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Review of seismological investigations related to 1998 M_w5.6 and 2004 M_w5.2 earthquakes in Krn Mountains

Pregled seizmoloških raziskav povezanih s potresoma 1998 M_w5,6 in 2004 M_w5,2 v Krnskem pogorju

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Ključne besede: potres, seizmologija, seizmotektonika, makroseizmika, žariščni mehanizem, popotresni niz, statična sprememba napetosti, lokalni seizmološki vplivi, metoda mikrotremorjev, Krnsko pogorje, Ravenski prelom

Abstract

Overview of extensive seismological studies of Krn Mountains earthquakes performed in two decades is given. Detailed macroseismic studies by using a new European Macroseismic Scale EMS-98 showed large variations in damage to buildings due to the influence of very heterogeneous sediments and partly also due to the differences in source radiation pattern. Site effects were carefully studied and it was proven by microtremor HVSR method that soil-structure resonance effects severely enhanced the damage in many places. Particularly important were seismotectonic studies based mainly on focal mechanisms and distribution of aftershocks. Combined with geological data these studies pointed to the complex structure of segmented Ravne fault, which is growing by interactions between individual fault segments. A wider area is characterised by a kinematic transition between Dinaric (NW-SE) strike-slip faults in W Slovenia and E-W trending Alpine structures with predominantly reverse faulting in Friuli. Other investigations included static stress changes on neighbouring faults, analyses of the time decay of extensive aftershock sequences and magnitude-frequency relations. All these studies have significantly fostered seismological research in Slovenia and have enhanced international cooperation. Following the 1998 earthquake a modern national seismological network was built composed of 26 stations equipped with broadband sensors, accelerometers and high-resolution digitizers. Together with cross-border exchange of real-time data the seismological monitoring has been significantly improved.

Izvleček

Podan je pregled obsežnih seizmoloških raziskav, ki so v dveh desetletjih sledile potresoma v Krnskem pogorju. Podrobne makroseizmične raziskave z uporabo nove Evropske potresne lestvice EMS-98 so pokazale velike razlike v poškodovanosti stavb zaradi vpliva zelo heterogenih sedimentov in deloma tudi zaradi sevalne funkcije posameznih potresov. Vplivi mehkih sedimentov so bili natančno raziskani, z uporabo metode spektralnih razmerij mikrotremorjev je bilo mogoče dokazati velik vpliv resonančnih učinkov med sedimenti in stavbami, ki so ponekod bistveno povečali škodo zaradi potresa. Posebno pomembne so bile seizmotektonske študije, ki so temeljile predvsem na žariščnih mehanizmih potresov in prostorski porazdelitvi popotresov. Skupaj z geološkimi podatki so razkrile zapleteno strukturo segmentiranega Ravenskega preloma, ki raste z interakcijo med posameznimi segmenti preloma. Za širše območje je značilen kinematični prehod med zmičnimi prelomi Dinarske smeri (NW-SE) v zahodni Sloveniji in Alpsko usmerjenimi (E-W) strukturami v Furlaniji s prevladujočim reverznim prelamljanjem. Druge raziskave so vključevale tudi analizo statičnega prenosa napetosti na sosednje prelome, analize časovnega poteka obsežnih popotresnih nizov in odnosa med magnitudo in frekvenco potresov. Vse te študije so pomembno spodbudile razvoj seizmologije v Sloveniji in razmahnile mednarodno sodelovanje. Po potresu leta 1998 je bila zgrajena moderna seizmološka mreža, ki je sestavljena iz 26 opazovalnic opremljenih s širokopasovnimi seizmometri, pospeškometri in visoko-ločljivimi digitalizatorji. Skupaj s čezmejno izmenjavo podatkov v stvarnem času se je bistveno izboljšala kvaliteta seizmološkega monitoringa.

Introduction

The earthquake on 12 April 1998 in Krn Mountains was according to its magnitude M_w5.6 the strongest earthquake in Slovenia in the 20th century. According to its maximum intensity VII-VIII EMS-98 it was surpassed only by the intensity VIII EMS-98 Brežice earthquake (Cecić et al., 2018) and by the Friuli 1976 earthquake, which reached maximum intensity VIII-IX in Slovenia in Podbela (Breginjski kot), but its epicentre was in Italy. In Krn Mountains another strong earthquake occurred on 12 July 2004 with M_w5.2 and maximum intensity VI-VII EMS-98 (fig. 1). Both earthquakes had strong impact on the development of seismological and earthquake geology sciences in Slovenia. The 20th anniversary of the 1998 earthquake is an opportunity for a review of extensive studies and developments in the interdisciplinary seismological research. In this paper a review of seismological investigations related to both earthquakes is given. These studies had positive impact on the development in many areas as seismological monitoring, seismotectonics, studies of aftershock sequences, stress change studies, macroseismics and site effects studies. Most of the studies related to both earthquakes were published by Slovenian and Italian researchers (Di Giacomo et al., 2014). A complementary review paper in this journal issue is devoted to extensive geological and seismotectonic investigation related to Krn Mountain earthquakes (Gosar, 2019). In the introductory part of that paper an overview of both earthquakes and their consequences is also given (Gosar, 2019).

Macroseismic investigations

After the 1998 earthquake the largest macroseismic survey in Slovenia so far was conducted. Macroseismic questionnaires were distributed to all voluntary observers (more than 4300) in the database of Uprava RS za geofiziko (Geophysical Survey of Slovenia) and 68 % were returned, which is very high percentage comparing to similar surveys (Cecić et al., 1999). Macroseismic data on damage to buildings and other effects were collected in the field by seismologists and integrated with the data contributed by official damage inspection commissions. Data were evaluated by means of the European Macroseismic Scale (EMS-98), which was in its final version published in the same year of earthquake occurrence (Grünthal, 1998). Therefore, this was one of the first comprehensive macroseismic surveys of a strong earthquake in Europe using a new scale. In Slovenia data were evaluated for more than 2000 localities (fig. 1) and macroseismic data collected from all other Central European countries to reveal the whole macroseismic field (Zupančič et al., 2001). The maximum intensity VII-VIII EMS-98 was observed in four villages: Lepena, Magozd, Spodnje Drežniške Ravne and Tolminske Ravne. Average radii of the areas of the same EMS-98 intensity were VII-13 km, VI-25 km, V-66 km, IV-180 km, III-422 km. More than 3000 damaged houses were examined (Godec et al., 1999). Older objects built of rubble and simple stone with wooden floors and poor quality mortar suffered damage most frequently, including partial collapse of walls or corners. Numerous houses had damage on roofs and chimneys and extensive cracks in walls. Some newer masonry buildings were also damaged, in many cases due to strong site effects (Zupančič et al., 2001). Large variations in damage within short distances were a very prominent characteristic of this earthquake. They cannot be explained by different vulnerability, because the building construction is similar in the whole area, but should be attributed to the amplifications in soft sediments (Gosar, 2007).

The 2004 earthquake had maximum intensity VI-VII EMS-98 in Čezsoča, Vodenca, and some parts of Bovec (Cecić et al., 2006). It was soon realized that the distribution of damage is slightly different in comparison to the 1998 event, although both epicentres were very close (Vidrih & Ribičič, 2006). Intensive retrofitting activities took place after the 1998 earthquake, but were not completely finished before the 2004 event (Godec et al., 2006). This partly influenced the assessment of the 2004 event intensities. Due to much higher magnitude of the 1998 earthquake, the intensities in most localities in the upper Soča river territory were from 0.5 to 2.0 degrees higher with respect to that observed for 2004 earthquake. But this was not the case for Čezsoča and Žaga, where the same intensities were observed, and for Srpenica and Trnovo ob Soči, where for the 2004 event even a higher intensity for 0.5 degree was observed (Zupančič et al., 2001; Cecić et al., 2006).

Gosar (2014) performed an analysis of the impact of fault mechanism radiation patterns on macroseismic fields to explain the observed differences. Although both earthquakes occurred on the Ravne fault, the focal mechanism of the first event was almost pure strike-slip, and a strike-slip with a small reverse component for the second one (fig. 1). This was explained as an active growth of the fault at its NW end (Kastelic et al., 2008). Radiation amplitude lobes were computed for three orthogonal directions. The

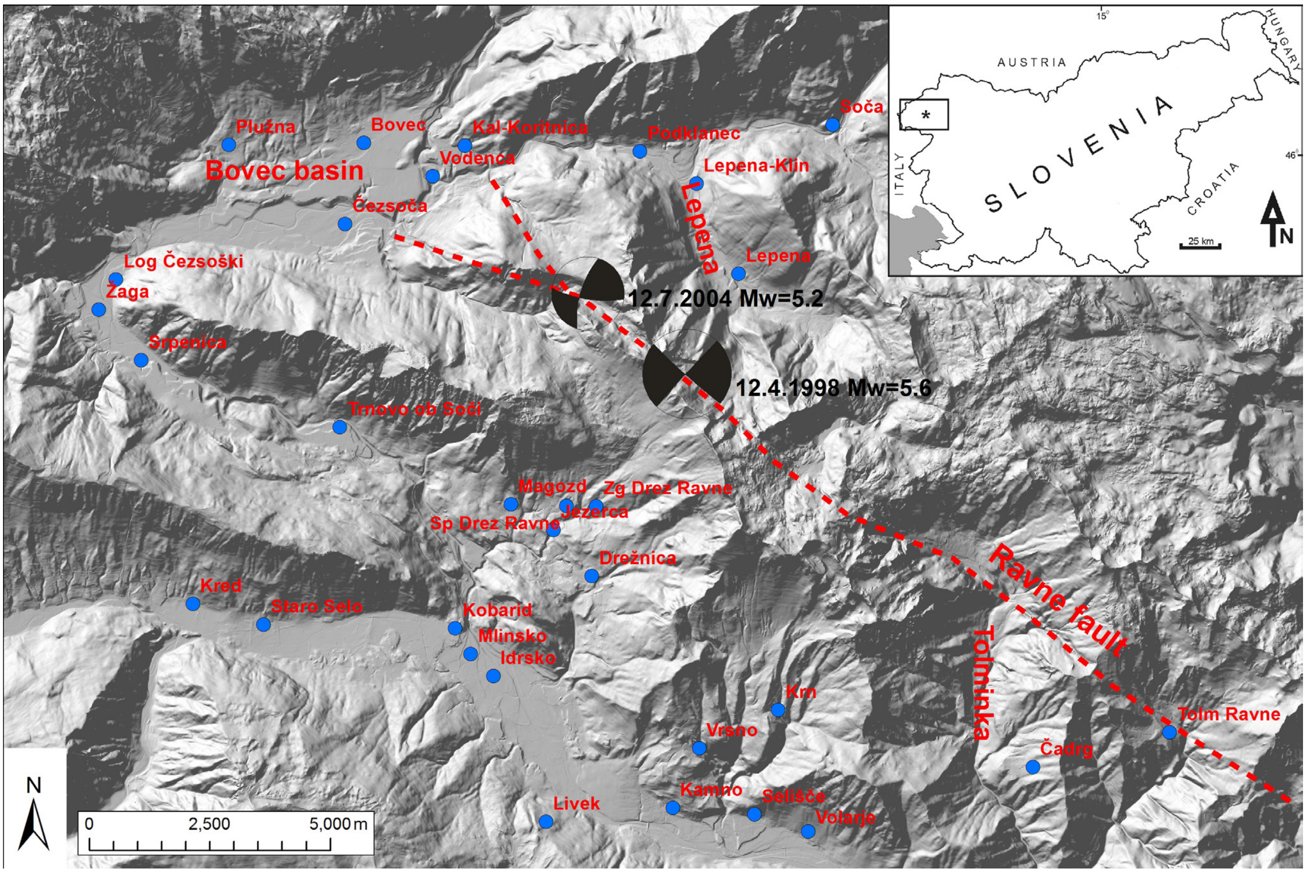

Fig. 1. The epicentral area of the Krn Mountains earthquakes with focal mechanisms of the 1998 (after Zupančič et al., 2001) and 2004 (after Kastelic et al., 2006) main shocks, the trace of the Ravne fault and locations for which the intensities were assessed. The estimated error for the location of epicentres is 1 km.

Sl. 1. Nadžariščno območje potresov v Krnskem pogorju z žariščnima mehanizmoma obeh glavnih potresov 1998 (po Zupančič et al., 2001) in 2004 (po Kastelic et al., 2006), traso Ravenskega preloma in lokacijami, na katerih so bile opredeljene intenzitete. Ocenjena napaka položaja nadžarišč je 1 km.

highest intensities of both earthquakes were systematically observed in directions of four (1998) or two (2004) large amplitude lobes in SH component (which corresponds mainly to Love waves), which have significantly different orientation for both events. As expected for the strike-slip mechanism of the 1998 event, the radiation pattern shows a very symmetrical four-lobe shape with all four amplitude lobes of almost the same size. On the other hand the small reverse component in the mechanism of the 2004 event results in a distinctively larger amplitude lobe in SW direction when compared to the other three lobes. The two settlements (Srpenica and Trnovo ob Soči) where the intensity of the 2004 event exceeds the intensity of the 1998 event are located in the direction of the highest P amplitude lobe of the radiation pattern. The study has shown that although both macroseismic fields are very complex due to influences of multiple earthquakes, retrofitting, site effects, and sparse distribution of settlements, unusual differences in observed intensities can be explained to some extent with different radiation patterns (Gosar, 2014).

Krn Mountain earthquakes and seismic hazard maps of Slovenia

At the time of the 1998 earthquake the official seismic hazard map in Slovenia was intensity map showing expected intensities in MSK scale for 500 years return period (Ribarič, 1987). According to this map the most western part of the upper Soča territory, which extends close to the towns of Bovec and Tolmin, belongs to the intensity IX and the rest mainly to the intensity VIII. The comparison of the 1998 event maximum intensities (VII-VIII EMS-98) with this map has shown that the predicted values were not exceeded (Zupančič et al., 2001). It should be noted that the differences in MSK and EMS-98 scales could be neglected in such a comparison. In 1998 there were no accelerographs installed in the area to measure ground motion accelerations. The nearest seismic station was in Italy, 16 km from the epicentre and the nearest seismic station in Slovenia in Vojsko, 36 km from the epicentre, equipped at that time with analogue seismograph.

After the 1998 earthquake several temporary seismological stations were deployed in wider epicentral area including three strong motion instruments (accelerographs) in Bovec, Kobarid and Drežnica, which are located less than 10 km from the epicentre of 2004 earthquake. Obtained accelerograms were the first modern digital strong motion data of a relatively strong earthquake recorded at close epicentral distances in Slovenia and are thus important for engineering seismology (Šket Motnikar & Prosen, 2006). However, it turned out that several factors could influence the measurements including site and building effects and instrument fixation. In Drežnica (5 km from the epicentre) peak horizontal acceleration of 0.38 g was recorded (fig. 2), but strong motion instrument was not fixed to the ground and its sliding during the earthquake could not be totally excluded, although it is not likely. In Bovec (7 km from the epicentre) peak horizontal acceleration of 0.48 g was recorded in a public library. Due to the damage to ceiling and falling of the books from the shelf close to the instrument, the accelerogram was significantly deformed. However, it is believed that basic accelerogram corrections removed the noise. In Kobarid (7 km from the epicentre) peak horizontal acceleration of 0.15 g was recorded. In comparison to established attenuation models, these values are much higher than expected for M_w5.2 earthquake. However the duration of strong shaking above the selected threshold was in all cases very short, and higher values appeared at short periods. Measured peak accelerations also do not correlate with observed damage and assessed intensities, which were expected for an earthquake of such magnitude. Although accelerograms were corrected, peak values could not be treated as effective ground accelerations (Šket Motnikar & Prosen, 2006).

According to the official seismic hazard map of Slovenia (Lapajne et al., 2001) all three stations are located in the area of 0.225 g design ground acceleration for return period of 475 years. This raised a question, if seismic hazard is underestimated in the upper Soča territory. Because for the 1998 much stronger earthquake, for which no measurements are available, even higher peak acceleration are expected in comparison to the measured 2004 values. The opinion of Lapajne et al. (2006) is that high uncertainties and measurement errors are possible due to the inappropriate installation of instruments. In addition such high values can be explained by several causes: increased vulnerability of building in which measurements were taken, local site effects, near-filed and fault directivity effects. The observed intensities also does not support the exceedance of effective values of ground acceleration (Lapajne et al., 2001).

Seismotectonic investigations based on seismological data

In a complementary paper on geological and seismotectonic investigations (Gosar, 2019), a review of seismotectonic investigations, which involved also field geological work and remote sensing studies is given. Here, a review will be given on investigations based mainly on seismological data that includes computation of earth-

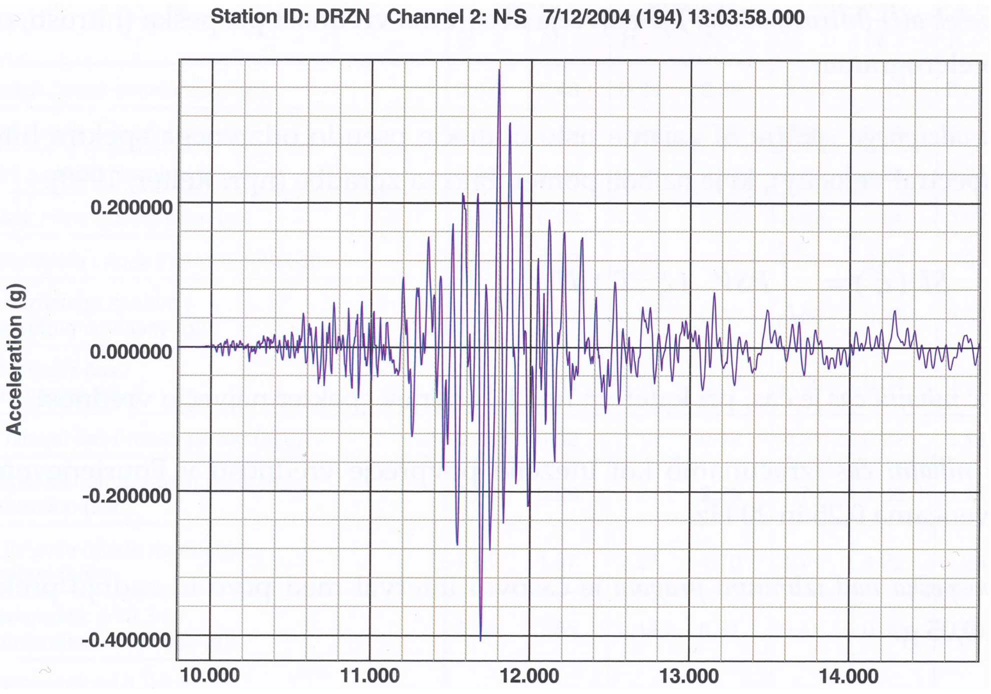

Fig. 2. The accelerogram of the 2004 Krn Mountains earthquake recorded at Drežnica (DRZN) station located 5 km from the epicentre. On the N-S component the peak acceleration of 0.38 g was recorded (after Šket Motnikar & Prosen, 2006).

Sl. 2. Akcelerogram potresa 2004 v Krnskem pogorju, zabeležen na seizmološki postaji Drežnica (DRZN), ki se je nahajala 5 km od nadžarišča. Na komponenti N-S je bil zabeležen največji pospešek 0,38 g (po Šket Motnikar & Prosen, 2006).

quake focal mechanisms, studies of a spatial distribution of aftershocks and moment distribution on the fault etc.

For any in-depth seismological study accurate locations of hypocentres are needed, taking into account distances of seismological stations and azimuthal coverage. For the 1998 earthquake the hypocentral parameters of aftershocks were obtained using adapted joint hypocentre determination (JHD) method (Bajc et al., 1999), and the average estimated location error is approximately 500 m. Hypocentres of the majority of the aftershocks stretch in a NW-SE elongated belt that is 10 km long and 3 km wide. They occurred along almost vertical fault plane at depths from just below the surface to 7 km (Zupančič et al., 2001). The ruptured area was estimated to be around 10 km × 7 km, which is close to published expected values for M_w5.6 earthquake that vary from length 8 km or area 42 km^2 to length 13 km or area 107 km^2. The fault plane solution of the main 1998 shock is almost pure dextral strike-slip (NW-SE plane) (fig. 1), but many aftershocks, which were mostly shallower, show different mechanisms. They mainly contain also a reverse component in the WNW-ESE plane. The major principal stress is approximately N-S (Zupančič et al., 2001).

Another preliminary study of the 1998 earthquake and its aftershock sequence was based mainly on data recorded by seismic stations located in Friuli-Venezia Giulia (Bernardis et al., 2000). Similar focal mechanisms as those by Zupančič et al. (2001) were obtained for the main shock and nine stronger aftershocks with magnitude 3.5-4.0. On the other hand, aftershocks with magnitude 3.0-3.5 show transtensional or even extensional focal mechanisms with orientation of planes from NW-SE to N-S. This type of focal mechanisms prevails over the fault plane solutions typical of low-angle NW-SE to NE-SW trending reverse faults. This suggests that the deformation recovery of the crustal volume affected by the main shock may be achieved through reactivation of several pre-existing faults (Bernardis et al., 2000).

An advanced relocation followed, which was based on 4000 aftershocks recorded by seismic networks in Slovenia, Italy, Austria and Croatia by adapting the joint hypocentre determination (JHD) method for teleseismic data to local earthquakes (Bajc et al., 2001). The relocated aftershocks are well organized along a trend of about N125° and the area of epicentres is 12 km × 3 km. Only five hypocentres were deeper than 10 km, all of them off-fault. The accelerograms of four stations of the Friuli network were inverted to study the source process of the main shock. The seismic moment of 4.5×10^{17} Nm was obtained and the average slip of 18 cm. The moment distribution shows the maximum energy release around the hypocentre of the main shock, confined into a region of 10 km × 6 km and decreasing towards the edges of the fault. The rupture was growing in a bilateral way starting from the hypocentre within 3 s (Bajc et al., 2001). The distribution of aftershocks is compatible with the slip; they are more frequent in shallower areas that didn't break during the main shock. The majority of the main shock energy release occurred towards the SE end, where there is a diffuse aftershock activity at the shallowest part. At the NW end, the aftershock distribution clearly shows an abrupt cut-off in activity, connected with the area of low energy release during the main shock (fig. 3). These observations indicate that the NW barrier close to the Bovec basin is stronger and related to the sharper change of the strike at the transition from Dinaric to Alpine structures than SE barrier at the Tolminka spring basin, which is within the Dinaric system (Bajc et al., 2001).

Seismotectonic characteristics of the 2004 earthquake were studied by Kastelic et al. (2006). The main shock occurred very close to the 1998 earthquake, but shows slightly different focal mechanism (fig. 1) with more pronounced reverse component in addition to prevailing strike-slip one. The aftershocks of the 2004 event are mostly located in the NW to WWN direction from those of the 1998 event and do not show such a uniform distribution (fig. 3). A group of aftershocks that have a prevailing strike-slip focal mechanisms continues in a NW-SE direction, while the aftershocks oriented in a WWN-EES to W-E direction show more pronounced reverse component. Such temporal and spatial distribution of the aftershocks depicts a contemporary activity on both NW-SE and WWN-EES to W-E oriented faults. The principal stress axis is oriented generally in N-S direction with only slight deviations for individual aftershocks (Kastelic et al., 2006). Integrated with structural geological data a further seismotectonic interpretation of the Ravne fault was given in Kastelic et al. (2008). The fault is growing by interaction of individual right stepping fault segments and breaching of local transtensional step-over zones. The fault geometry is controlled by the original geometry of the NW-SE trending thrust zone, modified by successive faulting within the fault zone. In a recent stress

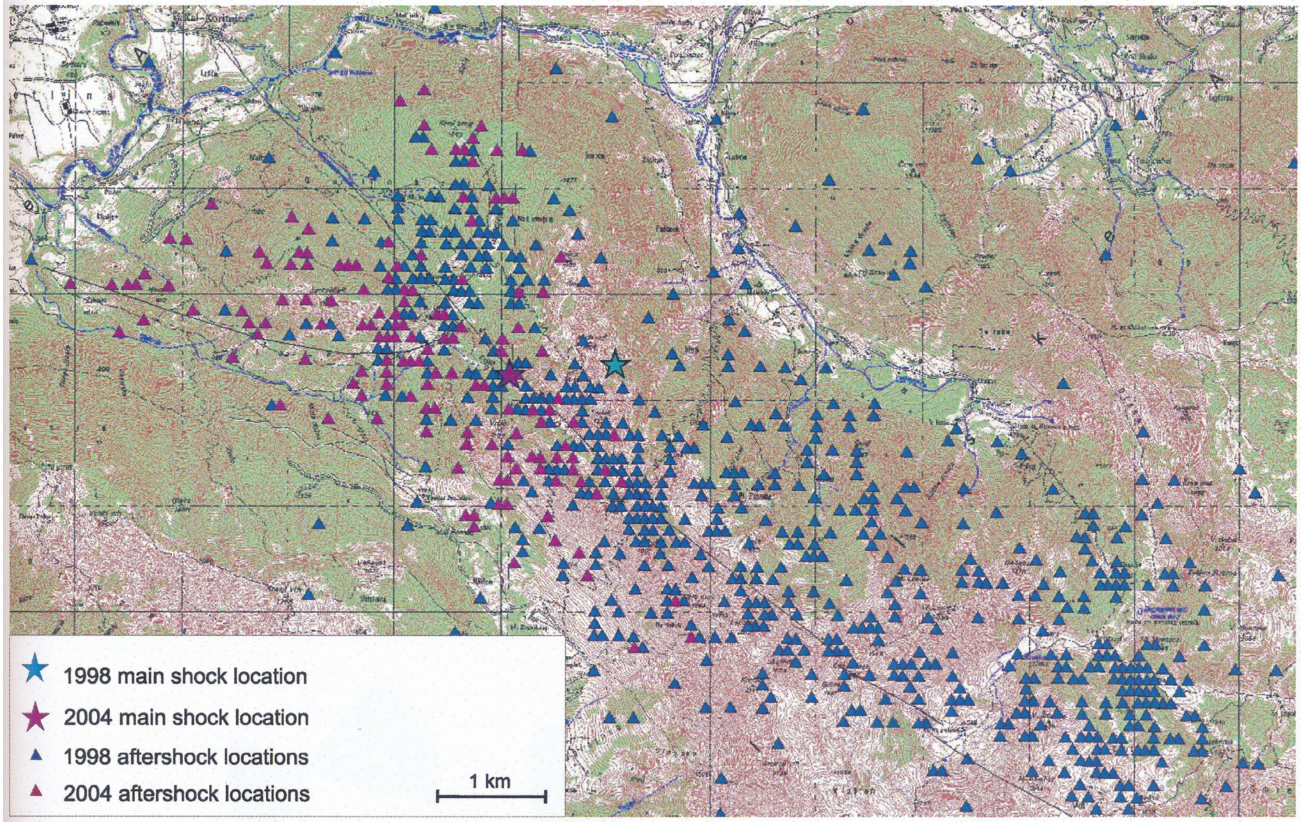

Fig. 3. Spatial distribution of aftershocks that followed the 1998 and 2004 earthquakes in Krn Mountains The estimated error for the location of epicentres is 0.5 km (after Kastelic, 2008).

Sl. 3. Prostorska porazdelitev popotresov, ki so sledili glavnima potresoma 1998 in 2004 v Krnskem pogorju. Ocenjena napaka položaja nadžarišč je 0,5 km (po Kastelic, 2008).

regime, the segmented fault is lengthening by active growth at its NW end. At epicentral depths, the fault system is accommodating recent strain along newly formed fault planes, whereas in the upper parts of the crust the activity is distributed over a wider deformation zone that includes reactivated thrust faults (Kastelic et al., 2008).

Herak et al. (2003) studied azimuthal anisotropy of P-wave velocity in Krn Mountains by measuring differences of travel times and travel paths towards the seismic stations located at different azimuths. The P-wave velocity varies from 6.0 km/s in the ENE-WSW direction to 6.4 km/s in NNW-SSE direction. Both directions closely match those of the mean regional principle stress components obtained from focal mechanisms. A large part of observed anisotropy may be explained by assuming that the hypocentral volume is pervaded by a system of vertical/subvertical extensive-dilatancy cracks aligned under the influence of local tectonic stress field (Herak et al., 2003)

Source parameters of the 2004 main shock and of 165 aftershocks ($0.8<M_L<3.5$) were investigated using records of Friulian stations in order to determine the corresponding source scaling relations (Franceschina et al., 2013). The main shock of the sequence is characterized by a seismic moment of $3.5 \cdot 10^{16}$ Nm and a corner frequency of 0.8 Hz, corresponding to a fault radius of approximately 1.5 km m and a stress drop of 4.9 MPa.

Bressan et al. (2016) studied the spatial organization of seismicity and the relation between fracture pattern and earthquakes in Friuli and W Slovenia. The orientation of planes that fit through the hypocentres shows a different disposition at the two depth intervals analysed. The shallower interval (0–10 km) is characterized by planes with highly variable orientations. These zones are characterized by high heterogeneity due to the superposition of different tectonic phases and by the maximum interference between Dinaric and Alpine domains. The orientation of the planes fitting the seismicity at 10–20 km depth is less dispersed, coinciding with the trend of Dinaric subvertical faults in the northern and eastern parts of the studied area, and with Alpine low-angle faults in the western and southern parts (Bressan et al., 2016).

In a recent study Bressan et al. (2018) investigated the stress and strain inversions from focal mechanisms in a revised seismotectonic zonation of NE Italy and W Slovenia inferred from 203 focal mechanisms, corresponding to earthquakes that occurred between 1984 and 2016. A dominant strike-slip stress field characterizes the eastern part of the area (Slovenia), while the seismotectonic zones of the central part (Friuli) are undergoing thrusting regime (Bressan et al., 2018).

Investigations of the time distribution of aftershocks and magnitude-frequency relations

Aftershock sequences of both earthquakes are the most thoroughly studied sequences ever performed in Slovenia. This was possible because the first portable seismograph was installed in Trenta already 9 hours after the 1998 earthquake and many followed in the next days. They recorded more than 7000 aftershocks till the end of 1998 (Zupančič et al., 2001). At the time of 2004 earthquake there was already a dense network of seismological stations in place. Extensive aftershock sequences after both events with several thousands of shocks lasted for more than one year. In 400 days the 1998 earthquake was followed by 104 and the 2004 one by 89 aftershocks with $M_L \geq 2{,}0$ (Gosar, 2008a). Both strongest aftershocks had magnitudes smaller for 1.4 and 1.3 with respect to the main shocks, which is slightly more than proposed by Bath's law (1.2). Time distribution of aftershocks has shown that the parameters of the modified Omori's law that describes the hyperbolic decay of aftershock activity with time, are very similar. This corresponds to the fact that both earthquakes occurred in the same hypocentral area. The value of the p parameter is around p=1.02. Aftershocks of the 1998 event clearly show secondary aftershock sequence which started with the strongest aftershock on 6 May 1998 (M_L=4.2), but there was no secondary sequence for the 2004 main shock. Analysis of the Gutenberg-Richter's magnitude-frequency relation has given the value of b parameter for the 1998 aftershock sequence between b=0.77 and 0.83 and for the 2004 sequence between 0.97 and 0.98. This means that the first earthquake was followed by more strong aftershocks. Obtained parameters of Omori's law and Gutenberg-Richter's relation are in good agreement with the values for similar aftershock sequences (Gosar, 2008a).

Gentili & Bressan (2008) studied eight aftershock sequences that occurred from 1977 and 2007 in NE Italy and W Slovenia, including 1998 and 2004 sequences. Among them the 1998 M_w5.6 earthquake was the strongest. For Omori's aftershock decay with time they obtained p parameter of p= 0.80 and 1.04 for 1998 and 2004 events respectively. Other sequences had values between p=0.80 and 1.00. The b parameter of the Gutenberg-Richter's relation was b=1.04 and 1.10 for 1998 and 2004 events respectively. Other sequences had values between b=0.80 and 1.10 (Gentili & Bressan, 2007; Gentili & Bressan, 2008). They computed also the probabilistic estimate of the aftershock rates and the largest aftershock in given time intervals.

Telesca et al. (2000) studied time-scaling behaviour for the 1998 aftershock sequence using Allan Factor (AF) method. The sequence of the occurrence times of the events with threshold magnitude 2.0 is characterised by scale-invariant behaviour from the time scale $\tau \sim 2 \cdot 10^4$ s with a scaling coefficient $\alpha \sim 0.9$, evaluated by a least-square method. By gradually increasing the threshold magnitude up to 2.9, the AF curves, associated, respectively with the processes of selected events with magnitude $M \geq M_{th}$, indicate a monotonic decrease of the value of the scaling exponent α. This monotonic power-law increase indicates the presence of fluctuations on many time scales and therefore of fractal clustering (Telesca et al., 2000).

Investigations of stress changes on neighbouring faults

Large earthquakes can trigger future earthquakes along neighbouring faults at short distances from the epicentre by transferring static or dynamic stresses. Two independent studies of Coulomb static stress changes were performed for the 1998 and 2004 earthquakes. In the first study (Ganas et al., 2008) they show that stress levels have increased along the active Ravne fault for all considered models, stress levels have decreased along the parallel (NW-SE) Idrija fault, stress levels in the crust have increased along the E-W direction, but have decreased in the N-S direction, because of stress shadow effect. A better correlation of the off-fault aftershock locations with stress maps incorporating the regional stress field was also obtained (Ganas et al., 2008).

Without knowing the previous study, although published, Bressan et al. (2009) performed a new study that includes also Coulomb stress changes analysis. They found a positive correlation of the Coulomb stress increase with the largest aftershock (M 4.6) and with a part of the aftershocks. Their modelling also shows that the Coulomb stress changes caused by the 1998 main shock and its largest aftershock were not sufficient to trigger the 2004 main shock. The spatial distribution of the 1998 and 2004 aftershocks correlate well with areas of increased Coulomb stress changes when the regional tectonic loading is also taken into account (Bressan et al., 2009).

In the next study Barnaba & Bressan (2013) compared 2002 Mount Sernio and the 2004 Krn Mountains aftershock sequences regarding static stress changes and seismic moment release. The Coulomb stress changes, calculated on the receiver fault of the largest aftershock, show that the aftershock sequences are mostly located in a stress shadow zone. The modelling of the Coulomb stress variations, which incorporates the regional stress field, fits better the aftershock pattern. The lack of correlation between the Coulomb stress perturbations and some of the aftershocks is attributed to stress heterogeneities not accounted in the model. The decay rate of the seismic moment release is different in the 2002 and 2004 sequences. According to this model, the distribution of stress in the aftershock volume appears more uniform in the 2004 sequence (Barnaba & Bressan, 2013).

Investigations of seismological site effects

As described in a review paper on geological and seismotectonic investigations (Gosar, 2019), strong variations in the damage to the buildings were observed within short distances in the upper Soča valley and especially in the Bovec basin. The variations in the damage can be attributed only in part to differences in building vulnerability, since the building typology is similar throughout the area. Soon after the 1998 earthquake, it became clear that seismological site effects had to play the most important role (Gosar, 2007). However, seismic microzonation study of the Bovec basin based on surface geological data and data from shallow geotechnical boreholes (Ribičič et al., 2000) has shown that it is not possible to explain most of the observed variations in the distribution of the damage with these data. One of the reasons for this is that the Bovec basin is filled with very heterogeneous glacial and fluvial deposits, which have different seismogeological properties and variate not only laterally but also vertically. At that time the microtremor horizontal-to-vertical spectral ratio (HVSR) method gained popularity in site effect studies and first portable instruments became available for effective measurements in the field. Two months after the 1998 earthquake a quick preliminary study using this method was performed at six points in the Bovec basin and two points in Drežniški kot (Mucciarelli & Monachesi, 1999). It was revealed that large variations in the shape of the HVSR curve exist between different parts of the town of Bovec, in village Kal-Koritnica and between Drežnica and Drežniške Ravne, which can be correlated with large variations in observed damage to buildings.

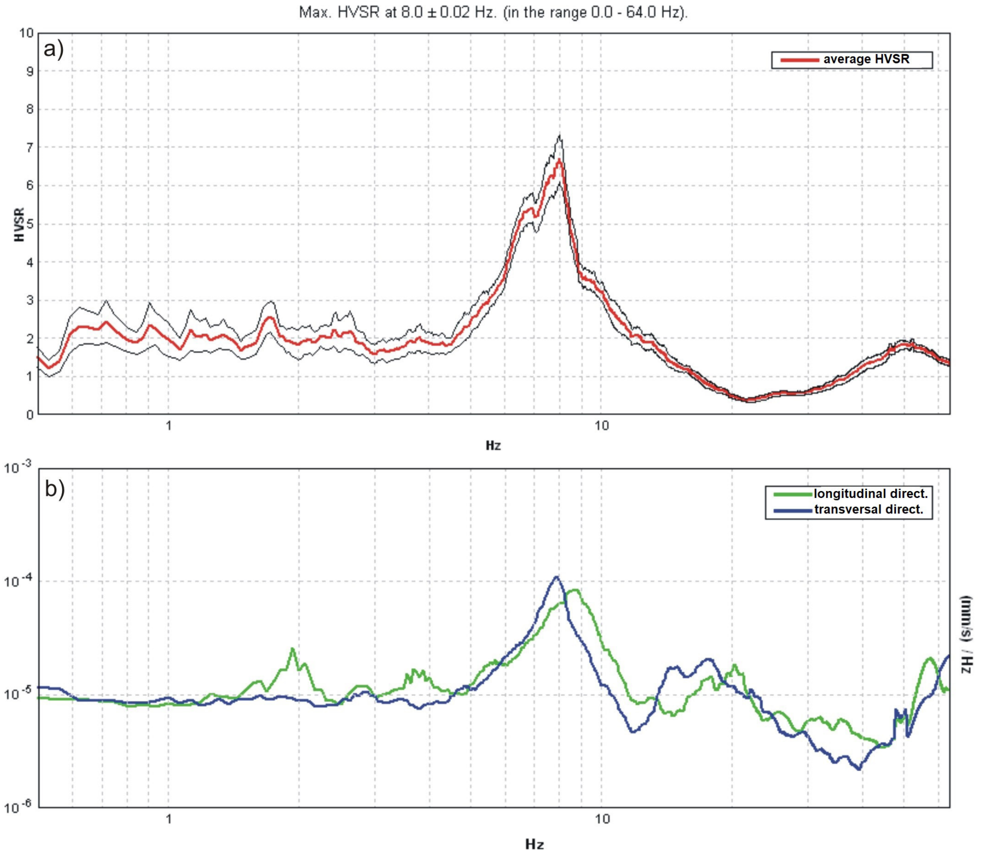

Fig. 4. An example of microtremor measurements in the Bovec basin that indicates probable resonance effects between soft sediments and buildings; a) The horizontal-to-vertical spectral ratio (HVSR) of the free-field measurement, b) The amplitude spectra of the microtremor measurement in the building (data after Gosar, 2007).

Sl. 4. Primer meritev z mikrotremorji v Bovški kotlini, ki kaže na verjetne resonančne učinke med mehkimi sedimenti in stavbo; a) Spektralno razmerje med horizontalnima in vertikalno komponento (HVSR) za meritve na prostem površju, b) Amplitudna spektra za meritve v stavbi (po Gosar, 2007).

This was the first indication that resonance effects between soft sediments and buildings could in some places enhance the damage. However, no subsurface geophysical or geotechnical information was available to explain the variations in observed resonance frequencies of sediments. Therefore geophysical investigations combining seismic refraction method, seismic velocity measurements in boreholes, and vertical electrical soundings were performed to reveal subsurface structures, lithology, the depth to the stiff rock, and to provide quantitative parameters on the distribution of the S-wave velocities with depth. Based on these data one-dimensional modelling of ground motion amplification was performed and the results were compared with the microtremor HVSR data (Gosar et al., 2001). Both methods showed significantly higher amplification in the frequency range of building vulnerability (2–10 Hz) in the Mala vas area of Bovec than in the central part of Bovec, which is consistent with the distribution of the damage. In Mala vas also several newer masonry buildings were highly damaged. Similar large differences in the HVSR peaks were observed between Spodnje Drežniške Ravne, where much higher damage (intensity VII-VIII EMS-98) was observed in comparison to nearby Drežnica (intensity VI-VII EMS-98) (Gosar et al., 2001).

Successful preliminary studies and further improvements of the microtremor HVSR method motivated a more in-depth study with this method in the Bovec basin (Gosar, 2007). The main advantage of the microtremor method is that with the measurements in the free-field it provides a resonance frequency of the sediments without knowing the S-wave velocity profile and the depth to the bedrock. In addition it can be efficiently applied to measure main resonance frequencies of buildings and thus enables soil-structure resonance studies (fig. 4). In the Bovec basin the method was applied in a 200 m dense grid of free-field measurements at 124 points. Large variations in the sediment frequency (3-22 Hz) were obtained (fig. 5), which cannot be related solely to

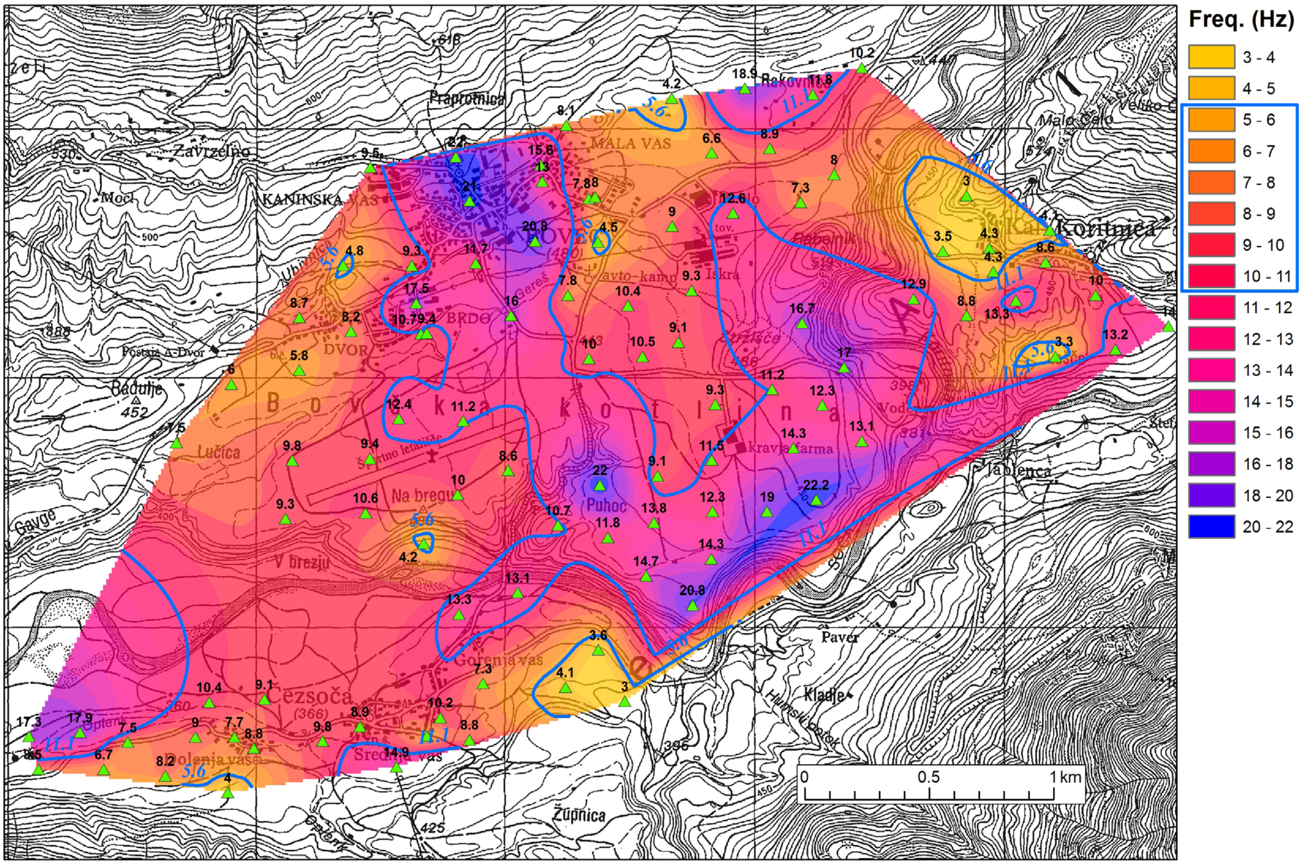

Fig. 5. The map of the resonance frequencies derived from microtremor measurements at 124 points in the Bovec basin. Blue contour lines indicate the borders of the areas in which the frequency range is between 5.6 Hzand 11.1 Hz. In the areas coloured orange, orange-red, light rose, or rose the probability of the occurrence of the resonance effects between soft sediments and buildings is high (as indicated in the legend on the figure), whereas in the areas coloured yellow, dark rose, red-violet, or blue, this probability is low (after Gosar, 2012).

Sl. 5. Karta resonančnih frekvenc v Bovški kotlini, izdelana na podlagi meritev v 124 točkah. Modra kontura omejuje območja, kjer so resonančne frekvence med 5,6 Hz in 11,1 Hz. V območjih, obarvanih z oranžno barvo in svetlimi lila odtenki, obstoja velika verjetnost resonančnih učinkov med mehkimi sedimenti in stavbami (kot je označeno tudi na legendi na sliki), medtem ko je v območjih, obarvanih z rumeno ali s temno lila oziroma modro barvo, ta verjetnost majhna (po Gosar, 2012).

the total thickness of the Quaternary sediments composed mainly of sand and gravel, but can be explained only by the presence of conglomerate or lithified moraine (more stiff sediments) at shallow depths. Considerable changes in fundamental frequencies were obtained especially in the town of Bovec with values as high as 22 Hz in the central part and values 6 Hz to 11 Hz in the adjacent Brdo and Mala vas districts. Additional measurements were performed in several houses of different heights (from two to four stories). Areas of likely soil-structure resonance were identified in Brdo, Mala vas, Čezsoča, and Kal-Koritnica (figs. 4 and 5). This is in agreement with the distribution of the damage due to both earthquakes, which was considerably higher in Brdo and Mala vas than in the central part of the town of Bovec, although the houses there are older. The microtremor method has proved to be an effective tool for assessment of the site effects in cases of complex geological structure commonly encountered in young Alpine basins filled with glaciofluvial sediments that are partly cemented (Gosar, 2007).

Following the 2004 earthquake, six accelerographs were deployed in a line across the Bovec basin to record aftershock sequence. Recorded data allowed comparison of different methods of site effect studies: standard spectral ratio using a reference station located on a bedrock at the edge of a basin and horizontal-to-vertical (H/V) methods using earthquake data and microtremors (Gosar, 2008b). Spectral ratio analyses showed that ground motion amplification occurs mainly in the frequency range of 5 Hz to 10 Hz, with corresponding amplitudes in the range of 6 to 11, but spectral ratios are quite complex and show a broad range of amplifications. Comparison of the results of the two H/V methods showed that the amplitudes obtained from microtremors are always lower than the amplitudes obtained from earthquake data. The difference was as high as for a factor of two. It was again revealed that the main reason for complex amplification spectra are irregular layers of stiff sediments (conglomerate, tillite) within sand and gravel, which result in large impedance contrasts at several interfaces within the Quaternary sediments (Gosar, 2008b).

The next microtremor HVSR study was performed in the Kobarid basin, because the town of Kobarid was also damaged in the 1998 (intensity VI-VII EMS-98) and the 2004 (intensity VI EMS-98) earthquakes. In a 100 m dense grid the measurements were taken at 106 free-field points (Gosar, 2010). The eastern part of the basin is characterized by the two well separated HVSR peaks, which indicate distinct shallow and deep impedance contrasts caused by shallow conglomerate inside sandy gravel or lacustrine chalk and the bedrock built of Cretaceous flysch. In the western part the observed frequencies are related to the total thickness of the Quaternary sediments. Microtremor measurements were also performed inside 19 characteristic buildings of different heights (from two to four stories). Longitudinal and transverse fundamental frequencies were determined from amplitude spectra. The hazard/probability of the occurance of the soil-structure resonance was assessed by comparing building frequencies with the free-field sediments frequencies. For two examined buildings a high danger of soil-structure resonance was predicted and for three buildings the estimated danger is of medium level. It turned out that the danger of soil-structure resonance exists in a relatively narrow transition zone between the deeper western part (low frequencies) and the thinner eastern part (high frequencies) of the basin (Gosar, 2010).

In the last decade the microtremor measurements were performed in five Slovenian towns (including Bovec and Kobarid) exposed to high seismic hazard. In the studies the free-field measurements to derive maps of sediment frequencies were combined with the measurements in 66 masonry buildings of different heights. Therefore, additional statistical analysis of the fundamental frequencies of the buildings versus number of floors (height) was performed to generalize the identification of possible soil-structure resonance (Gosar, 2012). Most Slovenian towns are located in shallow sedimentary basins where the free-field soft sediments frequencies are in the range of 2 Hz to 20 Hz. On the other hand, masonry houses with two and three floors represent the large majority of the building stock. To assess the possible occurrence of soil-structure resonance in general, an average fundamental frequency ± one standard deviation interval was computed for two and three floors high masonry buildings, which resulted in fundamental frequencies in the range of 5.6 Hz to 11.1 Hz. Comparison with the free-field maps has shown that this frequency range occupies 59 % of the area of the Bovec basin (fig. 5) and 22 % of the surveyed area of the Kobarid basin (Gosar, 2012). These findings have therefore important implications for seismic risk assessment, spatial planning, and retrofitting of damaged buildings in Bovec and Kobarid.

For the 1998 earthquake the amplification of the seismic ground motion was studied also for the town Gemona in Friuli, located 40 km from the epicentre. In the studies numerical modelling along the simplified structural model of a sedimentary basin was compared with the records from three seismic stations (Marrara et al., 2001). Accelerations between 0.01 and 0.04 g were recorded on bedrock and on alluvium respectively, indicating 4-5 times acceleration of the seismic ground motion due to soft sediments. The numerical simulations agree relatively well with the available observations and some discrepancies can be probably related to the inaccurate knowledge of the subsurface. The maximum peak ground accelerations, the Arias intensity and the response spectra show a significant amplification, especially for a station located on the alluvial fan sediments.

Influence of the Krn Mountains earthquakes on seismological monitoring in Slovenia

In 1998 the seismic network of Slovenia consisted of seven stations, six of them equipped with digital seismographs connected to the central computer in Ljubljana over dial-up phone lines, and one analogue seismograph in Vojsko. Vojsko was the closest Slovenian seismic station to the epicentral area in Krn Mountains at the distance of 36 km. The 1998 earthquake showed that the Slovenian seismological service is not adequately equipped to deliver basic earthquake parameters with sufficient accuracy and fast enough to the civil protection organizations, media, and general public. The earthquake on 31 August 1998 near Trebnje only emphasised the need for measures that would increase the effectiveness of the seismological service. In May 1999 the Government of Slovenia laid down a time schedule and financial plan for the modernisation of the national seismological network (Vidrih et al., 2006). Seismic stations are regarded as infrastructure of special importance for the performance of state public services for defence and protection. The project named Modernisation of the national network of seismic stations had the following primary goals:

- to set up a national earthquake alarm system with real-time communication with data processing centre and automatic data analyses,
- to define basic earthquake parameters (epicentre coordinates, focal depth, magnitude and intensity) as precisely as possible on the basis of the geophysical model of Slovenia's territory,
- to assess seismic hazard more accurately to provide better input for the needs of earthquake resistant design of buildings based on better knowledge of seismotectonic conditions in Slovenia,
- to integrate Slovenia's alarm system into the earthquake alarm systems of neighbouring countries and European seismological centres.

During the following seven years 26 modern seismological stations were built all over Slovenia (fig. 6). They were equipped with broadband three-component seismometers and high-resolution data loggers. Real-time seismic data are continually transmitted to the Data Processing Centre in Ljubljana, where two servers automatically process and store seismic records. Bearing in mind the importance of seismic observation in areas of high seismic hazard and risk, the network is denser in three areas:

- in the area of Ljubljana, characterised by high seismic hazard, that together with the fact that this is the most densely populated area of Slovenia, represents the highest seismic risk,
- in the upper Soča territory, which is the second area of the highest seismic hazard in Slovenia,
- in the area around Krško, because it is the location of the Nuclear Power Plant and also the area of increased seismic hazard.

The Slovenia national network was completed and officially opened in October 2006 (Vidrih et al., 2006). Through signed agreements with neighbouring countries, the seismic waveform data are exchanged in a real-time between all responsible institutions to ensure better seismological monitoring in the wider area at the junction of large geotectonic units of Alps, Dinarides and Pannonian basin. The whole area, which is located at the northern margin of the Adiatic microplate, is characterized by relatively high earthquake activity. The enlarged cross-border network substantially contributes to a more precise location of earthquakes and allows better seismotectonic characterization, which is important for realistic seismic hazard assessment.

The national seismic network is not a static one. It is continuously upgraded with better data loggers, more sensitive and precise seismometers and more reliable communication, storage and power supply systems. In addition, completed in the year 2018, all 26 stations are now equipped also with accelerometers, which significantly increases the dynamic range of observations.

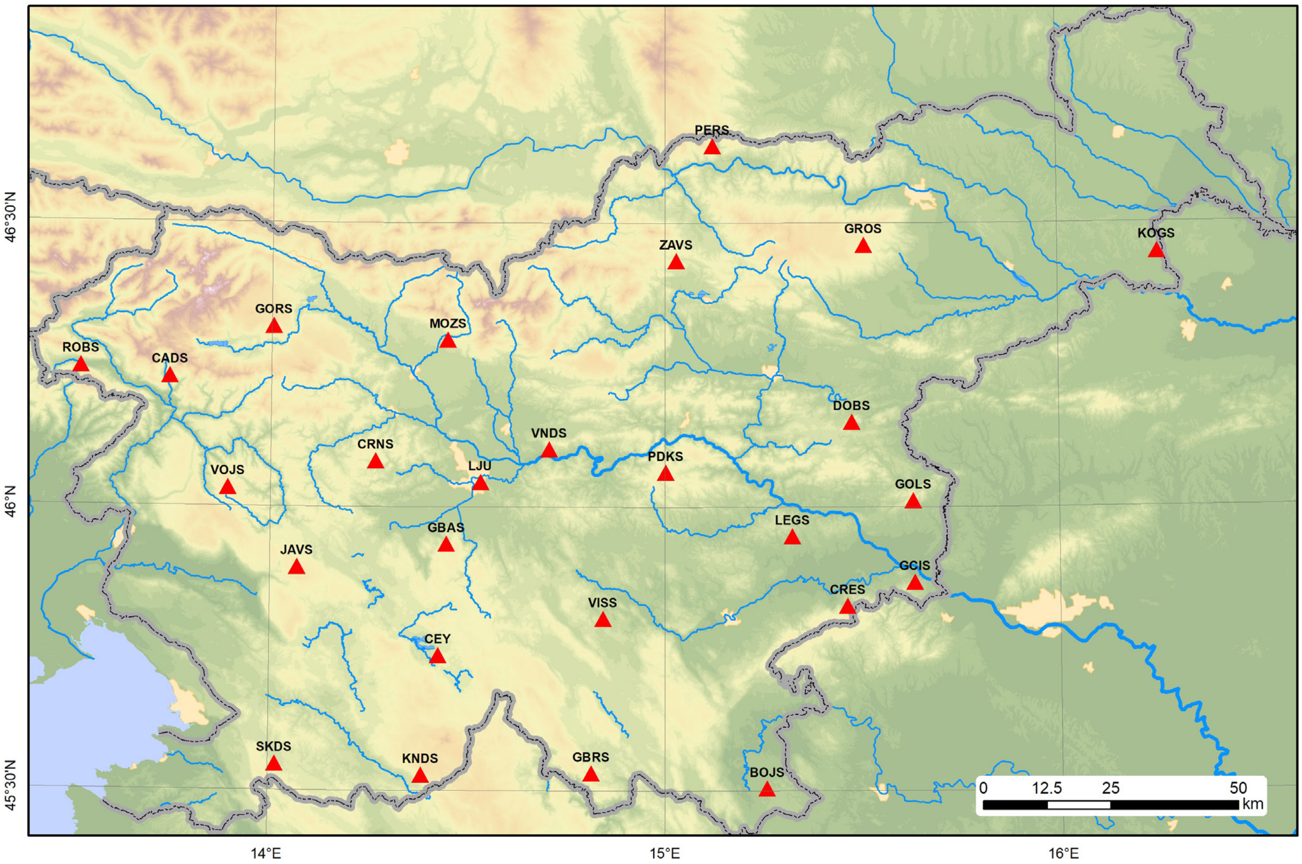

Fig. 6. The locations of the broadband seismic stations of a new Slovenian seismological network, which was built after the Krn Mountain earthquakes.

Sl. 6. Lokacije širokopasovnih potresnih opazovalnic nove državne mreže potresnih opazovalnic, ki je bila zgrajena po potresih v Krnskem pogorju.

Conclusions

The 1998 and 2004 earthquakes in Krn Mountains motivated a large number of researches in different branches of seismological science. The final version of European Macroseismic Scale (EMS-98) was published in the same year, and the 1998 earthquake was therefore one of the first strong events in Europe, for which the intensities were assessed using a new scale. Many advantages in statistical evaluation of macroseismic data and better definitions of vulnerability classes were clearly demonstrated in this cross-border study. Before 1998 the Julian Alps region was known for relatively small seismic activity in comparison to nearby Friuli region. Both earthquakes had changed the situation and many seismotectonic studies followed. The transition area between NW-SE oriented Dinaric strike-slip structures in W Slovenia and E-W oriented Alpine faults with predominantly reverse faulting in Friuli due to N-S oriented principal stress is of particular interest, because this is the region of the highest seismic hazard in the Alps and in Central Europe. Detailed studies of focal mechanisms and spatial distribution of aftershocks shed a light on complex structures related to segmented Ravne fault, which is lengthening by active growth at its NW end. Extensive aftershock sequences of both main shocks lasted for more than one year and it was important to study the exponential time decay of aftershocks and Gutenberg-Richter's magnitude-frequency relation and compare the results with similar sequences elsewhere. Studies of the static stress changes on neighbouring faults contributed to the understanding of the distribution of aftershocks. Large variations in damage to buildings at small distances motivated several site effect studies. Especially the microtremor HVSR method was proven to be very effective in identification of soil-structure resonance effects that took place at many locations in the Bovec basin.

The 1998 earthquake motivated a modernisation of the national seismological network. As a result, today Slovenia has a modern network of 26 seismic stations equipped with broadband sensors, accelerometers, and high-resolution digitizers. The international cooperation was also enhanced and thanks to it in Central Europe we currently have a real-time virtual network that has significantly improved the seismological monitoring. Krn Mountains earthquakes and a new Slovenian seismic network had significantly fostered a seismological research in Slovenia and motivated many interdisciplinary seismological studies.

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