Numerical Analysis of Tall Buildings Considering Dynamic Soil-Structure Interaction

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Abstract

Three-dimensional finite element analysis in time domain on dynamic soil-pile-structure interaction of a practical engineering is carried out in this paper. General-purpose finite element program ANSYS is used in the analysis. Commonly used equivalent linearity model is chosen as constitutive relation of soil. Viscous boundary of soil is implemented in ANSYS program. The influences of parameters, such as soil property, excitation, the rigidity of structure and buried depth, on dynamic characteristics, seismic response and interaction effect of SSI system are discussed.

Keywords: soil-structure interaction; numerical analysis; ANSYS program; viscous boundary; parameter analysis

Introduction

Over the last 40 years, the dynamic Soil-Structure Interaction (SSI) has attracted an intensive interest among researchers and engineers in the fields of structural dynamics, wave mechanics and soil dynamics over the world. The methods of their investigations consist of experimental study and analysis research. The analysis methods are generally divided into two kinds, analytical method and numerical simulation methods. Due to the underdevelopment of computer technology, analytical method was popular in the 1970’s. However, the analytical method can only be used to solve simple problems. Along with the rapid progress in the art of computer science, now numerical simulation methods are widely used to the study on SSI. Numerical simulation methods are roughly sorted into three kinds, such as substructure method (Wolf, J.P. 1985), finite element method and hybrid method (Yazdchi M. et al. 1999).

Shaking table model tests on dynamic soil-structure interaction system have been accomplished in Chinese State Key Laboratory for Disaster Reduction in Civil Engineering (Chen et al. 1999) (Lu et al. 2002). Through those tests, abundant experimental data are obtained. Based on shaking table model tests and combining general-purpose finite element program ANSYS, three-dimensional finite element analysis on dynamic soil-structure interaction test has been carried out (Chen et al. 2002) (Lu et al. 2002). Based upon above research findings, three-dimensional finite element analysis on a practical engineering considering SSI is fulfilled in this paper. In the computer simulation of SSI system, the nonlinear behavior of layered soil is simulated with the commonly used equivalent linearity model, and viscous boundary is adopted as boundary of soil. A computational method of investigation on practical engineering considering SSI by general-purpose finite element program ANSYS is proposed in this paper, which is of great advantage to the popularization of SSI study and promote the study outcomes to guide practical engineering.

Brief Description of a Practical Engineering

A cast-in-place frame structure supported on pile-raft foundation is studied in this paper. The layout of column grid is shown in Fig.1. The frame structure has 12 stories aboveground and one story underground. The height of underground floor is 2.8m, while the height of ground floor is 4.5m and the height of other floors is 3.6m. The thickness of cast-in-place floorslab is 120mm, the dimensions of column, boundary beam, walkway beam are 600×600mm, 250×600mm, and 250×400mm, respectively. The raft thickness of pile-raft foundation is 0.8m, the dimension of pile is 450×450mm, and the length of pile is 39m with 0.7m entering the bearing stratum. The layout of pile-raft foundation is shown in Fig.2. The deformed bar of grade II (The yield strength f_y is 340MPa) is adopted as main reinforcement, and the concrete grade is C30 (The compressive strength f_c’ is 1239 Siping Road, Shanghai 200092, P. R. China
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about 21MPa).

The distribution of soil near the First Shimen Road of Shanghai is adopted (DGJ08-11-1999). According to the classification of soil category defined in Shanghai local foundation design code of DGJ08-11-1999, the layers of soil from top to bottom are ①fill, ③very soft gray silty clay, ④very soft gray clay, ⑤gray clay, ⑤-1 gray silty clay, ⑤-2 terreverte clay, ⑦strawyellow-gray silty sand. The shear wave velocity and mass density of soil are shown in Table 1.

### Dynamic Constitutive Model of Soil

In this paper, equivalent linearization model of soil is adopted to simulate the material nonlinearity of soil. Based on the relationships of $G_d - \gamma_d$ and $D - \gamma_d$, a set of $G_d, D$ and $\gamma_d$ harmoniously is obtained by iteration. $G_d - \gamma_d$ denotes the relationship between dynamic shear modulus $G_d$ and dynamic shear strain $\gamma_d$, while $D - \gamma_d$ denotes the relationship between damping ratio $D$ and dynamic shear strain $\gamma_d$.

The soil’s skeleton curve of Davidenkov model is adopted in this paper, and the relationship of $G_d/G_{\text{max}} - \gamma_d$ is shown as Equation 1.

$$\frac{G_d}{G_{\text{max}}} = 1 - H(\gamma_d)$$  \hspace{1cm} [1]

Where

$$H(\gamma_d) = \left[\left(\frac{\gamma_d}{\gamma_r}\right)^{2B} \right]^{A} \left[ 1 + \left(\frac{\gamma_d}{\gamma_r}\right)^{2B} \right]$$  \hspace{1cm} [2]

$$G_{\text{max}} = \rho V_s^2$$  \hspace{1cm} [3]

$$\gamma_r = \gamma_r' (0.01\sigma_o')^{0.3}$$  \hspace{1cm} [4]

$G_{\text{max}}$ is the maximum dynamic shear modulus of soil, $\rho$ is the mass density of soil, and $V_s$ is the shear wave velocity of soil.

$\gamma_r$ is a shear strain for reference. $\sigma_o'$ is the average effective confining pressure of soil, and its unit is kPa.

The values of parameter $A$, $B$ and $\gamma_r'$ are shown in Table 2.

The hysteresis loop of soil $D/D_{\text{max}} - \gamma_d$ is expressed as following empirical formula.

$$\frac{D}{D_{\text{max}}} = (1 - \frac{G_d}{G_{\text{max}}})^\beta$$  \hspace{1cm} [5]

$D_{\text{max}}$ is the maximum damping ratio of soil. $\beta$ is the shape factor of curve $D/D_{\text{max}} - \gamma_d$, and 1.0 is chosen as $\beta$ for soft soil of Shanghai area. The value of $D_{\text{max}}$ is referred to Table 2.

In ANSYS program, there is a kind of parametric design language named APDL, which is a scripting language. Users can use it to automate common tasks or even build models in terms of parameters. The equivalent linearity model is realized in ANSYS program by using the APDL, and the calculation of material nonlinearity is realized automatically.

### Input Excitation

El Centro record and Shanghai artificial wave is adopted as input excitation. Frequency content of these two seismic waves is shown in Fig.3 and Fig.4.

### Viscous Boundary of Soil

The use of finite element method for SSI study dictates that the infinite medium be truncated along certain boundaries (called artificial boundaries) and thus be reduced to a finite region (called near field). In order to have meaningful results, the artificial boundaries, which actually do not exist, should be able to transmit waves from near to far field without reflections, or at least the wave reflections back into near field should be minimized. The artificial boundary conditions may be also interpreted as the constitutive equations for the interaction forces between near and far fields; thus their performance in SSI analysis depends on how correctly the equations describe these forces.

The artificial boundary conditions can be classified as viscous boundary, superposition boundary, paraxial...
boundary, extrapolation boundary and so on (Lysmer et al. 1969) (Lysmer et al. 1972) (White et al. 1977). The viscous boundary is the most commonly used boundary conditions in practice as it has a simple form suitable for finite element formulation and nonlinear analysis. The viscous boundary is adopted in this paper.

(1) Viscous boundary and its implementation by ANSYS program

Viscous boundary is equivalent to setting a series of dampers on artificial boundary to absorb wave energy. The damping coefficients of dampers have no relation to frequency.

The viscous normal stress $\sigma$ and shear stress $\tau$ on boundary are shown as Equation 6.

$$
\begin{align*}
\sigma &= a \cdot \rho \cdot v_p \cdot \dot{w} \\
\tau &= b \cdot \rho \cdot v_y \cdot \dot{u}
\end{align*}
$$

In Equation 6, $\dot{w}$ and $\dot{u}$ are the vertical velocity and tangential velocity of particle motion, respectively. $v_p$ and $v_y$ are the propagation velocity of $P$ wave and $S$ wave, respectively. $\rho$ is the mass density, $a$ and $b$ are undetermined coefficients.

Based on reflection theory and refraction theory of wave, the boundary can absorb reflection energy approximately when $a$ and $b$ are equal to 1.0. Therefore the stress condition of viscous boundary meeting the absorption of reflection energy is as shown in Equation 7.

$$
\begin{align*}
\sigma &= \rho \cdot v_p \cdot \dot{w} \\
\tau &= \rho \cdot v_y \cdot \dot{u}
\end{align*}
$$

When earthquake wave is inputted along X axis, the node forces of the nodes on boundary whose normal direction is X axis are expressed as following:

$$
\begin{align*}
P_x &= \rho \cdot v_p \cdot \dot{U}_x \cdot A = (\rho \cdot v_p \cdot A) \cdot \dot{U}_x \\
P_y &= \rho \cdot v_y \cdot \dot{U}_y \cdot A = (\rho \cdot v_y \cdot A) \cdot \dot{U}_y \\
P_z &= \rho \cdot v_z \cdot \dot{U}_z \cdot A = (\rho \cdot v_z \cdot A) \cdot \dot{U}_z
\end{align*}
$$

In Equation 8, $P_x$, $P_y$ and $P_z$ are the node forces along X axis, Y axis and Z axis, respectively. $\rho$ is the mass density of soil where the node is. $\dot{U}_x$, $\dot{U}_y$ and $\dot{U}_z$ are node velocities along X axis, Y axis and Z axis, respectively. $A$ is area that the node governs.

In this paper, viscous boundary is implemented by spring-damper element in ANSYS program.

(2) Comparison between the results of viscous boundary and free boundary

By using symmetry principle, the meshing of above practical engineering considering SSI is shown in Fig.5. Earthquake wave is inputted along transverse direction of the structure. Tenfold transverse size of structure is chosen as soil size, and viscous boundary is put on transverse boundary of soil. The viscous boundary is not drawn in Fig.5.

El Centro earthquake record, whose peak values of acceleration is adjusted to 0.1g, is inputted from the bottom of soil along X axis. In order to analyze the effect of the viscous boundary of soil, the computational analysis is carried out under following three conditions in this paper. ① Thirtyfold transverse size of structure is chosen as soil size, and free boundary is put on transverse boundary of soil. ② Tenfold transverse size of structure is chosen as soil size, and viscous boundary is put on transverse boundary of soil. ③ Tenfold transverse size of structure is chosen as soil size, and free boundary is put on transverse boundary of soil.

The plane center of ground floor is chosen as origin of coordinates. The comparison of displacement response between the above-mentioned condition ② and condition ① is shown in Fig.6. Above-mentioned condition ① is considered as infinite field in half space approximately. Point A13 in Fig.6 is the central point on the top of
structure, and its elevation is 44.1m. Point CX1 is on the surface of soil intersection with structure, and its coordinate is (7.05, 0, -0.6). It shows that the displacement time-history curves of corresponding points are coincident approximately. This conclusion can also be drawn from the comparison between other corresponding points in the soil-pile-structure system.

Table 3. shows the comparison of displacement peak value of points on soil surface along vibration direction between the above-mentioned three conditions. It shows that there is small difference between results under condition ② and condition ①, while the difference between results under condition ③ and condition ① is much bigger. Therefore the size of computational model and computer resource can be reduced greatly by using viscous boundary, and the computational accuracy is still assured.

SSI Study of Different Soil Properties
Suppose the equivalent dynamic shear modulus of above-mentioned soil of Shanghai area after calculation iteration is $G$. Three-dimensional finite element calculation on SSI of different soil properties, such as $0.2G$, $0.5G$, $1G$, $2G$, $3G$ and $5G$, is carried out. $0.2G$, $0.5G$, $1G$, $2G$, $3G$ and $5G$ denote that the dynamic shear modulus of soil are $0.2$, $0.5$, $1$, $2$, $3$ and $5$ times of $G$, respectively. El Centro earthquake record, whose peak values of acceleration is adjusted to $0.1g$, is inputted from the bottom of soil along X axis.

(1) Natural frequency
Table 4. shows the natural frequency of SSI system of different soil properties. It shows that natural frequency increases along with the increase of the dynamic shear modulus of soil, and furthermore, the increment of higher order is greater than lower order. The natural frequency of SSI system is lower than that of structure supported on rigid ground, that is to say, the natural frequency of the structure system decreases and period increases under consideration of SSI.

(2) Seismic response of structure
Fig. 7 shows the acceleration peak value, displacement peak value, interstory shear and overturning moment of structure. It shows that the seismic response of structure is very complicated along with the change of dynamic shear modulus of soil. By analysis of natural frequency of SSI system, it is found that participation of the first
mode shape is most notable along the vibration direction
when dynamic shear modulus is $0.2G$, while
participation of the second mode shape enhances
gradually along with the increment of dynamic shear
modulus of soil.

(3) Effect of SSI on displacement peak value of
structure supported by different soil

Table 5 displays the effect of SSI on displacement peak value of structure supported by soil having different properties. When SSI is not taken into account, the ground shock, which is inputted from structure bottom, is the acceleration time-history of surface point, adequately far away from structure. Issues drawn from Table 5 are as follows. 1) Displacement peak value of structure under consideration of SSI is commonly greater than that of structure supported by rigid ground. 2) SSI has notable effect on displacement peak value of structure at bottom part, while has less effect on displacement peak value of structure at top part. 3) The effect of SSI on displacement peak value of structure is greater along with the decrease of the shear modulus of soil.

(4) Effect of SSI in Shanghai soft soil area

Fig. 8 displays the effect of SSI in Shanghai soft soil area on acceleration peak value, interstory drift, interstory shear and overturning moment of structure. It shows that the acceleration peak value, interstory shear and overturning moment of structure under consideration of SSI are smaller than those under condition of rigid ground, respectively. The maximums of reduction are 10.4%, 8.2% and 7.7%, respectively. The interstory drift of structure under consideration of SSI is bigger than that under condition of rigid ground near the top of structure, while smaller than that near the bottom of structure. The maximum change is 36.6%. The maximum of acceleration peak value is at the top of structure, while maximums of interstory shear and overturning moment are at the bottom of structure. The maximum of interstory drift is between ground floor and the second floor above the ground floor, because the stiffness of underground floor is much bigger than that of the ground floor.

Seismic Response of Structure under Different Excitation

Fig. 9 displays the acceleration peak value, displacement peak value, interstory shear and overturning moment of structure under excitation of El Centro wave and Shanghai artificial wave. The acceleration peak values of El Centro wave and Shanghai artificial wave are both adjusted to 0.1g. It shows that the seismic response of structure under the excitation of Shanghai artificial wave is obviously bigger than that under the excitation of El Centro wave. The main reason is that the low frequency of Shanghai artificial wave is very abundant, and the frequency of SSI system is very low.

Effect of SSI on Displacement Peak Value of Structure with Different Rigidity

Table 6 displays the effect of SSI on displacement peak value of structure with different rigidity. The different
rigidity of structure is realized by adopting different grade of concrete. Issues drawn from Table 6 are as follows. 1) SSI has notable effect on displacement peak value of structure at bottom part, while has less effect on displacement peak value of structure at top part. 2) The effect of SSI on displacement peak value of structure is bigger along with the increase of structure rigidity.

Seismic Response of Structure with Different Buried Depth

Fig. 10 displays the acceleration peak value, displacement peak value, interstory shear and overturning moment of structure with one floor underground and two floors underground. It shows that the difference of seismic response of structure between these two conditions of buried depth is negligible. The main reason is the piles adopted in the example are very long and enter the bearing course.

Conclusions

In this paper, combining general-purpose finite element program ANSYS, research on practical engineering considering SSI has been carried out. Issues drawn from the study are as follows. 1) Natural frequency of SSI system increases along with the increase of dynamic shear modulus of soil. 2) Seismic response of structure under consideration of SSI is very complicated along with the change of dynamic shear modulus of soil. 3) SSI has notable effect on displacement peak value of structure at bottom part, while has less effect on displacement peak value of structure at top part. 4) The effect of SSI on displacement peak value of structure is greater along with the decrease of shear modulus of soil. 5) The seismic response of structure under the excitation of Shanghai artificial wave is obviously greater than that under the excitation of El Centro wave. 6) The effect of SSI on displacement peak value of structure is greater along with increase of structure rigidity. 7) When piles that are very long and enter the bearing course are adopted, the buried depth of structure has little effect on the seismic response of structure.

A computational method of investigation on SSI by general-purpose finite element program ANSYS is proposed, which is of great advantage to the popularization of SSI study and to the study outcomes to guide practical engineering.

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