Kawakami H., Haddadi H.R. and Sun Y.: Wave propagation analysis of earthquake strong ground motion records of vertical arrays (Geo-Eng 2000, An International Conference on Geotechnical & Geological Engineering, CD-ROM, 2000)

WAVE PROPAGATION ANALYSIS OF EARTHQUAKE STRONG GROUND MOTION RECORDS OF VERTICAL ARRAYS

Hideji Kawakami[1], Hamid R. Haddadi[2] and Yaonan Sun[3]

ABSTRACT

Recently developed methods for wave propagation analysis termed as SIORM and NIOM are compared using earthquake ground motion records of Samukawa vertical array in Japan. Three components of the earthquakes M6.5 of February 20, 1990 and M5.9 of February 2, 1992 are used in this analysis. For each component, P- and S- portions are analyzed separately at five elevations of the vertical array. Both methods provide identical models of wave propagation and illustrate stable peaks corresponding to propagation of P- and S- wave. The incident phase of P- and S- wave and its reflection from the ground surface are clearly depicted. Amplification of wave in shallow layers is observed in the results of both methods. Moreover, the ratio of the amplitudes of incident and reflected wave models provides some idea about damping in shallow ground layers.

INTRODUCTION

Among the methods used for evaluating the ground motion variations, cross-correlation has been the most common. However, the shape of cross-correlation function is greatly influenced by the wave propagation properties. The resolution of cross-correlation peaks may be poor for actual earthquake ground motion records when the concentration of power is within small time lags (Haddadi and Kawakami, 1998).

The unit impulse response calculation produces the cross-correlation function for a uniform input spectral density but the application of impulse response function is limited by a poor signal-to-noise ratio in the records (Bendat and Piersol, 1993; Haddadi & Kawakami, 1998).

The recently developed methods of simplified input output relation method, SIORM, (Kawakami & Bidon, 1997) and normalized input-output minimization method, NIOM, (Kawakami and Haddadi, 1998; Haddadi and Kawakami, 1998) give simple models of wave propagation and are shown to be more reliable than conventional correlation and impulse response functions. The methods are effective in detecting the arrival times of incident and reflected waves and in showing the amplification property of shallow layers. This paper applies SIORM and NIOM methods to strong ground motion records of Samukawa vertical array in Japan and compare the models of wave propagation obtained by those methods.

METHODOLOGY

SIORM method

The method of analysis of SIORM can be divided into two stages. First, the ground acceleration time series of k different observation points are considered and expressed using autoregression (AR) model. In order to express the time series in AR model, coefficient $a_{Mij}(m)$ is computed. After computing the coefficient $a_{Mij}(m)$, the corresponding time series at one observation point can be computed when a time series like a shape of a unit impulse at a particular time has been observed at the other observation point. With the result of the impulse response, the wave propagation properties can be determined.

The stationary time series in k dimension, $\{X(s)\} = \{x_1(s)\ x_2(s)\ \dots\ x_k(s)\}^T$ ($s = 1, 2, \dots, N$) (T denotes transposed vector or matrix), are expressed in AR model as:

[1] Professor, Dept. of Civil Engineering, Saitama University, 255 Shimo-okubo, Urawa, Saitama 338-8570, Japan
[2] Research Associate, Dept. of Civil Eng., Saitama University, 255 Shimo-okubo, Urawa, Saitama 338-8570, Japan
[3] Graduate Student, Dept. of Civil Eng., Saitama University, 255 Shimo-okubo, Urawa, Saitama 338-8570, Japan

$$\{X(s)\} = \sum_{m=1}^{M} [A_M(m)]\{X(s-m)\} + \{U(s)\} \tag{1}$$

where $\{U(s)\} = \{\varepsilon_1(s)\ \varepsilon_2(s)\ ...\ \varepsilon_k(s)\}^T$. The vector $\{U(s)\}$ is a k dimensional white noise with mean value of zero. Expressing equation (1) in terms of components, it can be expressed as:

$$x_i(s) = \sum_{m=1}^{M} \sum_{j=1}^{k} a_{Mij}(m) x_j(s-m) + \varepsilon_i(s) \tag{2}$$

where $i = 1, 2, ..., k$, $s = 1, 2, ..., N$ and $a_{Mij}(m)$ = the (i, j) element of $[A_M(m)]$.
By combining Levinson-Durbin algorithm and FPE (final prediction error) procedure (Akaike, 1972), M and the coefficients $a_{Mij}(m)$ can be computed precisely.

In SIORM, a unit impulse is set at a particular time at an observation point and the wave shape is not necessarily zero at any other time. The sum of squares and the sum of the squares of the difference between two successive values of the wave shape are minimized in order to obtain a smooth response function. Considering these conditions and using equation (2), the time series at the other observation point can be computed (see Kawakami and Bidon 1997).

NIOM method

The input and output models of a linear system in the frequency domain can be related by means of the transfer function $H(\omega)$. For the case of digitized earthquake ground motions of a multiple linear system, the output of a single linear system l at each frequency is specified by:

$$Y_l(\omega_i) = H_l(\omega_i) X(\omega_i) \qquad i = 1, ..., N-1; \quad \omega_i = \frac{2\pi i}{N\Delta t} \tag{3}$$

Δt is the sampling rate in the time domain and N is the number of samples. $X(\omega_i)$ and $Y_l(\omega_i)$ are the Fourier transforms of the digitized earthquake motion models at different locations. Using the method of Lagrange multipliers, square Fourier amplitude spectra of the ground motions at different locations are minimized when the input is subjected to a constraint. The constraint is considered such that the amplitude of input model at t=0 is unity. The Lagrange multipliers method is used to minimize the following summation.

$$\sum_{i=0}^{N-1} \left[c_0 |X(\omega_i)|^2 + k_0 \omega_i^2 |X(\omega_i)|^2 + \sum_{l=1}^{M} \left(c_l |Y_l(\omega_i)|^2 + k_l \omega_i^2 |Y_l(\omega_i)|^2 \right) \right] \tag{4}$$

In equation (4), c_0, k_0, c_l and k_l are weighting coefficients used for smoothing the results (see Haddadi and Kawakami 1998). The minimization procedure results in the following input and output models.

Table 1 : Soil profile and system layout of the Samukawa site. (Association for Earthquake Disaster Prevention of Japan, 1992)

Depth (m)	Soil Type	Density (g/cm^3)	P- velocity (m/sec)	S- velocity (m/sec)	Location of seismometer
0~4.5	Silt	1.55	750	110	GL
4.5~9	Sandy gravel	1.98	530	300	GL-4.5 m
9~17	Fine sand	1.89	1320		
17~21		1.84	1550		
21~31	Alluvial silt			230	
31~37	Coarse sandy gravel	1.67	1720	370	
37~44	Alluvial clay	1.67	1520	320	GL- 40 m
44~54				400	
54~56	Sandy gravel			850	
56~62		2.36	2280		GL- 55 m
62~82	Consolidated silt	1.93	1600	450	
82~88	Sandy gravel	2.38	2460	870	
88~100	Fine sand	1.89	1700	500	GL- 100 m

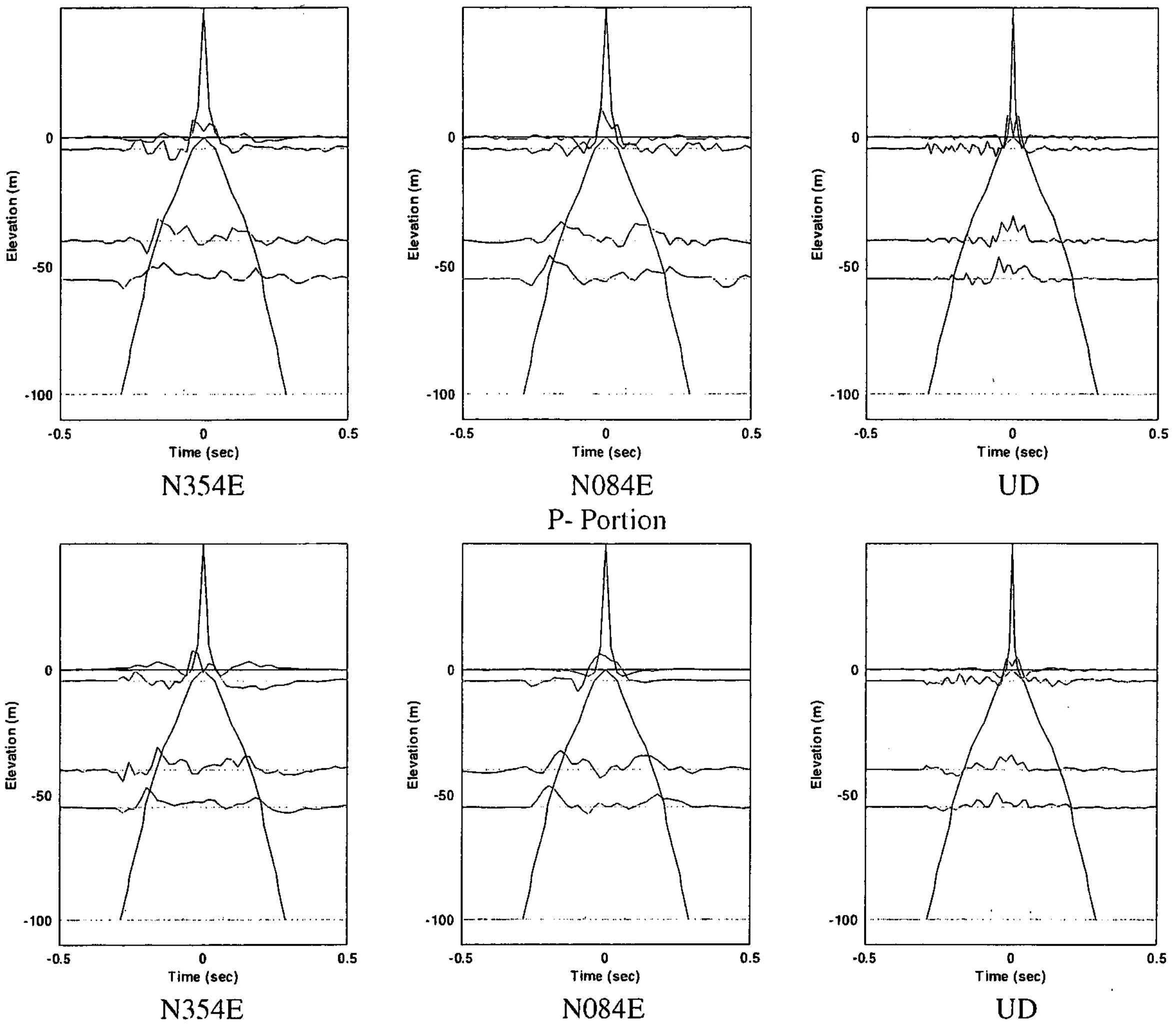

Figure 1 : Results of analysis of February 20, 1990 earthquake by SIORM at Samukawa vertical array

$$X(\omega_i) = N\Delta t \frac{\dfrac{1}{(1+\dfrac{k_0}{c_0}\omega_i^2)(c_0+\sum_{m=1}^{M} c_m |H_m(\omega_i)|^2)}}{\sum_{n=0}^{N-1} \dfrac{1}{(1+\dfrac{k_0}{c_0}\omega_n^2)(c_0+\sum_{m=1}^{M} c_m |H_m(\omega_n)|^2)}} \tag{5}$$

$$Y_l(\omega_i) = N\Delta t \frac{\dfrac{H_l(\omega_i)}{(1+\dfrac{k_0}{c_0}\omega_i^2)(c_0+\sum_{m=1}^{M} c_m |H_m(\omega_i)|^2)}}{\sum_{n=0}^{N-1} \dfrac{1}{(1+\dfrac{k_0}{c_0}\omega_n^2)(c_0+\sum_{m=1}^{M} c_m |H_m(\omega_n)|^2)}} \tag{6}$$

The input and output models of equations (5) and (6) would be transferred to time domain by inverse Fourier transform.

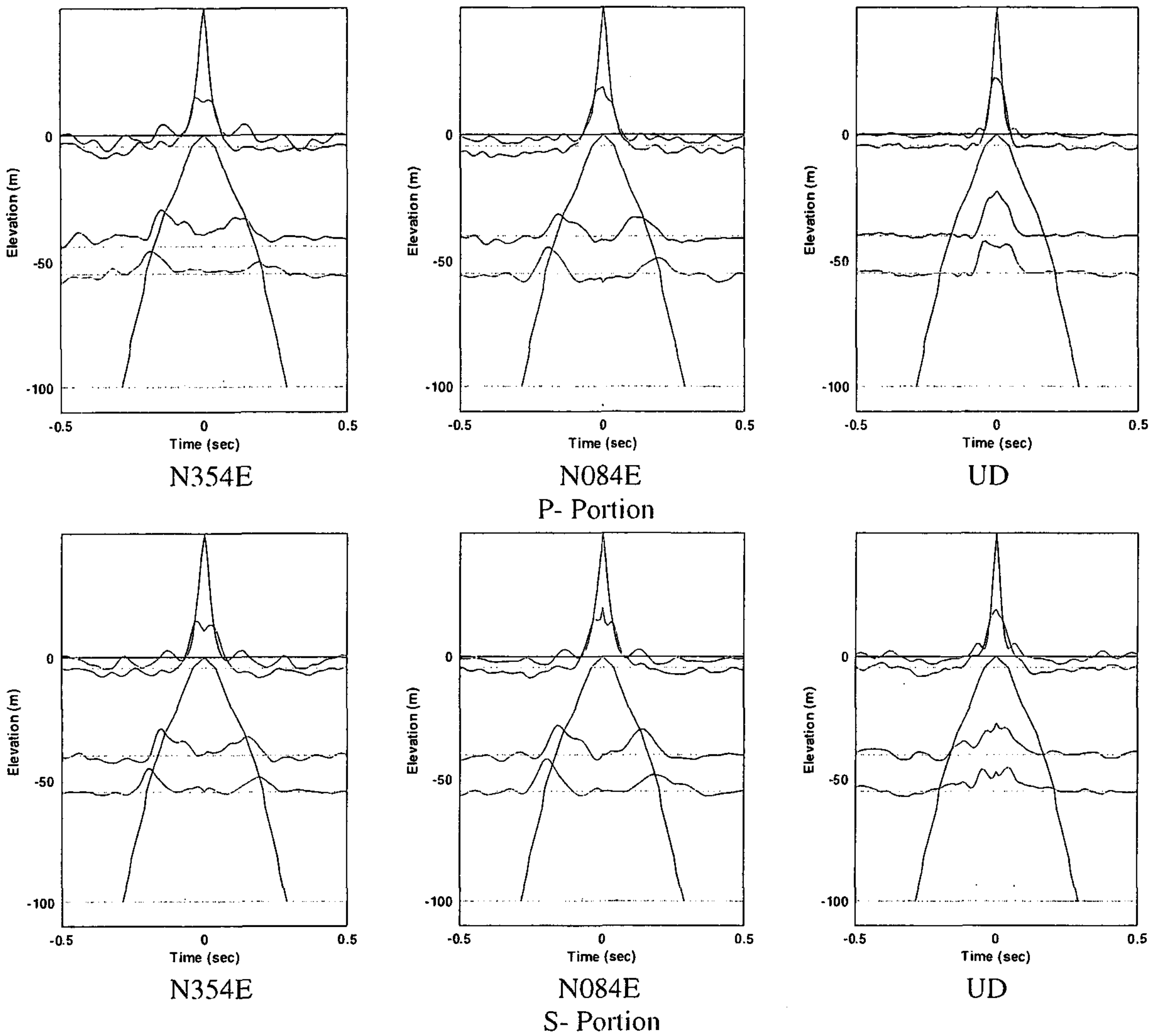

Figure 2 : Results of analysis of February 20, 1990 earthquake by NIOM at Samukawa vertical array

SAMUKAWA VERTICAL ARRAY

The abilities of SIORM and NIOM methods are considered by using the strong ground motions recorded at Samukawa site. The soil profile of Samukawa site is shown in Table 1. As shown in Table 1, there are 5 triaxial component seismometer at the vertical array.

ANALYSIS OF THE RECORDS

The earthquakes M6.5 of February 20, 1990 and M5.9 of February 2, 1992 recorded at the vertical array are selected for analysis. Each component of the earthquakes is divided into P- and S- portions and is analyzed separately. The results of analysis of February 20, 1990 earthquake by SIORM and NIOM are shown in Figures 1 and 2 and those for the earthquake of February 2, 1992 are shown in Figures 3 and 4. The input model of both methods is considered at ground surface with the unit amplitude at time t=0 and the responses at other elevations are shown. In all the figures, travel time curve of P- wave is shown by dash line and that of S- wave is shown by solid line. The travel time curves are obtained by using the geophysical measurements of wave velocity given in Table 1.

Although the methods of SIORM, in the time domain, and NIOM, in the frequency domain, are different, both provide similar and clear models of P- and S- wave propagation in ground layers. There are two stable peaks at each elevation corresponding to incident wave propagating upward and reflected wave from the ground surface propagating downward. The horizontal component models reveal the propagation of S- wave and those of vertical component show propagation of P- wave. The arrival time of P- and S- waves obtained by SIORM and NIOM methods agree with those of geophysical measurements. The remarkable point is that

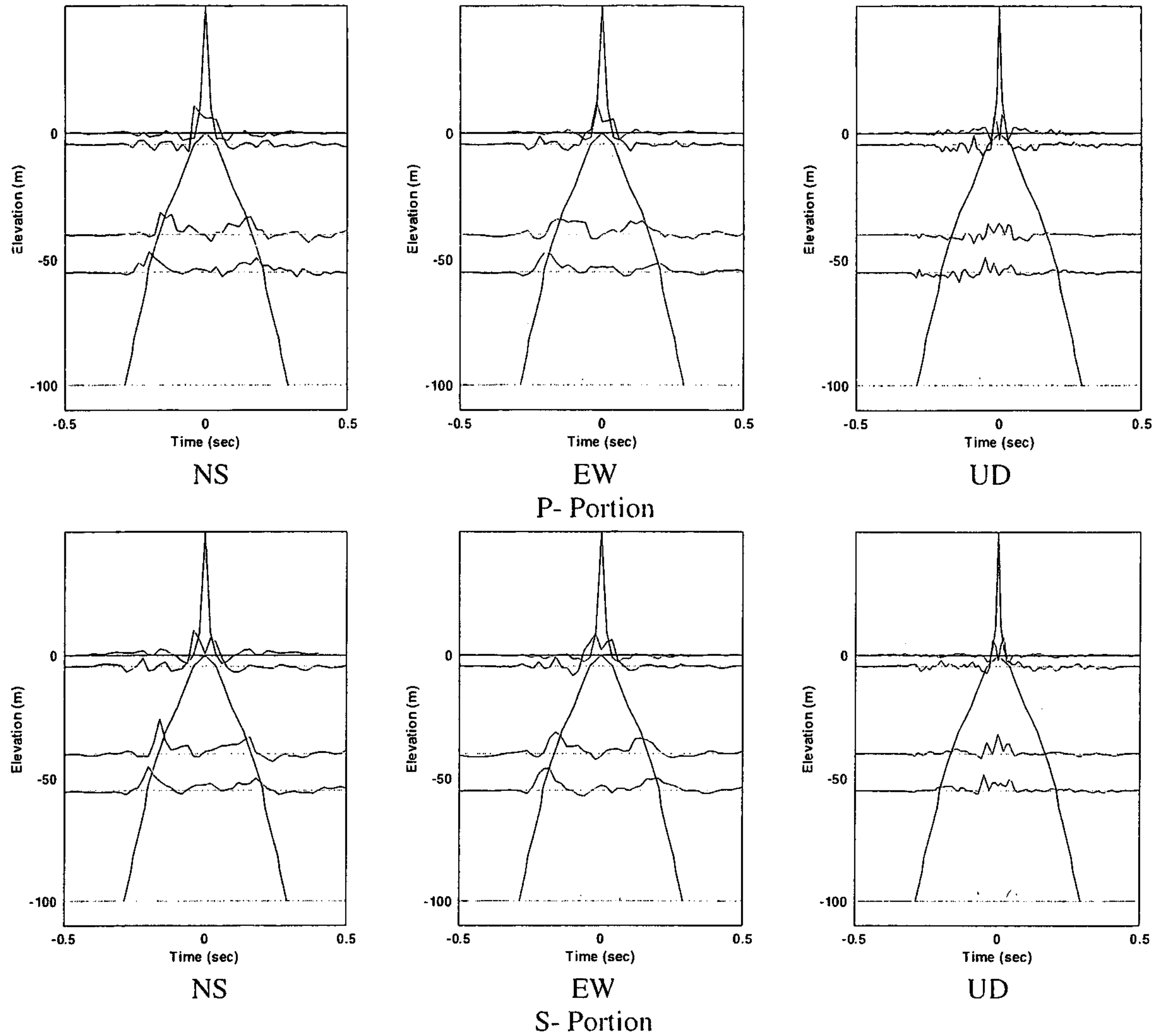

Figure 3 : Results of analysis of February 2, 1992 earthquake by SIORM at Samukawa vertical array

both of P- and S- portions of horizontal components propagate with the velocity of shear wave and both portions of vertical components propagate with the velocity of compressional wave. It may be concluded that S- wave is dominant in both portions of the horizontal component records and P- wave is dominant in those of vertical component.

The amplitude of the incident wave at lower elevations is smaller than that of upper elevations, which illustrates the amplification of wave in ground layers. At each elevation, the amplitude of reflected wave from the ground surface is smaller than that of the incident wave. It may be caused by partial reflection of wave at the ground layer boundaries and/or damping in soil layers.

Besides the two main peaks at each elevation due to propagation of incident and reflected (from the ground surface) waves, there are some other stable peaks in the models of both methods. Those peaks are not observed in the results of all observation points and could be due to multiple reflection of wave in ground layers.

CONCLUSIONS

The abilities of SIORM and NIOM methods for wave propagation analysis are illustrated by employing the strong motion records of Samukawa vertical array. While the models of SIORM and NIOM methods are very simple, some important properties of soil layers can be investigated by using those methods.

The incident P- and S- waves and the reflected phases from the ground surface at different observation points are clearly shown by analyzing the separate portions of horizontal and vertical components of ground motions. The models of both methods show that the amplitudes of the incident waves increase from lower to

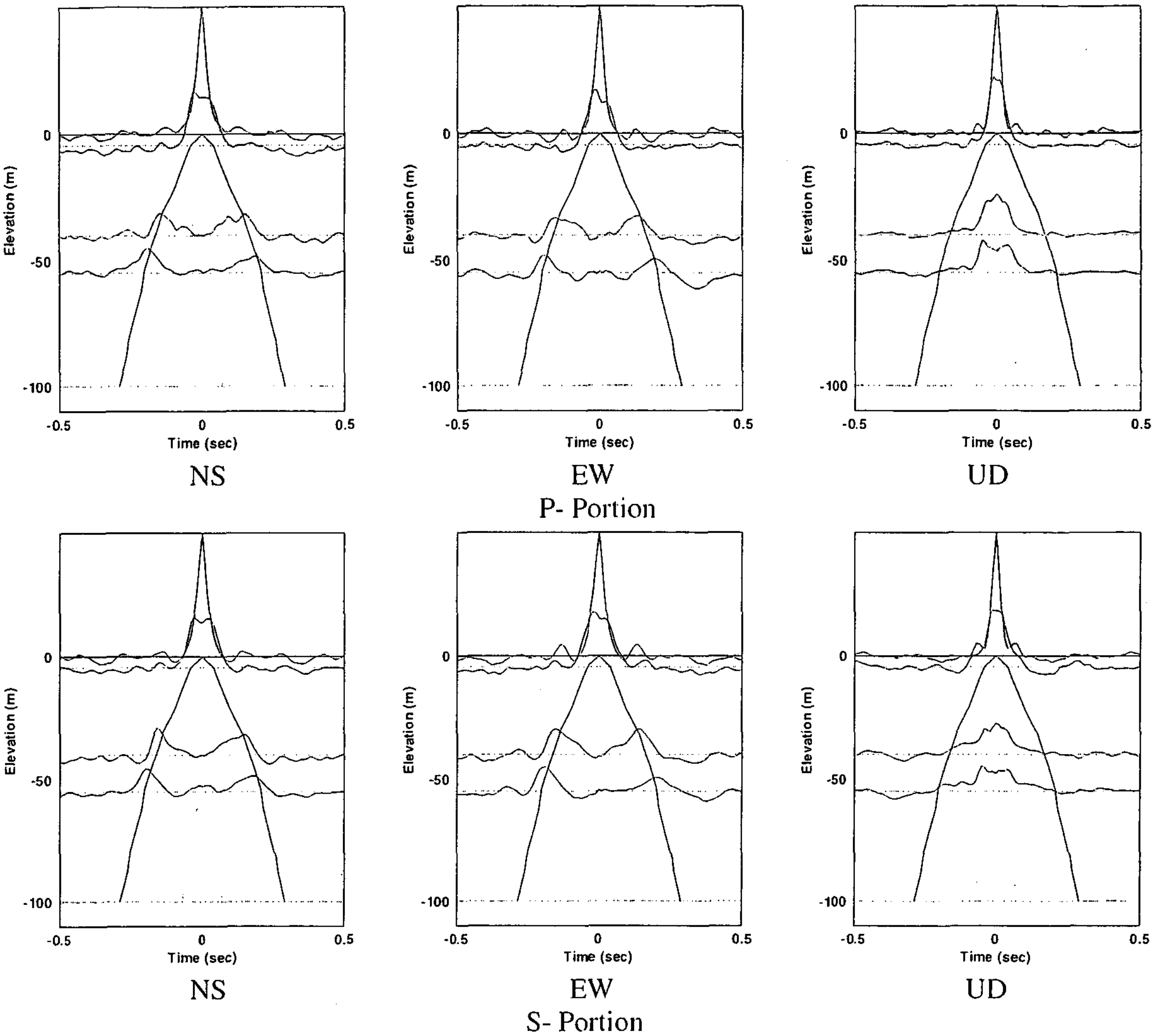

Figure 4 : Results of analysis of February 2, 1992 earthquake by NIOM at Samukawa vertical array

upper elevations and illustrate the effect of wave amplification of ground layers. Also, the amplitude of the model of reflected wave is smaller than that of the incident wave at each of the observation points. This may be due to partial reflection of waves at ground boundaries and/or damping in soil layers.

ACKNOWLEDGMENTS

The authors express their gratitude to the Nishimatsu Const. Co. Ltd. of Japan for providing the strong ground motion records at Samukawa vertical array.

REFERENCES

Akaike, H. (1972). "Statistical analysis and control of dynamic system". Science Inc. Tokyo, (in Japanese).

Association for Earthquake Disaster Prevention of Japan, (1992). "Strong motion array record database- Data manual" (in Japanese).

Bendat, J.S. and Piersol, A.G. (1993). "Engineering applications of correlation and spectral analysis". John Wiley & Sons, INC.

Haddadi, H.R. and Kawakami, H. (1998). "Modeling wave propagation by using normalized input-output minimization (NIOM) method for multiple linear systems". *J. Struct. Mech. Earthquake Eng., JSCE*, No. 584/ I-42, pp. 29-39.

Kawakami, H. and Bidon, P. (1997). "A simplified input output relation method using AR model for earthquake wave propagation analysis". *Earthquake Engrg. and Struct. Dyn.* Vol. 26, pp. 1041-1057.

Kawakami, H. and Haddadi, H.R. (1998). "Modeling wave propagation by using normalized input-output minimization (NIOM)". *Soil Dyn. Earthquake Engrg.* Vol. 17, pp. 117-126.