# Effect of the Nonlinearity of the Soft Soil on the Elastic and Inelastic Seismic Response Spectra

# 연약지반의 비선형성이 탄성 및 비탄성 지진응답스펙트럼에 미치는 영향

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## 국문요약

비탄성 지진해석은 구조물-지반 체계의 비선형 거동 때문에 내진설계를 위해 필요하고, 합리적인 내진설계를 위해서 지반-구조물 상호작용을 고려한 성능에 기준한 설계의 중요성도 인식되고 있다. 이 연구에서는 11개 중약진과 5개 강진 기록을 최대 가속도 0.075g, 0.15g, 0.2g와 0.3g로 조정하여 연약지반에 세워진 단자유도계에 대한 탄성과 비탄성 지진응답해석을 지반의 비선형성을 고려하여 수행하였다. 의사3차원 동적해석 프로그램을 사용하여 주파수 영역에서 지진하중을 암반에 작용시켜 구조물-지반 체계에 대한 지진응답해석을 한번에 수행하였다. 연구결과에 의하면 비선형 지반-구조물 상호작용 영향을 고려하는 것과 설계기준에 따라 내진설계를 하는 것 보다는 여러 가지 지반조건을 고려하여 성능에 기준한 내진설계를 수행하는 것이 필요하다. 또한 약진에 의한 연약지반의 비선형성이 비선형 지반에 의한 지진파의 증폭 때문에 탄성과 비탄성 지진응답에 심하게 영향을 미쳤는데 특히 탄성지진응답에서 두드러졌다.

**주요어** : 비탄성 지진해석, 성능에 기준한 설계, 지반-구조물 상호작용, 연약지반의 비선형성

## ABSTRACT

Inelastic seismic analysis is necessary for the seismic design due to the nonlinear behavior of a structure-soil system, and the importance of the performance based design considering the soil-structure interaction is recognized for the reasonable seismic design. In this study, elastic and inelastic seismic response analyses of a single degree of freedom system on the soft soil layer were performed considering the nonlinearity of the soil for the 11 weak or moderate, and 5 strong earthquakes scaled to the nominal peak acceleration of 0.075g, 0.15g, 0.2g and 0.3g. Seismic response analyses for the structure-soil system were performed in one step applying the earthquake motions to the bedrock in the frequency domain, using a pseudo 3-D dynamic analysis software. Study results indicate that it is necessary to consider the nonlinear soil-structure interaction effects and to perform the performance based seismic design for the various soil layers rather than to follow the routine procedures specified in the seismic design codes. Nonlinearity of the soft soil excited with the weak earthquakes also affected significantly to the elastic and inelastic responses due to the nonlinear soil amplification of the earthquake motions, and it was pronounced especially for the elastic ones.

**Key words** : inelastic seismic analysis, performance based design, soil-structure interaction, nonlinearity of the soft soil

## 1. Introduction

The effects of the soil-structure interaction on the seismic design of structures are realized, and the importance of the performance based seismic design is also recognized to design the structures more rationally making structures safer from the different levels of earthquakes. Soil-structure interaction analysis of a structure considering the site soil condition is necessary to predict the reasonable seismic response of a structure in the performance based seismic design.[1] But true nonlinear seismic analyses for the soil-structure interaction problem are practically difficult, and nonlinear analyses are performed for the approximate solutions.

In this study, seismic response analyses of a single degree of freedom (SDOF) system lying on the soft soil were performed in one step applying the earthquake excitations to the bedrock. For the nonlinear analyses, a linearized iterative method was utilized. Effects of the nonlinear soil layer on the seismic responses were investigated comparing the responses for the nonlinear soil with those for the linear soil and UBC-97.[2] Study was carried out for the surface medium size mat foundation built on the UBC soil type of $S_D$ using the 11 weak or moderate, and 5 strong earthquake records shown in Table 1 and 2 with the peak accelerations between 0.047g and 0.316g.[3]

## 2. Model

To investigate the effects of nonlinear soft soil layer on the seismic horizontal response of a struc-

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ture, seismic analyses were performed using the in-house software of P3DASS (Pseudo 3-D Dynamic Analysis of Soil-structure System). The program was developed to find linear or nonlinear stiffnesses of a massless rigid mat foundation with or without a pile group considering the soil-structure interaction effect and using the pseudo 3-D finite element method in the frequency domain.[4] This program was modified to reflect the effects of 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 in one step, 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 bedrock 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. Far field was reproduced by a consistent lateral boundary placed at the edge of the foundation for the linear analysis or at the distance of approximately 5-10 times of the radius of an equivalent circular foundation 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. (Figure 1)

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 responses are controlled by the first mode.

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, and unit weight of the soil was also taken to be 18.63kN/m$^3$. Poisson's ratio and damp-

Table 1 Summary of Weak and Moderate Earthquake Records (unit : m-sec)

| No. | EQ. Name | | Component | Max. Response | | | Natural Period | Duration | Site Soil |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Acc. | Vel. | Displ. | | | |
| 1 | Simulated EQ. | St. Louis | - | 1.044 | 0.126 | 0.0391 | 0.13 | 80.00 | Bedrock |
| 2 | | Seoul | | 1.072 | 0.047 | 0.0021 | 0.27 | 20.00 | |
| 3 | Helena Federal Bldg | 1935 | N-S | 0.458 | 0.007 | 0.0023 | 0.07 | 20.95 | |
| 4 | San Francisco Golden Gate | 1944 | E-W | 1.096 | 0.046 | 0.0043 | 0.44 | 39.72 | |
| 5 | | | N-S | 0.935 | 0.039 | 0.0019 | 0.52 | | |
| 6 | Parker Field Cholame | 1966 | N-S | 0.620 | 0.068 | 0.0350 | 0.16 | 44.11 | |
| 7 | San Fernando Lake Hughes | 1971 | E-W | 1.885 | 0.056 | 0.0092 | 0.15 | 36.89 | |
| 8 | | | N-S | 1.497 | 0.084 | 0.0185 | 0.19 | | |
| 9 | Northridge San Marino (SMA360) | 1994 | E-W | 1.139 | 0.074 | 0.0075 | 0.21 | 40.00 | |
| 10 | | | N-S | 1.467 | 0.073 | 0.0110 | 0.16 | | |
| 11 | ChiChi TCU046 | 1999 | E-W | 1.300 | 0.398 | 0.3737 | 0.18 | 85.00 | $S_B$ |

Table 2 Summary of Strong Earthquake Records (Unit : m-sec)

| No. | EQ. Name | | Component | Max. Response | | | Natural Period | Duration | Site Soil |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Acc. | Vel. | Displ. | | | |
| 1 | San Fernando | 1971 | SAD273 | 2.079 | 0.061 | 0.029 | 0.14 | 30.00 | Bedrock |
| 2 | Loma Prieta | 1989 | PRS090 | 1.960 | 0.324 | 0.059 | 0.48 | 40.00 | |
| 3 | | | SLC360 | 2.726 | 0.293 | 0.097 | 0.31 | 38.07 | |
| 4 | Northridge | 1994 | LAC090 | 2.578 | 0.128 | 0.029 | 0.17 | 40.00 | |
| 5 | | | LAC180 | 3.098 | 0.141 | 0.024 | 0.19 | | |

ing 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.[5] For the study, it was fitted to the lower boundary of the experimental damping curves suggested by Darendeli (Figure 2), assuming experimental factor ($\alpha$) and yielding shear strain($\gamma_y$) of 0.1 and $5\times10^{-5}$ respectively in the following equations of (1) and (2).[6] His normalized shear modulus reduction and soil damping ratio curves were proposed analyzing the dynamic experimental test results of large soil samples that has been collected at The University of Texas at Austin over the past decade.

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

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

where, G and $G_0$ are actual and initial shear moduli, $\gamma$ is shear strain, and 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 which is a small nominal one, and the mass density of a foundation was taken to be equal to 2400kg/m$^3$.

Sixteen earthquake records from 1935 to 1999 are selected to represent the weak, moderate and strong earthquakes. Eleven weak or moderate earthquake records are scaled to the nominal peak acceleration of 0.075g, 0.15g and 0.2g to represent the earthquakes for the zone 1, 2A and 2B in UBC, and five strong ones are scaled to the nominal peak accelerations of 0.3g to represent the earthquakes for the zone 3. Nonlinear seismic soil-structure interaction analyses were carried out in the frequency domain ranging up to 20Hz for the structural natural periods of 0-2 seconds.

## 3. Comparison of Elastic Response Spectra of a SDOF System

Elastic response spectra of a SDOF system built on a surface foundation were investigated for a rigid base, linear and nonlinear soils with the 0.075g, 0.15g, 0.2g and 0.3g excitations.

Elastic mean plus one standard deviation responses with a rigid base, linear and nonlinear soil layers are shown in Figure 3 through 5, summarized results of the previous study[7] and the expanded study for the strong excitation of 0.3g. Elastic mean plus one standard deviation seismic responses making approximately 84 per cent possibilities were calculated averaging the elastic seismic responses of a SDOF system for the different earthquakes, and the detailed procedures can be found in the previous study[7]. Elastic mean plus one standard deviation response with a rigid base shows a peak at the period of approximately 0.2 seconds which is around the fundamental periods of

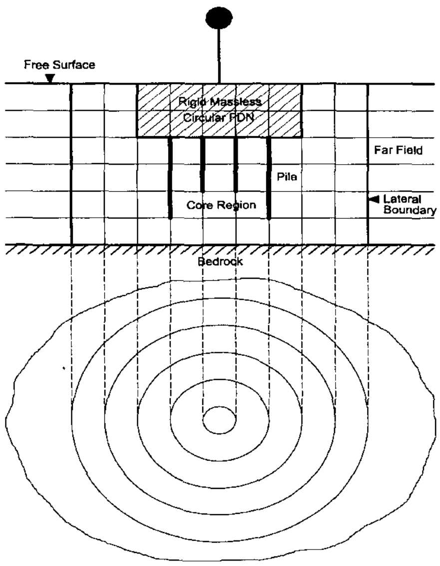


Figure 1 Pseudo 3-D F.E.M. Model

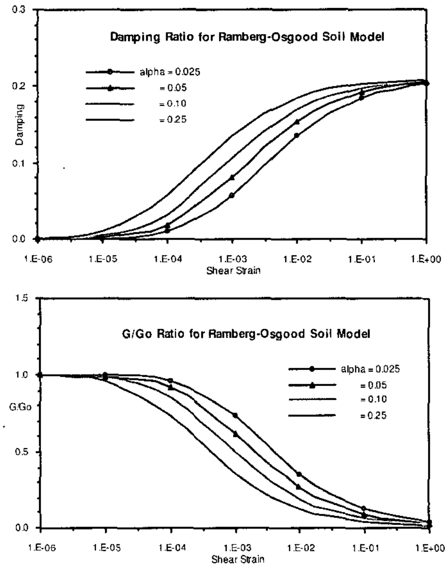


Figure 2 Ramberg-Osgood Model

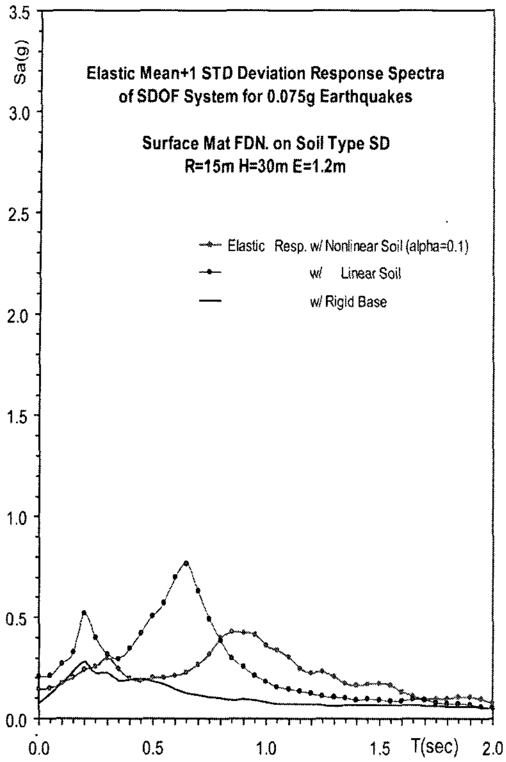


Figure 3 0.075g Elastic Mean+1S.D. resp.

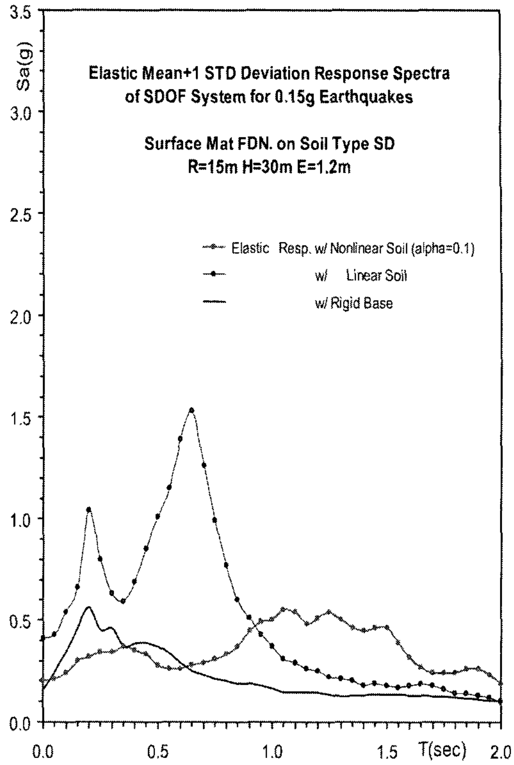


Figure 4 0.15g Elastic Mean+1S.D. resp.

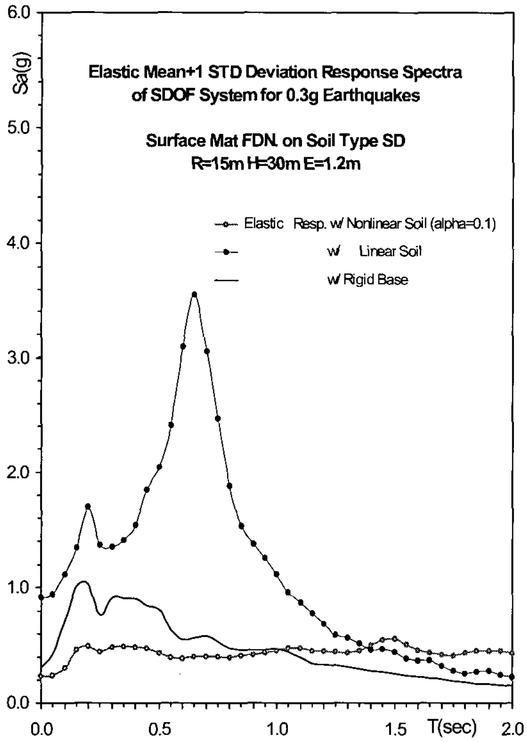


Figure 5 0.3g Elastic Mean+1S.D. resp.

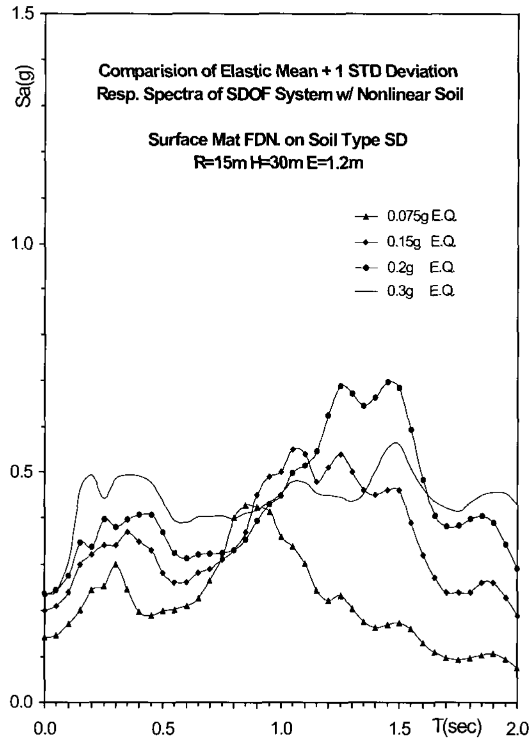


Figure 6 Elastic Resp. w/ Nonlinear Soil

earthquake records, and the peak responses with the rigid base shown in Figure 3 through 5 are linearly proportional to the earthquake excitations. Elastic mean plus one standard deviation response with the linear soil shows two peaks due to the amplification at the fundamental periods of the earthquake and the soft soil layer, and the responses are almost proportional to the earthquake excitations. However, the responses with the nonlinear soil layer show the change in the fundamental period of the system due to the reduced soil stiffness, and also show the drastically reduced responses in the fundamental period ranges of the earthquake motion and the soil layer due to the increased soil damping. The effect of the base isolation can be seen with the nonlinear soil layer in the fundamental period range of the earthquake, noticing smaller responses than those

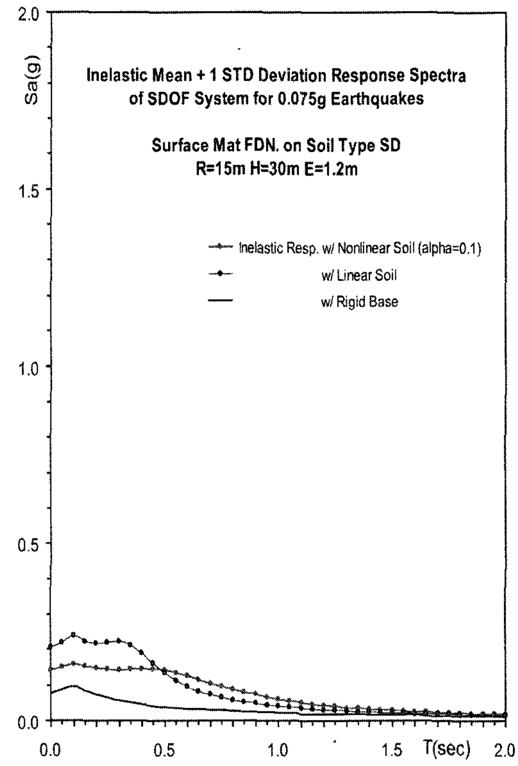


Figure 7 0.075g Inelastic Mean+1S.D. resp.

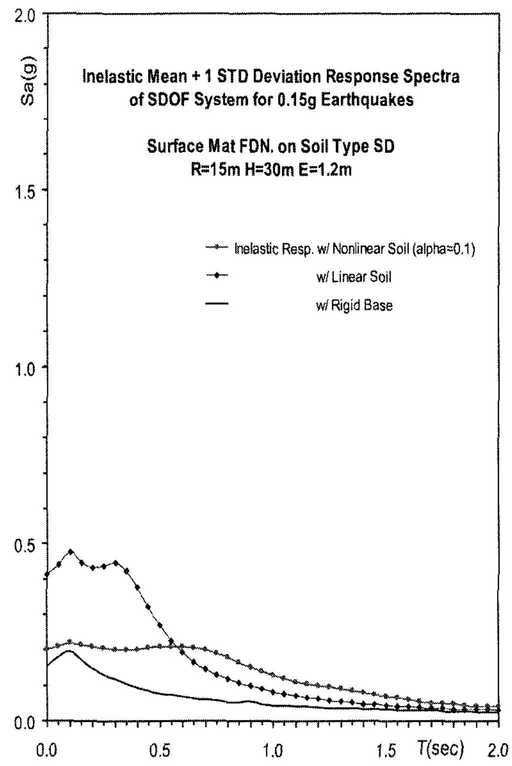


Figure 8 0.15g Inelastic Mean+1S.D. resp.

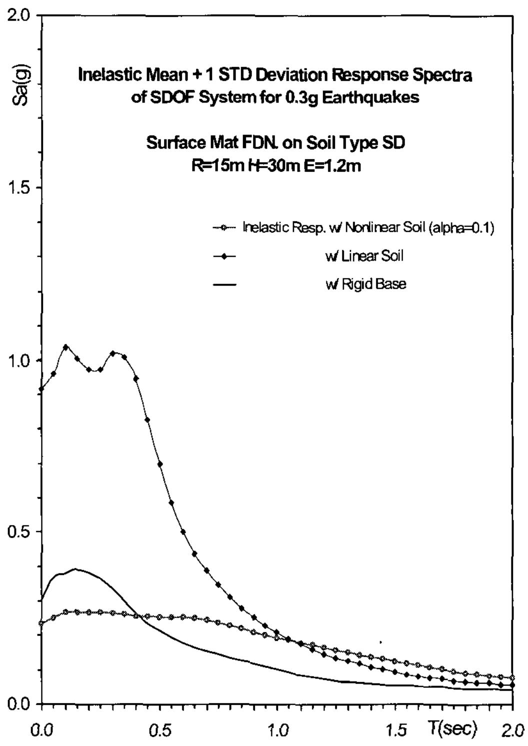


Figure 9 0.3g Inelastic Mean+1S.D. resp.

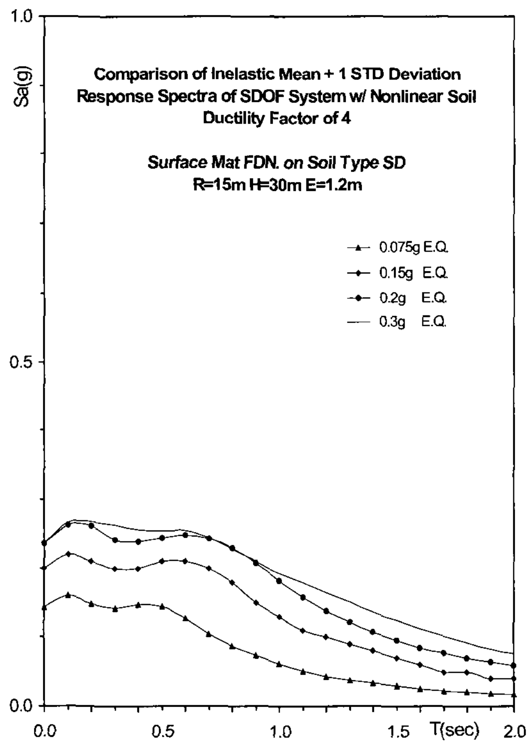


Figure 10 Inelastic Resp. w/ Nonlin. Soil

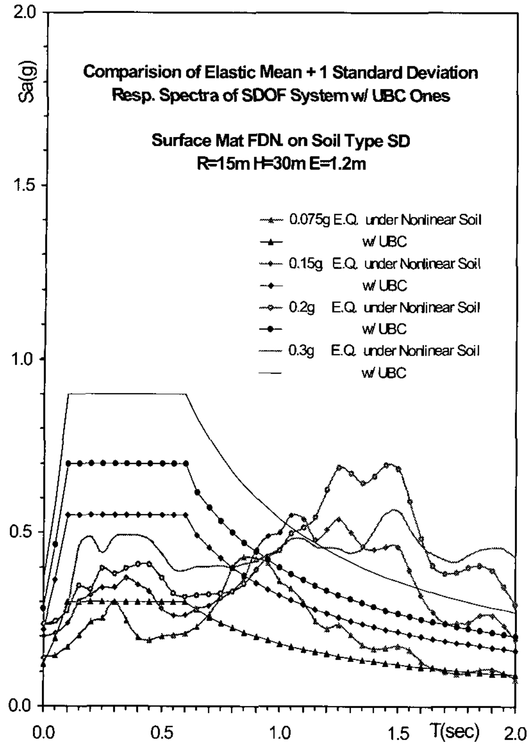


Figure 11 Elastic Mean+1S.D. vs UBC

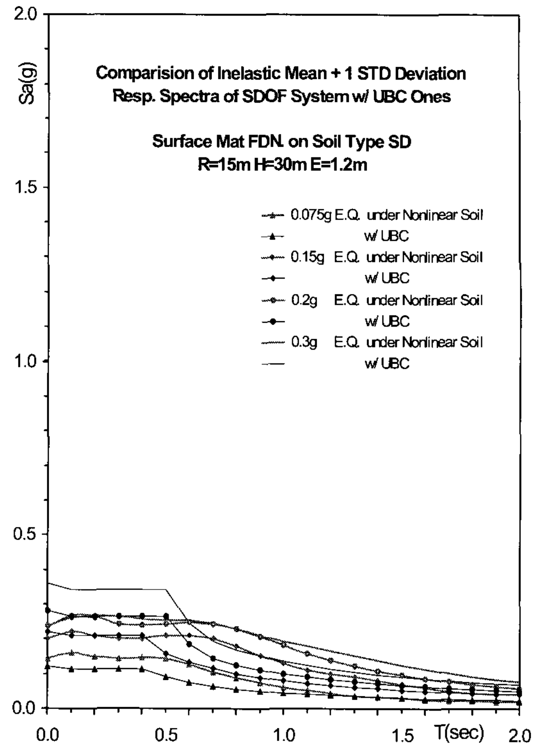


Figure 12 Inelastic Mean+1S.D. vs UBC

of the rigid base with the moderate and strong earthquakes.

Elastic mean plus one standard deviation response spectra with the nonlinear soil layer are shown in Figure 6. The responses with the nonlinear soil layer are affected by the earthquake exci tations in the fundamental period range of the earthquakes, however the effect of the soil amplification is more pronounced with the moderate earthquakes than with the strong ones.

It seems to be important to take into account the effects of the nonlinearity of the underlying soft soil in the seismic design of a structure.

## 4. Comparison of Inelastic Response Spectra of a SDOF System

Inelastic response spectra of a SDOF system built on a surface foundation were also investigated with a rigid base, linear and nonlinear soft soils for the same earthquake records and soil conditions of the elastic response spectra. The structural nonlinear property of a system was assumed to be perfect elasto-plastic with the ductility factor of 4 utilizing the bilinear model.

Inelastic mean plus one standard deviation responses of 0.075g, 0.15g and 0.3g excitations with a rigid base, linear and nonlinear soils are also shown in Figure 7 through 9. Inelastic mean plus one standard deviation response with a rigid base shows a peak at the period of approximately 0.1 seconds which is shorter than the fundamental periods of earthquake records, and the peak responses are linearly proportional to the earthquake excitations. Inelastic mean plus one standard deviation response with the linear soil shows two peaks due to the amplification of the earthquake and soft soil layer, and the responses are almost proportional to the earthquake excitations. However, the inelastic responses with the nonlinear soil layer show the change in the fundamental period of the system due to the reduced soil stiffness, and the responses between the fundamental period of the earthquake motion and that of the soil layer are drastically reduced and become smooth making the response nearly constant due to the reduced structural stiffness and increased soil damping. In case of the 0.3g strong earthquakes, the effect of the base isolation is also noticed with the nonlinear soil in the fundamental period range of the earthquake, showing smaller responses than those of the rigid base.

Inelastic mean plus one standard deviation response spectra with the nonlinear soil layer are shown in Figure 10. The responses with the nonlinear soil are smooth throughout the period and the soil amplification effect is still important in the seismic analyses. Inelastic responses are affected by the intensity of the earthquake excitation, however the effect of the nonlinearity of the soil layer is more significant with the stronger earthquake.

## 5. Comparison of Elastic and Inelastic Response Spectra with UBC ones

Elastic mean plus one standard deviation responses with the nonlinear soil are compared with the elastic responses of UBC for the soil type of $S_D$ in Figure 11. Elastic responses with the nonlinear soft soil have peaks at the periods of around 0.3 and 1.2 seconds, and are much smaller than those of UBC in the short period range due to the increased soil damping especially in case of the moderate and strong earthquakes. However, elastic responses with the nonlinear soil in the long period range are approximately 50-150% larger than those of UBC due to the soil amplification, which is pronounced in case of the weak or moderate earthquakes. It indicates that the effects of soil nonlinearity and soil amplification on the elastic responses are more significant with the moderate earthquakes.

Inelastic mean plus one standard deviation responses with the nonlinear soil are compared with the inelastic responses of UBC in Figure12. Inelastic responses with the nonlinear soil have smooth small peaks at the fundamental periods of the earthquake and the soil layer due to the nonlinear behavior of the system. In the short period range, inelastic responses with the nonlinear soil are similar to or a little bit larger than those of UBC except in the case of strong earthquakes, which is 20% smaller. In the long period range, inelastic responses with the nonlinear soil are larger than those of UBC, especially in the case of moderate earthquakes. Effect of the soil amplification on the inelastic responses is more significant with the stronger earthquakes.

Also, elastic and inelastic mean plus one standard deviation responses with the nonlinear soil shown in Figure 11 and 12 indicate that the low-rise or mid-rise buildings with the short fundamental periods could be designed too conservatively using the elastic or inelastic spectrum of UBC, however the seismic design with those of UBC might underestimate the seismic responses of the high-rise buildings with the long fundamental periods.

## 6. Conclusions

Seismic elastic and inelastic responses of a SDOF system with the soft soil layer are investigated utilizing the one step pseudo 3-D finite element method applying 11 weak or moderate, and 5 strong earthquake motions at the bedrock base. This method can take into account the nonlinear soil-structure interaction effects in one step, different from the substructure method. In this study, seismic analyses of a SDOF system on the soft soil layer were performed with the 0.075g, 0.15g, 0.2g and 0.3g excitations, and study results are as follows.

Seismic response spectra assuming a rigid base or a linear soil layer does not represent the true behavior of a structure-soil system built on the soft soil layer, and can make the seismic design undesirable resulting in too conservative design for the low-rise and mid-rise buildings or too underestimated one for the high-rise buildings. For the reasonable and economical seismic design, it is necessary to take into account the nonlinear soil-structure interaction effects and to perform the performance based seismic design for the various soil conditions rather than to follow the routine design procedures specified in the seismic design codes.

Soil nonlinearity and soil amplification due to the stronger earthquakes affect more on the seismic responses, however the effects of those are also significant with the weak earthquakes.

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