Seismic properties of surface layers in Shimizu by microtremor observations

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SUMMARY
Microtremor observations were conducted to investigate seismic properties of shallow ground in the urban area of Shimizu, Shizuoka, Japan, which locates above northeast part of the source fault of the anticipated Tokai mega earthquake. Two kinds of observation were carried out; one is to measure three directional motions at one location, and the other is array observation of vertical motions at three apexes of an equilateral triangle with the sensor distance of 3, 10 or 20 meters. Spatial distributions of the natural period obtained from H/V spectrum and Rayleigh wave velocity at the wave length of 40 meters based on the spatial autocorrelation (SPAC) analyses, conformed to the distribution of the characteristic period of ground calculated from SPT N-value profiles. Stratigraphic profiles of shear wave velocity were then estimated by using genetic algorithm assuming four layers ground system, and were consistent with N-value profiles at nearby locations.

Keywords: microtremor, H/V spectrum, dispersion relationship of Rayleigh waves, surface layers

1. INTRODUCTION

The urban area of Shimizu, Shizuoka, Japan is located above northeast part of the source fault of the anticipated Tokai earthquake with the magnitude larger than 8, therefore strong ground shaking is predicted to occur there during the mega seismic event (Shizuoka Prefecture Department of Emergency Management, 2003). Distribution of soil types, which mainly constitute the ground shallower than 5 meters from the surface, is shown in Figure 1 (Earthquake Preparedness Division of Shizuoka Prefectural Government, 1993). The populated area is surrounded by mountains and hills on north, west and south sides, and the Tomoe River gently runs from the southwest, bending through the plain area, into the port of Shimizu. There exist the Akihasan and Irieoka Rises on the both side of the river several kiro-meters from the mouth, as shown by red broken lines in Figure 1. These topographic features permitted a large calm water basin to emerge in the upstream side of the Rises during the period of high water levels thousands years ago, and then enabled formation of the Tomoe-gawa lowland by sedimentation of soft soil deposits (Oosaki et al., 2001). Sugiyama and Shimokawa (1990) characterized the surficial Holocene ground in the lowland area as soft muddy sediments with the thickness up to 40 meters underlain by sandy or gravelly deposits. Arai and Nozu (2006) conducted microtremor observations in Shimizu to clarify the deep structure of the ground, and estimated depths of bedrock surface by inverse analyses of observed H/V spectrum.

This paper describes the results of microtremor observations conducted in order to investigate the seismic properties of shallow ground in Shimizu.

2. OBSERVATION PROGRAM

Microtremors were observed at 32 locations in Shimizu as shown in Figure 1, during midnight from 11pm to 5am in order to avoid excessive influence of traffic vibrations. Two kinds of observations

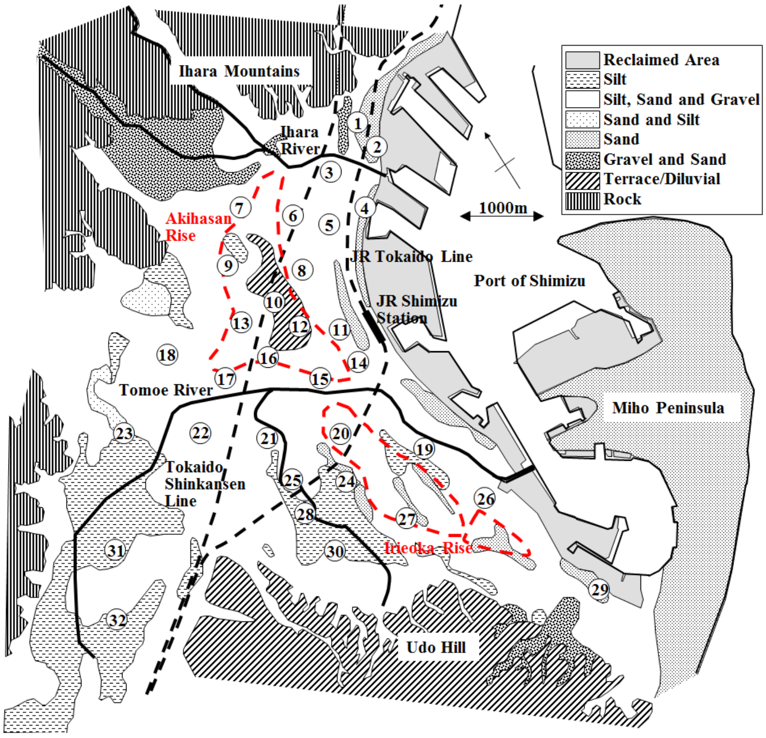

Figure 1. Geology of surface ground and microtremor observation points

were carried out in this study. One is to measure three directional motions at one point (two horizontal directions orthogonal with each other and one vertical direction) to calculate horizontal to vertical spectral amplitude ratios (H/V spectrum). The other is an array observation of vertical motions at three apexes of an equilateral triangle with the side length (sensor distance) of 3, 10 or 20 meters. Dispersion relationships of Rayleigh waves are computed by the spatial autocorrelation (SPAC) method with the average coherence from three pairs of motions observed at three apexes.

The seismometers used in this research were moving-coil velocity type with the natural period of 1 second (Katsujima PMK-110H/V). Electric signals from seismometers were amplified and processed to low-pass filters with the cut-off frequency of 30 Hz, and then sent to a personal computer via A/D converters (Keithley KPCMCIA-16AI-C). The sampling frequency was 200 Hz. We measured continuous microtremors for 180 seconds, and repeated two to six times for each kind of observation depending on the traffic noise. Five to eight sets of continuous record with the duration of 20.48 seconds were extracted to minimize influences of transient traffic vibrations, and were subjected to spectral analyses.

3. RESULTS AND DISCUSSION

3.1. Spatial Distributions of Natural Period and Characteristic Rayleigh Wave Velocity

Natural periods of ground were estimated from H/V spectra after the method proposed by Ohmachi et al. (1994) where the peak and trough periods were utilized for the estimation with categorization of H/V spectrum into four types. The obtained natural periods, T_0, are indicated by colours of circles plotted at the observation points in Figure 2. While background contour map in the figure denotes spatial variation of the characteristic period of the ground, T_G, computed from profiles of soil type and SPT N-value by equation (3.1) (Japan Road Association, 1990).

$$T_G = \sum \frac{4H_i}{V_{Si}} \tag{3.1}$$

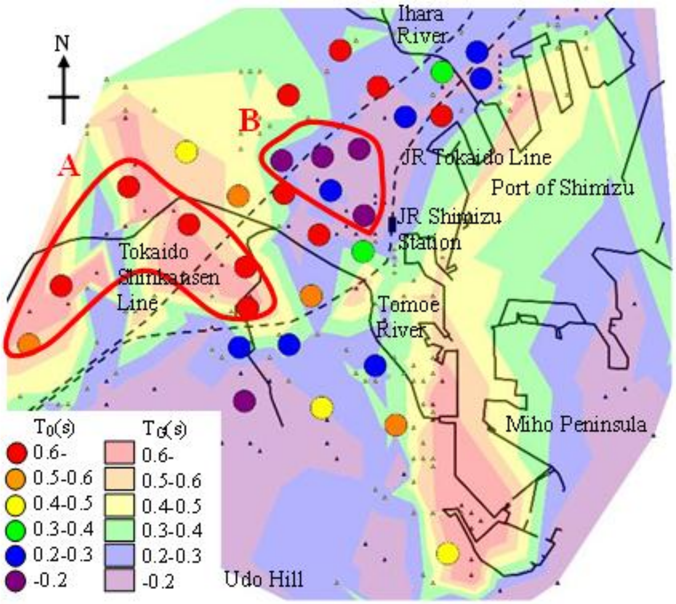

Figure 2. Spatial distributions of T_0 (circles) and T_G (background).

In the above equation, H_i and V_{si} respectively denote the thickness and shear wave velocity of i-th layer. The shear wave velocity is calculated from the average N-value of the layer by equation (3.2).

$$V_{Si} = \begin{cases} 80N^{1/3} & \text{(for sandy soils)} \\ 100N^{1/3} & \text{(for clayey soils)} \end{cases} \qquad (3.2)$$

Soil profiles at 203 locations were selected from the available ground boring data (Shizuoka Prefecture, 1997), with the criteria that the foundation layers (N-values larger than 50 for sandy soils, and larger than 25 for clayey soils) can be observed in the profiles.

It can be seen from spatial variation of the characteristic period that soft ground is widely formed around the main course of the Tomoe River upper than juncture and large bending. The natural periods estimated from microtremor observations in this area (surrounded by red broken line A in Figure 2) are longer than 0.5 seconds. In contrast, the area with short characteristic periods lies around the Akihasan Rise on the northwest of the JR Shimizu Station where the surface ground is composed from stiff diluvial deposits. Accordingly, the natural periods in this area (red broken line B) is shorter than 0.3 seconds. Distribution of natural period from H/V spectrum of microtremors thus conformed well to the variation of the characteristic period based on soil profile of the ground.

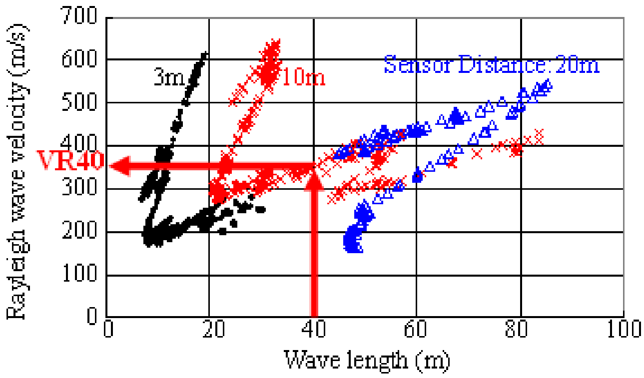

Figure 3. Dispersion relationship of Rayleigh wave velocity of microtremor for station 10

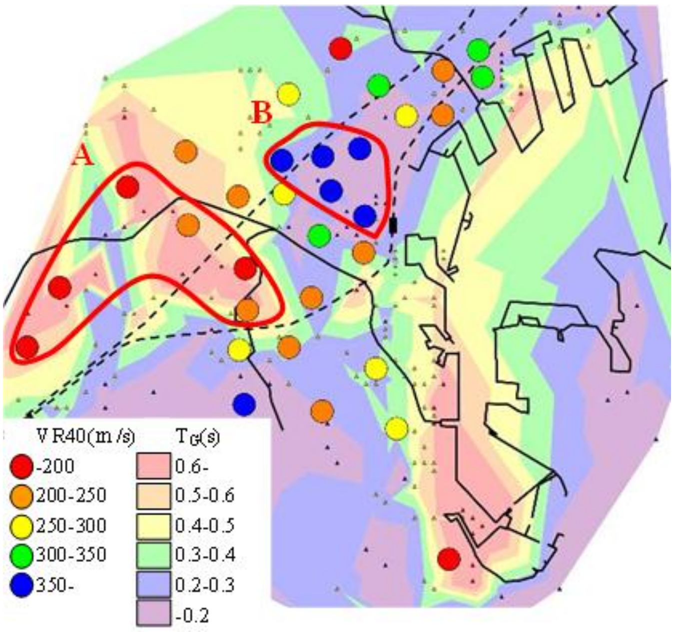

Figure 4. Spatial distributions of VR40 (circles) and T_G (background).

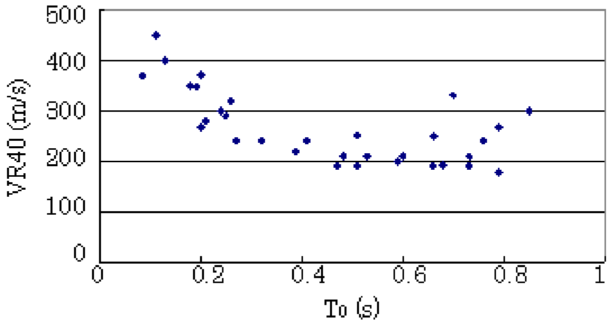

Figure 5. Relationship between T_0 and VR40.

The average shear wave velocity from the ground surface to the depth of 30 meters, VS30, have been found to show good correlation with the amplification factor of peak ground velocity within the surface ground in past earthquakes (e.g. Midorikawa et al., 1994). Konno and Kataoka (1999) observed that Rayleigh wave velocity of microtremors with the wave length of 40 meters, VR40, agree well with VS30. Dispersion relationships of Rayleigh waves obtained at the station 10 (for the location, see Figure 1) by SPAC analyses of the array observation results, are shown in Figure 3. Black solid circles, red crosses and blue open triangles denote the wave velocities from the data with the sensor distances of 3, 10 and 20 meters respectively. VR40 was obtained as indicated by red arrows in the figure.

Spatial distribution of VR40 is shown in Figure 4, in which the variation of the characteristic period, T_G, is drawn to contour map on the background. The Rayleigh wave velocities, VR40, are smaller than 250 m/s in the soft ground area around the Tomoe River previously mentioned with Figure 2. In contrast, they are larger than 350 m/s in the stiff ground area at the Akihasan Rise. Spatial variation of VR40 is thus consistent with that of T_G. One may observe that VR40 is correlated well with the natural period from H/V spectrum, T0, in Figure 5.

3.2. Estimation of Stratigraphic Profiles of Shear Wave Velocity by Using Genetic Algorithm

Shear wave velocity profiles have been inversely estimated to investigate the seismic properties of the ground, by matching computed and observed H/V spectra and/or dispersion relationships of Rayleigh waves associated with microtremor observations (e.g. Arai and Tokimatsu, 2005). Genetic algorithms have been successfully adopted as the optimization method for the inversion analyses (Yamanaka and Ishida, 1996), and are used here to estimate the stratigraphic profiles of shear wave velocity.

The fitness function employed in this study is given by equation (3.3)

$$F = \frac{w_s}{\left\{\frac{T_{0m} - T_{0h}}{T_{0m}}\right\}^2} + \frac{w_d}{\frac{1}{N_d}\sum_{i=1}^{N_d}\left\{\frac{VR_m(T_i) - VR_h(T_i)}{VR_m(T_i)}\right\}^2} \tag{3.3}$$

where T_{0m} denotes the natural period of the measured H/V spectrum. $VR_m(T_i)$ is the Rayleigh wave velocity at period T_i obtained from the regression analysis, in which the observed data were divided into several segments of period, and then regression lines were computed for all segments so that they were continuously jointed at the segment ends. T_{0h} and $VR_h(T_i)$ are the period at peak horizontal to vertical amplitude ratio and Rayleigh wave velocity, both of which were computed by means of the Haskell method (Haskell, 1953). The w_s and w_d are weights for the natural period and the dispersion relationship respectively, and were set as 0.3 and 0.7 in this study.

Surficial ground was modelled by three layers system underlain by the stiff basement. The soil density and P-wave velocity were assumed as 2000kg/m^3 and 1500m/s respectively for all layers. Resolutions of shear wave velocity were 10 m/s for the upper two layers and 20 m/s for the third and the basement layers. Resolutions of layer thickness were 0.5 meters for the upper two layers and 1 meter for the third layer. Strings were binary coded five bit long. Crossover could take place at random points on chromosome with the probability of 0.7, whereas the probability of mutation was 0.03. Fifty individuals were initially produced and processed for 100 generations. We repeated the calculations for 20 times per site

Results of the inversion analysis are shown in Figure 6 for station 21, which is located on the soft ground around the Tomoe River. The observed H/V spectrum is shown by a solid black line in Figure 6(a), while red (solid, broken and chain-dotted) lines indicate computed H/V spectra associated with soil profiles giving highest three fitness values among 20 trials. Black lines in Figure 6(b) denote dispersion relationships of Rayleigh waves deduced from array measurements with the sensor distances of 3, 10 and 20 meters. The green line was obtained by regression of measured dispersion curves, while red lines show dispersion relationships computed for the optimum three cases. It can be

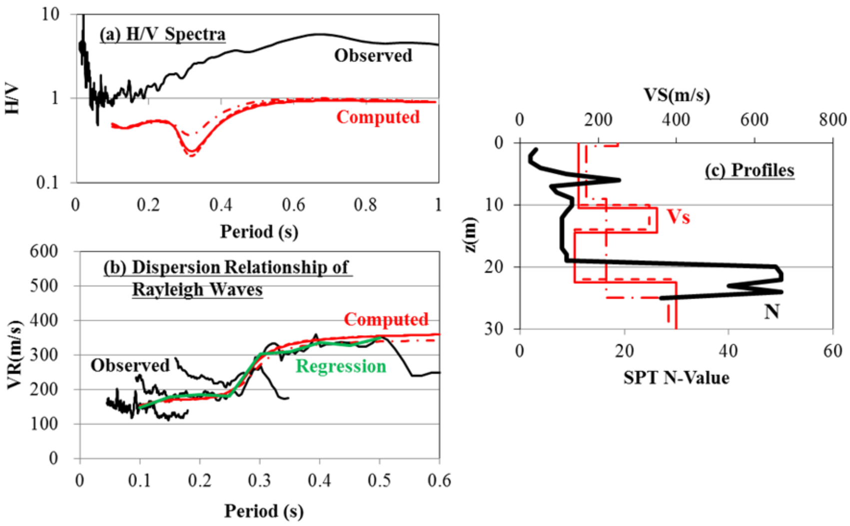

Figure 6. Observation and analysis results for station 21 (soft ground)

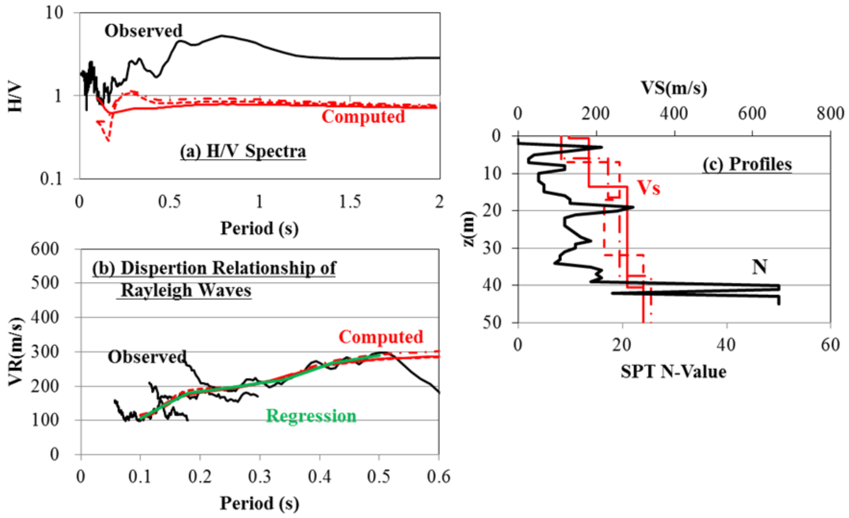

Figure 7. Observation and analysis results for station 31 (soft ground)

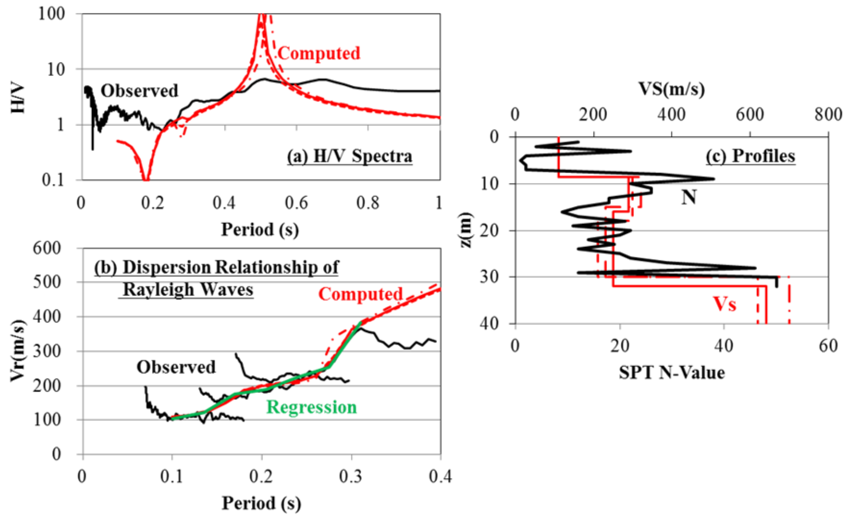

Figure 8. Observation and analysis results for station 32 (soft ground)

seen from Figure 6(c) that the shear wave velocities, V_S, increase suddenly with depth at around z=22 to 25 meters. This observation is well consistent with the variation of SPT N-value at the depth of 20 meters. Shear wave velocity at the ground surface is about 170 m/s at this location. The observation and analysis results for stations 31 and 32 are presented in Figures 7 and 8. These stations locate in the soft ground area on the upper side of the main course of Tomoe River compared to station 21. One may observe the gradual increase of shear wave velocity with depth at Station 31 in Figure 7(c), in accordance with the steady development of N-value with depth up to 40 meters. The V_S profiles for station 32 are depicted in Figure 8(c). There can be found abrupt changes in shear wave velocities at two depths (9 and 30 meters), which conform well to the N-value profile. The shear wave velocity at the ground surface ranges between 110 to 130 m/s at these two locations.

Observation and analysis results for stations 24, 28 and 30 are shown in Figures 9 to 11. One may observe that the depths to the stiff foundation layers estimated from microtremor observations, agree favourably with those detected in SPT N-value profiles. Station 30 is located near the Udo Hill, and the surface layer is thinner than stations 24 and 28 as shown in Figures 9(c) to 11(c). The shear wave velocities at the ground surfaces varied from 90 to 170 m/s, which are comparable to those observed in soft ground area mentioned earlier.

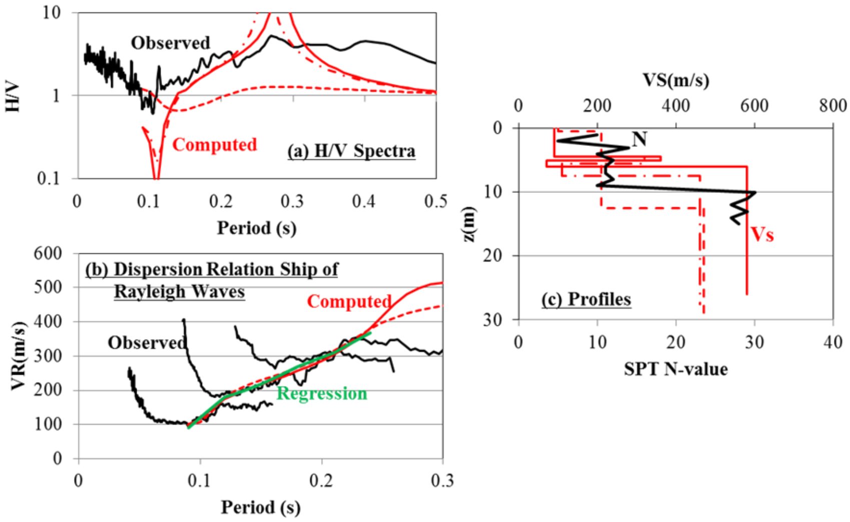

Figure 9. Observation and analysis results for station 24

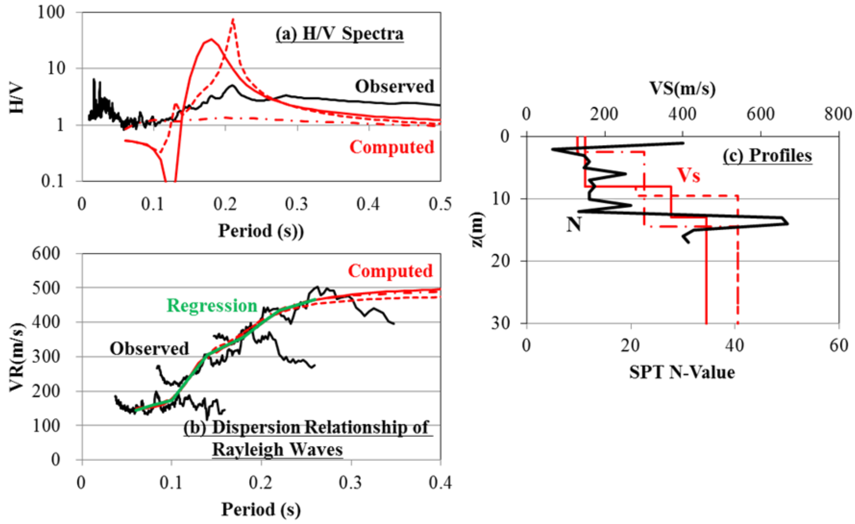

Figure 10. Observation and analysis results for station 28

4. CONCLUSIONS

Microtremor observations were conducted to investigate seismic properties of surface deposits in Shimizu, Shizuoka, Japan. Two kinds of observation were carried out at 32 locations; one is to measure three directional motions at one point, by which to compute H/V spectra, and then to estimate the site natural periods, T0. The other is an array observation of vertical motions at three apexes of the equilateral triangle with the sensor distances of 3, 10 and 20 meters. From the array observations, we calculated dispersion relationships of Rayleigh waves by SPAC analyses, and obtained Rayleigh wave velocities at the wave length of 40m, VR40.

From the spatial distributions of T0 and VR40, we found formation of soft ground in the lowland area near around the Tomoe river channel several kilo-meters upward from the mouth, and stiff ground at the Akihasan rise. These conform well to the distribution of the characteristic period of ground, TG, which is calculated based on thicknesses and SPT-N values of the surface layers from existing site investigation data. The stratigraphic profiles of shear wave velocity were then inversely analyzed at several points by using genetic algorithm, in which the natural periods by H/V spectra and dispersion

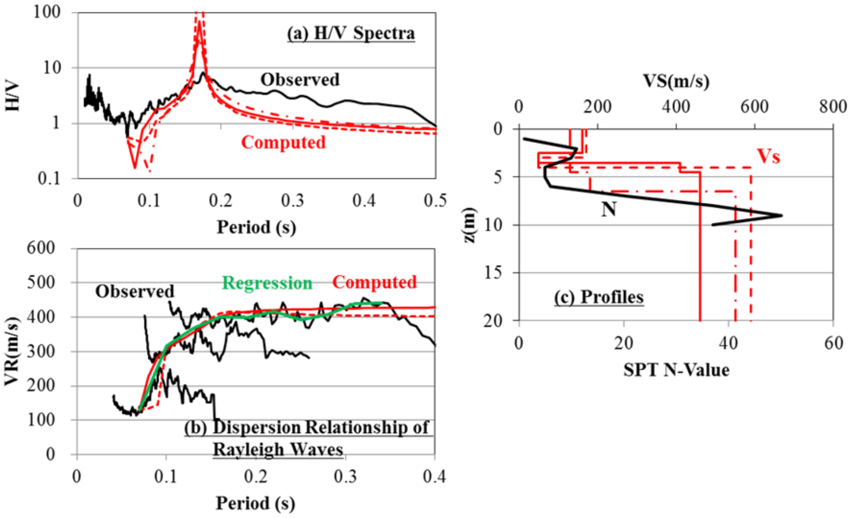

Figure 11. Observation and analysis results for station 30

relationships of Rayleigh waves were jointly employed as optimizing targets. The estimated profiles of shear wave velocity were favourably consistent with the variations of SPT-N value with depth.

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