Nonlinear Effects of a Soft Soil Layer on the Horizontal Seismic Responses of Buildings

건물의 수평방향 내진거동에 미치는 연약지반의 비선형 영향

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국문요약

지반 위에 세워진 구조물의 지진응답해석시 지반-구조물 상호작용 영향은 지반의 선형특성을 고려하여 간주되었는데, 최근 연구결과에 의하면 구조물 지진해석에서 연약지반의 비선형특성이 중요한 요소로서 인식되었다. 하지만 지반-구조물계의 복잡한 비선형 특성때문에 내진설계 기준에서 비선형 지반특성을 고려하기에는 아직도 어려움이 많다. 이 논문에서는 UBC 지반종류 S_D 지반 위에 놓인 중규모의 얕은 온통기초와 묻힌 온통기초 위에 세워진 건물에 대한 단자유도계 선형 지진해석을 연약지반의 비선형성을 고려하여 최대가속도가 0.17g와 0.36g인 Taft E-W 및 El Centro N-S 지진기록을 사용하여 수행하였다. 비선형 지진해석 결과를 선형해석 결과와 비교하였을 때, 비선형 응답스펙트럼의 최대가속도가 지반의 비선형성 때문에 상당히 줄어드는 것으로 나타나 지반의 비선형성을 고려한 더 효율적인 내진설계의 가능성을 보여주었다.

주요어 : 지반-구조물 상호작용, 비선형지반특성, 온통기초, 지진응답

ABSTRACT

Soil-structure interaction effects were taken into account for the seismic response analyses of structures built on the soil layers considering the linear soil behaviors. However, the nonlinear characteristics of a soft soil layer are recognized as an important factor in the seismic response analyses of structures in the recent studies. But it has still some difficulties to reflect the nonlinear soil behavior in the seismic design codes due to the complexity of the nonlinear characteristics of the soil-structure system. In this study, linear seismic response analyses of a single degree of freedom system representing a building built on a surface or an embedded medium size mat foundation built on the UBC soil profile type of S_D were carried out taking into account the nonlinear soil behavior of a soft soil. Seismic records of Taft E-W and El Centro N-S earthquakes having the peak acceleration of 0.17g and 0.36g are used. The study results of nonlinear seismic response analyses were compared with those of the linear ones. The nonlinearity of the soil layer decreased the peak acceleration of the linear response spectra considerably, indicating the possibility of more effective seismic design.

Key words : soil-structure interaction, nonlinear soil behavior, mat foundation, seismic response

1. Introduction

Recently the necessity and the importance of the nonlinear seismic analysis are recognized in the soil-structure interaction studies(1), and the high performance computer technology makes the nonlinear analyses of the complicate soil-structure interaction problem easier and the seismic analyses of a structure more reasonable. The nonlinear dynamic analysis of a soil layer could not be performed rigorously due to the complicate and various characteristics of the soil layer, however it is a problem that should be solved evidently in some day even though lots of difficulties are expected. The nonlinearity of a soil layer is not considered in most of seismic design codes including the UBC, and the reliability of the structural safety during the earthquake is not guaranteed.(2)

In this study, linear seismic response analyses of a single degree of freedom(SDOF) system were performed considering the nonlinear soil properties of shear modulus and damping ratio of a soft soil. Also the effect of the nonlinear characteristics of a soft soil layer on the seismic response spectra of SDOF system was investigated comparing the response spectra of a SDOF system built on the nonlinear soil layer with those for the linear soil using the Ramberg-Osgood nonlinear soil model. Study was carried out for surface and embedded medium size mat foundations lying on the soft soil of UBC soil profile type of S_D using the records of Taft and El Centro earthquakes.

2. Modelling

To investigate the effects of a nonlinear soft soil layer on the seismic horizontal response of a building, seismic analyses were performed using an in-house software of DAOFS(dynamic analysis of foundation-soil system). The program was developed for the dynamic analysis of the soil-structure interaction effects with the pseudo 3-D finite element method in the frequency domain.(3) The soil layer

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was assumed to rest on the hard rock and was divided into the cylindrical core region under the equivalent circular mat foundation and a far field. The soil in the core was discretized into the toroidal finite elements considering the circumferential and vertical displacements. The far field was reproduced by a consistent lateral boundary placed at the edge of the foundation. And the seismic analyses were carried out in the frequency domain ranging up to 10 Hz, mostly interested in the seismic analyses of a structure.

The soil layer was assumed to be homogeneous, inelastic, viscous and isotropic material located on the hard rock or rocklike stiff or dense soil layer with the soil depths(H) of 20m and 30m. Shear wave velocity of a soil layer was assumed to be 180m/sec(UBC soil profile type of S_D)(4) representing a soft soil layer with the approximate N-value of 15, and unit weight of the soil was also taken to be 18.62kN/m^3. Poisson's ratio and damping ratio of the soil were assumed to be equal to 0.3 and 0.05. Nonlinear constitutive equation of the soil was based on the Ramberg-Osgood model as shown in Fig. 1.(5)

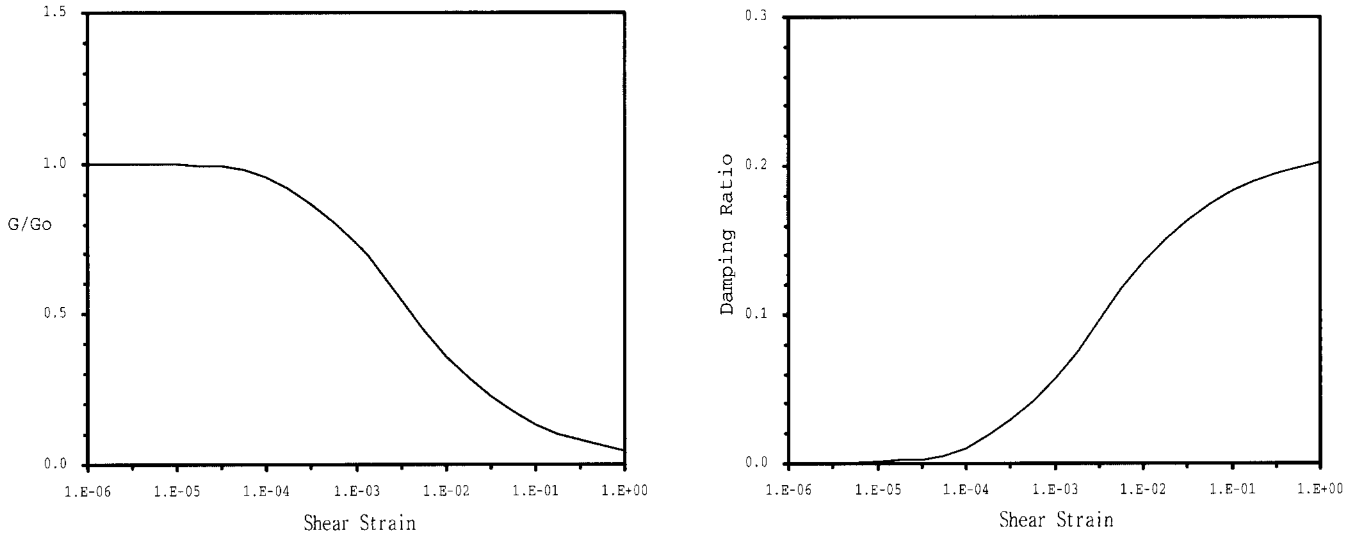
For foundation, medium size rigid mat foundations with the radius(R) of 15m were considered with the embedment (E) of 1.2m and 10m, because it was recognized in the previous study that the nonlinearity of the dynamic stiffnesses of a foundation-soil system is more pronounced with a medium size foundation.(6),(7) The mass density of a foundation of building basements was taken to be equal to 3.56kN/m^3, distributing uniformly along the depth of a foundation.

For building, the mass density of a building was assumed to be uniform along its height and was taken equal to 2.67kN/m^3, and the story height and the structural damping were also taken to be 3.3m and 0.05 respectively. Multi-story buildings were modeled as equivalent SDOF systems lumping three quarters of the total building mass at a height equal to the two-thirds of the building height, which is typical for buildings whose response is controlled by the first mode.(8)

3. Nonlinear seismic analysis of SDOF system

The seismic soil-structure interaction analyses of a building were performed with a SDOF model attaching equivalent horizontal and rotational springs to represent the foundation-soil system, and using the substructure method. The constants of equivalent springs(dynamic stiffnesses of the soil layer) were calculated applying a coupled force and moment at the rigid massless mat foundation. The applied forces were 10^{-3}(almost 0), 10^3, 10^4, 10^5 and 10^6kN, up to sufficiently large enough as a shear force of a building, and the coupled moments were calculated mutiplying them by 10^{-3}, 11, 22, 33 and 44m considering 5, 10, 15 and 20-story buildings. The surfaces of dynamic stiffnesses in the frequency domain were formed for each foundation-soil system as shown in Fig. 2 and 3, which are the cases of a 10-story building.

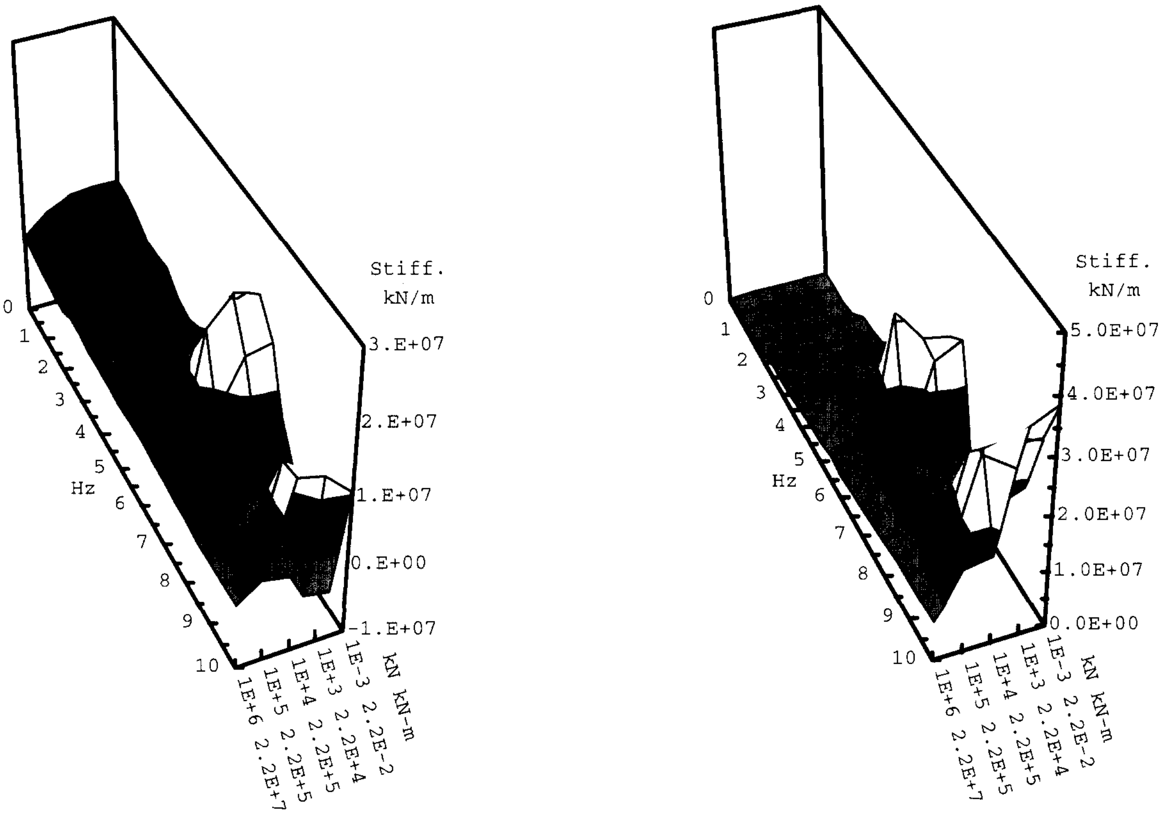
The seismic acceleration responses of a building were calculated by applying control input motions of earthquakes, modified the bedrock earthquakes taking into account the soft soil layer and the embedment of a foundation, to the base of a foundation.(9) Iteration for the nonlinear analysis of SDOF system was conducted until the assumed maximum base shear is converged to the calculated one interpolating the dynamic stiffnesses of a soil layer from the surface function of the dynamic soil stiffnesses(Fig. 2 and 3).



(a) G/Go Ratio for Ramberg-Osgood Model

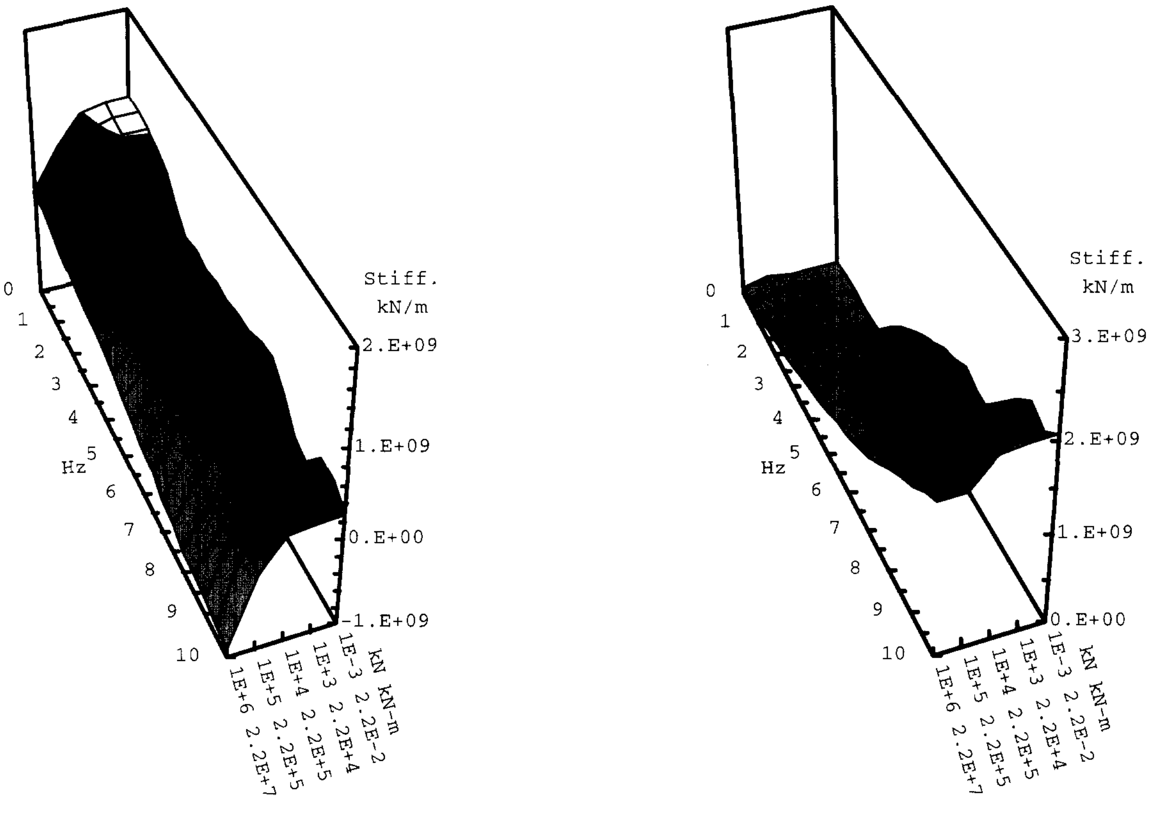
(b) Damping Ratio for Ramberg-Osgood Model

Fig. 1 Ramberg-Osgood model



(a) Real nonlinear horz. stiff. of surface FDN.

(b) Imag nonlinear horz. stiff. of surface FDN.

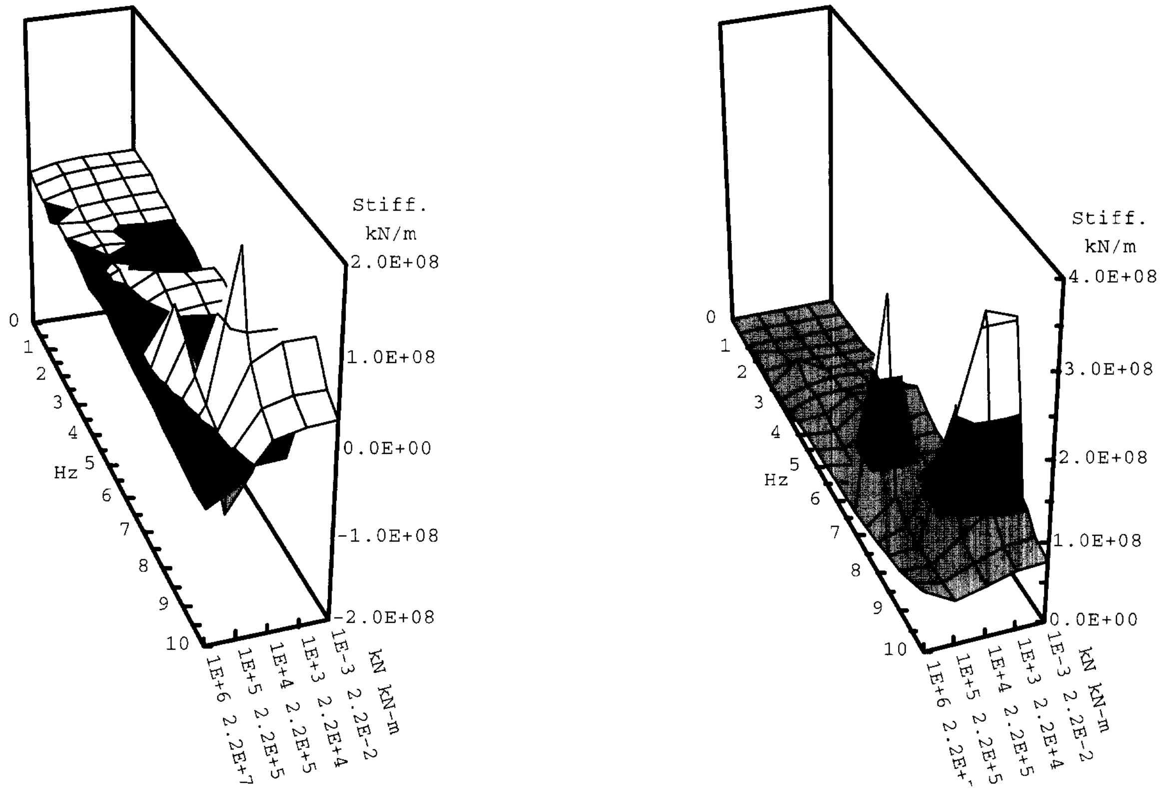


(c) Real nonlinear rock. stiff. of surface FDN.

(d) Imag nonlinear rock. stiff. of surface FDN.

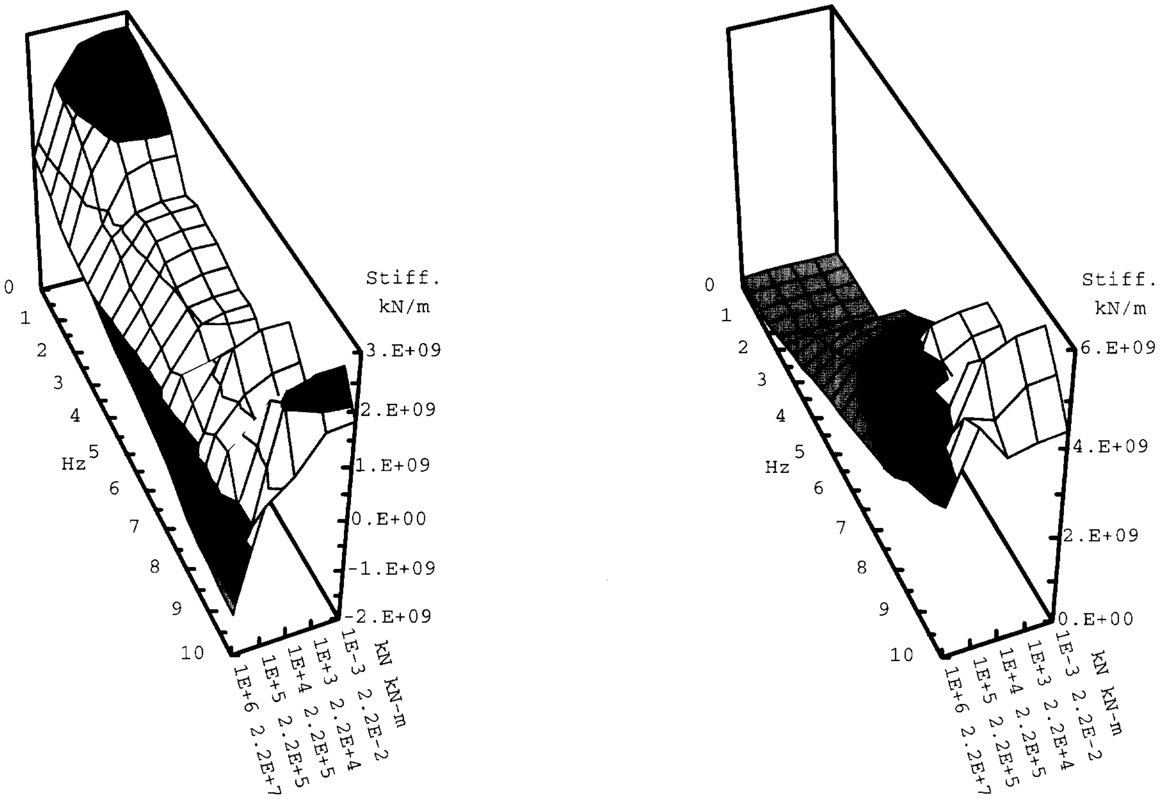
Fig. 2 Nonlinear soil stiffnesses of horizontal and rocking motions of a surface foundation

The study was performed for SDOF system built on surface and embedded foundations with the UBC soil type of S_D having the soil depths of 20 and 30m, using the E-W record of the 1952 Taft earthquake and the N-S one of 1940 El Centro earthquake, which have the peak accelerations of 0.17g and 0.36g respectively, representing the weak and



(a) Real nonlinear rock. stiff of embedded FDN.

(b) Imag nonlinear horz. stiff of embedded FDN.



(c) Real nonlinear rock. stiff of embedded FDN.

(d) Imag nonlinear rock. stiff of embedded FDN.

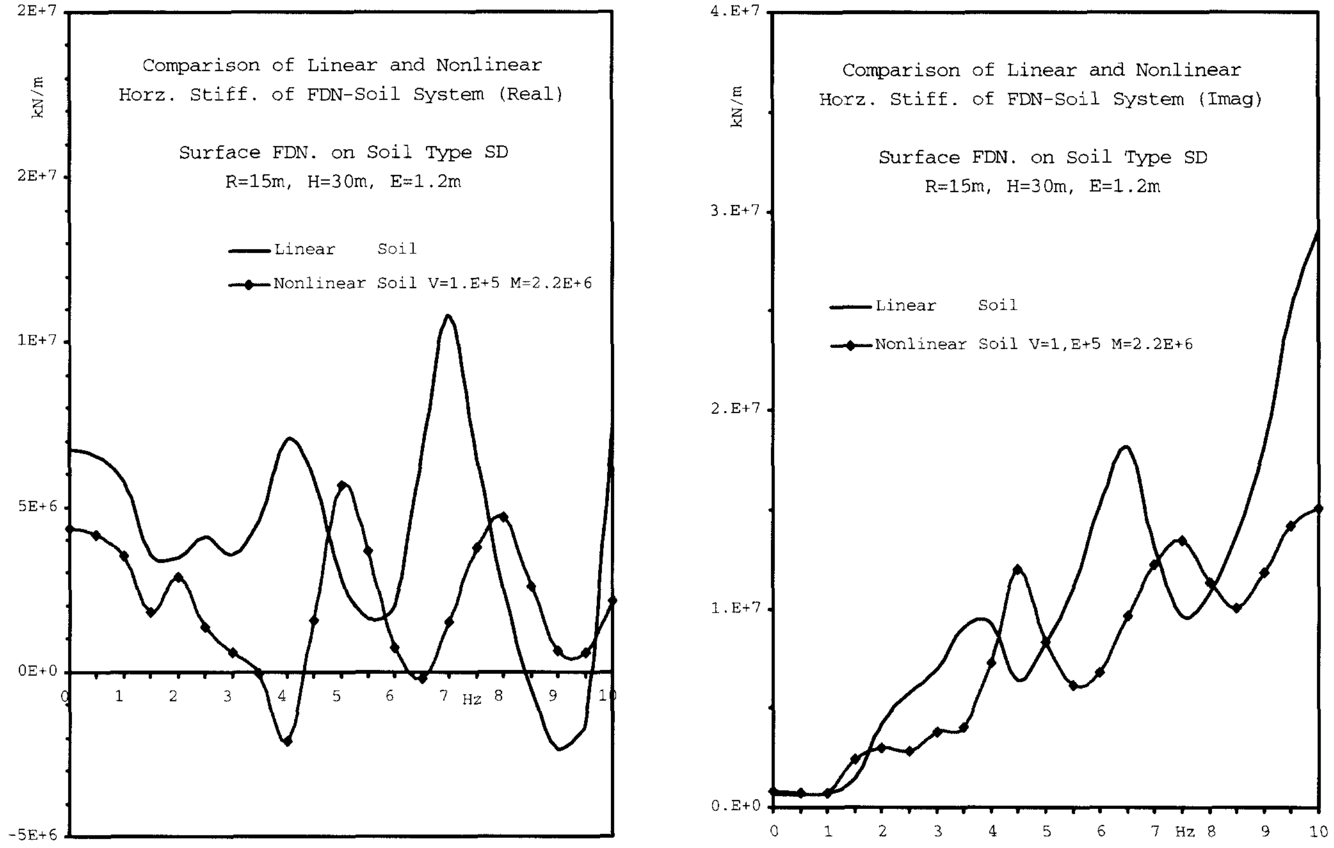
Fig. 3 Nonlinear soil stiffnesses of horizontal and rocking motions of an embedded foundation

strong earthquakes for the zone 2A and 3 of UBC-97.(10)

The acceleration response spectra of nonlinear analyses were compared with those of linear ones and rigid base cases(Fig. 6-9).

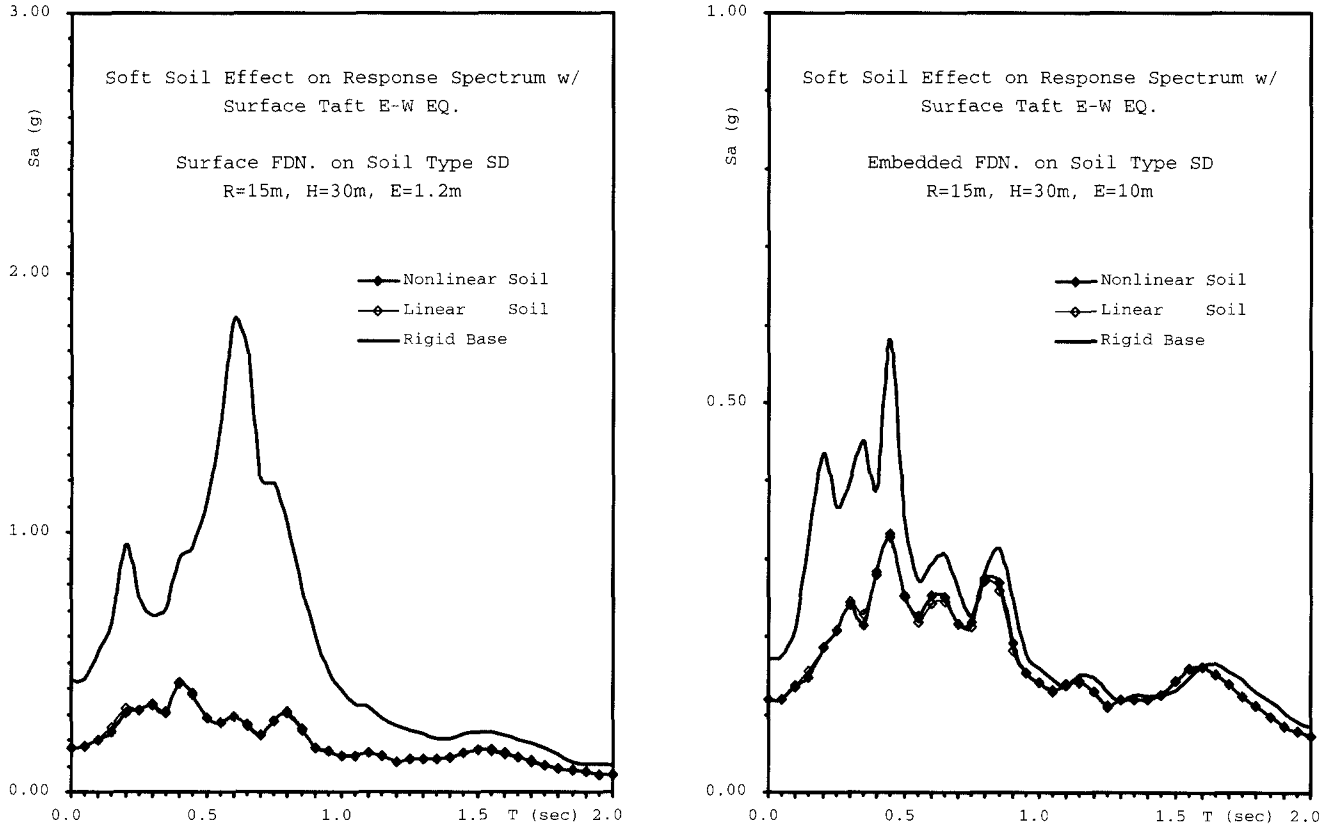
4. Effect of the nonlinearity of the soil layer

The frequency variation of the horizontal stiffnesses of the surface foundation-soil system is shown in Fig. 4 with



(a) (b)

Fig. 4 Comparison of linear and nonlinear horizontal stiffnesses of a surface foundation system



(a) (b)

Fig. 5 Response spectra of Taft earthquake applied on the free field surface of 30m soft soil layer linear and nonlinear soil behaviors. The nonlinear horizontal stiffnesses of a foundation-soil system was decreased more than 20% with the nonlinear soil behavior due to the degradation of the soil properties.

The linear and nonlinear response spectra of a building with surface and embedded foundations were shown in Fig. 5 applying the Taft earthquake motion to the free field surface of the soil layer to investigate the effect of the nonlinearity of the soil layer, and were also compared with the response spectra of the rigid base. The decrease of the acceleration response of a building due to the nonlinearity of the foundation-soil system was minimal, because the 20% change in the stiffnesses of the foundation-soil system was not critical as the stiffness of the foundation-soil system used in this study was almost 10 times greater than that of a building.

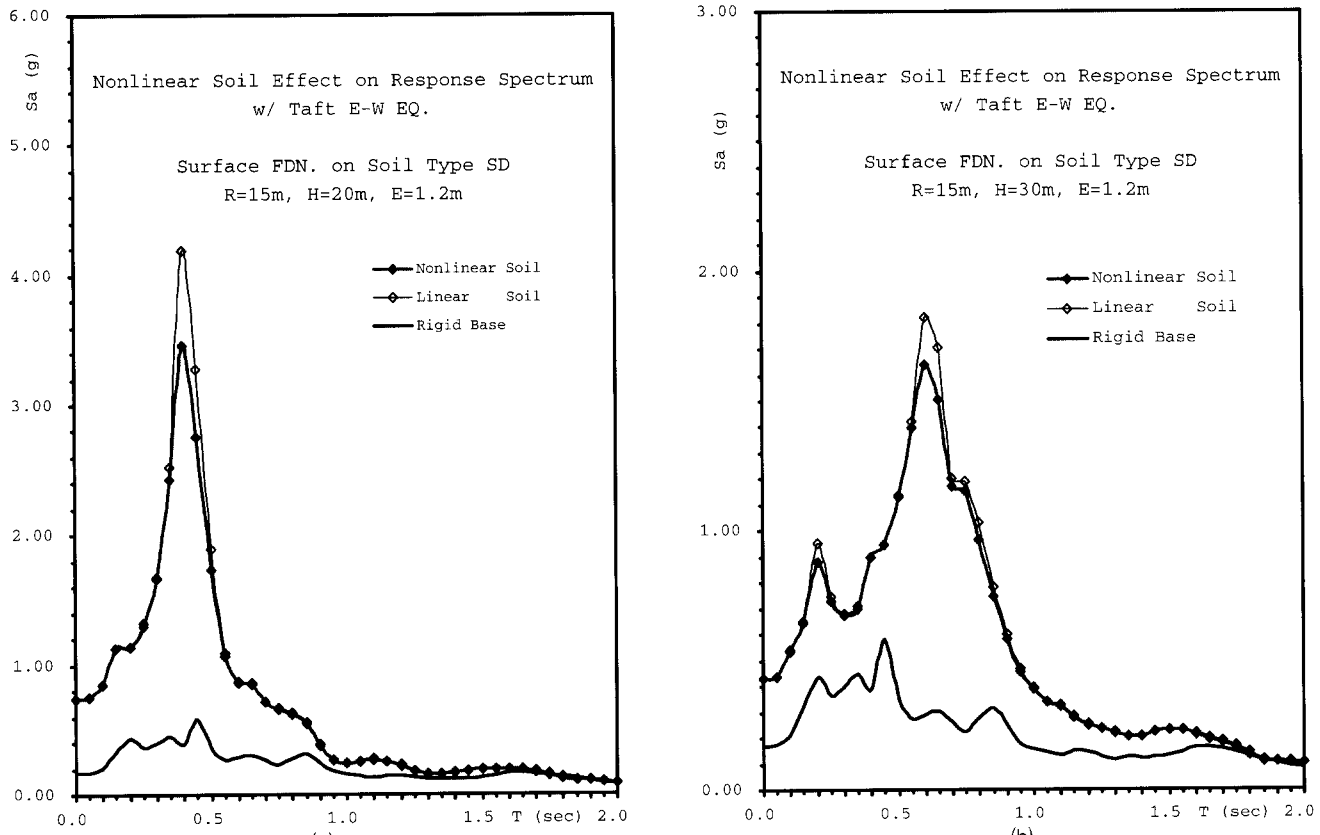
5. Nonlinear response spectra with Taft E-W earthquake

Fig. 6 and 7 show the acceleration response spectra of Taft E-W earthquake with surface and embedded foundations lying on linear and nonlinear soil layers. The fundamental period of Taft E-W earthquake is 0.45 seconds.

The results of dynamic analyses for a surface foundation built on the 20m soil layer show that the peak accelerations with nonlinear and linear soil layers are 4.39g and 3.47g at the period of 0.4 seconds, indicating approximately 20% decrease of the peak accelerations due to the nonlinear soil characteristics at or around the fundamental period of the soil layer. For a surface foundation on the 30m soil layer, the peak acceleration with nonlinear soil properties decreased about 10% from 1.82g to 1.64g at the period of 0.6 seconds which is approximately the fundamental period of the soil layer.

The maximum acceleration of the nonlinear response spectra of an embedded foundation built on the 20m soil layer decreased about 10% from 3.31g to 2.98g at the fundamental period of the soil layer, but that with the 30m soil layer decreased a little bit.

The nonlinear response spectra with Taft E-W earthquake show that the nonlinearity of a soil layer does not change much the period of the peak acceleration, and the response spectra decreased around the fundamental period of the soil layer due to the decreased stiffnesses of the foundation-soil system. However, the decrease of the stiffnesses of the foundation-soil system was caused by the increased base shear, which was resulted from the soil amplification of the bedrock earthquake. And the effect of the nonlinearity of the soil layer on the response spectra was larger with a surface foundation than with an embedded one.



(a) (b)

Fig. 6 Response spectra of Taft earthquake for surface foundation on soft soil with depths of 20m and 30m

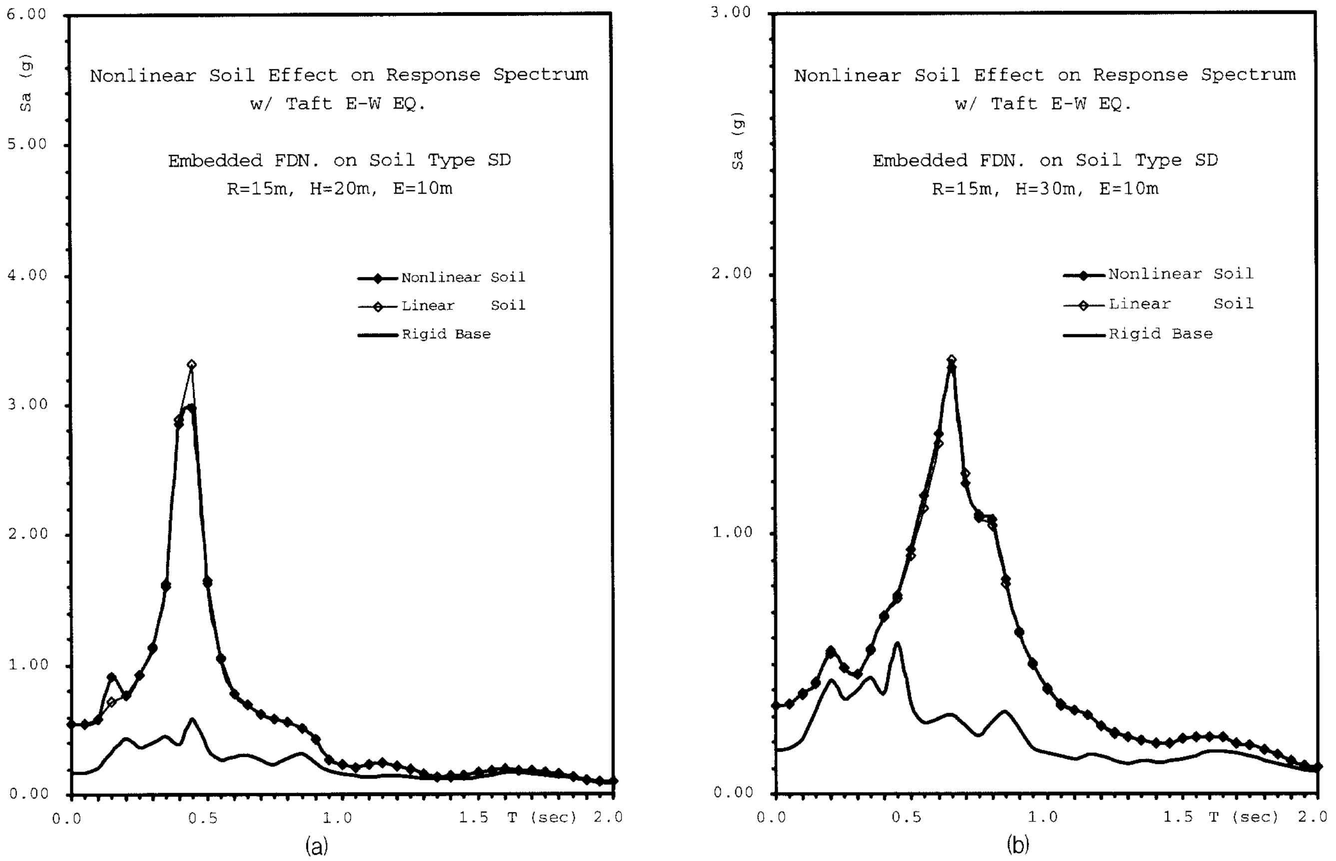


Fig. 7 Response spectra of Taft earthquake for embedded foundation on soft soil with depths of 20m and 30m

6. Nonlinear response spectra with El Centro N-S earthquake

Fig. 8 and 9 show the acceleration response spectra of El Centro N-S earthquake with surface and embedded foundations lying on linear and nonlinear soil layers. The fundamental period of El Centro N-S earthquake is 0.25 seconds.

The results of dynamic analyses for a surface foundation built on the 20m soil layer show that the peak acceleration with nonlinear and linear soil layers are 4.45g and 3.51g at the period of 0.45 seconds. The peak acceleration decreased approximately 20% at the fundamental period of the soil layer due to the nonlinear soil characteristics. For a surface foundation on the 30m soil layer, the peak acceleration with nonlinear soil properties decreased about 20% from 3.90g to 3.04g at the period of 0.6 seconds which is approximately the fundamental period of the soil layer.

The maximum acceleration of the nonlinear response spectra of an embedded foundation built on the 20m soil layer decreased about 10% from 4.19g to 3.68g at the fundamental period of the soil layer, but that with the 30m soil layer decreased about 8% from 3.35g to 3.06g.

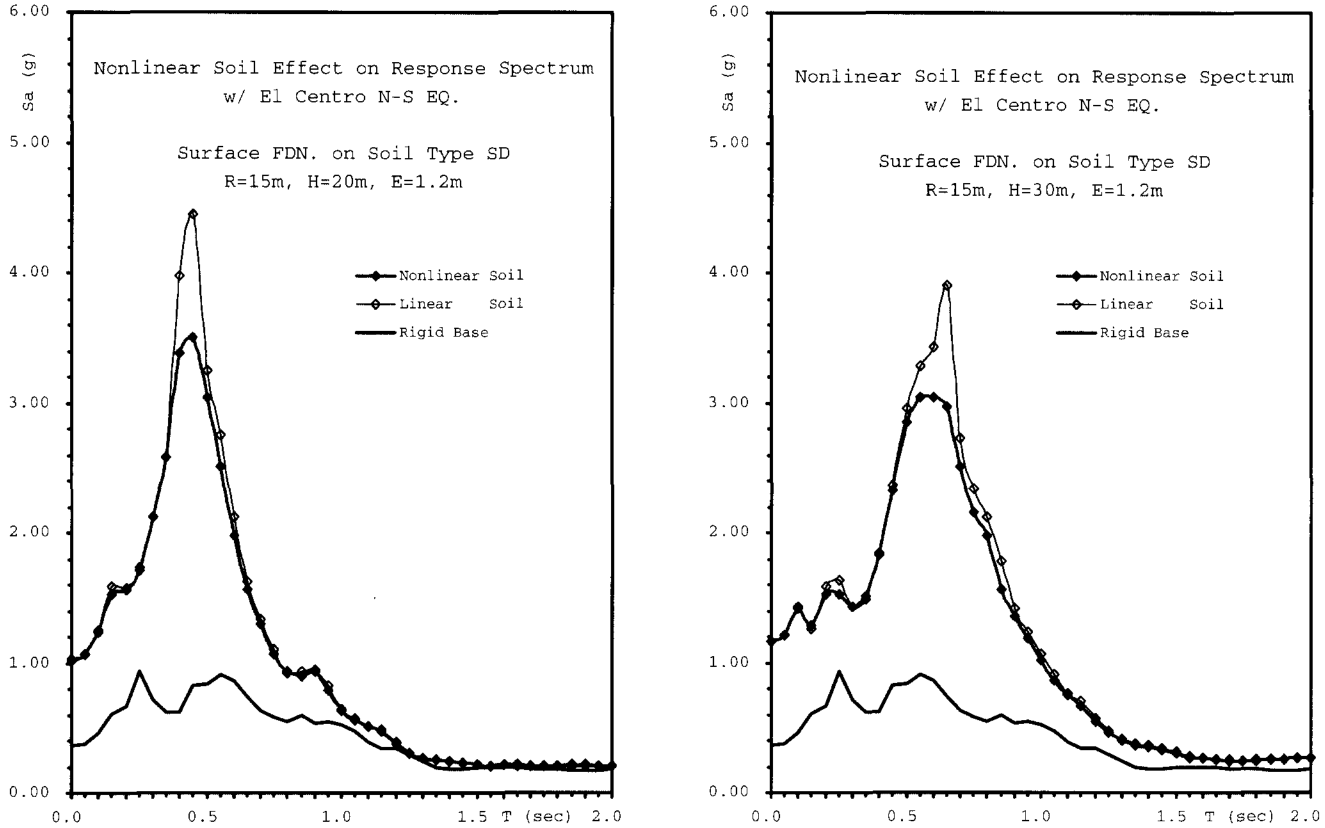
The nonlinear response spectra with El Centro N-S earthquake show almost similar trends with those of Taft E-W earthquake, and the intensity of a strong earthquake does not affect much on the nonlinearity of the seismic response of an elastic building.

7. Conclusions

In this study, the effects of the nonlinear soil characteristics on the seismic response of a building built on both surface and embedded mat foundations were investigated using E-W record of the 1952 Taft earthquake and N-S record of 1940 El Centro one. The results of this nonlinear study were compared with those of linear study, and the following conclusions are obtained.

The nonlinearity of a soil layer does not change much the fundamental period of the peak acceleration. The effect of the nonlinear soil layer on the response spectra of a building was more pronounced with the surface foundation than with the embedded one. And the maximum accelerations of the nonlinear response spectra decreased approximately 10-20% around the fundamental period of the soil layer, showing more decrease for a shallower soil layer with the weak earthquake.

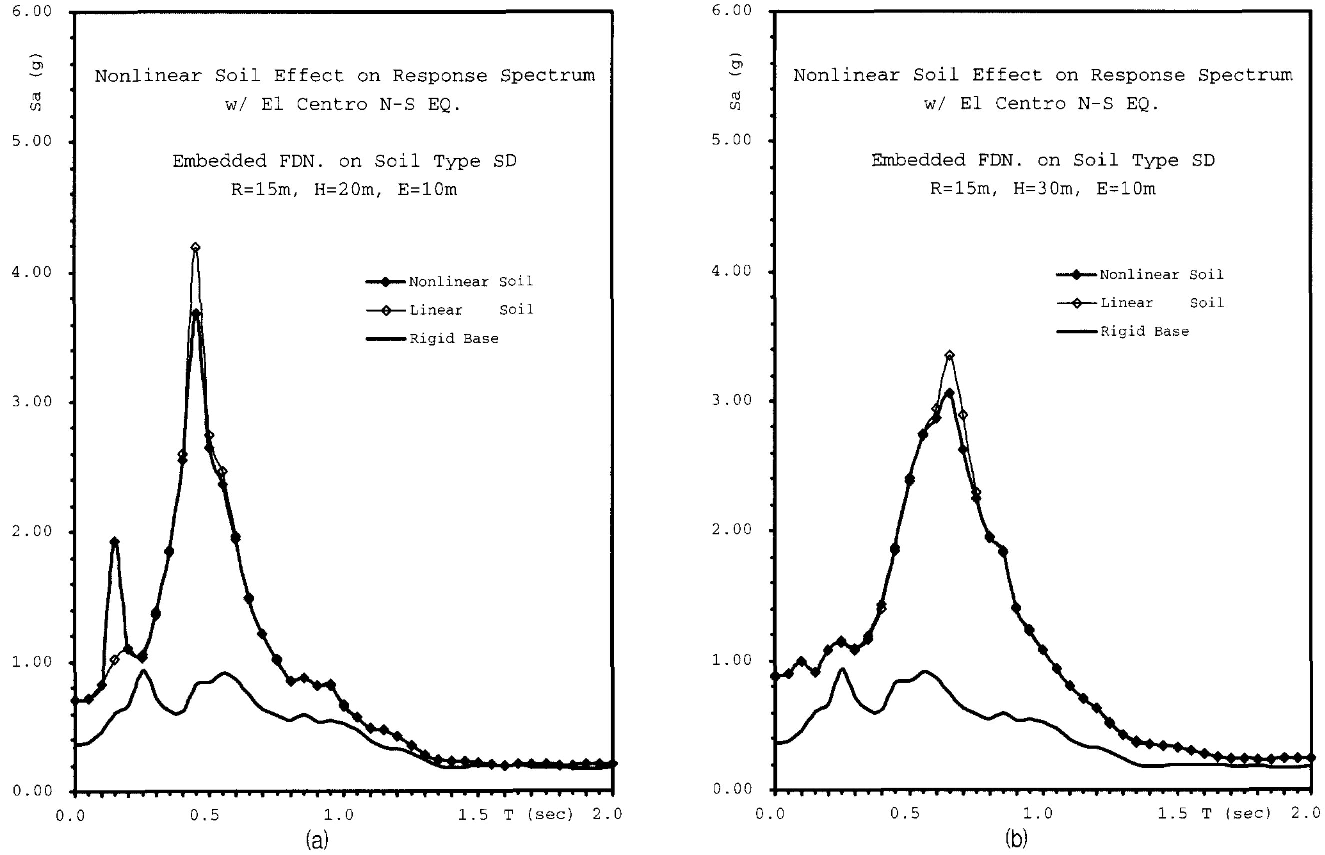
The nonlinear stiffnesses of a foundation-soil system were decreased about 20% with the nonlinear soil behavior. However, the decrease of the nonlinear response spectra due to the decrease of the stiffnesses of the foundation-soil system was minimal, because the change in the stiffnesses of the foundation-soil system was not critical as the stiffness of the foundation-soil system was much greater



(a)

(b)

Fig. 8 Response spectra of El Centro earthquake for surface foundation on soft soil with depths of 20m and 30m



(a)

(b)

Fig. 9 Response spectra of El Centro earthquake for embeded foundation on soft soil with depths of 20m and 30m than those of a building. The peak acceleration of the response spectra at the fundamental period of the soil layer was mainly due to the effect of the soil amplification of the bedrock earthquake.

The nonlinearity of the soil layer decreased the peak acceleration of the linear response spectra approximately up to 20% in this study, indicating that the conventional seismic analyses of a building considering the linear soil behavior may lead to the uneconomical results in point of the effective seismic design of a building even though they can give more margin of the seismic safety.

Also it is necessary to perform further studies on the nonlinear response spectra of a building lying on the nonlinear soil layer considering the inelasticity of a building, and to compare them with the UBC design spectra.

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