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The horizontal-to-vertical spectral ratio and its applications

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Abstract

The horizontal-to-vertical spectral ratio (HVSR) has been extensively used in site characterization utilizing recordings from microtremor and earthquake in recent years. This method is proposed based on ground pulsation, and then it has been applied to both S-wave and ambient noise, accordingly, in practical application also different. The main applications of HVSR are site classification, site effect study, mineral exploration, and acquisition of underground average shear-wave velocity structure. In site response estimates, the use of microtremors has been introduced long ago in Japan, while it has long been very controversial in this research area, as there are several studies reporting difficulties in recognizing the source effects from the pure site effects in noise recordings, as well as discrepancies between noise and earthquake recordings. In practice, the most reliable way is the borehole data, and the theoretical site response results were compared with the HVSR using shear wave to describe site response. This paper summarizes the applications of the HVSR method and draws conclusions that HVSR has been well applied in many fields at present, and it is expected to have a wider application in more fields according to its advantages.

Keywords: Earthquake recordings, Site effect, Site response, Horizontal-to-vertical spectral ratio (HVSR), S-wave spectral analysis, Ambient noise

1 Introduction

The horizontal-to-vertical spectral ratio (HVSR) technique we normally referred to is a method to retrieve information about the shallow-subsoil seismic properties, by single station measurements carried out on the Earth's surface, which are of great engineering interest. This approach was proposed by Nakamura [1] for site effect research, which overcome the difficulties of traditional using a reference site. Its proposal provides new ideas and methods for many aspects of research. However, the original purpose was to quantify site effects based on the Fourier amplitude spectrum ratio of components of the horizontal and vertical in ground pulsation at the same surface measurement point [1]. Due to HVSR simplicity in site acquisition and signal processing, it obtained great popularity although it is based on a lot of assumptions. Lermo et al. applied the H/V method to S-wave earthquake recordings that also developed the theoretical background for SV-wave
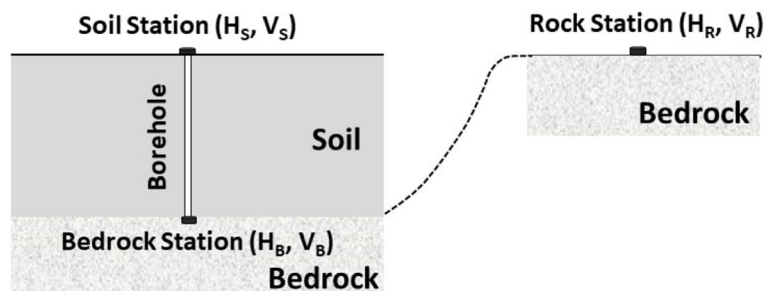
numerical inverse [2]. Then, Yamazaki and Ansary extended this approach to use of strong seismic acceleration records to assess site characteristics or site classification and other applications [3]. As HVSR does not require a ground model and can be utilized to not only microtremor but also earthquake records even strong-motion recordings, and only need a single seismogram, it attached a lot of attention. On the other hand, with the technical progress of digital strong vibration observation instrument, more and more high-quality strong vibration records are collected. It seems that the method of HVSR since was first proposed, it has been extended from ground pulsation to earthquake recordings and strong vibration recording, from Fourier amplitude to velocity response spectrum. It is not only cost-effective but also covered many kinds of field, and it has been the focal point of many investigations as reviewed in this area.

Nevertheless, with the popularity of HVSR method application, the precise physical explanation of the results provided by the HVSR technique remains somewhat controversial. The majority of them are related to the nature of the source and of its ambient-vibration wavefield. These differences in the H/V curve modeling may have an impact on the results of inversion programs used to speculate the subsoil formation profile from tentative measurements, as HVSR is not only clear in theory but also convenient in applications, which brings high heat in recent years.

2 Method: Specific principles or theory of HVSR

On the basis of Nakamura [1], HVSR definition proposed as the ratio of the Fourier amplitude between the horizontal and the vertical of motion, which recorded by a sensor on the free-surface, HVSR can be expressed as follows:

$$HVSR_s = \frac{H_s}{V_s} \tag{1}$$

Schematic diagram of soil, reference rock, and bedrock recordings

H_s is horizontal component of Fourier spectrum recording at surface, and V_s is vertical component of Fourier spectrum recording at surface, respectively. The proposal of HVSR is based on two assumptions: firstly, supposed at the bedrock, H/V Fourier spectral ratio ($HVSR_B$) is 1, that is, the horizontal and vertical waves travel equally on bedrock:

$$HVSR_B = \frac{H_B}{V_B} = 1 \tag{2}$$

In which H_B and V_B represent at bedrock the spectral of horizontal and vertical vibration of the base incident respectively.

Secondly, assuming that after the seismic wave propagates from the bedrock to the surface, the vertical component is basically no enlarged, that is, the vertical transfer function is considered as 1:

$$TF_V = \frac{V_S}{V_B} = 1 \tag{3}$$

As previously stated, V_B and V_S represent the amplitude spectra of the vertical component at bedrock and free surface respectively, TF_V is the vertical transfer function.

Just like the vertical transfer function, the transfer function of transverse component can be expressed as:

$$TF_H = \frac{H_S}{H_B} \tag{4}$$

Based on formula 2 and 3 the two assumptions, we can also write formula 4 as follows:

$$TF_H = \frac{H_S}{H_B} = \frac{H_S}{V_B} * \frac{V_S}{V_B} * \frac{V_B}{H_B} = \frac{H_S}{V_S} \tag{5}$$

That is the relationship between $HVSR_S$ and TF_H at free surface can be expressed as the same, that is to say $HVSR_S$ can be used as an alternative transfer function:

$$HVSR_S = TF_H \tag{6}$$

Not only the derivation of formula that TF_H is the same as $HVSR_S$, but also there is an agreement that the HVSR is similar to the result of empirical transfer function (*TF*), especially in the shape like alignment contains peaks and valleys, and thus can be used to strictly reveal the (horizontal component) fundamental frequency (f_0) in a site. Then

$$HVSR_S = TF_H * HVSR_B * \frac{1}{TF_V} \tag{7}$$

According to Nakamura [1], $HVSR_B$ is approximately uniform for ambient noise on average, which determined by windowed around S wave recordings, while it depends on the focal mechanism of earthquake; hence, due to the TF_H and TF_V being independent of the sources, $HVSR_S$ will also depend upon the source mechanism.

In traditional earthquake engineering, the site effect of ground motion is always quantified by the site -reference spectral ratio (SSR) of the horizontal component of S-wave motions recorded at the surface on the soil and on the rock (Borcherdt,1970)

$$SSR = \frac{H_S}{H_R} \tag{8}$$

In which H_R is the S-wave motion recorded the on the rock surface. If the sites are close enough, we can assume that $H_B \approx \frac{H_R}{2}$; That is

$$SSR = \frac{TF_H}{2} = \frac{HVSR_S}{2} \tag{9}$$

The site effect of ground motion can be also quantified by the horizontal transfer function utilized the S-wave, that is to say the site effect may be caused by the shear wave resonance of soil. However, HVSR of the ambient noise does not reflect the practical S-wave resonance, and the ambient noise HVSR cannot be used to characterize the site effect of earthquake ground motion because compared to the S-wave, they have different mechanism.

Based on a lot of research, the basic principle of HVSR method can be summarized as follows: when the site can be assumed to be relatively hard and flat or an ideal site for bedrock, it can be assumed that the site theoretically will not amplify the site effect on horizontally or vertically within a specific frequency band, that is, the horizontal and vertical vibrations should be roughly the same within a certain frequency range, which is verified by the ground pulsation data. For general sites with overburden or softer soil, the horizontal ground motion amplification is relatively significant in a certain band range, while the corresponding vertical ground motion does not significantly magnify within this band range. Then, the estimation of site predominate frequency and site amplification can be realized through the Fourier amplitude spectrum ratio (HVSR) of horizontal and vertical ground motion, whereas the amplitudes of the HVSR tends to underestimate the actual levels of amplification, that is, the amplification value of site response obtained by this method is quite different from that obtained by other methods, which may require more research and support.

3 Application: The application of HVSR

With the development of science and technology, HVSR is no longer simply applied to the site effect. And an important superiority of HVSR technology is that the influence of source and propagation path on the response spectrum is eliminated. Hence, there are many applications of HVSR, such as used in site classification, application of site effect research, inversion of velocity structure, and mineral exploration. These following applications are the most common and the most important; let us go through them one by one.

In the field classification and the site effect research, simple analysis is usually made on the basis of different wave velocities in many countries. For example, V30 was used in the USA and V20 was used in China for site classification and site effect analysis.

3.1 Site classification by HVSR

As is known to all, the HVSR spectral ratio curve can accurately gain the predominate period of the site. And the predominate period of sites is often used as an indicator of site classification in many countries, which is the original site classification by HVSR. Zara et al. and Lee et al. classified the sites according to the predominate period by the strong vibration recordings from Iran and Taiwan, respectively [4, 5]. The advantages of this method are that it is not subject to the reference site, simple and easy to operate, and low cost. But the biggest problem is that the predominate period of many sites are not unique, even the predominate period of bedrock site is not obvious, which makes it difficult to classify sites in this method. Although this method has many problems, it is

still the most commonly used for site classification. Ji et al. conducted HVSR analysis on the strong earthquake stations in southeast of Gansu based on the strong motion recordings from 2007 to 2015, obtained a reasonable site period of excellence, and classified the site [6]. Harinarayan and Abhishek Kumar united the horizontal-to-vertical spectral ratio method (HVSR), standard spectral ratio method (SR), and generalized inversion technique (GINV) to classify 4 sites in the area of eastern Uttarakhand. To further solve the directionality [7], Pinzon et al. considered the directionality impact on the vector combinations using the horizontal components of the ground motions, according to the predominant period through the average HVSR to classify the site of strong-motion stations. Combining local soil properties [8], Swathi and Neelima, depending on the type of the soil, predominate period, and H/V amplitude from microtremor recordings, classified the Vishakhapatnam city into three major zones [9]. Manisha (2020) used the HVSR estimation to classify sites based on the classical method utilizing predominate frequency, in order to assess the earthquake hazard and mitigate risks [undefined].

In order to make up the shortcoming of the predominate period method, Zhao et al. proposed spectral ratio curve matching method; the basic idea of this method is to match the average HVSR curve obtained from the strong vibration recordings of a site with four known empirical curves in uniform shape [11]. Kun Ji et al. used this method to re-classified Kik-net sites, and this method can also be used in 81stations in China; the results of site classification are acceptable and the proposed method is practicable. Facing the calculated results [12], S. Yang et al. on the basis of the shape showed the average HVSR curve (single-peak, double-peak, wide/multiple-peak, and flat) of many stations to classify sites, which is a typical spectral ratio curve matching method. Improvement always based on the spectral ratio curve matching method [13]; Saman et al. proposed a new algorithm that depends on HVSR curves of the recording stations and uses pattern recognition for a set of predefined curves for different site types; in this method, the site characteristics are based on the overall features of the HVSR curves, rather than just peak frequency [14].

With the progress of science and technology, some new approaches have emerged in recent years; in particular, the fusion of multiple methods has been well applied. P. Anbazhagan et al. used the aforementioned methods by comparative analysis such as the predominate period method, Vs30, spectral ratio curve matching, or PGA, which was a good result of the fusion and comparison of multiple methods for site classify [15]. Yumeng Tao and Ellen Rathje bring up a new scheme to divide the site into four categories; this classification method can distinguish sites according to whether the peak value of the empirical HVSR peak is clear and whether there are outcrop-resonances vs. pseudo-resonances in the empirical TF, the characteristics in the theoretical TF_s, and features of the V_s profile, in which it depends on the validity of one-dimensional hypothesis when identifying the pseudo-resonances and can be applied to non-downhole array sites [16]. Liliana Oliveira et al. considered it due to lack of V_{s30}, but there is a large amount of SPT data (standard penetration test, that is the number of hammer strokes required for the penetrator to penetrate into the soil) contained in a geotechnical database; a rapid method was developed to determine the N_{spt30} parameter, which is used as a proxy for the V_{s30} coefficient. HVSR used data which come from ambient

vibrations, and data which converged from separated geophysical reports were also utilized to validate and supplement the ground classification [17].

On the whole, as for the application of HVSR to site classification, whether it is the original method or the improved method, even the new method emerging in recent years, in essence, it is the extension of HVSR or the fusion application of multiple methods, which has also achieved good results. However, due to the different site classification standards in different areas around the world, we need to adjust the methods in different regions in the following work in order for it to be better applied in different types of site classification.

3.2 Site effect analysis

The HVSR method is raised for the study of the site effect based on two assumptions as mentioned above by Nakamura in 1989. The site effect is the surface damage of earthquake disaster within the scope of ground motion, and the difference of site conditions will directly lead to different degrees of earthquake disaster. Therefore, in the field of seismic engineering, researchers have been paying attention to the site effect under strong vibration. Among many research methods, HVSR method is widely used because it can be used to assess the site dynamic characteristics only by a single station vibration record. Compared with the traditional spectral ratio method, the H/V spectral ratio obtained by HVSR can be used as an index to reflect the site nonlinearity, which is widely used recently.

Bard et al. made an statement that in site response estimates, the use of microtremors has been introduced long ago in Japan, while it has long been very controversial in this research area [4], as there are several studies have reported difficulties in distinguishing source effects from pure site effects in noise recordings and discrepancies between noise and earthquake recordings. Satohetal (2001) compared the method HVSR with other traditional methods (empirical transfer function, traditional spectral ratio, linear inversion and Fourier spectrum analysis, etc.); the results show that the HVSR technology can effectively determine the predominant frequency of the site under the ground motion, but there is a great difference between HVSR and other methods in evaluating the site amplification [18]. I. Kassaras et al. applied the HVSR technology on ambient noise measurements for site response in free-field, especially in the amplification ratio and the peak frequency of the HVSR curves [19]. Seth Carpenter et al. commented that the average HVSR curves of S-wave is close to the mean spectral ratios of transfer function for frequencies that are roughly lower than the fifth natural frequency, which reflected the transfer functions of SH-wave at low frequencies, but HVSR extracted from ambient noise cannot estimate the frequencies of SH-wave transfer function which is higher than the fundamental at deep borehole sites [20]. As to earthquake records, Kawase et al. proposed a method utilized to calculate the earthquake ground motion at the site by using the horizontal-to-vertical spectral ratios of microtremors (MHVR) with double corrections using EMR (the same as MHVR) and vertical-to-vertical spectral ratios (VVR_S) for the corresponding category, which is a dual empirical correction procedure of S-wave amplification to HVSR of microtremor recordings for a direct estimation, which can be thought of as a natural but meaningful extension of the "Nakamura" technology [21]. Inspired by Kawase, Chuanbin Zhu et al. proposed a

procedure to calibration of seismic HVSR amplitudes for direct amplification estimation, which verified that the empirical transfer function and HVSR were close to each other in both amplitude and spectral form in frequency range of f_0 to 25 Hz. There are also some studies combining with the geological conditions of the site [22]; Manisha et al. showed the pseudo velocity response (PSV) and HVSR compared with the regional geological structure and summarized a clear relationship based on the geological settings in the area for most of the sites, and a distinct understanding is gained of the site effect evaluation [undefined]. Rocca et al. showed that the HVSR of seismic noise always changes significantly during period of severe weather; the amplitude of background noise increases over a wide frequency band; that is the result of HVSR which is not only caused by the amplitude of ambient noise but also the climate and topographic effect, besides being correlated with day-night cycle [23]. Through comparison, it is found that there have been a lot of researches on HVSR used in site response, but environmental noise HVSR still cannot be used in site response analysis due to its particularity.

3.3 Inversion of velocity structure

The purpose of velocity structure inversion is mostly to serve the above two applications, that is the ultimate purpose of many applications of HVSR inversion of velocity structure is to carry out field effect analysis, and only take HVSR inversion of velocity structure as a means. Noise or ground pulsation is usually used as the basic data to invert the shallow structure of the site in recent research. Herak took the recorded environmental noise as the research object and wrote a Matlab program for inversion of the shallow structure of the site with HVSR, which is applied to the actual research [24]. According to Bignardi et al., based on the research of Herak, the inversion of shallow structures in one-dimensional sites is extended to two-dimensional and three-dimensional sites [25]. Rong et al. applied HVSR of weak shear-wave motions as a tool to invert shear-wave velocity, compared the theory results with this empirical, and finally found that HVSR is similar to the empirical transfer function for non-linear site response. This is the example that HVSR is a tool for inversion velocity for the ultimate goal site effect [26]. Ruyun Tian et al. made an application of HVSR to inverse soil and rock mixed sedimentary strata of the S-wave velocity profile, which is using HVSR through some three-component observations to the analysis of ambient noise on the Loess Plateau, and the results are consistent with previous drilling data [27]. However, Zhenming Wang et al. commented that the HVSR of ambient noise can only provide the restraints on the average S-wave velocity or thickness, but it cannot provide a detailed S-wave velocity [28]. This put forward a higher requirement, that is, if you want to get detail velocity structure, and must be method fusion and improvement, which is the direction of our future efforts and research.

3.4 Some other applications

Marzieh Khalili (2019) uses microtremor data (HVSR-based method) to implement fault detection; scientifically, the thick of sediment should be obtained from the HVSR peak frequencies in an area of sediment properties do not change in the study area, and it can be inferred that the microtremor data and geoelectrical ways are useful and

reliable methods for detecting the underground structures such as hidden faults, especially in the urban areas [29]. Nasser Abu Zeid et al. used HVSR as an exploration tool to map the Palaeosols, which confirmed the presence of the paleo-surface which were embedded in clayey sediments. The HVSR method is also as a tool for utility detection of subsurface [30]. Fatma et al., in the study of oil seepage, accordingly used the HVSR method to get a subsurface mapping and obtained V_P and density profiles used to explore the distribution of oil reservoir seepage [31]. Nigel Cantwell et al. summarized several case studies on the application of HVSR survey methods to detect for exploration and mining of an underground layer of heavy mineral sand (HMS) deposit, and it is concluded that the HVSR as the effectiveness of fast and low-cost survey technology is mapped and also provide additional stratigraphic information to deposit in gaps between drillholes [32]. Jose Pina-Flores et al. through HVSR picked up the Rayleigh-wave dispersion curve of ambient noise and also showed that the shape of the HVSR is supported by the fundamental mode phase and group dispersion curves of experimental identification [33].

In a word, the application of HVSR method to mineral resources and other aspects is the exploration of underground structure.

4 Extension

The HVSR technique has been used ever since it was proposed, which is a useful tool used to estimate the resonance frequency of a field. However, HVSR noise measurements may depend on arbitrary events and may be affected by near-field transients. Because of the randomness of the noise wave field, the position and genre of source might change, thus affecting the estimation of HVSR. For instance, when the unstable HVSR was measured at different times of the day, the results differed in amplitude and shape of the HVSR curve, as well as in the deviation of f_0. In addition, the installation of equipment has a considerable impact on the quality and variability of HVSR measurements. There are two important factors that can introduce errors into the tentative HVSR which are as follows: first is the degree to which the sensors are isolated from weather activities such as wind and rain; second is the degree of coupling from the sensor to the ground. Hence, uncertainties arise in determining f_0; the practical problems of HVSR in application need to be deeply discussed and solved in practice, in order to enhance the quality of HVSR. For poor receiver coupling and adverse environment conditions, a robust statistical method should be used for HVSR data. Therefore, we need a better understanding of the advantages and limitations of the HVSR approach in order to play its advantages and avoid its disadvantages. It is expected to do the best in the applications.

5 Results and discussion

The ultimate goal, of course, is to reduce disaster losses for all we do. With its unique advantages, HVSR technique has achieved certain achievements in many aspects. We have been very clear about the principle of HVSR method, and the application based on this also involves aspects. In summary:

1. HVSR technique is proposed by ground pulsation, and its theory can also be applied to seismic and strong-motion network data. The biggest advantage of HVSR is that it can accurately determine the site predominant period f_0.

2. Although the HVSR theory is put forward based on the site effect, it can be extended to many fields in applications by its advantages.

3. In the process of applying HVSR technique, there are mainly two types of data selected; one is S-wave and the other is ambient noise. There are different applications relatively, involving site effect, site classification, mineral exploration, and average shear-wave velocity structure analysis of underground soil layer.

With the increase of urbanization, container backfilling, research, and stability of underground structure, safety of bridge and high-rise building design has also developed a lot. The analysis of subsurface soil layer and structure is particularly important. The best way to do this is to take a method mixed with some kind of manners, which is what we need to look for and work on next.

Abbreviations
HVSR: Horizontal-to-vertical spectral ratio; MHVR: Horizontal-to-vertical spectral ratios of microtremors; VVR$_S$: Vertical-to-vertical spectral ratios

Availability of data and materials
Data sharing does not apply to this article because no data set was generated or analyzed during the current research period.

Declarations

Ethics approval and consent to participate
This article is ethical, and this research has been agreed.

Consent for publication
The materials quoted in this article have no copyright requirements, and the source has been indicated.

Competing interests
There are no potential competing interests in our paper. And all authors have seen the manuscript and approved to submit to your journal. We confirm that the content of the manuscript has not been published or submitted for publication elsewhere.

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