STUDIA GEOMORPHOLOGICA CARPATHO-BALCANICA
VOL. XXXVII KRAKÓW 2003 PL ISSN 0081-6434
LANDFORM EVOLUTION IN MOUNTAIN AREAS

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MASS MOVEMENTS IN THE JULIAN ALPS (SLOVENIA) IN THE AFTERMATH OF THE EASTER EARTHQUAKE ON APRIL 12, 1998

Abstract. The Easter earthquake on April 12, 1998, in Julian Alps, besides enormous damage on residential and other buildings, has also caused a large number of slope failures. Hundreds of small rockfalls were released directly by the main earthquake or in the following days due to aftershocks. Most of them originated on the mountain crests and upper parts of slopes, which clearly confirms the thesis about the direct influence of relief on the amplitude of earthquake waves (i.e. topographic amplification). Besides those phenomena the article presents two other major events, which despite the time remoteness from the main earthquake, may be connected to ground movements caused by earthquakes: debris flow which on November 17, 2000, destroyed the mountain village of Log pod Mangartom, and landslide of December 22, 2001, above the Koseč village, which still threatens its inhabitants. The main reason why such natural events have not caused much more damage so far in Slovene mountains, is mostly in rather safe position of settlements what is also clearly visible on the potential landslide hazard map.

Key words: earthquake, mass movements, topographic amplification, rockfalls, landslide, debris flow, Julian Alps, Slovenia

GEOLOGIC AND GEOMORPHOLOGIC CHARACTERISTICS OF THE INVESTIGATED AREA

The Julian Alps are geologically a part of the Southern Alps, which geologists consider as part of the Dinarides, while geographically they belong with the Southern limestone Alps. They consist of several nappes of Mesozoic rocks, which originate along the Periadriatic lineament and were pushed from north-east to south-west. In the Julian Alps, an extensive nappe of Triassic rocks, mostly made of thick layers of Dachstein limestone and dolomite, was thrust onto the Cretaceous flysch rocks of the southern foothills. The carbonate nappe is severely dissected with faults of mostly Dinaric orientation from north-west to south-east. The most active among them is Idrija fault, which goes along the Soča River valley from Žaga across Kobarid to Tolmin and by Idrija and Cerknica towards the south-east. The Easter earthquake originated along a smaller fault a few kilometres to the north and parallel to the Idrija fault (Gosar et al. 1999).

Especially the carbonate rocks of the investigated area are tectonically heavily deformed and fractured, what is very favorable for the triggering of rockfalls and rockslides due to earthquake shocks. There are three dominant fracture systems in these rocks, almost rectangular one to the other: especially in Dachstein limestone there are distinctive bedding planes and, rectangular to them, two more fracture systems, originated from tectonic deformations. In this way the distinctive block structure developed, with average block size from 0.1 to 0.5 metres (Ribičič and Vidrih 1998b). Near the surface, the weakness of rock strata is intensified by mechanical and chemical weathering and, in many places, the strata inclination is parallel to the slope what is also very favorable for rock sliding.

From the point of view of recent tectonic activity, the investigated area is situated on the eastern edge of Friuli seismic zone, which is characterized by shallow earthquakes with hypocentre depths from 20 to 40 kilometres, and sporadic earthquake events. There are two explanations of seismic activity of this zone: according to the first one, in this area the African lithospheric plate is subducting towards north-east under the Eurasian plate (Gams 1976a, b), while according to the other, the area tectonically belong to the Adriatic microplate, on which occasional isostatic accommodations occur due to recent tectonic rising of Alps and Dinaric mountains (Ribarič 1980; Vidrih and Godec 1998; Boschi et al. 1999).

EARLIER EARTHQUAKES AND MASS MOVEMENTS IN JULIAN ALPS AND SURROUNDINGS

It is quite common that, especially in mountain areas, the earthquakes trigger ground movements, from smaller rockfalls and landslides to major rockslides. Even during the Easter earthquake of 1998 the inhabitants of the affected area were additionally frightened by the tremendous noise of falling rocks, which from the upper slopes rolled down to the lower-lying forests and stopped there. The direct link among such phenomena and ground movements due to earthquake is clearly visible but, in the case of much larger mass movements, the relation between earthquake shocks and the response of rock masses or weathered material is much more complicated, what consecutively lengthens the time lap between earthquake tremors and mass movements. What time difference can still be evaluated as a causal link, remains an open question in scientific literature.

It is already known that in the investigated mountainous area mass movements of various size have been triggered on mountain slopes by previous strong earthquakes. Probably the largest rockslide in all Europe, directly connected to earthquake, happened during catastrophic earthquake of January 25, 1348, whose epicentre was near the town of Villach in Carinthia, Austria. The magnitude of the earthquake was 6.6 on the Richter scale and its intensity was estimated as grade 10 on the EMS-98 scale. The earthquake was relatively shallow (hypocentre depth 6–8 kilometres) and it has totally destroyed the town of Villach and many nearby villages. On the southern slopes of Dobratsch Mountain (2,166 metres), it triggered several enormous rockslides, which slid into the valley bottom along the Gail River.

Even among the scientific community there are still considerations that this earthquake has caused the collapse of whole rockslide mass with volume of about 1 billion cubic metres (Ribarič 1980, 1994; Vidrih and Ribičič 1994; Ribičič and Vidrih 1998a). However, already A. Till (1907) realized that rockslides of 1348 started on the same place as much larger rockslide at the end of the Pleistocene period. This rockslide was enormously larger and dammed the Gail River into a large lake. The younger rockslides of 1348 have covered up only a part of the old rockslide, but were still of colossal dimensions as about 148 million cubic metres of rock masses covered the area of 6.11 square kilometres (Zorn 2001).

The catastrophic earthquake on March 26, 1551, near Idrija has also caused major rockslides. It was, up to now, the strongest known earthquake in Slovenia (M = 6.9, depth 15–20 kilometres, intensity 10 on the EMS-98 scale), and was most likely followed by an even stronger earthquake half an hour later with epicentre about 50 kilometres to the west in nearby Friuli (M = 7.0–7.2, depth 20 kilometres, intensity 10 on the EMS-98 scale; Ribarič 1980, 1994). Close to the epicentre of the first earthquake and at that time already famous mercury mine of Idrija, a large rockslide temporarily dammed the Idrijca River valley. Many rockslides were triggered in nearby Friuli as well (Ribarič 1980; Vidrih and Ribičič 1994).

The earthquake of May 6, 1976, originated in depths between 20 and 30 kilometres near the town of Tolmezzo by the Tagliamento River in Friuli, Italy, about 30 kilometres west from Slovene-Italian border (M = 6.5, intensity 9–10 on the EMS-98 scale; Ribarič 1994). At this occasion, the vibrations have also triggered many rockfalls and rockslides in the epicentre area, which blocked several roads and railway line, while on the Slovene side of the border earthquake shocks have only caused some smaller rockfalls in the mountainous areas.

Great changes in natural settings were also caused by the Easter earthquake of April 12, 1998, in the mountainous area between Bovec and Tolmin (Ribičič and Vidrih 1998b). According to seismological data the earthquake's hypocentre was in depth of only 8 kilometres. It reached the magnitude of 5.6 on the Richter scale and intensity of 7–8 on the EMS-98 scale (Gosar et al. 1999). Due to shallow hypocentre the seismic energy was released on a relatively small area of southern part of the Julian Alps, but much greater ground accelerations were achieved than during the deeper and a little more distant Friuli earthquake of 1976. According to these measurements, the effects of seismic waves on unstable rock masses were much more significant, too.

THE RELATIONSHIP BETWEEN EARTHQUAKES AND MASS MOVEMENTS

Several hundred rockfalls and rockslides in a comparatively small area, set in motion by Easter earthquake of 1998, could be hardly explained exclusively as a direct effect of earthquake shocks only, because the earthquake was not very intensive and many disintegrated and fractured rock masses were already moved by the earthquake of 1976. Field observations showed that the number of mass movements distinctively increases with altitude, in fact, the bulk of them occurred in the middle and upper parts of the slopes.

Most likely, such a distribution is not the consequence of differences in slope stability, because the lower slopes of Soča River valley are also very steep and unstable due to Pleistocene glacial activity and, therefore, rockslides and rockfalls frequently occur in these parts, too. After the Soča glacier retreat at the end of Pleistocene a major rockslide originated on southern slope of Polovnik Mountain near Srpenica village, which for quite some time dammed the Soča River. In the lake behind the barrier a thick layer of calcareous silt was accumulated (Winkler 1926; Šifrer and Kunaver 1978; Bavec 2001). On August 8, 1950, in the middle of the day (at 13.30), about 150 metres wide and 10 metres thick mass of limestone (about 80,000 cubic metres) was suddenly released along a distinctive bedding plane, parallel to the slope on the Javoršček Mountain (1,557 m), about 910 metres above the sea level, and stopped in the forest a few hundred metres lower (Planina 1952). On the main valley road Bovec–Vršič–Kranjska Gora several rockfalls from slopes above valley floor have been registered since 1993 (the largest event happened on December 19, 1993, at 0.17; about 7,500 cubic metres of material), due to what the endangered road had to be build under the galleries (Pavšek 1994a).

Such mass movements are distinctively sporadic and result of slow weakening of connection between rock mass and bedrock due to progression of exogenic geomorphic processes along bedding planes and other fissures. It is difficult to identify direct triggers of such movements, for they are just "normal" sequences of geomorphic landscape evolution (Natek 1989). As a very sudden event the rockslide on the Javoršček Mountain must be pointed out, because it happened in the middle of a sunny August afternoon (Planina 1952).

Detailed investigations of mass movements at earthquakes in other parts of the world have already confirmed the connection between surface dissection and behaviour of earthquake waves. D. N. Petley and W. Murphy with co-workers proved that higher frequency of mass movements on hilltops, ridges and upper parts of slopes can be ascribed to the influence of relief on the amplitude of earthquake waves. By increasing the relative altitude between valley floor and mountain tops, the ground accelerations and also the amplitude of earthquake waves increase, similar to the behaviour of high buildings (Petley and Murphy 2001; Murphy et al. 2002). During the earthquake of May 2, 1983, near Coalinga, on the western edge of the San Joaquin valley in California (magnitude of earthquake was 6.7 on the Richter scale) they measured the horizontal accelerations at the Pleasant Valley pumping station: at the bottom of the slope the maximum horizontal acceleration was 0.3 g, while on the top of the slope, only 25 metres higher, it was 0.5 g (Stewart 2002).

In the investigated area it is obvious that rockfalls and rockslides, triggered by the earthquake of 1998, start to appear only a few hundred metres above the valley floor. Most of them and the largest ones were released from the upper parts of slopes, like from the Skutnik (2,074 m)–Vršič (1,897 m) ridge between the Bovec Basin and Lepena Valley, around the Krn peak (2,244 m) and surrounding sharp-crested ridges, as well as on the Osojnica peaks (around 1,200 metres above see level) just above the sources of the Tolminka River. That is also the reason why none of the rockslides endangered settlements or main roads in valley bottoms, although their contribution to geomorphic transformation was pretty considerable.

ROCKSLIDES TRIGGERED BY THE EARTHQUAKE OF APRIL 12, 1998

As already mentioned, there are three, almost rectangular, fissure systems typical for Slovene alpine area, with average block size of 0.1–0.5 metre. Especially, the carbonate rocks are strongly fractured by tectonic movements due to its rigidity. On the surface, these fractures are even more distinctive due to processes of weathering and, during an earthquake, individual blocks can slide easily along such planes of weaknesses (Vidrih and Ribičič 1998).

Slope processes can be seen at work every day and everywhere in the mountains. On screes different rock fragments are gathering throughout the year and, especially, in spring, when temperatures rise above freezing point and the ice in fissures melts, many rock particles break off. However, these are mostly small, unnoticed rockfalls, but major events occur on rare occasions only, more frequently in connection with particular events, like earthquakes. During the Easter earthquake of 1998 there was about 100 larger rockslides registered in Julian Alps around the Soča River valley (Komac and Zorn 2002a).

During an earthquake it can happen that, due to differences in oscillations of particular blocks, the shear strength decreases suddenly along the fractures and a jump across little dents which form roughness of the fracture plane, can occur. When the gravitational stress component, parallel to the sliding plane, becomes larger than shear strength of the material, and the amplitude of oscillations larger than the irregularities on the fracture plane, the block can slide into a lower position. The rockslides and rockfalls released by the Easter earthquake of 1998 occurred mostly along vertical or steep-inclined fissures, along which the rock fragments are the most unstable in general (Vidrih and Ribičič 1998).

The area of greatest landscape changes, caused by the Easter earthquake, spreads from the small town of Bovec in the north-west across the mountain ridges south of the Lepena Valley to the Krn peak (2,224 m) and the Tolminka River valley in the south-east (Vidrih and Ribičič 1998) (Fig. 1). The earthquake moved a few million cubic metres of rocks, mostly in the south-western wall of the Krn peak and on the Osojnica peaks – in both cases more than one million cubic metres.

On the slopes of the Krn peak seven major rockslides and several smaller rockfalls occurred. They originated in places where Dachstein limestone of Norian/Rhetian age was fissured or tectonically fractured and dolomitized (Buser 1986). The slided material has buried an area of about 15 hectares below the south-western wall of the Krn peak. Rockslides on Osojnica have completely destroyed the mountain in three different locations, and covered an area of more than 30 hectares (Komac and Zorn 2002a). These rockslides also originated in Dachstein limestone, usually triggered along fissure systems of different directions, in strongly fractured rocks. As a consequence, the fracture planes of these rockslides are of distinctively irregular shapes.

Of particular interest was a large wedge-shaped rockslide from the Šija ridge above the Lepena Valley. It originated along a bedding plane and a tectonic fissure, which intersect one another and are both inclined in the direction of slope, as well as the upper irregular and almost vertical fissure on the rear side of the rockslide. During earthquake vibrations, the driving force exceeded the shear strength along the vertical fissure, as well as frictional resistance on both inclined planes. The rock mass slid along the sliding planes and over the very steep slope, fractured into large rock boulders on the way and broke into pieces when falling to the foot of the wall. There, a fan-like accumulation of rock debris formed which ended in the forest above the valley bottom (Vidrih and Ribičič 1998).

The described geomorphic processes which accompanied the Easter earthquake did not have greater impact on people, for they mostly originated in remote and uninhabited areas. Some damage was caused on mountain roads and pastures (in the Tolminka River valley a rockslide from Osojnica partly damaged the Polog alp lodge) and mountain paths, as well as monuments and other remnants from the First World War (Vidrih and Ribičič 1998; Komac and Zorn 2002a).

In comparison to the rockslides, triggered by the earthquake of 1998, the debris flow of November 2000 affected a much smaller area, but it partly destroyed the mountain village of Log pod Mangartom and took lives of seven people.

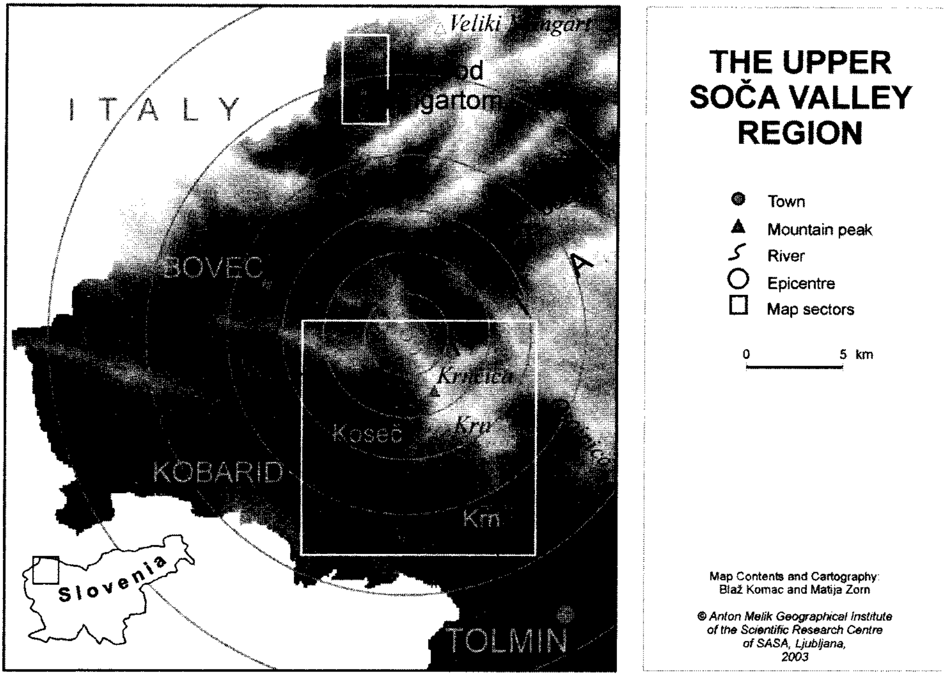

Fig. 1. The upper Soča River valley with the epicentre of the Easter earthquake of April 12, 1998 (Podobnikar et al. 2000)

THE DEBRIS FLOW OF LOG POD MANGARTOM

On November 15, 2000, a large landslide occurred on the Stovžje slope near the peak of Veliki Mangart (2,679 m), at the altitude of about 1,500 metres, almost 1,000 metres above the valley floor along the Koritnica River. Some hundreds of thousand cubic metres large mass at first settled in the Mangart stream valley. During the next day and a half, the region received an enormous amount of rain for, due to high temperatures, it was only snowing above 2,500 metres. Rain water and water from mountain brooks accumulated in the slided mass, which after 36 hours was completely saturated. In the night from November 16 to 17, the mass started to move as a debris flow, which roared successively down the Mangart, Predelica and Koritnica stream valleys and destroyed the mountain village of Log pod Mangartom. Seven people lost their lives, eight houses and eighteen non-residential buildings were destroyed or badly damaged. Next morning the local administration has evacuated the whole village and closed the access to the affected area. On the main road Bovec–Predel (border pass with Italy) two bridges were destroyed, too. The total damage on houses, roads and other infrastructure, and agricultural land was estimated at 14 million euro.

Table 1

Some characteristics of debris flow and its consequences

Area of origin	Area of movement	Area of accumulation
	SITUATION	
Debris flow release.	Sliding and flowing (speed up to 10 metres per second).	Accumulation if debris flow deposits.
Raibler layers over Main dolomite, periglacial and morainic material.	Main dolomite.	Main dolomite, fluvioglacial gravel, Holocene sediments of the Koritnica River.
25 hectares of mountain beech forest (*Fagus sylvatica*), mixed forest and *Pinus mugo* shrubs.	Forests on steep slopes, mostly mountain forest of *Fagus sylvatica* and European hophornbeam (*Ostrya carpinifolia*) with Scotch pine (*Pinus silvestris*) on drier locations.	Meadows and pastures, some fields.
Mountain pasture and mountaineering.		Permanently inhabited area.
	CAUSES AND TRIGGER	
Abundant precipitation (trigger); geological structure, sodden ground and increased instability due to heavy rainfall, rock strata inclination in the direction of slope, accumulation of water in loose masses, strong earthquakes in 1976 and 1998 and numerous aftershocks following the last earthquake (causes).		
	GEOMORPHIC PROCESSES	
The release of landslide and mass movement; liquefying during transport.	Liquefying of the landslide, debris flow and the receiving of additional water from springs, slopes and from the riverbed of Mangart stream (some 1,000 cubic metres).	Accumulation between the village of Log pod Mangartom and confluence of Koritnica with Možnica stream.
Reshaping of slopes by landslide, debris flow and later erosion of streams. Removal of about 1.2 million cubic metres of rock and debris during the main event and subsequent slower movements in the range of a few ten metres (January 2001); clay concretions (Petkovšek 2001) which subsequently disintegrated into pyramid-like piles; smaller mudflows.	Mostly erosion, which has not changed the morphology of slopes and valley floor. During flowing, the debris flow deposited about 400,000 cubic metres of material. Typical accumulation forms (elevated edges of debris flow, clay concretions).	Accumulation in the lower part of Predelica stream valley and as an alluvial fan in the Koritnica River valley (700,000 cubic metres). Part of material was subsequently washed away in suspension by flood waters, later the river changed it course, too. A thin crust formed on the surface of the debris, while inner parts remained liquid. Clay concretions.

CONSEQUENCES AND RECOVERY		
Destroyed local road and access to the Mangart Mountain and Mangart alp closed for more than a year. The construction of small barriers in the riverbed of Mangart stream is planned in the following years.	Destroyed bridge on the main road Bovec–Predel–Tarvisio (Italy) and water intake for the hydro power station of Možnica.	Seven people lost their lives. Eight residential and eighteen non-residential buildings were destroyed, as well as the bridge on the main road Bovec–Predel and hydro power station of Možnica and most of agricultural land. The inhabitants of Koritnica River valley were evacuated for some weeks, the total damage was 14 million euro.

The main reason for the landslide was the specific geological composition of the area. The landslide occurred in 100–200 metres thick layer of Julian/Tuvalian strata (Upper Triassic; in German language called Raibler layers after the village of Raibl, today's Cave del Predil in nearby Italy), which consist of limestone, argillaceous limestone, marlstone and marly shales. When exposed, the latter disintegrate into badly permeable clay consisting of different clay minerals (montmorillonite, kaolinite and illite), which can absorb water and swell. In dry conditions cracks develop on the surface, which can take large amounts of water. That is why the Raibler layers are so prone for mass movements. On Stovžje slope the additional factor was the rock strata inclination in the direction of slope angle, about 30 degrees towards south-south west. The lower part of the landslide mass consisted of Pleistocene morainic and periglacial debris and Holocene weathered material.

The main trigger for the debris flow was heavy rainfall, up to over 300 millimetres per day. In November 2000 the affected area received 1,234 millimetres of precipitation, which is about half of average yearly precipitation and four times of November average. The total amount of October and November precipitation exceeded 1,700 millimetres. Undoubtedly important was also an enormously high daily precipitation amount (on November 14 and 15, the weather station of Bovec measured 340 mm of precipitation; Markošek 2000). Under normal weather conditions the rain would change to snow at this altitude, because one fifth of yearly precipitation in the region is snow (Radinja 1978; Cegnar 2000).

Mass movements in this region were most probably accelerated by strong earthquakes, which affected the upper Soča River valley in 1976 and 1998. On unstable slopes, an earthquake can locally speed up the movement of slope material, which increases the infiltration of water into weathered material and fractured rock masses, and as a consequence, a quicker rise of groundwater level during heavy precipitation. The earthquakes, registered by seismographs immediately before the debris flow release, were to remote and to weak to contribute directly to the geomorphic activity. Between November 14 and 17, 2000, the seismographs have registered 21 earthquakes with magnitude 0.9 or more on the Richter scale in northwestern Slovenia. In five cases only the intensity was estimated at all, namely, in three cases as grade 3 and in two cases as grade 4 on the EMS-98 scale (Ribičič and Vidrih 2001). The influence of earthquakes on mass movements is long--termed and linked to pore and fracture-water activity, as well as to the increase of infiltration of larger amounts of water through the seismic fissures (Table 1).

LANDSLIDE AND DEBRIS FLOWS IN KOSEČ VILLAGE

Above the Koseč village (altitude 560–600 m) in the upper Soča River valley a large landslide started to move in the evening hours of December 22, 2001, which in time of writing this paper (spring of 2003) has not come to a halt yet. One part of the landslide consisted of a rockfall, another one of weathered material and debris and later on, the loose material moved farther down the Brsnik stream channel as a debris flow. The whole complex of events is simply called "a landslide above Koseč" (Komac and Zorn 2002b). The largest part of landslide stopped in the altitude of about 730 metres in the Brsnik stream valley, only about 130 metres above the Koseč village.

The causes of landslide movement were of geologic (stratigraphic and tectonic) and of geographic nature (springs, inclination of slopes, frost). The landslide was a consequence of various circumstances (causes), but the triggering factor remains unknown so far. Although the time gap between this event and the Easter earthquake of April 12, 1998, is larger than in the case of debris flow of Log pod Mangartom, the link between the events is quite compelling. Immediately after the earthquake, the villagers spotted some ground fissures perpendicular to the slope in the wood above the village; two larger fissures are still seen on the slope near the landslide. Along the fissures the surface subsided for almost a metre. Slope movements were also noticed next to the reservoir of a small hydroelectric power plant in the Brsnik stream valley below the village, where the movement broke a conduit pipe, which had to be lengthened for about ten centimetres.

A few years ago, smaller mass movements in similar bedrock have already happened in this area. About 50 metres wide landslide has destroyed a local road next to Krn village on April 18, 1994 (Pavšek 1994b). The area mostly consists of Lower Cretaceous flysch, composed of thin layers of marly shales, calcarenite, chert and limestone breccia (Buser 1986). The slopes above the Koseč village are made of alternate layers of reddish thin-bedded limestone and red marl with layers and nodules of chert. The strata are very fractured and therefore unstable, although the beds dip into the slope. On the contact between the layers of limestone and flysch some springs come to the surface and this water, seeping into the slope debris, can be considered as a trigger for accelerated mass movement, along with heavy rainfall or snow melting.

The landslide above the Koseč village is one of the largest in Slovenia in the last few years. The slope surface has been changed from the altitude of 1,200 metres down to the 730 metres, while the landslide itself is about 150 metres wide

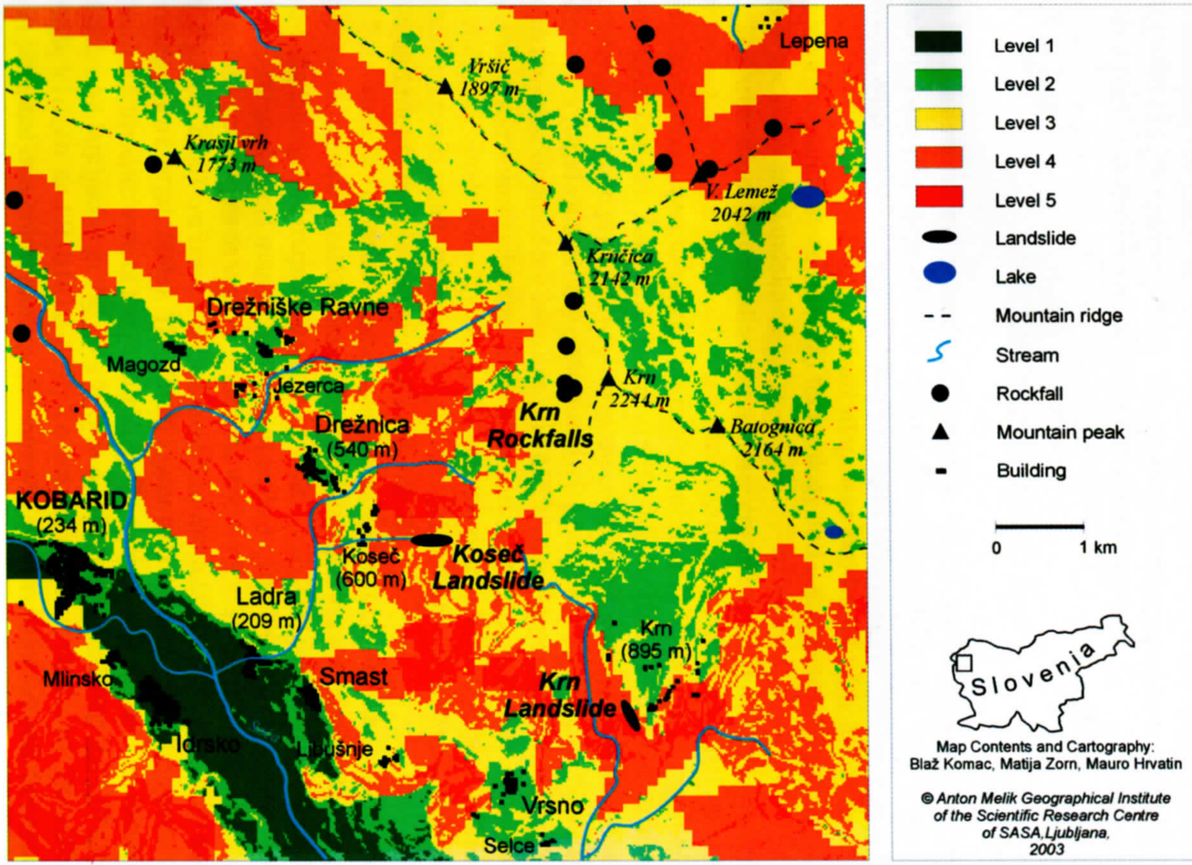

Fig. 2. The landslide hazard map of the area around Kobarid in the upper Soča River valley

and 5–10 metres thick. Up to now about 500,000 cubic metres of material has been displaced, although it is estimated that there is still somewhere between 675,000 and 1,350,000 cubic metres of unstable mass. The largest part of the landslide is at the moment relatively stable but, there are still open cracks around the landslide, and small rockfalls occur from the upper, steepest part of the slope. During rainfall the riverbed of Brsnik stream becomes more active too, along which smaller debris flows are moving down to the Soča River valley.

The landslide is a serious threat to the Koseč village with 61 inhabitants and it also threatens the Ladra village at the mouth of Brsnik stream into the Soča River valley with 153 inhabitants (2002). The goverment is planning to evacuate permanently a part of Koseč village directly below the landslide.

THE LANDSLIDE HAZARD MAP

For the assessment of landslide hazard in the Upper Soča River valley we selected a sampling area of 98.8 square kilometres from the surroundings of Kobarid, where several larger rockfalls of April 1998 and the landslide above the Koseč village occurred. The hazard map was produced with the help of geographic information systems (GIS) technology and it combines the potential hazards of rockfalls and landslides.

The area under investigation has a rather complicated geological structure. It is traversed by several faults of Dinaric (from north-west to south-east) and Alpine orientation (from west to east). The most important is Idrija fault along the Soča River valley betwen Žaga and Tolmin. In the higher parts of the mountains the Dachstein limestone prevails, while the lower parts of the slopes are made of Cretaceous flysch and Quaternary colluvium (Buser 1986). Strongly fractured rocks due to tectonic uplift of the area are one of the most important causes for intensive mass movements in this part of Julian Alps. Another part of the slope unstability is connected with the strong erosion of the Soča River and its tributaries and tectonic uplift, which results in height differences between the valley floors and mountain tops exceeding 2,000 metres.

To assess the landslide hazard we investigated rock structure, slope angles, slope curvature and forest coverage. To investigate the impact of rock structure, we used a digitalized soil map of Slovenia in scale 1 : 25,000 (*Pedološka karta...* 2002) and general geological map of Slovenia in scale 1 : 100,000 (Buser 1986). To calculate the slope angles as well as horizontal and vertical slope curvature (Hrvatin and Perko 2002) we used a digital elevation model with pixel size of 20 metres (Podobnikar et al. 2000). The forest cover and location of settlements were added from the database of the Anton Melik Geographical Institute. The location of rockfalls and landslides in the area is based mostly on published data (Pavšek 1994a,b; Vidrih and Ribičič 1998; Komac and Zorn 2002a, b). The differences in potential maximum earthquake intensity were not considered, because the whole area belong to the zone of maximum intensity of grade 9 on the EMS-98 scale for the period of 500 years (Vidrih and Ribičič 1998), the highest expected earthquake intensity in Slovenia (Fig. 2).

For each of the mentioned factors we have elaborated a map of risk assessment for mass movements with programme tools *Idrisi* 32.2 and *Surfer* 7.0. Risk levels were determined according to the published references (Perko 1992; Pečnik 2002).

The map shows five levels of potential hazard. The areas of low risk (levels 1 and 2) include 19.3 square kilometres, areas of moderate risk 43.7 square kilometres (level 3), while the areas of high risk (levels 4 and 5) include 35.8 square kilometres. The map also shows larger rockslides, the landslide above Koseč village and landslide next to Krn village.

The potential hazard map has been overlayed with data layer of housing. From the total of 941 buildings 82 per cent lie in the areas of low risk (levels 1 and 2), 14 per cent in the areas of moderate risk (level 3), and only 4 per cent of buildings lie in areas of high risk (levels 4 and 5).

The main control factors of landslide hazard in the area are the bedrock and slope inclination. The areas built of Cretaceous flysch are potentially more endangered by landslides than areas of limestone. The most endangered are flysch areas with slope inclination of 21 to 30 degrees.

Despite the extensive areas, directly endangered by mass movements, the majority of settlements is situated in potentially safe areas. However, the events of Log pod Mangartom and Koseč have clearly indicated that for the risk assessment due to mass movements it is necessary to consider the recent geomorphic processes in a larger area. Especially in the mountains, the processes of mass movements can originate in remote and otherwise unaccessible locations but, under specific circumstances, can reach lower populated areas of presumably lower risk level as well.

The landslide hazard maps could be of great use in spatial planning in Slovenia, too. Until now there are only a few hazard maps published in Slovenia, however their application is not compulsory as it is in neighboring Austria (Mikoš 1997).

CONCLUSIONS

Geomorphological analysis of distribution and characteristics of major mass movements, which were triggered by the Easter earthquake of April 12, 1998, in Julian Alps, has revealed its exceptional geomorphic effectiveness. Despite of its moderate magnitude (5.6 on the Richter scale) the earthquake has released more than a hundred of larger rockfalls and rockslides in the strongly dissected mountainous area of the upper Soča River valley. Its major effects on natural geomorphic processes may be attributed to considerable local intensity (7–8 on the EMS-98 scale), which was the consequence of shallow hypocentre (in depth of only 8 kilometres), and extremely strong vertical dissection of mountain relief in the area. Rel-

Photo 1. Debris flow above and in the Log pod Mangartom village. In the middle of the photograph is the peak of Veliki Mangart (2,679 m), to the left is the source area of the landslide of November 15, 2000. To the right below the mountain is the Koritnica River valley and the village of Log pod Mangartom with the fan deposited by November 17, 2000, debris flow (photo by Matija Zorn)

Photo 2. The path of the debris flow in the Mangart stream valley in the altitude of about 1,300 metres. On the right side of the photograph is seen how the landslide of November 15, 2000, affected the valley slopes for over 20 metres high. On the left side is the remaining part of the landslide which temporarily stopped in this place (photo by Karel Natek)

ative altitudes between valley floors and mountain tops exceed 2,000 metres, for which reason the effect of topographic amplification of earthquake waves has remarkably influenced the distribution of mass movements by altitude.

This explanation can be supported by the fact that lower parts of slopes are also distinctively unstable due to exaration effect of the Soča glacier during Pleistocene and later intensive vertical erosion of the Soča River and its tributaries but, during the earthquakes of 1976 and 1998, only a handful of small rockfalls occurred in lower parts of the valley slopes. Geomorphological survey has revealed several large post-Pleistocene mass movements in lower parts of slopes, while from the last decades two such rockslides are also known to happen "from out of nowhere": the first one occurred on August 8, 1950, on the slopes of Javoršček Mountain above Bovec (around 80,000 cubic metres of rocks), and the second one on December 19, 1993, in the Trenta valley (7,500 cubic metres of rocks). Both of them cannot be connected neither to earthquake nor heavy rainfall.

A major surprise was caused by a debris flow which partly destroyed the mountain village of Log pod Mangartom during the night from November 16 to 17, 2000. The huge landslide was triggered in the mountains high above the valley by heavy rainfall in the days preceding the event and during next two days, due to which the slided mass became liquid and as a debris flow plunged down into the valley. However, it is quite possible that the affected area was made unstable by earthquake tremors a year and a half earlier. The slopes of Stovžje are very remote and unaccessible, so nobody knows when the first movements started. But, local eyewitnesses have confirmed that, immediately after the Easter earthquake of 1998, the cracks in the ground, parallel to the later head scarp, appeared on the slopes above the Koseč village, while the landslide itself occurred two years and a half later.

Investigations of recent geomorphic processes of mountain areas in connection to earthquakes are in process in many earthquake active areas all over the world. However, it is amazing how the described events surprised the Slovene public and also, in some degree, geomorphologists and geologists as well. The lack of major natural disasters and great social changes in Slovenia in the last decades have strengthened the belief in invariability of the so called non-living nature but, these events should be considered as serious warnings of swift geomorphic dynamics, especially in the high mountains, which should also be taken into account in the future planning of human activities in the fragile mountainous environment.

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STRESZCZENIE

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RUCHY MASOWE W ALPACH JULIJSKICH (SŁOWENIA) W NASTĘPSTWIE TRZĘSIENIA ZIEMI 12 KWIETNIA 1998 ROKU

Praca przedstawia analizę geomorfologiczną skutków trzęsienia Ziemi w Alpach Julijskich w dniu 12 kwietnia 1998 roku. Było to wyjątkowe zdarzenie tektoniczne i geomorfologiczne. Powstały liczne ruchy masowe. Trzęsienie Ziemi 5,6 w skali Richtera spowodowało powstanie ponad stu wielkich obrywów skalnych i zsuwów skalnych w silnie rozczłonkowanym dorzeczu rzeki Soczy (Soča). Główne efekty geomorfologiczne były powiązane z lokalną intensywnością trzęsienia Ziemi (7–8 na skali EMS-98) i usytuowaniem hipocentrum na głębokości zaledwie 8 kilometrów, co przy wielkim rozczłonkowaniu rzeźby gór i dużych wysokościach względnych przekraczających 2 000 m, doprowadziło do znacznych przekształceń stoków. Dodatkowo elementem sprzyjającym wyzwalaniu wielkich ruchów masowych są glacjalne podcięcia stoków w plejstocenie oraz późniejsze ich rozczłonkowanie. Dla porównania omówiono również wcześniejsze zdarzenia geomorfologiczne w Alpach Julijskich wywołane trzęsieniami Ziemi w latach 1976 i 1998, oraz inne nie związane ze zjawiskami tektonicznymi (1950 i 1993).