Landslides (2017) 14:1537–1546
DOI 10.1007/s10346-017-0848-1
Received: 14 February 2017
Accepted: 22 May 2017
Published online: 23 June 2017

Mateja Jemec Auflič · Jernej Jež · Tomislav Popit · Adrijan Košir · Matej Maček · Janko Logar · Ana Petkovšek · Matjaž Mikoš · Chiara Calligaris · Chiara Boccali · Luca Zini · Jürgen M. Reitner · Timotej Verbovšek

The variety of landslide forms in Slovenia and its immediate NW surroundings

Abstract The Post-Forum Study Tour following the 4th World Landslide Forum 2017 in Ljubljana (Slovenia) focuses on the variety of landslide forms in Slovenia and its immediate NW surroundings, and the best-known examples of devastating landslides induced by rainfall or earthquakes. They differ in complexity of the both surrounding area and of the particular geological, structural and geotechnical features. Many of the landslides of the Study Tour are characterized by huge volumes and high velocity at the time of activation or development in the debris flow. In addition, to the damage to buildings, the lives of hundreds of people are also endangered; human casualties occur. On the first day, we will observe complex Pleistocene to recent landslides related to the Mesozoic carbonates thrust over folded and tectonically fractured Tertiary siliciclastic flysch in the Vipava Valley (SW Slovenia), serving as the main passage between the Friulian lowland and central Slovenia, and thus also an important corridor connecting Northern Italy to Central Europe. A combination of unfavourable geological conditions and intense short or prolonged rainfall periods leads to the formation of different types of complex landslides, from large-scale deep-seated rotational and translational slides to shallow landslides, slumps and sediment gravity flows in the form of debris or mudflows. The second day of the study tour will be held in the Soča River Valley located in NW Slovenia close to the border with Italy, where the most catastrophic Stože landslide in Slovenia recently caused the deaths of seven people, and the nearby Strug landslide, which is a combination of rockfall, landslide and debris flow. The final day of the Post-Forum Study Tour will start in the Valcanale Valley located across the border between Slovenia and Italy, severely affected by a debris flow in August 2003. The flow caused the deaths of two people, damaged 260 buildings; large amounts of deposits blocked the A23 Highway, covering both lanes. In Carinthia (Austria), about 25 km west of Villach, the Dobrač/Dobratsch multiple scarps of prehistoric and historic rockslides will be observed. Dobratsch is a massive mountain ridge with a length of 17 km and a width of 6 km, characterized by steep rocky walls. The 3-day study tour will conclude with a presentation of the Potoška planina landslide, a slide whose lower part may eventually generate a debris flow and therefore represents a hazard for the inhabitants and for the infrastructure within or near the village of Koroška Bela.

Keywords 4th World Landslide Forum 2017 · Post-Forum Study Tour · Landslide forms · Geological setting · Rainfall · Slovenia

Introduction

Slovenia (and its adjacent territories) is situated in southern Central Europe, where the Alps, the Pannonian plain and the Mediterranean meet, and covers a total area of 20,273 m^2. The main reason for numerous landslide forms in Slovenia lies in the complex geological and tectonic structure of the territory, lying on the Adriatic plate and being squeezed between the African plate to the south and the Eurasian plate to the north. The Adriatic plate rotates counter-clockwise, which causes movements particularly on the northern and eastern sides (Gosar et al. 2009). Numerous active faults and thrust systems affect the country and define its diverse morphology and unfavourable geological conditions. In general, the geological setting of Slovenia is very diverse and mainly composed of sediments or sedimentary rocks (53.5%), clastic rocks (39.3%), metamorphic (3.9%), pyroclastic (1.8%) and igneous (1.5%) rock outcrop (Komac 2005). Rockfalls are common in the mountain areas, as well as on steep slopes where carbonate rocks are found lying above clastic sediments. Landslides are typical for the terrain on gentle slopes, where clays, silts and marls are subjected to strong weathering, while complex deep-seated landslides are related to terrain composed of carbonate and clastic rocks. According to the information provided by the landslide susceptibility maps (Komac and Ribičič 2006; Komac et al. 2009), more than one-third of the Slovenian territory is highly prone to slope failures. In Slovenia, more than 10,000 landslides have been recorded in the past 25 years by the Administration for Civil Protection and Disaster Relief (ACPDR) and the Geological Survey of Slovenia (GeoZS), which translates into a landslide density of ~0.5 slides per km^2. Most of these slope failures can be categorized as landslides ranging in size from 10 to 1200 m^3, most of which have caused damage to buildings, infrastructure and agricultural land (Jemec Auflič et al. 2016). Among the many slides that have been recorded are those landslides whose volumes exceeded one million cubic meter and which, in addition to the damage done to buildings, also endangered the lives of hundreds of people and even resulted in human casualties. In Slovenia, precipitation represents one of the most important triggering factors for the occurrence of landslides. In the previous decade, extreme rainfall events in which a very high level of precipitation occurs in a relatively short period have become increasingly important and more frequent, causing numerous undesirable consequences. Three of the proposed visited landslides (Strug, Slano blato and Stože) rank among the greatest landslides in Slovenia, with special legislation passed to repair the damage they caused (Measures to Repair the Damage Caused by Certain Large-Scale Landslides in 2000 and 2001 Act, Official Gazette of RS, no. 3/06).

The aim of this paper is to present the variety of landslide forms in Slovenia and its immediate NW surroundings triggered over the last 3 decades in the frame of 4th World Landslide Forum Post-Forum Study Tour. The special emphasize will be on the geological, structural and geotechnical features of each individual landslide case that differ mainly in movement type, type of sediments and triggering factors. The landslides discussed (Fig. 1) are outlined in five main chapters according to their geographical location: Table 1 shows the main characteristics of landslides, while a view of landslides is given in Fig. 2; and can also be followed

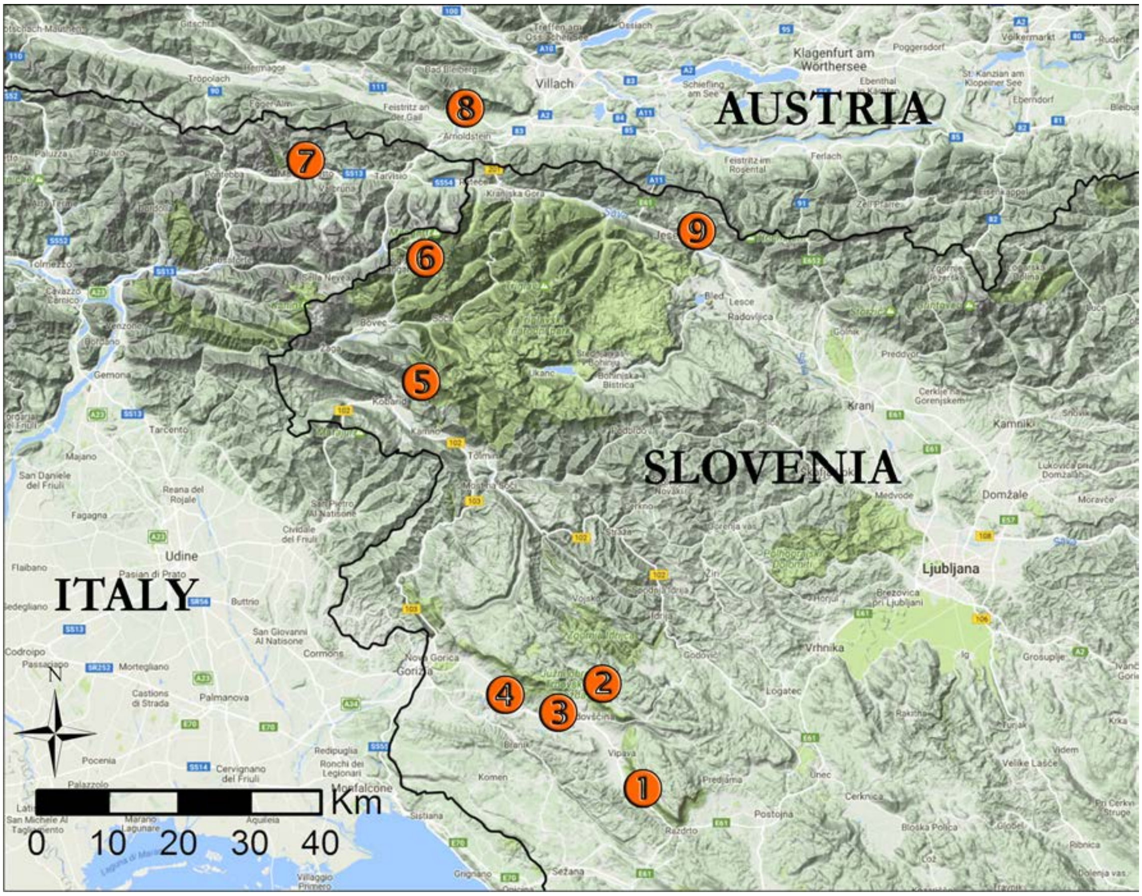

Fig. 1 Landslide locations in Slovenia and NW surroundings. *Numbers* correspond to the landslide descriptions that follow below and in Table 1

from the tour description of the 4th World Landslide Forum Post-Forum Study Tour (https://www.wlf4.org/forum-themes/#tour).

The Vipava River Valley

In the Vipava River Valley, in SW Slovenia, complex Pleistocene to recent landslides are related to the Mesozoic carbonates thrust over folded and tectonically fractured tertiary siliciclastic flysch. All the landslides described are precaused by this general geological setting. Such overthrusting has caused steep slopes and fracturing of the rocks, producing intensely weathered carbonates and large amounts of scree deposits. Elevation differences here are significant and range from 100 m at the valley bottom to over 1200 m on the high karstic plateau. The combination of unfavourable geological conditions and periods of intense short or prolonged rainfall (average precipitation is approximately 1700 to 2500 mm/year on the karstic plateau) has led to the formation of different types of complex landslides. Recently, carbonates have been breaking down in the form of steep fans of carbonate scree in the upper part of the valley, increasing the thickness of these sediment layers to well over 10 m. In the lower part, superficial deposits range from large-scale, deep-seated rotational and translational slides to shallow landslides, slumps and sedimentary gravity flows in the form of debris or mudflows reworking the carbonate scree and flysch material.

Rebrnice landslides

The Rebrnice area (No. 1 on Figs. 1 and 2) is a SW-facing slope that borders the Vipava Valley and the NE-lying Nanos Plateau in SW Slovenia. The area is geotectonically part of a complex SW-verging fold-and-thrust structure of the External Dinarides composed of a series of nappes of Mesozoic carbonates thrust over Palaeogene flysch (Placer 1981). This geotectonic position is reflected in the distinct asymmetric aspect of the valley slopes, where the upper part of the slope is marked by steep carbonate cliffs, while the middle and lower areas are more gently sloped and composed of flysch bedrock covered by numerous fan- and tongue-shaped Quaternary superficial deposits (Jež 2007; Popit et al. 2014). The superficial deposit of the fossil landslides covers an area of more than 2.8 mio km^3 and reaches a maximum thickness of 50 m. The sedimentary texture and structure of the complex fossil landslides in the Rebrnice area clearly indicate multiple depositional events and various gravitational mass movement processes, ranging from slides to flows (Popit et al. 2013). Accelerator mass spectrometry (AMS) radiocarbon dating of charred wood extracted from the Šumljak fossil landslide in the Rebrnice area (around 45,000 years) indicates a considerable range in the age of superficial deposit, which reaches back to at least as far as the last glacial cycle (Marine isotope stages 3) (Popit et al. 2013).

One of the main reasons for embarking on detailed geological and geomechanical research of superficial deposit was the construction of the motorway across this area. This road represents an important connection between central Slovenia and northern Italy. Technically, the construction was very demanding. Strong supporting structures were required to maintain both temporary and long-term stability of the landslides across vast sedimentary bodies. In the case of the Boršt viaduct, a foundation is made 13–22 m deep shafts with a smaller viaduct pillar in a centre, which enables movements of the upper less stable mass together while there are no earth pressures acting on a viaduct pillar. Nevertheless, many slope stability issues are still active concerns, and they indicate the need for remediation in some sections. Recently, we have been monitoring some very extensive reactivated landslides. A thick cover of Quaternary superficial deposit (carbonate scree deposit) and breccia, tectonic deformations in the flysch, the presence of groundwater and the specific geomorphological setting represent highly significant technical challenges for the management of landslides.

Stogovce landslide

The Stogovce landslide (No. 2 on Figs. 1 and 2) is located ca. 200 m below the carbonate overthrust front atop Eocene flysch (Petkovšek et al. 2011). In this area, the flysch bedrock is covered by weathered flysch and carbonate scree some 6–28 m thick. The scree is sometimes cemented into carbonate breccia. Individual larger carbonate blocks, some m^3 in size, are also present in the sediments (Verbovšek et al. 2017a). The landslide zone was active even before the triggering of the landside of 2010. These developments were observed on a local road as cracks and smaller slides, with the road in constant need of maintenance (Petkovšek et al. 2011). The Stogovce landslide was triggered by an extreme precipitation event on 18 September 2010 as two small rotation slips. In the following weeks, the slopes bordering the initial landslides were triggered until the landslide grew to 700 m wide and 200–300 m long. Approximately one million m^3 of carbonate rock debris and weathered flysch moved towards the Lokavšček torrent (Petkovšek et al. 2011). During this event, a 1-km-long section of local road leading to local villages on the carbonate nappe was destroyed, together with the power supply station that ran the water pumping station. It was also found that about 300,000 m^3 of material from the Stogovce landslide could generate debris flow if the landslide dammed the Lokavšček stream, which would pose a risk to nearby villages. Several vital structural remediation works and measures were undertaken, such as a new road, a power supply station and a small dam on the Lokavšček stream to provide dewatering of the potential natural dam.

Monitoring of the landslide is performed using GNSS probes and inclinometers and indicates movement in the range of 1–5 cm/year, with maximum values up to 3 cm/month (Verbovšek et al. 2017a). The GNSS probes also act as an early warning system when monitored movements exceed 10 cm per day.

Slano Blato landslide

The Slano blato landslide (No. 3 on Figs. 1 and 2) is located above the village of Lokavec in the Vipava River Valley. This landslide differs from other landslides in the Vipava Valley by a mud-dominated composition of the transported material and the occurrence of salt efflorescences (predominantly sodium sulphate of the thenardite-mirabilite system) on the landslide surface (Martín Pérez et al. 2016), hence the name Slano Blato, meaning ‘salty mud’. The main scarp is located near the carbonate overthrust atop Eocene flysch. In the more remote part of the landslide, there is a structural depression that renders the area relatively unstable, owing to the high underground water table it sustains (Placer et al. 2008). Historical sources report events in 1786 and 1885, when landslides flooded the villages and the main road at the bottom of the valley. At the end of the nineteenth century, the first retaining measures were taken: small check dams were erected in order to retain the mud and reduce the slope angle. The stream bed was widened, and a construction ban in the influence area was put into effect (Logar et al. 2005). These structural measures had badly deteriorated or been completely neglected, and the landslide was retriggered some 100 years later, on 17–19 November 2000 during a period of heavy rain. Since then, many researchers have investigated and monitored this landslide, largely in order to define displacement rates and the landslide’s particular characteristics that later formed the basis of the mitigation and remediation measures (Majes et al. 2002; Ribičič and Kočevar 2002; Logar et al. 2005; Placer et al. 2008; Mikoš et al. 2009; Maček et al. 2016; Martín Pérez et al. 2016). The landslide started as a rotational slide at the altitude of ca. 570 m. Within a few days, it had grown to a length of 500 m, and to 60–250 m wide and 10 m deep. The material moved consisted of clayish gravel in the upper area and weathered flysch in the lower area (Ribičič and Kočevar, 2002). Due to continuous rainfall at the time, together with the uneven landslide surface, lakes formed in the landslide area. The water wet the sliding mass and transformed it into a mudflow, with a downward maximum velocity of 60–100 m/day and coming to a halt at the altitude of 460 m (at ‘Mud Lake’). Earthflow events repeated several times in the years that followed (2001–2004), and occasionally, the material transformed into minor yet very rapid to extremely rapid mudflows. At the same time, the retrogressive rotational slide occurred above the main scarp, feeding the landslide with new unstable masses. The landslide is currently 1.4 km in length and boasts a volume of more than 1 million m^3.

In order to protect the village from potential landslides, a small rockfill dam was constructed in 2002, with a retention volume of 5000 m^3 and some 200,000 m^3 of material were removed from the landslide body. Between 2004 and 2007, several reinforced concrete shafts were constructed deep at the upper part of the landslide designed to stop its progressive widening. These shafts measure 8 m in diameter and run 24 m in depth, and serve both as a dewatering measure and as a retaining structure (Pulko et al. 2014). In addition to the shafts, a 2-m-high concrete dam was constructed to reduce the slope inclination below the shafts, the surface underwent a reshaping procedure, and a surface dewatering system was constructed. Another 13-m-high concrete dam is in construction to reduce erosion processes at ‘Slap’ (waterfall) location and prevent destabilization of the landslide body in the lower part of the Slano blato landslide. As a result of these retaining measures, the landslide is active only at the main scarp.

Selo landslide

The Selo landslide (No. 4 on Figs. 1 and 2) is a large landslide from Pleistocene Epoch composed predominantly of coarse carbonate material and characterized by its exceptional size and considerable runout length (Verbovšek et al. 2017b). Landslide extent area of the carbonate debris is 4.5 km, covering an area of more than 10 km^2,

Table 1 Summary of the presented landslides. Label "* class" in the Volume column indicates the volume class of debris flows according to Jakob (2005), where applicable

No	Name (year of activation)	Movement types	Sediment*	Volume (m^3 and class*)	Velocity	Monitoring techniques	Mitigation measures	References
1	Rebrnice (45,000 y, reactivated)	Complex landslides	Debris, mud, carbonate gravel, weathered flysch material, carbonate scree	2.8×10^6 m^3	Fossil events, reactivation: several cm/year	GNSS, inclinometers	Pile walls, retaining walls.	Jež (2007), Popit et al. (2013, 2014)
2	Stogovce (reactivated September 16–20, 2010)	Landslide	Weathered flysch and diluvium, carbonate scree and carbonate blocks	1×10^6 m^3	Several cm/year	GNSS, inclinometers	Sediment removal, construction of a new road	Petkovšek et al. (2011), Verbovšek et al. (in press)
3	Slano blato (reactivated in November 2000)	Earth slide, earth flow, mud flow	Weathered flysch	1×10^6 m^3	Max 100 m/day	Security camera, GNSS	Dewatering shafts and deep drainage trenches, sediment removal, retaining measures.	Logar et al. (2005), Fifer Bizjak and Zupančič (2009), Placer et al. (2008), Ribičič and Kočevar (2002), Mikoš et al. (2009), Majes et al. (2002), Maček et al. (2016), Martín Pérez et al. (2016)
4	Selo (>42,000 y)	Rock avalanche	Carbonate gravel, debris, mud, weathered flysch material, carbonate scree	190×10^6 m^3	Fossil event	None (fossil event)	None (fossil event)	Verbovšek et al. (2017b)
5	Strug (December 2001)	Complex landslide: rockslide, rock fall, earth slide, debris flows	Scaglia beds (marly limestones) over weathered Cretaceous flysch	Rock fall: 45,000 m^3 + cca 20 debris flows, each 100–1000 m^3	Rock fall: max 20–30 m/s Land-slide: max 1.6 m/day Debris flows: max 1 m/s	TLS, boreholes, Automatic Meteorological Station, Early warning system	Realignment of the torrent channel (large parabolic cross section), new bridge with a large span, sediment retention basin	Mikoš et al. (2005, 2006a, b)
6	Stože (November 17–19, 2000)	Debris slide, debris flow	Raibl formation (limestones, marly limestones, dolomites and marls) and glacial till (moraine)	1.5×10^6 m^3	Debris landslide: max ~ a few m/s Dry debris flow: max ~a few m/s Wet debris flow: ~ 20 m/s	ALS, boreholes, Early warning system	Drainage works in the source area, reforming of the slopes to form berms, natural succession (revegetation), realignment of the torrent Mangartski potok, debris flow breaker, realignment of the Koritnica River	Mikoš et al. (2004), Četina et al. (2006), Mikoš et al. (2006b)

Table 1 (continued)

No	Name (year of activation)	Movement types	Sediment*	Volume (m^3 and class*)	Velocity	Monitoring techniques	Mitigation measures	References
7	Malborghetto-Valbruna (August 29, 2003)	Debris flow	Dolomitic gravel, boulders and debris	1×10^6 m^3	Wet debris flow: ~ 20 m/s	None	Artificial channels, deposition basins, natural engineering, check dams	Calligaris et al. (2012), Hussin et al. (2015)
8	Dobratsch (1348)	Rockslide	Carbonate debris (megaboulder- to sand-size)	100×10^6 m^3	Approx. several 10 m/s (not observed)	None	None	Till (1907), Brandt (1981)
9	Potoška planina (eighteenth century)	Rockslide, landslide, debris flow	Scree, weathered clastic rocks in contact with Mezozoic carbonates	1.8×10^6 m^3	several m/y	GNSS, TLS, UAV photogrammetry, tachymetry, recording system	check dams	Jež et al. (2008), Komac et al. (2015); Peternel et al. (2017)

with an estimated volume of about 190×10^6 m^3. The estimated material balance, sediment volume and geometry indicate that the main landside deposit most likely corresponds to a large-scale collapse of the upper carbonate slope (escarpment) developed from rock avalanche. Parameters describing the geometric relationships of the Selo landslide (an apparent friction coefficient, defined as H/L ratio; Fahrböschung) and its estimated volume correlate with data for landslides of comparable size (e.g. Legros 2002), including some examples of typical rock-avalanches.

Radiocarbon dating of wood debris entrained by the Selo landslide and excavated from the underlying paleosol and basal layers of landslide deposits yielded radiocarbon-dead values, clearly indicating the pre-Holocene age of the landslide.

The Soča River valley

Strug landslide

The Strug landslide (No. 5 on Figs. 1 and 2) was initiated in a small watershed of the Brusnik Torrent in December 2001, above the village of Koseč in the Upper Soča River valley in NW Slovenia. The Strug landslide occurred at the contact point between highly permeable calcareous rocks (Cretaceous scaglia) thrust over largely impermeable clastic rocks (Cretaceous flysch)—a complex landslide featuring a combination of various unstable material (Mikoš et al. 2006a). The landslide was triggered by a single large rockslide that soon activated a rockfall, resulting (by virtue of its load) in a translational debris slide. In 2002, over 20 small debris flows (from 100 to ~1000 m^3) of gravels were initiated in the rockfall masses and started to flow from the rockfall source area over the landslide mass along the Brusnik Torrent channel towards the village of Koseč. The monitoring system was immediately put in place for the inhabitants of Koseč, using field data from geotechnical (boreholes, inclinometers, groundwater levels) and hydro-meteorological networks (precipitation, weather station, occasional discharge measurements).

The observed data (velocity), debris-flow head height and estimated volumes of single surges for debris flows flowing from the Strug source area, together with the estimated rockfall available for debris flow generation, were used to develop a numerical model for potential debris flows for a maximum estimated volume of 20,000 m^3. The Brusnik channel was much enlarged and reformed into a parabolic cross section with a constant longitudinal slope, and with mild curves (no sharp bends). Furthermore, a new bridge with nearly twice the span of the old bridge was constructed that reconnected two parts of the Koseč village. Lastly, a sediment retention basin was constructed downstream of the Koseč village and another one upstream of the Ladra village, to protect the village from torrential hyper-concentrated flows. Subsequent regular field measurements after December 2001 revealed that the Strug landslide had moved into a far less active phase (Mikoš et al. 2005), and debris flows were no longer being initiated in the rockfall source area, as they were limited by the generation of much less fresh rockfall—even though local thunderstorms in the Brusnik watershed (less than 1 km^2) brought with them enough water to generate debris flow.

Stože landslide

The Stože landslide (No. 6 on Figs. 1 and 2), which hit the village of Log pod Mangartom in western Slovenia minutes after midnight

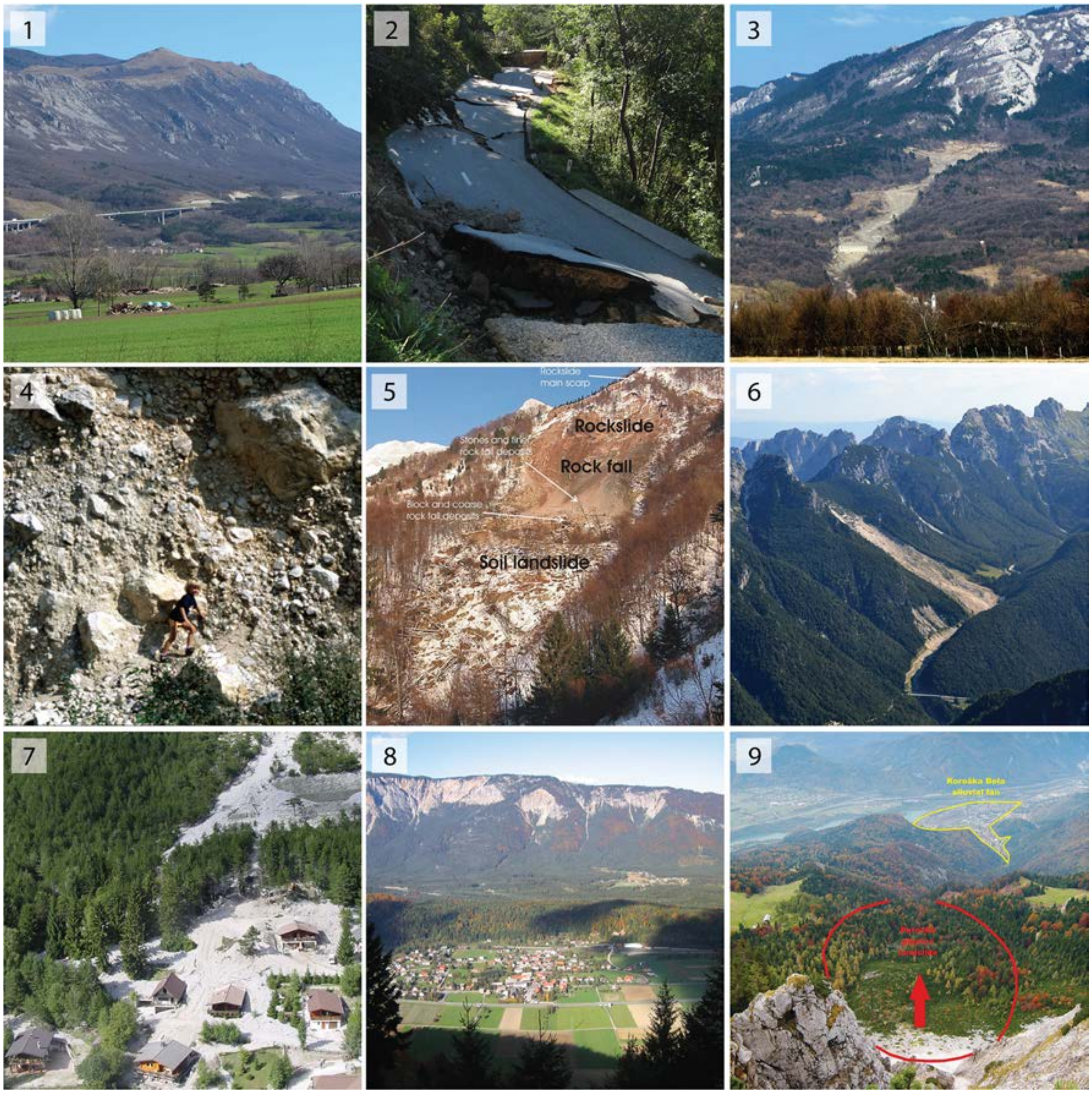

Fig. 2 View of landslides *1*: Rebrnice landslides, *2*: Stogovce, *3*: Slano Blato, *4*: Selo, *5*: Strug, *6*: Stože, *7*: Village of Cucco in the Malborghetto-Valbruna municipality, *8*: Dobratsch, and *9*: Potoška planina

on November 17, 2000, was the largest single natural catastrophe to be recorded in the territory of Slovenia in the second half of the twentieth century. The landslide event claimed seven lives and was the source of many discussions related to the possible cause (s) (local earthquake, heavy rainfall and other influences) and immediate triggering factors, as well as the responsibility for its tragic consequences. The Stože landslide was triggered in the Koritnica River catchment, which covers an area of 87 km^2. Permeable karst formations, glacial deposits and alluvial formations are prevalent in this mountainous catchment; the only formation of low permeability in the region is located in the sub-catchment where the Stože landslide occurred (Mikoš et al. 2004).

In two separate events, on November 15 and 17, 2000, near the Mangart Mountain (2679 m a.s.l.), NW Slovenia, two translational landslides composed of morainic material (glacial till) filled with silt fraction (Fig. 2), with a total volume of more than 1.5 million m^3 occurred on the Stože slope. The first landslide was associated with a dry debris flow, and the second landslide with a wet debris flow. The rain-gauging station in the village of Log pod Mangartom recorded 1638.4 mm of rainfall (more than 60% of the average annual precipitation) in the 48 days, leading up to the events (rainfall intensity of 1.42 mm/h in 1152 h). The Stože landslide (two debris flow) was triggered by high artesian pressures built up in the slope after prolonged rainfall. The devastating dry and wet debris flows formed as the result of the Stože landslide masses undergoing significant infiltration of rainfall and surface runoff into the landslide masses and their subsequent liquefaction (Mikoš et al. 2004).

Immediately after the event, the state and local administration for civil protection and disaster relief ordered the temporary evacuation of all inhabitants of the village, and an early warning system was put into place: the system worked based on monitored rainfall data, and several detectors that would be triggered by the heads of possible new debris flows that could be released in the destabilized source area on the Stože slope. Bridges and supply lines were also reconstructed. In the aftermath, specific legislation was adopted by the Government of the Republic of Slovenia, ordering the relocation of the houses that had been destroyed to safe areas as defined by a hazard and risk map. The Stože slope inclination was partially reduced and given freely over to natural succession (revegetation), deep drainage works were performed, and torrent channels were realigned. The main structural measure consisted in erecting a large 11-m-high reinforced-concrete break just upstream of the village of Log pod Mangartom in the event of any future debris flows that might be triggered on the Stože slope. The first phase during and immediately after the disaster (relief intervention of emergency units, especially those aimed at civil protection) can be described as concern-driven crisis management or as judgement-based crisis management, respectively. Quantitative risk assessment was part of the second remediation phase when legislation regarding enforcement measures was issued.

Valcanale Valley, Malborghetto-Valbruna (Italy)

On 29 August 2003, a particularly intense alluvial event gave rise to more than 1100 debris flows, which affected the municipalities of Tarvisio, Malborghetto-Valbruna and Pontebba, all sited along the Valcanale valley (No. 7 on Figs. 1 and 2), in the extreme northeast of Italy. The event caused two deaths and damaged 260 buildings, and large deposits were left blocking the A23 Highway; overall, the damage amounted to an estimated one billion euros (Boniello et al. 2010; Hussin et al. 2015). This extraordinary event saw 389.6 mm of rainfall in 12 h and an estimated return time of 500 years for periods of between 3 and 6 h (Borga et al. 2007), but this was not an exceptional, isolated event for the Valcanale Valley, where mean annual precipitation is from 1400 to 1800 mm. In fact, 20 critical rainstorms affected the valley over the previous century. The magnitude of the 2003 event is comparable to those verified on 11 September 1983 and on 22 June 1996. In the last decade (on 15 August 2008, 4 September 2009 and 19 June 2011), smaller flash floods occurred that created severe damage (Calligaris et al. 2012). These recurring events show that the mountainous area of the Friuli Venezia Giulia Region has seen critical hydrogeological conditions increasingly frequently in recent years, which is probably one of the consequences of climate change (IPCC 2013). Furthermore, the geological and structural features of the area play a major role in such developments. The Valcanale Valley is located at the contact point of two distinct geographical and geological units: the Carnic range and the Julian Alps, which presents significant differentiation in terms of lithotypes. The main structural element in the area is the so-called Fella-Sava line, an East–West-oriented back-thrust emerging along the valley bottom, where the Fella River flows. This back-thrust puts a mixed sedimentary succession in the south in contact with a carbonate platform in the north. North–South and NW–SE transfer faults interrupt the continuity of the back-thrust. Small torrents cross these secondary structures and flow out in the Fella River. The tectonic stresses associated with the heavy weathering of the mountain slopes favour both the fracturing of the rock masses and the production of huge quantities of loose material, both of which carry debris along the respective secondary streams. The nature of the clasts reflects the lithology of the overhead slopes: on the east side, carbonates dominate, while on the left, the debris is more heterogeneous, mixing the carbonate and siliceous natures of the different outcropping rocks.

We focus our attention on the right hydrographic side of the valley, in relation to the village of Cucco (municipality of Malborghetto-Valbruna), and in particular on three debris flow watersheds that can be considered one of the most significant expressions of the 2003 alluvial event. Taken together, the three basins were responsible for more than 100,000 m^3 of debris material flowing along the wooded fans, inundating the small village and reaching the national road downstream. After the event, several mitigation measures were realized that completely changed the old flow paths and the pre-existing morphology of the entire area, including check dams, artificial channels and retention basins with a combined storage capacity of roughly 150,000 m^3 of loose material. Numerous simulations were performed along these watersheds using the Flo2D software. Back analysis proved useful in identifying the parameters that allow better, more accurate reconstructions of the real events and were later used to test and confirm the efficiency of the erected structures, which ultimately drastically reduce the risks for the village of Cucco and the roads downstream.

Dobratsch (Austria)

The Dobratsch (Dobrač) massif (No. 8 on Figs. 1 and 2), also known as the Villacher Alpe, with its highest peak at 2166 m a.s.l., is located west of the city of Villach on the northern flank of the Gail Valley (valley floor at 550 m a.s.l.), which follows the Periadriatic Fault. At its base, the massif consists of red claystone, siltstone, sandstone and conglomerates of Permian to Lower Triassic age (Anderle 1977). Triassic limestone and dolomites make up the overwhelming part of the mountain massif, and the strata dip gently along the slope (towards the north). Tectonically the Dobratsch belongs to the Drauzug-Gurktal nappe system of the Austroalpine Superunit (Schmid et al. 2004). Multiple scars on the glacially over-steepened southern flank of Dobratsch testify to the many instances of slope failure. The area below comprises 23 km^2, the largest area of the Eastern Alps covered by historic and prehistoric rockslide deposits (Till 1907). The latter covers an area of 16 km^2 with an estimated volume of 800–900 × 10^6 m^3 (Brandt 1981). Six historic rockslides were triggered on 25 January 1348 by one of the strongest recorded earthquakes ever in the Eastern Alps, with an epicentral intensity of Io = 9–10 (MCS), which also very likely triggered the Velki Vrh rockslide in Slovenia (50 km E–SE of Dobratsch) (Merchel et al. 2014 cum lit.). The historic rockslides caused the damming of the River Gail, which ultimately destroyed some villages. According to the reconstruction by Brandt (1981), the mechanical differences between the 'hard' carbonatic rocks on top and the 'weak' silt to sandstones at the base led, together with partly karstified faults and joints, to the development of cracks and, eventually, a sliding plane. Finally, the fragmented and detached rock mass behaved like the flow typical of a rockslide. This is best illustrated and documented by the 'Rote Wand' event, which saw the largest volume, at 100 × 10^6 m^3 and the lowest Fahrböschung (travel angle) at 11° of all historic rockslides (Brandt 1981). The depositional area shows a layer of angular boulders and megaboulders (> 10 m in diameter), which rest on finer, matrix-supported clastic material. The age differences between the prehistoric and historic deposits are evident in soil formation and weathering characteristics.

The Upper Sava Valley (NW Slovenia)

Potoška planina landslide

The Potoška planina landslide (No. 9 on Figs. 1 and 2) is located in the Karavanke mountain range (NW Slovenia) above the densely populated settlement of Koroška Bela, which has almost 2200 inhabitants. Current landslide activity is evidenced by the 'pistol butt' trees, scarps and the deformation of local roads. Similarly, historical sources describe a severe debris flow at the end of the eighteenth century that destroyed nearly 40 houses in the village of Koroška Bela. The landslide covers an area of 0.2 km^2 with an estimated maximum volume of sliding mass of roughly 1.8×10^6 m^3 (Jež et al. 2008; Komac et al. 2015). In general, the broader area of the Potoška planina area exhibits highly complex geological and tectonic characteristics, which exert an influence on various slope mass movements. The upper part of the landslide consists of carbonate rocks and scree deposits that are largely prone to rockslides, while the main body of the landslide consists of heavily deformed Upper Carboniferous and Permian clastic rocks, which are characterized by complex dynamic movement, and is presumed to be a deep-seated slow-motion slide accelerated by the percolation of surface and groundwater (Jež et al. 2008; Komac et al. 2015, Peternel et al. 2017). Due to the presence of several springs at the contact point between scree and clastic rocks the landslide area is partially covered by wetlands, and the Bela stream increases the possibility of generating debris flow (Peternel et al. 2017). Based on UAV photogrammetry and tachymetric measurements, Peternel et al. (2017) monitored the toe of the landslide where, during an observation period of nearly 2 years, the assessed displacements ranged between 0.9 and 17.9 m. As a prevention measure, a recording system that provides real-time monitoring of landslide behaviour was installed as part of the European project Recall, which can play a role in the process of establishing an EWS in the future.

Discussion

In Slovenia and its immediate NW surroundings, a variety of landslide forms exist, presented in the 4th World Landslide Forum Post-Forum Study Tour. The main characteristics of landslide forms are summarized in Table 1. A fundamental common characteristic of landslides located in the Vipava River Valley and Soča River Valley (Slano blato, Rebrnice, Stogovce, Stože, Strug) is the high landslide velocity, due to heavy rainfall and soil wetting. These failures correspond to complex landslides (Cruden and Varnes, 1996), in which unstable masses develop into debris flow. In all cases, the sliding occurred in clastic rocks (mostly flysch) and located below steep slopes composed of highly permeable carbonate rocks. Due to faults and cracks in the surface rocks, a large part of precipitation is able to penetrate and supply the weathered clastic zones with additional water. In contrast, the geological complexity of each landslide area and surrounding caused the differences in movement types, sediment grain sizes and sliding surface. Triggering factors, particularly rainfall intensity and duration, play a key role in the activation of landslides in the Vipava River Valley, the Soča River Valley and the Upper Sava Valley as well for debris flows in the Valcanale Valley. All these landslide forms can be placed in the category of rainfall-induced landslides that became active in unfavourable geological conditions. For example, November 2000 was one of the wettest Novembers in the previous 20 years, and prolonged rainfall activated and triggered the Slano blato and Stože landslides. The rain gauge station near the Stože landslide, in the village of Log pod Mangartom, measured precipitation of 1638 mm for the 48 days before the event, which represents a recurrence interval of more than 100 years. The rain gauge station near Slano blato landslide recorded 590 mm of rainfall in 15 days. In December 2001, the Strug landslide was initiated as a combination of a primary rockfall, a secondary landslide and occasional debris flows from the rockfall source area during intense short rainfall. Moreover, a few exceptional meteorological events hit Slovenian territory and triggered numerous shallow landslides in the previous 10 years. One such event occurred in September 2010 when Stogovce landslide was triggered by intense short rainfall where more than 200 mm of rain fell in 48 h. Similar unfavourable conditions also prevail at the Potoška planina landslide, where debris flow flooded the village of Koroška Bela in the eighteenth century. While active movements and geo-mechanical properties of the soils at Potoška planina indicate that the landslide material could generate a debris flow during heavy rainfall, we saw that the very intense short rainfall events in the Valcanale Valley trigger more than 1000 instances of severe debris flow in August 2003, when 389.6 mm of rainfall fell in 12 h (estimated return time of 500 years). The variations of rainfall thresholds are mainly due to differences in lithological conditions, and in the case of soils, the variations in permeability and depth of sediments; the soil moisture conditions in areas with deep deposits of fine-grained soils (low permeability) are affected by long-term precipitation or water supply; in areas with shallower deposits of coarse-grained soils (high permeability), the response of the ground water conditions to precipitation and infiltration is faster.

Some of these slope movements were also triggered by earthquakes, such as the quake on April 12, 1998 (M_S 5.6), which triggered more than 100 slope failures, among them 50 rockfalls, and the earthquake 6 years later of July 12, 2004 (M_S 4.9), following which 50 rather superficial slope failures, including 38 rockfalls, were registered (Mikoš et al. 2006a, Mikoš et al. 2013). Major prehistoric earthquakes triggered huge rockslides in the Vipava Valley (Selo) and the Dobratsch rock slide.

Conclusions

Each year, tens to hundreds of slope instabilities occur in a relatively compact area in Slovenia, influenced by active tectonics, diverse geological settings and climate due to its position between the Alps, the Mediterranean Sea, the Dinarides and the Pannonian basin, which cause enormous damage to infrastructure and buildings. In the frame of the 4th World Landslide Forum Post-Forum Study Tour, the participants will be given the opportunity to explore the great diversity of the most devastating landslides, debris flows and mudflows (from fossil landslides to recent ones) in Slovenia and its immediate NW surroundings triggered over the last 3 decades. The pre-causal factor for the majority of landslides on these particular locations is the overthrust of a Triassic carbonate plateau over the clastic rocks (mostly flysch). Consequently, the weathering of both carbonate and clastic rocks caused significant fracturing. Landslides in Slano blato, Stože, Strug, Rebrnice, Stogovce, and Potoška planina and events in the Valcanale Valley can be placed in the category of rainfall-induced landslides that became active in unfavourable geological conditions while major prehistoric earthquakes triggered huge rockslides in the Vipava Valley (Selo) and the Dobratsch rockslide. A comparison of all the major complex landslides of past decades in Slovenia indicates that rainfall patterns and hydrogeological conditions play primary roles in triggering landslides and their development into debris flows. Many of the landslides are characterized by huge volumes and velocities at the time of activation or generating debris flow. In addition, they caused damage to buildings and endangered the lives of hundreds of people, as well as resulting in human casualties.

Acknowledgments

The authors would like to thank the Slovenian Research Agency, the Ministry of the Environment and Spatial Planning, the Administration for Civil Protection and Disaster Relief, the University of Ljubljana, the Geological Survey of Slovenia and others not directly mentioned in the paper for the support in the form of funding, co-funding and important data.

References

Anderle N (1977) Geologische Karte der Republik Österreich 1:50, 000, Blatt 200, Arnoldstein. Geologische Bundesanstalt (Geological Survey of Austria), Vienna

Boniello MA, Calligaris C, Lapasin R, Zini L (2010) Rheological investigation and simulation of a debris-flow event in the Fella watershed. Nat Hazards Earth Syst Sci 10:989–997

Borga M, Boscolo P, Zanon F, Sangati M (2007) Hydrometeorological analysis of the 29 August 2003 flash flood in the eastern Italian Alps. J Hydrometeorol:1049–1067

Brandt A (1981) Die Bergstürze an der Villacher Alpe (Dobratsch), Kärnten/Östereich Untersuchungen zur Ursache und Mechanik der Bergstürze. Ph.D. thesis. University Hamburg, Germany

Calligaris C, Zini L, Cucchi F (2012) Debris follow rainfall thresholds in Val Canale Valley: first steps into their redefinition. WIT Trans Eng Sci 73:49–57

Četina M, Rajar R, Hojnik T, Zakrajšek M, Krzyk M, Mikoš M (2006) Case study: numerical simulations of debris flow below Stože, Slovenia. J Hydraul Eng 132:121–131

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Shuster RL (eds) Landslides: investigation and mitigation, Transp res board, spec rep, vol 247, pp 36–75

Fifer Bizjak K, Zupančič A (2009) Site and laboratory investigation of the Slano blato landslide. Eng Geol 105(3–4):171–185

Gosar A, Košták B, Stemberk J, Šebela S (2009) Surface versus underground measurements of active tectonic displacements detected with TM 71 extensometers in Western Slovenia. Acta Carsologica 38(2/3):213–226

Hussin HY, Ciurean R, Frigerio S, Marcato G, Calligaris C, Reichenbach P, Van Westen CJ, Glade T (2015) Assessing the effect of mitigation measures on landslide hazard using 2D numerical runout modelling. Landslide Science for a Safer Geoenvironment 2:679–684

IPCC (2013) Summary for policymakers. In: Stocker TF, Qin D, Plattner GK, Tignor R, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis, contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK & USA

Jakob M (2005) A size classification for debris flows. Eng Geol 79(3–4):151–161

Jemec Auflič M, Šinigoj J, Krivic M, Podboj M, Peternel T, Komac M (2016) Landslide prediction system for rainfall induced landslides in Slovenia (Masprem) Geologija 59 (2): 259–271, doi: 10.5474/geologija.2016.016

Jež J (2007) Reasons and mechanism for soil sliding processes in the Rebrnice area, Vipava valley, SW Slovenia. Geologija 50(1):55–63

Jež J, Mikoš M, Trajanova M, Kumelj Š, Budkovič T, Bavec M (2008) Vršaj Koroška Bela – Rezultat katastrofičnih pobočnih dogodkov = Koroška Bela alluvial fan – The result of the catastrophic slope events; (Karavanke Mountains, NW Slovenia). Geologija 51(2):219–227 (in Slovenian with English abstract)

Komac M (2005) Statistics of the geological map of Slovenia at scale 1:250.000. Geologija 48:117–126. doi:10.5474/geologija.2005.011

Komac M, Ribičič M (2006) Karta verjetnosti pojavljanja plazov v Sloveniji v merilu 1:250.000 = Landslide susceptibility map of Slovenia at scale 1 : 250,000. Geologija 49(2):295–309

Komac M, Kumelj Š, Ribičič M (2009) Model dovzetnosti za pojavljanje drobirskih tokov v Sloveniji v merilu 1: 250.000 = Debris-flow susceptibility model of Slovenia at scale 1 : 250,000. Geologija 52(1):87–104 (in Slovenian with English abstract)

Komac M, Holly R, Mahapatra P, Van der Marel H, Bavec M (2015) Coupling of GPS/GNSS and radar interferometric data for a 3D surface displacement monitoring of landslides. Landslides 12:241–257

Legros F (2002) The mobility of long-runout landslides. Eng Geol 63:301–331

Logar J, Fifer Bizjak K, Kočevar M, Mikoš M, Ribičič M, Majes B (2005) History and present state of Slano blato landslide. Nat Hazards Earth Syst Sci 5:447–457

Maček M, Majes B, Petkovšek A (2016) Lessons learned from 6 years of suction monitoring of the Slano blato landslide. Rivista Italiana di Geotechnica 1:21–31

Majes B, Petkovšek A, Logar J (2002) Primerjava materialnih lastnosti drobirskih tokov iz plazov Stože, Slano blato in Strug = The comparison of material properties of debris flows from Stože, Slano blato and Strug landslides. Geologija 45(2):457–463 (in Slovenian with English abstract)

Martín Pérez A, González-Acebrón L, Košir A, Popit T (2016) Sandstone diagenesis, salt-induced weathering and landslide formation: the case of Slano Blato landslide, Slovenia. 32nd IAS International Meeting of Sedimentology, Marrakech

Merchel S, Mrak I, Braucher R, Benedetti L, Repe B, Bourlès DL, Reitner JM (2014) Surface exposure dating of the Veliki vrh rock avalanche in Slovenia associated with the 1348 earthquake. Quat Geochronol 22:33–42

Mikoš M, Četina M, Brilly M (2004) Hydrologic conditions responsible for triggering the Stože landslide, Slovenia. Eng Geol 73(3–4):193–213

Mikoš M, Vidmar A, Brilly M (2005) Using a laser measurement system for monitoring morphological changes on the Strug rock fall, Slovenia. Nat Hazards Earth Syst Sci 5(1):143–153

Mikoš M, Brilly M, Fazarinc R, Ribičič M (2006a) Strug landslide in W Slovenia: a complex multi-process phenomenon. Eng Geol 83(1–3):22–35

Mikoš M, Fazarinc R, Ribičič M (2006b) Sediment production and delivery from recent large landslides and earthquake-induced rock falls in the Upper Soča River Valey, Slovenia. Eng Geol 86:198–210

Mikoš M, Petkovšek A, Majes B (2009) Mechanism of landslides in over-consolidated clays and flysch. Landslides 6:367–371

Mikoš M, Jemec Auflič M, Ribičič M, Čarman M, Komac M (2013) Earthquake-induced landslides in Slovenia: historical evidence and present analyses. V: UGAI, Keizo (ur.), YAGI, Hiroshi (ur.), WAKAI, Akihito (ur.). Earthquake-induced landslides. In: Proceedings of the International Symposium on Earthquake-induced Landslides, Kiryu, Japan, 2012. Springer Verlag, Berlin, Germany, pp 225–233

Peternel T, Kumelj Š, Oštir K, Komac M (2017) Monitoring the Potoška planina landslide (NW Slovenia) using UAV photogrammetry and tachymetric measurements. Landslides 14(1):395–406. doi:10.1007/s10346-016-0759-6

Petkovšek A, Fazarinc R, Kočevar M, Maček M, Majes B, Mikoš M (2011) The Stogovce landslide in SW Slovenia triggered during the September 2010 extreme rainfall event. Landslides 8(4):499–506

Placer L (1981) Geološka zgradba jugozahodne Slovenije = Geologic structure of southwestern Slovenia. Geologija 24(1):27–60 (in Slovenian with English abstract)

Placer L, Jež J, Atanackov J (2008) Structural aspect on the Slano blato landslide (Slovenia). Geologija 51:229–234 (In Slovenian with English abstract)

Popit T, Košir A, Šmuc A (2013) Sedimentological characteristics of quaternary deposits of the Rebrnice slope area (SW Slovenia). V Knjiga sažetka. 3. znanstveni skup Geologija kvartara u Hrvatskoj s međunarodnim sudjelovanjem, Zagreb, 21st–23rd March 2013. Zagreb, HAZU.

Popit T, Rožič B, Šmuc A, Kokalj Ž, Verbovšek T, Košir A (2014) A lidar, GIS and basic spatial statistic application for the study of ravine and palaeo-ravine evolution in the upper Vipava valley, SW Slovenia. Geomorphology 204:638–645

Pulko B, Majes B, Mikoš M (2014) Reinforced concrete shafts for the structural mitigation of large deep-seated landslides: an experience from the Macesnik and the Slano blato landslides (Slovenia). Landslides 11(1):81–91

Ribičič M, Kočevar M (2002)Končna sanacija plazu Slano blato nad Lokavcem pri Ajdovščini = The final remediation of the landslide Slano blato above settlement Lokavec at Ajdovščina. Geologija 45(2):525–530 (In Slovenian with English abstract)

Schmid SM, Fügenschuh B, Kissling E, Schuster R (2004) Tectonic map and overall architecture of the alpine orogen. Eclogae Geol Helv 97(1):93–117

Till A (1907) Das große Naturereignis von 1348 und die Bergstürze des Dobratsch.- Mitteilungen der k.k. Geographischen Gesellschaft in Wien, Wien10–11; 534–645, Wien.

Verbovšek T, Kočevar M, Benko I, Maček M, Petkovšek A (2017a) Monitoring of the Stogovce landslide slope movements with GEASENSE GNSS probes. 4th World Landslide Forum proceedings by Springer Nature publishing, SW Slovenia. In: Mikoš M, Arbanas Ž, Yin Y, Sassa K (eds) Advancing Culture of Living with Landslides. Vol 3: Advances in Landslide Technology, 311-319. doi:10.1007/978-3-319-53487-9_35

Verbovšek T, Košir A, Teran M, Zajc M, Popit T (2017b) Volume determination of the Selo landslide complex (SW Slovenia): integrating field mapping, ground penetrating radar and GIS approaches. Landslides. doi:10.1007/s10346-017-0815-x

M. Jemec Auflič (✉) · **J. Jež**
Geological Survey of Slovenia,
Dimičeva ul. 14, 1000, Ljubljana, Slovenia
e-mail: mateja.jemec-auflic@geo-zs.si

T. Popit · **T. Verbovšek**
Department of Geology, Faculty of Natural Sciences and Engineering,
University of Ljubljana,
Ljubljana, Slovenia

A. Košir
Research Centre of the Slovenian Academy of Science and Arts,
Novi trg 2, Ljubljana, Slovenia

M. Maček · **J. Logar** · **A. Petkovšek** · **M. Mikoš**
Faculty of Civil and Geodetic Engineering,
University of Ljubljana,
Ljubljana, Slovenia

C. Calligaris · **C. Boccali** · **L. Zini**
Department of Mathematics and Geosciences,
University of Trieste,
Trieste, Italy

J. M. Reitner
Geological Survey of Austria,
Neulinggasse 38, 1030, Vienna, Austria