A STUDY ON THE RECOVERY PROCESS OF THE SHEAR WAVE VELOCITY AT SUBSURFACE INVESTIGATED FROM THE STRONG MOTION RECORDS OF THE 2003 TOKACHI-OKI EARTHQUAKE

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ABSTRACT :

The nonlinear soil response is examined by using KiK-net vertical array records by NIED from a large (the 2003 Tokachi-oki Earthquake; M8) and small (M~6) events. The TKCH07 station at Toyokoro in Tokachi-district, Hokkaido, is chosen to evaluate the nonlinear soil response. This site has very soft ground different from another KiK-net stations; S-wave velocity (Vs) is less than 200m/sec down to a depth of 30m. This station was observed peak ground acceleration (PGA) of 403.9cm/sec^2 (EW-component) during the Tokachi-oki Earthquake.
We construct the soil model (Vs and Qs (quality factor for S-wave) structures) at TKCH07 based on the S-wave spectral ratios from 22 small earthquakes by using the genetic algorithms (GA) inversion method. Next we estimate the recovery process on the shear wave velocity at subsurface using the 15 after shocks from September 26, 2003 to January 18, 2005. The JMA magnitudes of these aftershocks were 4.5 to 7.1 (largest aftershock).
We evaluate the shear wave velocity from GA inversion and from the convergence soil model in frequency dependent equivalent linear response analysis. The shear wave velocity was reduced 50% at main shock (M8.0) and recovered after the 20 minutes furthermore reduced again at largest aftershock (M7.1) after 78 minutes from main shock. Finally we discuss from other investigations whether this recovery process is characteristics of TKCH07 station or not.

KEYWORDS: KiK-net Vertical Array, Non-linearity of the Ground, Inversion Analysis of the Genetic Algorithm, Seismic Response Analysis Shear wave velocity Reduction

1. INTRODUCTION

The seismic response at surface depends on the source effect, pass effect and site effect. In this study, the non linear effects in the site effect are examined by means of the vertical array seismic records. Many examples of nonlinearity have been shown using weak and strong motions observed at the surface but few examples are shown using vertical array records. The vertical array records give us more direct and reliable site responses than the surface records because site responses can be evaluated directly by calculating spectral ratio between surface and borehole motions.

Satoh et al. (2001) evaluated soil nonlinearity by inversion for S-wave velocities and frequency-dependent damping factors using 1995 Hyogo-ken Nanbu earthquake array records. Iai et al. (1995) calculated the surface wave by effective stress analysis using 1993 Kushiro-oki earthquake array records and showed the accelerogram changing spike form by cyclic mobility.

The KiK-net is composed of vertical pair of strong motion seismographs across the all of Japan distributed by the National Research Institute for Earth Science and Disaster Prevention (NIED).

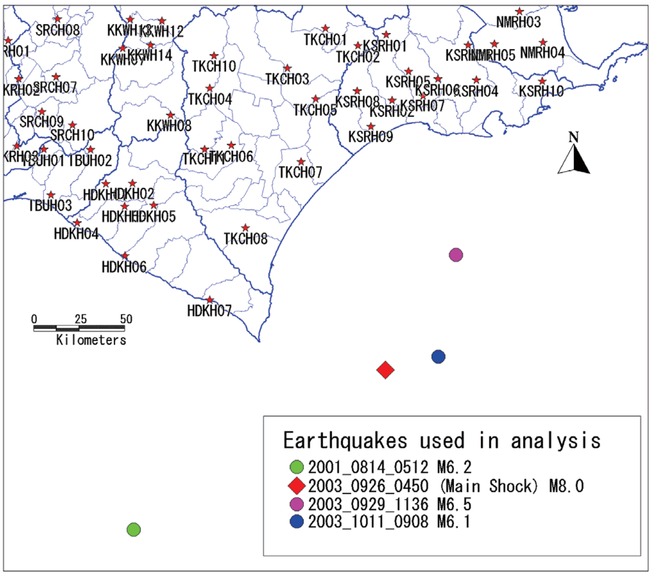

Figure 1 KiK-net stations and epicenter of earthquakes.

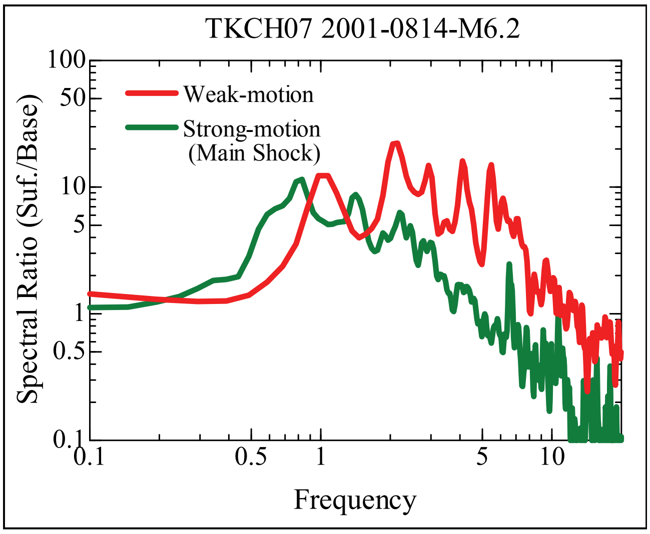

Figure 2(a) Spectral ratio of suf./base SM & WM(1).

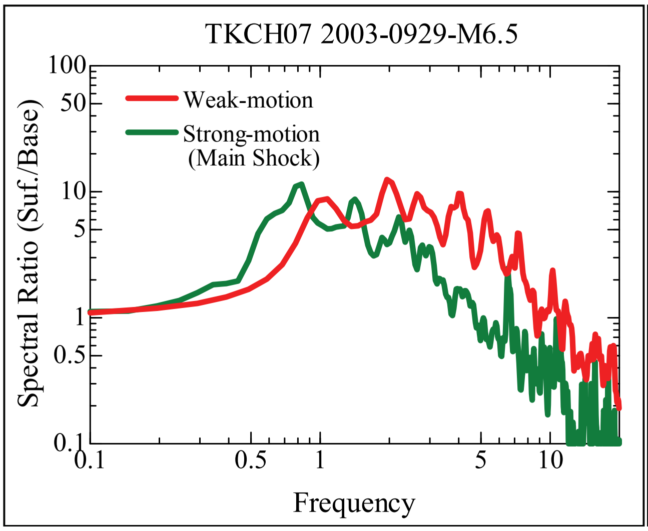

Figure 2(b) Spectral ratio of suf./base SM & WM(2).

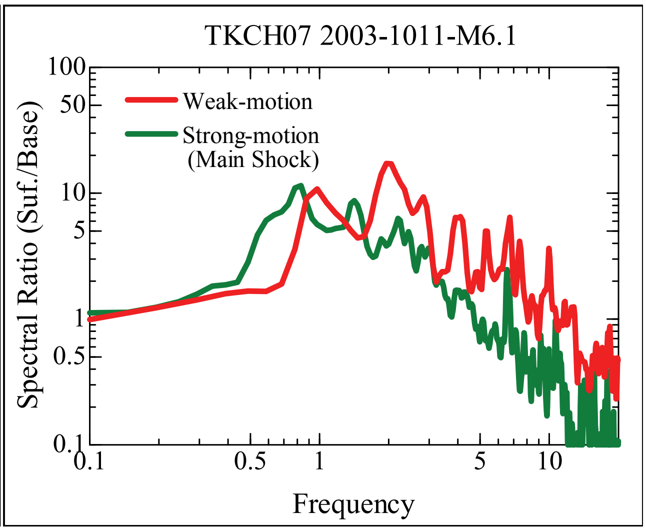

Figure 2(c) Spectral ratio of suf./base SM & WM(3).

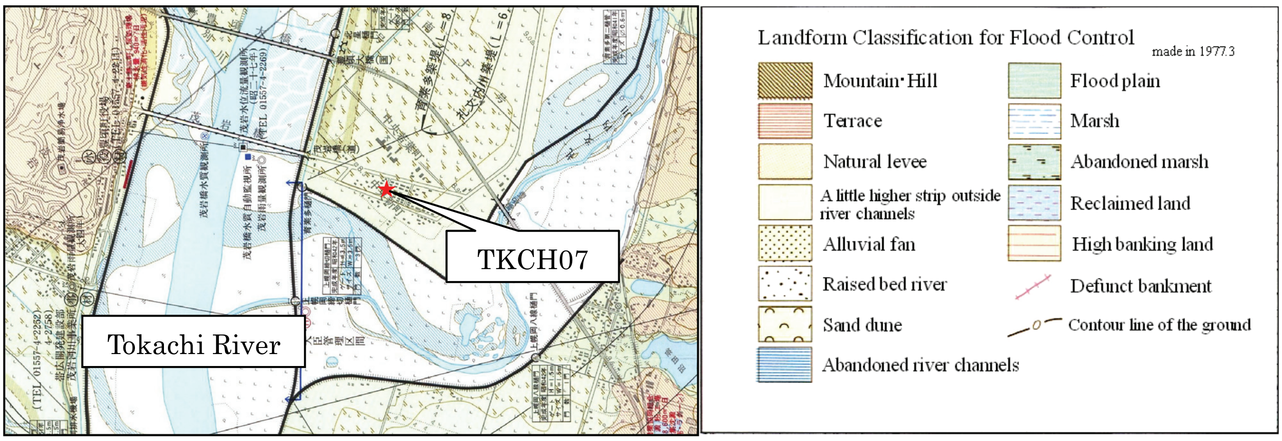

Figure 3 The landform classification for flood control at TKCH07 (Toyokoro) station.

These records are very useful to analyze the non linear effects but not so use because of the almost satiations located at the mountainous regions. The 2003 Tokachi-oki Earthquake occurred at Sept. 26 with JMA magnitude is M_J=8.0 and focal depth is 42km. During the 2003 Tokachi-oki Earthquake, the data were recorded at the 106 stations within the 112 stations in the Hokkaido district.

Figure 1 shows the epicenter map of the main shock (M_J=8.0) and other weak motions earthquake (M_J =6.1-6.2) because of the showing the effect of nonlinearity of the subsurface ground. The effect of the nonlinearity of subsurface ground were verified that the reduction of the fourier spectrum suf./base ratio at high frequency (about more than 10Hz) and the predominant frequency of the fourier spectrum ratio moving to the lower frequency.

The fourier spectrum suf./base ratios are calculated by the main shock and weak motions at all KiK-net stations of the Hokkaido district. Figures 2(a) to (c) show the ratio of the KiK-net TKCH07 (Toyokoro) station. The TKCH07 (Toyokoro) station is located at Tokachi district in the Hokkaido (see Figure 1). The green lines of Figures 2(a) to (c) show the ratios of the same main shock but the red lines are different weak motions. The Figures 2(a) to (c) are the almost same shape of the characteristics of the nonlinear effects but different weak motions. This analysis estimates the records of the KiK-net TKCH07 (toyokoro) station by means of the clearly appearance of the effect of the nonlinearity. Figure 3 shows the landform classification of the nearby TKCH07 (toyokoro) station. As shown in Figure 4, this contains the soil column of the TKCH07 (toyokoro) station. The S-wave velocity (Vs) at the TKCH07 station were distributed less than Vs=200m/sec that thickness of the layer was about 30m.

2. INVERSION ANALYSIS

The inversion analysis is used in this study because of the quantitative estimation of the nonlinear effect of soil response. Many researchers developed the inversion analysis methods. We apply genetic algorithm (GA) inversion because the GA inversion is highly applicable in the complex layered S-wave velocity inversion.

We first inverse S-wave velocity and thickness of each layers fixing the Q-value and then we inverse Q-value. Q-value inversion is analyzed by the Eqn. (2.1) with fixing n=0.5, 0.6, 0.7 to avoid trade-off between Q_0 and n. Eqn. (2.1) shows Q_0: initial Q value, f: frequency of spectral ratio.

$$Q = Q_0 \times f^n \tag{2.1}$$

Figure 5 shows the epicentral map using the data set of inversion analysis. We chose 22 earthquakes that magnitudes of JMA are 4.1-6.4, focal depths are greater than 50km and epcentral distances are within the two times of the focal depths because of the satisfying the vertical input S-wave. Figure 6 shows the observed S-wave spectral ratios (suf./base) of the 22 eq. and the geometric mean (G.M.) that is the target spectral ratio of the GA inversion analysis.

In the GA inversion analysis, the parameter (=misfit) of the Eqn. (2.2) is searched to minimize the residual between observed and theoretical spectral ratios.

$$misfit = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{\log R_{obs}(f_i) - \log R_{cal}(f_i)}{f_i^{0.5}}\right] + T_{diff} \tag{2.2}$$

As shown Eqn. (2.2), T_{diff} is the penalty value without the case of the averaged the S-wave travel time of the surface to the borehole. The R_{obs} and R_{cal} mean the observed and theoretical spectral ratios respectively. The N equals data number and f is frequency of the spectral ratio. The Q value GA inversion is used Eqn. (2.3) with the misfit value.

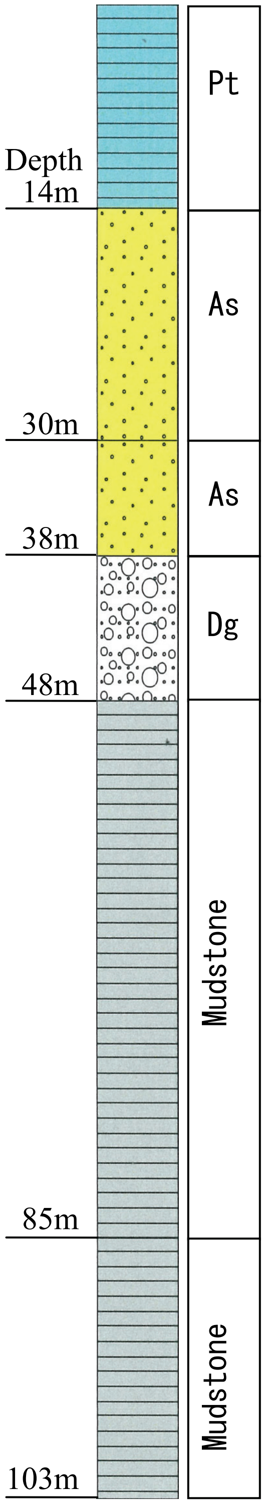

Figure 4 The soil column of the TKCH07 (Toyokoro) Station.

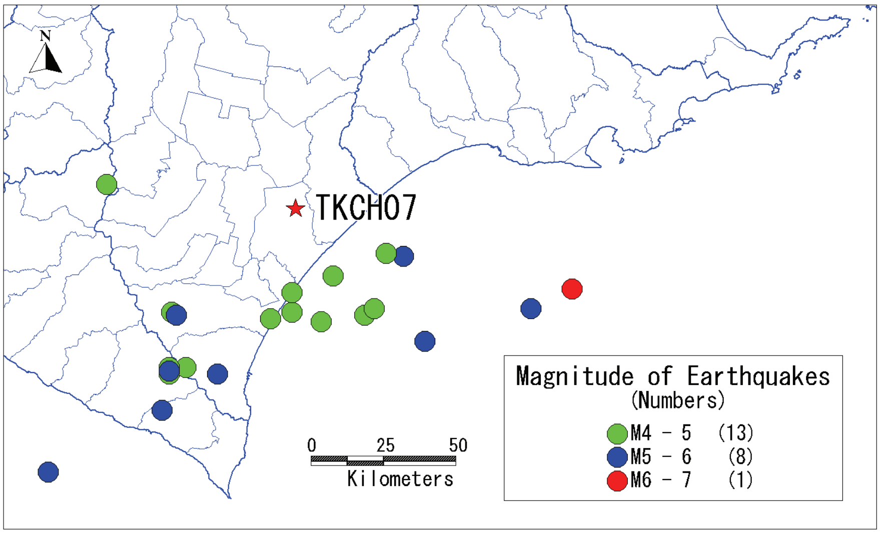

Figure 5 The epicenter of the 22 eq. at TKCH07 station using GA inversion analysis.

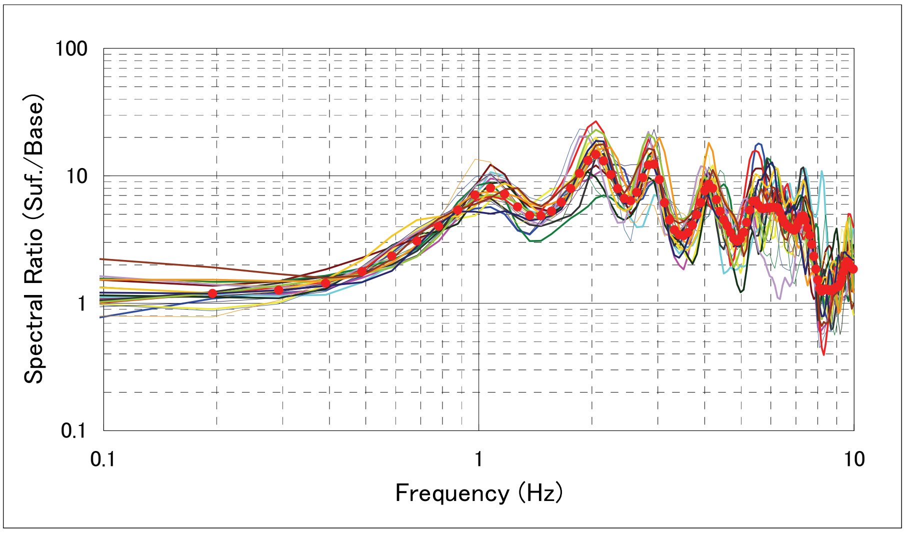

Figure 6 Observed S-wave spectral ratios (suf./base) of the 22 eq. and the G.M. mean.

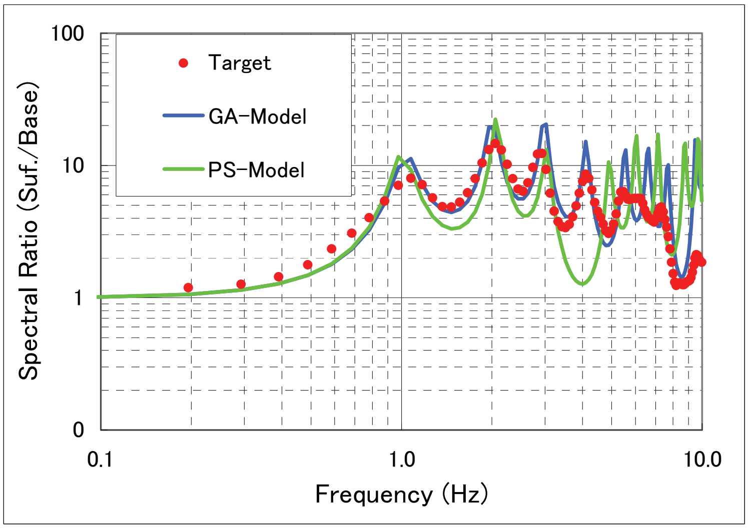

Figure 7 The calculated spectral ratio using GA inversion model and original PS-logging model.

$$misfit = \frac{1}{N}\sum_{i=1}^{N}\left|\log R_{obs}(f_i) - \log R_{cal}(f_i)\right| + W\sum_{K=2}^{nl}\left|Q_{0k} - Q_{0k-1}\right| \quad (2.3)$$

The W in the Eqn. (2.3) means weight function of the Q_0 value. Figure 7 shows the calculated spectral ratio using GA inversion model and original PS-logging model. The GA inversion model is more fitted with the target spectral ratio until 4-th predominant frequency. Nevertheless PS-logging model is different from the target spectral ratio in the Figure 7.

Figure 8 shows the result of the GA inversion with velocity and the thickness of layers. As shown in Table 1, the S-wave velocity at the nearest surface is Vs=51m/sec. This value is very low between the usual S-wave velocity values. The Swedish weight sounding and micro tremors array observation were carried out by Takai et al. (2005). The very soft humus soil is distributed and S-wave velocity at the nearest surface is Vs=60m/sec by means of the array micro tremor analysis.

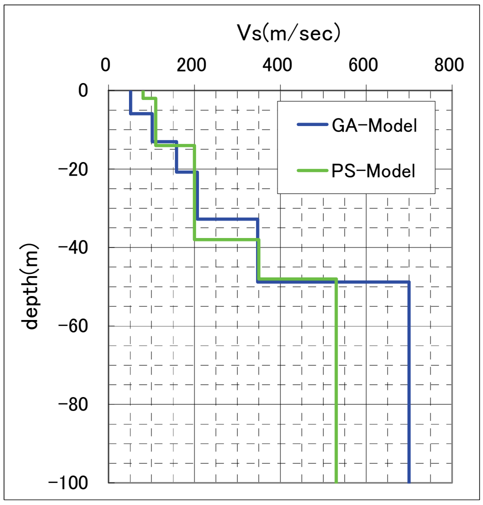

Figure 8 S-wave velocity layer model of the inversion analysis and PS-logging.

Table 1 The results of the GA inversion analysis.

Layer No.	GA inversion velocity layers [PS logging velocity layers]		GA inversion Q value								
	S-wave velocity (m/sec)	Thickness (m)	Q_0	h_0(%)	n	Q_0	h_0(%)	n	Q_0	h_0(%)	n
1 (Pt1)	51[80]	5.9[2.0]	4.0	12.5	0.7	4.9	10.2	0.6	6.7	7.5	0.5
2 (Pt2)	102[110]	7.1[2.0]	7.2	6.9		5.7	8.8		7.2	6.9	
3 (As1)	158[110]	7.8[10.0]	7.2	6.9		10.3	4.9		13.4	3.7	
4 (As2)	207[200]	12[24.0]	26.1	1.9		60.7	0.8		32.4	1.5	
5	347[350]	16[10.0]	140.5	0.4		147.6	0.3		53.0	0.9	
6	700[530]	51.2[52.0]	188.1	0.3		183.3	0.3		88.1	0.6	
	sum of layers thickness (m)	100.0	misfit=0.01313			misfit=0.01271			misfit=0.01220		

3. S-WAVE VELOCITY RECOVERY PROCESS ANALYSIS

The S-wave velocity recovery process after 2003 Tokachi-oki Earthquake main shock is evaluated by the GA inversion S-wave velocity model (Table 1) using aftershocks records. Figure 9 shows the epicenters of 16 after shocks using recovery process analysis.

The linear response analysis are simulated the maximum acceleration (PGA) by the GA inversion S-wave velocity model (Table 1) using borehole acceleration wave of each aftershocks. Figure 10 shows the observed PGA and simulated PGA. In weak motions of after shocks, simulated PGA correspond observed PGA linearly but main shock (MS) and largest aftershock (LAS) are found smaller observed PGA than simulated PGA. This result shows the effect of the nonlinearity of the subsurface soil.

We estimate the S-wave velocity model using the GA inversion analysis by the observed spectral ratios of the Eq.02, Eq.03, Eq.04 (LAS), Eq.14 and Eq.15 at Figure 9. As shown Figure 11(a) to 11(e), the GA inversion analysis result is good correspondence between the observed target spectral ratios and the simulated spectral ratios by the S-wave velocity model.

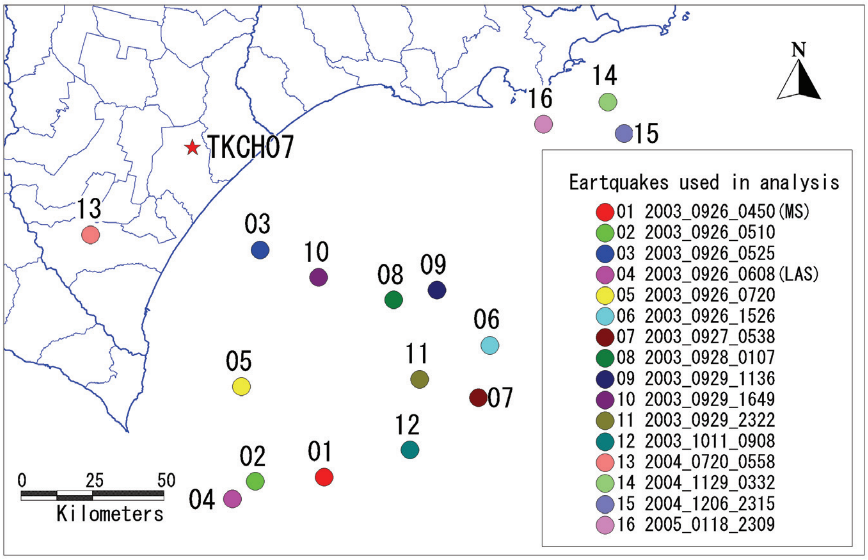

Figure 9 Data sets of earthquakes using S-wave velocity recovery process analysis.

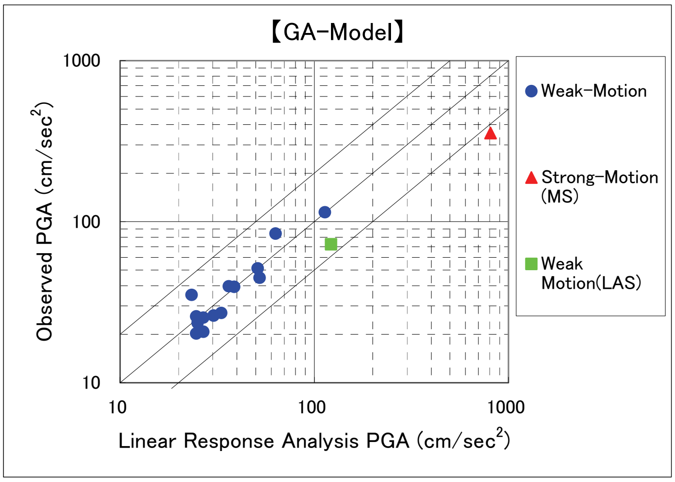

Figure 10 The results of the linear response analysis using GA inversion S-wave velocity model.

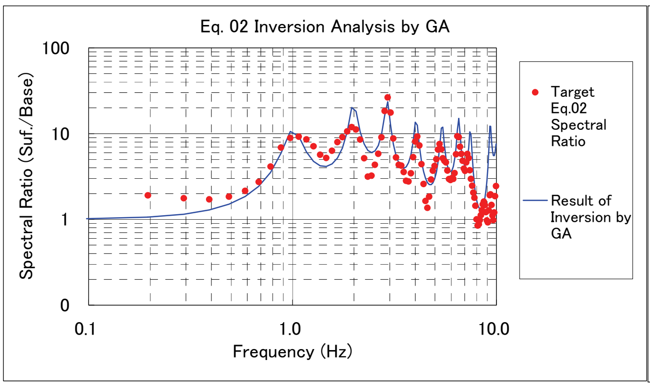

Figure 11(a) The theoretical spectral ratio using the GA inversion S-wave velocity model and observed Eq.02 target spectral ratio.

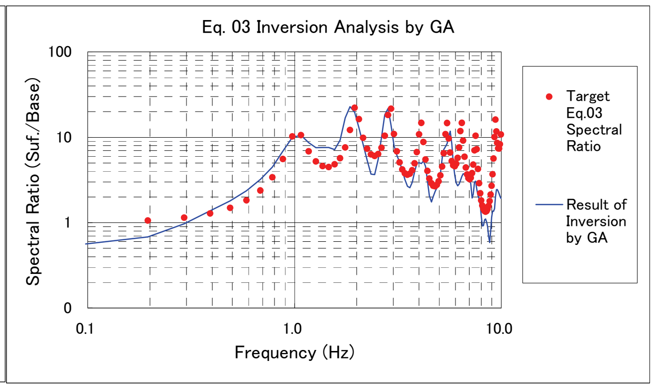

Figure 11(b) The theoretical spectral ratio using the GA inversion S-wave velocity model and observed Eq.03 target spectral ratio.

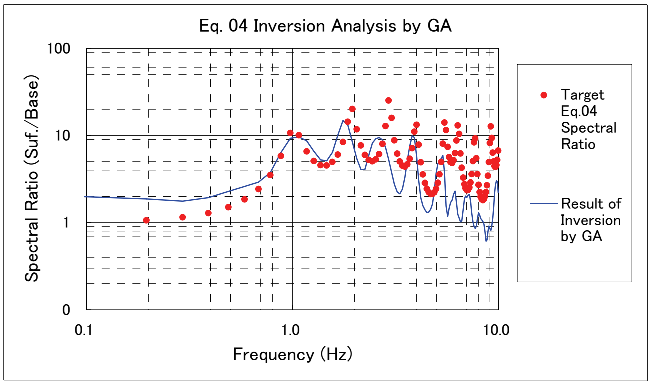

Figure 11(c) The theoretical spectral ratio using the GA inversion S-wave velocity model and observed Eq.04 target spectral ratio.

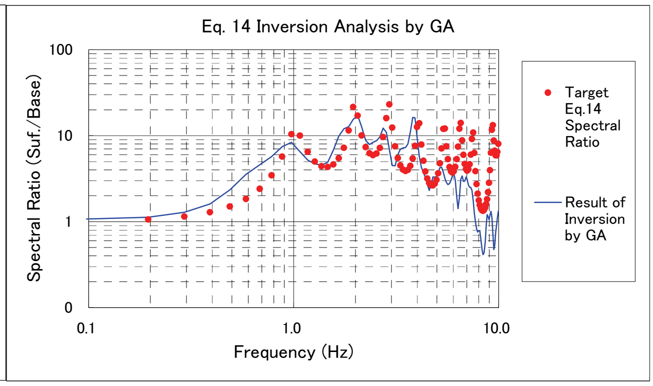

Figure 11(d) The theoretical spectral ratio using the GA inversion S-wave velocity model and observed Eq.14 target spectral ratio.

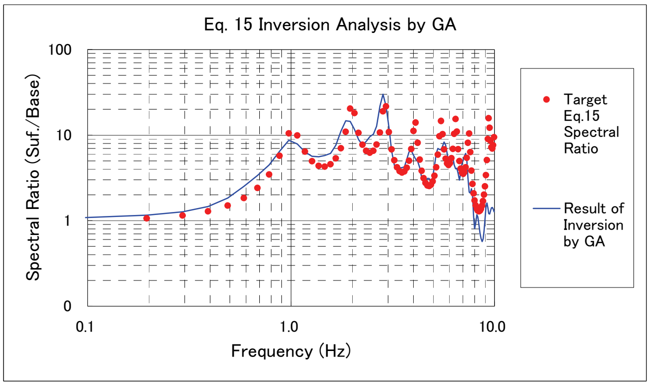

Figure 11(e) The theoretical spectral ratio using the GA inversion S-wave velocity model and observed Eq.15 target spectral ratio.

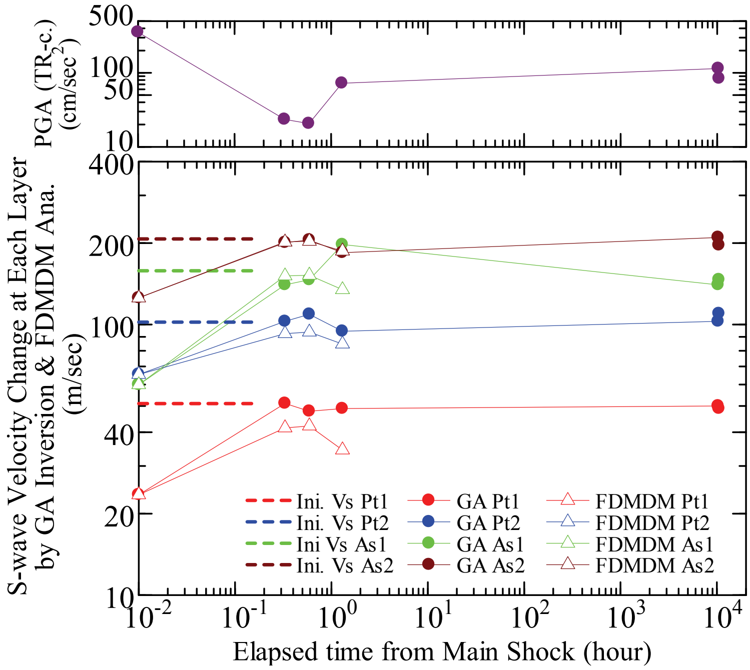

Figure 12 S-wave velocity recovery process calculated from GA inversion and Frequency Dependent Moduli and Damping Method (FDMDM).

Figure 12 shows the initial S-wave velocity (Table 1) of the 4 layers from the nearest surface and the final S-wave velocity of each layer at the main shock (plotted at the 10^{-2} hour of the horizontal axis on Figure 12) from the equivalent linear response analysis using frequency dependent moduli and damping method (FDMDM) from Yamamoto & Sasatani (2007). Figure 12 also shows the S-wave velocity of each layer simulated GA inversion analysis using the spectral ratios of the Eq.02, Eq.03, Eq.04 (LAS), Eq.14 and Eq.15 at Figure 9.

The S-wave velocity of each layer are reduced by 50% of the initial S-wave velocity at 2003 Tokachi-oki Earthquake main shock and then are recovered initial values at after shock Eq.02 that the elapsed time from main shock is 20 minutes (0.33 hours). The S-wave velocity of each layer are reduced again at the largest aftershock (LAS) that the elapsed time from main shock is 78 minutes (1.3 hours) and gradually recovering the S-wave velocity of each layer.

4. CONCLUSIONS

In order to simulate and predict strong motions theoretically, nonlinear effect should be quantitatively estimated. We examined the S-wave velocity model inverted from the weak motions before and after the 2003 Tokachi-oki Earthquake at the TKCH07 (Toyokoro) station. Following this analysis, we estimated the S-wave recovering process using 16 after shocks of the 2003 Tokachi-oki Earthquake.

The S-wave velocity of each layer are reduced by 50% of the initial S-wave velocity at main shock and then are recovered initial values at after shock Eq.02 that the elapsed time from main shock is 20 minutes (0.33 hours). And then the S-wave velocity of each layer are reduced again at the largest aftershock (LAS) that the elapsed time from main shock is 78 minutes (1.3 hours) and gradually recovering the S-wave velocity of each layer. These results of analysis differ from Arai (2006) that S-wave velocity is reduced 20% at main shock and gradually recovered to the 6×10^3-9×10^3 hours using K-NET and JMA stations at Ojiya during 2004 Mid Niigata Prefecture Earthquake and that after shocks. This difference suggests that the subsurface soil type is very important that the humus soil is distributed at the TKCH07 (Toyokoro) but loose sandy soil is distributed at Ojiya.

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