약진에 의한 연약지반의 비선형성을 고려한 비탄성 응답스펙트럼

INELASTIC RESPONSE SPECTRA CONSIDERING THE NONLINEARITY OF THE SOFT SOIL DUE TO THE WEAK SEISMIC EXCITATIONS

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국문요약

강진을 고려한 지진설계 규준은 약진지역에서는 불필요한 경제적 손실을 가져올 수 있고, 지반-구조물 상호작용을 고려한 성능기준 설계가 합리적인 지진설계를 위해서 중요하다는 것이 인식되었다. 이 연구에서는 연약지반 위에 놓인 단자유도계의 탄성, 비탄성 지진응답 해석을 지반의 비선형성을 고려하여 최대지진가속도를 0.07g와 0.11g로 조정한 11개 중, 약진에 대해 수행하였다. 지진응답해석은 지반-구조물체계에 대해 유사 3차원 동적해석 프로그램으로 암반에 지진기록을 입력하여 한 단계에 일괄적으로 수행하였다. 연구 결과에 의하면 고정지반이나 선형지반을 가정한 지진응답 스펙트럼은 구조물-지반체계의 실제적인 거동을 보여주지 못하는 것으로 나타났으며, 합리적인 지진설계를 위해서는 지진규준에 정해진 일상적인 설계절차에 따라서 수행하는 것보다 다른 성질을 가진 여러 지반에 대해서 성능기준 지진설계를 수행하는 것이 필요하다. 약진을 받는 연약지반의 비선형성도 입력지진동을 증폭시켜 탄성, 비탄성 지진응답 스펙트럼에 심하게 영향을 미쳤으며, 그 현상은 특히 탄성 응답스펙트럼에서 두드러졌다.

1. Introduction

The response spectra specified in most of the seismic design codes are basically developed considering the strong earthquakes. However weak and moderate earthquake records of relatively short duration has the characteristics of narrow banded energy content giving the narrow banded spectral peaks. Using seismic design spectra developed for the strong earthquakes may result in unnecessary investment and economical loss for the buildings to the

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countries in the low or moderate seismic area.(1)

The importance of structure-soil interaction for the seismic design of structures is now commonly recognized, and the importance of the performance based seismic design is also recognized to protect structures from the strong earthquakes after Northridge Earthquake. The soil-structure interaction analysis of structures taking into account the site soil conditions is necessary to predict reasonably the seismic response of a structure in the performance based seismic design.(2) But a true nonlinear seismic analyses for the soil-structure interaction problem are practically difficult, and nonlinear numerical seismic analyses are 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 whole soil-structure system possible.

In this study, seismic response analyses of a single degree of freedom (SDOF) system lying on the soft soil 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 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.(3) Study was carried out for surface medium size mat foundations built on the UBC soil profile type of S_D using 11 records (9 recorded and 2 simulated ones) shown in Table 1.

Table 1. Summary of Input Earthquake Records

No.	EQ. Name		Component	Max. Response (m-sec)			Natural Period (sec)	Duration (sec)	Site Soil
				Acc.	Vel.	Displ.			
1	Simulated EQ.	St. Louis	-	1.044	0.126	0.0391	0.13	80.00	Bed-rock
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	1944	E-W	1.096	0.046	0.0043	0.44	39.72	
5	Golden Gate		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	1971	E-W	1.885	0.056	0.0092	0.15	36.89	
8	Lake Hughes		N-S	1.497	0.084	0.0185	0.19		
9	Northridge	1994	E-W	1.139	0.074	0.0075	0.21	40.00	
10	San Marino (SMA360)		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	SB

2. Model

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 P3DASS (Pseudo 3-D Dynamic Analysis of Soil-structure System). The program was developed 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, with or without a pile group considering the soil-structure interaction effect utilizing the pseudo 3-D finite element method in the frequency domain.(4) The effects of the nonlinear soil properties due to the earthquake was reflected by performing the nonlinear analysis for the one dimensional multi-degree of freedom system representing the multi-level free field soil layer.

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 the far distance (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.

Seismic analyses were carried out in the frequency domain up to 20 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.

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 rocklike stiff or dense soil layer with the soil depth (H) of 30m. Shear wave velocity of a soft soil layer was assumed to be 180m/sec (UBC soil type of S_D), 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, Ramberg-Osgood model was fitted to the lower boundary of the experimental damping curves suggested by Darendeli as shown on Fig. 2, assuming experimental factor (α) and yielding shear strain (γ_y) of 0.1 and $5\text{x}10^{-5}$ respectively in the following equations of (1) and (2).(5)

$$G = \frac{2.G_o}{1+\sqrt{1+4\alpha\frac{\gamma}{\gamma_y}}} \qquad (1)$$

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

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

Darendeli's 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.

For foundation, a medium size rigid mat foundation with the radius (R) of 15m was considered with the embedment (E) of 1.2m. The mass density of a foundation was taken to be equal to 2400kg/m^3.

Nine earthquake records and two artificial ones simulated for St. Louis and Seoul are selected to represent the moderate earthquakes. All the records are scaled to the nominal peak accelerations of 0.07g and 0.11g, which are the seismic level of Zone 1 and 2A of UBC.

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 0.07g and 0.11g excitations.

Elastic responses of the 0.11g excitation with a rigid base, linear and nonlinear soil layers are shown in Fig. 3-5 for the 11 earthquakes, including the mean plus one standard deviation response with approximately 84 per cent possibilities averaging them. Elastic mean plus one standard seismic responses of two excitations with a rigid base, linear and nonlinear soils are compared in Fig. 6 and 7 respectively. Mean plus one standard deviation response with a rigid base shows a peak at the period of approximately 0.2 seconds which is the fundamental period of earthquake records. 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. The peak responses due to the earthquake and soil amplification become approximately twice and six times larger than that of the rigid base. However, the peak responses are reduced drastically up to approximately 50% and the fundamental period of the system elongates approximately 1.5 times from 0.67 seconds to 0.95 seconds due to the nonlinearity of the soft soil.

Fig. 8 shows elastic mean plus one standard deviation response spectra with the linear and nonlinear soft soil layers for two excitations. It is clear that the nonlinearity of the soft soil affects significantly on the elastic seismic response of a structure due to the reduced stiffness and the increased damping of the soil, and the effects of the nonlinearity of the underlying soft soil should be considered in the seismic design of a structure. Seismic design assuming linear soil conditions might result in a serious underestimation of design forces for the mid-rise buildings, even though it can be designed too conservatively for the low-rise ones.

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 responses of the 0.11g excitation with a rigid base, linear and nonlinear soils are shown in Fig. 9-11, and inelastic mean plus one standard deviation responses of the 0.11g and 0.07g excitations with a rigid base, linear and nonlinear soils are compared in Fig. 12 and 13. Inelastic mean plus one standard deviation responses with the linear soil of two excitations show peaks of 0.35g and 0.19g, which are 2.5 times amplified but approximately 60% less than those of elastic ones. Inelastic mean plus one standard deviation responses with the nonlinear soil are almost constant on the order of 0.17g and 0.15g respectively at the short period range smaller than 0.6 seconds, showing smooth peaks at the fundamental periods of the earthquake and the underlying soil layer of 0.1 seconds and 0.65 seconds.

Inelastic mean plus one standard deviation responses with linear and nonlinear soft soils are compared in Fig. 14 for two excitations. The nonlinear soft soil layer reduces the inelastic response in the short period range up to approximately 50%, however it amplifies them in the middle period range which is around the fundamental period of a soil layer of 0.6 seconds up to approximately 30%.

5. COMPARISON OF RESPONSE SPECTRA WITH UBC-97 ONES

Elastic mean plus one standard deviation responses with the nonlinear soil for the t재 excitations are compared with the elastic ones of UBC in Fig. 15. Elastic responses with the nonlinear soft soil layer have a peak at the period of around 0.95 seconds, which is much longer than the fundamental period of the underlying soil layer of 0.67 seconds due to the soil amplification effect and the reduced soil stiffnesses. Elastic responses with the nonlinear soft soil in the short period range are reduced approximately 40% for the 0.11g excitation and 10% for the 0.07g one rather than those of UBC due to the increased damping of the soil layer showing little effect of weak excitations, however those in the middle period range are increased approximately twice due to the soil amplification of the earthquake motions, indicating the importance of the effects of soil amplification and soil nonlinearity.

Inelastic mean plus one standard deviation responses with the nonlinear soil for t재 excitations are compared with the inelastic responses of UBC in Fig. 16. Inelastic responses with the nonlinear soft soil have smooth small peaks at the fundamental periods of the earthquake and the soil layer due to the nonlinear behavior of the system, showing almost constant responses at the short period range. Inelastic responses with the nonlinear soil are similar with those of UBC in the short period range, however they are approximately 70% and 100% larger.

6. Conclusions

Seismic responses of a SDOF system with the soft soil are investigated utilizing the one step pseudo 3-D finite element method applying 11 earthquake motions at the base. This method can take into account the nonlinear soil structure interaction effects in one step, different from the substructure method. In this study, elastic and inelastic seismic analyses of a SDOF system on the soft soil layer were performed with the weak earthquakes of 0.07g and 0.11g, and study results are as follows.

Seismic responses assuming a rigid base or a linear soil layer does not represent the true behavior of a structure-soil system, and can lead the seismic design to the undesirable results. For the reasonable seismic design, 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 design procedures specified in the seismic design codes.

Nonlinearity of the soft soil excited with the weak seismic motions also affected significantly on the elastic and inelastic seismic response spectra of a SDOF system due to the nonlinear soil amplification of the earthquake motions, and it was pronounced especially for the elastic response spectra of a structure.

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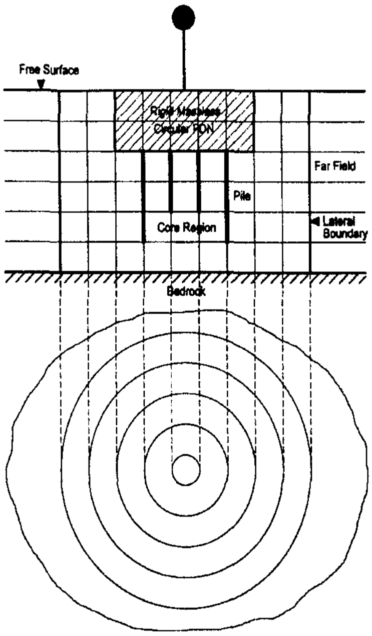


Fig.1 Pseudo 3-D Finite Element Model

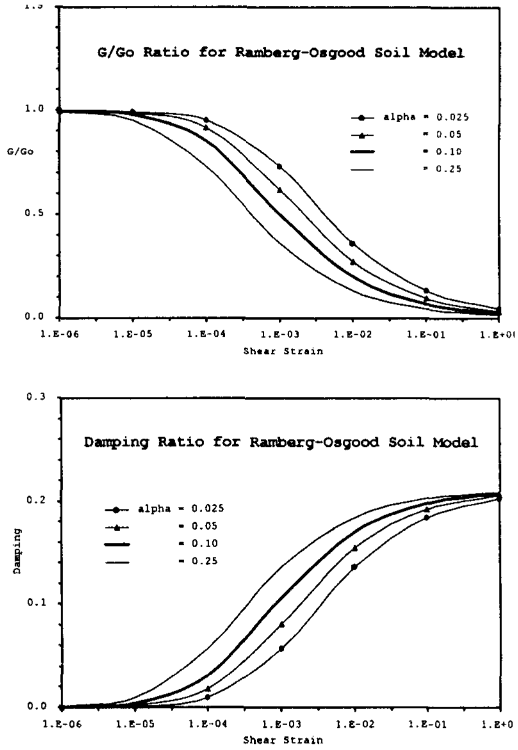
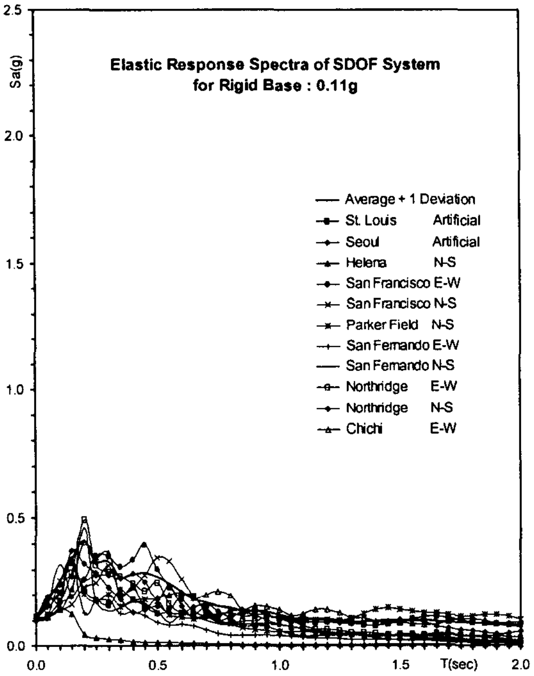


Fig.2 Ramberg-Osgood Model



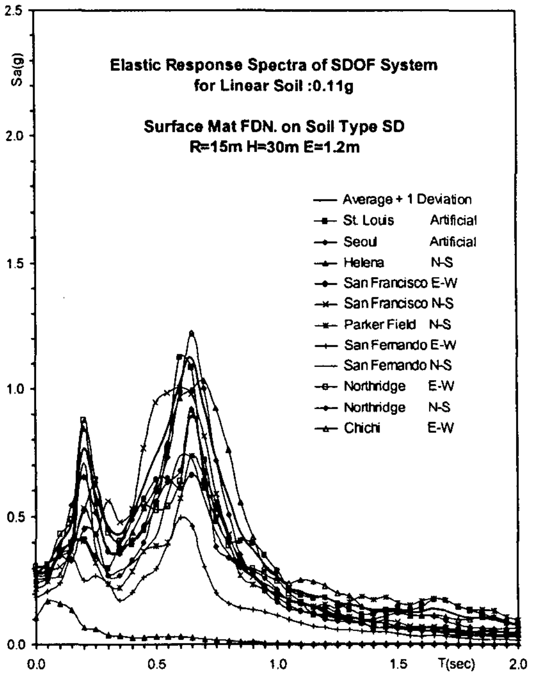


Fig.3 0.11g Elastic responses : Rigid Base Fig.4 0.11g Elastic responses : Linear Soil

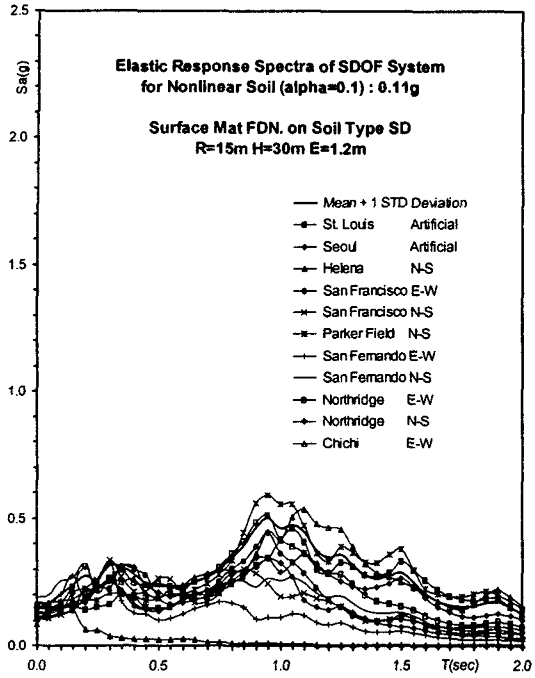


Fig.5 0.11g Elastic respon. : Nonlinear Soil

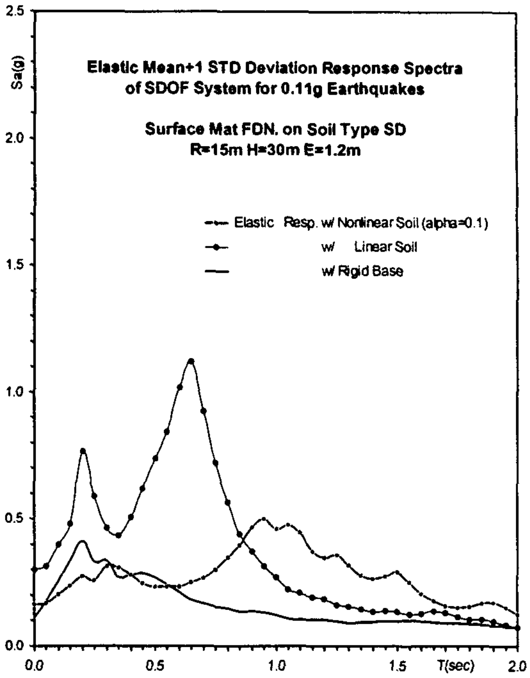


Fig.6 0.11g Elastic Mean+1S.D. responses

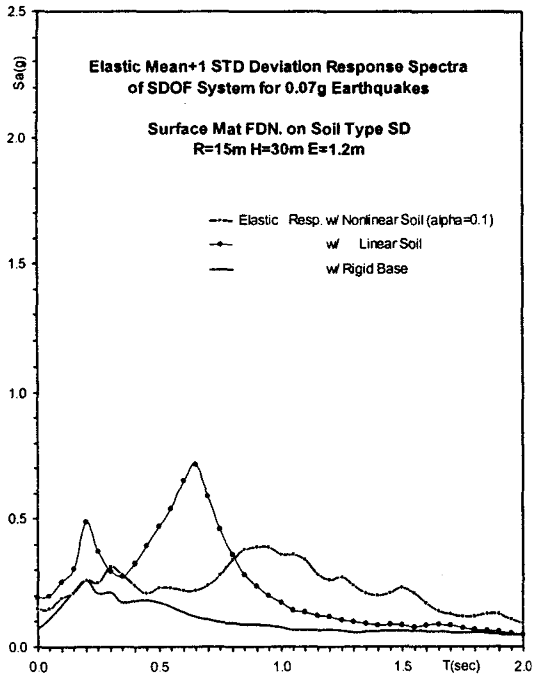


Fig. 7 0.07g Elastic Mean+1 S.D. responses

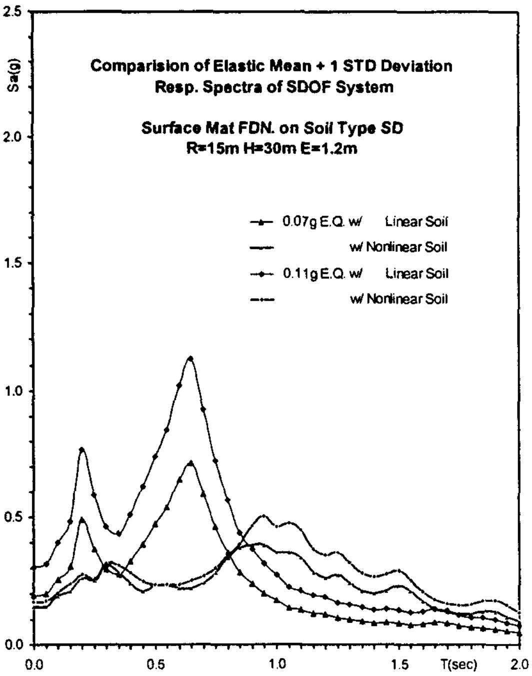
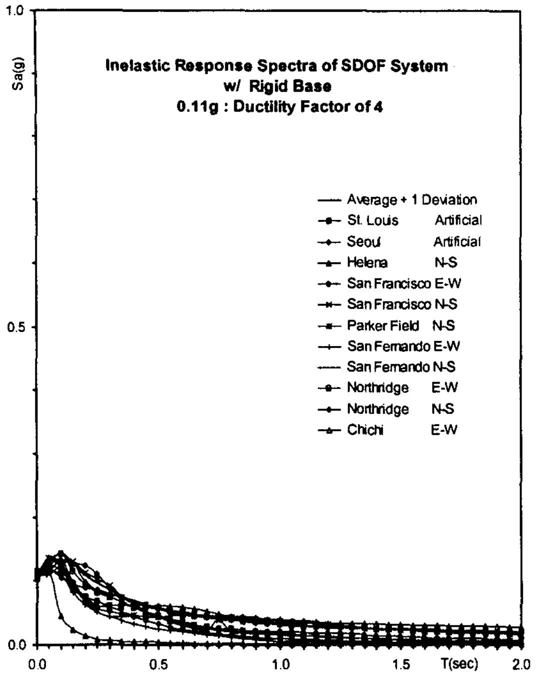


Fig. 8 Elastic Mean+1 S.D. responses



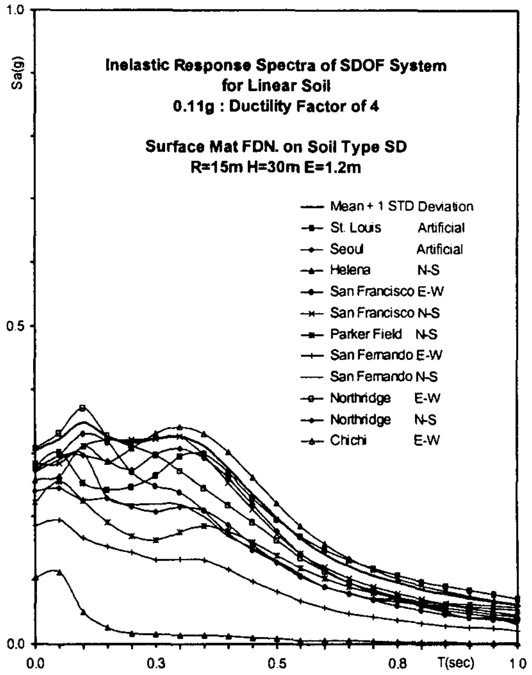
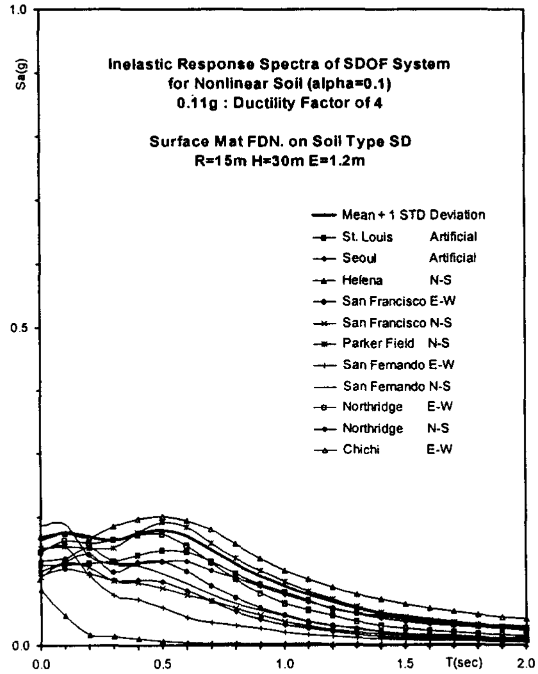


Fig.9 0.11g Inelastic responses: Rigid Base

Fig.10 0.11g Inelastic responses: Linear Soil



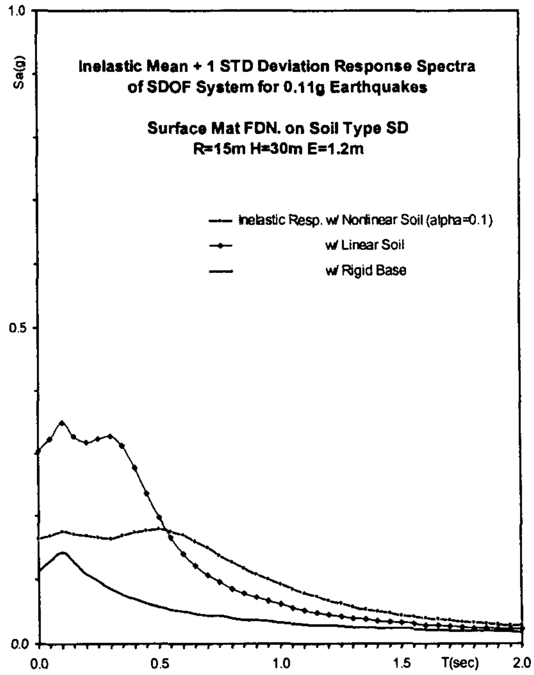


Fig.11 0.11g Inelastic respon: Nonlinear Soil

Fig.12 0.11g Inelastic Mean+1S.D. respon.

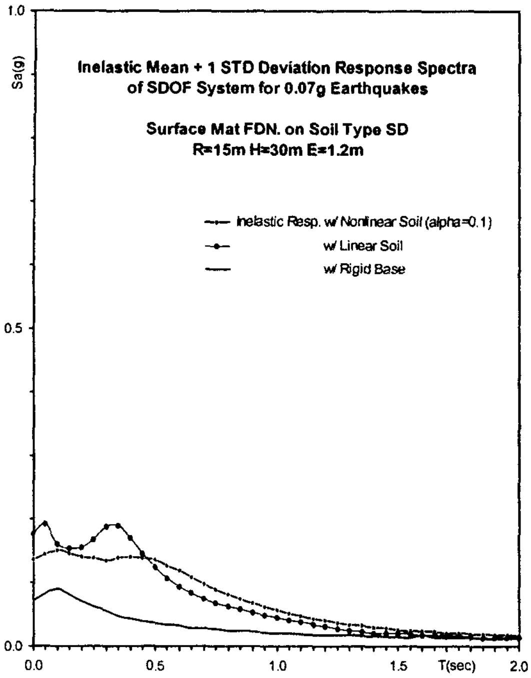


Fig.13 0.07g Inelastic Mean+1S.D. responses

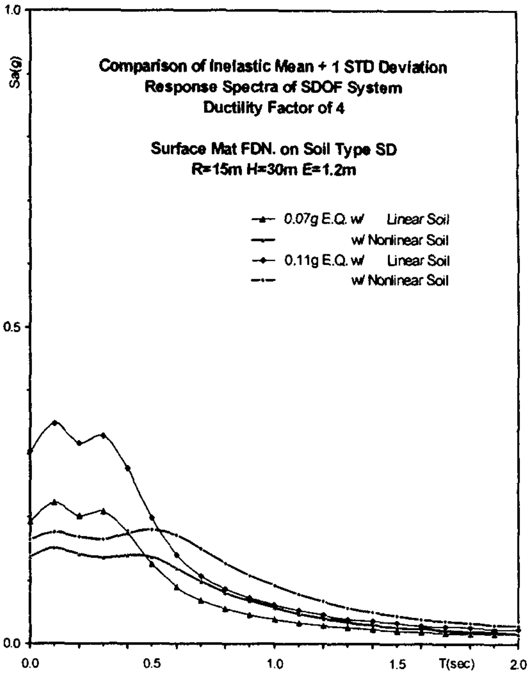


Fig.14 Inelastic Mean+1S.D. responses

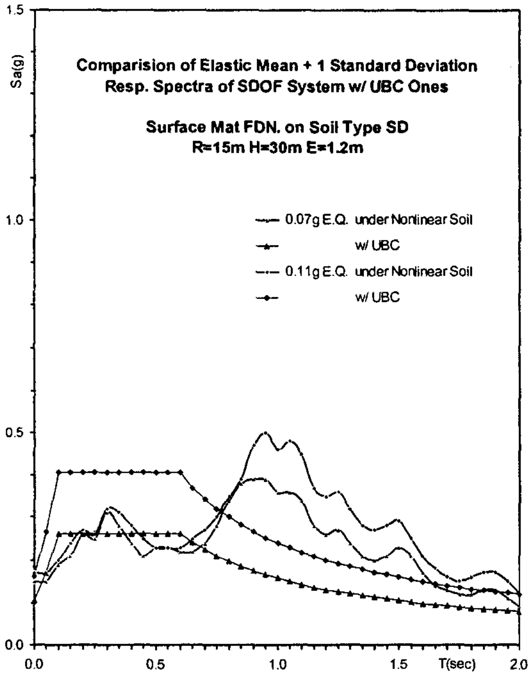


Fig.15 Elastic Mean+1S.D. vs UBC Resp.

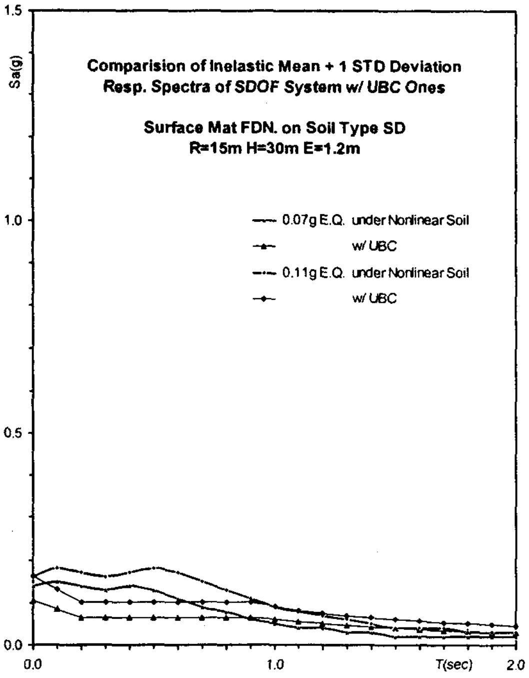


Fig.16 Inelastic Mean+1S.D. vs UBC Resp