13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3177

NONLINEAR SEISMIC RESPONSE ANALYSIS OF PILE-SOIL-STRUCTURE INTERACTION SYSTEM

WANG Feng-Xia[1] HE Zheng[2] OU Jin-Ping[3]

SUMMARY

In this paper, by using ANSYS® software, a modified lumped-mass simplified nonlinear pile-soil-structure interaction (PSSI) model is established for shear-type RC frame structure under moderate and large earthquakes with rocking effect, dynamic nonlinearity of interaction between pile and soil, the contact state between pile and soil, raft and soil. Seismic response of a 4-storey building supported on piles is analyzed with respect to linear and nonlinear pile-soil systems using this model, and is compared with the behavior of buildings with rigid base under moderate and large earthquakes. A simplified model is presented to apply for the engineering applications.

INTRODUCTION

Under moderate and large earthquakes, the pile-soil-structure interaction (PSSI) system presents the evident nonlinear feature. In this case, it is necessary to take account of the nonlinearities induced in the soil of the free field by seismic waves and of the additional nonlinear effects created by the structural vibrations.

Approximate theories have to be used because the rigorous approach to the nonlinearity of pile-soil-structure system is difficult. Lumped-mass model proposed by Penzien [1] is a popular approximate method to solve the soil-structure interaction account for its convenient application to engineering practices.

Many FEA softwares with the development of the computer technologies have been developed to the high quality engineering tools, which can be used to design, and analysis. Such as ANSYS®, that can provide a common platform for fast, efficient analysis in a lot of important areas. Thus, the soil and structure interaction should utilize this effective tool, too.

In this paper, a modified lumped-mass simplified model is established for shear-type RC frame structure under moderate and large earthquakes based on the Penzien, by using ANSYS® software. Using this

[1] PH.D. student, School of Civil Engineering, Harbin Institute of Technology, Harbin, China, email:irise1970@hit.edu.cn
[2] Associate Professor, School of Civil Engineering, Harbin Institute of Technology, Harbin, China, email:Hezheng@hit.edu.cn
[3] Professor, School of Civil Engineering, Harbin Institute of Technology, Harbin, China, email:Oujingping@hit.edu.cn

model, a 4-storey building supported on piles is analyzed with respect to linear and nonlinear pile-soil systems, and is compared with the behavior of buildings with rigid base under moderate and large earthquakes. Furthermore, the parametric influence of the system is studied. It suggests that the contact state of pile and soil changes from contact and slippage to separation under seismic load, and the behavior of the building supported on a pile foundation is different from a rigid base. Moreover, the nonlinear seismic response of a building including the PSSI effect is different from the linear response. The model built by ANSYS® is easy to apply for the engineering applications.

COMPUTATION MODEL AND PARAMETER DETERMINATION

Computation model

The hypotheses of the model are as follows: super-structure is simplified to shear-type RC frame structure, the pile group is assembled into single pile with the abilities of bending and shearing, and super-structure, piles and soil around piles present linear behavior, lateral soil resistance is nonlinear, furthermore, the contact nonlinear effect between piles and soil is taken into account.

governing equations

In present, Penzien model is one of soil-pile interaction system models widely used in practice, because it is simple and conceptual definitude. But this model does not consider the dynamic effect of soil around pile directly, and motion input is multi-points input format with different soil layer different motion input.

The modified model takes account of several factors based on the Penzien model. First, free-field ground (soil around pile) simulated by PLANE element is considered into the model directly, and the viscous damping elements (COMBIN14) are set at the boundary of the free-field ground to simulate the radiation damping, thus motion input in this model can be input from the rock with the one motion input datum, so this model simplifies the computation process and presents dynamic interaction between the piles and soil factually. Second, pile is simulated by BEAM element and two vertical springs (CONTAC12) at the end of raft present the rocking effect. Third, using p-y curve simulates the nonlinear resistance between pile and soil, then the contact state of the interface between pile and soil is presented under dynamic load with contact elements,. The PSSI model is shown in Figure 1.

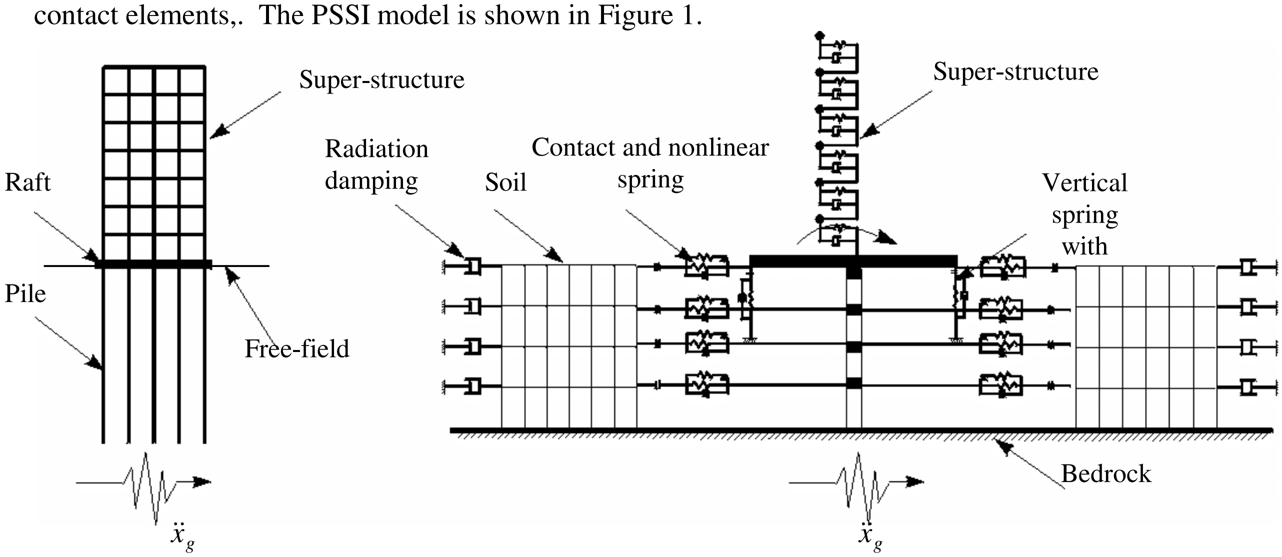


Figure 1. Simplified model of a pile-soil-structure system

The governing equations referred in [2] and [3] can be given as follows:

Super-structure:

$$\mathbf{M}_{\mathbf{r}}(\ddot{\mathbf{x}}_{\mathbf{r}} + \ddot{\boldsymbol{\theta}}\mathbf{h}) + \mathbf{C}_{\mathbf{r}}\dot{\mathbf{x}}_{\mathbf{r}} + \mathbf{K}_{\mathbf{r}}\mathbf{x}_{\mathbf{r}} = -\mathbf{M}_{\mathbf{r}}\mathbf{1}\ddot{\mathbf{x}}_{g} \tag{1}$$

Pile foundation: $$\mathbf{M_P \ddot{x}_P + C_P \dot{x}_p + K_p x_P + F = M_p 1} \ddot{x}_g \tag{2}$$

Raft: $$\sum_{i=1}^{n} m_{ri}(\ddot{x}_{ri} + h_i\ddot{\theta} + \ddot{x}_g) + m_0(\ddot{x}_0 + \ddot{x}_g + \frac{h}{2}\ddot{\theta}) + f_0 = 0 \tag{3}$$

$$J_0\ddot{\theta} + \sum_{i=1}^{n} m_{ri}h_i(\ddot{x}_{ri} + h_i\ddot{\theta} + \ddot{x}_g) + m_0(\ddot{x}_0 + \ddot{x}_g + \frac{h}{2}\ddot{\theta})\frac{h}{2} + M = 0 \tag{4}$$

Soil around pile: $$\mathbf{M_s \ddot{x}_s + C_s \dot{x}_s + K_s x_s - F = M_s 1} \ddot{x}_g \tag{5}$$

In which the subscript **r**, **p** and **s** stand for superstructure, pile and soil, respectively; **M, C and K** are the mass, damping and stiffness matrices, respectively; **X**, **h** and **F** are the displacement vector, floor height vector of super-structure and lateral soil resistance vector, respectively; m_0, J_0, θ, h and x_0 are the mass, the moment of inertia, the rotation angle, the thickness and the relative displacement of the raft, respectively; f_0 and M are the horizontal resistance and resistant moment of raft given by soil; h_i is the distance from the floor to the raft; $\ddot{x}_g$ is the acceleration of motion input.

Parameter determination

Super-structure parameter

Super-structure is simplified to shear-type structure, whose parameters determined according to the reference [4].

The horizontal resistance and resistant moment of raft

The horizontal resistance of raft is computed by the equation (6)

$$f_0 = k_0(x_0 - x_s) + c_0(\dot{x}_0 - \dot{x}_s) \tag{6}$$

where k_0 is the lateral soil resistant stiffness coefficient of the raft, which can be developed as

$$k_0 = b_{f0}\frac{m^* h^2}{2} \tag{7}$$

where b_{f0} is the computational width of the side of the raft, which is determined by the reference [5]; c_0 is the damping factor; and m^* is the resistance factor of the soil to raft, which is referred to the reference [6].

The resistant moment of raft can be computed with equation (8)

$$M = K_{\theta\theta}^{cap}\theta \tag{8}$$

where $K_{\theta\theta}^{cap}$ is the total rotational stiffness, can be determined by the reference [7]

$$K_{\theta\theta}^{cap} = K_{RR} + \Sigma K_{\theta\theta} \tag{9}$$

where K_{RR} is the rocking stiffness of a pile group, $K_{RR}=\Sigma r_i.\times F_i$, in which r_i is distance between the center of rotation and the pile heads center, and F_i is the axial force at the pile heads, $\Sigma K_{\theta\theta}$ is the rotational stiffness at the head of pile, when the heads of a pile group are the raft, the equation (9) can be modified as equation (10).

$$K_{\theta\theta}^{cap} = K_{RR} + K_{\theta\theta} \tag{10}$$

where $K_{\theta\theta}$ is the rotational stiffness of the raft, $K_{\theta\theta} = \frac{8Gr_0^3}{3(1-\nu)}$, $r_0 = \sqrt[4]{\frac{4I_0}{\pi}}$, I_0 is the moment of inertia of the raft, G is the shear module of soil, ν is the Poisson's ratio of soil.

In this model, the rocking effect is simulated by the two vertical springs considering the contact influence between the raft and soil at the side of raft; the vertical spring stiffness can be developed as

$$K_\theta = \frac{K_{\theta\theta}^{cap}}{R^2} \tag{11}$$

where R is the distance from the center of the raft to the side of the raft.

Lateral soil resistant stiffness coefficient determination

There are many methods to determine the lateral soil resistant stiffness coefficient, in which the most commonly used method to solve the nonlinear lateral soil resistance is p-y relation curve. Lateral loads on piles are resisted by the surrounding soil whose behavior is characterized by lateral soil resistance per unit length of pile, p, as a function of lateral displacement, y. The p-y relation is generally developed on the basis of a semi-empirical curve, which reflects nonlinear resistance of the local soil surrounding the pile at specified depth. The two most commonly used p-y models are those proposed by Matlock (1970) for soft clay and by Reese et al. (1974) for sand. In this paper, the p-y model proposed by Reese for sand is used to analysis the 4-storey building supported on piles. The parameter determination of p-y relation curve can be referred to the reference [6].

PSSI system damping

In the pile-soil-structure system, the damping includes two parts: the material damping and the radiation damping .The material damping is approximated with the Rayleigh approach. The damping matrix is

$$\mathbf{C}=a\mathbf{M}+\beta\mathbf{K} \tag{12}$$

where α and β are coefficients. The values of a and β are computed by using the first and second modal frequencies (j=1 and j=2) with equation (13)

$$\xi_j = \frac{\eta}{2} = \frac{1}{2}\left(\frac{\alpha}{\omega_j} + \beta\omega_j\right) \tag{13}$$

for the steel structure $\xi_1 = \xi_2$ =1%, and for the reinforced concrete structure $\xi_1 = \xi_2$ =5%. In this paper, the equivalent damping ratio [8] is taken as

$$\tilde{\xi} = \frac{\tilde{\omega}^2}{\omega_s^2}\xi + \left(1 - \frac{\tilde{\omega}^2}{\tilde{\omega}_s^2}\right)\xi_g + \frac{\tilde{\omega}^3}{\omega_s^3}\frac{\bar{s}^3\bar{m}}{\bar{h}}\left[0.036\frac{2-\nu}{\bar{h}^2} + 0.028(1-\nu)\right] \tag{14}$$

where $\tilde{\xi}$ is the equivalent damping ratio; ξ and ξ_g are the super-structure damping ratio and the material damping ratio of the soil; ω_s and $\tilde{\omega}$ are the first frequency of the super-structure and the PSSI system; $\bar{s}$ is the ratio of the stiffness of the super-structure to the soil, which is computed as $\bar{s} = \frac{\omega_s h^*}{v_s}$; $\bar{m}$ is the mass ratio, $\bar{m} = \frac{m^*}{\rho a^3}$; $\bar{h}$ is the slenderness ratio, $\bar{h} = \frac{h^*}{a}$,and where $h^*$and m^* are the equivalent high and mass of the first mode shape of the super-structure, v_s and ρ are shear-wave velocity and the mass density of the soil, a is the characteristic length of the bottom of the super-structure.

The radiation damping which is simulated by the viscous damping elements (COMBIN14) set at the boundary of the free-field ground can be computed using equation (15) referred to the reference [9].

$$c_s' = a_i m_{si} \tag{15}$$

where m_{si} is the mass of the soil layer; a_i is valued according to the way proposed by Seed, $a_i=\lambda_i\omega_i$, in which λ_i =0.05, and $\omega_i = v_{si}/(2h_{si})$, h_{is} is the thickness of the soil layer.

BUILDING THE MODEL WITH ANSYS® SOFTWARE

Choosing the element

Using the before-mentioned method, the model is established by ANSYS® software. Seven kinds of elements are used in this model, which are MASS21, COMBIN14, PLANE42, BEAM3, CONTAC12, COMBIN40 and LINK1 elements. MASS21 element is used to simulate the mass of the super-structure, and COMBIN14 element is used to simulate the stiffness of super-structure and the radiation damping at the boundary of the soil, and PLANE42 element is used to simulate the free-field soil and the raft, and BEAM3 element is used to simulate the pile, and CONTAC12 element with the contacting ability is used to simulate the rocking spring of the side of raft, and COMBIN40 element with the contacting and nonlinear ability is used to simulate the nonlinear lateral soil resistance between the soil and pile. LINK1 element is the dumb element to help simulate floors of the super-structure and the rocking effect.

Building the model

Building the model using ANSYS® software includes two parts: building the geometric model and building the mechanical model. Building the geometric model uses the direct generation method to define the nodes and elements of a model directly on the basis of the geometric size. And then, the geometric model is turned into the mechanical model using constraint equations to establish the special associations among nodal degrees of freedom and applying the boundary condition to the model. The key problem in this model is how to simulate the rocking effect of the PSSI system, the actions referred [10] are shown in Figure 2. First, the cross point of the PLANE42 element simulating the raft, the BEAM element simulating the pile and the LINK1 element simulating the first floor of the superstructure is turned into rigid point using the following constraint equation in ANSYS® format.

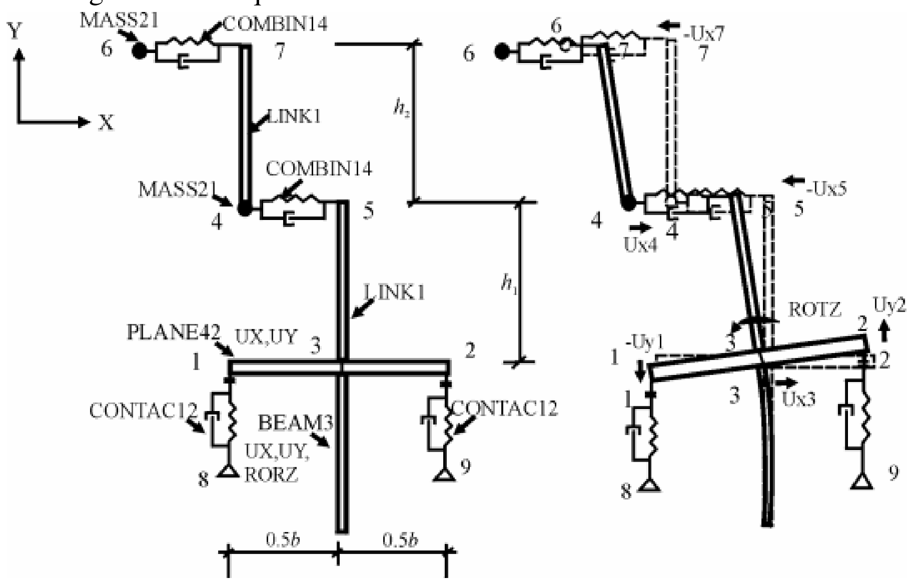


Figure 2. Simulating to rocking effect

$$\text{CE,1,0,2,UY,1,1,UY,-1,3,ROTZ,-}b \tag{16}$$

Then, the LINK1 elements simulating floors are coupled with the cross point using the constraint equations, so that the LINK1 elements simulating floors can keep the same rotation angle with the top of the BEAM3 element simulating the pile. The constraint equation of the LINK1 element simulating the first floor is as

$$\text{CE,2,0,3,UX,1,5,UX,-1,3,ROTZ,-}\ h_1 \tag{17}$$

In the same way, the constraint equations of the LINK1 elements simulating other floors can be generated in the similar form.

Finally, the two vertical springs to simulate the rocking effect are set at the sides of the raft, with the constraint equation (18).

$$CE,4,0,8,UX,1,1,UX,-1 \tag{18}$$

In this way, the rocking effect can be simulated in the model by ANSYS® software.

ANALYTIC RESULT BY ANSYS® SOFTWARE

In this paper, the transient dynamic analysis (called time-history analysis) is used to analyze the seismic response of a 4-storey building supported on piles. In ANSYS® software, three transient dynamic analysis methods are available: full, reduced and mode superposition, where the full solution method solves directly and needs no additional assumptions, and is suit to nonlinear problem.

The input motion is the time history of the horizontal displacement and input from the bedrock at the bottom of the pile group.

Computation model of a 4-storey frame supported on a pile group

A 4-storey and 3-spans frame supported on a pile group with the raft is analyzed as a typical common structure in II site as shown in Figure 3, and the seismic fortification intensity of the building area is 8°. The weight for the first and the forth floors is 1200kN, the weight for other floors is 1000kN; the first story stiffness is 0.544×10^5 kN/m, other story stiffness is 0.723×10^5 kN/m; the thickness and width of the raft are 1m and 4m, the section of the pile is $0.9\times0.9\text{m}^2$, and the length of the pile is 15m, the elastic modulus of the concrete is $3.0\times10^4\text{N/mm}^2$; the soil around the pile is sand with moderate consistency, the elastic modulus of the soil: $E = 86\text{MPa}$, the Poisson's ratio of the soil: v=0.25,the angle of internal friction for soil: $\varphi = 35°$, and $K_h = 15000\text{kN/m}^3$.

The time history of the horizontal ground acceleration employed is shown in Figure 4, with 3000 points at equal spacing of 0.01 sec, and the peak value are 0.22g and 0.40g. This time history of the acceleration is translated to the time history of the displacement.

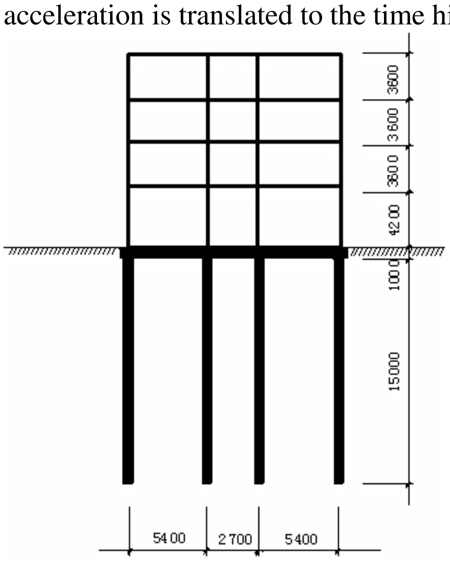


Figure.3 4-storey and 3-spans frame supported on a pile group with the raft

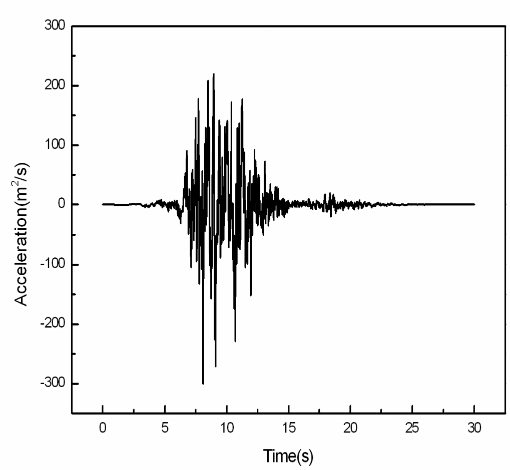


Figure.4 The time history of acceleration from Boston earthquake (0.22g)

The result of analysis

The seismic analysis for the frame using the before-mentioned model is done with the nonlinear pile foundation under the moderate (the peak of the acceleration is 0.22g) earthquake and large (the peak of the acceleration is 0.40g). Then this response is compared with the responses of the rigid foundation and the linear pile foundation to investigate the influence of the pile-soil interaction and nonlinear effect of the pile foundation on the super-structure.

The maximum interstory shear, interstory displacement and story displacement of the frame in different conditions of foundation are computed under the moderate earthquake (0.22g) and the large earthquake (0.40g). As shown in Table 1 the maximum interstory shear and the minimum story displacement are in the case of the rigid foundation. The interstory shear of the linear foundation condition is larger than that of the nonlinear foundation condition, and the story displacement of the linear foundation condition is smaller than that of the nonlinear foundation condition. The natural frequencies in different conditions of foundation are shown in Table 2. It can be seen that the natural frequency of the nonlinear foundation condition is smallest.

The time histories of the displacement of the top story in three different foundation conditions are shown in Figure 5 for the moderate earthquake (0.22g) and Figure 6 for the large earthquake (0.40g). From Figures 5 and 6, it can be illustrated that the maximum displacement of the top story is in case of the nonlinear foundation condition.

Table 1. The maximum interstory shear, interstory displacement and story displacement of the frame

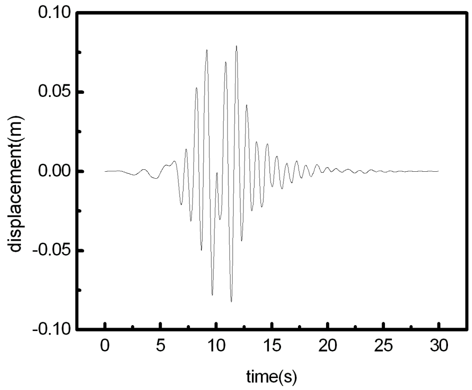
	Number of story	maximum interstory shear (kN)		maximum interstory displacement (m)		maximum story displacement (m)	
		Rigid	SSI	Rigid	SSI	Rigid	SSI
Moderate earthquake (0.22g)	1	1139.0	887.0 (1029.0)	0.0209	0.0163 (0.0186)	0.0500	0.0559 (0.0570)
	2	927.0	813.3 (913.1)	0.0128	0.0112 (0.0126)	0.0542	0.0651 (0.0599)
	3	750.8	650.6 (728.9)	0.0107	0.0093 (0.0104)	0.0644	0.0731 (0.0694)
	4	448.0	420.6 (444.8)	0.0068	0.0064 (0.0067)	0.0711	0.0798 (0.0750)
Large Earthquak e (0.40g)	1	2071	1996 (1998	0.0381	0.0367 (0.037)	0.0910	0.1060 (0.097)
	2	1686	1716 (1660)	0.0233	0.0237 (0.0229)	0.0986	0.1244 (0.1219)
	3	1365	1288 (1325)	0.0195	0.0184 (0.0189)	0.1171	0.1421 (0.1394)
	4	814.5	789.98 (808.8)	0.0123	0.0119 (0.0122)	0.1292	0.1585 (0.1449)

annotation: The numerical value in () is the result in the case of the linear foundation condition.

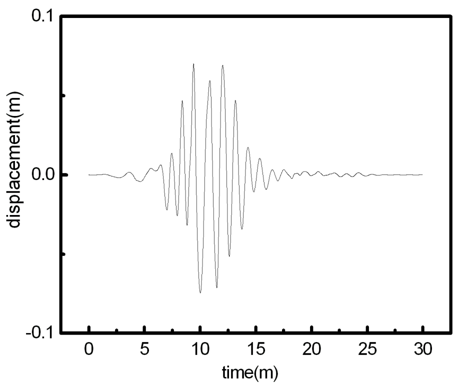
Table 2.Natural frequencies in different foundation conditions

Condition of foundation	Rigid	SSI(linear)	SSI(nonlinear)
ω_1	14.85	13.77	6.594
ω_2	18.36	16.89	11.66
ω_3	23.59	21.24	18.64
ω_4	24.51	24.34	24.26

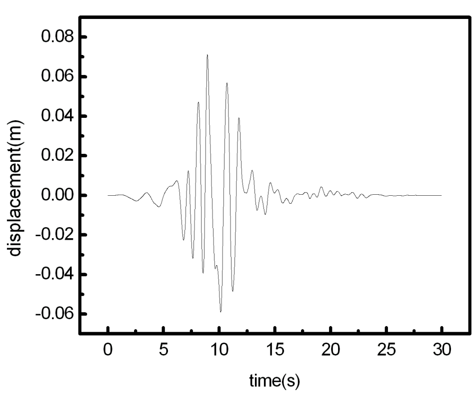
The contact states between the pile and the soil is shown in Figure 7 for the moderate earthquake (0.22g) and Figure 8 for the large earthquake (0.40g). In Figures 7 and 8, "$\text{stat}=1$" stands for that the contact state between the interfaces of the pile and soil is close, "$\text{stat}=3$" stands for that the contact state between the interfaces of the pile and soil is open, and "$\text{stat}=2$" stands for that the contact state between the interfaces of the pile and soil is slip. From Figures 7 and 8, it can be shown that the contact state between the pile and the soil changes from contact and slippage to separation with seismic load under the moderate and large earthquakes.



(1) Nonlinear foundation condition

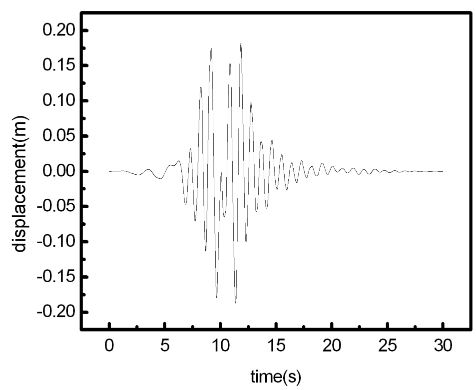


(2) Linear foundation condition

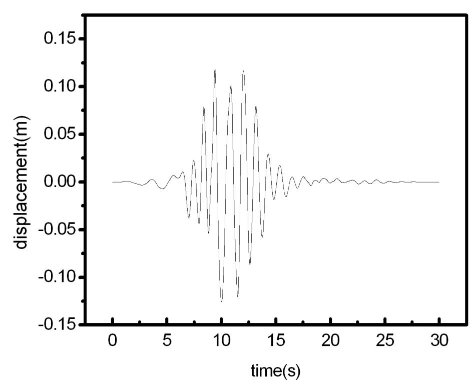


(3) Rigid

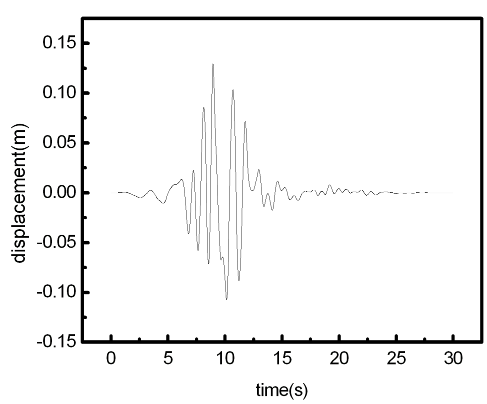
Figure 5. The time history of the displacement of the top story under moderate earthquake



(1) Nonlinear foundation condition



(2) Linear foundation condition



(3) Rigid

Figure 6. The time history of the displacement of the top story under large earthquake

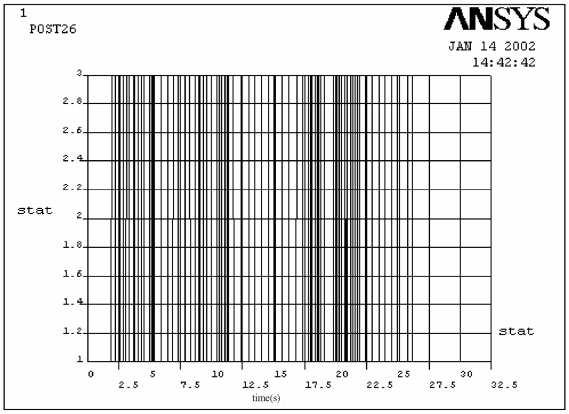


Figure 7.the contact state between the pile and soil under moderate earthquake

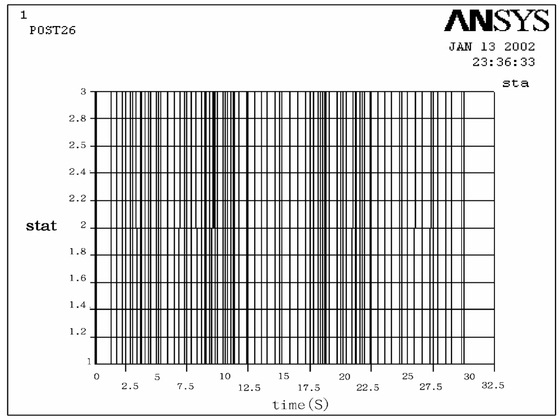


Figure 8.the contact state between the pile and soil under large earthquake

CONCLUSIONS

Through the seismic response analysis of the frame supported on a pile group under the moderate and large earthquakes, the following conclusions can be summarized:

1. The modified simplified nonlinear pile-soil-structure interaction (PSSI) model can consider the influence of the free-field on the super-structure directly, the nonlinear effect, and simplified the input method of Penzien model. Thus, it can be applied to engineering conventionally.
2. The analysis shows that the contact state of the pile and the soil changes from contact and slippage to separation with the seismic load under the moderate and large earthquakes. So it is necessary to consider the contact nonlinear effect in PSSI system.
3. In the case of nonlinear foundation condition, the seismic behavior is different from that in the rigid foundation condition and linear foundation condition.

REFERENCES

1. Penzien J, Scheffey C. F., Parmelee R. A. “Seismic analysis of bridges on long piles.” ASCE, 1964; 90(EM3): 223-254.
2. Hui Li, “Soil-structure dynamic Interaction .” ChongQing: PH.D. Dissertation in ChongQing Jianzhu University, 1998:63-69.
3. Takewaki I. “Inverse Stiffness Design of Shear-Flexural Building Models Including Soil-Structure Interaction .” Engineering Structures, 1999;Vol.21: 1045- 1054.
4. Xi-an Zhao, “Construction and Structure Design of the tall buildings .” China architecture & building press, 1992: 203-204.
5. “Technical Code for Building pile foundation.” JGJ 94-94. Beijing: China architecture & building press, 1995: 251-252.
6. Ren-li Hu. “The analysis and design of the pile foundation of bridge.” Beijing: China railroad press, 1987: 86-161.
7. Liam Finn W. D, Wu G, Thavaraj T. “Soil-Pile-Structure Interaction Proceedings of Seismic Analysis and Design for Soil-Pile-Structure Interaction.” Minneapolis, Minnesota: 1997:1-20.
8. Wolf J. P. “Foundation Vibration Analysis Using Simple Physical Models [M]. PTR Prentice Hall Englewood Cliffs.” 1995.
9. Song-tao Wang, Zi Cao. “Modern aseismatic design method.” Beijing: China architecture & building press, 1997: 58-162.
10. Feng-Xia Wang. “Seismic performance analysis of piles with raft -soil-structure interaction.” Harbin: Master Thesis in Harbin Institute of Technology, 2002: 22-50.