유연한 기초 위에 세워진 구조물의 지진거동

Seismic Response of Structure on Flexible Foundation

김 용 석*
Kim, Yong Seok

국문요약

그 동안 구조물에 대한 지진해석이 기초와 지반의 특성을 무시하고 기초가 매우 단단한 것으로 가정하고 수행되었다. 최근 구조물-지반 상호작용에 관한 연구결과 구조물 지진거동이 기초와 지반의 특성에 따라 심하게 영향을 받을 수 있다는 것이 알려졌다. 전형적인 구조물-지반 상호작용 영향은 무한강성 무질량 기초의 운동학적 상호작용과 지반과 구조물 사이에서 발생하는 관성상호작용이다. 운동학적 상호작용은 묻힌 기초의 경우에는 중요하지만, 수직으로 전달되는 지진파를 받는 지표면상 기초의 경우에는 무시될 수 있다. 이 논문에서는 멕시코시티 4개 건물에 대해 관성상호작용만을 고려하고 1985년 멕시코시티 동서방향 지진기록을 사용하여 구조물의 지진거동을 조사하였다. 연구는 지표면상 기초나 말뚝기초를 가진 구조물에 대해 선형 및 비선형 지반조건을 고려하여 수행하였으며, 연구결과를 매우 견고한 기초를 갖는 구조물에 대한 것과 비교하였다.

주요어 : 지진거동, 구조물-지반상호작용, 말뚝기초, 비선형지반

ABSTRACT

Seismic analyses of structures were carried out in the past assuming a rigid base and ignoring the characteristics of foundations and the properties of the underlying soil. Resent soil-structure interaction studies show that seismic response of structure can be affected significantly by these fators. Typical effects of the soil-structure interaction are the kinematic interaction of a rigid massless foundation and the inertial interaction between underlying soil and structure. The kinematic interaction effect is particularly important for embedded foundations and can be ignored for surface foundations with vertically propagating waves. In this study, seismic response of structure was investigated with four buildings in Mexico City considering only the inertial interaction effect and using the E-W components of the 1985 Mexico City earthquake records. The study was carried out for surface foundations and pile foundations with linear and nonlinear soil conditions, comparing the results with those of the rigid base.

Key words *: seismic response, soil-structure interaction, pile foundation, nonlinear soil*

1. Introduction

Seismic analyses of buildings subjected to earthquake excitation were carried out in the past assuming a rigid base regardless of the characteristics of the foundation and the properties of the underlying soil. It is, however, recognized that these factors can affect significantly the structural response. The effects of foundation and soil, commonly known as soil-structure interaction, can be studied in two separate phrases.(1)

First, the motion of a massless foundation, before any structure is built, would be different from that recorded at the free surface of the soil. The differences will consist in general of a filtering of the translational motions in the high frequency range and the appearance of rotational motions. This effect is known as kinematic interaction, which is a function of the geometry of the foundation and the type of propagating waves, and particularly important for embedded foundation.

Second, once the structure is built, the inertia

* member · Assistant Professor, Dept. of Architecture, Mokpo National University

forces generated by the structural vibrations will give rise to base shear, axial forces and overturning moments which will alter the motion of the foundation. The acceleration of the base of the structure will thus be different from the one that would be recorded on the free surface of the soil or the one of the foundation by itself. This effect is known as inertial interaction.

The kinematic interaction does not affect significantly the seismic behavior of surface foundations unless one considers horizontally travelling waves and the effect can be ignored in most cases for the analysis. However, the seismic response of the structure on a flexible foundation will be affected significantly by the inertial interaction. In this study, only the inertial interaction effect was considered to estimate the effect of flexible surface or pile foundations including linear and nonlinear soil conditions, on the response of structures applying the horizontal seismic motions at the base of the foundation.

2. Modelling of System

A substructure approach was used for the analysis of structures on flexible foundations. It was assumed that the motion at the base of the surface foundations was the same as that at the free field neglecting the kinematic interaction.

The foundations stiffnesses were determined in the frequency domain using a pseudo 3-D finite element model suggested by Angelides.[2] It was assumed that the layered soil deposit rests on a much stiffer rock. The soil was divided into a cylindrical core region under the equivalent circular foundation and a far field. The soil in the core region was modelled by toroidal finite elements discretizing the displacements in the vertical and radial directions. The displacement in the circumferential direction was expanded into a Fourier series with n=1 for horizontal and rocking excitation. The far field was reproduced by a consistent lateral boundary used by Blaney et al.[3] The lateral boundary was placed at the edge of the foundation for the linear analyses and at a distance of approximately 15 pile radii from the edge of the foundation for the nonlinear studies.

The piles in a square arrangement were idealized assuming an equivalent circular arrangement that would produce the same rotational moment of inertia with respect to the minor axis of the foundation, and the soil annuli were arranged to coincide with the locations of the piles. It was also assumed that all piles around a soil ring had the same horizontal displacements varying with $\cos\theta$ for the horizontal and rocking excitation. The dynamic stiffness matrices for the piles considered as 3-D linear members were then added to the appropriate terms of the dynamic stiffness matrix of the finite element region.[4]

For nonlinear analyses, the Ramberg-Osgood soil model was used with the yield strain 5×10^{-5}, α =0.025 and r=2. The soil properties were adjusted according to the level of strains at the end of each linear elastic analysis using an iterative equivalent linearization method, but the soil in the far field and the piles were assumed to remain elastic.

Finally seismic analyses of the structure supported on an elastic medium represented by the dynamic stiffness matric of the foundation were performed in the frequency domain applying the base motions.[5]

3. Seismic Response of Structure

3.1 Introduction

To assess the effect of pile foundation on the seismic response of buildings, four reinforced concrete buildings in Mexico City, supported on pile foundation, were considered. In addition analyses were conducted assuming mat foundation to compare the results. The characteristics of the buildings are summarized in Table 1. The mass density of the buildings was assumed to be uniform along the height and taken as 3535 KN/m^3, and 5% structural damping was also assumed. The fundamental period of the buildings on a rigid base was estimated multiplying 0.1 by the number of stories.

Rectangular foundations were idealized as equivalent circular foundations. Young's modulus and unit weight of the piles were taken as those of concrete, 2.07×10^7 KN/m^2 and 23.6 KN/m^3 respectively, and 0.5% internal damping was assumed for the piles. Buildings A, C and

Table 1 Building Properties

(unit : m-sec)

BLDG	Story	Building Size	Height	Pile			Equivalent FDN Radius	Period
				Number	Diameter	Length		
A	9	9.39x23.20	24.5	21	0.60	22.0	8.32	0.9
B	10	25.0x40.00	30.0	194	0.35	35.0	17.84	1.0
C	11	13.6x27.86	30.0	47	0.40	20.0	10.98	1.1
D	19	30.0x42.76	78.8	272	0.60	21.3	20.21	1.9

D have floating piles, while the piles in building B were end bearing.

The soil has a depth of 35 m, unit weight of 14.1 KN/m^3, shear wave velocity of 70 m/sec, a Poisson's ratio of 0.4 and 10% internal damping.

The dynamic horizontal and rocking stiffness of pile groups in an equivalent circular arrangement were computer at frequencies of 0, 0.25, 0.5, 0.75, 1, 2, 3, 4, 5 and 10 Hz. The range of primary interest in this study is 0 to 1 Hz. Analyses were conducted in the frequency domain interpolating the stiffness for the intermediate frequencies.

The buildings were modeled as single degree of freedom systems, close coupled multiple degree of freedom systems and equivalent shear beams. All models were subjected to the E-W component of the record obtained at the SCT building during the 1985 Mexico City earthquake, which had a predominant frequency of 0.5 Hz and lasted for about 180 seconds. This motion was assumed to occur at the free surface of the soil neglecting any possible filtering or kinematic interaction effects caused by the pile foundations.

3.2 Results for Single Degree of Freedom Model

The equivalent SDOF model for each building was obtained by lumping three quarters of the total mass of the building at a height equal to two thirds of the total height, and the stiffness of the system was computed by matching the natural frequency of the building. (Table 2)

Table 3 shows for each system the natural frequency, effective damping and absolute acceleration of the mass considering the building on a rigid base, on a pile foundation or on a surface mat foundation with linear and nonlinear soil behavior. It can be seen that in all cases the flexibility of the foundation results in a decrease in the natural frequency and an increase in the effective damping, and nonlinear soil behavior causes a further reduction in the natural frequency.

Table 2 Characteristics of SDOF Model

(unit : KN-m-sec)

Building	Period	Equivalent Height	Equivalent Mass	Equivalent Stiffness	Damping Ratio
A	0.9	16.3	1443.7	7179.	0.05
B	1.0	20.0	8105.8	32653.	0.05
C	1.1	20.0	3071.2	10225.	0.05
D	1.9	52.5	27325.8	30493.	0.05

Table 3 SDOF Model

(unit : Hz-m-sec)

Building		Rigid Base	Pile Foundation		Surface Foundation	
			Linear	Nonlinear	Linear	Nonlinear
A	f_o	1.11	0.83	0.80	0.73	0.66
	D_{eff}	0.05	0.10	0.09	0.10	0.10
	a_{max}	2.41	2.47	2.59	2.79	3.50
B	f_o	1.00	0.83	0.79	0.66	0.59
	D_{eff}	0.05	0.14	0.15	0.14	0.13
	a_{max}	2.36	2.64	2.73	3.22	3.92
C	f_o	0.91	0.66	0.60	0.60	0.51
	D_{eff}	0.05	0.10	0.10	0.10	0.11
	a_{max}	2.72	3.52	4.23	4.26	4.20
D	f_o	0.52	0.30	0.23	0.26	0.20
	D_{eff}	0.05	0.09	0.12	0.09	0.12
	a_{max}	8.13	1.65	0.63	1.01	0.37

The effect of these changes in the natural frequency and effective damping is illustrated graphically in Figures 1 through 4 for the pile foundations with the linear soil. It is interesting to notice that for Buildings A, B and C the amplitude of the peak decreases due to the increase in effective damping, but the amplitude at 0.5 Hz, which is the predominant frequency of the

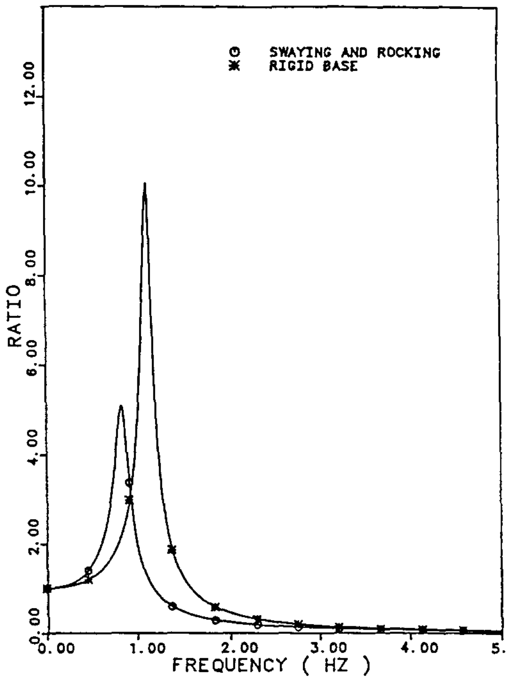

Fig. 1 Transfer Funct. of Top w.r.t. Ground
BLDG. A : SDOF Model (w/Pile)

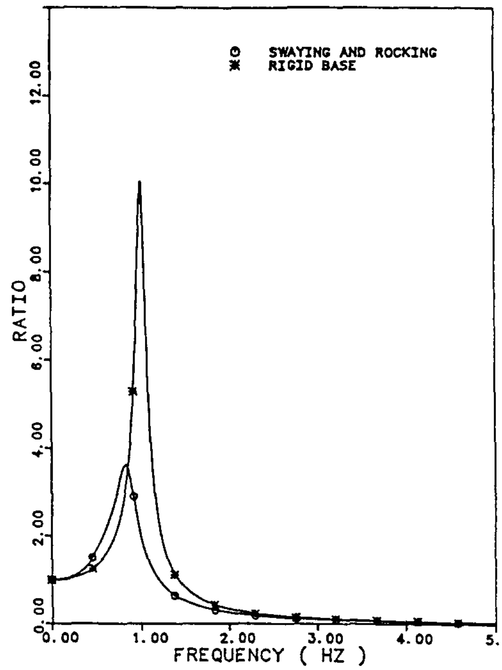

Fig. 2 Transfer Funct. of Top w.r.t. Ground
BLDG. B : SDOF Model (w/Pile)

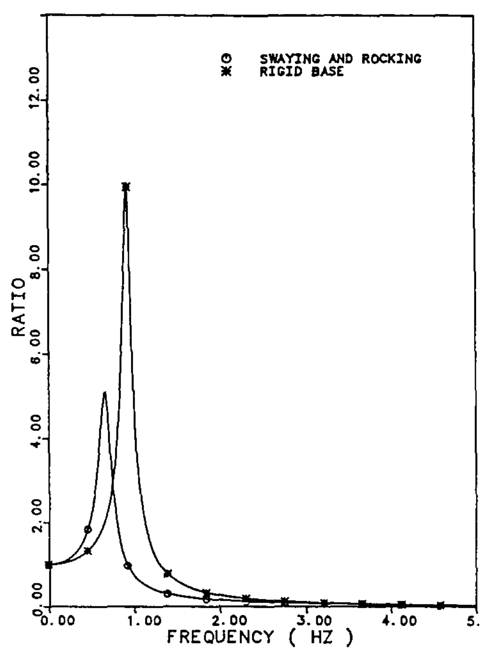

Fig. 3 Transfer Funct. of Top w.r.t. Ground
BLDG. C : SDOF Model (w/Pile)

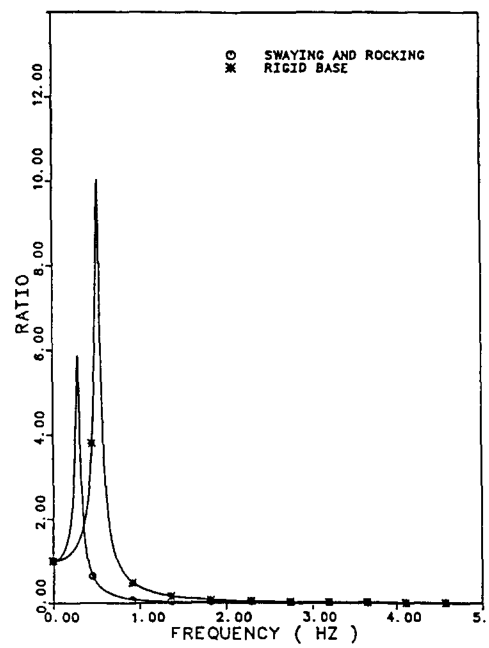

Fig. 4 Transfer Funct. of Top w.r.t. Ground
BLDG. D : SDOF Model (w/Pile)

earthquake, is higher than for the rigid base. For Building D, on the other hand, the amplitude around 0.5 Hz decreases substantially. Due to the changes in the natural frequency and effective damping, Building A, B and C experience an increase in the response acceleration. The increase is always smallest for the pile foundation with the linear soil, followed by the pile foundation with nonlinear soil, the mat foundation with linear soil, and finally the mat foundation with nonlinear soil.

Table 4 shows the maximum base shear and overturning moment for each building as well as the maximum relative displacement of the mass with respect to the ground. The trends for the base shear and overturning moment are similar to those for the maximum absolute acceleration of the mass. The much larger increases in maximum relative displacement compared to the absolute accelerations for Building A, B and C are significant from a practical point of view when considering neighboring structures and the possibility of hammering effects. However, the reductions of the maximum relative displacements for building D are smaller than those of the accelerations.

Table 4 SDOF Model

(unit : KN-m)

Building		Rigid Base	Pile Foundation		Surface Foundation	
			Linear	Nonlinear	Linear	Nonlinear
A	y_{max}	0.05	0.09	0.10	0.13	0.20
	V_{max}	3479.	3555.	3733.	4027.	5054.
	M_{max}	56868.	58100.	60993.	65800.	82594.
B	y_{max}	0.06	0.11	0.12	0.18	0.27
	V_{max}	19100.	21392.	22139.	26121.	31776.
	M_{max}	381916.	427733.	442636.	522254.	635340.
C	y_{max}	0.08	0.20	0.28	0.29	0.50
	V_{max}	8342.	10816.	12992.	13072.	16640.
	M_{max}	166812.	216246.	259723.	261324.	332696.
D	y_{max}	0.74	0.49	0.31	0.40	0.25
	V_{max}	22077.	45035.	24818.	27630.	14798.
	M_{max}	11662599.	2365067.	1303415.	1450909.	777251.

It can be concluded that for the soil conditions of Mexico City the flexibility of the foundation has a negative effect on the seismic response of building having an initial natural frequency on a rigid base of about 1 Hz. The buildings perform better on pile foundations than on a surface mat foundation. However, the building which has an initial natural frequency on a rigid base close to the predominant frequency (0.5 Hz) of the earthquake, benefits from the inertial interaction effects, showing more pronounced effects for surface mat foundations.

3.3 Results for Multi-Degree of Freedom Models

To assess the validity and accuracy of the equivalent SDOF model, the buildings were also modeled as close coupled MDOF systems with lumped masses of each story and connecting springs. The stiffness of the springs was selected to provide the same natural frequency. The main difference between this model and the equivalent SDOF system will be the inclusion of the higher modes of vibration of the structure.

The results for the MDOF models are summarized in Tables 5 and 6. It can be seen that the natural frequency of the first mode with a flexible foundation is essentially the same as computed for the SDOF systems, and the effective damping associated with the first mode is similar to that of the SDOF model. The maximum acceleration at the top of the building, the maximum shear force and overturning moment at the base, and the maximum relative displacement at the top are somewhat larger than those of the equivalent SDOF system, even for the rigid case. However, the general effects of the foundation flexibility are similar to those discussed for the SDOF models.

The analyses with the MDOF models indicate again that the flexibility of the foundation has a detrimental effect on the seismic response of buildings with a natural frequency on a rigid base of about 1 Hz, and is beneficial for the building with a natural frequency on a rigid base close to 0.5 Hz.

Table 5 MDOF Model

(unit : Hz-m-sec)

Building		Rigid Base	Pile Foundation		Surface Foundation	
			Linear	Nonlinear	Linear	Nonlinear
A	f_0	1.11	0.83	0.80	0.74	0.66
	D_{eff}	0.05	0.09	0.08	0.09	0.08
	a_{max}	2.67	2.92	3.15	3.55	4.58
B	f_0	1.00	0.83	0.79	0.67	0.60
	D_{eff}	0.05	0.14	0.17	0.13	0.13
	a_{max}	2.58	3.09	3.28	4.16	5.22
C	f_0	0.91	0.66	0.60	0.60	0.52
	D_{eff}	0.05	0.09	0.09	0.09	0.10
	a_{max}	3.04	4.45	5.66	5.71	7.60
D	f_0	0.52	0.30	0.23	0.26	0.20
	D_{eff}	0.05	0.08	0.10	0.08	0.10
	a_{max}	9.76	3.32	1.81	2.33	1.59

Table 6 MDOF Model

(unit : KN-m)

Building		Rigid Base	Pile Foundation		Surface Foundation	
			Linear	Nonlinear	Linear	Nonlinear
A	y_{max}	0.06	0.13	0.15	0.19	0.31
	V_{max}	4147.	4850.	5063.	5361.	6585.
	M_{max}	57604.	65492.	69018.	74285.	93851.
B	y_{max}	0.07	0.16	0.18	0.27	0.40
	V_{max}	23621.	29569.	31176.	35327.	42214.
	M_{max}	381272.	487144.	510049.	600515.	731855.
C	y_{max}	0.10	0.29	0.43	0.43	0.76
	V_{max}	9913.	14104.	16751.	16680.	20626.
	M_{max}	169081.	242691.	294155.	294060.	370993.
D	y_{max}	0.94	0.73	0.48	0.60	0.40
	V_{max}	251206.	44181.	24426.	26121.	14019.
	M_{max}	11967318.	264930.	1374719.	1600488.	821922.

3.4 Results of Shear Beam Models

In addition to the MDOF models, the buildings were modelled as continuous shear beam with uniform mass and stiffness along the height. The corresponding results are presented in Tables 7 and 8. The results are very similar to those obtained with the MDOF models.

Table 7 Shear Beam Model

(unit : Hz-m-sec)

Building		Rigid Base	Pile Foundation		Surface Foundation	
			Linear	Nonlinear	Linear	Nonlinear
A	f_0	1.11	0.83	0.80	0.74	0.66
	D_{eff}	0.05	0.10	0.09	0.09	0.09
	a_{max}	2.62	2.82	3.03	3.40	4.31
B	f_0	1.00	0.83	0.79	0.67	0.59
	D_{eff}	0.05	0.15	0.18	0.14	0.13
	a_{max}	2.61	3.01	3.18	3.99	4.98
C	f_0	0.91	0.66	0.60	0.60	0.52
	D_{eff}	0.05	0.09	0.09	0.09	0.10
	a_{max}	3.04	4.26	5.40	5.44	7.07
D	f_0	0.53	0.30	0.23	0.26	0.20
	D_{eff}	0.05	0.08	0.10	0.08	0.10
	a_{max}	9.95	3.15	1.69	2.19	1.48

Table 8 Shear Beam Model

(unit : KN-m)

Building		Rigid Base	Pile Foundation		Surface Foundation	
			Linear	Nonlinear	Linear	Nonlinear
A	y_{max}	0.06	0.12	0.13	0.17	0.28
	V_{max}	4316.	4578.	4761.	5032.	6118.
	M_{max}	57578.	59365.	62573.	67318.	84821.
B	y_{max}	0.07	0.14	0.16	0.25	0.37
	V_{max}	24488.	28057.	29520.	33222.	39500.
	M_{max}	380974.	447695.	469677.	551587.	673217.
C	y_{max}	0.10	0.27	0.39	0.40	0.70
	V_{max}	10211.	13308.	15755.	15679.	19341.
	M_{max}	169148.	224058.	271928.	271467.	342908.
D	y_{max}	0.93	0.70	0.46	0.58	0.38
	V_{max}	252483.	41920.	41920.	24506.	13775.
	M_{max}	11955249.	2556415.	1345575.	1535123.	805458.

4. Conclusions

This study shows clearly that the flexibility of the foundation can have a very significant effect on the seismic response of buildings with soil conditions like those in Mexico City. For buildings with a natural frequency of about 1 Hz on a rigid base, soil structure interaction lead to an increase in accelerations, forces and particularly displacements aggravating their situation. A pile foundation (and particularly bearing piles) is to be preferred from a dynamic point of view because of the increased rotational stiffness. Bearing piles have, however, problems associated with the continued consolidation of the clay deposit. Buildings with a natural frequency of 0.5 Hz, which is the natural frequency of the soil deposit and the predominant frequency of the earthquake motions, would experience a very large response on a rigid base, and interaction effects are beneficial pushing the system away from the area of maximum earthquake energy and resulting in considerable reductions in the accelerations, forces and displacements. A mat foundation considering nonlinear soil behavior, if acceptable from a static point of view would be even more beneficial in this case.

References

1. Roesset, J.M., *A Review of Soil-Structure Interaction,* Lawrence Livermore Laboratory, June 1980, 125pp.
2. Angelides, D.C., and Roesset, J.M., "Nonlinear dynamic stiffness of piles," Research Report R80-13, Dept. of Civil Engineering, M.I.T, 1980.
3. Blaney, G.W., Kausel, E., and Roesset, J.M., *"Dynamic stiffness of piles," Proceedings, First International Conference on Numerical Methods in Geomechanics,* ASCE, 1976.
4. Tyson, T.R., and Kausel, E., "Dynamic analysis of axisymmetric pile groups," *Research Report R80-07,* Dept. of Civil Engineering, M.I.T., 1983, 67pp.
5. Kim, Y.S., "Dynamic Response of Structures on Pile Foundations," Ph.D. Dissertation, University of Texas at Austin, May 1987, 272pp.