비선형 지반을 고려한 암반지진에 의한 구조물의 수평방향 탄성거동

Horizontal Elastic Response of a Structure to Bedrock Earthquake with the Nonlinear Soil Layer

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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 탄성지진거동에 매우 중요하고, 성능에 기준한 지반의 비선형성을 고려한 구조물의 내진설계가 필요하다는 것을 잘 보여주고 있다.

1. Introduction

Recently, the importance of the performance based seismic design is recognized to protect structures from the strong 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. 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

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affect significantly on the seismic response of a structure.[1]

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 as a whole system 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 elastic 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. Study was carried out for surface medium size mat foundations lying on the UBC soil profile type of S_D using the N-S record of 1940 El Centro earthquake, which has the peak acceleration of 0.36g representing the strong earthquake for the zone 3 of UBC-97.

2. Modelling

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.[2] This program reflects 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 performs a response analysis of a SDOF system in a whole, taking some advantages for the nonlinear analyses and saving efforts to solve the iterative nonlinear problems. The program was validated for the linear response spectra of a SDOF system, and the results showed that the pseudo 3-D finite element method is a reliable one shot method for the response analysis of the soil-structure interaction system.

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) 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 30 Hz, 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.[3]

For building, the mass density of a building was assumed to be uniform along its height and was taken equal to 272 kg/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.[4]

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 180 m/sec (UBC soil type of S_D) representing a soft soil layer, 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. For the study, the curves shown on Fig.2 were generated assuming experimental factor (α) of 0.025, 0.05, 0.1 and 0.25 and yielding shear strain (γ_y) of $5x10^{-5}$ in the following equations.

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

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

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.[5] 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 $1.786x10^7 kN/m^2$, 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 30 m respectively. The pile arrangements of 6x6, 8x8, 10x10 and 12x12 were assumed for the four different fundamental period ranges of a building as shown in Table 1.

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 x 26.6m (Ro = 15m)	6 x 6
B	0.5 - 1.0	6 - 10		8 x 8
C	1.0 - 1.5	11 - 15		10 x 10
D	1.5 - 2.0	16 - 20		12 x 12

3. Comparison of Nonlinear Seismic Stiffnesses of a Surface Mat foundation

The nonlinear seismic horizontal and rocking stiffnesses 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 $5x10^4$ kN and $1.65x10^6$ kN-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.3, 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.4 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 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.

4. 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 $5x10^4$ kN and $1.65x10^6$ kN-m with the excitation of the El Centro N-S Earthquake. The pile group was assumed to have an arrangement of 10x10 piles for both bearing and floating pile groups. Nonlinear horizontal stiffnesses in Fig.5 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.

The nonlinear rocking stiffnesses of a surface mat foundation with or without piles are shown in Fig.6. 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 stiffnesssses. 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.

5. Comparison of Elastic Response Spectra for Surface Mat Foundation

Elastic response spectra of a SDOF system built on a surface foundation 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.7 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 higher period range exceed considerably the responses for the linear soil.

Elastic responses of a surface mat foundation were also compared with the elastic response spectra of UBC-97, representing the zone 3 for 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. The 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 lower period range and detrimental in the higher 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.

6. Comparison of Elastic Response Spectra for Pile Foundations

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.8. 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 lower 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 lower 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, 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.

7. Conclusions

Elastic horizontal responses of a structure with and without a pile group lying on the soft soil layer (soil type of S_D) were investigated utilizing the frequency domain pseudo 3-D finite element method. 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 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.

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.

For effects of a pile group, 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 taking into account the nonlinearity of the underlying soil instead of following the code specified seismic designs methods.

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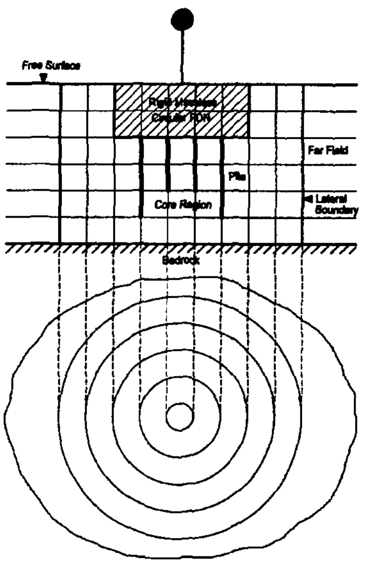


Fig.1 Pseudo 3-D Finite Element Model

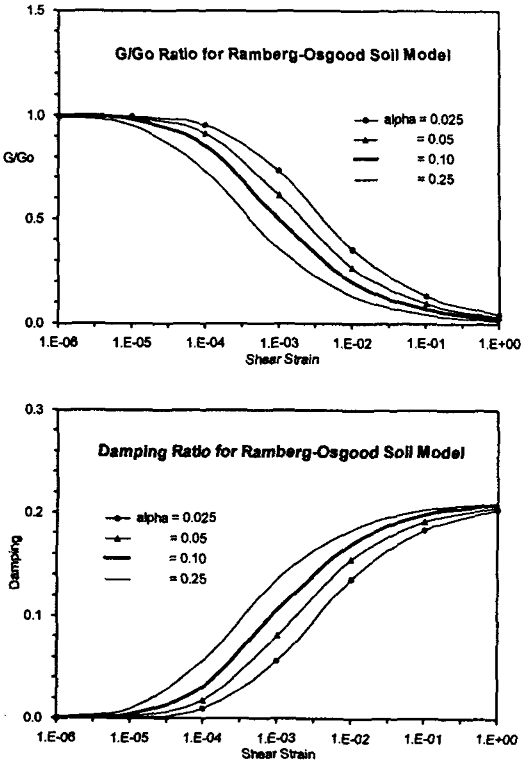


Fig.2 Ramberg-Osgood Model

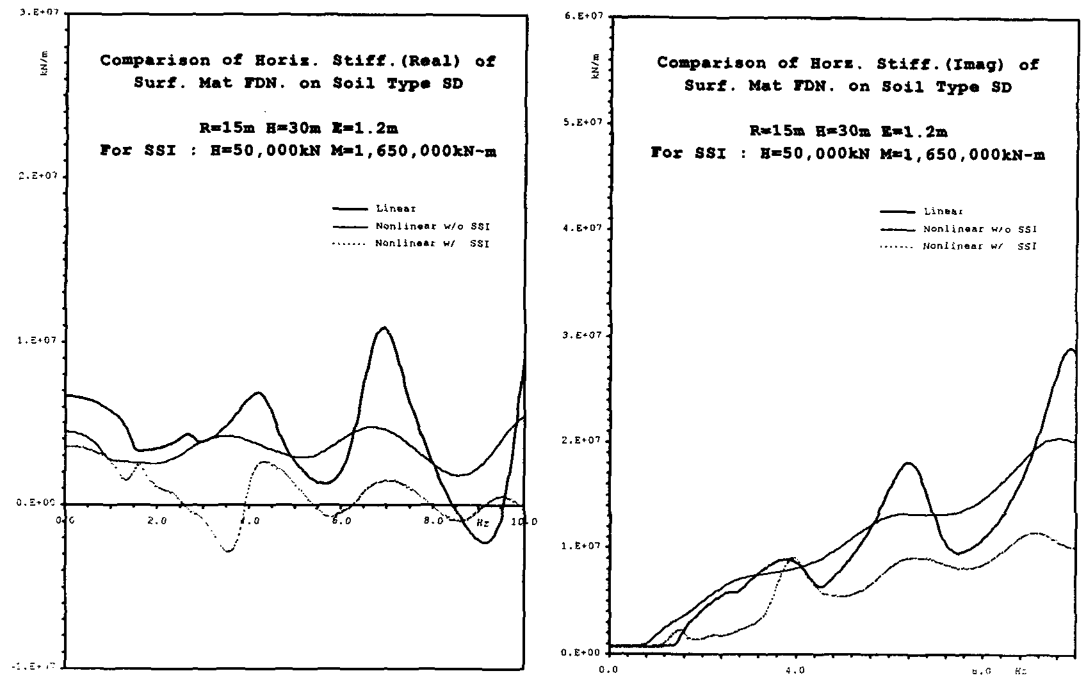


Fig.3 Comparison of Horizontal Stiffnesses of Surface Mat FDN. on Soil Type of S_D

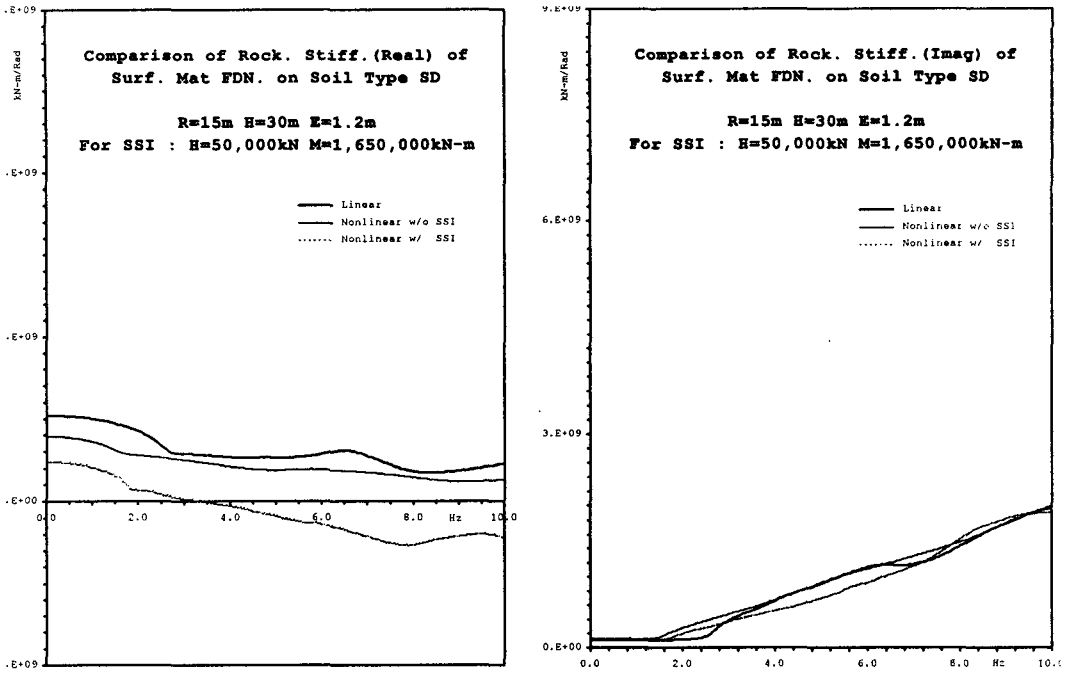


Fig. 4 Comparison of Rocking Stiffnesses of Surface Mat FDN. on Soil Type of S_D

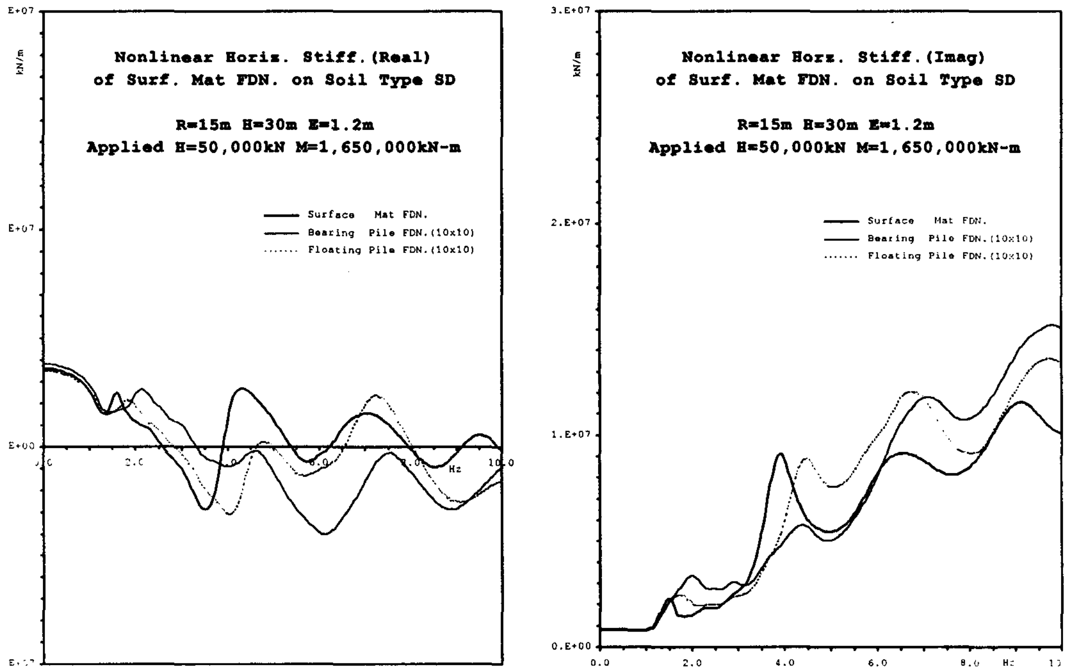


Fig.5 Comparison of Nonlinear Horz. Stiff. of a Mat FDN. w/ or w/o a Pile Group

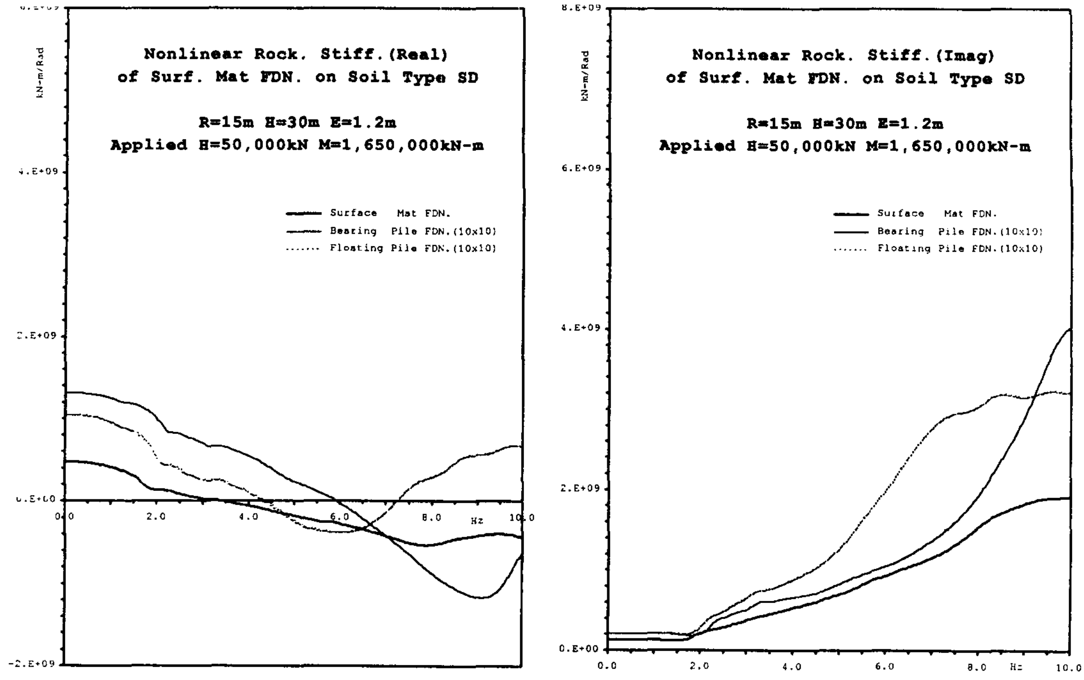
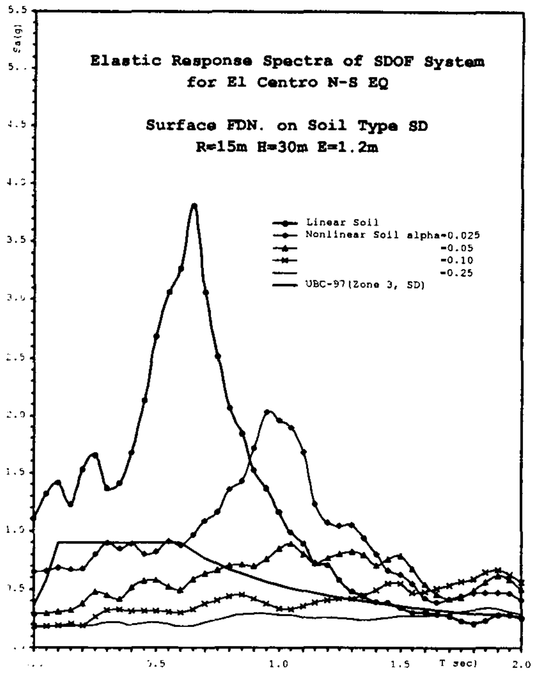


Fig.6 Comparison of Nonlinear Rocking Stiff. of a Mat FDN. w/ or w/o a Pile group



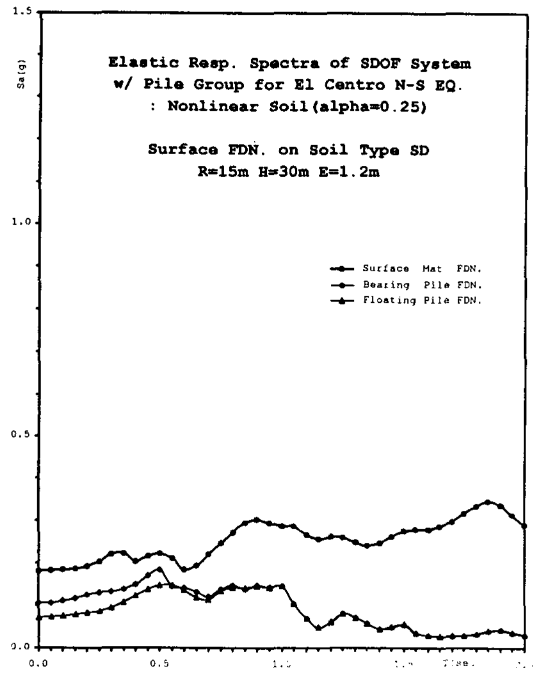


Fig.7 Elastic Resp. Spectra of Mat FDN. Fig.8 Resp Spec of Pile FDN:Nonlinear Soil