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Chapter 3

MITIGATION OF LARGE LANDSLIDES AND DEBRIS FLOWS IN SLOVENIA, EUROPE

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Abstract

In Slovenia, a small central European country, in the second half of the 20th century minor landslides of different forms (shallow landslides, slides, slumps – average volume of 1000 m^3, rarely 10,000 m^3) were prevailing, mainly triggered during short and intense rainfall events or after prolonged rainfall periods of moderate intensities. Unfavorable geological conditions are the main causes for a high slide density (≈ 0.4 slide per 1 km^2) in Slovenia, despite good vegetation conditions (more than 60% covered by forests).

Experiences with mitigation of large landslides were rare until the last decade, when four large landslides (Stože, Slano Blato, Strug, and Macesnik) with volumes of the order of 1 million m^3 were triggered and urged for fast mitigation. They can be placed in the category of rainfall-induced landslides that became active in unfavorable geological conditions.

The Stože Landslide with a volume of around 1.5 million m^3 was initiated in November 2000 as a debris landslide on the Stože slope in morainic material above the village of Log pod Mangartom in W Slovenia after a wet autumn period with no snow accumulation but rising runoff coefficients. It turned from a debris landslide on a hill slope into a catastrophic debris flow due to low inertial shear stress caused by high water content.

The Slano Blato Landslide also formed in fossil landslide masses on a contact of calcareous and flysch formations during wet autumn period in November 2000. It is ever since progressively enlarging behind the main scarp via retrogressive slumping of new and freshly weathered material that due to high water pore pressures turns into a viscous earth flow.

The Strug Landslide is a very good example of a complex slope movement, which started in December 2001 as a rockslide with a consequent rock fall that triggered secondary landslides and caused occasional debris flows. In 2002 over 20 debris flows were registered in the village of Koseč below the Strug Landslide, mainly on days with a daily rainfall accumulation of 20 to 30 mm. In 2003 and 2004 no further debris flows could be observed, therefore these events in the Strug landslide area were defined as material and not rainfall driven events.

The Macesnik Landslide above the village of Solčava in N Slovenia near the border with Austria was triggered in autumn 1989. Till 1994 there were no activities on the landslide. In the period between 1994 and 1998 the advancement of the landslide on the slope was utmost intense. Firstly, the landslide destroyed state road, and a new pontoon bridge had to be built instead. In 1996, the landslide advanced and destroyed a turn on the same state road. In 1999, a large rock outcrop stopped the advancement of the landslide. Further advancement would possibly destroy several farmhouses on its way down the valley towards the Savinja River. Possible damming of this alpine river would cause a catastrophic flooding.

The ongoing mitigation of these landslides is subjected to a special law adopted in 2002 (revised in 2005). The final mitigation is planned to be finished before the end of 2010, with estimated costs of 60.5 Mio € for all activities planned. These costs should be added to the estimated sum of 83.5 Mio € as the final remediation costs for all other registered active small-sized landslides in Slovenia. Practical experiences in Slovenia with large landslides up to now show that only strict and insightful co-ordination, interdisciplinary approach and adequate financial support may lead to a successful mitigation.

I. Introduction

The Republic of Slovenia being an independent and sovereign country since 25 June 1991 is located in Central Europe between the Alps and the Adriatic Sea. It has an area of 20,273 km^2, bordering Italy (232 km), Austria (318 km), Hungary (102 km), and Croatia (670 km). Its coastline on the Adriatic Sea is 46 km long. In 2005 for the first time Slovenia had more than 2 million inhabitants (in 2007, population density of close to 100 per km^2 compared to the world average of 43 per km^2) in over 6,000 settlements (SURS, 2007), half of them with up to 100 inhabitants only. The City of Ljubljana as the capital has less than 300,000 inhabitants (12.8% of the state population). The daily migration to workplaces and schools is high and it is important for the national economy and living conditions in general. A network of 1,200 km of railways and close to 39,000 km of roads connects the country. There is also high transit traffic through the country. Tourism is one of the strategic fields of development. Recreation on water (canyoning, canoeing, white water rafting, and fishing) attracts more and more tourists, mostly foreign. Slovenia is known for its varied landscape and high biodiversity. The Slovenian territory, which represents only 0.014% of our planet's land surface, is home to 2% of all known species of plants and animals.

The estimated direct (economic) damages caused by natural disasters in Slovenia are on average above 2% of GDP (in 2007 the GDP was 34.5 billion Euro or 17,076 Euro per capita – that is more than 25.000 USD per capita – reaching 89% of the average of the EU-27) with some exceptional years, as in 1990, when the flood-related economic damage itself, caused by heavy floods, was above 20% of the annual national GDP (ADCPR, 2005). Earthquakes are the most destructive natural hazards in Slovenia. The strongest historical earthquake with the epicenter in the territory of Slovenia happened on 26 March 1511 in the vicinity of Idrija (second largest mercury mine in Europe) with the estimated magnitude of 6.9. The strongest earthquake in the 20th century was registered on 12 April 1998 with the surface magnitude M_S = 5.7 and the estimated intensity after the European Macroseismic Scale (EMS-98) between VII and VIII (Gosar *et al*., 2001). This is much less than in some places elsewhere in the world, e.g. the magnitude of the 921 Chi-Chi earthquake on 21 September, 1999 in Taiwan (M_L = 7.3, M_W = 7.6; Lin *et al*., 2006), triggered nearly 26,000 landslides in central Taiwan (Cheng *et al*., 2005), and increased the frequency of debris flows by reducing the intensity and amount of precipitation required for triggering debris flows as well as accelerated landslides during the subsequent heavy rains (Lin *et al*., 2003).

Most hazardous natural disasters apart from earthquakes, fires in the natural environment (on average more than 1,000 in a year), and droughts/heat waves (causing the highest damages in the last decade!), are rock falls, land slides, and fluvial erosion processes in many torrents and rivers. Mass wasting and soil erosion are noticeable on 43% of Slovenian territory (around 8,800 km^2 of labile and potentially unstable slopes). This area is crisscrossed by some 8,000 km of torrents that drain nearly 400 torrential watersheds (Mikoš, 1995; Repe, 2002). Floods and landslides are complex natural phenomena caused by local natural conditions and, with further development, more and more influenced by human activity. In Slovenia, generally speaking, unfavorable geological conditions, steep terrain and abundance of precipitation (rainfall) are the major causes of these disasters.

II. Natural Conditions in Slovenia

A. Precipitation and Run-Off

Slovenia has three different climates: continental, alpine and (sub-)Mediterranean. The average annual precipitation is around 1500 mm and the average annual runoff is around 1000 mm. Slovenia is thus rich in water resources, comprising mainly of groundwater and springs. Of its territory, 16,500 km^2 drains into the Danube River (the Black Sea), and 3,750 km^2 into the Adriatic Sea.

The average annual precipitation varies within Slovenia for a factor of nearly 5 (from 750 mm per year in NE continental climate of the Prekmurje plains over around 1000 mm per year in SW sub-Mediterranean climate to 3300 mm per year in NW alpine climate of the Julian Alps – climatologically the highest long-term precipitation in the Alps). The steep terrain strongly influences all types of precipitation. In Slovenia, the worst case is the combination of frontal precipitation with the orographically forced convection precipitation. The Upper Soča River basin bordering Italy is the region with highest precipitation in Slovenia. The long-term statistical analysis of heavy rainfall events shows more than 40 such events a year. More than 400 mm a day and more than 100 mm in an hour have been registered in the past. Hourly values are comparable to the rainfall intensity during typhoons elsewhere in the world, e.g. in Taiwan, but not so the daily values: Ophelia in 1990 (106 mm/h; 370 mm/day), Herb in 1996 (113 mm/h; 1749 mm/day), Zebert in 1998, Xangsane in 2000, and Toraji in 2001 (Lin and Jeng, 2000; Cheng *et al*., 2005; Chen, 2006; Chen *et al*, 2006; Lin *et al*., 2006).

The dense hydrologic network of surface waters (26,989 km stream channels with an average density of 1.33 km per km^2, in some areas more than 2 km per km^2, in karstic areas well below 1 km per km^2) (Kolbezen and Pristov, 1998), was created due to terrain of low permeability and high annual precipitation. Slovenia is situated in the headwater areas of larger alluvial rivers, thus flash torrential floods are the most frequent ones. The exceptions are the Drava and Mura rivers, flowing to Slovenia from Austria. For Slovenia, pluvial and to a less extent nival run-off regimes are prevailing. There is also significant snowfall but at lower altitudes the snow pack disappears several times during the wintertime.

Floods in Slovenia can occur all over the year, but most of them and the heaviest ones occur in spring and autumn. The humid climate causes high flows with less obvious distinctions between flood discharges with different recurrence intervals: the ratio between

Q_{100} and Q_5 is around 1.4 for large alluvial rivers in Slovenia (Kolbezen and Pristov, 1998). In Slovenia, there are no large natural lakes or artificial reservoirs that would significantly affect natural flood conditions (Mikoš, 2008).

In the last decades, natural reforestation (succession) of abandoned agricultural land has been very intense. Today, wooded areas cover 66.0% of the country's surface, all agricultural areas 27.8%, and built-up areas 2.8% to mention the most important categories of land cover (SURS, 2007). On the one hand, the dense vegetation cover helps to effectively reduce soil erosion, but on the other hand it has also reduced low flows and caused hydrological droughts in streams in warm summers of the last decade.

The precipitation measurements started in the mid-19th century, much like in other parts of the Austro-Hungarian monarchy. Today, there are 290 ombrometers and 49 ombrographs in operation. For precipitation measurements a C-band meteorological radar situated in the central part of the country is also used (Kolbezen and Pristov, 1998).

Figure 1. Relief map of Slovenia – 20,273 km^2 (from http://ksh.fgg.uni-lj.si/ewnsi/).

B. Hydrogeology and Relief

Slovenia is a mountainous and hilly country (Figure 1). Only 8.6% of its territory is areas with terrain inclination less than 4% (digital terrain model 20 x 20 m; SURS, 2007). The plain lowlands consist of very permeable alluvial gravel and sand deposits with large aquifers vulnerable to pollution. An important hydro-geological characteristic of Slovenia is that about 44% of its territory is karstic (Mikoš *et al*., 2004a), characterized by special landforms and subsurface drainage. The karst region has low stream density, surface waters soon disappear underground, and reappear in strong karstic water sources, and the region occasionally suffers from droughts. Exceptions are the karstic poljes. These are the only areas where living conditions are favorable for human settlements, but they are also regularly flooded during the wet period of the year (especially in spring and autumn). Flooding is often caused simply by the limited capacity of the karstic sinks.

In the calcareous formations of the alpine region, rocks are overlaid by thin soils where rock slides and rock falls are prevailing, especially during strong earthquakes. Other parts of the country consist of (semi)impervious rocks of different steepness. These rock formations are mainly overlaid by unconsolidated or partially consolidated fine-grained soils, exhibiting high spatial variability. There, land sliding is the prevailing slope instability phenomenon.

C. Flooded Areas

Moderate flush floods, torrential floods and karstic floods are yearly events in Slovenia and therefore the population is familiar with these phenomena. The large inundated areas are in lowland areas along large alluvial rivers and on karst poljes. In these areas, agricultural land of intensive production and some vital traffic connections are under threat. The total inundated areas under extreme flood event (Q_{100}) comprise about 700 km^2 or 3.5% of the total surface, among those are 25 km^2 of urban areas, i.e. parts of the City of Celje (3rd largest town; close to 40,000 inhabitants) and the south part of Ljubljana (Mikoš *et al*., 2004a).

III. Land Sliding and Erosion Processes in Slovenia

Practically two thirds of Slovenian territory are subjected to different erosion processes and slope instability phenomena, as shown e.g. on the general landslide susceptibility map and the general earthquake-induced landslide hazard map of Slovenia (Mikoš *et al*., 2004a). Slope instabilities in rocks and soils in Slovenia are bound above all to geological and morphological conditions. In the Alps, rock slides and rock falls are frequent. For example, numerous rock falls and slides were observed in western Slovenia during large earthquakes in the years 1976, 1998 and 2004 (Mikoš and Fazarinc, 2000; Vidrih *et al*., 2001; Mikoš *et al*., 2006b). Rock falls are also present in those areas, where rivers have incised through hard carbonaceous rocks and made gorges into the lower lying soft clastic sediments. Landslides are present first of all on hillsides and slopes of heights of the perialpine terrain composed of carbonaceous and clastic rocks. Large landslides in such rock strata are frequent, where the thick weathered surface layer is sliding. Beneath the steep slopes made of carbonaceous rocks, alluvial fans, scree and talus are frequent and strongly subjected to sliding, especially where overlying the clastic rocks. In eastern Slovenia, hilly terrain with relatively gentle slopes and wide valleys is composed of clayey and silty soils, in some places also marl, sand and clayey gravel. These soft rocks are subjected to strong weathering and as such form the basis for frequent soil slumps in thick weathered surface layers and along the inclined clayey layers. Landslide-safe areas in Slovenia are karst plateaus and karst heights, wide lowland basins and alluvial valleys.

The annual average sediment production in headwater areas in Slovenia is estimated at around 5 million m^3 in an average hydrological year (Mikoš, 1995), and no new estimations have been made recently. The specific annual average sediment production is estimated at

250m^3/km^2/year or given as a denudation rate of 250mm in 1000 years (Mikoš and Zupanc, 2000), being much higher in active sediment sources (Mikoš, 1995). On average, nearly half of this material (around 2.3 Mio m^3 a year) reaches the hydrological network and could be transported towards sedimentation basins (Mediterranean & Black Sea) (Mikoš, 1995). Nearly 0.5 Mio m^3 a year is on average temporarily deposited within the fluvial system, mainly in artificial reservoirs, built for hydropower plants along major Slovenian rivers (Soča, Sava, and Drava) in Slovenia (Mikoš, 2000a; 2000b).

Land sliding is not only a threat for buildings of any kind and to infrastructure in general, but also changes the morphology of the terrain. Landslides often release (destabilize) large amounts of sediments, which not only stay on slopes but also reach the fluvial network. Under catastrophic conditions, land sliding may lead to a torrential outburst, debris flow or dam-brake wave, as was in November 2000 the case with the first Stože debris landslide that turned after 35 hours into deadly debris flow (Mikoš *et al*., 2004b).

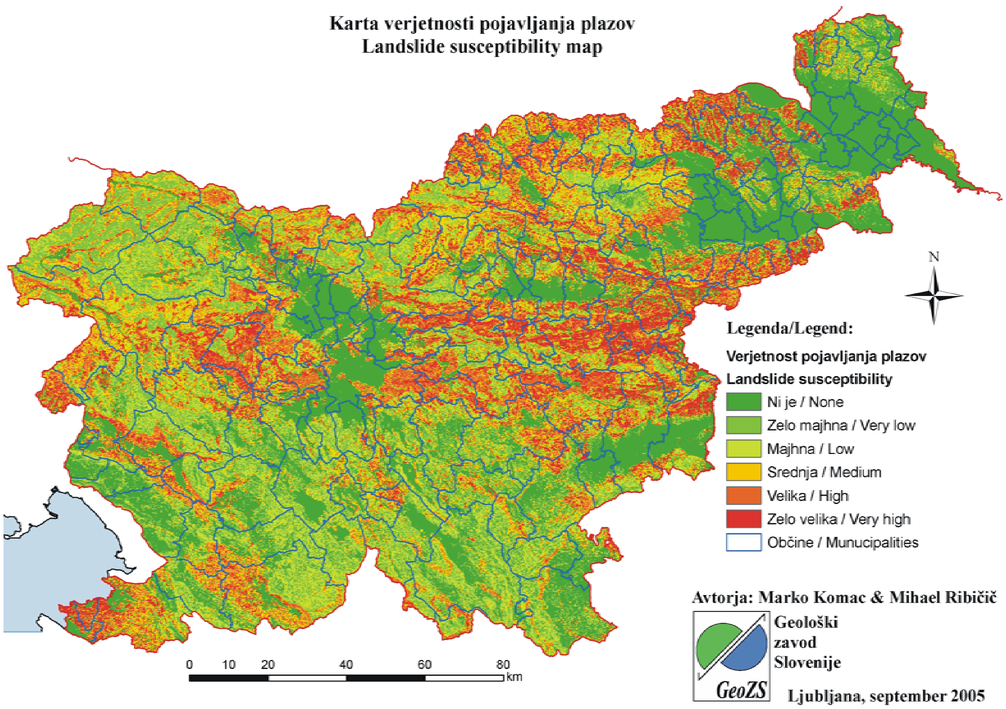

Figure 2. Landslide susceptibility map of Slovenia.

Minor landslides in Slovenia are of different forms (mainly shallow landslides, with abundance of smaller slides and slumps). They are mainly triggered during short and intense rainfall events or after prolonged rainfall periods of moderate intensities. The order of their average volume is 1000 m^3, rarely 10,000 m^3. Some of them have already been stabilized using technical measures, others are still active. Unfavorable geological conditions are the main causes for such a high slide density (> 1 slide per 10km^2), despite good vegetation conditions in Slovenia. Such high slide density was confirmed in perialpine Slovenia using multivariate statistical methods (Komac, 2006). As a result of such an approach, a landslide susceptibility map of Slovenia was prepared (Figure 2). The next contributing factor is the abundance of precipitation and high number of days with daily totals above 20 mm. Many slumps and slides are triggered during short and intense rainfall events or after prolonged rainfall periods of moderate intensities.

In Slovenia, over 6000 active and mainly minor landslides have been registered so far. Not all of them are part of the official landslide inventory cadastre that was incorporated into the GIS environment, i.e. software application called GIS-UJME, developed and maintained by the Ministry of Defense (ACPDR, 2005). The landslide inventory maps include more than 3500 landslides, but not rock falls and rock slides, and are one of the 85 geo-referenced databases incorporated in this system – such as databases on infrastructure, flood hazard maps, avalanche cadastre, earthquake hazard maps, fire hazard maps, etc. This electronic database is used as an internet application by the Ministry of Defense in regional Notification Centers for coordination purposes during immediate disaster relief actions led by the Civil Defense units, and as an intranet application being the information basis for their training in the Protection and Rescue Education and Training Center and for preparation of civil protection and disaster relief plans in the Administration of the Republic of Slovenia for Civil Protection and Disaster Relief (ACPDR, 2005). Unfortunately, this database is (still) not directly used for planning activities in the Ministry of the Environment and Spatial Planning in the field of hazard prevention.

IV. Large Landslides in Slovenia

In the last decades of the 20th century smaller rainfall-induced landslides were prevailing, especially during strong local summer thunderstorms or showers and during torrential floods, as in the case of numerous slumps and earth flows in the Kozarica and Lahomnica catchments during the 1989 flood (Fazarinc and Mikoš, 1992). Large flooding in the Savinja River basin in 1990 was associated with a large landslide near the village of Luče, and it took several

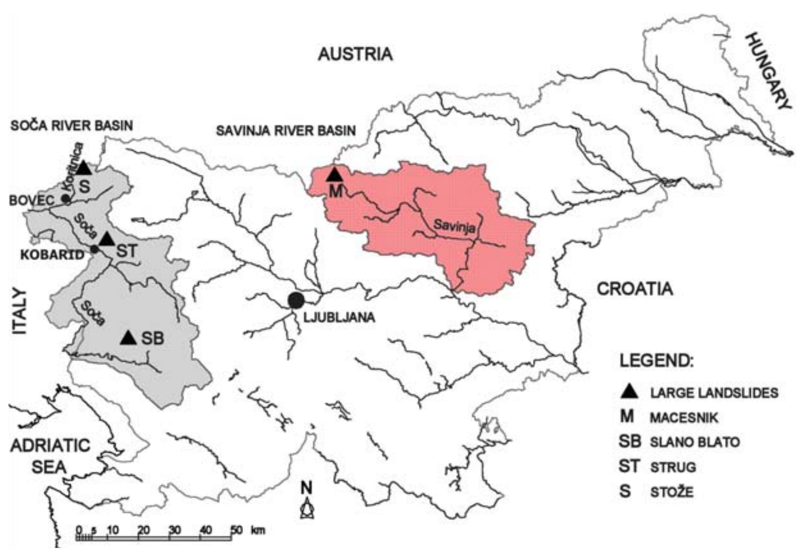

Figure 3. Locations of the four presently active large landslides in Slovenia (from Mikos et al., Natural Hazards and Earth System Sciences, Vol. 5, No. 6, 2005, p. 948).

years before the affected area could be successfully rehabilitated. Near the village of Solčava, in the same event in 1990, the Macesnik landslide (Figure 3) was initiated in a large old fossil landslide. This landslide grew up to a volume over 2 Mio m^3, despite the technical measures executed in mid-90's, and is still active. In the last years, three more large landslides (Stože, Slano Blato, Strug; Figure 3) were triggered in Slovenia. Each of them had a volume of the order of 1 Mio m^3.

The Stože landslide and Slano Blato landslide were triggered in the very wet year 2000. In December 2001, the Strug landslide was initiated as a combination of a primary rock fall, a secondary landslide and occasional debris flows from the rock fall source area during intense rainfalls (Mikoš *et al*., 2006a). All of them can be placed in the category of rainfall-induced landslides that became active in unfavorable geological conditions. Similar experiences can be found elsewhere in the Alps and in the Carpathians.

A. Stože Landslide

The Stože Landslide in W Slovenia with a volume of around 1.5 million m^3 was initiated on November 15, 2000 as a debris landslide on the Stože slope in a moraine (glacial till) above the village of Log pod Mangartom in W Slovenia after a wet autumn period (1638.4 mm in 48 days before the event, more than 60 % of the average annual precipitation) with no snow accumulation but rising runoff coefficients. It turned from a debris landslide on a hill slope (possibly caused by artesian pressures, Figure 4) into a catastrophic debris flow (Figure 5) due to low inertial shear stress caused by high water content (Mikoš *et al*., 2004b).

Figure 4. The Stože slope after the debris landslide.

The Stože debris flow had two phases: the first (dry) one ended after less than 1 km in the channel of the Mangart Creek, and the second (wet) one initiated after 35 hours by rainfall and infiltration, when it traveled through a narrow channel of the Predelica Torrent for 4 km to Log pod Mangartom (Figure 6 and further downstream to the narrow Koritnica River valley, stopping after 7 km. This debris flow was the largest event of this kind in the last century in Slovenia.

Figure 5. Helicopter view of the debris-flow pathway from the source area on the Stože slope across the regional road Bovec-Tarvisio (Italy).

Figure 6. Helicopter view of the debris flow deposits in Log pod Mangartom after the devastating debris flow in November 2000 – the Predelica Torrent flows from above into the Koritnica River, coming from the right.

The debris flow reached the village in a few minutes, killed 7 people in their homes, destroyed 6 and severely damaged 23 residential or farm buildings as well as devastated nearly 15 ha of agricultural land, mainly pastures. The Stože debris flow was mainly depositing its masses along its flow path and only locally eroding some very narrow sections. Debris deposits were locally deep as much as 10 meters, and were so wet that large machinery was unable to work on it for nearly two weeks. Finer fractions of debris masses were immediately transported downstream in suspension together with wooden debris, and deposited along the Soča River, where some local flooding was caused (Brilly *et al*., 2002).

The maximum flow velocity of the debris flow was estimated to be well over 10 m/s in the steep and narrow channel of the Predelica Torrent, and between 3 and 5 m/s in the more open valley of the Koritnica River. These estimated values were confirmed using one- and two-dimensional mathematical models for debris flows (Četina *et al*., 2006). As the main triggering factor, prolonged rainfall of 1638.4 mm in 46 days prior to the event with the return period well above 100 years was recognized by a hydrologic analysis (Mikoš *et al*., 2004b). The remaining masses on the Stože slope are the main reason for concern and possible new debris flows in the future.

One- and two-dimensional mathematical modeling of debris flows (Četina *et al*., 2006) was also used for optimization of the two main river channel form in the area (Predelica Torrent and Koritnica River) to convey debris flows and floods (Fazarinc *et al*., 2006), and to prepare the hazard map for the village of Log pod Mangartom (Mikoš *et al*., 2006d). This map was used to declare safe areas for construction of buildings (houses) destroyed by the November 2000 debris flow. In 2008, the mitigation is slowly coming to its end; also the construction of a new 110-m long arch bridge across the Mangart Creek that was destroyed by the debris flow in November 2000 (Figure 5).

The total direct economic damages were estimated at more than 10 million USD. If the Stože debris flow magnitude is compared to other case studies documented in the Alps (van Steijn, 1996), it can be put into the group of "very high-magnitude" events. Even though its return period cannot be estimated from the local historical data, one can roughly estimate it to be well above 100 years.

B. Strug Landslide

The Strug Landslide is a very good example of a complex slope movement that was triggered as a rockslide on the south-west slopes of the Planica Mountain (1376 m a. s. l.) in the Krn Mountains above the Koseč village (650 m a. s. l.) near Kobarid in the Julian Alps, W Slovenia (Figure 7). It had an estimated volume of 95,000 m^3 and was triggered at the contact between high permeable calcareous rocks (Cretaceous scaglia) thrusted over nearly impermeable clastic rocks (Cretaceous flysch). After a sudden drop of 15 m in December 2001, the rockslide average velocity exponentially slowed down to less than 10 m/year until the end of 2002, and came to a practical still stand in 2003. A few days later in December 2001, a rock fall with an estimated volume of 45,000 m^3 was initiated within the rockslide. The kinetic push of the rock fall caused the immediate displacement of a translational soil landslide with a volume of 180,000 m^3 that partially slipped into the torrential ravine of the Brusnik Stream (Figure 8). After the rockslide suddenly dropped for 15 m in December 2001, its velocity exponentially slowed down to less than 10 m per year until the end of 2002, and came to a practical still stand in 2003 (Mikoš *et al*., 2006a).

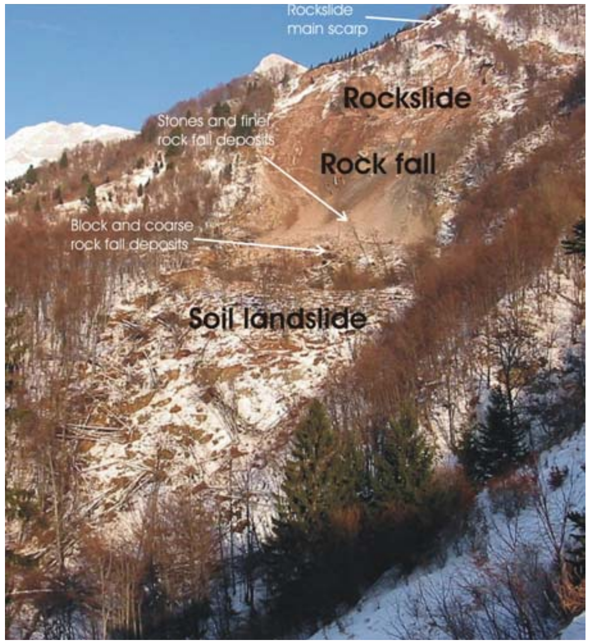

Figure 7. The Strug Landslide source area in December 2001.

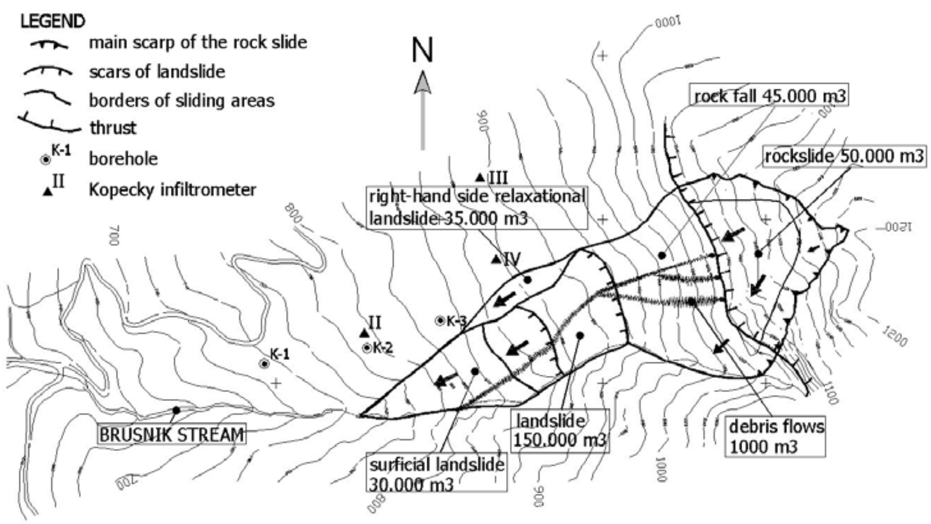

Figure 8. The Strug Landslide is a nice example of a so-called complex landslide (from Mikos et al., Natural Hazards and Earth System Sciences, Vol. 6, No. 2, 2006, p. 262).

Soon after the rock fall in December 2001, a question arose whether debris flows could be initiated in rock fall masses during prolonged rainfalls, possibly as soon as in the first wet period of 2002. Therefore, the channel of the Brusnik Stream was enlarged. A parabolic cross section was chosen to enable good conveyance for possible debris flows, and a small arch bridge in the village was replaced by a larger one.

After the rainfall in spring 2002, small debris flows made of clayey gravels, up to several 100 m^3, started to flow from the zone of accumulation of the rock fall over the landslide along the channel of the Brusnik Stream (Figure 9). The construction works in the Brusnik channel were completed just before the first debris flow reached the village of Koseč on April 22, 2002. More than 20 debris flow events, with volumes between some 100 m^3 and 1,000 m^3, were registered to reach Koseč village in 2002 and passed through the new regulated Brusnik Stream channel towards the Soča River. The enlarged and regulated Brusnik channel successfully withstood all debris flows without any overtopping.

Figure 9. The enlarged parabolic channel of the Brusnik Stream in Koseč was protected using rip-rap and as such in 2002 it was conveying more than 20 debris flows with the magnitude from around 100 m^3 to around 1000 m^3.

The statistical analysis showed that debris flows were initiated at daily rainfall between 20 to 30 mm, depending on the antecedent precipitation (Mikoš *et al*., 2006a). This value may be taken as a specific hydrologic threshold for this site. The decrease of rock fall activity was studied by field measurements of erosion processes in the rock-fall deposits using laser scanner technique (Mikoš *et al*., 2005a). Because in 2003 and 2004 no more debris flows were registered, the conclusion was drawn that debris flow events were rainfall-induced but governed also by the availability of rock fall debris in its zone of accumulation (Mikoš *et al*., 2005a). Nevertheless in future, under extreme conditions, new debris flows from the same source may be expected to reach Koseč.

One- and two-dimensional mathematical modeling of debris flows (Mikoš *et al*., 2006c) was used to prepare the hazard map for the village of Koseč. The same mathematical models were used as successfully applied for the Stože Landslide case (Četina *et al*., 2006). For the determination of the designed debris-flow with the total volume of 25,000 m^3, hydrological modeling was applied (Sodnik and Mikoš, 2006).

Using the results of mathematical modeling, the proposed enlargement of the channel of the Brusnik Creek through the village of Koseč was optimized. In 2002, the major part of the reforming of a torrential channel to a parabolic shape has been successfully executed, and the channel withstood all debris flows in 2002. The debris-flow modeling showed that some minor corrections should be done in order to secure the village of Koseč the safety against the designed debris flow with the total volume of 25,000 m^3. As an additional measure, two retention basins are planned to be built in 2009 in the lower reach of the Ročica Torrent (of which the Brusnik Creek is a tributary) to protect the village of Ladra from possible hyper-concentrated sediment flows.

C. Macesnik Landslide

The Macesnik landslide above the village of Solčava in N Slovenia near the border with Austria was triggered in autumn 1990. Today, the landslide crown is at the altitude of 1360 m. Until 1994 there were no activities on the landslide. In the period between 1994 and 1998 the advancement of the landslide on the slope was utmost intense, even though the torrential agency was trying to stop the landslide by mainly executing surface drainage works that were soon after their completion out of function and in need of continuous repair. During its advancement phase in late 1990's the landslide destroyed the state road at the altitude of approximately 1110 m, and a new pontoon bridge had to be built instead. In 1996, the landslide advanced again and destroyed a turn on the same road at the altitude of 1000 and 980 m, respectively. In 1999, the landslide advancement was luckily stopped by a large rock outcrop, and the toe of the landslide is nowadays at the altitude of 840 m (Mikoš *et al.*, 2005b). Its further advancement will possibly destroy three farm houses near the toe and several more on the way down the valley towards the Savinja River. The damming of this large river would cause a catastrophic flooding.

D. Slano Blato Landslide

The Slano Blato landslide is nowadays more than 1290 m long, 60 to 400 m wide and 3 to 12 m deep with a volume of more than 800,000 m^3 (Logar *et al.*, 2005). Its source area is located in the Eocene flysch formation on a slope below a large limestone high karst plateau, called the Trnovski gozd, which overlooks the Vipava River valley in western Slovenia (Figure 10). The landslide in this locality was first mentioned about 200 years ago and in 1887 it flowed as a fast moving earth flow and reached and destroyed the main road in the Vipava River valley 2 km away from its origin. The restoration of the landslide area (check dams, surface drainage works) was performed by the Austrian torrential service and took over 10 years – it was finished in 1906 (Logar *et al.*, 2005).

The landslide was triggered again after a wet autumn in November 2000, when a large slump was initiated within the old fossil landslide. It is ever since progressively enlarging behind the main scarp via retrogressive slumping of new and freshly weathered flysch material that due to high water pore pressures turns into a viscous earth flow. From this source area high on the slope, it has been moving down slope mainly as a slow moving viscous earth flow with occurrences, during rainy periods, of rapid mudflows initiated in wet earth-flow masses. It exhibits periods of different activity. In dry periods or in freezing conditions it behaves as a group of several slow to moderately fast moving landslides. In rainy periods it moves much faster with maximum displacements of up to 90 meters a day. Today, it still presents a hazard to the relatively new residential houses in the village of Lokavec at the toe of the slope.

Figure 10. The Slano Blato landslide on the slopes of the Trnovski gozd plateau seen from the Vipava valley.

V. General on Mitigation of Large Landslides in Slovenia

These four large landslides and their mitigation were the reason for proposing a special law that was adopted in 2002, and revised in 2005. Their final mitigation is planned to be finished before the end of 2010. According to an agreed decision, a landslide is called large when it directly threatens human lives and its estimated mitigation costs are close to 1 Mio € or more. Along with this arbitrary designation, three more landslides were proclaimed to be large and their mitigation was included into the special law on mitigation of large landslides in Slovenia. All these three landslides are rather slow (less than few cm/year) but they threaten several houses or a part of a village. Their volumes, however, are much less than 1 Mio m^3 and are therefore not treated in this paper on mitigation of large landslides in Slovenia.

As defined by this law, a special governmental four-member professional committee (nominated experts from the fields of engineering geology, geotechnical engineering, and hydraulic engineering) supports all activities of the Ministry of the Environment and Spatial Planning on the mitigation of large landslides. A total sum to cover the costs for all the planned activities in terms of the final mitigation of these large landslides in Slovenia was estimated at 60.5 Mio €. This should be added to the estimated sum of 83.5 Mio € as the final remediation costs for other registered active smaller landslides in Slovenia. The majority of the financial sources will be used for measures on local and public roads.

Sediment production of these large landslides is comparable to the annual average sediment production in Slovenia (around 5 Mio m^3 on average a year on 20,273 km^2). Nevertheless, the sediment delivery to the fluvial system from large landslides is very different. These may occasionally release large amounts of sediment debris, entering the fluvial network and increasing sediment supply from headwaters. An important point is whether or not the slid masses reach the watercourses. If the process of land sliding changes into faster moving mass wasting phenomena, such as mud flows (Slano Blato landslide) or debris flows (Stože and Strug landslides), the unstable landslide masses may contribute large amounts of sediment to the fluvial system (Mikoš *et al*., 2006b).

The proposed non-structural and structural measures on large landslides before their final mitigation were defined in the special law adopted for their final mitigation, and can be divided into:

1. intervention measures (mechanical removal of landslide masses and debris deposits, temporary evacuation of endangered persons, daily field observations) to assure high level of protection in case of immediate emergency (heavy rainfall, fast or large landslide displacements) during the landslide mitigation phase before its final mitigation will be reached in the field, and
2. final mitigation measures, where these are a chain of very different activities: field and laboratory investigations (aero-photogrammetry, geological mapping, boreholes, inclinometers, geophysical methods, infiltration tests, discharge measurements, laboratory investigations on material properties …); mathematical modeling (slope stability, debris flows, mud flows); recognizing/defining future hazards (possible hazard scenarios) and especially assessing the remaining risk after the completion of the proposed measures; planning and construction of mitigation measures (proposing acceptable solutions, preparation and acceptance of State Location Plans, project documentation, construction on site); post-mitigation observations (surveying and remote sensing, warning systems).

It is clear from the variety of possible mitigation measures and from the fact that each landslide is a story for itself to be treated individually, but taking into account the experiences gained on other landslides, that only an interdisciplinary team of highly experienced professionals may guide the lengthy mitigation process of several large landslides and redirect the mitigation activities under fast changing circumstances.

The mitigation of large and deep-seated landslides asks for heavy constructions that can stabilize such unstable slopes. Usually, this kind of large supporting structures, such as supporting walls or similar concrete structures cannot be successfully built in fast moving landslide masses. One option is to build them during dormant phases of a landslide (i.e. during dry periods without rain or in cold winter time). In this case adequate financial support must be available, but this is not the case if the fiscal year ends in November and the budget for the next one is, for example, adopted in April. The other more robust option is to slow down the landslide movement. In order to slow down a fast moving landslide (> 10 cm a day) it is often necessary first to drain surface waters by drainage works and then to lower groundwater level in the landslide. The latter measure can be done by digging deep drain trenches. They may go as deep as 6 to 8 meters in rather wet soils, where additional berms in order to dig deeper are not possible. In the case of deep-seated landslides (> 10 m thick), wet soil conditions do not allow us to dig drain trenches all the way down to the sliding surface to efficiently slow down sliding. In such cases reinforced concrete (RC) deep wells (dowels) may come under consideration. This type of structure is known from road construction as a kind of supporting structure for large viaducts and bridges. Their advantage is that once they are built, they have the function of retaining (supporting) as well as draining.

We used RC wells as structural mitigation measures on two large deep-seated landslides in Slovenia: the Macesnik and the Slano Blato landslides, respectively (Pulko *et al*., 2005). In 2004 we firstly built two wells on the Macesnik landslide and then in two phases we built altogether eight RC wells on the Slano Blato landslide in order to stabilize the upper part of these two deep-seated and over 1-km long landslides. The RC wells were made of reinforced concrete, 5 m in diameter and over 20 m in height in order to found them into the non-weathered rock below the sliding surface. For their design the field and laboratory data on geological conditions as well as landslide material properties were used in a numerical model to estimate design loads. Under such labile field conditions, their construction was a challenge, but they proved as an effective structural measure providing the stabilization of two large deep-seated landslides in their upper part. This fact was proven by a clear decrease of measured displacements of the landslide masses after their completion (Mikoš *et al*., 2005b). Further RC wells are planned to be constructed on both landslides in order to gradually stabilize the whole landslide. Even though the RC wells were meant as a temporary measure, they are definitely part of the final remediation of these large deep-seated landslides. In the continuation of this paper, the experiences with the mitigation of the Macesnik landslide and the Slano Blato landslide will be given in more detail.

VI. Mitigation of the Macesnik Landslides

The surface drainage works in the upper part of the landslide, executed in the period 1994–1998, were unsuccessful and did not help to stabilize the landslide. The first extensive engineering geologic and geotechnical investigations on the landslide started in 2001. From then on regular measurements of the landslide surface displacements in the selected cross sections have been performed on this rather long but deep landslide (Figure 11).

The usage of point data from the boreholes disclosed changes in the inclination of the landslide base (sliding surface), which explained the higher landslide thickness where the inclination changes and different landslide dynamics (relative displacements) as measured on its surface in the selected cross sections.

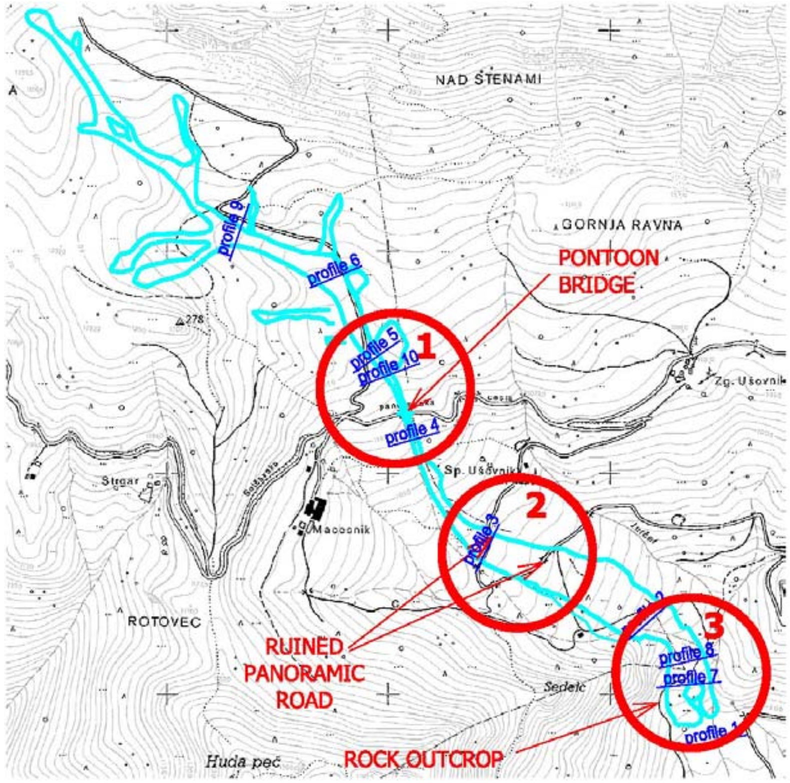

Figure 11. The three parts of the Macesnik landslide with the landslide contour and the cross sections for measurements of the landslide surface displacements (*from Mikos et al., Natural Hazards and Earth System Sciences, Vol. 5, No. 6, 2005, p. 949*).

Figure 12. The Macesnik Landslide in its upper part showing the execution of surface drainage works in 2004 (*from Mikos et al., Natural Hazards and Earth System Sciences, Vol. 5, No. 6, 2005, p. 952*).

Because the slid masses are heterogeneous (mainly dark-grey stiff clay with layers of more permeable clayey gravels of different thickness at different depths) and not knowing the exact values of water pressures on the sliding surface, the remediation measures (lowering of water pressures and supporting structures) were planned only on the basis of »idealized« conditions prevailing in separate landslide reaches, as follows:

1. Lowering of water pressures by deep drainages is technologically possible (up to the depth of 8 m) only in the upper part of the landslide above the pontoon bridge.
2. The sequence of supporting structures on such a long landslide should be planned in such a way that no overtopping by slid masses from above or subsidence and sliding of masses away from the structures may occur.

On the basis of all executed field and study investigations, field measurements, and experiences the planned remediation of the Macesnik landslide will follow the division of the landslide by supporting and drainage structures into three areas (Figure 11):

1. Upper part of the landslide with the area above and around the pontoon bridge.
2. Middle part of the landslide with the area at the turn of the ruined road.
3. Lower part of the landslide around and above the rock outcrop that stopped further landslide advancement.
4. Supporting structures should be formed by grouping together several RC wells.

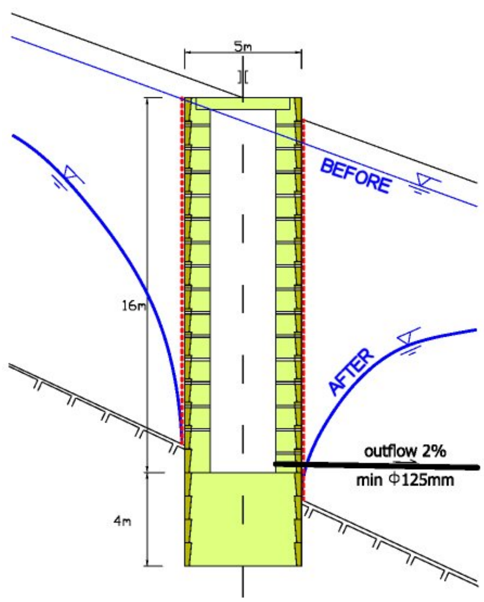

Figure 13. The drainage function of a RC well.

As the precaution measure, a mechanical warning system was established below the landslide toe. In 2002, the proposed remediation measures started to be executed from the upper part of the landslide in the down-slope direction. In the upper part of the landslide above the pontoon bridge peripheral surface drainage works were formed mainly on the stable ground outside the landslide (Figure 13). In summer 2003, above the pontoon bridge three parallel deep drainages were constructed to slow down the landslide displacements in the area and to make possible the execution of two RC wells above the bridge. In spring 2004, in the upper part of the landslide two additional deep drainages were constructed. In late 2004, the landslide above the pontoon bridge was stopped so that between the pontoon bridge and the lower end of the deep drainage system two RC wells were built.

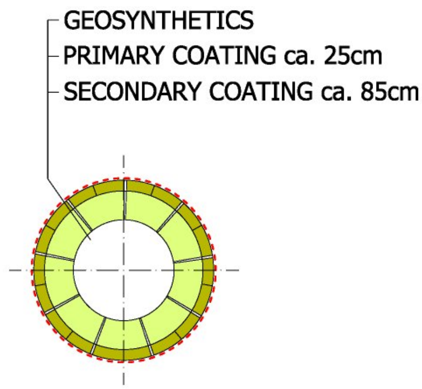

Figure 14. A horizontal section of the RC well.

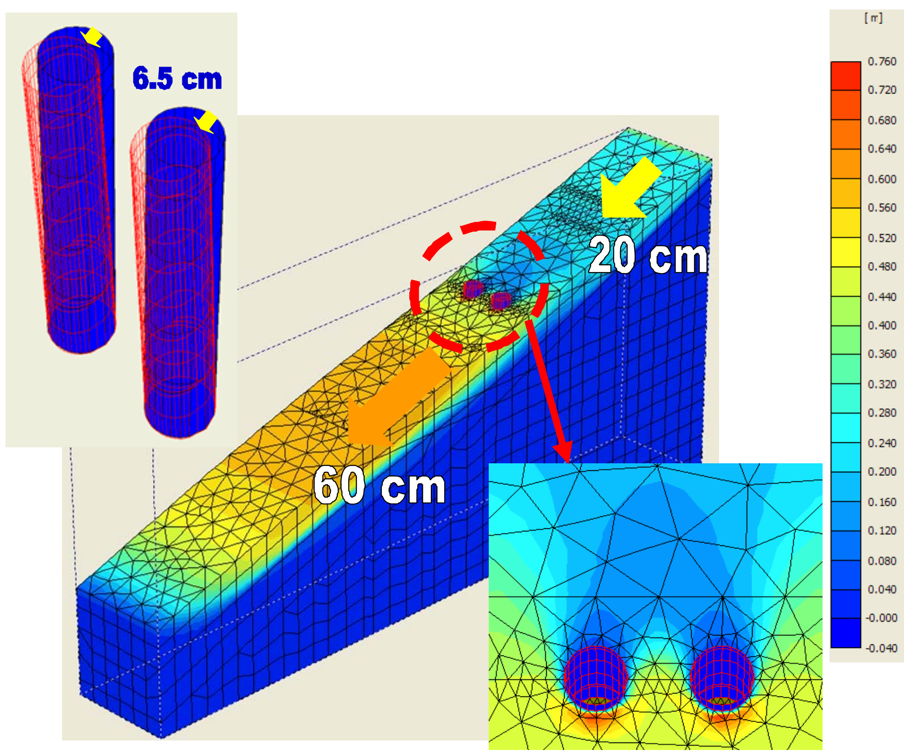

Figure 15. Displacements isolines (scale is given in meters) for two reinforced concrete wells on the Macesnik landslide, computed by PLAXIS® 3D.

If an RC well (dowel) should have supportive as well as drainage function (Figure 13), the following demands should be fulfilled:

1. The primary coating (during digging, Figure 14) should stand all loads of the landslide (F ≅ 1.10).
2. The primary coating of the well should be adequately perforated so that ground water could infiltrate into the central part of the well.
3. The primary coating of the well should be separated from the landslide masses by using an adequate geo-synthetic material. From it the water should be able to enter the central part of the well through the perforations of the primary coating.
4. After digging out the well and the execution of the primary coating with a thickness between 30 and 50 cm to the prescribed depth, the execution of a reinforced concrete foundation plate follows.
5. The prescribed safety factor for the well (F > 1.25) will be reached only after the execution of the reinforced concrete secondary coating with a thickness of 80 cm is ensured.
6. From the central part of the well an outlet pipe (drainage) should be executed to make possible the gravitational outflow of the infiltrated water from the well.

On the basis of the stability analyses (using Plaxis® 3D, displacement isolines are given in Figure 15), for each RC well with a diameter of 5 m and a depth of 22 m (18 m of the landslide mass and 4 m of rock base) the following loads were determined: axial forces 4,350 kN; bending moments 37,650 kNm; shear forces 9,160 kN; and vertical total stresses 1,540 kN/m^2.

The executed remediation (stabilization) measures in the upper part of the Macesnik landslide (above the pontoon bridge) made the landslide in this part to practically stop. Furthermore, the displacements in the other two parts of the landslide also effectively slowed down.

The landslide is rather deep in its middle part (area 2 on Figure 11), where it is crossed by the ruined panoramic road twice. In the place of the present upper road turn the landslide depth is more than 16 m, and in the place of the lower road turn the depth is more than 22 m, respectively. In this area, two lines of support structures made of RC wells are proposed – in 2007, the upper line above the upper road turn made of two RC has been finished. During such a step-wise mitigation of a large landslide in a down-slope approach it could happen that some of the initially proposed measures are left out or executed in a smaller extent. Nevertheless, the estimated costs for the final remediation of the Macesnik landslide are over 16.0 Mio €.

VII. Mitigation of the Slano Blato Landslide

The mitigation started soon after the triggering of the landslide. In the first phase, i.e. in 2001 and 2002, around 260,000 m^3 of landslide masses were removed from the lower part close to the landslide toe and put to a dumping site in order to control the advancement of the viscous earth flow. Furthermore, the channel of the Grajšček stream that springs in the landslide area was enlarged downstream of the landslide toe in order to convey occasional very muddy flows from the bare landslide area through the village of Lokavec.

In the second phase of the landslide mitigation, we used the promising results, achieved with the execution of two deep RC wells on the Macesnik landslide. As a consequence of this reasoning, at the end of the summer 2004, 3 such RC wells were started to be built using the same technology in the upper part (source area) of the Slano Blato landslide. The second reason for such a supporting structure in the upper part of the landslide was the expected large landslide displacement (> 10 m) in late 2004 as a consequence of the forthcoming autumn rainfall (Mikoš *et al*., 2005c).

Figure 16. The upper part of the Slano Blato landslide with partially finished reinforced concrete deep wells on its right-hand side (square is 100 x 100 m).

At the end of October 2004, two deep RC wells were already excavated to the depth of –9 m (to the bottom of the landslide or to the top of the rock base), and the third deep RC well (on the far left side looking up the slope) was excavated to the depth of –6 m. Its bottom reached only to the half of the depth of the landslide.

After intense rainfall at the end of October 2004 (monthly rainfall accumulation in October 2004 was 363 mm), and on 1 November 2004, large amounts of surface waters and strong inflow of groundwater into the rock depression below the landslide in its upper part, i.e. in below the area with RC wells, caused the fast landslide displacement that happened in the night between 1 and 2 November 2004. The translational displacement of the wells was nearly 20 m, and the wells also tilted backwards.

Despite the fact that they were displaced, the RC wells decreased the total landslide displacements in this area and captured large amounts of groundwater, which would turn the landslide masses into a viscous flow – a normal process observed during wet periods. In the period from 31 October to 6 November 2004, each well captured between 100 and 120 m^3 of water in 12 hours. The decreased displacements in the area were achieved to a large extent by the drainage effect of the RC wells under construction, even though they were excavated only to the contact between the landslide and the rock base.

At the end of 2004, two displaced but undamaged deep RC wells were finished using the same technology: their primary coating of 25 cm was in the inside finished by an 85 cm thick secondary coating. In March 2005, the third displaced and damaged deep RC well was rehabilitated using new technology. Using this new technology, at the same time 4 deep RC wells were built in 2005 in the right-hand side of the landslide (Figure 16).

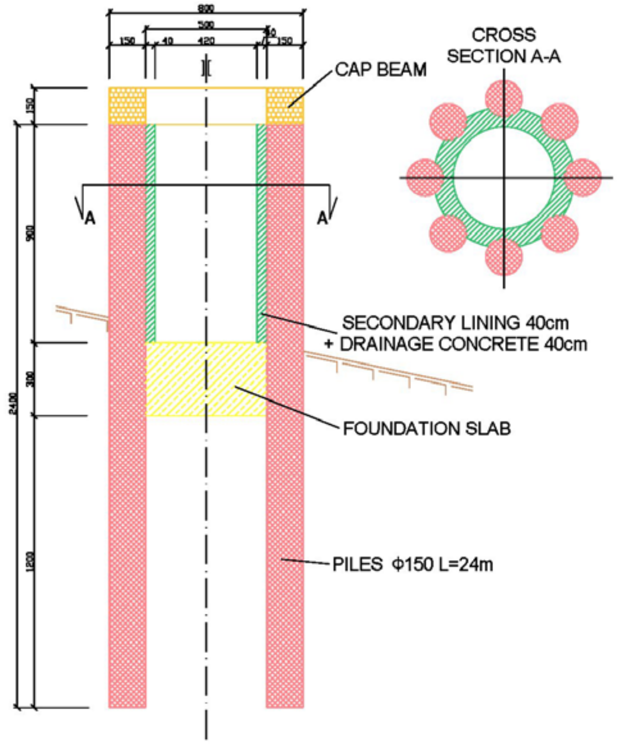

Figure 17. Details of RC wells on the Slano Blato landslide.

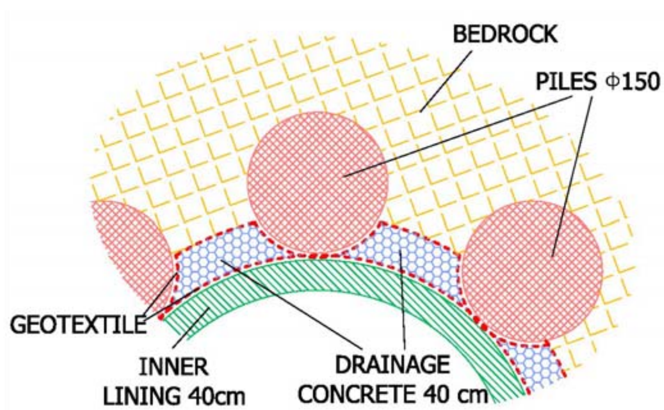

Figure 18. The detail of embedded draining concrete into the primary and secondary coating of the RC well.

In the first phase, the so called primary coating of the well was executed by drilling 8 RC Benotto piles with the diameter of 150 cm to the depth of 24 m (well below the sliding surface), which were then on their top connected by a reinforced concrete 2-m high beam. The centre of the piles was on a circle with the diameter of 6.5 m, so that the final inner diameter of the primary coating was 5.0 m (Figure 17). In the second phase, the excavation between the piles to the depth of –15 m followed. At this depth, a 3-m thick concrete foundation plate was executed. Above its top there was a drainage pipe drilled out of the well to the landslide surface for gravitational outflow of the captured water infiltrating into the well through the drainage concrete (Figure 17) and thus securing not only the supporting but also the draining function of the well. As a final mitigation of the landslide in its upper part, the finalization of the curtain of more than 10 RC deep wells all together is planned to be finished until 2010.

All planned and executed deep RC wells were designed on the loads (bending moments, transversal and axial forces), given from numerical analyses using commercial software (Plaxis® 3D Foundation). For modeling the vicinity of the wells (soils, rocks) the Hardening Soil Model was applied, and the well was modeled as a shell.

VIII. Conclusions

On the basis of this review paper, one can conclude that a major part of Slovenia is subjected to dangerous natural hazards, such as earthquakes, fires, landslides, floods, and rock falls. In the last decade the number of disasters is rising, handicapping state budget and budgets of over 200 local communities. These are in most cases incapable of covering economic damages, as well as organizing and financing mitigation of larger natural disasters (droughts, floods, large landslides). It is therefore legally regulated that mitigation in such cases goes to the debit of the state.

In 2009, Slovenia will celebrate 125 years of organized torrential service (started in the former Austrian-Hungarian monarchy in 1884). Several stony structures built 100 years ago and more are today still in good shape and in function – so far so good. What is troublesome in Slovenia is further historical development of the second half of the 20th century related to the planning and execution of torrential structures. In the 50's and 60's of the last century, labor-intensive manual work was still prevailing thus making possible the construction of a diffuse network of small but effective torrential measures such as check dams, gabions, dense drainage works, and reforestation. By using concrete more and more as the prevailing construction material, and thus also civil mechanization, the construction sites were limited to places easily reachable by machines. With this field practice, the maintenance of the existing dense network of torrential infrastructure was far more difficult to execute. The final blow to such a policy was given in 90's after Slovenia had become an independent democratic republic in 1991, when green ecologism prevented any substantial investments in the water management sector by decimating its financial resources for a decade. The protection of natural resources grew into overprotection, not acknowledging that a continuous maintenance of the existing protective infrastructure at a high level is essential to keep the protection of mankind and its property against natural hazards at least on the same level as the one reached in the past.

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).

In Slovenia, the RC deep wells, well known from road construction, were successfully used in two different designed forms for the first time as supportive and draining construction for large landslide mitigation. Before applying this mitigation technique, it was at utmost importance to stabilize a landslide to such an extent by e.g. deep drainage trenches and surface drainage works that the execution of deep wells was made possible.

In the last years, several debris flows (Stože, Strug) draw attention and as a response to them, torrent and river channels were optimized to convey water and sediment flows as well as rare debris flows using the results of one- and two-dimensional mathematical modeling of debris flows.

In Slovenia, the ongoing mitigation of the large landslides is subjected to a special law adopted in 2002 (revised in 2005). The final mitigation is planned to be finished before the end of 2010, with estimated total costs of 60.5 Mio € for all activities planned. These costs should be added to the estimated sum of 83.5 Mio € as the final remediation costs for all other registered active small-sized landslides in Slovenia. Because the mitigation process of large landslides is due to restricted financial resources not finished in a year or two, the organizational aspect becomes very important.

A special governmental (inter-ministerial) commission is leading all activities on large landslides, which is helped by a professional committee (experts in the fields of engineering geology, geotechnical and hydraulic engineering).

Possible measures on large landslides before their final mitigation can be divided into intervention measures (mechanical removal of landslide or debris-flow mass, temporary evacuation of inhabitants, and daily observations) in case of emergency (heavy rainfall, large landslide displacements) and final mitigation measures. The latter are a chain of very different activities:

- field and laboratory investigations (aerophotogrammetry, geological maps, boreholes, inclinometers, geophysical methods, infiltration tests, discharge measurements, material properties ...);
- modeling (slope stability, debris flows, mudflows);
- future hazard assessment (possible scenarios);
- mitigation measures (proposing solutions, project documentation, construction);
- post-mitigation observations (surveying and remote sensing, warning systems).

In Slovenia, practical experiences with mitigation of large landslides up to now show that only a strict and insightful co-ordination, interdisciplinary approach and adequate financial support may lead to successful large landslide mitigation.

Because the national legislation covering the mitigation of large landslides is not up-to-date, we suffer from long-lasting mitigation process. The main cause is on one hand the restrictive annual budget that can be applied, and on the other hand the rather complicated planning procedures needed for executing proposed structural mitigation measures in the field. Such an approach might help to carefully propose and design adequate structural measures, but it also causes additional costs because landslides are active, they enlarge according to their own dynamics and ask for higher financial resources for their mitigation if the mitigation spreads over a longer period of several years.

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