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A novel horizontal to vertical spectral ratio approach in a wired structural health monitoring system

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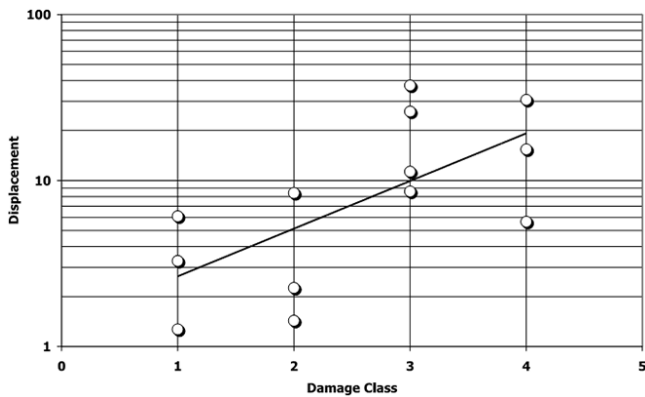*Correspondence to:* F. P. Pentaris (fpentaris@gmail.com)

Abstract. This work studies the effect ambient seismic noise can have on building constructions, in comparison with the traditional study of strong seismic motion in buildings, for the purpose of structural health monitoring. Traditionally, engineers have observed the effect of earthquakes on buildings by usage of seismometers at various levels. A new approach is proposed in which acceleration recordings of ambient seismic noise are used and horizontal to vertical spectra ratio (HVSR) process is applied, in order to determine the resonance frequency of movement due to excitation of the building from a strong seismic event. The HVSR technique is widely used by geophysicists to study the resonance frequency of sediments over bedrock, while its usage inside buildings is limited. This study applies the recordings inside two university buildings attached to each other, but with different construction materials and different years of construction. Also there is HVSR application in another much older building, with visible cracks in its structure. Sensors have been installed on every floor of the two university buildings, and recordings have been acquired both of ambient seismic noise and earthquakes. Resonance frequencies for every floor of every building are calculated, from both noise and earthquake records, using the HVSR technique for the ambient noise data and the receiver function (RF) for the earthquake data. Differential acceleration drift for every building is also calculated, and there is correlation with the vulnerability of the buildings. Results indicate that HVSR process on acceleration data proves to be an easy, fast, economical method for estimation of fundamental frequency of structures as well as an assessment method for building vulnerability estimation. Comparison between HVSR and RF technique shows an agreement at the change of resonance frequency as we move to higher floors.

1 Introduction

Horizontal to vertical spectra ratio (HVSR) method was first proposed by Nogoshi and Igarashi (1971) and was subsequently widely spread by Nakamura (1989). HVSR has been applied by Dimitriu et al. (1999), who found the fundamental frequency of the ground. Yuncha and Luzon (2000) tested the HVSR technique in low and high impedance contrast between surface and bedrock. Their results show that the HVSR technique can give reliable results when the impedance contrast between surface layer and bedrock is high. The above authors introduce the problem of superposition of different incoming P-SV waves in HVSR. This problem is discussed in detail by Fäh et al. (2001), who apply the HVSR method using both classical and wavelet techniques, find stable recordings and use an inversion method of genetic

algorithm in order to present the S velocity without P wave effect on an ambient vibration measurement. They use an empirical model which may not be applicable at every site due to the need for training based on stable data values which may vary with geographical location.

The classic method of spectral ratio has been used by Parolai et al. (2004), who observed that fundamental frequency is stable in time but unstable in amplitude for a site. They conclude that HVSR should be verified with a lot of measurements, and they address that the spectrum analogy remains almost the same for seismic and environmental noise. They also conclude that high impedance contrast between surface sediment layer and bedrock can reveal the fundamental frequency when the higher harmonics are hidden. The combination of HVSR results combined with geological data is

Figure 1. Damaged and calculated inter-storey displacement index correlation by Mucciarelli et al. (2001).

applied by Panou et al. (2005), in the large area of Thessaloniki, where they find similarities between HVSR results and the geological data and suggest that HVSR is a reliable method for site characterization. HVSR is applied by Lombardo and Rigano (2007), who use this method in order to characterize the terrain in an urban area, by recording measurements from different terrains and comparing the ambient noise with preliminary seismic recordings. They address the need for validation of the results with earthquake recordings. HVSR has also been applied by Sokolov et al. (2007) in earthquake recordings in which they study rock site amplifications in the large area of Taiwan. Wavelet analysis in HVSR has been applied by Carniel et al. (2008) using the key point advantage of wavelet analysis method (namely the ability to analyse data in both time and frequency domain) in order to improve the ability of HVSR for site effect estimation. The main disadvantage is the high complexity of the algorithm application. Another technique for improving HVSR is by self-organizing map (SOM) applied again by Carniel et al. (2009), who apply this neural network technique (SOM) for site characterization, but this method is computationally inefficient as it requires educating the neural network, for every site amplification analysis. Accelerometers and seismometers recording seismic and ambient noise activity have been used by Chávez-García et al. (2010), estimating spectral ratios of a site, presenting the local transfer function of case study buildings. Their main finding was the requirements for lower noise of accelerometers and seismometers in order to study efficiently the ambient vibrations.

2   Related work on HVSR method in structural health monitoring

Triwulan et al. (2010) claim that geological characteristics of a region, structural characteristics of a building and also the correlation of both geology and structure can be described by the application of HVSR data recorded on the ground of the building and inside the building. They apply HVSR method in both ground and buildings in order to study the natural frequency, the index of vulnerability, the amplification factor of the ground as well as indexes of vulnerability of buildings and ground.

Ambient noise in concrete reinforced building, affected by subway trains, is also studied in Beijing by Luo et al. (2011), who present the resonance frequency of the building on each floor. They study the range of the fundamental frequency of the building (around 2.4 Hz), the frequency which is generated by the nearby traffic on the building (around 10 Hz) and the geological fundamental frequency of the region in which the building is located (around 2–3 Hz). They indicate that, although the amplification of the site is critical for the specific building, its damping ratio of 0.17 is very effective in structural integrity.
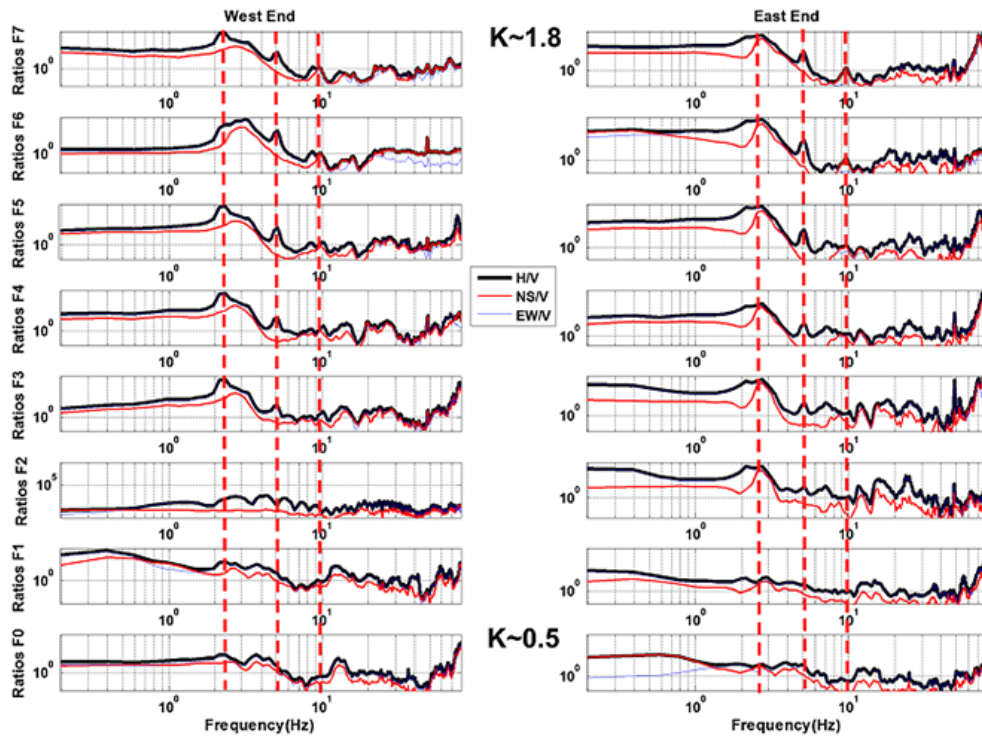
Mucciarelli et al. (2001) claim that study of microtremors and weak motion provides fast and reliable data for site amplification and structure vulnerability compared with other traditional methods (like geological study by drilling), and the correlation of damage and structural integrity is with physical parameters and not normalized adimensional indexes. Furthermore, they apply the technique (filtering of the signals and avoid wind, traffic and man-made disturbance effect) based on empirical decomposition method to estimate the structural vulnerability of buildings under seismic excitation. Figure 1 presents their proposed index of damage with inter-storey displacement.

Liu et al. (2014) applied ambient noise survey on a seven-floor building using seismometers in order to assess the site amplification in an urban area and to study the ability of HVSR to assess building vulnerability under strong motion excitation. The HVSR results are shown in Fig. 2. They consider that ambient noise could be used for earthquake and seismology engineering in urban areas, but they do not correlate these HVSR results with specific building vulnerability characteristics. Vertical red dashed lines present the resonance frequencies.

Literature reveals that HVSR application of ambient seismic vibration in structural health monitoring is limited. HVSR is used to evaluate the fundamental frequency of the surface layer over bedrock. By studying HVSR in buildings, there is the ability to study the fundamental frequency of the building excited by environmental noise of seismic activity, and compare it with the fundamental frequency of the surface around the building. The study of HVSR outside and inside the building potentially can provide two factors: initially, how close the fundamental frequency of the building is to the fundamental frequency of the surface layer, and also how high the amplitude of this frequency is.

2.1   Case study infrastructures

Case study includes two different university buildings, which are attached to each other on one side. They have different
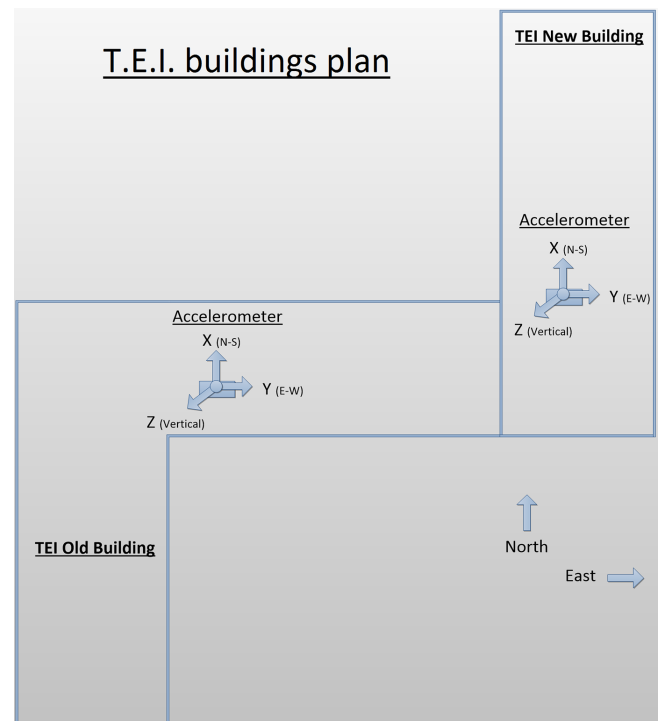
Figure 2. HVSR with black colour, N–S/V with red colour and E–W/V with blue colour on each floor for both sides (east and west) by Liu et al.(2014).

construction materials and different years of construction. In more detail, the two buildings host the Chania branch of the Technological Institute of Crete (TEI). Building (A) was built on the west side in 1995, with concrete, glass and steel, while building (B) was built on the east side in 2007 with concrete. Table 1 presents characteristics for both buildings, and Fig. 3 illustrates the schematic diagram of the two buildings, showing the sensor's location.

Sensors recorded data at various instances throughout a day, in order to study the effect of human activity during day and night.

HVSR method is applied for every floor of the buildings in order to discover the effect of floor amplification on each floor and the similarities which may exist under seismic and environmental noise. The approach of studying the HVSR on each floor in a building, under seismic activity, and ambient noise and correlate the increase of HVSR value with the building internal drift, is done for first time. In this context this work proposes an index which is correlated with HVSR disturbances from floor to floor in a building and could probably present the vulnerability of a building (under excitation) on every floor.

Figure 4 presents a map of the HVSR frequency for the large area of the city of Chania. Case study buildings are located in the geographical region where recorded HVSR frequency is in the range of 0.49–0.69 Hz (in the red square of

Figure 3. Schematic plan of the TEI building at Chania. The location of the sensors is presented for each building.

Table 1. Characteristics of the TEI buildings at Chania

Building code	Age (years)	Size (m)	Shape (direction)	Floor height	Number of rooms	Number of floors
A	19	30.62 × 18.03	Rectangle (N–S)	3.65	7 5	4 4
		11.29 × 43.30	Rectangle (E–W)	3.65		
B	7	51.55 × 21.85	Rectangle (N–S)	3.67	15	4

Figure 4. Case study building location is indicated. This map presents frequency of recorded HVSR for the broader area of Chania (Papadopoulos, 2013).

Fig. 4). The HVSR amplitude for the area close and on the case study university buildings is in the range of 2.40–2.54.

The instrumentation that is used in this work is from the wired structural health monitoring (SHM) system which is deployed in the Technological Educational Institute of Crete, Chania, with accelerometers of high sensitivity, sample rate at 125 Hz, and configured in triggered mode (Pentaris et al., 2013).
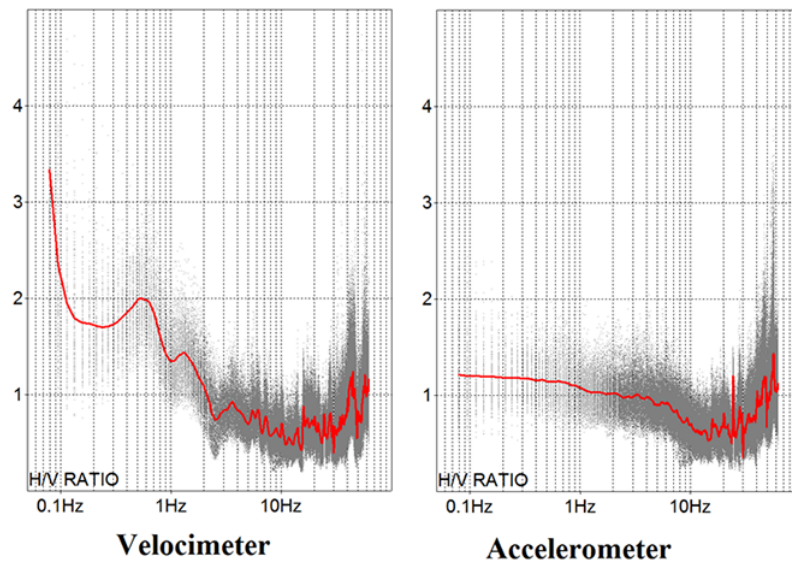
2.2 Instrumentation for HVSR recordings

In this study three kinds of sensors are used, in order to present the recording capabilities of each approach. Initially a Reftek accelerometer 130-SMA is used with a scale range of ± 4 g, dynamic range of 112 dB at 1 Hz and a sensitivity of $1.6 \, \mathrm{V} \, (\mathrm{g} \, \mathrm{m}^{-1})^{-1}$. The frequency response is from flat DC up to 500 Hz. More information about Reftek accelerometer 130-SMA can be found at www.reftek.com (last access: 1 December 2013). Next a Guralp CMG-3ESP velocimeter is used, which is a broadband seismometer with response from 0.016 Hz until 50 Hz,
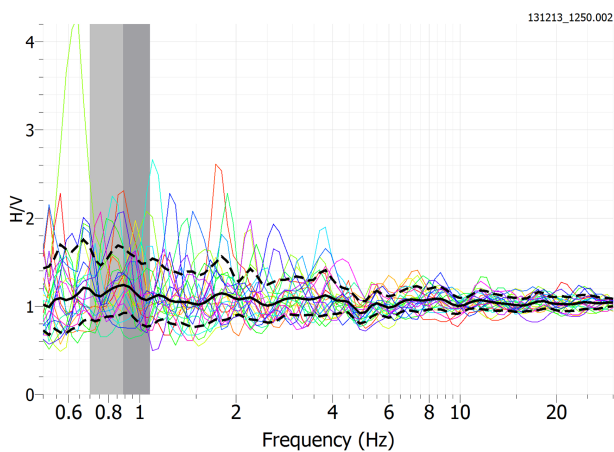
sensitivity $2 \times 1000 \, \mathrm{V} \, (\mathrm{m} \, \mathrm{s}^{-1})^{-1}$ and dynamic range higher than 140 dB. More details about Guralp Seismometer are on http://www.guralp.com (last access: 1 December 2013). Also HVSR is studied by seismometer Lennartz Le3D/5s. The sensitivity is $400 \, \mathrm{V} \, (\mathrm{m} \, \mathrm{s}^{-1})^{-1}$ with a frequency spectrum from 0.2 to 100 Hz. The sensitivity of the seismometer is flat between 0.4 and 100 Hz. Details about the ground velocity sensor Lennartz LeD/5s can be found at http://www.lennartz-electronic.de (last access: 10 November 2013).

2.3 Comparison of velocimeter and accelerometer sensors for HVSR method

HVSR is applied in seismometers and accelerometer, in order to study whether they have the same sensitivity, the same levels of electronic noise, and whether the recorded data have the same ability to reveal the HVSR data. The recording of the ambient noise will be divided in specific length segment and will be processed by Fourier transform, presenting the frequency spectrum with the resonance frequencies.

Figure 5. Data of Guralp velocimeter (left graph) and REFTEK accelerometer 130-SMA (right graph), analysed with HVSR technique for a recording of 60 min length on the ground floor of the old building of TEI Chania.
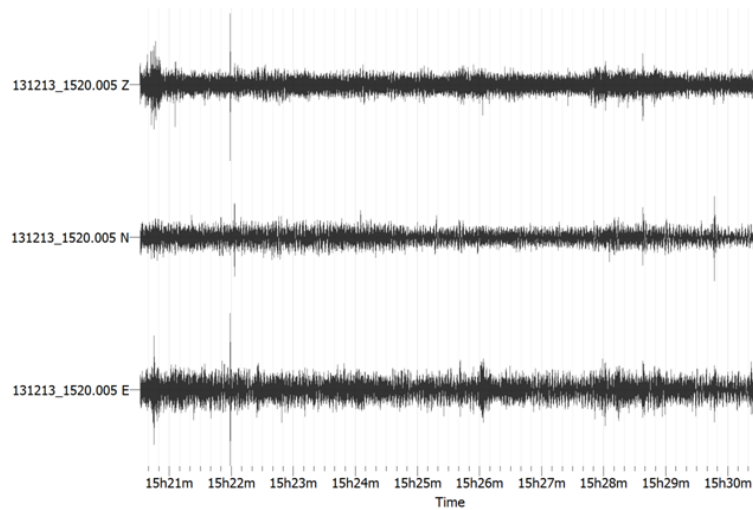

Figure 6. HVSR analysis of Lennartz LeD/5s velocimeter, for recording of 60 min length, on the ground floor of old building of TEI Chania.

Figures 5 and 6 agree with the findings of Chávez-García et al. (2010) in which both instrumentations present the same characteristics for frequencies higher than 2 Hz. Also the HVSR frequency and amplitude, from Figs. 5 and 6, recorded on the ground floor of old building of TEI at Chania, and for frequency spectrum higher than 2 Hz, are strongly related to the recorded HVSR frequency and amplitude of the surrounding area of TEI buildings (see Fig. 4, which presents the HVSR map of the large region and shows HVSR frequency close to 0.5–0.6. The lower HVSR amplitude (2.0) on the ground floor of TEI (related to the HVSR amplitude of 2.5 for the surrounding open field of TEI) is expected as building functions like a filter with specific transfer function, where
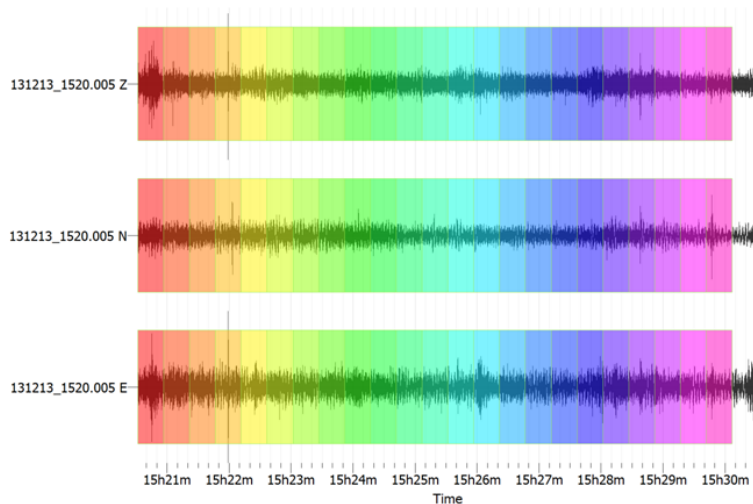
energy of ambient noise is slightly weakens, from the open field to the building infrastructure. In the case study experiment the fundamental frequency of both new and old building is much higher than 2 Hz (around 5.5 Hz). Fundamental frequency was computed from fast Fourier transform (FFT) of acceleration recordings at every floor of both buildings. HVSR method through specific accelerometers can function properly for the suggested approach of HVSR in SHM. The fundamental frequency of almost 5.5 Hz was recorded in every floor of the building. From the recordings of seismometers in both buildings, the FFT reveals that below 2 Hz the seismic acceleration has very low amplitude. As a result of the specific structures, the accelerometers that have an eigenfrequency of 1 Hz and are able to measure frequencies higher than 1 Hz are very efficient for studying HVSR method at these buildings. Other measurements that applied in the surround area outside the buildings of TEI Chania (with accelerometer) presented that HVSR resonance frequency is very close to the values of frequency spectral of velocimeter for frequencies higher than 2 Hz (Fig. 5).

2.4 Recordings of acceleration for both buildings

In this work, recordings from high-sensitivity accelerometers are going to be analysed with HVSR method. The recordings are from earthquakes that occurred in the wired area of the buildings and affected them, from midnight and noon recordings of ambient noise (each of 20 min recording duration). Each recording has been captured from every wired accelerometer (in every floor) of the new and the old building. The analysed data are discussed in detail in order to present similarities and differences. HVSR data are studied, from earthquakes, midnight ambient noise and midday

Figure 7. 10 min recording of ambient noise on the second floor of the new building of TEI Chania.
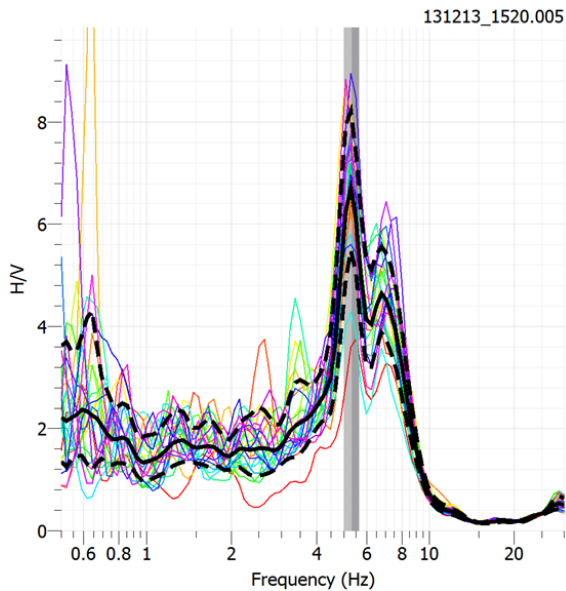

Figure 8. The time window (top) of 25 s for the previous recording with the HVSR result (bottom). Different colours corresponding in different time windows. Grey background colour presents the automatic recognition of fundamental frequency of the Geopsy program.

ambient noise, all recorded from the accelerometers of the wired structural health monitoring system of Technological Educational Institute in the city of Chania. One measurement of each kind for each sensor is presented. The analysis of all recorded data proves that there are very few and low-range disturbances in the measurements, and almost all the amplitudes and resonance frequencies are the same in HVSR graphs, for each kind of measurement.

2.5 Analysis of HVSR with specific processing software

Analysis of data with HVSR method is achieved by specific software (Geopsy) (www.geopsy.org, last access: 1 November 2013), developed in the frame of SESAME program (Site Effects assessment using Ambient Excitations). The
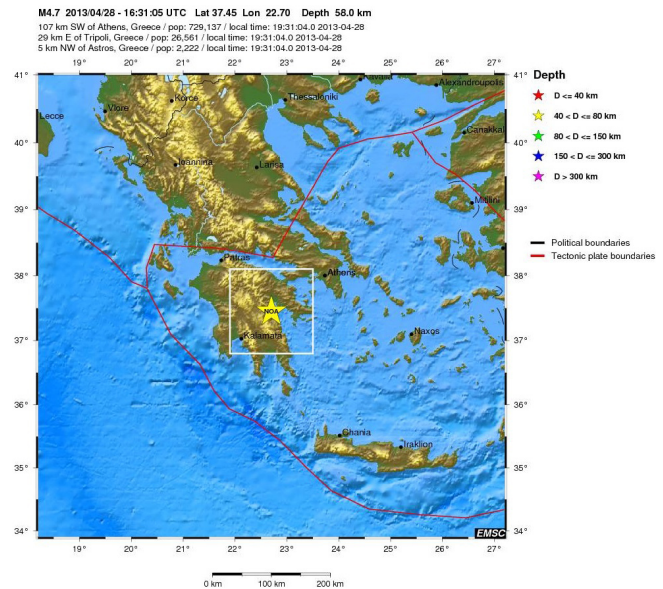
data process enquires specific procedures. Initially there is mean removal in the recordings. Then there is the specification of time.This section includes band pass filtering of the data in the frequency spectrum 0.5–30 Hz, range that it in the range of interest for in structural health monitoring (this frequency range includes the majority of resonance frequencies for structures and buildings), application of time window of 25 s according with the minimum frequency measured (0.5 Hz), no overlap of the windows and finally computation of frequency spectrum with fourier transform for the components north–south, east–west and Vertical and every time window. The next process part is referred in the parameters of smoothing of data. The Ohmachi and Konno smoothing method is applied with smoothing constant value at 40 and cosine taper width at 5 %. Finally there is computation of

Figure 9. The time window of 25 s for the above recording (left) with the HVSR result (right). Different colours corresponding in different time windows. Grey background colour presents the automatic recognition of fundamental frequency of the Geopsy program.

Figure 10. The 28 April 2013, 16:33 UMT time seismic event at 37.45 (latitude) 22.70 (longitude) 58.0 km (depth) by EMSC (http://www.emsc-csem.org).

horizontal to vertical ratio for every time window with log step of 100 number of samples and presentation of HVSR results. The horizontal component is computed by the geometric mean of N–S and E–W component for every time window with the relation $H(t) = \sqrt{\mathrm{N–S}(t) \times \mathrm{E–W}(t)}$. In case study recordings all time windows are kept (even if they present very high amplitudes) in order to reveal the effect that they have on the structures. There is interest also for microtremors (man-made excitation) and not only for microseismicity (environmental noise) because both affect the structural characteristics of a structure. Below, Fig. 7 presents the three components of a 10 min duration recording. (Vertical component is Z, north–south N and east–west E.) As the figure shows, some noises excitations are presented on three components and other only on two or one.

Figure 8 presents the same recording (with Fig. 7) of ambient noise acceleration on three components, windowed with specific length of 25 s (with different colour each time window), in order to separate specific time durations of the recording signal and analyse it with HVSR technique. Figure 9 presents the HVSR of the corresponding time window (for each colour). Such Fig. 9 presents the sum of HVSR plots of all the time windows of 25 s duration. The highest amplitude of HVSR plots is indicated with grey bold line on the background of graph in Fig. 9. The specific frequency is presented for the highest amplitude around 5.5 Hz. The corresponding amplitude reach up to 9. There is a dispersion on amplitudes because each time window (of Fig. 8) contains different amount of energy. Artificial noises that induces in case study recordings, contain more energy. Such in order
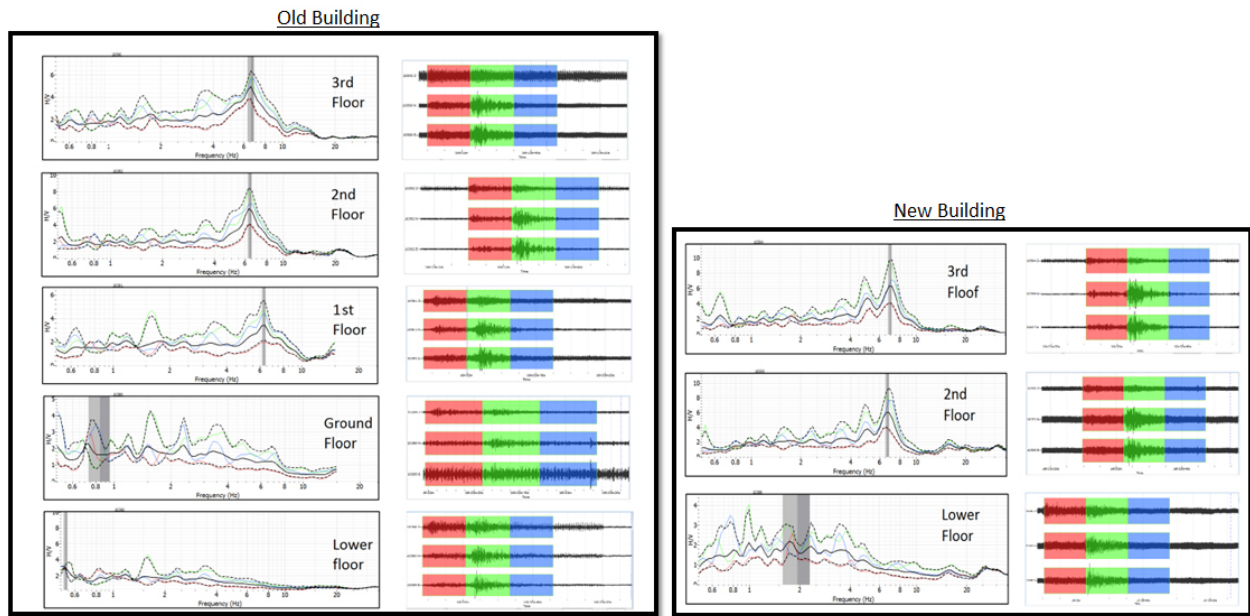
to approximate the real HVSR value there is a statistical approach of many time windows in order to indicate the containing artificial noises and minimize their effect.

3   Data analysis

In this part of study there is process analysis of an earthquake that occurred at 28 April 2013 at 16:31 UTC 250 km away from the buildings at TEI Chania, with a magnitude of 4.7 M. Data were recorded by 130-SMA instrumentation. On Fig. 10 is depicted the map epicentre of the case study earthquake.

Figure 11 reveals the HVSR analysis of the seismic event of Fig. 10, as it was recorded by the SMA accelerometers on TEI buildings at Chania (old and new building). The acceleration time series have been separated in three time duration zones (red, green and blue) with 25 s time duration, each time window. Red window contains the "primary wave" of the earthquake, green the "secondary wave" and blue the "after the secondary wave". Figure presents that the amplitude of HVSR plot is higher as the energy is getting higher. Such the HVSR amplitude plot of P wave is much lower than the S wave plot. Also the HVSR amplitude rises as the floor rises. Another four seismic tests will reveal if the HVSR remains stable due to different parameter seismic excitation on both case study buildings. Figure 12 presents broad region map of these four seismic events with code names 1 (top left), 2 (top right), 3 (bottom left) and 4 (bottom right).

Below Fig. 13 presents the computation of HVSR for seismic event with code names 1 (top left), 2 (top right) of Fig. 12. On Fig. 13, HVSR plot graph with label A3OB is the recording of old building third floor, HVSR plot graph

Figure 11. HVSR recordings on 28 April 2013, 16:33 UMT (28 April 2013, 19:33 LT) on the old (left) and new (right) building of TEI in Chania for the above seismic event. With red colour is 25 s window of *P* wave, with green the 25 s window of *S* wave and with blue the 25 s window of after *S* wave window.

with label B2OB is the recording of old building second floor, HVSR plot graph with label C1OB is the recording of old building first floor, HVSR plot graph with label D0OB is the recording of old building ground floor, HVSR plot graph with label ELOB is the recording of old building lower floor, HVSR plot graph with label F3OB is the recording of new building third floor, HVSR plot graph with label G2OB is the recording of new building second floor, and HVSR plot graph with label HLOB is the recording of new building lower floor.

On Fig. 14 are presented the computations of HVSR for seismic events with code names 3 (bottom left), 4 (bottom right) of Fig. 11.

3.1 One-hour time duration HVSR recordings of ambient noise during noon and midnight

It is going to present an HVSR recording of 30 min duration at noon (13:00 LT) in order to study the HVSR rise from floor to floor. Figures 15 and 16 present the HVSR recordings at noon and at night, on the old building of TEI with the presentation of, 25 s time duration windows, which are extended in the whole length of the recording.
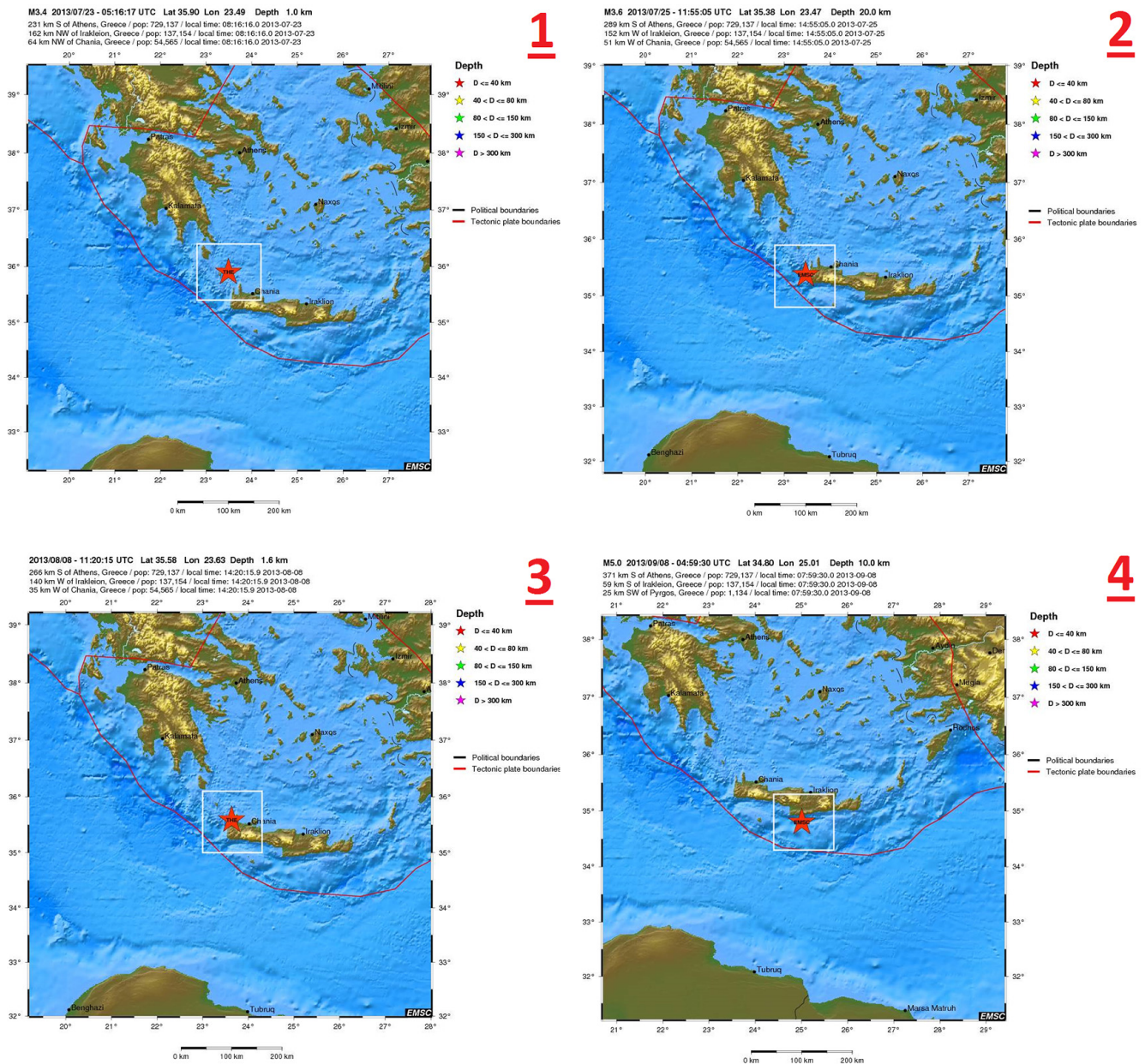
On Fig. 17, is presented the HVSR analysis of ambient noise, five months later for the old and the new building of TEI at Chania. The label of the HVSR plot graphs, refers to the same floor and building, as with Figs. 13 and 14.

From Figs. 15, 16 and 17 we conclude that resonance frequencies of both buildings remain stable for each floor and also the amplitude remains the same for each corresponding

frequency. Furthermore, the increase of the amplitude for old and new building follows the same pattern. For the old building, on the third floor, the first resonance frequency is in the range of 6 Hz and second at 8 Hz. The same resonance frequencies are reveal on the second floor and first floor with lower HVSR amplitude, during noon and midnight. On the ground floor and lower floor of the old building the energy of the ambient noise is so low, that there is no effect from the transfer function of the building, and the ambient noise of the surround area is revealed on the lower floors of the building (the HVSR outside TEI is in the range of 0.55–0.65 Hz). For the new building on the third floor the first resonance frequency is presented in the range of 5.7 Hz and the second in the range of 8 Hz. On the second floor the value of HVSR lower. On the lower floor of the new building the energy of ambient noise is again so low, that it is not able to excite the resonance frequencies of the building and such the HVSR plot is almost a smooth curve, highlighting the HVSR value of the area outside TEI.

3.1.1 Measurements with Lennartz seismometer

In this section it is going to analyse HVSR measurements that were recorded in old and new building of TEI Chania and also in a public building located in the city of Chania Technical Chamber of Greece (TEE). Below Fig. 19 presents HVSR recordings for lower ground, first and second floor of the old building TEI. Length of time duration recording is on 10 min. The same time duration of acceleration recording is
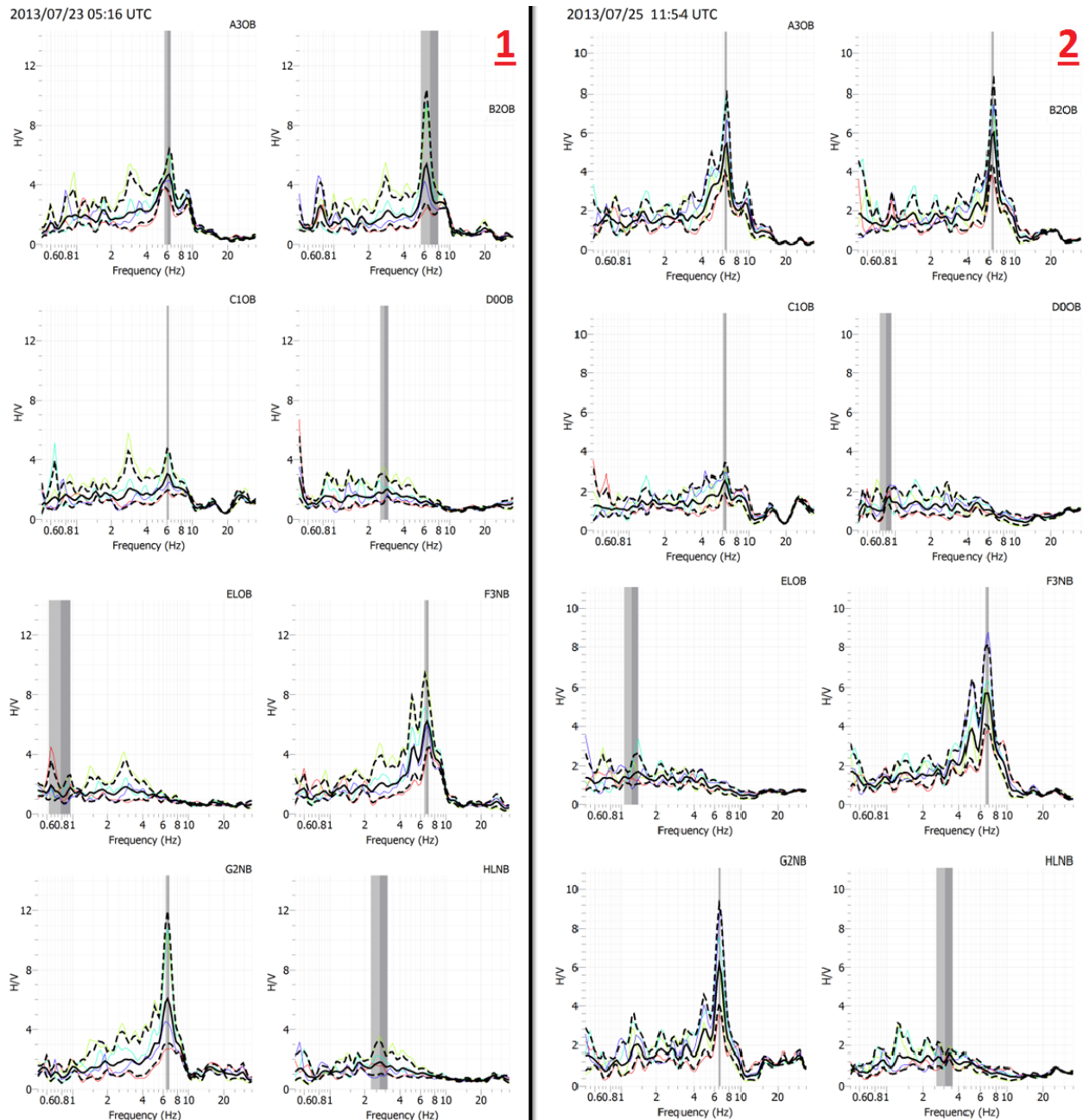
Figure 12. Four seismic events with code names 1 (top left), 2 (top right), 3 (bottom left) and 4 (bottom right) by EMSC (http://www.emsc-csem.org).

on Fig. 18 which presents HVSR recordings for outside and inside the building of TEI.

On Fig. 20 is presented HVSR recordings for lower, ground and first floor of the new building TEI. Length of time duration recording is on 10 min. Figure 21 presents HVSR recordings for second and third floor of the new building TEI.

On this part of the study will be presented the HVSR from acceleration recordings of the TEE building located in the city of Chania. Figure 22 presents the HVSR plots for the lower ,ground and first floor of the case study building.

Every kind of HVSR measurement in the old and new building, reveals that HVSR rises with higher rate in the old building and with lower in the new building. Under earthquake excitation or under ambient noise, old building, which has been affected by much more load from seismic and man-made excitation but also from the time (as it is much older than the new building), presents higher HVSR rise, from floor to floor. Also the TEE building which is a very old building, with many visible cracks on its structure presents much higher HVSR rise than the two buildings of TEI. HVSR rise could function as an indicate from possible
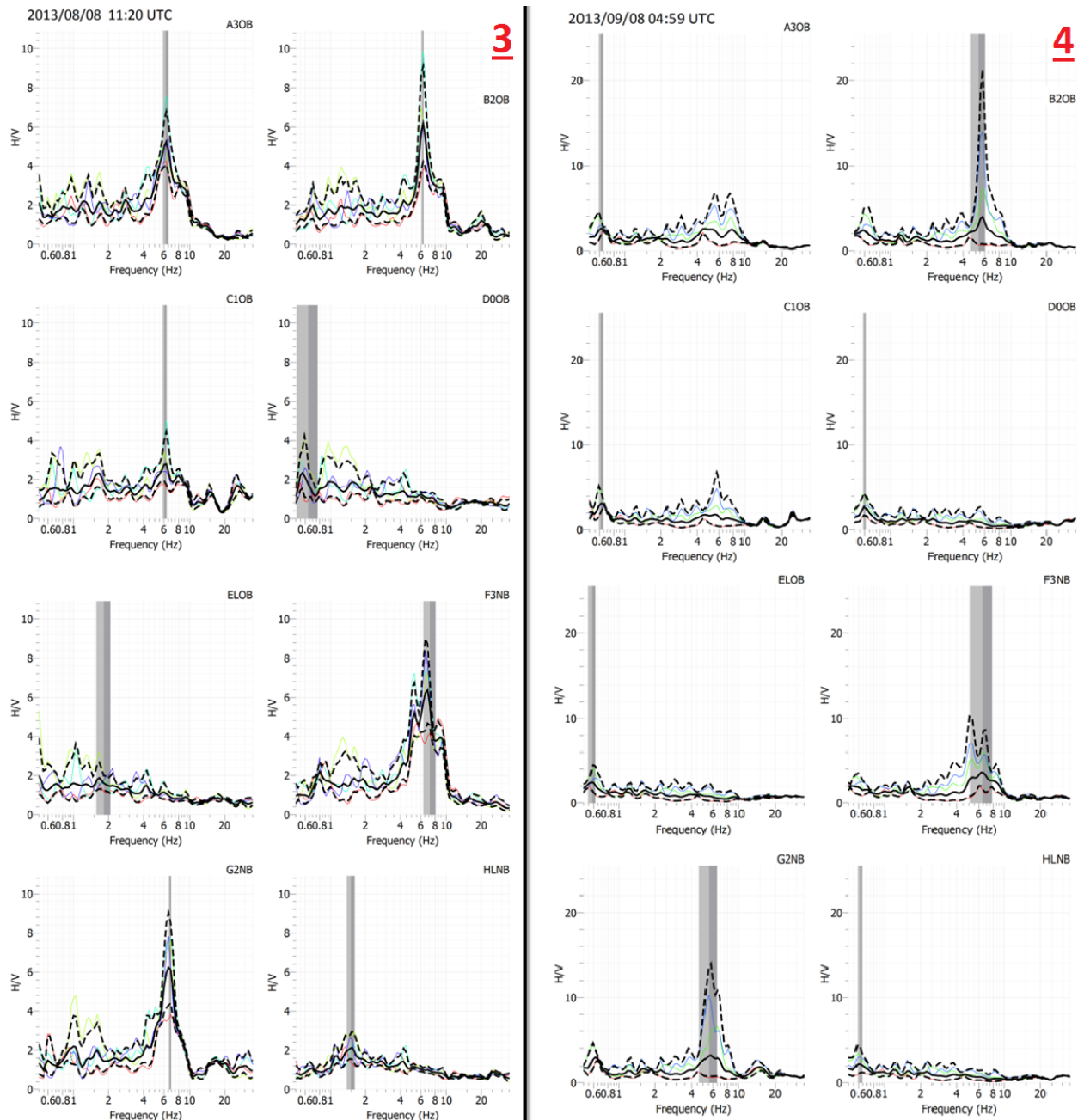
Figure 13. HVSR analysis of seismic events with code names 1 (left) and 2 (right).

high vulnerability of a structure. From the above recordings, it is observed that in both earthquakes the FR was almost the same for the old and the new building for each floor. As the floor goes higher the FR also goes higher. The windows that include S waves have much higher FR than the windows with P waves and the windows after S waves. In the programmed recordings of 30 min at noon and night the HVSR is much more lower at every floor but it also rises as the floor gets higher with a much more low rate that in seismic events.

4   Results

Accelerometers present lower HVSR than seismometers. This is expected as acceleration is the derivative of speed. The HVSR recordings of accelerometers are the derivative of HVSR of seismometers. The resolution of accelerometers, from frequency spectrum higher than 2 Hz is very high, compared with resolution of seismometers, presenting all the resonance frequencies of the structures with great detail. For buildings that fundamental frequency is higher than
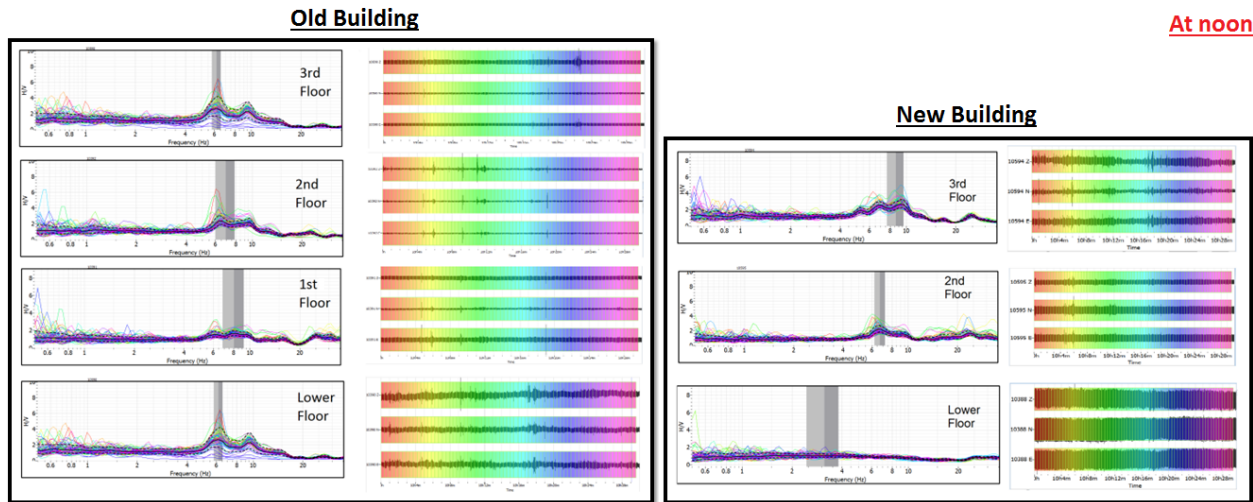
Figure 14. HVSR analysis of seismic events with code names 3 (left) and 4 (right).
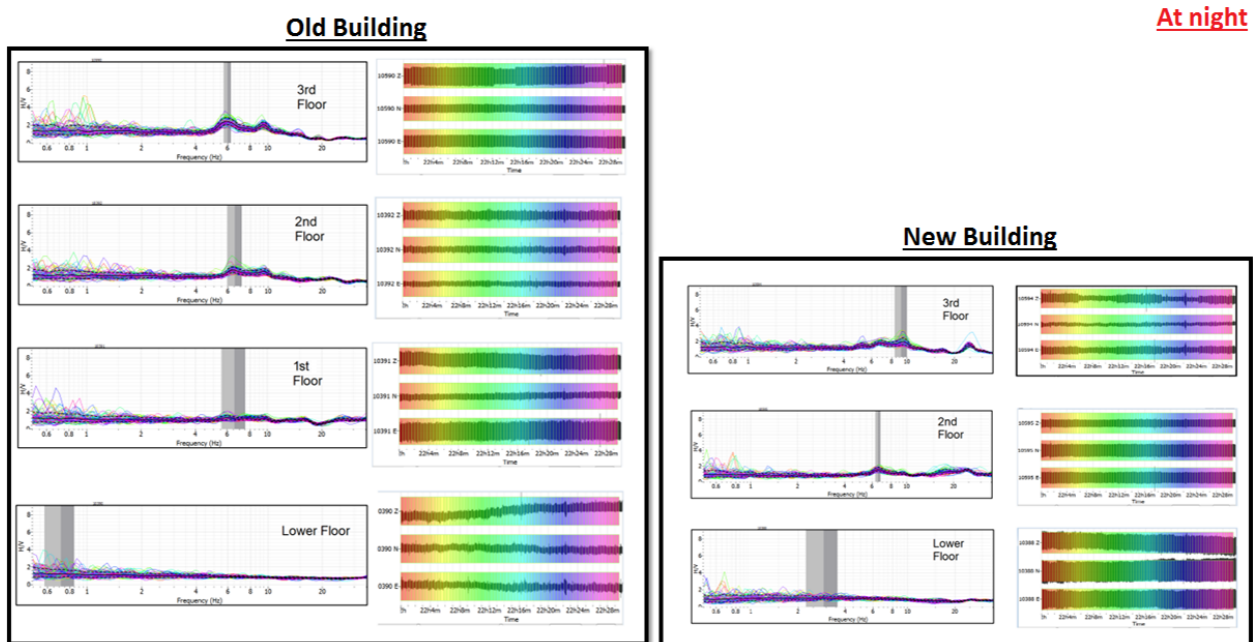
2 Hz accelerometers could be used of HVSR measurements. As the floor gets higher the amplitude of the HVSR index rises in the range of resonance frequencies. This indicates that the differential acceleration from floor to floor increases and such increase the vulnerability of the structures as the getting higher. (There is specific threshold of differential acceleration from floor to floor that indicates damage when the value overpasses this threshold).

HVSR plots of ambient noise of old and new TEI buildings, for each floor reveal that:

– Analysis of acceleration recordings under seismic activity present the same frequency spectrum under FFT analysis and under FR analysis.

– Processing of ambient data with HVSR method and earthquake data with FR method, present almost the same analogy of amplitudes increase, for the same frequencies.

Figure 15. Programmed 30 min HVSR recordings on 8 May 2013, 10:00 UMT (8 May 2013, 13:00 LT) on the old building of TEI. On the right is the presentation of 25 s time duration windows which are extended in the whole length of the recording.

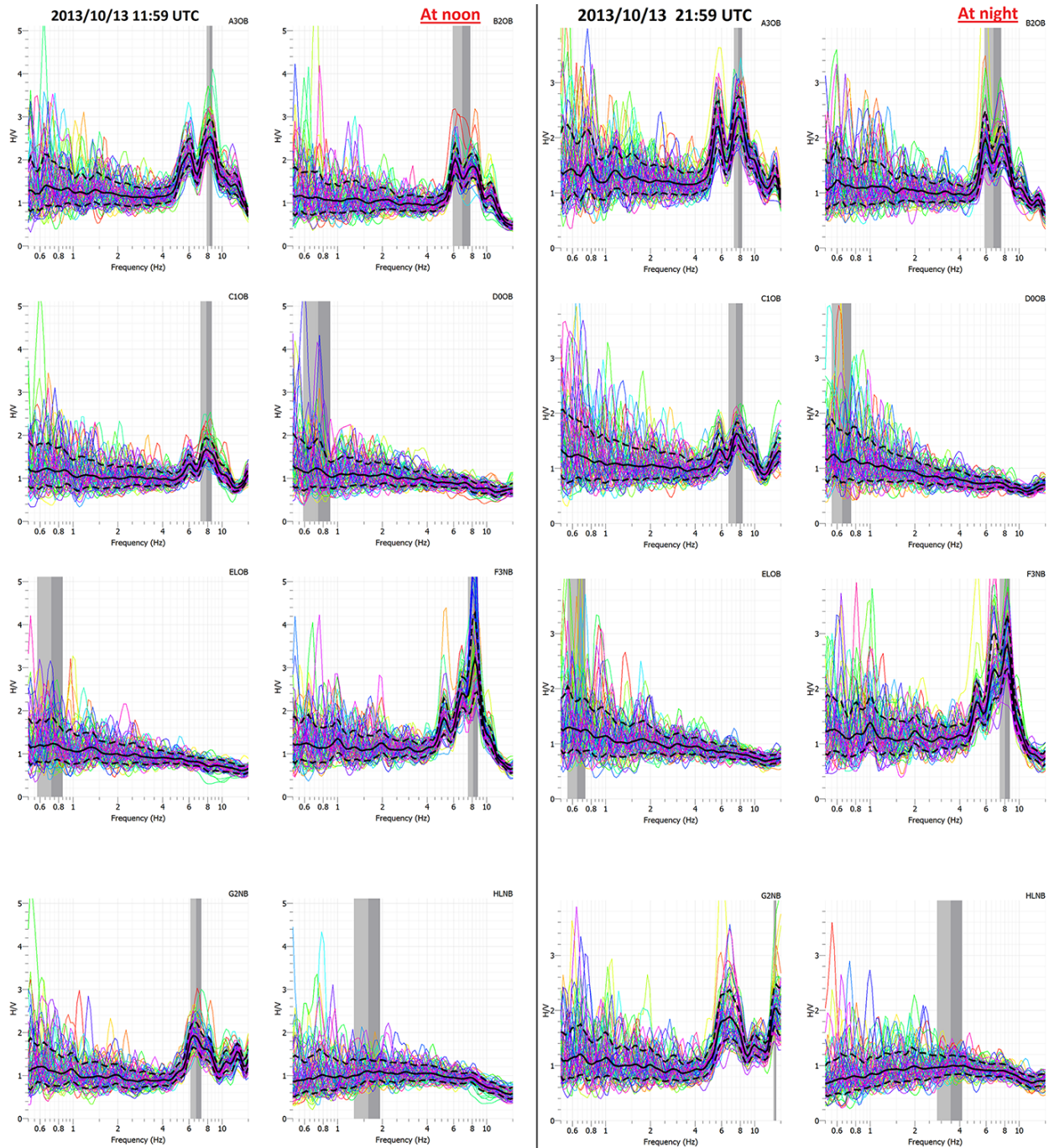**Figure 16.** Programmed 30 min HVSR recordings on 7 May 2013, 22:00 UMT (8 May 2013, 01:00 LT) on the old (left) and new (right) building of TEI. On the right is the presentation of 25 s time duration windows which are extended in the whole length of the recording.

– Old building of TEI, is revealed to have higher receiver function (RF) under earthquake excitation, but also higher HVSR under night and day ambient noise.

Conclusively ambient noise analysed with HVSR method could present the amplitudes that affect each floor of a structure and also present an index (Figs. 23 and 24) of effect of seismic activity on each floor of a building. This index is the tilt of the graph from floor to floor in each building for each kind of measurement and presents how the HVSR rises as the

floor gets higher in each condition (under earthquake excitation, and/or under ambient noise during night and noon).

5 Description of the proposed index

The specific index presents the change of HVSR of the fundamental frequency of the structure from one floor to another. In ideal conditions this index should be stable. As the HVSR increase the influence of site amplification in the specific structure increases. And if the HVSR increase on
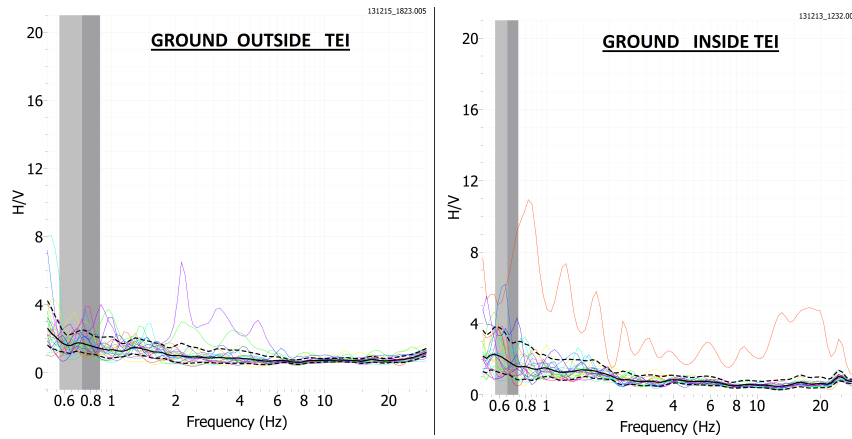
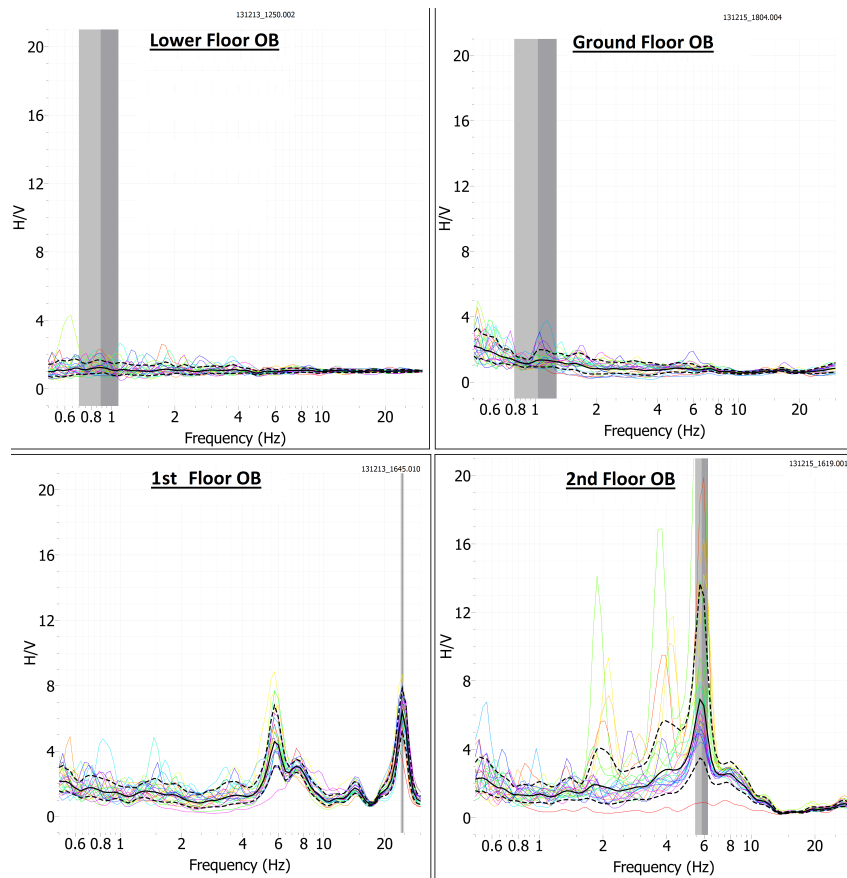**Figure 17.** HVSR analysis of ambient noise recording with time duration of 1 h.

higher floors it indicates that there is higher vulnerability of the structure in higher floors. The fundamental frequency of HVSR recordings at each floor is being measured and there is comparison of the increase of the value of HVSR, and it is correlated this rise with the increase of probably vulnerability of the structure. On Figs. 23 and 24, is presented the rise of HVSR maximum amplitude value, for the three case scenarios (night, noon and under seismic excitation) for the old and the new TEI building respectively.

There is effort to approach this index from the field of digital signal processing rather than the civil engineering, and correlate the increase of HVSR with the increase of the amplitude of structure acceleration of the building. This approach is instead of a simple value of horizontal to vertical spectral rations to study the rate of increase or decrease of

Figure 18. HVSR plots of outside area (left figure) and inside building of TEI on the lower floor (right figure).
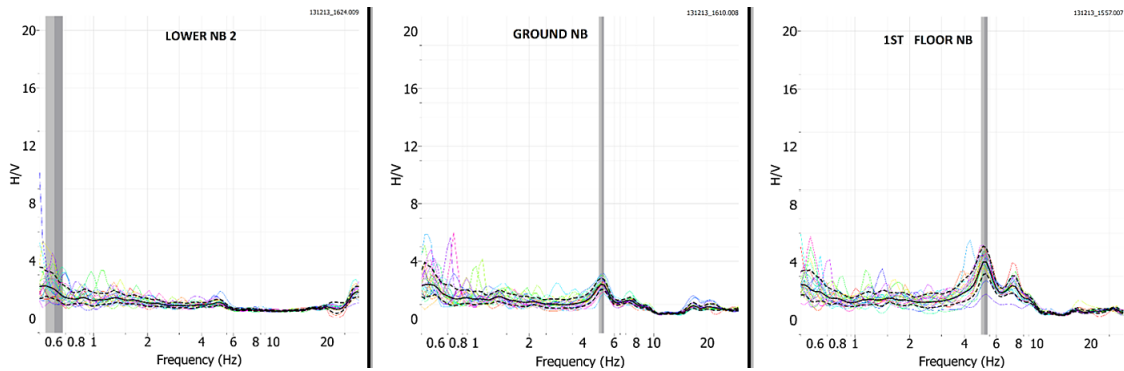

Figure 19. HVSR plots of acceleration recordings for lower floor old building (top left figure), ground floor old building (top right figure), first floor old building (bottom left figure) and second floor old building (bottom right figure).
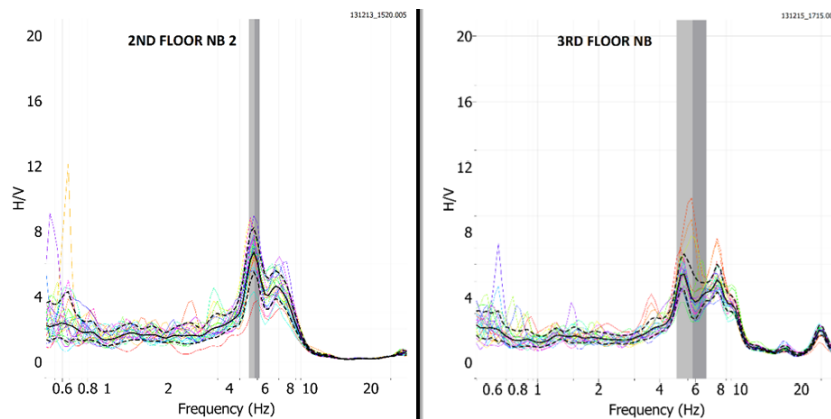
this value as the floor gets higher or lower. The RF under seismic excitation, as well as the HVSR under night and day ambient noise, is higher for the old building in relation with the new one.
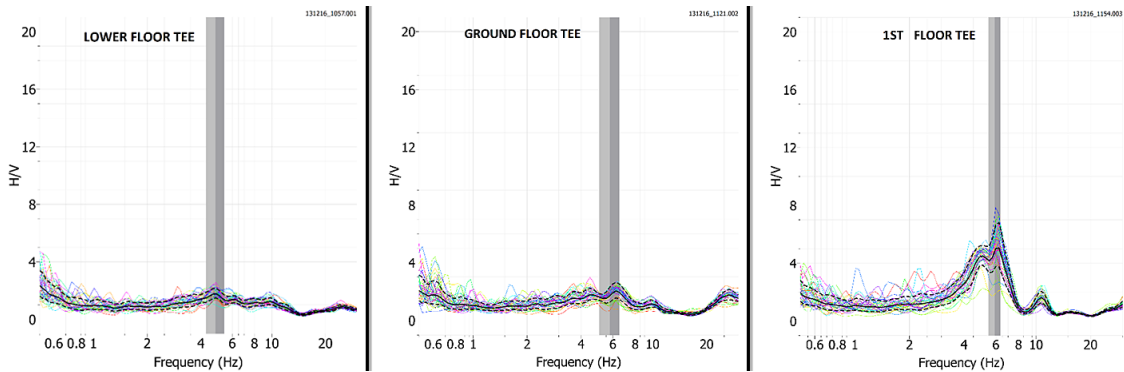
6   Laboratory validation

The proposed approach is verified by results of laboratory model. On a metallic model (Dexion) of dimensions 2 m (height) 1.2 m (length) 50 cm (width) with four rack levels have been placed four accelerometers Reftek 130-SMA, one

Figure 20. HVSR plots of acceleration recordings for lower floor new building (left figure), ground floor new building (middle figure) and first floor old building (right figure).
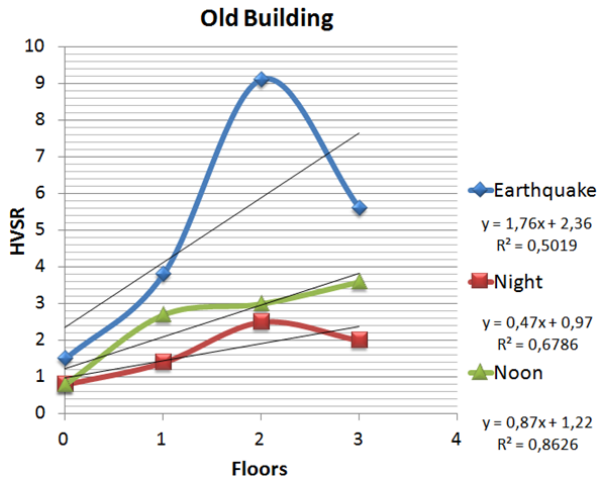

Figure 21. HVSR plots of acceleration recordings for second floor new building (left figure), and third floor new building (right figure).
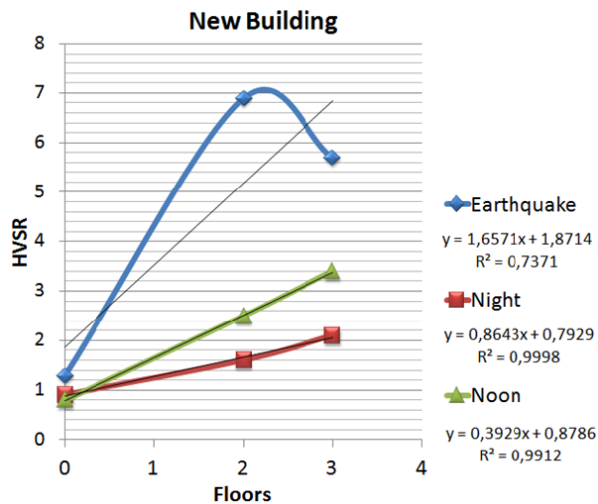

Figure 22. HVSR plots of acceleration recordings for lower floor of TEE building (left figure), ground floor of TEE building (middle figure) and first of TEE building (right figure).

on each level. The metallic columns of model is connected with the racks through screws. Two damage scenarios are applied in the specific case study. Initially there is no damage at all. All screws are absolute screwed. HVSR recordings of 1-hour time duration are applied in every level during day and night. The same HVSR recordings of 1 h are applied also for the second scenario (damaged scenario). In this

case study artificial damage has been introduced in the model through the relax of specific screws in the right corner of the third rack. The results of the data analysis reveal that HVSR rises as the damaged introduced to the system (as stiffness of model is reduced). This is also correlated with higher structural vulnerability of the model. The accelerometer sensors have specific maze which is added on the total maze of the

Figure 23. HVSR recordings from the 9 March 2013, 07:43 UMT time seismic event (blue line), the 12 March 2013 midnight recording (red line) and the 12 March 2013 noon recording of the old building of TEI in Chania.

Figure 24. HVSR recordings from the 9 March 2013, 07:43 UMT time seismic event (blue line), the 12 March 2013 midnight recording (red line) and the 12 March 2013 noon recording of the new building of TEI in Chania

rack-based model. Also they are stable related the metallic model. On Fig. 25 is presented the photo of metallic Dexion. Figures 26 and 27 present the HVSR analysis of ambient noise acceleration recording of the metallic model, for the undamaged scenario. Figures 28 and 29 present the increase of the maximum amplitude of the HVSR value, for the damaged scenario. Also on Figs. 26, 27, 28 and 29 the HVSR plot graphs with label 1_LEV is the recording of first (lower) rack of the metallic model, and respectively label 2_LEV is the recording of the second rack, 3_LEV the recording of the third rack and 4_LEV the recording of the fourth (highest) rack.
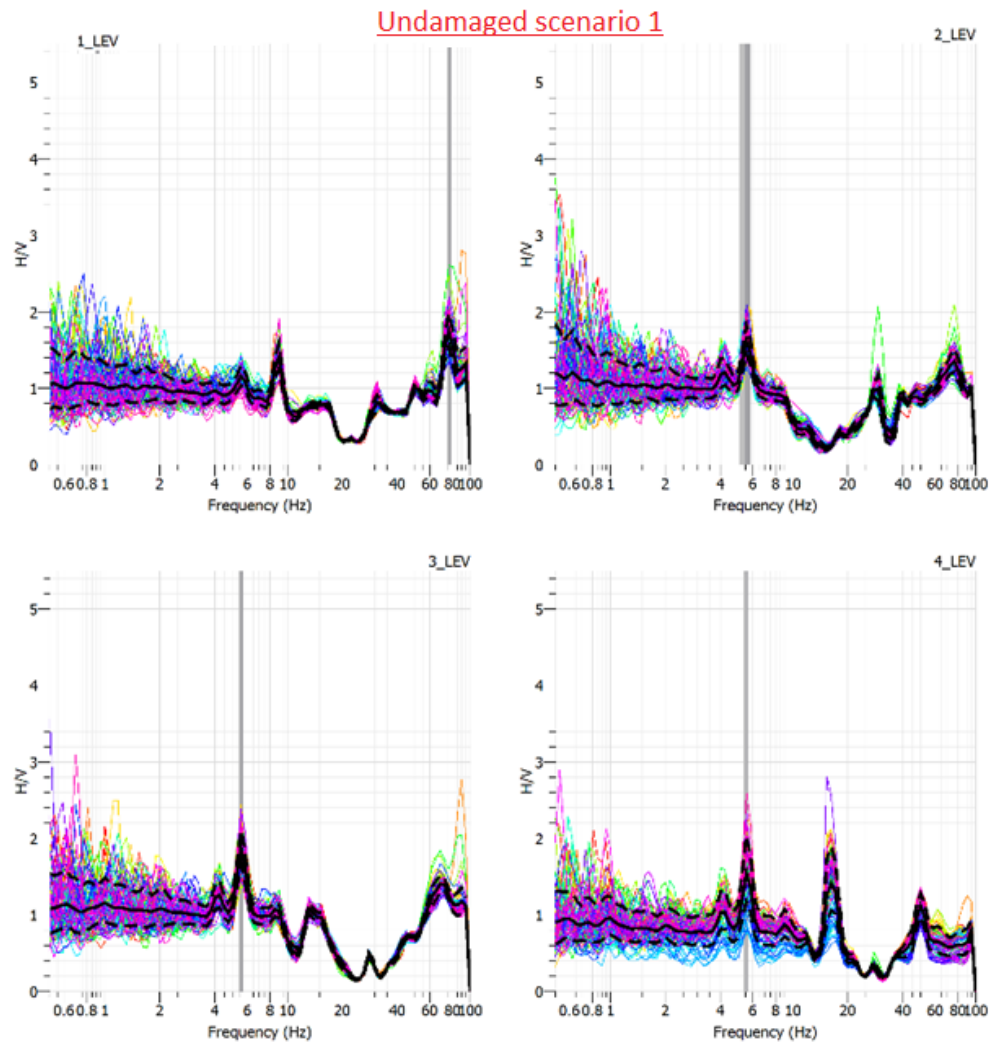

Figure 25. Metallic Dexion model.

Resonance frequencies (at 6 and 8 Hz) are almost stable and very close to the value of 2 for all levels. The HVSR rise is very low. The range of the values is from 1.5 until 2.5.

Resonance frequencies have an HVSR range from 1.8 up to 3.5. Also there is frequency shift at all response frequencies in damaged scenario related the undamaged scenario. At damaged scenarios, ambient noise creates HVSR rate much higher than in undamage scenario. Also the increase of the HVSR index from level to level is higher in damage case than the undamaged.

7 Discussion

HVSR technique has been used in order to present the impact of seismic activity in two building (different age), and how it differs from floor to floor. In this work there is a prototype approach of HVSR method in SHM recordings. SHM data gathered from wired SHM system are analysed by HVSR method. These data present the effect of ambient noise on the ground floor, the second and the third of two university buildings and also present the effect of amplification site which could define vulnerability of each floor and the whole building. This work uses HVSR technique to compare ambient noise in both buildings (an old 19 years and a new 7 years), search the site amplification in ground floor, second and third and try to find out if these recordings extract interesting findings in terms of site amplification. Also is trying to find out possible differences and similarities in the structural response of both buildings under
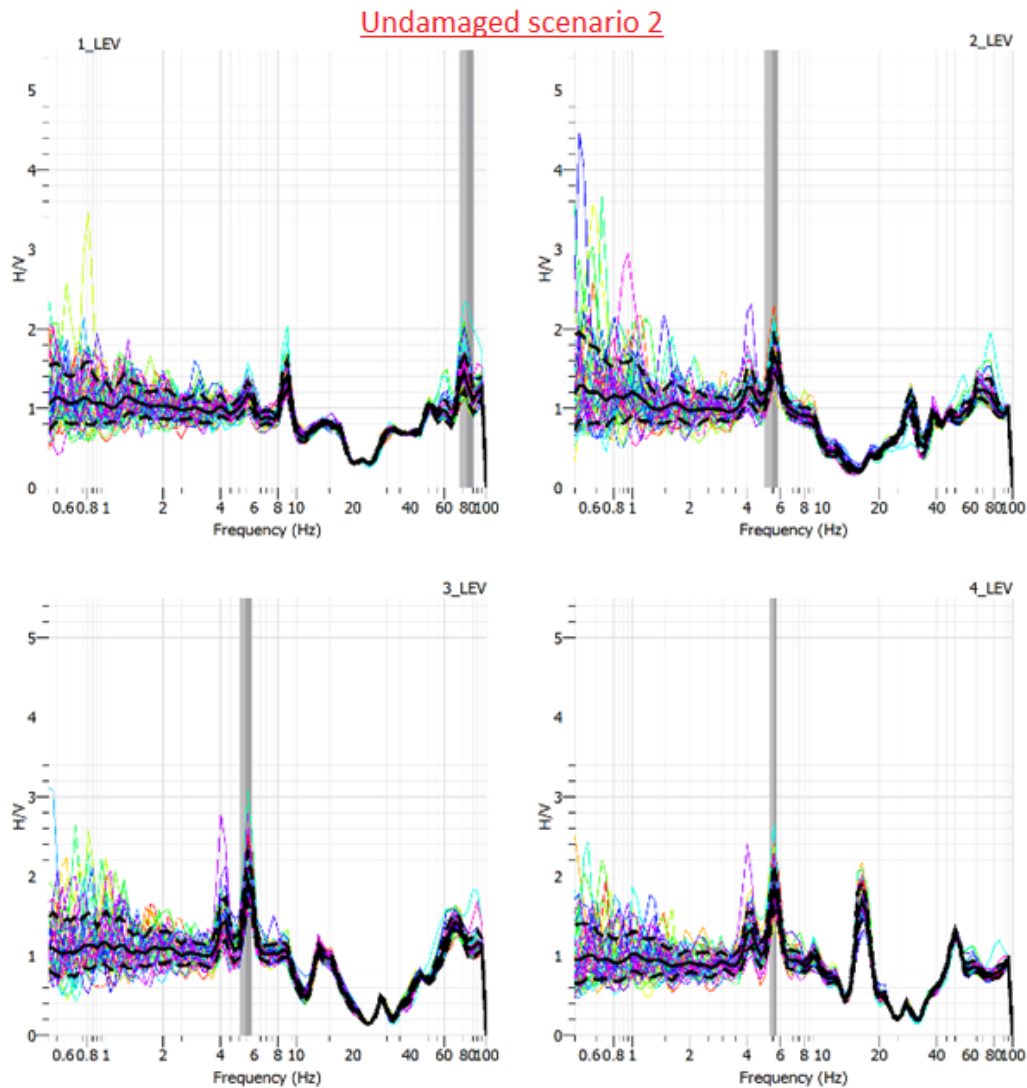
Figure 26. HVSR analysis of ambient noise recording, for undamaged scenario 1 of the metallic model.

seismic and ambient excitation. From the earthquake data it is observed that HVSR is much higher in every floor than the programmed time measurements and also that these values follow the pattern of the seismic acceleration of the building (the transfer function of the building) where the amplitude of seismic acceleration of the second floor is higher than the amplitude of the third floor.
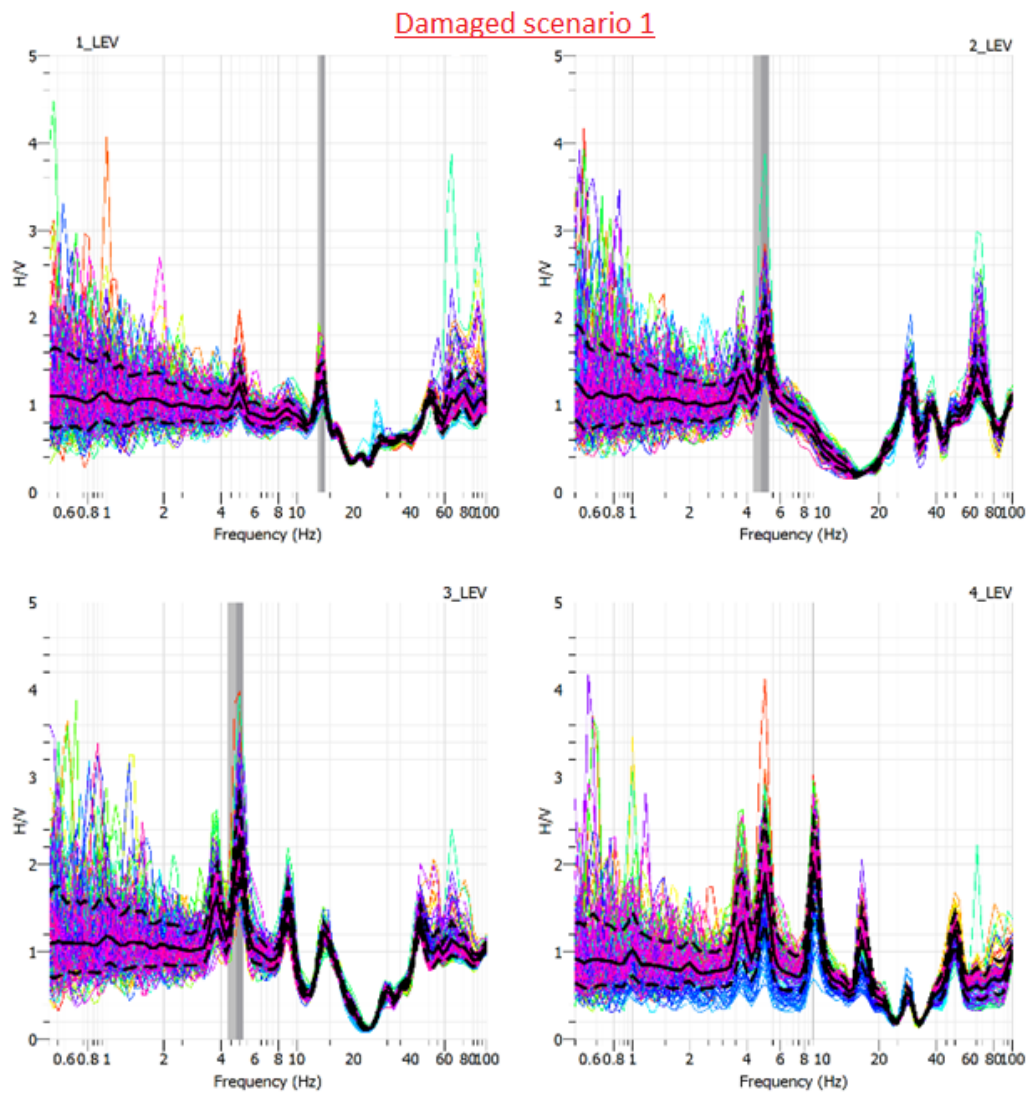
8   Conclusions

Horizontal to vertical spectral ratio (HVSR) and receiver function (RF) methods, have been applied in microtremors and earthquake acceleration recordings, in order to study the resonances frequencies and their spectral amplitude, that exist in two concrete buildings, in a high seismogenic region. These frequencies are in the range 5.5–6.5 Hz. The site amplification on the area that case study buildings are located, is much lower (around 0.7 Hz). The HVSR rise as floor gets

higher. In this study the increase of HVSR is strongly related to the age of the buildings and the visible cracks in the beams. HVSR also indicates higher differential acceleration from floor to floor and such higher structural vulnerability. This work presents for first time an approach of HVSR by implementation of the method for structural health monitoring. More specifically it applies HVSR in each floor of buildings, finds out the different HVSR values and suggests a new index which compares and analyses the HVSR of the fundamental frequency in each floor of a building and how this value changes. Also it searches the possibility of correlation of this value with the vulnerability of a building and presents that as HVSR rises as floor gets higher the vulnerability of the building could rise for these floors. Analysis of building vulnerability provided by HVSR and/or RF method, is a very cost effective and fast method which use simple acceleration recordings and provides information for structural vulnerability. The data results of this study reveal that earthquake
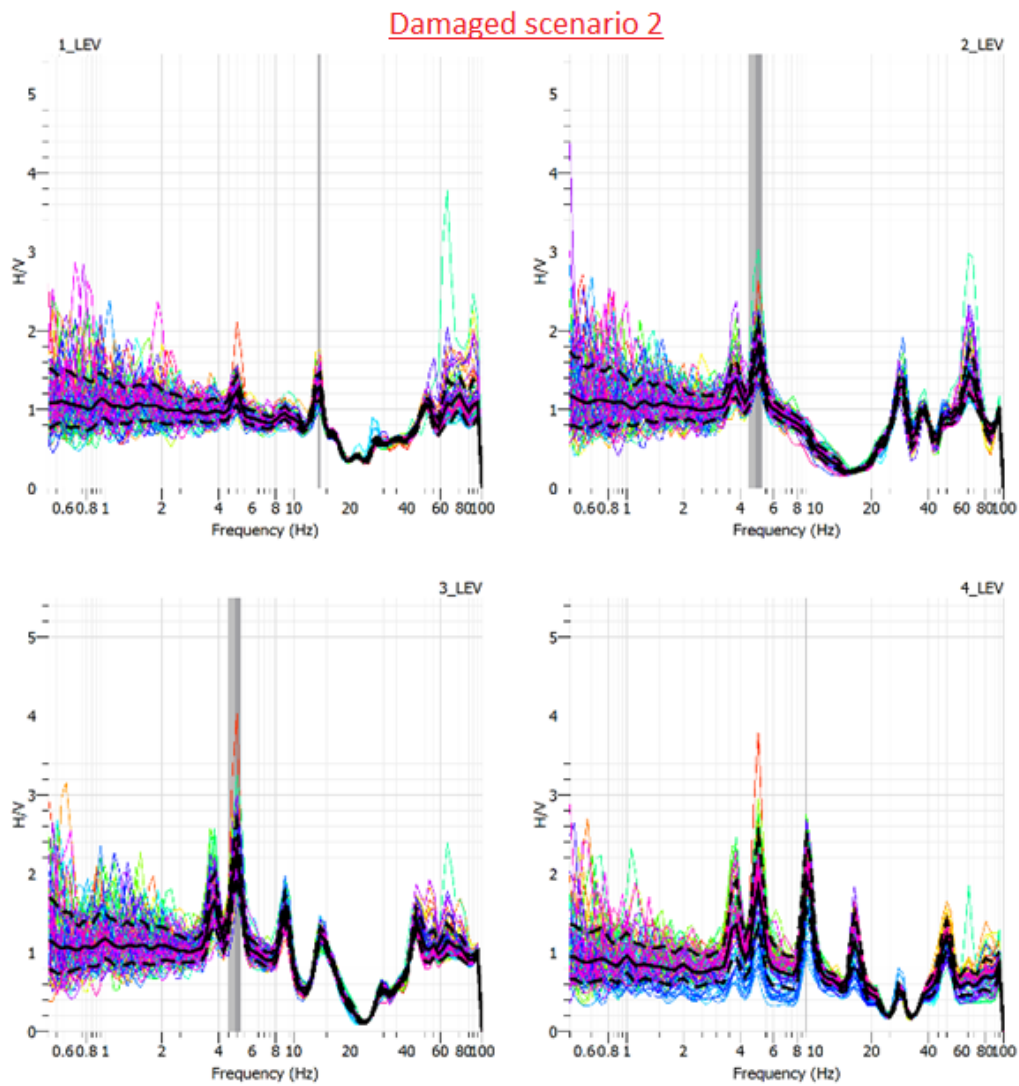
Figure 27. HVSR analysis of ambient noise recording, for undamaged scenario 2 of the metallic model.

excitation follow the same analogy of RF rise (as the floor rises) as the HVSR of ambient noise excitation. This could indicate the way that a structure could response under strong seismic excitation, by recording simple environmental noise (microtremors).

Figure 28. HVSR analysis of ambient noise recording for damaged scenario 1 of the metallic model.

Figure 29. HVSR analysis of ambient noise recording for damaged scenario 2 of the metallic model.

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