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SIMPLIFIED ANALYSIS OF HORIZONTAL EARTHQUAKE ACTION ON THE STRUCTURES SUPPORTED BY PILES CONSIDERING EFFECTS OF NONLINEAR SOIL-STRUCTURE INTERACTION

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SUMMARY

Based on the preceding study of nonlinear soil-pile interaction and the results computed using ANSYS program, the simplified analysis procedure of the structure supported by piles, with the effects of nonlinear soil-structure interaction and under the horizontal earthquake action, is presented. The material nonlinearities, including nonlinear soil behavior and nonlinear structure behavior, and artificial boundary are applied in this procedure. Using this method, a ten-story frame building supported by piles is analyzed. Four cases are considered: 1) elastic analysis with an assumption of rigid ground, 2) inelastic analysis with an assumption of rigid ground, 3) elastic analysis with soil-structure dynamic interaction (SSI), 4) inelastic analysis with SSI. Some preliminary conclusions in these analyses are: 1) the super-structure is safer when SSI is not considered under the horizontal earthquake action, 2) the story drifts and absolute accelerations of super-structures decrease obviously under the horizontal earthquake action when SSI is considered, 3) the story drifts and absolute accelerations of super-structures in elastic analysis are larger slightly than in inelastic analysis, but the difference is small, 4) the soil responses near the piles may decrease when SSI is considered.

INTRODUCTION

In past decades, lots of effective researches have been done in the domain of SSI [1]. However, the main studies are still focused on the linear domain. As well known, plasticity may be appear in the soil and structures in the earthquake, especially in rare earthquake. The properties may be obviously different in the super-structures between the elastic condition and the plastic condition. So the nonlinear properties in the study of SSI must be studied. If the soil is very thick, the shallow foundation is not suitable. The deep foundation, such as piles, always is applied. Once the plies are applied, the dynamic pile-soil interaction must be considered. The pile-soil interaction is more complex than the interaction between shallow foundation and soil. The main purpose of this paper is to study the properties of frame building supported by piles and considered material nonlinearities under the earthquake action. By using ANSYS program, two analysis models of a ten-story frame structure, which considered SSI and not considered SSI, are established. The 3-D problem is simplified to 2-D problem. Beam elements are used for super-structures

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and piles, plane strain elements for soils. According to the elastic analysis and inelastic analysis, some preliminary conclusions are: 1) the super-structure is safer when SSI is not considered under the horizontal earthquake action, 2) the story drifts and absolute accelerations of super-structures decrease obviously under the horizontal earthquake action when SSI is considered, 3) the story drifts and absolute accelerations of super-structures in elastic analysis are larger slightly than in inelastic analysis, but the difference is small, 4) the soil responses near the piles may decrease when SSI is considered.

BASIC THEORETICS FOR ANALYSIS

The motion equation of soil-structure system under the horizontal earthquake action is expressed as

$$M\ddot{u} + C\dot{u} + Ku = -M\ddot{x}_g \tag{1}$$

where: *M*£¬*C* and *K* are mass matrix, damping matrix and stiffness matrix of soil-structure system respectively. $\ddot{u}$, $\dot{u}$ and *u* are acceleration vector, velocity vector and displacement vector of the finite element node respectively. $\ddot{x}_g$ is the acceleration time history inputted.

Mass matrix *M* is obtained from mass matrix of super-structures, piles and soil, and stiffness matrix *K* is from stiffness matrix of super-structures, piles and soils. *K* is a constant matrix in the elastic analysis, but *K* varies with node displacement vector in the inelastic analysis. Damping *C* depends on frequency of system generally. It is quite difficult that damping is determined accurately in the analysis. Rayleigh damping is adopted in this paper. It is given by

$$C = \alpha M + \beta K \tag{2}$$

Where: α and β are constants, called Rayleigh coefficient, which can be calculated by circular frequency ω_i and damping ratio ξ_i. In structural engineering, the Rayleigh coefficient can be obtained from the circular frequencies of the first and second mode and corresponding damping ratios. The expressions are

$$\alpha = \frac{2\omega_1\omega_2(\xi_1\omega_2 - \xi_2\omega_1)}{(\omega_2^2 - \omega_1^2)}$$
$$\beta = \frac{2(\xi_2\omega_2 - \xi_1\omega_1)}{(\omega_2^2 - \omega_1^2)} \tag{3}$$

Where $\xi_1 = \xi_2 = 0.05$ adopted in the analysis.

The motion equation can be solved by Newmark integral method directly in the elastic analysis. The method is expanded from linear-acceleration method. The precision and stability of this method are dependent on parameter γ and δ. It is unconditionally stable when $\delta \geq 0.5, \gamma \geq 0.25(0.5+\delta)^2$, that is, the interval Δt does not influence the stability of solution [2].

The immediate integration cannot be used in the inelastic analysis because the stiffness matrix *K* is changed in the process of calculation. So iteration methods are used. In this paper Newton-Raphson method is adopted. The convergence solution can be gotten easily. A new tangent stiffness matrix is formed in every iteration step.

Several problems must be taken into account in the analysis of SSI under the horizontal earthquake action, such as the simulation of soil, the simulation of reinforced concrete material and constitutive relation of inelastic materials.

The simulation of infinite field of soil is an important research content in the analysis of SSI under the earthquake action. A finite soil body extracted from infinite soil field usually is regarded as analysis object in the finite element analysis. But the artificial boundaries bring some error in dynamical analysis. In order to eliminate the error, some boundaries, such as viscous boundary and transmitting boundary etc., are presented. Based on the research of Qingjun Chen[3], the influence of boundary can be ignored when the

ratio between the distance from the boundary to the base and the width of the base is greater than or equal to 6. Free boundary is applied in the analysis models, and the distance from the boundary to the base is 6 times the width of base.

The reinforced concrete is used to the super-structures and piles. The areas of the reinforced bar is equal to the areas of concrete by equivalent principle of Young modulus in the analysis. In inelastic analysis, the material of the supper-structure is regarded as Bilinear Isotropic Hardening (BKIN) material that obeys Von Mises yield criteria, and the yield strength is that of the equivalent concrete material. The Drucker-Prager (DP) material, that obeys Drucker-Prager yield criteria, is applied to soil. And the yield surface of this material does not changed with the yield of the material, so there are no hardening criteria for DP material.

The principle of superposition is correct in the elastic analysis. Various loads are applied to the system respectively, and corresponding responses of system can be calculated respectively. But in the inelastic analysis, the principle of superposition is not applicable. So the horizontal earthquake action and gravity must be considered in the analysis at the same time. The gravity will be regarded as a dynamic load, applied to system together with horizontal earthquake action. But the gravity dynamic load will produce some dynamic response at the initial stages of loading. The results of analyses show that the dynamic effect of gravity persists for 5s approximately. In order to eliminate the effect, the gravity is applied to system solely for 5s before the horizontal earthquake action is applied.

ANALYSIS MODEL

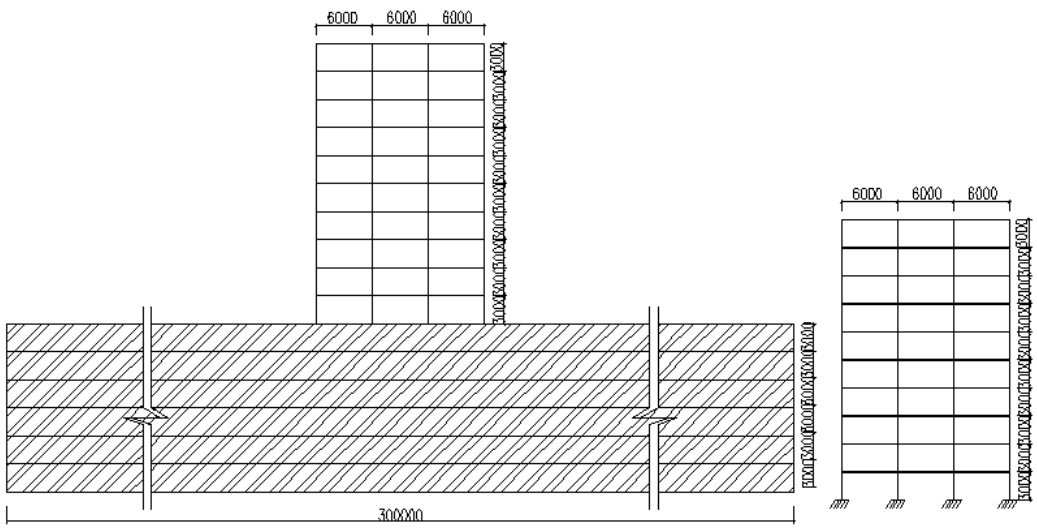
Based on the above analysis, four cases are presented 1) the elastic analysis with an assumption of rigid ground (RG, or non-SSI), 2) the inelastic analysis with an assumption of rigid ground (non-SSI and inelastic), 3) the elastic analysis considered soil-structure dynamic interaction (SSI), 4) inelastic analysis considered SSI (SSI and inelastic). The models are shown in Fig.1. There are 6 layers in the soil body whose whole thickness is 18m in the SSI model. The parameters of soil are showed in the Tab.1. Based on the analysis above, the length of the soil body is 300m. The free boundary is used as the lateral boundary, the fixed boundary as the bottom boundary. The piles foundation is adopted. And the piles foundation is equal to single pile by equivalent principle of stiffness. The super-structure is a ten-story frame structure. The dimension of section of beams is 300mmx600mm, The dimension of section of columns is 600mmx600mm. Removed the soil and piles from the SSI model, the RG model can be formed. The fixed boundary on the end of columns in the bottom story is applied in the RG model.

El Centro wave is used as an input for time history analysis. The peak value is adjusted to $1\,m/s^2$. The position of input for the SSI model is in the bottom of soil. For RG model, the acceleration time history response from free field analysis is used as the input in the bottom of columns.

In the analysis using ANSYS, beam elements BEAM3 and BEAM23, which are used in elastic and inelastic analysis respectively, are used for super-structures and piles, and plane strain elements PLANE42 are used for soils [4].

Tab. 1 Soil Parameters

No. of soil layer	Depth (m)	Thickness (m)	Density (kg/m^3)	Poisson ratio	Damping ratio	Young Modulus (MN/m^2)	Cohesive Strength (MN/m^2)	Friction Angle(°)
6	0	3	2000	0.20	0.05	17.28	2.00	25
5	3	3	2000	0.20	0.05	30.72	2.50	25
4	6	3	2100	0.20	0.05	40.82	3.00	25
3	9	3	2100	0.20	0.05	50.40	3.50	25
2	12	3	2200	0.20	0.05	52.80	4.00	25
1	15	3	2200	0.20	0.05	76.03	4.50	25



(a) SSI model (b) RG model

Fig.1 Analysis models

ANALYSIS OF RESULTS

The displacement of nodes, the node force of elements, the stress and strain of elements in the analysis models is computed using ANSYS program. The nodes on the left column of the super-structure and the nodes in the middle column of the soil are regarded as the investigative objects.

The response in the soil for three cases is analyzed. The peak value of acceleration on the interested node in the soil is shown in Fig. 2. The trend about the peak value of acceleration varied with the depth of the soil is similar. Without considering of SSI (expressed as non-SSI), the peak value of acceleration in the condition of elastic soil is a little more than that in the condition of inelastic soil. But in the condition of inelastic soil, the peak value of acceleration of non-SSI is greater than that of SSI. In Fig. 3, the difference of peak value of acceleration in the condition of inelastic soil between SSI and non-SSI is varied with the depth of soil, and the difference on the top of soil is greater than that in the bottom. The acceleration time history on the top of the soil for three cases is shown in Fig. 4. The frequencies for three cases are very similar, but the amplifications are different. The amplification in the condition of inelastic soil considering SSI is less than that in other two cases, the amplification in the condition of elastic soil without considering of SSI is the greatest one.

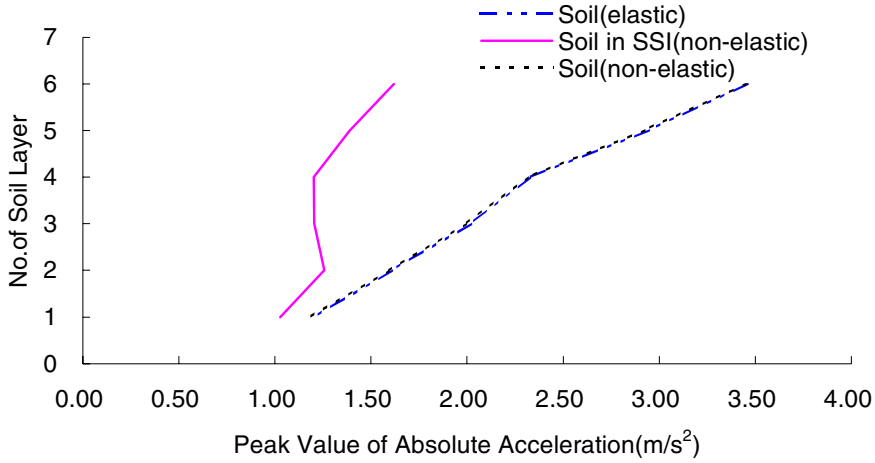


Fig. 2 The peak values of acceleration in the soil

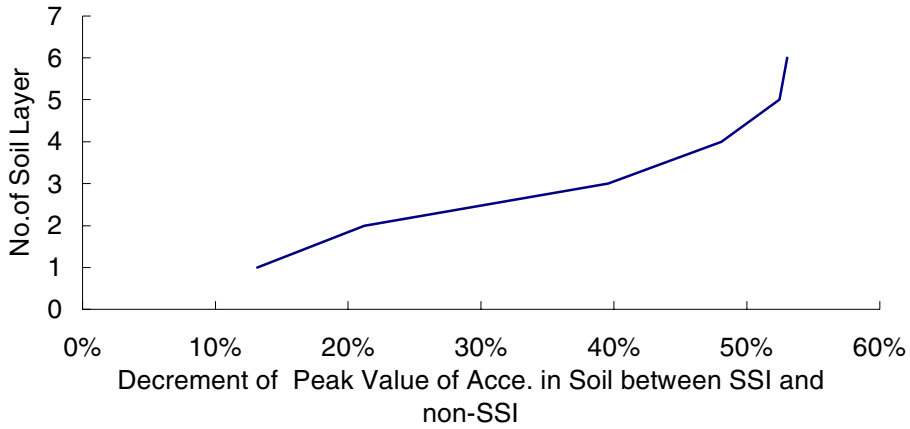


Fig. 3 The difference of peak value of acceleration in inelastic soil between SSI and non-SSI

The conclusions obtained from the analysis of the soil for three cases are,

(1)The difference of response caused by material property in soil is very small. The probable reasons are: the inelastic soil is regarded as the Drucker-Prager material, and the plastic component is small in above analysis.

(2)The acceleration response near the piles in the condition of inelastic soil is different between non-SSI and SSI. The peak value of acceleration on the top of the soil for SSI model is only 50 percent for non-SSI model, and the decrement is smaller when the depth of soil is greater.

The response in the super-structure for four cases is analyzed. The story drift of the interested nodes of the super-structure is shown in Fig. 5. The peak value of story draft of SSI is smaller than that of non-SSI in all stories except for the bottom story in the elastic analysis and the inelastic analysis. But the difference is different between the elastic analysis and the inelastic analysis, the difference of middle stories in the inelastic analysis is greater than that of the upper and lower story, the difference of all stories in the elastic analysis is almost same (Fig. 6). For the SSI model, the story drift of all stories in the inelastic analysis is less than that in the elastic analysis. But for the RG model, the story drift of middle stories in the inelastic analysis is larger than that in the elastic analysis (Fig. 5).

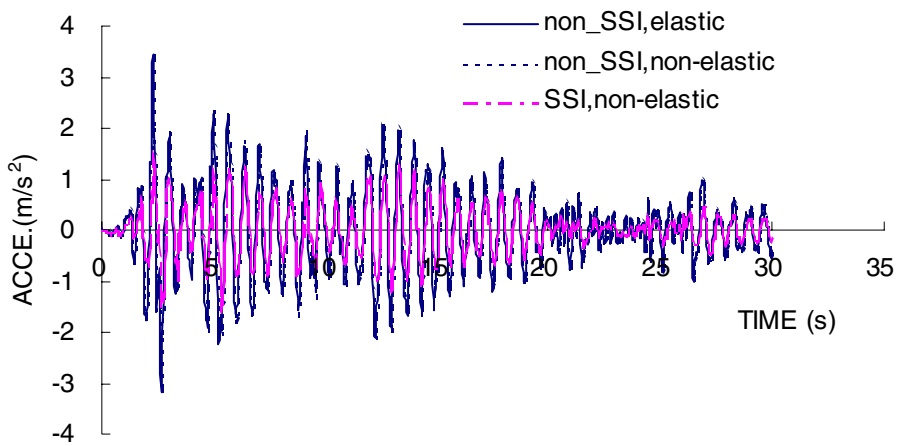


Fig. 4 The acceleration histories on the top of the soil

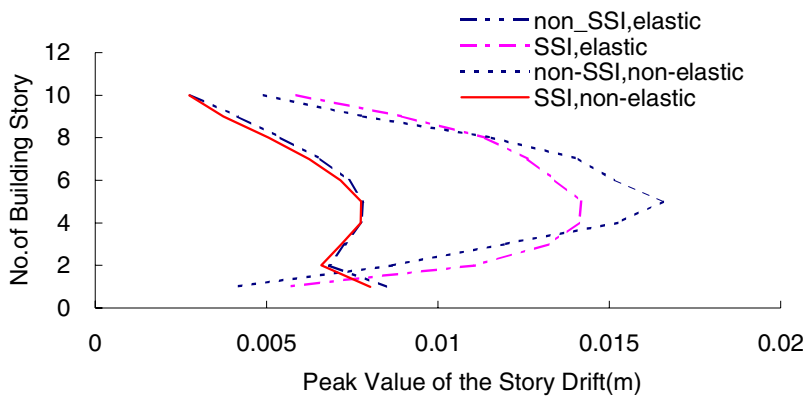


Fig. 5 The peak values of the story drift in the super-structure

The peak values of acceleration in the interested nodes of the super-structure in different cases are shown in Fig. 7. The peak values of acceleration in the node of middle stories are less than that in the node of other stories. Both the elastic analysis and the inelastic analysis, the peak values of acceleration in the node of all stories for the SSI model are less than those for the RG model. From Fig. 8, the difference of the peak value of acceleration between the SSI model and the RG model are different. In the elastic analysis, the difference of upper stories is lesser and that of lower stories is greater. But in the inelastic analysis, the difference of all stories is almost same. Both the elastic analysis and the inelastic analysis, the difference of the middle stories is greatest. The acceleration time history in the node of the top story for four cases is shown in Fig. 9. The frequencies for four cases are very similar, the effect of filtering frequency is remarkable for the SSI model. The amplifications for four cases are different. The amplification is the greatest for RG model in the elastic analysis, and that is the smallest for SSI model in the inelastic analysis.

Based on the above analyses about the super-structure, it is shown that,

1) Both the elastic analysis and the inelastic analysis, the peak value of story drifts and the absolute accelerations of super-structure decrease obviously under the effect of earthquake when SSI is considered. The decrements are over 50% in some stories. But the response value of the SSI model in the inelastic analysis is the least.

2) The story drifts in the bottom story of the SSI model may increase.

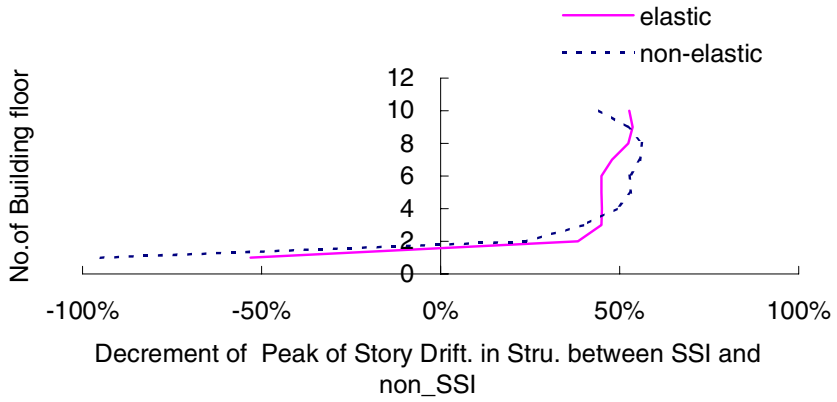


Fig. 6 The difference of the story drift between SSI and non-SSI

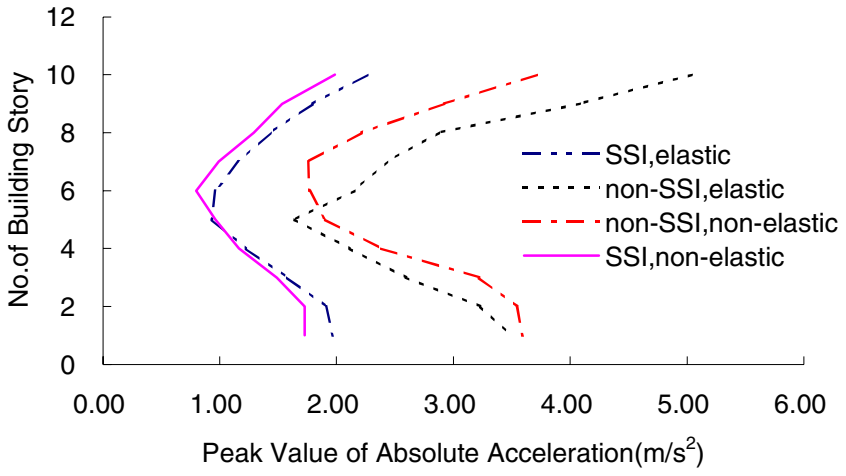


Fig. 7 The peak values of acceleration in the super-structure

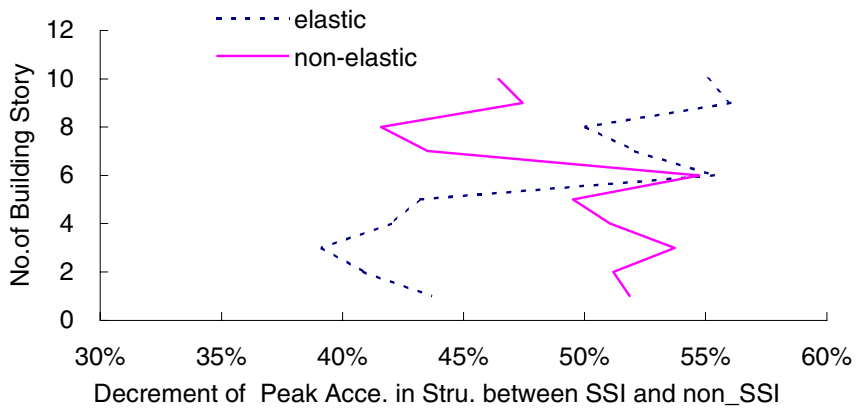


Fig. 8 The difference of acceleration between SSI and non-SSI

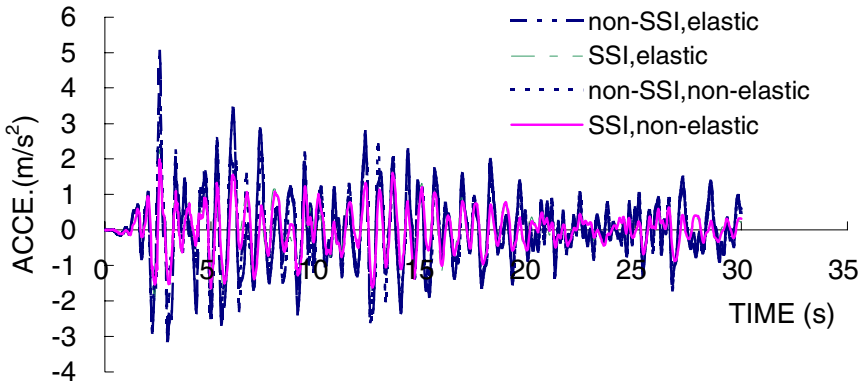


Fig. 9 The acceleration histories on the top story in the super-structure

CONCLUSIONS

The following Some preliminary conclusions according to the analysis can be drawn,
(1) The super-structure is safer when SSI is not considered under the horizontal earthquake action. When the effect of SSI is considered the response of the super-structure can be reduced properly;
(2) The influence of the inelastic condition on story drifts and absolute accelerations is not very great;
(3) The soil responses near the piles may decrease when SSI considered.

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