1729

ANALYSIS OF SOIL NONLINEAR PROPERTIES AT PORT ISLAND BY NIOM METHOD DURING 1995 HYOGO-KEN-NANBU EARTHQUAKE IN JAPAN

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SUMMARY

Discussed are the results of analysis of horizontal and vertical component wave propagation in surficial layers at Port Island vertical array site where large-scale liquefaction was observed during the Hyogo-Ken Nanbu earthquake of January 17, 1995 by using NIOM method. The results are compared with those of the events occurred on December 6, 1974 and February 2, 1995. The liquefied layers showed non-linear soil properties but there is not any change in physical properties of underneath layers. S- wave and P- wave velocity variations in the liquefied layers are considered by analyzing the horizontal and vertical component records. The large decrease of S- and P- wave velocity in the liquefied layers is observed during the earthquake. The models obtained for ground layers below depth 16 m do not show remarkable change in wave velocity during all the studied events. The amplitudes of the models are also stable during the mentioned events below depth 16 m whereas, it varies above that elevation. The ratio of incident to reflected (from the ground surface) wave amplitude gives some idea about variation of damping in the liquefied layers.

INTRODUCTION

In many studies, soil characteristics are investigated by separating the site effect from the source and path effects in ground motion records. For this purpose, the transfer function of soil layer is usually obtained either by using the earthquake records at ground surface and at a nearby surface rock site (reference site) or by using the vertical array records. The critical assumption in the first approach is that the reference site is equivalent to the input motion at the base of the soil layers. However, surface-rock sites can have a site response of their own, which could lead to an underestimation of amplification for a range of frequencies (Steidl et al, 1996). The borehole stations may provide valuable records of ground motion at different elevations that can be used to study physical properties of soil layers. Unfortunately, the vertical arrays of ground motion are not so widely used as the horizontal arrays.

This paper studies the properties of soil layers during the mainshock and aftershocks of the January 17, 1995 Hyogo-Ken Nanbu earthquake (hereafter, Hyogo earthquake) at the Port Island site by using the Normalized Input-Output Minimization (NIOM) method (Kawakami and Haddadi, 1998; Haddadi and Kawakami, 1998). The method provides simple models of wave propagation by considering the statistical correlation of the earthquake ground motions at different observation points.

METHODOLOGY

Assume a linear soil system in the frequency domain is subjected to the input of $F(\omega_i)$ at one observation point and the output of $G(\omega_i)$ is obtained at the other observation point. The transfer function of the system would be computed by the following equation.

$$G(\omega_i) = H(\omega_i)F(\omega_i) \qquad (1)$$

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The same transfer function that defines the relation of the actual ground motion input, $F(\omega_i)$, and output, $G(\omega_i)$, should satisfy the relation of the input model, $X(\omega_i)$, and the output model, $Y(\omega_i)$, as follows:

$$Y(\omega_i) = H(\omega_i) X(\omega_i) \tag{2}$$

The statistical correlation between the input and output is made by minimizing the summation of square Fourier amplitude motions when the input model is subjected to a constraint such that its amplitude is unity at t=0. The Lagrange multipliers method is applied for this purpose which gives the following equation.

$$L = \sum_{i=0}^{N-1} \left\{ c_0 \left| X(\omega_i) \right|^2 + k_0 \omega_i{}^2 \left| X(\omega_i) \right|^2 + c_1 \left| Y(\omega_i) \right|^2 + k_1 \omega_i{}^2 \left| Y(\omega_i) \right|^2 \right\} - \lambda \left\{ \frac{1}{N\Delta t} \sum_{i=0}^{N-1} X(\omega_i) - 1 \right\} \tag{3}$$

In equation (3), the weighting coefficients of c_0, c_1, k_0 and k_1 are used to smooth the fluctuations caused by noise in the results. The procedure of minimizing equation (3) provides simple models of input, $X(\omega_i)$, and output, $Y(\omega_i)$, of the system as follows:

$$X(\omega_i) = N\Delta t \frac{\dfrac{1}{(1+\dfrac{k_0}{c_0}\omega_i{}^2)(c_0 + c_1 \left| H(\omega_i) \right|^2)}}{\displaystyle\sum_{n=0}^{N-1} \dfrac{1}{(1+\dfrac{k_0}{c_0}\omega_n{}^2)(c_0 + c_1 \left| H(\omega_n) \right|^2)}} \tag{4}$$

$$Y(\omega_i) = N\Delta t \frac{\dfrac{H(\omega_i)}{(1+\dfrac{k_0}{c_0}\omega_i{}^2)(c_0 + c_1 \left| H(\omega_i) \right|^2)}}{\displaystyle\sum_{n=0}^{N-1} \dfrac{1}{(1+\dfrac{k_0}{c_0}\omega_n{}^2)(c_0 + c_1 \left| H(\omega_n) \right|^2)}} \tag{5}$$

ANALYSIS OF THE GROUND MOTION RECORDS

The effect of liquefaction on ground motion is studied by considering the horizontal and vertical component records of Hyogo earthquake at Port Island vertical array. The results of analysis are compared with those of the events of December 6, 1974, and February 2, 1995, to illustrate the effect of liquefaction on ground motion.

Port Island vertical array

The main port facilities in Kobe harbour are located on reclaimed land along the coast and on two man-made islands, Port Island and Rokko Island, which are joined by bridges to the main land. The fills beneath Port and Rokko Islands were constructed using residual soil formed by weathering of granite (Masa soil), which was obtained from borrow sites in the Rokko mountains. The soil profile of Port Island vertical array (Table 1) shows that the sand and clay interlayered stratum is overburdened with the reclaimed layer (Department of Urban Development, Kobe city, 1995). Geophysical measurements have shown a relatively low P- and S- velocity layer from depth of 19 to 27 m where the SPT N value is also decreased. There are four accelerometers located at ground surface and at depths of 16, 32 and 83 m. Those accelerometers have registered valuable records before, during and after the Hyogo earthquake.

Table 1 Soil profile and characteristics of Port Island vertical array site (Department of Urban Development, Kobe City, 1995)

Depth (m)	Soil type		P- velocity (km/s)	S- velocity (km/s)	SPT N value (min-max)	Poisson Ratio	Location of seismometer
0-2.0	Sandy gravel	Reclaimed	0.26	0.17	5.2 (3.6-6.6)	0.13	GL-0.0 m
2.0-5.0	Sandy gravel		0.33			0.32	
5.0-12.6	Sandy gravel		0.78	0.21	6.5 (2.3-16.0)	0.46	
12.6-19.0	Sand with gravel		1.48			0.49	GL-16.0 m
19.0-27.0	Alluvial clay		1.18	0.18	3.5 (2.8-4.0)	0.49	
27.0-33.0	Diluvial sand	Sand and clay interlayered stratum	1.33	0.25	13.5 (4.2-38.0)	0.48	GL-32.0 m
33.0-50.0	Sand with gravel		1.53	0.31	36.5 (8.0-94.7)	0.48	
50.0-61.0	Diluvial sand		1.61	0.35	61.9 (17.0-112.5)	0.48	
61.0-79.0	Diluvial clay			0.30	11.7 (10.3-13.0)	0.48	
79.0-85.0	Sand with gravel		2.00	0.32	68 (13.5-200.0)	0.49	GL-83.0 m

Ground motions

The mainshock and aftershocks of Hyogo earthquake were recorded by triaxial accelerometers at Port Island vertical array at four elevations. Three components of the mainshock and aftershocks are recorded in a time span of 6 minutes that are valuable data for analyzing wave propagation in liquefied media. There are some other events recorded before and after the Hyogo earthquake at the Port Island site. The events of Dec. 6, 1974 and February 2, 1995 are also used in this paper to compare the linear properties of soil layers with non-linear properties that observed during the Hyogo earthquake. Figure 1 shows the EW and UD components of the Hyogo earthquake mainshock time history at different elevations of the Port Island site.

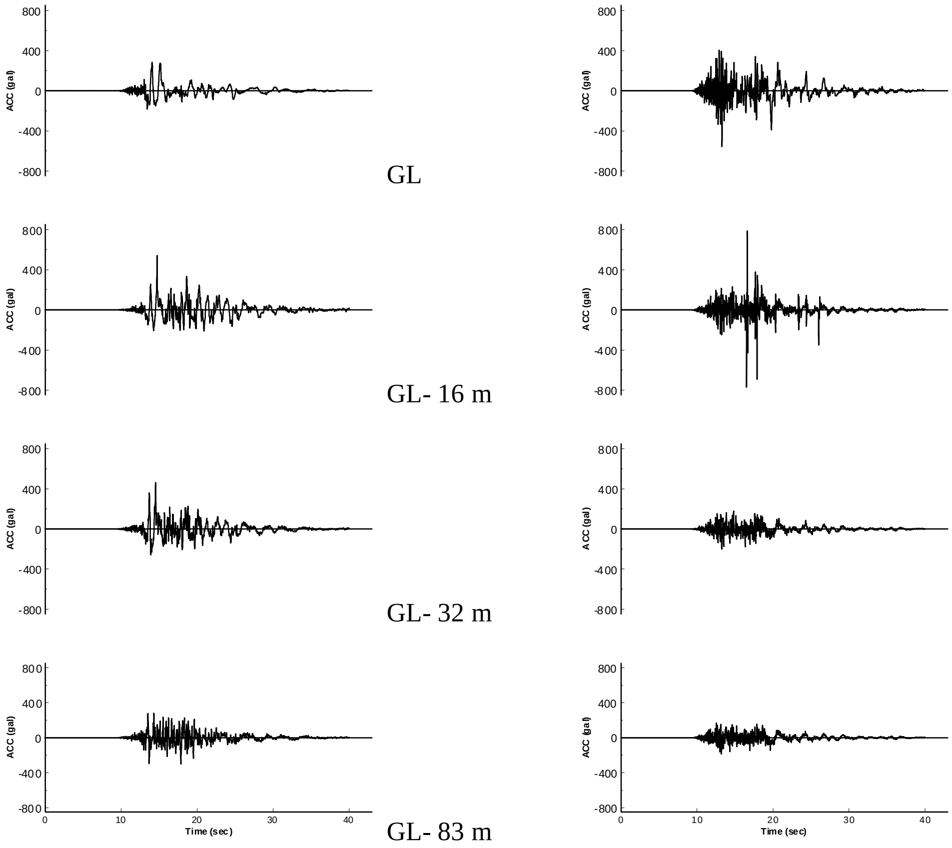
The ground motion records are analyzed by using NIOM method and the obtained models of wave propagation are discussed for each case. The results of analysis by NIOM method are compared with the travel time curve of incident wave (solid line) and that of reflected wave from the ground surface (dashed line) by using geophysical measurements of wave velocity. As horizontal and vertical components of ground motions dominantly propagate with S- and P- wave velocity respectively, the travel times of horizontal models are compared with S- wave travel times and those of vertical component are compared with P- wave travel times. The models obtained by NIOM method contain a unit impulse at zero time as the input model and the outputs are obtained at the other elevations. The weighting coefficients of c_0=1, c_1=0.1 and k_0=0.001 in equations (4) and (5) are used to smooth the fluctuations caused by noise.

DATA ANALYSIS

Horizontal component ground motion models

Dec. 6, 1974 earthquake

The event of Dec. 6, 1974 was recorded at ground surface, depth of 32 m and depth of 83 m. The results of analysis of NS component records by NIOM method are shown in Figure 2.



EW component **UD component**

Figure 1 Time histories of the Hyogo earthquake mainshock

The models of ground motion at depths of 32 and 83 m show two clear peaks. The first peak corresponds to the incident wave at each location and the second one is due to reflected wave from the ground surface. The arrival times of the incident and reflected waves agree with those of geophysical measurements.

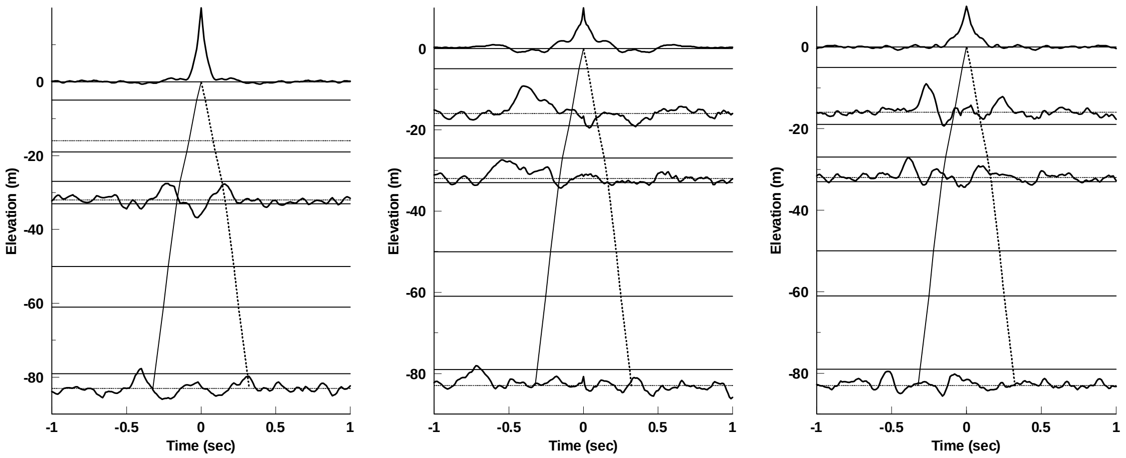
January 17, 1995 Hyogo earthquake

The Hyogo earthquake mainshock and several aftershocks are recorded within a time span of 6 minutes at all observation points of the Port Island site. Besides the mainshock, four aftershocks are analyzed in this paper. The aftershocks are recorded after 180, 220, 300 and 320 seconds from the beginning of the mainshock and will be identified hereafter as aftershock 1 to aftershock 4. Also, a segment (from 23.44 to 33.76 second) of EW component of mainshock that is recorded after the beginning of liquefaction is analyzed.

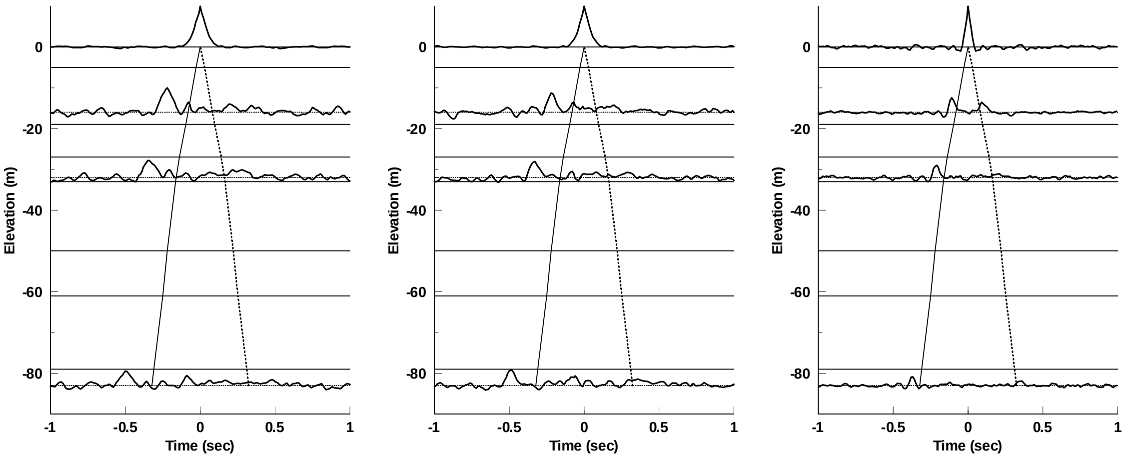
The results of analysis of EW component ground motion of Hyogo earthquake are shown in Figure 2. The large impulse at each elevation shows the arrival time of wave at that location. Some other peaks are also observed in the models. Among those peaks, the reflected phase from the ground surface is distinguished in some of the models. Comparison of arrival time of wave at each elevation with that of elastic wave obtained by downhole well shooting illustrates the effect of liquefaction on ground motion.

The results of analysis show a dramatic decrease of shear wave velocity in the mainshock that continues during the aftershocks. The decrease of wave velocity is observed in the liquefied layers in the uppermost 16 m layers and to some extent in the layers between depths of 16 m and 32 m. Comparison of arrival time of the incident peak of the model with that of downhole well shooting shows that there is not any change of wave velocity below depth of 32 m. However, there is a clear trend of recovering wave velocity from the mainshock to aftershock 4.

The models obtained for mainshock show the amplification of wave in the layers below the depth of 16 m but it is not amplified any more for the upper layers. However, wave amplification in the reclaimed portion is observed again from aftershock 3 that shows the ground condition is recovering by passing time.



Event of Dec. 6, 1974 **Mainshock of Hyogo Earthquake** **aftershock 1**



Aftershock 3 **Aftershock 4** **Event of Feb. 2, 1995**

Figure 2 The results of analysis of the events (EW component) recorded at Port Island vertical array by using NIOM method

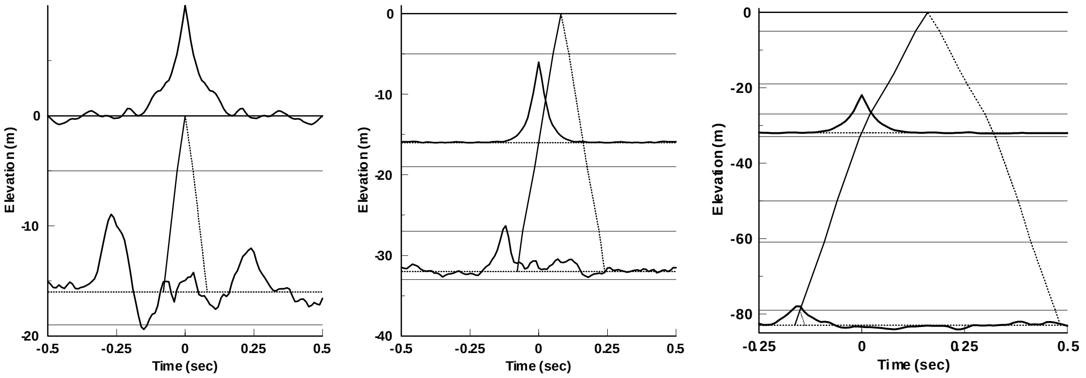


Figure 3 The results of analysis of Hyogo earthquake aftershock 1 (EW component) for the cases that input model is considered at different elevations

Feb. 2, 1995 earthquake

The results of analysis of Feb. 2, 1995 event (EW component) are illustrated in Figure 2. This figure shows that S-wave velocity is mostly recovered to the original condition. The effect of wave amplification between the depth of 16 m and ground surface is observed clearly. The ratio of reflected wave from the ground surface to incident wave at depth 16 m is larger in the model obtained for this earthquake than those of the mainshock and aftershocks. This may suggest that damping is decreased from the time of mainshock to the event of Feb. 2, 1995.

As Figure 2 shows, the input model of wave propagation is always considered at ground surface and the outputs are assumed at lower elevations. One may consider the input model at other locations than the ground surface. It may illustrate easier the velocity variation at different ground layers. For instance, Figure 3 shows the results of analysis when the input model is considered at different elevations for aftershock 1. This figure clearly shows that wave velocity is decreased mostly in the reclaimed layers between the depth of 16 m and ground surface. The velocity of S- wave is decreased to some extent between the depth of 16 m and 32 m but no change is observed below the depth of 32 m.

Vertical component ground motion models

Vertical component of the event of Dec. 6, 1974 is not recorded and the results of analysis of Hyogo earthquake and the later event of Feb. 2, 1995 are discussed in this section.

Hyogo earthquake

Simple models of wave propagation are made by using the NIOM method for vertical component ground motion of the Hyogo earthquake. The results of analysis of mainshock and aftershocks are shown in Figure 4. This figure compares the arrival times of P- wave with those obtained by downhole well shooting.

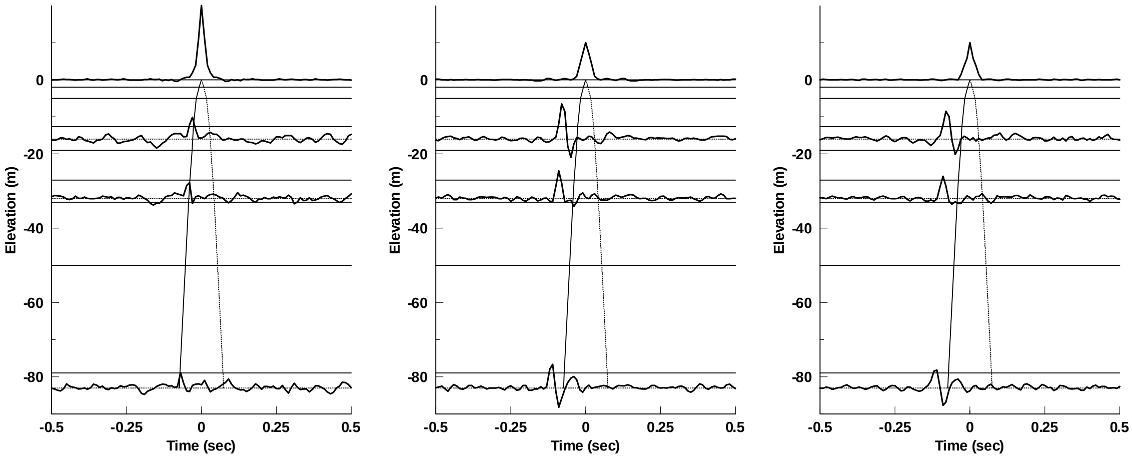
Unlike the horizontal component, the vertical component of mainshock ground motion does not show any change in velocity of P- wave and the results of analysis are in complete agreement with those of downhole well shooting. The reason why vertical component of the mainshock does not show any decrease in velocity may be found out by noting to the liquefaction effect. It may be concluded that liquefaction is mainly occurred during the S- portion of the mainshock. Therefore, the vertical component of mainshock in which P- wave is dominated is affected less by liquefaction. The same trend as the horizontal component is observed in variation of P- wave velocity during the aftershocks. It is decreased dramatically during the first two aftershocks but increased gradually later.

The effect of wave amplification is observed in the models during the vertical component of mainshock. The model of aftershock 1 shows that vertical component ground motion is amplified gradually to GL-16 m but it is not amplified any more in the liquefied layers. There is some evidence of deamplification of ground motion observed in the results during this aftershock. As time passes from aftershock 1 to aftershock 4, the effect of amplification of vertical ground motion becomes clear again in the results.

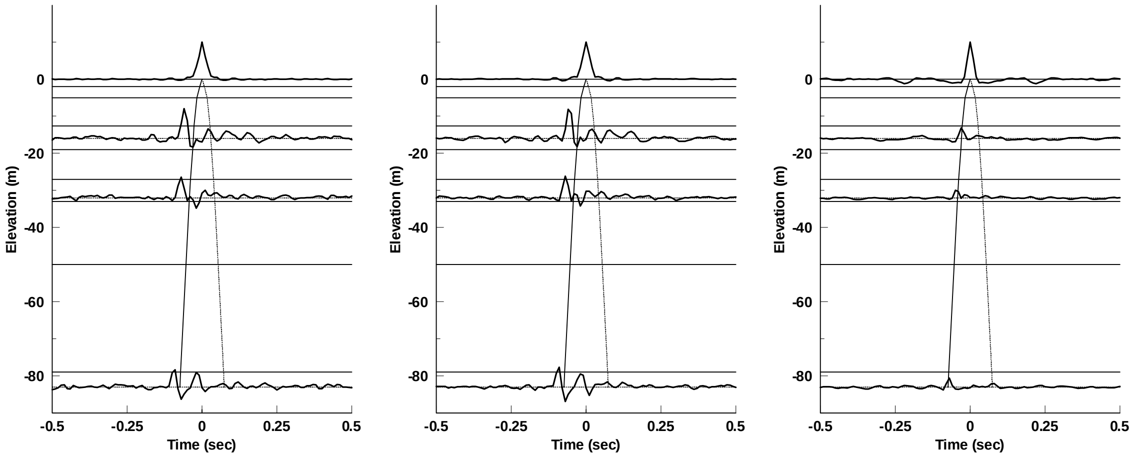
Feb. 2, 1995 earthquake

The results of analysis of the vertical component ground motion of this event are shown in Figure 4. This figure shows a complete recovery of P- wave velocity to its original value. The arrival time of wave at each observation point is in agreement with that of the well shooting. The amplification of wave from lower elevations to upper elevations is clearly observed in the results

Figure 5 shows the result of analysis of Hyogo earthquake aftershock 1 (UD component) when the input model is considered at different elevations. This figure also confirms that there is not any change of P- wave velocity in the layers below GL- 32m.



Mainshock **Aftershock 1** **Aftershock 2**



Aftershock 3 **Aftershock 4** **Event of Feb. 2, 1995**

Figure 4 The results of analysis of the events (UD component) recorded at Port Island vertical array by using NIOM method

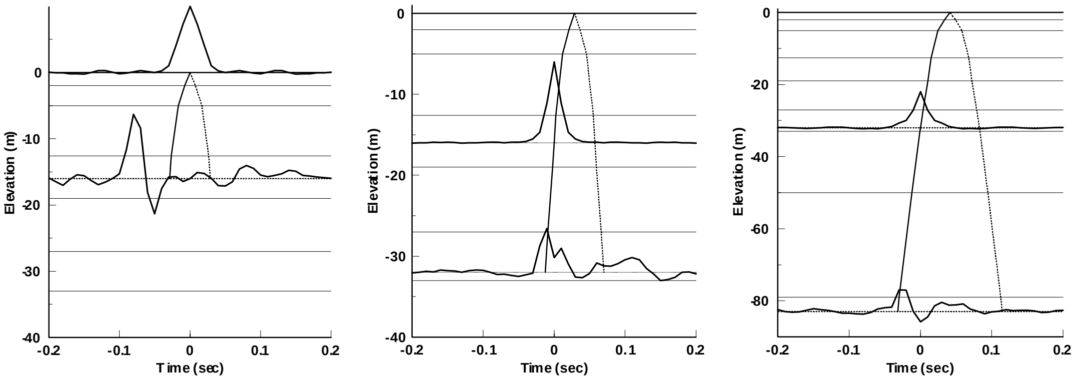


Figure 5 The results of analysis of Hyogo earthquake aftershock 1 (UD component) for the cases that input model is considered at different elevations

CONCLUSIONS

The method of Normalized Input-Output Minimization (NIOM) is used to model wave propagation at Port Island vertical array site in Japan. The properties of soil layers during liquefaction are studied by using the records of January 17, 1995, Hyogo earthquake and its aftershocks and the results are compared with those of other events that did not cause liquefaction.

Velocities of P- and S- waves are decreased dramatically during the Hyogo earthquake. The recovering trend of wave velocity is observed from the time of occurrence of mainshock to the event of February 2, 1995.

Liquefaction has also affected the other soil properties such as wave amplification and damping. The original behaviour of wave amplification illustrated in models of the December 6, 1974 earthquake is changed during the horizontal component of mainshock and aftershock 1. The horizontal component is not amplified in the liquefied portion but the amplification happens again afterwards and it approaches the original condition during the earthquake of February 2, 1995. The same trend is observed during the vertical component except that the change of amplification is evident during the aftershocks.

Comparison of the incident amplitudes of the models to reflected amplitudes from the ground surface gives some idea about variation of damping during the Hyogo earthquake. The ratios of mentioned amplitudes at depth of 16 m propose an increase of damping during the mainshock of Hyogo earthquake and the trend of recovering is observed afterwards.

ACKNOWLEDGEMENT

The authors express their gratitude to the Department of Urban Development, Kobe City, for providing the ground motion at Port Island vertical array.

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