Bedrock Structure Estimation Using Microtremors in Kochi Plain, Japan

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SUMMARY:
Microtremor measurements using arrays of sensors were conducted at a site in the Kochi plain, Japan, where is highly at risk of damage due to the forthcoming Nankai earthquake. The spectral analyses of the array records yield dispersion characteristics of Rayleigh waves and horizontal-to-vertical (H/V) spectral ratio of surface waves, and joint inversion of these data results in S-wave velocity (V_S) profile down to cherty bedrock with V_S over 1 km/s at the site. Conventional microtremor measurements using one three-component sensor were performed at 125 stations in the Kochi plain, resulting in the H/V spectra within the plain. Based on relationship between H/V peak periods of microtremors and depths to cherty bedrock from the inverted V_S profile and available borehole data, two-dimensional bedrock structures across the plain are roughly estimated. This confirms that the microtremor method could be an effective tool for estimating multi-dimensional bedrock structure of sedimentary deposit.

Keywords: Microtremor, H/V Spectrum, Kochi Plain, Bedrock Structure, Nankai Earthquake

1. INTRODUCTION

Kochi, a core city in the southern part of Shikoku island, Japan, is highly at risk of damage due to the forthcoming Nankai earthquake (e.g., Central Disaster Management Council of Japan, 2003). The city of Kochi is situated on a plain formed by several rivers (called Kochi plain), and its geological setting could be a deep sedimentary deposit. From catastrophic earthquakes in the last several decades, it has been widely recognized that the site effect evaluation is one of the key components for preventing or mitigating earthquake disasters. To evaluate site effects quantitatively, one-, two-, or three-dimensional S-wave velocity (V_S) structure of sedimentary deposit should properly be determined down to seismic bedrock. In the Kochi area, however, deep V_S structure of the sediment has not been investigated enough.

It is too expensive and time-consuming to estimate multi-dimensional deep V_S profiles using conventional geophysical or geotechnical methods because of a large number of boreholes to be needed. For this purpose, the microtremor survey method has been developing for multi-dimensional V_S profiling in an economical manner.

Recent studies, for example, have indicated that (1) surface waves (Rayleigh and Love waves) dominate in microtremors, (2) the frequency-wave number (*f*-*k*) spectral analysis (Capon, 1969) of microtremor vertical motions measured with arrays of sensors at a site can yield dispersion characteristics of Rayleigh waves, and (3) the inverse analysis of dispersion data results in a sedimentary V_S structure at the site (e.g., Horike, 1985; Tokimatsu, 1997; Okada, 2003). It was also revealed that the horizontal-to-vertical (H/V) spectral ratios (Nakamura, 1989) of microtremors measured with one three-component sensor at a site correspond to those of surface waves and reflect a bedrock V_S structure at the site (e.g., Tokimatsu and Miyadera, 1992; Tokimatsu, 1997; Arai and Tokimatsu, 2004).

Based on the results of the microtremor studies, Arai and Tokimatsu (2005) have indicated that the reliability of V_S structure down to bedrock improves significantly with the joint inversion of both microtremor dispersion and H/V data compared to the dispersion curve inversion. It has also been shown that combined use of both array and conventional microtremor measurements could permit to evaluate of two- or three-dimensional V_S structure down to bedrock (e.g., Arai and Tokimatsu, 2008).

Thus, the objective of this study is to explore the applicability of multi-dimensional V_S profiling (mainly bedrock structure estimation) using microtremors based on the field investigation conducted in the Kochi plain.

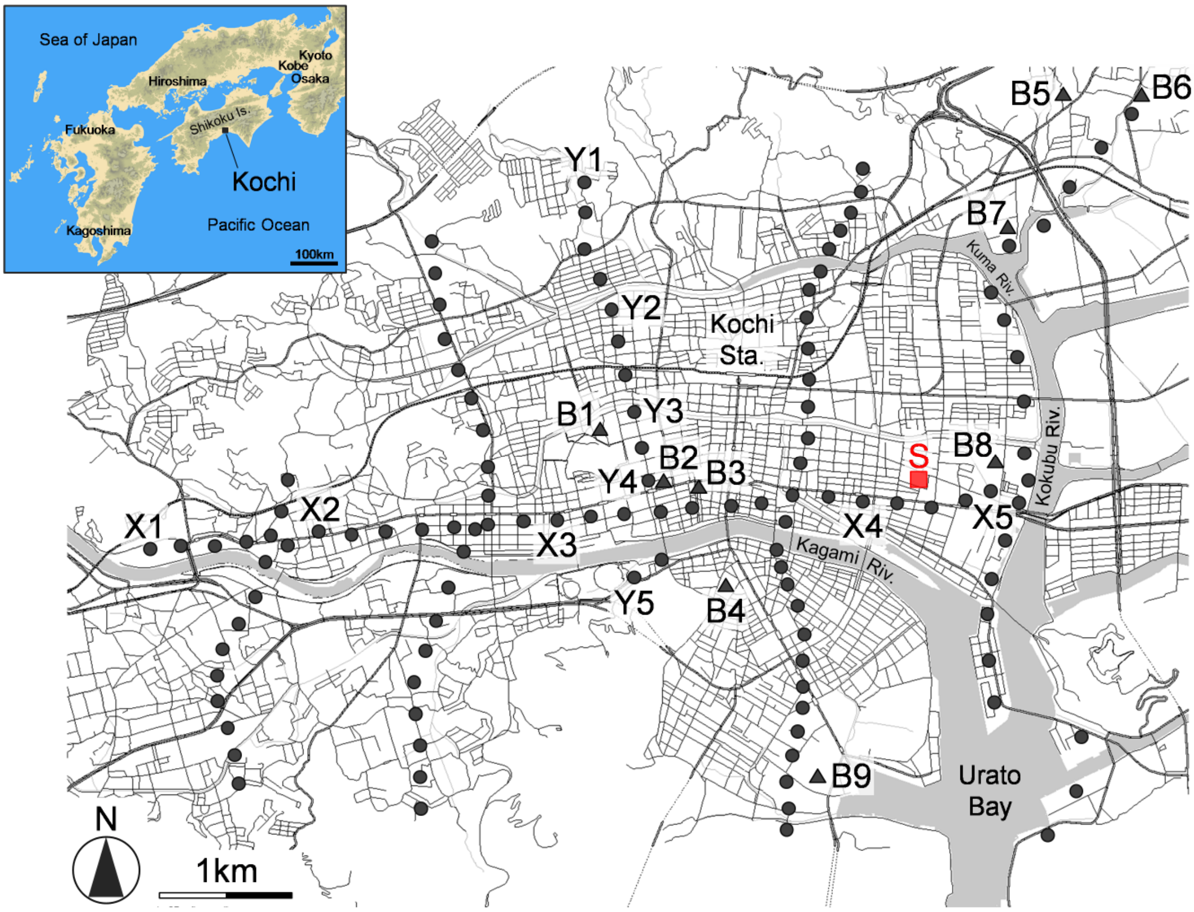

Figure 1. Map showing observation lines and sites for microtremor measurements in Kochi plain (solid red square: array measurement, solid gray triangle/circle: conventional measurement with/without borehole data)

2. MICROTREMOR MEASUREMENT

Fig. 1 illustrates a map of the Kochi plain. Microtremor measurements using arrays of sensors were conducted at Site S shown in the figure as a solid red square. Solid gray triangles and circles in the figure indicate 125 stations where microtremor conventional measurements with one three-component sensor were conducted. These stations are fallen on six observation lines, one with the west-east (W-E) direction and remaining five with the north-south (N-S) directions, which are crossing the plain as shown in the figure. The distance between two adjacent stations ranged from 50 to 200 m depending on the variation of microtremor H/V spectrum with distance.

Sites X1-X5 and Y1-Y5 shown in Fig. 1 are typical stations along the W-E and the N-S observation lines, respectively. Sites X2-X5 and Y2-Y4 are located within the plain while Sites X1, Y1, and Y5 are on the hill areas surrounding the plain.

The data acquisition system and sensors used for both types of measurements are the same as those employed in the previous studies (e.g., Arai and Tokimatsu, 2004, 2005, 2008). Thus, the data acquisition system consists of amplifiers, low-pass filters, 24-bit analog-to-digital (A/D) converters, and a note-type computer; which are all built in a portable case. The sensor unit has moving coil velocity type elements with natural period of either 1 or 5 s, which is chosen depending on site and observation conditions.

For the array observations, the sensor array configuration is close to a circular one with six stations, and six arrays with different radius (1, 2.5, 5, 10, 20, 40 m) are used. For each array, microtremor vertical motions are measured simultaneously at all stations with two horizontal motions at the center for 5-20 minutes and digitized at an appropriate sampling frequency between 100 and 1000 Hz. For the conventional observations, three-component microtremors are measured at each station for 5-10 minutes and digitized at a sampling rate of 200 Hz. About 10-20 sets of data consisting 4096 points each are made from the recorded motions excluding traffic-induced vibrations, and used for the following spectral analyses.

3. V_S STRUCTURE ESTIMATION USING MICROTREMOR ARRAY DATA

The high-resolution frequency-wave number (*f-k*) spectral analysis (Capon, 1969) is used to determine dispersion curve of microtremor vertical motions recorded with each array at Site S. In the *f-k* analysis, the effective wavelength for any array is limited to the value in between twice the minimum sensor distance and three times the maximum sensor distance of the array. This corresponds to 1-3 times the diameter for a circular array.

The H/V spectral ratios are derived for microtremors observed at the center of the arrays and at all the stations shown in Fig. 1. The microtremor H/V value at a period T, $(H/V)_m(T)$, is defined as

$$(H/V)_m(T) = \sqrt{\frac{P_{NS}(T) + P_{EW}(T)}{P_{UD}(T)}} \tag{3.1}$$

where $P_{UD}(T)$ is the Fourier power spectrum of vertical motion, and $P_{NS}(T)$ and $P_{EW}(T)$ are those of two orthogonal horizontal motions. The power spectra are determined by using the direct segment method (Capon, 1969) without any smoothing window.

The dispersion curve and H/V spectrum determined for Site S are shown in Figs. 2(a) and 2(b), respectively, as open circles. The observed H/V spectrum has a distinct peak at a period of 1.2 s, and the dispersion curve is detected in a period range shorter than the H/V peak period.

A joint inverse analysis (Arai and Tokimatsu, 2005) is conducted using the microtremor dispersion and H/V data shown in Figs. 2(a) and 2(b). In the inversion, the following assumptions are made: (1) the soil profile down to seismic bedrock at the site consists of a six-layered half-space, (2) the fifth and bottom layers correspond to cherty and granitic bedrocks with V_S of 1.2 and 2.5 km/s, respectively, and (3) the depth to granitic bedrock is 1 km, which are based on available geological and geophysical information in the Kochi plain (refer to Central Disaster Management Council of Japan, 2003; see Table 1). This leaves unknown thicknesses and S-wave velocities of top four layers above the cherty bedrock with V_S of 1.2 km/s to be sought in the inversion, with P-wave velocity (V_P) and density (ρ) being dependent on V_S at each layer (e.g., Arai and Tokimatsu, 2008).

Solid red line in Fig. 2(c) shows the S-wave velocity profile estimated from the joint inverse analysis at Site S. Solid red lines in Figs. 2(a) and 2(b) are the dispersion curve of Rayleigh waves and the H/V spectrum of surface waves, respectively, computed for the soil profile estimated at the site, considering the effects of fundamental and higher modes (Tokimatsu et al., 1992; Tokimatsu, 1997; Arai and Tokimatsu, 2004). In the figures, the computed theoretical values show fairly good agreement with the observed ones at the site. In Fig. 2(c), the standard errors of the parameters at the top four layers evaluated in the inversion (Matsu'ura and Hirata, 1982; Horike, 1985; Yuan and Nazarian, 1993; Arai and Tokimatsu, 2004) are shown as chained gray lines. The standard error ratios of the estimated parameters are generally less than 0.1 in any soil layer at the site, indicating that the estimated V_S profile is reasonable. From Fig. 2(c), it is indicated that the depth to cherty bedrock with V_S over 1 km/s is about 90-100 m and that to engineering bedrock with V_S over 400 m/s is about 40 m at Site S where is near the central part of the Kochi plain (see Fig. 1).

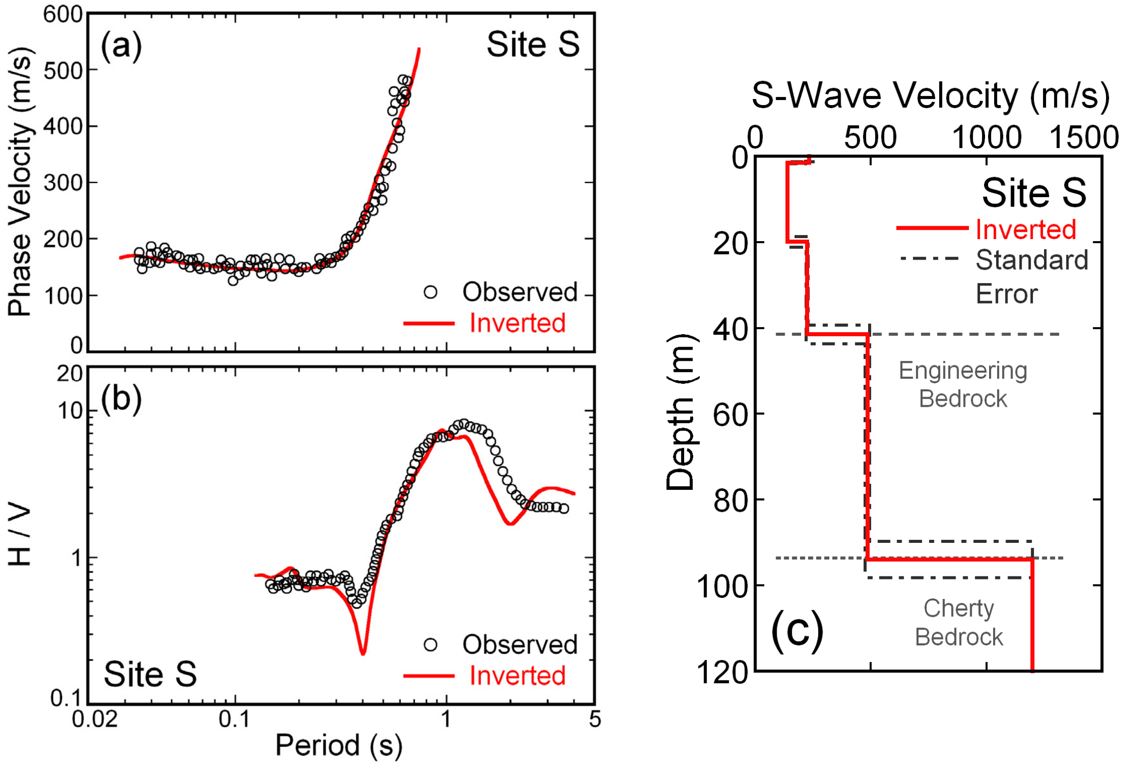

Figure 2. Results of microtremor array measurements at Site S in Kochi plain: (a) dispersion curves, (b) H/V spectra, and (c) S-wave velocity profile estimated by joint inversion using both dispersion and H/V data

Table 1. Bedrock Velocity Structure Inferred from Geological and Geophysical Information in Kochi Plain (refer to Central Disaster Management Council of Japan, 2003)

Rock Type	Depth (km)	Density (kN/m^3)	V_P (km/s)	V_S (km/s)
Chert	< 1	21	2.7	1.2
Granite	> 1	23	5.2	2.5

4. H/V SPECTRA OF MICROTREMORS

Figs. 3 and 4 show the microtremor H/V spectra at Sites X1-X5 and Y1-Y5, respectively. At Sites X1, Y1, and Y5 located on the hills, the observed H/V spectra have no significant peaks. This suggests that the bedrock could outcrop at these sites. At Sites X2-X5 and Y2-Y4 located within the plain, on the other hand, the observed H/V spectra have significant peaks.

Along the W-E observation line X1-X5 (Fig. 3), the H/V peak period increases eastward, i.e., from 0.4-0.7 s at Sites X2-X3 to 1-1.3 s at Sites X4-X5, which are located 300-400 m apart from the array observation site (Site S) with the H/V peak period of 1.2 s (see Fig. 2(b)). From Fig. 4, the H/V peak periods at Sites Y2-Y4 vary from 0.4 to 0.7 s along the N-S observation line Y1-Y5. These variations of H/V peak periods suggest that the V_S profile varies drastically along the lines passing through Sites X1-X5 and Y1-Y5. Similar reports can be found in the previous studies by Mori et al. (2001).

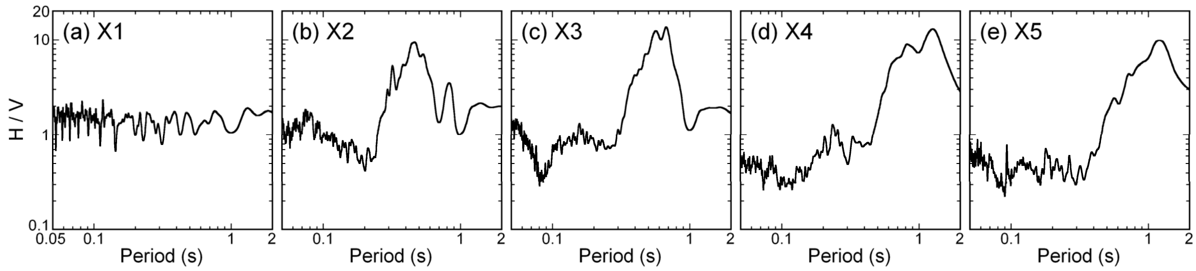

Figure 3. H/V spectra of microtremors at Sites X1-X5 along west-east observation line in Kochi plain

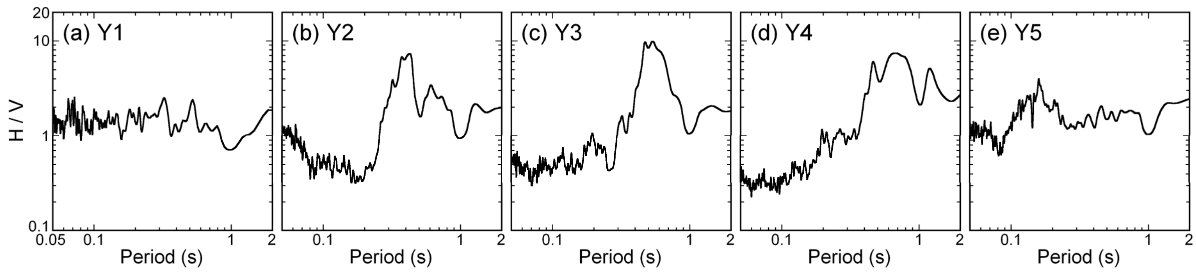

Figure 4. H/V spectra of microtremors at Sites Y1-Y5 along north-south observation line in Kochi plain

5. BEDROCK STRUCTURE ESTIMATION USING MICROTREMOR H/V DATA

5.1. Relationship between H/V Peak Period and Bedrock Depth

On the target area, PS-logging data down to cherty bedrock with V_S over 1 km/s are available at Sites B1-B9 shown in Fig. 1 as solid gray triangles (e.g., Editorial Committee for Ground Diagram of Kochi, 1992), where microtremor H/V spectra were determined. The depths to cherty bedrock, D_B (in m), from the borehole data are shown in Fig. 5 as open circles against the microtremor H/V peak periods, T_P (in s), for the sites. Also plotted as a solid red square in the figure is D_B estimated from microtremor array observation at Site S against T_P at the site (refer to Fig. 2). With the figure, there is a good correlation between D_B and T_P, which is modeled as

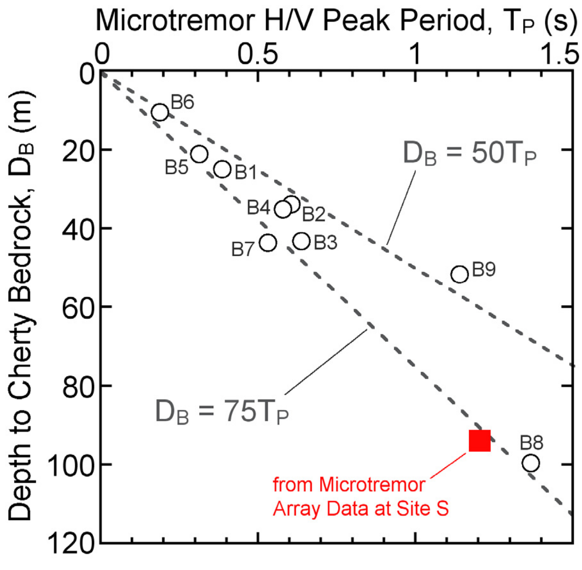

Figure 5. Relationship between H/V peak period of microtremors and depth to cherty bedrock with V_S over 1 km/s in Kochi plain

$$D_B = 50T_P \sim 75T_P \tag{5.1}$$

Fig. 6(a) illustrates V_S profile down to cherty bedrock at Site B4, and the H/V spectrum of microtremors observed at the site is shown in Fig. 6(b) as solid black line. Chained and broken light-gray lines in Fig. 6(b) indicate H/V spectra of fundamental Rayleigh modes (Haskell, 1953) at the site, which are computed from the velocity structures down to cherty and engineering bedrocks with V_S over 1 km/s and 400 m/s, respectively. With Figs. 6(a) and 6(b), based on the studies by Tokimatsu and Miyadera (1992), it is suggested that the microtremor H/V peak in the target area could mainly be controlled by cherty bedrock structure rather than engineering one. We have also confirmed that the same suggestion is resulted from similar comparison between observed and theoretical H/V spectra at Site S. Thus, the depth to cherty bedrock with V_S greater than 1 km/s in the Kochi plain could approximately be estimated using Eqn. 5.1.

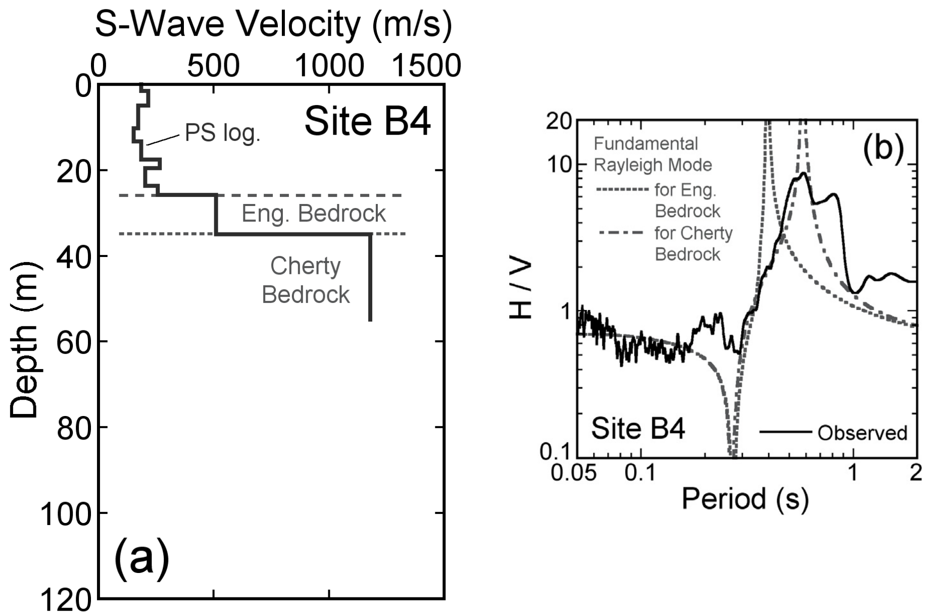

Figure 6. (a) V_S profile, and (b) observed and theoretical H/V spectra at Site B4 in Kochi plain

5.2. Bedrock Structures Estimated from Microtremor Data

Figs. 7 and 8 show two-dimensional (2-D) cherty bedrock structures thus estimated for the W-E and the N-S observation lines X1-X5 and Y1-Y5, respectively, using Eqn. 5.1 with the observed microtremor H/V spectra. Solid black circles and squares shown in the figures indicate the depths to cherty and engineering bedrocks, respectively, which are based on additional borehole data except those at Sites B1-B9 employed for Figs. 5 and 6. Also indicated in Fig. 7 as two horizontal red broken lines are the depths to cherty and engineering bedrocks estimated from microtremor array measurements at Site S (refer to Fig. 2(c)). In Figs 7 and 8, the cherty bedrock structures estimated from microtremors are roughly in good agreement with the borehole data added, indicating that the estimated bedrock structures in the plain could reliably be reasonable.

With Figs, 7 and 8, it is suggested that the depth to cherty bedrock having V_S over 1 km/s varies from place to place within the Kochi plain. Bedrock almost outcrops near the edge zone of the plain (e.g., Sites X1, Y1, and Y5), but dips moderately toward the western area in the plain (Sites X2-X3, Y2-Y4) and their depths estimated are about 20-60 m. These figures also suggest that a 1 km-wide hidden valley with a maximum depth of about 100 m runs from the north to the south in the central part of the plain. Probably, the valley formed by stream erosion during ice ages, when the sea level was much lower than that of today, has been buried by stream deposition in the recent epoch.

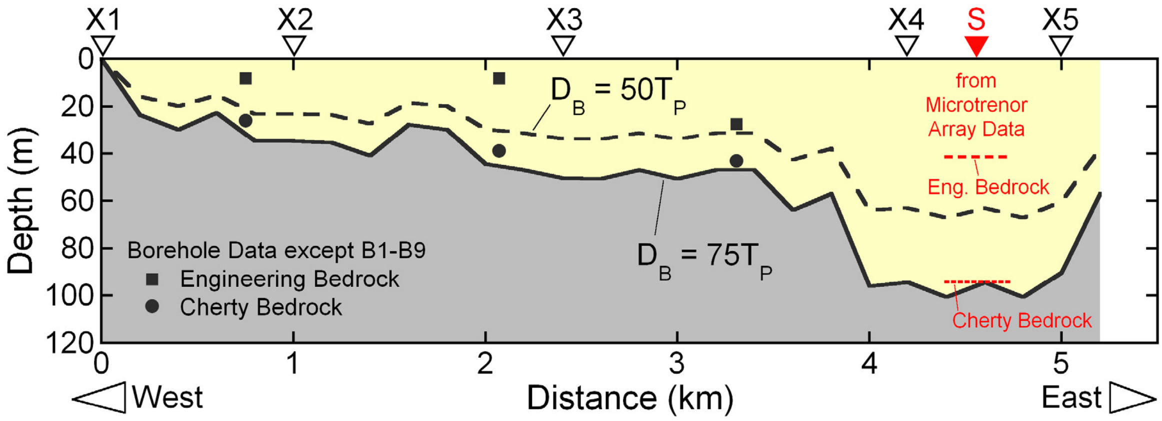

Figure 7. Two-dimensional cherty bedrock structure estimated from microtremors along west-east observation line (Sites X1-X5) in Kochi plain

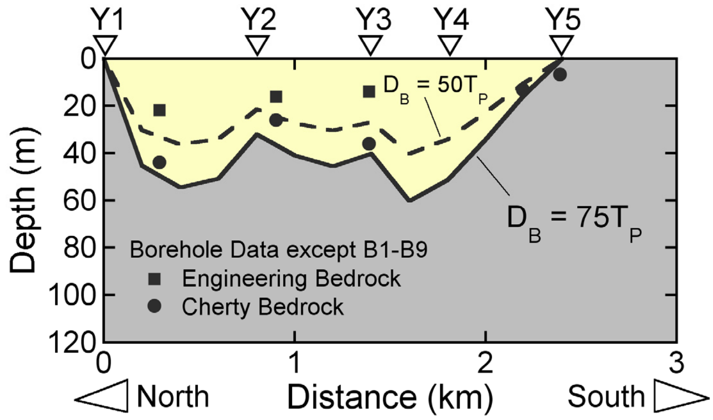

Figure 8. Two-dimensional cherty bedrock structure estimated from microtremors along north-south observation line (Sites Y1-Y5) in Kochi plain

6. CONCLUSIONS

Microtremor measurements using arrays of sensors were conducted at a site in the Kochi plain, Japan, and a joint inverse analysis of both dispersion and H/V data observed results in V_S profile down to cherty bedrock with V_S over 1 km/s. Conventional microtremor measurements using one three-component sensor were performed at 125 stations within the plain, and their H/V spectra are determined. Based on relationship between H/V peak periods of microtremors and depths to cherty bedrock from the inverted V_S profile and available borehole data, two-dimensional bedrock structures across the plain are roughly estimated. This confirms that the microtremor method could be an effective tool for estimating multi-dimensional bedrock structure of sedimentary deposit.

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