PREVERJANJE ZANESLJIVOSTI INSTRUMENTOV ZA BELEŽENJE HORIZONTALNO-VERTIKALNEGA SPEKTRALNEGA RAZMERJA MIKROTREMORJEV

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izvleček

Nepreverjeni seizmološki merilni sistemi lahko povzročijo oporečno karto potresne mikrorajonizacije. Karta potresne mikrorajonizacije, ki je namenjena potresno odpornemu načrtovanju, je lahko zasnovana - poleg nekaterih drugih postopkov - na podlagi analize spektralnega razmerja vodoravnih in navpične komponente mikrotremorjev. Mikrotremorje beležimo z modernimi seizmološkimi sistemi. Spremembe v prenosni funkciji seizmološkega sistema, če le-te niso zabeležene in upoštevane, vplivajo na rezultat in s tem tudi na interpretacijo meritve ter tako posledično na zanesljivost celotnega postopka priprave karte potresne mikrorajonizacije. Zato je potrebno seizmološke sisteme primerno verificirati. Razvili smo postopek, kjer s pomočjo dveh referenčnih seizmoloških sistemov preverimo vpliv prenosih funkcij testiranega sistema na krivuljo spektralnega razmerja mikrotremorjev, ne da bi vnaprej poznali prenosne funkcije kateregakoli od sistemov. Postopek smo prikazali na seizmometru Lennartz LE-3D/5s in na seizmoloških sistemu TROMINO, kjer smo za referenčna seizmometra uporabili širokopasovna seizmometra STS-2.

ključne besede

potresna mikrorajonizacija, spektralno razmerje med vodoravnima in navpično komponento, vibracije tal, mikrotremor, prenosna funkcija seizmološkega sistema, kalibracija in zanesljivost seizmološkega sistema

HOW TO TEST THE RELIABILITY OF INSTRUMENTS USED IN MICROTREMOR HORIZONTAL-TO-VERTICAL SPECTRAL RATIO MEASUREMENTS

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Abstract

The reliability of a horizontal-to-vertical spectral ratio (HVSR) curve depends on the results obtained by a verified seismological system. Seismic microzonation provides the basis for a site-specific risk analysis and it can be evaluated using the microtremor HVSR method, where the data are recorded using modern seismological systems. Changes in the transfer function of seismological systems affect the HVSR curve and, consequently, also its interpretation, if these changes are not detected and taken into consideration while performing the microtremor spectral calculations. The reliability of the seismic microzonation performed by such a procedure becomes questionable. An algorithm is developed with a two references system, where the influence of the transfer function on the HVSR curve by the tested system can be evaluated without any a-priori knowledge regarding the transfer functions of any of the systems. This approach is applied to a Lennartz Le-3D/5s seismometer and to a TROMINO seismological system, where two Streckeisen STS2 seismometers are used as the reference systems.

Keywords

seismic microzonation, horizontal-to-vertical spectral ratio method, ambient vibrations, microtremor, seismic system transfer function, reliability and calibration of seismic systems

1 INTRODUCTION

Seismic microzonation is the process of estimating the response of soil layers under earthquake excitations and thus the variation of the earthquake characteristics on the ground surface [1]. Microzonation provides the basis for a site-specific risk analysis, which can assist in the mitigation of earthquake damage [2]. The dynamic characteristics of a site, such as the predominant period, the amplification factor, the shear-wave velocity and the standard penetration test values can be used for seismic microzonation purposes. The shear-wave velocity measurement and the standard penetration test are generally considered to be expensive and are not feasible for a large number of sites for the purpose of microzonation. The microtremor measurement has become a popular method for determining the dynamic characteristics of a site and is being extensively used for microzonation. Microtremors are short-period vibrations resulting from coastal effects, atmospheric loading, the wind's interaction with structures and vegetation, and cultural sources. The microtremor horizontal-to-vertical spectral ratio (HVSR) method, initially proposed by Nogoshi and Igarashi [3] and later popularized by Nakamura [4], is widely used for microzonation projects in order to identify possible site effects [5], [6], or to identify the main frequencies of buildings and their vulnerability to earthquakes [7]. The main advantages of the HVSR method are the simple and low-cost measurements that can be performed at any time and at any location without any specific knowledge regarding the geological structure of what is beneath the ground. This method produces an estimate of the site's geological conditions by providing the peak period of amplification from the HVSR. The amplification occurs where the ratio of amplitudes is greater than one [8]. However, the HVSR technique is not sufficient to characterize the complexity of site effects, in particular the absolute values of the seismic amplification [5].

In HVSR measurements, three seismic sensors that are perpendicular to each other, simultaneously measure

the ground movements in two horizontal and one vertical direction. A simple, vague recipe for the instruments in HVSR measurements that most people are applying is [7]: "Take whatever instrument you think is able to measure very weak ground motion, let it work on the site of your choice for the time you want, at the sample rate you prefer. Whatever A/D converter you use is fine. Aim for stationarity during quiet periods at night-time or, if you prefer, record heavy road traffic. Taper or not, filter or not, base-line correct or not, then perform an FFT, or some other time-domain/frequency-domain transform on separate components, then add averaging, to your taste. Before or after this last operation, take the ratio of the horizontal to vertical spectra, select the average of all the ratios (or the average plus the standard deviation) et voilà, site amplification is ready".
This simple recipe should not be acceptable without hesitation, because a seismic instrument can have an influence on the HVSR calculation and finally on the result and interpretation. Seismic sensors are mostly based on the inertial principle, where the ground motion is measured relative to the inertial reference mass [9]. Modern seismic sensors convert ground motion into electric signals. In a conventional, inertial, short-period seismometer, the ground acceleration is first converted into a relative displacement between the seismic mass and the frame, and then this displacement or its velocity is converted into an electrical signal. Experience has shown that their eigenperiod and the attenuation may change with time up to several tens of percent, especially when these instruments are repeatedly deployed in temporary installations [9]. Changes of this order can cause imperfections in the HVSR measurements. When the ratio of the transfer functions is not 1, it can bias the H/V curve and consequently also its interpretation. Figure 1 shows the ratio between the horizontal and vertical transfer functions for a 4.5-Hz geophone, in the case when the eigen frequency, the damping coefficient and the transduction constant between the vertical and horizontal sensors differ by only 5%. For the same reason "Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations" [5] do not recommend the use of sensors that have their natural frequency above the lowest frequency of interest. Broadband seismometers use the negative force feedback to keep the motion of the mass small. Using this principle, the mechanical imperfections of the sensor are mostly avoided [10]. The feedback principle of a broadband seismometer also means that at some predefined frequency the sensors have a flat response and it also means that the transfer properties of the sensors in this frequency band are stable. Because of this, the producer of a seismometer guarantees the long-term stability of the seismometer's transfer function and they do not specify any corrections in the time period in their calibration certificates (e.g., [11]). These seismometers are not easy to use in the field for short-term experiments because of their relatively long stabilization time, as well as their sensitivity to temperature and pressure variations.

When using broadband or short-period seismometers, it appears necessary to check or validate the instruments in the studied frequency band for an optimal analysis of the HVSR curve. The two following situations need to be checked:

- Does the ratio of the transfer functions affect the HVSR curve?
- Can the self-noise of an instrument affect the HVSR curve?

The instruments can be checked with a reference seismological system using the ground noise, where both the reference and the tested system are placed next to each other - this is the most popular way [12], [13]. This technique was also used in extensive research work [14], where the influence of the instruments on the HVSR curve for ambient vibrations was investigated. These authors compared the differences between the HVSR curves of reference and tested systems for 18 sensors.

The main disadvantage of using the difference between a tested and a reference seismometer to define the quality of the tested system is that the seismic signal is not canceled out: the difference is a function of the transfer functions and of the seismic signals. If the ratio of the HVSR curves between the tested and the reference system is used instead of the difference itself, the seismic signal is canceled out. But in this case we need to be careful how to interpret the results. Reference systems are usually broadband seismometers, with a similar or better quality level than tested systems. But the comparison with this type of reference systems is often wrongly equated with a calibration. In a calibration procedure, the reference system needs to be periodically (at least annually, unless otherwise justified or required) calibrated by a higher-level standard or by an external reference, and all the procedures and changes of the reference instrument need to be traceable. The traceability is defined, in this case, as an unbroken chain of comparisons to national or international standards with stated uncertainties at each step.

Broadband seismometers usually come with a so-called "certificate of calibration" provided by producers. But after that, these seismometers are very rarely, if it at all, compared or calibrated using higher-level standards.

The reason for this is very simple. A high-quality broadband seismometer, such as the STS-2 from Streckeisen, the Trillium 240 from Nanometrics or the CMG-3T from Guralp, which can reach the price of a mid-level car, are usually permanently and precisely installed at a seismic station, with the main purpose being to detect seismic signals. Because of the known long-term stability of seismometer's transfer function (e.g., [11]), a periodic de-installation, transportation to an institution where the calibration is performed, and once again installation at the seismic station, may cause more problems than are solved by a regular calibration: it is difficult to place the seismometer exactly as it was before; the out-of-operation time of the seismic station can be prolonged; after the reinstallation, the seismometer needs days to be stabilized again [15]; and there is always a risk that the instrument will be damaged during the transport. These types of seismometers are usually just periodically controlled with test (or calibration) signals, which are built in acquisition units. (Using test signals from acquisition units is often wrongly equated with calibration. The test signal sources are also not periodically calibrated by higher-level standards or by an external reference.) Only in cases when the response of a seismometer to the test signals is unusual is the seismometer returned back to the manufacturer for verification. Situations where broadband seismometers are used as reference units are very rare and are more or less coincidental. Because of this we need to be aware that when using a broadband seismometer as a reference unit, the parameters of the tested systems are only defined or estimated relative to this particular, non-calibrated reference unit.

By using two broadband seismometers - of higher quality than those of the tested system - at the same time as the reference units, the uncertainty of the measurement results can be minimized. The purpose of this paper is to present a simple test to check the reliability of the instruments used in the HVRS method by using two reference systems without any a-priori knowledge of the transfer function of any of the systems. This approach will be applied to a Lennartz Le-3D/5s [16] and to a TROMINO seismological system [17] where two Streckeisen STS-2 seismometers [15] are going to be used as the reference systems.

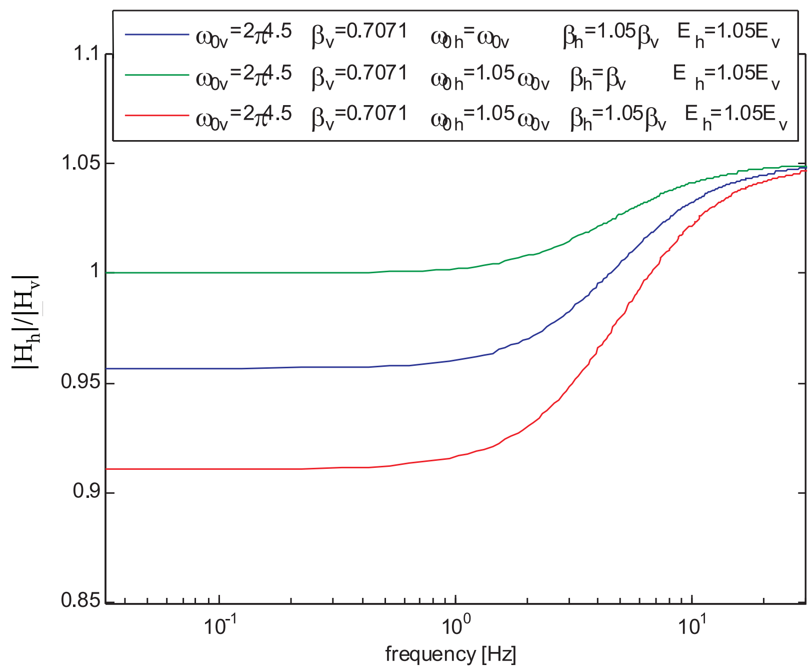

Figure 1. An electrodynamic seismometer, also called a geophone, converts the motion of a mass into an electrical signal using an electromagnetic velocity transducer. The frequency-dependent complex response functions depend on the eigen frequency ω_0, the damping factor β and the transduction constant E [18]. The plot depicts the ratio of the transfer functions for a 4.5-Hz geophone in two-dimensional space (vertical and horizontal), when the difference between the eigen frequencies, the damping coefficients and the transduction constants of the vertical and horizontal sensor is only 5%.

2 MATHEMATICAL MODEL

We present the model in two-dimensional space, using the horizontal and the vertical directions. The measurement is performed by seismological systems with two similar sensors with a linear transfer function, being orthogonal to each other and set up one in the vertical and the other in the horizontal direction. First, we will assume that both the vertical and horizontal sensors detect the same (seismic) signal *x*. The output y_h of the horizontal sensor can be written as the convolution of the input signal *x* with the sensor's transfer function h_h:

$$y_{\mathrm{h}} = h_{\mathrm{h}} \otimes x\,, \qquad (1)$$

Here, the symbol $\otimes$ denotes the convolution. Similarly, the output y_v of the vertical sensor is the convolution of the input signal *x* with the sensor's transfer function h_v:

$$y_{\mathrm{v}} = h_{\mathrm{v}} \otimes x \qquad (2)$$

We assume here, that there is no internal noise. These equations translate into the frequency domain as:

$$Y_{\mathrm{h}} = H_{\mathrm{h}} X\,, \qquad (3)$$
$$Y_{\mathrm{v}} = H_{\mathrm{v}} X\,, \qquad (4)$$

where Y_h, Y_v, *X*, H_h and H_v represent the Fourier transforms of y_h, y_v, *x*, h_h and h_v. Assuming that both systems are linear and noise-free, the output power spectral density (PSD) can be expressed by:

$$\mathrm{P_{hh}} = H_{\mathrm{h}} H_{\mathrm{h}}^{*} \mathrm{P}_{xx}\,, \qquad (5)$$
$$\mathrm{P_{vv}} = H_{\mathrm{v}} H_{\mathrm{v}}^{*} \mathrm{P}_{xx}\,, \qquad (6)$$

The symbol * denotes the complex conjugation, and $\mathrm{P_{xx}} = XX^*$ is assumed to be the coherent ground-motion power spectral density. The horizontal-to-vertical spectral ratio HVSR is defined as

$$\mathrm{HVSR} = \sqrt{\frac{\mathrm{P_{hh}}}{\mathrm{P_{vv}}}}\,. \qquad (7)$$

When the same seismic signal *x* is detected by both systems, the HVSR ratio is affected only by differences in the transfer functions of the used sensors. The ratio of the square magnitude of the transfer functions of the tested seismological system reduces in this particular case to:

$$\frac{H_{\mathrm{h}} H_{\mathrm{h}}^{*}}{H_{\mathrm{v}} H_{\mathrm{v}}^{*}} = \mathrm{HVSR}^2 = \frac{\mathrm{P_{hh}}}{\mathrm{P_{vv}}}\,. \qquad (8)$$

The instruments where this ratio is 1 are trustworthy and can be used in the HVSR measurements.

Under real circumstances, the signals of the horizontal and the vertical components are very rarely equal. A more realistic case is that we have different seismic signals in the horizontal and the vertical directions. Equations (5) and (6) are now rewritten:

$$\mathrm{P_{hh}} = \mathrm{H_h H_h}^{*} \mathrm{P}_{x_h x_h} \qquad (9)$$
$$\mathrm{P_{vv}} = \mathrm{H_v H_v}^{*} \mathrm{P}_{x_v x_v} \qquad (10)$$

The expression $\mathrm{P}_{x_h x_h} = X_h X_h^*$ is assumed to be the coherent ground-motion power spectral density in the horizontal direction and $\mathrm{P}_{x_v x_v} = X_v X_v^*$ the coherent ground-motion power spectral density in the vertical direction.

A simple procedure to check the reliability of the HVSR of particular instruments involves putting it close to a reference seismological system with an equal or better quality class. The output PSD of the reference instrument can be expressed by using the index '*r*':

$$\mathrm{P_{h_r h_r}} = \mathrm{H_{h_r} H_{h_r}}^{*} \mathrm{P}_{x_h x_h} \qquad (11)$$
$$\mathrm{P_{v_r v_r}} = \mathrm{H_{v_r} H_{v_r}}^{*} \mathrm{P}_{x_v x_v} \qquad (12)$$

where $\mathrm{H_{h_r}}$ and $\mathrm{H_{v_r}}$ represent the Fourier transforms of the references sensors' transfer functions $h_{\mathrm{h_r}}$ and $h_{\mathrm{v_r}}$. Let us presume that the reference system is not calibrated, as written and defined in the previous section. In this case, the ratio of transfer functions of the reference systems $\left|\mathrm{H_{h_r}}\right| / \left|\mathrm{H_{v_r}}\right|$ is unknown. If, for testing purposes, we use the difference of the HVSR curves of a tested and of a reference system, a function of both transfer functions and also of a seismic signal is obtained:

$$\Delta = \mathrm{HVSR} - \mathrm{HVSR_r} = \sqrt{\frac{\mathrm{P}_{x_h x_h}}{\mathrm{P}_{x_v x_v}}} \left(\sqrt{\frac{\mathrm{H_h H_h}^{*}}{\mathrm{H_v H_v}^{*}}} - \sqrt{\frac{\mathrm{H_{h_r} H_{h_r}}^{*}}{\mathrm{H_{v_r} H_{v_r}}^{*}}} \right) =$$
$$= f\left(X_h, X_v, \mathrm{H_h}, \mathrm{H_v}, \mathrm{H_{h_r}}, \mathrm{H_{v_r}}\right), \qquad (13)$$

where the index *r* represents the reference system. Because this expression still includes the unknown seismic signal, equation (13) cannot be applied to uniformly evaluate the influence of the transfer function of the system under test on the calculated HVSR ratio. The ratio of HVSR between the tested and reference system caused the seismic signal to be canceled out. If the reference system is ideal, meaning $h_{\mathrm{h_r}} = h_{\mathrm{v_r}}$, the information about the transfer function can be evaluated:

$$\sqrt{\frac{\mathrm{H_h H_h}^{*}}{\mathrm{H_v H_v}^{*}}} = \sqrt{\frac{\mathrm{P_{hh}}}{\mathrm{P_{vv}}}} \frac{1}{\mathrm{HVSR}_r}\,. \qquad (14)$$

Using a non-calibrated reference system, the ratio of HVSR between the tested and the reference is still an unknown function:

$$\sqrt{\frac{H_h H_h^* H_{v_r} H_{v_r}^*}{H_v H_v^* H_{h_r} H_{h_r}^*}} = \sqrt{\frac{P_{hh}}{P_{vv}}} \frac{1}{HVSR_r}. \qquad (15)$$

In the case where only one non-calibrated reference system is used, there is no information about in which frequency band or if at all, the calculation is trustworthy. A more promising procedure to check the reliability of the HVSR of particular instruments is by putting it close to two reference seismological systems, where both references system have much better characteristics than the tested one. We will assume that these two seismological systems are composed of two high-quality broad-band seismometers, which have the manufacturer's "certificate of calibration", but were never calibrated again after that.

The first step is to define the frequency interval where the two systems can be used as a reference.

The frequency interval where the two systems can be used as reference units is defined by:

$$\frac{HVSR_{r_1}}{HVSR_{r_2}} = 1, \qquad (16)$$

where the indices r_1 and r_2 refer to the first and second reference systems. In reality, this is almost never true. While seismometer manufacturers certainly attempt to build their instruments with equal characteristics, in practice there will almost always be some difference, at least in the mechanical alignment of the two systems and in small deviations in the transfer functions and generator constants. Considering this, equation (16) needs to be adjusted by:

$$\left| \frac{HVSR_{r_1}}{HVSR_{r_2}} - 1 \right| \le \delta; \ \delta \ll 1. \qquad (17)$$

The value δ represents an acceptable error. In the HVSR calculations, this ratio is represented by smoothed PSD estimates [5]. The PSD estimates of seismic signals can be noisy themselves, and the smoothing would make them much cleaner [12]. At the same time, the smoothing of the PSD makes it possible to use reference systems with different sampling rates than off the tested system. The value δ depends on a smoothing procedure, and in our cases it was 0.02. The frequency interval where the reference system can be used is defined by the range where δ is continuously below this value.

Although we have two reference systems, we still do not know which of them is better. The next step is to use both reference systems to evaluate the ratio of the transfer functions of the tested system. The easiest way is just to employ the average value using both reference systems from equation (14):

$$\widehat{\frac{|H_h|}{|H_v|}} = \sqrt{\frac{P_{hh}}{P_{vv}}} \left(\frac{HVSR_{r_1} + HVSR_{r_2}}{2HVSR_{r_1} HVSR_{r_2}} \right). \qquad (18)$$

Another possibility is to calculate the average value for the square ratio of the transfer functions first, and then to take a square root of the complete expression:

$$\widehat{\frac{|H_h|}{|H_v|}} = \sqrt{\frac{P_{hh}}{P_{vv}} \left(\frac{HVSR_{r_1}^2 + HVSR_{r_2}^2}{2HVSR_{r_1}^2 HVSR_{r_2}^2} \right)}. \qquad (19)$$

The third possibility is to estimate the ratio of the transfer functions by using a simple mathematical manipulation. First, equation (13) is rewritten in a different form:

$$\left(\frac{H_h H_h^*}{H_v H_v^*} - \frac{H_{h_{r_1}} H_{h_{r_1}}^*}{H_{v_{r_1}} H_{v_{r_1}}^*} \right) \frac{P_{x_h x_h}}{P_{x_v x_v}} = \frac{P_{hh}}{P_{vv}} - HVRS_{r_1}^2. \qquad (20)$$

At this point we will assume that both reference systems are ideal and the ratio of the transfer functions of the reference systems are equal: $H_{hr_i} H_{hr_i}^* = H_{vr_i} H_{vr_i}^*$ for i=1, 2. The left-hand side of equation (20) reduces to:

$$\left(\frac{H_h H_h^*}{H_v H_v^*} - 1 \right) HVRS_{r_1}^2 = \frac{P_{hh}}{P_{vv}} - HVRS_{r_1}^2. \qquad (21)$$

Using equation (16), the right-hand side of equation (21) can be rewritten using the second reference system ($HVRS_{r_1}^2 = HVRS_{r_2}^2$):

$$\left(\frac{H_h H_h^*}{H_v H_v^*} - 1 \right) HVRS_{r_1}^2 = \frac{P_{hh}}{P_{vv}} - HVRS_{r_2}^2. \qquad (22)$$

Using equation (22), the square ratio of the transfer functions is:

$$\frac{H_h H_h^*}{H_v H_v^*} = \frac{\frac{P_{hh}}{P_{vv}} - HVRS_{r_2}^2 + HVRS_{r_1}^2}{HVRS_{r_1}^2}. \qquad (23)$$

The right-hand side of equation (23) can be written as an average value of both combinations of reference systems:

$$\overline{\frac{H_h H_h^*}{H_v H_v^*}} = \frac{1}{2} \left(\frac{\frac{P_{hh}}{P_{vv}} - HVRS_{r_2}^2 + HVRS_{r_1}^2}{HVRS_{r_1}^2} + \frac{\frac{P_{hh}}{P_{vv}} - HVRS_{r_1}^2 + HVRS_{r_2}^2}{HVRS_{r_2}^2} \right) \qquad (24)$$

Equation (24) can be rewritten as:

$$\widetilde{\frac{|H_h|}{|H_v|}} = \sqrt{\frac{\frac{P_{hh}}{P_{vv}} \left(HVRS_{r_2}^2 + HVRS_{r_1}^2 \right) - \left(HVRS_{r_2}^2 - HVRS_{r_1}^2 \right)^2}{2HVRS_{r_1}^2 HVRS_{r_2}^2}}. \qquad (25)$$

If both reference systems are ideal ($HVRS_{r_2}^2 = HVRS_{r_1}^2$), then equation (25) is transformed into equation (14). If the square part of the right-hand side of equation (25) is neglected ($\left(HVRS_{r_2}^2 - HVRS_{r_1}^2\right)^2 \approx 0$), then this equation reduces to equation (19). Equation (25) is only valid in the frequency interval where both reference systems are almost equal, and considering this equation (25) can be expanded using the Taylor series:

$$\frac{\widetilde{|H_h|}}{|H_v|} = \sqrt{\frac{\frac{P_{hh}}{P_{vv}}\left(HVRS_{r_2}^2 + HVRS_{r_1}^2\right)}{2HVRS_{r_1}^2 HVRS_{r_2}^2}}\left(1 - \frac{1}{2}\frac{\left(HVRS_{r_2}^2 - HVRS_{r_1}^2\right)^2}{\frac{P_{hh}}{P_{vv}}\left(HVRS_{r_2}^2 + HVRS_{r_1}^2\right)}\right). \quad (26)$$

This is the next relation for the "estimation" of the ratio of the transfer functions of the tested system. Using equation (26) another condition must be fulfilled for the frequency interval where two reference systems can be used:

$$\frac{\left(HVRS_{r_2}^2 - HVRS_{r_1}^2\right)^2}{\frac{P_{hh}}{P_{vv}}\left(HVRS_{r_2}^2 + HVRS_{r_1}^2\right)} \le \delta_t;\ \delta_t \ll 1. \quad (27)$$

The value δ_t depends on the smoothing procedure and in our case it was 0.0002. In the frequency interval where both reference systems are almost equal, the differences between equations (18), (19) and (26) are practically insignificant, and any of the three equations can be used.

The benefit of using two reference systems instead of one is that we have a defined frequency interval where the test can be performed. Also, no information regarding the transfer functions of the reference systems are needed to evaluate the influence of the tested system on the HVSR calculation. Again (as in equation (8)) the tested instruments, where this ratio is 1, are trustworthy and can be used in the HVSR measurements. But when using a non-ideal reference system, a small deviation δ_h from the value 1 can be allowed:

$$\left|\frac{\widetilde{|H_h|}}{|H_v|} - 1\right| \le \delta_h;\ \delta_h \ll 1. \quad (28)$$

The value δ_h depends on a smoothing procedure and in our cases it was 0.05.

In a similar way and with the same assumptions, the estimation of the square magnitude of the transfer function of an unknown system can be evaluated using equation (19):

$$\widetilde{H_k H_k^*} = \left(\frac{P_{kk}(P_{kr_1kr_1} + P_{kr_2kr_2})}{2P_{kr_1kr_1}P_{kr_2kr_2}}\right);\ k=h,v\ , \quad (29)$$

or using equation (25):

$$\widetilde{H_k H_k^*} = \frac{P_{kk}(P_{kr_1kr_1} + P_{kr_2kr_2})}{2P_{kr_1kr_1}P_{kr_2kr_2}}\left(1 - \frac{(P_{kr_1kr_1} - P_{kr_2kr_2})^2}{P_{kk}(P_{kr_1kr_1} + P_{kr_2kr_2})}\right); \quad (30)$$

$$k=h,v\ .$$

Here, the index 'k' represents the horizontal (h) and the index 'v' the vertical (v) component, respectively. In this case, the transfer function of the reference system needs to be flat in the frequency interval of the observation or the power spectra of the reference systems need to be corrected using the instrumental correction.

3 INFLUENCE OF THE INSTRUMENTAL NOISE

All the previous equations are based on an assumption that the self-noise of all the instruments involved is negligibly small (e.g., much smaller than the seismic signal). This requirement is also applied to instruments used in the measurements of the HVSR calculations of ambient vibrations. The self-noise can affect the calculation because it appears to increase the seismic signal. The error is the result of self-noise, and it can be represented by:

$$\sqrt{X_k X_k^* + N_k N_k^*} = \sqrt{X_k X_k^*}(1 + er_k)\ ;\ k=h,v\ . \quad (31)$$

The symbol N_k represents the Fourier transform of the instrumental noise n_k (k = h, v) and the symbol er_k represents an error. We assume that the instrumental noise and the seismic signal are uncorrelated. The last equation can be rewritten:

$$\sqrt{1 + \frac{N_k N_k^*}{X_k X_k^*}} = (1 + er_k)\ ;\ k=h,v\ . \quad (32)$$

The ratio between $X_k X_k^*$ and $N_k N_k^*$ is:

$$\frac{X_k X_k^*}{N_k N_k^*} = \frac{1}{(1 + er_k)^2 - 1}\ ;\ k=h,v\ . \quad (33)$$

The seismic noise spectra are usually represented by the PSD plots and reported in dB relative to 1 $(m/s^2)^2$/Hz or to 1 $(m/s)^2$/Hz. The acceptable difference between the seismic signal and the instrumental noise (in dB) is calculated with the predefined value of er_k:

$$\Delta_{dB} = 10\log_{10}\left(\frac{X_k X_k^*}{N_k N_k^*}\right) = 10\log_{10}\left(\frac{1}{\left(1 + er_k\right)^2 - 1}\right). \quad (34)$$

If an error of 1% is acceptable, then the seismic signal X_k needs to be larger than the self-noise N_k by at least 17 dB.

In the case of a 5% acceptable error the difference needs to be at least 10 dB. If the difference is lower than these values, the self-noise starts to affect the calculations. It is preferable that the self-noise of a particular instrument should be evaluated before its first use in the HVSR calculations. The self-noise can be obtained using "Three-channel Correlation Analysis Techniques" [19]. Before any analysis of an HVRS calculation, the difference between the PSD of a seismic signal and the PSD of the instrumental noise needs to be estimated and defined, because the self-noise can have an influence on the measurements.

4 CASE STUDIES

Side-by-side measurements using different seismic instruments were performed at the same time in September 2008 at the Golovec Observatory, Ljubljana (LJU). Two STS-2 seismometers [15] were used as the reference systems. The first STS-2 seismometer was connected to the Quanterra Q730 [20] acquisition unit and the second one was connected to the EarthData PR6 [21] acquisition unit. The data were sampled at 200 sps. The input in our experiment was a one-hour, finite-length time seismic data segment. The power spectral density (PSD) estimations for both reference systems are depicted in Figure 2. The Welch method for the power spectral density estimation was applied using a Matlab® built-in function. The frequency response of the STS-2 seismometers lies in the frequency interval between 0.008 Hz and 50 Hz. Figure 3 shows the curves that were calculated using equations (17) and (27). Because the HVSR of the tested signal is also included in equation (27), the HVSR of LE-3D/5s was used for the calculation. From Figure 3 it is possible to estimate the frequency interval where two reference system systems can be used in this experiment to be between 0.1Hz and 9 Hz.

4.1 LENNARTZ LE-3D/5S SEISMOMETER (S/N 059)

The Lennartz LE-3D/5s [16] seismometer is widely used for microtremor measurements. Theoretically, it has a flat response to the velocity from 0.2 Hz. The Lennartz LE-3D/5s seismometer (s/n 059, manufactured in 1992) was connected to an Earth Data PR6 acquisition unit [21], and the signal was sampled at 200 samples per second. The HVSR curve of the LE-3D/5s system differs slightly for both STS-2 systems only at low frequencies (Figure 4).The evaluated ratio for the LE-3D/5s seismometer s/n 059 shows us that this seismometer can be used for reliable HVSR measurements beyond 0.25 Hz without any problems (Figure 5). Because of this the value of δ_h can be defined as 0.05. In the frequency range between 0.11 Hz and 0.25 Hz the instrumental correction for all the components is needed for this seismometer. Below 0.11 Hz the self-noise of the LE-3D/5s instrument critically affects this particular measurement. As

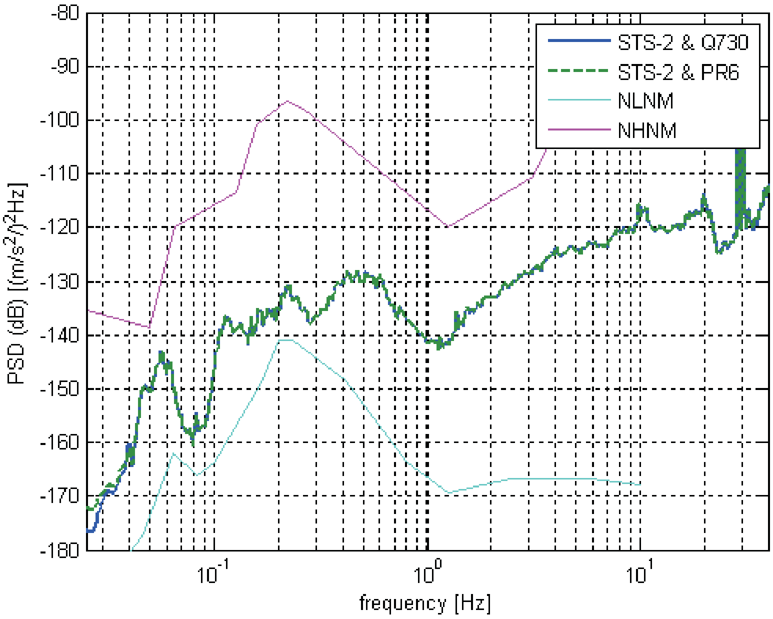

Figure 2. Power spectral density curves for the vertical component for both reference systems, compared to the standard seismic noise models of the Earth [22].

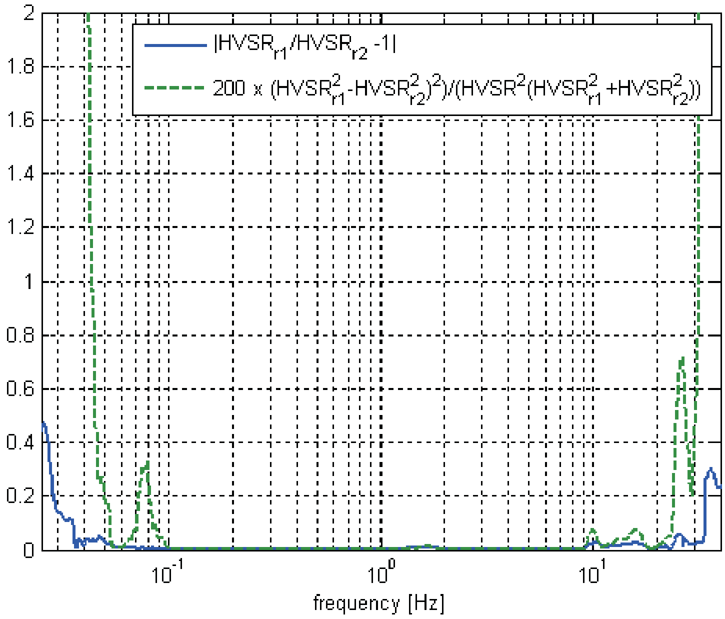

Figure 3. The frequency interval where two references seismological systems can be used in this experiment was defined by equation (17) (blue line) and by equation (27) (green line). In equation (27) the HVSR of LE-3D/5s is also used and for a clearer presentation the curve is multiplied by a factor of 200. In the frequency interval between 0.1 Hz and 9 Hz two seismological systems with STS-2 seismometers can be used as reference systems. Equation (27) gives more sharp boundaries and looks more useful, but we recommended using both equations.

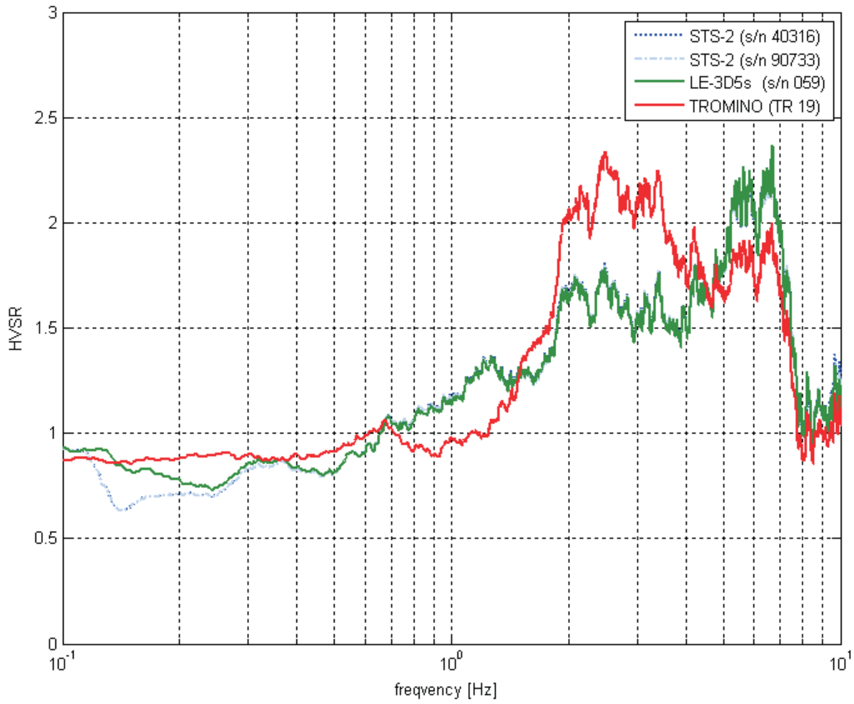

Figure 4. The HVSR for 4 seismological systems, two STS-2 seismometers (STS-2 s/n 40316, connected to the Q730, STS-2 s/n 90733 connected to the PR6 acquisition unit), the LE-3D/5s seismometer (s/n 59 connected to the PR6 acquisition unit) and the TROMINO instrument (TR-00019). The HVSR of the TROMINO instruments noticeably differs in the frequency interval from 0.8Hz to 8 Hz compared to the HVSR of systems with STS-2 seismometers, while the HVSR of LE-3D/5s system only differs slightly at lower frequencies.

is clear from Figure 5, the ratio of the transfer functions drastically changes its slope at 0.11Hz. This situation can be explained by the influence of the instrumental noise. Using figure 6 one can define an acceptable difference between the PSD of the estimated self-noise curve and the PSD of the recorded seismic signal for the LE-3D/5s seismometer to be approximately 15 dB.

4.2 TROMINO (TR-0019)

TROMINO systems [17] are mostly used for micro-tremor measurements. They are composed of three orthogonal electrodynamic velocity sensors, a GPS receiver, a digitizer and a recording unit with a flash-memory card. All the parts are integrated into a common case. The Tromino under the test (TR-19) was manufactured in 2005 and was in service in January 2008. This Tromino belongs to the first generation of these instruments. The Trominos released in the following years were completely redesigned and should have better characteristics. In our test, the TROMINO instrument data were sampled at 256 sps. The HVSR curves for the TROMINO instrument noticeably differ from the HVSR curves of systems with STS-2 seismometers (Figure 4). When the self-noise of the system is estimated and using a boundary of the allowed 15 dB difference between the seismic noise PSD and the instrument self-noise PSD (Figure 6), which is defined on the basis of the Lennartz Le-3D/5s seismometer, then in this particular case the self-noise of the instrument affects the HVSR calculation below 3Hz. Because of this, the ratio of the transfer functions - as depicted in Figure 7 - for the TROMINO system (TR- 19) cannot be correctly evaluated in this particular case below 3 Hz. The self-noise of the TROMINO system (TR-19) is high: it is much higher than the NLNM (New Low Noise Model, [22], [23]). This instrument cannot be used without any instrumental correction for all the components in the frequency interval between 3 Hz and 8 Hz. Above 8 Hz, just the transduction constants of all components need to be redefined. In this particular case, we cannot say anything about the ratio of the transfer functions below 3 Hz, because of the relatively high instrumental noise with respect to the seismic noise.

5 CONCLUSIONS

The document "Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations" [5] states that "The first requirement, before any extraction

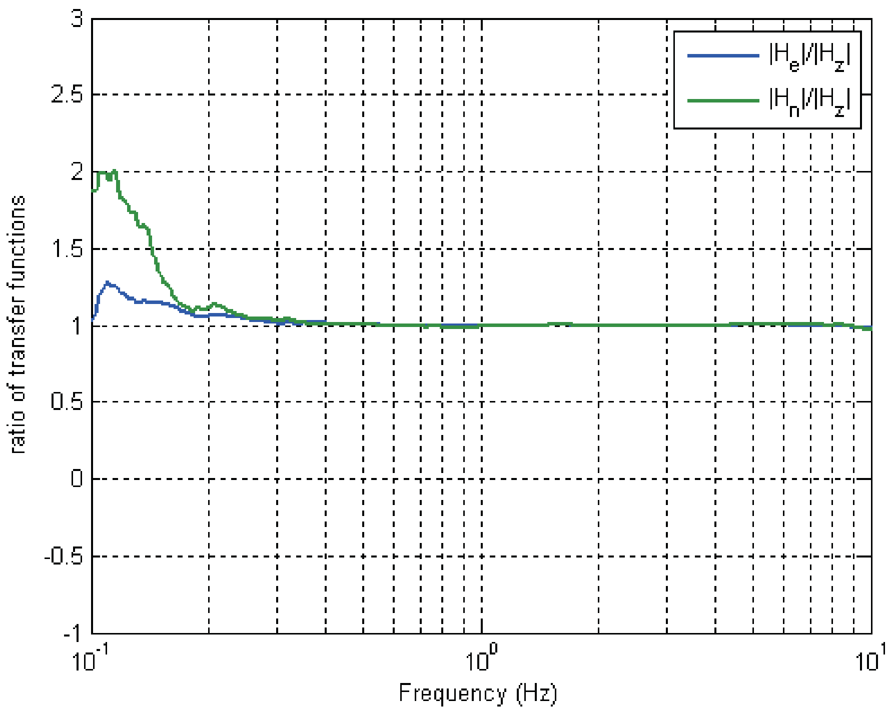

Figure 5. The ratio of transfer functions for an LE-3D/5s seismological system computed using equation (26), the ratio of the transfer functions of the E-W and the vertical component (blue line), the ratio of the transfer function of the N-S component and the vertical component (green line). The ratio of the transfer functions drastically changes its slope at 0.11Hz and can be explained by the influence of the instrumental noise.

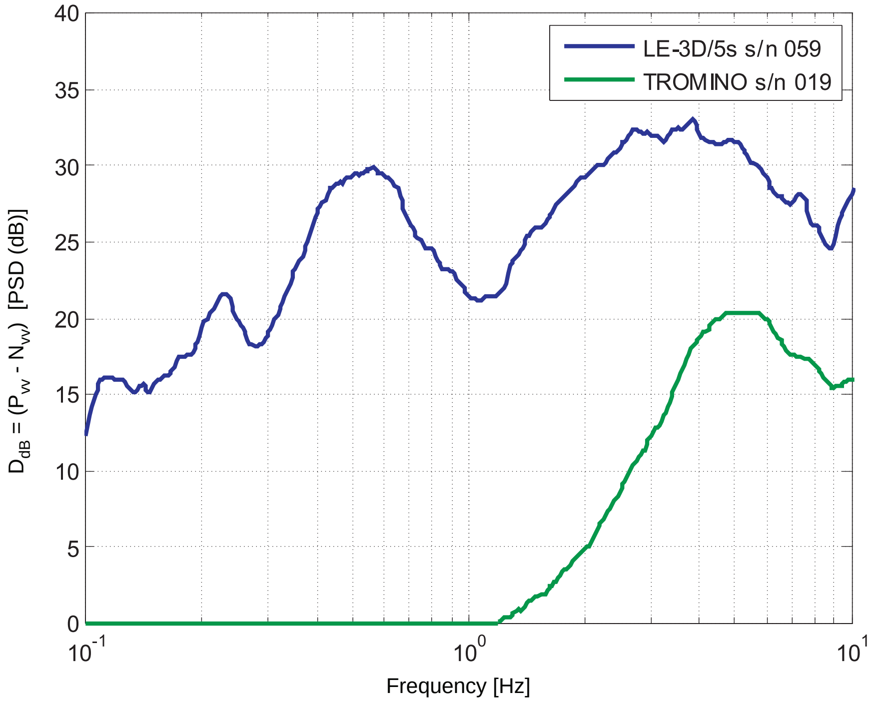

Figure 6. The difference between the PSD of the estimated self-noise curve (N_{vv}) estimated by "Three-channel Correlation Analysis Techniques" [19] and the PSD of the recorded seismic signal (P_{vv}) for the LE-3D/5s seismometer (s/n 59) and TROMINO (TR 19), for the vertical component. The self-noise of the TROMINO instrument is considerably higher.

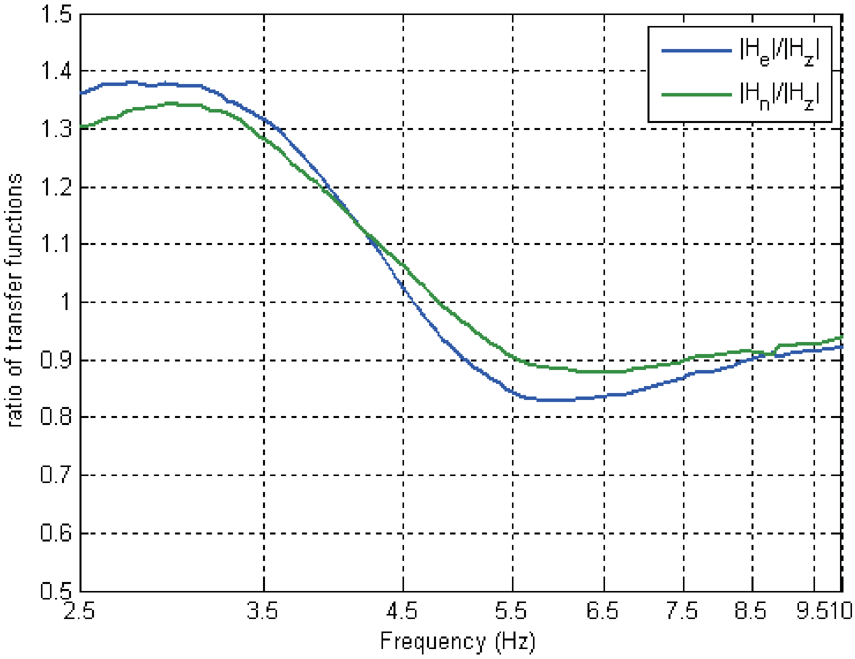

Figure 7. The ratio of the transfer functions of the TROMINO TR-19 seismological system computed using equation (26): the ratio of the transfer function of the E-W component and the vertical component (blue line) and the ratio of transfer function of the N-S component and the vertical component (green line). Below 3 Hz, the self-noise of the Tromino TR-19 affects the calculation and below this frequency, the ratio of the transfer functions cannot be calculated in this particular case.

of information and any interpretation, concerns the reliability of the HVSR curve." The basic presumption is that the HVSR curves obtained using different seismological systems at the same time and at a same place, need to be equal or at least very similar. In this study we presented two important sources in seismological systems that can cause insurrections in the HVSR curves and therefore an incorrect interpretation. The first source of error is the self-noise of an instrument that needs to be negligibly small. The second source of error is the use of non-calibrated instruments or if the transfer function is not considered in the HVSR calculations. In our paper a simple algorithm is presented that enables the reliability of the instruments used in the HVSR measurements using two broadband seismometers with better quality than tested systems as references units.

In order to maintain the integrity of the recorded data, the seismograph systems need to be periodically verified. This verification is important to ensure that the instrument is performing as it was designed to, and that it measures accurately the true ground vibration [24]. Although the seismographs are designed for use in a rugged environment, they are still sophisticated electronic monitoring devices. Therefore, preventative maintenance becomes an important part of the annual verification process [25]. A simple case to confirm these findings are instruments used in our test.

Using a non-calibrated instrument in measurements - without a correction for its transfer function - can cause unreliability in the estimated dynamic characteristics of a site and consequently of evaluated seismic microzonation.

Because of this, we have developed a straightforward method - using two reference seismometers – to evaluate the influence of the instrument's transfer function on the validity of the HVRS procedure, without any a-priori knowledge in terms of the transfer function of any of the systems.

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