Landslide Risk Reduction in Croatia: Scientific Research in the Framework of the WCoE 2014–2017, IPL-173, IPL-184, ICL ABN

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Abstract

In this paper scientific activities of the Croatian Landslide Group (CLG), World Centre of Excellence on Landslide Risk Reduction (WCoE) of the International Consortium on Landslide (ICL) for the period 2014–2017, are shortly described. The results of scientific research are presented through the fields of landslide science: landslide identification and mapping, landslide investigation and testing, landslide monitoring, landslide modelling and landslide stabilization and remediation. It is concluded that the resulting landslide inventory maps, regional empirical rainfall intensity-duration thresholds, kinematic landslide models and soil strength parameters, landslide movement prediction models, numerical models and simulations and behavior of geotechnical construction for landslide stabilization provide necessary information for landslide risk management in Croatia. Besides applied scientific research, the general objectives of ICL WCoE are achieved in the framework of two Croatian IPL Projects and regional ICL Adriatic-Balkan Network.

Keywords

Croatian landslide group • ICL WCoE • Landslide science • Landslide risk reduction

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Introduction

The Croatian Landslide Group (CLG) from University of Rijeka and the University of Zagreb encompass scientists from the fields of engineering geology and geotechnics dealing with scientific research on landslides, i.e., landslide science. Scientists from the CLG started joint research in 2009 in the framework of the bilateral Japanese-Croatian scientific SATREPS FY2008 Project (2009–2014) aimed at enhancement of landslide research in Croatia through collaboration with scientists from Kyoto and Niigata universities. Based on outcomes of the SATREPS FY2008 Project, CLG become a World Centre of Excellence on Landslide Risk Reduction (WCoE) of the International Consortium on Landslide (ICL) for the period 2014–2017. The general objectives of ICL WCoE are: (1) to strengthen the International Programme on Landslides (IPL) and IPL Global Promotion Committee; (2) to create “A Global Network of entities contributing to landslide risk reduction”; and (3) to improve the global recognition of “Landslide Risk Reduction” and its social-economic relevance, and entities contributing to this field.

This article presents scientific research of the CLG in the period 2014–2017, related to the following topics: landslide identification and mapping, landslide investigation and testing, landslide monitoring, landslide modelling and landslide stabilization and remediation. Here are also incorporated IPL and ICL activities of the CLG, IPL Projects 173 and 184, and the regional ICL network, the Adriatic-Balkan Network (ICL ABN). The scientific research of CLG is also considered in terms of its application to landslide risk reduction on a national and international level.

Landslide Identification and Mapping

Extreme weather conditions in winter and spring of 2013 (re) activated more than 900 shallow landslides in North-Western Croatia, as it is recorded by the Croatian National Protection and Rescue Directorate (DUZS). Bernat Gazibara et al. (2016) compiled a catalog of 85 precipitation events that have caused landslides in the continental part of Croatia, within an area of approx. 10,500 km^2 (Fig. 1), and covering the period between June 2006 and October 2014. Three counties show a high average frequency of 2.4–4.8 precipitation events per year. The paper presents a preliminary analysis of precipitation conditions and a comparison with global and national ID (Intensity-Duration) thresholds. For example, annual precipitation in 2010, 2013 and 2014 was 20–40% higher than the Mean Annual Precipitation (883.6 mm) in the last 152 years, according to data from the Zagreb-Grič meteorological station, located in the central part of NW Croatia. Analysis of data showed that during January, February and March 2013, cumulative monthly precipitation was 130–190% higher than the average monthly values for the same period from 1862 to 2014. The cumulative precipitation for a 3-month period in 2013 has the highest value in the last 150 years (Bernat et al. 2014c). A comparison between precipitation conditions that caused landslides in NW Croatia and published global ID thresholds shows that precipitation conditions are lower than the threshold curves proposed by Caine (1980), Crosta and Frattini (2001), and Guzzetti et al. (2008). The best fit to the analyzed precipitation data shows the global ID threshold for soil slips according to Clarizia et al. (1996). A catalog of precipitation events will serve as the basis for further more comprehensive spatial and temporal probabilistic analysis for defining regional empirical threshold for shallow soil slides formed in Upper Miocene and Quaternary sediments of NW Croatia. Precipitation events analyses performed in this study were based on limited landslide inventory data (Mihalić Arbanas et al. 2016a). Therefore, more reliable analyses require a more detailed landslide inventory of small (<10^5 m^3) superficial to moderately shallow (<20 m) landslides, characteristic of the study area.

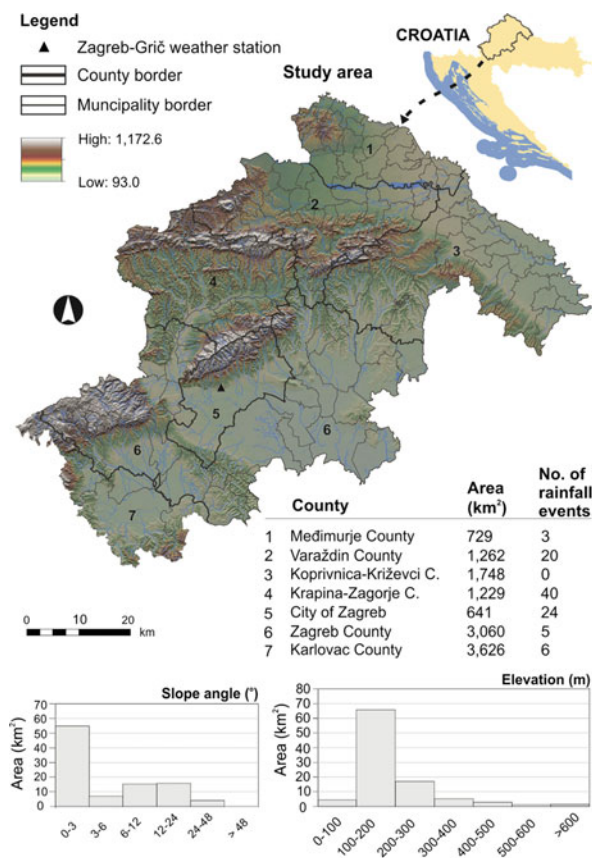

Fig. 1 Relief map of NW Croatia with the number of precipitation events in catalog (Bernat Gazibara et al. 2016)

A seasonal landslide inventory for the hilly area of the Medvednica Mt. (City of Zagreb in central part of NW Croatia), compiled based on records of reported landslide events from January to April 2013, contains 55 landslides (Bernat et al. 2014b). All recorded landslides are soil slides; 51% are superficial landslides (depth <1 m, area <200 m^2) formed in colluvial deposits overlaying engineering soil and soft rocks (marls); and 49% are shallow landslides (estimated depth 3–12 m, area <14,000 m^2) developed in stratified Upper Miocene (silty and sandy soils) and Quaternary sediments (heterogeneous mixtures of unfoliated, mostly impermeable fine grained soils). Figure 2 shows part of the geomorphological inventory compiled for the test area of the Medvednica Mt. hills (21 km^2) based on visual interpretation of airborne LiDAR (Light Detection and Ranging) DTM data from December 2013, with a spatial resolution of 15 × 15 cm (Bernat Gazibara et al. 2017). Landslide identification resulted in a landslide inventory map indicating the contours of 783 landslides, which implies an average landslide density of 37.28 landslides per square kilometer. Seventy-five percent of the landslides had an area between 159 and 2018 m^2. The area of the smallest identified landslide in the test area is 43 m^2. Only a minor number of landslides were reactivated in 2013 and two of them, showed in Fig. 2, are fully or partially located inside a zone of agricultural areas.

Podolszki (2014) also performed conventional visual interpretations of stereoscopic aerial photographs from 1964 at a scale of 1:8000 for the hilly area of the Medvednica Mt. He derived a landslide inventory map with an area of 54.14 km^2 for 963 landslides, which gives an average landslide density of 17.8 landslides per square kilometer. Stereoscopic analysis of historical aerial photographs from 1964 over a large scale enabled the identification of landslides over a range from 78 m^2 to 281,886 m^2. The landslide areas of most of the landslides (90.6%) range from 200–3600 m^2, which is in accordance to abovementioned results of application of new innovative LiDAR technologies. The reliability of aerial photo identification is estimated as very low, because only 50% of all mapped landslides were evaluated as reliable, based on certainty of identification, which implies only 9 reliably identified landslides per square km. Moreover, the quality of mapped landslide contours is very low because of forested terrain that makes it difficult or even impossible to map small and shallow landslides.

The geomorphological environment composed of carbonate and flysch rocks, located in a coastal part of Croatia, are prone to a variety of landslide types. Research on landslide identification in the Vinodol Valley (Primorsko-Goranska County) within the wider zone of the northern Adriatic coast, has been undertaken in the framework of doctoral research by Đomlija (2017). Đomlija et al. (2016) identified geomorphological processes causing slope instabilities in the Vinodol Valley, fluvial erosion and landslides. There are three types of fluvial erosion processes: planar, rill and gully erosion. Figure 3a illustrates linear erosion processes on steep slopes composed of hard carbonate rocks. Figure 3b shows denudational slope in the central part of the Valley composed of sylicyclastic soft

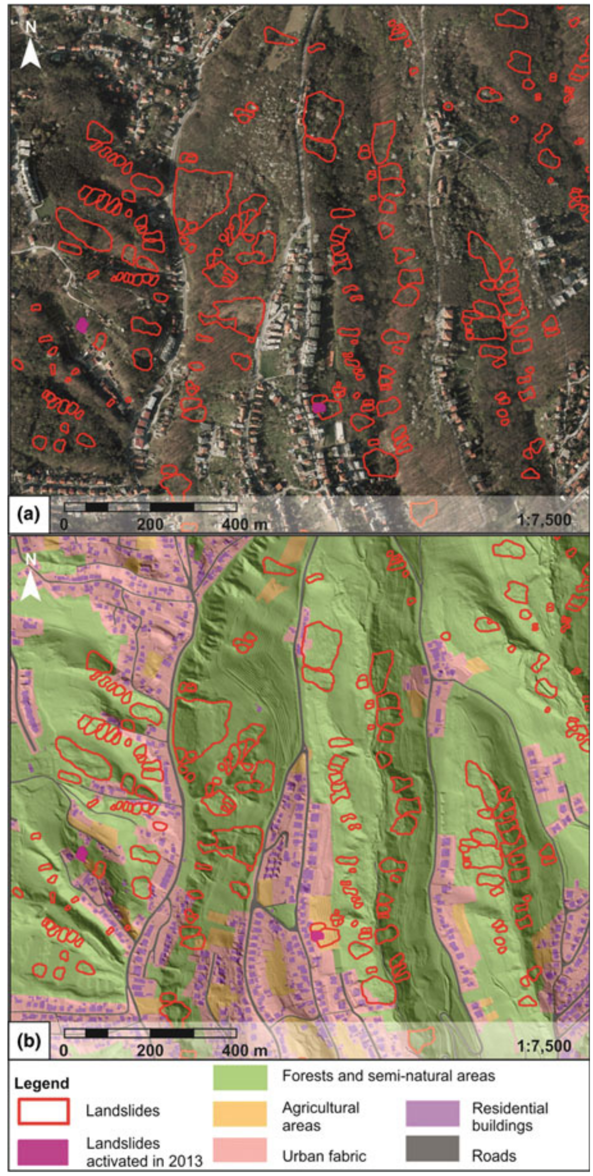

Fig. 2 Geomorphological inventory compiled for the test area of the Medvednica Mt. hills, based on visual interpretation of airborne LiDAR DTM data from December 2013 with a spatial resolution of 15 × 15 cm (Bernat Gazibara et al. 2017): **a** Landslide contours depicted on the orthophoto map at the scale 1:5000; **b** Landslide contours depicted on the official land use map of the City of Zagreb

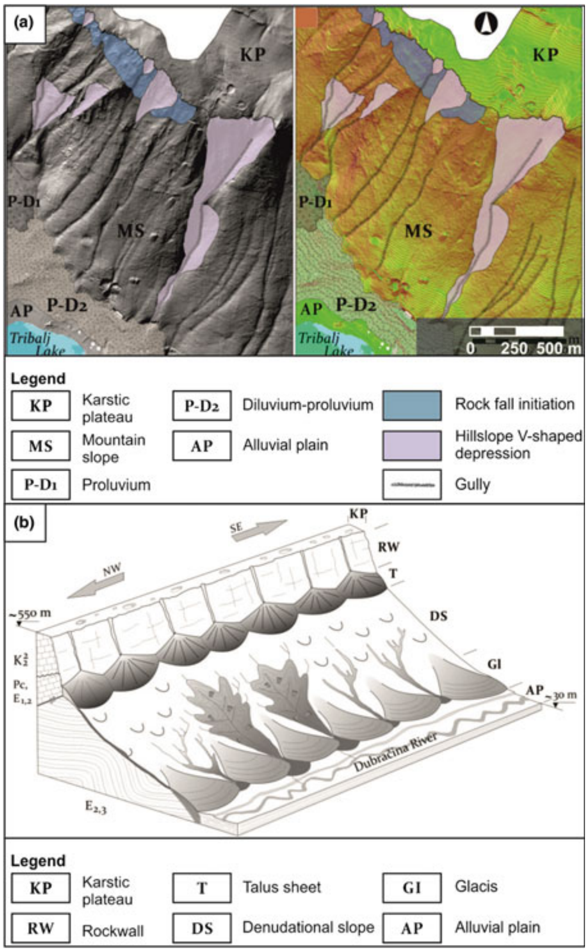

Fig. 3 Identified geomorphological phenomena and geomorphological units in the Vinodol Valley according to Đomlija et al. (2016): **a** Rock falls and gullies on the steep slopes composed of carbonate rocks; **b** Simplified model depicting geomorphological units in the central part of the Vinodol Valley

rocks in which excessive erosion is dominant, especially in some sub-basins, resulting in badland relief type. Bernat et al. (2014a) gave review of literature dealing with causes of excessive erosion in the Salt Creek catchment in the Vinodol Valley, related to mineralogical composition of flysch bedrock. Table 1 lists processes and phenomena in the central part of the mineralogical composition of flysch bedrock. Table 1 Vinodol Valley. Landslides classified according to classification by Hungr et al. (2014) encompass rock falls, breccia falls, boulder/debris/silt falls, rock block topples, gravel/sand/silt topples, rock slides (wedge, planar, rotational), debris slides, clay/silt slides (planar, rotational), breccia spreads, rock avalanches, mud flows, rotational earthflows, soil creep and slope deformation. Đomlija et al. (2014) present an applied methodology of identification and mapping, which is a visual interpretation of morphological features of instability phenomena on LiDAR-derived imagery from March 2012 with a 1 m-resolution. The methodology proved to be useful for identifying and mapping of variety of landforms and phenomena resulting from different types of hazardous geomorphological processes developed in carbonate rock masses, flysch and its derivative materials, classed as superficial deposits. The research shows the necessity of identification of geomorphological units, as a base for compilation of a landslide inventory and susceptibility and hazard analyses. Moreover, conditions in geological and geomorphological environments composed of carbonate and flysch rocks are complex, requiring analysis of the interrelationships of landslides and erosion hazards. Đomlija et al. (2016) showed that spatial density of landslides in zones of excessive erosion is extremely high, resulting in necessity of identification of landslide and erosion phenomena.

Landslide Investigation and Testing

This section presents research which results in quantitative characterization of the landslide site, including identification of the geometry of relatively homogenous zones of soil/rock, as well as the constructive properties of the material within the zones. Constructive properties are those parameters that allow the prediction of a material's strength, deformation, or permeability, in response to changes over time due to stress or other environmental conditions (Dowding 1979).

Surface observations and engineering geologic mapping were undertaken at the area of the Valići Lake landslide (Rječina River Basin in Primorsko-Goranska County), as a part of urgent measures, immediately after landslide reactivation in February 2014 (Mihalić Arbanas et al. 2016b). The purpose of the detailed mapping of this active landslide formed in weathered flysch (siltstones and sandstones), as well as the adjacent region that could contribute to causes of movement, was to provide the foundation for numerical modelling of the landslide (Arbanas et al. 2016), planning subsurface investigations and locating instrumentation for landslide monitoring. Collection of surface data included access to existing information, i.e., use of topographic maps, and field site inspection. Airborne LiDAR-derived imagery from March 2012 with a spatial resolution of 1 × 1 m was used for a comprehensive overall view of the landslide site. Figure 4a shows contours of the large deep historical landslide (landslide area of 1.3×10^6 m^3, landslide depth of 28.5 m) interpreted using a high-resolution bare-earth DEM. The estimated dimensions of the landslide body of the

Table 1 Geomorphological units in the central part of the Vinodol Valley with attributed hazardous processes and phenomena (Đomlija et al. 2016)

Geomorphological unit		Movement processes	Movement phenomena	Erosion processes	Erosion phenomena
KP	Karstic plateau	Slope deformation	Rock slope deformations	Sheet washing Gullying	Gullies
MS	Mountain slope	Falling	Rock falls		
		Toppling	Rock block topples		
		Sliding	Rock planar slides Rock wedge slides Rock rotational slides		
		Slope deformation	Rock slope deformations		
RW	Rockwall	Falling	Rock falls		
		Toppling	Rock block topples		
		Sliding	Rock planar slides Rock wedge slides		
		Flowing	Dry debris flow		
T	Talus sheet	Flowing	Dry debris flows	No processes	No phenomena
Br	Talus breccias	Falling	Breccia fall	Sheet washing	No phenomena
		Spreading	Breccia spreads		
DS	Denudational slope	Falling	Boulder/debris/silt falls	Sheet washing Rilling Gullying	Rills Gullies
		Toppling	Gravel/sand/silt topples		
		Sliding	Debris slides Clay/silt rotational slides Clay/silt planar slides		
		Flowing	Mud flows		
		Complex	Rotational slide-earthflows		
		Creeping	Soil creep		
Gl	Glacis	Sliding	Clay/silt rotational slides Clay/silt planar slides		
		Complex	Rotational slide-earthflows		
AP	Alluvial plain	No processes	No phenomena	No processes	No phenomena

historical landslide are length of 350 m and width of 135 m. The toe of the historical landslide reached the bank of the Valići reservoir 250 m upstream of the Valići dam. During construction of the Valići dam and lake in 1960, the historical landslide was partially remediated by a surface and subsurface drainage system. Figure 4b presents a predictive model for reactivation of the historical landslide in 2014 (landslide volume of 3.68×10^5 m^3, landslide depth of 20 m) and its relative position to Valići Lake, which is endangered by potential movement of the landslide. The movement of the reactivated landslide of approx. 12–15 m down the slope caused substantial damage to the local road. The trigger for landslide reactivation in 2014 was a 15-day rainfall event with 302.6 mm of cumulative rainfall from 30 Jan to 13 Feb 2014.

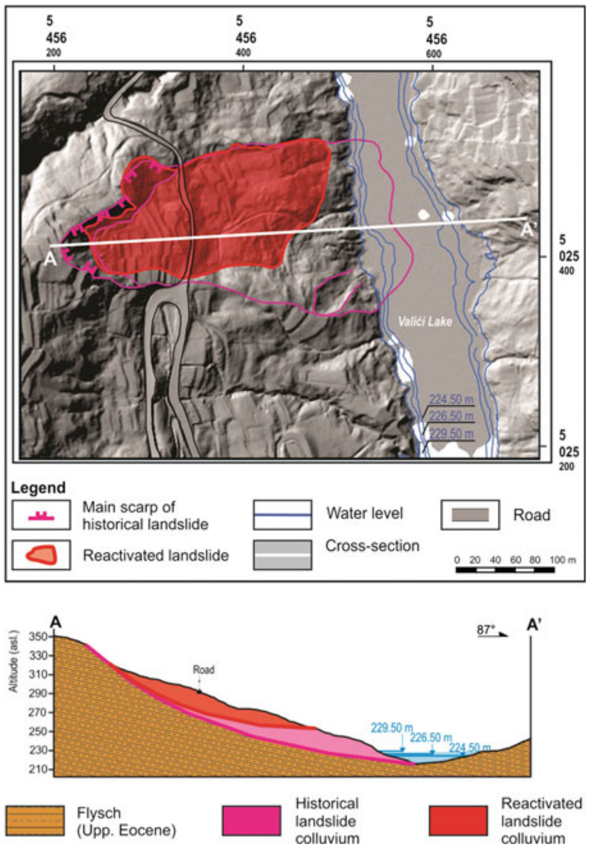

Fig. 4 Valići Lake landslide reactivated in February 2014 (Mihalić Arbanas et al. 2016b): **a** Landslide map with contours of an historical landslide visually identified using airborne LiDAR DTM data from May 2012, 1 m-resolution, and landslide contours of the reactivated landslide; **b** Engineering geological cross-section showing the historical and reactivated landslides

Identification of digital surface models derived from the point cloud data obtained with terrestrial and airborne laser scanning (TLS and ASL) was applied to rock slope characterization for the purpose of stability analyses and design of remedial measures. Sečanj et al. (2017) presented visual and semi-automatic identification of rockfall-prone areas on the steep slopes above the historical town of Omiš (Splitsko-Dalmatinska County), situated on the southern part of the Adriatic Coast. The ancient town of Omiš is a tourist destination, cultural and historical heritage site. The residential part of Omiš, along with its historical landmarks, are located at the toe of the steep slopes of Omiška Dinara Mt., composed of a massive, blocky to very blocky carbonate rock mass. People and material goods are highly endangered by rock falls from steep slopes with a total area of approx. 15 ha and a maximum slope height of 277 m. To identify rockfall-prone areas on steep slopes, discontinuities and unstable rock blocks were mapped in detail using remote sensing. Potentially unstable rock blocks were identified based on kinematic analysis. The volume of hazardous rock blocks varies in size from 0.1 to 1235 m^3. The same approach in investigation and interpretation of remote sensing data was used for rock slope characterization of road slope cuts along county roads in National Park Krka on the north side of the Brljan Lake (Šibensko-Kninska County), cut in a very blocky and disintegrated carbonate rock mass. Total length of the slope cuts along county road is 900 m, maximal height of the slopes is 65 m and slope angles vary from 30° to 90°. The road is placed just in the bottom of the slope cuts, without a rock fall catchment zone, which makes the road very risky, especially for people. Identification of columnar rock blocks in the base of ancient Momjan Castle from the 13th century (Istrian County in the north Adriatic Coast) built on a cliff was conducted by interpretation of point cloud data obtained using terrestrial laser scanning (TLS). Vertical columnar rock blocks have been continuously forming along multiple sets of vertical discontinuities intersecting a mega-bed (thickness of about 10 m) of calcareous rock in flysch, underlain by marl. Weathering along vertical discontinuities in the hard rock, as well as weathering of soft rock in the base of columnar blocks, is the main preparatory causal factor of rock toppling. These instabilities in the foot of the Castle foundations seriously endanger this cultural heritage site with the threat of complete ruination of the Castle.

Research on the changes of engineering properties of flysch rock mass due to weathering in the wider zone of the northern Adriatic coast (Rječina River and Vinodol Valley in Primorsko-Goranska County and Istrian Peninsula) have been undertaken in the framework of doctoral research by Vivoda Prodan (2016). Vivoda Prodan et al. (2016) analyzed the effects of weathering on the shear strength of siltstones from the flysch rock mass. Six weathering grades of siltstone member were identified, based on material color, state of discontinuities, presence or absence of the original rock structure, and uniaxial strength. X-ray analyses revealed significant increase of clay mineral (phyllosilicates) content, especially chlorite and illite, with increasing weathering grade and a consequent increase in cation exchange capacity (CEC) and water adsorption. Identification of physical and mechanical properties and the residual strength of different weathering grades of siltstones were performed on the soil-like material produced in laboratory conditions by crushing samples to sand-sized particles. The testing procedure, using ring shear device ICL-1 (described in Oštrić et al. 2014) and direct shear devices, enabled simulation of slip surface development in remolded material from flysch slopes

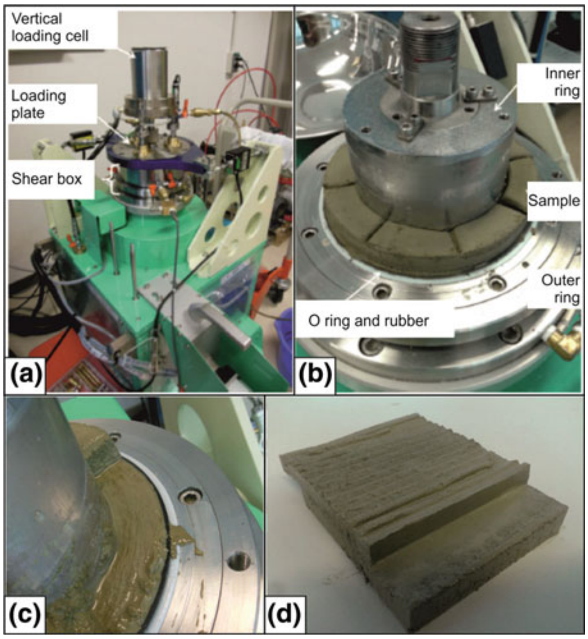

Fig. 5 Siltstone sample in a ring shear device: **a** during and **b** after testing. The sliding surface is shown after shearing in **c** the ring shear device and **d** the direct shear device (Vivoda Prodan et al. 2016)

(Fig. 5). The test results indicate increase of liquid limits, plasticity indexes and decrease of peak and residual shear strength with increase in weathering grade of siltstones from flysch rock masses. Vivoda Prodan and Arbanas (2016) also performed a series of drying–wetting cycles to simulate natural conditions of the weathering process involved in the disintegration of the rock mass material into sand-sized and smaller particles to establish the relationship of geotechnical properties and durability with weathering of siltstones from a flysch rock mass in the Istria Peninsula. According to the results of the study, weathering has a significant influence on the plasticity of soil-like remolded material of siltstones in terms of increase of liquid limit and plasticity index with increasing weathering grade. The uniaxial compressive strength determined with a Schmidt hammer and the Point Load Test (PLT) decreases with increasing siltstone weathering grade. The study showed that determination of durability of siltstones requires calculation of a degradation ratio and the modified degradation ratio as additional parameters that indicate the manner of disintegration of siltstones of different weathering grades. According to the classification based on the slake durability index, the siltstone samples of different weathering grades from Istria are classified in a higher durability class than in classifications based on the fragmentation during the slake durability test. The obtained laboratory results indicate that weathering has a significant influence on the plasticity, uniaxial compressive strength, durability characteristics and shear strength of the siltstones. Application of the described research results are demonstrated by use of different physical-mechanical parameters of different weathering states of siltstones in numerical simulations of behavior of the Valići Lake landslide (Vivoda Prodan and Arbanas 2017).

Landslide Monitoring

Integrated automated monitoring system of the large and deep Kostanjek landslide (City of Zagreb) in soft rocks of Upper Miocene age in the continental part of Croatia was established in the period of 2011–2013 (Krkač et al. 2014c). External triggers at the Kostanjek landslide have been measuring with a rain gauge and accelerometers, displacements at the surface by GNSS sensors and extensometers, subsurface displacement have been measured by vertical extensometers and an inclinometer; while hydrological monitoring consists of groundwater level (GWL) measurements and discharge measurements. Krkač et al. (2014b) reviews the monitoring parameters which have been continuously and discontinuously observed at the Kostanjek landslide. The Kostanjek landslide presents a hazard and risk for approx. 290 buildings (mostly residential houses) in an area of 1 km^2 in the urban part of the city of Zagreb. Automated data transmission from all sensors makes the monitoring system suitable for the establishment of an early warning system (EWS), which is planned in collaboration with City administration responsible for emergency management (Krkač et al. 2014a).

In a doctoral thesis, Krkač (2015) presents analysis of a temporal data series of movement and GWL captured by the Kostanjek landslide monitoring system in the period from January 2013 to January 2015. Analysis of movement measurements showed that 90% of total displacement (426.09 mm) happened during five periods of accelerated displacement. Statistical analysis revealed that the periods of accelerated displacements are a consequence of nine periods of GWL increase. Analysis of precipitation data proved that changes in GWL happened during wet periods, i.e., the same amount of precipitation will have a different influence on GWL in dry and wet periods. For this reason, modeling of the relation between precipitation and GWL, and GWL and landslide movement, are performed separately. Statistical methods used for precipitation and GWL and GWL and landslide movement modeling were multiple linear regression and random forests. The purpose of the modeling was prediction of GWL based on precipitation data, as well as prediction of movement based on GWL data. Based on

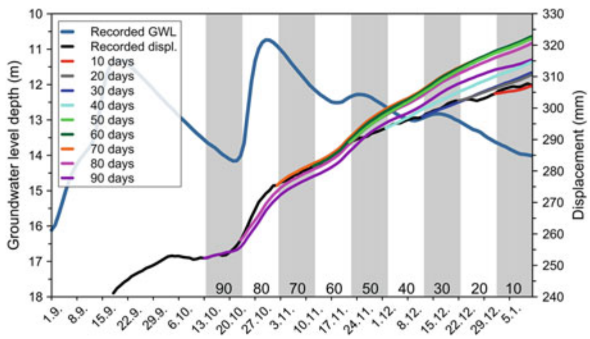

Fig. 6 Prediction of landslide displacement by random forests from groundwater level data (Krkač et al. 2016)

comparison of multiple linear regression and random forests models, performed using mean square error and correlation coefficient between modeled and measured values, as well as k-fold cross validation and validation, it is concluded that better results have been achieved using random forests. Krkač et al. (2016, 2017) presents a methodology for prediction of landslide movements using random forests, a machine learning algorithm based on regression trees. The process of landslide movement prediction is divided into two separate models: (1) a model for prediction of GWL from precipitation data; and (2) a model for prediction of landslide movements from GWL data. In a GWL prediction model, 75 parameters were used as predictors, calculated from precipitation and evapotranspiration data. In the landslide movement prediction model, 10 parameters calculated from GWL data were used as predictors. Model validation was performed through the prediction of GWL and prediction of landslide movements for periods from 10 to 90 days (Fig. 6). The validation results show the capability of the model to predict the evolution of daily displacements from predicted variations of GWL for the period of up to 30 days. A practical contribution of the developed method is the possibility of automated predictions of landslide movement, updated and improved on a daily basis, which would be an important source of information for decisions related to crisis management in the case of risky landslide movements.

Integrated automated monitoring system of the large and moderate shallow landslide Grohovo (Rječina Valley in the City of Rijeka) in flysch rocks was established in the period of 2010–2011 (Arbanas et al. 2014b, c). The Grohovo landslide is the largest active landslide (landslide area of 10 ha; landslide volume of 3×10^6 m^3) along the Croatian part of the Adriatic coast, formed at the contact of fresh and weathered siliciclastic rock (i.e., flysch; Benac et al. 2014) covered by debris with limestone boulders. The landslide represents the reactivated part of a much larger historical landslide of unknown age (estimated landslide area of 40 ha), with the main scarp formed in limestone rock mass visible as a cliff at the top of landslide. The Grohovo landslide is complex landslide which exhibits two types of movement, rock falls and debris sliding. Landslide reactivation in 1996 shifted attention to the high level of landslide hazard and necessity of its monitoring. The comprehensive monitoring system of the Grohovo landslide consists of geodetic and geotechnical monitoring. Geodetic monitoring includes geodetic surveys with a robotic total station and displacement measurements of GPS sensors. Equipment for the geotechnical monitoring includes vertical inclinometers, and long-span and short-span wire extensometers. Pore pressure gauges and weather station are aimed at monitoring of landslide causal factors. All monitoring equipment is connected in one system, with continuous monitoring and automated transmission of the data. The main disadvantage of the system is power supply. Ljutić et al. (2014) describes problems related to the installation and working of the system, as well as solutions which should improve the system for successful continuous work.

Landslide Modeling

Numerical modeling of Croatian landslides has been performing using LS-RAPID Software since 2013. LS-RAPID Version 2.03 Beta10, developed in 2013, is described in He et al. (2014). This landslide simulation software is developed to reproduce the initiation process and the runout process from stable state until deposition within the same model. It can simulate the initiation and motion of landslides triggered by earthquakes, rainfall or the combined effects of rainfall and earthquakes. The modeling is based on the following key parameters: the shear resistance at the steady state, the peak friction angle, cohesion, the shear displacements at peak and the onset of steady state and the lateral pressure ratio with physical meaning.

Landslide modeling using LS-RAPID software was performed for the Grohovo landslide (Vivoda et al. 2014) and the Valići Lake landslide (Arbanas et al. 2016, 2017) in the Rječina River Valley, and the Kostanjek landslide in the City of Zagreb (Gradiški et al. 2013, 2014). Vivoda et al. (2014) implemented the deterministic 3D landslide stability analyses of the wider area (approx. 40 ha) of the Grohovo landslide to found out possible landslide reactivation under unfavorable groundwater conditions inside the area of the historical landslide. The topography of the Grohovo landslide was determined using 10 m-resolution DEM data. The limestone rock mass is situated at the top of the slopes, while the siliciclastic rocks and flysch are situated on the lower slopes and the bottom of the valley. Depth of the sliding mass varies from 3 to 10 m and the slip surface is formed in flysch bedrock. The final result of the modeling was a failure probability map, converted from the simulation model. The long-term rainfalls and consequent ground water level rise were detected as the main triggering factor for the Grohovo landslide reactivation. Arbanas et al. (2016) used LS-RAPID software to determine possible scenarios for the Valići Lake landslide movement for four scenarios with different reservoir water levels at the foot of the landslide, which correspond to full reservoir, dam overflow level, and two lower safety levels. The foot of the landslide is submerged in the reservoir and the magnitude of motion, run off sliding path, and deposition of the sliding mass will significantly depend on the reservoir water level. Analyses showed that in a case of a high reservoir water level, the sliding mass would fill the reservoir, causing the water level to rise and waves (tsunamis) which would overflow the Valići dam, resulting in significant damage downstream along the Rječina River channel. Numerical simulation results enabled an estimation of landslide risk for the cases of different scenarios of reservoir water level (Arbanas et al. 2017). Gradiški et al. (2013, 2014) performed simulation of the Kostanjek landslide motion using LS-RAPID software in a case of rising ground water level and a possible earthquake. It was found that the eastern and central parts of the landslide are more unstable than the western part. An earthquake with an acceleration of 0.344 cm/s^2 will cause movements of the whole existing landslide body. The LS-RAPID simulation software was used for deterministic landslide susceptibility analyses in the flysch area of North Istria after identification of typical landslide phenomena on flysch slopes (Arbanas et al. 2014a; Peternel et al. 2016). This region is identified as an area of frequent, small and shallow instability phenomena, mostly triggered by rainfall. The deterministic landslide susceptibility analyses were also performed for the part of the City of Buzet area (Dugonjić Jovančević 2013; Dugonjić Jovančević et al. 2014a, b, 2016) to identify the zones susceptible to sliding caused by rising ground water levels. Ground water level is taken into account through the pore pressure ratio, which gradually increases due to superficial water infiltration. Žic et al. (2015) analyzed propagation of a possible mudflow from the Grohovo landslide downstream through the Rječina watercourse to the City of Rijeka using a smoothed-particle hydrodynamics (SPH) model. Based on conducted computational simulations, it can be concluded that the potential mudflow propagation is unlikely to threaten the urban part of the city of Rijeka and that it is unlikely to cause substantial effects on the environment or lead to loss of human lives.

Table 2 Landslides and designed remedial measures in the period 2013–2017 by the CLG

Landslide name	Landslide type	Landslide area (m^2)	Remedial measures
Gabrovica	Debris slide	83	Gabion wall
Cerina 1	Debris slide	100	Gabion wall
Muellerov Brijeg	Debris slide	198	Pile wall
Črnica	Rock fall	200	Rock anchoring
Cerina 2	Debris slide	210	Gabion wall
Sovinjak	Soil slide	351	Concrete wall
Sv. Martin	Soil slide	500	Gabion wall
Marovići	Soil slide	525	Gabion wall
Braslovje	Soil slide	532	Gabion wall
Gradišće	Soil slide	709	Gabion wall
Cerina 3	Debris slide	760	Gabion wall
Grohovski put	Soil slide	850	Pile wall
Remete 1	Soil slide	877	Gabion wall
Galgovo-Zagrebačka	Debris slide	1.200	Gabion wall
Grdanjci	Rock slide	1.269	Gabion wall
Grohovo-HEP	Debris slide	1.547	Pile wall
Momjan Castle	Rock topple	1.600	Rock anchoring
Havišće	Rock falls	2.000	Rock anchoring
Brljan	Rock falls	20.000	Rock anchoring, rock fall barriers
Omiš	Rock falls	150.000	Rock anchoring, rock fall barriers

Landslide Stabilization and Remedial Measures

To improve understanding of remedial constructions on slope stability, two research studies based on in situ-testing, long-term monitoring and numerical analyses were conducted. Jagodnik, in the framework his Ph.D. thesis (Jagodnik 2014) tested behavior of horizontally loaded piles on a testing site constructed in natural sandy gravels. Individual piles, group of piles and pile walls are very often applied as effective remediation measures of landslides (Popescu 2001). The research resulted with *p-y* curves of piles exposed to controlled horizontal loads in the head of a pile (Jagodnik and Arbanas 2015a, b) that would enable better control of forces in piles used as a remedial measure for landslides. Grošić in his Ph.D. thesis (Grošić 2014) analyzed time-dependent deformation of reinforced cuts in flysch rock masses based on long-term monitoring results. The analysis results have indicated significant time-dependent deformation in slopes built of weak rock masses and consecutive redistribution of the forces in rock mass reinforcement elements over time that can lead to the progressive failure of a slope (Grošić and Arbanas 2014). This finding pointed to the necessity of long-term analyses of remedial constructions at slopes in weak rock masses.

Field investigation, soil and rock laboratory testing and landslide remediation designs of several recent landslides were also conducted, as a part of CLG's activities in landslide risk reduction. Most of the investigated landslides occurred as sliding processes which affected roads in the North-Western part of Croatia, Istria and outback of the City of Rijeka, while rock fall phenomena endangered cultural heritage and urban areas in coastal parts of Croatia (Istria and Dalmatia). The investigated landslides and developed remediation measure design methods in the period 2013–2017 are listed in Table 2.

Discussion and Conclusions

The scientists from the Croatian Landslide Group (CLG) deal with basic and applied landslide science in the field of engineering geology and geotechnics (civil engineering), working at the two Croatian universities. As a stakeholder of the "Sendai Framework for Disaster Risk Reduction 2015–2030", which involves academic, scientific and research entities, the CLG focuses on disaster risk factors and scenarios, including emerging disaster risks in the medium and long term; increases research for regional, national and local applications; supports action by local communities and authorities; and supports the interface between policy and science for scientifically based options for decision making.

Described research of disaster risk factors undertaken by the CLG encompasses:

(i) Compilation of landslide hazard inventories in the form of geomorphological inventories of shallow landslides and of different types of landslides associated with erosion phenomena (multi-hazard approach);
(ii) Landslide susceptibility assessment to map initiation and runout zones of rock falls;
(iii) Hazard assessment by compilation of seasonal landslide inventories and catalogs of precipitation events to determine the size and probability of potential landslide occurrences for a given return period;
(iv) Determination of environmental risk factors by analyzing a landslide material's strength, deformation, or permeability in response to changes over time due to other environmental conditions, i.e., weathering.

Research of disaster risk scenarios was performed by modelling of the initiation and motion of the most dangerous landslides: reactivation of the Grohovo landslide under unfavorable groundwater conditions inside the area of a historical landslide and propagation of a possible mudflow from the landslide; initiation and runout of the Valići Lake landslide for different reservoir water levels and possible filling of the lake; and reactivation of the urban Kostanjek landslide due to rising ground water level and possible earthquake. Emerging landslide risk has been determined in the form of most frequent landslide initiations and reactivations as a consequence of higher frequency of precipitation events identified as triggering factors. Results of landslide hazard identification and assessment are important for medium risk analysis as well as for long-term risk assessment necessary for adaptation to climate changes and extreme weather conditions.

Scientific activities focused on landslide risk factors listed from (i)–(iii) are implementing in the framework of the IPL Project 173. Research on landslide risk factors described under (iv) and landslide risk scenarios are part of IPL Project 184. All described research in the fields of landslide identification and mapping, landslide investigation and testing, landslide monitoring, landslide modelling and landslide stabilization and remediation are aimed at local, national and regional applications for landslide risk reduction. Additionally, the CLG is leading member of the regional scientific network of landslide scientists, the ICL ABN. Network activities include joint activities related to landslide risk reduction with the scientific and academic institutions from Croatia, Slovenia and Serbia, scientific institutions from Albania and Slovenia, professional association from Bosnia and Herzegovina and local government from Croatia.

Research results in the form of landslide hazard maps, prognostic models and landslide remediation designs support action by local communities and authorities managing landslide risk. Scientific CLG activities support the interface between policy and science for scientifically based options for decision making in the systems of land-use planning, construction, civil protection and environmental protection.

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