



Engineering-geological conditions of landslides above the settlement of Koroška Bela (NW Slovenia)

Inženirskogeološke značilnosti plazov v zaledju naselja Koroška Bela (SZ Slovenija)

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Abstract

This paper focuses on the studying of landslides in the hinterland area of the Koroška Bela settlement, NW Slovenia. Research has shown that these landslides have the potential to mobilize the material into a debris flow. The area of interest is located on the Karavanke mountain ridge, above the settlement of Koroška Bela, which lies on the outskirts of the town of Jesenice. In order to recognize and understand the kinematics of landslides and their triggering mechanisms, a multidisciplinary approach using engineering-geological and geotechnical investigations was applied. Thus, landslide source areas were determined based on engineering-geological mapping. Furthermore, landslide boundaries, types of landslides and sediments that are involved in processes of sliding were mapped in detail. Geotechnical monitoring is beneficial in evaluating rates of movement and failures in the ground under real conditions in the field. Current investigations as well as historical evidence and previous research prove that the hinterland of Koroška Bela is prone to various types of landslides that together form a source area that has the potential to mobilize into larger debris flow.

Izvleček

Članek se osredotoča na proučevanje plazov v zaledju naselja Koroška Bela v severozahodni Sloveniji, ki na podlagi dosedanjih raziskav predstavlja potencialno izvorno območje za nastanek drobirskih tokov. Obravnavano območje se nahaja v Zahodnih Karavankah nad vasjo Koroška Bela v bližini Jesenic. Za prepoznavanje in razumevanje kinematike plazov in njihovih sprožilnih dejavnikov smo aplicirali interdisciplinarni pristop, ki je obsegal inženirskogeološke in geotehnične raziskave. Na podlagi inženirskogeološkega kartiranja smo določili izvorna območja plazov in njihov obseg, vrsto plazov in vrsto sedimenta, ki sestavlja plazeči material. Geotehnični sistem za opazovanje je pripomogel k oceni velikosti premikov v samem telesu plazov pri realnih pogojih. Obsežne raziskave zaledja potoka Bela nad Koroško Belo so poleg zgodovinskih virov in preteklih raziskav potrdile domneve o dovzetnosti tega območja za nastajanje mastnih (drobirskih) tokov, kakor tudi zemeljskih plazov in skalnih podorov.

Introduction

The fact that Slovenia is highly susceptible to landslides underlines the need for the intensive study and monitoring of landslides in Slovenia, with the aim of defining prevention measures and mitigation measures in order to reduce the hazards associated with landslides. The past decade has seen four large landslides (Stože, Slano Blato, Strug and Koseč) with volumes of approximately 1×10^6 m³ (Jemec Auflič et al., 2017). In the case of the Stože landslide that occurred in Novem-

ber 2000 above the village of Log pod Mangartom in NW Slovenia and caused seven casualties and destroyed farm and residential buildings, the monitoring system consisted of 13 geodetic object points, 8 inclinometers for monitoring absolute displacements and streamflow measurements (Majes, 2001; Mikoš et al., 2006a; Četina et al., 2006; Mikoš, 2011). In the same period, reactivation of the Slano Blato landslide occurred above the village of Lokavec. The landslide was investigated using geophysical methods, geomechanical boreholes and engineering-geological mapping

of the wider area (Majes et al., 2002; Ribičič & Kočevar, 2002; Logar et al., 2005; Fifer Bizjak & Zupančič, 2009; Mikoš et al., 2009; Maček et al., 2016). One year later, in 2001, the Strug landslide occurred above the village of Koseč. In that instance, the monitoring system consisted of periodical engineering-geological mapping, precipitation measurements, terrestrial laser scanning, geotechnical (inclinometers) and hydrological (piezometers) monitoring (Mikoš et al., 2005; Mikoš et al., 2006b; Mikoš et al., 2006c).

This paper summarizes observation of the landslides above the settlement of Koroška Bela (NW Slovenia) using engineering-geological and geotechnical monitoring. Based on the previous investigation and given geological conditions and field surveys, the area of interest reflects number of source areas that have the potential to mobilize the material there into a debris flow. The most active and characteristic are the Urbas and Čikla landslides (Jež et al., 2008; Peternel, 2017; Sodnik et al., 2017; Peternel et al., 2017a).

Historical sources describe the broader area of Koroška Bela as known to have experienced several debris-flow events in the recent geological past. The most recent of these events occurred back in the 18th century and caused the partial or total destruction of more than 40 buildings and cultivated areas in a Koroška Bela village located in the area of the debris fan deposits (Lavtižar, 1897; Zupan, 1937).

The first investigation and research of the Koroška Bela alluvial fan and its hinterland began in 2006 within the Target Research Project (TRP): "Debris flow risk assessment in Slovenia". Within the TRP project, the following activities were applied: geological mapping of the hinterland of Koroška Bela (at scale 1: 5,000); and an investigation of alluvial fan deposits and debris flow modelling using the Flo-2D model. The thrust of the investigations indicated that the alluvial fan is composed of a sequence of diamicton layers and related subaeric sediments that had been deposited by several debris flow events in the past (Mikoš et al., 2008; Jež et al., 2008).

The first monitoring was established at the Urbas landslide using InSAR and GNSS technologies. InSAR and GNSS results showed relatively large (up to 32 mm horizontal and up to 15 mm vertical) displacements over the course of the monitoring period of six months (feb.–aug./2011), indicating a displacement of the central-upper and south-eastern parts of the landslide body (Komac et al., 2012a; Komac et al., 2012b; Komac et al., 2014).

In order to evaluate the kinematics of Urbas landslide and also to understand the specifics of a sliding processes, to assess the surficial displacement rates and changes in the surface topography a periodical monitoring using tachymetric measurements, UAV photogrammetry, and terrestrial laser scanning (TLS) was applied (Peternel et al., 2017b; Peternel, 2017).

Presently, some 2,200 inhabitants live in the area of the alluvial fan of past debris flows. With this risk potential in mind, monitoring the sliding mass and assessing the displaced material volumes is crucial, and more important than the purely scientific value of any assessment efforts (Peternel et al., 2017b).

In this regard, the Koroška Bela hinterland was investigated using a combination of detailed engineering-geological mapping, together with geotechnical, geophysical and geodetic methods. With this paper we present the results obtained from the engineering-geological mapping and the geotechnical monitoring system using inclinometer measurements for the Urbas and Čikla landslides.

Site-specific geotechnical data is essential in evaluating movements and failures in the ground under real field conditions, and for the design and implementation of a monitoring system and early warning system for this large landslide. That data provides important information related to the characterization and strength of the geological structures involved and the kinematics of the unstable areas there.

The most common geotechnical instrumentation installed to monitor landslides consists in piezometers to measure groundwater levels and instruments like inclinometers to measure displacements.

Slope inclinometers have been used to determine the magnitude, rate, direction, depth, and type of landslide movement (Stark & Choi, 2008). This information is essential to understanding the cause and behaviour of landslides (Stark & Choi, 2008).

Geological settings

The broad area of the hinterland of Koroška Bela exhibits fairly complex geological and tectonic conditions (fig. 1). Geological units of the study site are mainly represented by Upper Carboniferous and Permian sedimentary clastic rocks – Permian carbonates and Triassic to Lower Jurassic carbonate rocks (Jež et al. 2008). The main slope instabilities are related to tectonic contacts between the Upper Carboniferous to

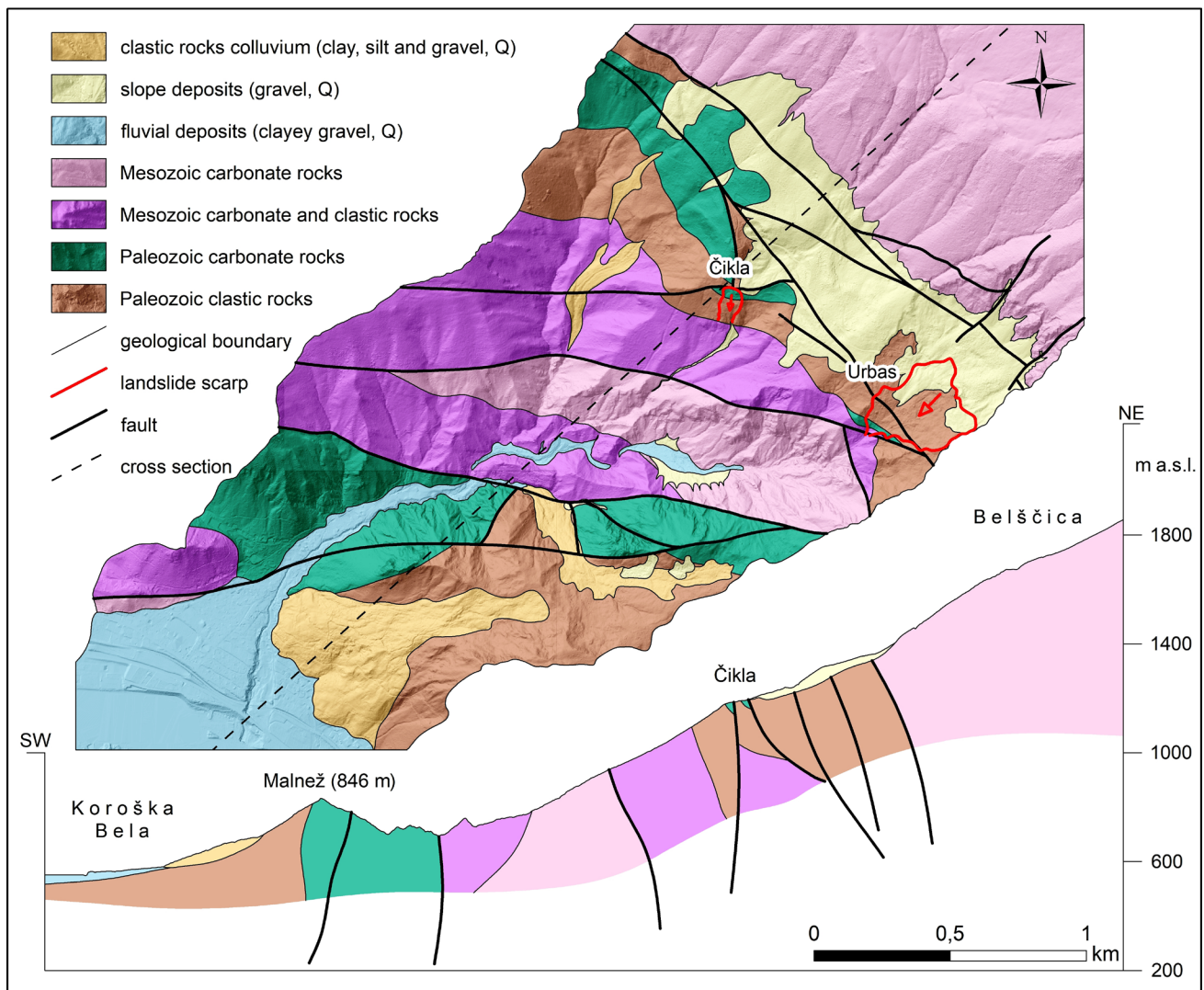


Fig. 1. Geological map and cross section of the hinterland of Koroška Bela.

Permian clastic rocks (claystone, siltstone, sandstone and conglomerate) and different Permian and Triassic carbonate and clastic rocks. The contact is represented by several reverse faults dipping approximately 70° to the NE (Jež et al., 2008).

In terms of tectonics, the area is part of the Košuta fault zone and is dissected by numerous NW-SE faults linking two major fault zones (the Sava and Periadriatic fault zones) (Jež et al., 2008). Due to active tectonics the Upper Carboniferous and Permian clastic rocks are heavily deformed, and, consequently, very prone to fast and deep weathering. Carbonate rocks in the uppermost parts of the Karavanke ridge are also subject to physical and chemical weathering, resulting in large quantities of talus and scree material covering the part lying below the clastic rocks.

These landslide events are largely related to soft fine-grained and tectonically deformed clastic rocks, most of which are covered with large quantities of carbonate scree material.

Landslides descriptions

The territory of interest is located in the Karavanke mountain ridge in north-western Slovenia (46.26° N, 14.8° W), above the settlement of Koroška Bela that lies on the outskirts of the town Jesenice. The study area extends between an elevation of 600 m at the surface of the alluvial fan and 2100 m at the summit of peak Belščica. The area is characterized by medium- to high-slope gradients ranging from 30° to 70° . It covers an area of approximately 6 km^2 .

The Karavanke mountain ridge is characterised by an annual average precipitation of about 2600–3200 mm, distributed over 70–100 days. The study area has two precipitation peaks, with the main peak falling in autumn, and the second precipitation peak in spring. The lowest precipitation rate is recorded in summer (Internet).

Due to its lithological and structural conditions and precipitation rates the area of the Koroška Bela hinterland is highly prone to land-

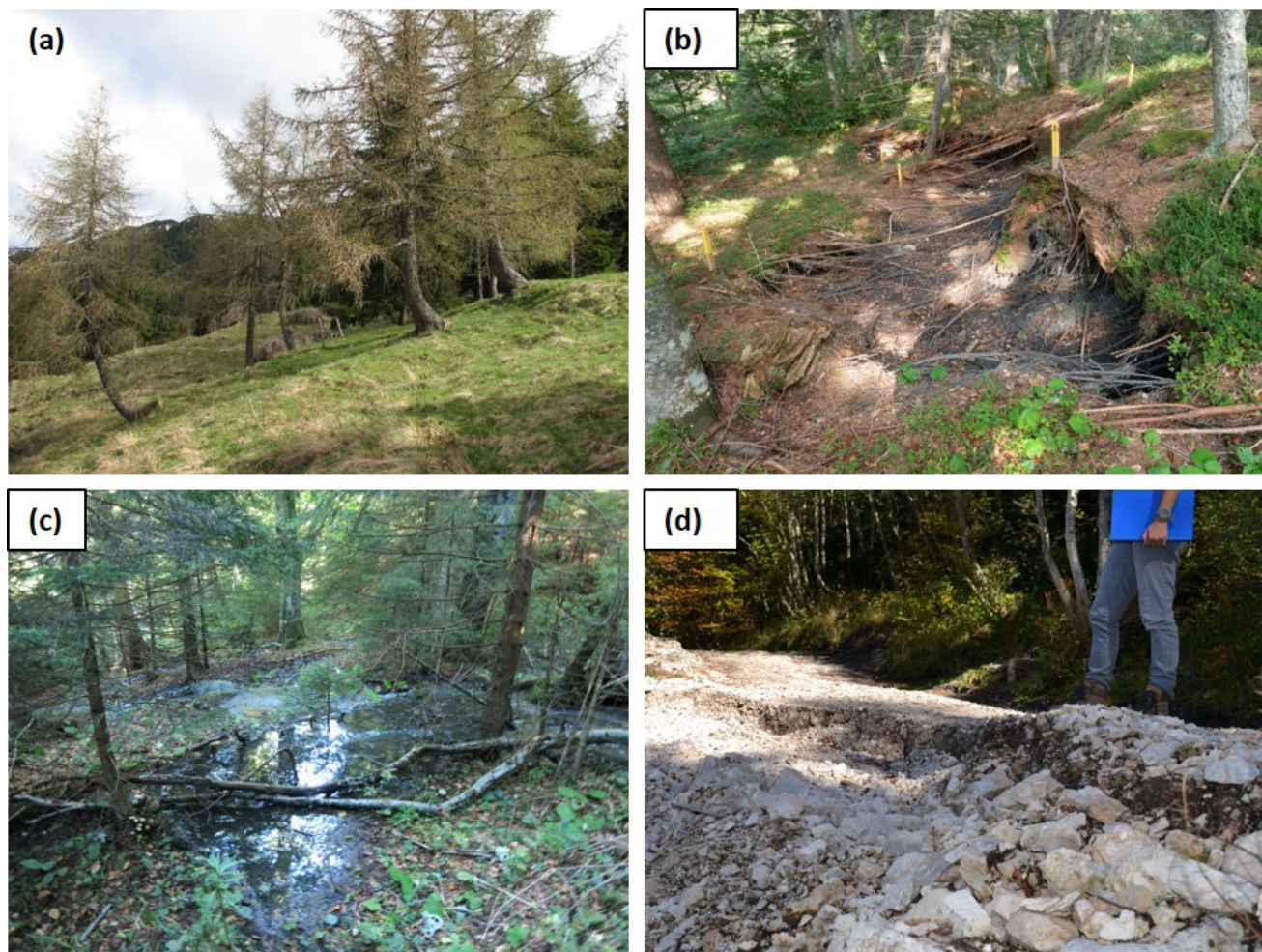


Fig. 2. Failure features on the surface: (a) Hummocky terrain with curved trees (b) Longitudinal tension cracks (c) Ponds on the surface (d) Subsidence of road

slides. The upper part of the Urbas landslide at the main scarp and the part below are dominated by rockslides and runoff of the scree material. The main body of both landslides is formed by heavily deformed and weathered clastic rocks and is presumed to be a rotational deep-seated slow-motion slide that has accelerated predominantly with the percolation of surface and ground water (Jež et al. 2008; Komac et al. 2012). At the main body of the Čikla landslide a vast structure of carbonate rocks is also included, which locally disintegrate into a form of rockfall.

The morphology of the entire hinterland of Koroška Bela is characterized by irregular and hummocky terrain comprised of protrusions and depressions of various sizes. Such activity is evidenced by “pistol butt” trees (fig. 2a), longitudinal tension cracks (fig. 2b), erosion slumps and ponds on the surface (fig. 2c), as well as the common deformation of local roads (fig. 2d).

A greater spatial density of springs and wetlands is evident at the contact between scree and clastic rocks, partly supplied from the in-

filtration. Two of the most significant of these are the Urbas (1275 m.a.s.l) and Čikla springs (1190 m.a.s.l.).

The monitoring sites are located at the Urbas and Čikla landslides, which are currently considered to be the most active parts of the Bela stream hinterland based on previous investigations and field observations. The Urbas landslide is crossed by the Bela stream; meanwhile, the Čikla landslide is crossed by the Čikla torrent, which is a tributary of the Bela stream. Both landslides have a gully-type morphology. The sliding mass is composed of tectonically deformed and weathered Upper Carboniferous and Permian clastic rocks covered with a large amount of talus material, which is prone to slope instability. Additionally, the Bela stream and its Čikla tributary cause significant erosion and increase the possibility of the sliding mass mobilizing downstream. The active parts of the Urbas and Čikla landslides are characterized by bare ground with fallen trees, rugged surfaces, strong gully erosion and flank ridges.

Methods

In order to recognize and understand the landslides and their dynamics it is crucial to apply an engineering-geological approach. It is also essential to set up a flexible and reliable monitoring system to monitor changes through time and space. Changes on the surface and observation of absolute displacements can be monitored using various surveying techniques.

The Koroška Bela hinterland has been investigated by combining detailed engineering-geological mapping, geotechnical, geophysical and geodetic methods. This paper reports the results of engineering-geological mapping and geotechnical monitoring using inclinometer measurements. Hydrogeological investigations are represented in Janža et al., 2018. The spatial distribution of all applied methods is shown in fig. 3.

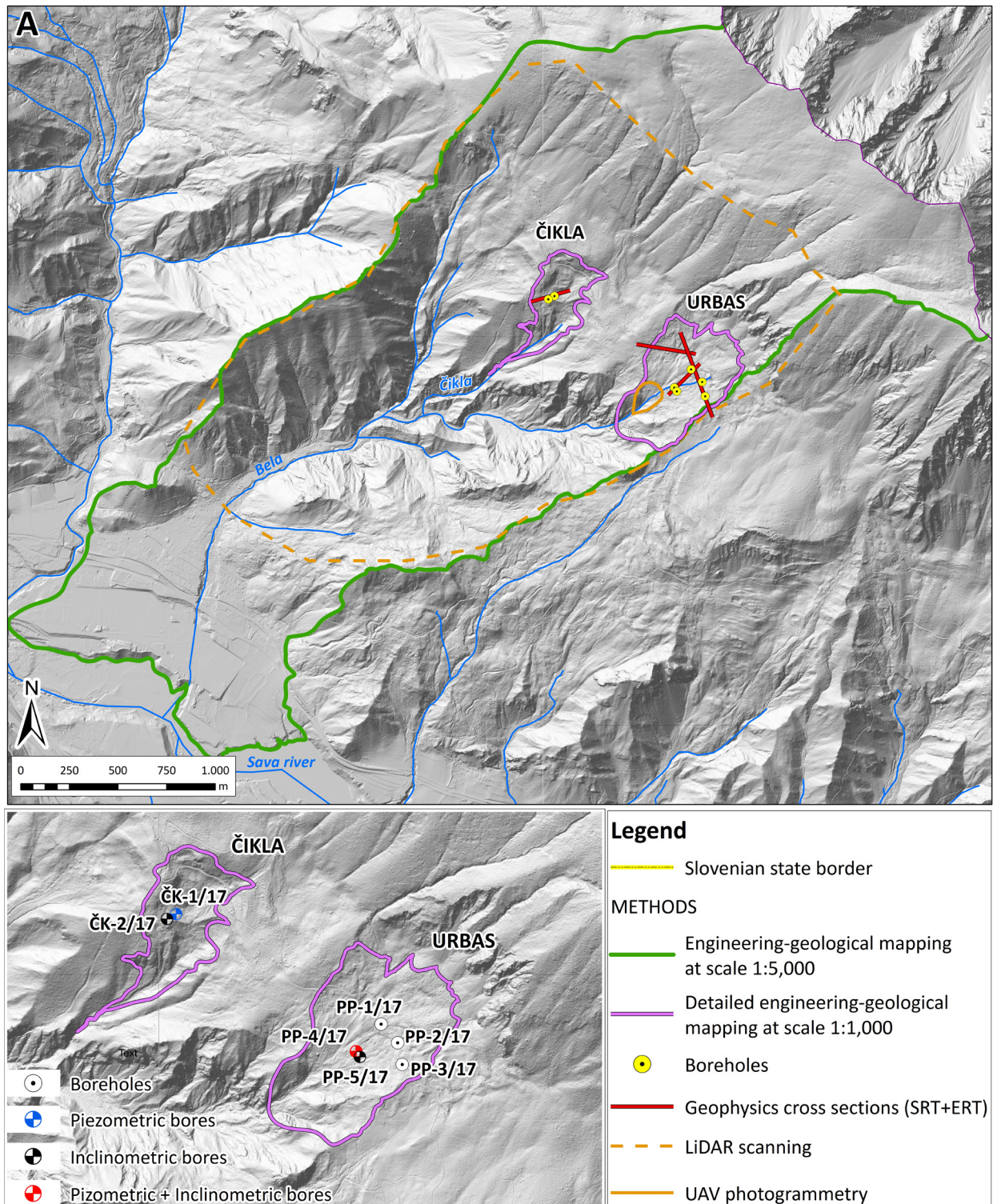


Fig. 3. Spatial distribution of applied methods (Peternel et al., 2017a).

Landslide identification and mapping

The field survey and the analyses of a 1-m grid digital elevation model (DEM) derived from lidar data were used for engineering-geological and geomorphological mapping.

The entire hinterland of the Bela stream was geologically mapped at scale 1: 5,000, while selected important landslides were mapped at scale 1: 1,000.

In the frame of detailed engineering-geological mapping the following features were determined: landslide boundaries at the ground surface and landslide failure features on the surface (main and secondary scarps, shear zones, tension cracks, ponds, curved trees, deformation of local roads). Additionally, monitoring locations and related techniques (type of monitoring, data acquisition and locations) and geomechanical boreholes were also defined.

Geotechnical investigation

An important part of the investigation of the Urbas and Čikla landslides involved the core drilling and core logging of 7 boreholes that was undertaken in September 2017. The locations for the boreholes were determined based on a field survey and logistical factors (accessibility of area) (fig. 3).

Using the information provided by core logging allowed us to identify the main lithological units in the study area. Subsurface conditions, absolute displacement rates and measurements of ground water levels were interpreted on the basis of 4 boreholes equipped with inclinometers or piezometers (Table 1).

Boreholes PP-4/17, PP-5/17 and ČK-2/17 were equipped with inclinometers. Inclinometer measurements at PP-4/17 and PP-5/17 were taken using a Digitilt inclinometer probe with a measurement interval of 0.5 m. The full equipment consisted of the probe, a heavy-duty control cable wound on a slip-ring reel, the DataMate II readout and DigiPro2 software. The PVC inclinometer casings have longitudinal grooves in two perpendicular directions A and B (in which case direction A has to be determined southward) to ensure the probe remains oriented in the desired direction. The grooves of the guide casings were oriented in the expected direction of movement of the Urbas and Čikla landslides.

The main purpose of employing inclinometer measurements was to determine absolute and displacement rates. The results are presented as displacement profiles (fig. 8), which are used to determine magnitude, depth, direction and rate of ground movement.

Results

Engineering-geological maps

Based on engineering-geological mapping of the Bela stream hinterland at scale 1: 5,000, the most extensive and active landslides are the Urbas and Čikla landslides. In order to reconstruct the extension and kinematics, detailed mapping at scale 1: 1,000 was applied for both landslides.

As a result, the Urbas and Čikla landslides were divided according to landslide prone areas (figs. 4, 5):

Table 1. List of boreholes.

	Borehole	Location	GKX	GKY	Depth (m)	Groundwater level * (m)	Type of observation wall
1	PP-1/17	Urbas	433762	143830	40,0	7,80	none
2	PP-2/17	Urbas	433818	143766	29,0	11,2	none
3	PP-3/17	Urbas	433834	143692	31,0	21,30	none
4	PP-4/17	Urbas	433675	143735	33,0	3,70	Inclinometer
	PP-4 -Ppl/17	Urbas	433676	143737	15,0	3,1	Piezometer
	PP-4-Pgl/17	Urbas	433675	143736	6,0	3,2	Piezometer
5	PP-5/17	Urbas	433689	143717	40,0	8,8	Inclinometer (13 m) - destroyed
6	ČK-1/17	Čikla	433059	144207	40,0	31,1	Piezometer
7	ČK-2/17	Čikla	433027	144191	39,0	8,5	Inclinometer

*groundwater level data were set after the drilling.

Table 1 also shows data about groundwater level for each borehole. Groundwater level measurements were taken manually after the drilling. All information about hydrogeological investigations and groundwater dynamics are represented in Janža et al., 2018.

- stable areas without clear landslide features,
- potentially unstable areas with some landslide and geomorphological features that indicate persisting sliding in the past or consist of soft sediments,
- active areas that are characterized by numerous features that are the result of active landslide (e.g. bare ground, open cracks, tilted trees, etc.).

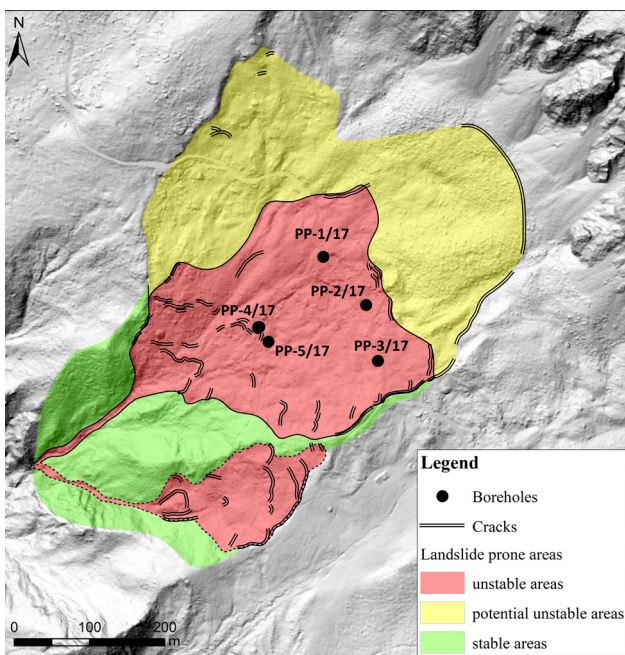


Fig. 4. Map of Urbas landslide-prone areas with contribution landslide.

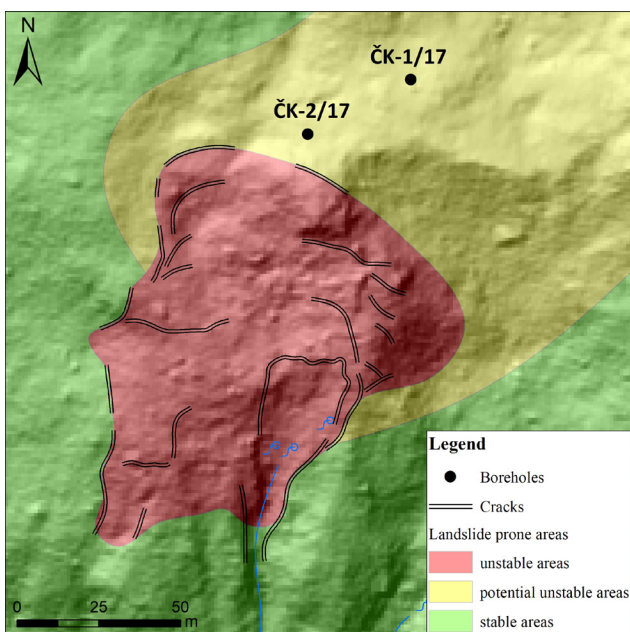


Fig. 5. Map of Čikla landslide-prone areas.

The active part of the Urbas landslide (fig. 4) extends over an area measuring some 320×420 m and covers an area of approximately $85,320 \text{ m}^2$. The entire landslide including potentially unstable areas measures up to 460×560 m.

In the case of the Čikla landslide (fig. 5), the active area covers an area of 105×130 m, and is actively progressing toward NE, with a surface area extending over an area of approximately $8,000 \text{ m}^2$.

Core logging

The results of the core logging for the Urbas landslide are shown in figure 6.

In borehole PP-1/17 a core was drilled up to 40.0 m. According to the detailed core logging of PP-1/17 three main lithological units were recognized. The uppermost layer (0–7.8 m) is represented by Quaternary Unit (Q) debris deposits that are composed of scree material (GW) and scree material with clayey or/and silty binder (GC/GM). A lower depth (7.8–13.2 m), the silty and clay debris (ML, CL) prevail over talus debris. At a depth of 13.2 m the bedrock appears as grey, heavily deformed Upper Carboniferous and Permian clastic rock. Three slip surfaces are presented in boreholes PP-1/17 at depths of 11.2, 13.2 and 15.0 m. The determined slip surfaces are related to wet segments, to contacts between soil and soft rock, and to a segment inside highly tectonized PC-siltstone.

In borehole PP-2/17, the core was drilled down to 29.0 m. The upper layer (0–2.7 m) of PP-2/17 is represented by scree material containing silt and clay particles (GW/(CL)/(GC)). This layer gradually becomes a silt section with individual layers of silty gravel and silty sand (2.7–8.3 m). At a depth of 8.3 m, the section of grey, heavily-deformed Upper Carboniferous and Permian carbonate and clastic rock appears. Between 8.3 and 13.0 m the section is represented by limestone, sandstone and sandy marlstone. Further down (13.0–19.0 m) PP-2/17 is represented by a section of limestone that at a depth of 19 m becomes limestone breccia. In borehole PP-2/17 two slip surfaces were recognized at depths of 3.5 and 8.3 m. The first is related to a wet core segment, while the second represent the contact between soil and soft rock immediately above the bedrock.

In the third borehole of PP-3/17, the total length of the core is 31.0 m. In the upper part it starts with a 3.9 m layer of Quaternary Unit (Q) debris deposits (GW). At a depth of 3.9 m the grey, completely weathered Upper Carboniferous and Permian clastic rock appears. From engineering-geological point of view this layer can be

classified as the residual soil (silt) of weathered PC siltstone without any recognizable structure.

Three slip surfaces are presented at depths of 7.7, 12.5 and 15.7 m. The determined slip surfaces are related to segments inside completely weathered PC siltstone.

In borehole PP-4/17, the core was drilled down to 33.0 m and was equipped with an inclinometer. The uppermost layer (0–3.80 m) is represented by Quaternary Unit (Q) debris deposits that are composed of scree material (GW) and scree material with clay matrix. From 3.8 to 13.75 m

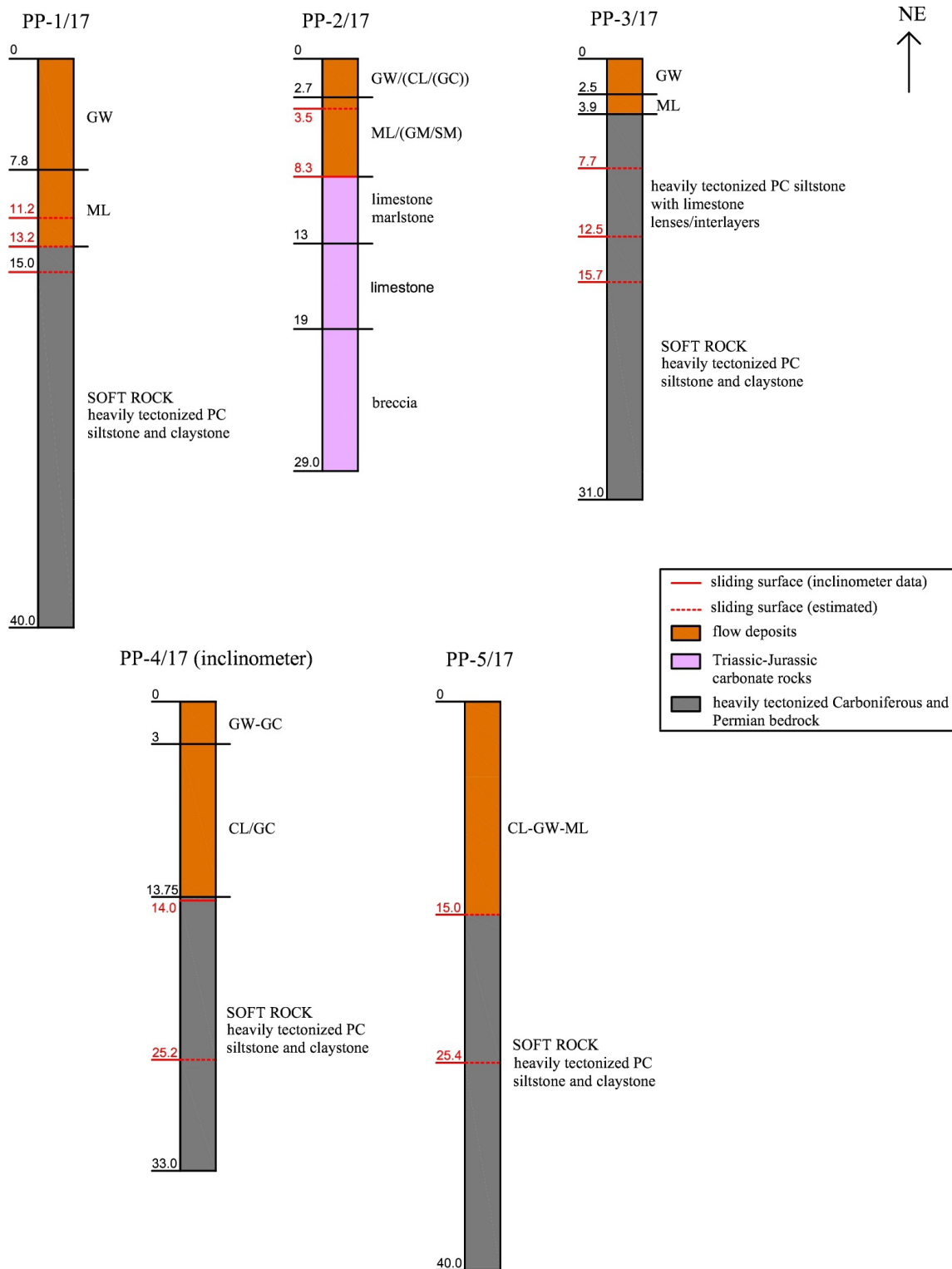


Fig. 6. Geotechnical borehole logs of the Urbas landslide. The locations of the boreholes are shown in fig. 3.

the carbonate scree is mixed with clay debris (CL). At a depth of 13.75 m the bedrock appears as grey, heavily-deformed Upper Carboniferous and Permian clastic rock. In borehole PP-4/17 two slip surfaces were recognized at depths of 14.0 and 25.2 m. The first was recognized based on inclinometer measurements, while the second is related to a segment inside well-weathered PC-siltstone and a wet zone.

In the fifth borehole of PP-5/17, the core was drilled to 40.0 m. The upper layer (0–16.0 m) of PP-5/17 is represented by alternating scree material (GW), scree material with silty binder (GM) and sand (SM), clay (CL) or silty (ML) debris. The bedrock appears at a depth of 16.0 m as a grey, heavily-deformed Upper Carboniferous and Permian clastic rock. Two slip surfaces are presented in PP-5/17 at depths of 15.0 and 25.4 m. The determined slip surfaces are related to wet segments, to contacts between soil and soft rock, and to a segment inside highly-weathered PC-siltstone.

The area of the Čikla landslide was investigated through 2 boreholes. Borehole ČK-1/17 was equipped with a piezometer, while ČK-2/17 was

equipped with an inclinometer. Both boreholes were drilled in area that was considered as potentially unstable areas in the immediate hinterland of the currently active landslide (fig. 5). The results of core logging for the Čikla landslide are shown in figure 7.

In borehole ČK-1/17, the core was drilled down to 40.0 m and was equipped with a piezometer. Hydraulic conductivity of borehole sections and groundwater level fluctuations in ČK-1/17 are presented in Janža et al., 2018. According to detailed core logging of ČK-1/17, three main lithological units were recognized. The uppermost layer (0–29.5 m) is represented by Quaternary Unit (Q) debris deposits that are the consequence of fossil alluvial events. Deposits are composed of scree material (GW) with limestone blocks and scree material with silty binder. At a depth of 29.5 m the residual soil is composed of completely tectonized and weathered Upper Carboniferous and Lower Permian siltstone, with lenses of marlstone that gradually transit into massive siltstone.

In the second borehole of ČK-2/17, the total length of the core is 39.0 m. The uppermost layer (0–4.9 m) some 4.9 m thick is composed of silty

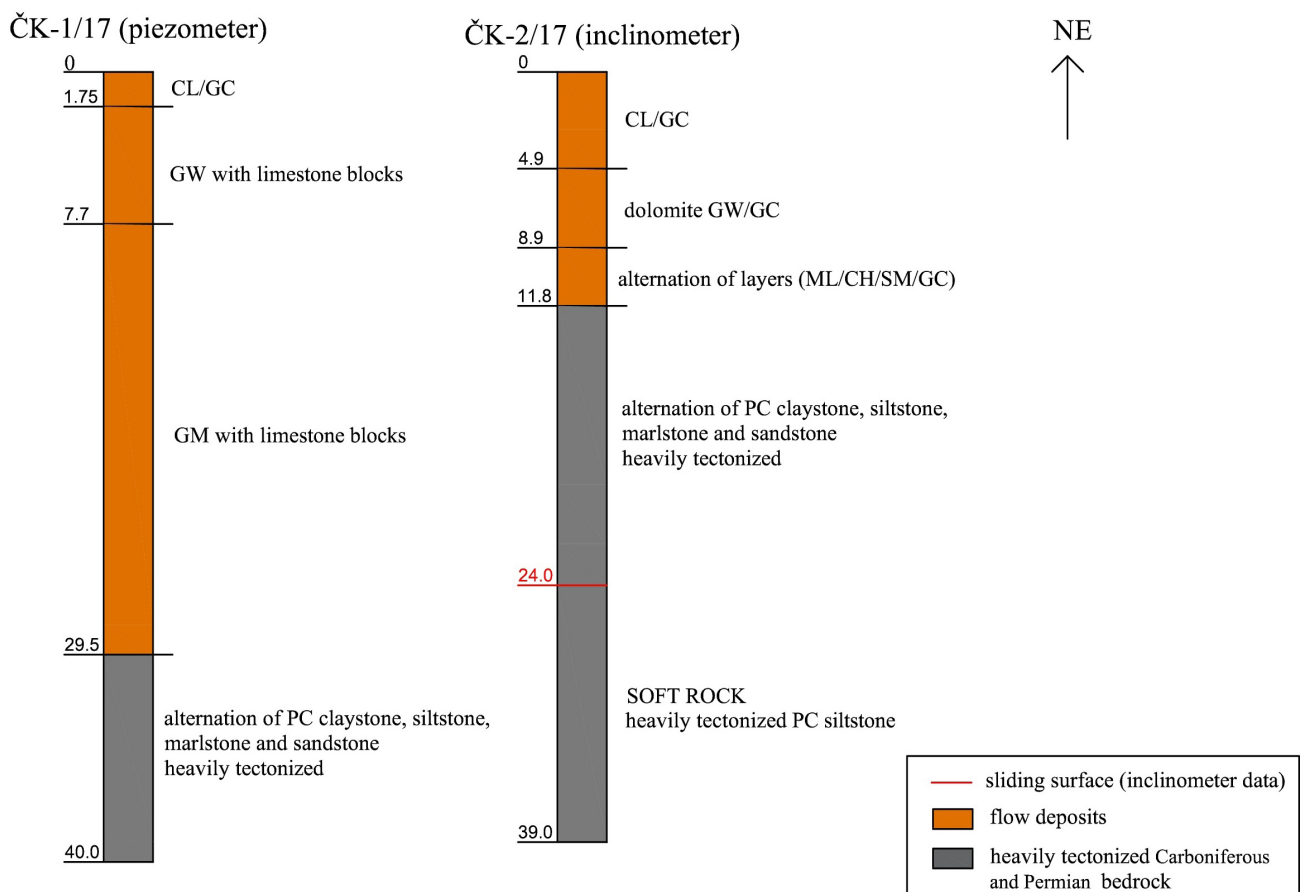


Fig. 7. Geotechnical borehole logs of the Čikla landslide. The locations of the boreholes are shown in fig. 3.

clay (CL) and clayey gravel (GC) with a transition into silty sand (SM) and clay (CH). At a depth of 4.9 m to 8.9 m a layer of dolomite gravel and gravel with clay matrix appears, followed by a section (8.9–11.8 m) of alternating layers (ML, CH, SM, GC). At a depth of 11.8 m a section (11.8–24.0 m) of completely tectonized and weathered Upper Carboniferous and Permian clastic rock appears. This layer is composed of alternation of gravel and clayey gravel with alternating layers (SM, CH, ML) followed by silty sand with gravel. At a depth of 24.0 m a grey, completely deformed Upper Carboniferous and Lower Permian siltstone appears. Due to drilling, primary sedimentary structures of the rocks are largely unrecognizable in the core.

Inclinometer measurements

PP-4/17 and ČK-2/17 were equipped with two inclinometers that reached down to significant depths (between 39 and 40 m) beyond the expected slip surface (Table 1). The grooves of the inclinometer (Aos, Bos) were oriented in the direction of the expected movement. Inclinometer monitoring was performed between September 2017 and May 2018. Until now, data has been collected for 3 observation periods for inclinometer PP-4/17, and for 2 observation periods for ČK-2/17 (Table 2).

The zero measurement at the inclinometer borehole PP-4/17 was taken on 28 September 2017. The zero measurement (for borehole ČK-2/17) and the first reading (for borehole PP-4/17)

Table 2. Observation periods of inclinometer monitoring.

Observation period	Date	Length of observation period	Inclinometer
1 st	28 September – 12 October 2017	2 weeks	PP-4/17
2 nd	12 October – 27 October 2017	2 weeks	PP-4 /17 +ČK-2/17
3 rd	27 October 2018 – 23 May 2018	7 months	PP-4 /17 +ČK-2/17

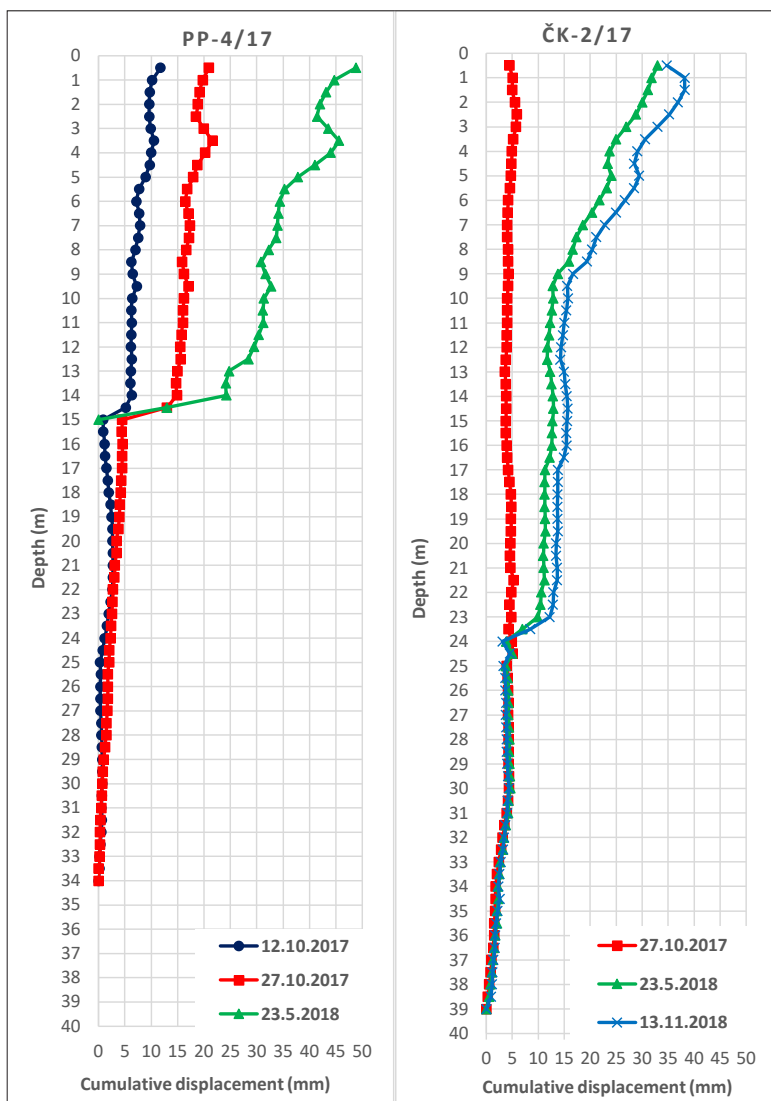


Fig. 8. Displacement measured by the inclinometers installed at PP-4/17 (Urbas landslide) and ČK-2/17 (Čikla landslide).

were performed on 12 October 2017. Follow-up measurements were performed on 27 October 2017, with the last on 24 May 2018 (Table 2). As the dates indicate, monitoring covered a period of 8 months.

The displacement vertical profiles of the 2 inclinometer measurements at PP-4/17 and ČK-2/17 are shown in figure 8. The inclinometer installed in borehole PP-4/17 shows cumulative absolute displacements in the slope face direction of some 24 mm between October 2017 and May 2018 down to a depth of 14 m. Based on core logging the slip surface is related to heavily deformed Upper Carboniferous and Permian clastic rocks. The last measurement showed that the inclinometer installed in borehole PP-4/17 was cut at a depth of 14 m (fig. 8).

Although that borehole ČK-2/17 was located in the area that was considered as potential unstable area (approx. 15 m behind the crown crack of active landslide), inclinometer installed in borehole ČK-2/17 showed significant displacements at a depth of 24 m. The measurements detect absolute cumulative displacements near 12 m over a period of 1 year (fig. 8). As in PP-4/17, the slip surface is related to heavily deformed Upper Carboniferous and Permian clastic rocks.

Discussion

This research focuses on the observation of large landslides that represent a direct risk to the settlement of Koroška Bela below. With this risk in mind a multidisciplinary monitoring approach was applied – specifically, slope mass instabilities were identified and investigated through detailed field investigations, including engineering-geological mapping, geophysical investigations and core logging of 7 boreholes (figs. 3, 6, 7). Applied surveys show that spatial distribution of the slope material and the relationships between lithological units are closely related to mass movement processes that have occurred in the past. The sliding mass is composed of tectonically deformed and weathered Upper Carboniferous and Permian clastic rocks covered with a large amount of talus material that is prone to slope instability.

The Urbas landslide spreads out over an area of nearly 90,000 m² and was estimated to include up to 1 million m³ of sliding material. Sliding is expected to progress towards the north. The Čikla landslide, however, covers a significantly smaller area, but inclinometers indicate the sliding surface near the 25 m point. Additionally, in April 2017 a part of the Čikla landslide was

transformed to debris-flow, which came to a halt about 500 m down from the Čikla stream. Additionally, the Bela and Čikla streams causes significant erosion and contributes significantly to the mobilization of the sliding mass downstream. After Varnes (1978) classification and based on the determined depth of slip surfaces, both landslides are understood to be deep-seated rotational slides.

Additionally, two boreholes were equipped with pressure probes with recorders to observe fluctuations in groundwater levels. These observations, which involved hydraulic tests, show complex and heterogeneous hydrogeological conditions predisposed by geological and tectonic settings and active mass movements that cannot be uniformly described (Janža et al., 2018).

Conclusions

In this study, the landslides above the settlement of Koroška Bela (NW Slovenia) were observed using engineering-geological mapping and through geotechnical investigations. By combining inclinometer data with core logging and engineering-geological surveys, the extension and kinematics of relevant active movements were reconstructed. The presented study reveals that the Urbas and Čikla landslides are deep-seated landslides such as Macesnik landslide (Pulko et al., 2014) and Rebernice landslide (Popit et al., 2017). Based on engineering-geological mapping and previous investigations the Urbas and Čikla landslides represent the most active landslides of the Bela stream hinterland. The Urbas landslide covers an area of approximately 85,320 m², while the Čikla landslide extends over an area of approximately 8,000 m². Due to the geological and tectonic conditions of the study area, both landslides are prone to different landslides: rockslides and runoff of scree material, deep-seated landsliding at the main body, and debris flow. Based on inclinometer readings, the Urbas landslide is moving at a maximum rate of down to a maximum depth of 14 m, while at the Čikla landslide significant displacements were registered at a depth of 22.5 m.

This research finds and proves that mechanisms of landslides in the hinterland of the Koroška Bela settlement are related to: (1) geological and tectonic conditions affecting rocks that are heavily deformed, and, consequently, very prone to fast and deep weathering, (2) surface and underground water circulation in the wider landslides area and weak geomechanical properties of the lithological units of the study area.

In the future, integration of the geomorphological, geotechnical and geophysical information obtained, together with the monitoring data provided by the inclinometers installed there will provide particularly relevant information for a better understanding of the behaviour and kinematics of the studied instabilities. Furthermore, this data represents input data that can be used in the 3D modelling of sliding surfaces and volume assessment, and in the planning of mitigation measures and risk management strategies.

In order to estimate the real effect of the tectonic, geological and meteorological conditions (e.g. amount of precipitation, snow melt, etc.) on the kinematics of landslides further, upgraded application of established monitoring (e.g. rain gauges, geotechnical sensors, etc.) is recommended. Similarly, future additional research on the relationship between precipitation, groundwater levels and landslide dynamics site is required (and planned), in order to determine correlations between displacement rates and long-term rainy periods and/or snowmelt.

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