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Analysis of Soil-Structure Interaction with Finite Element Method

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Abstract. Analysis of dynamic behavior of soil-structure interaction (SSI) is a complicated problem due to the complexities of soil behaviors and dynamic analysis. It is difficult to solve SSI with analytical methods. However, numerical methods with highly developed computer technique are efficient. Based on the advanced nonlinear finite element analysis software MSC.Marc, SSI on loess ground is studied. An approach for the application of MSC.Marc in SSI analysis is presented and an example is given. Hyperbolic soil constitutive relationship and viscous boundary conditions are adopted in the soil model. Moreover, contact between the embedded columns and the adjacent soil is considered. Response spectrum analysis of the result is carried out. Some conclusions about the seismic response of soil-structure system under different soil stiffness and different soil-layer thickness conditions are given. A new way of analyzing SSI for loess ground is provided.

Introduction

In 1904, Lamb studied the vibration of elastic ground [1] , which is believed to be the beginning of soil dynamics. In 1936, based on Lamb's solution, Reissber investigated the vibration of a rigid circular foundation on elastic space surface and it is the beginning of SSI analysis. In 1938, Jacobso considered the effects of ground on superstructure under earthquake conditions using the elastic restoring moment of a cantilever model. In 1956, Bycroft presented the analytical solutions of shift, rotation, torsion and vibration of circular and rectangular foundations [2]. In 1967, based on Bycroft's solutions, Parmelee interpreted the basic rules of SSI with some basic equations [3]. After 1970s, numerical methods of SSI developed rapidly because of the highly developed computer technique. Meanwhile, the construction of large-scale structures, such as nuclear power plants, speeds the study of SSI.

In common engineering practice, however, the application of the research findings of SSI is difficult. For numerical methods, some urgent problems need to be solved: the application of nonlinear dynamic soil constitutive models and proper soil boundary conditions.

In this paper, an example with hyperbolic soil constitutive model and viscous boundary conditions is analyzed and the effects of SSI on ground acceleration and acceleration spectrum are discussed.

Establishment of Calculating Model

The schematic diagram of main part of mesh model is shown in Fig. 1.

Structure Model. The structure model is a transverse frame of a reinforced concrete framed building with raft foundation [4]. The main body of the building is eight-story and the story height is 3.3m. The story height of the tower atop of the building is 3.0m. The thickness of the floor slab is 0.1m and the height of the foundation beam is 1.2m. The diagrams of the transverse frame and the longitudinal frame are shown in Figs. 2.

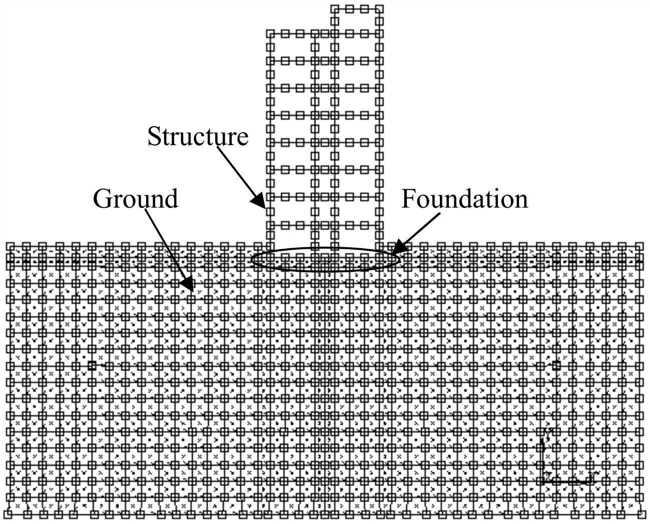
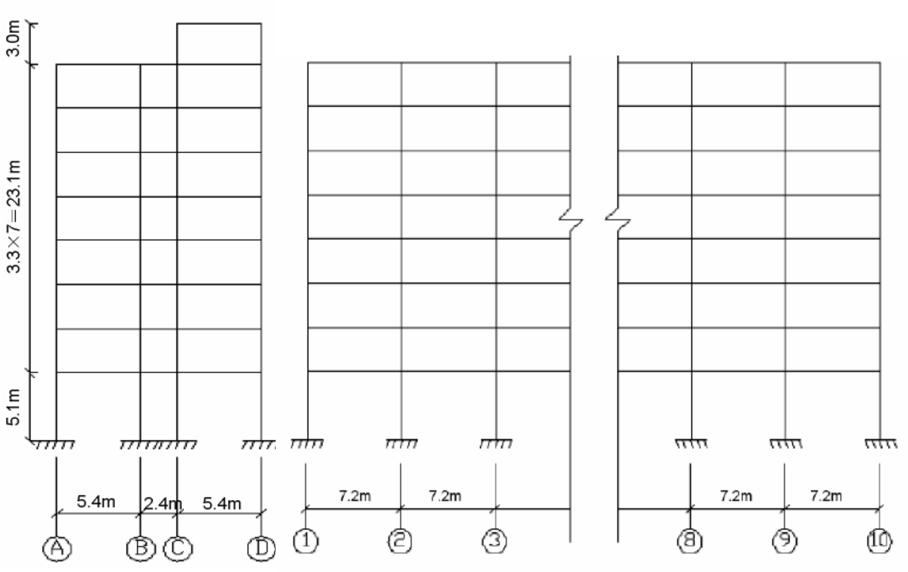


Fig.1 Schematic diagram of main part of mesh model

The building consists of 10 transverse frames and one intermediate transverse frame is analyzed with 2-D FEM. With respect to the two side transverse frames, the loading of each floor is regarded as a ninth of the gravity loading representative value [4] that is obtained by bottom shear method. Representative values of gravity loading are shown in Fig. 3. The additional loading besides the gravity loading of columns and beams is applied to beams by adjusting beam density.



Figs. 2 Transverse and longitudinal frames

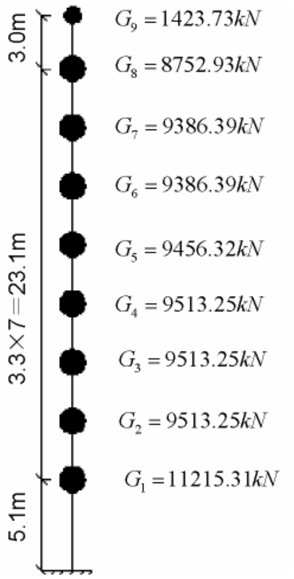


Fig. 3 Gravity loading representative values

Damping ratio ξ of the building is 0.05 and the frequency of its first vibration mode is 2.318Hz obtained by dynamic modal analysis technique with MSC.Marc.

Coefficients α and β of Rayleigh damping can be calculated as follows:

$$\alpha = 2\pi f\xi = 0.672, \tag{1}$$

$$\beta = \frac{\xi}{2\pi f} = 0.00372 \cdot \tag{2}$$

Density and Young's modulus of all members are shown in Table 1.

Table 1 Parameters of members

Members	Foundation	Column		Beam
		Bottom floor	Other floors	
Density [kg/m^3]	2500	2500	2500	47622
Young's modulus [MPa]	3.15×10^4	3.15×10^4	3.0×10^4	3.0×10^4

In the calculating model, it is assumed that columns of bottom floor are fully constrained in the foundation.

Soil Model. In the paper, the soil is considered to be an isotropic and hyperbolic constitutive model [5] shown in Fig. 4.

Constitutive equation is written as follows:

$$\tau = \frac{\gamma}{a + b\gamma} \cdot \tag{3}$$

Where τ is shear stress, γ is shear strain, $1/a$ is the maximum shear modulus G_{max} and $1/b$ is the maximum shear stress τ_{ult}. G_{max} and τ_{ult} can be obtained by laboratory dynamic triaxial tests.

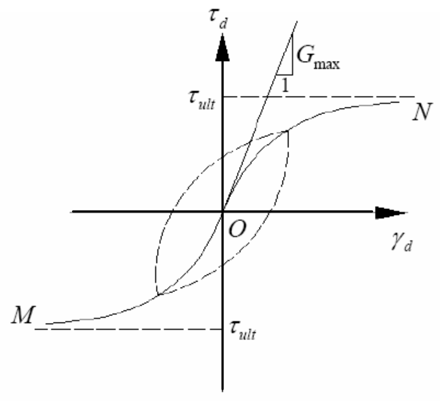


Fig. 4 Hyperbola constitutive model

The natural soils used in the laboratory dynamic triaxial tests are taken from Xianyang City, Shaanxi Province, China. Three types of these soils TK2, TK7 and ZK5, whose basic parameters are shown in Table 2, are used in this paper. They are all loessial silty clay. The maximum shear modulus gradually increases from TK2 to ZK5.

Table 2 Parameters for loessial silty clay

Soil number	Density[kg/m^3]	Maximum shear modulus [MPa]	Coefficients of hyperbola model		Coefficients of rayleigh damping	
			a	b	Mass coefficient α	Stiffness coefficientβ
TK2	1940	58.5	1.71E-08	5.10E-05	2.439	0.013
TK7	1880	71.4	1.40E-08	4.50E-05	2.645	0.014
ZK5	1970	84.0	1.19E-08	2.50E-05	2.645	0.014

As to the bottom nodes of the soil model, only horizontal acceleration is allowed and the acceleration agrees with the earthquake record. It is similar to shaking table test.

The lateral boundary of the soil model is defined as viscous boundary that is presented by

Lysmer et al [6]. On this boundary, the energy of the wave that transmits out of the soil model is absorbed by boundary dashpots. Boundary reaction forces σ (normal stress) and τ (shear stress) are obtained by

$$\sigma = a_V \rho v_P u_V \,, \tag{4}$$

$$\tau = b_V \rho v_S \omega_V \,. \tag{5}$$

Where u_V and ω_V are horizontal and vertical velocity of lateral boundary nodes; a_V and b_V are dimensionless parameters and they are both defined as 1 in this paper [6].

The buried depth of the foundation is 2.5m and the height of the foundation beam is 1.2m. Therefore, part of the column is embedded in the soil and the contact between the embedded column and the adjacent soil should be considered. In the calculating example, pressure on the contact interface of the embedded column and the adjacent soil will be mobilized when the normal relative displacement decreases; the embedded column and the adjacent soil will be detached when the normal relative displacement between them increases and the pressure will disappear.

The width of soil model largely affects the accuracy of the result. Therefore, it is important to determine a proper width. In this paper trial calculation with soil TK2 is carried out. In the trial calculation, time step is 0.02 second and the total time is 1 second. EL-Centro earthquake wave is adopted. The width respectively are 200m, 300m, 400m, 500m and 600m. Acceleration-time history curves are shown in Fig. 5. It is shown that when the width is greater than 300m, the effect of the width on the result can be ignored. In the following calculating example, the width of soil model takes 400m.

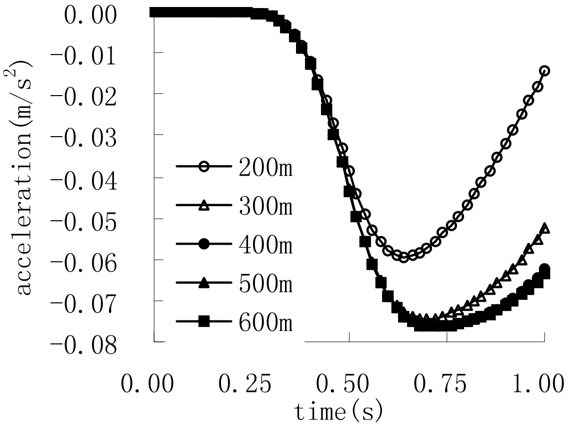


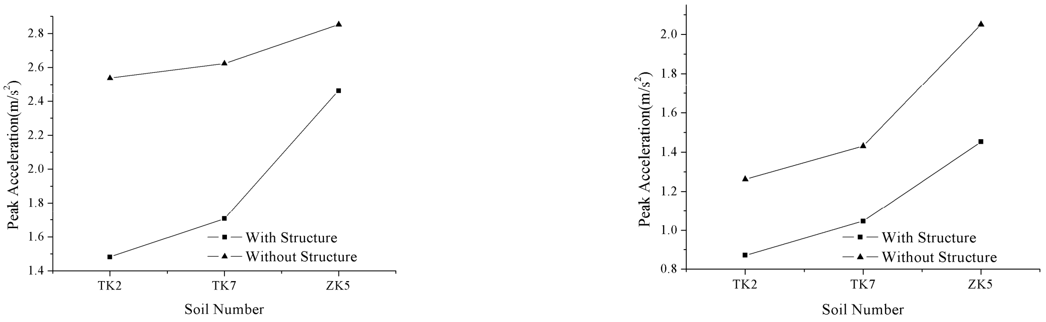
Fig. 5. Results under different widths of soil model

Calculation Results and Discussion

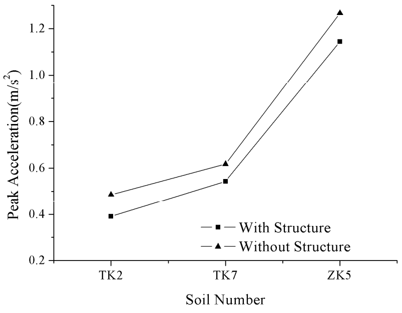
In the example, EL-Centro earthquake wave is applied and the width of the soil model is 400m. Based on MSC.Marc, the example is analyzed. Peak accelerations and peak acceleration spectra of ground face are obtained from the numerical analysis.

Effects of SSI on Peak Accelerations of Ground Surface. Fig. 6 (a), (b) and (c) are peak accelerations of ground surface of different soils under different soil thicknesses 30m, 50m and 70m when the effects of SSI are and are not considered. Peak accelerations increases when the stiffness of soil increases, whether or not the effects of SSI are considered; peak accelerations decrease because of the effects of SSI and the maximum decrease scale is up to 37.15%. Decrease scales of peak acceleration with different soil thicknesses are given in Fig. 7. As a whole, the thicker the soil is, the smaller the decrease scale is (ZK5 is an exception when its thickness is 30m).

Effects of SSI on Peak Acceleration Spectra of Ground Surface. Peak acceleration spectra of ground surface of different soils under different soil thicknesses when the effects of SSI are and are not considered are shown in Fig. 8. Peak acceleration spectra increases when the stiffness of soil increases, whether or not the effects of SSI are considered; peak acceleration spectra decrease due



(a) Soil thickness: 30m (b) Soil thickness: 50m



(c) Soil thickness: 70m

Fig. 6 Calculating results of ground surface accelerations

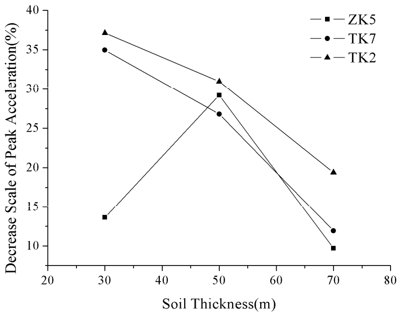
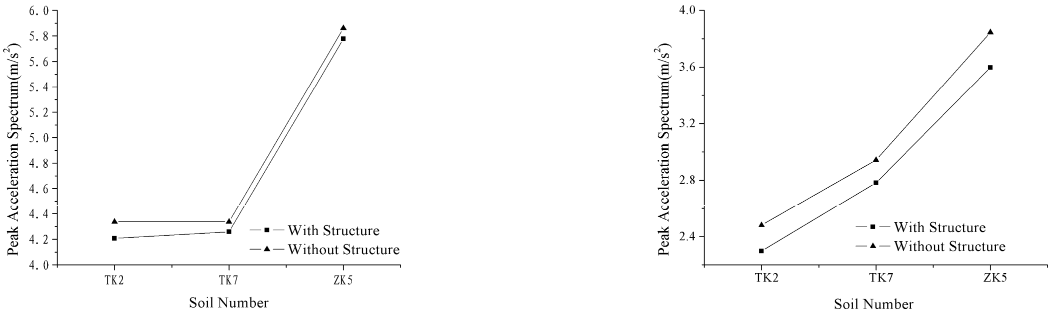
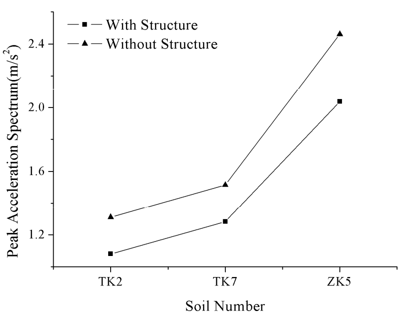


Fig. 7 Decrements of ground surface acceleration due to SSI



(a) Soil thickness: 30m (b) Soil thickness: 50m



(c) Soil thickness: 70m

Fig. 8 Calculating results of ground surface acceleration spectra

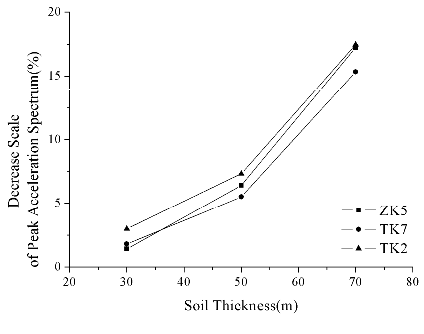


Fig. 9 Decrements of ground surface acceleration spectra due to SSI

to the effects of SSI. Decrease scales of peak acceleration spectrum are shown in Fig. 9. In contrast with the condition of peak accelerations, the thicker the soil is, the larger the decrease scale of peak acceleration spectra is.

Concluding Remarks

In this paper, based on finite element method and the second development of software MSC.Marc, an calculating example about loessial silty clay ground with hyperbolic soil constitutive model and viscous boundary conditions is analyzed. The effects of SSI on ground acceleration and acceleration spectrum are discussed. Some conclusions are drawn.

1. Peak accelerations of ground surface decrease because of the effects of SSI. The thicker the soil is, the smaller the decrease scale is.
2. Peak acceleration spectra of ground surface decrease because of the effects of SSI. The thicker the soil is, the larger the decrease scale is.
3. Both with and without superstructure, the larger the maximum soil shear modulus is, the larger both accelerations and spectra of ground surface are.

More efforts will be made to study SSI by the author. Some problems will be considered in the further study. Firstly, the delayed curve needs to be considered in soil model. Secondly, the accuracy of the result will be improved largely if transmitting boundary [6] can be applied. Otherwise, more rational damping model of soil will be helpful for the accuracy of the result.

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