연약지반이 수직방향 지진하중을 받는 구조물의 수직방향 반응에 미치는 영향

Effects of the Soft Soil Layer on the Vertical Response of a Structure Excited with the Vertical Component of Earthquakes

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국문요약

일본 고베지진 후 구조물 수직방향 내진거동의 중요성은 잘 인식되었으나, 대부분의 내진설계규준에서는 지반조건을 규정하지 않아 수직방향 구조물 내진해석시 대개 토질과 기초조건을 무시하고 수행하였다. 이 논문에서는 연약지반이 Taft 지진과 El Centro 지진의 수직방향 지진하중을 받는 구조물의 수직방향 반응에 미치는 영향을 알아보기 위해 기초크기, 기초밑 지반깊이, 기초근입깊이 및 말뚝기초가 수직방향 내진반응스펙트럼에 미치는 영향에 대해 연구하였는데, 지반은 UBC-97에서 분류한 S_A, S_C, S_E를, 기초크기는 중, 대형 기초를, 기초밑 지반깊이는 30m와 60m를, 기초근입깊이는 0m와 15m를 고려하였으며, 연약지반에 설치한 말뚝은 기성제 콘크리트 선단지지말뚝을 고려하였다. 연구결과에 의하면 기초크기는 구조물의 수직방향 내진반응에 별 영향이 없지만, 지반깊이는 수평방향 내진해석에서처럼 기초밑 60m까지 고려해야 하며, 연약지반 위에 설치된 묻힌기초와 얕은 말뚝기초는 구조물의 수직방향 내진거동을 크게 증폭시켰다.

주요어 : 수직방향 내진거동, 연약지반, 묻힌기초, 말뚝기초

ABSTRACT

The importance of the vertical response of a structure was well recognized after the Hyogoken-Nanbu earthquake of Japan. However, most of the seismic design codes does not specified the site soil profiles, and the soil and foundation conditions were mostly neglected in the vertical seismic analyses of a structure. In this paper, the effects of foundation size, soil layer depth under the foundation, foundation embedment and pile foundation on the vertical seismic response spectra for both surface and embedded mat foundations were studied to investigate the effects of the soft soil layer on the vertical response of a structure excited with the vertical components of Taft and El Centro earthquakes, considering the soil profile types of S_A, S_C, S_E in UBC-97, the medium and large size foundations, the soil layer depth under the foundation of 30 and 60m, the foundation embedment of 0 and 15m, and the precast reinforced concrete bearing piles installed in the soft soil deposit. According to the study results, the foundation size has a little effect on the vertical seismic response, however, the soil layer depth under the foundation of 60m has to be considered for the vertical seismic analysis of a structure as for the horizontal one. The embedded pile foundations as well as the surface ones built on the soft soil layer amplified the vertical seismic response of a structure very much.

Key words *: vertical seismic response, soft soil layer, embedded foundation, pile foundation*

1. Introduction

The vertical seismic response of a structure was underestimated and ignored in the dynamic analysis of a structure. However, the huge damages of structures due to the vertical seismic excitations were well recognized after the Hyogoken-Nanbu Earthquake of Japan.[1] Also the vertical seismic analyses

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본 논문에 대한 토의를 6월 30일까지 학회로 보내주시면 그 결과를 게재하겠습니다.

of a structure were mostly carried out neglecting the soil and foundation conditions under the structure and most design codes does not specify the site conditions for the vertical seismic analysis of a structure. The necessity of the vertical seismic analyses of a structure with the soft soil condition should not be overlooked, and the vertical seismic design codes for the structure built on the soft soil layer must be prepared as for the horizontal ones.

In UBC-97, soil layers were classified into five categories as shown in Table 1, and the soil property of the site was determined averaging the soil properties of the top 30m of the soil layers.[2] However, it is controversial to take into account only the top 30m soil deposit to characterize the specified site. Also the elastic design response spectra of UBC-97 were constructed using the seismic coefficients of Ca and Cv specified in the code with the damping ratio of 0.05 without reflecting the effects of foundation embedment and pile foundation.

In this paper, the effects of the soft soil layer on the elastic vertical seismic response spectra were studied with the vertical excitations investigating the effect of foundation size, soil depth, foundation embedment, and pile foundation for both surface and embedded mat foundations.

2. Modelling

For the study, substructure modelling method was utilized to construct the vertical response spectra of a structure taking into account the soft soil conditions under the foundation. The Pseudo 3-D finite element method in the cylindrical coordinate was used to find the stiffness matrix of the massless foundation representing the foundation and soil layer resting on the hard rock or very dense soil layer.[3],[4],[5] For pile foundation, pile arrangement in the square grid form was modified into the equivalent circular one having the same rotational moment of inertia with respect to the minor axis of the foundation, and the dynamic stiffnesses of the piles as 3-D linear members were calculated and then added to the corresponding terms of those of a finite soil element.[6],[7] The response of a structure was calculated simplifying the structure as a single degree of freedom system and attaching the soil springs at the bottom of a structure. And seismic analyses in the frequency domain were carried out in the frequency range of 0 to 10 Hz corresponding to the structural fundamental period range of 0.1 to 3 seconds.

The soil properties were assumed to be homogeneous, linear elastic, viscous and isotropic. Two different soil layer thicknesses of 30m and 60m were considered to investigate the

Table 1 Soil profile types in UBC-97

Soil Profile Type	Soil Profile Description	Average Soil Properties for Top 30m	
		Shear Wave Velocity(m/sec)	SPT N-value
S_A	Hard Rock	> 1500	-
S_B	Rock	760 - 1500	
S_C	Very Dense and Soft Rock	360 - 760	> 50
S_D	Stiff Soil Profile	180 - 360	15 - 50
S_E	Soft Soil Profile	< 180	< 15

effects of soil depth on the seismic response of a structure. Soil profile types of S_A, S_C and S_E classified in UBC-97 representing the rock, very dense soil and soft soil were studied with the shear wave velocities of 1500, 360 and 150 m/sec, and the unit weights of the corresponding soil were also assumed to be 24.51, 21.55 and 17.62 KN/m^3, respectively. Poisson's ratio of 0.3 and damping ratio of 0.05 were assumed for the soil deposit.

For foundation, medium and large size mat foundations with the radius of 15m and 25m were modelled with the embedment of 0m and 15m. The mass density of a foundation was assumed to be uniform along the depth of the foundation and 3.56KN/m^3. For the pile foundation, 350mm diameter precast reinforced concrete bearing piles were considered assuming the properties to be Young's modulus of 2058KN/cm^2, unit weight of 23.52KN/m3, Poisson's ratio of 0.25 and damping ratio of 0.05, and the pile arrangements of 18x18 and 33x33 were also assumed for medium and large size foundations, respectively, with the pile spacing of approximately four times the pile diameter.

For buildings, it was assumed that the story height is equal to be 3.3m, and the damping ratio of a building is 0.05. Also the mass density of a building was assumed to be 2.67KN/m^3 distributing uniformly along its height. For the modelling of a building, the equivalent SDOF system was built by lumping three quarters of the total mass of the building at the height equal to two thirds of the total height, and the stiffness of the system was estimated from the vertical fundamental period of a building built on a rigid base.

Seismic analyses were performed using the vertical records of 1952 Taft Earthquake (Fig. 1) and 1940 El Centro Earthquake(Fig. 2) with the peak accelerations of 0.105g and 0.21g, respectively.[8] And the response spectra were constructed normalizing the spectral accelerations(SA) by the gravity acceleration of g (980cm/sec^2).

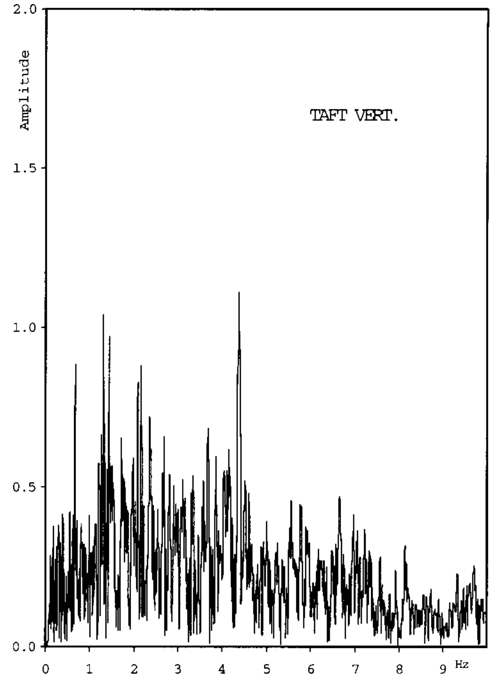

Fig. 1 Fourier spectrum of Taft earthquake

3. Effects of the foundation size

Seismic analyses of a structure for both medium and large size mat foundations were performed to investigate the effects of the foundation size on the response of a structure with the vertical component record of Taft Earthquake. The study was carried out for the surface mat foundation(E=0m) with the soil depth of 60m(H=60m). Three different cases with the shear wave velocities (Cs) of 1500, 360 and 150m/sec, respectively (corresponding to the body wave velocities

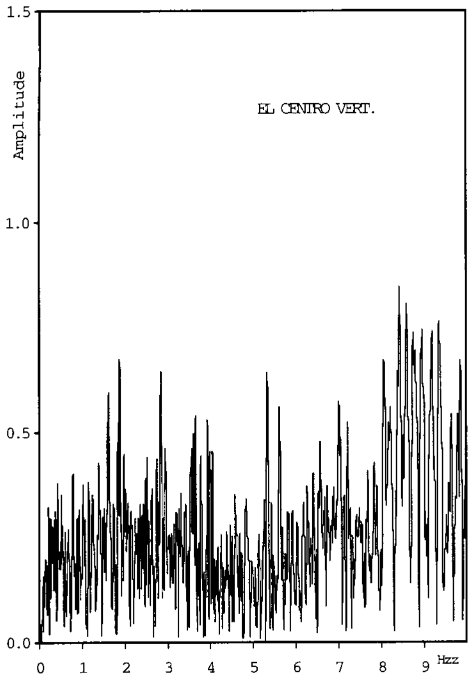

Fig. 2 Fourier spectrum of El Centro earthquake

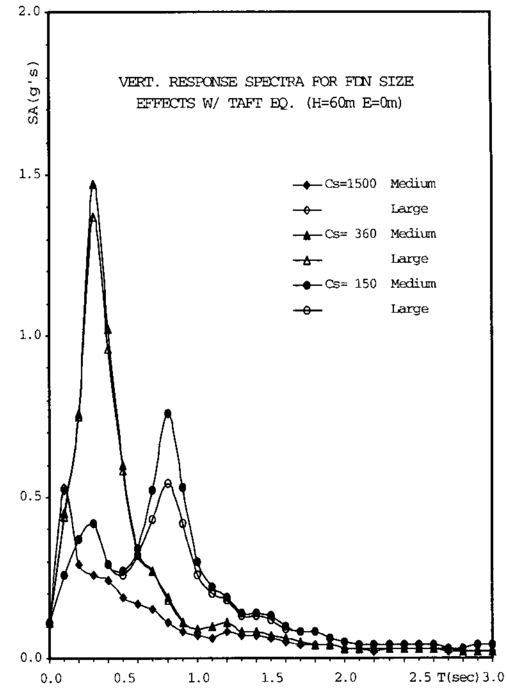

Fig. 3 Response spectra for fdn. size effect

of 2826, 678 and 283m/sec) were considered for the soil property.

The results of seismic analyses for the effects of the foundation size are shown in Fig. 3. In case of the shear wave velocity of greater than 360m/sec, the response spectra of a structure with medium and large size foundations show almost no difference in the whole fundamental period range, even though there were some difference in the responses of a structure built on the soft soil layer having the shear wave velocity of 150m/sec at the fundamental period range of the soil layer.

However, study results show that there is a little effect of the foundation size on the response spectra of a structure with the different soil properties including the soft soil, indicating that the trend of the response spectra of a structure with different foundation sizes is similar and it is practical to study the vertical response of a structure only with the large size foundations.

4. Effects of the thickness of a soil layer

It is recognized that the thickness of the soil layer under the foundation affects on the seismic response of a structure with the horizontal excitations.[9] To investigate the depth effects of the soil layer on the response of a structure with the vertical excitations, vertical seismic analyses of a structure using the 1952 Taft Earthquake were performed for the soil depths under the foundation of 30m and 60m with three different soil properties of the shear wave velocities of 1500, 360 and 150 m/sec, including both surface and embedded mat foundations.

The results of vertical seismic analyses of structure are shown in Fig. 4, 5 and 6. In case

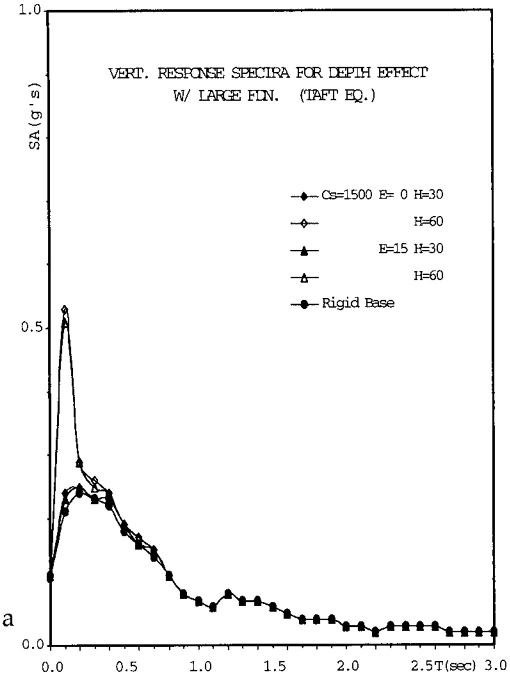

Fig. 4 Response spectra for depth effect(1)

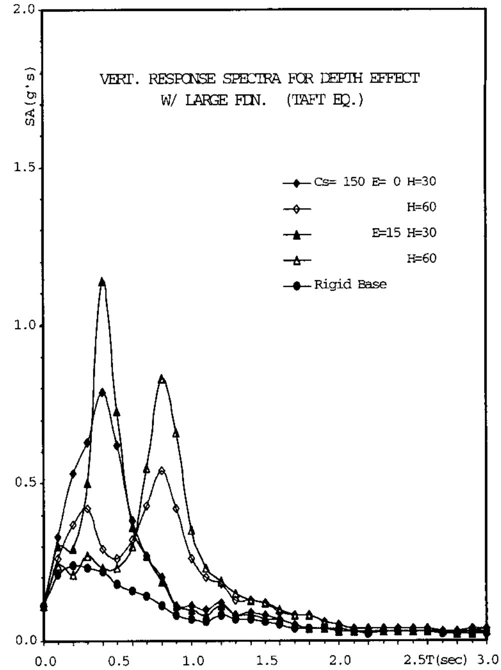

Fig. 6 Response spectra for depth effect(3)

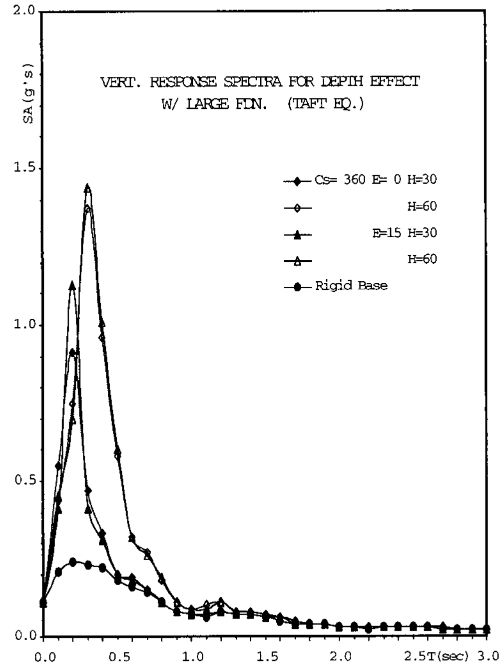

Fig. 5 Response spectra for depth effect(2)

of the shear wave velocity of 1500m/sec, the response spectra of a structure built on both surface and embedded foundations with the 30m deep soil is almost similar to those with the rigid base, however those with the 60m deep soil show the amplification of the response at the fundamental period of the soil layer for the body wave. For the cases of soft soil layers with the shear wave velocities of 360 and 150 m/sec, the response spectra of a structure show that the fundamental period of a structural system is changed due to the different soil depth and the peak responses are increased with the deeper soil layer for both surface and embedded foundations.

Study results indicate that it is not enough to consider only the top 30m soil deposit as specified in the UBC-97 code when the soil layer is thicker than 30m, and it is necessary to take into account the soil deposit under the foundation of 60m, as it was recognized in the horizontal case, to investigate the effects of various parameters on the response spectra of a structure for the vertical excitations.

5. Effects of the embedment of a foundation

Embedment effects of a large size foundation on the vertical response of a structure, assuming the soil layer depth under the foundation of 60m, were investigated for both surface(E=0m) and embedded(E=15m) mat foundations with three different soil properties (soil type S_A, S_C, S_E in UBC-97) using the vertical records of Taft and El Centro Earthquakes.

Fig. 7 and 8 show the study results with the shear wave velocity of 1500m/sec (body wave velocity of 2826m/sec). The vertical response spectra with the embedded foundation are almost the same as those with the surface one due to the rock-like soil layer, however the acceleration response spectra show amplified peaks at the fundamental period of a soil layer due to the boundary effect comparing those of the rigid base.

Study results for the shear wave velocity of 360m/sec are also shown in Fig. 9 and 10, indicating almost similar results between surface and embedded mat foundations.

Reponse spectra for the soft soil layer having the shear wave velocity of 150m/sec are shown in Fig. 11 and 12. The fundamental periods of the structural system are changed due to the effects of the soft soil layer, and the peak accelerations are amplified approximately 50% and 30% with Taft and El Centro Earthquakes, respectively, due to the effects of the embedment of a foundation.

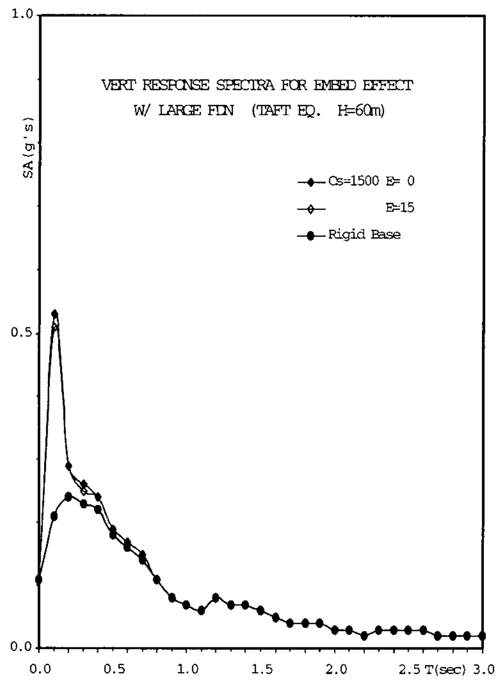

Fig. 7 Resp. spectra for embedment effect(1)

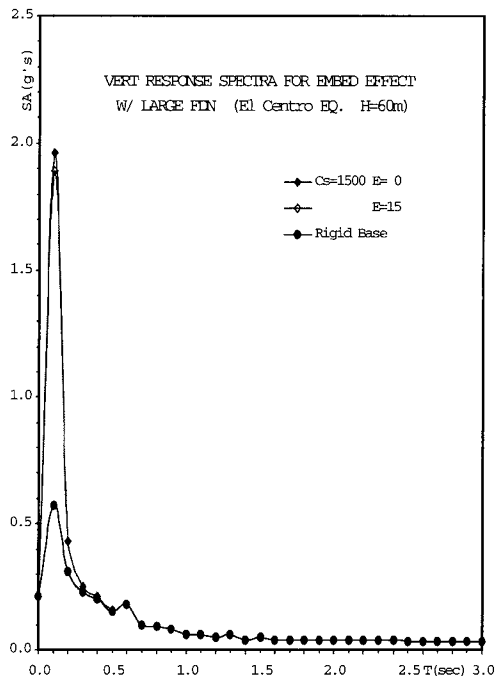

Fig. 8 Resp. spectra for embedment effect(2)

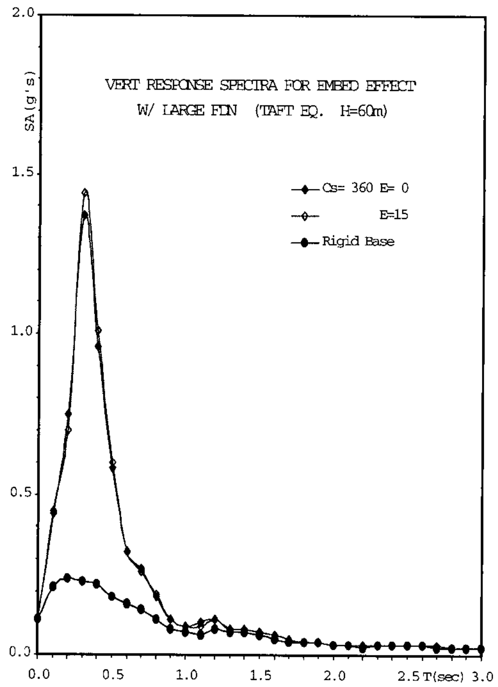

Fig. 9 Response spectra for embedment effect(3)

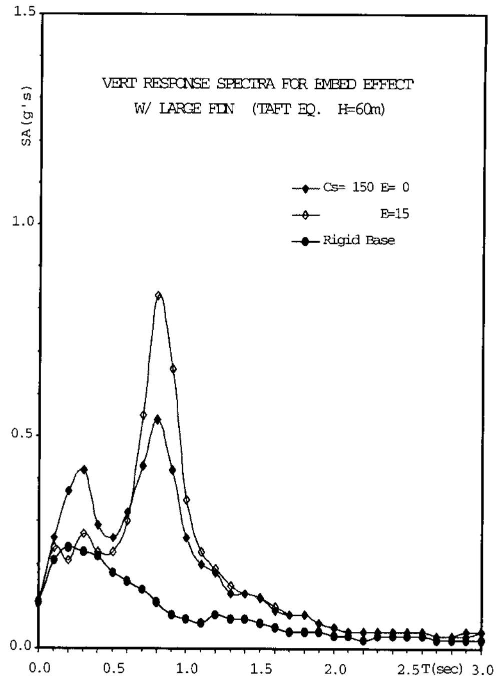

Fig. 11 Response spectra for embedment effect(5)

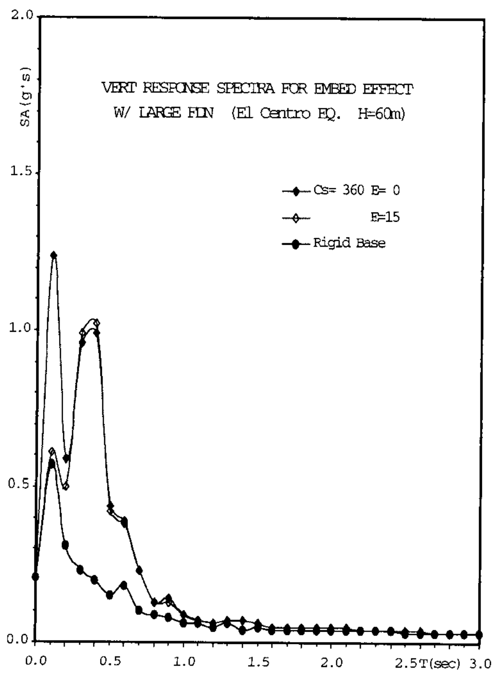

Fig. 10 Response spectra for embedment effect(4)

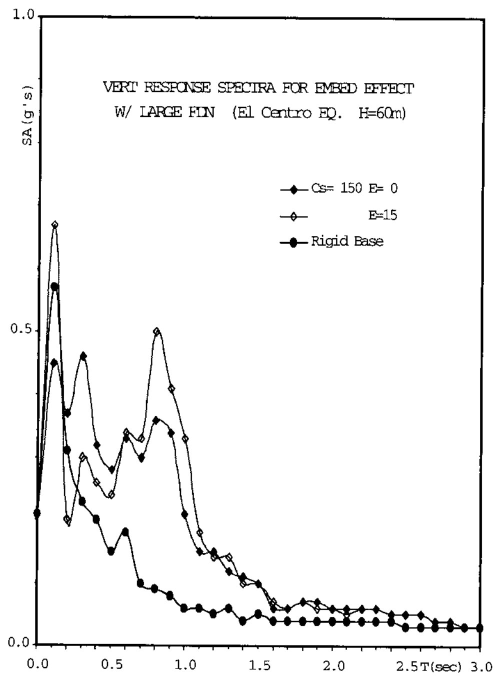

Fig. 12 Response spectra for embedment effect(6)

6. Effects of the pile foundation

Vertical response of a structure with the large size pile foundation was studied with the soil layer thickness of 30m and 60m using Taft and El Centro Earthquakes to investigate the effects of the precast reinforced concrete bearing piles on the vertical response of a structure built on the soft soil layer having the shear wave velocity of 150m/sec. The study was performed for both surface and embedded mat foundations with and/or without bearing piles.

In case of the soil layer thickness under the foundation of 30m, the results shown on Fig. 13 and 14 indicates that the vertical peak acceleration of a structure built on the surface pile foundation increased approximately 100% at the fundamental period of a soil layer with both Taft and El Centro Earthquakes due to the bearing piles, however the effects of the bearing piles on the vertical response of a structure built on the deep embedded one(E=15m) were minimal and can be ignored in the vertical seismic analyses of a structure.

For the case of the soil layer thickness of 60m, the study results are shown on the Fig. 15 and 16. The general trends of the effects of the bearing piles on the vertical response of a structure were similar with those in case of the soil layer thickness of 30m. However, the peak acceleration at the fundamental period of the soil layer amplified approximately 60% with the surface pile foundation for both Taft and El Centro Earthquakes, and that at the fundamental period of the foundation embedded soil layer increased approximately 30% with the embedded pile foundation for the El Centro Earthquake.

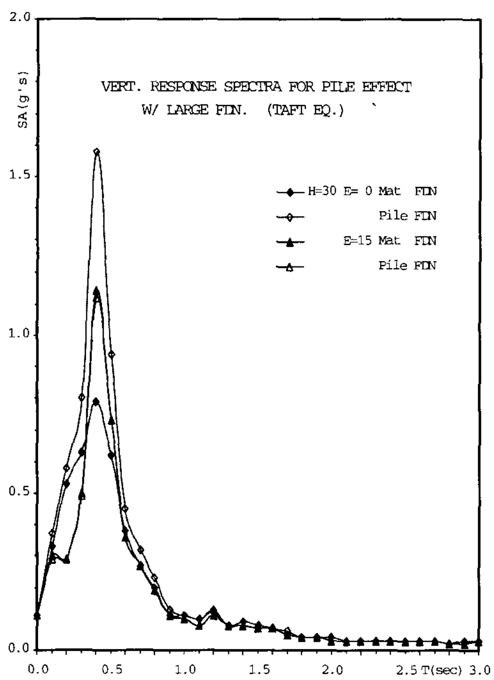

Fig. 13 Response spectra for pile effect(1)

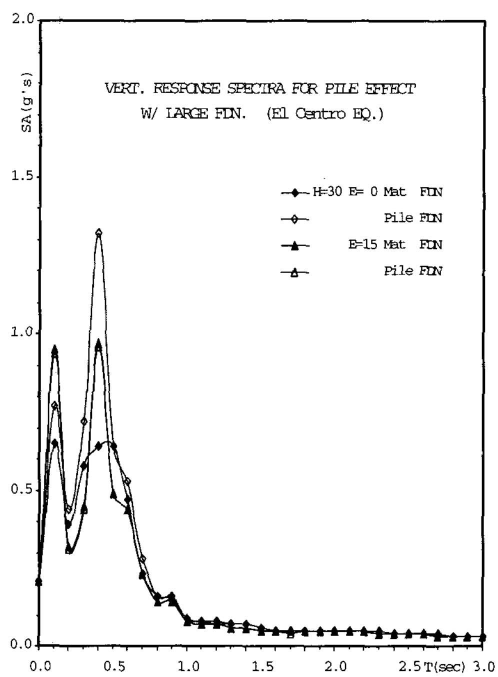

Fig. 14 Response spectra for pile effect(2)

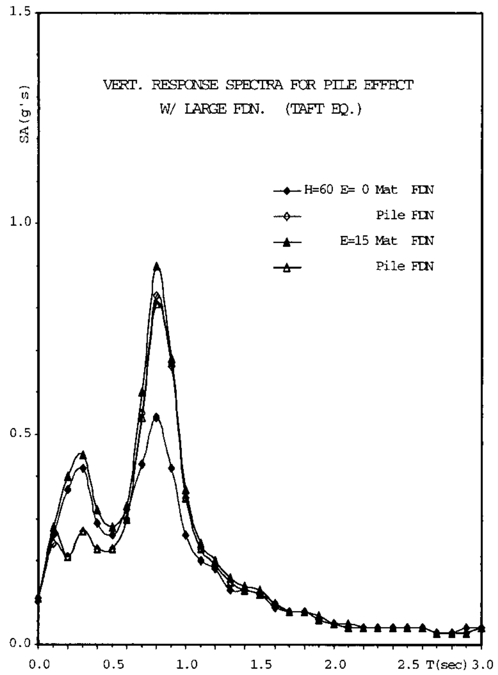

Fig. 15 Response spectra for pile effect(3)

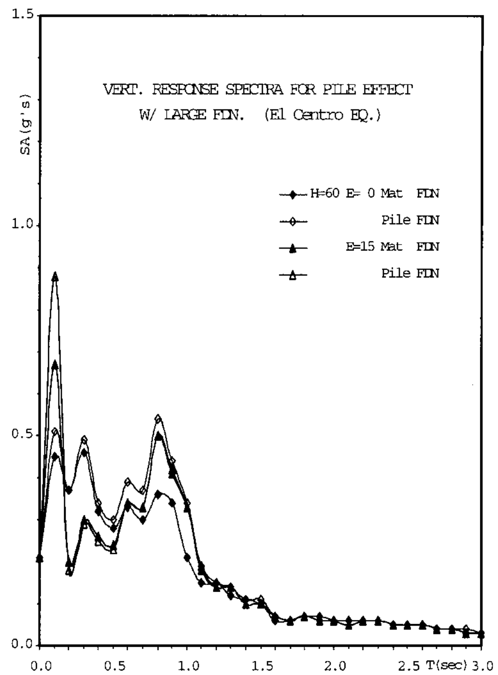

Fig. 16 Response spectra for pile effect(4)

As a result of this study, the effects of the pile foundation on the vertical response of a structure are dependent on the characteristics of the foundation system and the magnitude of the applied earthquake, which is somewhat different from the horizontal case where the effects of the bearing piles were negligible.[9]

7. Conclusions

The vertical seismic analyses of a structure were performed to investigate the effects of soil layer thickness under the foundation, foundation embedment and pile foundation on the vertical response of a structure built on both surface and embedded mat foundations with and/or without the precast reinforced concrete bearing piles using the vertical records of 1952 Taft Earthquake and 1940 El Centro Earthquake, and the final conclusions are as follows.

The size of the foundation has a little effect on the vertical response spectra of a structure with the different soil profile types.

The soil depth under the foundation changed the fundamental period of the structural system and the peak acceleration of a structure at the fundamental period of the soil layer for the body wave, indicating that it is necessary to consider the soil layer thickness under the foundation of up to 60m to investigate the various effects on the vertical response spectra of a structure properly as recognized in the horizontal case.

The vertical response spectra of a structure built on the rock-like or very dense soil layers (soil type S_A, S_C in UBC-97) were not affected by the foundation embedment, however those built on the soft soil (soil type S_E in UBC-97) were amplified approximately 50% and 30% with Taft and El Centro Earthquakes due to the effects of the embedment of a foundation.

The vertical peak acceleration of a structure built on the surface pile foundation was increased approximately up to 100% at the fundamental period of a soil layer due to the effects of the bearing piles, and that built on the embedded one was also increased approximately 30% with the strong 1940 El Centro Earthquake, emphasizing the consideration of the pile foundation in the vertical seismic analyses of a structure built on the soft soil layer.

Also it is recommended to perform further researches on the vertical response of a structure built on the various soft soil layers using the wide range of exciting earthquakes to prepare the design spectra for the vertical seismic design of a structure.

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