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# Ground structure and its seismogeological characteristics influencing local seismic effects of the 1998 and 2004 Upper Posočje earthquakes in Slovenia

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In 1998 and 2004, two strong earthquakes shook the NW region of Slovenia. On the basis of a detailed inventory, the damages to structures were classified into five damage grades, defined in accordance with the European Macroseismic Scale (EMS). After both earthquakes, extensive geological and geophysical investigations were carried out, including geological mapping, the excavation of 60 pits, drilling of 20 boreholes down to depths of 20 m, seismic measurements, geo-electrical measurements and seismic microtremor investigations. Since 1990, local seismic effects in Slovenia have been addressed through consecutive rules covering static calculations for the structures being built; the first of these rules was the old Slovenian regulation (Uradni list SFRJ 31/81), and the other two were the last Eurocode 8 (EU8-94 and EU8-SIST EN 1998-1:2005) regulations.

In this report, we describe studies on how local ground conditions increase seismic effects on structures. On the basis of mentioned data in previous paragraph, we attempted to establish how reliably this influence can be defined. A forecast of local seismic effects was compared with actually established damage to structures. A statistical analysis was conducted in 27 selected areas (settlements) with similar geological conditions.

Through a comparison of ground-type impact assessments performed using geological mapping and drilling, geo-physical measurements and measurements of microtremors with actually established damage to structures, it was found that forecasts were more reliable if they were made with proper consideration of all relevant factors together. However, despite implementing forecasts using this type of multidisciplinary approach, the forecasts for some areas can be completely incorrect in terms of seismic effects. The best forecast was found to be produced using the last EU8 (EU8-SIST EN 1998-1:2005), while the old Slovenian (Uradni list SFRJ 31/81) and first EU8 (EU8-94) regulations produce less reliable results.

*Keywords*: earthquakes in NW Slovenia, European Macroseismic Scale, Eurocode 8, ground types, earthquake damage assessment, forecast of local seismic effects

## 1. Introduction

Local seismic effects and, consequently, the level of damage to structures are primarily influenced by the geological structure of the ground and its seismogeological characteristics. It is for this reason that all past and present regulations applicable to static calculations related to earthquake-safe construction duly consider this fact. However, the question of how reliably this influence can be assessed has been raised.

Between 1990 and 2008, the local structure of the ground and its influence on seismic effects have been addressed in three consecutive rules covering static calculations related to structures built in Slovenia. The first of these resulted from Yugoslav regulations, while the second two were first implemented with the introduction of European codes and standards in association with Slovenia joining the European Community (hereafter referred to as EU8-94). Since January 1, 2008, the use of the EU8-SIST EN 1998-1:2005 regulation has been mandatory in Slovenia.

Local seismic intensity at certain points on the Earth's surface is governed by complex phenomenon. It depends mostly on the regional and local geological structure of the ground, geomechanical and seismic characteristics of near-to--surface and deeper layers, terrain morphology and other local geo-seismic effects (Raptakis, 2000) that will be dealt with in greater detail later in the paper.

In 1998 and 2004, two strong earthquakes shook the region of upper Posočje in Slovenia. The one that occurred in 1998 was registered as the strongest earthquake of the $20^{th}$ century in Slovenian territory (Vidrih at al., 2004). After both earthquakes, and especially after the one in 1998, geological and geo-physical investigations and inventories on damage to structures and nature were conducted. The relatively good knowledge of the seismogeological characteristics of the Upper Posočje area obtained in this way and recorded data on the damage to structures and nature assist in ascertaining the applicability of ground type categorization for the static assessment of structures that have been and will be constructed as part of the after-earthquake reconstruction process.

In this report, we first provide some general characteristics of both earthquakes and the results of field research on seismogeological characteristics of the ground. This is followed by an analysis of damage to structures in connection with the local geological structure of the ground. A historical review of legislation addressing the impact of the ground on structures during an earthquake that has been used since 1998 in post-earthquake reconstruction processes in the Posočje area are also provided.

In the conclusion, we discuss the applicability of categorizations according to all three ground type tables that determine seismic coefficients of the ground and provide their suitability regarding the actual effects on structures incurred in both the 1998 and 2004 earthquakes.

## 2. General data on both earthquakes

The table below provides basic data on the time, location and intensity of both earthquakes.

*Table 1: Basic seismic data on the 1998 and 2004 earthquakes.*

| Date | April 12, 1998 | July 12, 2004 |
|---|---|---|
| Coordinates | 46.31° N; 13.63° E | 46.31° N; 13.62° E |
| Time | 10:55 UTC | 13:04 UTC |
| Magnitude | $M_L$ = 5.6 | $M_L$ = 4.9 |
| Intensity | VII-VIII as per EMS | VI-VII as per EMS |
| Depth | 8 km | 8 km |

The hypocenters of both earthquakes were close together and at the same depth; however, the magnitude of the first earthquake was considerably higher (Figure 1):

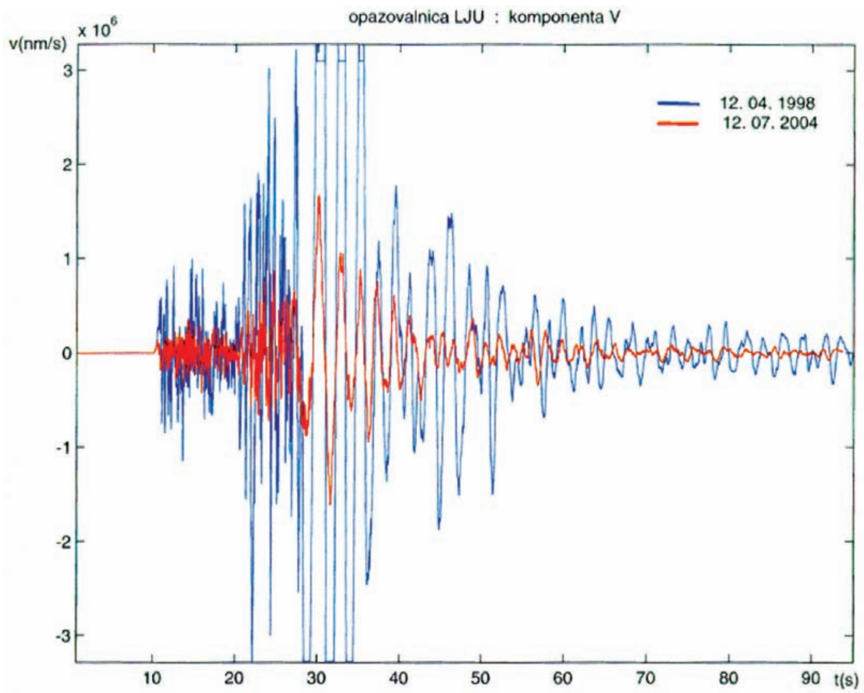


**Figure 1**. Seismographs of the 1998 earthquake (blue record) and the 2004 earthquake (red record) obtained at the Ljubljana seismic station.

The epicenter of the first earthquake, which occurred on April 12, 1998, was approximately 8 km SE from Bovec. The event occurred in the form of a right-lateral (dextral) displacement of the vertical Ravne fault running in the NW–SE direction as a result of the Adriatic microplate thrusting under the Julian Alps (Zupančič et al., 1999). It was felt by the population of all of Slovenia and in all countries extending to central Europe.

A questionnaire completed by approximately 3100 registered external monitors of the Slovenian seismic office assisted in analyzing the seismic effects on people. The results obtained from that survey were combined by data obtained in the narrow region of seismic influence provided by damage inventory commissions established for this purpose.

The data collected were then evaluated according to the European Macroseismic Scale (EMS) (Grünthal ed., 1998). In the 1998 earthquake, approximately 300 structures suffered damage of Grades 4 and 5, which indicates that the degree of destruction was so great that their reconstruction was not possible. Grade 4 means very heavy damage of structure and Grade 5 complete to almost complete destruction. The majority of these structures were built before World War II from local construction material: limestone blocks tied with weak mortar, mostly without any foundations (Godec at al., 1999).

The second earthquake addressed here, which occurred on July 12, 2004, was considerably weaker than the first one, with a calculated magnitude of $M_L$=4.9. It occurred in association with the same fault system several hundred meters to the northwest. Its hypocenter was also approximately 8 km under the surface. As shown by the monitors' questionnaires and other data collected from journalistic reports and seismic stations the earthquake was felt not only by the population of the upper Posočje area, but also by the populations of nearby regions in Italy, Austria and Croatia. Following this earthquake, 35 mainly old structures were classified as presenting a damage grade of 4, and only one structure presented the highest possible damage grade of 5. Some structures that had been damaged in the first earthquake incurred repeated damage.

As shown by later analyses, an incomplete damage inventory of the 2004 earthquake was collected with no consideration of the criteria after the first earthquake; for this reason, it was only poorly suitable for a more detailed analysis.

Nevertheless, the 2004 earthquake provided unexpected findings. In certain areas, especially in Čezsoča, the seismic effects were increased by a whole EMS scale degree, which is evident in the comparative diagram of seismic records obtained by two portable field-type seismic stations erected immediately after the earthquake, as shown below (Figure 2).

The initial primary wave recorded by the seismograph erected in the village of Čezsoča was substantially stronger than that recorded by the seismograph located in Vrsnik. It is assumed that one of the influential factors re-

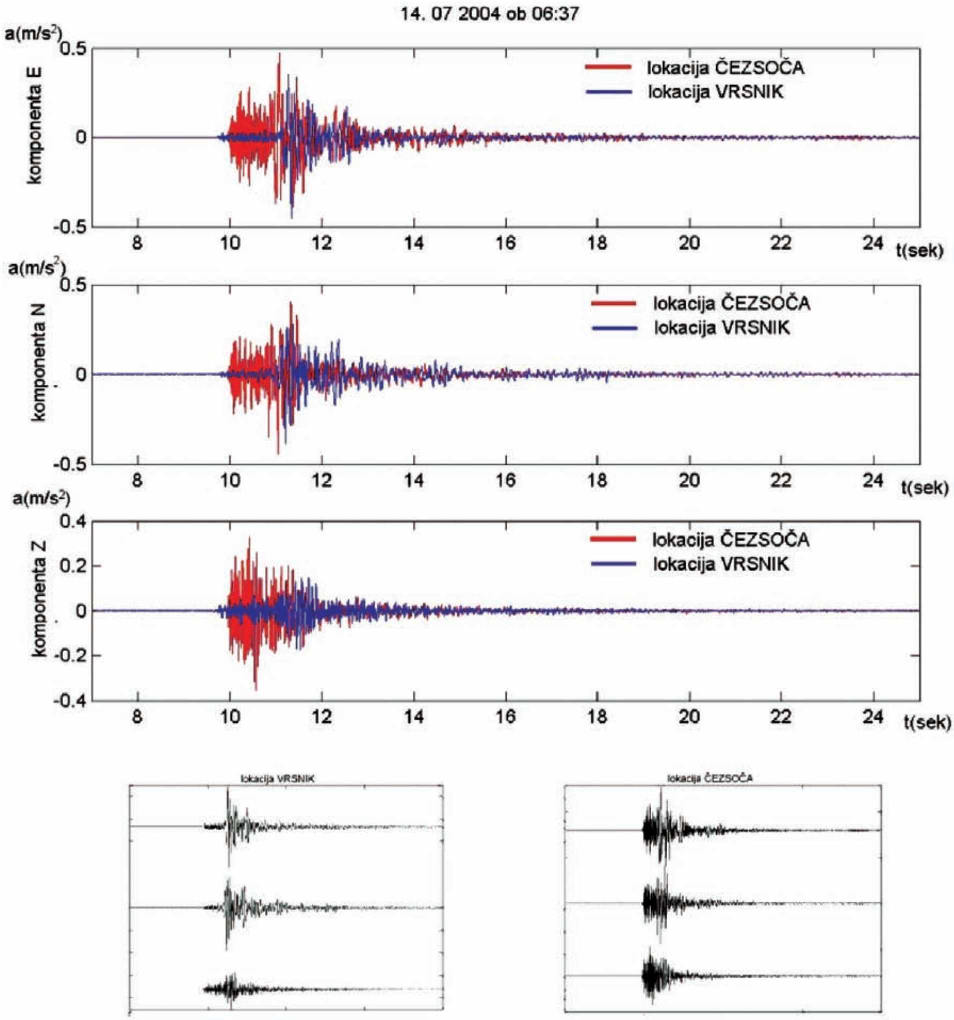


**Figure 2.** Comparison of the records of the strongest aftershocks in Čezsoča (red) and Vrsnik (blue) occurring two days after the main earthquake in 2004.

lated to intensification that occurred in the 2004 earthquake but not in the 1998 earthquake is the diffusion of seismic waves along a strong fault running in the direction of Čezsoča because the epicenter of the 2004 earthquake was located slightly to the northwest. This increase by a seismic degree caused by tectonics was multiplied over a greater distance due to a heterogeneous structure more than a 150 m thick made of alluvial ground in the Čezsoča area consisting of gravel, as well as sandy and lake chalk layers.

## 3. Field research

In the first few months after the 1998 earthquake, field investigations were aimed at suppressing the outcomes of the earthquake and defining the foundation conditions for new buildings to replace the demolished ones; these investigations were also aimed at determining the appropriate use of space and preventive measures to reduce the damage in the event of subsequent seismic events and defining the seismo-geological characteristics of the ground. For this purpose, the following investigations were conducted:

– Updated remmaping of the of the upper Posočje area and the Bovec basin, with amendments to the existing geological map of this area;

– Excavation of 60 sounding pits next to damaged structures to define the surface structure of the ground and the quality of footing structures required to set the conditions for the foundations of new buildings and for the reconstruction of damaged buildings;

– Drilling of twenty geo-mechanical boreholes down to 20 m depths in the most seismically affected areas;

– Geo-physical investigations: seismic and geo-electrical measurements required to determine the seismic characteristics of the ground (P and S waves) and the characteristic thickness of the layers;

– Inventory of the damage to nature, especially rock falls and landslides, allowing the determination of seismic effects in a building-free area.

Data obtained by damage-to-structure inventory commissions were also used in analyses. Additionally, measurements of seismic tremors were performed in the study area (Gosar, 2007). All data were GIS processed. The above-mentioned investigations resulted in numerous scientific and professional outcomes. These encompass general and concrete geological-seismic-geotechnical data, from which we will take only those data relevant to the analysis of local impacts of the ground addressed in this article.

A survey map of seismic microzonation at a scale of 1:25000 and one for the Bovec basin at a scale of 1:10000 were produced on the basis of the renewed appraisal of geological structures and data from other investigations. According to the regulations of that period (1998), which will be presented later, the mapped terrain was classified into three categories, A, B and C. The seismic hazard map of Slovenia (Ribarič, 1987) was the basis for the determination of seismic degrees as follows: alpine and hilly regions based on limestone and dolomites were classified into category A; terrain formed from clastic rocks (especially flysch) and thick gravel-filled sediments was classified into category B; and areas with slope morainic alluvia and scree were classified as category C.

The detailed field investigations encompassed all seismically affected settlements where the structure of the ground was being established. The Table 2 below provides the ground structure and the assessed allowable estimated

*Table 2: Geological structure of sites considered in the analysis of seismic effects.*

| Place | Structure of surface layers | Base rock | Bearing capacity (kN/m$^2$) |
|---|---|---|---|
| Bavšica | Sandy gravel or slope talus on valley flanks deposited deposited in layers up to 10 m thick | carbonates | 250 |
| Bovec-Brdo | Silty clays or clays with limestone pieces, with transition to clayey scree | clastites | 150 |
| Bovec-Dvor | Fatless and sandy clays and clayey scree | clastites | 150 |
| Bovec-Industrial zone | Soča gravel of great thickness | clastites | 250 |
| Bovec-Klanc | Morainic slope talus | clastites | 200 |
| Bovec-Kot | Morainic clayey scree and clays | clastites | 150 |
| Bovec-Mala vas | Clays and clayed-up gravel | clastites | 150 |
| Bovec-Podklopca | Sandy limestone gravel | clastites | 250 |
| Bovec-Ravni laz | Slope morainic material | clastites | 200 |
| Bovec-Rupa | Clayey scree and poorly-rounded gravel | clastites | 200 |
| Bovec-Trg golobar. žrtev | Clayed-up moraine | clastites | 200 |
| Bovec-Vodenca | Soča gravel | clastites | 250 |
| Čezsoča | Soča gravel | clastites | 250 |
| Drežnica | Weathering clayey-gravel cover of flysch | clastites, carbonates | 200 |
| Drežniške ravne (1) | Moraines and slope talus | clastites | 200 |
| Jezerca | Morainic slope talus | clastites | 250 |
| Kal-Koritnica | Diluvial clayey slope talus and sandy Soča gravel | carbonates | 150 |
| Kobarid | Gravel alluvia, clays and silts on the top | carbonates | 200 |
| Koseč | Cretaceous sandstones and limestones | clastites | 200 |
| Kred | Clayey flysch weathered soil (diluvium) | clastites | 150 |
| Lepena | Sandy gravel or scree | carbonates | 250 |
| Log Čezsoški | Soča gravel | carbonates | 250 |
| Magozd | Clay and clayey slope talus and rockfall material | clastites | 200 |
| Soča | Soča gravel | carbonates | 250 |
| Srpenica | Soča gravel | carbonates | 250 |
| Staro selo | Clayey scree and clays | carbonates | 150 |
| Trnovo ob Soči | Soča gravel | carbonates | 250 |
| Žaga | Soča gravel | carbonates | 250 |

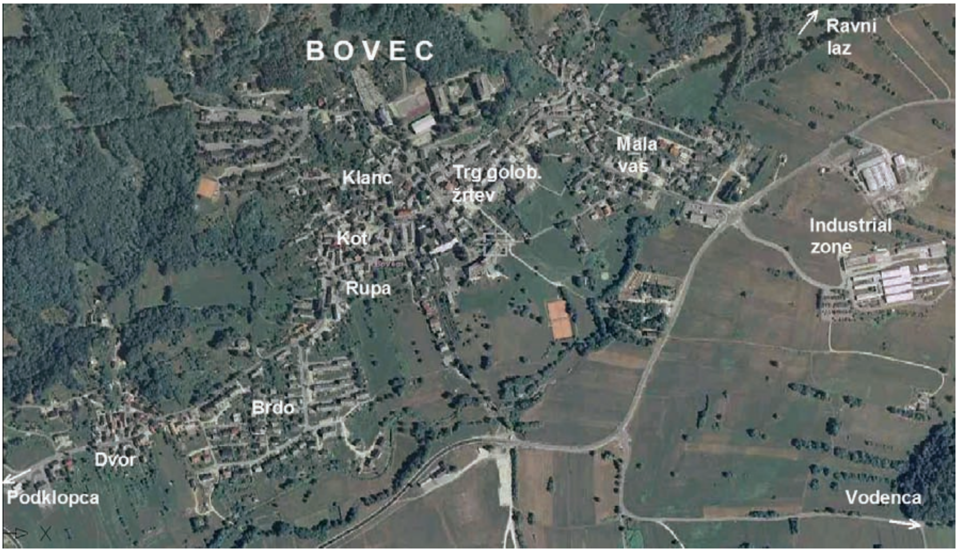


**Figure 3.** Bovec and its regions from Dvor to the Industrial zone.

ground-bearing capacity for the settlements located in the Bovec area encompassed in the analysis. Locations of these sites are shown on the maps provided by Figures 3 and 4.

The thickness of alluvial and other deposits, as well as their composition, were determinded by boreholes. Twenty boreholes were produced. In each of these, standard penetration tests (SPT) that provided values mostly between 15 and 50 blows were obtained, which indicates sediments belong to the class of medium density. However, local layers with a low value of number of blows under 15 were obtained in Mala vas, whereas particularly high values were obtained in conglomerated deposits. In each borehole, measurements of seismic velocities were performed using the up-hole method.

Based on the established ground structure, its seismic effect can be determined. In the treated areas, there are no extremely favorable conditions, i.e., foundations of structures on rock that is not clearly weathered or cracked. However, there is also no possibility of a great increase of local seismic effects due to an extremely unfavorable ground structure, which could cause extreme seismic effects, such as liquefaction. The least favorable conditions established by geological mapping combined by depth research were identified in Mala vas, where layers of gravel, sand, silt and clay exhibit rapid mutually interchanges, with additional layers being found with a penetration under 15 blows. In most Bovec areas and in other sites located on slopes, glacial moraine deposits (tills) of different thicknesses occur. Sites located in lowlands are based on the Soča River and gravel deposits of its tributaries, where the


**Figure 4.** Upper Posočje, where the survey sites considered in the analysis are located.

penetration tests showed 15 to 50 blows at a distance of 30 cm. Gravels can be cemented into conglomerates; however, thin-deposited lake clay can also occur between them.

Considering the described geological conditions of the study areas, the seismic effects were categorized according to the following Table 3.

Several ground structures and their seismic characteristics were also established by geo-physical investigations. Refraction profiles of more than one kilometer lengths were performed at seven locations by measurements of P and S waves. They were accompanied by 35 geo-electrical measurements serving to complete the information on ground structure, which was obtained by seismic measurements. In the areas of damaged settlements, measurements of seismic

*Table 3: Categorization of local seismic effects considering the described geological conditions.*

| Ground structure | Areas in case | Local seismic effect |
|---|---|---|
| Weathered cover with a thickness of up to 3 m overlying a flysch basis | Drežnica, Koseč, Kred | 1 (very low) |
| Deposits of plain medium dense to dense gravel soils of great thickness, locally changed into conglomerates | Bavščica, Bovec-Podklopca, Bovec- Vodenca, Kobarid, Log Čezsoški, Soča, Srpenica, Staro selo, Trnovo ob Soči | 2 (low) |
| Slope morainic alluvia, medium dense to dense, locally consolidated and with a sandy basis | Bovec-Ravni laz, Jezerca, | 3 (medium) |
| Deposits of plain medium dense gravel soils of great thickness with intermediate layers of sand and silt | Bovec-Ind.cona, Čezsoča, Kal-Koritnica, Žaga | 3 (medium) |
| Slope morainic alluvia with intermediate layers of silt and clay, or changed by slope transport into clayey scree overlaying a flysch basis | Bovec-Brdo, Bovec-Dvor, Bovec-Klanc, Bovec-Kot, Bovec-Rupa, Bovec-Trg gol. žrtev, Lepena, Magozd, Drežniške ravne | 4 (high) |
| Soft deposited sediments with a thickness above 10 m | Bovec-Mala vas | 5 (very high) |

*Table 4. Survey of boreholes and seismic research results.*

| Location | Local seismic effect | Surface layers | | | Deposits | | | | Basis | | Geological structure |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Vp | Vs | Thick. | Vp | Vs | Min. thick. | Max. depth | Vp | Vs | |
| Bovec-Dvor | | | | <2.4 | | | | >17 | | | Beneath clayed-up cover – clayey scree and lake clays |
| Bovec-Ind. zone | | | | | | | | >20 | | | Soča sandy gravel with layers of sand |
| Bovec-Klanc | 2 (low) | 400 | 250 | <3 | 1750 | 800 | 3-5 | >20 | 3100 | 1200 | Morainic alluvia and scree |
| Bovec-Mala vas | 5 (very high) | 250 | 125 | <5 | 900 | 400 | 2-5 | >20 | 2900 | 1200 | Interchanging soft to stiff alluvia deposits – clay, silts and gravels |
| Bovec-Trg golobar. žrtev | | | | <4 | | | | >20 | | | Beneath anthropogenic filled-in materials, morainic scree prevails |
| Čezsoča | | | | | | | | >20 | | | Sandy gravel with layers of sand |
| Drežniške ravne | 4 (high) | 400 | 150 | <4 | 1000 | 500 | 6-9 | 18 | 2800 | 1050 | Heterogeneous morainic alluvia |
| Kal-Koritnica | 3 (middle) | 350 | 150 | <4 | 750 | 450 | 4-10 | >18 | 3250 | 1500 | Clayed-up small-sized scree and piled limestone boulders |
| Magozd | 3 (middle) | 350 | 150 | <4 | 900 | 500 | 5 | 10 | 3350 | 1400 | Clayey scree and moraine with huge limestone boulders |

tremors (microtremors) in the ground and in buildings were performed. For the Bovec area, microtremor measurements in a grid of 200 m × 200 m were also performed (Gosar, 2008). For individual areas addressed with boreholes and geo-physical measurements, data are summarized in the Table 4.

The borehole and seismic investigations show that at almost all locations, plain alluvia and slope moraine and scree sediments was deposited in very thick layers. The first and the second type of alluvia result from fluvio-glacial processes. In both horizontal and vertical directions, they quickly change from solid conglomerate and gravel layers to soft deposited lake sediments. This is also evident from seismic wave transfer velocities reaching between 100 to 300 m/s in a surface cover of up to 5 m thickness and from 1000 to 1600 m/s in deposits. In the treated areas, basis cretaceous flysch prevails. Measurements showed that the lowest values of seismic wave transfers through surface layers occurred in the area of Mala vas in Bovec, followed by Koritnica and Magozd. Somewhat better conditions were found in Drežniške Ravne, while the best conditions were observed in Klanec, which is part of Bovec, and this is quite expected because measurements were performed in an area where flysch was close to the surface.

The geo-electrical measurements performed in the Čezsoča area showed that the flysch basis is more than 100 m deep; they also indicated the possible existence of sandy-silty layers or layers of lake chalk, which could be the reason for the large amount of damage incurred to structures during the 2004 earthquake in the village of Čezsoča.

The first microtremor measurements were performed in Bovec in the area of a Square known as Trg golobarskih žrtev, in Mala vas, in the eastern and western parts of Koritnica, in Čezsoča in the area of the village and in its southern environs, in Spodnje Drežniške Ravne and in the village of Drežnica (Gosar at al, 2001).

Compared to the centre of Bovec, the first measurements showed significant frequency intensifications in Mala vas; in the areas of Kal-Koritnica, where thicker sediments occur; in the area of the village of Čezsoča, in comparison with its southern environs, where the sediments are wedged out; and in Spodnje Drežniške Ravne in the area of thicker morainic alluvia compared with Drežnica, where flysch occurs under a thinner weathering cover.

Subsequently, more detailed and systematic microtremor measurements were performed in the Bovec town area (Gosar, 2007). These measurements were conducted according to the HVRS method. For different grounds in Bovec, the results are shown in Table 5. The highest level of damage due to resonance occurring between the ground and structures is to be expected in the frequency range of 7–11 Hz.

According to the above table, an increased impact of ground oscillation, which indicates possible interference with oscillations in buildings, is provided for the areas of Bovec-Dvor, Bovec-Industrijska cona and Bovec-Mala vas.

*Table 5. Results of recent HVRS microtremor measurements made for the treated areas of Bovec (acc. to Gosar, 2007) and of older measurements made for other sites.*

| Bovec area | Fundamental frequency peak | Increased impact on structures |
|---|---|---|
| Bovec-Brdo | 12–14 | |
| Bovec-Dvor | 7–9 | x |
| Bovec-Industrial zone | 9–12 | x |
| Bovec-Klanc | 13–18 | |
| Bovec-Kot | 11–13 | |
| Bovec-Mala vas | 7–13 | x |
| Bovec-Rupa | 13–16 | |
| Kal-Koritnica | | x |
| Čezsoča | | x |
| Drežniške Ravne | | x |

## 4. Analysis of the stuctural damage

During the 1998 earthquake, 3390 damaged buildings were registered. On the basis of a detailed inventory of damage to structures, the damage to these structures was classified into one of five damage grades from Grade 1 to Grade 5, which were defined in accordance with the European Macroseismic Scale (Grünthal, 1998).

Almost all structures damaged in both earthquakes were built of limestone blocks, which are a local material used for construction, bonded together with weakly connecting mortar and based on weak foundations. In larger villages, buildings are also made of bricks, while buildings made of quality reinforced concrete structural elements are rare. All structures damaged during the 1998 earthquake were categorized into vulnerability classes from A to F, according mentioned European Macroseismic Scale.

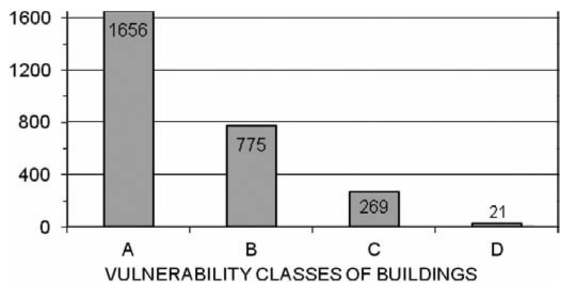


**Figure 5.** Vulnerability classes of buildings in the upper Posočje area.

*Table 6. Data on damage to structures in selected areas registered after the 1998 earthquake.*

| Place | Number | | | | Damage assessment | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | A | B | C | D |
| Log Čezsoški | 0 | 7 | 4 | 0 | 0.00 | 2.00 | 2.25 | |
| Bovec-Vodenca | 7 | 3 | 1 | 0 | 1.00 | 1.00 | 1.00 | |
| Staro selo | 3 | 0 | 0 | 0 | 1.00 | | | |
| Žaga | 21 | 8 | 0 | 0 | 1.05 | 1.00 | | |
| Koseč | 38 | 22 | 22 | 0 | 1.05 | 1.14 | 1.00 | |
| Kred | 13 | 10 | 1 | 0 | 1.08 | 1.00 | 1.00 | |
| Jezerca | 21 | 16 | 3 | 1 | 1.20 | 1.00 | 1.00 | 1.00 |
| Trnovo ob Soči | 19 | 58 | 10 | 0 | 1.47 | 1.22 | 1.10 | |
| Kobarid | 30 | 30 | 10 | 7 | 1.63 | 1.27 | 1.00 | 1.00 |
| Bovec-Dvor | 26 | 10 | 0 | 0 | 1.65 | 1.00 | | |
| Bovec-Podklopca | 3 | 6 | 3 | 0 | 1.67 | 1.00 | 1.00 | |
| Drežnica | 4 | 0 | 0 | 0 | 1.75 | | | |
| Bavšica | 10 | 2 | 1 | 0 | 1.80 | 1.00 | 1.00 | |
| Bovec-Kot | 11 | 6 | 0 | 1 | 2.00 | 1.00 | | 1.00 |
| Čezsoča | 10 | 4 | 2 | 0 | 2.00 | 2.25 | 2.00 | |
| Bovec-Industrial zone | 71 | 11 | 3 | 0 | 2.01 | 1.27 | 1.00 | |
| Soča | 73 | 14 | 7 | 0 | 2.05 | 1.00 | 1.00 | |
| Bovec-Rupa | 8 | 9 | 43 | 0 | 2.25 | 1.44 | 1.00 | |
| Bovec-Brdo | 35 | 14 | 5 | 0 | 2.26 | 2.86 | 1.00 | |
| Srpenica | 5 | 7 | 4 | 0 | 2.40 | 1.00 | 1.00 | |
| Magozd | 7 | 0 | 0 | 0 | 2.57 | | | |
| Bovec-Klanc | 9 | 10 | 4 | 0 | 2.67 | 1.70 | 1.00 | |
| Bovec-Trg golob. žrtev | 20 | 13 | 10 | 0 | 3.15 | 1.54 | 1.00 | |
| Kal-Koritnica | 36 | 30 | 3 | 3 | 3.19 | 1.60 | 1.00 | 1.00 |
| Lepena | 46 | 13 | 5 | 0 | 3.20 | 2.00 | 1.00 | |
| Bovec-Ravni laz | 61 | 51 | 13 | 2 | 3.21 | 2.37 | 2.46 | 1.00 |
| Drežniške ravne | 23 | 23 | 0 | 0 | 3.26 | 2.39 | | |
| Bovec-Mala vas | 34 | 54 | 7 | 0 | 3.29 | 2.57 | 1.86 | |

The reasons for such large seismic effects on structures during the 1998 earthquake are actually based on their extremely high vulnerability, given that the majority of them fall into the two most vulnerable classes A and B (Figure 5).

During the 2004 earthquake, the damage to structures occurred mostly in areas where considerable influence of the ground provoked additional intensification of seismic effects. Therefore, in the town of Čezsoča, a several number of structures that were only slightly damaged during the 1998 earthquake incurred heavy damage during the 2004 earthquake.

A statistical analysis was conducted in selected areas with similar geological conditions. Damage assessment grades ranging from 1 to 5 for inspected buildings with vulnerabilities ranging from A to D were combined within the investigated areas, and the average damage values and numbers of buildings in an individual damage grade were calculated (Table 6). The average value allowed the assessment of ground type effects on the damage to structures. In the Table, the areas are provided in a successive order from the lowest to the highest vulnerability in class A.

For the building vulnerability assessment from B to D, the damage assessment value was additionally normalized by the division of values with an average damage value (Table 7).

From the Table 7, we can see that in areas where several structures of vulnerability class B occur, their damage assessment value should also be considered, while buildings of higher quality construction types (class C and D) are less numerous, and thus, they can be eliminated from the damage assessment value of the selected areas. For further analysis of the damage assessment values in the selected areas, the first two columns, A and B, related to the building vulnerability were used.

From the Table 7, it is possible to define seismic effects of the ground resulting from the 1998 earthquake events for the selected areas in relation to surface and deep ground structures and their seismic characteristics. Data from the 2004 earthquake were not subjected to this analysis due to the unsuitability of the structure damage inventory methodology.

The distance of the analysed sites from the earthquake epicenter may also be an important influential factor (Figure 6).

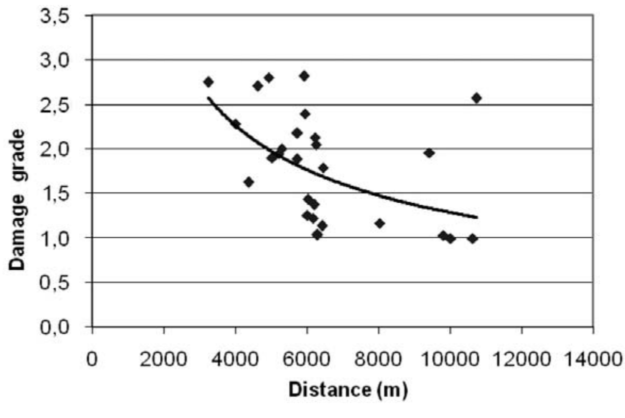


**Figure 6.** Correlation between the distance of sites from the epicenter and mean values of damage to structures.

*Table 7. Normed values of damage per vulnerability classes.*

| Place | Normalized average | | | | Average | Average |
|---|---|---|---|---|---|---|
| | A | B | C | D | (A–B) | (A–C) |
| Log Čezsoški | 0.00 | 1.33 | 1.84 | 0.00 | 0.66 | 1.06 |
| Bovec-Vodenca | 0.50 | 0.66 | 0.82 | 0.00 | 0.58 | 0.66 |
| Staro selo | 0.50 | 0.00 | 0.00 | 0.00 | 0.25 | 0.17 |
| Žaga | 0.53 | 0.66 | 0.00 | 0.00 | 0.60 | 0.40 |
| Koseč | 0.53 | 0.76 | 0.82 | 0.00 | 0.64 | 0.70 |
| Kred | 0.54 | 0.66 | 0.82 | 0.00 | 0.60 | 0.67 |
| Jezerca | 0.60 | 0.66 | 0.82 | 1.00 | 0.63 | 0.69 |
| Trnovo ob Soči | 0.74 | 0.81 | 0.90 | 0.00 | 0.77 | 0.82 |
| Kobarid | 0.82 | 0.84 | 0.82 | 1.00 | 0.83 | 0.83 |
| Bovec-Dvor | 0.83 | 0.66 | 0.00 | 0.00 | 0.75 | 0.50 |
| Bovec-Podklopca | 0.84 | 0.66 | 0.82 | 0.00 | 0.75 | 0.77 |
| Drežnica | 0.88 | 0.00 | 0.00 | 0.00 | 0.44 | 0.29 |
| Bavšica | 0.90 | 0.66 | 0.82 | 0.00 | 0.78 | 0.79 |
| Bovec-Kot | 1.00 | 0.66 | 0.00 | 1.00 | 0.83 | 0.56 |
| Čezsoča | 1.00 | 1.50 | 1.64 | 0.00 | 1.25 | 1.38 |
| Bovec-Industrial zone | 1.01 | 0.84 | 0.82 | 0.00 | 0.93 | 0.89 |
| Soča | 1.03 | 0.66 | 0.82 | 0.00 | 0.85 | 0.84 |
| Bovec-Rupa | 1.13 | 0.96 | 0.82 | 0.00 | 1.04 | 0.97 |
| Bovec-Brdo | 1.13 | 1.90 | 0.82 | 0.00 | 1.52 | 1.28 |
| Srpenica | 1.20 | 0.66 | 0.82 | 0.00 | 0.93 | 0.90 |
| Magozd | 1.29 | 0.00 | 0.00 | 0.00 | 0.64 | 0.43 |
| Bovec-Klanc | 1.34 | 1.13 | 0.82 | 0.00 | 1.23 | 1.10 |
| Bovec-Trg golobar. žrtev | 1.58 | 1.02 | 0.82 | 0.00 | 1.30 | 1.14 |
| Kal-Koritnica | 1.60 | 1.06 | 0.82 | 1.00 | 1.33 | 1.16 |
| Lepena | 1.60 | 1.33 | 0.82 | 0.00 | 1.47 | 1.25 |
| Bovec-Ravni laz | 1.61 | 1.57 | 2.01 | 1.00 | 1.59 | 1.73 |
| Drežniške ravne | 1.63 | 1.59 | 0.00 | 0.00 | 1.61 | 1.07 |
| Bovec-Mala vas | 1.65 | 1.71 | 1.52 | 0.00 | 1.68 | 1.63 |

The above diagram indicates a trend in the damage to structures decreasing in relation to distance. Moreover, the diagram shows that in the case of such small differences in distance from the epicenter, the structure of the ground has a greater influence on damage to structures than distance itself. In further analyses, the influence of the distance of sites from the epicenter was neglected.

## 5. Description of legislation used for ground type determination

At the time of the 1998 earthquake, regulations introducing dynamic coefficients depending on the ground category were used in Slovenia for the determination of ground structure influence (Ur.l. 31, 1981). In the Table 8, a description of the ground structure for each individual category is given.

With Slovenia's accession to the European Union, EUROCODE 8 (1994) began to be used as a parallel regulation, which divided the ground into sub-categories A1, A2, A3; B1, B2, B3; C1 and C2 with respect to seismic effects.

After 2005, a new Eurocode 8 began to be used, and from the beginning of 2008, which has also been officially applicable in Slovenia. It presents a new ground type distribution, with ground types A, B, C, D, E, S1 and S2.

## 6. Comparison of assessed and actual impacts of local structures on seismic intensity

First, it should be assessed to what extent the seismo-geological conditions evaluated by geological mapping and drilling, refraction measurements and measurements of microtremors correspond to the actually established local effects incurred during the 1998 earthquake. In the Table 9, a forecast of local seismic effects is compared with the actually established damage to structures classified into vulnerability classes A and B. We can see that, in general, the forecasts hold up well. However, they can also vary considerably. All forecasts for Bovec-Mala vas indicate local seismic effects as being most expressive, which fully corresponds to the actual damage to structures.

The forecast made on the basis of geological structures does not hold true in Žaga, where the forecast of the thickness and structure of alluvial deposits of the Soča River was most likely too pessimistic. In the case of Koseč and Kred,

*Table 8. Description of ground types in relevant regulations.*

| Category of ground | Structure of the ground |
|---|---|
| A | Rocky and medium-rocky ground (crystal rocks, shales, carbonate rocks, limestone, marl, well cemented conglomerates and similar components). Very compact solid ground less than 60 m thick composed of stabile layers of gravel, sand and hard clay above hard geological formations. |
| B | Compact and medium-compact ground and very compact solid ground more than 60 m thick composed of stabile layers of gravel, sand and hard clay above hard geological formations. |
| C | Less compact and softer ground, more than 10 m thick composed of soft gravel, medium-stiff sand and hard molding clay, with or without layers of sand or other incoherent materials. |

*Table 9. Comparison of 1998 earthquake damage to structures with local seismic effect determination according to different methods.*

| Place | Actual damage | | Forecast of local seismic effect | | |
|---|---|---|---|---|---|
| | A | B | Geological structure | Refraction measurements | Microtremor |
| Log Čezsoški | 0.00 | 1.33 | low | | |
| Bovec-Vodenca | 0.50 | 0.66 | low | | |
| Staro selo | 0.50 | 0.00 | low | | |
| Žaga | 0.53 | 0.66 | medium | | |
| Koseč | 0.53 | 0.76 | very low | | |
| Kred | 0.54 | 0.66 | very low | | |
| Jezerca | 0.60 | 0.66 | medium | | |
| Trnovo ob Soči | 0.74 | 0.81 | low | | |
| Kobarid | 0.82 | 0.84 | low | | |
| Bovec-Dvor | 0.83 | 0.66 | high | | Increased effect |
| Bovec-Podklopca | 0.84 | 0.66 | low | | |
| Drežnica | 0.88 | 0.00 | very low | | |
| Bavšica | 0.90 | 0.66 | low | | |
| Bovec-Kot | 1.00 | 0.66 | high | | |
| Čezsoča | 1.00 | 1.50 | medium | | Increased effect |
| Bovec-Industrial zone | 1.01 | 0.84 | medium | | Increased effect |
| Soča | 1.03 | 0.66 | low | | |
| Bovec-Rupa | 1.13 | 0.96 | high | | |
| Bovec-Brdo | 1.13 | 1.90 | high | | |
| Srpenica | 1.20 | 0.66 | low | | |
| Magozd | 1.29 | 0.00 | high | middle | |
| Bovec-Klanc | 1.34 | 1.13 | high | low | |
| Bovec-Trg golob. žrtev | 1.58 | 1.02 | high | | |
| Kal-Koritnica | 1.60 | 1.06 | medium | middle | Increased effect |
| Lepena | 1.60 | 1.33 | high | | |
| Bovec-Ravni laz | 1.61 | 1.57 | medium | | |
| Drežniške Ravne | 1.63 | 1.59 | high | high | Increased effect |
| Bovec-Mala vas | 1.65 | 1.71 | very high | very high | Increased effect |

which are located on flysch slopes with weathering soil, the impact of terrain morphology almost certainly caused an increase of seismic effects. In the case of Drežnica, which was only slightly damaged overall during the earthquake, the evaluation of actual damage was lower than shown by the calculations due to the presence of only a few poorly constructed buildings. For structures located in the hamlet of Soča, we can find no explanation for to low forcast. In the case of Srpenica, gently deposited soft coherent layers mixed among gravel, which were not foreseen in advance, caused the increased seismic effects.

Refraction measurements, especially the determination of shear wave velocity (Vs), lead to quite closely corresponding forecasts if we discard seismic measurements in the area of Bovec-Klanec. In this area, where a seismic profile was obtained outside the village, the measurements were performed on essentially better terrain compared to in the village itself.

The microtremor measurements performed in the Bovec-Mala vas and Drežniške Ravne areas show duly increased seismic effects. Other sites where the HVRS method results in an increased effect also fall into the upper class of actual damage; however, in relatively numerous areas with large amounts of damage to structures, the microtremor measurements do not result in potentially increased effects.

During the ten-year post-earthquake reconstruction process, the identification of foundation conditions for numerous new buildings and the construction other damaged structures was accompanied by the determination of ground type following relevant regulations applicable in that period. If we compare the type of ground according to the regulations in force in this period with actually incurred damage, we can assess the extent of the applicability of certain regulations, as well as their ability to provide a suitable assessment of local seismic effects. This comparison was made based on the data presented the Table below, where the selected sites were classified with respect to the calculated actual damage to structures belonging to vulnerability classes A and B, as well as on the given ground classification according to all three regulations (Table 10).

Classification of the ground according to Slovenian regulations, dividing the terrain into three classes (A, B and C for good, medium and bad ground), proves to be much too rigid, showing no differences in local seismic effects of the ground. Additionally, classification into a certain class is often a consequence of an assessment made on the basis of local surface conditions. Therefore, in Table 7, grade C, indicating the weakest soil, was given to the analysed areas of Kred, Bovec-Kot, Bovec-Brdo and Magozd, where the surface layers are composed of slope talus (resulting from tills) formed from hardly molding clays with transfers to clayey gravels. The problem arises of the fact that for a case of gently deposited sediments with thickness of several meters but smaller than 10 m because no adequate description of such circumstances is given in the regulations.

EUROCODE 8–94, providing ground effect determination and including 8 classes (A1, A2, A3, B1, B2, B3, C1 and C2), enables experts to carry out much easier classification due to a greater number of classes. However, a disadvantage of these regulations lies in the fact that they do not address either the definition of the thickness of surface layers or the effects of soft layers covering a solid basis, which are often very important for local seismic effects. The consequence of these disadvantages is an often problematic classification according to EU8-(98), giving no actual local seismic effects. This was also evident in the

*Table 10. Comparison of damage to structures with classification of the ground according to regulations covering seismic effects of the ground.*

| Place | Actual damage | | Classification of ground into classes acc. to relevant regulations | | |
|---|---|---|---|---|---|
| | A | B | SLO | EU93 | EU05 |
| Log Čezsoški | 0.00 | 1.33 | B | A2 | B |
| Staro selo | 0.50 | 0.00 | B | B3 | D |
| Bovec-Vodenca | 0.50 | 0.66 | B | A2 | B |
| Žaga | 0.53 | 0.66 | B | A2 | B |
| Koseč | 0.53 | 0.76 | B | B1 | A |
| Kred | 0.54 | 0.66 | C | B3 | D |
| Jezerca | 0.60 | 0.66 | B | A2 | B |
| Trnovo ob Soči | 0.74 | 0.81 | B | A2 | B |
| Kobarid | 0.82 | 0.84 | B | B2 | C |
| Bovec-Dvor | 0.83 | 0.66 | B | B2 | C |
| Bovec-Podklopca | 0.84 | 0.66 | B | A2 | B |
| Drežnica | 0.88 | 0.00 | B | B1 | A |
| Bavšica | 0.90 | 0.66 | B | A2 | B |
| Bovec-Kot | 1.00 | 0.66 | C | B2 | C |
| Čezsoča | 1.00 | 1.50 | B | A2 | B |
| Bovec-Industrial zone | 1.01 | 0.84 | B | A2 | B |
| Soča | 1.03 | 0.66 | B | A2 | B |
| Bovec-Rupa | 1.13 | 0.96 | B | B2 | C |
| Bovec-Brdo | 1.13 | 1.90 | C | B2 | C |
| Srpenica | 1.20 | 0.66 | B | A2 | B |
| Magozd | 1.29 | 0.00 | C | B2 | E |
| Bovec-Klanc | 1.34 | 1.13 | B | B2 | E |
| Bovec-Trg golob. žrtev | 1.58 | 1.02 | B | B2 | C |
| Kal-Koritnica | 1.60 | 1.06 | B | B2 | C |
| Lepena | 1.60 | 1.33 | B | A2 | B |
| Bovec-Ravni laz | 1.61 | 1.57 | B | A2 | B |
| Drežniške Ravne | 1.63 | 1.59 | C | B2 | E |
| Bovec-Mala vas | 1.65 | 1.71 | C | B3 | E |

upper Posočje area because the correlation between actual damage and classification according to Eurocode 8 dating for 1994 is very low.

A major step forward regarding the assessment of local seismic effects was made in the introduction of the new EUROCODE 8 regulations for 2005 (with classes of ground types ranging from A to E and with two special types, S1 and S2). The regulations for 2005 were upgraded by the Slovenian national appendix (EU8-SIST EN 1998-1:2005) and approved for obligatory application in Slovenia from the beginning of 2008. These regulations first introduce a map of design ground accelerations in the area of Slovenia substituting the old seismic map with a return period of 500 years dating from 1987 (Ribarič, 1987). The determination of local ground structure effects depends not only on descriptive factors, but also on measurable characteristics of sediments, such as the results of standard penetration tests (SPT), shear seismic wave velocity (Vs) in the upper 30 m and the undrained shear strength of soils (Cu). Some of these measurements were performed in the upper Posočje area; however, not enough to completely determine the local seismic effects of the ground. The consequence of this and of the extremely complex conditions of geological structures resulted in categorization of the ground into the EU8-05 classes, which do not correspond best with the actual damage.

## 7. Conclusion

In this study, we analysed the influence of local ground structure on increased seismic effects on human-built structures. On the basis of data collected during the 1998 and 2004 earthquakes, we attempted to establish methodology for reliable determination of this influence. Moreover, we were interested in determining which ground type classificationis most applicable for the analysed cases in these two earthquakes.

The better the knowledge of the structure, seismological characteristics and thickness of surface layers and the type of rock basis, the greater the possibility to appropriately forecast relevant seismic effects. However, the more complex the geological structure of the ground and the less well-investigated it was in the past, the greater the scope of necessary investigations shall be. Through comparisons of ground type impact assessments performed by geological mapping and drilling, geo-physical measurements and measurements of microtremors with actually established damage to structures, it was found that the forecasts were more reliable if they were made with appropriate consideration of all characterisitcs determined in these investigations together. The regulations presently applicable in the European Union take this into account, as in addition to the collection of spatial data on the expansion of layers used to define ground type for the purpose of further determination of local seismic effects, they propose the implementation of field measurements, including the determination of ground density and seismic characteristics of sediments.

In spite forecasts being implemented using this type of multidisciplinary approach, in the case of the two upper Posočje earthquakes, examination of their effects showed that forecasts can be completely incorrect regarding seismic effects. A considerable number of examples of this phenomenon are given in this article. For example, the assessment of seismic effects based on geological structures gives an incorrect forecast for the areas of Kred and Koseč, and the refraction measurements are much too optimistic for the area of Bovec--Klanc. The microtremor measurements made in compliance with the HVRS method underestimate the earthquake effects in the areas of Bovec-Klanc and Bovec-Kot when compared with actual damage. The best example of how a forecast can deviate from reality is the example of the village of Čezsoča, where during the considerably stronger earthquake of 1998, less damage to structures was registered than in case of the 2004 earthquake, in spite of the fact that the epicenters of both earthquakes were located on the same tectonic fault, at the same depth and only several hundred meters apart.

Our analysis of different regulations used to forecast local effects of the ground also showed that caution should be taken in making forecasts. In the case of extremely good or bad ground conditions, the classification can be forecast well; however, problems arise in forecasts made for complex or relatively poorly known geological structures. Thus, in the upper Posočje area, the thickness of moraine deposits, position of consolidated breccia layers and softer clayey, silty or sandy inputs between them were often not known. Similarly, in lowland sediments of Soča, neither the positions of gravel bound into conglomerates nor lake chalk layers between them were known. In areas of small villages located in hilly regions located in hilly regions in Slovenia, a lack of slope sediment thickness data is often a problem. Consequently, our forecasts often deviate from actually established seismic effects in the area.

With the adoption of Eurocode 8 for 2005 a step forward was made with respect to better forecasting of local seismic effects of the ground. However, these regulations require more detailed data on local geological structures and physical characteristics of the ground, and thus, they are applicable only in areas where these data exist. Such areas are mostly found in larger villages and towns built on alluvial plains, where many investigations related to the deep foundations of tall structures have been conducted. In areas like the upper Posočje region, these regulations are less reliable. In addition to the fact that data on ground structures and characteristics are often not available, forecasts are also hindered by rapid changes in local morphological and seismo-geological conditions. As demonstrated by the analyses described in this article, in many cases, even when there is an excellent understanding of geological-seismic conditions, forecasts of the expected local seismic effects of the ground do not correspond with actual seismic effects related to damage to structures.

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SAŽETAK

## Geološke i geotehničke značajke tla koje su utjecale na lokalne učinke potresa iz 1998. i 2004. u Gornjem Posočju u Sloveniji

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Dva snažna potresa u sjeverozapadnom dijelu Slovenije dogodila su se 1998. i 2004. Oštećenja na građevinama, koja su zabilježena u popisu šteta nastalih ovim potresima, klasificirana su u pet kategorija prema Europskoj makroseizmičkoj ljestvici (EMS). Neposredno nakon potresa provedena su opsežna geološka i geofizička istraživanja koja su obuhvaćala: geološko kartiranje, iskop 60 istraživačkih jama, bušenje 20 bušotina do dubine od 20 m, seizmička mjerenja, geoelektrična mjerenja i mjerenje mikroseizmičkih nemira. Od 1990. godine, utjecaji lokalnog tla u Sloveniji se uzimaju u obzir primjenom odgovarajućih pravila za proračunavanje potresom opterećenih konstrukcija; napočetku primjenom Slovenskih propisa (Službeni list SFRJ 31/81), a kasnije Eurokoda 8 (EU8-94 i EU8-SIST EN 1998-1:2005).

U ovom članku se opisuju istraživanja utjecaja lokalnog tla na pojačanje seizmičkog djelovanja na građevine. Na temelju podataka o oštećenjima i podataka iz prethodno spomenutih istraživačkih radova, nastojalo se odrediti koliko je moguće pouzdano procijeniti taj utjecaj. Predviđeni lokalni seizmički efekti uspoređeni su s registriranim oštećenjima građevina. Provedena je statistička analiza na 27 odabranih lokaliteta (naselja) sa sličnim geološkim uvjetima.

Usporedbom procjene utjecaja lokalnog tla, koji je određen na temelju geološkog kartiranja i bušenja, kao i geofizičkih ispitivanja i mjerenja mikroseizmičkih nemira, s registriranim oštećenjima građevina, zaključeno je da je predviđanje puno pouzdanije ako se promatraju svi relevantni faktori zajedno. Međutim, usprkos tome što je primijenjen multidisciplinarni pristup, za neke su lokacije dobivene potpuno pogrešne prognoze seizmičkih efekata. Može se zaključiti da je najbolja prognoza dobivena primjenom EU8-SIST EN 1998-1:2005, dok su manje pouzdani rezultati dobiveni primjenom Slovenske norme (Službeni list SFRJ 31/81) i EU8-94.

*Ključne riječi*: potresi u sjeverozapadnoj Sloveniji, Europska makroseizmička ljestvica, Eurokod 8, tipovi tla, procjena oštećenja od potresa, predviđanje lokalnih seizmičkih efekata

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