Elastic Horizontal Response of a Structure to Bedrock Earthquake Considering the Nonlinearity of the Soil Layer

지반의 비선형성을 고려한 암반지진에 의한 구조물의 수평방향 탄성거동

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국문요약

지반조건은 구조물의 지진거동에 매우 큰 영향을 미치고 성능에 기준한 내진설계에 중요한 요소이다. 이 논문에서는 지진에 의한 지반의 비선형성을 포함한 지반의 비선형성이 구조물의 탄성지진거동에 미치는 영향을 지반 구조물 일괄해석 유한요소법과 지반의 비선형성을 구현하기 위해 Ramberg-Osgood 토질모델에 대한 근사 선형 반복해석법으로 연구하였다. 연구는 말뚝기초의 유무를 고려한 주기가 변하는 선형 단자유도계에 지표에서 기록된 1940년 El Centro 지진을 적용하여 수행하였다. 연구결과에 의하면 연약지반의 비선형 특성 영향이 구조물의 탄성 지진거동에 매우 중요하고, 성능에 기준한 지반의 비선형성을 고려한 구조물의 내진설계가 필요하다는 것을 잘 보여주고 있다.

주요어 : 성능기준내진설계, 지반 비선형성, 탄성지진거동, 일괄해석 유한요소법, 말뚝기초

ABSTRACT

Site soil condition affects significantly on the seismic response of a structure and is a critical factor for the performance based seismic design of a structure. In this paper, the effects of nonlinear soil properties on the elastic response spectra of a structure including the nonlinearity of a soil due to the earthquake excitation is investigated using one step finite element approach for the entire soil structure system and approximate linear iterative procedure to simulate the nonlinear soil behavior with the Ramberg-Osgood soil model. Studies were carried out for a linear SDOF system of a variable period with and without a pile group for the 1940 El Centro earthquake recorded on ground rather than rock. The study results showed clearly that the effect of the nonlinear behavior of a soft soil is very important on the elastic seismic response of a structure suggesting the necessity of the performance based seismic design.

Key words : performance based seismic design, nonlinear soil behavior, elastic response, one step finite element approach, pile group

1. Introduction

The importance of the performance based seismic design is recognized to protect structures from the strong earthquakes after 1994 Northridge and 1995 Hyogoken-Nanbu Earthquakes, and lots of studies are under way to prepare the next generation of the seismic design codes based on the performance limit states. For the performance based seismic design, the site soil condition of a structure is a critical factor on the response of a structure.(1) Also it is well recognized in the soil-structure interaction studies that it is not satisfactory and unreasonable to utilize the simple procedures specified in the traditional seismic design codes such as Uniform Building Code(UBC) etc. to take into account the effects of the underlying soil layer, and that the nonlinear soil properties also affect significantly on the seismic response of a structure.(1) However the seismic response analyses for the soil layer is not so simple and lots of technical difficulties have to be solved, especially for the case of the nonlinear soil properties. Even though a true nonlinear seismic analysis for the soil layer is practically difficult, nonlinear numerical seismic analyses can be performed for the approximate solutions. Recently the high performance computer technology makes the nonlinear analyses of the complicate soil-structure interaction problem easier and the seismic analyses of a complete soil-structure system possible.

In this study, seismic response analyses of a linear single degree of freedom(SDOF) system lying on the soft soil with and without a pile group were performed for the complete soil-structure system modifying the substructure finite element approach to one step finite element one and applying the earthquake excitations to the bedrock. For the nonlinear analyses, a linearized iterative method was utilized. The effects of the nonlinear soil layer on the seismic response spectra of a SDOF system were investigated comparing the response spectra for the nonlinear soil with those for the linear soil and UBC-97.(2) Study was carried out for surface medium size mat foundations lying on the UBC-97 soil profile type of S_D using the N-S record of

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본 논문에 대한 토의를 2002년 8월 31일까지 학회로 보내 주시면 그 결과를 게재하겠습니다. (논문접수일 : 2001. 3. 29 / 심사종료일 : 2002. 5. 2)

1940 El Centro earthquake, which has the peak acceleration of 0.36g representing the strong earthquake for the zone 3 of UBC-97. In UBC-97, the soil property of the site was determined averaging the soil properties of the top 30m soil layers.

2. Modeling

To investigate the effects of nonlinear soft soil properties on the seismic horizontal response of a structure, seismic analyses were performed using an in-house software of pseudo 3-D dynamic analysis of soil-structure system. The program was first developed to find the linear or nonlinear stiffnesses of a massless rigid mat foundation with or without a pile group taking into account of the soil-structure interaction effect utilizing the pseudo 3-D finite element method in the frequency domain.[(3),(4)] In this study, this program was modified to reflect the effects of the nonlinear soil properties due to the earthquake performing the nonlinear analysis for the one dimensional multi-degree of freedom system representing the multi-level free field soil layer, and to perform a response analysis of a SDOF system for the complete soil-structure system in one step finite element approach, taking some advantages for the nonlinear analyses and saving efforts to solve the iterative nonlinear problems.

The soil layer 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 for the linear analysis or at a distance of approximately 5-10 radii from the edge of the foundation for the nonlinear one. The soil properties at the far field as a free field were assumed to be constant, which were pre-estimated through the nonlinear seismic analysis of the free field. For the pile foundation, the finite elements were discretized to coincide with the boundaries of the equivalent circular pile arrangement transformed from the rectangular one (Fig. 1).[(5)] The piles were assumed to be elastic and having the same properties in the same soil layer at each boundary. And the SDOF system was assumed to be attached at the top center of a mat foundation.

The seismic analyses were carried out in the frequency domain ranging up to 30Hz, sufficiently wide for the nonlinear seismic soil-structure interaction analyses, for the structural fundamental periods of 0-2 seconds which is the fundamental period range of the majority of structures.[(6)]

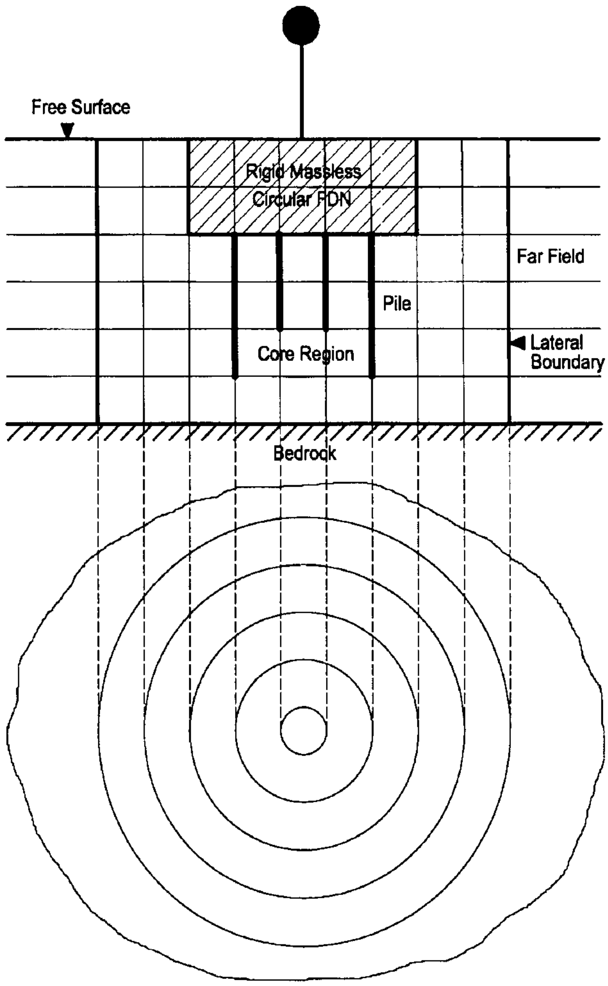
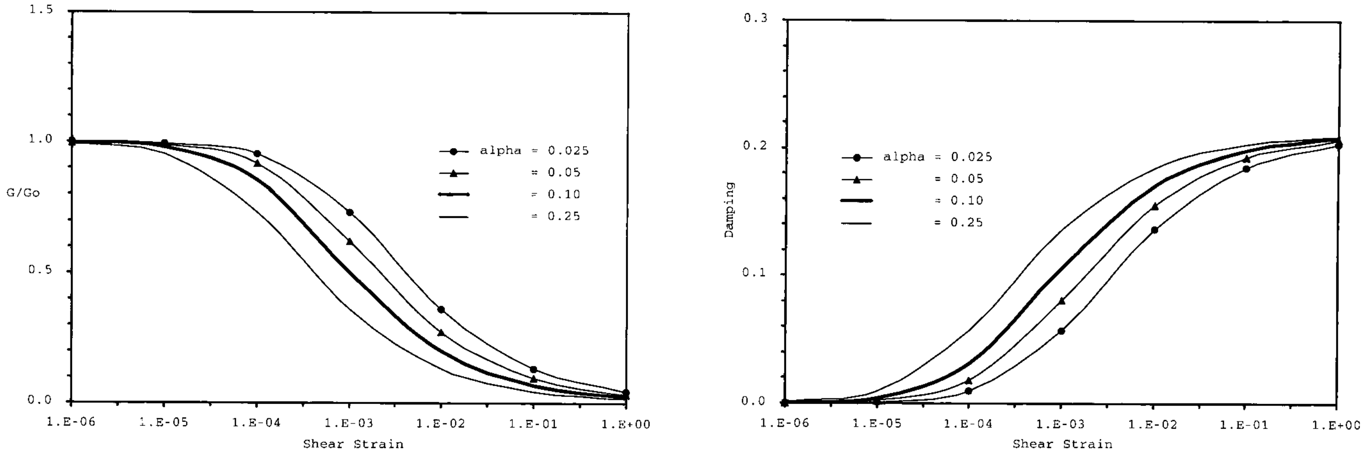


Fig. 1 Pseudo 3-D finite element model

For building, the mass density of a building was assumed to be uniform along its height and was taken equal to 272kg/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 responses are controlled by the first mode.[(7)]

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 depth (H) of 30m. Shear wave velocity of a soil layer was assumed to be 180m/sec(UBC soil profile type of S_D) representing a soft soil layer with the approximate N-value of 15, and unit weight of the soil was also taken to be 18.63kN/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.[(8)] For the study, the curves shown on Fig. 2 were generated assuming experimental factor (α) of 0.025, 0.05, 0.1 and



(a) G/Go ratio for Ramberg-Osgood soil model
(b) Damping ratio for Ramberg-Osgood soil model

Fig. 2 Ramberg-Osgood Model

0.25 and yielding shear strain (γ_y) of 5×10^{-5} in the following equations of (1) and (2). The curves represent the nonlinear properties of soft, moderate and stiff soils taking into account the effects of mean effective confining soil pressure and soil plasticity, which are relatively important to define them.

$$G=\frac{2\,G_0}{1+\sqrt{1+4\alpha\dfrac{\gamma}{\gamma_y}}} \tag{1}$$

$$D=\frac{2}{3\pi}\frac{\sqrt{1+4\alpha\dfrac{\gamma}{\gamma_y}}-1}{\sqrt{1+4\alpha\dfrac{\gamma}{\gamma_y}}+1} \tag{2}$$

where, G and G_0 are shear moduli, γ is shear strain, D is damping ratio.

For foundation, a medium size rigid mat foundation with the radius (R) of 15m was considered with the embedment (E) of 1.2m, 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.[9] The mass density of a foundation was taken to be equal to 2400kg/m^3, distributing uniformly along the depth of a foundation. For the pile foundation, 400mm diameter precast high-strength reinforced concrete(PHC) piles were considered assuming the equivalent properties to be pile radius of 0.2356m, Young's modulus of 1.786×107kN/m^2, unit weight of 11.19kN/m^3, Poisson's ratio of 0.25 and damping ratio of 0.05. For each building, the effects of floating and end bearing pile foundations on the linear and nonlinear responses of a structure were studied assuming the length of piles to be 22.5 and 30m respectively. The pile arrangements of 6×6, 8×8, 10×10 and 12×12 were assumed for the four different fundamental period ranges of a building as shown in Table 1

3. Validation of pseudo-3D finite element method in the frequency domain

The linear response spectra of a SDOF system utilizing the pseudo 3-D finite element method were compared with those of the substructure method to validate the pseudo 3-D finite element method applying the El Centro earthquake record. The result of the finite element method in Fig. 3 shows a good agreement with that of the substructure method throughout the whole frequency range even though there is some difference, indicating the pseudo 3-D finite element method is a reliable one shot method for the response analysis of the soil-structure interaction system.

4. Comparison of nonlinear seismic stiffnesses of a surface mat foundation

The nonlinear seismic horizontal and rocking stiffnesses

Table 1 Pile arrangements for a building

Foundation type	Building fundamental period range(sec)	Building stories	Foundation size	Pile arrangement (Dia. 400mm)
A	0.0 - 0.5	1 - 5	26.6m × 26.6m (Ro = 15m)	6 × 6
B	0.5 - 1.0	6 - 10		8 × 8
C	1.0 - 1.5	11 - 15		10 × 10
D	1.5 - 2.0	16 - 20		12 × 12

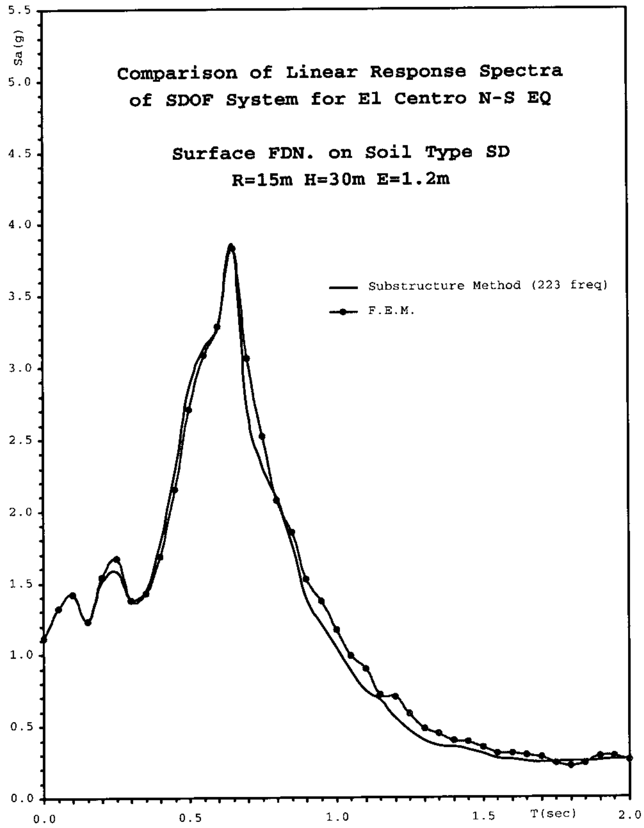
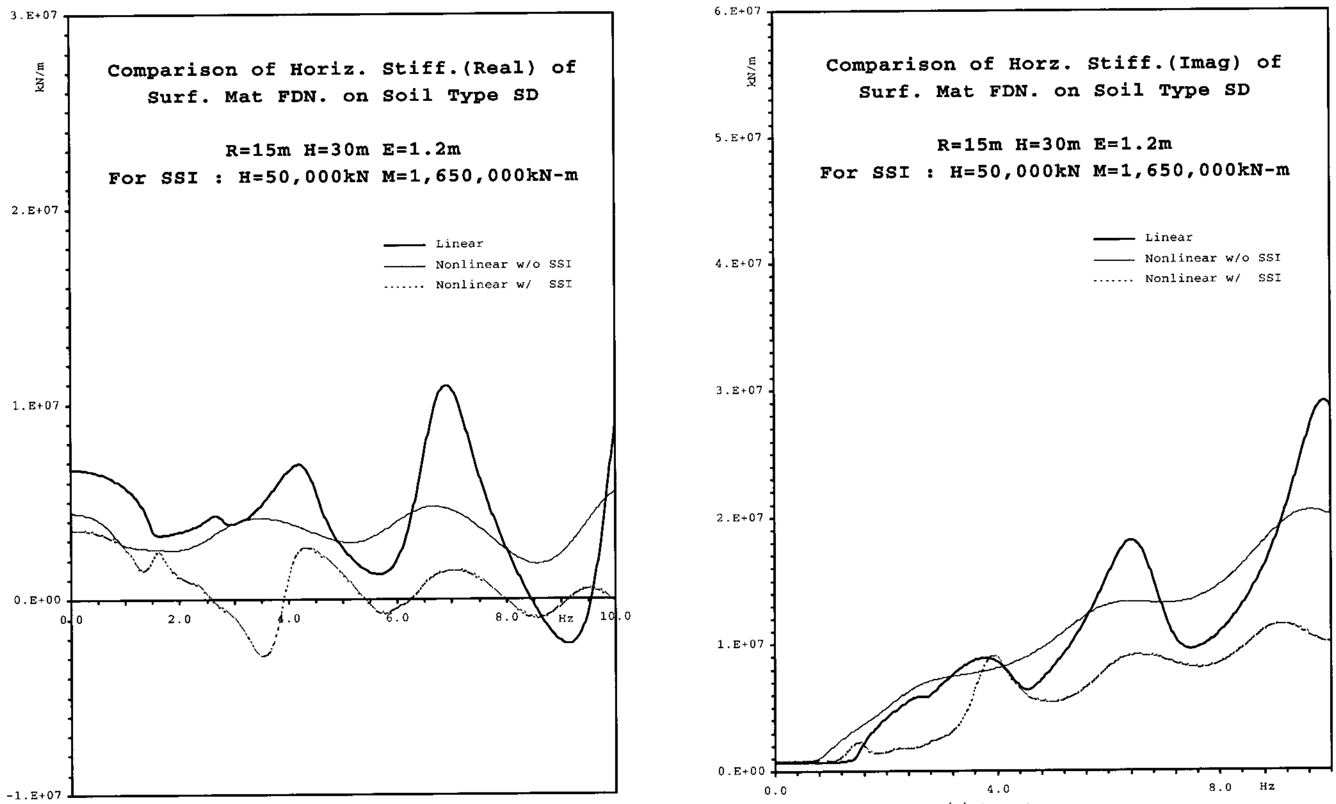


Fig. 3 Substructure method vs FEM

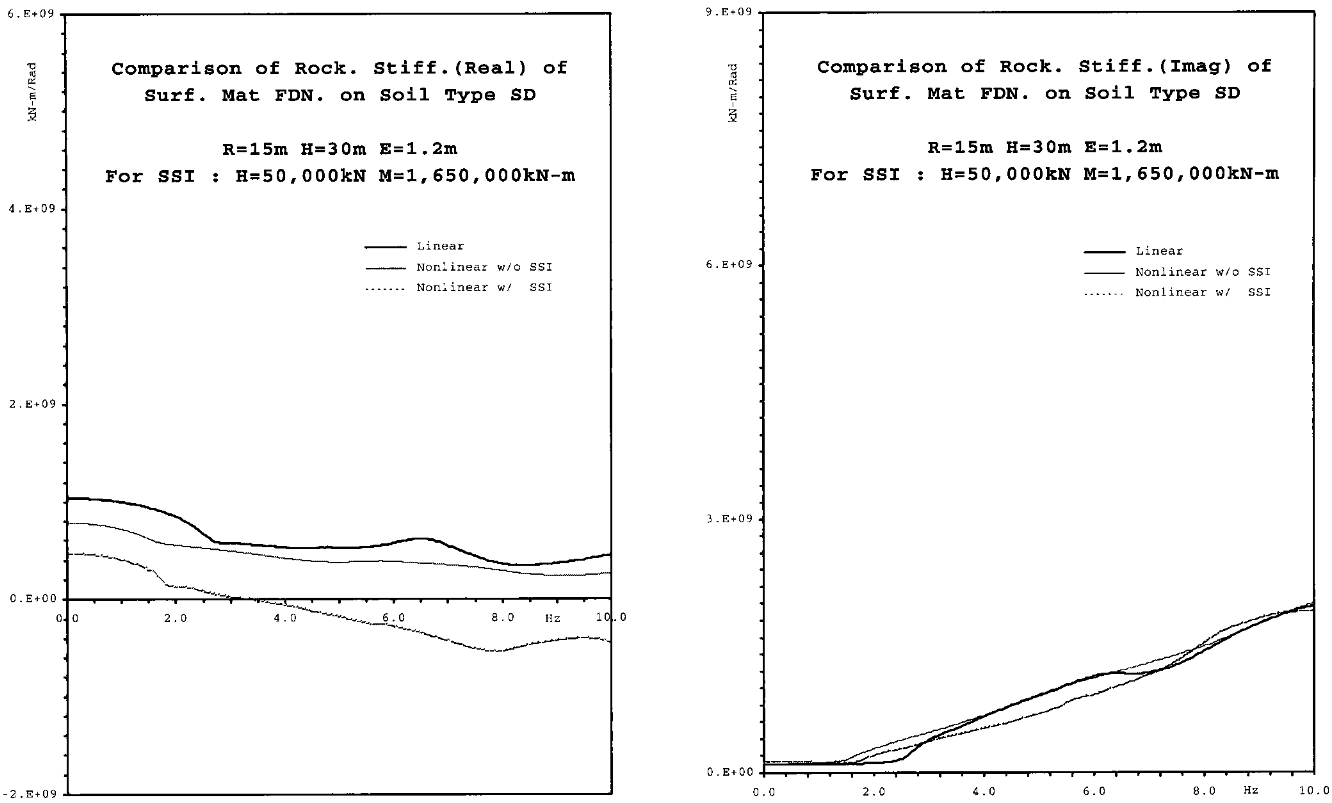
of a surface massless rigid mat foundation with and without the effect of the soil-structure interaction(SSI) were compared with the linear ones to investigate the effects of the nonlinearity of a soil layer and the SSI. The earthquake motion was applied to the bed rock under the soft soil layer to evaluate the nonlinear soil properties of soil layers changed due to the exciting earthquake, which will represent the soil properties of the far field in the nonlinear finite element analysis. Also, the effects of the soil-structure interaction were investigated applying a horizontal force and rotating moment of 5×10^4kN and 1.65×10^6kN-m(approximately corresponding to the inertia forces at the structural period of 1.5 seconds) at the top center of a massless rigid foundation simultaneously with the bed rock earthquake.

In Fig. 4, it can be seen that nonlinear horizontal stiffnesses for the real part without the SSI effects are about 20-30% smaller than the linear ones, but those for both real and imaginary parts in the lower frequency range are almost the same showing some averaging fluctuations in the higher frequency range. However, both real and imaginary parts of nonlinear horizontal stiffnesses with the SSI effects are reduced considerably from the linear ones. The real part of nonlinear rocking stiffnesses without the SSI effects shown in Fig. 5 are about 25% smaller than the linear ones in the lower frequency range and a little bit smaller in the higher frequency range, but those for the imaginary part are almost the same in the whole frequency range. And, the real part of nonlinear rocking stiffnesses with the SSI effects is reduced very much from the linear ones, but



(a) Real part (b) Imaginary part

Fig. 4 Comparison of horizontal stiffnesses of surface mat foundation on soil type of S_D



(a) Real part (b) Imaginary part

Fig. 5 Comparison of rocking stiffnesses of surface mat foundation on soil type of S_D

the imaginary part of them is almost identical to that of linear rocking stiffnesses in the whole frequency range.

Study results indicate that the effect of the nonlinearity of a soil layer on the horizontal and rocking stiffnesses of a surface mat foundation due to the bed rock earthquake excitation is limited to the real part of them in the lower frequency range, however the nonlinearity due to the soil-structure interaction is pronounced as a whole. It seems mainly because the nonlinearity of the soil due to the bed rock excitation is decreased gradually as a soil layer goes upward, however the nonlinearity of a soil due to the soil-structure interaction is concentrated around a rigid mat foundation.

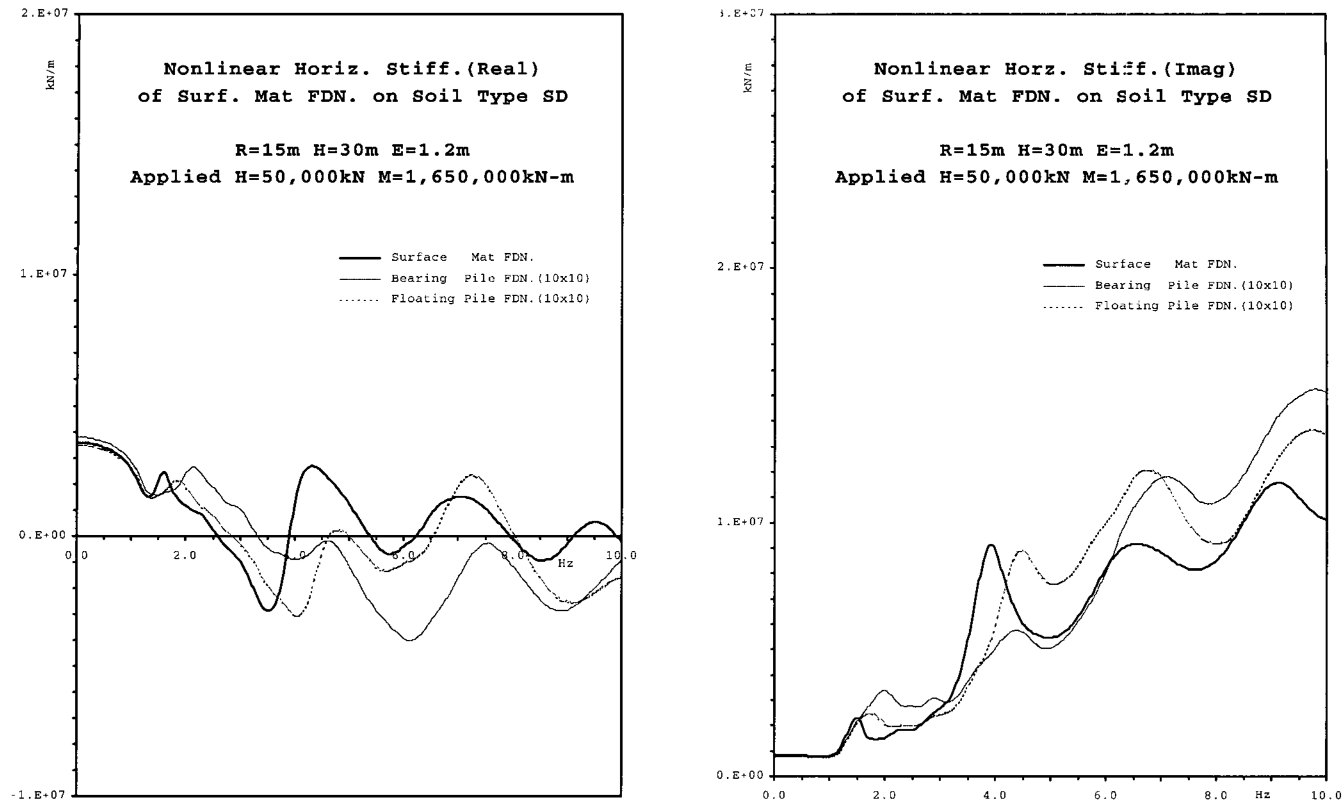
5. Effects of a pile group on the nonlinear stiffnesses of a surface mat foundation

Nonlinear horizontal and rocking stiffnesses of a massless rigid surface mat foundation(having a small embedment of 1.2m) with or without a pile group were studied applying inertia forces of 5×10^4kN and 1.65×10^6kN-m with the excitation of the El Centro N-S earthquake. The pile group was assumed to have an arrangement of 10×10 piles for both bearing and floating pile groups. Nonlinear horizontal stiffnesses in Fig. 6 show that the real stiffnesses of pile foundations are a little bit larger than those of a surface mat foundation in the lower frequency range, and the imaginary stiffnesses are also somewhat larger in the higher frequency range. This indicates that the effect of pile groups on the horizontal stiffnesses of a surface mat foundation is not significant even though there are some difference and frequency variations in stiffnesses.[3]

The nonlinear rocking stiffnesses of a surface mat foundation with or without piles are shown in Fig. 7. The real part of rocking stiffnesses of both bearing and floating pile foundations were increased more than approximately 2-3 times those of a surface mat foundation in the lower frequency range, indicating a significant effect of a pile group on the rocking stiffnessses. The imaginary part of rocking stiffnesses of a bearing pile foundation is a little bit larger than that of a mat foundation in the lower frequency range, but it is increased quite a bit in the higher frequency range. However, the imaginary part of rocking stiffnesses for a floating pile foundation increases gradually with the frequency indicating more radiation damping. It can be noticed that a bearing pile foundation has larger rocking stiffness, but less radiation damping than a floating one.

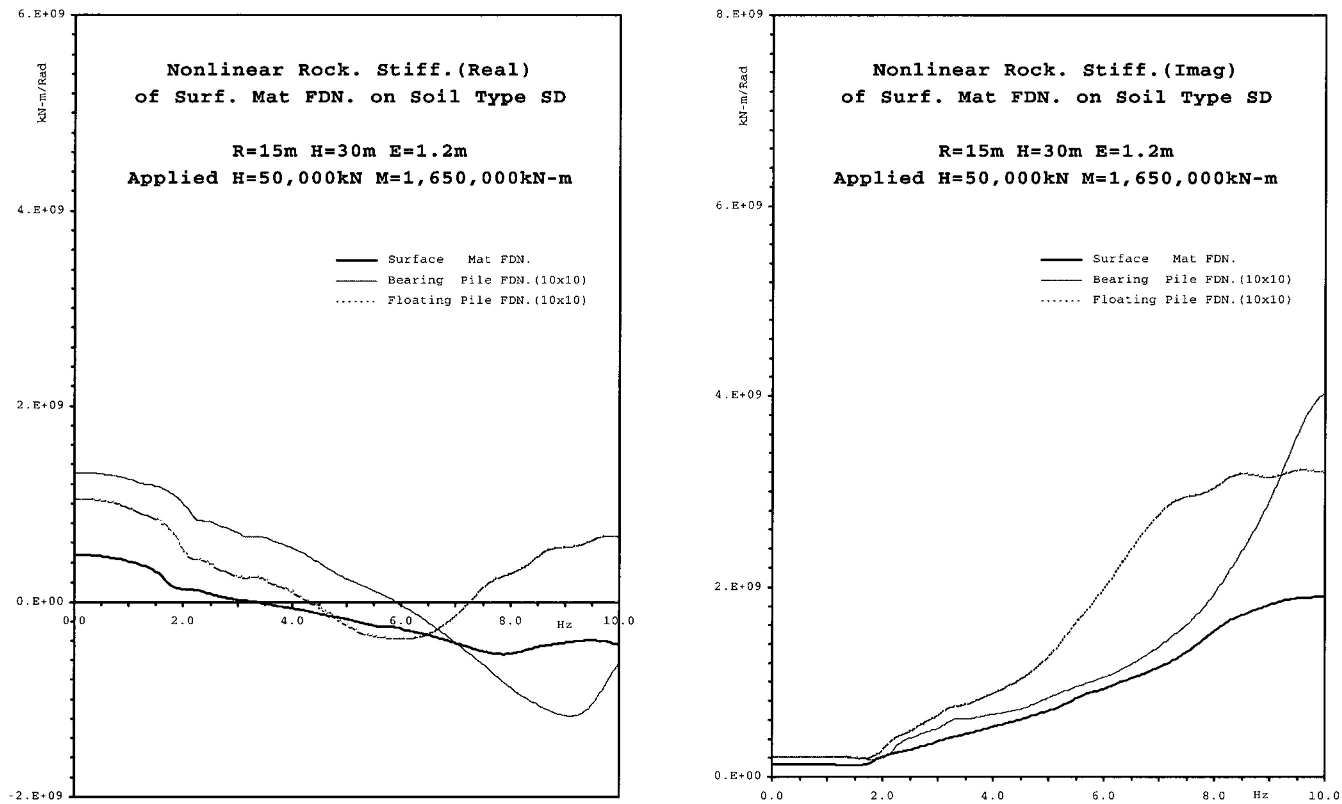
6. Base motions of mat foundations with the non-linear soil layer

The base motions of a massless rigid mat foundation in



(a) Real part (b) Imaginary part

Fig. 6 Comparison of nonlinear horizontal stiffness of a mat foundation w/ or w/o a pile group

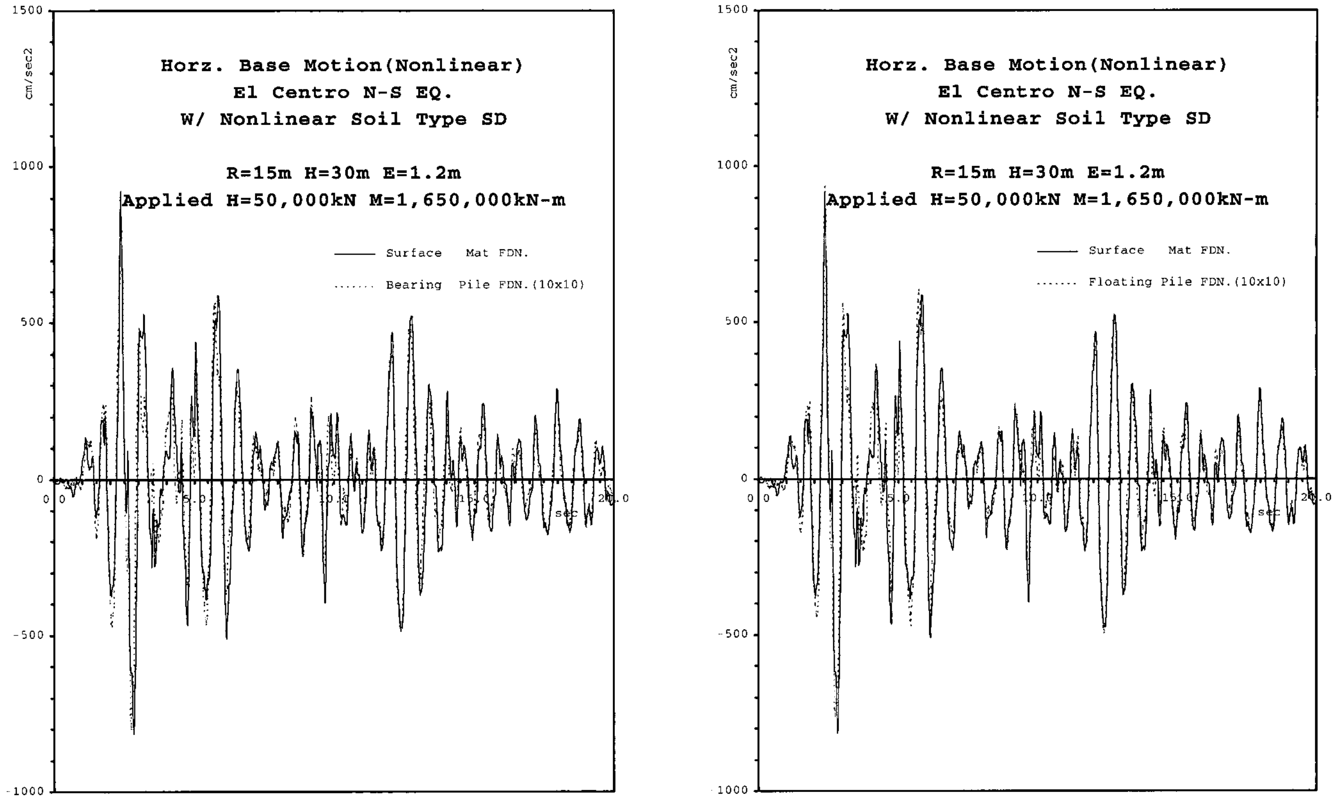


(a) Real part (b) Imaginary part

Fig. 7 Comparison of nonlinear rocking stiffness of a mat foundation w/ or w/o a pile group

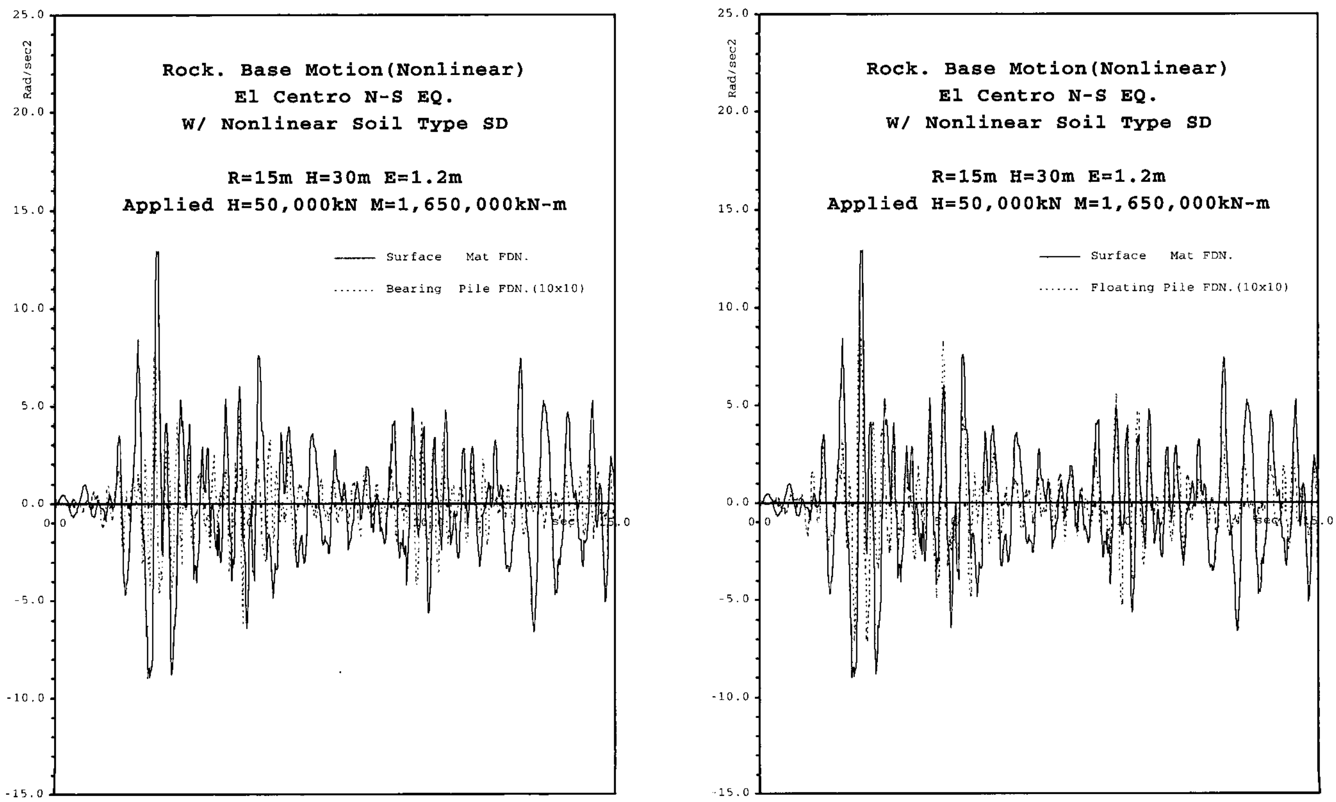
the nonlinear soil layer were also investigated with and without a pile group. Horizontal and rocking base motions of El Centro N-S earthquake with the nonlinear soil were shown in Fig. 8 and 9.

It can be seen in Fig. 8 that the horizontal base motions of both bearing and floating pile foundations are very similar to each other with a little difference in amplitude and phase. And they are also similar to the horizontal base motions of a mat foundation without a pile except some difference in amplitude, indicating that the effect of a pile group is negligible on the horizontal base motion. The rocking base motions of a bearing pile foundation



(a) (b)

Fig. 8 Comparison of nonlinear horizontal base motions of mat and pile foundation



(a) (b)

Fig. 9 Comparison of nonlinear rocking base motions of mat and pile foundation shown in Fig. 9 are reduced considerably comparing with those of a mat foundation or a floating one. The rocking base motions of a floating pile foundation are quite similar to those of a mat foundation at the beginning, but the amplitudes are decreased considerably after 5 seconds.

The study results show that the effects of pile groups on the base motions of a mat foundation lying on the nonlinear soil layer have in general similar trends to those on the stiffnesses as could be expected.

7. Comparison of elastic response spectra for surface mat foundation

Elastic response spectra of a SDOF system built on a surface foundation (E=1.2m) were investigated for the linear and nonlinear soils with the El Centro N-S earthquake record, considering four different nonlinear soil properties specified by the α of 0.025, 0.05, 0.1 and 0.25.

Elastic responses of a SDOF system with a nonlinear soil layer shown in Fig. 10 decrease gradually as the soil properties become softer having smaller stiffness and more damping(i.e. as the α becomes larger). The fundamental periods of the system become larger due to the weaker soil stiffness, and the maximum responses are reduced due to the increased damping. However, the elastic responses of a system with the nonlinear soil in the longer period range exceed considerably the responses for the linear soil.

8. Comparison of elastic response spectra for pile foundations

Fig. 11 shows the elastic response spectra of a SDOF system built on surface mat foundation, bearing pile foundation and floating one lying on the linear soil with the excitation of the El Centro N-S earthquake. The elastic responses of a SDOF system with a pile group of bearing or floating piles are almost the same as those of a surface mat foundation, showing that a pile group has a negligible effect on the horizontal elastic response of a SDOF system built on the linear soil.

Elastic response spectra of a SDOF system with a surface mat foundation were compared with those for bearing and floating pile foundations as shown in Fig. 12. The α for the nonlinear soil model was taken as 0.25 to represent the weak soft soil. Elastic responses of a structure with a floating pile foundation were almost identical to those of a bearing one showing a little smaller differences in the shorter period range. This seems because the stiffness of a pile group reduces the amplification of the earthquake excitation. And elastic responses with a bearing pile group is a little bit smaller than those of a surface mat foundation in the shorter period range, but show large decrease as the period goes up.

It is clear that the pile group stiffens the soft soil layer in some degree reducing the seismic responses of a structure,

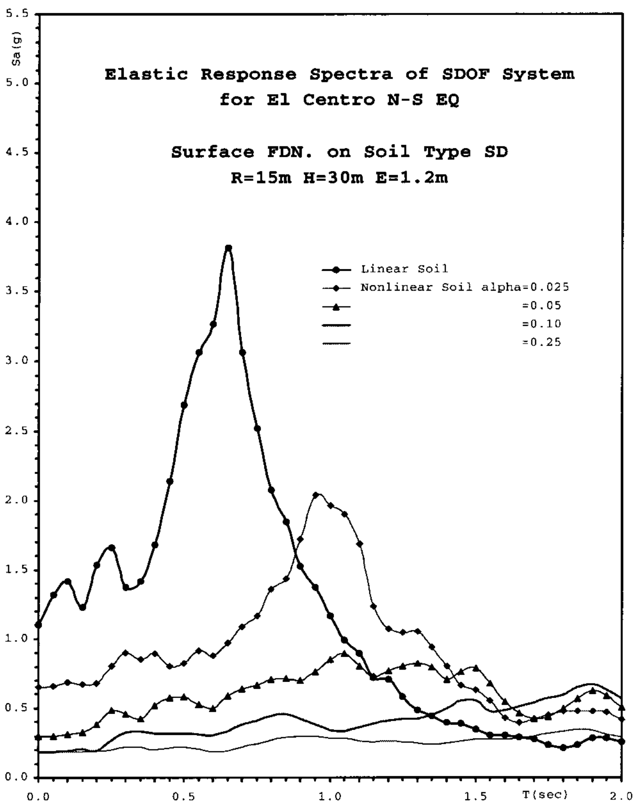


Fig. 10 Elastic response spectra of mat foundation

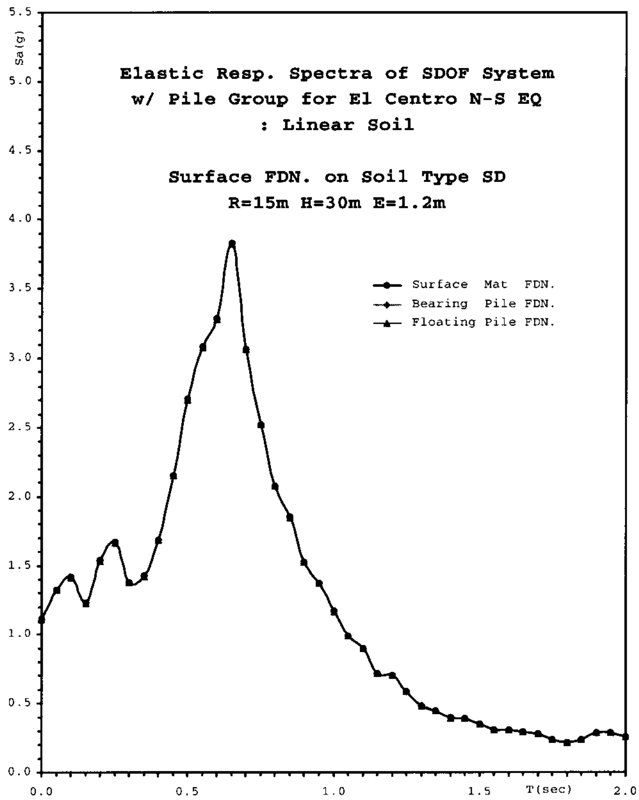


Fig. 11 Response spectra of pile foundation w/ linear soil

especially in the high period range. However, the reduction of seismic responses due to a pile group is not so large in the absolute point of view.

9. Comparison of response spectra of surface mat foundation with UBC ones

Elastic responses of a surface mat foundation without a pile were compared with the response spectra of UBC-97 in Fig. 13 for the cases of the α of 0.025, 0.05, 0.1 and 0.25, which represent the soft, moderate and stiff soils. The elastic response spectra of UBC-97 represent the responses for the zone 3 of a strong earthquake with the soil type of S_D.

Elastic responses of a surface mat foundation with the nonlinear soil type of S_D have peaks at the periods of longer than 0.65 seconds with the liner soil, showing higher peaks of the acceleration with the stiffer soil. The peak response is almost two times that of UBC-97, but the responses at the period range of maximum responses of UBC-97 are approximately one-third of UBC-97 ones. Also, the responses of a structure with a pile foundation will be smaller than those of UBC-97 even if the effect of a pile group is taken into account.

In this study, elastic responses of a SDOF system with the nonlinear soil condition have some differences from those of UBC-97, indicating the nonlinearity of the soft soil is beneficial in the shorter period range and detrimental in the longer period range. This suggests that it is necessary to perform seismic analyses of a structure lying on the soft soil layer taking into account the site soil conditions instead of just following the routine seismic design procedures defined in the codes.

One should notice on the other hand that in this work the El Centro earthquake was used as input at the base of the soil deposit. Since this record was obtained on ground rather than rock, there may be some degree of duplication in the soil amplification effects. In order to reach broader conclusions in the comparison with code type design spectra it would be more appropriate to use as base excitation a record registered on rock outcrop.

10. Conclusions

In this study, elastic horizontal responses of a structure with and without a pile group lying on the soft soil layer (soil type of S_D in UBC-97) were investigated utilizing one step pseudo 3-D finite element method and applying the earthquake excitations to the bedrock directly. The nonlinear soil properties were generated by the Ramberg-Osgood model. Elastic responses were studied taking into account the soil nonlinearities due to the seismic excitation and the soil-structure interaction. The study results are as follows.

The soil nonlinearity due to the soil-structure interaction

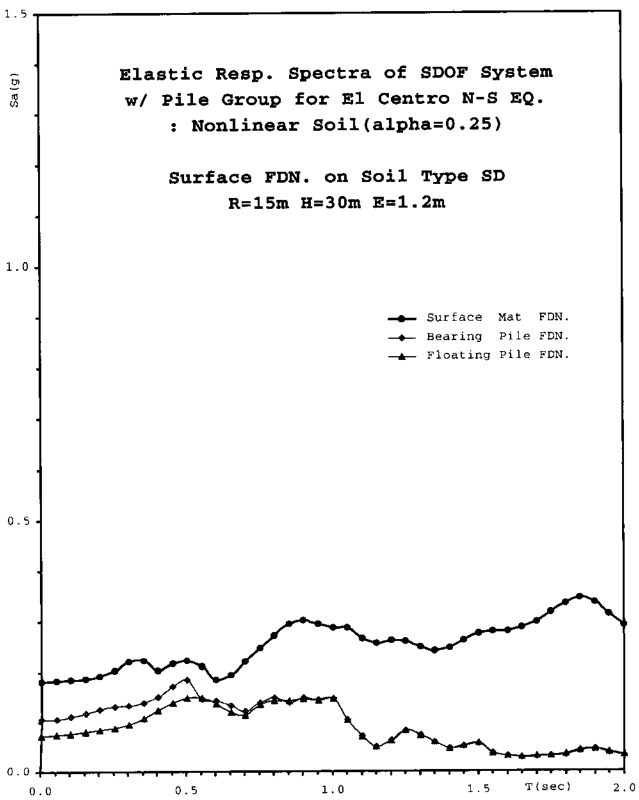


Fig. 12 Response spectra of pile foundation w/ nonlinear soil

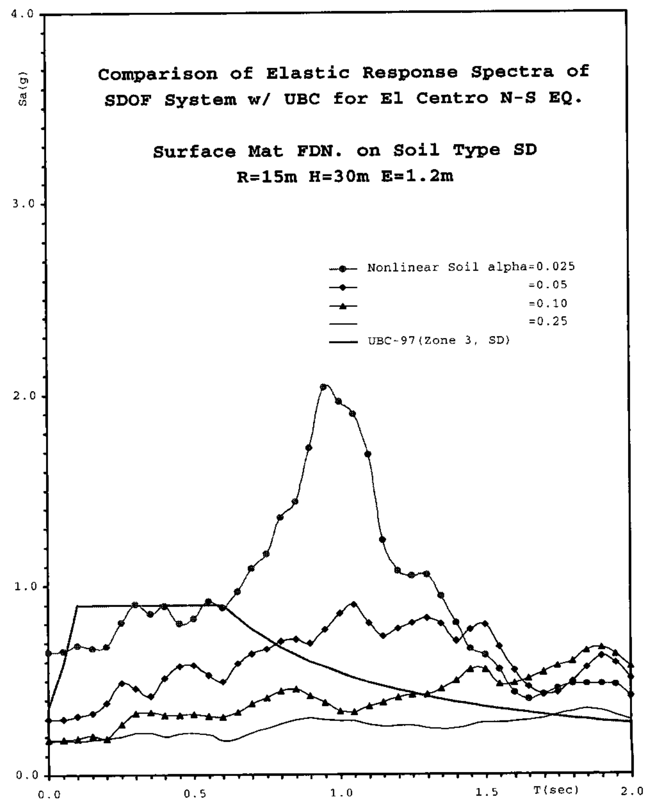


Fig. 13 Response spectra of mat foundation vs UBC

affected very much on the horizontal and rocking stiffnesses of a foundation. However the nonlinear soil effect due to the earthquake excitation is limited on the real part of the stiffnesses in the lower frequency range.

The effect of a pile group on the nonlinear stiffnesses of a foundation was significant for the case of rocking, especially with the real part of the rocking stiffness. Also the rocking base motion of a foundation was considerably reduced by a pile group with the nonlinear soil, which was pronounced with the bearing piles. However the effect of a pile group was negligible on the swaying motion of a foundation.

Elastic peak responses of a structure with a surface mat foundation become smaller as the nonlinearity of the soft soil increases, and the period of the peak response becomes longer. The acceleration response of a structure with a softer soil was smaller than the maximum acceleration of the exciting earthquake showing the effect of the base isolation due to the nonlinear soft soil layer.

Effects of a pile group built in the linear soil layer were almost negligible on the elastic response of a structure, but both bearing and floating pile groups in the nonlinear soil layer reduced the horizontal elastic response of a structure in the whole frequency range, showing almost the same trends with some difference. However, the reduction of seismic responses due to the pile groups is small in the absolute point of view.

Finally, the study results showed that the elastic responses of structures are highly dependent on the nonlinear soil properties, suggesting the performance base seismic design of structures for the complete soil-structure system taking into account the nonlinearity of the underlying soil instead of following the code specified seismic design methods.

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