INVERSE ANALYSIS OF DYNAMIC SOIL PARAMETERS USING ACCELERATION RECORDS

Toshikazu IKEMOTO[1], Masakatsu MIYAJIMA[2] And Masaru KITAURA[3]

SUMMARY

This paper deals with an inverse analysis by combining genetic algorithm search with S-wave multiple reflection theory. The purpose of the inverse analysis is to identify the dynamic soil parameters by using down-hole array records. Genetic algorithm search based on the mechanism of natural selection and natural genetics, has widespread applications in many kinds of optimization problems. This method searched the minimum of the sum of squared differences between observed Fourier amplitude spectra and calculated one. The application of the method to actual acceleration records was discussed. The availability of the proposed method was verified through comparison of the results of observation and calculation at the ground surface at the site of the Chiba experiment station.

INTRODUCTION

It has been suggested that one of the principal causes of damage during large earthquakes may be attributed to an amplification of upwards waves by local geological and soil conditions. Dynamic soil parameters for soil conditions have important impact on the amplification of ground motions in ground response analysis. Nevertheless dynamic soil parameters such as Young's modulus and damping ratio are not investigated well. Several inverse analyses have been introduced to the parameter estimation in soil dynamics by many researchers. The extended Bayesian method based on ABIC was applied to inverse analysis of dynamic soil properties using seismometer array records[Honjo et al., 1997]. Methods for inverse analyses in soil dynamics, which are classified by the time domain problem, frequency domain problem and modal analysis, have been proposed[Hoshiya and Saitoh, 1984]. A method presented by Honda et al. was applied to many horizontal response accelerations monitored at multi-layered soil deposits and dams [Honda et al., 1995]. A method for system identification based on the auto algorithm-regressive moving average time series model was developed[Toki et al, 1978], however, the method was improved in the convergence of solution for identification of soil parameters by using the modified successive linear programming[Sawada et al., 1992]. Phase velocities of Rayleigh wave analysis were calculated in the frequency domain by the F-K spectral [Satoh et al., 1998]. A method for the amplification of horizontal ground motions by using the simplex method was proposed by the authors [Zhai et al., 1997]. Most methods used in optimizations were traditional gradient-based search methods. This approach, however, had difficulties associated in selecting discontinuous solution space and in considering non-linearities. Unlike the traditional optimization methods, genetic algorithm efficiently finds an optimal solution from the complex and possibly discontinuous solution space. Genetic algorithms have been applied to an effective optimization search technique in various fields, including the identification problem[Kim and Ghabossi, 1998]. In the field of structural engineering, for example, genetic algorithms have been successfully applied to obtain the optimal solution for the structural members.

[1] *Department of Civil Engineering, Kanazawa University, Kanazawa, Japan Email:tikemoto@t.kanazawa-u.ac.jp*
[2] *Department of Civil Engineering, Kanazawa University, Kanazawa, Japan*
[3] *Department of Civil Engineering, Kanazawa University, Kanazawa, Japan*

This paper deals with the inverse analyses in soil dynamics by combining the genetic algorithm search with S-wave multiple reflection theory. As this paper focuses on the amplification of horizontal ground motions, the method developed by the authors was used to identify the dynamic soil parameters. This study focuses the effects of local site and geological conditions on amplification of horizontal ground motions.

SEISMIC RECORDS

The ground acceleration records of several earthquakes which occurred from 1986 to 1989 have been obtained at the site of the Chiba Experiment Station of Institute of Industrial Science, University of Tokyo[AEDP, 1992]. The records could be measured directly with seismometer at/in surface ground. The strong-motion seismograph layout is shown in Figure 1(a). Figure 1(b) shows the down-hole array and SPT-*N* value. This figure shows the soil profile at the site where the down-hole array records were obtained. Soft subsoil profile of this site consists of loam, sandy clay and fine sand. The acceleration records observed at the deepest layer and at the surface of ground were needed to search a solution for the optimization in the inverse analysis. The bottom at the deepest layer of down-hole array was treated as the bedrock, and the corrected accelerations recorded at the ground surface and the bedrock were used as an input data in the convergent calculation. The acceleration wave of the perpendicular for seismic transverse direction was obtained from two horizontal components at each site.

The seismic records at the Chiba array are listed in Table 1. The number of total records of horizontal accelerations at the ground surface and at the bedrock surface was twenty-eight in seven earthquake events. The ground motions were not strong, and the maximum accelerations for horizontal components were fairly small and less than 100cm/s^2 at the ground surface. Therefore, the nonlinear behavior of ground motion did not need to be considered in calculation. The accelerometers could measure the ground vibration in frequencies from 0.1 Hz to 30 Hz and the frequency ranges focused here were 0.1 Hz to 10 Hz for horizontal ground motions. The duration of sampling was 10 seconds of the principal motion. The sampling time step of acceleration was 0.01 second.

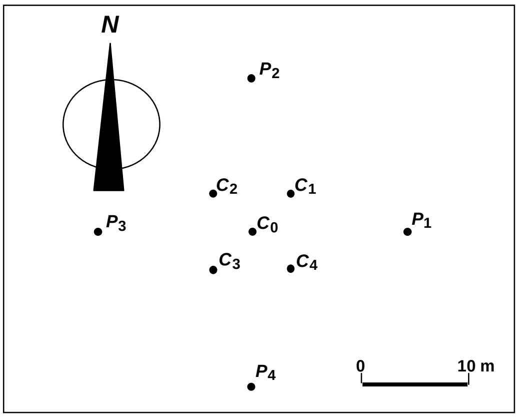

Figure 1(a): Layout of the down-hole array

METHOD OF ANALYSIS

The study applied the multiple reflection theory to S-wave propagation and used genetic algorithm to firstly determine shear wave velocity V_s, thickness of a layer H and shear damping ratio h_s of a ground. The ground response, i.e., acceleration and Fourier spectrum at the ground surface were calculated from the assumed soil parameters by using the multiple reflection theory. The objective function minimized the sum of squared differences between Fourier amplitude spectra of observed and calculated. Genetic algorithm search was effectively used in this optimization problem as a numerical procedure.

Parameter estimation

Dynamic soil parameters such as shear velocity V_s, damping ratio h_s and thickness of a layer H must be previously determined for ground response analysis. We directly evaluated those parameters at each soil layer for many unknown quantities. We assumed V_S was the same in each layer and h_s was also the same in all layer.

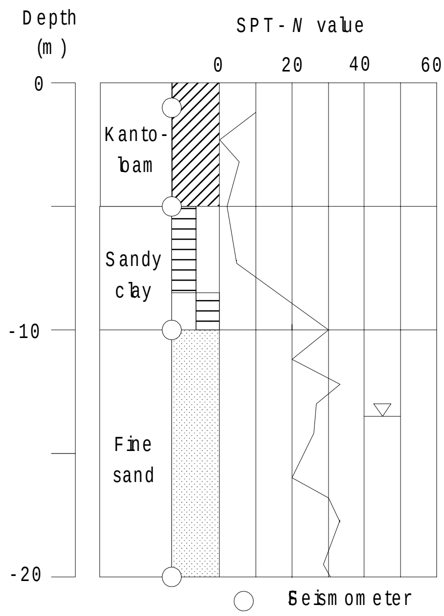

Figure 1(b): Down-hole at observation stations and SPT-*N* value

For simplicity, the path of the seismic waves arriving near the

Table 1: Seismic records at the Chiba array

No.	Data	M	Depth(km)	Distance(km)	Max. Acc.(cm/s^2)
1	1986/6/24	6.5	73	105	53.4
2	1986/11/22	6	151	131	5.3
3	1987/2/6	6.7	35	219	10.5
4	1988/1/16	5.2	48	38	90.9
5	1988/3/18	6	96	42	54.9
6	1988/8/12	5.3	69	62	47.2
7	1989/2/19	5.6	55	48	49.2

ground surface was assumed to be almost vertical. This study applied the multiple reflection theory to S-wave propagation. The method was employed in one dimensional wave propagation through horizontally layered strata. The responses of ground at any depth in the soil were calculated by using the shear modulus, the thickness, damping ratio, soil density at each layer and input acceleration record in the multiple reflection theory. The transfer function between two observed sites, i.e., at the surface ground and at the bedrock, in the vertical array, was calculated.

Objective function of inverse analysis

The acceleration recorded at the bedrock and at the surface ground were needed to calculate an objective function for the optimization in the inverse analysis. This paper minimized the sum of squared differences between Fourier amplitude spectra of observed and calculated horizontal accelerations. To let the objective functions converge, Fourier amplitude spectra between recorded and calculated accelerations were smoothed with Parzen's window. J_s was the objective function to be minimized to determine soil parameters;

$$J_s = \sum_{i=1}^{n} (x_i - X_i)^2 \to \min. \quad (1)$$

where J_s: objective function for horizontal component, x_i: the Fourier amplitude spectrum of recorded acceleration in the i-th frequency. X_i: that of calculated acceleration, n: sampling number of Fourier coefficient. It is not easy to obtain the optimized value, because of the high nonlinearity in the objective function.

Genetic algorithms

Genetic algorithms have been developed to explain and simulate the adaptive processes of biological systems, i.e. natural evolution. In genetic algorithms, organisms or chromosomes evolving under a certain environment is presented by bit strings. Each string consists of several genes, and the combination of consecutive genes in the string presents parameters of the problem to be optimized. Strings evolve over generations to adapt to a given environment using genetic algorithm operators.

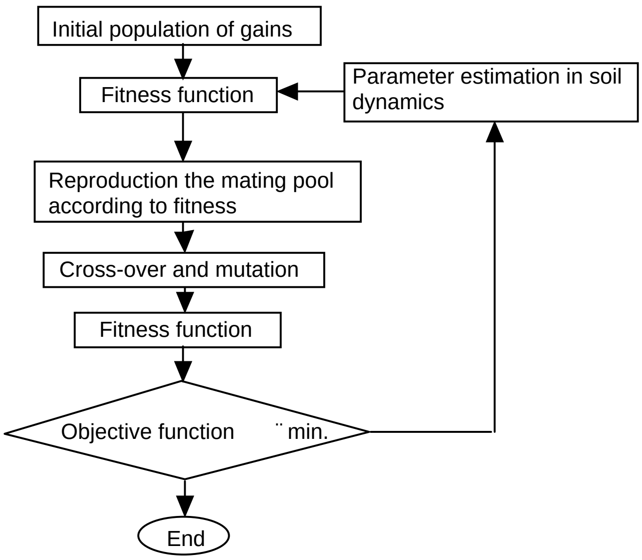

Figure 2: A flow diagram for genetic algorithm search

Figure 2 shows a flow diagram for genetic algorithm search method. There are three genetic algorithm operators: selective reproduction, cross-over and mutation. In every generation, a set of strings is selected into the mating pool based on their relative fitness. The strings are given more chance of passing their genes into the next generation. This process of natural selection, i.e. survival of the fittest is operated by selective reproduction. New strings are created by exchanging the genes between two old strings(cross-over). Mutation operator was applied to a specified low rate to change the randomly selected genes in the new generation. Genetic algorithms search is not simple random sampling. They efficiently exploit historical information to speculate on new search points with the expected improved performance.

Genetic algorithms are very simple and powerful methods compared with the traditional gradient-based search methods because genetic algorithms do not need the reformulation of the problem to search a non-linear and non-differentiable space. The fitness function is formulated as a polynominal function of the output of the optimization. Therefore, by using genetic algorithms, parameter can be estimated by simply considering them in the fitness function. Genetic algorithms are probabilistic searching techniques which explore the new searching space as well as the historical information of the searching space. The value of the probability of mutation was set to 0.5% and number of genes was 400 according to the general experience in the generation.

CASE STUDIES

Numerical simulations of the proposed method using genetic algorithm have been performed on the parameter estimation. The proposed method was applied to two cases for eight layers in a ground. One has nine unknown parameters such as eight V_s and one h, the other has seventeen variables such as eight V_s, eight H and one h_s.

Nine variables

Figure 3 shows comparison of Fourier spectra of the observed and calculated accelerations at the ground surface. It was evident from this figure that the calculated accelerations were in good agreement with the observed ones. In practice, it is very difficult to produce an accurately identified model in the high-frequency range. Table 2 shows mean, standard deviation and coefficient of variation of V_s for each soil type and shear damping ratio h_s, respectively. Distribution of identified V_s at each depth for the minimum value of objective function is shown in Figure 4. PS logging was performed at the site, i.e. the shear velocity V_s in upper layer was directly measured as 140m/s. As a result of calculation, the mean of *S*-wave velocity in the layer was obtained for minimum objective functions. The mean of calculated V_s was 112m/s. The mean value of calculated shear velocity V_s was estimated to be close to the observed one obtained from PS logging. The analytical results show that shear wave velocity increases with the depth of surface layer.

Figure 5 shows the calculated and observed maximum acceleration values for horizontal component. The broken line represents the line with 45 degrees inclinetion. Although, the calculated maximum accelerations for horizontal component at the ground surface are slightly larger than recorded ones. The agreement between the points and the line is quite good for all of data.

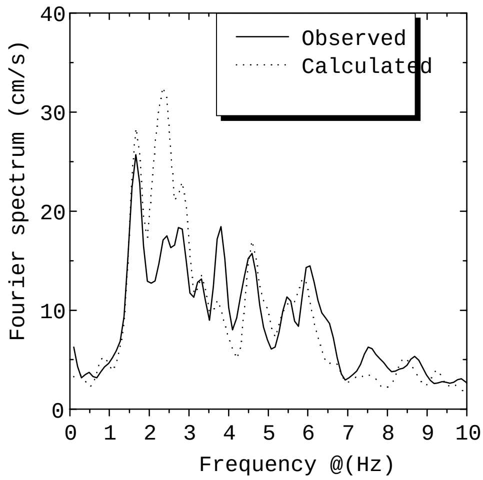

Figure 3: Comparison of Fourier spectra of recorded and calculated horizontal accelerations at ground surface for nine variables

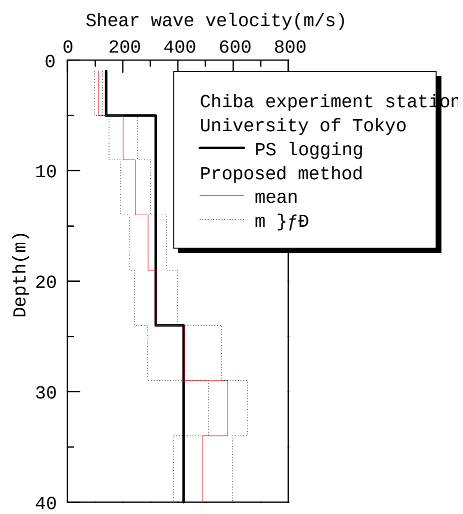

Figure 4: Identified V_s for the minimum value of objective function

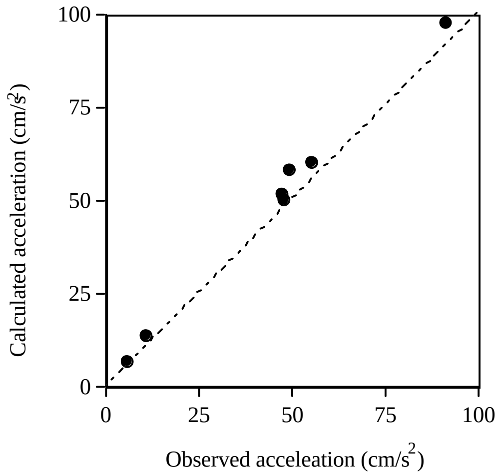

Figure 5: Comparisons of calculated and observed maximum accelerations

Table 2: Mean, S.D. and COV of shear velocity and damping ratio

Layer	Shear velocity (m/s)			Damping ratio		
	Mean	S.D.	COV	Mean	S.D.	COV
1	112	15	0.13			
2	202	52	0.26			
3	245	54	0.22			
4	291	66	0.23	0.05	0.01	0.2
5	320	79	0.25			
6	425	134	0.32			
7	580	70	0.12			
8	490	107	0.22			

S.D. :Standard deviation COV : Coefficient of variation

Figure 6 shows comparison of Fourier spectra of observed and calculated accelerations at the ground surface. The ground motions of the actual earthquake were not strong; the maximum accelerations of the observed and calculated were similar in this case. The fundamental mode was obtained by the multiple reflection theory. The shape of spectra of observed acceleration was similar to that of calculated acceleration. Distribution of identified V_s at each depth for the minimum value of objective function is shown in Figure 7. Since of the distribution of calculated V_s for depth is similar to observed one, the accuracy of the solution for V_s and H is good. Table 3 shows mean, standard deviation and coefficient of variation of V_s and H for each soil type and shear damping ratio h_s, respectively. From these results, it was concluded that the value at the 1-5 m depth lay within 133 m/s for V_s. The calculated mean values of V_s at the third layer and the fifth layer were 291 m/s and 416 m/s. The values obtained by PS logging were 320 m/s and 420 m/s, respectively. These values were estimated to be close to the PS logging value. Although, actual damping ratio at that site was not obtained, it seemed that the calculated h_s was closed to the actual damping ratio of the surface ground, because the shape of observed Fourier spectra was similar to the calculated one.

We already presented the results of soil parameter estimation under seismic excitation by using the traditional gradient-based search method[Ikemoto et al., 1998]. The calculated shear velocities were in good agreement with those of the recorded for a few number of unknown parameters. However, V_s obtained by the method was not well as the number increased. It is shown that the performance of the proposed method with some variables is far superior to that of the traditional gradient-based search method.

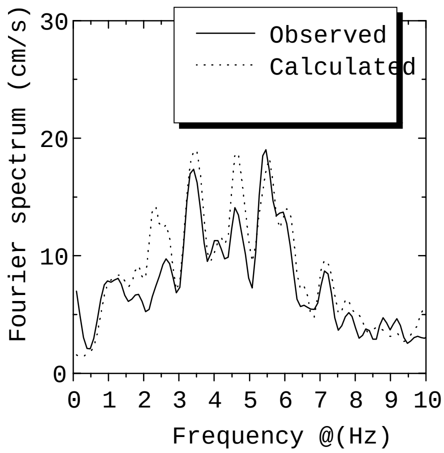

Figure 6: Comparisons of Fourier spectra of recorded and calculated accelerations at ground surface for seventeen variables

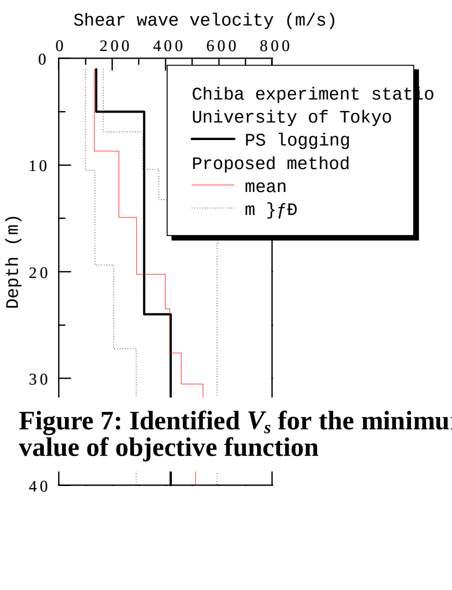

Figure 7: Identified V_s for the minimum value of objective function

Table 3: Mean, S.D. and COV of shear velocity, thickness and damping ratio

	Shear velocity (m/s)			Thickness of layer(m)			Damping ratio		
Layer	Mean	S.D.	COV	Mean	S.D.	COV	Mean	S.D.	COV
1	133	34	0.26	7.7	1.8	0.23			
2	225	90	0.4	6.2	2.7	0.44			
3	291	84	0.29	5.4	2.5	0.46			
4	400	109	0.27	3.3	2.8	0.85	0.06	0.03	0.5
5	416	127	0.31	4.1	3.3	0.8			
6	460	116	0.25	2.9	2	0.69			
7	540	59	0.11	5.1	3.2	0.63			
8	514	80	0.16	4.4	2.3	0.52			

S.D. :Standard deviation COV : Coefficient of variation

CONCLUSIONS

The purposes of this study are to present the inverse analysis by combining genetic algorithm search with the multiple reflection theory and to search the most suitable dynamic soil parameters by using the down-hole array records. We discussed the application of the method to the actual acceleration records. The method was applied to two cases for eight layers model. From the results of two cases, the mean values in those cases were estimated to be very close to the PS logging values.

The advantages of the proposed method are primarily its simplicity and flexibility. There is considerable flexibility in the formulation of the fitness function, and different weights are assigned to the objective in order to control fine-estimation as desired. Another advantage of the proposed method is easy expansion to non-linear problem.

ACKNOWLEDGMENT

The authors wish to thank their sincere appreciation to University of Tokyo, for supplying us the down-hole array records data. The research reported in this paper was funded by grants of Fukada Geological Institute. This support is gratefully acknowledged.

REFERENCES

Association for Earthquake Disaster Prevention(1992), *Strong motion array record database*, B-801-3 (in Japanese).

Kim Y. J. and Ghaboussi J.(1999), “A new method of reduced-order feedback control using genetic algorithms”, *Earthquake Engineering and Structural Dynamics*, 28, pp.235-254.

Honda, H., Kojima, K. and Arai, K. (1995), “Back-analysis of dynamic soil parameters based on actual accelerations during earthquake”, *Journal of Japan Society of Civil Engineers*, 517, III-31, pp.125-133(in Japanese).

Honjo, Y., Iwamoto, S., Sugimoto, S., Onimaru, S. and Yoshikawa, M.(1997), “Inverse analysis of dynamic soil properties based on seismometer array records using the extended Bayesian method”, *Soils and Fundations*, 38, 1, pp.131-143.

Hoshiya, M. and Saitoh, E.(1984), “Structural identification by extended Kalman filter”, *Proceedings of American Society of Civil Engineers*, 110, EM12, pp.1757-1770.

Ikemoto, T., Wasada, S., Miyajima, M. and Kitaura, M.(1998), “Inverse anaysis of dynamic soil parameters using actual acceleration during earthquake”, *Proceedings of the 10th Earthquake Engineering Symposium*, Vol.2, pp.1405-1410.

Satoh, T., Kawase, H., Matsushima, S. and Sugimura, Y. (1998), “Estimation of S-wave velocity structures of deep underground in the Sendai region based on array measurements of microtremors”, *Journal of Architectural Institue of Japan*, 503, pp.101-108(in Japanese).

Sawada, T., Tsujihara, O., Hirao, K. and Yamamoto, H.(1992), “Modification of SLP and its application to identification of shear wave velocity and quality factor of soil”, *Journal of Japan Society of Civil Engineers*, 446, I-19, pp.205-213(in Japanese).

Toki, K., Sato, T. and Oki, Y.(1978), ”Detection of dynamic properties of structural systems by the auto- regressive moving average method”, *Annual report of Disaster Prevention Research Institute, Kyoto University*, 21, B-2, pp.1-12(in Japanese).

Zhai, E., Miyajima,M. and Kitaura, M. (1997), " Nonlinear amplifications of vertical ground motions in the 1995 Hyogoken Nambu earthquake", *Journal of Japan Society of Civil Engineers*, 582, III-41, pp.1-10