

## SIMULATION OF MICROTREMOR H/V RESPONSE TO THREE SIMPLE SEDIMENT/STRUCTURE MODELS

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### **ABSTRACT:**

In order to evaluate the 2D effects of sediment thickness variation on the resonant frequency of the horizontal to vertical spectral ratio (H/V) of the microtremor measurements, we numerically simulated the ambient noise superposition and interference in three sediment models: the flat layer sediment, a dip layer sediment and a thrust fault, with the 2D finite difference time domain (FDTD) method. First, we created the sediment/structure model. Second, we used the FDTD method to simulate the propagation of the ambient noise with the excitation of the randomly distributed noise sources in the uppermost part of the crust. The responses of the model were recorded at the receiver arrays on the surface. Then, the synthetic ambient data were processed with the horizontal to vertical component H/V spectral ratio method to extract the variation of the resonant frequency for a given sediment structure. We compared the H/V derived sediment thickness results with the initial models and found that simulation results can produce credible images of the subsurface structure which can matched with the initial models in a great agreement. We conclude that numerical simulation of microtremors with the FDTD method can provide a reference model for the purpose of planning real-world field measurement and assisting the comprehension of field H/V results. This work is supported by the Ministry of Science and Technology of China with Project No. 2006DFA21650 and the Institute of Earthquake Science with Project No. 0207690229.

### **KEYWORDS:**

FDTD, simulation, microtremor, sediment, H/V spectral ratio

### **1. INTRODUCTION**

In the study of seismic hazard reduction, the local site effect is defined as the characterization of the influence of the near-surface geology of a site to the behavior of the propagating seismic waves. Due to the vast variation in site effect, even a moderate earthquake may cause destructive damage of civil infrastructures at a disadvantageous site. A variety of field methods have been tested to evaluate the site effects to prevent or mitigate earthquake hazard. In general, it has been widely accepted that the S-wave velocity (Vs) profile can be a good parameter to be used in evaluating the site effects quantitatively. However, getting the *in situ* S wave velocity in boreholes can be too expensive to carry out in a large area. Thus, studies of using non-invasive and indirect measurements to assess or supplement the shear wave velocity measurements are attractive to the earthquake engineering community and have attracted a great deal of attention.

Since the 1950s, ambient seismic noise has been used to obtain the information of the soil amplification. Nogoshi and Igarashi (1970, 1971) are among the first to apply the horizontal to vertical spectral ratio (H/V) to microtremor measurements. The H/V method was popularized by Nakamura (1989) and is known as the Nakamura's technique. He used only one recording station with a three-component sensor to observe a site and approximated the amplification factor of the site for the vertically incident S waves. This method can eliminate the influence of the source effect. Many experimental results have proven that the H/V ratio method is valid in the investigation of the site effect in earthquake engineering (Chen et al., 2008). It can be used as a practical and economical way to obtain bedrock depth information to assess the potential site effects for earthquake damages.



### **2. BASIC THEORY**

The innumerable earthquake disaster experiences indicate that local soil dynamic properties take an extremely important role in determining the earthquake responses of a civil structure. The local transfer function is an important parameter to describe the dynamic properties. Through the analysis of the transfer function, it is possible to obtain the on-site resonant frequency and the amplification factors, which are the key parameters to understand the soil dynamic properties.

Two techniques have been widely used to calculate the spectral ratios of microtremors. One is called the reference station method, in which a recorder is placed on the hard rock as a reference site and another recorder is placed on the sediments. The spectral ratio of the ambient noise can be used to estimate the transfer function between rock and soil site (Lermo et al., 1988; Lachet et al., 1996). The other method is the Nakamura's technique. Both methods can eliminate the influences of the source effect and highlight only the local site effect.

A simple two-layer model explains its basic principle: A hardrock basement is covered by a soft sedimentary layer of thickness h and S-wave velocity Vs. This system's transfer function will reach maxima when the thickness of the soft sediment is equal to a quarter of the wavelength of the shear waves propagating in it.. With the calculation of  $(H/V)_s$  spectrum, we can find the site resonant frequencies corresponding to the peaks of this spectrum, which can be expressed as (Ibs-von Seht and Wohlenberg, 1999)

$$f_r = \frac{n \cdot v_s}{4h}$$
 with  $n = 1, 3, 5, ...$  (2.1)

Using only the fundamental frequency (n=1), which has the maximum energy, we can infer the sediment thickness as

$$h = \frac{\lambda}{4} = \frac{v_s}{4f_r} \tag{2.2}$$

### **3. SIMULATIONS**

Based on the aforementioned principles, we used the FDTD method to simulate the wave propagation in the shallow part of the crust (in both the sediments and the bedrock) produced by the randomly distributed sources on the surface. Then, we used the horizontal to vertical component spectral (H/V ratio) method to process the synthetic ambient data and extract the variation of the resonant frequency and invert the sediment thickness of the given sediment model. We compared the result with the initial model to analyze the numerical error of the simulation. In the following we will discuss the simulation and inversion results of three main kinds of models: flat layer sediment with different depths, dip layer sediment and the normal and reverse faults.

### 3.1. The flat layer Sediment

The parameters of the flat layer sediment model (Figure 1a) are listed in Table 1. Figure 1b illustrates the location of the random sources and the receivers. The location of the sources which is treated as the environmental noise was generated by uniform distribution random function. The total number of the random sources is 250, and they are distributed between the ground surface and the depth of 20 meters.

Figure 1c shows the horizontal and vertical velocity fields in the flat layer sediment model at the simulation time of 0.75 sec. Because the duration of 0.75 sec is too short for the microtremor simulation, the velocity fields propagate only near the ground surface, the deeper region of the model is still in equilibrium. In practice, the

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total observation time of microtremor measurement is always set to be one to two hours, to record sufficiently long data that can reflect the characteristics of the bedrock distribution and make the wave field stable. In our research, the total simulation time is set to 600 sec.

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2D cell number	2500×1000	Depth of Sediment (m)	150, 250, 350		
Cell size (m)	5	$V_P/V_s$ of Sediment (m/s)	700 /404		
Center frequency (Hz)	4	$V_P / V_s$ of Bedrock (m/s)	2000 /1155		
Sampling interval (s)	0.00125	Total number of sources	300		
Simulation time (s)	600	Total number of receivers	50		





Figure 1 (a) the flat layer sediment model used for the simulation; (b) the distribution of the sources (top) and the receivers (bottom); (c) the snapshots of the horizontal (top) and vertical velocity (bottom) of the random waves at 0.75s of the elapsed time generated by the microtremor sources.

Figure 2a is the oscillogram of the record of the first channel in three-component, where most of the high frequency components cover all over the oscillogram. It is difficult to analyze the characteristics of the low frequency components directly from the oscillogram. Figure 2b shows the Fourier spectrum and the H/V spectral ratio of the channel corresponding to Figure 2a, and Figure 2c plots the H/V spectral ratios for all recording channels. According to Eqn. 2.1, and for the fundamental mode (n = 1), we can get the fundamental frequency corresponding to the H/V spectral ratio peak value.

$$f_r = \frac{n \cdot v_s}{4h_0} = \frac{1 \times 404}{4 \times 150} = 0.6733 \ (Hz)$$

Figure 2c shows that the dominant frequency of the H/V spectral ratio calculated from the geophones is well matched to the theoretical value.



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Figure 2 (a) the oscillogram of the first channel of the three-component geophones; Vew: east-west direction; Vns: north-south direction; Vud: up-down direction; (b) FT amplitude and H/V spectral ratio of the first channel. (c) H/V spectral ratios for all channels.

The inverted depths for the sediment models with different thicknesses generated by the H/V spectral ratio method are shown in Figure 3. It seems that for the simple flat layer sediment model, the inferred thickness of the shallow sediment model from the H/V methods is reasonably able to recover the 'true' thickness.



Figure 3 The inverted depths for the flat layer sediment models with different thicknesses. The green boxes indicate the location of geophones and the red stars indicate the location of random sources. The green line and red line are the ground surface and the bedrock surface, respectively. The Inferred interface depths are plotted by the blue stars. The thickness of the sediment is 150m (a), 250m (b) and 350m (c)

### 3.2. The dip layer Sediment

For reassemble more realistic geological conditions, the dip layer sediment model is also studies in our simulation research. The dip layer model is set up by the parameters in Table 2.

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2D cell number	2500×1000	Depth of Sediment (m)	150-350		
Cell size (m)	5	$V_P/V_s$ of Sediment (m/s)	700/404		
Center frequency (Hz)	4	$V_P / V_s$ of Bedrock (m/s)	2000/1155		
Sampling interval (s)	0.00125	Total number of sources	300		
Simulation time (s)	120	Total number of receivers	50		

2D cell number	2500×1000	Depth of Sediment (m)	150-350
Cell size (m)	5	$V_P/V_s$ of Sediment (m/s)	700/404
Center frequency (Hz)	4	$V_P / V_s$ of Bedrock (m/s)	2000/1155
Sampling interval (s)	0.00125	Total number of sources	300
Simulation time (s)	120	Total number of receivers	50



Figure 4 Inversion results of the dip layer model

(a) The H/V spectral ratios for all 50 locations. (b) Fundamental peak frequency vs receiver location. (c) Inferred interface depth vs receiver location

Figure 4a illustrates the distribution of the H/V spectral ratios, clearly can be observed that the peak frequency has a range of 0.2-0.6 Hz. This phenomenon is also clear in the peak frequency-receiver location diagram

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(Figure 4b). In the Figure 4b, the peak frequency values of the H/V spectral ratio gradually change from 0.58Hz of the channel 1 to 0.27Hz of the channel 50, because the deeper sediment has the lower dominant frequency, which is related to the dip layer bedrock interface of the model. The inferred depths derived from the H/V spectral ratio is in good agreement with the model, except some instable points near the right boundary, which may be caused by the imperfection of the absorption boundaries in that FDTD method and the effect of absorption.

### 3.3. The normal and reverse fault model

To analyze more complicated geological models, we set up a geological fault model, and analyze the effect of strong variation of geological structure in the horizontal direction. First, the normal fault model is set up by two layers, where the upper layer is a homogeneous low-velocity sediment layer, and the lower layer is combined by a medium with linear vertical velocities ( $V_P$  varies from top to bottom). The normal fault is generated by the leap of the lower layer. The dip is 45 degrees and the vertical offset is 150m.



Figure 5 Inversion results of the normal fault model (a) The H/V spectral ratios for all 50 locations. (b) Fundamental peak frequency vs receiver location. (c) Inferred interface depth vs receiver location

From the H/V spectral ratios, it can be seen that the dominant frequencies over all channels take an identical variation with the normal fault interface. The incorrect inversion depths on the fault corner are caused by the scattering of the keen-edged points in the model. The inversion depths are still well matched with the model values, and can be treated as a model combined by a flat layer model and a dip layer model. However, the vertical resolution of the inversion depths is not sufficient to recognize a normal fault structure. Anyway, the results are used to detect the bedrock interface.

As the second example of the fault model, the parameters of the reverse fault model are the same as those of the normal fault model. The reverse fault model is also constructed by two layers, but the hade is 135 degrees. The vertical offset is also 150m.



Figure 6 Inversion results of the reverse fault model (a) The H/V spectral ratios for all 50 locations. (b) Fundamental peak frequency vs receiver location. (c) Inferred interface depth vs receiver location



The instable depth points in the reverse fault are related not only to the scattering of the keen-edged points in the model, but also to the complicated geological structure of the reverse fault. In the inferred depth profile (Figure 6c), it can be clearly seen that, far from the reverse fault, the inversion results on the hanging wall are better than those on the foot wall. The inversion depths on the fault can be associated with the reverse fault interface, but only with the depths of the hanging wall and the foot wall. We can also see that the inversion of the foot wall is worse than that of the hanging wall, because it suffers from the effect of the reverse fault interface and the hanging wall.

### 4. CONCLUSIONS

Using three typical sediment models, we have simulated the microtremor record by the 2D FDTD method. With the H/V spectrum ratio method, we processed the records to get the sediment characteristics. The results of this research show that, in the flat layer sediment model situation, the H/V spectral ratios are strongly associated with the sediment/bedrock interface, and then the inferred depths can match very well with the initial model. Compared to the flat layer- sediment model, for other models with strong variations in the horizontal direction, i.e. the dip layer sediment model and the fault model, the precision of their inferred depths has much deviation. The reasons is that difference types of elastic wave fields can interfere with each other in the complicated geological region, and it is difficult for the standing wave fields of surface waves to get a steady state so that the dominant frequencies can't be built up corresponding to the depths of the sediments. In the sediment depths-varied region, the site microtremor responds can be controlled by the strong dominant frequencies on both sides and form a transitional zone, where the inversion results are instable. Conclusively, the statistical characteristics of H/V inversion depths can change with horizontal variation in a layered model, and they are dominated by the standing wave on both sides. Thus, it is necessary to carry out further data processing and analysis. In this paper our results show that the H/V spectral ratio method takes a high stability and reliability in the data processing and interpretation of the site microtremor measurement and evaluation. In data processing, only one channel was considered in the H/V spectral ratio method. This means that all channels were inverted independently. This inversion method only analyzes the information inside the channels, leading to less information all over the site. To improve the inversion precision and stability, further studies of the H/V spectral ratio method should focus on combining the inversion with other a priori information.

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