UBC-97에 분류된 깊은 지반 위에 세워진 구조물의 지진응답 스펙트럼에 관한 연구

Study on the Seismic Response Spectra of a Structure Built on the Deep Soil Layers Classified in UBC-97

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국문요약

구조물-지반 상호작용에서 알려진 것처럼 구조물 지진응답은 구조물하부 지반조건에 따라 영향을 받는데 UBC-97을 포함한 여러 내진설계규준에서 지반상태 영향을 반영하고 있다. 이 연구에서는 기초크기, 기초밑 지반깊이, 입력지진 작용점 및 기초 근입깊이 등의 영향을 살펴보고, 깊은 지반 위에 세워진 구조물의 평균응답스펙트럼을 UBC-97 탄성응답스펙트럼과 비교하기 위해 구조물-지반 상호작용을 고려한 지진해석을 가상3차원 유한요소법과 부구조물법을 이용하여 1952년 Taft와 1940년 El Centro 지진기록으로 주파수영역에서 수행하였다. 연구결과에 의하면 기초크기는 구조물 응답에 별 영향이 없고, 기초저면 지반깊이는 구조물체계의 고유주기와 최대가속도를 변경시켰다. 또 입력지진의 합리적 작용점은 기초저면이라는 것이 확인되었으며, 깊은 지반 위에 놓인 기초의 근입은 저주기영역에서 구조물 응답을 상당히 줄어들게 하였다. 한편 30m 깊은 지반 위에 세워진 구조물의 평균가속도와 UBC-97 가속도를 비교한 결과 UBC-97 탄성응답스펙트럼에 의한 구조물 내진설계가 안전하지 못할 수도 있으므로 UBC-97 지진계수의 할증이 필요하다.

주요어 : 구조물-지반 상호작용, UBC-97, 입력지진, 깊은 지반, 평균응답스펙트럼

ABSTRACT

Seismic responses of a structure are affected by soil conditions under the structure, known as the structure-soil interaction(SSI), and some seismic design codes including UBC-97 reflect the effects of the site soil profiles. In this study, seismic analyses considering SSI effects were performed to compare the average response spectra of a structure built on deep soil layers with the elastic ones of UBC-97, investigating the effects of mat foundation size, soil layer thickness under the foundation, control point of the input seismic motion, and embedment of a mat foundation in the frequency domain utilizing pseudo 3-D finite element and substructure methods with 1952 Taft and 1940 El Centro Earthquakes. According to study results, the size of a foundation had little effect on the structural response, but the soil layer thickness under a foundation changed the fundamental period of the structural system and the peak acceleration. Also the base of a foundation was confirmed as a reasonable control point of the input motion, and the embedment of a foundation resting on the deep soil layer decreased the responses of a structure quite a bit in the lower period range. Comparison of average accelerations of a structure built on the 30m deep soil layer with those of UBC-97 showed that seismic design of a structure based on the elastic response spectra of UBC-97 might be unsafe, requiring the increase of seismic coefficients of UBC-97.

Key words : *SSI, UBC-97, input seismic motion, deep soil layer, average response spectra*

1. Introduction

The rational and systematic seismic design of structures is an important issue for structural engineers to protect structures from unpredictable earthquake disasters, and many researchers and engineers are still trying to improve the seismic design codes taking into account various uncertain factors affecting on

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본 논문에 대한 토의를 2000년 6월 30일까지 학회로 보내 주시면 그 결과를 게재하겠습니다.

the seismic response of a structure. The structure-soil interaction(SSI) was one of the well-known uncertain factors in the seismic analyses of structures, but study results on the SSI during the last two decades have improved very much the seismic design codes including UBC-97. However, the complicate characteristics of the soil layer under the structures are reflected too generally in the static seismic design codes, and unreasonable results could be generated designing structures by them due to the technical difficulties to include the factors of the soil layer unspecified in the code.(1),(2) So it is necessary to develop the seismic design codes to take into account the uncertain factors in the soil-foundation system.

Three main effects of the structure-soil interaction on the seismic analysis of a structure are the amplification of the seismic wave due to the soft soil under the foundation known as soil amplification, the kinematic interaction of the foundation, and the inertial interaction between a structure and the underlying soil deposit. Soil amplification is the effect of the soil layer which amplifies the seismic motion at the base of the soil layer differentiating the one at the free surface of the soil layer. Kinematic interaction is the effects of the foundation geometry and the type of propagating waves, which are the filtering of the translational motions in the high frequency range due to the foundation geometry and the generation of the rotational motions of the massless rigid foundation before a structure is built. So kinematic interaction is more significant with the embedded foundation than with the surface one. Inertial interaction generates the inertia forces by the structural vibration after a structure is built, which are base shear, axial force and overturning moment altering the motion of the foundation. The acceleration at the base of a structure is different from that of the foundation itself or that recorded at the free surface or at the foundation level in the soil.(3)-(5)

The static force and dynamic analysis procedures in the UBC-97 code take into account the characteristics of the soil layer defining the site soil profile types into five categories (SA through SF as shown in Table 1) averaging the soil properties of the top 30.48m(100feet) of the soil profile.(6) However, this soil profile classification can be applied only to the ideal and typical soil profile types up to the soil layer thickness of approximately 30m, and only the limited part of the effects of the SSI can be reflected in the seismic response of a structure neglecting the modification of the input motion and the embedment effect of the foundation (kinematic interaction).

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
S_F	Soil requiring site-specific evaluation		

For the study, preliminary parametric studies were performed to evaluate the effects of the foundation size for medium and large mat foundations, and those of the soil layer thicknesses under the surface or embedded mat foundation of 30m and 60m with the soil profile types specified in the UBC-97 code. Also the effects of the input seismic motions were studied assuming the recorded earthquakes as bedrock or free surface ones. Finally, the effects of the embedment of the foundation on the seismic response of a structure were investigated comparing the response spectra of a structure for the embedded mat foundation with those for the surface one. Also, the average peak accelerations of a structure were compared with those of UBC-97 to suggest the modification of the elastic response spectrum of UBC-97 for the deep soil layers.

2. Modelling of the Structure-Soil System

Seismic analyses of a structure were performed to investigate the effects of the soil layer under the foundation on the response of a structure using the substructure method, and the dynamic stiffnesses of a rigid massless foundation resting on the soil deposit and the transfer functions at the base of the foundation (T.F. of the input motion) with respect to the bedrock motion were calculated in the frequency domain utilizing the pseudo 3-D finite element method.(7)

The structure-soil system was subdivided into two different substructures for the modelling, i.e. super-structure and rigid massless circular foundation, having the same area with a rectangular one (aspect ratio of less than 4),(8) built on the soil layer. The layered soil deposit was assumed to be resting on hard rock or relatively stiffer soil layer, and was divided into the cylindrical core region in which the soil properties are nonlinear and a far field having the linear soil ones. The layered soil in the core region was discretized into the toroidal finite elements considering the circumferential and vertical displacements, and the far field was reproduced by a consistent lateral boundary placed at the edge of the foundation.(Fig. 1)(9)

Dynamic stiffness matrix of the foundation and the soil layer were assembled from the outside column to the inside one starting with the boundary stiffness matrix K_b representing the far field for each frequency ω, imposing zero displacements at the bottom of the soil layer and applying the horizontal force and the moment to the rigid massless foundation, and condensed to obtain a matrix $K_c^* = K_c - \omega^2 \cdot M$ (K_c and M are static stiffness and mass matrices) at the inner column along the axis of the core.(4)

For the transfer functions of the input motion, dynamic stiffness matrix of the foundation

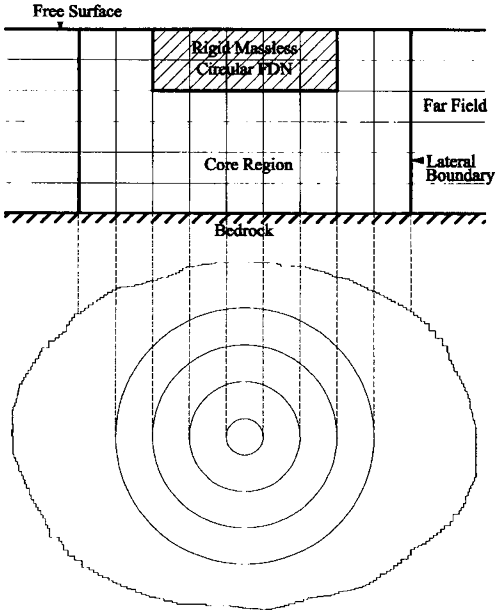

Fig. 1 Foundation-soil system modelling

and the soil layer were assembled from the inner column to the lateral boundary imposing zero vertical displacements along the axis of the cylindrical core and unit displacements at the bottom of the soil layer, and condensed to obtain a matrix K_c^{**} at the nodes along the lateral boundary. Defining U_b the displacement vector along the boundary, U_{bf} and P_{bf} displacements and nodal forces along the boundary in the far field caused by the seismic waves, the equilibrium equation at the lateral boundary is

$$(K_c^{**}+K_b)\cdot U_b = K_b\cdot U_{bf}+P_{bf} \tag{1}$$

Solving the above equation, the horizontal and vertical displacements of the corner node of the foundation can be calculated, and the transfer functions of horizontal and rotational motions are obtained dividing the horizontal displacement by the free field one on the surface and the vertical one by both the radius of the foundation and the free field one on the surface. In this study, the following transfer functions obtained from the parametric studies are used for the modification of the input motion.(10),(11)

$$TF(U)=\begin{cases}\cos\frac{\pi}{2}\frac{f}{f_o} & \text{for } f\le \alpha\cdot f_o\\ \cos\frac{\pi}{2}\,\alpha & \text{for } f\ge \alpha\cdot f_o\end{cases}$$

$$TF(\phi)=\begin{cases}\beta\left(1-\cos\frac{\pi}{2}\frac{f}{f_o}\right) & \text{for } f\le f_o\\ \beta & \text{for } f\ge f_o\end{cases} \tag{2}$$

where α, β values are given in Fig. 2 as a function of the embedment ratio with respect to the radius of the foundation (E/R).

The soil layer was assumed to be homogeneous, linear elastic, viscous and isotropic material located on the hard rock, or a rock-like stiff or dense soil layer with the soil thicknesses of 30m and 60m. Shear wave velocities of soil layers were assumed to be 1500, 360 and 150m/sec representing hard rock, very dense and soft soil layers classified as S_A, S_C, S_E in the UBC-97 code, and unit weights of the soil were also assumed to be 23.57, 21.53 and 17.60kN/m^3 respectively. Poisson's ratio and damping ratio of the soil were assumed to be equal to 0.3 and 0.05.

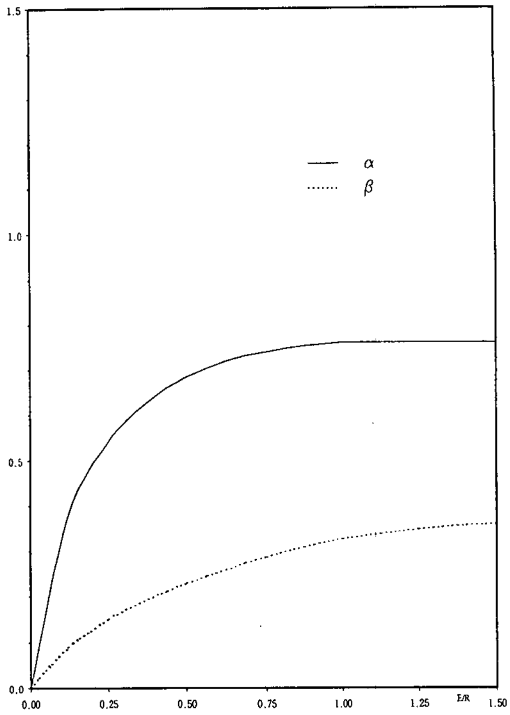

Fig. 2 α, β factor vs E/R

For foundation, medium and large size mat foundations with the radius of 15m and 25m respectively were considered for the study with the embedments of 0m and 15m. The mass density of a foundation was assumed to be equal to 3.56kN/m^3, distributing uniformly along the depth of the foundation. The dynamic stiffnesses of the foundation were calculated in the frequency range of up to 5Hz, mostly satisfactory in the seismic analyses of a structure.

For structure, the mass density of a structure was assumed to be uniform along its height and was taken equal to 2.67kN/m^3, and the structural damping ratio of 0.05 was considered. The story height was also taken to be 3.3m, and the fundamental period of a building on a rigid base was estimated multiplying the number of stories by 0.1.

Study was carried out scaling the E-W record of the 1952 Taft earthquake, and the E-W and N-S records of the 1940 El Centro earthquake to represent the seismic zone 2A, 2B and 3 of the UBC-97 code by the effective peak ground acceleration (EPGA), which was obtained averaging the 5% damping response spectra in the fundamental period range from 0.1 to 0.5 seconds and dividing the result by the standard factor of 2.5.(12) The input earthquake motion was applied to the rigid base under the soil layer assuming the bedrock earthquake, however the free field input motion was also tested to investigate the effects of the input motion. The seismic analyses of a structure was carried out in the frequency range from 0.33 to 10 Hz (fundamental period range from 0.1 to 3 seconds), and the response spectra were constructed normalizing the spectral acceleration (SA) by the gravity acceleration of g (980cm/sec^2).

3. Effects of the Foundation Size

To investigate the effects of the foundation size on the seismic response of a structure, seismic analyses of a structure built on the medium and large size mat foundations were performed with the E-W record of Taft earthquake. Study was carried out for the surface mat foundation (E=0m) with the soil layer depth of 60m (H=60m). Three different soil properties with the shear wave velocities of 1500, 360 and 150m/sec respectively were considered for the soil layer.

The results of seismic analyses of a structure for the foundation size effects are shown in Fig. 3. In case of the shear wave velocity of greater than 360m/sec, the seismic response spectra of a structure with medium and large size foundations show almost the same results in the whole period range. With the soft soil layer having the shear wave velocity of 150m/sec, the responses of a structure around the fundamental period range of the soil layer show some difference.

However, study results on the effects of the foundation size show that there is a little effect of the foundation size and the trend of the response spectra of a structure with the different foundation sizes is similar, indicating

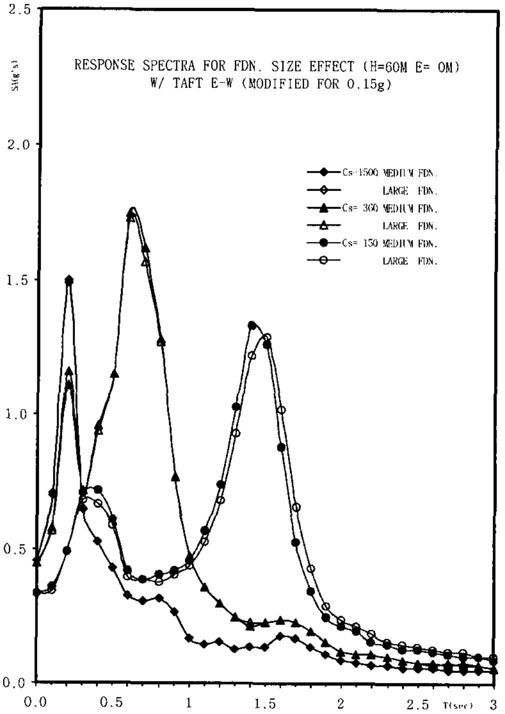

Fig. 3 Response spectra for fdn. size effect

that it is reasonable and practical to study the horizontal seismic response of a structure only with the large size foundations.

4. Effects of the Soil Layer Depth

The depth of the soil layer under the foundation is an important factor for the dynamic stiffness of the foundation-soil system and will affect on the seismic response of a structure. To investigate the soil layer thickness effects on the acceleration response of a structure, seismic analyses of a structure built on the large size surface and embedded mat foundations were carried out for the soil layer thicknesses under the foundation of 30m and 60m with three different soil properties of the shear wave velocities of 1500, 360 and 150 m/sec respectively using the E-W record of Taft Earthquake and assuming it as a bedrock earthquake.

The results of seismic analyses of a structure for the effects of the soil layer depth are shown in Fig. 4, 5 and 6. In case of the shear wave velocity of 1500m/sec, the responses of a structure built on both surface and embedded foundations with the deeper soil layer thickness under the foundation of 60m were amplified largely at the fundamental period of the soil layer.(Fig. 4) For the cases of soft soil layers with the shear wave velocities of 360 and 150m/sec, the response spectra of a structure show that the fundamental periods of a structural system are changed due to the different soil layer thickness, and the peak responses are also decreased or increased with the deeper soil layer for both surface and embedded mat foundations.(Fig. 5, 6)

Study results on the effects of the soil layer depth indicate that it is not reasonable to take

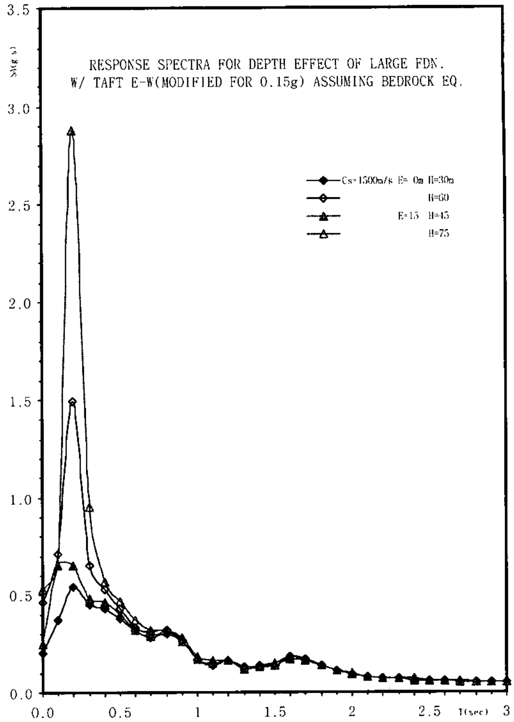

Fig. 4 Response spectra for soil depth effect(1)

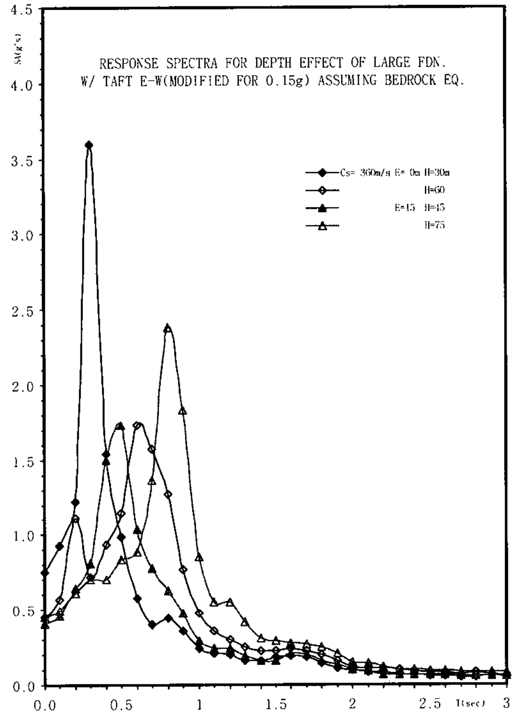

Fig. 5 Response spectra for soil depth effect(2)

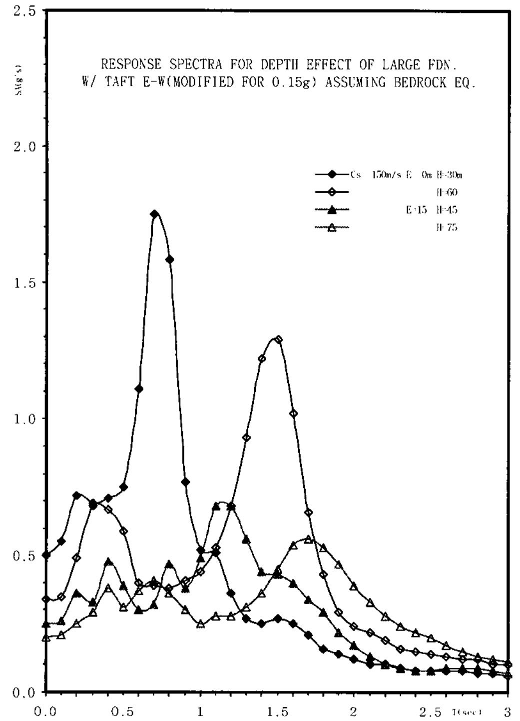

Fig. 6 Response spectra for soil depth effect(3)

into account only the top 30m soil deposit if the stiffer or rocklike soil layer is located deeper than 30m, and it is necessary to take into account the whole soil deposit under the foundation to investigate the response of a structure properly as specified in the UBC-97 code.

5. Effects of the Control Point of the Input Motion

For the some time, it was controversial to locate the seismic input motion to the free surface on the soil deposit, however it was recognized from the results of recent researches that it is unreasonable to apply the input motion to the free surface on the soil layer (especially for the soft soil one), because most earthquake records are specified at the bedrock or the outcropping of the rock.$^{(4)}$ However, the input motion and the control point of the input motion are not mentioned for the seismic analyses of a structure in most seismic design codes, leading to the unrealistic results in some cases.

In this study, the effects of the location of the input seismic motion were studied applying the earthquake record directly to the free surface on the soil layer (still mostly common in the seismic analyses of a structure), and the modified earthquake record to the base of the mat foundation taking into account the soil amplification of the bedrock earthquakes due to the soil layer under the foundation. Study was performed for a structure built on the large size surface mat foundation with the soil layer depth of 60m, and the shear wave velocities of the soil layer were assumed to be 1500, 360 and 150m/sec using the E-W record of El Centro earthquake, and the results were compared with those of the rigid base.

Assuming the free surface earthquake, the seismic responses of a structure built on the hard rock or very dense soil layer having the shear wave velocity of greater than 360m/sec were almost the same as those built on the rigid base (Fig. 7, 8), even though the responses of a structure rested on the soft soil layer with the shear wave velocity of 150m/sec were about 25% smaller.(Fig. 9) However, assuming the bedrock earthquake, the seismic responses of a structure built on the soil profile types of S_A and S_C show the amplified peaks at the fundamental periods of the soil layer approximately 3.2 to 4.8 times larger than the peaks of a structure with the free surface earthquake (Fig. 7, 8), and the responses of a structure with the soft soil show the large amplification at the fundamental period of the soil layer separately from the amplified peak at the fundamental period of the earthquake.(Fig. 9)

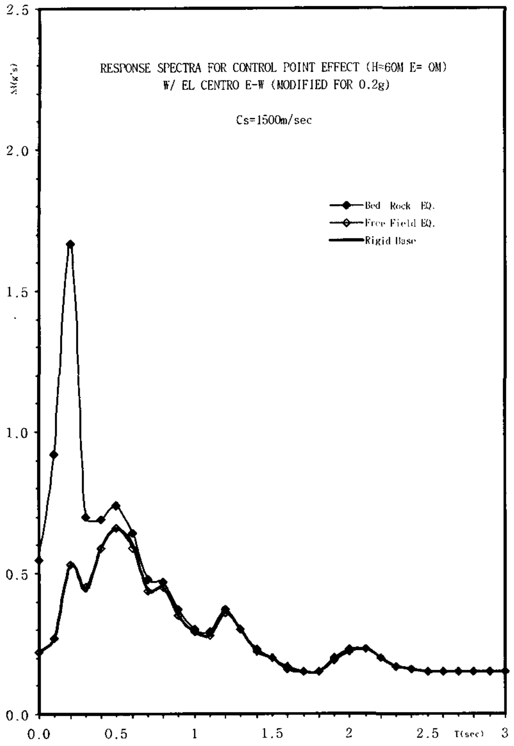

Fig. 7 Resp. spectra for control point effect(1)

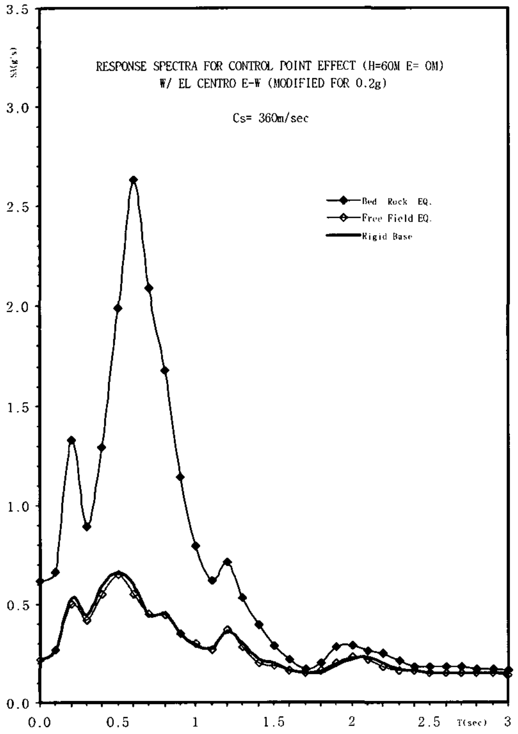

Fig. 8 Resp. spectra for control point effect(2)

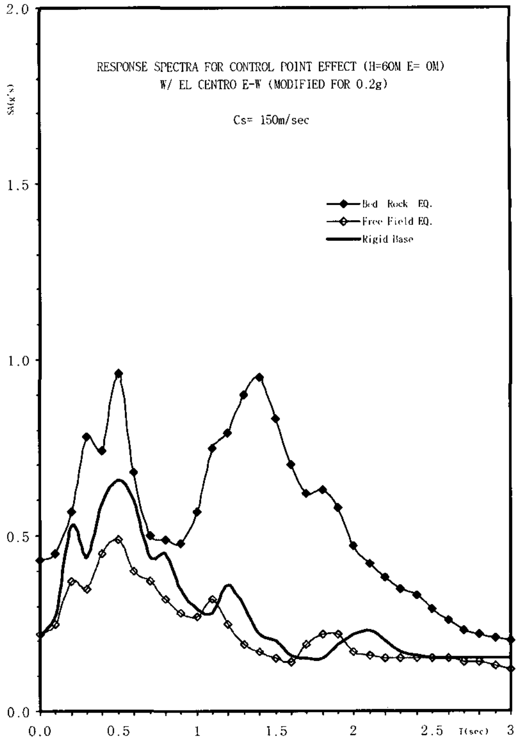

Fig. 9 Resp. spectra for control point effect(3)

Study results on the effects of the control point of the input motion show that it affects significantly the responses of a structure due to the soil amplification of the bedrock earthquake especially for the soft soil profiles, which was well confirmed with the records of the 1985 Mexico earthquake.$^{(13)}$ So it is realistic and reasonable to apply the input seismic motion to the base of the foundation modifying the bedrock earthquake for the input motion at the base of the foundation taking into account the soil amplification and kinematic interaction effects.

6. Effects of the Embedment of a Foundation

Embedment effects of a large size foundation on the response of a structure, assuming the soil layer thickness of 30m, were investigated for both surface (E=0m) and embedded (E=15m) mat foundations with three different soil properties (soil profile type S_A, S_C, S_E in UBC-97) applying the modified records of Taft and El Centro earthquakes to the base of the foundation.

Fig. 10, 11, and 12 show the results with the shear wave velocity of 1500m/sec. The response spectra for the embedded foundation are almost the same as those for the surface one with all earthquake records due to the rock-like soil profile, however the response spectra show amplified peaks at the fundamental period of the soil layer.

Study results with the shear wave velocity of 360m/sec are also shown in Fig. 13, 14, and 15, indicating the similar results between surface and embedded mat foundations for all earthquakes. However, the peak accelerations at the

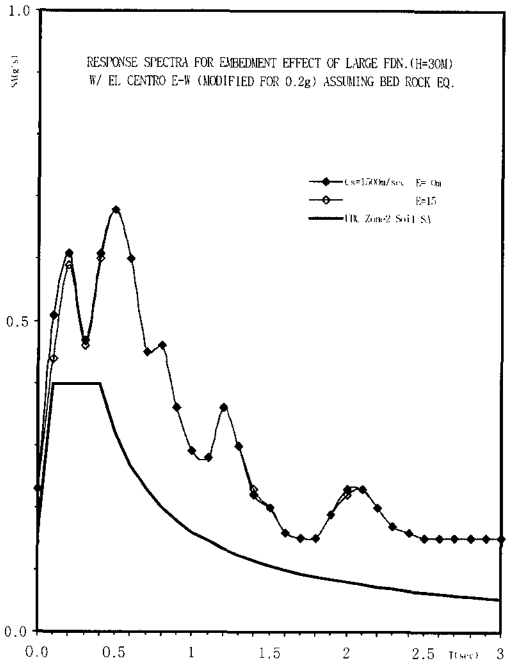

Fig.11 Resp. spectra for embedment effect(2)

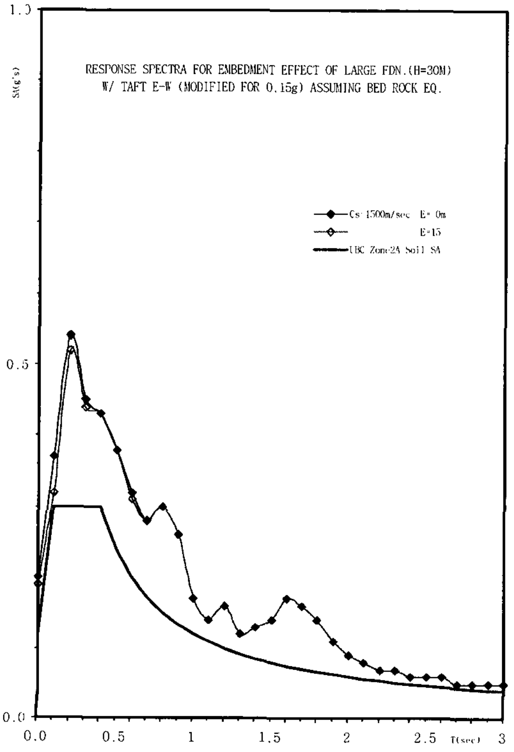

Fig. 10 Resp. spectra for embedment effect(1)

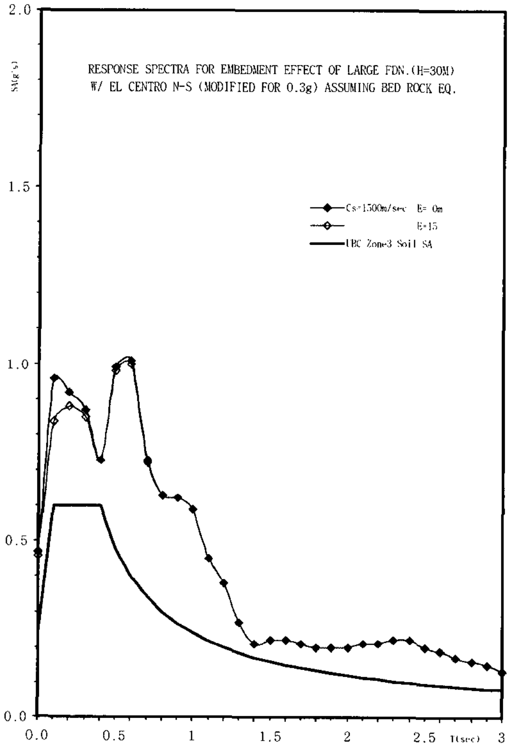

Fig. 12 Resp. spectra for embedment effect(3)

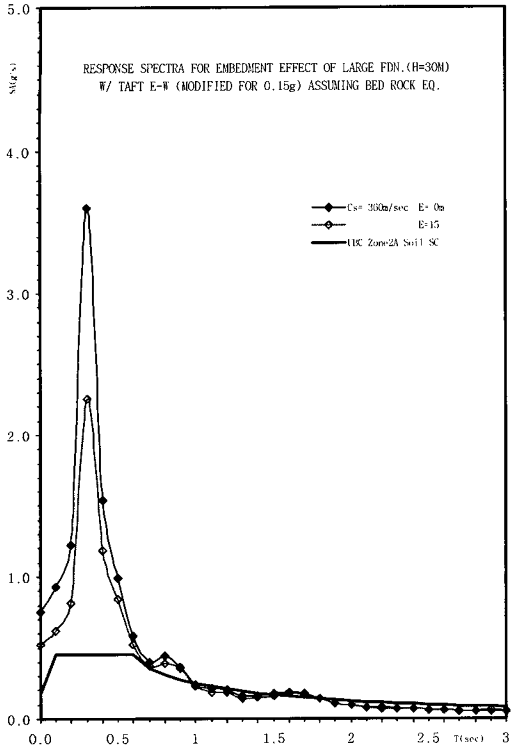

Fig. 13 Resp. spectra for embedment effect(4)

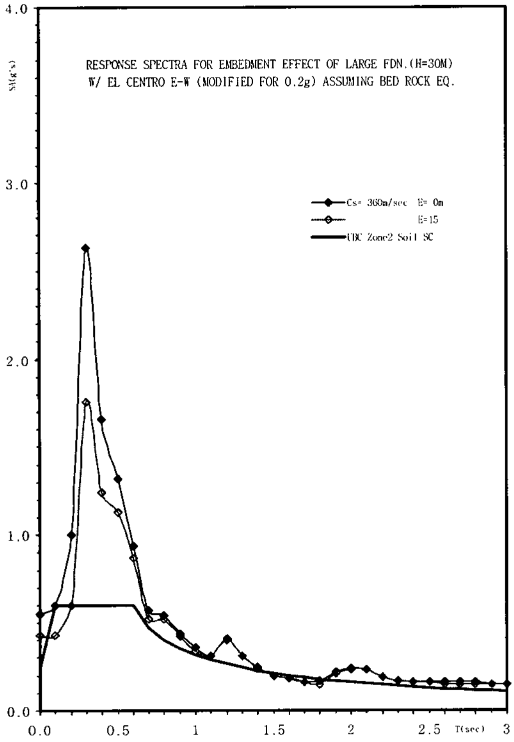

Fig. 14 Resp. spectra for embedment effect(5)

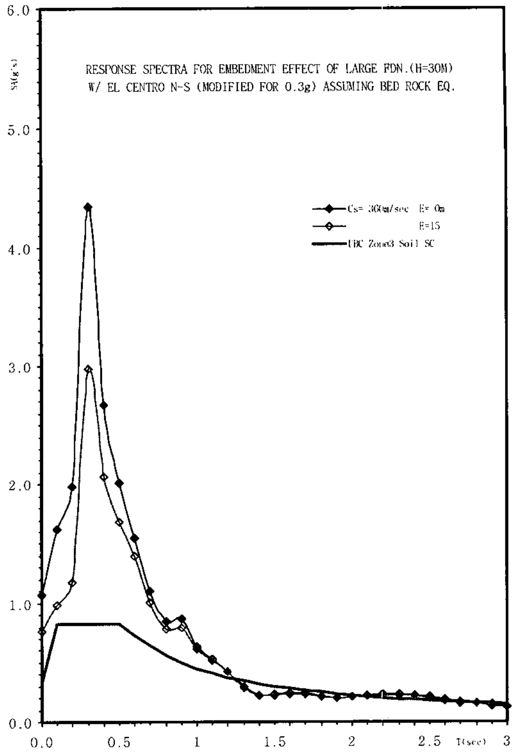

Fig. 15 Resp. spectra for embedment effect(6)

fundamental period of the soil layer were decreased about 30% due to th e embedment effects.

And, response spectra with the soft soil layer having the shear wave velocity of 150m/sec are shown in Fig. 16, 17, and 18. The fundamental periods of the structural system are changed slightly, and the accelerations are decreased maximum approximately 40% in the period range below the fundamental period of the soil layer due to the effects of the embedment of a foundation.

7. Comparison of the Average Peak Acceleration With That of UBC-97

The response spectra of a structure were also compared with those of UBC-97 in Fig. 10-18, and the ratios of the peak average acceleration with respect to that of UBC-97

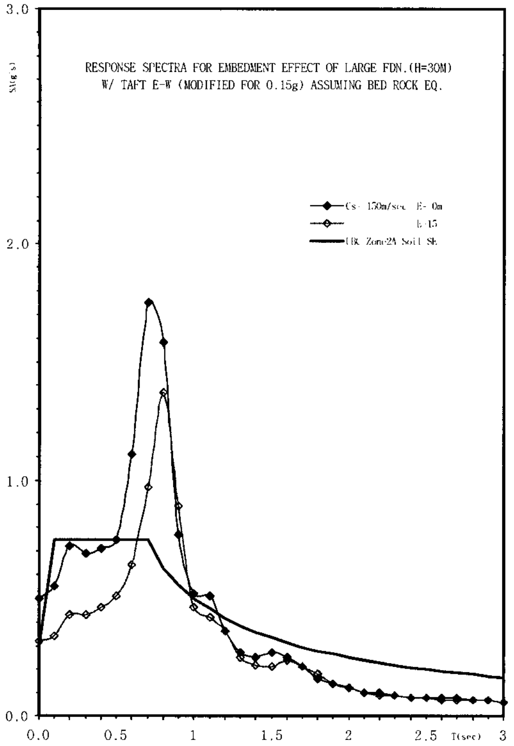

Fig. 16 Resp. spectra for embedment effect(7)

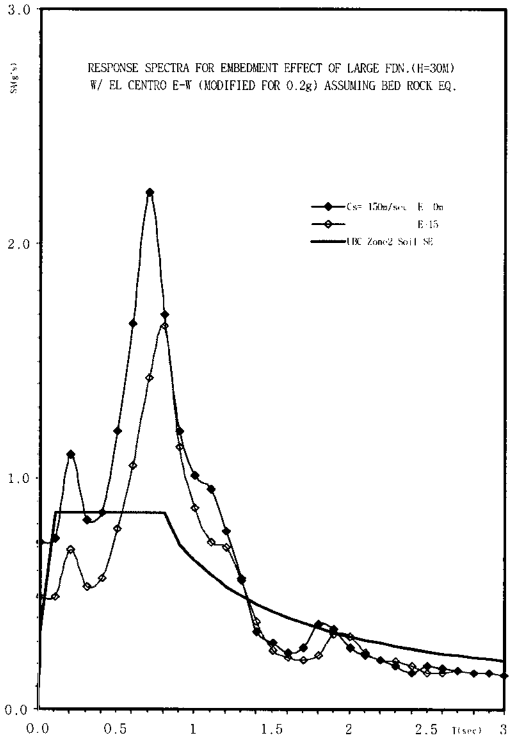

Fig. 17 Resp. spectra for embedment effect(8)

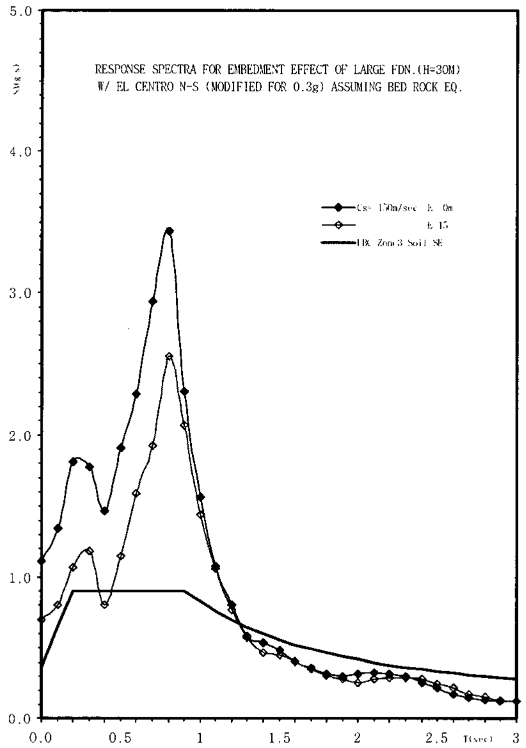

Fig. 18 Resp. spectra for embedment effect(9)

are shown in Table 2.

For the shear wave velocity of 1500m/sec, the peak response of a structure was appeared near the fundamental period of the exciting earthquake of 0.2 seconds, and the ratio of the average peak acceleration in the period range from 0.1 to 0.5 seconds was approximately 1.5 times larger than that of UBC-97 for the seismic zone 2A, 2B and 3.

In case of the shear wave velocity of 360m/sec, the peak acceleration was appeared around the fundamental period of the soil layer of 0.33 seconds, and the ratios of the average peak acceleration were 3.7, 2.4 and 3.1 for the earthquakes representing the seismic zone of 2A, 2B and C respectively.

The responses of a structure built on the soft soil layer with the shear wave velocity of 150m/sec show the distinct peak accelerations

Table 2 Comparison of average peak acceleration w.r.t. that of UBC-97 (unit : g)

Shearwave velocity (m/sec)	Period of peak acc. (sec)	Averaging period range (sec)	Average peak acceleration comparison	Zone 2A (0.15g) Taft E-W	Zone 2 (0.2g) El Centro E-W	Zone 3 (0.3g) El Centro N-S
1500	0.2	0.1-0.5	Study result	0.43	0.58	0.89
			UBC-97	0.30	0.40	0.60
			Ratio	1.5	1.5	1.5
360	0.3	0.1-0.5	Study result	1.66	1.44	2.53
			UBC-97	0.45	0.60	0.82
			Ratio	3.7	2.4	3.1
150	0.8	0.6-1.0	Study result	1.19	1.60	2.51
			UBC-97	0.64	0.77	0.90
			Ratio	1.9	2.1	2.8

at the fundamental period of the underlying soil layer of 0.8 seconds caused by the soft soil layer. The ratios of the average acceleration with respect to that of UBC-97 were approximately 1.9, 2.1 and 2.8 for the seismic zone of 2A, 2B and C respectively.

The average ratios for three different soil properties of hard rock, soft rock and soft soil were 1.5, 3.1 and 2.3, showing the largest ratio with the soft rock. The variation of the ratios between the average peak acceleration and that of UBC-97 is inconsistent with the variations of the soil properties and the intensity of the exciting earthquakes. Study results indicate that seismic design of a structure based on the elastic response spectra of UBC-97 might be unsafe, requiring that the seismic coefficients of the UBC-97 code have to be increased about 50-200% depending on the soil types to ensure the structural safety.

8. Conclusions

The seismic analyses of a structure were performed to investigate the effects of foundation size, soil layer thickness under the foundation, control point of the input motion and foundation embedment on the seismic response of a structure built on both surface and embedded mat foundations using the E-W record of 1952 Taft earthquake, the E-W and N-S ones of 1940 El Centro earthquake, and the conclusions are as follows.

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

The deep hard rock amplified the peak response of a structure drastically, and the deep soil layer 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, indicating that it is necessary to consider the whole rock or soil layer under the foundation to investigate the response of a structure properly.

The effects of the control point of the input seismic motion are significant on the responses of a structure. It is reasonable to apply the input seismic motion to the base of the foundation modifying the bedrock earthquake at the base of the foundation for the input motion, and the effects of the soil amplification have to be reflected on the seismic design codes.

The acceleration response of a structure built on the rock-like soil layer (soil type S_A in UBC-97) was not affected by the foundation embedment, however that with the very dense or soft soil layer (soil type S_C, S_E in UBC-97) was decreased approximately 30-40% in the lower period range due to the effects of the embedment of a foundation.

The average peak acceleration of a structure built on the deep soil layers showed the big difference from that of UBC-97 with the ratios of 1.5, 3.1 and 2.3, indicating seismic design of a structure with the elastic response spectra of UBC-97 might be unsafe and requiring approximately 50-200% increase of the seismic coefficients of the UBC-97 code depending on the soil profile types to guarantee the structural safety.

And it is recommended to perform further researches on the seismic response of a structure built on the various deep soft soil layers using the wide range of exciting earthquakes and considering the nonlinearity of the structure-soil system to develop reasonable design spectra with the deep soft soil layers.

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