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

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

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Ključne besede: potres, seizmotektonika, učinki potresa, skalni podori, Evropska potresna lestvica, intenzitetna lestvica potresnih učinkov na okolje (ESI lestvica), Krnsko pogorje, Ravenski prelom

Abstract

A review of geological and seismotectonic investigations conducted in the two decades after the 12 April 1998 earthquake in Krn Mountains, according to its magnitude the strongest earthquake in Slovenia in the 20th century, is given. Many of these studies have wider scientific meaning than expected from the size of the earthquake. This was the first case in Slovenia that a strong earthquake was undoubtedly related to a particular fault. Seismotectonic studies of seismogenic Ravne fault revealed that it is an actively propagating strike-slip fault growing by interaction of individual right stepping fault segments and breaching of local transtensional step-over zones. Airborne laser scanning (LiDAR) of Idrija and Ravne faults, which resulted in high resolution bare earth digital elevation model, was in 2005 for the first time used to study surface expression of an active fault in Europe. Among the primary characteristics of the 1998 earthquake were extensive environmental effects expressed mainly as massive rockfalls. They were systematically documented and evaluated for intensity assessment using European Macroseismic Scale (EMS-98) and Environmental Seismic Intensity (ESI) scale introduced in 2007, because application of the data on damage to buildings was limited in sparsely populated high mountains epicentral area. These studies were pioneering due to novelty of both intensity scales, indicating their strong points and weaknesses. Large variations in damage to buildings in the upper Soča valley at similar epicentral distances pointed to strong site effects due to very heterogeneous glacial and fluvial deposits in sedimentary basins and valleys. Therefore, different seismic microzonation maps were prepared to evaluate the influence of soft sediments on seismic ground motion. Conducted studies fostered development of several earthquake geology research methods in Slovenia as tectonic geomorphology, evaluation of environmental seismic effects and seismotectonics. They had positive impact also on the university education in the fields of geophysics, seismology and structural geology.

Izvleček

Podan je pregled geoloških in seizmotektonskih raziskav opravljenih v dveh desetletjih po potresu 12. aprila 1998 v Krnskem pogorju, ki je bil po magnitudi najmočnejši potres v Sloveniji v dvajsetem stoletju. Mnoge od teh študij imajo širši znanstveni pomen kot bi pričakovali glede na velikost potresa. Prvič v Sloveniji, da je bil močan potres nedvoumno pripisan nekemu prelomu. Seizmotektonske študije seizmogenega Ravenskega preloma so pokazale, da je to aktivno napredujoč zmični prelom, ki raste z interakcijo med posameznimi segmenti in preskoki med lokalnimi transtenzijskimi conami. Letalsko lasersko skeniranje (LiDAR), s katerim pridobimo visokoločljiv digitalen model višin golega površja brez vegetacije, je bilo v letu 2005 na območju Idrijskega in Ravenskega preloma prvič uporabljeno v Evropi za študij površinskega odraza aktivnega preloma. Med glavnimi značilnostmi potresa 1998 so bili obsežni učinki v naravnem okolju, izraženi predvsem kot veliki skalni podori. Ti so bili sistematično dokumentirani in ovrednoteni za določitev intenzitete po Evropski potresni lestvici (EMS-98) in Environmental Seismic Intensity (ESI) lestvici, ki je bila uvedena v letu 2007, ker je bila uporaba podatkov le o poškodbah objektov v nadžariščnem območju zelo omejena, saj je zaradi visokogorja to redko poseljeno. Ker sta obe lestvici novi, so bile te študije v mnogih vidikih pionirske in so pokazala na njihove prednosti in slabosti. Velike razlike v poškodbah objektov v zgornjem Posočju na primerljivih nadžariščnih oddaljenostih, so pokazale

na velik seizmični vpliv heterogenih ledeniških in rečnih sedimentov, ki zapolnjujejo kotline in doline. Zato so bile izdelane različne karte potresne mikrorajonizacije in ocenjen vpliv mehkih sedimentov na potresno nihanje tal. Izvedene raziskave so imele pomemben vpliv na razvoj raziskovalnih metod potresne geologije v Sloveniji kot so tektonska geomorfologija, analiza učinkov potresov na naravno okolje in seizmotektonika. Pozitivno so vplivale tudi na razvoj univerzitetnega izobraževanja na področju geofizike, seizmologije in strukturne geologije.

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 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 NE Italy. In Krn Mountains another strong earthquake occurred on 12 July 2004 with M_w5.2 and maximum intensity VI-VII EMS-98. 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 very extensive investigations and developments in the multidisciplinary field of earthquake research. In this paper a review of geological and seismotectonic investigations related to both earthquakes is given. Many of these studies had strong influence on the development of different important scientific disciplines in Slovenia as tectonic geomorphology, environmental earthquake effects studies, site effects studies and paleoseismology. These disciplines undergone very fast development in the world in the last two decades, facilitated by new techniques as airborne laser scanning (LiDAR), advances in microtremors method and geophysical shallow subsurface characterisation etc. A complementary review paper in this issue is devoted to advances in extensive seismological investigation related to both Krn Mountains earthquakes (Gosar, 2019b).

Krn Mountains earthquakes in 1998 and 2004

The 12 April 1998 M_w5.6 earthquake occurred on the Ravne fault approximately 8 km SE from Bovec. It caused extensive damage to buildings in the upper Soča valley, but no casualties. The maximum intensity VII-VIII EMS-98 was observed in four villages: Lepena, Magozd, Spodnje Drežniške Ravne and Tolminske Ravne (Živčić et al., 1999; Zupančič et al., 2001). Mainly older buildings, built of rubble and simple stone, were damaged (fig. 1), but also some newer masonry buildings. The problem of macroseismic evaluation of this event was that the application of intensity scales based on damage to buildings and effects on humans and objects was limited

Fig. 1. In 1998 earthquake mainly older buildings, built of rubble and simple stone, were damaged (left), but also several monuments (right) (photo: A. Gosar).

Sl. 1. Ob potresu 1998 so bile poškodovane predvsem starejše stavbe zgrajene iz neobdelanega kamna (levo) in tudi številni spomeniki (desno) (foto: A. Gosar).

in the epicentral area, because it is very sparsely populated high mountain area. The earthquake was followed by long aftershocks sequence. Another strong earthquake with M_w5.2 occurred on 12 July 2004 on the same fault, with only slightly different focal mechanism. The maximum intensity of this event was VI-VII EMS-98, and it caused a casualty of a mountaineer hit by a fallen rock. The distance of both earthquakes to the towns of Bovec and Kobarid was 6-9 km (Zupančič et al., 2001). In the scientific literature there is a slight confusion regarding the name of the 1998 event, because in some early studies, especially those conducted by Italian researchers, they named it Bovec or Kobarid earthquake (Di Giacomo et al., 2014). Later some authors used also the name upper Soča valley (Posočje) earthquake. However, we believe that the only correct name is Krn Mountains earthquake and this name now prevails in the published literature (Di Giacomo et al., 2014).

Seismotectonic investigations

A preliminary evaluation of seismotectonic characteristics of 1998 earthquake was performed by Bernardis et al. (2000), but it was based mainly on focal mechanisms and aftershock distribution, without any geological field work. The earthquake was attributed to Čez Potoče fault named after Čez Potoče pass located 2 km north of Mt. Krn. However, such a name is not known in a geological literature and the correct name of this fault is Ravne fault after Tolminske Ravne (Buser, 1986). In the work of Bernardis et al. (2000), the fault was put in a regional tectonic context of the general crustal structure of NW Slovenia and Friuli area.

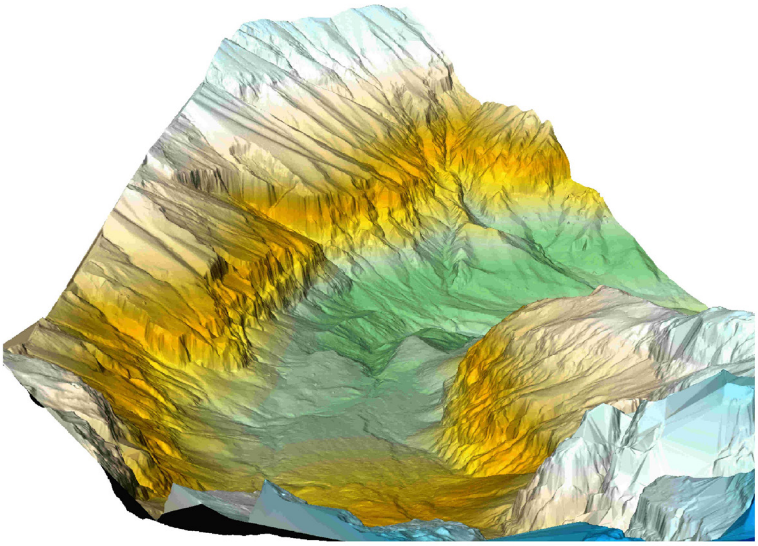
Fig. 2. The view of seismogenic Ravne fault across Tolminka spring basin towards NW (photo: A. Gosar).

Sl. 2. Pogled na seizmogeni Ravenski prelom prek območja izvira Tolminke proti NW (foto: A. Gosar).

The first seismotectonic analysis of the 1998 earthquake has shown that it occurred on a dextral strike-slip subvertical Ravne fault (figs. 2 and 3) oriented in NW-SE direction (Zupančič et al., 2001). This was the first case in Slovenia that a strong earthquake was undoubtedly related to a particular fault mapped in the field. Earlier, such seismotectonic relations were mainly precluded by large errors in earthquake foci locations due to very sparse distribution of seismological stations. The hypocentral depth of the 1998 event was 7.6 km No surface rupture was found and based on distribution of aftershocks the fault rupture dimensions were assessed on 10 km × 7 km. The seismotectonic analysis was based on focal mechanisms, field observations and ortho photo aerial images. It was revealed that recent seismic activity in NW Slovenia is related to strike-slip Dinaric faults (fig. 3) as well as to thrusting along Southalpine thrust front and parallel planes (Zupančič et al., 2001). The area is located at the kinematic transition between E-W striking thrust faults of the Alpine system in Friuli and NW-SE striking dextral

Fig. 3. Detailed view of the Ravne fault plane in a gully above Planina na Polju with clear indications of strike-slip character of this fault (photo: A. Gosar).

Sl. 3. Pogled na drsno ploskev Ravenskega preloma v grapi nad planino Na Polju, kjer se jasno vidijo strukture, ki kažejo na zmičen značaj tega preloma(foto: A. Gosar).



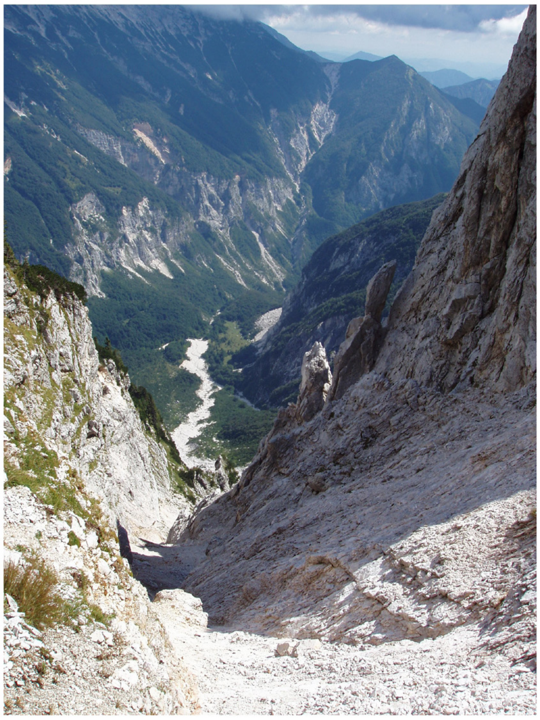


Fig. 4. 3D view of a Digital Elevation Model of the Ravne fault and Tolminka spring basin towards SE derived from LiDAR survey (left) and photo of the same area (right) (photo: A. Gosar).

Sl. 4. 3D pogled na Ravenski prelom in območje izvira Tolminke proti SE na digitalnem modelu višin izdelanem iz LiDARskega snemanja (levo) in fotografija istega območje (desno) (foto: A. Gosar).

strike-slip faults of the Dinarides system in NW Slovenia. The fault plane solution of 1998 event shows almost pure strike-slip mechanism with only minor reverse component.

Further seismotectonic analysis of the 1998 earthquake (Bajc et al., 2001) was based on relocation of hypocentres, strong motion (accelerograms) data inversion, field geological inspection and study of digital elevation models. From strong motion inversion it was revealed that the rupture was confined between 3 and 9 km depth and that it propagated bilaterally between two structural barriers. In the NW the barrier is related to the junction between Dinaric and Alpine structures and related sharp change in the geometry of faulting. The SE barrier is within the Dinaric system and at the surface expressed as Tolminka spring perched basin (fig. 4), a 1 km restraining step-over (Bajc et al., 2001). First evidence of the segmentation of more than 40 km long Ravne fault has strong implications for seismic hazard assessment and motivated further detailed research.

The second strong earthquake on 12 July 2004 opened many new questions on its seismotectonic characteristics, because the distribution of damage was slightly different, although the epicentre was very close (1.5 km distance) to the 1998 event (Vidrih & Ribičič, 2004). Seismological analyses showed slightly different focal mechanism with more pronounced reverse component (Kastelic et al., 2006). In addition, aftershocks were mostly distributed NW to WWN from those of 1998 event and do not show such a uniform spatial distribution. Spatial and temporal distribution of aftershocks depicts a contemporary seismic activity on NW-SE and WWN-EES to W-E oriented faults (Kastelic et al., 2006).

In 2005, when airborne laser scanning (LiDAR) was still very rare and expensive (Gosar, 2007), we had, through international cooperation, an unique opportunity to survey Idrija and Ravne faults with this very promising method (Cunningham et al., 2007), which after a decade strongly changed the science of tectonic geomorphology, through providing high resolution bare earth digital elevation models. Measurements were very successful especially on the Idrija fault where details of near fault structures and Quaternary terraces were revealed. Based on this study a location in Kanomljica valley was proposed for later paleoseismological studies. On the Ravne fault the most interesting results were obtained in the Tolminka spring basin (fig. 4), where LiDAR images revealed several branches of the fault. It was interpreted as active transtensional basin within overall transpressional regime (Cunningham et al, 2006). This investigation represents the first application of airborne LiDAR in Europe for the purpose of mapping the surface expression of seismogenic faults.

The most comprehensive seismotectonic analysis of the Ravne fault was done within the Ph.D. thesis of Kastelic (2008) and Kastelic et al. (2008). It was revealed that Ravne fault is an actively propagating strike-slip fault growing by interaction of individual right stepping fault segments and breaching of local transtensional step-over zones. The spatial distribution of aftershocks shows that activity on strike-slip segments and thrust faults is contemporaneous. The Ravne fault is a structure that lies in an area subjected to multiple tectonic events under different regional stress conditions. 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 wide deformation zone that includes reactivated thrust faults (Kastelic et al., 2008).

Investigations of the effects of earthquakes on natural environment

Most prominent characteristics of the 1998 earthquake is that it had extensive effects on the natural environment in Julian Alps expressed mainly as rockfalls, which where is some cases very large. For the moderate magnitude (M_w5.6) event, such a great extent of rockfalls was not expected, therefore it immediately draws attraction of researchers and many thorough studies followed. Besides rockfalls, several other environmental effects occurred as well, which were also systematically documented and analysed.

Fig. 5. Very large rockfall caused by the 1998 earthquake in which the whole SE face of the Osojnica Mountain above Tolminka valley collapsed (photo: A. Gosar in May 1998).

Sl. 5. Zelo velik skalni podor nastal ob potresu 1998 v katerem se je podrlo celotno SE ostenje Osojnice nad dolino Tolminke (foto: A. Gosar, maj 1998).

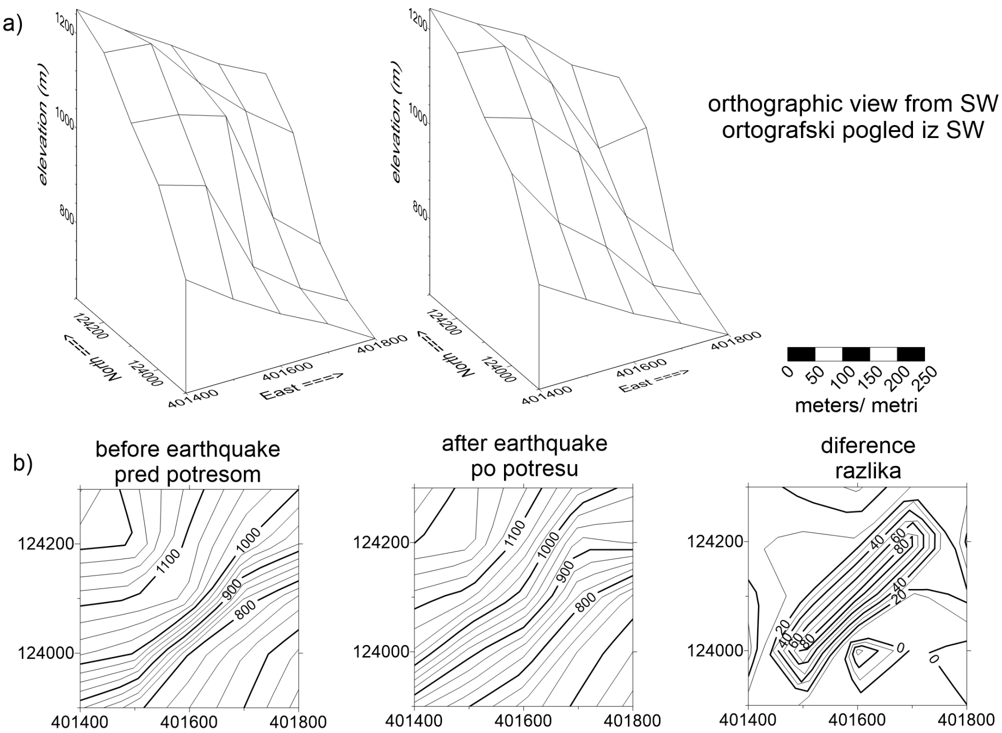


Fig. 6. Rockfall on the Osojnica Mountain was clearly reflected in Digital Elevation Models (DEM) showing pre- and post--earthquake topography. From the difference between both DEMs the volume of the rockfall was estimated on $3{\cdot}10^6$ m^3 (after Gosar, 1999b).

Sl. 6. Skalni podor na Osojnici se jasno odraža v digitalnem modelu višin (DMV), ki kaže topografijo pred in po potresu. Iz razlike obeh DMV je bila prostornina podora ocenjena na $3{\cdot}10^6$ m^3 (po Gosar, 1999b).

Analyses of rockfalls and seismic intensity scales

All rockfalls were systematically mapped soon after the 1998 earthquake to assess further risks to infrastructure and buildings (Ribičič, 1998). From the seismogeological point of view a further in-depth study was performed by Vidrih & Ribičič (1999). They documented all larger rockfalls and did the first evaluation of the applicability of a new European Macroseismic Scale (EMS-98) to assess intensity. For the epicentral area between Lepena and Tolminka valleys they proposed, based on effects on nature, maximum intensity VII-VIII EMS-98, which is in accordance to damage related intensity assessment in four villages in the same area. Since some of the rockfalls were very large (fig. 5), Gosar (1999b) investigated the possibility to use Digital Elevation Models (DEM) derived from aerial photography surveys before and after the earthquake to estimate their volumes (fig. 6). The volumes of the two largest rockfalls were quantitatively assessed to be $15 \cdot 10^6$ m^3 (Veliki Lemež in Lepena valley) and $3 \cdot 10^6$ m^3 (Osojnica in Tolminka valley).

In a further study (Vidrih et al., 2001) on the applicability of EMS-98 for assessing intensities for 1998 event, it was realized that the EMS-98 scale (Grünthal, 1998) is not sufficiently detailed in the description and evaluation of effects on the natural environment. It is deficient especially in quantitative description of environmental effects characteristic for particular intensity degrees. In EMS-98 environmental effects are rather briefly described on two pages and corresponding table (Grünthal, 1998). In this table for each type of effects three intensity ranges are presented: a) the possible range of observations, b) the range of intensities that is typical for this effect, and c) the range of intensities for which this effect is most usefully employed as diagnostic (Grünthal, 1998). One of the main problems of this table is that the same phenomenon is ascribed to a very wide range of intensity degrees, which prevents its practical use in assessing intensities. Therefore, Vidrih et al. (2001) proposed a different approach, reducing the intensity extent of phenomena appearance by introducing, in analogy to buildings, terrain vulnerability regarding strong shaking, the frequency of appearance and the level of damage with individual phenomena.

The introduction of a completely new and first scale at all devoted only to environmental effects - Environmental Seismic Intensity scale (ESI) in 2007 (Guerrieri & Vittori, 2007) motivated a new research on effect on natural environment aimed to evaluate the applicability of ESI to 1998 earthquake (Gosar, 2012; Gosar, 2014). All environmental effects were described, classified and evaluated again. These effects include rockfalls (fig. 7), landslides, fallen boulders (fig. 8), secondary ground cracks and hydrogeological effects. It was realized that only rockfalls (all together 78 were registered) are widespread enough to be used for intensity assessment. They

Fig. 7. A typical example of medium size rockfall occurred at V. Šmohor in Krn Mountains. The top of not very steep mountain collapsed (photo: A. Gosar in August 2003).

Sl. 7. Značilen primer srednje velikega podora se je zgodil na V. Šmohorju v Krnskem pogorju. Vrh ne preveč strme gore se je podrl (foto: A. Gosar, avgust 2003).

Fig. 8. A huge boulder in Dolič valley, very close to the epicentre of the 1998 earthquake, resulted from the rockfall on the Lipnik Mountain. The hight of the boulder is 5 m (photo: A. Gosar in September 2004).

Sl. 8. Ogromen balvan v dolini Doliča, zelo blizu nadžarišča potresa, je nastal zaradi podora na Lipniku. Višina balvana je 5 m (foto: A. Gosar, september 1998).

were classified into five categories according to their volume. Distribution of very large, large and medium size rockfalls has clearly defined an elliptical zone, elongated along the strike of the seismogenic fault, for which the intensity VII-VIII was assessed. This isoseismal line was compared to the VII-VIII EMS-98 isoseism derived from damage-related macroseismic data, which has similar elongated shape, but is slightly larger. This isoseism is defined by four points only and its size is strongly controlled by a single intensity point (Tolminske Ravne) lying quite far from other three points (Lepena, Magozd, Spodnje Drežniške Ravne), at the location where local amplification is likely. In this study the ESI 2007 scale has proved to be an effective tool for intensity assessment in sparsely populated mountain regions not only for very strong, but for moderate earthquakes as well (Gosar, 2012).

The size of the area affected by earthquake induced rockfalls depends on the magnitude (M_w) and on the maximum intensity (I_{max}). The established 180 km^2 area (r=7.6 km) for 1998 M_w 5.6 event was compared with two worldwide datasets for magnitude dependence (Gosar, 2019a). For the given magnitude the affected area is considerably below the upper bound limit established from both datasets. The same is valid for the Friuli M_w 6.4 earthquake with a 2050 km^2 affected area. However, comparison with the ESI scale definitions has shown that the area affected by the 1998 I_{max} VII–VIII event is significantly larger than the one proposed by this scale, but smaller for the 1976 I_{max} X event. This could not be explained by differences in hypocentral depth or focal mechanisms of both events. The results of this study have implications for seismic hazard assessment and for understanding environmental effects caused by moderate earthquakes in mountain regions (Gosar, 2019a).

The 2004 earthquake caused significantly less rockfalls than 1998 one. This was expected due to lower magnitude and the fact that most vulnerable slopes had already broken in stronger 1998 event. Anyway, 44 rockfalls were analysed, but only five of them were a bit larger (Vidrih & Ribičič, 2004). However, a fallen rock hit a mountaineer in Krn Mountains who died. Two very big landslides in Log pod Mangrtom and in Koseč near Kobarid fortunately did not react to seismic shaking due to relatively low intensity at their epicentral distance. Some very long cracks were developed along the edge of the Soča river terraces, which have contributed somewhere to the damage to buildings (Vidrih & Ribičič, 2004). The most complete review and documentation of all effects of 1998 and 2004 events on natural environment was prepared in Ph.D. thesis of Vidrih (2006) and later published in a monograph (Vidrih, 2008).

Rockfalls and landslides in several cases reached valley streams and rivers and significantly changed normal input of rock material. Therefore, Mikoš et al. (2006) studied sediment production and delivery from earthquake-induced rockfalls in the Upper Soča valley.

Analyses of other seismic effects on natural environment

The 1998 earthquake had curiously enough a substantial effect on the groundwater levels on Sorško and Kranjsko polje, located 60 km east of the epicentre. As recorded by four piezometers, it caused fluctuations in groundwater levels ranging from 23 to 82 cm (Uhan & Gosar, 1999). No fluctuations were recorded before or after the main shock, and no other fluctuations were reported from elsewhere. Therefore, an (hydro)geological interpretation of the observed phenomenon is not possible.

A short part of the Bohinj lake southern shore built of glaciofluvial debris slid into the water (Vidrih & Ribičič, 1999), but no evidence of liquefaction was found. It is located 25 km east of the epicentre where the intensity of 1998 event was VI EMS-98 and liquefaction is very unlikely at expected ground shaking.

In the areas of highest intensities VII-VIII EMS-98 there were some reports of cracks in the flat ground (in Magozd) (Vidrih & Ribičič, 1999). They resulted from strong ground shaking and cannot represent possible surface faulting or slope movements.

Since at the time of the 1998 earthquake there was a large amount of fresh snow (more than 0.5 m) in Krn Mountains, some interesting phenomena, which can be classified in-between snow avalanche, landslide and debris flow occurred. The most characteristically one occurred in Lepena valley (fig. 9). A mixture of snow, soil and rock slid down a steep ravine as an avalanche for more than 500 m of elevation difference. When it reached the valley floor, the debris was deposited as a debris flow in a wide fan (Vidrih & Ribičič, 1999; Gosar, 2012).

Seismic microzonations

Among important characteristics of 1998 and 2004 earthquakes were large variations in damage to buildings of similar vulnerability class at comparable epicentral distances. These variations were explained by prominent site effects within sedimentary basins (Bovec basin, Kobarid basin etc.) filled with heterogeneous glacial and fluvial sediments (fig. 10). In addition, strong resonance effects between soft sediments and buildings were proved at several locations using microtremor HVSR method (Gosar, 1999a). However, extensive studies using this method are presented in a complementary review paper on seismological investigation (Gosar, 2019b). Here only seismic microzonations motivated by observed prominent site effects that are based on geological and geotechnical data will be reviewed.

Within the project aimed to support retrofitting of damaged buildings several maps in different scales were prepared (Ribičič et al., 2000). In the general engineering-geological map of the upper Soča area was classified in hard rocks, medium hard rocks, slope sediments and alluvial sediments with geological and geotechnical description of each unit with relation to conditions for building foundations. Based on this division, a general seismic microzonation map of the area was prepared with soil classification to three

Fig. 9. Triggered by the 1998 earthquake, a mixture of snow, soil and rocks slid down a steep ravine in Lepena valley as an avalanche and created a fan shaped debris flow in the valley floor (photo: A. Gosar in May 1998).

Sl. 9: Mešanica snega, zemlje in skal je sprožena s potresom 1998 zdrsnila po strmi grapi v pobočju doline Lepene in v dnu doline povzročila nastanek pahljačastega drobirskega toka (foto: A. Gosar, maj 1998).

groups. At that time a new seismic hazard map showing ground acceleration for Slovenia was not yet available. Therefore, the seismic microzonation map was prepared to be used with the old seismic hazard map showing expected intensities for a return period of 500 years. According to this map NW Slovenia was characterized by expected intensities of VIII and IX on MSK scale and seismic microzonation provides intensity increments. For a Bovec basin a more detailed geotechnical map was prepared in which rocks and sediments were classified in eight types. Based on it, a detailed seismic microzonation of the Bovec basin was prepared, which shows that most of the area is characterised by $VIII_2$ and $VIII_3$ intensities (Ribičič et al., 2000; Ribičič, 2011). Considering also resonance effects between sediments and structures, preliminary microtremor method investigations were carried out in affected area to explain large variations in damage to buildings due to site effects (Gosar, 1999a; Gosar, 1999c). It turned out that resonance effect could play important role in distribution of damage especially in the Bovec basin filled with heterogeneous sediments (fig. 10).

A step forward in seismic microzonation based on detailed engineering geological mapping was performed for Breginjski kot (the most western part of Slovenia) (Kokošin, 2011), which suffered the highest damage (intensity VIII-IX EMS-98) in the Friuli 1976 earthquake sequence and significantly lower damage (VI-VII EMS-98 in Kobarid) in the 1998 earthquake due greater distance from the epicentre and lower magnitude event. According to the old seismic hazard map, the whole Breginjski kot is assessed as intensity IX MSK and according to the new hazard map to design ground acceleration of 0.250 g. First, a detailed engineering geological mapping in scale 1: 5000 was conducted. On the basis of this mapping, a soil classification was carried out according to the Medvedev method (intensity increments) and the Eurocode 8 standard (soil factors) and two microzonation maps prepared to be applied with both seismic hazard maps. The microzonation clearly points out the dependence of damage distribution to local site effects in the case of Friuli earthquake (Kokošin & Gosar, 2013).

Within the project Earthquake risk in Slovenia (POTROG – Potresna ogroženost Slovenije), there was a need to prepare a seismic microzonation maps of all areas where according to the official seismic hazard map of Slovenia a design ground acceleration for 475 years return period is assessed on 0.225 and greater. This includes also the whole upper Soča River territory. A seismic microzonation of this area in accordance to the Eurocode 8 standard was prepared in the frame of a diploma thesis (Trobec, 2012). However, this microzonation was based on existing data only (basic geologic maps, engineering geological maps and seismic microzonation of Breginjski kot) without any field investigations. Therefore, it is intended only for the general risk assessment studies and civil protection planning and not for the purpose of earthquake engineering design. The classification of rocks and sediments accord-

Fig. 10. Heterogeneous glacial and fluvial sediments in the Bovec basin were responsible for large variations in seismological site effects and consequently to the degree of buildings damage. A rockfall occured in the wall above the Soča river during the 1998 earthquake (photo: A. Gosar in May 1998).

Sl. 10. Zaradi heterogenih ledeniških in rečnih sedimentov v Bovški kotlini, so bile tam velike razlike v seizmoloških vplivih na potresno nihanje tal in posledično razlike v stopnji poškodovanosti stavb. Med potresom 1998 je v steni nad reko Sočo nastal tudi večji skalni podor (foto: A, Gosar, maj 1998).


Fig. 11. Soft lacustrine sediments as exposed in abandoned clay pit near Srpenica can significantly amplify seismic ground motion and are classified as ground type E according to the Eurocode 8 standard. a) General view of thin bedded lacustrine deposits, b) close view of very soft sediment (photo: A. Gosar).

Sl. 11. Mehki jezerski sedimenti, kot so razgaljeni v opuščenem glinokopu pri Srpenici, lahko znatno ojačajo potresno nihanje tal in jih klasificiramo v vrsto tal E po standardu Evrokod 8. a) pogled od daleč na tanko plastovite jezerske sedimente, b) bližnji pogled na zelo mehek sediment (foto: A. Gosar).

ing to Eurocode 8 was as follows. Solid rocks as carbonates, marlstone, sandstone, breccia, flysch rocks and shale represents ground type A. Alluvium of Lepenjica river represents ground type B, older Quaternary sediments ground type C and younger Quaternary sediments and fluvial sediments of Bovec basin ground type D. Ground type E is represented by fine grained river sediments, diamicts overlying ground type A, lacustrine chalk (fig. 11) and alluvium near Kobarid (Trobec, 2012). By application of soil factors the maximum design ground acceleration for a return period of 475 years in the area is 0.425 g on ground type E (soil factor 1.7, design ground acceleration on rock 0.250) in Breginjski kot, which is close to the highest values assessed in Slovenia. This value is surpassed only in the Ljubljana Moor where on very soft lacustrine and marsh sediments (ground type S_1) the design ground acceleration on solid rock of 0.250 g can be increased in the northern part by soil factor of 2.55 on 0.635 g and in other parts the design ground acceleration on solid rock of 0.225 g can be increased on 0.575 g (Zupančič et al., 2004).

Macroseismic data collected for strong earthquakes are not used only to study particularities of the macroseismic field related to distribution and properties of soft sediments in epicentral area where highest intensities are observed. They are valuable also at larger epicentral distances. In such study macroseismic data was used to investigate the influence of geological site effects on earthquake intensities (for all together 11 earthquakes) in greater Ljubljana area located around 80 km from epicentres of Krn Mountains earthquakes. The maximum intensities of 1998 and 2004 earthquakes in wider Ljubljana area and for the strongest 1998 aftershock were V EMS-98. The results showed a systematic increase in observed seismic intensities as the seismogeological characteristics of the ground deteriorated (Jerše et al., 2013; Jerše et al., 2015). Only one ground type (D) showed slightly lower intensity than expected. This may be due to some unrevealed geological factors or very limited macroseismic data available for this particular ground type which is relatively rare in wider Ljubljana area.

Conclusions

Geological and seismotectonic investigations related to the 1998 and 2004 earthquakes in Krn Mountains performed in two decades had in several cases much wider scientific meaning that could be expected from the size and effects of both events. This is reflected also in large number of citations of many studies obtained in international scientific literature. Since new European Macroseismic Scale (EMS-98) was after preliminary version from 1992 in its final form presented in 1998 (Grünthal, 1998), this was one of the first strong European earthquakes macroseismicaly evaluated by using this scale (Cecić et al., 1999; Zupančič et al., 2001). Especially important were first attempts to apply EMS-98 to evaluate seismogeological effects expressed as massive rockfalls in extent not expected for the magnitude of the event (Vidrih & Ribičič, 1999; Vidrih et al., 2001). It was realised that EMS-98 scale is not sufficiently detailed in description of effects on the natural environment, especially in quantitative description of effects characteristic for particular intensity. Later presentation of Environmental Seismic Intensity Scale (ESI) (Guerrieri & Vittori, 2007) motivated a new study which proved that it is an effective tool for intensity assessment in sparsely populated mountain regions also for moderate earthquakes (Gosar, 2012). Application of airborne laser scanning (LiDAR) of the Ravne and Idrija faults to reveal their geomorphological and structural features was a pioneering LiDAR study applied for tectonic geomorphology in Europe (Cunningham et al., 2006). Both earthquakes motivated first thorough, modern and quantitative seismotectonic studies of an active fault in Slovenia. The seismogenic Ravne fault was recognized as a typical example of actively propagating strike-slip fault which is growing by interaction of segments and breaching of local transtensional step over zones (Kastelic et al., 2008). During recent preparation of a seismotectonic model for a new seismic hazard map of Slovenia, it was realised that thorough understanding of segmented faults behaviour is of key important for realistic earthquake hazard modelling. Studies of geological and seismotectonic characteristics of the 1998 and 2004 earthquakes were important also for university education of geology in Slovenia as two Ph.D. thesis were prepared (Vidrih, 2006; Kastelic, 2008) and at least eight diploma theses related to these topics at the University of Ljubljana, Faculty of Natural Sciences and Engineering. These studies foster education in different geological fields: structural geology and active tectonics, geophysics, seismology, engineering geology and Quaternary geology.

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