A Theoretical Investigation into H/V Ratio Peak Frequencies Based on Numerical Simulation

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Abstract H/V ratio, especially the peak frequency of it, is an important indicator for local site effect and has wide range of uses in Seismology research and engineering. Former study mainly focused on the explanation of the first or the single peak frequency of H/V ratio, some ascribed it to the resonance of S wave, others argued that it is caused by the polarization of Rayleigh Wave. However, it is common in both numerical simulation and practical use that H/V ratio has more than one peak, but the cause for these multiple peaks hasn't been clearly studied, it has been explained as the result of multiple layers underground. We use numerical method to simulate the propagation of ambient noise in a layered model, and study the H/V ratio it induces. We find that the H/V ratio has multiple peaks, and all of the peak frequencies are very close with the first order and higher order of S wave resonance frequencies. We then propose an new evidence to support the claim that the peak frequencies of H/V ratio is caused by S wave resonance, along with an new explanation for multiple peaks. We provide further evidence for our conclusion based on numerical simulation.

Introduction

H/V ratio was first introduced by Nogoshi and Igarashi in 1971, and wide spread by Nakamura(Nakamura 2000). It uses the ratio of the horizontal and vertical Fourier spectra in the same observation station. We use H_b, V_b to denote the horizontal and vertical Fourier spectra in the basement, and H_s, V_s to denote the same Fourier spectra at the surface. Since the amplification of the site is mainly horizontal, the amplification of the site can be written as $\frac{H_s}{H_b}$. Nakamura, based on bore hole investigations together with strong motion records analysis, proposed that the basement has no amplification effect, and $H_b = V_b$ in the basement. Since that, we can rewrite the site effect as $\frac{H_s}{V_s}$, abbreviated as H/V(Borcherdt 1970).

H/V ratio method has several advantages compared with traditional methods. First, traditional methods use seismic waves to inverse the underground velocity structure, which makes it inapplicable to region with few or no seismic events. Second, compared with set receivers in basement, H/V ratio method can reduce the expense because it can be completed based on the observation on the surface. Besides, Nakamura has proposed that H/V ratio peak frequencies are closely related with the first order resonance frequency of the site.

Since the reasons above, H/V ratio has many applications. It has been used to study the site effect(Scarfi et al. 2016, Braganza et al. 2016), inverse the underground velocity structure(Giulio et al. 2016, Fh, Kind, and Giardini 2003), and classify the type of the site based on the ratio's shape.

Besides the success in applications, there are also many theoretical analyses that support the relationship between the resonance frequencies and H/V ratio(Field and Jacob 1993, Lachetl and Bard 1994, Lermo and Chvez-Garca 1994, Wakamatsu and Yasui 1996, Tokeshi and Sugimura 1998). However, many other analyses conclude that the H/V ratio peak frequencies depends on the polarization of Rayleigh surface wave(Bard 1999, Konno and Ohmachi 1998, Fh, Kind, and Giardini 2001). Sylvette(Sylvette et al. 2006) used numeric experiments to simulate ambient noise in a small area, and changed the quality factor. He discussed the relationship between peak frequency in H/V ratio and the polarization of Rayleigh wave, and he proposed that the peak frequency accords with the fundamental frequency of S wave resonance. But in his experiments, he mainly focused on the first peak frequency of H/V ratio and didn't make further investigation into the following peaks. Whereas in either simulations or applications, it is possible that the H/V ratio has multiple peaks. The reasons for these multiple peaks are not clear, Liu has explained with the exists of multiple layers underground. Moreover, without specific and quantitative explanation, the uses of H/V ratio for inversion lack an uniform formula. We use numeric experiments and calculate the H/V ratio for ambient noise, and discuss the relationship between multiple peaks and S wave resonance. We conclude that the peak frequencies, no matter the first or the followings, are caused by S wave resonance, and we also do further numeric experiments to verify our conclusions.

Data Preparation and Processing

Preparation

We use reflectivity to calculate theoretical seismograph. Our model is a thin low-speed layer over half-space basement, which can be seen at Figure 1. The parameters for our model can be seen in Table 1. Our model simulate the propagation of ambient noise caused by human and natural activities at or near the surface in a small area of layered ground(Ritzwoller, Levshin, and Barmin 2012, Gu et al. 2007, Wang et al. 2017, Demuth, Ottemöller, and Keers 2016, McNamara and Buland 2004).

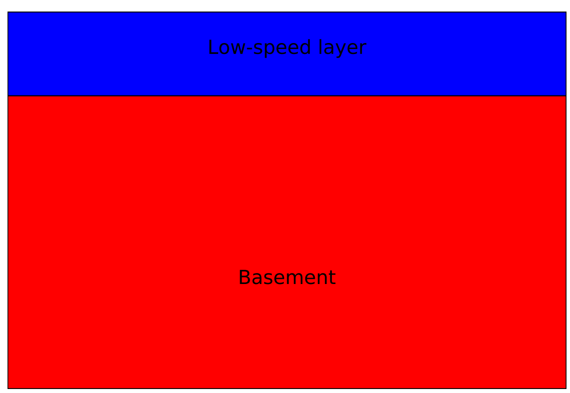

Figure 1: **Model**

Table 1: Original parameters for the model

Thickness(m)	V_p(km/s)	Q_p	V_s(km/s)	Q_s	$\rho(kg/m^3)$
25	0.4	120	0.2	60.0	1.9
1000	5.5	260	3.0	130	2.5

Note that we use a thickness of 1000km basement to substitute for infinite half-space. We set 100 sources in the model, with their positions, origin time and strength randomly. The distribution of the sources and receiver in can be seen in Figure 2.The positions are in uniform distribution, with both x, y direction in range $[-5, 5]$km, and all the sources are in the top layer.The receiver is set at the point$(0, 0)$. The origin time is in uniform distribution in range $[0, 35]$s. Our record is from 0s to 40.96s, with 2048 points(every 0.02s one point). Finally, our seismograph is shown in Figure 3.

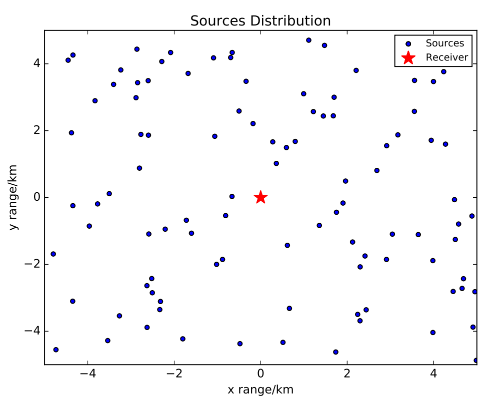

Figure 2: Distribution of the sources and receiver in xy plane.

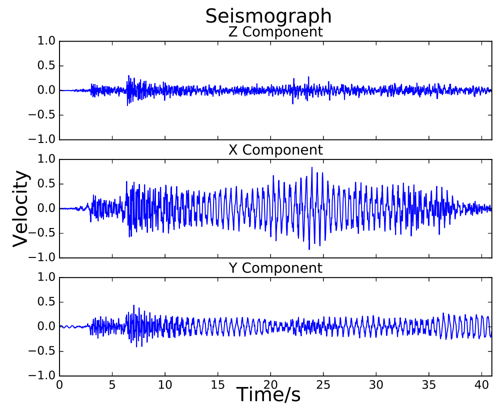

Figure 3: Three components seismic record for ambient noise.

Processing

We first add a cosine taper with width 0.95 to our raw data. Then we use calculate the Fourier spectra of the three components. We use moving average to smooth our spectra to avoid dividing by 0 in final step, and the width for the moving average is chosen as 15 points. Then we calculate the horizontal spectra as $f_h = \sqrt{f_x^2 + f_y^2}$, and vertical spectra as $f_v = f_z$. Finally, we get H/V spectra as $\frac{f_h}{f_v}$. The H/V ratio curve can be seen in Figure 4. Since the frequency of our sources is only in the range $[1, 20]$Hz, we only consider the H/V ratio in this frequency range.

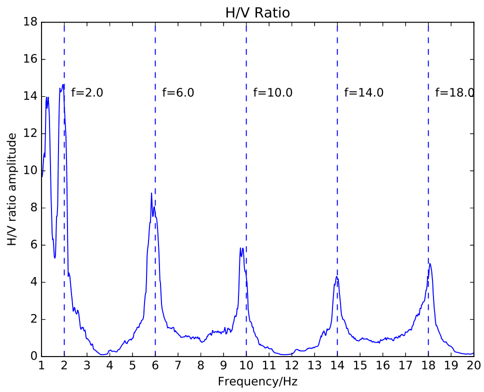

Figure 4: H/V ratio for the record. The dashed lines show the resonance frequencies $\frac{V_{s1}}{4h}(2n+1)$for this model. It can be seen clearly that all the peak frequencies of H/V ratio are very close to the resonance frequencies.

There are multiple peaks in the ratio curve, and all of the peak frequencies are according with the S wave resonance frequencies, which are given by $\frac{V_{s1}}{4h}(2n+1)$, where V_{s1} is the S wave velocity in the top layer, h is the thickness of the layer, and n is integer(Rial, Saltzman, and Ling 1992, Parolai 2002).

Influence of S Wave Velocity and Thickness

Since the S wave resonance frequencies depend on V_{s1} and h, we then consider the effect of changing these two parameters. The result is shown in Figure 5.

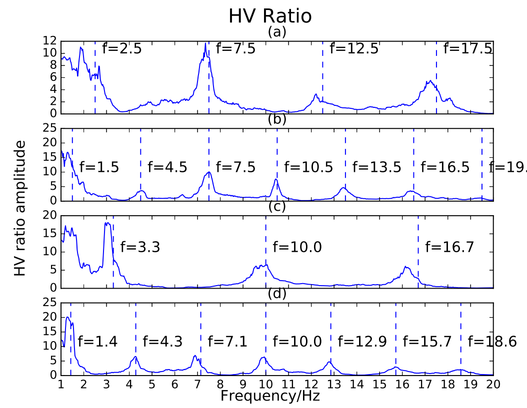

Figure 5: Different V_{s1} and h. The dashed lines represent the S wave resonance frequencies of the model. In (a) and (b) we change V_{s1} from 0.2km/s to 0.25km/s and 0.15km/s respectively. In (c) and (d) we change h from 25m to 15m and 35m respectively.

We can see that in all the circumstances, though the S wave resonance frequencies for the model change, the peak frequencies of H/V ratio are still at around.

Influence of Other Parameters

We then make an investigation into other parameters. Since the S wave resonance frequencies has no relationship with other parameters in our model, we expect that H/V ratio peak frequencies will not change with these parameters. The result surely verify our suppose and can be seen in Figure 6.

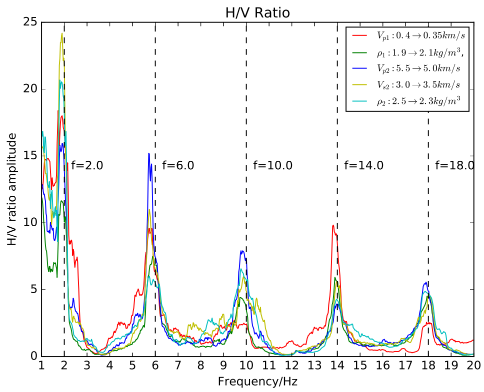

Figure 6: Changing other parameters. Compared with original model, changing other parameters shows no influence on H/V ratio peak frequencies.

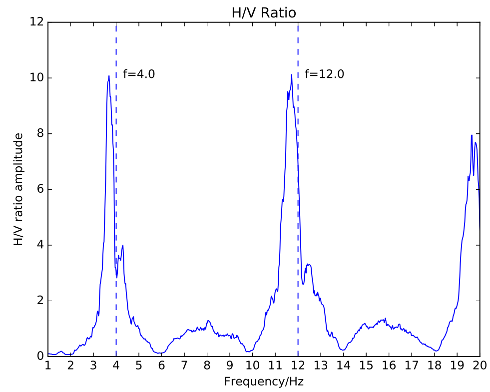

Figure 7: Reciprocal of the H/V ratio. The dashed lines denote the theoretical P wave resonance frequencies.

Further Verification

We then use other evidences to support our conclusion. Given the explanation of S wave resonance, it is natural to suspect whether P wave resonance will be reflected on H/V ratio.If it will, P wave resonance, whose peak frequencies are given by $\frac{V_{p1}}{4h}(2n+1)$, will induce valleys in the curve, in another word, it will cause peaks in V/H ratio. We simply use the reciprocal of our original data for drawing Figure 4, and draw Figure 7 as follows.

Notice that in the figures above, the peak frequencies of our curves are always a bit smaller than the theoretical resonance frequencies. One reason is that the theoretical resonance frequencies are computed for perpendicular reflection, where the incidence angle and reflection angle $\theta = 0$. However, in actual there may be a very small incidence angle $\theta \neq 0$, the theoretical resonance frequencies are then given by $\frac{V\cos\theta}{4h}(2n+1)$, and is smaller than the former formula.

Conclusion

We study the H/V ratio for ambient noise in a thin low-speed layer over half space basement. We find out that the peak frequencies of H/V ratio are very close with fundamental and higher order S wave resonance frequencies for different parameters. We then look at P wave resonance and find that it will cause peaks in V/H ratio. We think our study provides new evidence that the cause of H/V ratio is S wave resonance, and the relationship between P wave resonance and V/H peaks may be meaningful in application.

Data and Resources

The data we used are generated by reflectivity.f. The figures in our paper are plotted by Matplotlib.

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