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ORIGINAL ARTICLE

Comparative analysis of strong motion (SM) records from the July 2017 Ohrid seismic sequence

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Abstract During the months of June–July 2017, the Lake Ohrid area in the southwestern Macedonia experienced a series of small to intermediate earthquakes. More than a thousand earthquakes occurred in that period, all in the epicentral area about 10 km east-northeast from Ohrid city center. The earthquakes showed characteristics of a swarm with 50 of them having magnitudes of 3 or greater and the strongest reaching magnitude M5.0. The earthquakes caused concern among the people in Ohrid and neighboring cities and villages and prompted the installation of two networks of temporary stations. One network was deployed in the epicentral area to determine in more detail the earthquakes' depth and source parameters. The other urban network of instruments was installed to monitor the influence of the ground on the amplification of shaking and the dynamics of structures in the city of Ohrid. In this study, a selection of the urban network strong motion (SM) records was analyzed for the first time. Accelerograph records from a magnitude M3.1 earthquake recorded at eight places in the city and from the two earthquakes with magnitudes M4.2 and M5.0 recorded at the permanent seismological station Ohrid (code OHR) were used. The results of the behavior of the instrumented building were also compared with the findings of previous experiments. The differences in the spectral values on the SM records from the stations were investigated in respect to the ground conditions and location where the instruments were installed, i.e., bedrock and sediments at the sites. The power spectra and the H/V ratio of the earthquake records from the 2017 seismic sequence in the Ohrid area were also viewed in respect to the Eurocode-8. In addition to being used as part of standard engineering practice, this information about the local soil conditions can be of interest to geophysicists in seismic and geotechnical investigations, as well as in seismic risk-assessment applications.

Keywords Earthquake · Strong motion records · Response-spectra analysis

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1 Introduction

During the months of June–July 2017, the Lake Ohrid area experienced a series of small to intermediate earthquakes. According to the catalog of earthquakes from the Skopje Seismological Observatory at PMF-UKIM, more than a thousand earthquakes occurred in that period as a swarm, with 50 of them being of magnitude 3 or greater. The strongest earthquake, magnitude M5.0, happened on 3 July 2017 and had a maximum intensity of VII degrees on the EMS-1998 scale. The epicenter of that earthquake and all aftershocks were located about 10 km east from Ohrid center, in the vicinity of the village of Skrebatno. The earthquakes caused concern among the people in Ohrid and neighboring cities and villages and prompted the installation of two networks of temporary stations to monitor the seismicity in more detail.

One network was deployed by the Seismological Observatory at PMF-UKIM in the epicentral area, to better determine the earthquakes' depth and the source mechanism. The second network of instruments was installed by the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) at UKIM, to monitor the influence of the surface conditions on the amplification of shaking and dynamics of structures in the Ohrid urban area.

The comparative analysis was done using the accelerograph records from a magnitude M3.1 earthquake recorded in eight places in the city and from the two earthquakes with magnitudes M4.2 and M5.0 recorded only on the permanent seismological station Ohrid (code OHR), because they occurred before the network of temporary stations was installed. The measurements of the instrumented building were also compared with the previous experiment performed in 2009 (Dojcinovski et al. 2010).

It is known that attenuation and local site conditions can influence earthquake ground motion (Sinadinovski and McCue 2003), resulting in different amplitudes and frequency spectrum. Since the epicenter of the main event was located at a distance of about 10 km from the stations in the urban network, the regional ground attenuation analysis was not possible with such a dataset. Instead, the available strong motion (SM) records were analyzed assuming the waves' propagation from the same seismic zone, and this experiment only addressed the site effects due to the local surface deposits underneath the stations in the city of Ohrid.

We performed additional spectral analysis to find out more about the influence of the earthquakes with different magnitudes on the behavior of buildings and the site response. These results are of considerable importance to the engineers in designing the building code and its implementation. Besides engineering practice, more detailed information of local soil conditions can be of further interest to geophysicists in other seismic and geotechnical investigations (for example microzonation), as well as seismic risk assessment.

The Ohrid region is of special national importance based on its historical and cultural heritage. Lake Ohrid is also scientifically important for a number of disciplines including Biology (due to its endemic species), Hydrology (water-inflow variation), Chemistry (the chemical content and the origin of karst springs), and Paleoclimatology (evolution and reconstruction of paleoenvironment) among others. Thus, these seismological studies can be viewed as another contribution towards better understanding of the natural processes that influence the geotectonic system of the area.

2 Seismic activity

The territory of Macedonia, situated in the Eastern Mediterranean seismic belt, is an intra-plate area of active tectonics within the Southern Balkan Extensional Regime—SBER region (Burchfiel et al. 2006). It has a complex geological, tectonic, and seismotectonic environment (Fig. 1) and contains zones which are characterized with probability of high seismicity.

The area is extensively investigated by many authors and various views and interpretations have been expressed about its geodynamics. Here, we chose the original definition of seismic zonation according to Arsovski and Petkovski (1975), as adapted by Milutinovic et al. (2017).

Seismicity of Macedonia is related to destructive tectonic processes associated primarily with vertical movement of the tectonic blocks. Two regions of specific neotectonic features are well distinguished: West Macedonia, characterized by longitudinal (NE-SE) and Central and East Macedonia with transverse (E-W) stretching of principal tectonic morphostructures. The boundaries between these two regions are separated with the relatively stable Pelagonian massif.

Balkan Peninsula has been struck by a number of destructive earthquakes which caused a considerable number of human fatalities and material losses. From historical records, it can be seen that Macedonia has experienced numerous medium-to-large earthquakes, the largest in the last century occurring on the border with Bulgaria in 1904 with an estimated magnitude of 7.5 to 8.0 (Hadzievski 1976) or 7.5 (Eurocode-8).

The 1963 Skopje earthquake, of magnitude M6.1, which occurred in the central zone, caused heavy loss of life and property in the capital city. More than 1000 people were killed, around 4000 were injured and more

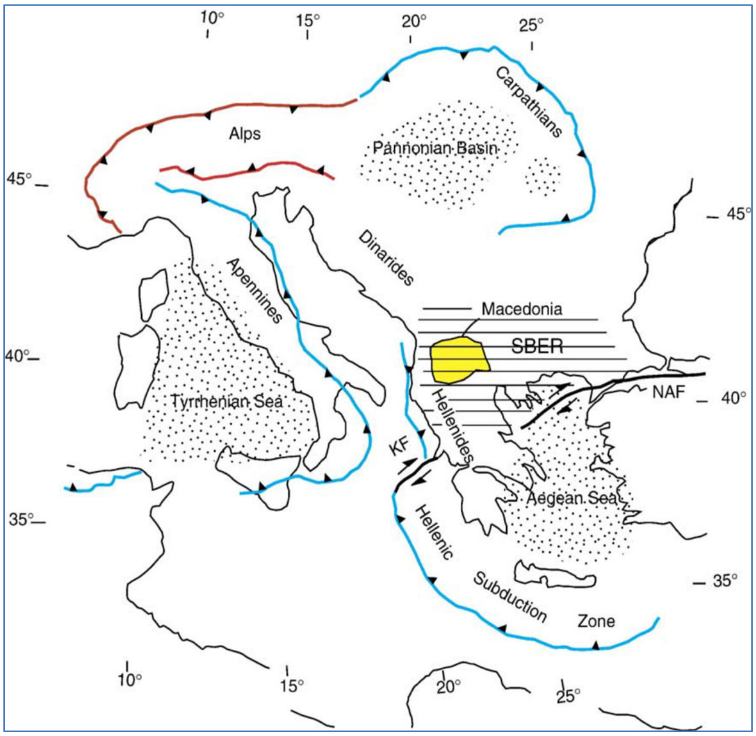


Fig. 1 Location of Macedonia (yellow) in respect to the tectonic map of the Eastern Mediterranean region. Blue lines with barbs are retreating subduction boundary and red barbed lines are advancing subduction boundaries from late Cenozoic to recent time. Dotted areas are back arc regions of late Cenozoic extension and subsidence. NAF, North Anatolian Fault; KF, Kefalonia fault. (After Burchfiel et al. 2006)

than 200,000 people were left homeless (UNESCO report 1968; Petrovski 2003). The material losses were equivalent to 15% of the Gross National Product of Yugoslavia which, adjusted to present rates, would amount to one billion US dollars.

The 2017 seismic sequence occurred in the zone of West Macedonia, near the intersecting part of two tectonic blocks called "Pestani-Ohrid-Struga" and "Ohrid-Korcha". A number of faults are expressed completely or partly in their relief and earthquakes with magnitudes 5.0 or more have been relatively frequent. The strongest earthquakes that occurred in the last century in the Ohrid area were those in 1906 (M = 6.0), 1911 (M = 6.7), and 1960 (M = 6.4).

Figure 2 shows the urban station locations and the earthquakes that occurred during the June–July 2017 period in the Ohrid epicentral area and the 1911 event, displayed on the digital-elevation map with faults determined by geological and geophysical methods.

Lake Ohrid Basin is surrounded by Paleozoic metamorphics in the northeast and north and Mesozoic ultramafic, carbonatic, and magmatic rocks in the east, northwest, west, and south. Paleocene to Pliocene units are present in the southwest. With the basin development, Neogene sediments from Pliocene to recent times were deposited in the lows (Hoffmann et al. 2010). The sedimentation began in the Late Miocene with the formation of a pull-apart basin; subsidence and further extension account for the major dynamic component resulting in several hundred meters of sediments. Lake Ohrid Basin is flanked by active N-S trending normal faults that have an expression as fault scarps in the present-day landscape. The most active faults are between the Ohrid depression and the host mountain east of Ohrid, which are characterized with vertical cascade movements accompanied with seismicity.

Before the strongest earthquake from the seismic sequence hit Ohrid area on 3 July 2017, the only strong motion records regularly collected were from the seismological station OHR, depicted as a blue triangle in Fig. 3. Soon afterwards, a team from IZIIS Institute installed seven accelerographs at four urban places: Opstina (city hall of Ohrid), Turizam (Faculty of Tourism), Obodin, and KAM Market, represented as black triangles in the same Fig. 3. Subsequently, it was possible to analyze the ground motion recorded with eight instruments from the next considerable event—an earthquake with magnitude M3.1 which occurred on 23 July 2017 23:40 UTC.

The KAM Market location was instrumented with accelerographs at ground level and on the 3rd, 6th, and

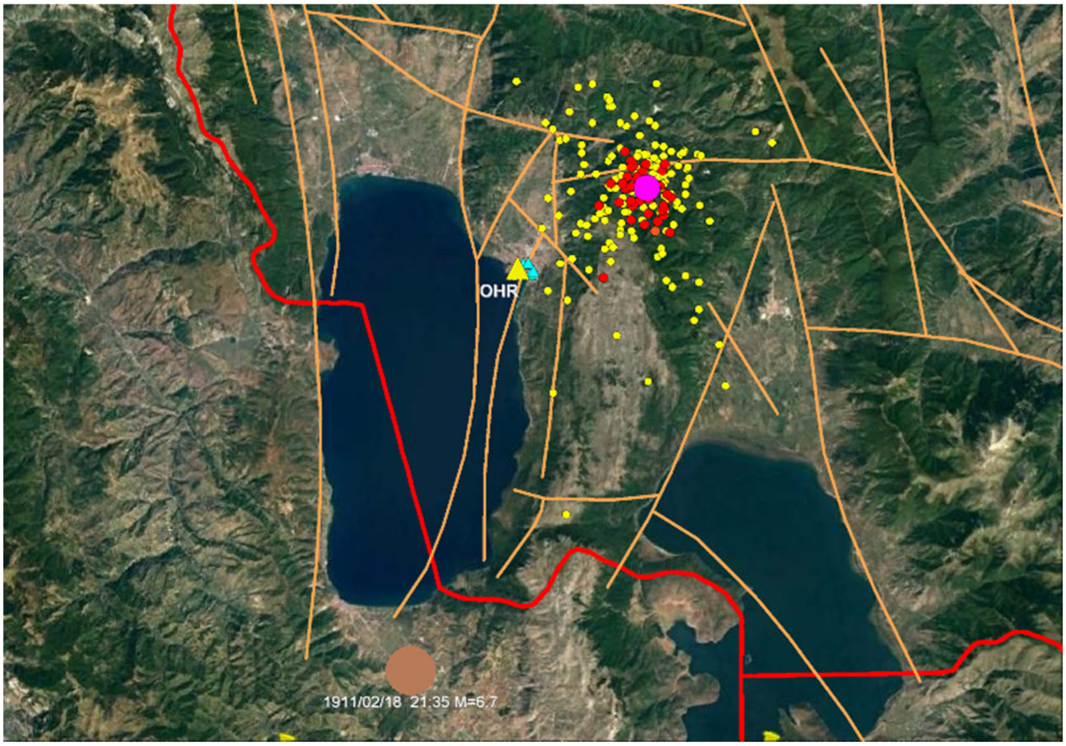


Fig. 2 The epicentral location of the main M5.0 earthquake (magenta) and quakes that occurred during the June–July 2017 seismic sequence in the Ohrid epicentral area. (Yellow circles, M ≤ 3.0; red circles, M > 3.0; brown circle, historical 1911 event). Urban station locations are represented by triangles. Background is the digital-elevation map with the lakes (in blue) and the faults determined by geological and geophysical methods (orange lines)

9th floors of the building above. It is a high-rise building constructed in the late 1970s. The building has an approximately square floor plan (24 × 24 m) and a height of nearly 33 m. It is a RC frame building with square columns with cross section dimensions that are the largest at the ground floor and gradually decrease to the top of the building. It has 11 levels in total and in the middle section of the building, in the direction of one of the symmetry axes, there are RC diaphragms that at one end of the building, enclose the staircases. The foundations of all elements (columns and diaphragms) are constructed on pillars. The same building was chosen for instrumentation as in the previous study which was a part of 3D network in the city of Ohrid (Petrovski et al. 1995, Dojcinovski et al. 2010).

3 Strong motion records

In the KAM Market, Obodin, Faculty of Tourism, and city hall of Ohrid locations, at epicentral distances of approximately 9 km, the acceleration was recorded by Guralp instruments deployed at all those sites. Typically, this is a digital instrument positioned on a surface base over the top of layers comprised of lake and marsh sediments.

The 3-component acceleration records of the 23 July 2017 23:40 UTC magnitude M3.1 earthquake at the locations: city hall of Ohrid, Obodin, and Faculty of Tourism are shown in Fig. 4. All values on the Y-axis are displayed as units in the local scaling for each instrument and later converted into percentage of the gravity constant—g (Table 2).

The 3-component acceleration records of the 23 July 2017 magnitude M3.1 earthquake at the KAM Market location and the building above are shown in Fig. 5. The values on the Y-axis are again displayed as units in the local scaling for each instrument and later converted into percentage of the gravity constant—g (Table 2).

In the seismological station OHR at epicentral distance of approximately 10 km, the earthquakes were recorded by Kinemetrics WR-1 wide-range seismometers and MicroStep digitizer. Then the acceleration was obtained by differentiating of the ground velocity recordings. All acceleration records and converted

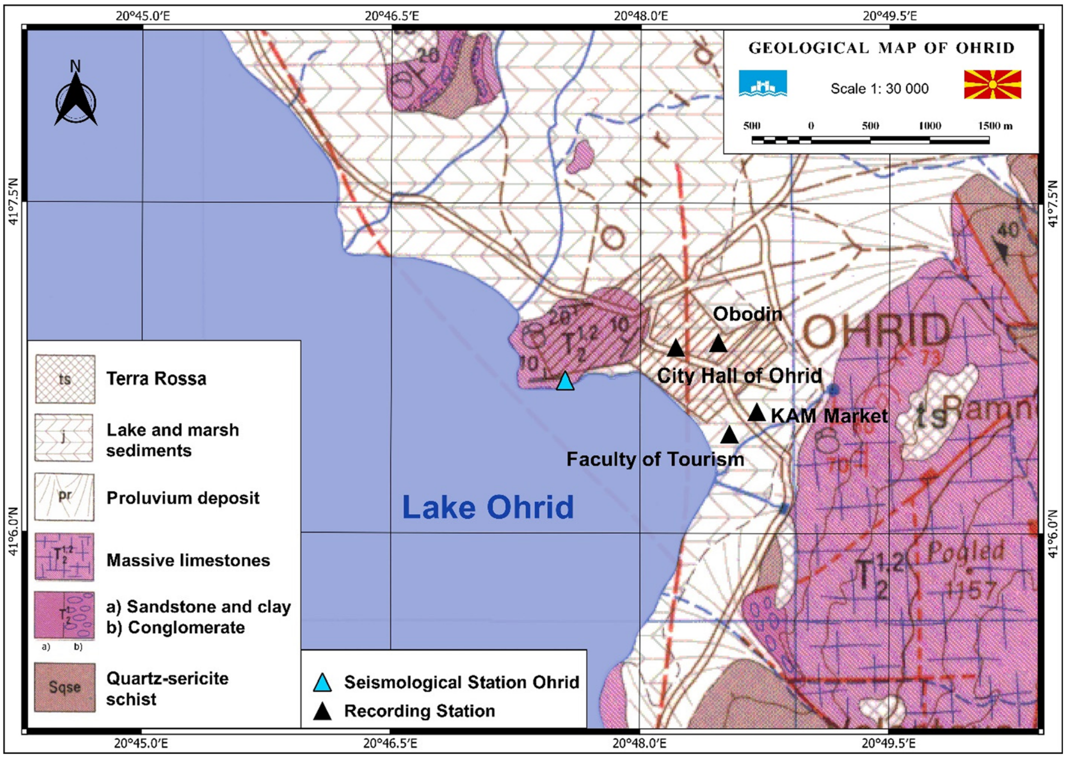


Fig. 3 The locations of the strong-motion stations from the urban network superimposed on the geological map of Ohrid area

velocity records were corrected according to: baseline linear correction and Butterworth 4-pole bandpass 0.10–25-Hz filtering.

Three records of earthquakes coming from almost the same seismic origin and depth but with different magnitudes were selected. Their parameters calculated by the HypoDD program are shown in Table 1.

The 3-component acceleration record of the 23 July 2017 23:40 UTC magnitude M3.1 earthquake at seismological station OHR is shown in Fig. 6. All values on the Y-axis are displayed as units in the local scaling for each instrument and later converted into percentage of the gravity constant—g (Table 2).

Filtered 3-component acceleration record of the 3 July 2017 18:30 UTC M4.2 earthquake at seismological station OHR location is shown in Fig. 7, while the filtered 3-component acceleration record of the 3 July 2017 11:18 UTC magnitude M5.0 earthquake at seismological station OHR location is shown in Fig. 8.

Since all those selected earthquakes occurred at epicentral distances of 9 to 10 km, the records from the urban network cannot be used to improve the local ground attenuation functions (for example, Pekevski (2002)). The purpose of this magnitude range was primarily to investigate the influence of the event size on the characteristics of the recorded waveform at the site, without considering the path component in the wave propagation.

The maximum acceleration at each site was done first by measuring peak-to-peak values from the records for the three selected magnitudes M3.1, M4.2, and M5.0. Then for all 3-components, the values were converted and expressed as the gravity constant—g (Table 2).

Since the earthquake waves come from the east-northeast direction in respect to the urban network, the E-component and the N-component recorded the highest values of acceleration. The maximum amplitudes measured at the Z-component in general are about 50% smaller than the horizontal components. The differences in the amplitude values of the SM records can be primarily attributed to the ground conditions at the sites where the instruments were installed, i.e., bedrock as opposed to sedimentary layers.

4 Spectral analysis

Most of the graphics and the spectral analysis were done by using Tsoft, SeismoSpect, and Origin software

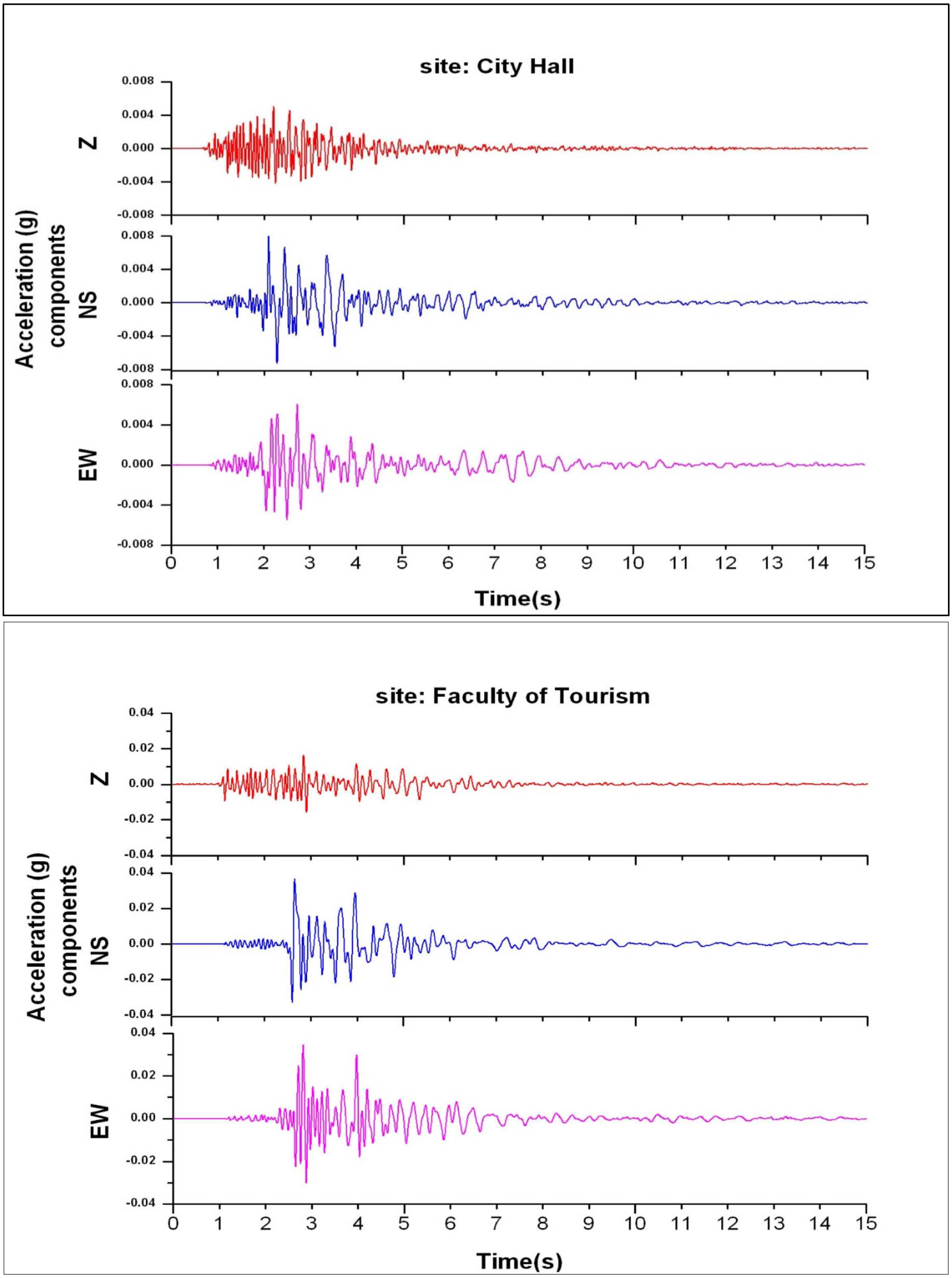


Fig. 4 The acceleration records of the 23 July 2017 magnitude M3.1 earthquake at locations: top—city hall, middle—Faculty of Tourism, bottom—Obodin

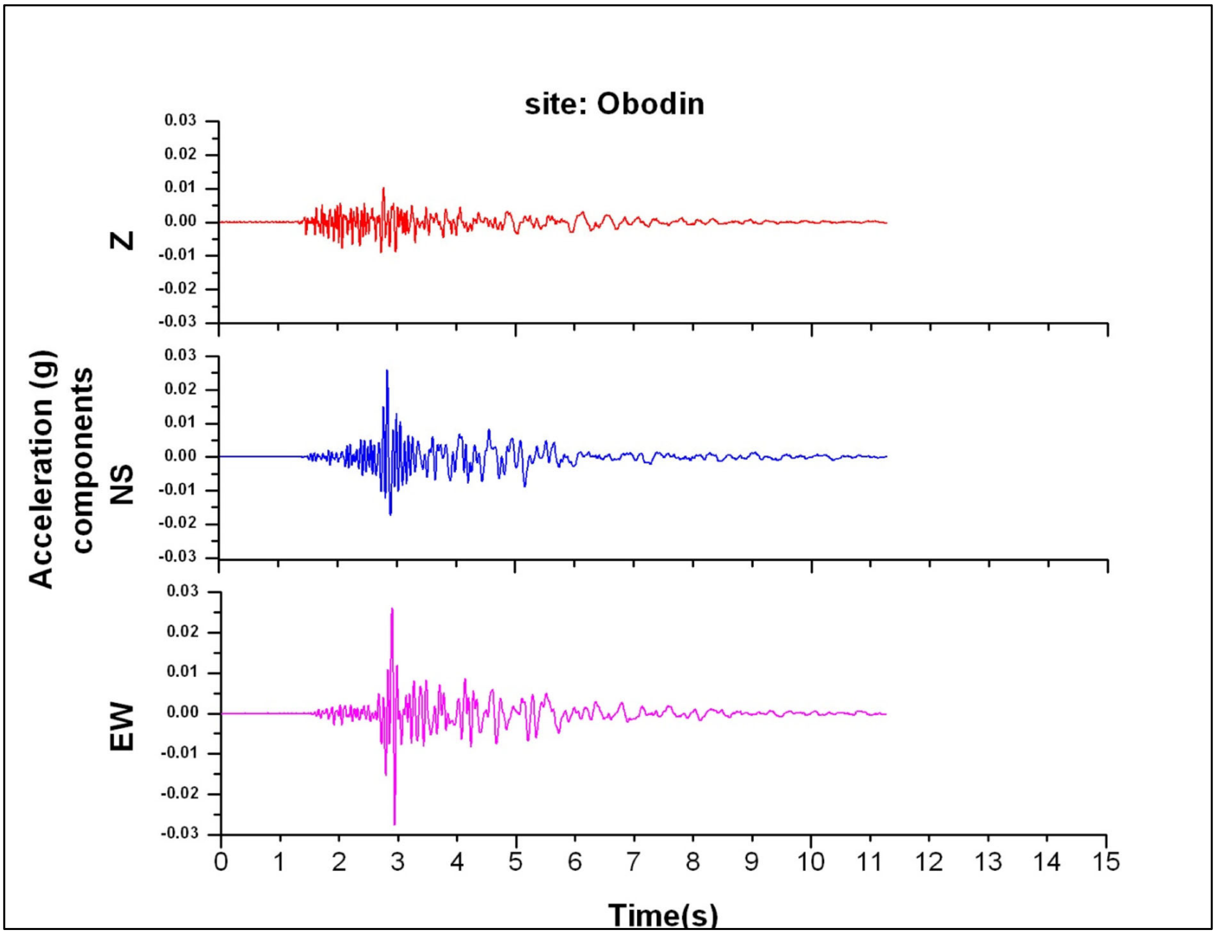


Fig. 4 continued.

packages (Van Camp and Vauterin 2005). The 3-component power spectra of the 23 July 2017 23:40 UTC magnitude M3.1 earthquake at locations: city hall, Faculty of Tourism, and Obodin is shown in Fig. 9. Here, the Y-axis represents the squared amplitudes of the Fourier transform operated on the traces. The highest values are mainly distributed between 1 to 2 Hz and 2 to 5 Hz with some lower frequencies probably caused by the instrument-base coupling.

The 3-component power spectra of the 23 July 2017 23:40 UTC M3.1 earthquake at KAM Market location and the building floors above are shown in Fig. 10. The values are mainly distributed near the peak of 2 Hz with another grouping of higher frequencies after 4 Hz.

These frequencies were compared with the measured vibrations for the building's natural periods of oscillation determined in previous experiments. At the time of realization of the 3D array, ambient and forced vibration measurements were performed on the building in order to define its dynamic characteristics and basic natural frequencies in two orthogonal directions and of torsion, modal shapes, damping, and soil-structure interaction. The power spectra from this earthquake and the results obtained earlier are in close agreement showing the dominant frequency of about 2 Hz and the higher modes of 3.5 to 6.5 Hz. It was noted that the values of the basic natural frequency of the building had changed over the last 40 years. It decreased from 2.08 Hz by 5% due to a complex process of aging of materials and modification of the interior walls, as well as the 'micro' damages caused by the seismic activity to which the building was exposed in the last four decades (Dojcinovski et al. 2010).

The 3-component power spectra of the three earthquakes with magnitude 3.1, 4.2, and 5.0 at seismological station OHR is shown in Fig. 11. The values show a typical shift towards longer periods with the increase of the magnitude of the events.

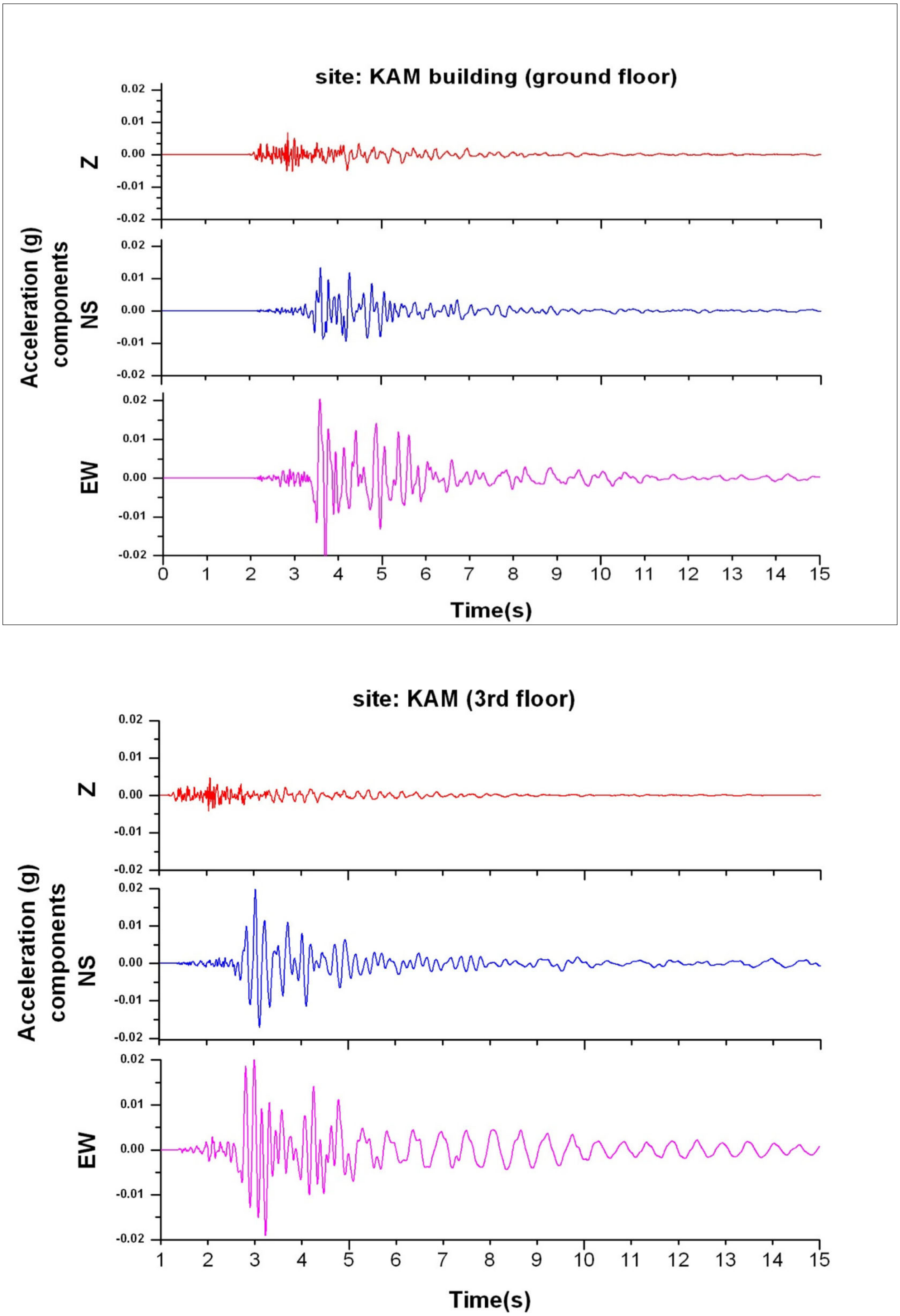
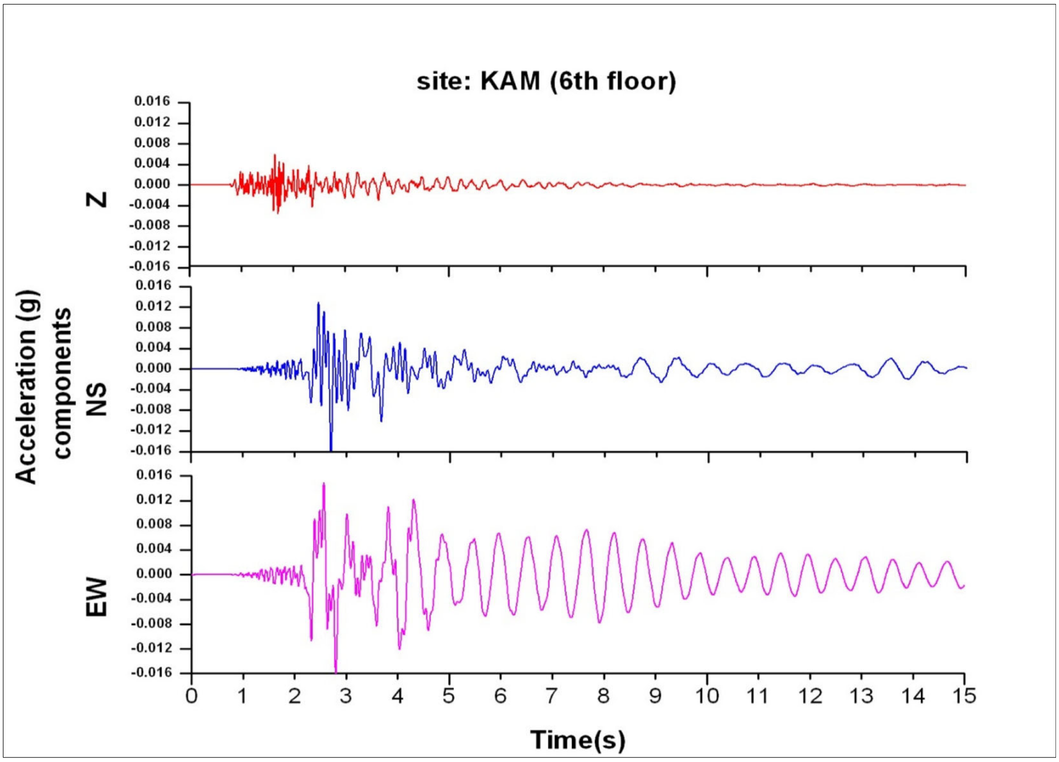


Fig. 5 The 3-component acceleration record of the 23 July 2017 23:40 UTC M3.1 earthquake at location KAM Market building: top—ground level, second from the top—3rd floor, third from the top—6th floor, bottom—9th floor



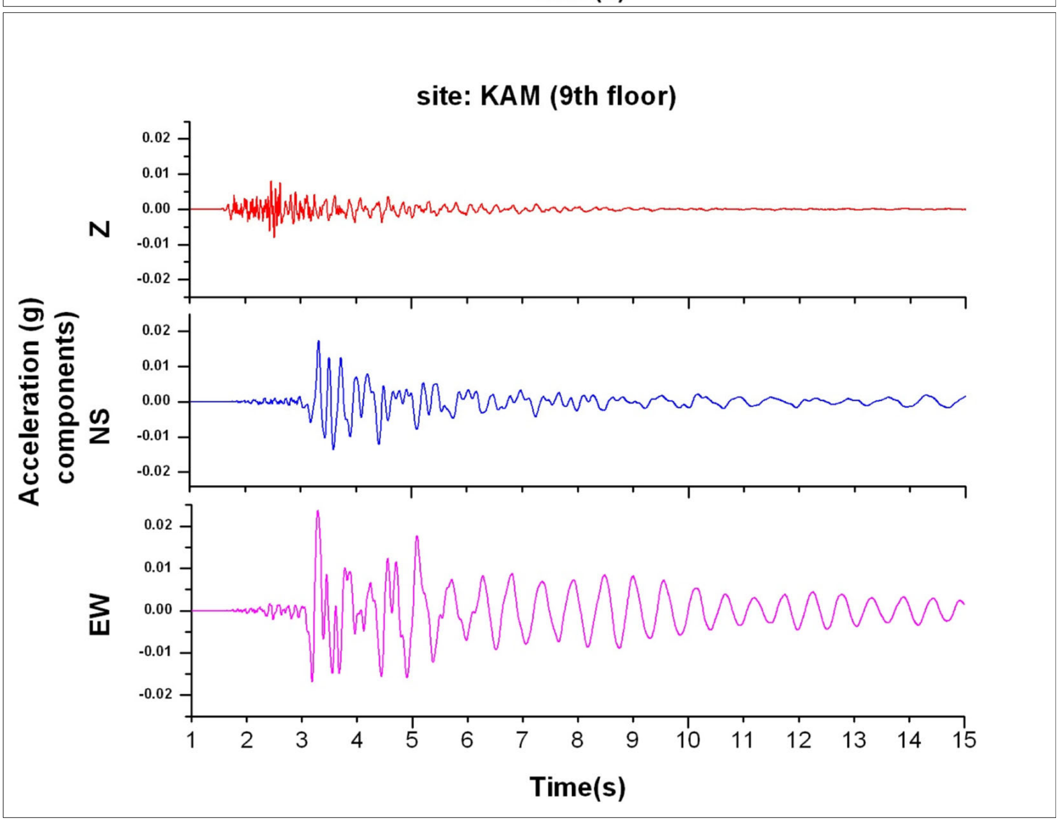


Fig. 5 continued.

Table 1 Seismic parameters of the selected earthquakes recorded in OHR station

Date/time	Latitude	Longitude	Depth	Magnitude
23 July 2017 23:40 h	41.169	20.907	7.4	3.1
3 July 2017 18:30 h	41.164	20.902	8.2	4.2
3 July 2017 11:18 h	41.161	20.906	8.8	5.0

These power spectrum of the strongest earthquake from the 2017 seismic sequence in the Ohrid area were displayed in respect to the Eurocode-8 (MKC EN 1998-1:2012) design. Figure 12 shows period vs pseudo-acceleration; the 3-component spectra for the strongest event with magnitude M5.0 is drawn in respect to the design spectra used in the building code for three soil types: A, B, and C. The recorded traces for periods between 2 and 8 s are close to the design spectra curves.

Table 2 Maximum acceleration recorded at the stations from the Ohrid urban network

Location	Mag	Z(g)	N(g)	E(g)
KAM Market ground floor	3.1	0.00687	0.01339	0.02048
3rd floor bldg	3.1	0.00481	0.01987	0.02013
6th floor bldg	3.1	0.00599	0.01302	0.01488
9th floor bldg	3.1	0.00796	0.01755	0.02371
Obodin	3.1	0.01034	0.02593	0.02621
Faculty of Tourism	3.1	0.01642	0.03656	0.03476
City hall of Ohrid	3.1	0.00507	0.00821	0.00607
Seismic station—OHR	3.1	0.00168	0.00233	0.00159
Seismic station—OHR	4.2	0.00713	0.00771	0.02372
Seismic station—OHR	5.0	0.07993	0.04493	0.06757

Consideration of further details regarding the design spectra and modifications is subject of an ongoing process by the State Standardization Institute.

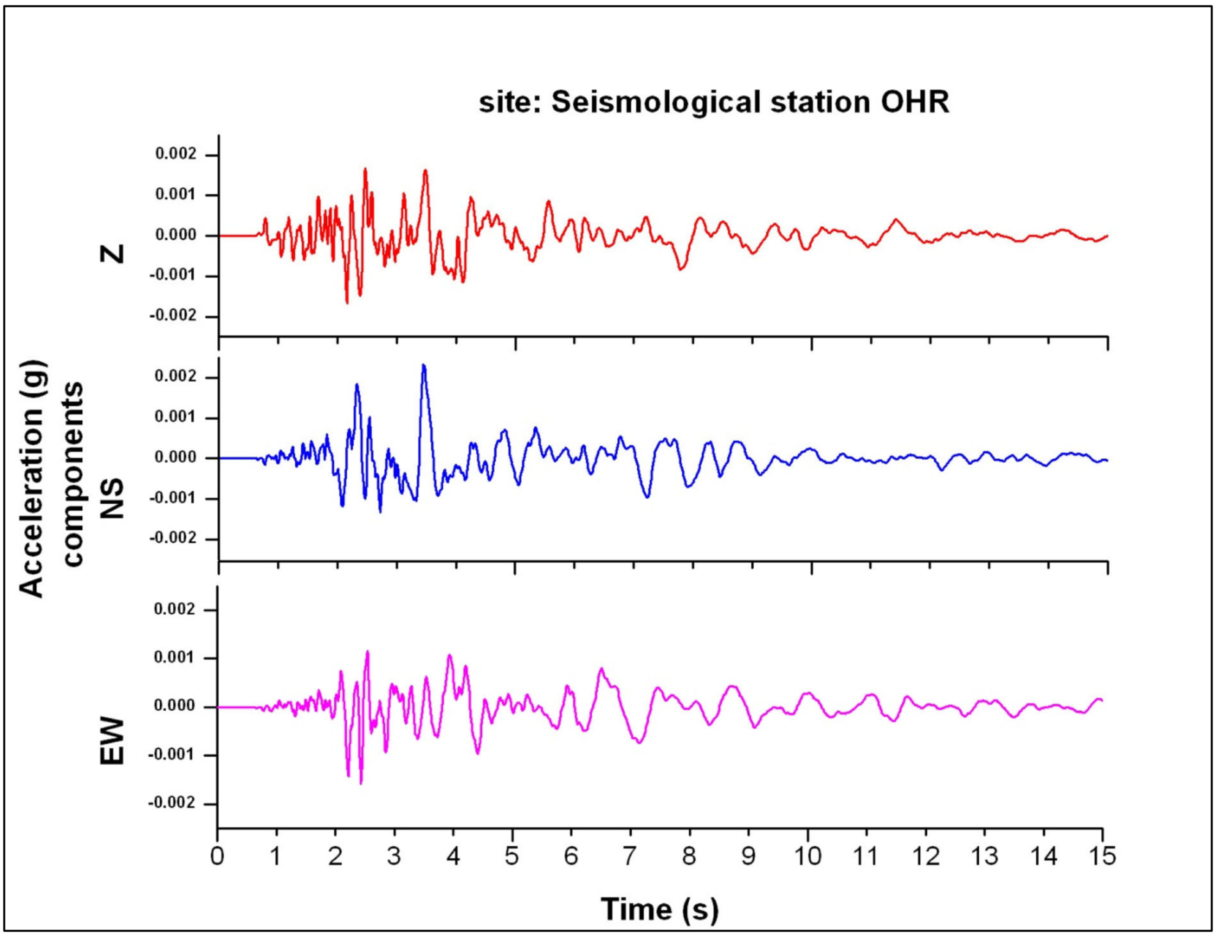


Fig. 6 The acceleration record of the 23 July 2017 23:40 UTC M3.1 earthquake at seismological station OHR: top—Z-component, middle—N-S component, bottom—E-W component

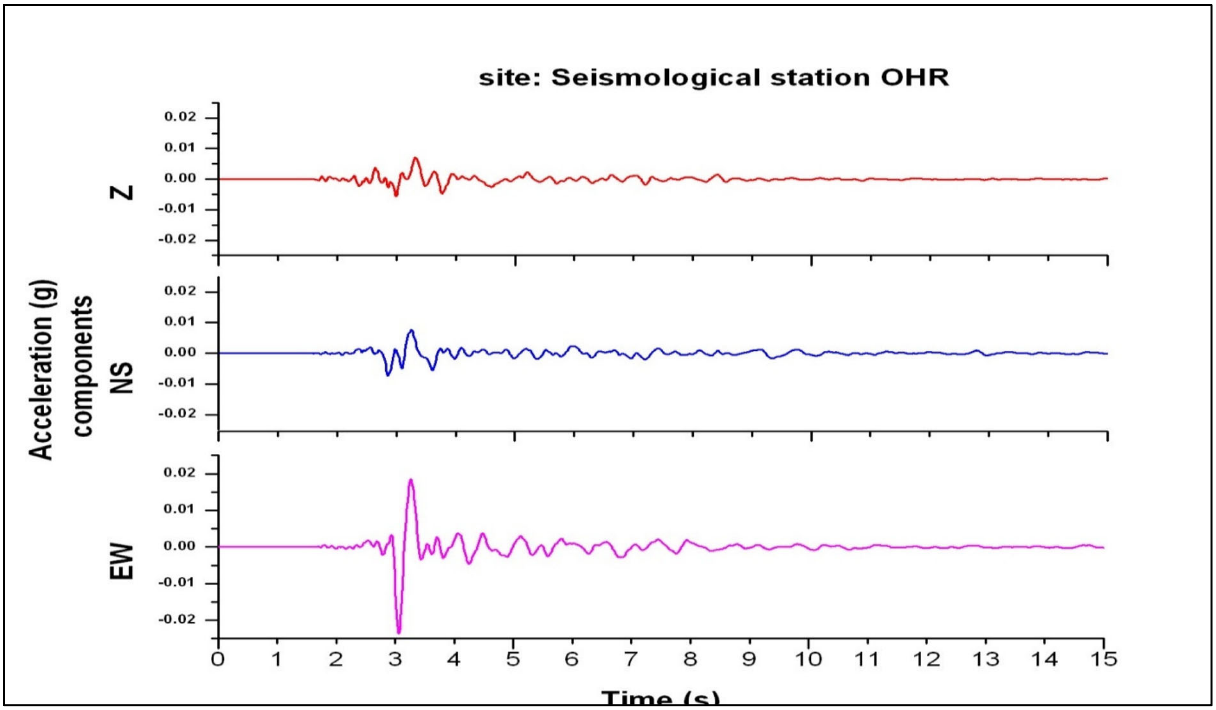


Fig. 7 The acceleration records of the 3 July 2017 18:30 UTC magnitude M4.2 earthquake at seismological station OHR: top—Z-component, middle—N-S component, bottom—E-W component

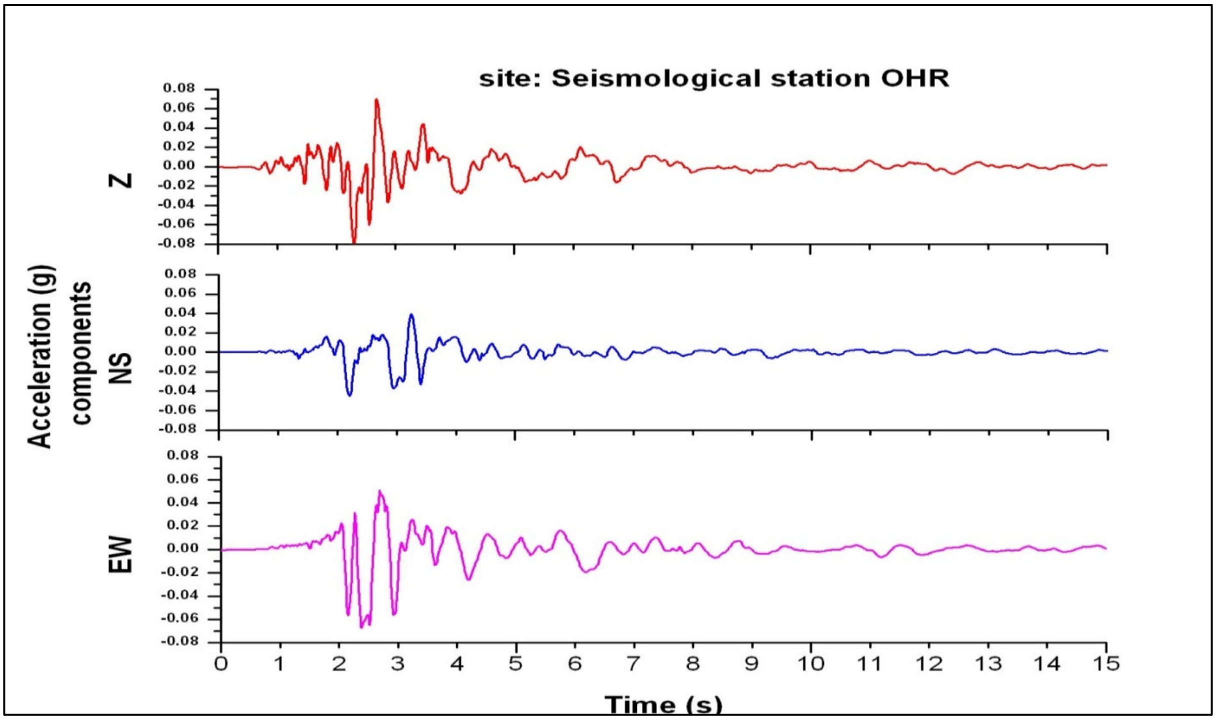


Fig. 8 The acceleration records of the 3 July 2017 11:18 UTC M5.0 earthquake at seismological station OHR: top—Z-component, middle—N-S component, bottom—E-W component

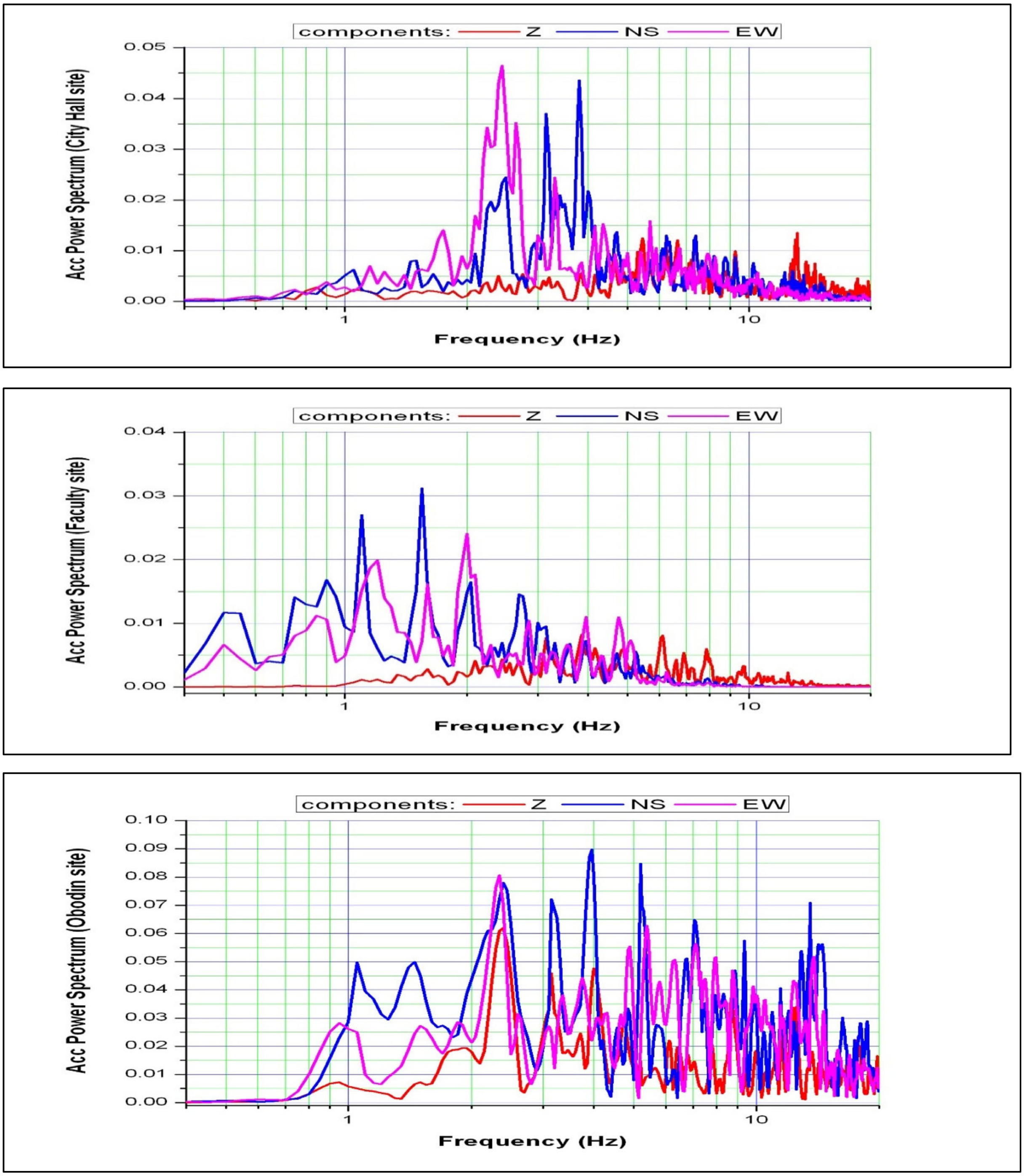


Fig. 9 The power spectrum of the 23 July 2017 23:40 UTC M3.1 earthquake at location: top—city hall, middle—Faculty of Tourism, bottom—Obodin

The accelerograms from the 2017 seismic sequence in the Ohrid area collected with the urban strong motion stations network were also analyzed with the Nakamura method (Nakamura 1989). The theory is based on the observation that on soft ground, the horizontal motion is larger than the vertical motion. However, on rock, the

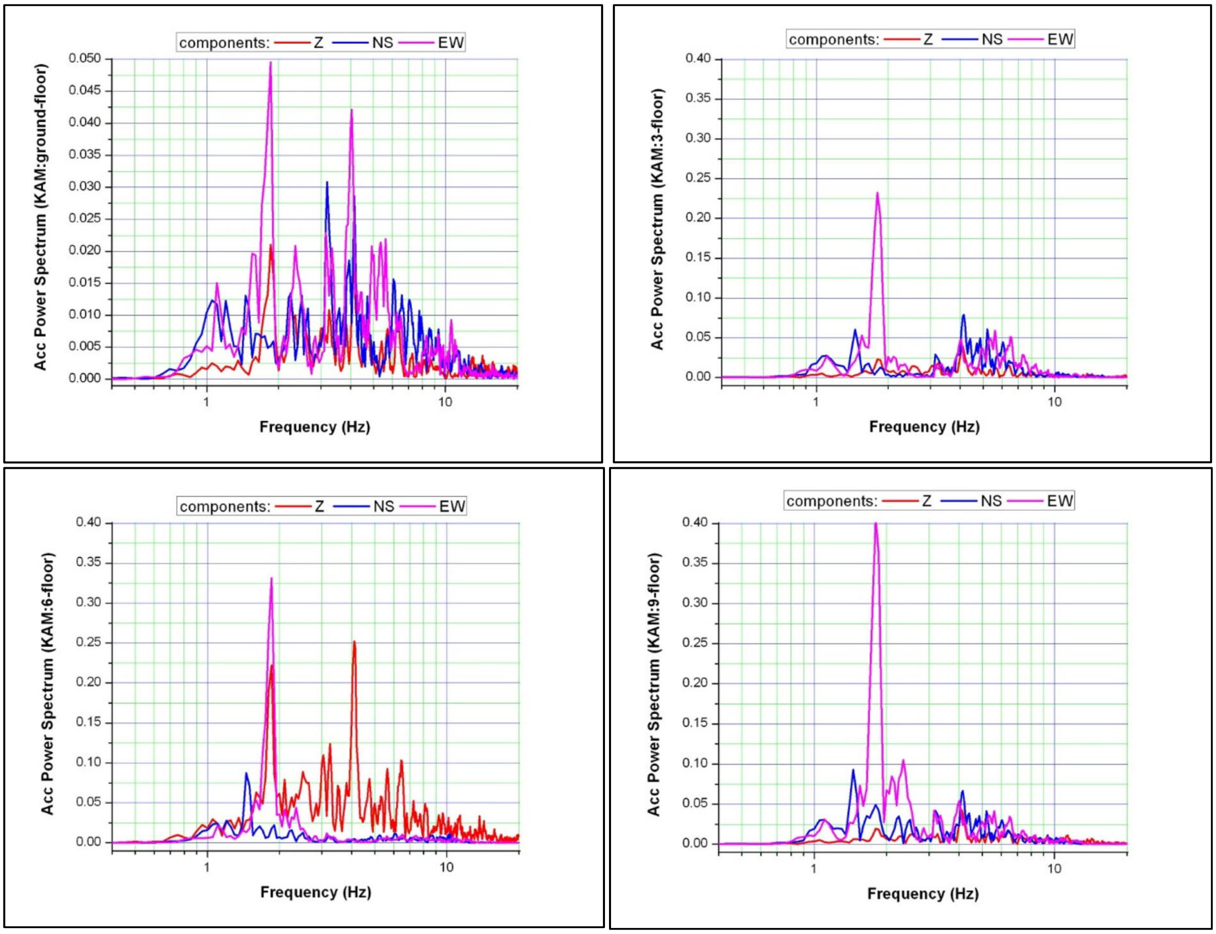


Fig. 10 The power spectrum of the 23 July 2017 23:40 UTC M3.1 earthquake at KAM location: top left—ground floor, top right—3rd floor, bottom left—6th floor, bottom right—9th floor

horizontal and vertical motions should be similar, both in the maximum amplitudes and in the waveform content.

Here, the horizontal to vertical ratio was derived from the maximum amplitudes and their corresponding frequencies and the values were compared to the ground characteristics of each site in the urban network. Only the data from the earthquake with magnitude M3.1 were used to estimate the H/V spectral ratios in this case, because the stations become operational after the biggest seismic event with magnitude M5.0.

Relative horizontal vs vertical ratio of the 23 July 2017 23:40 M3.1 earthquake at locations: seismological station OHR, KAM Market, city hall, Faculty of Tourism, and Obodin is shown in Fig. 13.

These results were compared to the available geological maps and borehole data. The H/V values for the stations deployed over the sediments exhibit a peak of around 1 Hz that could be associated with an overall deposit depth of around 125 m. The station city hall has a dominant peak at 3 Hz, equivalent to 45 m of the sedimentary layers underneath that location, which might indicate a different formation, faulting, or level of the water table. The predominant peaks and frequency found on the Seismic station OHR record, where the instrument is installed on rock, are within the range of expected values for velocities in limestones.

The prevailing frequencies of 1 Hz or 1 s found on the records of the instruments installed over sedimentary layers suggest that the amplification of the vibration at the station sites is related to the depth of the deposits. Vibration with frequencies of around 1 Hz is of special interest to civil engineers due to possible resonance effects within certain common building types.

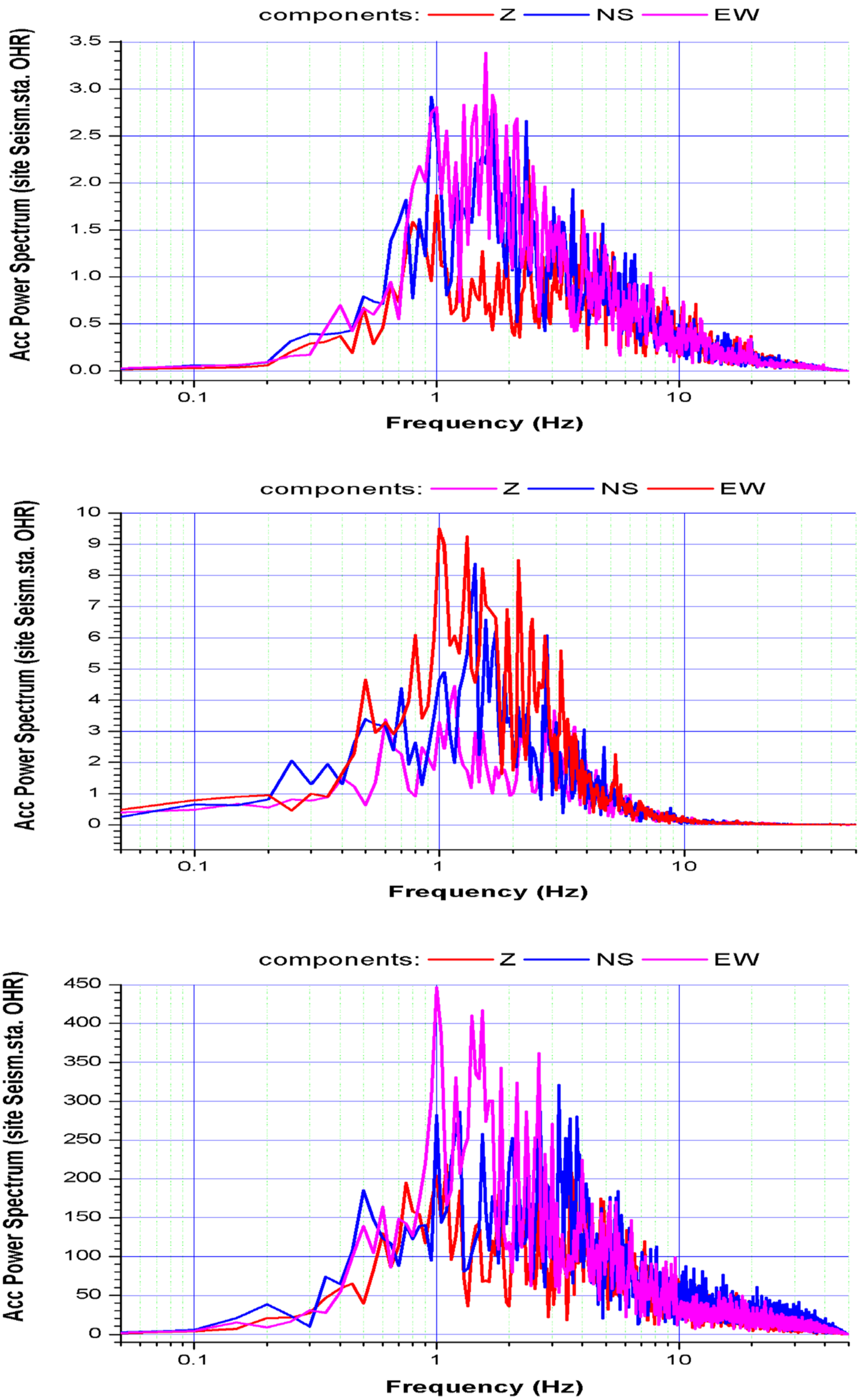


Fig. 11 The power spectra of the three earthquakes at the seismological station OHR location: top—magnitude 3.1, middle—magnitude 4.2, bottom—magnitude 5.0

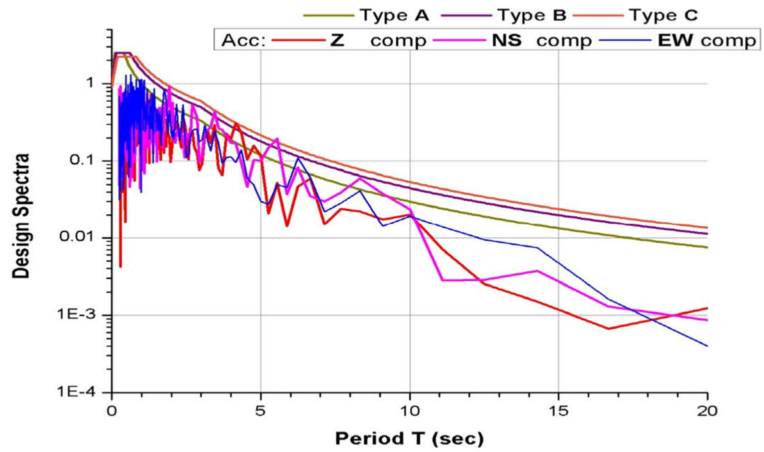


Fig. 12 The response spectra of the three components of the magnitude 5.0 earthquake at the seismological station OHR in respect to the Eurocode-8 (MKC EN 1998-1: 2012) design

5 Summary and discussion

During the months of June–July 2017, the Lake Ohrid area experienced a series of small to intermediate earthquakes. According to the catalog of earthquakes from the Skopje Seismological Observatory at PMF-UKIM, more than a thousand earthquakes occurred in that period as a swarm, with 50 of them being of magnitude 3 or greater. The strongest earthquake, magnitude M5.0, happened on 3 July 2017 11:18 UTC and had maximum intensity of VII degrees on the EMS-1998 scale. The epicenter of that earthquake and all aftershocks were located about 10 km east from Ohrid city center.

The earthquakes caused concern among the people in Ohrid and neighboring cities and villages and prompted the installation of two networks of temporary stations to monitor the seismicity in more detail. One network of instruments was deployed by the Seismological Observatory at PMF-UKIM in the epicentral area, to better determine the earthquakes' depth and the source mechanism. The second network was installed by the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) at UKIM, to monitor the influence of the surface conditions on the amplification of shaking and dynamics of structures in the Ohrid urban area. Since the earthquake swarm occurred at epicentral distances of 9 to 10 km, the records from the urban network cannot be directly used for the purpose of improving the local ground attenuation functions.

Comparative analysis was done using the accelerograph records from a magnitude M3.1 earthquake recorded in eight places in the city and from the two earthquakes with magnitudes M4.2 and M5.0 recorded only on the permanent seismological station Ohrid (code OHR), because they occurred before the network of temporary stations was installed. The behavior of the instrumented building was also compared to the measured data of the previous experiments.

Assuming that the seismic waves propagated through the same path from the origin, the differences in the values on the SM records from the stations can be primarily attributed to the ground conditions and location where the instruments were installed, i.e., bedrock at the site of the seismological station OHR and sediments at the sites of city hall of Ohrid, Faculty of Tourism, Obodin, and KAM Market, represented as triangles in Fig. 3.

The power spectra of the strongest earthquake from the 2017 seismic sequence in the Ohrid area was compared with the design spectra for the building code. Further work regarding the seismicity of Macedonia and the design spectra is the subject of an ongoing process between the joint committees formed by the State Standardization Institute.

In addition, the horizontal to vertical ratio was derived from the maximum value on the records of the stations from the urban network and was compared to the ground characteristics using the earthquake with magnitude M3.1 to estimate the predominant frequency for each site. These results were compared to the available geological maps and the borehole data. The H/V values for the stations deployed over the sediments exhibit a peak or around 1 Hz that could be associated with an overall depth of the deposits of around 125 m, except one site: city hall of Ohrid that might indicate a different formation, faulting, or level of the water table. The predominant peaks and frequency found on the seismological station OHR record, where the instrument

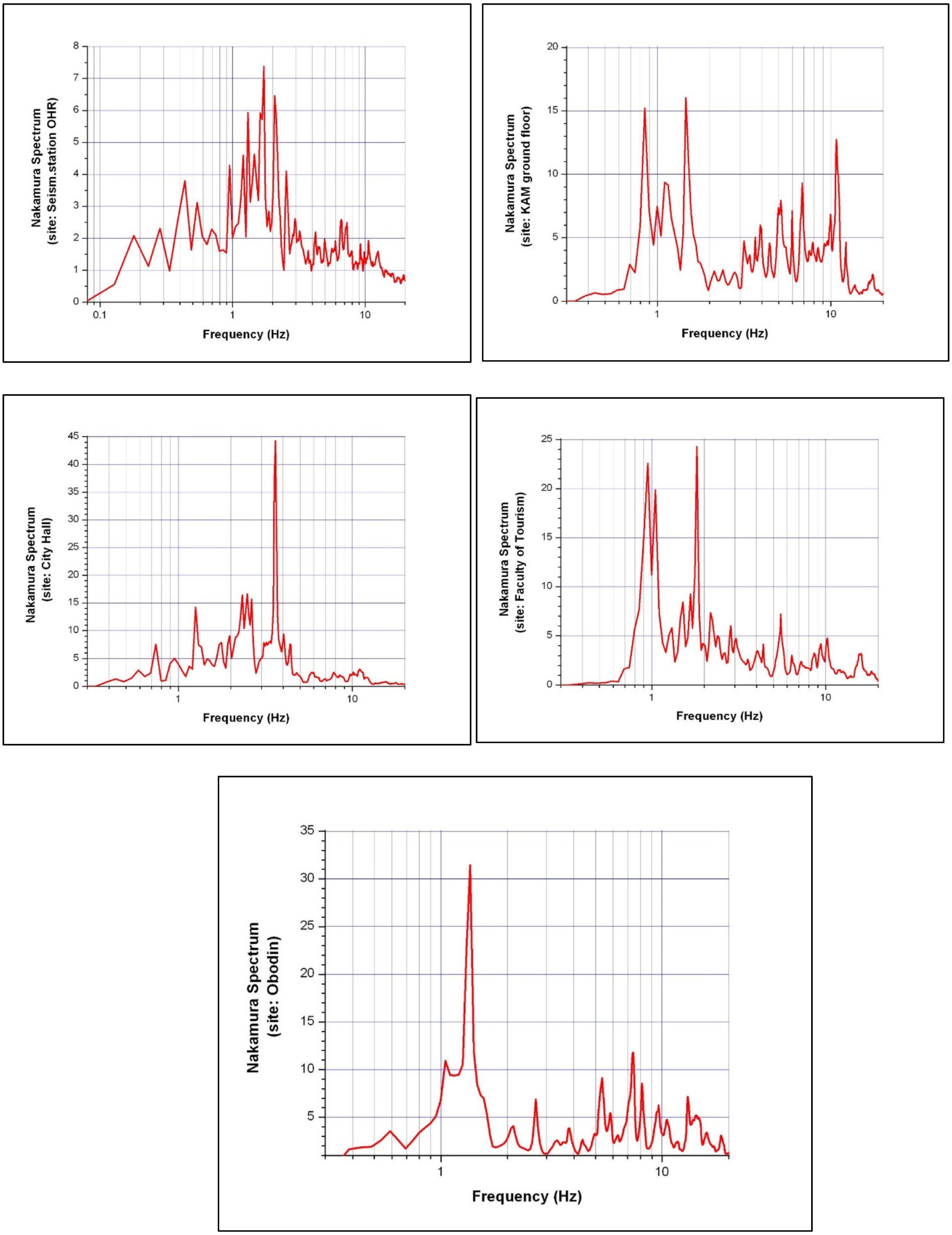


Fig. 13 The horizontal vs vertical ratio of the 23 July 2017 23:40 UTC M3.1 earthquake at locations: top left—seismological station OHR, top right—KAM Market, middle left—city hall, middle right—Faculty of Tourism, bottom—Obodin

is installed on rock, are in the order of the expected values for the velocities in limestones.

The prevailing frequencies of 1 Hz or 1 s found on the records of the instruments installed over sedimentary layers suggest that the amplification of the vibration at the station sites is related to the depth of the deposits. Vibration with frequencies of around 1 Hz is of special interest to civil engineers due to possible resonance effects within common building types. Besides application in engineering and building construction, this information about the local soil conditions is of benefit to geophysicists in seismic and geotechnical investigations and seismic risk assessment.

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