Analysis of Elasto-plastic Soil-Structure Interaction System Using Pushover Method

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SUMMARY:
As a simplified method, pushover analysis has been widely used in nonlinear seismic analysis and evaluation of seismic force resisting capacity of structures. In this paper, the pushover method is modified and adopted for the nonlinear seismic analysis of soil-structure interaction (SSI) system. Firstly, the conventional pushover method is modified so as to be more suitable for the nonlinear seismic analysis of SSI system. Then an elasto-plastic analysis model is developed for pushover analysis. Frame structures are analyzed considering various foundation conditions. Based on the research in this paper, the pushover method is improved and its application field is also broadened, and the influence degree of SSI to the elasto-plastic capacity of structures is achieved.

Keywords: Pushover method, Soil-structure interaction, Elasto-plastic reaction, Frame structure

1. INTRODUCTION

The dynamic behaviour of soil-structure interaction systems has been paid wide attention to during the past few years, and has attained a series of achievements (Liping.Liu ,2004). As a simplified method for nonlinear seismic performance of structures, the pushover analysis can get more information than the static linear analysis and even the dynamic analysis. In addition, the pushover method is easy to carry out, resulting in its popularity among the researchers and the engineers (Pu et al (2000), Dasui et al(2004)).

Some researchers have devoted into the research about the application of pushover method in the analysis of soil-structure interaction. Mengpu et al (2005) studied the feasibility of application pushover method to analyze the seismic performance of soil-structure interaction system. Fengxia et al (2006) transformed the multiple degrees of freedom soil-structure interaction system into single degree of freedom system by using twice equivalent, and provided the method of how to get the capacity spectrum of soil-structure interaction system. Qingjun et al (2007) carried out the plane static elasto-plastic analysis which based on the capacity spectrum method aimed at high-rise frame structure with pile foundation.

The nonlinear seismic analysis of the SSI system with pushover method is studied in this paper. First, pushover method is justified to be used in the nonlinear seismic analysis of SSI system by addressing three modelling issues. Then the elasto-plastic analysis model for the pushover method is proposed. Five SSI frame structures with different ground conditions are designed and studied using pushover method to investigate the elasto-plastic capacity of different SSI systems.

2. APPLICATION OF PUSHOVER METHOD FOR SSI SYSTEM

As a simplified method for nonlinear seismic analysis, the pushover method applies lateral loads under certain pattern on the structure and increases the loads until the structure reaches preset target lateral displacement criterion. The pushover method can produce the capacity curve which describes the relation of bottom shear and lateral top displacement of the structure. With this curve and the demand spectrum the seismic performance of the structure can be evaluated.

Compared with the structure system with fixed supports, the structural period, damping and vibration mode shapes of the soil-structure interaction system are quite different. The period and damping in the SSI system are increased. Considering these factors, the following issues should be addressed first if the pushover analysis is used.

(1) A reasonable SSI model. It is to reasonably simulate the interaction of the foundation and the soil surrounding it. The factor of the foundation soil has an important influence in the SSI analysis.

(2) A reasonable distribution mode of the lateral load. Mostly there are uniform distribution mode, inversed triangle distribution mode and the curve type distribution mode in the application of lateral load. While considered the more complex vibration modes and the influence of the foundation, the curve type mode should be used.

(3) A reasonable demand spectrum. The influence of the damping ratio in foundation soil should be taken into account when determining the demand spectrum. In other words, when transforming the response spectrum of design code into the demand spectrum, the damping ratio should be modified according to the damping ratio of the soil.

3. PUSHOVER METHOD CONSIDERING THE SOIL-STRUCTURE INTERACTION SYSTEM

3.1 Simplified model of soil-frame structure interaction system

The plane frame structure with embedded foundation is taken as the study object in the paper. The horizontal and rocking constraints between soil and foundation are replaced with horizontal spring-dashpot and rocking spring-dashpot respectively. Foundation is simplified as a rectangular rigid mass block. The frame beam and column are simulated with beam element. The simplified model of soil-frame structure interaction system is shown in Figure 3.1

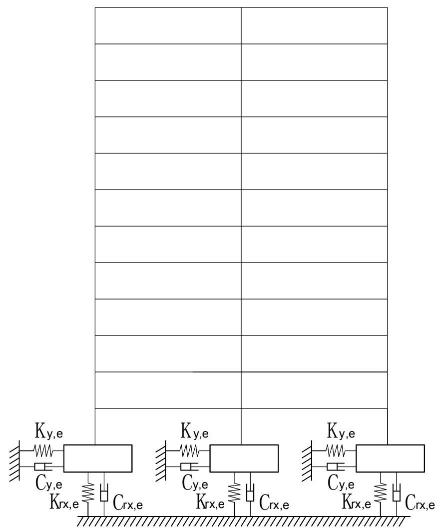


Figure 3.1 simplified model of soil-frame structure interaction system

In Figure 3.1 the stiffness of the horizontal spring-dashpot and rocking spring-dashpot are calculated according to the formula provided by Gazetas G.(1990). The horizontal and rocking stiffness of embedded foundation are as follows

$$K_{y,emb} = \bar{k}_y K_y [1 + 0.15\left(\frac{D}{B}\right)^{0.5}][1 + 0.52\left(\frac{hA_w}{BL^2}\right)^{0.4}] \tag{3.1}$$

$$K_{rx,emb} = (1 - 0.20a_0) K_{rx} \{1 + 0.92\left(\frac{d}{L}\right)^{0.6}[1.5 + \left(\frac{d}{L}\right)^{1.9}\left(\frac{D}{d}\right)^{0.6}]\} \tag{3.2}$$

In the formula, Ky, Krx are the horizontal and rocking stiffness of surface foundation, which are defined by

$$K_y = \frac{2GL}{2-v}\left(2+2.50\left(\frac{A_b}{4L_2}\right)^{0.85}\right) \tag{3.3}$$

$$K_{rx} = \frac{G}{1-v} I_{bx}^{0.75}\left(\frac{L}{B}\right)^{0.25}\left(2.4+\frac{B}{2L}\right) \tag{3.4}$$

where D= embedded depth of foundation in soil, d= contact depth between foundation and soil, h=D-d/2, B and L= half-width and half-length of the plan, I_{bx}= polar moment of inertia of the bottom surface of foundation, Aw= area of foundation side contact with soil, Ab= actual area of bottom surface of foundation, a0=ωB /Vs, ω= main frequency of seismic wave, Vs= shear wave velocity of the soil, G and v are the shear modulus and poisson's ratio. $\bar{k}_y$ is the dynamic stiffness coefficient of the foundation which is determined by the table of(a0，B /L).

The damping of horizontal and rocking of the embedded foundation are calculated according to the formula provided by George G.(1990).

$$C_{y,emb} = C_y + 4\rho V_s Bd + 4\rho V_{La} Ld \tag{3.5}$$

$$C_{rx,emb} = C_{rx} + \rho I_{bx}\left(\frac{d}{B}\right)\left(V_{La}\left(\frac{d^2}{B^2}\right)+3V_s + V_s\left(\frac{B}{L}\right)\left(1+\left(\frac{d^2}{B^2}\right)\right)\right)$$
$$\left(0.25+0.65\sqrt{a_0}\left(\frac{d}{D}\right)^{\frac{-a_0}{2}}\left(\frac{D}{B}\right)^{-\frac{1}{4}}\right) \tag{3.6}$$

In the formula Cy, Crx is the horizontal and rocking damping of surface foundation which defined by

$$C_y = (\rho V_s A_b)\bar{c}_y \tag{3.7}$$

$$C_{rx} = (\rho V_{La} I_{bx})\bar{c}_{rx} \tag{3.8}$$

where, ρ is the density of the soil, $V_{La} = V_s/(1-v)$, $\bar{c}_y, \bar{c}_{rx}$ is the damping adjustment coefficient of surface foundation, which is determined by the table of (a0、B /L).

3.2 Distribution mode of the lateral load in pushover method

For the SSI system, the lateral load should be applied on each floor of the superstructure, and on foundation. In the paper, the lateral load method recommended in literature (Mengfu et al (2005)) is adopted.The rigid foundation is regarded as a floor, and included as an extra floor to the superstructure. The lateral load modes of the frame structure considering SSI are shown as the follows:

$$F_i = \frac{W_i h_i^k}{\sum_{i=1}^{n} W_i h_i^k + W_f Z_0^k} V_b \tag{3.9}$$

$$F_f = \frac{W_i h_i}{\sum_{i=1}^{n} W_i h_i + W_f Z_0} V_b \tag{3.10}$$

where, W_f and W_i are the foundation weight and the the i^{th} floor's weight respectively. F_i, F_f and V_b represent the i^{th} layer's horizontal load increment, the foundation centric horizontal load increment and the basement shearing force increment respectively. h_i is the altitude from the i^{th} floor to the basement; Z_0 is the altitude from the rigid block centroid to the basement.

3.3 Equivalent damping of SSI system

In demand spectrum, damping ratio is an important influencing factor. Normally the damping ratio of soil is larger compared with the upper structure. So the damping ratio of SSI system is greater than the rigid foundation system. According to the literature (Wolf , 1985), The equivalent damping ratio of SSI system can be calculated by the following formula.

$$\xi_e = \frac{\omega_e^2}{\omega_s^2}\xi + (1-\frac{\omega_e^2}{\omega_s^2})\xi_g + \frac{\omega_e^3}{\omega_s^3}\frac{\bar{s}^3\bar{m}}{\bar{h}}[0.036\frac{2-\nu}{\bar{h}^2} + 0.028(1-\nu)] \tag{3.11}$$

In the formula, ω_e is the equivalent frequency of the SSI system, which calculated by the following formula.

$$\frac{\omega_e^2}{\omega_s^2} = \frac{1}{1+\frac{\bar{m}\bar{s}^2}{8}[\frac{2-\nu}{\bar{h}^2}+3(1-\nu)]} \tag{3.12}$$

where, ω_s is the fundamental frequency of upper structure, $\bar{s} = \omega_S H / V_s$ is stiffness ratio, $\bar{h} = H / a$ is slenderness ratio, $\bar{m} = m / \rho a^3$ is mass ratio, a is the foundation radius.

4 NONLINEAR SEISMIC PERFORMANCE ANALYSIS OF SOIL-STRUCTURE INTERACTION SYSTEM

4.1 Design of structural example

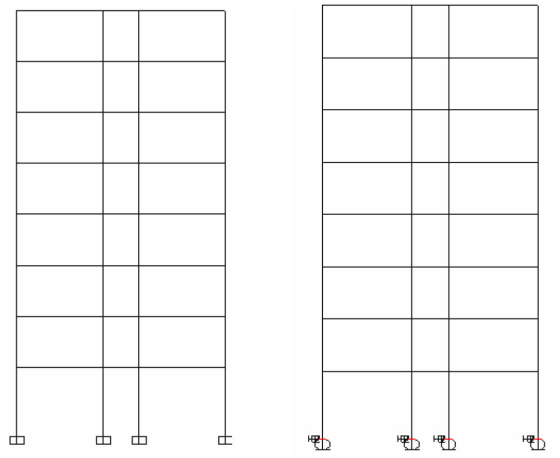
The main parameters of frame structure example are as follows. Seismic intensity is 9. Design characteristic period of ground motion is 0.3 sec. The shape of structural plan is rectangular by 12.3m ×48m. The column spacing is 5.1m along direction B, and 2.1m, 5.1m, 6m along direction L. The story number is 8. The story height is 3.9m for bottom story, and 3m for other stories. The column section size is 0.8m×0.8m. The beam section size is 0.25m×0.5m. Strength grade of concrete is C30. The longitudinal reinforcing bars are HRB335, and stirrups are HPB300. The structural example is designed by China code. The side reinforcement of column is 3500mm^2, top reinforcement of beam is 2100 mm^2, and the bottom is 1200mm^2.

The reinforced concrete spread foundation with buried depth of 0.9m is used in the structural example. In order to consider the influence of different ground soil conditions, four shear wave velocities, including 500m/s, 250m/s, 150m/s, 100m/s are considered. Horizontal stiffness and rocking stiffness of foundations are calculated by formulas (3.1), (3.2) and listed in Table 4.1. Equivalent damping ratios of SSI system under different ground conditions are calculated by formula (3.11) and listed in Table 4.1

Table 4.1 Calculation parameters of analysis model

No.	Shear wave speed (m/s)	Soil mass density kg/m^3	Poisson's ratios	Damping ratio	Size of foundation m	Horizontal stiffness kN/m	Rocking stiffness kN.m	Horizontal damping coefficients kN.s/m	Rocking damping coefficients kN.m^3	Equivalent damping coefficient
Non_SSI	-	-	-	-	-	-	-	-	-	0.050
SSI1	500	2200	0.20	0.15	1.7	5337773	4016161	8142361	891225	0.055
SSI2	250	2000	0.25	0.17	1.7	1247791	973615	3793111	443866	0.060
SSI3	150	1800	0.30	0.19	1.7	416175	337983	2105081	261389	0.062
SSI4	100	1600	0.40	0.20	1.7	182407	179486	1484179	217822	0.065

An interior frame of example structures is selected. It is analyzed as planar frame with SAP 2000. In order to consider the influences of floor slab, stiffness of beam is amplified by 2 times. In SSI model, the base soil is simulated by a horizontal spring-dashpot systems. And the damper is simulated by LINK element. The analysis models of structure with fixed supports and SSI system are shown in Figure 4.1.



(a) Non_SSI (b) SSI

Figure 4.1 Structure models with fixed supports and SSI system

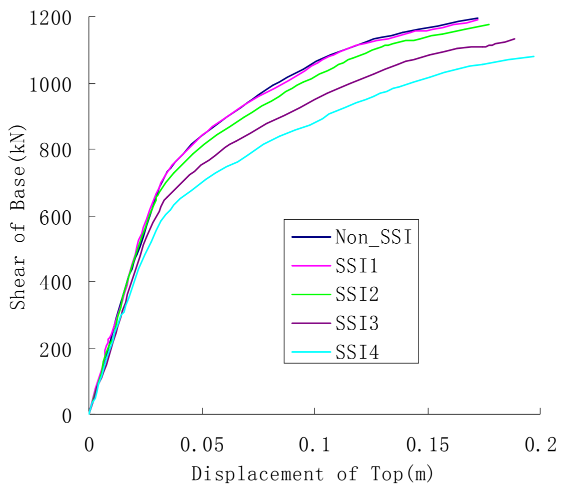


Figure 4.2 Relationship between structural base shear and top lateral displacement

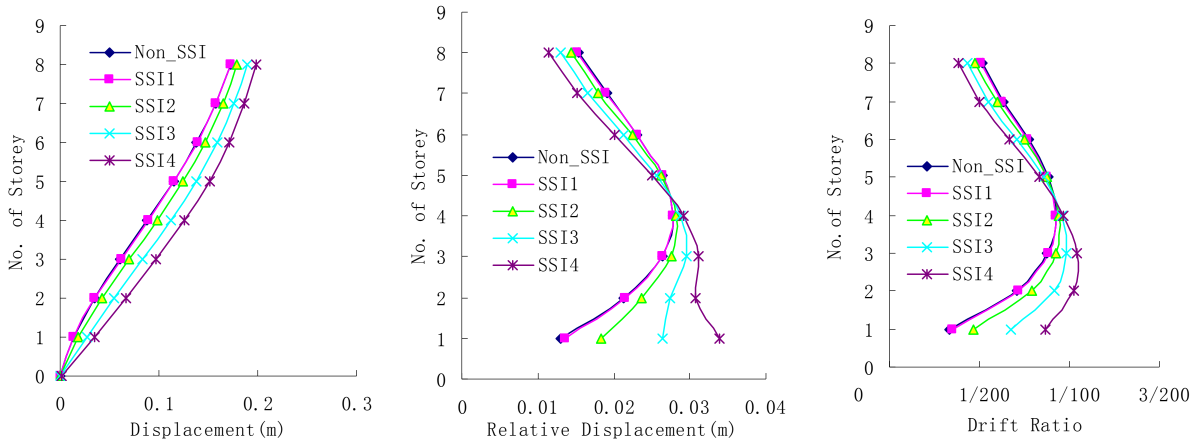


Figure 4.3 floor displacement and inter-story drift

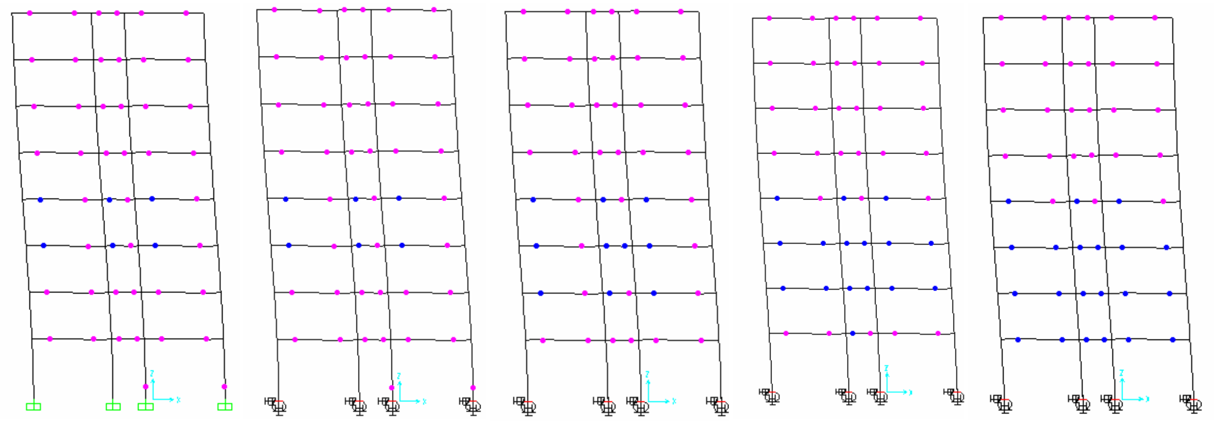
4.2 Results of pushover analysis

5 models in Table 4.1 were analyzed by the modified pushover method with lateral load modes defined by Eqns. (3.9) and (3.10). The capacity curves of 5 models are shown in Figure 4.2, which shows the relationship between structural base shear and top lateral displacement. As the curves show, effects of SSI are not obvious in the elastic stage. But in nonlinear stage; SSI can decrease the capacity curves. The softer the foundation soil is, the more the curves get reduced. The curves of floor displacement and inter-story drift ratio are shown in Figure 4.3. SSI can increase structural displacement and inter-story drift of bottom floor, while reduce inter-story drift of upper floor near the top of structure; and this is more obvious with softer foundation soil.

Table 4.2 shows the performance points of the 5 models. The conclusion can be got that SSI have certain effects on structural behaviors. When the SSI is considered, the base shear of performance point is reduced and lateral drift is increased. Figure 4.4 shows the distribution of plastic hinges of 5 models. The figure shows that SSI influence distribution and level of plastic hinges to some extent.

Table 4.2 Parameters of performance points (Unit: kN, m)

Performance Point	Non_SSI	SSI1	SSI2	SSI3	SSI4
Vb,un	(1191.1,0.172)	(1187.1,0.171)	(1174.4,0.177)	(1129.2,0.188)	(1079.4,0.197)
Sa,Sd	(0.178,0.127)	(0.176,0.126)	(0.169,0.132)	(0.156,0.142)	(0.144,0.151)



(a) Non_SSI (b) SSI1 (c) SSI2 (d) SSI3 (e)SSI4

Figure 4.4 Distribution of plastic hinges

5. CONCLUSION

Through above analysis, the following conclusions are drawn:
(1) For the nonlinear analysis of SSI system using pushover method, some modifications should be made in terms of structural modelling, equivalent damping and lateral load pattern, etc.
(2) SSI has certain effects on structural behavior. For frame structure, SSI can reduce displacement and related responses and avoid the development of plastic hinges in given conditions.

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