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VELOCITY STRUCTURE INVERSIONS FROM HORIZONTAL TO VERTICAL (H/V) SPECTRAL RATIOS OF EARTHQUAKE MOTIONS

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ABSTRACT

In this study, the illumination of an observation site from the source is assumed to be produced only by incident plane waves. The average of normalized ground motion spectral densities will then depends only on depth and a one dimensional description of wave propagation for a diffuse field of ground motions can be applied. Thus, the imaginary part of the Green function at the free surface when source and receiver are both at the same point is proportional to the square of the absolute value of the corresponding transfer function for a plane, vertically incident wave with unit amplitude. Average strong motion H/V spectral ratio of observed data at a particular site can then be computed and compared to the ratio of theoretical horizontal and vertical transfer functions corresponding to the 1D soil structure of the considered site. A series of inversions of underground 1D structure from the bedrock to the surface from observations sites in the Kyoto prefecture, Japan, is then carried out with a Genetic Algorithm code, following the proposed theory for earthquake H/V ratios.

INTRODUCTION

Site effects are of great importance in seismology and earthquake engineering because they modify the frequency content of the incident wave and lead to an amplification of the wave propagating inside the site (e.g. soft sedimentary basins). As a result, the damage pattern of the engineering structures is often linked to the subsurface geology. The deployment of vertical arrays has permitted detailed wave propagation analysis of one dimensional soil columns, leading to obtain quantitative physical parameters, such as shear-wave velocity, pressure-wave velocity and damping factors, through different inversion techniques. However, as vertical arrays are not always available, it would be quite useful to be able to invert soil columns parameters with only seismic signal at the surface.

In this study, strong ground motion in elastic layered media is considered. All sites are assumed to be “sufficiently” flat layered sites and we restrict ourselves to earthquake sources with small epicentral distances and deep enough, such that surface waves are not dominant or do not appear yet. The surface waves can then be neglected and the illumination can be conceived as produced by incident plane waves. In that case, the average of normalized ground motion spectral densities will depend only on depth and a one dimensional description of wave propagation for a diffuse field of ground motions can be applied. Thus, the imaginary part of the Green function at the free surface when source and receiver are both at the same point is proportional to the square of the absolute value of the corresponding transfer function for a plane, vertically incident wave with unit amplitude.

Average strong motion H/V spectral ratio of observed data at a particular site can then be computed and compared to the ratio of theoretical horizontal and vertical transfer functions corresponding to the 1D soil structure of the considered site. A series of inversions of underground 1D structure from the bedrock to the surface from observations sites in the Kyoto prefecture, Japan, is then carried out with a Genetic Algorithm code, following the proposed theory for earthquake H/V ratios.

AVERAGE HORIZONTAL TO VERTICAL SPECTRAL RATIO

All sites considered in this study are supposed to be "sufficiently" flat layered sites, such that 1D seismic wave propagation can be assumed (as small as 7 km from Table 1, we cannot say that it is deep enough). Moreover, we keep only a short window of the actual earthquake ground motions observed at the sites of interest. The time window chosen lasts 20 s and begins just before the arrival of S-wave. As long as these conditions are respected, the local structure around an observation site will be illuminated mostly by plane body waves from the source, including multiple scattering waves, so that the expression for the average horizontal to vertical (H/V) spectral ratio can be obtained as Equation (1).

$$\frac{H(\omega)}{V(\omega)} = \sqrt{\frac{Im\left(G_{11}^{1D}(x,x,\omega)\right) + Im\left(G_{22}^{1D}(x,x,\omega)\right)}{Im\left(G_{33}^{1D}(x,x,\omega)\right)}}$$

where $Im\left(G_{ij}^{1D}(x,x,\omega)\right)$ is the ijth component of the imaginary part of the one dimensional Green function between source x and receiver x at frequency ω.

As we consider only a one dimensional Green function, we can write; $G_{11}^{1D}(x,x,\omega) = G_{22}^{1D}(x,x,\omega)$ and Equation (1) becomes:

$$\frac{H(\omega)}{V(\omega)} = \sqrt{\frac{2Im\left(G_{11}^{1D}(x,x,\omega)\right)}{Im\left(G_{33}^{1D}(x,x,\omega)\right)}}$$

By summing motions of a large enough number of seismic events, we can assume that the ground motion is spatially homogeneous in a statistical sense. Therefore, the motion will depend only on depth and we can apply a one dimensional description of wave propagation for a diffuse field of ground motions.

Claerbout (1968) established the relationship between reflection response and autocorrelation of surface motion for one dimensional layered media. Kawase et al. (2011) derived a corollary of Claerbout's result for a plane, vertically incident wave with unit amplitude propagating into multiple horizontal layers overlaying a half space; and found that the imaginary part of the Green function at the free surface for the surface source is equal to the square of the absolute value of the corresponding transfer function, divided by four times the frequency and the half-space impedance:

$$Im\left(G_{ii}^{1D}(0,\omega)\right) = \frac{1}{4\omega\rho_H c_H}|TF_i(0,\omega)|^2$$

where $TF_i(z,\omega)$ is the ith component of the transfer function at depth z and frequency ω, ρ_H is the mass density and c_H is either P- or S-wave velocity of the half-space, depending whether we consider the vertical or the horizontal component of the transfer function. By writing Equation (3) for both horizontal and vertical motions, Kawase et al. (2011) showed that the H/V spectral ratio can be written as:

$$\frac{H(0,\omega)}{V(0,\omega)} = \sqrt{\frac{2\alpha_H}{\beta_H}} \frac{|TF_1(0,\omega)|}{|TF_3(0,\omega)|}$$

where α_H and β_H are P- and S-wave velocities of the half-space.

We can then compare the ratio of transfer functions from Equation (4) obtained with a theoretical 1D soil column and the observed ratio of horizontal and vertical square power spectral densities averaged on several seismograms. The ratio of transfer function will be then considered as a characteristic function associated with each set of soil layers properties and the H/V ratio as the objective function for the inversion of the soil column. The inversion is performed using a Genetic Algorithm code (De Martin, 2010; De Martin et al., 2010), in which the horizontal and vertical transfer functions are computed with the Thomson-Haskell propagator matrix method (Thomson, 1950; Haskell, 1953).

EARTHQUAKE DATA

In this study, we focus on soil column inversions performed at three sites from K-NET (KYT008 and KYT009) and KiK-net (KYTH04) networks. We selected 32 seismograms between 1997 and 2009, with epicenter less than 200 km from the observation sites and with PGA superior to 3 cm/s², so as to avoid having too much noise. Dates, depths, magnitudes, distances from observation site and PGA of all seismograms used in this study are given in Table 1.

Table 1. Characteristics of seismmograms used in this study

Date	Depth (km)	Magnitude	Distance from site (km)			PGA (cm/s²)		
			KYT008	KYT009	KYTH04	KYT008	KYT009	KYTH04
2009/02/18 – 06:47	9	5.2	94.1		82.4	6.81		8.647
2008/08/30 – 18:28	15	4.2	45.7	43.33	32.7	9.70	8.53	14.843
2008/08/08 – 04:35	15	4.2	44.8		32.7	5.26		8.295
2007/04/15 – 12:19	16	5.4	106.0	92.55	94.1	8.21	9.64	8.521
2007/01/22 – 02:16	13	4.5	100.4		88.2	7.03		6.147
2006/06/03 – 00:48	7	4.1	32.7	32.09	19.8	15.85	6.59	42.071
2006/02/16 – 23:10	14	4.4	104.6		91.3	8.26		5.996
2005/12/24 – 11:02	43	4.8			117.0			5.325
2004/12/01 – 23:30	13	4.0	44.9	31.26	35.1	5.63	7.51	7.706

2004/10/05 – 08:33	12	4.8	116.3		105.4	3.54		3.933
2003/12/23 – 14:34	9	4.4	91.3		78.5	13.40		6.304
2003/03/13 – 21:04	14	4.1	59.6		48.0	14.21		5.608
2003/02/06 – 02:37	15	4.5	25.0	10.73	20.7	241.93	131.93	63.328
2002/07/16 – 20:09	16	4.2	32.7	18.54		37.32	123.57	
2002/04/28 – 10:34	56	4.3	87.3		79.1	19.24		3.952
2001/12/28 – 03:28	7	4.2			37.6			6.508
2001/08/25 – 22:21	10	5.1	27.0	14.50		84.44	267.01	
2001/04/16 – 19:05	14	4.0	53.4		40.4	32.26		10.063
2001/01/12 – 08:00	10	5.4	85.6		99.1	19.22		5.299
2001/01/06 – 11:48	48	4.6			141.1			3.720
2000/10/31 – 01:43	44	5.5	138.0	123.61	130.9	34.76	39.37	8.246
2000/10/06 – 13:30	11	7.3	186.0	196.23		36.56	56.40	
2000/06/07 – 06:16	22	6.1	176.3			11.19		
2000/06/05 – 09:54	10	4.7	82.5			15.75		
2000/05/16 – 04:09	16	4.3	33.8	21.56		277.92	279.90	
1999/11/07 – 03:34	14	4.8	96.5			16.41		
1999/08/21 – 05:33	70	5.4	135.0			12.45		
1999/03/16 – 16:43	12	4.9	48.5	40.74		57.13	58.31	
1999/02/12 – 03:16	15	4.0	33.6			35.66		
1998/04/22 – 20:32	10	5.4	106.2			36.50		
1997/09/07 – 02:19	17	4.2		13.79			408.37	
1997/01/08 – 22:36	13	4.0	16.1	1.71		413.37	191.79	

After eliminating accelerograms not recorded or with PGA inferior to 3 cm/s², there are 28 earthquakes left for station KYT008, 13 for station KYT009 and 19 for stations KYTH04. Kawase et al. (2011) showed that the summation of synthetic waveforms converges quite fast to the theoretical prediction, such that we do not need many ground motions to get convergent ratios. Therefore, we assume that we have enough recorded earthquake motions to have a good quality of the observed H/V ratio. This assumption should however be investigated more thoroughly. Indeed, as can be seen from the localizations of the earthquakes and three observations sites shown in Fig. 1, the spatial homogeneity of the ground motion does not seem to have been reached. Particularly, it appears that there are more earthquakes located south and east of the observation sites than north and west.

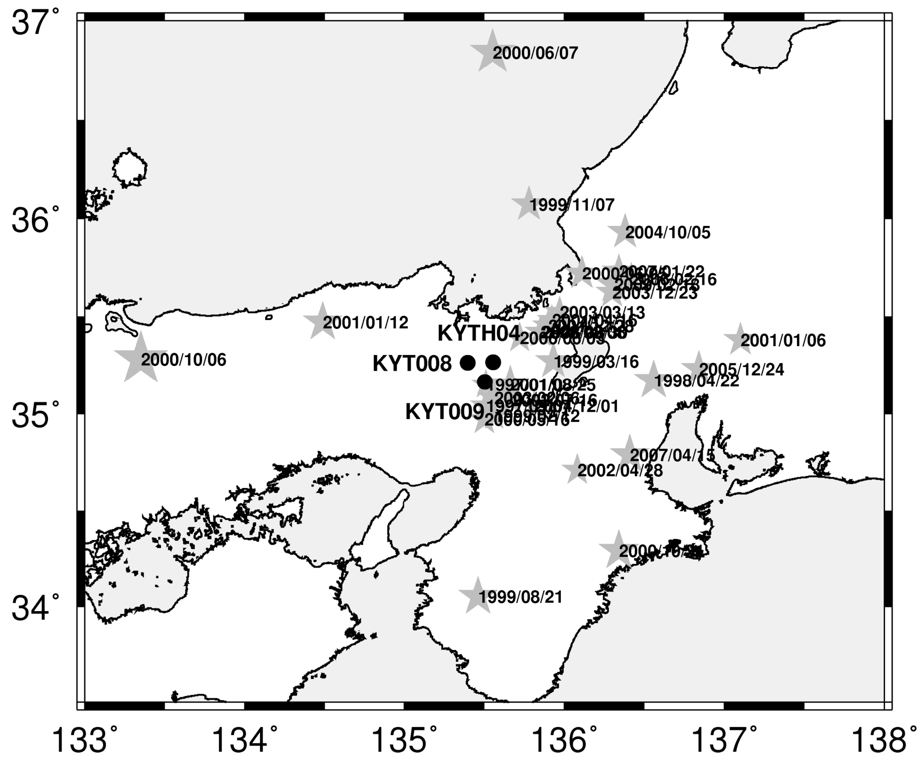

Fig. 1. Localization of earthquakes and observation sites.

INVERSION OF THREE SOIL COLUMNS

Inversions of soil columns at observation sites in the Kyoto and Osaka, prefectures, Japan were carried out. We show here the results obtained for three soil columns with a relatively good agreement between the objective function and the best ratio of transfer functions found at the end of the inversion.

First observation site: K-NET station KYT008

Information about soil layers properties was provided by previous studies (Kawase and Matsuo, 2004; Kawase, 2006), and was used to establish an initial velocity log of the soil column. Initial values of S-wave velocity (Vs_0), P-wave velocity (Vp_0) and thickness (TH_0) of each layer are given in Table 2.

Table 2. Initial values and intervals of variation of soil column parameters.

Layer number	Vs_0 (m/s)	Variations of Vs	Vp_0 (m/s)	Variations of Vp	TH_0 (m)	Variation of TH

1	100.00	$0.50 * Vs_0 – 1.25 * Vs_0$	600.00	Not inverted	1.80	$0.50 * TH_0 – 1.25 * TH_0$
2	100.00	$0.50 * Vs_0 – 1.25 * Vs_0$	600.00	Not inverted	0.20	Not inverted
3	650.00	Not inverted	1839.70	Not inverted	0.70	Not inverted
4	650.00	Not inverted	1839.70	Not inverted	0.30	Not inverted
5	650.00	Not inverted	2267.00	Not inverted	0.45	Not inverted
6	650.00	$0.50 * Vs_0 – 1.25 * Vs_0$	2267.00	Not inverted	6.77	$0.50 * TH_0 – 1.25 * TH_0$
7	1784.92	Not inverted	3519.38	Not inverted	10.00	Not inverted
8	3348.73	$0.45 * Vs_0 – 1.20 * Vs_0$	5833.82	$0.50 * Vp_0 – 1.25 * Vp_0$	340.00	Not inverted
9	3348.73	$0.45 * Vs_0 – 1.20 * Vs_0$	5833.82	$0.50 * Vp_0 – 1.25 * Vp_0$	160.00	Not inverted
Bedrock	3400.00	$0.45 * Vs_0 – 1.20 * Vs_0$	5909.70	Not inverted		

Some soil layers parameters have only little influence on the corresponding theoretical horizontal and vertical transfer functions, such that any value of these parameters will give nearly the same ratio of transfer functions. Hence, these parameters will not be easy to invert as many possible values could provide a good fit between the observed H/V ratio and the theoretical ratio of horizontal and vertical transfer functions. Therefore, we choose to invert only around ten parameters for each station, selecting those which seem to be the most influential. The other parameters are set constant and are given the initial value. By restricting the search domain of the Genetic Algorithm, we aim to obtain a unique solution. Moreover, to avoid local minima and check whether the solution found is unique, ten independent inversions with the same input parameters are carried out and we keep the ten best velocity logs obtained for each inversion.

The range intervals of variation of the inverted parameters are indicated in Table 2. It should be noted that the initial value of an inverted parameter has no influence on the result of the inversion; it only helps choosing the interval of variation of this parameter. As the inversion is performed with a Genetic Algorithm, the inverted parameters can only take discrete values. In this study, we divide the intervals of variation into fifteen equal parts, such that the inverted parameters can take sixteen different values.

It should be noted that only the ratio between P- and S-wave velocities of the half-space can be inverted by this method, as can be deduced from Equation (4). For simplification, we choose to invert only S-wave velocity of the half-space and set P-wave velocity constant. However, any couple of P- and S-wave velocities with the same ratio between both velocities can be considered as a solution.

Results of the inversion are shown in Fig. 2. On the left panel (a), we can see the objective H/V ratio computed from earthquakes data in black plain line, the ratio of horizontal and vertical transfer functions corresponding to the initial velocity log in black dotted line and all the best ratios of horizontal and vertical transfer functions corresponding to the best velocity logs found by the ten inversions in grey lines. The center panel (b) shows the corresponding S-wave velocity and P-wave velocity logs. The black line is the initial log and the grey lines are the best logs obtained by the ten inversions, corresponding to the best ratios on the left panel. The right panel (c) is a detail of the center panel (b) and shows the velocity logs of the first 30 meters.

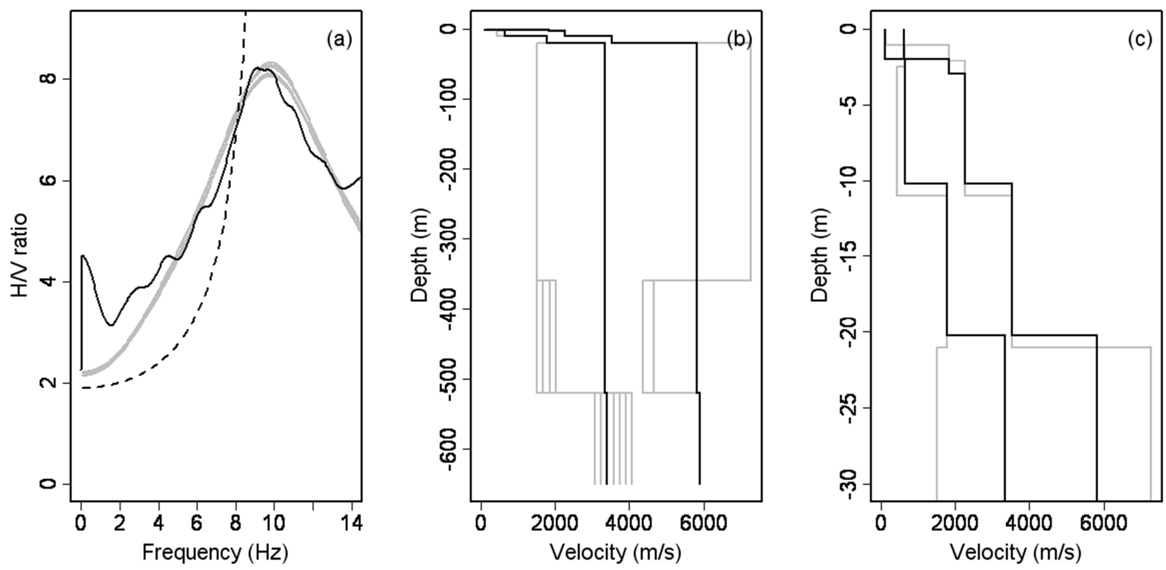

Fig. 2. Results of the inversion for observation site KYT008.

There is a good agreement between the theoretical ratio of horizontal and vertical transfer functions obtained from the inversion and the objective H/V ratio obtained from earthquakes data, particularly for the higher frequencies (higher than 4 Hz). The agreement is less good for the lower frequencies. All the independent inversions give the same value of P-wave velocity, thickness and S-wave velocity of the shallow layers, which indicates a good convergence of the inversion. However, the S-wave velocity of the deepest layers is not well resolved. Indeed, a large range of different values can be obtained from the different independent inversions. The effect of the deepest layers on the ratio of transfer functions can be seen especially at the lower frequencies. Meanwhile, at low frequency, the fit between the observed H/V ratio and the ratio of transfer functions is not very good. It seems that, in the domain of search chosen for this inversion, no actual good solution can be found, such that the algorithm hesitates to choose the best one among several solutions.

A quick parametric study was carried out to check which parameters could have the biggest influence on the theoretical ratio of horizontal and vertical transfer functions. Figure 3 shows the variations of the theoretical ratio when each parameter is changed one at a time. The first row corresponds to the S-wave velocities of the nine soil layers and the bedrock; the second row corresponds to the P-wave velocities of the nine soil layers; the third row corresponds to the thicknesses of the nine soil layers. In each figure, the black line represents the theoretical ratio of horizontal and vertical transfer functions in function of frequency corresponding to the initial velocity log. The two grey lines correspond to the theoretical ratio when only one parameter varies and takes either the minimal value, either the maximal value of the intervals of variation given in Table 2.

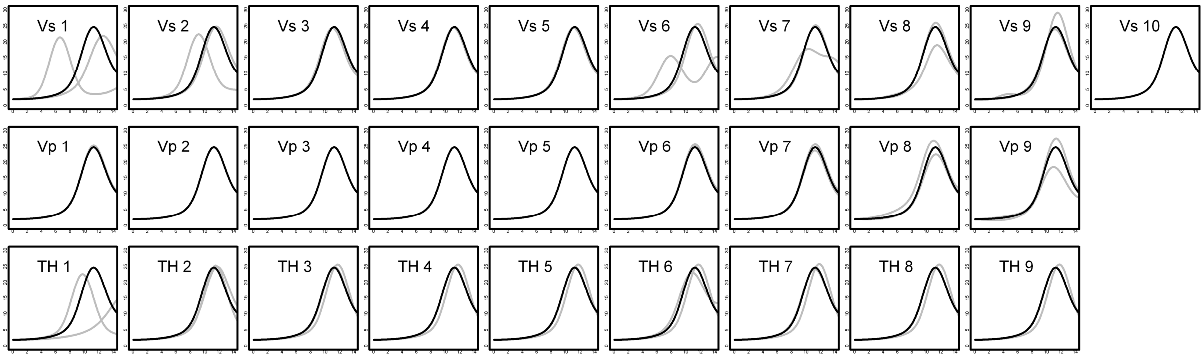

Fig. 3. Variations of theoretical H/V ratio for observation site KYT008 when changing a single parameter (S-wave velocity, P-wave velocity or thickness of each layer) at once.

As can be seen from Fig. 3, the S-wave velocities of layers 1, 2 and 6 and the thickness of layer 1 seem to have the strongest influence on the theoretical H/V ratio. The solution obtained from the inversion for these parameters can then be considered as rather robust. The other inverted parameters (S-wave velocities of layers 8 and 9, P-wave velocities of layers 8 and 9 and thickness of layer 6) have only a slight influence on the theoretical H/V ratio, such that the robustness of the solution from the inversion is more uncertain for these parameters. Finally, the S-wave velocity of the bedrock does not seem to have any influence on the theoretical H/V ratio, which explains why the algorithm has difficulty to find a solution for this parameter.

<u>Second observation site: K-NET station KYT009</u>

Initial value of S-wave velocity (Vs_0), P-wave velocity (Vp_0) and thickness (TH_0) of each layer are given in Table 3. The ranges of variation of the inverted parameters are also indicated in Table 3.

Table 3. Initial values and intervals of variation of soil column parameters.

Layer number	Vs_0 (m/s)	Variations of Vs	Vp_0 (m/s)	Variations of Vp	TH_0 (m)	Variation of TH
1	60.00	0.50 * Vs_0 – 1.25 * Vs_0	150.00	0.50 * Vp_0 – 1.25 * Vp_0	1.80	0.50 * TH_0 – 1.25 * TH_0
2	60.00	0.50 * Vs_0 – 1.25 * Vs_0	150.00	Not inverted	0.20	Not inverted
3	400.00	Not inverted	1400.00	Not inverted	1.00	Not inverted
4	400.00	Not inverted	1400.00	Not inverted	0.60	Not inverted
5	400.00	Not inverted	1400.00	Not inverted	2.40	Not inverted
6	850.00	Not inverted	3410.00	Not inverted	0.95	Not inverted
7	850.00	0.50 * Vs_0 – 1.25 * Vs_0	3410.00	0.50 * Vp_0 – 1.25 * Vp_0	113.05	Not inverted
8	2226.19	Not inverted	4172.46	0.50 * Vp_0 – 1.25 * Vp_0	620.00	Not inverted
9	3250.94	Not inverted	5689.09	Not inverted	630.00	Not inverted
10	3265.14	0.50 * Vs_0 – 1.25 *	5710.11	0.50 * Vp_0 – 1.25 *	480.00	Not inverted

		Vs_0		Vp_0		
Bedrock	3400.00	$0.50 * Vs_0 – 1.25 * Vs_0$	5909.70	Not inverted		

Results of the inversion are shown in Fig. 4. On the left panel (a), we can see the objective H/V ratio computed from earthquakes data in black plain line, the ratio of horizontal and vertical transfer functions corresponding to the initial velocity log in black dotted line and all the best ratios of horizontal and vertical transfer functions corresponding to the best velocity logs found by the ten inversions in grey lines. The center panel (b) shows the corresponding S-wave velocity and P-wave velocity logs. The black line is the initial log and the grey lines are the best logs obtained by the ten inversions, corresponding to the best ratios on the left panel. The right panel (c) is a detail of the center panel (b) and shows the velocity logs of the first 30 meters.

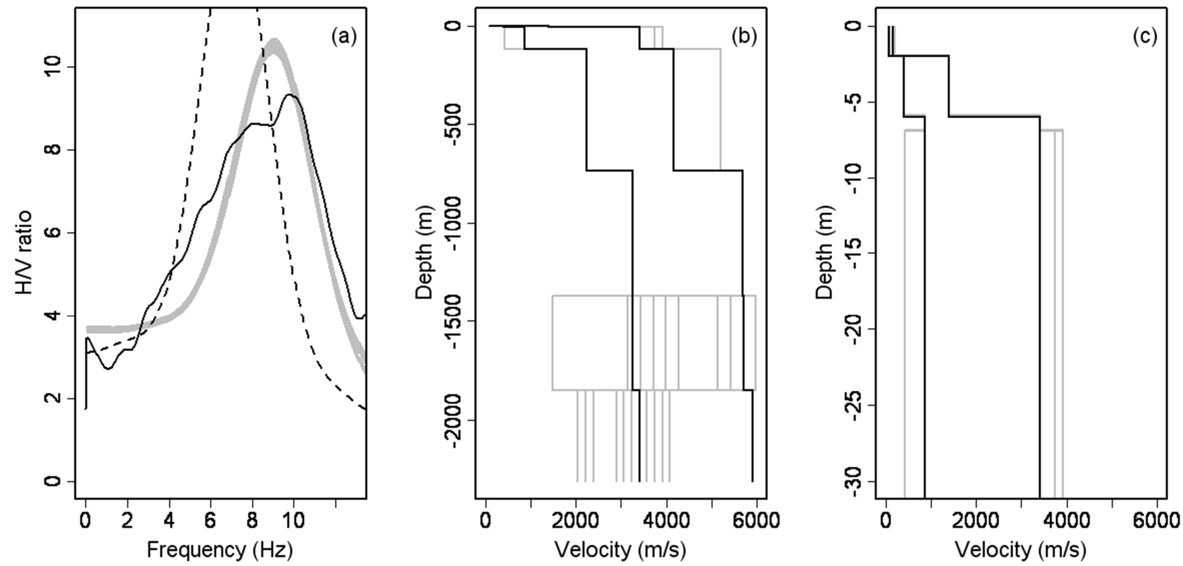

Fig. 4. Results of the inversion for observation site KYT009.

The agreement between the theoretical ratio of horizontal and vertical transfer functions obtained from the inversion and the objective H/V ratio obtained from earthquakes data is satisfactory for the whole range of frequencies where the inversion is performed. An amplitude peak is found at the same frequency but with a slightly different form. As in the previous case, all the independent inversions give the same value of P-wave velocity, thickness and S-wave velocity of the shallow layers, which indicates a good convergence of the inversion. However, the S-wave and P-wave velocities of the deepest layers are not well resolved. Indeed, a large range of different values can be obtained from the different independent inversions. This could again be explained by the difficulty to fit the ratio at low frequency.

The results of the parametric study are shown in Fig. 5. The first row corresponds to the S-wave velocities of the ten soil layers and the bedrock; the second row corresponds to the P-wave velocities of the ten soil layers; the third row corresponds to the thicknesses of the ten soil layers. In each figure, the black line represents the theoretical ratio of horizontal and vertical transfer functions in function of frequency corresponding to the initial velocity log. The two grey lines correspond to the theoretical ratio when only one parameter varies and takes either the minimal value, either the maximal value of the intervals of variation given in Table 3.

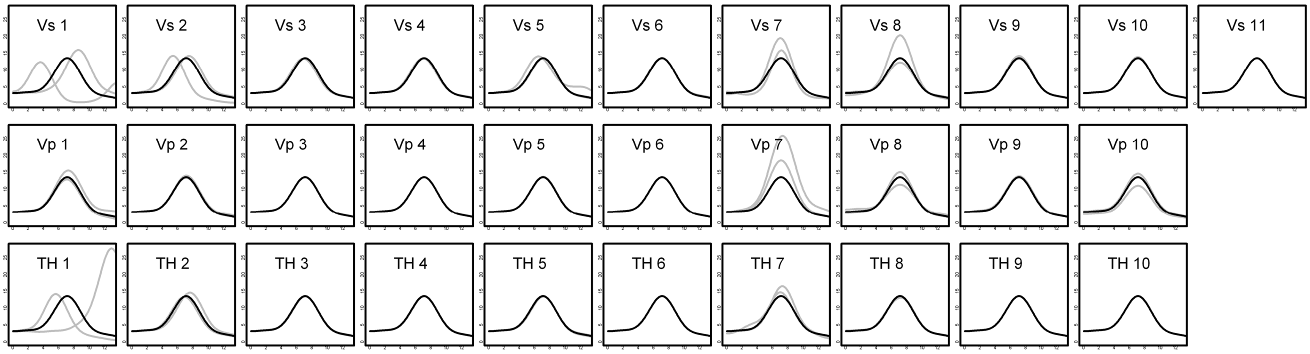

Fig. 5. Variations of theoretical H/V ratio for observation site KYT009 when changing a single parameter (S-wave velocity, P-wave velocity or thickness of each layer) at once.

As can be seen from Fig. 5, the S-wave velocities of layers 1, 2 and 7, the P-wave velocity of layer 7 and the thickness of layer 1 seem to have the strongest influence on the theoretical H/V ratio. The solution obtained from the inversion for these parameters can then be considered as rather robust. The other inverted parameters (P-wave velocities of layers 1, 8 and 10) have only a slight influence on the theoretical H/V ratio, such that the robustness of the solution from the inversion is more uncertain for these parameters. Finally, the S-wave velocities of the tenth layer and the bedrock do not seem to have any influence on the theoretical H/V ratio, which explains why the algorithm has difficulty to find a solution for these parameters.

<u>Third observation site: KiK-net station KYTH04</u>

Initial value of S-wave velocity (Vs_0), P-wave velocity (Vp_0) and thickness (TH_0) of each layer are given in Table 4. The intervals of variation of the inverted parameters are also indicated in Table 4.

Table 4. Initial values and intervals of variation of soil column parameters.

Layer number	Vs_0 (m/s)	Variations of Vs	Vp_0 (m/s)	Variations of Vp	TH_0 (m)	Variation of TH
1	220.00	Not inverted	470.00	Not inverted	1.00	Not inverted
2	1050.00	0.50 * Vs_0 – 1.25 * Vs_0	3160.00	Not inverted	11.00	Not inverted
3	1380.00	0.50 * Vs_0 – 1.25 * Vs_0	3160.00	0.50 * Vp_0 – 1.25 * Vp_0	22.00	Not inverted
4	1680.00	0.50 * Vs_0 – 1.25 * Vs_0	3690.00	0.50 * Vp_0 – 1.25 * Vp_0	20.00	Not inverted
5	1960.00	0.50 * Vs_0 – 1.25 *	5290.00	Not inverted	76.00	Not inverted

		Vs_0				
6	2462.86	Not inverted	4522.73	$0.50 * Vp_0 – 1.25 * Vp_0$	50.00	Not inverted
7	3162.00	$0.45 * Vs_0 – 1.20 * Vs_0$	5557.46	$0.50 * Vp_0 – 1.25 * Vp_0$	20.00	Not inverted
Bedrock	3400.00	$0.45 * Vs_0 – 1.20 * Vs_0$	5909.70	Not inverted		

Results of the inversion are shown in Fig. 6. On the left panel (a), we can see the objective H/V ratio computed from earthquakes data in black plain line, the ratio of horizontal and vertical transfer functions corresponding to the initial velocity log in black dotted line and all the best ratios of horizontal and vertical transfer functions corresponding to the best velocity logs found by the ten inversions in grey lines. The center panel (b) shows the corresponding S-wave velocity and P-wave velocity logs. The black line is the initial log and the grey lines are the best logs obtained by the ten inversions, corresponding to the best ratios on the left panel. The right panel (c) is a detail of the center panel (b) and shows the velocity logs of the first 30 meters.

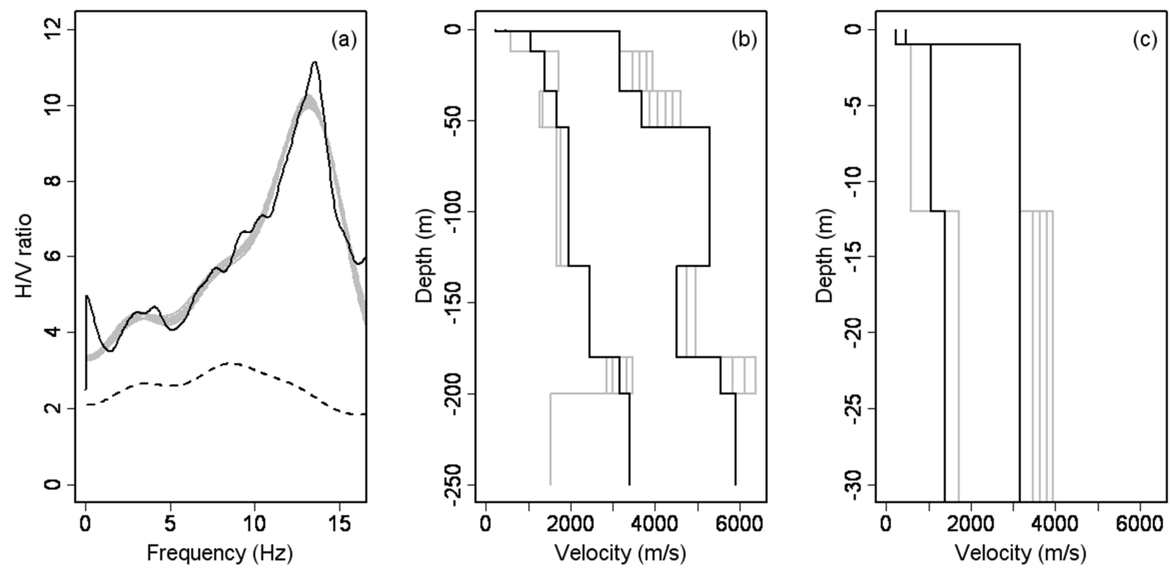

Fig. 6. Results of the inversion for observation site KYTH04.

There is a good agreement between the theoretical ratio of horizontal and vertical transfer functions obtained from the inversion and the objective H/V ratio obtained from earthquakes data for the whole range of frequencies where the inversion is performed. All the independent inversions give nearly the same values of S-wave velocity, which indicates a good convergence of the inversion. However, the P-wave velocities are not well resolved. Indeed, a large range of different values can be obtained from the different independent inversions. It seems that the P-wave velocity of the soil layers has less influence on the ratio of transfer functions, such that this parameter is more difficult to invert.

The results of the parametric study are shown in Fig. 7. The first row corresponds to the S-wave velocities of the seven soil layers and the bedrock; the second row corresponds to the P-wave velocities of the seven soil layers; the third row corresponds to the thicknesses of the seven soil layers. In each figure, the black line represents the theoretical ratio of horizontal and vertical transfer functions in function of frequency corresponding to the initial velocity log. The two grey lines correspond to the theoretical ratio when only one parameter varies and takes either the minimal value, either the maximal value of the intervals of variation given in Table 4.

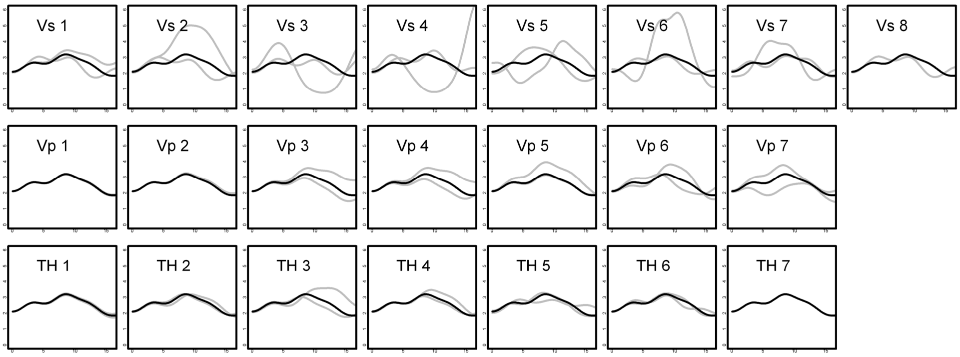

Fig. 7. Variations of theoretical H/V ratio for observation site KYTH04 when changing a single parameter (S-wave velocity, P-wave velocity or thickness of each layer) at once.

As can be seen from Fig. 7, the S-wave velocities of layers 2, 3, 4, 5 and 7 seem to have the strongest influence on the theoretical H/V ratio. The solution obtained from the inversion for these parameters can then be considered as rather robust. The other inverted parameters (P-wave velocities of layers 3, 4, 6 and 7) have only a slight influence on the theoretical H/V ratio, such that the robustness of the solution from the inversion is more uncertain for these parameters. Finally, the S-wave velocity of the bedrock seems to have a slight influence on the theoretical H/V ratio, which explains why the algorithm can more easily invert this parameter for this observation site than for the two other observation sites.

DISCUSSION

The velocity structure obtained from the inversion with the genetic Algorithm for the three observation sites taken as example gave theoretical predictions of the H/V ratio close to the observed H/V ratio. However, further investigation should be made to assert the precision of the H/V ratio. Particularly, we do not know whether the number of seismograms selected in this study is sufficient or not. Moreover, the spatial homogeneity in a statistical sense of the seismic events used in this study should be asserted. Uncertainty in the computation of the H/V ratio from observed earthquakes data should be evaluated, in order to establish the uncertainty with which the parameters of the soil column are inverted.

We encountered more difficulties when trying to invert the parameters of the deepest soil layers. Supplementary inversions could be made with only the deepest layers parameters varying and while fitting the ratio of transfer functions against the observed H/V ratio only for the lower frequencies. However, this could be done only if we ascertain that the observed H/V ratio is well evaluated also for the low frequencies.

Only some parameters were inverted, such that the velocity logs obtained by the inversion are not the unique ones which could explain the observed H/V ratio. This should be taken into account while comparing the results of the inversion with the method exposed in this study to results of other inversions with different methods.

CONCLUSION

Horizontal to vertical spectral ratios of earthquake motions were used to perform inversions of 1D velocity structure from the bedrock to the surface with a Genetic Algorithm code for three observations sites in the Kyoto, prefecture, Japan. A good agreement was found between observed H/V ratio and their theoretical prediction using the best velocity logs obtained from the inversion. However, the deepest layers remained difficult to be inverted. Moreover, the precision with which the observed H/V ratio is computed should be established, to evaluate the precision of the inversion.

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