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IDENTIFICATION OF TIME-VARYING PREDOMINANT PERIOD AND DAMPING CONSTANT IN NONLINEAR SEISMIC RESPONSE OF SOFT SOIL DEPOSIT

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SUMMARY

This paper deals with the identification of the time-varying predominant period and damping constant of soft soil deposits in nonlinear seismic responses based on strong seismic motion records. The identification technique originally proposed by J.L.Beck is expanded for its application to nonlinear seismic response problems. An optimal measure-of-fit between the observed record and the calculated response is evaluated by using the complex method. As a result of this study, it is clearly evident from the analysis that the predominant period and the damping constant become greater than their linear values.

INTRODUCTION

It is well known that the ground develops a nonlinear behavior during strong earthquakes. For a typical nonlinear seismic response of soft soil deposits, the predominant period grows longer and the magnification of the acceleration amplitude between the ground surface and the base becomes smaller. These phenomena occur as a results of decreasing shear moduli and increasing hysteretic damping of soils caused by the strong seismic excitation. This study deals with the identification of the time-varying predominant period and the damping constant of soft soil deposits in nonlinear seismic response based on strong seismic motion records.

Through this paper, the authors present (1) a time-variant identification method (Ref. 1), expanding the technique proposed by J.L. Beck (Ref. 2) for its application to nonlinear seismic problems, (2) the characteristics of the method through a numerical application by using a linear model, and (3) the results of a real field application utilizing strong seismic records.

TIME-VARIANT IDENTIFICATION METHOD

A brief description of the method used in this study is presented. In the normal modal equation of multi-degree-of-freedom system, by multiplying a component of the modal matrix of the i-th degree of freedom on the j-th mode ϕ_{ij} to both sides of the equation, the following equation is obtained:

$$\ddot{u}_{ij}(t)+2h_j\omega_j\dot{u}_{ij}(t)+\omega_j^2u_{ij}(t)=-\beta^0_{ij}\ddot{x}_0(t) \qquad (1)$$

where, $u_{ij}(t)=\phi_{ij}q_j(t)$, $\beta^0_{ij}=\phi_{ij}\beta_j$. ω_j, h_j, β_j and $q_j(t)$ are the natural angular frequency, the damping constant, the participation factor and the normal coordinate of the j-th mode, respectively. $x_0(t)$ is the acceleration wave as an input motion, and t is the time.

$u_{ij}(t)$ is the j-th mode component of the displacement of the i-th degree of freedom $x_i(t)$ and is obtained by solving Equation (1) using the input motion $x_0(t)$. According to Beck's technique, the predominant period $T_j=2\pi/\omega_j$, the damping constant h_j and the participation factor β_j are determined so that the measure-of-fit J_{ij} becomes minimum. The measure-of-fit J_{ij} is evaluated using the Equation (2) for an observed record $x_i(t)$ and the calculated response $u_{ij}(t)$.

$$J_{ij} = \int_{t0}^{t1} \{x_i(t) - u_{ij}(t)\}^2 \, dt \Big/ \int_{t0}^{t1} x_i(t)^2 \, dt \qquad (2)$$

where, t0 and t1 are the starting and the ending times of a specific period range. The smaller the value J_{ij} is, the higher the degree of agreement between $x_i(t)$ and $u_{ij}(t)$.

There is a problem if Equation (2) is employed in identifying the predominant period and the damping constant of a ground with nonlinear seismic response. This problem is presented in Figure 1. Let us assume that the predominant period, $T_1=0.7$ seconds, at the ground during the first two-second specific period range will change to 1.2 seconds at the next two-second interval due to the nonlinear behavior. There are no problems for the identification of the predominant period T_1 using Equation (2) for the first specific period range. However, for the second interval, even if $T_1=1.2$ seconds, J_{ij} is not zero because a phase lag is produced at the starting time of two seconds by the difference between the calculated wave and the observed records. J_{ij} from Equation (2) takes a large value even though the phase lag is small. Therefore, it is difficult to identify the predominant period exactly. This problem gets complicated after a time of four seconds. Thus, in this paper, the following equation, which takes into account the phase lag, is proposed for the measure-of-fit during the identification of the nonlinear seismic response problems.

$$J_{ij}(\pm d\tau) = \int_{t0}^{t1} \{x_i(t) - u_{ij}(t \pm d\tau)\}^2 \, dt \Big/ \int_{t0}^{t1} x_i(t)^2 \, dt \qquad (3)$$

Where, $d\tau$ is the phase lag. It is an arbitrary time constant with a value $0 \leqq d\tau \leqq (t1-t0)$. $x_i(t)$ is either a displacement, a velocity or an acceleration. To locate the minimal J_{11} point , the complex method (Ref. 3), is employed.

NUMERICAL STUDIES BY THE PROPOSED METHOD

To clarify the characteristics of the proposed method, numerical studies were carried out for a linear model of the ground. The model is a homogeneous soil deposit as shown in Figure 2. The predominant period T_1 and the participation

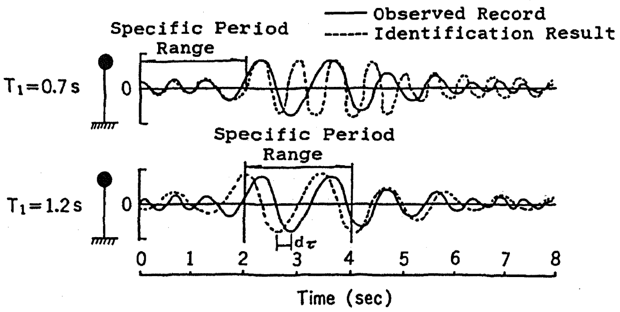


Fig.1 Applicability of Beck's Technique to Nonlinear Seismic Analysis Problem

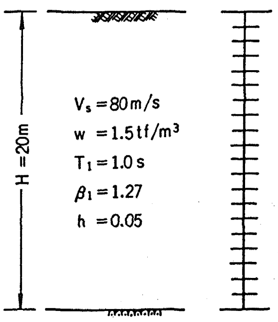


Fig.2 Linear Model

factor β_1 of the first mode are 1.0 second and 1.27, respectively. The response at the ground surface was computed by using one-dimensional lumped-mass system with 20 degrees of freedom (Figure 2) subjected to the 1940 El-Centro Earthquake record, NS component, with a peak acceleration of 100.0 cm/s^2. The damping constants h_1 for all the modes were taken to be 0.05.

In the numerical studies, the response waves at the ground surface were utilized as the observed records. The identification of the predominant period T_1, the damping constant h_1 and the participation factor β_1 of first mode was carried out. In studies, ϕ_{11} was taken to be 1.0, so that $\beta^0{}_{11} = \beta_1$.

Table 1 shows the identification results for the relative displacement, the relative velocity and the relative acceleration in which the considered specific period range is two seconds. The results show that the accuracy of the prediction of the predominant period T_1 is acceptable. However, it is not always suitable for estimating the damping constant h_1 and the participation factor β_1. The results also show that J_{11} for the relative velocity or the relative displacement is smaller than that for the relative acceleration.

Figure 3 compares observed records $x_1(t)$ and calculated response waves based on the identification results $u_{11}(t)$. The agreement between $x_1(t)$ and $u_{11}(t)$ in case of the relative displacement and the relative velocity is quite good but not so much for the relative acceleration due to the excitation of the high frequency component.

Figure 4 presents the contour lines of J_{11} for the relative acceleration. The horizontal and vertical axes in Figure 4 are the damping constant h_1 and the

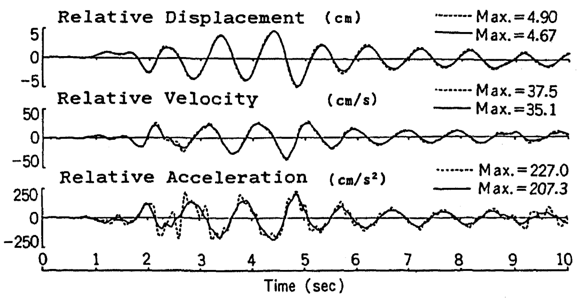


Fig.3 Comparison between $x_1(t)$ and $u_{11}(t)$ on Linear Model

Table 1 Identification Results based on Linear Model

Motion Items	Examined Values	Specific Period Ranges (sec)				
		0 ～ 2	2 ～ 4	4 ～ 6	6 ～ 8	8 ～10
Displ.	T_1(sec)	0.986	0.993	0.986	1.000	1.004
	h_1	0.051	0.046	0.044	0.030	0.025
	β_1	1.310	1.322	1.304	1.226	1.273
	J_{11}	0.005	0.005	0.002	0.006	0.015
Vel.	T_1(sec)	1.013	0.981	0.985	0.999	0.963
	h_1	0.028	0.087	0.045	0.030	0.040
	β_1	1.264	1.796	1.259	1.187	1.456
	J_{11}	0.019	0.029	0.005	0.008	0.050
Acc.	T_1(sec)	0.977	0.982	0.982	0.983	0.978
	h_1	0.010	0.035	0.049	0.033	0.035
	β_1	1.179	1.275	1.285	1.022	1.314
	J_{11}	0.062	0.198	0.051	0.045	0.253

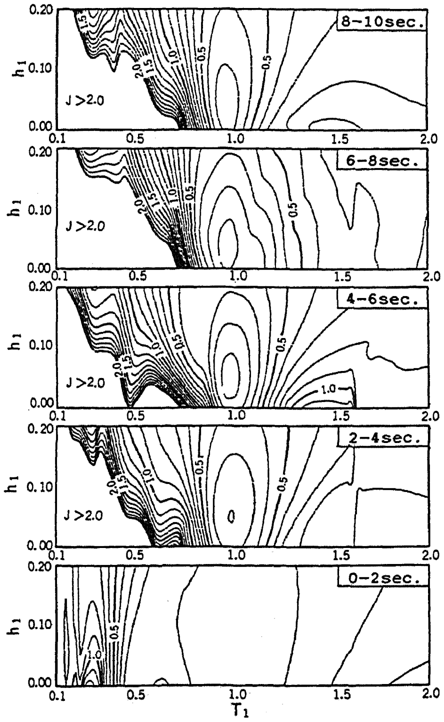


Fig.4 Contour Lines of J_{11} for Relative Acceleration based on Linear Model

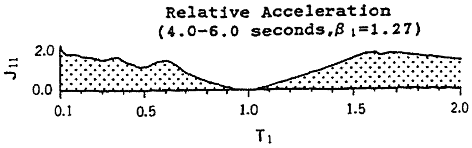


Fig.5 Relation between T_1 and J_{11} on Linear Model

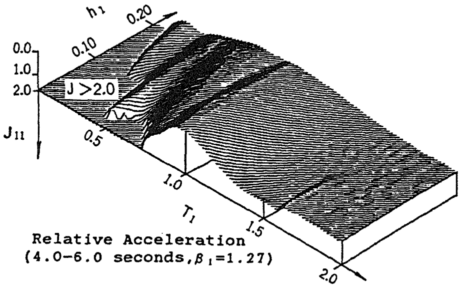


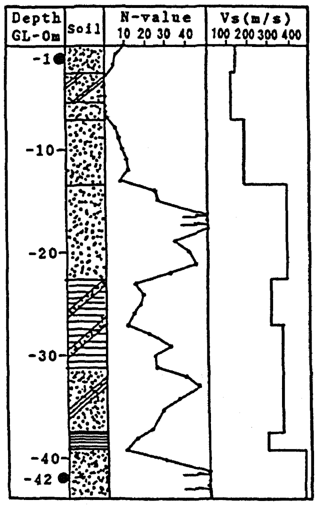
Fig.6 Birds-Eye View of J_{11} on Linear Model

predominant period T_1 of the ground, respectively. The participation factor β_1 is 1.27. Though the patterns of the contour lines at each specific period range is different from one another, the minimum J_{11} point is around T_1=1.0 second and h_1=0.05 at each range. Oval shaped contour lines can be seen along the vertical axis making it difficult to estimate the damping constant. This is reflected on the predicted results of the damping constant h_1 shown in Table 1.

Figure 5 shows the relation between T_1 and J_{11} at the specific period range from 4 to 6 seconds in which h_1=0.05 and β_1=1.27. Although J_{11} has the global minimum at T_1=1.0 second, the existence of many local minimum points is clearly shown in Figure 5. Therefore, it is important to select the initial values carefully to find the global minimum J_{11}. Figure 6 indicates a bird's-eye view of J_{11} at the same specific period range shown in Figure 4.

IDENTIFICATION BASED ON THE STRONG SEISMIC RECORDS

The authors carried out the identification of the time-varying predominant period and damping constant of soft soil deposits in nonlinear seismic response based on strong seismic records. The soil profile and the location of the accelerometers at the seismic observation site are shown in Figure 7. The soil condition, from the surface to approximately G.L.-14 m, is a loose sand layer, and



● : Location of Accelerometer

Fig.7 Soil Profile

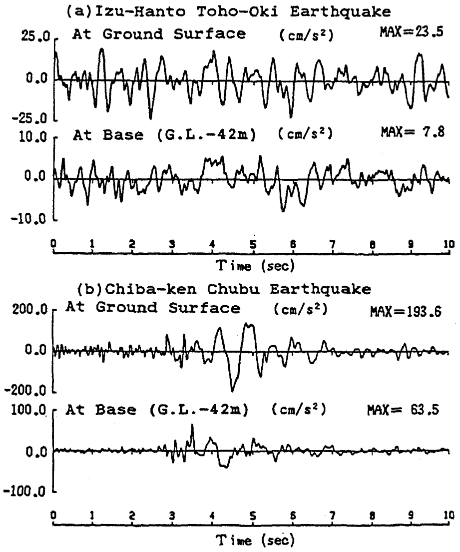


Fig.8 Strong Seismic Motion Records

its shear wave velocity Vs is 110 to 190 m/s^2. Two accelerometers are installed at G.L.-1 m and G.L.-42 m, respectively.

The observed records shown in Figure 8(a) were obtained during the Izu-Hanto Toho-Oki Earthquake (June 29, 1980, J.M.A. -Japan Meteorological Agency- scale magnitude M=6.7, epicentral distance ⊿=22 km, focal depth D=10 km). The peak accelerations at the ground surface (G.L.-1 m) and at the base layer (G.L.-42 m) were 23.5 cm/s^2 and 7.8 cm/s^2, respectively. Figure 8(b) indicates the records obtained during the Chiba-ken Chubu Earthquake (September 25, 1980, M=6.1, ⊿=22 km, D=80 km). In this case, the peak accelerations at both points were 193.6 cm/s^2 and 63.5 cm/s^2, respectively. The transfer functions between the ground surface and the base layer are shown in Figure 9. They were calculated using both the records shown in Figure 8 and the observed records of the other smaller earthquakes. As can be seen, there is no difference in the predominant period, T_1=0.5 seconds, of the transfer functions between the Izu-Hanto Toho-Oki Earthquake and the smaller earthquakes. On the other hand, the predominant period moves to 0.7~0.8 seconds in the Chiba-ken Chubu Earthquake (Ref. 4).

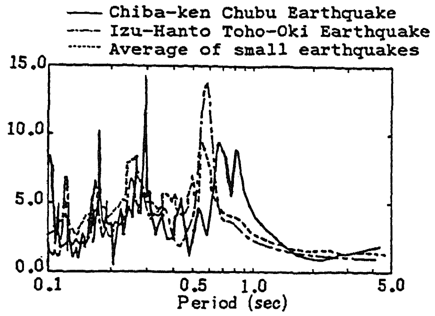


Fig.9 Transfer Function between Ground Surface and Base

Table 2 Identification Results based on Observed Records during Izu-Hanto Toho-Oki Earthquake

Motion Items	Examined Values	Specific Period Ranges (sec)				
		0 ~ 2	2 ~ 4	4 ~ 6	6 ~ 8	8 ~10
Displ.	T_1(sec)	0.491	0.565	0.540	0.563	0.562
	h_1	0.011	0.024	0.001	0.148	0.001
	β_1	1.706	0.869	0.801	1.217	2.708
	J_{11}	0.057	0.201	0.325	0.044	0.441
Vel.	T_1(sec)	0.501	0.563	0.534	0.562	0.537
	h_1	0.027	0.036	0.001	0.152	0.001
	β_1	1.483	0.886	0.813	1.205	2.231
	J_{11}	0.049	0.092	0.209	0.009	0.472
Acc.	T_1(sec)	0.508	0.575	0.537	0.559	0.539
	h_1	0.028	0.028	0.001	0.150	0.001
	β_1	1.499	0.999	0.801	1.185	1.927
	J_{11}	0.036	0.078	0.151	0.008	0.432

Table 3 Identification Results based on Observed Records during Chiba-ken Chubu Earthquake

Motion Items	Examined Values	Specific Period Ranges (sec)				
		0 ~ 2	2 ~ 4	4 ~ 6	6 ~ 8	8 ~10
Displ.	T_1(sec)	0.560	0.570	0.759	0.671	0.698
	h_1	0.013	0.234	0.087	0.048	0.090
	β_1	1.453	1.881	1.899	1.117	1.005
	J_{11}	0.463	0.346	0.036	0.024	0.168
Vel.	T_1(sec)	0.548	0.578	0.744	0.677	0.692
	h_1	0.033	0.030	0.094	0.065	0.114
	β_1	1.262	1.240	1.898	1.015	1.011
	J_{11}	0.295	0.134	0.028	0.020	0.060
Acc.	T_1(sec)	0.518	0.586	0.738	0.679	0.715
	h_1	0.045	0.050	0.100	0.061	0.089
	β_1	1.368	1.322	1.898	1.001	1.000
	J_{11}	0.121	0.051	0.021	0.034	0.036

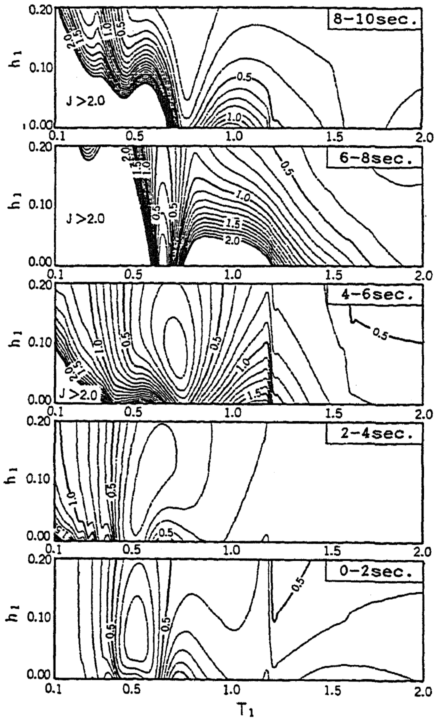


Fig.10 Contour Lines of J_{11} for Relative Acceleration based on Observed Records during Chiba-ken Chubu Earthquake

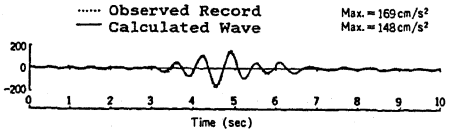


Fig.11 Comparison between Observed Record and Response Acceleration based on Identification Results

Table 2 and Table 3 present the results of identification for which the predominant period T_1, the damping constant h_1 and the participation factor β_1 for each specific period range of two seconds, were estimated. As shown in Table 2, the time-variation of the predominant period T_1 obtained from the *Izu-Hanto Toho-Oki* Earthquake record is small, and therefore, the ground response is likely to be in the linear range. In the case of Chiba-ken Chubu Earthquake, indicated in Table 3, the predominant period T_1 changes from 0.52, to 0.74, seconds and the damping constant h_1 varies from 0.045 to 0.10. It seems that the increments of the predominant period and of the damping constant are due to the nonlinear response of the ground for the principal motion period from 4 to 6 seconds of the records.

Figure 10 presents the contour lines of J_{11} for each specific period range of two seconds of the relative acceleration of the Chiba-ken Chubu Earthquake records. The horizontal and vertical axes in Figure 10 show the predominant period T_1 and the damping constant h_1 of the ground, respectively. The participation factor β_1 is 1.62 which is calculated with the initial shear modulus of the soil deposit. It is found that the minimum point of J_{11} in the oval shaped contour lines travels in the longer period and the higher damping constant directions.

Figure 11 shows a comparison of the relative acceleration between the observed record and response calculated using the identification results in Table 3. Both of the compared waves were passed through a low pass filter of 2.0 Hz. The similarity of the two waves is quite good and the estimated results of the time-varying predominant period T_1 and damping constant h_1 of the ground can be considered acceptable.

CONCLUSIONS

As a result of this study, the following conclusions are presented:

(1) The identification technique for the time domain proposed by J.L.Beck is sufficient to estimate the predominant period without the damping constant.

(2) It is important to adequately select the initial values of the predominant period and the damping constant in searching for the minimum value of J by the optimization method, because many local minima occur in the searching space.

(3) The identification results of the records obtained for a small earthquake, indicate no variation of the predominant period with time. Therefore, the ground response is likely to be within the linear range. On the other hand, it is found from the identification results that a longer predominant period and an increased damping constant occurred due to the nonlinear response of the ground in the principal motion period of the records obtained from strong earthquakes.

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