INVERSION OF VELOCITY STRUCTURES IN THE GRENOBLE BASIN USING HORIZONTAL-TO-VERTICAL SPECTRAL RATIOS

E. Ito(1), H. Kawase(2), C. Cornou(3), and F. Nagashima(4)

(1) Program-Specific Researcher, DPRI, Kyoto University, ito@sere.dpri.kyoto-u.ac.jp
(2) Program-Specific Professor, DPRI, Kyoto University, kawase@sere.dpri.kyoto-u.ac.jp
(3) Professor, ISTerre, University of Grenoble Alpes, cecile.cornou@univ-grenoble-alpes.fr
(4) Program-Specific Assistant Professor, DPRI, Kyoto University, nagashima@sere.dpri.kyoto-u.ac.jp

Abstract

Kawase et al. [1] recently proposed a method to calculate pEHVR (pseudo Earthquake Horizontal-to-Vertical spectral Ratios) from MHVR (Microtremor Horizontal-to-Vertical spectral Ratios) together with EMR, which is the spectral ratio between EHVR (Earthquake Horizontal-to-Vertical spectral Ratios) and MHVR at one hundred sites in Japan. They calculated EMRs for five categories based on the fundamental peak frequencies in MHVR. They found that pEHVR is much closer to EHVR than MHVR. They used their inversion code to invert one-dimensional S- and P-wave velocity structures from EHVR based on the diffuse field theory [2]. They found that velocity structures inverted from pEHVR are much closer to those from EHVR than those from MHVR.

However, when we apply this method to other countries, the EMR in Japan may not be directly applicable, because EMR should be a function of the average velocity structure from the bedrock to the surface, which may not be the same. If we want to calculate EMR in other countries as in Japan, we need to collect sufficient amount of data, which would not be easy in seismically not so active regions. This study is the first step to establish a simple way to get EMR and invert the velocity structures using a basin specific EMR. Here we used the Grenoble basin in France as a test field and calculated EMR and pEHVR from observed earthquakes and microtremors.

We first calculated pEHVR at five earthquake seismic observation sites in the Grenoble basin using the observed MHVR and the EMR in Japan to check the applicability of the EMR in Japan. We found that pEHVR seemed to be overestimated in almost all the frequency range higher than the fundamental peak frequency.

We then assumed that EMR specific for the Grenoble basin would be EMR in Japan multiplied by a modification factor α. We determined α such that the sum of the logarithmic misfits of amplitude between pEHVR and observed EHVR at five sites become minimum. After we got the optimal α to be 0.28 by using a two-step grid search, we found that the new pEHVRs showed quite a good match with the observed EHVRs in a wide frequency range.

We inverted velocity structures by pEHVR, MHVR, and observed EHVR at these sites to check the validity of the pEHVR inversion. We used the reference velocity model derived from the measured S- and P-wave velocities in the borehole located in the northeastern side of the basin. We found that the velocity structures by pEHVR are much closer to those by observed EHVR than those by MHVR. In these inversions, theoretical EHVRs from the inverted velocity structures are always very close to the target HVRs.

We made the average velocity structure for the deeper part based on the results inverted at five sites in order to control velocities of the deeper part in the whole basin inversions, and then made a new reference model for each site based on this averaged velocity structure. The inverted velocity structures using the new reference models and pEHVRs are close to those with the original model as well as those from EHVR. We will apply the method to all the valid microtremor sites inside the Grenoble basin to delineate the whole basin structure.

Keywords: Microtremor; Horizontal-to-Vertical Ratios; Diffuse Field Concept; Site Effect; Basin effects

1. Introduction

It is quite important to get velocity structures that explain the characteristic of S-wave amplification for site amplification evaluation from observed earthquake motions, since it may directly affect the structural damage caused by earthquakes. Nagashima et al. (2014) [2] proposed the method to invert one-dimensional S-wave velocity structures down to the seismological bedrock from earthquake HVR (EHVR) based on the diffuse field theory recently proposed by Kawase et al. (2011) [3]. However, this method is not applicable to the sites where the observed earthquake is difficult to obtain.

Kawase et al. (2018) [1] proposed the method to transform Horizontal to Vertical spectral ratios of Microtremors (MHVRs) to Horizontal to Vertical spectral ratios of earthquakes (EHVRs) by multiplying MHVR by EMR, which is the averaged ratio between observed EHVRs and MHVRs at K-NET and KiK-net sites in Japan. They calculated EMRs at 100 sites and they categorized these EMRs into five categories depending on the fundamental peak frequency of MHVR for 0.2 to 1Hz, 1 to 2 Hz, 2 to 5 Hz, and 5 to 10 Hz, and 10 to 20 Hz. The obtained horizontal to vertical ratio by EMR is called pseudo EHVR (pEHVR). They confirmed that pEHVRs show similar shape to EHVRs compared to those of MHVRs. Fig. 1 shows the averaged EMRs in Japan for the normalized frequency and Fig. 2 shows three examples of the resultant pEHVRs in comparison with the observed EHVRs and MHVRs. We can see the spectral shape of pEHVR is almost identical to the one of observed EHVRs and the characteristic of MHVRs are quite different from those of EHVRs, which shows how the proposed EMR can effectively works for filling the gap.

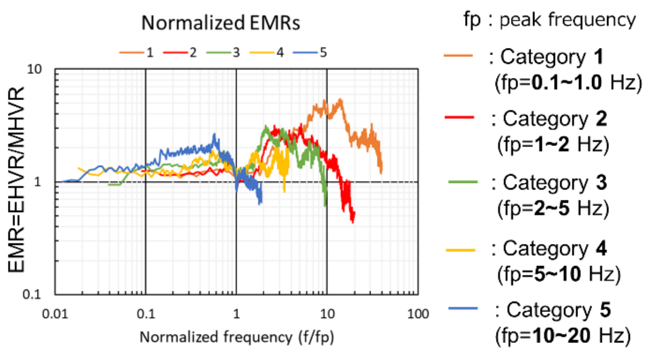

Fig.1 – The averaged EMRs in Japan for all five categories.

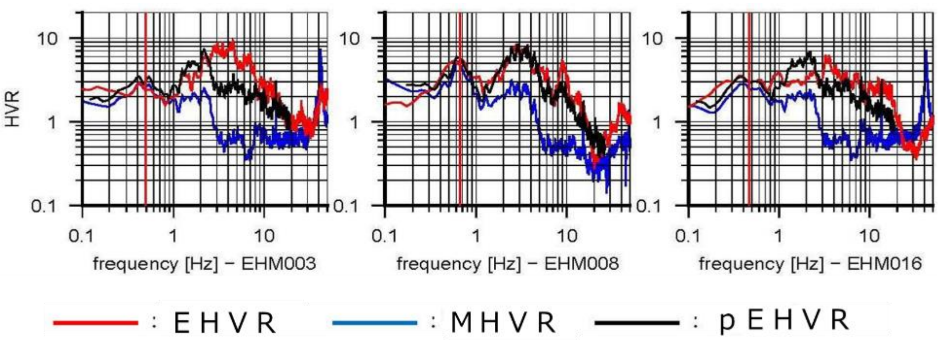

Fig. 2 – Comparison of pEHVR calculated from MHVR and the EMR in Japan (Category 1), with MHVR and observed EHVR at three sites in Japan (from Kawase et al., 2018 [1]).

When we apply this method to the data in a region with different tectonic settings, however, it would be desirable to use EMR specific for the region, rather than to substitute directly the EMR in Japan, since EMR depends on the velocity structure and so it is not always the same in different regions around the world. The final goal of this study is to propose an easier way to get EMR for a seismologically quiet region outside Japan and to delineate the velocity structures from pEHVR using the EMR specific for the area. Aiming at the goal we used the data at the earthquake observation sites in the Grenoble basin in France. We calculated the EMR specific for the Grenoble Basin, and checked the validity of the method by comparing pEHVRs with observed EHVRs, and also compared the velocity structures from pEHVRs with those from observed EHVRs inverted by using the reference model constructed based on the borehole date at one site in the basin. Then we constructed the new reference model which has a detailed deeper part based on the results. The new reference model will be used for the velocity structure inversion at the sites where we do not have observed earthquake data.

2. The previous study in the Grenoble basin and calculation of EMR correction specific for the Grenoble Basin (EMRG)

Several studies on the geophysical properties of the Grenoble basin sediment filling have been performed in the past. Gueguen et al. (2007) [4] derived the predominant frequency contour map using the microtremor data which were observed at more than 300 sites, as shown in Figure 3. Guillier et al. (2007) [5] studied the stability of MHVR by using the data in the Grenoble Basin. Vallon (1999) [6] delineated the geological boundary depth contour map by using the gravity data, which is also shown in Figure 3.

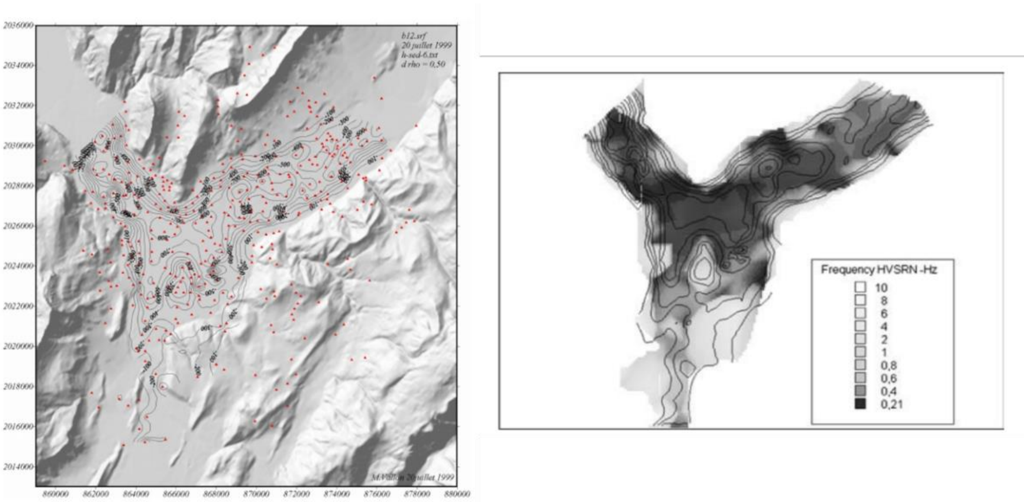

Fig. 3 – The depth contour of the geological boundary from the gravity anomaly by Vallon (1999) [6] (on the left) and the fundamental peak frequency by Gueguen (2007) [4] (on the right)

We calculated EMR for the Grenoble Basin, hereinafter called EMRG, based on the EMR in Japan because we do not have a sufficient number of earthquake observation sites in the Grenoble Basin. We analyzed the microtremor and strong ground motion data at five earthquake observation sites in the Grenoble basin. The strong ground motion data was provided through EIDA seismic data distribution site. The fundamental peak frequency of MHVR at each site was within the

Category 1 in the EMR in Japan, where the fundamental peak frequency of MHVR is within 0.2 to 1 Hz. Fig. 4 shows the location of the five sites used.

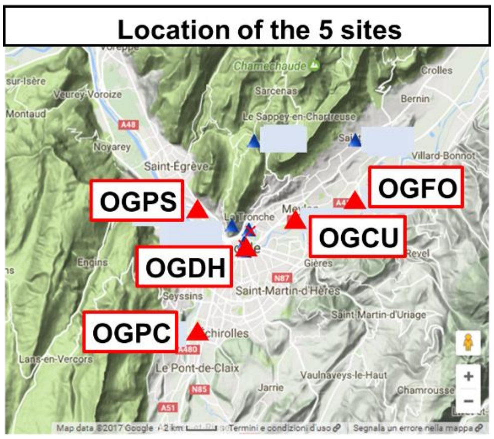

Fig. 4 – The location of five sites in the Grenoble Basin.

In order to make pEHVR closer to the observed EHVR for five sites, we defined EMR$_G$ and pEHVR can be estimated by equation (1) and (2), by assuming that the spectral shape of EMR$_G$, should follow the shape of EMR in Japan and only the amplitude would be different with a modification factor α. We calculated each EMR$_G$ by changing α from 0.1-0.5.

$$EMR_G = 10^{\alpha log EMR} \quad (1)$$

$$pEHVR = MHVR * EMR_G = MHVR * 10^{\alpha log EMR} \quad (2)$$

Then we searched α until the sum of logarithmic residuals of amplitude between pEHVRs and observed EHVRs at five sites became the minimum value, following the equation (3).

$$M = \frac{\Sigma(\log(obsEHVR)-\log(pEHVR))^2/f}{\Sigma(\log(obsEHVR)^2)/f} \quad (3)$$

After the first search by changing α from 0.1-0.5 at the interval of 0.1 and the second by α from 0.2-0.3 at the interval of 0.01, we found that the optimal α is 0.28.

3. Comparison of the pEHVR calculated from EMR$_G$ with other HVRs

We compared the best pEHVR, which is pEHVR calculated by EMR$_G$ with α=0.28 with MHVR, pEHVR calculated from the EMR in Japan, and the observed EHVR. We found that pEHVR was closer to the observed EHVR, compared to MHVR and pEHVR from the EMR in Japan. We also found that pEHVR from the EMR in Japan was overestimated especially in the higher frequency range than the fundamental peak frequency. This would be because the EMR in Japan reflects the average basin structure in Japan, which is softer than the structure in the Grenoble Basin, and so the EMR in Japan in the frequency range higher than the fundamental peak is much higher in amplitude as shown in Fig. 5. This result suggests that we need to calculate the EMR specific for the target region outside Japan, instead of using the EMR in Japan, if the tectonic settings are significantly different from those in Japan. Fig. 5 shows the comparison of the pEHVR with other HVRs at each site.

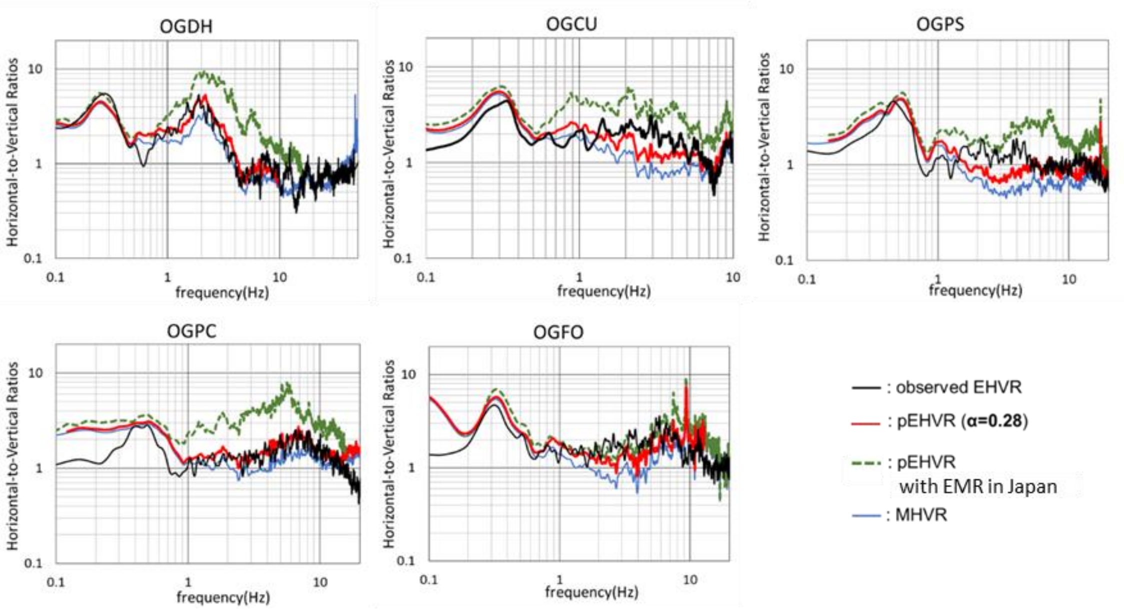

Fig. 5 – Comparison of the pEHVR calculated from EMRG with other HVRs at five sites.

4. Validation of the pEHVR from EMRG

We inverted the velocity structures from pEHVR from EMRG with α=0.28, MHVR, and the observed EHVR at five sites and checked the similarity of the velocity structures by pEHVRs to those by observed EHVRs, compared to those by MHVRs.

We used the 1-D velocity structure inversion method for observed EHVR through Hybrid Heuristic Search (HHS) method proposed by Nagashima et al. (2014) [2], based on the diffuse field concept proposed by Kawase et al. (2011) [3]. For the inversion, we made the velocity structure used as a reference, which we call the reference model, based on the borehole data at one site with the name of G04, which gave the information down to the geological bedrock. Fig. 6 shows the location of G04 and Fig. 7 shows the velocity structure at G04. G04 is a broad-band site co-located with OGFO for 5 months (Chaljub et al., 2006 [7])

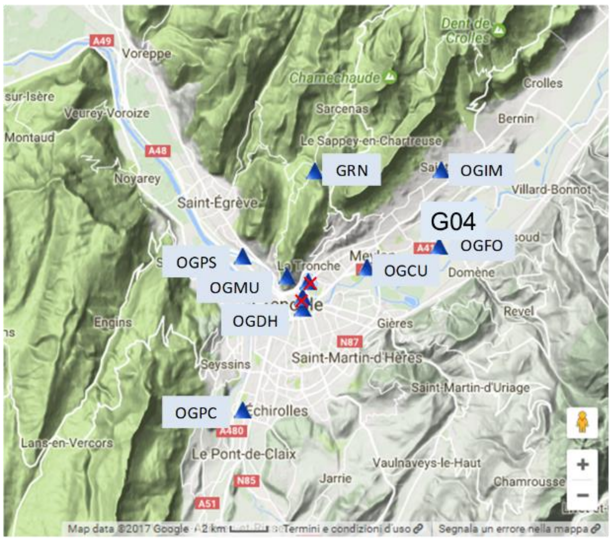

Fig. 6 –The location of G04

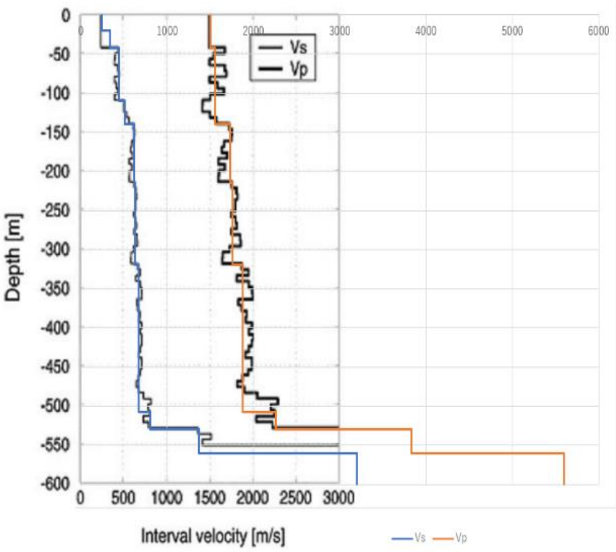

Fig. 7 –The velocity structure from borehole data at G04

We found that inverted velocity structures from pEHVR were closer to those by the observed EHVR, comparing with those by MHVR. Fig. 8 shows the comparison of the velocity structures inverted from pEHVRs, MHVRs, and observed EHVRs, together with the reference models at five sites. We call the process we have explained so far as Step-1 and the one from the next chapter as Step-2, for the better understanding of the process on the paper.

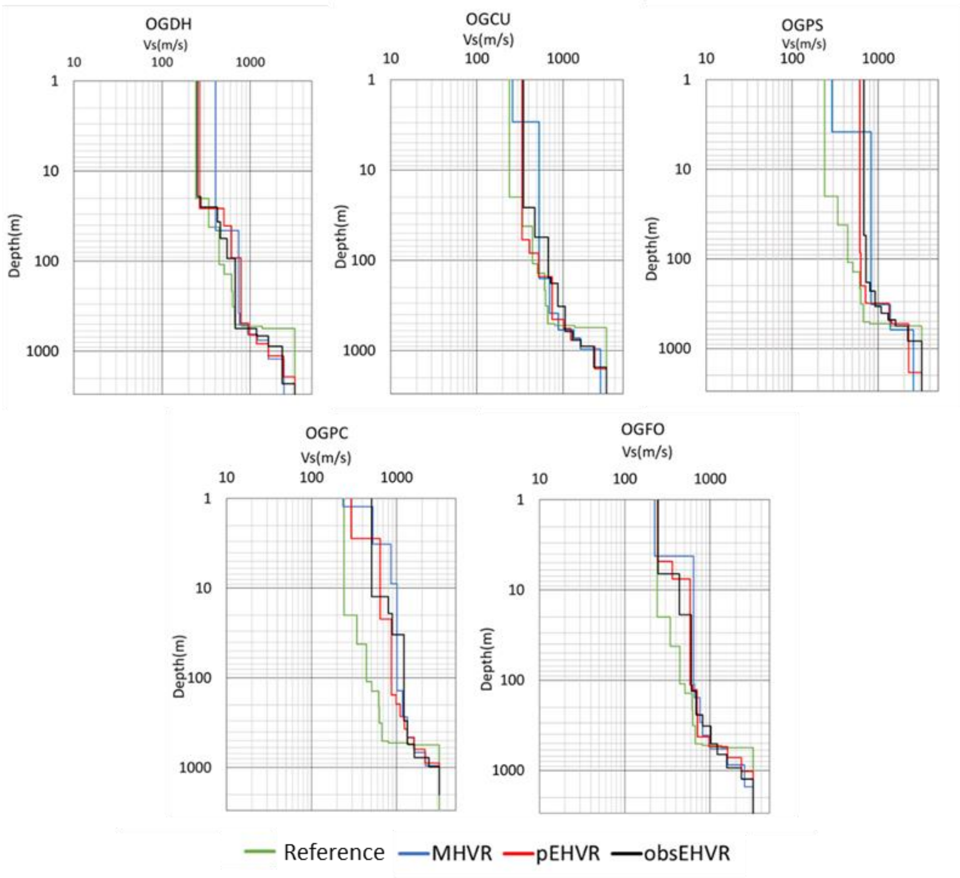

Fig. 8 –Comparison of the velocity structures inverted from pEHVRs, MHVRs, and observed EHVRs, together with the reference models at five sites.

5. Reference model construction from the inversion results in Step-1

The reference model that we used for the inversion in Step-1 is made from the borehole data at G04, which provides us P- and S-wave velocity information down to 550 m. Below that depth, the rock formation was found and its P- and S-wave velocities were assumed to be those at the seismological bedrock by the geophysical exploration. However, after getting the inverted velocity structures, we found that there exist a couple of layers with increasing velocities down to the real seismological bedrock, which shows up much deeper than 550 m. Therefore, it would be better to use a reference model with a more detailed deeper part in order to constrain the searching range in the inversion when we use pEHVR for the sites where we do not have observed EHVR. This is because pEHVR, which is coming from MHVR, cannot constrain the structure in the deeper part as good as the observed EHVR. Thus, we tried to construct a scheme to make a reference model of the deeper part from the fundamental peak frequency for each site based on the results at five OG-series sites in Step-1. In the same context, we also check again the common characteristics of the shallower part and make a new shallower part model based on the results in Step-1. Then we combine the deeper and shallower parts to make a reference model for inversion. From now on, we call this reference model based on the empirical relationship of the inverted structures in Step-1 as the new reference model and call the reference model used in Step-1 as the original reference model.

In order to define the boundary between the shallower and deeper parts at each site, we would like to know which depth is controlling the fundamental peak frequency inside the Grenoble Basin. So we compare the observed fundamental peak period T_0 with the theoretical T_0, which is defined as the inverse of the average S-wave velocity to the certain depth Z, Avs_z, multiplied by 4 times the depth Z, that is (4*Z/Avs_z).

This is the one-quarter wavelength theory for the resonance period T_0 of an equivalent two-layered structure. We tested the threshold S-wave velocity for Z to be either 0.8 km/s, 1.3 km/s., or 3.2 km/s. Fig. 9 shows the three relationships between T_0 from the observed pEHVR and T_0 from the theory. It turned out that T_0 is controlled by the depth down to the layer with an S-wave velocity of 1.3 km/s, that is, Z1.3. From that result, we regarded Z1.3 as the boundary between the shallower and deeper parts.

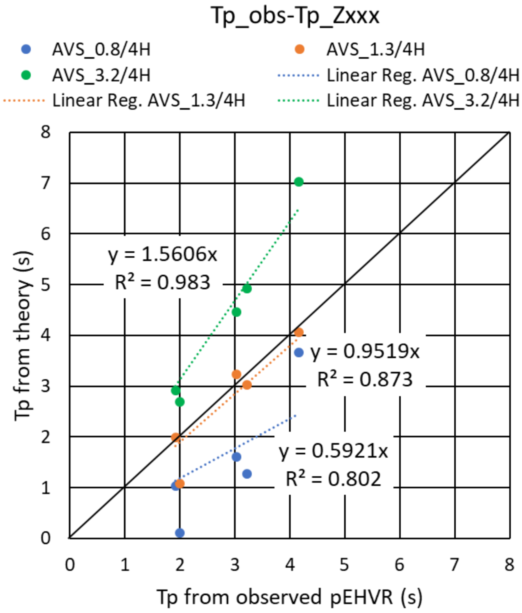

Fig. 9 –Relation between T_0 from observed pEHVR and T_0 from theory.

For the deeper part, we first construct the detailed deeper model as a representative model by averaging the velocity structures in the deeper parts in Step-1, assuming only three layers. The deeper part at each site is calculated based on this representative model. As a result of the averaging operation in S-wave velocities for three representing layers, we got 1.33 km/s layer, 1.56 km/s layer, and 2.35 km/s layer. Fig. 10 shows those velocity structures with the averaged three layers resulted in the inversions in Step-1 at five sites and the depth-averaged deeper velocity structure calculated from them used as a representative model of the deeper part for the calculation of the reference model at each site in Step-2.

In order to make the new reference model, we first need to estimate Z1.3 at each site where we want to analyze since we regarded Z1.3 as the bottom of the shallower part. We also need the depth of the real seismological bedrock Z3.2, when we construct the deeper model at each site based on the representative model shown in Fig. 10.

In order to get the equation to calculate estimated Z1.3 and Z3.2, we checked the correlation between T_0 from pEHVR and the depth down to the threshold Vs layer. Fig. 11 shows the relationships between T_0 from the observed pEHVRs and Z0.8, Z1.3, and Z3.2 at five sites. We found that Z1.3 and Z3.2 are linearly correlated with T_0, and the regression coefficient of 183 m/s, with which we can translate the observed T_0 into the estimated Z1.3. We also calculate the average ratio between Z3.2 and Z1.3, so that we can estimate Z3.2 from Z1.3 at each site as shown in a black sold line. We found that it is 2.54 times. We also found that the gravity boundary depth by Vallon (1999) [6] is nearly equal to Z1.3, as shown in Fig. 11 in yellow symbols. This correlation will be used in the validation of the method proposed in this paper after performing the velocity structure inversions for the sites in Step-2.

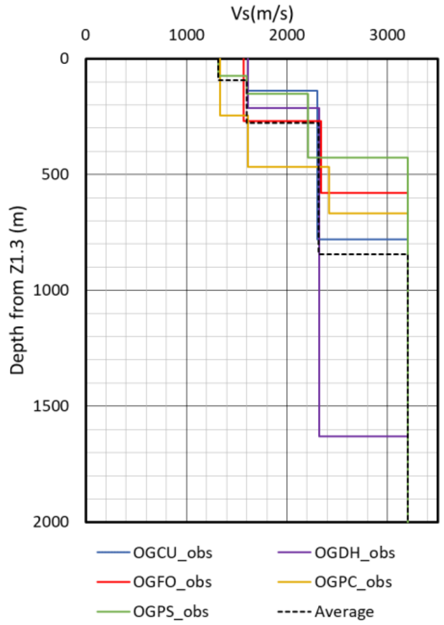

Fig. 10 – Velocity structures in solid lines resulted in Step-1 at 5 sites and averaged deeper velocity structure calculated from them in black dotted line.

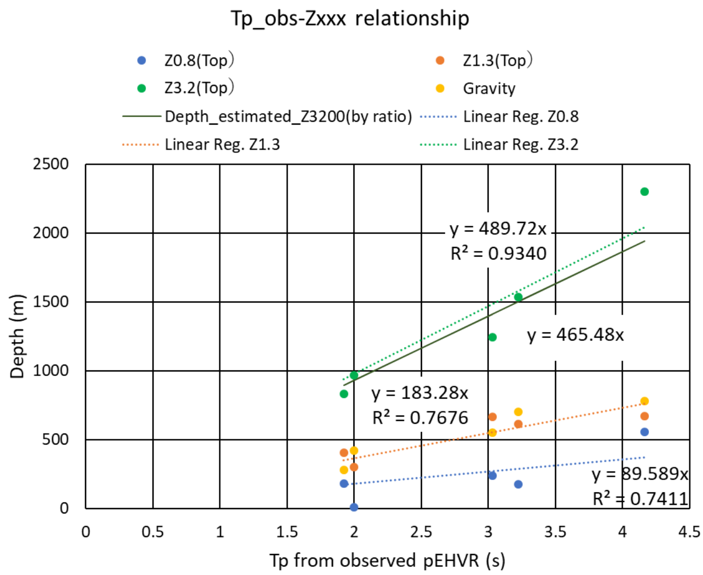

Fig. 11 – Relation between the depth and T_0 from observed pEHVR and Z0.8, Z1.3, and Z3.2 at 5 OG-series sites.

Based on the relation we got above, the new reference model at each site is constructed as follows: After reading the T_0 at a site, Z1.3 and Z3.2 are calculated by the equation (4) and (5).

$$Z1.3=183*T_0 \quad (4)$$

$$Z3.2=2.54*Z1.3 \quad (5)$$

Here the value of 183m/s is the regression coefficient and the value of 2.54 is the average ratio between Z1.3 and Z3.2 at five sites as shown in Fig. 11. The average coefficient of 183 m/s suggests that the average S-wave velocity of the basin above the layer with Vs=1.3km/s is 4 times of this value, that is, 733 m/s from the quarter-wavelength theory.

The thickness of i-th layer in the deeper part Hi_d is calculated by proportionally distributing the thickness of the deeper part from the representative model shown in the black dotted line in Fig. 10. For estimated Z1.3 and Z3.2 at each site, the equation (6) is used:

$$Hi\_d=Hi\_d\_rep*(Z3.2-Z1.3)/(Z3.2\_rep-Z1.3\_rep) \quad (6)$$

where Hid_rep is the thickness of i-th layer of the deeper part, Z3.2_rep and Z1.3_rep are those of the representative model in Fig. 10.

The thickness of i-th layer in the shallower part Hi_s is calculated by proportionally distributing the thickness in the shallower part of the original reference model, as shown in equation (7) below:

$$Hi\_s=Hi\_s\_ori*Z1.3/Z1.3\_ori \quad (7)$$

where Hi_s_ori is the thickness of i-th layer of the original reference model.

6. Validation of the new reference models for OG-series sites

After making the new reference models at the five OG-series sites, we inverted again the velocity structures using these new reference models in order to check the validity of the new reference model. Fig. 12 shows the comparison of the velocity structures inverted from the original reference model, the new reference model, and the observed EHVR. Fig. 13 compares EHVRs of the inverted velocity structures with new reference models and the original reference models, with the observed EHVRs. We can see the velocity structures and the resultant EHVRs with the new reference models are very close to those with the original reference model.

7. Summary and future tasks

We calculated the EMR for the Grenoble basin, which we call EMR_G by assuming that the shape of EMR_G should follow the shape of the EMR in Japan and only the amplitude would be different with a modification factor α. By changing α from 0.1 to 0.5, we found the best α to be 0.28. We found that pEHVRs using EMR_G with α=0.28 at five sites in the Grenoble basin were closer to observed EHVRs compared to microtremors and pEHVR using the EMR in Japan.

In order to check the validity of pEHVRs, we inverted velocity structures from pEHVRs, MHVRs, and observed EHVRs at five OG-series sites in the Grenoble basin using the reference model constructed from the borehole data at G04, which we call the original reference model. We found that the velocity structures by pEHVRs were closer to those by observed EHVRs, compared to those by MHVR.

We proposed a strategy for deriving a new reference model for each site based on the averaged deeper velocity structure from OG-series sites and the shallower part of the original reference model in a proportional manner. The velocity structures using the new reference model for each site are sufficiently close to those with the original reference model.

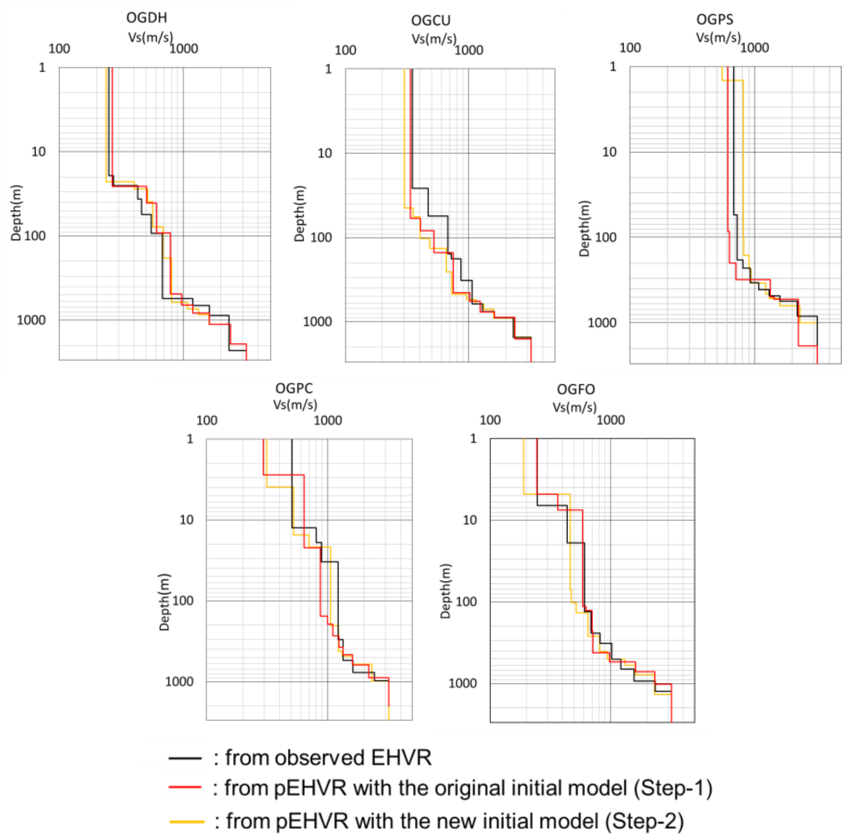

Fig.12– Comparison of the velocity structures inverted from pEHVR using the original reference models, those from pEHVRs using the new reference models, together with those from the observed EHVRs

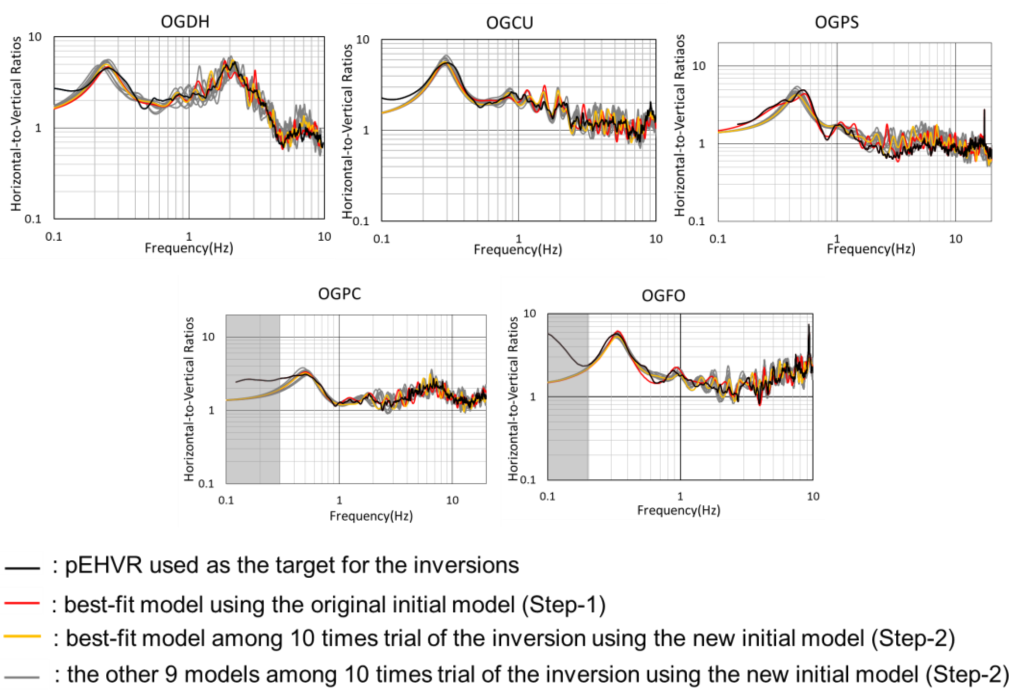

Fig. 13 – Comparisons of EHVRs from the velocity structures inverted from the original reference model and the new reference models, together with the pEHVRs used as the targets.

For future tasks, we will apply the proposed method that includes definition of the reference model based on equations (4) to (7) to the sites where we do not have observed EHVRs and invert the velocity structures by using the pEHVRs with EMR_G. Then we will make the whole basin structure model by interpolating the data from the results. We will check the validity of the method by comparing EHVRs obtained by inputting the bedrock ground motion to the bottom of the model with the observed EHVRs at the strong ground motion observation sites. The effects of 2D/3D amplification in the horizontal and vertical amplification can be considered by Finite Difference or Spectral Element methods as in Chaljub et al. (2006) [7].

8. Acknowledgements

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