
Earthquake-Induced Landslides in Slovenia: Historical Evidence and Present Analyses

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Matjaž Mikoš, Mateja Jemec, Mihael Ribičič, Magda Čarman and Marko Komac

Abstract

The paper gives a short overview of the historical earthquakes on the territory of Slovenia since AD 792, with the 1511 Idrija Earthquake ($M_M = 6.8 \pm 0.3$) as the strongest earthquake in this record. Firstly, seismotectonic characteristics of Slovenia are presented together with the seismological map of Slovenia. Secondly, a national landslide database and landslide occurrence map (cadastre) is discussed. Furthermore, different (statistical) models are presented that have been used to prepare landslide (also debris flows and rock falls) susceptibility maps of Slovenia at scale 1:250,000. The role of earthquakes as triggering factors in these models is discussed. Moreover, a field case study is discussed; the conclusions reached by the analysis of the numerous rock falls initiated during the 1998 Posočje earthquake ($M_L = 5.6$; the strongest earthquake in the 20th century with the epicenter in the territory of Slovenia) and the 2004 Posočje earthquake ($M_{LV} = 4.9$) is presented. A short final section on legislative framework in Slovenia with regard to hazard and risk mapping of slope instabilities respectively mass movements (including earthquake-induced landslides) is given.

Keywords

Landslides · Maps · Rock falls · Seismology · Slovenia · Susceptibility

M. Mikoš (✉)
Faculty of Civil and Geodetic Engineering,
University of Ljubljana, UL FGG, Jamova c. 2,
SI-1000 Ljubljana, Slovenia
e-mail: matjaz.mikos@fgg.uni-lj.si

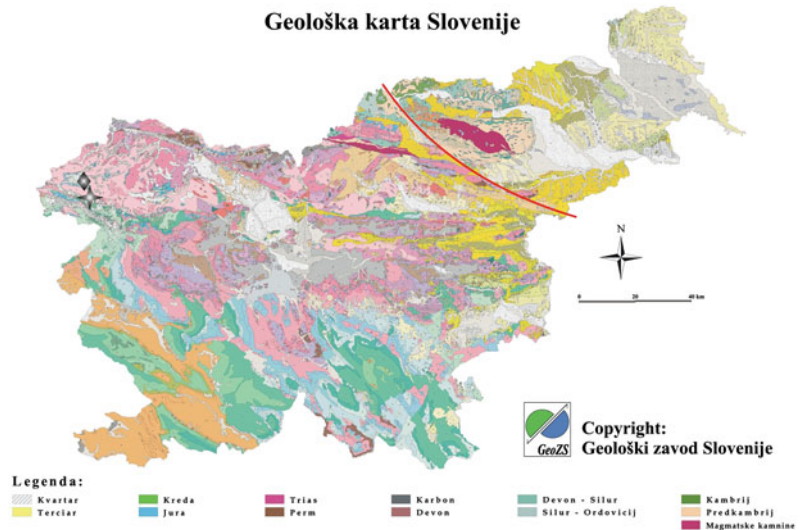
M. Ribičič
Faculty of Natural Sciences and Technology,
University of Ljubljana, Ljubljana, Slovenia

M. Jemec · M. Čarman · M. Komac
Geological Survey of Slovenia, Ljubljana, Slovenia

1 Introduction

Slovenia is a small Central European country that lies between the Alps and the Mediterranean Sea, where the Adriatic/Apulian sub-plate hits the Eurasian tectonic plate, forming the Periadriatic Seam; to south of it there are the Southern Alps, reaching to Slovenia. Slovenia has a historical

Fig. 23.1 A Geological map of Slovenia at scale 1:500,000 (after Buser and Draksler 1990). Red line represents Periadriatic lineament, the diamond represents the 1998 earthquake epicenter and the star represents the 2004 earthquake epicenter



record of frequent but not very strong earthquakes that are less violent as elsewhere in Europe (the 1693 Sicily Earthquake $M = 7.5$, the Lisbon 1755 Earthquake $M = 8.7$, the 1783 Calabria Earthquake $M = 7.0$, the 1908 Messina Earthquake $M = 7.2$). Fortunately, many earthquakes in Slovenia are not strong enough to trigger landslides ($M < 4$ after Keefer (1984) or $M < 4.3 \pm 0.4$ after Malamud et al. (2004)). Strong earthquakes are therefore not the most frequent natural hazard in Slovenia, where floods and rainfall-induced landslides are much more frequent (Mikoš et al. 2004).

In Slovenia, landslides are mainly occurring in the lower mountainous, in the Alpine foothills and hilly central part of Slovenia, in the flysch areas in northern Slovenia, and the hills of eastern and northeastern Slovenia. Rock falls and rock slides are common in the northern and north-western Slovenia, in steep gorges or canyons and thrusts area where carbonate rocks overthrust the softer rocks (usually flysch). Debris flows are rare events and occur in the Alps, Karavanke Mountain, on Pohorje and the Alpine foothills. Before going to the analyses of earthquakes as triggering factors for the before mentioned mass movements, let us present a short description of seismotectonic characteristics of Slovenia together with a short overview of past earthquakes in Slovenia.

2 Seismotectonic Characteristics of Slovenia

The Slovenian territory is tectonically divided by the Periadriatic Seam (line); to its north there is the European plate (Eastern Alps), and to the south of it there is the Adriatic microplate, whose northern margin (Southern Alps, Dinarides) is highly deformed and backthrusted onto the central, less deformed part of the Adriatic microplate (Adriatic Basin) (Poljak et al. 2000). Numerous thrusts and faults are responsible for a rather complex geological setting, shown on a Geological map of Slovenia at scale 1:500,000 (Fig. 23.1).

Using data on historical earthquakes (estimated locations and magnitudes since 792 A.D.) led to a special catalogue prepared for seismic hazard assessment in Slovenia (Živčič et al. 2000). According to this assessment, the territory of Slovenia can be considered to be one of moderate seismicity (Poljak et al. 2000) (see Fig. 23.2).

3 Short Overview of Historical Earthquakes in Slovenia

In Europe, twelve-degree earthquake intensity scales are used. Still in use in Southern Europe is the Mercalli-Cancani-Sieberg Scale or MCS

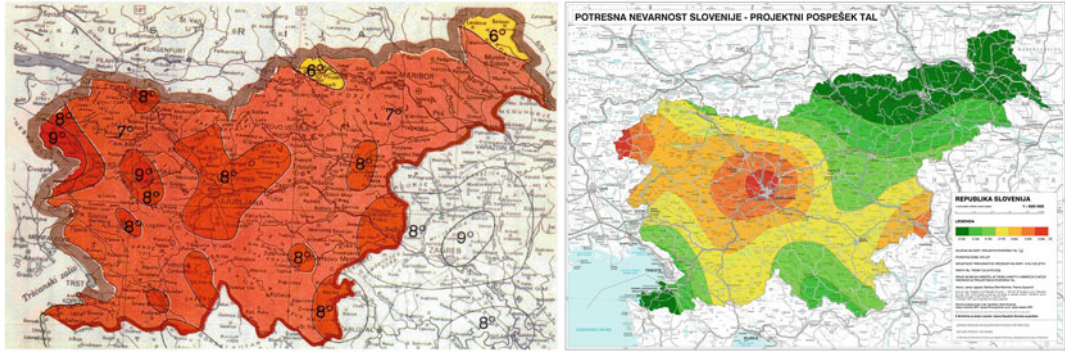


Fig. 23.2 A Seismological map of Slovenia—EMS map (Ribarič 1987) (left) and a Design Ground Acceleration map (more correct name for the map is a Peak Ground Acceleration map—PGA) (Lapajne et al. 2001) (right).

The color legend defines Peak ground accelerations as follows: *dark green*—0.1 g; *green*—0.125 g; *light green*—0.15 g; *yellow*—0.175 g; *light orange*—0.2 g; *orange*—0.225 g; *red*—0.25 g

Scale. In 1964, the first version of the MSK Scale was published by Medvedev, Sponhauer and Karnik (Medvedev et al. 1965). In 1998, the European Macroseismic Scale or EMS-98 Scale was introduced by the European Seismological Commission, now de-facto standard in Europe. In Japan, the seven-degree Japanese Meteorological Agency Scale or the JMA Scale was used; recently modified to a ten-degree scale or JMA 1996 Scale.

As already said, strong earthquakes are rather rare in Slovenia, but they nevertheless have proved in our history to be very dangerous, even though only now and again. The oldest event in the catalogue of earthquakes in Slovenia (Ribarič 1982) dates back to 792 A.D. Since this event, there has been 1 event of maximum intensity X MSK, two of intensity IX MSK and 11 events that reached the maximum intensity VIII MSK; only three earthquakes of intensity VIII MSK have occurred in the last 200 years (Poljak et al. 2000). The strongest ever earthquake that has happened on the territory of Slovenia (Slovenia was as independent state established in 1991) is the 1511 Idrija Earthquake ($M_w = 6.8 \pm 0.3$) and the second strongest was 1895 Ljubljana Earthquake ($M_w = 6.1 \pm 0.2$).

In the 20th Century was very strong earthquake the 1976 Friaul Earthquake ($M_w = 6.1 \pm 0.1$) with the epicenter in Italy but close to NW Slovenia. This region in NW Slovenia is a

seismically very active area. On April 12, 1998, the strongest earthquake of the last 100 years occurred in the Upper Soča valley ($M_M = 5.8$, maximum intensity VII-VIII EMS). Another strong earthquake shook this area on July 12, 2004 ($M_w = 4.9$, maximum intensity VI-VII EMS-98). These two earthquakes triggered numerous rock falls reported at the end of this paper. Also the 1974 Kozjansko Earthquake in SE Slovenia ($M_w = 4.8$, maximum intensity VII EMS) triggered numerous new landslides and some old ones reactivated (Vidrih 2008).

4 Analysis of Rock Falls Initiated by Two Recent Earthquakes in Slovenia

In the last two decades, W Slovenia was struck by two strong earthquakes (epicenters are shown in Fig. 23.1). The first event occurred on 12 April 1998 at 10:55UTC with a moment magnitude of 5.6 (diamond in Fig. 23.1). The area that was affected was the Upper Soča valley and the Bovec basin in NW Slovenia (Bajc et al. 2001; Zupančič et al. 2001). The total seismic moment was 4.5×10^{17} Nm (10^{24} dyn-cm) implying an average, co-seismic slip of 0.18 m (Bajc et al. 2001). There was no surface rupture.

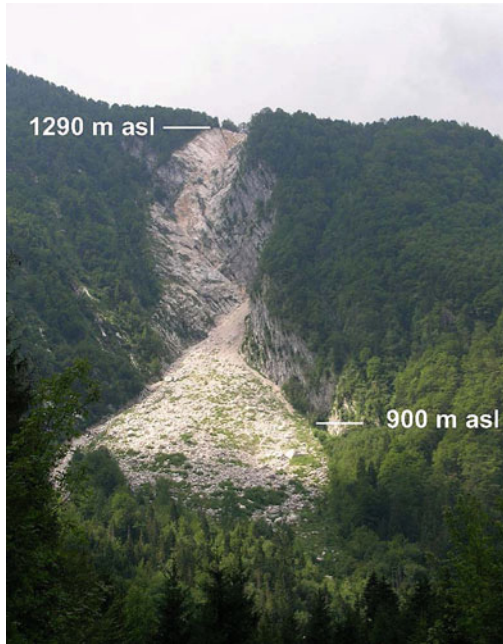


Fig. 23.3 Large rock wedge failure triggered by the Easter 1998 earthquake in the Lepena valley (W Slovenia)

The Easter 1998 Earthquake caused more than 100 failures, among them 50 rockfalls (Vidrih et al. 2001; Mikoš et al. 2006). About 260,000 m³ of rock fall material will remain on hill slopes with no potential of reaching the river network (see example in Fig. 23.3), while ~ 480,000 m³ may be released to watercourses in a longer period during extreme events. About 200,000 m³ of rock fall debris was deposited in areas from where the material was released to watercourses during rainfall events. As a consequence of the 1998 earthquake, hyperconcentrated flows were observed during floods in some torrential tributary channels of the Upper Soča River (Mikoš and Fazarinc 2000).

A second earthquake ($M_w = 5.2$; $M_S = 4.9$) occurred on 12 July 2004 at 13:04UTC close to the epicentre of the 1998 event (star in Fig. 23.1). Both events show right-lateral, strike-slip kinematics (Bajc et al. 2001; Kastelic et al. 2006). After the earthquake of July 12, 2004, 50 rather superficial slope failures including 38 rockfalls were registered.

5 Slovenian National Landslide Cadastre and Database

In early 2000, several Slovenian Ministries were prepared for financing the construction of the National Landslide Database. The existing landslides data were collected from the different sources. Data were organized in cadastres and internal databases (see Fig. 23.4). The main sources were Geological Survey of Slovenia, Administration of the Republic of Slovenia for Civil Protection (URSZR), The Directorate of the Republic of Slovenia for Roads (DRSC), Ministry for the Environment, Spatial Planning and Energy (ARSO) and other sources (geo-technical companies, municipalities...). The gathered data were acquired in different formats. They were first analyzed and the duplicates removed. Then the data were merged into the centralized database. Komac et al. (2005) stated that the quality is/was questionable to a certain degree because the different databases were rarely updated. The different database attributes and missing or multiplied data were the dominating problem (Komac et al. 2005). At the end of the project there were 6602 slope mass movements in the database, 49.3 % of them (3257) with known location (Komac et al. 2007). The database is unfortunately not operational since 2005.

6 Landslide Susceptibility Map

Based on the extensive national landslide database the Landslide susceptibility map of Slovenia at scale 1:250,000 were completed (Fig. 23.5). The map was derived using statistical analyses of landslide preparatory factors (lithology, slope inclination, slope curvature, slope aspect, distance to geological boundaries, distance to structural elements, distance to surface waters, flowlength, and landcover type) on a landslide learning set (random but geologically representative 65 %) and tested on the remaining test set (35 %). The univariate statistical

Fig. 23.4 A Landslide occurrence map of Slovenia

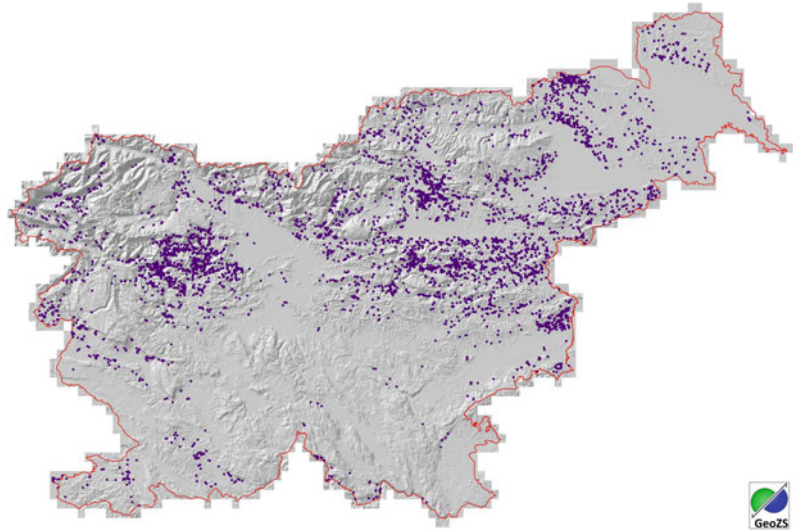
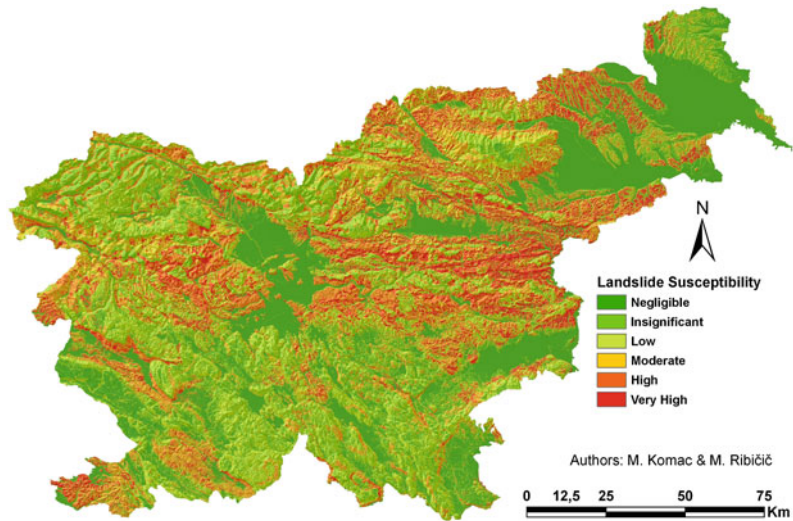


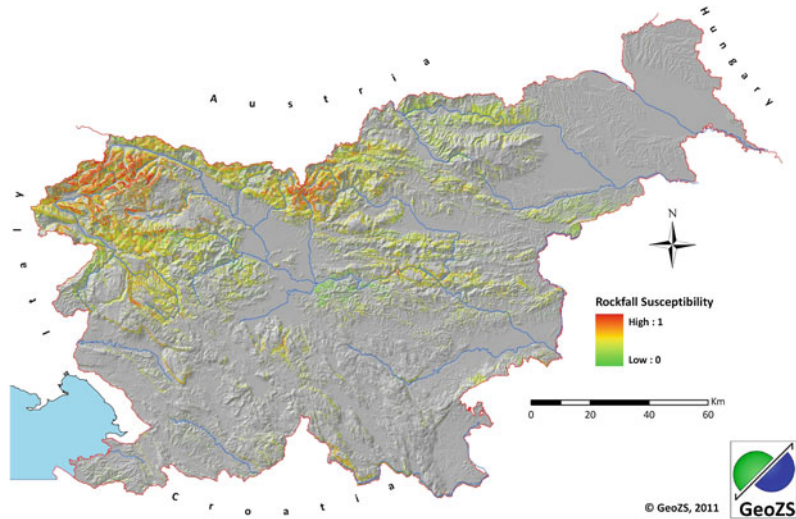
Fig. 23.5 A Landslide susceptibility map of Slovenia (from Komac and Ribičič 2006)



analyses (*Chi Square*) were conducted using GIS in raster format with the 25×25 m pixel size. These results were later used as a basis for the development of the weighted linear susceptibility model where several models with various factor weights variations based on previous research were developed. The relation of landslide occurrence to the triggering factors (maximum 24-h rainfall intensity with the return

period of 100 years and average annual rainfall) was assessed. The analyses showed that the annual rainfall above 1000 mm proved to be the critical triggering factor for landslide occurrence in more loose soils and above 1600 mm in less resistant rocks. Furthermore, the daily rainfall intensity above 100 mm proved to be critical for landslide occurrence, especially in more loose soils and in less resistant rocks.

Fig. 23.6 A Rockfall susceptibility map of Slovenia



7 Rockfall Susceptibility Map

In Slovenia, rockfall susceptibility was relatively poorly investigated. Therefore, a new Map of rockfall susceptibility in Slovenia in scale 1:250,000 was produced (Fig. 23.6) using GIS with the latest spatial data, such as the latest lithological map of Slovenia in scale 1:250,000. The most important factors in the production of the map were: lithology, slope angle and distance to tectonic-structural elements. The existing rockfall susceptibility map, produced in 1997, was also used for the comparison.

To identify areas with high probability of rockfall occurrence, Chi-square analyses with a linear weighted sum model approach was selected on the basis of selected spatio-temporal factors to simplify the approach and to make it transferable to other regions. Unfortunately, there are not enough adequately representative data about rockfalls in Slovenia (consistent rockfall cadastre does not exist and not many historical studies have been done so far) for the quantitative statistical analysis available. This is why expert estimation was used as a complementary approach to Chi-square analysis, with the emphasis on location rather than on

time of a rockfall occurrence. Expert estimation approach was based on the experience and historical events gathered from chronicles and eyewitnesses. Cross-validation was performed on 125 such known historical events. This approach is limited mainly by subjectivity and has difficulties with sound argumentation, but at the given state it was a reasonable way to evaluate a Chi-square analysis and to define areas with high(er) probability of rockfall occurrence.

Based on the calculations of several linear models with different weight combinations of spatio-temporal factors and the results of their rockfall susceptible areas prediction success, the best factors' weight combination was selected.

The presented rockfall susceptibility map forms a basis for spatial prediction of rockfall triggering areas. It also gives a general overview of areas susceptible to rockfall in Slovenia and offers guidance for areas of further and more detailed research and the rockfall run-out zones.

This new rockfall susceptibility map complements the set of maps of susceptibility to different mass slope movements (landslides and debris flows susceptibility maps), which have been produced at the Geological Survey in Slovenia in the last five years.

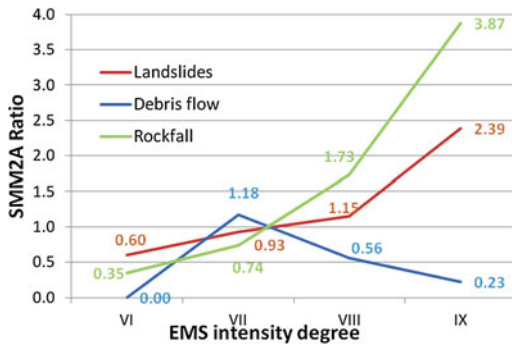


Fig. 23.7 Values of slope mass movements (landslides, debris flows and rockfalls) to area ratio (SMM2A) in relation to EMS intensity degree values

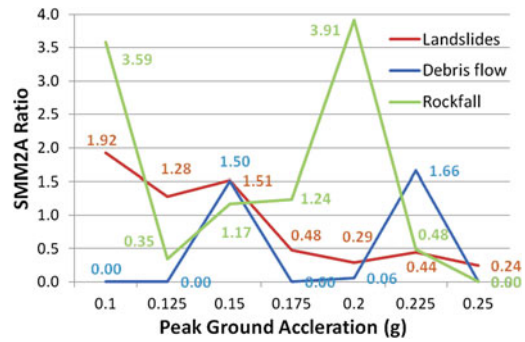


Fig. 23.8 Values of slope mass movements (landslides, debris flows and rockfalls) to area ratio (SMM2A) in relation to peak ground acceleration values (g)

8 Analysis of Slope Mass Movements in Relation to Seismic Intensity in Slovenia

To assess the potential occurrence of three different types of slope mass movements as a result of seismic activity landslide (3693), debris flow (16) and rockfall (110) populations were analyzed according to their spatial occurrence. The analysis based on a simple overlay assessment between point occurrences and areas of different seismic intensity. For the information on the latter we took two sets of seismic data, an EMS intensity degree map (Fig. 23.2—left; Ribarič 1987) and the Design Ground Acceleration (that is actually a Peak Ground Acceleration—PGA) map (Fig. 23.2—right; Lapajne et al. 2001). Slope mass movements were compared to both of the datasets. The results of overlay assessment were normalized to neutralise the impact of the seismicity class area proportion. The slope mass movement to area ratio (SMM2A) that gives realistic occurrence perspective was calculated as following:

$$\text{SMM2A} = \frac{(\text{NSMM}_{\text{class}}/\text{NSMM}_{\text{total}})/(\text{A}_{\text{class}}/\text{A}_{\text{total}})}{\quad} \quad (23.1)$$

where $\text{NSMM}_{\text{class}}$ represents the number of slope mass movement occurrences within a specific class of seismic activity, $\text{NSMM}_{\text{total}}$ represents the total number of slope mass

movement occurrences, A_{class} represents the area of a specific class of seismic activity and A_{total} represents the total area of the analysis (t.i. area of Slovenia).

The occurrence ratio of landslides and rockfalls (Fig. 23.7) show expected correlation with higher EMS intensity degree values. These results clearly show the influence of earthquake intensity as being one of more important triggering factors for landslide and rockfall occurrence. If we, very simplified, assume that the SMM2A ratio value of 1 shows the threshold above which the earthquakes have an influence on the landslides and rockfall occurrence, we can conclude that the EMS intensity degree value of VIII (and higher) influences the triggering of these two slope mass movements. In the case of debris flow similar statement is impossible as the only EMS intensity degree value at which the threshold is reached is VII, but with increasing intensity values the ratio drops substantially. The most probable reason for this is that the major triggering factor for debris flows is rainfall and rarely earthquakes.

In the case of slope mass movements' occurrences in relation to PGA values (Fig. 23.8) the distribution of landslides has a negative related trend, t.i. as PGA values increase the SMM2A ratio decreases. Such a relation is most probably the result of the fact that the areas with the highest GPA values lay in the plains where landslides seldom occur. Occurrences of debris flow and rockfalls show

poor results of correlation with the PGA values. For the debris flows this could be explained with by two facts, first being too small population of debris flow occurrences analyzed and/or second being that most probably rainfall dominates the triggering of these types of slope mass movements.

9 Slovenian Legislation in the Field of Earthquake-Triggered Landslides

Upon its accession to the European Union, Slovenia was forced to adopt its legal and economic system to the common European values. In this respect, new Waters Act was adopted in 2002 that established a special Water Fund. This fresh approach should help to keep the relatively high level of safety against natural hazards in Slovenia, especially against floods. This new Waters Act also prescribes the preparation and acceptance of hazard and risk maps for different natural hazards as a prevention tool. These maps will then be used in spatial planning as a legal basis in the process issuing building permits. At this moment, the preparation of methodologies how to prepare such hazard and risk maps under Slovenian conditions are under way and these methodologies will be given legal status. By doing that we are trying to catch up with the other alpine countries in Europe (Đurović and Mikoš 2004).

10 Conclusions

Slovenia is a small Central European country that lies between the Alps and the Mediterranean Sea, where the Adriatic/Apulian sub-plate hits the Eurasian tectonic plate, forming the Periadriatic Seam. The northern margin of the Adriatic microplate (Southern Alps, Dinarides) is highly deformed and backthrusted onto the central, less deformed part of the Adriatic microplate. Numerous thrusts and faults are responsible for a rather complex geological setting in Slovenia.

Using a database on historical earthquakes since AD 792, the territory of Slovenia can be considered to be one of moderate seismicity. Since AD 792, there has been 1 event of maximum intensity X MSK, 2 of intensity IX MSK and 11 events that reached the maximum intensity VIII MSK; only 3 earthquakes of intensity VIII MSK have occurred in the last 200 years. The strongest ever earthquake that has happened on the territory of Slovenia (Slovenia was as independent state established in 1991) is the 1511 Idrija Earthquake ($M_M = 6.8 \pm 0.3$) and the second strongest was 1895 Ljubljana Earthquake ($M_M = 6.1 \pm 0.2$).

In the last two decades, W Slovenia was struck by two strong earthquakes. The Easter 1998 Earthquake caused more than 100 failures, among them 50 rockfalls. After the earthquake of July 12, 2004, 50 rather superficial slope failures including 38 rockfalls were registered.

Until 2005, a Slovenian National Landslide Cadastre and Database was established, followed by Landslide Susceptibility Map and Rockfall Susceptibility Map of Slovenia in scale 1:250,000.

In the last years, an analysis of slope mass movements in relation to seismic intensity in Slovenia has been performed. To assess the potential occurrence of three different types of slope mass movements as a result of seismic activity landslide (3693), debris flow (16) and rockfall (110) populations were analyzed according to their spatial occurrence. From legislative point of view, the preparation of methodologies how to prepare hazard and risk maps for landslides, rock falls and debris flows in Slovenia are under way.

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