



Study of Landslides in Flysch Deposits of North Istria, Croatia: Landslide Data Collection and Recent Landslide Occurrences

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Abstract

The northeastern part of the Istrian Peninsula in Croatia is built of Palaeogene flysch deposits, in which instability is common and where a large number of landslides, with significant consequences, have been recorded. Study of landslides in flysch deposits of North Istria will be conducted as one of the main activities of ongoing IPL-184 Project. It includes analyses and recognition of sliding mechanisms to use in landslide modelling and to determine landslide susceptibility and hazard in flysch rock mass deposits. Several landslide types, mechanisms and conditions occur in the study area. The majority of studied landslides occurred during the spring and winter. Generally, the landslides are of rotational and translational sliding type, and rarely rock falls and debris flows. Local roads and rarely other structures and facilities suffered major damage as a consequence of the landslides. Landslide inventories, as well as landslide susceptibility maps, have never been carried out in the study area. Today's knowledge about landslides in this area is based on investigations of individual landslides and partial scientific research. After the project started, some of the activities from all stages of the project have been initiated. The proposed first stage of the project includes supplementation of the existing database, and field investigations of recent and existing landslides in the study area, as well as soil sampling for laboratory testing. Moreover, the methods used for landslide susceptibility and landslide hazard assessment are presented. This paper presents the current state of investigations and research in the initial stage of the IPL-184 Project.

Keywords

Landslide • Flysch • Data collection • Landslide mechanism

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Introduction

The northeastern part of the Istrian Peninsula has a long history of landslide occurrences and many papers have described instability phenomena there. Benac (1994), in his doctoral thesis, described landslides in the Plomin area on the east coast of the Istrian peninsula; Mlinar et al. (1995) described the Raspadalnica landslide near the city of Buzet; Arbanas et al. (1999) described small landslides which are frequent in this area; Arbanas et al. (2006) described debris flows at the foot of the Čićarija Mountain range; and Arbanas et al. (2010) described mechanisms of the translational Brus landslide. Different authors wrote

papers regarding rock mass strength aspects (Arbanas et al. 2006, 2007, 2010; Benac et al. 2009). A review of research results on recent landslides that occurred in the central and northern parts of the Istrian Peninsula over the past 35 years is presented in Dugonjić Jovančević and Arbanas (2012). Just a few papers present landslide hazard assessments in the area (Mihalić et al. 2011; Dugonjić Jovančević et al. 2014).

In terms of geology, the Istrian Peninsula, situated in the northwestern part of the Adriatic Sea, is formed in flysch rock mass deposits called Gray Istria due to the gray colour of the exposed flysch rock mass. The Istrian Peninsula can generally be divided into three geological units: the Red Istria area in the southern and southwestern part of the peninsula has carbonate rocks covered by red-coloured deposits of Mediterranean soil, or so called terra rossa; the White Istria area, which includes the Čićarija Mountain range and part of the Učka Mountains, has white carbonate rocks visible at the surface; and the Gray Istria area in the central part of the peninsula has Palaeogene flysch deposits (Arbanas et al. 2011).

In typical areas, the flysch bedrock is covered by Quaternary deposits, except in isolated areas where there is more erosion (Dugonjić Jovančević and Arbanas 2012).

The total area included in the study area of this IPL-184 Project covers about 550 km², and the volume of recent landslides exceeds 500,000 m³.

IPL-184 Project: Study of Landslides in Flysch Deposits of North Istria, Croatia: Sliding Mechanisms, Geotechnical Properties, Landslide Modelling and Landslide Susceptibility

The expected duration of the IPL-184 Project is four years, and it includes three senior researchers and six young researchers. The main objectives of the Project are: study of triggering factors and landslides mechanisms of instabilities in flysch formations in North Istria, Croatia; laboratory analyses of soil materials from the flysch deposits using ring shear apparatus; modelling of typical instabilities in flysch deposits: back analyses; identification of conditions which cause landslides in flysch deposits and recommendations for landslides susceptibility and hazard mapping in flysch areas.

The Project activities are listed in Table 1. The first stage consists of data collection; field investigations of existing landslides in the study area and soil sampling for laboratory testing. During the second stage of the project the main activities will be laboratory testing of soil samples and establishment of landslide numerical models based on back analyses and laboratory testing results. The third stage includes spatial analyses of the geotechnical model, spatial

Table 1 Plan of working phases, their duration and expected results for the IPL-184 project

Working phases	Expected results	Time frame
First phase: data collection, field investigations	Field database establishment	12 months
Second phase: laboratory testing, numerical modelling	Geotechnical properties database	12 months
Third phase: spatial analyses	Landslide susceptibility maps, landslide hazard maps for pilot area	10 months
Fourth stage: deterministic landslide analyses	Recommendations for landslide susceptibility and hazard maps preparation in the flysch area of North Istria	8 months
Fifth stage: investigation presentation	Presentation of results to the local authorities in the study area	6 months

analyses of the existing landslide distribution (landslide inventory) and landslide susceptibility and hazard mapping in a pilot area inside the study zone, based on the results of previous investigations.

In the fourth stage, a systematic particular deterministic analysis of landslides susceptibility based on 3D stability analyses will be carried out for the pilot area. Based on the results obtained in the third and fourth stages, recommendations for landslide susceptibility and hazard mapping in the flysch area of North Istria will be prepared. Even during following stages, all the activities from earlier phases will be continued until the end of the project.

In the fifth stage, recommendations will be presented to the local authorities in the study area: the County of Istria, and the cities of Buzet, Pazin and Buje, as well as other municipalities located in study area, as helpful measures for future urban planning.

The expected benefits of the Project are multiple: for society (through implementation of the project's results in physical planning); for local authorities (through better understanding of conditions for land-use planning); for companies that maintain facilities such as roads and pipelines (through indentifying landslide hazards for existing and new facilities); and for scientists (through new knowledge of landslide behaviour in flysch deposits).

Supplementation of the Existing Database

The creation of the landslide database for the study area (Fig. 1) began in 2008 at the Department of Hydrotechnics and Geotechnics, Faculty of Civil Engineering, University of Rijeka, using existing documentation collected from the

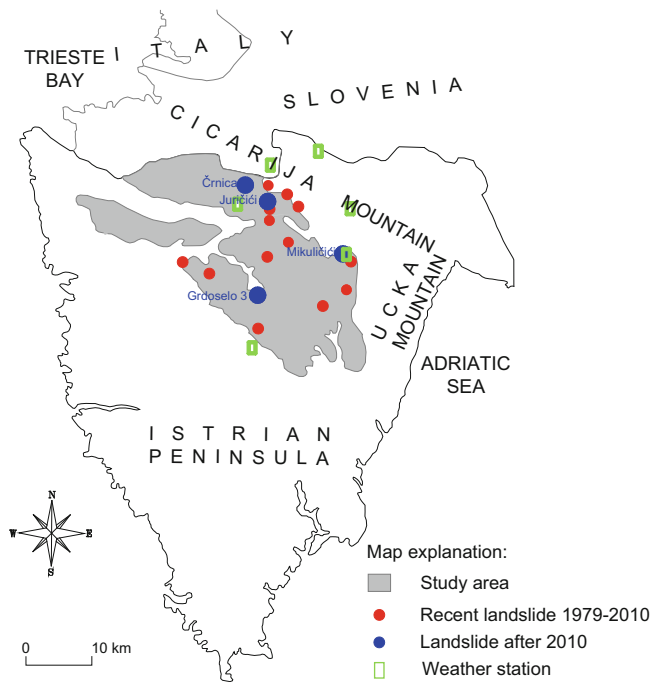


Fig. 1 Map of the Istrian Peninsula with the location of the study area and documented landslides

department's archives and from the archives of the Istrian County Roads Office and the Civil Engineering Institute of Croatia (Dugonjić Jovančević and Arbanas 2012). These documents included geological and geotechnical data from geotechnical field studies for remediation works on landslides. Figure 1 shows the locations of recent landslides documented from 1979 to 2010 for previous research (Dugonjić Jovančević and Arbanas 2012) and landslides documented after 2010 in the first stage of the current IPL-184 Project. Many landslides that occurred in this period are not documented in this paper because they cannot be substantiated. They will be included in the landslide inventory map for the study area which is planned to be done in the third phase of the project.

The database for the studied landslides contains basic information about their location, type, dimensions and time of occurrence, as well as other data from geological and geotechnical studies, laboratory test reports, and remediation designs, as shown in Table 2.

It was observed that landslides on flysch slopes have multiple styles and retrogressive distribution (Cruden and Varnes 1996). Landslides in the area generally cover relatively small slope areas (Arbanas et al. 2007, 2011; Dugonjić Jovančević and Arbanas 2012). In most cases, the slides are rotational, while other types of instability are rare (Arbanas

et al. 2010; Mihalić et al. 2011; Dugonjić Jovančević and Arbanas 2012). The sliding surface usually forms inside the weathered flysch rock mass, between the cover and the fresh bedrock. Instabilities initially develop through the weathering of superficial flysch deposits exposed to atmospheric activity and unfavourable hydrological conditions. Weathering of the flysch rock mass, and processes of erosion and accumulation of the weathered material, which form potentially unstable deposits, are very significant causal factors for landslide initiation in the area. Weathering grades from the cover surface to the flysch bedrock are shown on a profile in the study area (Fig. 2).

Because of the different grades of weathering (ISRM 1985), the strength parameters of soils in the landslide bodies show considerable variation. The strength properties of the flysch bedrock were difficult to assess due to disturbance of the flysch rock mass during the sampling, while the tested samples were collected from different parts of the landslide body, although rarely from the surface of rupture. Different test methods were employed, using different direct shear apparatus, ring shear apparatus and triaxial apparatus.

The volumes of the investigated slope instabilities vary from 700 to 175,000 m³; the average slope angle is between 15 and 30 %, and the thickness of superficial deposits varies from 0.5 to 11 m (Table 2). An overview of the documented landslide dimensions, based on the Multilingual Landslide Glossary (WP/WLI 1993) is shown in Table 3. By analyzing the sliding causes and triggering factors it was concluded that almost all landslides in the study area were initiated by a rise in groundwater level caused by rainfall, and consequently by a decrease of effective strength caused by increasing pore pressure (Dugonjić Jovančević and Arbanas 2012; Arbanas et al. 2011; Dugonjić Jovančević et al. 2014). It is clear that the landslides occurred after long rainy periods, while short-term rainfalls have significant influence on erosion.

Recent Landslide Occurrences 2010–2013

The Grdoselo 3 Landslide occurred in autumn 2011 (Fig. 3a). It is located on a local road on which two more landslides (Grdoselo 1, 2) occurred in the past. The natural slope balance was disturbed and hydrogeological conditions changed during road construction. A large amount of water was flowing on the slope and infiltrating into the road embankment. Infiltration continued until the flysch rock mass was reached and then the groundwater level rose.

The Grdoselo 3 Landslide was caused by a combination of heavy rainfall and human activity that significantly

Table 2 Database of recent landslides in the study area

Location	Time of occurrence	Type of instability	Estimated volume (m ³)	Average slope angle (%)	Cover thickness (m)	Triggering factor
Krbavčiči	January 1979	Rotational I	59,000	15–20	0.5–10.0	Rainfall
Krbavčiči 1	January 1979	Translational I	176,000	15–20	1.0–10.0	Rainfall
Staraj	Spring 1993	Rotational I	1,900	10–30	3.5–4.0	Rainfall
Krušvari	Spring 1993	Rotational I	68,500	14	1.5–9.0	Rainfall/human
Raspadalica 1	1992	Translational I	900	50–70	1.5–3.5	Rainfall
Raspadalica 4	1994	Rotational I	4,100	50–70	2.5–5.5	Rainfall
Čiritež	1995	Rotational I	37,000	14	5.0–10.0	Rainfall
Raspadalica 2	1995	Rotational I	2,900	55–70	2.5–6.5	Rainfall
Raspadalica 5	1995–1999	Rotational I	13,400	50–70	4.0–11.0	Rainfall
Grdoselo 1	Winter 2002	Rotational I	1,800	25	0.5–6.5	Rainfall/human
Grdoselo 2	Winter 2002	Rotational I	2,300	25	0.5–5.5	Rainfall/human
Krbavčiči-reactivated	January 2003	Debris/earth flow	35,000	15–30	0.5–10.0	Rainfall/human
Ivančiči	Spring 2004	Fall	1,500	15–30	1.0–3.6	Rainfall
Vidaci	Winter 2004	Fall	1,400	35–55	1.0–2.5	Rainfall
Drazej	January 2005	Rotational I	9,800	30	4.5–8.0	Rainfall/human
Brus	Spring 2005	Translational I	35,000	15	0.5–1.5	Rainfall
Marinci	Spring 2006	Rotational I	1,800	30	8.0–8.5	Rainfall/human
Juradi	November 2010	Translational I	47,000	10–25	6.0–11.0	Rainfall/human
Kaldir	Winter 2010	Rotational I	2,000	22–30	7.0–9.0	Rainfall
Grdoselo 3	Spring 2011	Rotational/translational I	6,400	42–68	3.8–4.0	Rainfall
Mikuličiči	Autumn 2011	Rotational I	700	50–76	4.8–4.8	Rainfall
Juričiči	November 2012	Rotational I	1,700	57–85	3.0	Rainfall/human

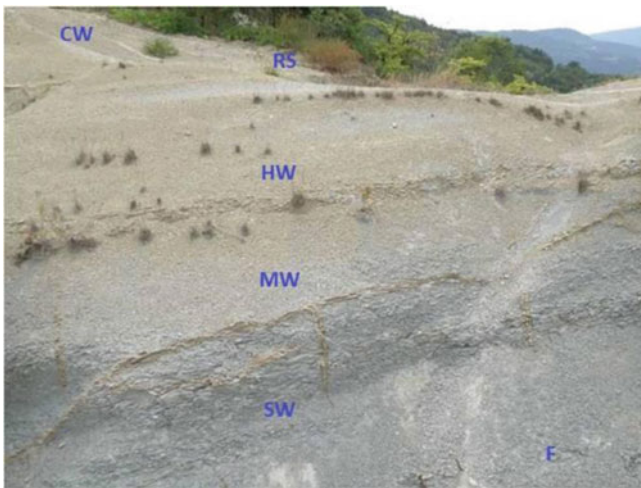


Fig. 2 Weathering profile in flysch rock mass (ISRM 1985): *F* fresh, *SW* slightly weathered, *MW* moderately weathered, *HW* highly weathered, *CW* completely weathered, *RS* residual soil

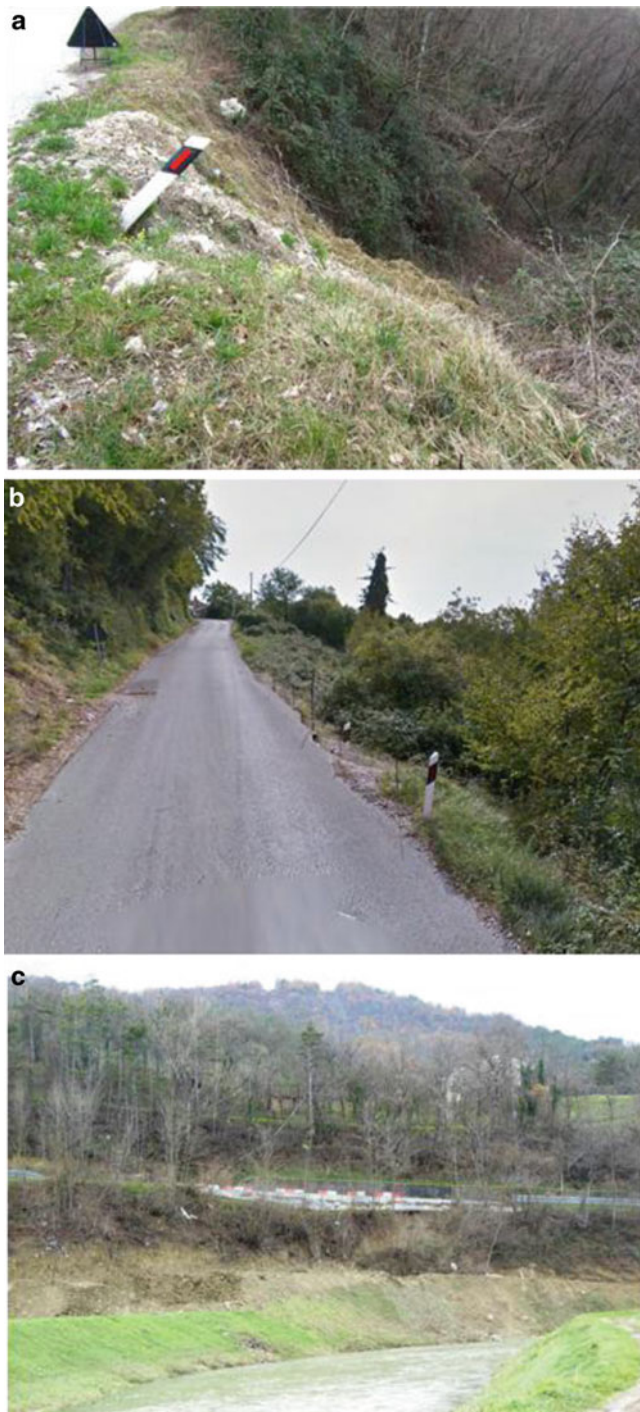
changed slope geometry. Field investigations were conducted in autumn 2011 and consisted of engineering geological mapping, borehole drilling and laboratory testing. The sliding surface was located at the contact between the superficial slope deposits and flysch bedrock. This is a translational type of landslide, and its boundaries were determined from a 35 m long subsidence of the pavement and accumulation of material in the toe.

The Mikuličiči Landslide occurred on the local Lupoglav–Vranja road, and damaged 15 m of the road embankment (Fig. 3b). The average inclination of the slope was approximately 33° in the lower part of the slope to 52° on the slope above the road.

Field investigations were carried out and a geological cross-section was prepared. The geological profile includes embankment fill, colluvium deposits and flysch rock mass in the bedrock and limestone on the top of the slope above the road. Undisturbed heterogeneous flysch rock mass is classified in C, D and E groups, with a Geological Strength Index

Table 3 Dimensions of landslides in the study area

Dim. (m)	Krbavčići (1979)	Krušvari (1993)	Krbavčići (2003)	Dražej (2005)	Brus (2005)	Marinci (2006)	Juradi (2010)	Mikuličići (2011)	Grdoselo 3 (2011)	Juričići (2012)
L	242	115	140	48	208	23	63	31	106	13
L _d	240	80	137	45	142	21	55	31	106	12
L _r	220	115	130	25	142	20	60	13	80	13
W _d	55	145	40	50	37	15	150	25	40	55
W _r	45	85	50	49	37	14.5	145	25	42	55
D _d	10.0	4.5	6	4	8–10	2	8	2	2	2.5
D _r	12.5	7	10	8	10	8.5	11	2	2.5	2.5

**Fig. 3** Photographs taken after sliding: (a) The Grdoselo 3 landslide, (b) the Mikuličići landslide and (c) the Juričići landslide

(GSI) of between 40 and 20 (Marinos and Hoek 2001). The remedial works design proposed a cantilever retaining wall 5.5 m high at the road edge founded in the bedrock and boring a drain system across the road up to limestone.

Excavation of a wastewater trench in the toe of the slope, in combination with period of heavy rainfalls, caused the Juričići Landslide in November 2012 (Fig. 3c). At that time 35 m of local road was damaged, and during the rainy spring of 2013, the width of the landslide enlarged another 30 m and the landslide head scarp damaged the road. The Juričići Landslide is a shallow rotational landslide, which involved 3 m of the clayey cover deposits, together with the road embankment, bringing material down the slope into the landslide toe. Further landslide widening potentially could have occurred due to small hydrodynamic or geometry changes in the slope, so emergency remedial work needed to be done. Construction of a gabion wall at the road edge, 71 m in length and founded on concrete piles, is still in progress (Autumn 2013).

Conclusions

Conditions that predispose flysch slopes to future landslides include the presence of clayey superficial deposits over the flysch bedrock on a slope with suitable inclination and kinematic conditions for sliding. Admission of water into the slope, with the inclination of the almost-impermeable flysch bedrock either retaining the groundwater at a location or promoting groundwater flow close to the slope inclination, and conditions in which the slope is exposed to a sufficiently long, continuous period of rainfall are main triggering factors for the activation of landslides on the flysch slopes of Gray Istria.

According to the well-known and widely applied principle “The past and the present are keys to the future” (Varnes 1984; Carrara et al. 1995), it is assumed that new landslide occurrences on the flysch slopes of Istria will appear in morphological, geological, hydrogeological and geotechnical conditions that are similar to the conditions associated with recent landslide occurrences (Dugonjić et al. 2008; Dugonjić Jovančević and Arbanas 2012). This is an important assumption for the future landslide susceptibility and landslide hazard analyses planned for the coming phases of the IPL-184 Project.

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