)} = \sum_{n=0}^{2} t_{1,n} u_n^{sp} + \sum_{n=0}^{4} t_{2,n} u_n^{s(p-1)} \tag{13}$$

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.(13) 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.(13). In this study, the total displacement is decomposed into the free field displacement and the scattering displacement in the side boundary region, that means

$$\mathbf{u} = \mathbf{u}^f + \mathbf{u}^s \tag{14}$$

Where, $\mathbf{u}^f$ is the free field displacement and can be calculated by Thomson-Haskell propagator matrix method[9-10]. $\mathbf{u}^s$ 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.(13). Thus, the total displacements of the boundary nodes at the time level p+1 can be obtained by Eq.(14) .

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

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F} \tag{15}$$

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:

$$\mathbf{C} = a\mathbf{M} + b\mathbf{K} \tag{16}$$

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

$$a = \frac{2\xi\omega_i\omega_j}{\omega_i + \omega_j} \tag{17}$$

$$b = \frac{2\xi}{\omega_i + \omega_j} \tag{18}$$

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:

$$(b_1\mathbf{M} + b_4\mathbf{C} + \mathbf{K})\mathbf{u}^{p+1} = \mathbf{F}^{p+1} + \mathbf{M}(b_1\mathbf{u}^p - b_2\dot{\mathbf{u}}^p - b_3\ddot{\mathbf{u}}^p) + \mathbf{C}(b_4\mathbf{u}^p - b_5\dot{\mathbf{u}}^p - b_6\ddot{\mathbf{u}}^p) \tag{19}$$

where,

$$b_1 = 1/(\beta\Delta t^2) \qquad b_2 = 1/(\beta\Delta t) \qquad b_3 = 1 - 1/(2\beta) \tag{20}$$

$$b_4 = \gamma\Delta t b_1 \qquad b_5 = 1 + \gamma\Delta t b_2 \qquad b_6 = \Delta t(1 + \gamma b_3 - \gamma) \tag{21}$$

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

$$\mathbf{F}_k = \left\{F_{kx}, F_{ky}, F_{kz}, M_{kx}, M_{ky}, M_{kz}\right\}^T \tag{22}$$

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

$$\mathbf{F}_k^p = \begin{Bmatrix} F_{kx}^p \\ F_{ky}^p \\ F_{kz}^p \end{Bmatrix} = \frac{1}{\Delta t}\sum_{L}^{N}\mathbf{C}_{kL}(\mathbf{u}_L^p - \mathbf{u}_L^{p-1}) + \sum_{L}^{N}\mathbf{K}_{kL}\mathbf{u}_L^p \tag{23}$$

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 (include node k).

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

$$\mathbf{F}_D^p = \sum_{k=1}^{m}\mathbf{A}_k^T\mathbf{F}_k^p \tag{24}$$

$$\mathbf{F}_D^p = \left\{F_{Dx}^p, F_{Dy}^p, F_{Dz}^p, M_{Dx}^p, M_{Dy}^p, M_{Dz}^p\right\} \tag{25}$$

$$\mathbf{A}_k = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta z_k & -\Delta y_k \\ 0 & 1 & 0 & -\Delta z_k & 0 & \Delta x_k \\ 0 & 0 & 1 & \Delta y_k & -\Delta x_k & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{26}$$

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 exerted on foundation by structure at node i at time $p\Delta t$

$$\mathbf{F}_i^p = \left\{ F_{ix}^p, F_{iy}^p, F_{iz}^p, M_{ix}^p, M_{iy}^p, M_{iz}^p \right\}^T \tag{27}$$

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

$$\mathbf{F}_S^p = \sum_{i=1}^{n} \mathbf{A}_i^T \mathbf{F}_i^p \tag{28}$$

$$\mathbf{F}_S^p = \left\{ F_{Sx}^p, F_{Sy}^p, F_{Sz}^p, M_{Sx}^p, M_{Sy}^p, M_{Sz}^p \right\} \tag{29}$$

$$\mathbf{A}_i = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta z_i & -\Delta y_i \\ 0 & 1 & 0 & -\Delta z_i & 0 & \Delta x_i \\ 0 & 0 & 1 & \Delta y_i & -\Delta x_i & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{30}$$

Where, n is number of structure element nodes connecting with foundation, $\mathbf{A}_i$ is a transformation matrix, and $\Delta x_i, \Delta y_i$ 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.(24) and Eq.(28), that is

$$\mathbf{F}^p = \mathbf{F}_D^p + \mathbf{F}_S^p = \sum_{k=1}^{m} \mathbf{A}_k^T \mathbf{F}_k^p + \sum_{i=1}^{n} \mathbf{A}_i^T \mathbf{F}_i^p \tag{31}$$

The equilibrium equation of the foundation can be written as

$$\mathbf{M}_F \ddot{\mathbf{u}}_F^p = \mathbf{F}^p \tag{32}$$

$$\ddot{\mathbf{u}}_F^p = \left\{ \ddot{u}_{Fx}^p, \ddot{u}_{Fy}^p, \ddot{u}_{Fz}^p, \ddot{\theta}_{Fx}^p, \ddot{\theta}_{Fy}^p, \ddot{\theta}_{Fz}^p \right\}^T \tag{33}$$

$$\mathbf{M}_F = \begin{bmatrix} M_{Fx} & 0 & 0 & 0 & 0 & 0 \\ 0 & M_{Fy} & 0 & 0 & 0 & 0 \\ 0 & 0 & M_{Fz} & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{Fx} & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{Fy} & 0 \\ 0 & 0 & 0 & 0 & 0 & I_{Fz} \end{bmatrix} \tag{34}$$

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.(32), the motions of foundation at time $(p+1)\Delta t$ can be written as

$$\mathbf{u}_F^{p+1} = 2\mathbf{u}_F^p - \mathbf{u}_F^{p-1} + \Delta t^2 \mathbf{M}_F^{-1} \mathbf{F}^p \tag{35}$$

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

$$\mathbf{u}_i^{p+1} = \mathbf{A}_i \mathbf{u}_F^{p+1} \tag{36}$$

For soil node, Eq.(36) can be written in details as

$$\mathbf{u}_k^{p+1} = \begin{Bmatrix} u_{kx}^{p+1} \\ u_{ky}^{p+1} \\ u_{kz}^{p+1} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta z_k & -\Delta y_k \\ 0 & 1 & 0 & -\Delta z_k & 0 & \Delta x_k \\ 0 & 0 & 1 & \Delta y_k & -\Delta x_k & 0 \end{bmatrix} \begin{Bmatrix} u_{Fx}^{p+1} \\ u_{Fy}^{p+1} \\ u_{Fz}^{p+1} \\ \theta_{Fx}^{p+1} \\ \theta_{Fy}^{p+1} \\ \theta_{Fz}^{p+1} \end{Bmatrix} \tag{37}$$

For structure node, Eq.(36) can be written in details as

$$\mathbf{u}_i^{p+1} = \begin{Bmatrix} u_{ix}^{p+1} \\ u_{iy}^{p+1} \\ u_{iz}^{p+1} \\ \theta_{ix}^{p+1} \\ \theta_{ix}^{p+1} \\ \theta_{ix}^{p+1} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta z_i & -\Delta y_i \\ 0 & 1 & 0 & -\Delta z_i & 0 & \Delta x_i \\ 0 & 0 & 1 & \Delta y_i & -\Delta x_i & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} u_{Fx}^{p+1} \\ u_{Fy}^{p+1} \\ u_{Fz}^{p+1} \\ \theta_{Fx}^{p+1} \\ \theta_{Fy}^{p+1} \\ \theta_{Fz}^{p+1} \end{Bmatrix} \tag{38}$$

2.4 Procedures for soil-foundation-structure interaction analysis

Assuming that the responses of the soil-foundation-structure system are known before time $p\Delta t$, the responses at time $(p+1)\Delta t$ can be calculated as follows

（1） The displacements of internal node of soil at time $(p+1)\Delta t$ can be calculated using Eq.(5).

（2） The displacements of artificial boundary node at time $(p+1)\Delta t$ can be obtained by MTF Eq.(13) and Eq.(14).

（3） The displacements of rigid foundation at time $(p+1)\Delta t$ can be computed by Eq.（35）. Thus, the displacements of soil node and structure node connecting with foundation can be obtained by Eq.(37) and Eq.(38) respectively.

（4） Given the displacements of soil node at time $(p+1)\Delta t$, the forces exerted on the foundation by soil at time $(p+1)\Delta t$ can be obtained by Eq.(23) and Eq.(24).

（5） Given the displacement constraints of the structure nodes connecting with foundation at time $(p+1)\Delta t$, the displacements of the structure can be calculated by Eq.(19). Thus, the forces exerted on the foundation by structure at time $(p+1)\Delta t$ can be obtained by Eq.(28). The other variables such as stain and stress can be obtained through FEM procedures.

（6） Repeating the steps above, the response of the soil-foundation-structure system can be obtained at successive time.

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. In this study, the response of structure is calculated through ANSYS software.

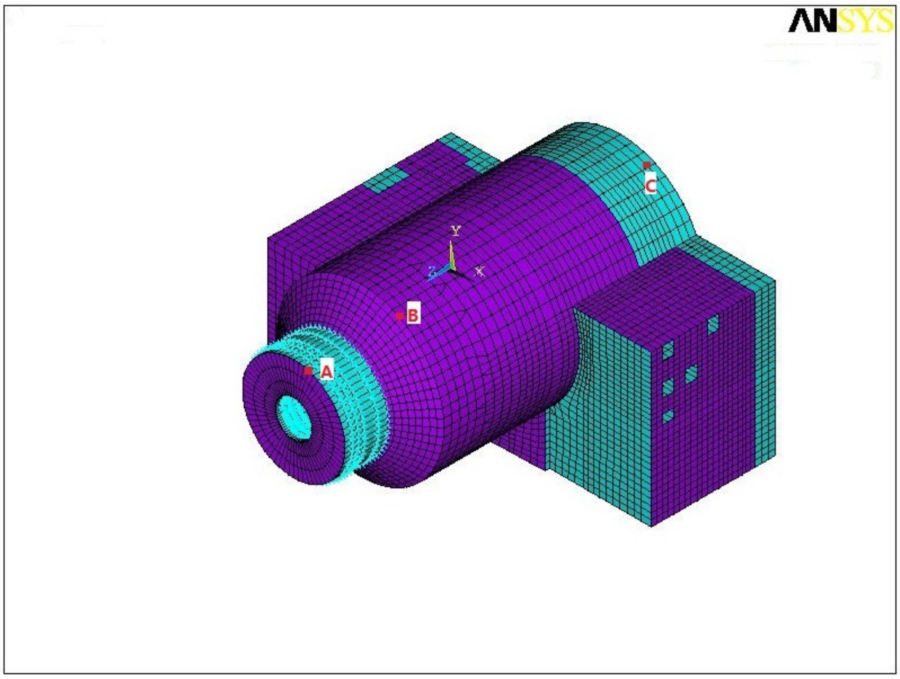


Fig.1 Three-dimensional model of nuclear structure

Number of soil layer	Shear wave speed(m/s)	Mass density (10^3kg/m^3)	Poisson ratio	Damping ratio	Thickness (m)
1	320	1.95	0.488	0.005	20
2	554	1.6	0.420	0.005	20
3	1600	2.8	0.394	0.005	20

Table 1：Material properties of soil layers

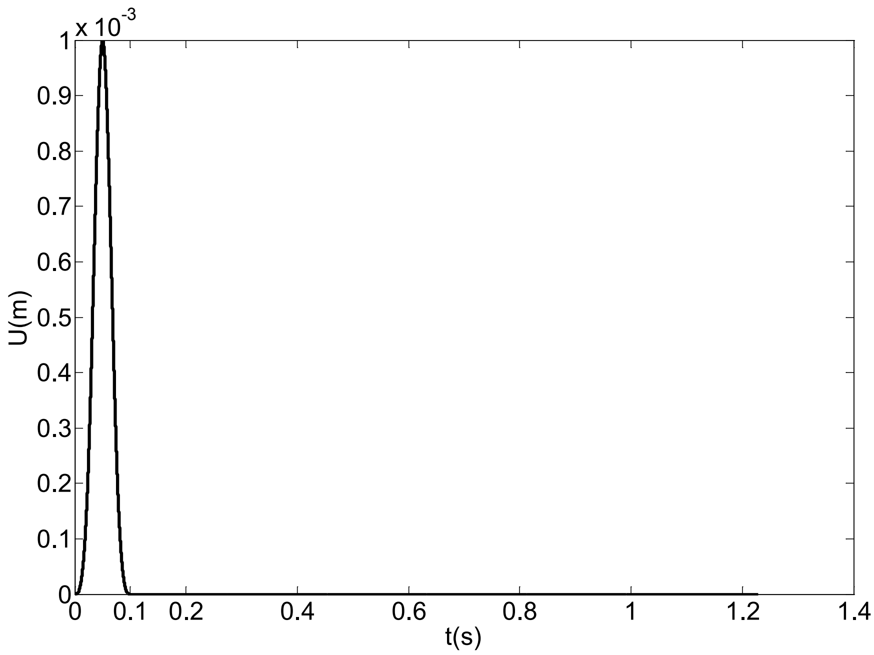


Fig.2 Input displacement in x direction

The nuclear structure model is shown in Fig.1, and the number of elements and associated nodes is 597686 and 700194 respectively. The dimension of the foundation is 92m×60m×16m. The dimension of the calculated soil is 640m×360m×60m. Eight-node hexahedral elements are employed to model the soil media. The dimension of the soil element is 2m×2m×2m, and the total number of soil elements and the associated nodes is 1728000 and 1801131 respectively. The parameters of soil layer are shown in Table 1. The time steps for soil and structure are 0.00005s and 0.00125s respectively. The default Newmark parameters $\beta=1/4$ and $\gamma=1/2$ are selected. The transmitting boundaries are imposed on five soil boundary surfaces (four side boundaries and one bottom boundary). The input seismic displacement is also shown in Fig.2.

Here, only the displacements of some points in soil-structure system are given. Fig.3 through Fig.11 show the displacements of points A , B and C on structure (shown in Fig.1). Fig.12 through Fig.17 show the displacements of points D (110, 32, 0) and E (400, 52, 0) in soil. Fig.18 and Fig.19 show the displacements of foundation. It can be observed that there are free vibrations after the impulse response in Fig.6, Fig.9 and Fig.18. The frequency of these free vibrations is about 2.38Hz, which is less than the corresponding natural frequency of the structure due to the SSI effect. There are also indications of high frequency instability in Fig.10, Fig.11 and Fig.19,which need to be investigated further.

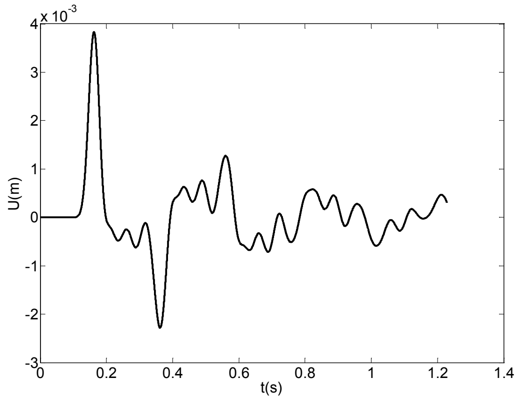


Fig.3 Displacement of point A (as Shown in Fig.1) on structure in x direction.

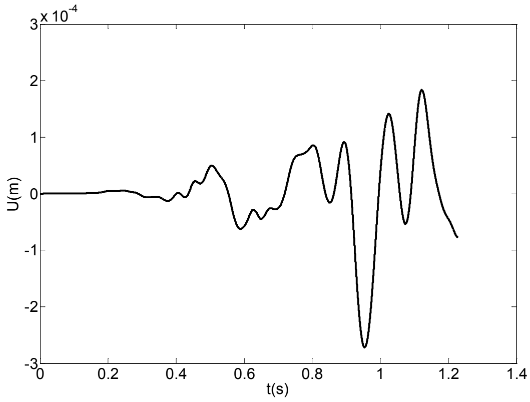
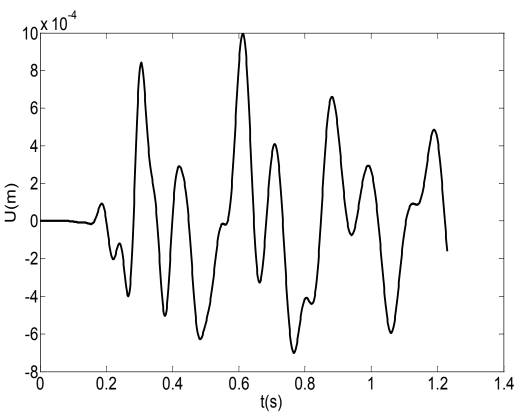


Fig.4 Displacement of point A (as Shown in Fig.1) on structure in y direction.



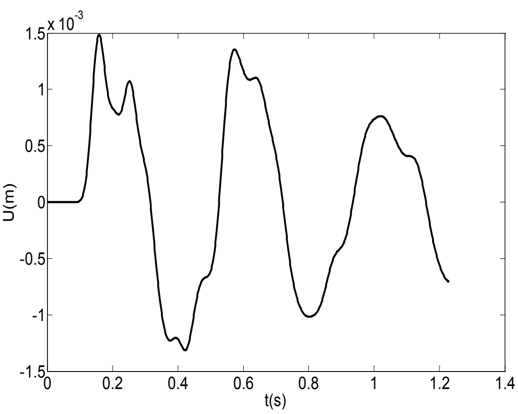


Fig.5 Displacement of point A (as Shown in Fig.1) on structure in z direction.

Fig.6 Displacement of point B (as Shown in Fig.1) on structure in x direction.

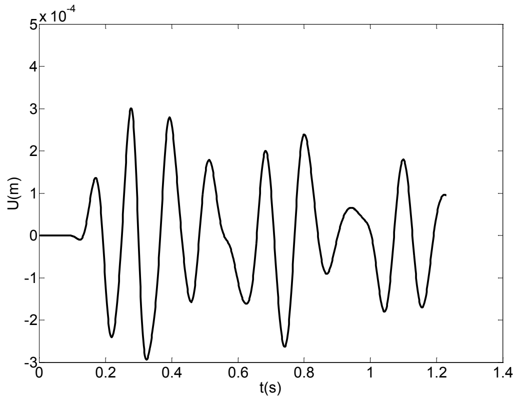


Fig.7 Displacement of point B (as Shown in Fig.1) on structure in y direction.

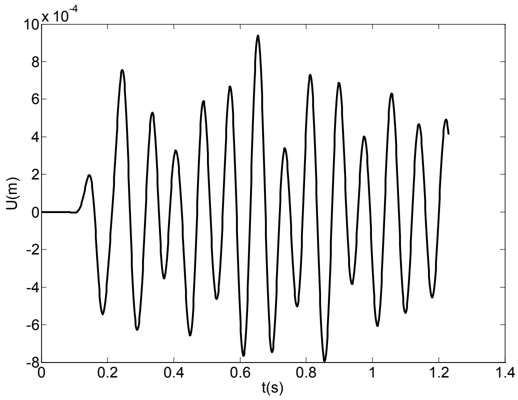


Fig.8 Displacement of point B (as Shown in Fig.1) on structure in z direction.

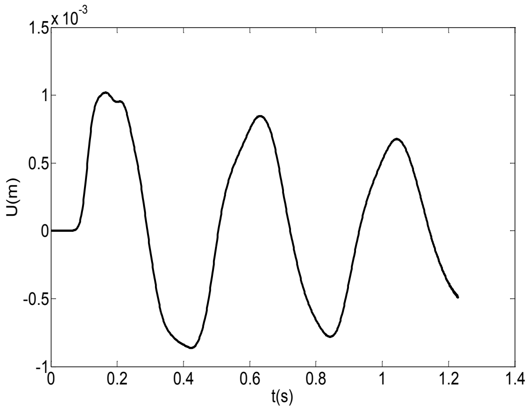


Fig.9 Displacement of point C (as Shown in Fig.1) on structure in x direction.

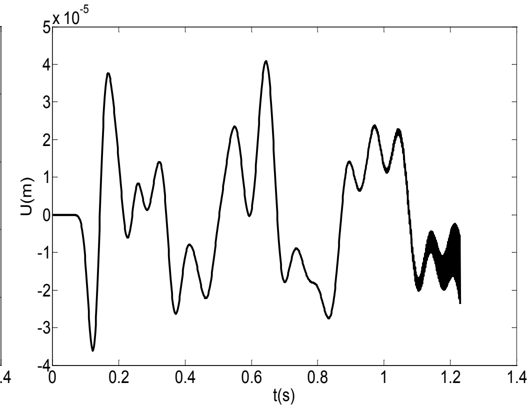


Fig.10 Displacement of point C (as Shown in Fig.1) on structure in y direction.

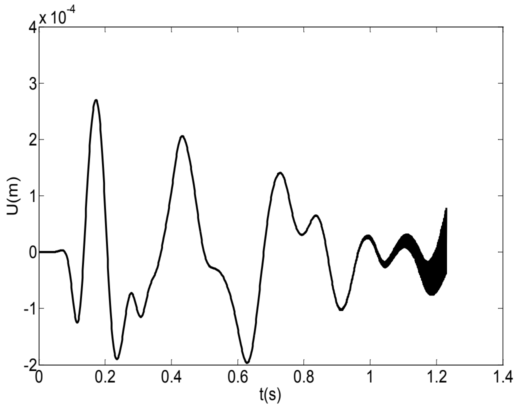


Fig.11 Displacement of point C (as Shown in Fig.1) on structure in z direction.

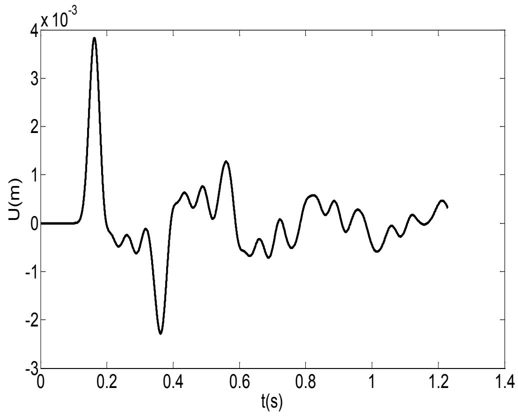


Fig.12 Displacement of point D in soil in x direction.

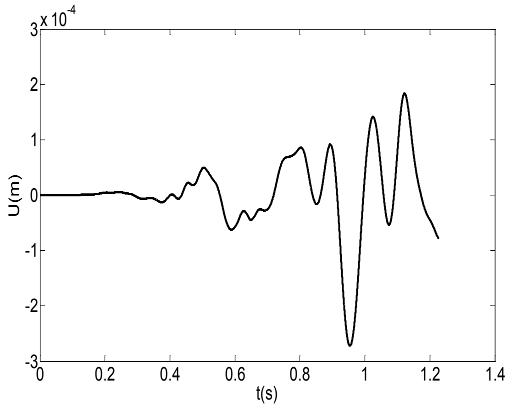


Fig.13 Displacement of point D in soil in y direction.

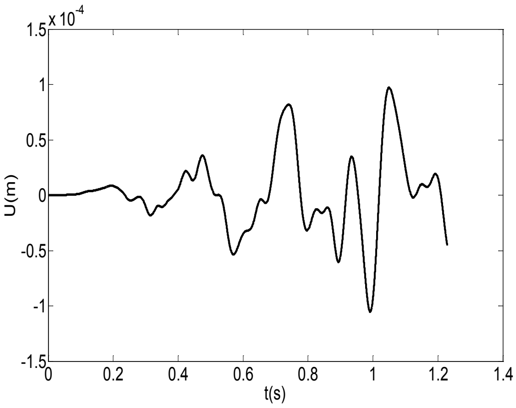


Fig.14 Displacement of point D in soil in z direction.

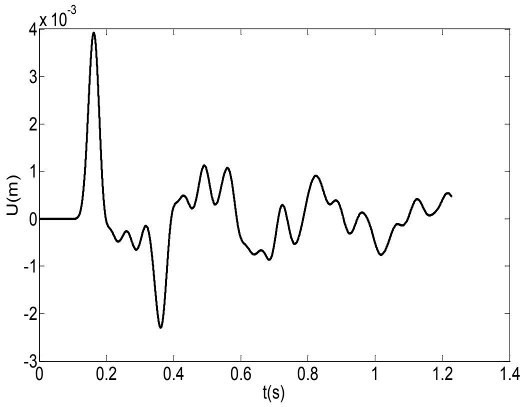


Fig.15 Displacement of point E in soil in x direction.

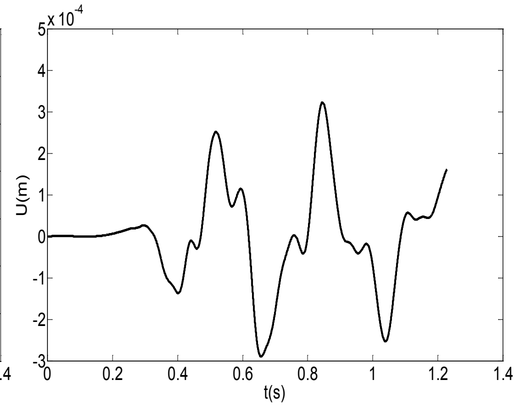


Fig.16 Displacement of point E in soil in y direction.

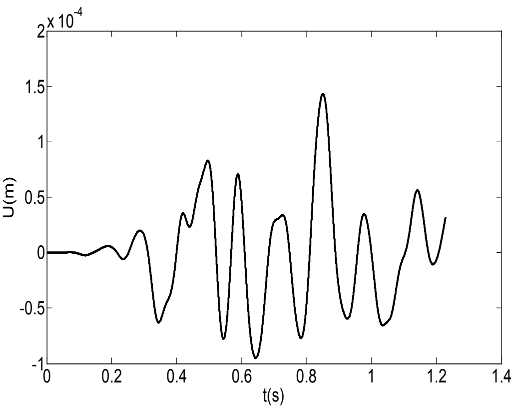


Fig.17 Displacement of point E in soil in z direction.

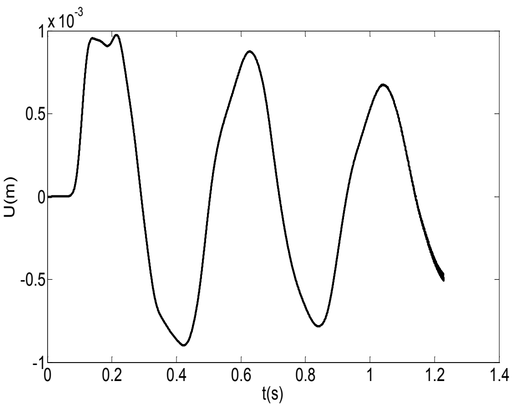


Fig.18 Displacement of foundation in x direction.

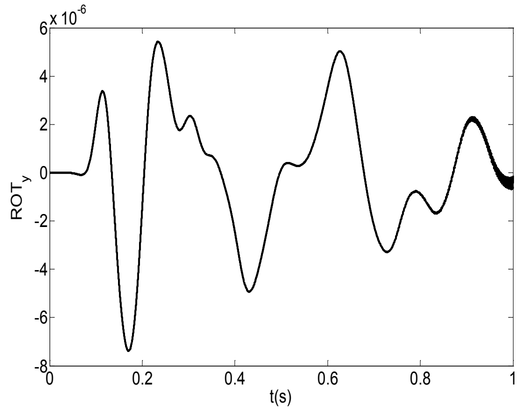


Fig.19 Rotation of foundation in y direction.

4 CONCLUSIONS

In this paper we have described a method for analyzing three-dimensional dynamic soil-structure interaction in time domain. The proposed method may be used as an auxiliary approach for the seismic capacity evaluation of interactive soil-foundation-structure systems. The method developed is applied to a nuclear power plant structure model, and found to be quite efficient and economical. The characteristics of this method are:

(1) 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.
(2) The influence of the unbounded soil is considered by imposing local transmitting boundary.
(3) The seismic inputs can be any combination of three-dimensional motions. Therefore, the ground motion input can be assumed to act along any direction in the considered space.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of this work by the National Natural Science Foundation of China (No.51378260,N0.51178222).

REFERENCES

[1] J.Lysmer, F.Ostadan, , C.Chin. Computer Program: SASSI2000 – A System for Analysis of Soil-structure Interaction. University of California, Berkeley, California, 1999.

[2] X.Zhang, J.L.Wegner, J.B.Haddow. Three dimensional dynamic soil-structure interaction analysis in the time domain, Earthquake Engineering and Structural Dynamics,28,1501-1524, 1999.

[3] D.Pitilakis, M.Dietz, D.M.Wood, D.Clouteau, and A.Modaressi. Numerical simulation of dynamic soil-structure interaction in shaking table testing.Soil Dyn Earthquake Eng，28，453-467,2008.

[4] B.Jeremic, G.Jie, M.Preisig, N.Tafazzoli. Time domain simulation of soil–foundation–structure interaction in non-uniform soils. Earthq. Eng. Struct.Dyn. 38 (5), 699–718,2009.

[5] J.Kabanda, O-S.Kwon, G.Kwon,. Time and frequency domain analyses of the Hualien Large-Scale Seismic Test. Nuclear Engineering and Design 295 , 261–275,2015.

[6] J.L.Coleman, C.Bolisetti, A.S.Whittaker. Time-domain soil-structure interaction analysis of nuclear facilities. Nuclear Engineering and Design 298,264–270, 2016.

[7] T.J.R.Hughes, K.S.Pister, R.L.Taylor.Implicit-explicit finite elements in nonlinear transient analysis.Computer Methods in Applied Mechanics and Engineering,17/18,159-182,1979.

[8] Z.P.Liao, H.L.Wong. A transmitting boundary for the numerical simulation of elastic wave propagation.Soil Dyn.Earthq.Eng.,3,174-183,1984

[9] W.T.Thomson.Transmission of elastic waves through a stratified solid medium. J.Appl.Phys.,21,89-93. 1950.

[10] N.Haskell. The dispersion of surface waves on multilayed media. Bull.Seism.Soc.AM.43,17-34,1953.