ESTIMATION OF DYNAMIC CHARACTERISTICS OF SOIL-BUILDING INTERACTION SYSTEM

S. Tamori (I)
Y. Irie (II)
Y. Kitagawa (III)
Y. Osawa (IV)
Presenting Author: S. Tamori

SUMMARY

The influences of soil layers and elasto-plastic behavior of soil on the dynamic characteristics of a soil-building interaction system are investigated and equivalent stiffness and damping coefficient of the ground are estimated by comparing the results of vibration tests and those of theoretical analyses. It is pointed out from these results that the soil layers play important role in estimating parameters of the interaction system and there are cases when the radiation damping value of layered soil is smaller and the amplification factor larger than that of the half-space soil.

INTRODUCTION

In order to estimate appropriate parameters for the interaction model, earthquake observations, microtremor observations and vibration tests were carried out at model foundations, a model building and a field site.

It is mainly intended in this paper to estimate equivalent stiffness and damping coefficient and to investigate the influences of soil layers and elasto-plastic behavior of the soil on the dynamic characteristics of the soil-building interaction system by comparing the results of earthquake observations and vibration tests and with the results of the theoretical analysis.

DOUBLE-LAYERED SOIL-BUILDING INTERACTON MODEL

Modelling of the Soil-Building Interaction System

The theoretical model of the soil building interaction system consists of the followings; i) A three-dimensional visco-elastic soil medium which is double layered and ii) A continuous shear type building which has a rigid foundation, rested on the ground as shown in Fig. 1.

The input earthquake motion is an SH-wave incident vertically. A compliance theory by Kobori et al. (Ref. 1) is employed to estimate transfer functions to the ground, and for the elasto-plastic analysis, an equivalent linearization method is employed to take account of a elasto-plastic behavior of the upper layer only.

Equivalent stiffness, Ke', and damping coefficient, Ce', are expressed by means of the transfer functions, f_1 and f_2, which are derived by the compliance theory as follows;

(I) Graduate Student, Div. of Eng., Univ. of Tokyo, Tokyo, Japan.
(II) Associate Prof., Faculty of Eng., Univ. of Utsunomiya, Tochigi, Japan.
(III) Head of Dynamic Div., Building Res. Inst., Min. of Const.,Ibaragi,Japan.
(IV) Professor, Earthquake Research Institute, Univ. of Tokyo, Tokyo, Japan.

$$Ke' = f_1/(f_1^2 + f_2^2), \quad Ce' = -f_2/\, a_0(f_1^2 + f_2^2), \quad f_1 + f_2 = \tilde{\tilde{f}}(V_0)/\tilde{\tilde{f}}(Pe^{iwt})$$

where $\tilde{\tilde{f}}(\ \ )$ is Fourier transfer function, V_0 is displacement, Pe^{iwt} is vibration force, and a_0 is non-dimensional frequency.

Three non-dimensional parameters were introduced for the theoretical analysis as follows; i) The shear wave velocity ratio, the lower layer to the upper one, (Cs)2/(Cs)1, ii) The ratio of the upper layer depth to the width of half the foundation, H/b, and iii) The ratio of the building height to the width of the foundation, l_0/b. The parameters of the standard case are shown in Tables 1 and 2.

Half-space Soil and Double-layered Soil Model

Transfer functions, f_{1h} and f_{2h}, equivalent stiffness, Keh', and damping coefficient, Ceh', which are calculated by changing the ratio, (Cs)2/(Cs)1, only in the standard case, for horizontal motion are shown Figs. 2 and 3. As seen in these figures, as the shear wave velocity ratio, (Cs)2/(Cs)1, increases, the peak of f_{1h} becomes sharp and resonance frequency becomes high because a resonance phenomenon becomes more marked, and the equivalent stiffness is increases in the low frequency range, but this relation in the stiffness is reversed near resonance frequency, $a_0=\pi/4$. The equivalent damping coefficient becomes smaller as the shear wave velocity ratio increases in the low frequency range, but it becomes closer to that of a half-space soil model in the high frequency range.

Transfer functions, f_{1h} and f_{2h}, and equivalent stiffness, Keh', and damping coefficient, Ceh', which are calculated by changing the ratio, H/b,only in the standard case, are shown in Figs. 4 and 5. As seen in Fig. 4, the transfer functions of the layered soil model is closer to those of the half-space model as depth of the upper layer becomes thicker, while when the depth becomes thinner, they are closer to that of half-space consisting of the lower layer only. In this case, when H/b is more than 8, the soil can be considered as half-space of the upper layer.

In order to investigate how the resonance frequency of a building affects the influence of soil layers on a building response, normalized response spectra and RS-value at the top of the building were calculated by changing the ratio of the building height to the width of the foundation, l_0/b.

The RS-value is expressed as follows;

$$\text{RS-value} = \sqrt{\int_0^T \ddot{y}(t)^2 dt/T}$$

where $\ddot{y}(t)$ is acceleration response, and T is time duration. Input motions for the analysis are harmonic wave with constant spectrum, which corresponds to pulse, and the N-S component of the 1940 El Centro earthquake. The ratio of the shear wave velocity to the width of half the foundation, (Cs)1/b, is 20, so that fixed-base resonance frequency of the building is 2.5 Hz in the standard case.

The RS-value which was calculated by changing the ratio l_0/b is shown in Figs. 6 and 7. Six shear wave velocity ratios (Cs)2/(Cs)1 and ratios H/b are considered respectively. As seen in Fig. 6, the influence of the ratio (Cs)2/(Cs)1 on RS-value is relatively large when l_0/b is 1.0 to 5.0, and as (Cs)2/(Cs)1 becomes larger, the RS-value becomes larger because radiation damping effect becomes smaller. As seen in Fig. 7, the influence of the ratio H/b is large when l_0/b is 0.5 to 5.0 also, and as H/b becomes smaller, the RS-value becomes larger because the radiation damping effect becomes smaller when the depth of the upper layer become thinner.

The normalized response spectra versus fixed-base resonance frequency of the building are shown in Figs. 8 and 9. As seen in these figures, the influences of soil layers are negligible in low and high frequency ranges, but in intermediate frequency range of about 1.0 to 5.0 Hz, the influence becomes large. When (Cs)2/(Cs)1 is infinite, the response spectrum is 1.3 times, and when H/b is 1/2, it is 1.9 times at most that of the half-space soil model.

Double-Layered Elastic and Elasto-plastic Soil Model

In order to consider elasto-plastic behavior of the upper layer soil, a equivalent linearization method is employed for the analysis (Ref. 2). The hysteresis loop of the soil is a Hardin-Drnevich model (Ref. 3) with reference strain, Er of 3.0×10^{-4}, but expression of equivalent damping factor, heq, is modified as follows;

$$heq = h_0(1-\mu_s/\mu_t)+h_t$$

where h_0 is increment of the damping factor of 0.15 , μ_s is shear modulus at a certain strain, μ_t is initial shear modulus and, h_t is initial damping factor of 0.025. Poisson's ratio of the soil is 0.45. Other parameters for the analysis are the standard case values, which are listed in Tables 1 and 2.

Response spectra at the top (Ut) and the foundation(Ub) of the building excited by El Centro (NS) are shown in Fig. 10. The spectra are calculated by changing the ratio l_0/b in the standard case and are normalized by maximum input acceleration at the boundary between the upper and lower layers. As seen in Fig. 10, the response spectra (Ut) of the elasto-plastic model are relatively smaller by about 60 % than that of the elastic model near 2.0 Hz at most , and this fact infers that the influence of inelastic behavior of the soil due to the interaction effect is large near this frequency . The response spectra (Ub) of the elasto-plastic model is larger than that of an elastic one in the frequency range 1.0 to 2.5 Hz.

VIBRATION TESTS AND EARTHQUAKE OBSERVATIONS

Outline of Models and Site

A site where vibration test and earthquake observations were carried out has three layers; First, surface soil (Cs=140 m/s, GL. to -3 m), second, Kwanto loam (Cs=250 m/s,GL. -3 to -15 m), third, clayey gravel (Cs=600 m/s, deeper than -15 m). The model building and the foundation are the following three types; Model A has an RC-foundation (4x4x1m) and an RC-superstructure which has the same size as the foundation, while Model B (2x2x1m) and Model C (2x4x1m) have only RC-foundations (Ref. 4 and 5). The results of the vibration tests and the parameters used in the theoretical analysis are listed in Table 3 and 4 respectively.

Results from Vibration Tests

Equivalent stiffness, Keh, and damping coefficient, Ceh, for horizontal motion and resonance curves obtained from Model B are shown in Fig. 11. The calculated stiffness and damping coefficient from the double-layered soil model with the parabolic stress distribution under the foundation are in a good agreement with the experimental one at resonance frequency, 13.5 Hz. While the calculated stiffness of the elasto-plastic model with the parabolic stress distribution has slightly better agreement with the experimental one than that of the elastic model, in any case, the calculated results are larger about 30% in stiffness and are double in damping coefficient compared with experimental ones.

There is little difference in resonance curves between the calculated results of the double-layered model and the half-space ones because the resonance frequency is in a range where the influence of soil layers is relatively small.

Equivalent stiffness, Keh, and equivalent damping coefficient, Ceh, for horizontal motion and resonance curves from Model C are shown in Fig. 12. The calculated results of the double-layered model with the parabolic stress distribution have good agreement with the experimental ones near the resonance frequency 13.2 Hz. However, the calculated damping coefficient is four times the experimental one near the resonance frequency, and so the calculated resonance amplitude is 56% of that of the experimental one.

Results from Earthquake Observations

The Fourier spectra of responses for Model A excited by the earthquake, SFB-06 are shown in Fig. 13. In the figure, Ut and Ub correspond to response at a top and a foundation of Model A, respectively. In this case, stress distribution under the foundation is assumed to be that for rigid base. The results of the double-layered elastic soil model have better agreement with the observed ones than those of the half-space elastic soil model, but the amplitude of the theoretical is slightly smaller than that of observed one.

ESTIMATION FOR ELASTO-PLASTIC BEHAVIOR OF INTERACTION SYSTEM BY DOUBLE-LAYERED SOIL-BUILDING MODEL

To investigate more realistically the influence of elasto-plastic behavior of the soil on dynamic characteristics of the interaction system, response analyses were carried out for Model A using accelerograms observed at the site, but the maximum amplitude of these was relatively small, so it was normalized at 200 gal to 1000 gal for the analysis. Parameters for hysteresis of soil were obtained by a dynamic test, Er of 1.5×10^{-3}, h_t of 0.01 and h_0 of 0.066, although results were scattered (Ref. 6).

Fourier spectra of responses at the top of Model A excited by two components(NS and EW) of SFB-02 earthquake are shown in Fig. 14, and maximum amplitude ,resonance frequency of the system and average shear strain of the upper layer are listed in Tables 5 and 6.

As seen in Fig. 14 and Tables 5 and 6, resonance frequency of the elastic soil model is 3.2 Hz and that of the elasto-plastic model with maximum input acceleration of 1000 gal is 2.8 Hz. The ratio of the resonance frequency of the elasto-plastic model to the elastic model is then 0.87 and the ratio of the amplification factor of that is 0.68 for SFB-02 (NS) earthquake. For the SFB-02 (EW) earthquake, the ratio of the resonance frequency is 0.90 and the ratio of the amplification factor is 0.91.

As mentioned above, there are cases when the resonance frequency of the elasto-plastic soil model is lower by 10 to 20%, and when the amplification factor is smaller by 10 to 30% compared with the elastic soil model.

CONCLUSION

The results of the investigation are summarized as follows;

Results from the theoretical investigation by the elastic and the elasto-plastic double-layered soil model

1) When the shear wave velocity ratio, lower layer to upper, is infinite, the response spectrum is 1.3 times, and when the ratio of the upper layer depth to the width of half the foundation is 1/2, it is 1.9 times larger than that of the half-space soil. But these effects of the soil layers can be negligible when fixed-base resonance frequency of the building is low or high.

2) The response spectrum of the elasto-plastic soil model excited by El Centro (NS), normalized at maximum acceleration of 1000 gal, is smaller by 60% compared with the elastic soil model when fixed-base resonance frequency is near 2.0 Hz, but this effect can be negligible when the resonance frequency is low or high.

Results from the experimental data combined with the theoretical analysis.

1) The theoretical results agree well with the results of the vibration tests of Models B and C, when the stress distribution is assumed to be parabolic. Meanwhile good results were obtained for earthquake observations of Model A when rigid base distribution was employed. The reason for the difference in the stress distributions is due to the different amplitude levels marked during the vibration tests and the earthquake.

2) The response analysis of Model A by the elasto-plastic soil model shows that if input maximum acceleration had been 1000 gal, the average shear strain of the upper layer would have been about 2.0×10^{-3}, and the resonance frequency of the system would have been lower by 10 to 20% and the amplification factor lower by 10 to 20% compared with the elastic soil model.

These results, especially by the elasto-plastic soil model, are obtained by a certain theoretical model and input motions, so further investigation must be necessary to obtain a general effects of inelastic behavior of a soil on the interaction system.

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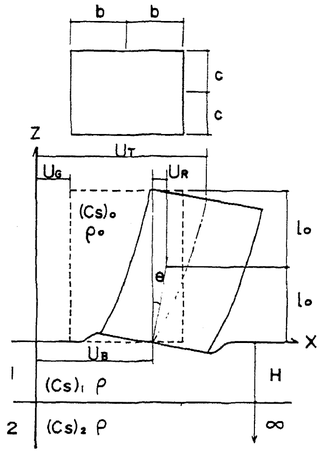

Fig. 1 Theoretical model

Table 1 Parameters of soil

$\frac{(Cs)_2}{(Cs)_1}$	layer number	ρ	ν	h_t (%)
2	1	1.5	0.25	2.5
	2	1.5	0.25	2.5

Cs: Velocity of S-wave
ν: Poissons' ratio
ρ: Soil density
h_t: Damping factor of soil

Table 2 Parameters of building

$\frac{c}{b}$	$\frac{l_0}{b}$	h_0 (%)	$\frac{(Cs)_0}{(Cs)_1}$	$\frac{\rho_0}{\rho}$	$\frac{H}{b}$
1	2	1.0	2	0.2	2

h_0: Damping Factor of building

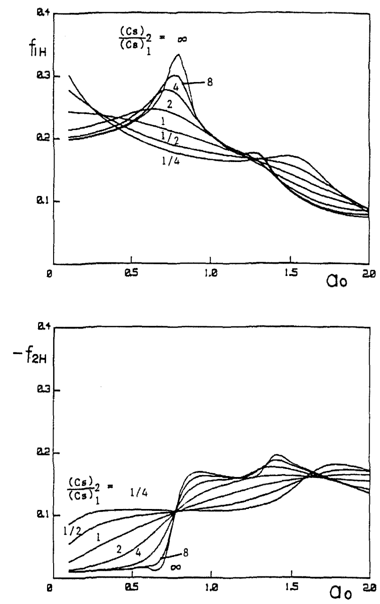

Fig. 2 Transfer functions

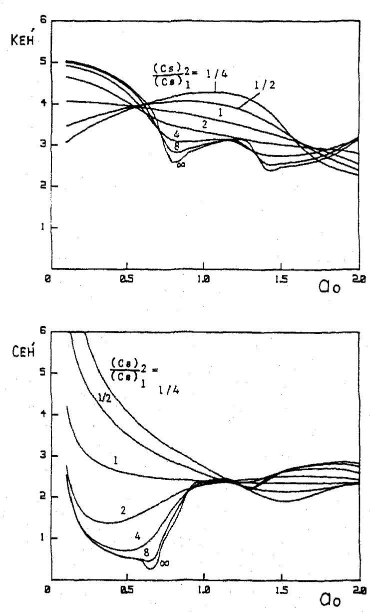

Fig. 3 Equivalent stiffness and damping coefficient

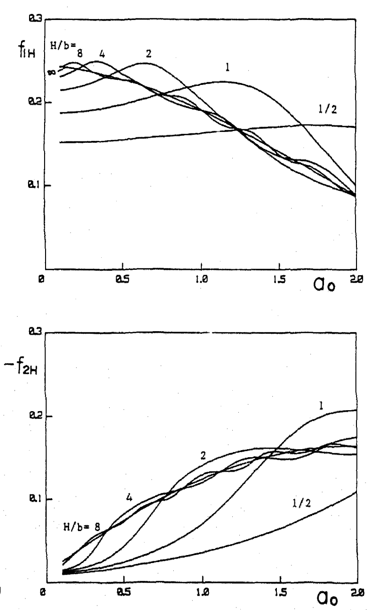

Fig. 4 Transfer functions

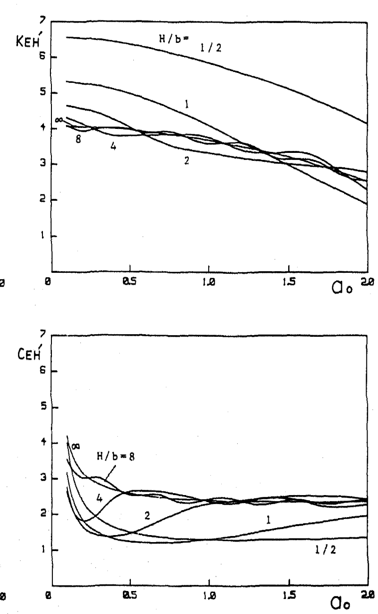

Fig. 5 Equivalent stiffness and damping coefficient

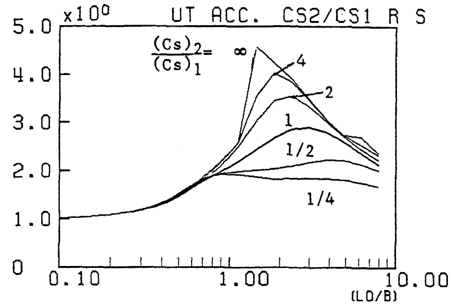

Fig. 6 RS-values of accerelation response

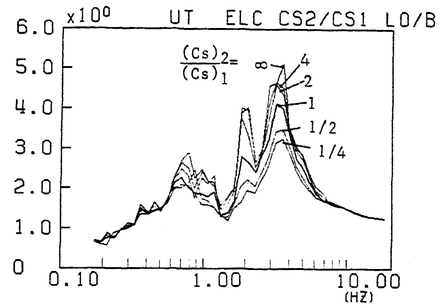

Fig. 8 Response spectra

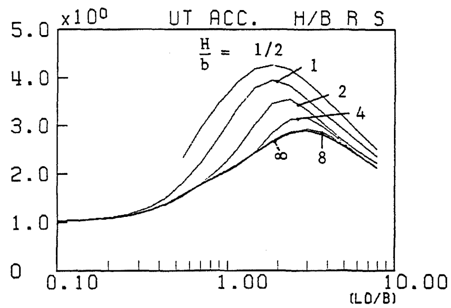

Fig. 7 RS-values of accerelation response

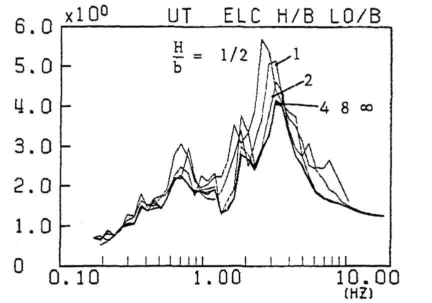

Fig. 9 Response spectra

Table 3 Tests results

item / model	Force (ton)	fr (Hz)	h (%)
A	0.1	3.4	2.0
B	0.2	13.5	9.1
C*	0.5	13.2	9.9

* Vibrated in longitudinal direction

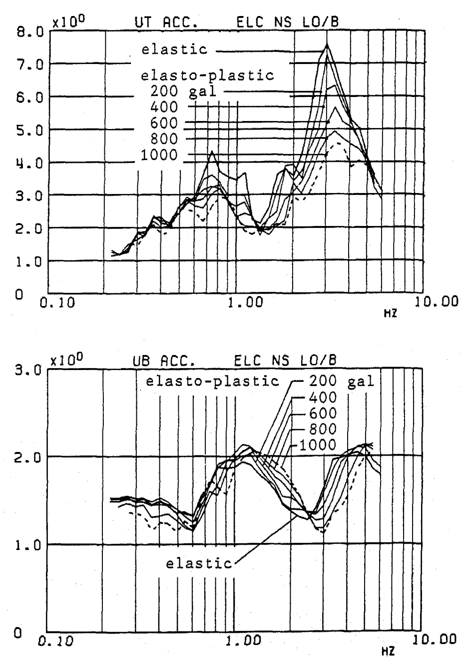

Fig. 10 Response spectra for various input maximum accelerations

Table 4 Parameters of theoretical model

Depth (m)	Soil Model: layered	Soil Model: half-space	Building Model*
3	ρ=1.439 (t/m^3) Cs=140.0 (m/s) ν=0.453	ρ=1.439 (t/m^3) Cs=140.0 (m/s) ν=0.453	fr = 3.85 (Hz) h = 0.65 (%)
	ρ=1.439 (t/m^3) Cs=250.0 (m/s) ν=0.432		

* Model A

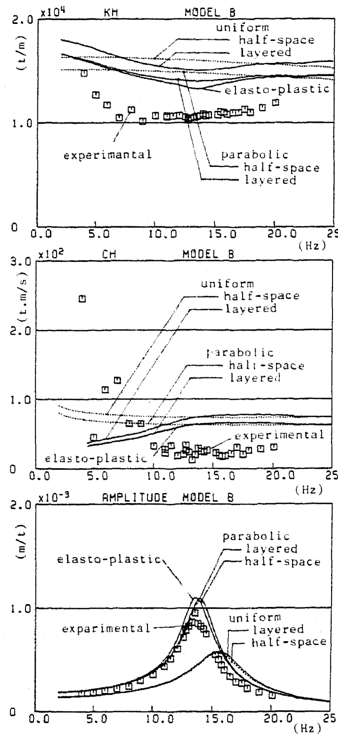

Fig. 11 Equivalent coefficients and resonance curves of Model B

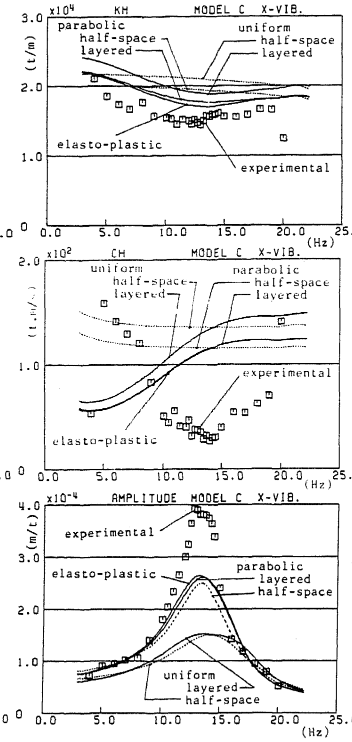

Fig. 12 Equivalent coefficients and resonance curves of Model C

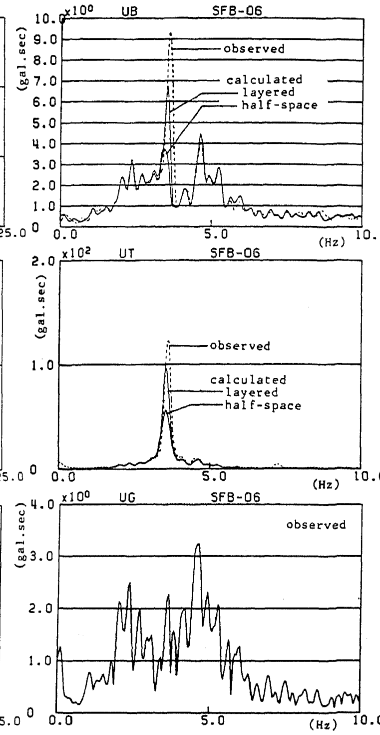

Fig. 13 Observed and calculated Fourier spectra of Model A

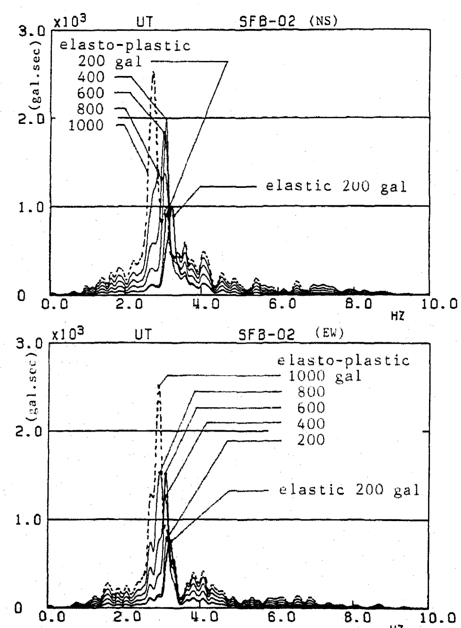

Fig. 14 Fourier spectra of Model A for various input maximum accelerations

Table 5 Results from SFB-02 (NS)

model	elastic	elasto-plastic				
max. acc. input response (gal)	200 641	200 561	400 1016	600 1486	800 1877	1000 2192
fr (Hz)	3.21	3.16	3.09	3.00	2.91	2.79
strain $(x10^{-3})$	0.21	0.23	0.50	0.84	1.22	1.87

fr: Resonance frequency

Table 6 Results from SFB-02 (EW)

model	elastic	elasto-plastic				
max. acc. input response (gal)	200 395	200 393	400 742	600 1092	800 1433	1000 1808
fr (Hz)	3.21	3.19	3.14	3.06	3.00	2.91
strain $(x10^{-3})$	0.16	0.16	0.34	0.55	0.82	1.12