The research of applied pushover method in the earthquake resistance analysis of soil-structure interaction system

Liu Liping[1], Xia Kui[2] and Cao Xuan[2]

[1] *Associate Professor,College of Civil Engineering, Chongqing University, Chongqing, P.R.China*
[2] *Graduate student, College of Civil Engineering, Chongqing University, Chongqing, P.R.China*
Email: Liuliping@cqu.edu.cn,zhhllp@163.com

ABSTRACT :
The non-linear earthquake resistance analysis of soil-structure interaction system is complex. The time history analysis method of non-linear earthquake resistance analysis is a well fitted method, but it is difficult to use because of the complexity of analysis model and uncertain input of earthquake motion. As a simplified method, pushover method has been widely applied in the capability evaluation of structure earthquake resistance. In the paper the pushover method was applied to study seismic behavior of frame-shearwall structure considered soil-structure interaction. The plane frame-shearwall structure of tall building was taken as a research model, the structure was simulated by beam element, and the ground was simulated by parameter model. Firstly the non-linear time history analysis method was adopted to analyses the top displacement, story drift and the order of yield of the model. Then based on the result of the non-linear time history analysis method, the applicability of pushover method in soil-structure interaction system was studied. Finally pushover method was applied to analysis the structure earthquake resistance capability of frame-shearwall structure consideried soil-structure interaction.

KEYWORDS:
pushover method; earthquake resistance analysis; tall building; soil-structure interaction.

1 Introduction

The study on soil-structure dynamics interaciton (abbreviated as SSI) has attracted widly attention，and has gotten a lots of useful results(Liu Liping 2004). The main method of study for SSI is time-history analysis method. This method can obtain structure status at any time, which is regarded as one of the best methods for the study of SSI. But because of the complexitythe of analysis model, the difficulty of dealing with computing data the uncertainty of ground motion and so on to limit its use. Static pushover analysis method is a simplified calculation method on structural nonlinear responses, in most of cases it can get more information than static elastic and dynamic analysis(Yang Pu 2000).
The pushover method has be applied in the study of SSI by domestic and abroad researcher. Wang Mengfu etc. (2005) studied the feasibility that applied pushover method to analysis of framework structure considering SSI. The plane framework analysis model was made, and the soil was simulated by spring. The lateral load mode and target displacement were studied. And verified the feasibility that applied pushover method to study of framework structure considering SSI by a example. Wang Fengxia etc. (2006) transformed an SSI system into an equivalent SDOF system through twice equivalence, and the pushover method considering SSI effects (abbreviated as SSIPA) was put forward. Cheng Qingjun etc. (2007) adopted the capacity spectrum method to perform nonlinear static seismic response analysis for high-rise frame structures with group piles resting on natural foundation soils, the pushover analysis model of soil-pile-structure interaction system was established, group piles simulated by springs and group piles stiffness determined by Davies method.
It is necessary that study the feasibility of applied pushover method to analysis of frame-shearwall structure considering SSI. In the paper, the feasibility of applied pushover method to analysis of frame-shearwall structure considering SSI is studied based on others' research results. The plane frame-shearwall structure of tall building was taken as a research model, the super-structure was simulated by beam element, and the ground was simulated by parameter model. Firstly the non-linear time history analysis method was adopted to analyses the

top displacement, drift displacement and the order of yield of the model. Then based on the result of the non-linear time history analysis method, the applicability of pushover method in soil-structure interaction system was studied. Finally pushover method was applied to analysis the structure earthquake resistance capability of frame-shearwall structure considering SSI.

2. Pushover analysis method for frame-shear wall structure considering SSI

2.1 The principle and hypothesis of static pushover analysis method

Static pushover analysis method is a simplified method for nonlinear seismic response analysis. One of simulating lateral inertia forces is put on the analyzing model and is enlarged step by step till the structure gets into a target displacement, then the structure seismic behavior is evaluated. The hypothesis of static pushover analysis are:

(1) Seismic response of a structure is related to equivalent single-degree-of-freedom system. This implies that seismic response of structure is only controlled by first vibration mode.

(2) Deformation along the structure is expressed by shape vector. On the process of seismic, shape vector keeps invariant in despite of the magnitude of structural deformation.

(3) Floor stiffness in itself plane is infinite, the stiffness out of plane can not be considered.

The principle of static pushover analysis method is:

(1) Structure is simplified as an equivalent single-degree-of-freedom system. The maximum inelastic displacement on the effect of fortification level seismic is calculated, which is taken as the target displacement.

(2) Two-dimensional or three-dimensional model is built for structural analysis.

(3) Seismic action is simplified as inverted triangular distribution, uniform distribution or curve distribution, then takes it for calculation model of structure.

(4)Using load increment to carry out nonlinear static analysis till the structural peak displacement gets into target displacement.

(5)Find out plastic hinge timely and modify total stiffness matrices continuously on the process of napping.

(6)When the structure gets into target displacement, structural internal force and deformation can be used as bearing capacity and deformation requirement of structure. Obtaining bearing capacity and deformation requirement of structure successively then comparing to permissible value, thus evaluates structure for its seismic behavior.

2.2 Analysis model of the frame-shear wall structure considering SSI

The analysis model is shown in Figure 1. It is a simplied plane model that upper –structure consist of shearwall, coupling beam and frame, and the base is simplified to a rigid mass block, the soil is simulated by a level spring and a rotation spring. The parameters of springs are determined by the static stiffness of the buried rectangular foundation. The upper frame beam and frame column is simulated by beam element. Because the shell element isn’t provided plastic hinge in SAP2000, the shear walls is simulated by beam element to consider the platic performance of shear walls. The quality matric created by reactor-quality method.

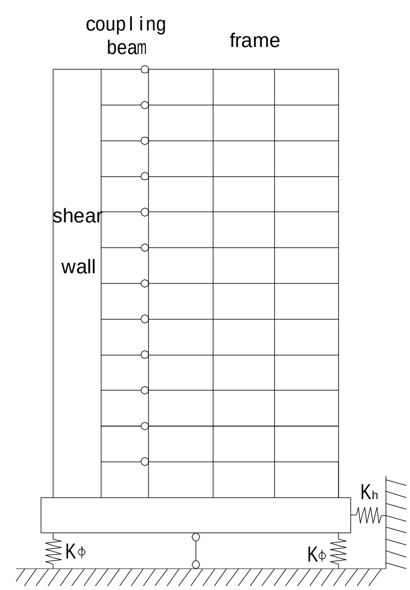


Figure 1 Pushover analysis model of frame-shearwall structure considering SSI

2.3 Static stiffness of the buried rectangular foundation

The parameters of springs in Fig.1 are determined by the static stiffness of the buried rectangular foundation. The static stiffness of the buried rectangular foundation adoted the

following formula which given by literature (Pais A 1988). Static stiffness of the surface foundation:
Horizontal stiffness:

$$K_{hy}^{0}=\frac{GB}{2-n}[6.8(L/B)^{0.65}+0.8(L/B)+1.6] \tag{2.1}$$

Rocking stiffness:

$$K_{fX}^{0}=\frac{GB^{3}}{1-n}[3.2(L/B)+0.8] \tag{2.2}$$

Static stiffness of the buried foundation:
horizontal stiffness:

$$K_{hy}^{s}=K_{hy}^{0}[1+[0.33+\frac{1.34}{1+L/B}](E/B)^{0.8}] \tag{2.3}$$

Rocking stiffness:

$$K_{fX}^{s}=K_{jX}^{0}[1+E/B+[\frac{1.6}{0.35+L/B}](E/B)^{2}] \tag{2.4}$$

in the formula, G is shear modulus of the soil, n is poisson ratio of the soil,B is half length of the short side of the rectangular foundation ,Lis half length of the long side of the rectangular foundation,E is depth of foundation.

2.4 Lateral load mode

In the pushover analysis of the structure based on rigid foundation hypothesis, there are three lateral load modes such as triangular distribution, uniform distribution and curve distribution. In the most case uses the linear distribution such as triangular distribution and uniform distribution which mainly represents the effect of the first vibration mode, and usually applied to regular low-rise building. When the building layer increases, the high vibration mode influence shoule be considered, the nonlinear lateral load mode needs to use.The lateral load mode of the frame-shearwall structure considering SSI is different from rigid foundation hypothesis. Besides of horizontal inertia forces of superstructure, the horizontal inertia forces of foundation must be considered. In the paper, the lateral load method recommended by literature (Wang Mengfu 2005) is adopted. Regards the rigid foundation as a floor, and includes n floor's superstructure to compose a (n+1) structure system. The lateral load modes of the frame-shearwall structure considering SSI are shown as the follow:
(1)Uniform distribution

$$F_{i}=\frac{W_{i}}{\sum_{i=1}^{n}W_{i}+W_{f}}V_{b} \tag{2.5}$$

$$F_{f}=\frac{W_{i}}{\sum_{i=1}^{n}W_{i}+W_{f}}V_{b} \tag{2.6}$$

In above equation, W_f , W_i expresses the foundation weigh and the ith floor's weight separately. F_i, F_f and V_b represents the ith layer's horizontal load increment, the foundation centroid's horizontal load increment and the basement shearing force increment separately.
(2)Triangular distribution

$$F_{i}=\frac{W_{i}h_{i}^{k}}{\sum_{i=1}^{n}W_{i}h_{i}^{k}+W_{f}Z_{0}^{k}}V_{b} \tag{2.7}$$

$$F_f = \frac{W_i h_i}{\sum_{i=1}^{n} W_i h_i + W_f Z_0} V_b \qquad (2.8)$$

In the formula, h_i is the altitude that the ith floor leaves the basement; Z_0 is the altitude that the rigid block centroid away from the basement.

(3) Curve distribution

$$F_i = \frac{W_i h_i^k}{\sum_{i=1}^{n} W_i h_i^k + W_f Z_0^k} V_b \qquad (2.9)$$

$$F_f = \frac{W_i h_i^k}{\sum_{i=1}^{n} W_i h_i^k + W_f Z_0^k} V_b \qquad (2.10)$$

which,

$$k = \begin{cases} 1.0 & (T < 0.5s) \\ 1.0 + \frac{T - 0.5}{2.5 - 0.5} & (0.5s \le T \le 2.5s) \\ 2.0 & (T \ge 0.5s) \end{cases} \qquad (2.11)$$

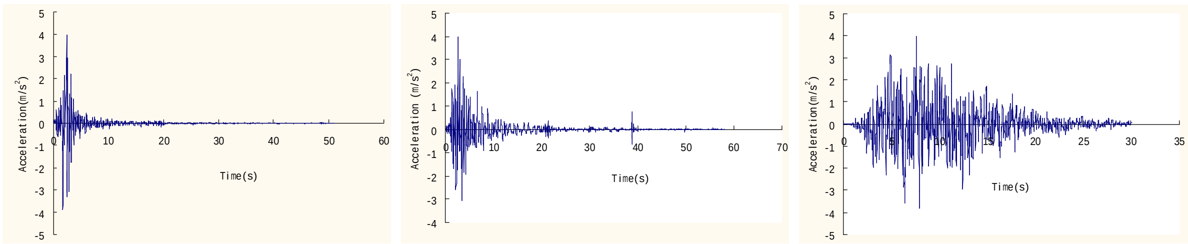
3 Feasibility study of applied pushover method to analysis of frame-shearwall structure considering SSI

Comparative analysis was used to study the feasibility of applied pushover method to analysis of frame-shearwall structure considering SSI. The relation between the results of plane model frame-shellwall structure considering SSI, which gotten by non-linear time history analysis method and pushover method was obtained. Then the feasibility of pushover methods for the SSI system was studied

The examples of 12 story reinforce concrete framework-shearwall structure were designed based on the model shown in Fig.1. The height of Storey is 3 m, the distance of column is 6 m, the left-edge span is layouted shear walls, the right three spans are arranged columns, the beams between the framework and shear walls are regarded as rigid link. In order to study the effect of shear wall, two analysis models were designed, one with more shear walls and another with less shear walls, marked as Model 1 and Model 2, respectively. In the two models, the columns section are 0.8 mx0.8m and the beams section and the link beams are 0.3mx0.7m. The shear wall section is 0.2 mx2m in Model 1, and 0.2 mx4m in Model 2. The strength grade of concrete is C30, the strength of reinforcing steel bar in the beams, columns and shear walls is HRB335, and stirrup is HPB235.

The size of foundation is 24 m × 1m ×3m, and the quality is 180 ton. The distance between nature centroid and basis of the foundation is 1.5m. The Site classification is II, and the corresponding parameters of soil are: density of soil ρ is 2000Kg/m^3, poisson ration n is 0.35, shear wave velocity Vs is 489m/s. The antiseismic classification is grade 8, and and the corresponding parameter of basic design acceleration of ground motion is 0.2g. According to these parameters, the examples were designed.

For gotten the result of above examples calculated by non-linear time-history analysis, two actual seismic waves and one artificial seismic wave were selected according to the Code for Seismic Design of Buildings (GB50011-2001). The peak acceleration was adjusted to the maximum acceleration of the rare earthquake corresponding grade 8 of antiseismic classification, that is 0.408g. Then the average of the result calculated by three seismic waves was taken as the final result. The three seismic waves are shown in Figure 2.



(a) USA00074 (b) USA02152 (c) S1

Figure 2 Seismic waves for non-linear time-history analysis

Three lateral load modes, inverted triangle distribution, uniform distribution and curve distribution, were used in static pushover analysis method for above examples. Comparing the conclusion obtained by different lateral load modes of pushover mothod with that obtained by non-linear time-history analysis method, the results are shown in Figure 3 to Figure 7.

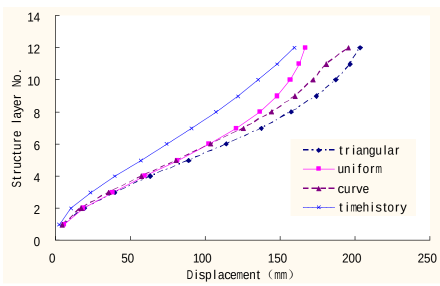


Figure 3 Story peak displacement of Model 1 calculated by different methods

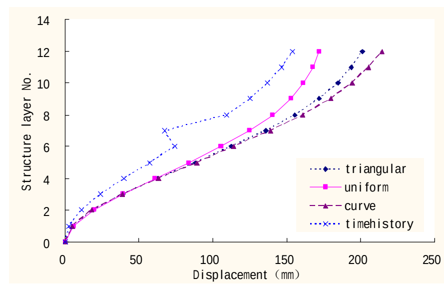


Figure 4 Story peak displacement of Model 2 calculated by different methods

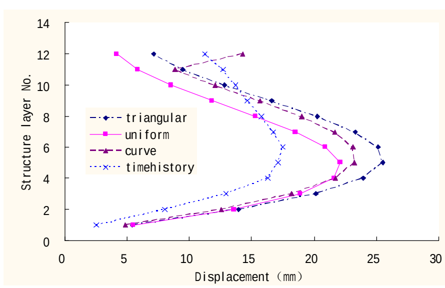


Figure 5 Story drift of Model 1 calculated by different methods

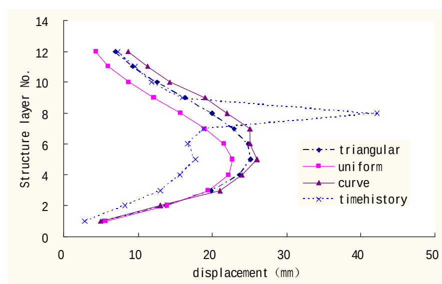
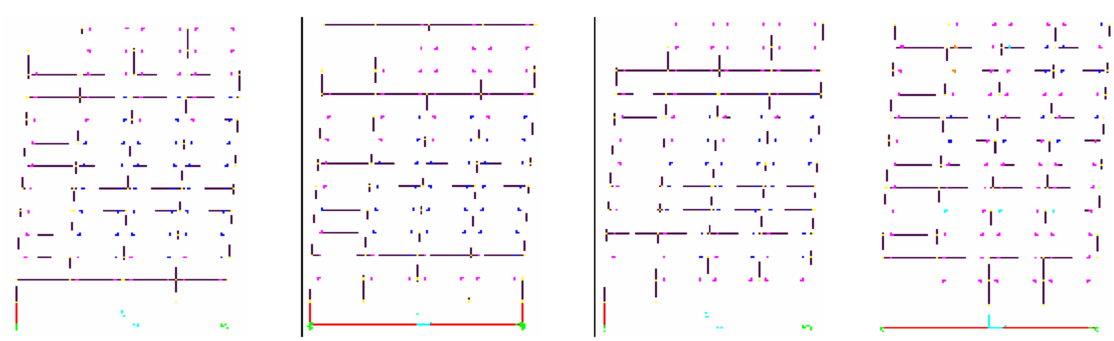


Figure 6 Story drift of Model 2 calculated by different methods



(a) triangular lateral load (b) uniform lateral load (c) curve lateral load (d) time history load

Figure7 Plastic hinges distribution of superstructure

Compared the results calculated by pushover method and time history method (Figure 3 to Figure7), it is showed that there are a little different but the trends are same, and there is no best in three purshover lateral load mode. Therefore, the pushover analysis method is suitable for seismic analysis of frame-shear wall structure considered soil-structure interaction, but three kinds of lateral load patterns which are suitable for seismic analysis of frame-shear wall structure considering soil-structure interaction need further study.

4 Application of pushover method to study seismic behavior of frame-shearwall structure considering SSI

In the part, the seismic behavior of frame-shearwall structure considering SSI was studied by pushover method. Two type of model were establised, one was considered SSI (abbreviated as SSI) and the other was not considered SSI (abbreviated as NON-SSI). SSI models was the same models (Model 1 and Model 2) shown in Part 3. NON-SSI models(marked as Model 3 and Model 4) were designed based on SSI models. As rigid-plastic and spring was subtracted, fixed connection set on the bottom of column and shearwall, Model 1 was changed to Model 3 , and Model 2 was changed to Model 4. Compared the calculated results of two type of model, the seismic behavior of frame-shearwall structure considering SSI was studied.

To reveal the effect of soil-structure interaction, the Site classification is IV, and the corresponding parameters of soil are: density of soil ρ is 2000Kg/m^3, poisson ration n is 0.35, shear wave velocity Vs is 120m/s. The antiseismic classification is grade 7, and and the corresponding parameter of basic design acceleration of ground motion is 0.15g. According to these parameters, the examples were designed.

The pushover method was used in SSI models and NON-SSI models. The lateral load mode was triangular distribution, uniform distribution and curve distribution respectively. The average of story peak displacement and the average of story drift, calculated for the results of three lateral load mode, were regard as the final results. The plastic hinges distribution of superstructure was the results calculated by uniform lateral load. The results of comparative analysis are shown in Figure 8 to 12.

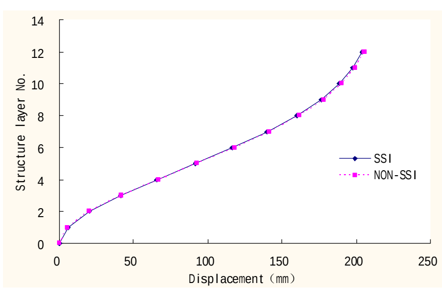


Figure 8 Story peak displacement of model 1 compared with model 3's

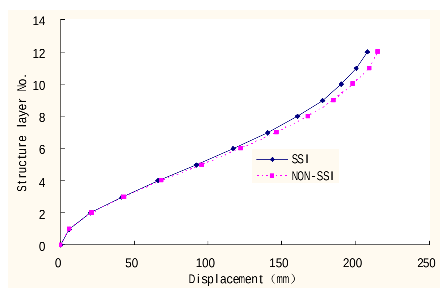


Figure 9 Story peak displacement of model 2 compared with model 4's

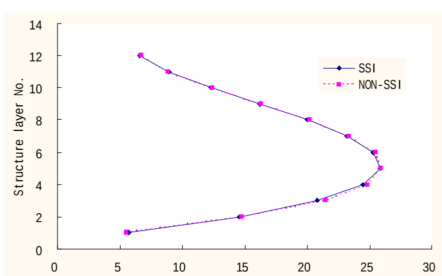


Figure 10 Story drift of model 1 compared with model 3's

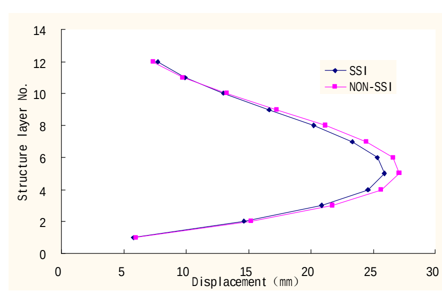
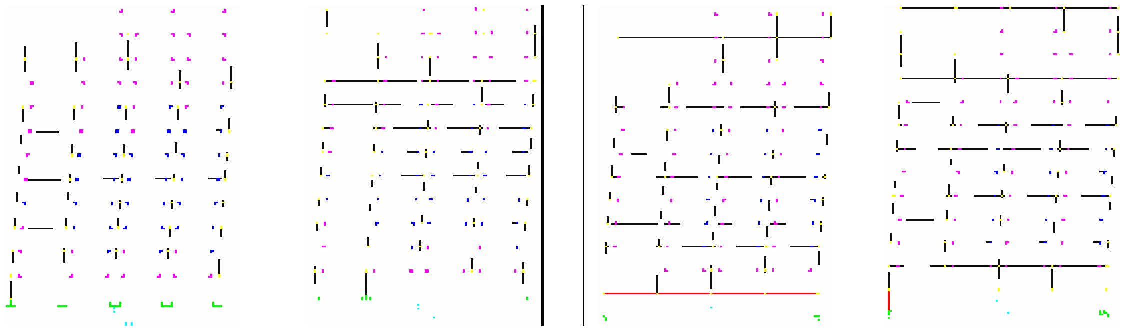


Figure 11 Story drift of model 2 compared with model 4's



(a) model 3 (NOS-SSI) (b) model 4 (NOS-SSI) (c) model 1 (SSI) (d) model 2 (SSI)

Figure 12 Plastic hinges distribution of superstructur under uniform lateral load

The results indicate that the story peak displacement and story dift of the structure are reduced as considered SSI, and the order and distribution of plastic hinges are alike between the NON-SSI's results and SSI's result, but the degree of plastic hinges is decreased. The similar conclusion has been shown in the literature (Liu Liping 2004).

5. Conclusion

(1) The results of pushover analysis method is a little different from that of time-history analysis. But the trend of the story peak displacement, story drift and plastic hinges distribution, calcluated by two methods, is the same. So the pushover methods can be applied for seismic analysis of frame-shearwall structure considered SSI.
(2)Compared to conventional nonlinear static analysis method, the pushover method considered SSI has its particularity. It's necessary to study the determination method of lateral load mode for pushover method.
(3)Triangular distribution, uniform distribution and curve distribution three lateral load mode, which is the best lateral load mode for purshover method is needed study.
(4) The story peak displacement and story dift of the structure are reduced as considered SSI, and the order and distribution of plastic hinges are alike between the NON-SSI's results and SSI's result, but the degree of plastic hinges is decreased.

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