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NONLINEAR SEISMIC RESPONSE ANALYSIS OF HORIZONTALLY LAYERED SOIL DEPOSITS

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SUMMARY

Nonlinear seismic response analyses were carried out in order to identify the suitable number of subdivisions of a soil layer for the one-dimensional lumped-mass model,and the optimal value of the coefficient η used in determining the effective strain from the maximum strain in the equivalent linear analysis. From the studies, it is found that two for each layer of deposit is sufficient, and the value of η is 0.4 which agrees with the observed records.

INTRODUCTION

The step-by-step integration method and the equivalent linear analysis method have been used to analyze the nonlinear seismic response of soil deposits. In the nonlinear seismic response analysis of horizontally layered soil deposits, the analytical results vary according to the number of subdivisions in each layer of soil stratum for the one-dimensional lumped-mass model. In the equivalent linear analysis, the analytical results depend on the coefficient η which is used in determining the effective strain from the maximum strain. The accuracy of nonlinear seismic response results becomes difficult to be precise because a strict method for deciding the number of subdivisions and the coefficient η does not exist presently.

Looking for a better understanding of the problem, parameter studies were carried out for model of a homogeneous soil deposit and for an actual soil deposit. The step-by-step integration method and the equivalent linear analysis method were used in the analysis of the models. Modified Hardin-Drnevich and modified Ramberg-Osgood models were adopted in the step-by-step integration method of nonlinear seismic response analysis. When comparing the analytical results with the observed records, the degree of agreement was judged from the value of the parameter J . The obtained results are studied in order to determine the necessary number of subdivisions of the layers in the soil deposit to be taken for analysis, and also to determine the value of the cofficient η for which the minimum value of J is obtained.

PARAMETER STUDIES OF A HOMOGENEOUS SOIL DEPOSIT

Analytical Models A model of a homogeneous soil deposit is shown in Figure 1. The characterestics of the soil deposit are : Predominant period T_1=1.0 seconds, Thickness H=20m, Shear wave velocity V_s=80m/s and specific weight

$w=1.5tf/m^3$. Table 1 shows the cases of parameter studies under consideration. Three different number of subdivisions N are chosen namely, N=5 (spacing s=4m), N=20 (s=1m), N=40 (s=0.5m). As for the input motion, records of 1940 El-Centro earthquake, NS component and the 1968 Tokachioki-Hachinohe earthquake, EW component were utilized. For both records, the maximum acceleration was normalized to 100 gals.

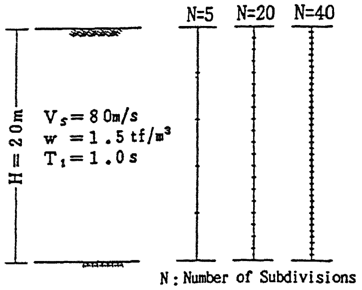

Fig. 1 Homogeneous Soil Profile and Analytical Models

Table 1 Analytical Cases

Nonlinear Analysis Method		N	Input Motion
Step-by-step Integration Method (12 cases)	Modified Hardin-Drnevich Model	5 20 40	El-Centro NS-Component Tokachioki -Hachinohe EW-Component
	Modified Ramberg-Osgood Model		
Equivalent Linear Analysis Method (24 cases)	$\eta=0.50$	5 20 40	El-Centro NS-Component Tokachioki -Hachinohe EW-Component
	$\eta=0.65$		
	$\eta=0.80$		
	$\eta=1.00$		

N : Number of Subdivisions

For the nonlinear seismic analysis of the one-dimensional lumped-mass model the step-by-step integration method was adopted using the Modified Hardin-Drnevich (M-H-D) model (Ref. 1) and the Modified Ramberg-Osgood (M-R-O) model (Ref. 2) as the dynamic stress-strain models. There are four analytical cases regarding the coefficient η for the equivalent linear analysis method : η=0.5, 0.65, 0.80, and 1.00. The initial shear modulus was calculated by the expression $G_0=\rho Vs^2$, where ρ and Vs are density and shear wave velocity of the soil, respectively. The reference strain γ_r and the maximum damping constant h_{max} for the step-by-step integration method were decided from experimental results oftained for sandy soil (Ref. 3). For the equivalent linear analysis method, the $G/G_0\sim\gamma$ and $h\sim\gamma$ relations were also decided from those experimental results (Ref. 3).

Analytical Results and Considerations Table 2 shows the analytical results of the step-by-step integration method. It was found that the maximum accelerations at ground surface varied considerably depending upon the number of considered subdivisions. A difference of 35% (48.0gal to 35.5gal) between the cases of N=5 and N=40 is observed in the results of M-R-O model for El-Centro wave. Consequently, when caluculating the maximum acceleration at the ground surface by using the step-by-step integration method, the posibility of the occurence of such a big discrepancy must be kept in mind. On the other hand, it was found that the influence of the number of subdivisions on the maximum velocity and displacement, was minute.

Table 2 Maximum Accelerations at Ground Surface (Step-by-step Integration Method)

Number of Subdivisions		El-Centro NS		Tokachioki EW	
		M-H-D	M-R-O	M-H-D	M-R-O
Maximum Acc. (gal)	5	31.9	35.5	42.2	50.9
	20	36.4	41.7	40.4	57.1
	40	37.3	48.0	38.6	59.3
Maximum Vel. (kine)	5	13.4	13.8	22.6	28.1
	20	13.4	13.9	21.9	28.1
	40	13.4	13.9	21.9	28.3
Maximum Displ. (cm)	5	4.3	4.3	8.7	9.9
	20	4.0	4.2	9.3	9.7
	40	4.0	4.2	9.3	9.6

Figure 2 shows the distributions of the maximum strain. It can be seen hat there is a similarity between the strain for the model with a small number of subdivisions and the average strain for the model with a large number of subdivisions.

Table 3 shows the analytical results for the equivalent linear analysis method. It was found that the influence of the number of subdivisions on the response at the ground surface was small. However, the maximum accelerations vary greatly when the coeffient η is changed. A difference of 62% (78.4gal to 48.4gal) between the case when η=0.5 and that when η=1.0 occurred in the value of the maximum acceleration for the Tokachioki wave. The maximum acceleration at the ground surface decreased when the coefficient η was increased. The reason of this change is a large decreasing of the shear modulus of the soil. The value of the coefficient η were taken from 0.5 to 0.8. It is seen from Table 3 that the maximum acceleration varied in a 37% (78.4gal to 57.4gal) for the considered range of the coefficient η. The effect of a change in the number of subdivisions on the maximum velocity and the maximum displacement, was small. Figure 3 shows that the maximum strain increases when the coefficient η is increased.

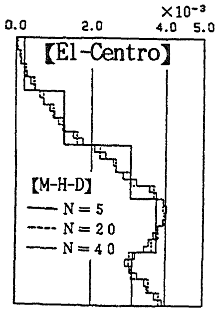

Fig. 2 Distributions of Maximum Strain for Step-by-step Integration Method

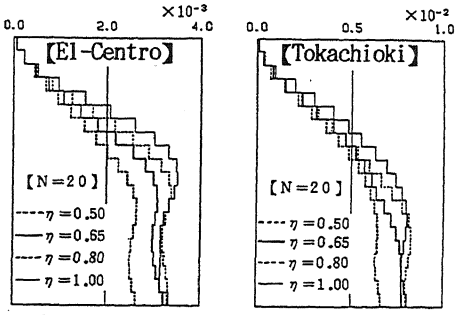

Fig. 3 Distributions of Maximum Strain for Equivalent Linear Analysis Method
(Comparison by Changing Coefficient η)

Table 3 Maximum Accelerations at Ground Surface (Equivalent Linear Analysis Method)

Number of Subdivisions		El-Centro NS				Tokachioki EW			
		η=0.50	η=0.65	η=0.80	η=1.00	η=0.50	η=0.65	η=0.80	η=1.00
Maximum Acceleration (gal)	5	.57.6	49.6	45.6	42.3	78.4	67.2	57.4	48.4
	20	57.8	49.6	45.6	42.2	78.4	67.2	57.5	49.4
	40	57.7	49.4	45.6	42.2	78.4	67.2	57.5	49.5
Maximum Velocity (kine)	5	14.2	13.3	14.0	14.9	29.8	31.7	30.4	28.5
	20	14.2	13.3	14.0	14.9	29.8	31.7	30.4	28.6
	40	14.2	13.3	14.0	14.9	29.8	31.7	30.4	28.6
Maximum Displacement (cm)	5	3.5	4.2	4.5	4.6	8.6	9.4	10.0	10.3
	20	3.5	4.2	4.5	4.6	8.6	9.4	10.0	10.3
	40	3.5	4.2	4.5	4.6	8.6	9.4	10.0	10.3

STUDIES OF ACTUAL SOIL DEPOSIT

Analytical Models A similar study was carried out for an actual soil deposit using the strong motion records obtained by seismic observation. The site of the seismic observation was Sodegaura, Chiba-ken. Figure 4 shows the soil profile and the analytical models. The accelerometers were installed at depths of GL-1m and GL-42m. For the first model the layered soil deposit is divided into of twelve segments (N=12) for each soil layer. Twelve is the minimum number of segmwnts, because of soil type and the number of accelerometers. In the second model (N=22), two segments are taken for most of the layers and the total number of subdivisions is about twice the number of segments of the first model. For the third model (N=44), the number of subdivisions is approximately four times the number taken for the first model. In this case, four segments have been taken for each layer.

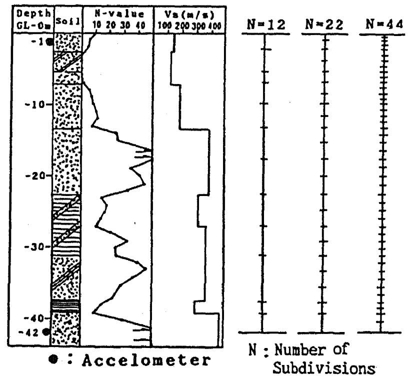

Fig. 4 Soil Profile and Analytical Models

Figure 5 shows the observed strong motion records of the Chiba-ken Chubu Earthquake on September 25, 1980 (J.M.A. scale magnitude M=6.1, epicentral distance Δ=22km, focal depth D=80km). The maximum accelerations at the base and at the ground surface were 63.5 gals and 193.6 gals, respectively.

Figure 6 shows a comparison between the transfer function of the observed record and the average transfer function of small earthquake records registered at the site. It can be seen that the predominant period moved from 0.55 seconds to 0.65 and 0.80 seconds suggesting that a nonlinear behavior was developed due to the strong motion of the Chiba-ken Chubu Earthquake.

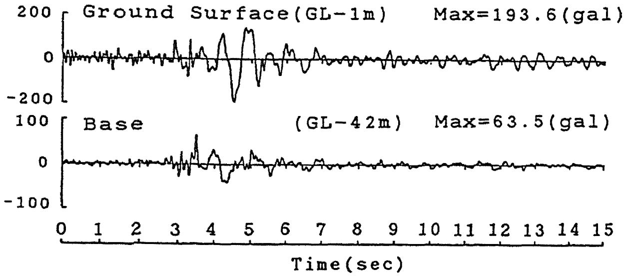

Fig. 5 Observed Acceleration Records
(Chiba-ken Chubu Earthquake on September 25, 1980)

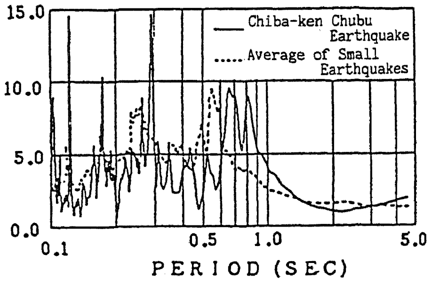

Fig. 6 Transfer Function
(Ground Surface/Base)

For the step-by-step integration method, the initial shear modulus was calculated by the expression $G_0 = \rho Vs^2$. The reference strain γ_r was decided from experimental results obtained for sandy soil (Ref. 3) and clayey soil (Ref. 4). The maximum damping constant h_{max} was evaluated by Tazoh et al.'s method (Ref. 5). For the equivalent linear analysis method, the $G/G_0 \sim \gamma$ and $h \sim \gamma$ relations were also decided from experimental results obtained for sandy soil (Ref. 3) and clayey soil (Ref. 4).

Analytical Results and Considerations Table 4 shows the maximum value of accelerations, velocities, and displacements at ground surface for the step-by-step integration method and the equivalent linear analysis method. After changing the number of subdivisions a difference of 4% (154.7gals to 148.6gals) occurred, resulting in the maximum acceleration when using M-R-O model. On the other hand, a difference of 27% (61.0gals to 47.9gals) occurred in the results when the M-H-D model was used. However, the differences in the maximum velocities and displacements due to changes in the coefficient η, were very small.

Table 4 Maximum Responses Based on Strong Motion Record

Number of Subdivisions		Equivalent Linear Analysis Method				Step-by-step Integration Method	
		η=0.50	η=0.65	η=0.80	η=1.00	M-H-D	M-R-O
Maximum Acceleration (gal)	12	117.8	107.9	101.9	95.0	47.9	148.9
	22	118.0	107.2	100.0	94.8	55.8	154.7
	44	117.0	106.3	100.0	93.8	61.0	152.3
Maximum Velocity (kine)	12	12.7	11.9	11.7	11.6	10.2	15.1
	22	12.7	11.9	11.6	11.5	9.7	15.2
	44	12.6	11.8	11.5	11.5	9.8	15.3
Maximum Displacement (cm)	12	1.5	1.5	1.6	1.8	1.7	2.2
	22	1.5	1.5	1.6	1.8	1.6	2.2
	44	1.5	1.5	1.6	1.8	1.6	2.2

The maximum responses obtained for the equivalent linear analysis method were hardly influenced at all by the changes in the number of subdivisions. On the contrary, the maximum acceleration, velocity and displacement varied by 25%, 10%, 20%, respectively, due to the changing coefficient η.

The degree of agreement between the observed and the computed waves is estimated by the value of J which is defined by the following equation.

$$J = \frac{\int_{t_0}^{t_1} \{ x(t) - u(t) \}^2 \, dt}{\int_{t_0}^{t_1} x(t)^2 \, dt} \qquad (1)$$

where, x(t) and u(t) are the observed wave and the computed wave, t_0 and t_1 are the starting and the ending time of the interval for which the agreement between both waves is determined. The smaller the value of J, the better the degree of agreement between the observed and the computed waves.

Table 5 shows the values of J that were calculated from each pair of computed and observed waves. The adopted starting and ending time were $t_0=3.5$ and $t_1=5.0$, respectively. This time interval corresponds to the principal motion. The values of J for the M-R-O model were smaller than those for the M-H-D model for the step-by-step integration method. Futhermore, for the M-R-O model, the value of J=0.191, which corresponds to the model with N=22, was the smallest for the acceleration. It is to be noted that the difference between the models with N=22 and N=44 was very small. The values of J for the model with N=44 (Velocity;J=0.112, Displacement;J=0.247) were the smallest found for both the velocity and the displacement. The difference between the models N=44 and N=22 was also very small. The similarity in the results obtained for N=44 and N=22 suggests that taking two segments for each soil layer is sufficient when decideing the total number of subdivisions to be considered in the analysis.

Table 5 Value of J Obtained by Nonlinear Seismic Analysis

Motion Item	Nonlinear Seismic Analysis Method		Number of Subdivisions		
			12	22	44
Acc.	Step-by-Step Integration Method	M-H-D	0.747	0.615	0.632
		M-R-O	0.204	0.191	0.192
	Equivalent Linear Analysis Method	$\eta=0.30$	0.297	0.293	0.293
		$\eta=0.40$	0.232	0.232	0.233
		$\eta=0.50$	0.267	0.265	0.265
		$\eta=0.65$	0.367	0.367	0.367
		$\eta=0.80$	0.473	0.465	0.472
		$\eta=1.00$	0.612	0.607	0.604
Vel.	Step-by-Step Integration Method	M-H-D	0.670	0.521	0.535
		M-R-O	0.120	0.116	0.112
	Equivalent Linear Analysis Method	$\eta=0.30$	0.230	0.226	0.225
		$\eta=0.40$	0.166	0.166	0.167
		$\eta=0.50$	0.203	0.200	0.201
		$\eta=0.65$	0.307	0.307	0.307
		$\eta=0.80$	0.420	0.412	0.419
		$\eta=1.00$	0.575	0.570	0.567
Displ.	Step-by-Step Integration Method	M-H-D	1.828	1.394	1.418
		M-R-O	0.253	0.249	0.247
	Equivalent Linear Analysis Method	$\eta=0.30$	0.254	0.252	0.252
		$\eta=0.40$	0.223	0.223	0.225
		$\eta=0.50$	0.274	0.272	0.272
		$\eta=0.65$	0.401	0.401	0.400
		$\eta=0.80$	0.573	0.560	0.572
		$\eta=1.00$	0.857	0.848	0.844

In the case of the equivalent linear analysis method, the value of J shows almost no variation due to changes in the number of subdivisions. The value of 0.4 of the coefficient η yielded the minimum values of J for acceleration, velocity and displacement.

Figure 7 shows the distributions of the maximum strain for the step-by-step integration method and for the equivalent linear analysis method. Figure 8 shows the comparisons between the observed and the analytical waves when the value of J was minimum in the step-by-step integration method and in the equivalent linear analysis method.

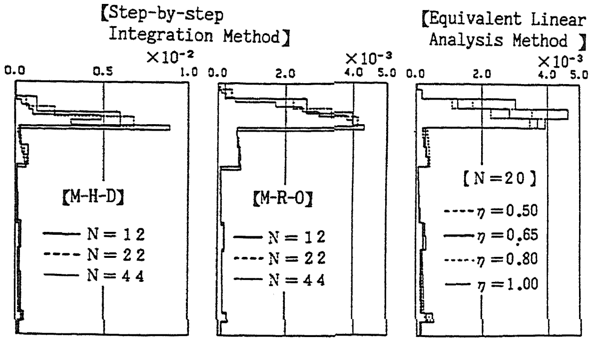

Fig. 7 Distributions of Maximum Strain for Actual Soil Deposits

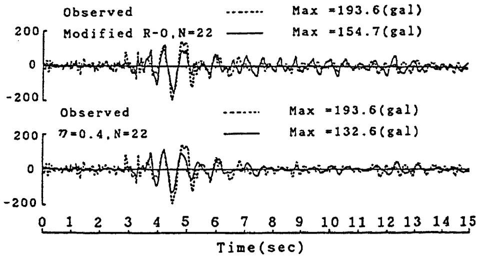

Fig. 8 Comparison Between Analytical Results and Observed Records

CONCLUSIONS

The conclusions obtained through this study are as follows:

(1) No significant differences in the maximum velocity and displacement between the observed and the calculated waves occurred for the step-by-step integration method, due to changes in the number of subdivisions of the model. However, a 35% difference was found for the maximum acceleration.

(2) For the equivalent linear analysis, although the influence of the number of subdivisions on the maximum responses was very small, large differences occured by changing the coefficient η.

(3) As for the dynamic model, the results of the Modified Ramberg-Osgood model agreed more with the observed data than the results of the Modified Hardin-Drnevich model.

(4) In regards to the number of subdivisions to be considered in the analysis, two segments for each layer was found to be sufficient.

(5) The value of the coefficient η that produced the minimum values of J was 0.4.

It is worthy to mention that in regards to the coefficient η, Ohsaki (Ref. 6) stated that the optimum coefficient η could not be easily determined, because η should be defined as a function of the maximum strain. Further investigations need to be carried out in determining the optimum value of the coefficient η.

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