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SEISMIC RESPONSE BEHAVIOR OF SOFT SOIL DEPOSITS

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SUMMARY

In order to examine the acceleration response spectrum of soft soil deposits considering its nonlinear behavior, nonlinear seismic response analyses are carried out for five soft soil deposits with predominant periods of 0.54 - 1.72 seconds. It is found that the acceleration response spectrum ratios exceed the specifications for highway bridges set by the Japan Road Association for almost all periods. Additionally, studies are made on the ratio of the nonlinear response to the linear response. It is found that this response ratio is more than 1.0 for values of the ratio between the period of the response wave and the predominant period of the ground greater than 1.1.

INTRODUCTION

It is well known that nonlinear seismic response behavior of soft soil deposits is developed during strong earthquakes. Therefore, in the design of earthquake-resistant structures, it is very important to determine an acceleration response spectrum for soft soil deposits which takes into account the seismic nonlinearity of the soil.

The authors carried out seismic observations for five soft soil deposits with predominant periods of 0.54 - 1.72 seconds. Based on the observed records obtained at each base layer, nonlinear seismic response analyses by the equivalent linear method and the step-by-step method using the modified Ramberg-Osgood and Hardin-Drnevich models (Refs. 1, 2) were carried out. The maximum value of the acceleration of the input motion in each case was normalized to 100, 150 and 200 cm/s^2.

First of all, this paper presents the acceleration response spectrum for soft soil deposits considering the nonlinearity of the soil, and shows the comparison between the research results and the spectrum specified by the Japan Road Association. Secondly, to evaluate the ratio of nonlinear response to the linear one, seismic response analyses of soft soil deposits and the steady-state response characteristics of soil are also investigated.

NONLINEAR SEISMIC RESPONSE ANALYSES

Five Soft Soil Deposits Nonlinear seismic response analyses were carried out for the five soft soil deposits shown in Table 1 (Ref. 3). The predominant period of

Table 1 Five Soft Soil

No.	Ground Name	Depth from GL to Base (m)	Predominant Period (sec)	Input Motion	Dynamic Model
1	A	60.0	0.54	4 Records for Each Ground Amax= 150 Gal	Modified H-D Model Modified R-O Model Equivalent Linear
2	B	85.0	0.88		
3	C	40.0	0.95		
4	D	30.0	1.41		
5	E	55.0	1.72		

the ground in each case is 0.54 to 1.72 seconds, as calculated by the one-dimensional lumped-mass model. The number of lumped-masses in each case is 22 for Ground-A, 25 for Ground-B, 24 for Ground-C, 28 for Ground-D, and 27 for Ground-E. These sites are all seismic observation points, and an accelerometer is installed at the base layer.

<u>Analytical Method and Soil Properties</u> The equivalent linear method and the step-by-step method using the modified Ramberg-Osgood model (modified R-O model) and the Hardin-Drnevich model (modified H-D model), were used in the nonlinear seismic response analysis of soft soil deposits.

The initial shear modulus G_0 was obtained using $G_0 = \rho Vs^2$ for each of the soils, where ρ and Vs are the density and the shear wave velocity of the soil. The shear modulus ratio $G/G_0 \sim$ strain γ relation and the damping constant heq $\sim$ strain γ relation were obtained from the curves proposed by Iwasaki et al. (Ref. 4). The reference strain γr and the value of hmax were based on the above mentioned $G/G_0 \sim \gamma$ and heq $\sim \gamma$ curves. In the equivalent linear analysis, the coefficient used in evaluating the effective strain from the maximum strain was decided to be 0.65.

<u>Input Motion</u> The input motion for nonlinear seismic response analyses was chosen from the observed records obtained at each base layer. The maximum value of the acceleration of the input motion was normalized to 150 cm/s^2. Furthermore, in order to investigate the influence of these maximum values, the analysis using the modified R-O model was carried out for 100 and 200 cm/s^2.

ACCELERATION RESPONSE SPECTRUM RATIO

<u>Method</u> Using the response at the ground surface obtained from the nonlinear seismic response analyses, the acceleration response spectrum ratios were calculated for a damping constant of 0.05. Figure 1 shows averaged results for each method. Figure 2 shows the results for the modified R-O model. Both results are the average for the 20 cases which are a combination of 5 soft soil deposits and 4 input motions. In both figures, the solid line with triangular marks shows the spectrum ratio using 277 observed records for ground type Ⅳ which is a soft soil deposit as defined in the specifications for highway bridges by the Japan Road Bridges Association.

<u>Results</u> The period range for which the ratios are sensitive to the nonlinear response of the ground is about 0.5 - 3.0 seconds. In Figure 1, although the result of the equivalent linear analysis is close to the ratio of the specifications in this period range, the results of the modified R-O and H-D models are considerably greater than those of the specifications. It is found that the influence on the spectrum ratios due to a change in the maximum acceleration of the input motion is unexpectedly small.

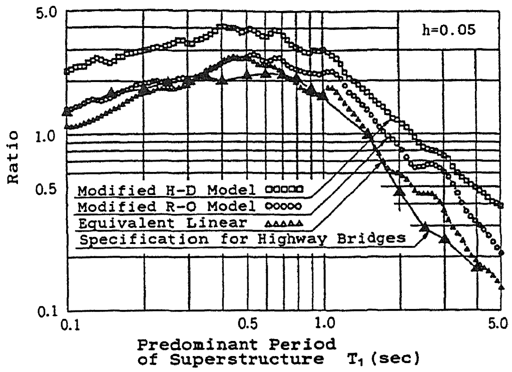

Fig. 1 Acceleration Response Spectrum Ratio
(Averaged Results for Each Method)

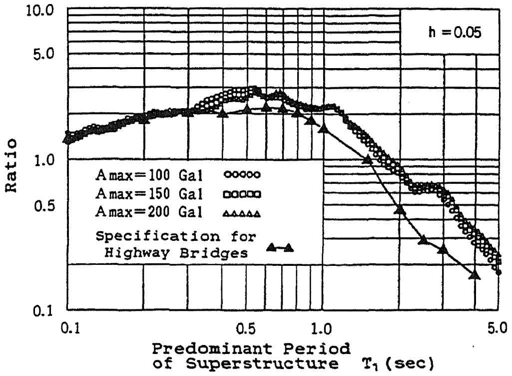

Fig. 2 Acceleration Response Spectrum Ratio
(for Modified Ramberg-Osgood Model)

RATIO OF NONLINEAR RESPONSE TO LINEAR RESPONSE

Results The authors also carried out a linear seismic response analysis for the five soft soil deposits shown in Table 1, and compared the nonlinear seismic response with the linear response at the ground surface. Figure 3 shows the ratios of the Fourier spectrum amplitudes of the nonlinear response and the linear response for each method. Figure 4 shows the results for the modified R-O model. Both results are the average of the 20 cases under analysis. The horizontal axis, λ, in both Figures is the ratio of the period T of the response wave to the predominant period T_1 of the ground. T_1 is calculated based on the initial stiffness of the soil.

The ratio in Figures 3 and 4 can also be understood as the transfer curve which relates the nonlinear seismic response of the ground surface with the linear response. If the ratio $\zeta(\lambda)$ equals 1.0, the nonlinear response coincides with the linear response. However, the range of values of λ for which the ratio $\zeta(\lambda)$ does not equal 1.0 indicates the influence of the nonlinearity of the ground. Therefore, it can be concluded that the value of the ratio $\zeta(\lambda)$ expresses the nonlinearity of the ground.

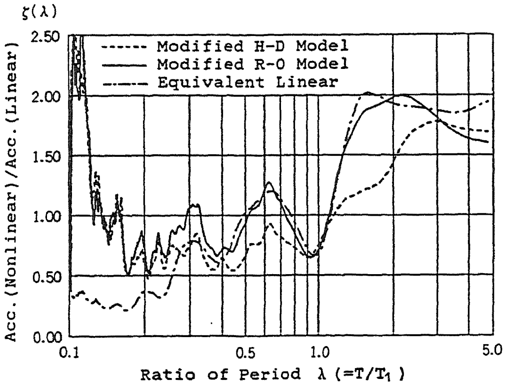

Fig. 3 Ratio of the Nonlinear Response to the Linear Response (Averaged Results for Each Method)

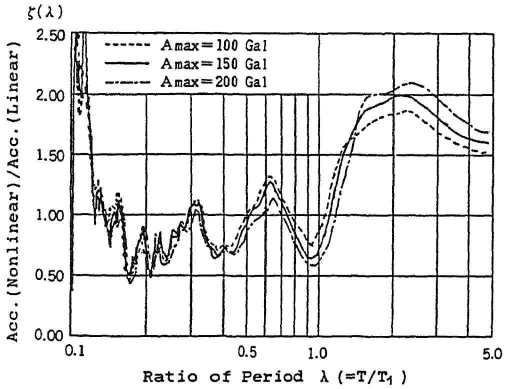

Fig. 4 Ratio of the Nonlinear Response to the Linear Response (for Modified Ramberg-Osgood Model)

Discussion of the Results In Figure 3, a remarkable difference between the three nonlinear seismic response analysis methods can be seen when $\lambda < 0.2$. Although the values of the ratio $\zeta(\lambda)$ for the equivalent linear analysis are $\zeta(\lambda) = 0.3 \sim 0.4$, those for the modified R-O and H-D models are $\zeta(\lambda) > 1.0$ in this period. In previous research results on nonlinear seismic response analyses of ground, it has been shown that the nonlinear response results obtained by using the modified R-O and H-D models usually contain a lot of high frequency response, while the results of the equivalent linear analysis give little high frequency response. The results shown in Figures 3 and 4 confirm these findings.

In the period range $0.5 < \lambda < 5.0$, the value of $\zeta(\lambda)$ for all methods is more than 1.0 when $\lambda > 1.1$ and is less than 1.0 for $0.8 < \lambda < 1.1$. In the period range of $\lambda > 1.0$, although the maximum value of $\zeta(\lambda)$ for the modified H-D model is 1.75, those for the modified R-O model and for the equivalent linear analysis are both 2.0. Since the modified H-D model, for which the hysteresis curve is determined by Masing's law, gives excessive damping, the response acceleration at the ground surface calculated by using this model is smaller than these values obtained by using the modified R-O model and the equivalent linear analysis. This can be seen from the result shown in Figure 3. The period range of λ which gives the maximum value of $\zeta(\lambda)$ appears differently for each method. Whereas the values for the modified R-O model and the equivalent linear analysis are 1.5～2.2, that for the modified H-D model is 3.0. It is found from these values that the predominant period T_1 of the ground increases up to 1.5 times its linear value, because of the nonlinearity of the ground which the value of the maximum acceleration of input motion at the base is 150 cm/s^2.

It is also found from the results obtained for different maximum values of input motion which are shown in Figure 4 that the value of $\zeta(\lambda)$ becomes greater in the period range $\lambda > 1.1$ and conversely becomes smaller in the period range $0.5 < \lambda < 1.1$, according to the value of input acceleration.

DYNAMIC RESPONSE OF ONE-DIMENSIONAL MODEL UNDER STEADY-STATE LOADING

Resonance Curve and Phase Curve The authors investigated the relationship between the response ratio $\zeta(\lambda)$ and the period ratio λ based on the dynamic responses of a nonlinear system with one degree of freedom under a steady-state loading. The formulation for the steady-state response of the modified R-O and H-D models was made by the slowly varying parameters method (Ref. 5). When the slowly varying parameters method is employed, the resonance and phase curves of the nonlinear model are given by the following equations, assuming the strain γ as $\gamma = \gamma a(t) \sin(pt+\psi(t)) = \gamma a(t) \sin\theta(t)$ for an external force $Q \sin pt$.

$$\text{resonance curve:} \quad C^2(\gamma a) + \{S(\gamma a) - \gamma a\, p^2\}^2 = F^2 \tag{1}$$

$$\text{Phase curve:} \quad \tan\phi = -C(\gamma a) / \{S(\gamma a) - \gamma a\, p^2\}$$

where p is the angular frequency of excitation, γa is the maximum strain of the model, and ϕ is the phase angle between response and excitation. F is related to the external force Q, and is obtained from Q/mh (m is the mass of model and h is the height from the mass point to the base). In addition,

$$C(\gamma a) = \frac{1}{\pi}\int_0^{2\pi} R(\gamma a \sin\theta) \cos\theta \, d\theta \tag{2}$$

$$S(\gamma a) = \frac{1}{\pi}\int_0^{2\pi} R(\gamma a \sin\theta) \sin\theta \, d\theta$$

where $R(\gamma)$ describes the hysteresis curves of the dynamic model of the soil.

Analytical Results In order to compare the results of the nonlinear seismic response analysis shown in Figure 3 with those of the steady state response, the resonance curves of the modified R-O and H-D models are expressed as a ratio of the nonlinear to the linear response as follows:

$$\zeta(\lambda) = \frac{\gamma a}{\gamma s}(\text{nonlinear}) / \frac{\gamma a}{\gamma s}(\text{linear}) = \gamma a(\text{nonlinear}) / \gamma a(\text{linear}) \tag{3}$$

The ratio of the nonlinear response to the linear response for the resonance curve of the modified R-O and H-D models is shown in Figure 5. The results of the modified R-O model are obtained using a maximum damping constant hmax=0.20.

The resonance curves in Figure 5 are shown with the reference strain γr against the static strain γs caused by an external force Q, that is, $\gamma r/\gamma s$ as a parameter. It is found from a comparison between the results of Figures 3 and 5 that the shape of the resonance curves corresponds to the nonlinear seismic response analyses. However, the value of the ratio of the nonlinear response to the linear response for the resonance curves is considerably greater than the results of the nonlinear seismic response analysis. One of the reasons for this is the difference in the vibration of the system for which the results in Figure 3 are

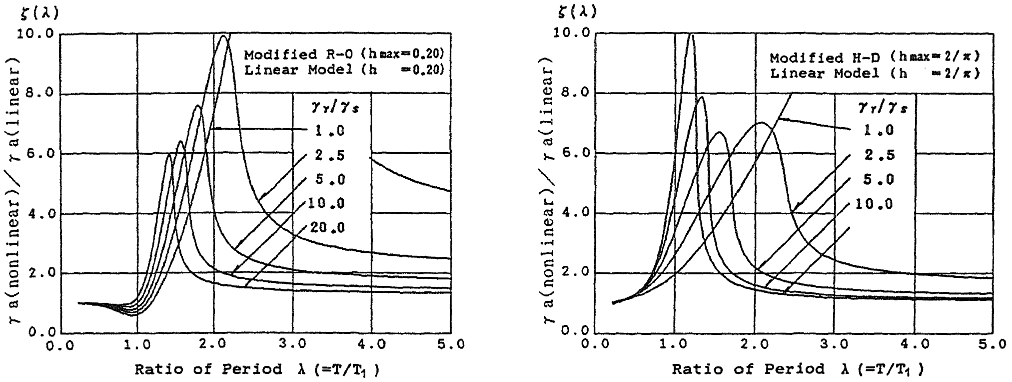

Fig. 5 Ratio of the Nonlinear Response to the Linear Response for the Resonance Curves

a non-steady-state problem, whereas the results in Figure 5 are a steady-state problem. Therefore, the resonance curves evaluate excessively the nonlinearity of the soil.

CONCLUSIONS

A total of 60 cases of nonlinear seismic response analyses were carried out. The analytical results were expressed by means of an acceleration response spectrum ratio, and a ratio of the nonlinear response to the linear response at the ground surface. The conclusions drawn from this study are as follows:

(1) The acceleration response spectrum ratios, taking into account the nonlinearity of the soil, exceed the specifications for highway bridges set by the Japan Road Association for almost all periods.

(2) The influence on the spectrum ratios, due to differences in the values of the maximum acceleration of the input motion, is unexpectedly small.

(3) The ratio of the nonlinear response to the linear response is more than 1.0 in the range of period ratio $\lambda > 1.1$ and is less than 1.0 for $0.8 < \lambda < 1.1$.

(4) The ratio of the nonlinear response to the linear response, obtained by a one degree of freedom system under steady-state loading, corresponds to that obtained for the nonlinear seismic response analyses.

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