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Overview of recent ambient noise measurements in Croatia in free-field and in buildings

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The paper describes some recent applications of the measurements of ambient vibrations (microseismic noise) in Croatia. They include free-field measurements, as well as those done within buildings. Data obtained in the field at the studied localities are consistent with the properties of shallow geological structures known to exist there. In Zagreb, Horizontal-to-Vertical Spectral Ratios (HVSR) indicate thick alluvial cover (over 100 m) that gradually gets thinner towards the slopes of the Mt. Medvednica. A similar situation – on a smaller scale – is also encountered in Ston, where HVSR profiles reveal several tens of meters thick sedimentary cover over the bedrock which gets exposed at the Bartolomija hill. Analyses of records from Ston and Dubrovnik suggest that soil-building resonance must be seriously considered. Measurements in the buildings were analysed by a newly developed software package FREDA – a suite of Matlab routines. Based on tests on synthetic and real data it is concluded that spectral methods are in general more robust and less dependent on parameters of the algorithm employed, than time-domain analyses. Spectral algorithms are also better in resolving higher modes. Applications to real buildings proved that analyses of shaking induced by ambient vibrations in most cases lead to well constrained, reliable, and time independent estimates of frequencies and damping of the buildings' vibrational modes for small excitation levels.

Keywords: ambient vibrations, microtremors, HVSR, soil-building resonance

1. Introduction

Measurements of microtremors have been used in Croatia for assessing local site effects since 1960-ies. Based on works of Kanai (1957a, b), the measurements were used to constrain and verify available geotechnical models by estimating the fundamental soil period, but there have also been attempts to compare the spectrum of recorded noise with the theoretical amplification spectra. Limited mostly by the need to digitize analogue recordings by hand and by capabilities of the instruments of that time, such measurements gradually faded away. They have gained new impetus as the topic reappeared in literature

(Nakamura, 1989) and digital instruments started to replace the old ones in the 1990-ies. However, only after acquisition of truly portable dedicated instruments for the measurements of ambient vibrations within the NATO SfP 980857 project (2005–2008, http://nato.gfz.hr), the quality and quantity of measurements increased to the level required by today's standards. This paper presents a concise overview of measurements done in recent years in the free-field as well as in the buildings. Some of the material related to measurements until 2007 was presented also by Herak (2009) and Herak and Herak (2009).

2. Free-field measurements

From a large number of measurements done all over Croatia (over 1000 over the last 5 years), three cases will be presented here – the ones of Zagreb, Ston and Dubrovnik. Zagreb is a city with population approaching one million, and a history of large earthquakes. The most important one that occurred in 1880 (epicentral intensity VIII–IX °MCS) beneath the NE flanks of the Mt. Medvednica damaged all of the houses in the city, and practically defines the seismic hazard in Zagreb. In spite of rich seismic history, Zagreb still does not have an official seismic microzonation. One of the goals of the NATO-project was to test new methods and procedures to be used to produce a map of seismic microzonation, and microtremor measurements are expected to provide important information.

As a part of the Dubrovnik Republic, the city of Ston was one of the first townships in this part of the world that developed according to the strict urban code enforced from the 14th century. Earthquakes are frequent there. The most recent devastating one occurred in 1996 (M = 6.0, intensity VIII °MCS in Ston), and Ston needed almost a decade to recover. Detailed damage reports exist in the archives, so it was hoped that they could be compared to the noise measurements.

The Dubrovnik greater area is the most seismically active one in Croatia. Its seismic history includes many devastating earthquakes. The most important is the one of 1667 (intensity about IX °MCS), when the shaking and subsequent fire caused devastation of such extent that the prosperous Dubrovnik Republic never really recovered from. The Dubrovnik old town is today under the UNESCO protection, and earthquake hazard is high on the list of priorities of the city government.

2.1. Measurements in Zagreb

The Zagreb metropolitan area encompasses over 640 km^2. Geologically it consists of thick (100 m or more) alluvial sediments (clays, sands, gravel) in the Sava river valley, that gradually get thinner as we approach the Medvednica mountain to the north which mainly consist of green slates, shales, and limestones. In the course of preliminary investigations which should ultima-

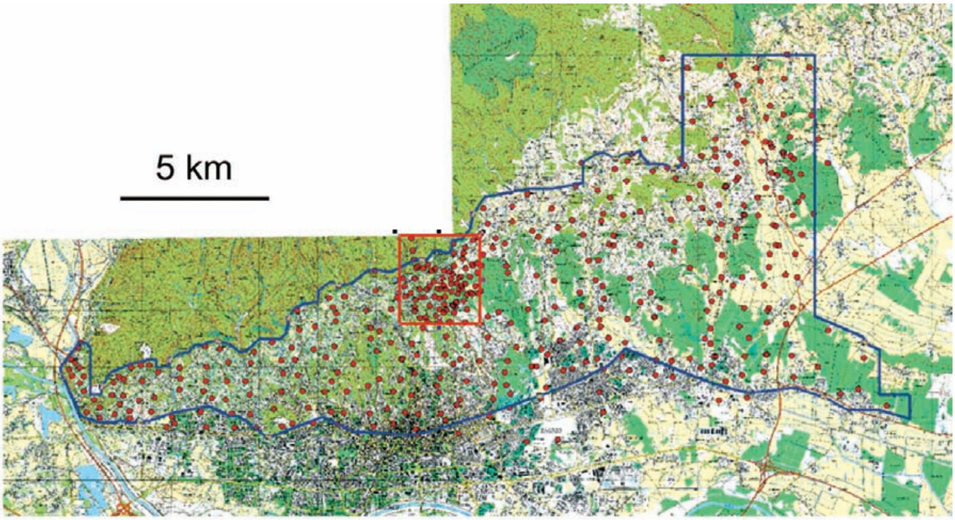


Figure 1. Location of measurements of ambient vibrations in the Podsljeme area in Zagreb. The red rectangle shows the area presented in Fig. 2.

tely lead to the microzonation of the city, we have made over 650 measurements of ambient vibrations, most of them in the proluvial Podsljeme area (about 160 km^2, Fig 1.) where the Sava valley meets the mountain flanks. The HVSR technique used to process measurements consists of computing ratios of horizontal and vertical spectra of microtremors (see, for instance: Nakamura, 1989; Lachet et al., 1996; Scherbaum et al., 2003; Panou et al., 2005; Havenith et al., 2007; Gosar, 2007; Cara et al., 2008; D'Amico et al., 2008; Gosar and Martinec, 2009 and papers in Mucciarelli et al., 2009). These spectra resemble, often in great detail, the theoretical amplification spectra of the soil layers, thus enabling us to quickly verify existing geotechnical models, and determine fundamental frequencies of soil deposits.

The instrument used was the portable Tromino (produced by Micromed, Italy), a small all-in-one package with 3-component geophones, digitizer, GPS-timing, batteries and 512 Mb flash memory for storage. Measurements started in the 2007, but were mostly done in the period 2009–2010. All of them lasted for 20 minutes, and were processed uniformly: each trace was divided into non-overlapping 20-s long segments, and spectra for all three components were computed for each of them. The three spectra were then smoothed with the Konno-Omachi (1998) smoothing function, and HVSR was computed as the ratio of the geometrical mean of spectra of the two horizontal components and the spectrum of the vertical one. The final HVSR curve was obtained by averaging individual HVSR for all segments.

Figure 2 presents typical HVSR obtained in an approximately 3 km $\times$ 3 km area in the Podsljeme zone. It is seen that in the south the spectra are charac-

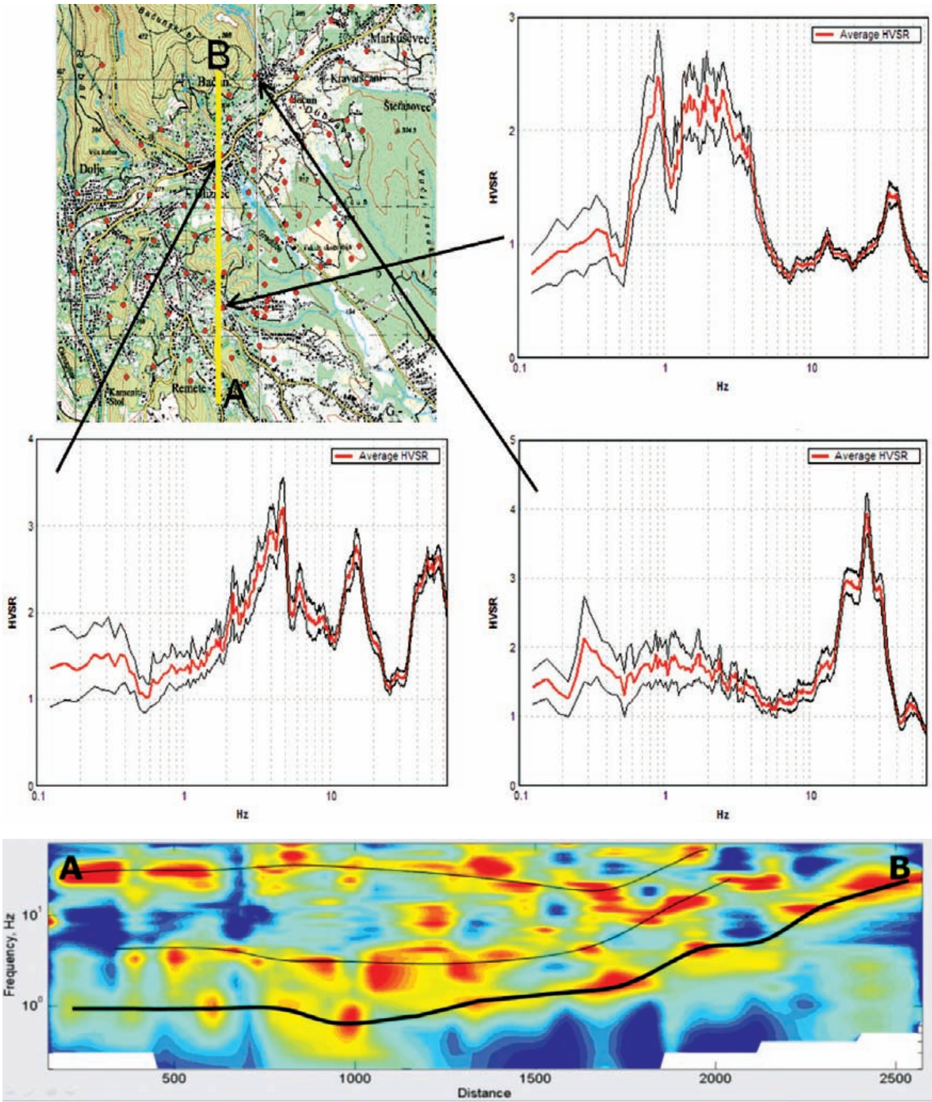


Figure 2. *Top left:* Map view of the part of the Podsljeme area in Zagreb which was chosen as the test neighbourhood for the HVSR measurements (see the red rectangle in Fig. 1 for location). Red dots show the locations of measurement points. The foothills of the Mt. Medvednica are in the northern and north-western part. The yellow AB-line shows the location of the profile in the bottom. *Top right and middle:* Examples of the measured HVSR curves (mean ± 1 standard deviation), showing how the dominant frequency shifts towards higher values as we move along the profile from A to B. *Bottom*: HVSR profile AB (see the map on the top). Only measurements within 500 m from the profile line are considered. Warm colours correspond to high normalized HVSR values. The lines are drawn to emphasize features, and have no direct geological interpretation, although clear systematic increase of the predominant frequency with the thinning of the sedimentary cover close to B is evident.

terized by relatively broad low-frequency peaks (ranging from 0.85 to 2 Hz), indicating presence of thick alluvial deposits. Moving towards the north, the HVSR peaks shift towards the higher frequencies (about 3–6 Hz), as the sedimentary cover gets thinner. Reaching the foothills of the Mt. Medvednica, the

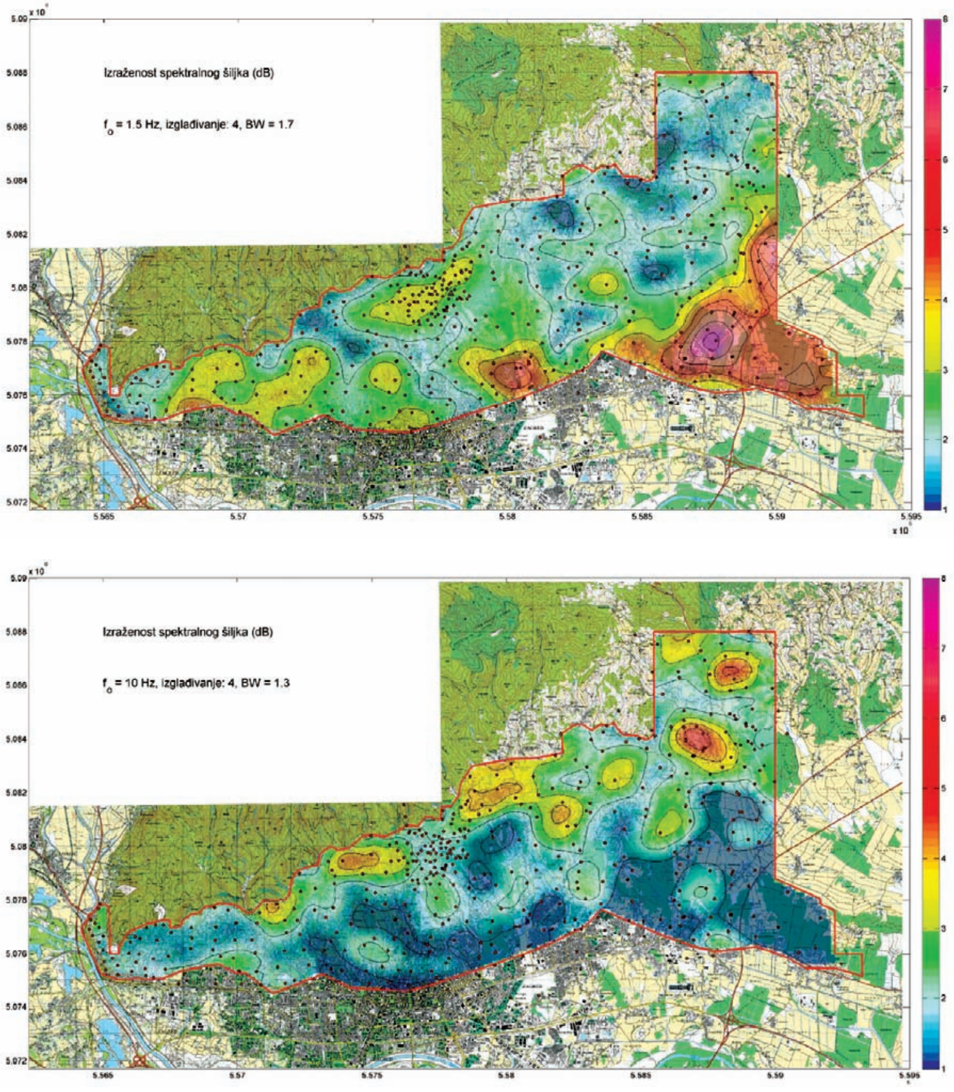


Figure 3. Preliminary results of mapping the prominence of the observed HVSR peak in dB above the average amplitude within the frequency band [(fo – fo/BW), (fo + fo BW)]. BW is bandwidth, taken as BW =1.7 for f_o = 1.5 Hz (*top*), and BW = 1.3 for f_o = 10.0 Hz (*bottom*). Colours in the red part of the spectrum indicate more expressed peaks.

bedrock gets very close to the surface, as indicated by HVSR peaks found at frequencies above 10–20 Hz.

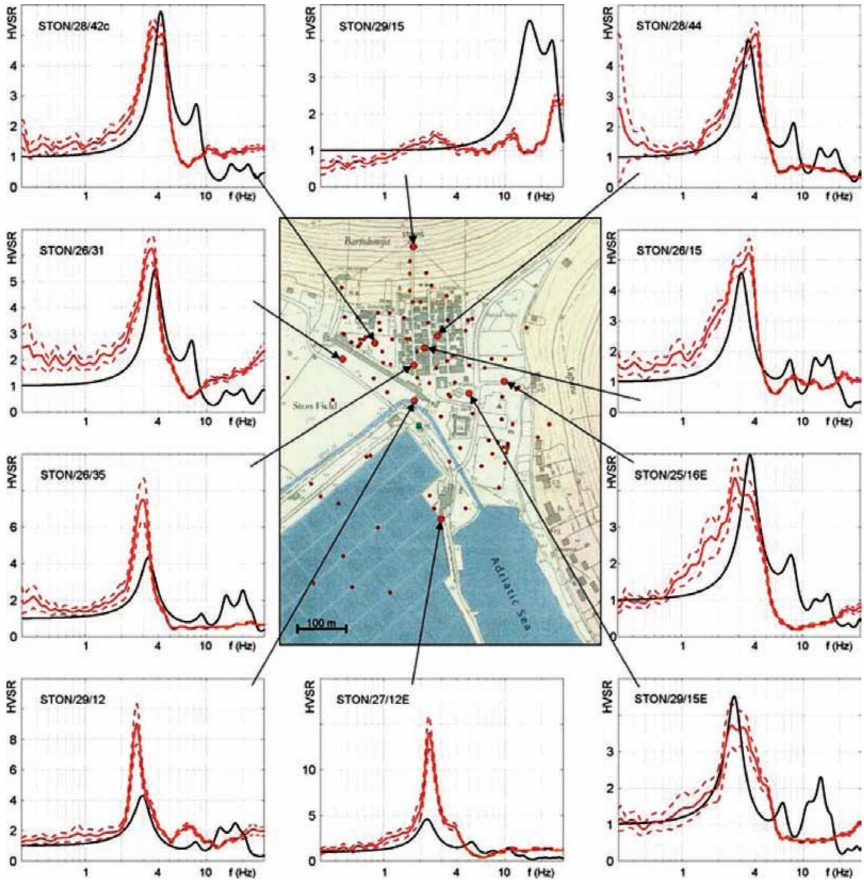
The HVSR profile (shown in Fig. 2) is 2500 m long. This is a spatial spectrogram constructed of all HVSR measured within 500 m from the profile trace. It clearly shows systematic increase of predominant frequencies as one moves from left (south, A) to right (north, B). Assuming an average S-wave velocity of 300 m/s in the whole sedimentary layer above bedrock, the observed variation of fundamental frequency maps into thickness variation from over 100 m in the south to only a few meters in the north, which is in agreement with (very few) available geotechnical data.

The maps of the prominence of the HVSR peaks (Fig. 3) in the neighbourhood of f_0 = 1.5 Hz and f_0 = 10 Hz clearly show how the hazard of soil-structure resonance quickly changes in space. Tall buildings with low natural frequencies are clearly threatened more in the south-eastern part of the area. Smaller houses, on the other hand, are in greater danger more to the N and NW, where the most prestigious residential areas in Zagreb are found. The houses there are typically 1–3 storeys high, with expected fundamental frequencies of about 7–15 Hz (Gallipoli et al., 2010). According to our measurements so far, this is also the only place in Zagreb where such buildings are in danger due to soil-structure resonance during earthquake shaking.

2.2. Measurements in Ston

In Ston ambient noise measurements were done in three campaigns in 2006 and 2008, as reported in the microzonation study by Herak et al. (2010). A total of 99 free-field points were measured, as shown in Fig. 4. They were processed as described in the previous section. The town itself is situated between the Bartolomija hill, and the shallow Ston channel. Limestones prevail in the bedrock. According to a few boreholes, there is about 15–30 m of weathered loose material (mostly sands) above the bedrock beneath the town. Our measurements confirm this as the fundamental frequency all across the plane beneath the Bartolomija vary between 2 and 4 Hz. As we start climbing up the

Figure 4. *Top:* Plan of Ston, with measurement locations (red). Selected horizontal-to-vertical spectral ratios (HVSR) are also shown. Red – observed, ambient noise. 95% confidence limits are indicated by red dashed lines. Black – theoretical body-waves HVSR (see Herak et al, 2010 for description of models and procedures). Note the variable vertical scale! *Bottom*: a) HVSR profile running from the salterns in the south (A) to the Stoviš tower on the Bartolomija hill in the north (B). Only points within 50 m from the profile trace (blue) are considered. b) Smoothed HVSR profile obtained by gridding of the HVSRs (each normalized by its maximum) measured at places indicated by white lines. Relative amplitudes are colour-coded (see the colour-bar). c) Theoretical normalized HVSR profile for body waves. d) Theoretical normalized HVSR profile for surface waves. See Herak et al., (2010) for details on the models and computational procedures. (From Herak et al., 2010). ⇒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HVSR
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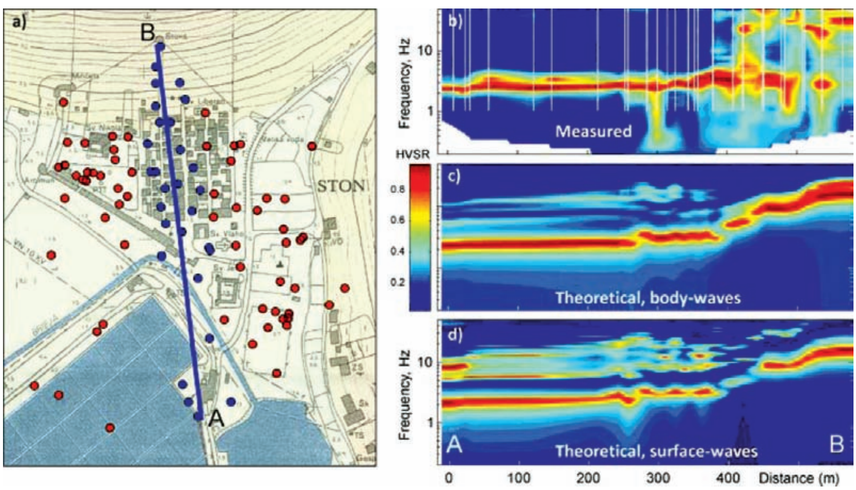
a)
B
A
STON
b)
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Frequency, Hz
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c)
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d)
Theoretical, surface-waves
Distance (m)

hill, the layers' thickness rapidly decreases and the dominant frequency increases to over 20 Hz.

Fundamental frequencies of stone houses in Ston vary between about 3 and 6 Hz, depending on their height, shape and position. This frequency interval coincides well with the dominant soil frequencies beneath the town centre, which, together with high amplification, may explain severity of the damage (VIII °EMS) caused by the 1996 earthquake whose epicentre was 16 km away. Fig. 5 shows comparison of the spatial distribution of the damage to the building stock in Ston with the linear dynamic amplification factor (DAF). It is defined (*e.g.* Herak, 2008; Herak et al., 2010) as an integral measure of the expected increase of peak acceleration on the ground surface due to modification of the spectrum of incoming wave field by a horizontal stack of sedimentary layers above the base rock. Although it is strictly defined only when the amplification spectrum (AMP) of the soil is known, in the first approximation HVSR of ambient noise may be used as proxy for AMP. Fig. 5 (left) shows mapped values of DAF, and the frequency of the HVSR peak (right). Although the pattern of damage is far from homogeneous, notably more severely damaged houses occurred in the southern and south-eastern parts of the town, where amplification (DAF) is the highest (between 2.5 and 3.5). The buildings close to or on the hill-slopes (DAF < 2) sustained mostly only moderate damage or remained unaffected. Similar conclusions are reached when the damage is compared to the soil predominant frequency, f_{max} (Fig. 5) – houses on soil with $f_{max} > 6$ Hz were considerably less damaged than those in the flat land ($f_{max} < 3.5$ Hz).

During the 1996 earthquake, the largest horizontal acceleration ever in Croatia was recorded by the instrument located at the entrance to the Ston salterns (blue rectangular fields in the Ston plan in Fig. 4). Horizontal acceleration of about 0.64 g, and much smaller vertical one (Fig. 6) indicate that significant soil amplification occurred there. This assumption is confirmed by Herak et al. (2010) who showed that observed amplification level is in excellent agreement with the corresponding DAF value of about 4 in Fig. 5. Here I also present the synthetic accelerogram (Fig. 6) computed by assuming an earthquake source 16 km away at the depth of 10 km, and the magnitude $M = 6.0$. The Fourier spectral amplitudes at the bedrock level were computed as suggested by Trifunac (1993) and Lee and Trifunac (1995). This spectrum was multiplied by the theoretical amplification spectrum for the soil model at the site (see Herak et al., 2010), and random vibration theory was used to generate synthetic time series. The Berlage function with parameters chosen to reflect expected duration of significant shaking (Trifunac and Brady, 1975) was finally used to shape the synthetic signal. Comparison of observed and synthetic time-series of acceleration show that the synthetic one exhibits all main features of the recorded accelerogram, most notably its frequency content, as well as the absolute level of acceleration. This further strengthens the conclusion that local soil amplification enhanced significantly the damage to the buildings in Ston.

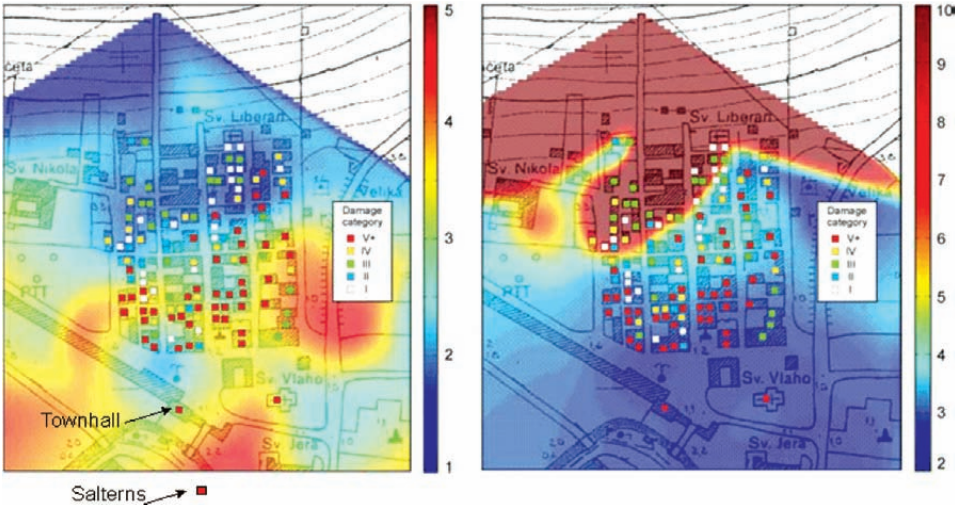

Figure 5. Mapped values of amplification (DAF, *left*) and predominant frequency (f_{max}, *right*) determined on the basis of measured HVSR of ambient vibrations. f_{max} values are truncated at 10 Hz only for plotting. (From Herak et al., 2010).

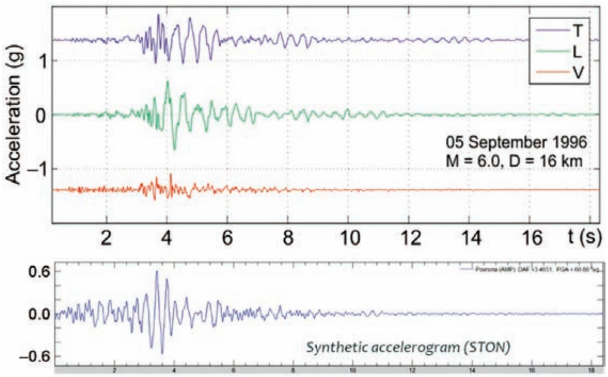

Figure 6. *Top:* Recorded strong-motion records of the 1996 earthquake in Ston (salterns). The peak recorded acceleration reached 0.64 *g*. *Bottom:* Synthetic accelerogram generated by taking the expected linear amplification spectrum of soil into account. Note the similarity in shape, amplitude and spectral content.

2.3. Measurements in Dubrovnik

Free-field ambient noise measurements in Dubrovnik were done in the course of the M.E.E.T.I.N.G. INTERREG/CARDS-PHARE project in 2008 (http://www.meeting.rgh.hr), in order to assess their applicability for the future microzonation of Dubrovnik. A total of 49 measurements were done in

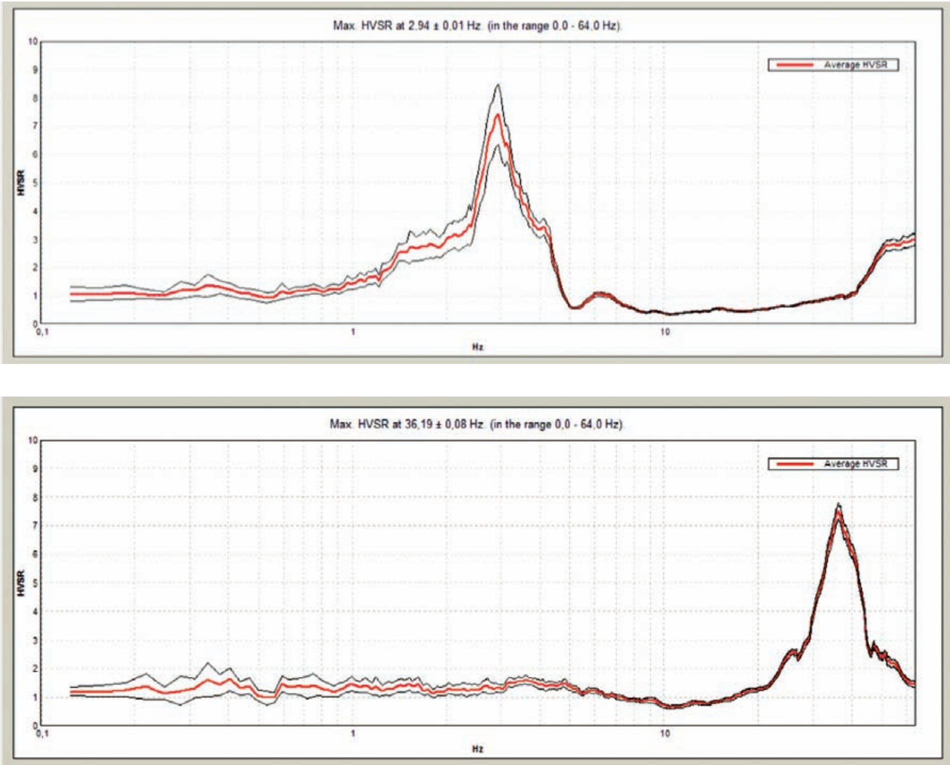

Figure 7. Examples of HVSR curves measured in Dubrovnik. *Top:* Stradun street, in front of the St. Blasius church; *Bottom:* Gardens of the Franciscan monastery, close to the Minčeta tower in the NW part of the city walls. Black lines denote one standard deviation.

the streets, parks, courtyards, gardens, *etc*. of the city. Two examples of measured HVSR curves are shown in Fig. 7. The Stradun measurement exhibits a clear peak at 3 Hz, indicating a cover of several tens of meters above bedrock, which is expected as this area of the old town is known to have been built on reclaimed land. On the contrary, the gardens of the Franciscan monastery seem to lie on top of the bedrock covered only by a thin vegetation cover, which is indicated by a very high dominant frequency of about 35 Hz.

The spatial spectrogram of measurements along the line beginning beneath the city walls in the south and ending on the flanks of the Srđ hill in the north (Fig. 8) reveals that most of the old town sits on 20–30 m of soft material, which thins out towards the end of the profile.

Results obtained in Zagreb, Ston, Dubrovnik and other places in Croatia clearly confirm applicability of the microtremor HVSR technique in cases of both thick and thin sedimentary covers in determining the soil fundamental frequency and linear amplification properties.

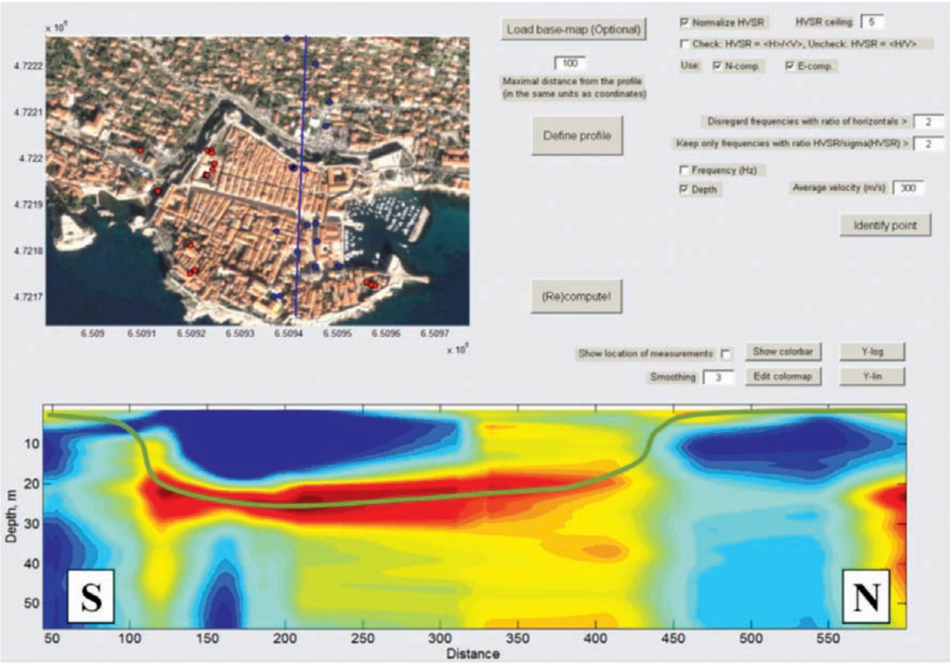

Figure 8. Spatial spectrogram of the HVSR measurements along the N–S profile across the old town in Dubrovnik. The frequencies on the ordinate have been mapped to the depth assuming S-wave velocity of 300 m/s. Only measurements within 100 m from the profile are considered (blue circles). The green line just accentuates features observed and is not necessarily delineating geological features.

3. Measurements in buildings

An important aspect of the NATO SfP 980857 project was estimation of buildings' free periods of oscillation in order to asses each construction's potential for resonance with the soil layers it is founded upon. As resonance effects will depend also on the damping of the structure, it was of interest to compile a program that will simultaneously estimate periods of free vibrations and their respective damping from the records of ambient vibrations in buildings and in the free field. These efforts resulted in a collection of Matlab routines, assembled together in a graphical user interface (GUI) FREDA (FREquency–Damping Analyses). The GUI is shown in Fig. 9. Main features of FREDA include:

– plain ASCII files of ambient vibration time-histories as input;
– instrument corrections (for displacement and velocity);
– correction for the reference spectrum (excitation signal);
– 5 modes of analyses:

A) *Time domain:*
– Slightly modified nonparametric analyses (NonPaDAn, Mucciarelli and Gallipoli, 2007)
– Bandpass NonPaDAn
B) *Frequency domain:*
– Spectral single-peak transfer function analyses
– Spectral sweep transfer function analyses
– HVSR

– Each analysis mode may also be used with the *random decrement* (Cole, 1971) signature of the signal as input;

– Uses real or synthetic signals;

– Output graphics (eps, jpg).

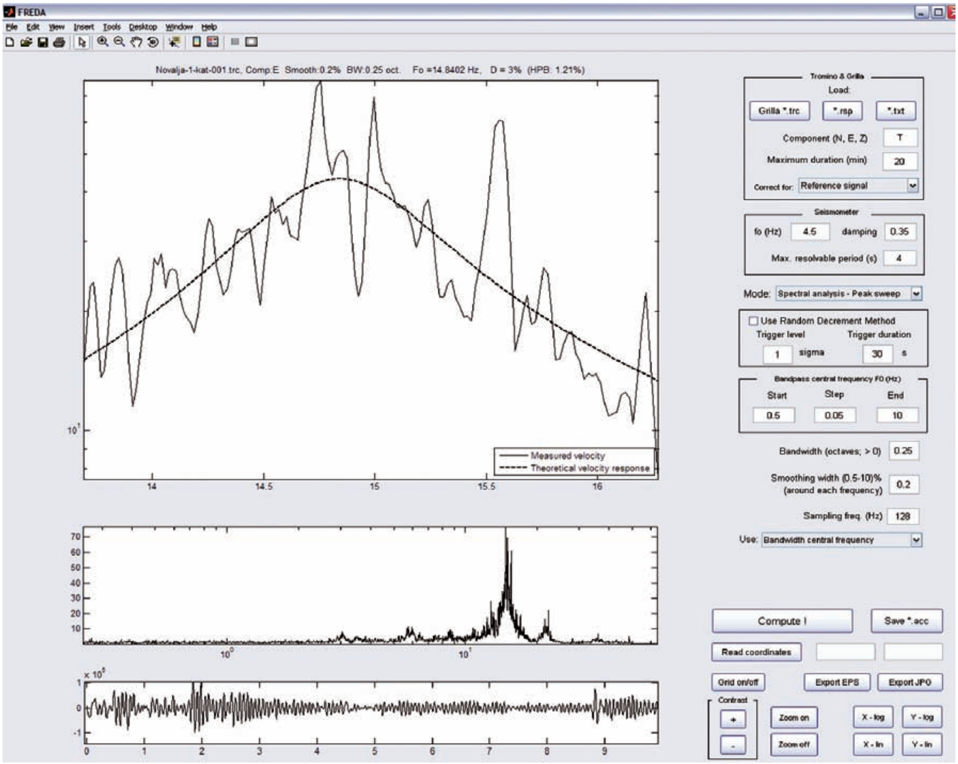

Figure 9. FREDA graphical user interface (GUI), showing an example of the spectral single-peak transfer function analyses. The bottom subplot shows the first 10 seconds of the 20 minutes long measured noise time series of the transversal horizontal component of the building vibrations induced by ambient noise. Above it is its Fourier spectrum divided by the spectrum of the free-field noise. The main window shows the blow-up of the selected peak and the best fitting single-degree-of-freedom (SDOF) theoretical response. All controls for choosing the mode of analyses and various parameters are in the right part of the GUI.

The program has been tested extensively using synthetic signals as well as measurements on many building types. The comparison of results reveals that estimates of frequencies and damping obtained by spectral methods are in general more robust and less dependent on parameters of the respective algorithm, than the findings based on time-domain analyses. Spectral algorithms are also much better in resolving higher modes. The random decrement method is in most cases found to be inferior to spectral or band-pass procedures using original signal.

In particular, the use of HVSR is not recommended, although it may yield reasonable frequency estimates in some instances. However, there is no theoretical basis for its application as we can not safely assume that horizontal and vertical spectra do not differ at the ground level. This is especially dangerous if soil amplification is significant (with prominent HVSR peaks), in which case the free-field HVSR may contaminate building response, leading to false identification of possible resonance. All subsequent analyses were done using spectra of vibrations measured in the building, divided by the corresponding spectra of the excitation signal (microtremors recorded in the vicinity of the building). Similar approach was used by Gosar et al. (2010) who proposed a spectral ratio between the measurement taken at the top floor of the building and at the basement for both horizontal components. It is named floor spectral ratio (FSR). This approach is useful also if a free-field measurement close to the location of the building is not available.

Application to a real building is illustrated by an example of one of the highest skyscrapers in Zagreb (26 floors). Fig. 10 shows FREDA analyses of recordings of the ambient-noise induced vibrations in the centre of the terrace at the top of the building. At least 5 modes are discernible, with the following frequencies (f_i) and damping (D_i, % of critical): f_1 = 0.44 Hz, D_1 = 1.0%; f_2 = 0.73 Hz, D_2 = 1.4%; f_3 = 1.95 Hz, D_3 = 1.6%; f_4 = 3.83 Hz, D_4 = 2.0%; f_5 = 4.72 Hz, D_5 = 3.0%. Comparison of the spectra of vibrations simultaneously recorded at the corners and in the centre (Fig. 10), suggests that frequency of 0.73 Hz corresponds to a predominantly twisting mode, as its amplitudes at corners are notably larger than in the centre.

The measurements were also conducted in buildings in Ston. For example, Fig. 11 shows the spectrum of the longitudinal oscillations of the town hall building corrected for the input spectrum of the ambient vibrations recorded in the free-field, close to the building. The building's fundamental mode has the frequency of 3 Hz, quite close to 2.5 Hz which characterizes the soil transfer function. Taking into account that the building frequencies tend to decrease during severe shaking, it is almost certain that the soil-building resonance must have occurred during the Ston earthquake of 1996, and that this resonance was largely responsible for extensive damage that the building suffered.

In Dubrovnik, 17 measurements in buildings were done in the course of the M.E.E.T.I.N.G. project in 2008. Fig. 12 shows spectra recorded in two adjacent, practically identical buildings in the very centre of the Old town – the Scientific Library building (blue lines), and the building of the Institute for the Restoration of Dubrovnik (red lines) which has been seismically retrofitted and reinforced. It is interesting to note how the Institute's building is characterized by the shift of its natural frequency towards higher frequencies (compared to the Library), as a result of increased stiffness achieved by retrofitting. The fundamental frequency of soil beneath the historical Dubrovnik city centre (3–4 Hz, see above) roughly matches the frequency of the Library building, which puts it danger regarding possible soil-building resonance in future earthquakes. The shift of the fundamental frequency of the Institute's building to 5–6 Hz might be large enough to avoid such resonance and thus reduce future earthquake induced damage. Encouraged by this result, a campaign of measurements in one of the housing blocks in Stradun, just opposite the St. Blasius church (see Fig. 7 for the free-field HVSR) was performed in 2010. Preliminary results indicate that the block has the transversal fundamental frequency of about 5.0 Hz (Fig. 13), with overtones at 7.5 and 20 Hz. The damping for low-level excitation was estimated between 1.8% and 2.9% of crit-

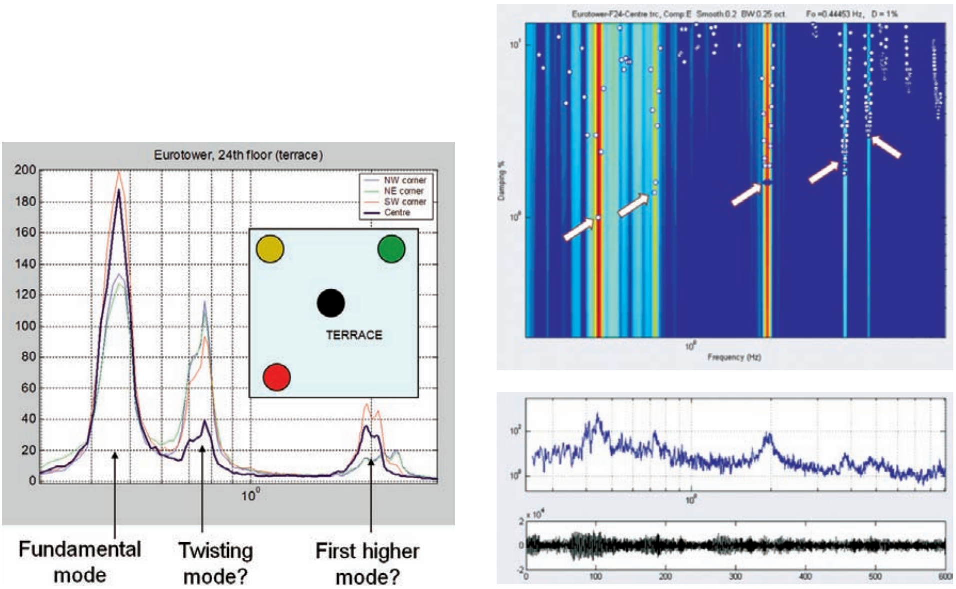

Figure 10. *Left:* Spectra of horizontal vibrations on top of the 26-storey building in Zagreb (divided by the corresponding free-field spectra), measured simultaneously at three corners and in the middle of the terrace. Notice how the peak at 0.73 Hz is the only one whose amplitude varies with the location (and is the smallest in the centre), indicating a twisting mode. *Right*: Spectral sweep analyses in FREDA of vibrations measured in the centre of the terrace. The top subplot presents results, clearly marking at least five vibrational modes (damping is on the ordinate, frequency on the abscissa). The middle subplot is the amplitude spectrum of the horizontal component of recorded velocity. In the bottom, the time-series of measured vibrations are shown.

Figure 11. *Top*: Spectrum of vibrations induced by the ambient noise (longitudinal direction) of the town hall building in Ston, 2^{nd} floor. *Bottom*: HVSR of microseismic noise measured in front of the building. The peaks nearly coincide, indicating that the soil-structure resonance may have occurred and was responsible for the heavy damage (photo in the inset) during the Ston earthquake of 1996.

ical. Depending on the nonlinear behaviour of the block during strong shaking, which results in reduction of the natural frequency, this may or may not be far enough from about 3 Hz (measured in the free-field some 50 m away) to avoid resonance. This block is scheduled for retrofitting, and our measurements will serve to monitor and document the actual change in dynamical properties induced by the reinforcement.

Analyses as presented above were done in over 150 buildings in Croatia, most of them in Zagreb (Fig. 14). The estimates of the fundamental periods and dampings for the reinforced-concrete buildings were presented by Prevolnik (2008), and this dataset has been incorporated into the set of south-European buildings described by Gallipoli et al. (2010). The height (H) – period (T) relationship they obtained ($T = 0.016\ H$, with H in meters) is proposed as

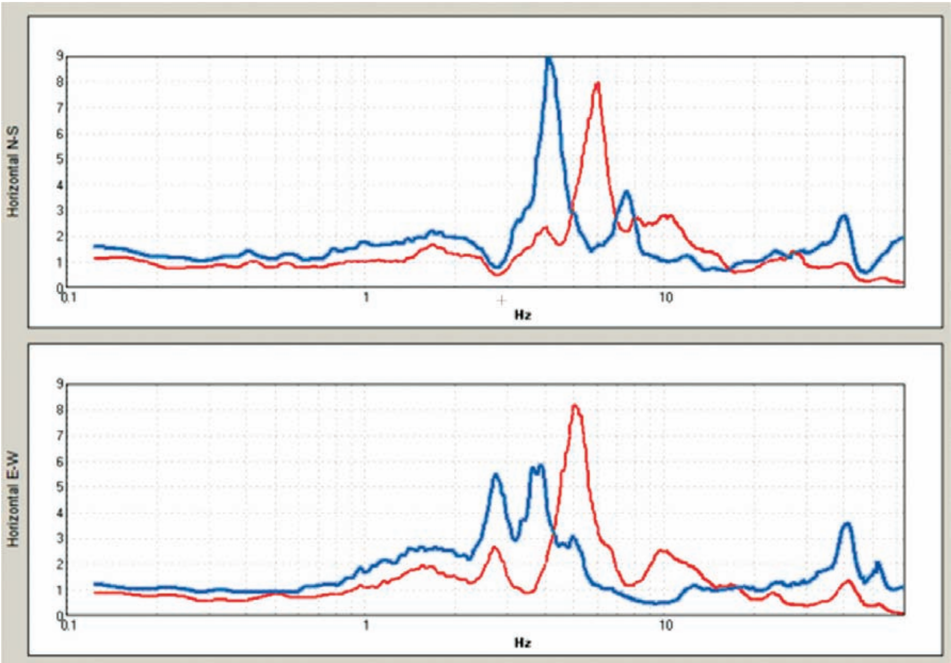

Figure 12. Standard spectral ratios (building/free-field) of ambient vibrations in the buildings of the Scientific Library (blue), and the Institute for the Restoration of Dubrovnik (red). N–S (*top*) and E–W (*bottom*) roughly correspond to the longitudinal and transversal directions, respectively.

part of the Croatian National Annex to the Eurocode-8. The damping values for small excitation levels provided by ambient vibrations (Fig. 14, right) obey the rule-of-thumb „damping (%) = fundamental frequency (Hz)“ for small amplitudes (Jeary, 1986).

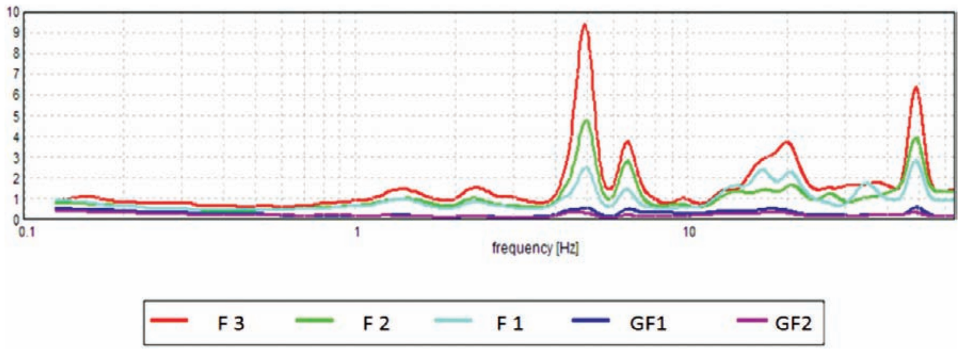

Figure 13. Standard spectral ratios (building/free-field) of vibrations in the housing block in Dubrovnik (Stradun, near the Sponza palace) recorded on the ground floor (GF1, GF2), and on floors 1, 2, 3 (F1, F2, F3).

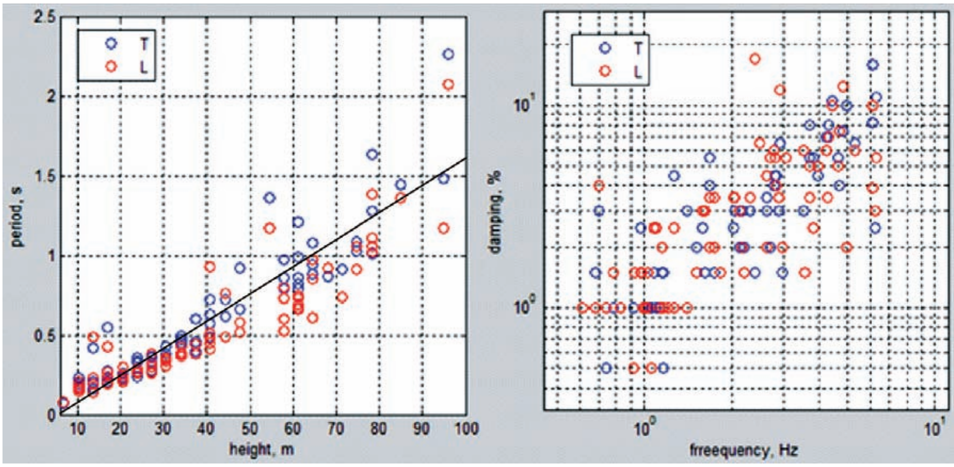

Figure 14. Fundamental periods vs. height (H) of the building (*left*) and damping values (*right*) in 73 RC-buildings in Croatia measured by ambient vibration technique and analysed by the FREDA program package. Longitudinal and transversal components are shown by red and blue circles, respectively. The relation for the set of European buildings (T = 0.016 H, Gallipoli et al., 2010) is shown in the left subplot.

Herak and Herak (2010) reported a case study of long-term observation (19 months) of the building of the Geophysical Department in Zagreb by a broad-band seismograph. They observed significant variation of fundamental periods and damping with the amplitude of excitation and with the seasonal changes of meteorological parameters.

The stability of measured spectra was checked by repeated measurements during different times in a day, seasons, and weather conditions. Typical variation of estimated frequencies was found to be within a few percent. For damping the values varied not more than ±1% of the critical damping.

4. Conclusions

Recent measurements of the free-field ambient vibrations in Croatia proved to be valuable in providing additional insight into the geotechnical properties of the soil, especially in constraining the fundamental frequency of sedimentary deposits, but also for estimating overall soil amplification levels. These findings are encouraging, and suggest that ambient noise measurements should be considered in any future microzonation study.

Measurements of ambient vibrations in buildings were shown to be efficient and quick, yielding reliable, accurate and temporally stable estimates of frequencies and damping of the buildings' vibrational modes for small amplitude excitation. Combining the free-field measurements with those within houses and other structures can point to constructions likely to exhibit soil-structure resonance. The measurements done so far form initial nucleus of the building inventory, a collection of fundamental periods, damping, spectral shapes, and other data which can prove important in documenting buildings' structural integrity and assessing the degree of possible damage in future earthquakes.

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SAŽETAK

Pregled nedavnih mjerenja mikroseizmničkoga nemira u Hrvatskoj na otvorenom terenu i u zgradama

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Prikazani su rezultati i interpretacija nedavnih mjerenja mikroseizmičkog nemira u Hrvatskoj, kako onih na terenu, tako i u zgradama. Terenski podaci prikupljeni u Zagrebu, Stonu, Dubrovniku i na drugim lokacijama konzistentni su sa spoznajama o građi površinskih slojeva. U Zagrebu HVSR spektri ukazuju na postojanje debelih aluvijalnih naslaga debljine veće od 100 m koji se stanjuju s približavanjem Medvednici. Slična je situacija, samo na manjoj skali, i u Stonu, gdje se nekoliko desetaka metara duboka osnovna stijena sasvim približava površini na brdu Bartolomija. Analiza mjerenja u Stonu i Dubrovniku ukazuje na mogućnost nastajanja rezonancije između tla i zgrade tijekom potresa. Mjerenja vibracija građevina uzrokovanih mikroseizmičkim nemirom analizirana su pomoću novorazvijenog programskog alata FREDA. Rezultati testova sa sintetičkim i realnim signalima ukazuju na to da su algoritmi bazirani na analizi spektara mnogo stabilniji u odnosu na analizu u prostoru vremena. Oni su bolji i u razlučivanju viših modova, te manje ovise o odabranim parametrima. Mjerenja u zgradama jeftina su i u velikoj većini slučajeva omogućuju pouzdane procjene vlastitih frekvencija te prigušenja vibracijskih modova pojedine građevine za oscilacije malih amplituda. Usporedbom izmjerenih dominantnih frekvencija osciliranja zgrade s vlastitim frekvencijama tla na kojem se ona nalazi, može se procijeniti opasnost pojave rezonancije zgrada-tlo za vrijeme potresa.

Ključne riječi: mikroseizmički nemir, HVSR, rezonancija građevina-tlo

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