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ESTIMATION OF DEPTH OF ENGINEERING BEDROCK USING MICROTREMORS OBSERVED ON GROUND SURFACE

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ABSTRACT

This study presents a method of identifying S-wave velocity structure and the depth of engineering bedrock using the H/V spectral ratio (the spectral ratio of horizontal to vertical components) of microtremors which are assumed to be dominated by Rayleigh wave. The real subsurface grounds are modeled by an equivalent two layered model with one surface layer and the bedrock. S-wave velocity and depth of engineering bedrock are identified in two steps: In the first step, S-wave velocities of the engineering bedrock are estimated by using microtremors at several sites where the depth of engineering bedrock is known from borehole tests, and these S-wave velocities are averaged. In the next step, the depths of engineering bedrock are identified by microtremors at other locations, assuming that the S-wave velocity of engineering bedrock is known (it is estimated in the first step). This method is applied to Tokushima City and Arida City in Japan and the maps describing the characteristics of surface ground are drawn.

INTRODUCTION

It is important to understand the structure and the dynamic characteristics of subsurface ground for the earthquake-resistant design of structures. In alluvial plains, where the subsurface ground soil is relatively soft and most cities are located in Japan, the structure of subsurface layers of soil greatly influences the motions of the ground.

Structure of subsurface ground is generally investigated by physical methods for soil survey such as the borehole test, and observation of microtremors at the ground surface. Since the method with microtremors is most simple and economical among the tests and observations, it has been frequently applied in recent years.

Nakamura and Ueno (1986) reported that the H/V spectral ratio (spectral ratio of horizontal component to vertical component of microtremors) was stable and resembled the characteristics of amplification of SH waves. Since his report was issued, observations of microtremors have been widely applied to the estimation of the dynamic characteristics of

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subsurface ground. Simultaneously theoretical studies on the characteristics of microtremors have been continued. Ohmachi et al. (1994) discussed the relation of microtremors and surface wave, and insisted that microtremors consist mainly of Rayleigh wave referring to the similarity of H/V spectral ratios of SH wave and Rayleigh wave. Tokimatsu and Miyadera (1992) confirms that the H/V spectral ratio of microtremors resembles to that of Rayleigh wave.

Recently, microtremors have been used to identify the shear wave velocity of subsurface laminated layers of ground down to bedrock. In general, array observations of microtremors are carried out to extract the dispersion curve of Rayleigh wave, which is used as the target in the identification problem [e.g., Horike (1985), Tokimatsu et al. (1992)]. The theoretical dispersion curve of Rayleigh wave is calculated for the assumed ground model, which is modified to fit the dispersion curve extracted from the microtremors. However, some researchers identified the shear wave velocity of subsurface layers using H/V spectral ratios of microtremors observed at a site [Nishikawa et al. (2003), Arai and Tokimatsu (2004)]. This method is convenient, but difficult because there are many local minimums in the optimization since the thickness and shear wave velocity of the sedimentary layers are simultaneously identified. There is a trade-off between the two properties in the identification problem. However, the identification can be successfully performed when some of the parameters are fixed. For example, in the case of the ground model with a sedimentary layer on the engineering bedrock, if one of the three parameters such as shear wave velocity of sedimentary layer or engineering bedrock or thickness of sedimentary layer is known, the other two parameters can be identified.

In this study a new method is proposed to identify the topography of engineering bedrock over the area of several kilometers square. The geographical distribution of the thickness and shear wave velocity of the sedimentary layer is estimated with the two-stage identification algorithm using H/V spectral ratio of microtremors in the low frequency band. Subsurface ground is modeled by a sedimentary layer on the engineering bed rock. In the first stage, shear wave velocity of the sedimentary layer and the engineering bed rock is estimated by H/V spectral ratio of microtremors at the site where the thickness of the sedimentary layer was investigated by the borehole test. The value of shear wave velocity of the engineering bedrock is considered to be consistent over the target area, though that of the sedimentary layer depends on the site. Then, the estimated value of shear wave velocity of engineering bedrock is regarded as the representative value over the target area. Since in practice there is estimation error due to various reasons, the identification is carried out at some other sites in the same way and the mean value of identified shear wave velocity of the engineering bed rock is used. In the second stage, shear wave velocity and thickness of the sedimentary layer are identified using H/V spectral ratios at the sites where no surveys have been carried out, with the shear wave velocity of engineering bedrock fixed to the value estimated in the first stage. A similar approach was tried by Nishikawa et al. (2003). However, the feature of the method proposed in this study is that the Rayleigh wave is extracted and used in the procedure of identification. Additional parameters are then introduced to stabilize the calculation.

METHOD OF IDENTIFICATION

Rayleigh wave is supposed to be dominant in microtremors observed at the ground surface according to the conventional research [Tokimatsu and Miyadera (1992)]. H/V spectral ratio of microtremors observed at a site is considered to correspond to the theoretical one of

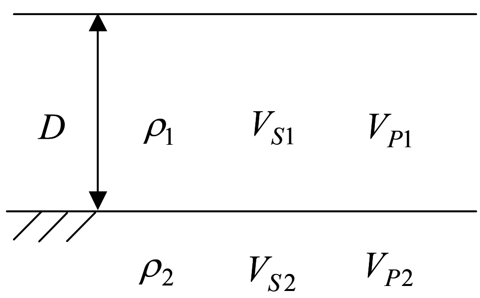

Figure 1. Ground model

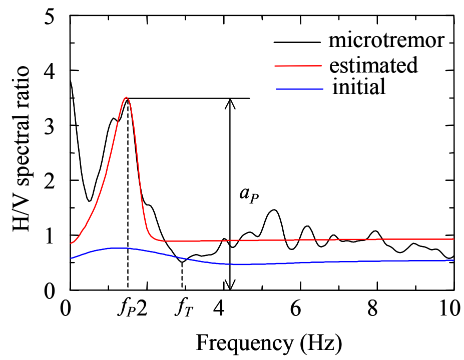

Figure 2. H/V spectral ratios of microtremors and theoretical Rayleigh wave

Rayleigh wave calculated by Haskell (1953). Fig.1 shows the subsurface ground model which consists of a sedimentary layer on the engineering bedrock. D,ρ,Vs and Vp denote the depth of the sedimentary layer, density, shear wave velocity and primary wave velocity, respectively. These parameters are to be identified. The identification problem of ρ_1,Vs_1, Vp_1, ρ_2,Vs_2, Vp_2 and D is carried out by minimizing the objective function as shown in Eq.1.

$$Se(\mathbf{x}) = \sum_{i=1}^{N_f} \{\beta \cdot A_R(\mathbf{x}; f_i) - A_M(f_i)\}^2 \qquad (1)$$

where A_R and A_M denote theoretical H/V spectral ratio of Rayleigh wave and that of microtremors, respectively. $\mathbf{x}$, f_i, and N_f denote the vector of unknown parameters, i-th discrete frequency and the total number of discrete frequency points, respectively. Though the Rayleigh wave is considered to be dominant in the microtremors observed at ground surface, it is not easy to perfectly extract only the Raleigh wave. Love wave as well as Rayleigh wave are considered to be contained in the horizontal component of observed microtremors. The H/V spectral ratio is expected to be rather large compared with the theoretical one of the Rayleigh wave because of the existence of Love wave. β in Eq.1, which is introduced as another unknown parameter, plays the role of adjusting the peak level of the theoretical H/V spectral ratio. Fig.2 shows an example of the results of identification. H/V spectral ratio of microtremors and theoretical ones are illustrated. Only the first mode is considered in the calculation of the theoretical H/V spectral ratio of Rayleigh wave. The shape of the H/V spectral ratio of microtremors is characterized by f_p, f_T and a_p as shown below.

1) f_p (peak frequency) ; determined by $Vs_1/4D$.
2) f_T (trough frequency) ; related to the frequency at which the primary wave is dominant, and is determined by Vp_1/Vs_1.
3) a_p (amplitude of peak) ; determined by impedance ratio ($\rho_1 Vs_1/\rho_2 Vs_2$) .

Since there is the relation of the trade-off between the parameters, some of them need to be known. In the identification, densityρ_1, ρ_2 and primary wave velocity of engineering bedrock Vp_2 are fixed to the values estimated from the priori and/or statistical information. Therefore the unknown parameters are reduced to $\mathbf{x} = \{Vs_1, Vp_1, Vs_2, D, \beta\}^T$.

The method of identification mentioned above can be applied to the area in which Vs_2 is regarded as being consistent. The procedure of identification is as follows.

i) Vs_1, Vp_1, Vs_2, β are identified using the H/V spectral ratio of microtremors observed at the site where the borehole test was performed and the depth of the top of the engineering bedrock is known.
ii) Identification is carried out in the same way at some other sites where the borehole test was performed. The average of the estimated Vs_2 is regarded as the representative value of shear wave velocity of the engineering bedrock over the target area.
iii) Vs_1, Vp_1, β, D are identified using the H/V spectral ratios observed at other arbitrary sites.

At this point a contour map of the depth of the top of the engineering bedrock can be drawn.

APPLICATION

The proposed method is applied to Tokushima city in Tokushima prefecture and Arida city in Wakayama prefecture, Japan.

Observation of microtremors

Microtremors were observed at 140 and 85 sites in Tokushima and Arida city, respectively. Tokushima city is located on the alluvial plain which has been developed along the class A river Yoshino. Yoshino River is one of the three largest rivers in Japan whose width near the mouth is over one kilometer. The alluvial plain is composed of very soft ground and the engineering bedrock is not very hard. Arida city is located in the middle of Wakayama prefecture. It has been developed along the class B River Arida. The alluvial plain in Arida city spans east to west. The plain is surrounded by mountains in the north and south. The engineering bedrock in Arida city is relatively hard. The sites where microtremors were observed are illustrated in Figs.3 and 4. The observations were performed late at night or very early in the morning at such places as the play grounds and the unoccupied spaces located more than ten meters from a driveway. Microtremors of three components were observed for two or three minutes at each site. The velocity of ground motions of one vertical and two horizontal directions was recorded at intervals of 0.01 second. The portable ambient vibration monitoring system (SC-35N) and servo velocity meter (VSE-15D) were used, both of which are manufactured by Tokyo Sokushin Co., LTD. The portable system consists of an amplifier, a 16-bit analog-to-digital converter and a laptop computer. The data transmitted from the connected velocity meters were recorded on the hard disk of the computer. The overall characteristic of frequency of the apparatus was reported

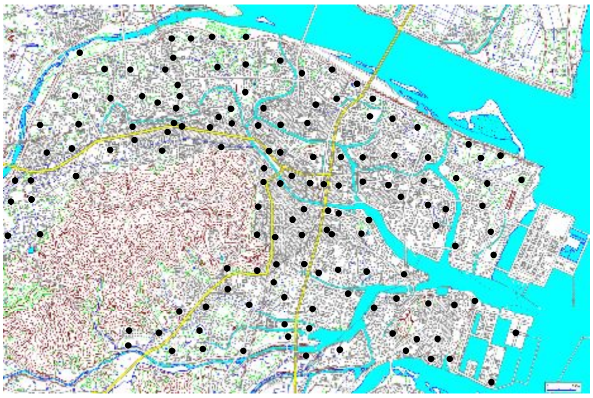

Figure 3. Observation sites of microtremors in Tokushima city

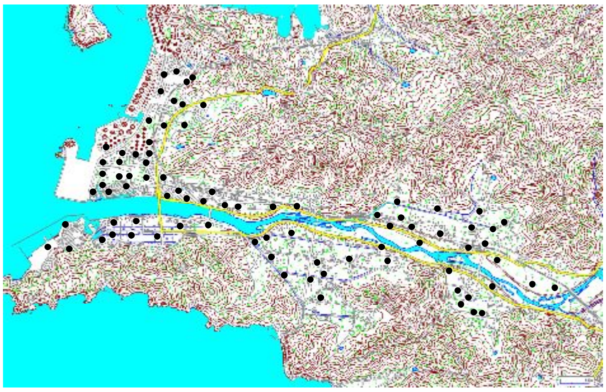

Figure 4. Observation sites of microtremors in Arida city

to be flat over 0.2 Hz. However, since there were cases in which H/V spectral ratios were unstable in between 0.2 and 1.0 Hz, the spectral ratios in the frequency band over 1.0 Hz were used in the calculation.

H/V spectral ratio

First the index $IQ(\theta)$ is calculated by Eq.2 [Sawada et al. (2000)] in order to identify the direction of the Rayleigh wave.

$$IQ(\theta) = \int_{f_{\min}}^{f_{\max}} |Q_{x'z}(f)| df \Big/ \int_{f_{\min}}^{f_{\max}} |S_{x'z}(f)| df \tag{2}$$

where θ, $S_{x'z}(f)$, $Q_{x'z}(f)$ denotes the azimuth for the coordinate transformation of two horizontal components, the cross power spectrum between the vertical component and the horizontal component which is synthesized to the direction of θ, the imaginary part of $S_{x'z}(f)$, respectively. $f_{\min}$ and $f_{\max}$ are the lower and upper limits to which 1.0Hz and 10.0Hz are given, respectively. The index $IQ(\theta)$ represents how Rayleigh wave is superior in the direction of θ. It ranges in value from 0.0 to 1.0. The horizontal component, which is synthesized with θ in order to maximize $IQ(\theta)$, is used to calculate the H/V spectral ratio. This procedure is performed at the different intervals of 20.48 seconds over the recorded time history. Only the H/V spectral ratios, in which the values of $IQ(\theta)$ are relatively large, are averaged. The criteria of $IQ(\theta)$ are 0.8 and 0.7 in Tokushima and Arida city, respectively.

Results of identification and discussion

Tokushima city

The data of borehole test are available at as many as 23 sites in Tokushima city. Fig.5 shows the values of shear wave velocity of the engineering bedrock which are estimated using the microtremors observed at the nearest site to the each borehole test site. The density of 1.8

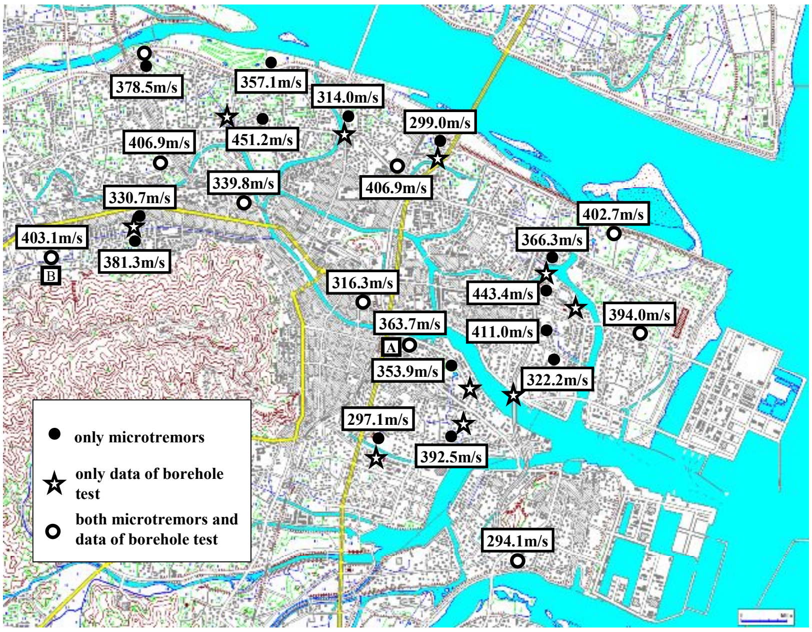

Figure 5. Shear wave velocity estimated in the first-stage identification in Tokushima city

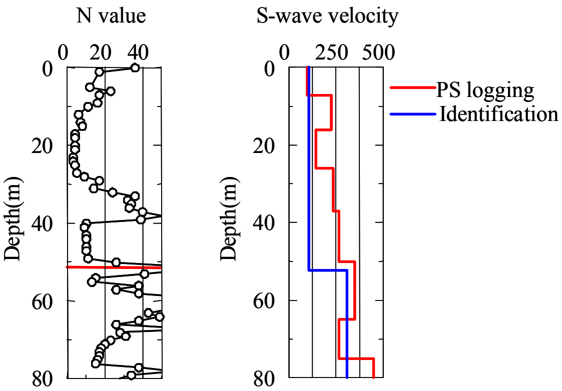

Figure 6. N value and shear wave velocity estimated by PS logging and identification at site A in Tokushima city

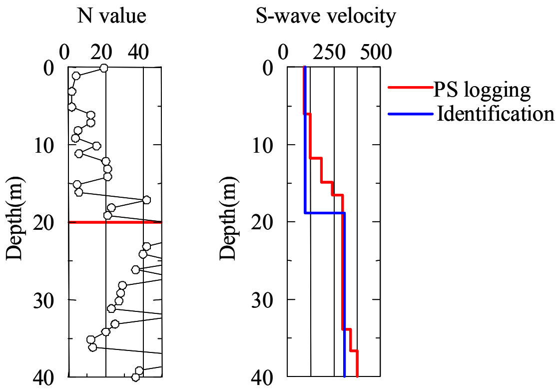

Figure 7. N value and shear wave velocity estimated by PS logging and identification at site B in Tokushima city

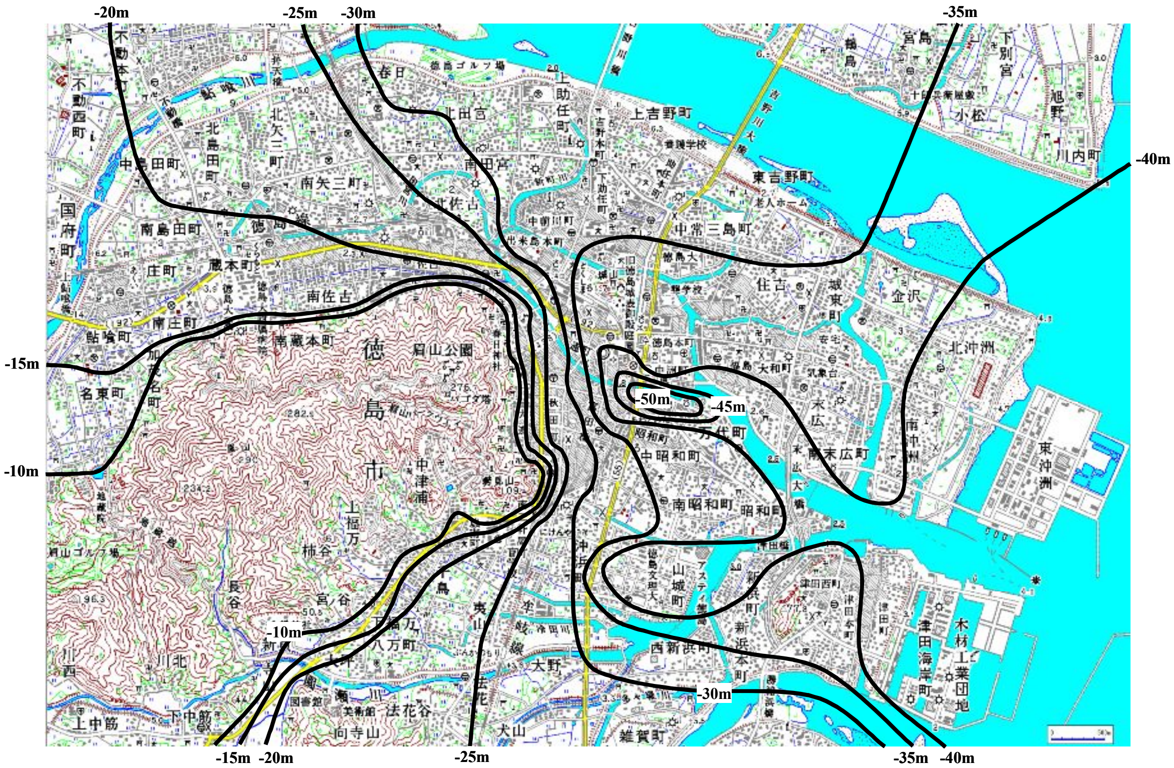

Figure 8. Contour map of depth of top of engineering bedrock estimated with microtremors in Tokushima city

g/cm^3 and 2.0 g/cm^3 are given to the sedimentary layer and engineering bedrock based on the priori information, respectively. The primary wave velocity of 2000 m/sec is given to the engineering bedrock. The estimated values of shear wave velocity of engineering bedrock are between about 300 and 450m/sec. Their average is 370m/sec, which is regarded as the representative over the target area. Then, the shear wave velocity and the depth of the sedimentary layer are identified at each observation site of microtremors with the shear wave velocity of engineering bedrock fixed to 370m/sec. The results of identification are compared with those of PS-logging and borehole tests at the sites A and B. The estimated values of shear wave velocity and thickness of sedimentary layer are illustrated in Figs. 6 and 7. Judging form the N value, the red horizontal line is regarded as the top of engineering bedrock in each figure. The depth of the top of the engineering bedrock, which were estimated with the microtremors, coincided with those of the red lines. Thus the accuracy of the estimated depth of the top of the engineering bedrock is confirmed. The contour map of the depth of the top of the engineering bedrock is illustrated in Fig.8.

Arida city

In the same manner as in Tokushima city, first the shear wave velocity of the engineering bedrock was identified. Borehole tests were carried out at the seven sites as shown in Fig.9. The estimated values of shear wave velocity of the engineering bedrock at or near the sites are also illustrated in the figure. The variation of the estimated values is a little larger than that in Tokushima city, probably because the target area is elongated from east to west and the geological features are more complicated. Their average is 450m/sec, which is regarded as the

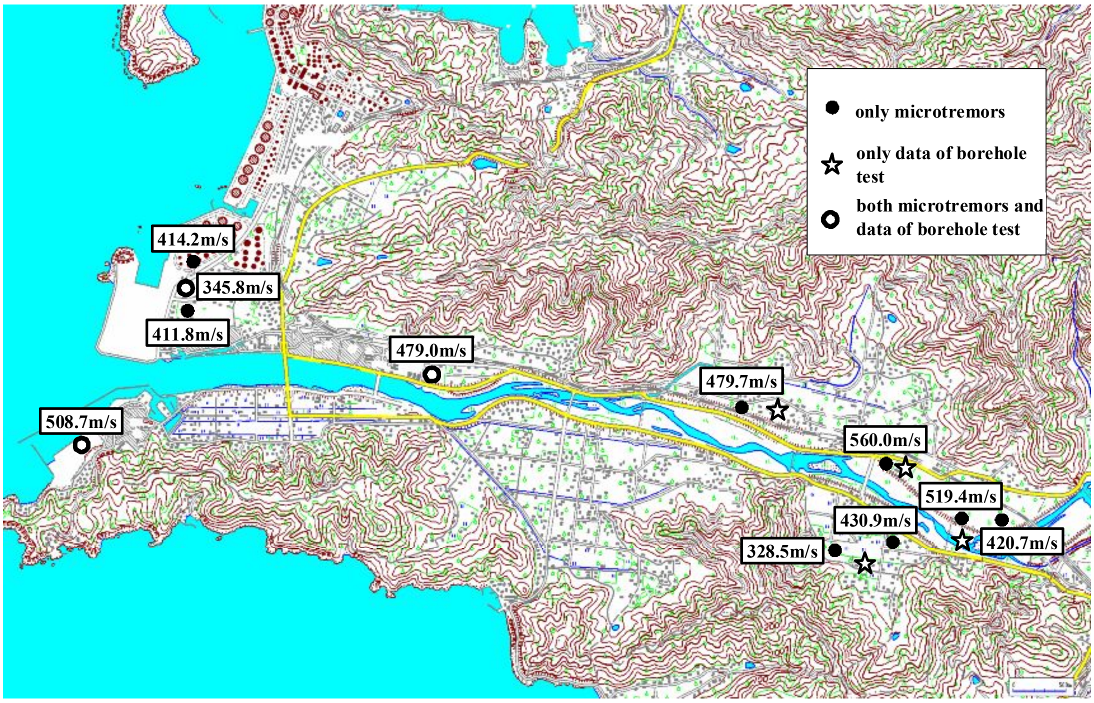

Figure 9. Shear wave velocity estimated in the first-stage identification in Arida city

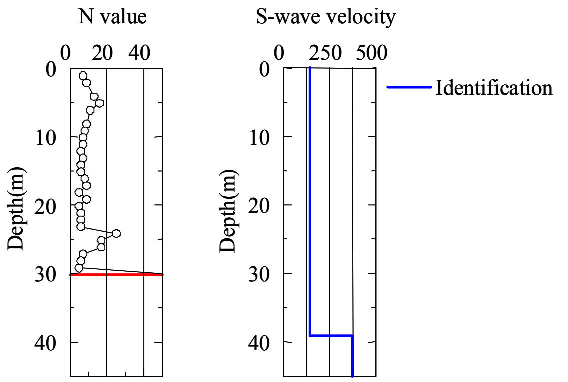

Figure 10. N value and shear wave velocity estimated by PS logging and identification at site C in Arida city

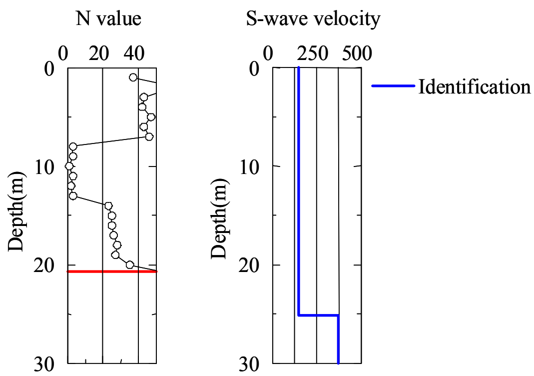

Figure 11. N value and shear wave velocity estimated by PS logging and identification at site D in Arida city

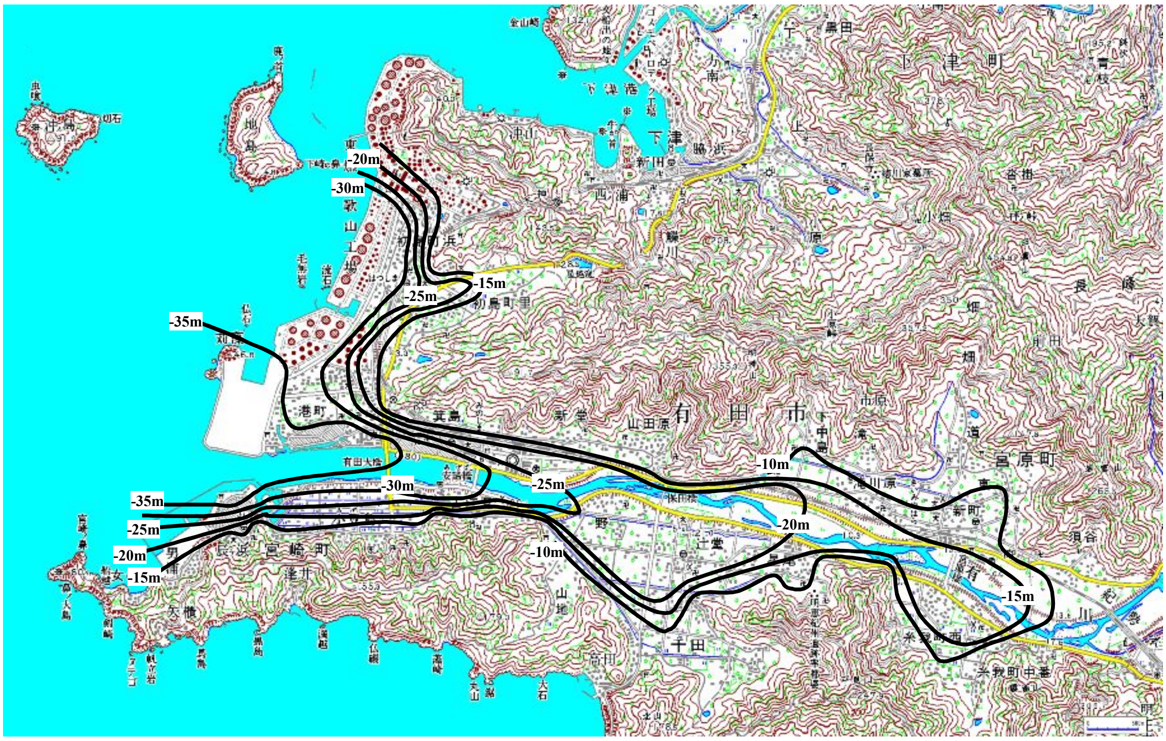

Figure 12. Contour map of depth of top of engineering bedrock estimated with microtremors in Arida city

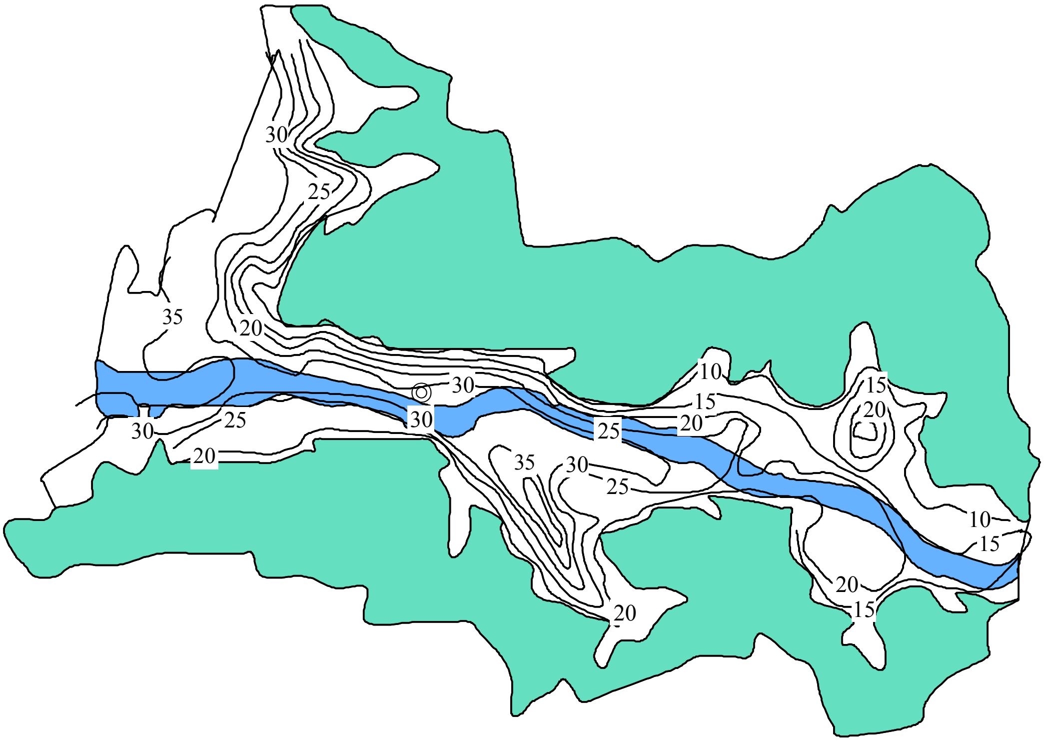

Figure 13. Conventional study on the depth of top of engineering bedrock estimated in Arida city [Tsujihara et al (2003)]

representative over the target area. The values of the depth and shear wave velocity of the sedimentary layer estimated at the borehole test sites C and D are illustrated in Figs. 10 and 11, respectively. PS-logging test has not been performed. The top of the engineering bedrock estimated with microtremors is 20 ~ 30 % deeper than that estimated with N value by the borehole test as indicated by the red line in the figure. The contour map of the depth of top of the engineering bedrock is illustrated in Fig.12. In Arida city the contour map, which is shown in Fig. 13, was made by Tsujihara et al. (2003) with microtremors in a different manner. They estimated the depth of the top of the engineering bedrock by Eq. 3.

$$H = TV/4 \quad (3)$$

where H, T and V denote the depth of the top of the engineering bedrock, the predominant period estimated H/V spectral ratio of microtrmors and the shear wave velocity of the sedimentary layer, respectively. Figs. 13 and 14 do not contradict each other except for some slight differences.

CONCLUSIONS

A method is proposed to identify the shear wave velocity and the depth of the top of engineering bedrock over an area of several kilometers square, using H/V spectral ratios of microtremors which are assumed to consist mainly of Rayleigh wave. This method is applied to Tokushima city in Tokushima prefecture and Arida city in Wakayama prefecture, Japan.

The major results are as follow.

1) The depth of the top of the engineering bedrock estimated by the proposed method coincides with that estimated by borehole and PS-logging tests in Tokushima city.
2) The contour maps of the depth of the top of the engineering bedrock made by the proposed method in Arida city do not contradict with the conventional study. However, applying to such areas as Arida city where the geological features are supposed to be different depending on the position, the area should be divided into several sections in which the shear wave velocity of the engineering bedrock is almost identical.

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