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Rockfall analyses and rockfall protection at the Raspadalica Rockfall, Croatia

Analyse des éboulements et protection contre les éboulements, l'éboulis Raspadalica, Croatie

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ABSTRACT: The Raspadalica rockfall is well known location with numerous rockfall occurrences from 100 m high limestone cliff in the past that caused significant damages and victims at the railway Buzet - Pula in Istria, Croatia. Structural and kinematic analysis of possible future rockfall were carried out following the modern approaches and recent techniques in rockfall hazard analysis. Modern approaches include application of remote-sensing techniques enabled to ensure digital terrain models (DTM) from three-dimensional high-resolution point cloud (3D HRPC) of the cliff surface; engineering geological mapping using combination of remote-sensing techniques and field mapping. In this paper the methods and results of field and remote sensing investigation of the cliff structural and kinematic analysis results, identification of rockfall sources, as well as analysis of necessary protection measures and their positions at the slope above the railway route.

RÉSUMÉ : L'éboulis Raspadalica est un site très connu, qui a eu dans le passé de nombreuses chutes de pierres à partir d'une falaise de calcaire de 100 m de haut, qui ont causé des dommages importants et des victimes sur la ligne chemin de fer Buzet - Pula en Istrie, Croatie. L'analyse structurelle et cinématique des éventuels éboulements futurs a été réalisée en suivant les approches modernes et les techniques récentes dans l'analyse des risques d'éboulement. Les approches modernes comprennent l'application de techniques de télédétection permettant de faire des modèles numériques de terrain (MNT) à partir d'un nuage de points tridimensionnel haute résolution (3D HRPC) de la surface de la falaise ; la création des cartes géologiques en utilisant une combinaison de techniques de télédétection et de cartographie sur le terrain. Dans cet article, les méthodes et les résultats de l'enquête sur le terrain et par télédétection et l'analyse structurale et cinématique de la falaise ont pour résultat l'identification des sources d'éboulements, ainsi que l'analyse des mesures de protection nécessaires et de leurs positions sur la pente au-dessus de la voie ferrée.

KEYWORDS: rockfall, remote sensing, kinematic analysis, rockfall protection.

1 INTRODUCTION

Rockfalls are one of the most frequent and dangerous type of landslides that can cause high number of fatalities as well as high economic and social damage. Rockfalls include detachment, fall, rolling and bouncing of rock fragments from the slope, singly or in clusters, and the fragments can be defragmented during impacts (Hungr et al., 2014). A rockfall occurrence can vary from small fragments to massive blocks of different volumes and shapes falling down, rolling and bouncing along a slope (Dorren, 2003; Volkwein et al., 2011). The high speed, mobility and energy of falling rocks disable getting a necessary time for fast response through evacuation or protection (Dorren, 2003; Ritchie, 1963; Siddique et al., 2019; Volkwein et al., 2011).

The Raspadalica Cliff is an almost vertical 100 m high limestone slope (Figure 1) situated at the contact of two geomorphological units, namely the hilly Paleogene Flysch Basin and the elevated Ćićarija Mountain Range in the northern part of the Istrian Peninsula, Croatia (Arbanas et al., 2006). The Raspadalica wider location is well known by numerous instabilities occurred as rockfalls from the Raspadalica Cliff and landslides (Dugonjić Jovančević and Arbanas, 2012) already caused significant damage at the railway route situated at the flysch slope in the foot of the cliff.

The history of the rockfall occurrences from the Raspadalica Cliff is known from 1951 when several traffic interruptions on the railway were caused by several landslides and rockfalls that endangered stability of railway embankment as well as traffic safety. From 1951, numerous instability occurred followed by series of field investigations, remediation designs and implementation of remedial measures, but a threat from rockfalls is still present (Udovič et al., 2021).

Figure 1. A view at the Raspadalica Cliff, Istria Peninsula, Croatia.

The rockfalls from the Raspadalica Cliff have not been documented before 1963, but it was noticed that several of them reached the tracks and caused traffic interruptions. From 1964 to nowadays, the rockfalls beside the breakages of railway facilities threated people's lives and train traffic. The three most important rockfalls occurred on 18 November 1975 with human causalities, 11 August 1992 and 10 February 1999 with significant damage of railway facilities. The rockfall mass in the February 1999 hit and completely destroyed the stone wall in the central part of the cliff. This section was renewed by 5 m height embankment built from coarse stone debris material during 2000 and 2001. The last significant rockfall occurred on 16 December 2013 (Figure 2) that caused interruption of railway traffic for several months and it was followed by rockfall protection measures based on field investigations in 2012.

In determination of the detailed geological structure of the cliff and the causes of rockfall occurrences at the Raspadalica Cliff several campaigns of field investigations were carried out during the last decade. The first one carried out for the remedial measures and rockfall protection design was conducted using traditional methods of engineering geological survey and mapping, and it was limited by cliff height to the rock mass in the foot of the cliff (Grošić, 2012a). Traditional geological and geotechnical field survey consisted of field mapping of cliff face; direct measuring of discontinuity orientations and dip direction, persistence, spacing, aperture, and roughness; as well as determination of discontinuity wall weathering grades and discontinuity infilling limited to the accessible zone at the foot of the cliff. The second one started in 2019 and it was based on the remote sensing techniques based on Unmanned Aerial Vehicle (UAV) photogrammetry data (Antoine et al., 2020; Froideval et al., 2019; Giordan et al., 2020) in combination with data collected by traditional survey (Francioni et al., 2019).

2 GEOLOGICAL SETTINGS OF RASPADALICA CLIFF

The Raspadalica Cliff is located in the northern part of the Istrian Peninsula, Croatia at the border of the Paleogene Flysch Basin (so called Gray Istria) and the geomorphologically dominant elevation of the Ćićarija Mountain Range (so called White Istria) which mostly consists of carbonate rocks. This area is a part of the overthrust structure that stretches in direction NW-SE. The kinematics of the structural elements on the margin between the overthrust carbonate unit, the Ćićarija Mountain Range, and the Paleogene Flysch Basin, is based on the relation of the relatively rigid (carbonate rocks) and relatively ductile (flysch rock complex) media during simultaneous deformations. The effects of the deformations are most distinctive at the contact (i. e. overthrust zone) between the limestone and flysch rock complex.

Figure 2. Photo of the rockfall originated from the Raspadalica Cliff on 16 December 2013 (Udovič et al., 2021).

Recent gravitational sliding of huge carbonate rock blocks over the flysch bedrock are also identified.

The Eocene flysch bedrock complex, formed by turbidite sedimentations, is lithologically very heterogeneous with frequent vertical and lateral alternations of diverse lithological sequences: marls, siltstones, fine-grained sandstones, as well as very distinctive layers of calcarenites. At the foot of the cliffs, the coarse-grained fragments originating from the cliffs mixed with the silty clay from the flysch weathering zones to form few-meter-long slope deposits at the foot of the of the Ćićarija Mountain carbonate rock complex (Arbanas et al., 2006).

Raspadalica Cliff is a part of the Ćićarija Mountain Range built of Paleogene limestone and the contact of the limestone rock mass of the cliff and the flysch complex in the lower part of the slope is characterized by reverse fault at the dip of approximately 23 degrees (Figure 3). The limestone mass is homogeneous, fine-grained and well stratified. The thickness of beds ranges from 10 centimeter to 2 meters with several interlayers of coal several centimeter thick. The general dip of the bedding planes is relatively favorable and inclined into the slope with minor variations along the cliff. Detailed description of the structural model of the cliff is described in the following chapters.

3 THE 3D STRUCTURAL MODEL ESTABLISHMENT

In the recent years, a use of Unmanned Aircraft Vehicle (UAV) photogrammetry as spatial data collection method was developed. The products generated from UAV photogrammetry usually consider dataset such as point clouds, high-resolution digital surface models, high resolution digital orthophoto, photorealistic 3D models and visualizations (James and Robson, 2012; Bishop, 2013). In this study custom made Vertical Takeoff and Landing (VTOL) rotary wing hexacopter UAV was used as the aerial platform equipped with the Sony Alpha 7R digital camera with the 36.3-megapixel full-frame (35.9 mm x 24 mm) CMOS sensor and the Sony FE 35mm high-quality Carl Zeiss lens (Udovič et al., 2021). Based on two flight missions dense 3D high resolution point cloud (3D HRPC) with about 32 million points was generated as well as high resolution digital surface model and orthophoto with an average ground sampling distance (GSD) of 2 cm.

Traditional geological and geotechnical field survey was conducted to determine the main lithology, discontinuity sets,

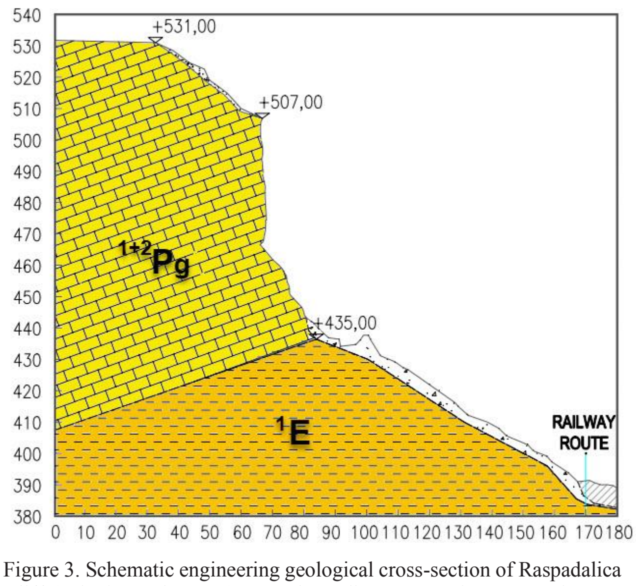

Figure 3. Schematic engineering geological cross-section of Raspadalica Cliff (Udovič et al., 2021). Overthrust limestone Paleogene rock mass ($^{1+2}$Pg) lies on Eocene flysch deposits (^{1}E). The flysch deposits are covered with talus material originated from limestone cliff.

faults, and structural geological model of the Raspadalica Cliff. The geological and geotechnical surveys were conducted at 1:500 scale developed for the wider zone of cliff area. Field investigations were combined with the study at the orthophoto (in scale 1:5000) and 3D HRPC for better understanding of geological and geomorphological features at the study area. Traditional geotechnical survey was conducted to determine the characteristics of the main discontinuity sets at the cliff, as well as to carry out a rock mass classification using Geomechanical classification (Rock Mass Rating, RMR) (Bieniawski, 1989) and Geological Strength Index (GSI) (Marinos and Hoek, 2000).

Once the 3D HRPC model was established, the cliff was analyzed to identify the main characteristics of the rock mass structure as well as to detect and map the discontinuities and discontinuity sets, orientation and dip of discontinuities, spacing of discontinuities, persistence of discontinuities and roughness of discontinues. Due to increasing use of UAV photogrammetry and *SfM* technique for establishment of 3D HRPC models, different automatic and semi-automatic techniques and methods were developed to detect and mapping the discontinuities and discontinuity sets (Alptekin et al., 2019; Anders et al., 2016; Farmakis et al., 2020; Giordan et al., 2020; Nesbit et al., 2018; Riquelme et al., 2018; Stead et al., 2019), orientation and dip direction of discontinuities (Anders et al., 2016; Dewez et al., 2016; Farmakis et al., 2020; Kong et al., 2020; Liu et al., 2019; Menegoni et al., 2019; Riquelme et al., 2017, 2014; Vanneschi et al., 2019; Zhang et al., 2019), spacing of discontinuities (Bonetto et al., 2020; Giordan et al., 2020; Nagendran et al., 2019; Riquelme et al., 2015; Salvini et al., 2018; Zhang et al., 2019), persistence of discontinuities (Bonetto et al., 2020; Kong et al., 2020; Riquelme et al., 2018) and roughness of discontinuities (Caudal et al., 2020; Giordan et al., 2020; Mastrorocco et al., 2016; Menegoni et al., 2019; Mikita et al., 2020; Salvini et al., 2020). In this study a combination of traditional geological and geotechnical field survey (Bolla and Paronuzzi, 2020) and remote sensing techniques are employed to detect and map the discontinuities and discontinuity sets, orientation and dip of discontinuities as well as other discontinuity features necessary for analyses of rockfall occurrences and their consequences. Based on identified discontinuities and discontinuity sets features, the representative block volumes are determined for each of discontinuity sets according to the equation proposed by Palmstrom (Palmstrom, 2001).

The structural model of the Raspadalica Cliff is established based on both traditional geological and geotechnical field survey and remote sensing analysis. Detailed analyses of field survey and remote sensing data pointed to five slightly different zones, but because of their properties and rock block standings according to the general orientation and dip of cliff face. These zones (Zone I to V) are presented at the 3D HRPC (Figure 5) while the borders that separate zones are determined analyzing changes in orientation and dips of the main joint sets as well as changes in rock block volumes (Udovič et al., 2021).

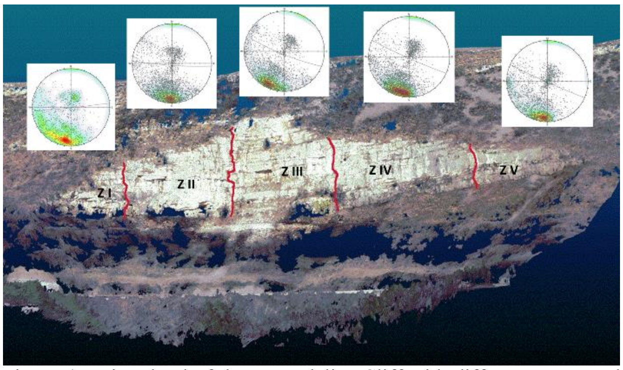

Figure 4. Point cloud of the Raspadalica Cliff with different zones and stereonet plots for each zone.

The field investigations are based on traditional in situ survey conducted by traditional engineering geological cliff face rock mass mapping in the foot of the cliff without possibilities to reach upper part of the cliff and to determine rock mass and discontinuities properties in all part of the cliff. To identify discontinuity sets and their dips and dip orientations the *Cloud Compare* software (CloudCompare, 2015) was employed. The cliff face was divided in five zones (Figure 4), and for each segmented zone an extraction of joint planes using the *Cloud Compare Facet* and *Compass* plugins (Dewez et al., 2016; Nagendran et al., 2019) (Fast Marching procedure) were employed to identify their orientations (dip directions and dips). The spacing between the joints for each joint sets necessary to determine block volumes was determined using *Cloud Compare Distances* tool where the distances in different cliff face zones are measured and analyzed. The other discontinuity features (separation, infilling, discontinuity wall roughness and weathering grade) were obtained by *in situ* traditional geological and geotechnical surveys.

Analyzing the features observed and registered in the field as well as general geological structure of the cliff, the discontinuities are grouped in three main joint sets as follows. Joint sets 1 and 2 are mostly subvertical with dip from 75 to 85 degrees and are almost perpendicular sets of discontinuities, where the joint set 1 is almost parallel to the cliff face (mean dip direction of 5-10 or 190-205 degrees) while the joint set 2 is almost normal to the cliff face and just occasionally exposed (mean dip direction of 90-110 or 275-280 degrees). Joint set 3 presents bedding and it dips from NE (dip direction 0-25 degrees) to NW (dip direction 230-305 degrees), but these variations are caused by relatively gentle dip (15–30 degrees) and are highly dependent on measurement location. Detailed mean values of joint sets orientations and dip directions, discontinuity features and block volumes for each cliff zone are presented in Table 1.

Table 1. The mean values of joint sets orientations and dip directions, discontinuity features and block volumes for each cliff zone based on results of *in situ* traditional geological and geotechnical surveys, remote sensing survey and data analysis.

Zone	Joint set	Dip / Dip direction	Disc. spacing (cm)	Block volume (m^3)
Z I	JS 1	85/10	300-500	1.2-10.0
	JS 2	80/280	80-100	
	JS 3	30/305	50-200	
ZII	JS 1	85/190	>100	0.5-15.0
	JS 2	85/110	100-300	
	JS 3	25/25	50-200	
Z III	JS 1	75/205	50-300	0.01-18.0
	JS 2	80/110	20-300	
	JS 3	20/230	10-200	
Z IV	JS 1	85/10	50-300	0.03-25.0
	JS 2	75/280	50-300	
	JS 3	15/0	50-300	
Z V	JS 1	75/5	300-500	0.05-18.0
	JS 2	80/90	80-100	
	JS 3	20/10	50-200	

4 KINEMATIC ANALYSIS

When the structural model of the Raspadalica Cliff was established based on both traditional geological and geotechnical field survey and remote sensing analysis, it was possible to analyze causes of instability and detachment of rock blocks from the cliff face and initiation of rockfall occurrences. Although at first sight the structural elements of the Raspadalica Cliff didn't indicate the causes of the frequent rockfall initiation reported in the studied area, the deeper analyses point to causes of reasonable instability.

The structural model of the Raspadalica Cliff indicates very low probability of occurrence of the general circular failure through the rock mass, while the historical evidences pointed to rockfalls caused by detachment of a particular block or group of blocks. To identify possibility of failures associated with the present joint sets and their orientations, the kinematic analyses of plane, wedge and toppling failure mechanisms (Wyllie and Mah, 2004) were carried out based on joint sets discontinuity features data collected by both traditional geological and geotechnical field survey and remote sensing survey and data analysis. Kinematic analyses were carried out employing Rocscience *Dips* software (Rocscience, 2020). Exported data about discontinuity planes (facets) orientations (dip and dip directions) extracted using *Cloud Compare Facet* plugin were imported in *Dips* software and kinematic analyses were carried out for each type of failure mechanism.

The results of conducted analyses pointed to almost no probability of wedge failure because of almost orthogonal orientation of two subvertical joint sets (Join set 1 and 2), where the Joint set 1 is parallel to the cliff face. The remaining three analyzed failure mechanisms (plane, block or direct toppling and flexural toppling) (Wyllie and Mah, 2004), indicated the presence structural conditions likely to cause these failures in several parts of the cliff in all cliff zones but with relatively low probability of occurrence. Results of conducted analyses are presented in Figure 5 for Zone III, where the major rockfalls occurred in the past, for sliding and toppling failure mechanisms.

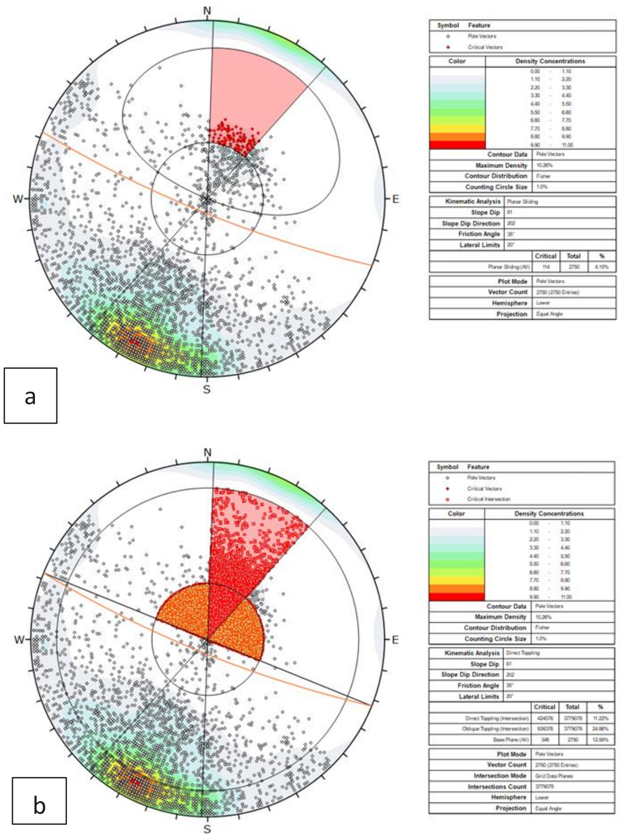

Figure 5. Results of conducted kinematic analyses for Zone III using Rocscinece *Dips* software.

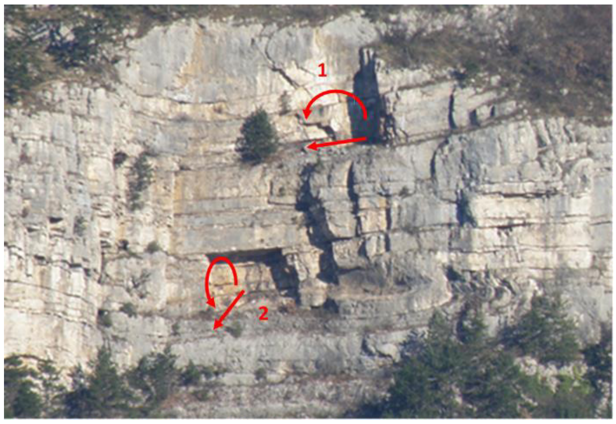

Figure 6. A view at the middle part of Raspadalica Cliff (Zone III) with two signs of the rockfall instability in the past (1,2).

To identify objective causes of instability initiation, more detailed analyses were directed to the microlocations at the cliff face from where the rock blocks were detached leaving clear signs and structural elements that impacted the instabilities. Analyzing several main signs of instability, it was found that they were caused by a combination of joint influence of the two instability mechanisms (sliding and toppling) at rock blocks at the cliff face, Figure 6.

Figure 6 presents a part of the Zone III in the middle part of the cliff. Instability 1 in the upper part of the cliff face was caused by joint influence of sliding and toppling mechanisms and both movements (displacement and rotation) were parallel to the cliff face. Stability analyses pointed on satisfying factor of safety (FoS) for each particular mechanism, and only a combination of mechanisms caused the rock block detachment. The instability 2 in the lower part of the cliff face was caused by joint influence of sliding and toppling mechanisms and both movements (displacement and rotation) were almost orthogonal to the cliff face. The bedding plane is to slightly inclined to cause block sliding, while the bed above the fallen block prevented rotation, but simultaneous action of two mechanisms enabled rockfall initiation.

These two joint mechanisms are associated with some other processes which had influences on weakening of joint friction forces caused by lateral stress relaxation, weathering and softening of joints infilling (coal interlayer) caused by freeze and thaw process, rock mass weathering processes, as well as caused by water (hydrostatic pressure of water in subvertical discontinuities, impact on reduction of effective stresses at bedding planes) and temperature impacts (pressure after water freezing in subvertical discontinuities, spreading and shrinking of rock mass during temperature effects of insolation).

5 ROCKFALL PROTECTION

Since the rockfalls threatened the railway route from the construction time, the necessity of railway route rockfall protection was identified very early after the start of the traffic. Rockfall events caused the Railways Technical Office to construct a 120 m long and 2 m high stone masonry wall in the foot of the cliff forming a ditch to retain detached rock mass in 1964. This wall had an important role in stopping the most of small detached blocks, but the bigger blocks and fragmented material bounced over the wall and reached the railway facilities. The rockfall mass in the February 1999 hit and completely destroyed the stone wall in its central part. This section was renewed by 5 m height embankment built from coarse stone debris material during 2000 and 2001. The last significant rockfall occurred on 16 December 2013 (Figure 3 and 7) that caused interruption of railway traffic for several months and it was followed by rockfall protection measures construction.

Figure 7. Digital orthophoto map of the western part of the Raspadalica Cliff. On the left side (red arrow) is location of the rockfall occurred on 16 December 2013 that destroyed stone masonry wall; on the right side (black arrow) part of stone embankment. Red lines are rockfall barriers installed above the railway facilities.

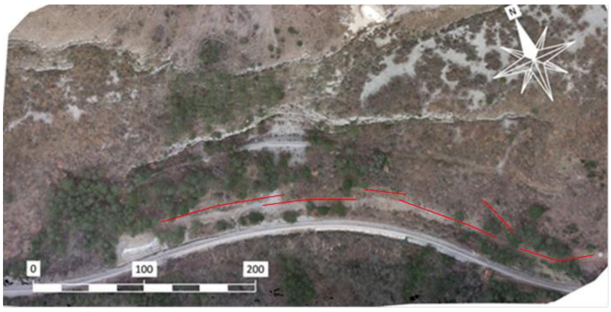

Figure 8. Locations of installed rockfall barriers (red lines) below the Raspadalica Cliff at the digital orthophoto map.

The rockfall barriers were designed (Grošić, 2012b) and installed in several segments above the railway facilities in total length of 400 m (Figure 8). The rockfall protection barriers were installed as it follows: one barrier 100 m length, 3 m height with energy absorption capacity of 1.000 kJ; one barrier 90 m length, 3 m height with energy absorption capacity of 500 kJ; and three barriers 60, 60 and 90 m length, 3 and 2,50 m height with energy absorption capacity of 250 kJ. All barriers were installed in the lower part of the slope, just above the tracks. In selection of barrier locations, height and energy absorption capacity, 2d and 3d block rockfall analyzes were not performed, and barrier locations were selected based on assumed rockfall trajectories based on historical occurrences. Preliminary analyses of the fall of the relevant volume block have shown that the barriers do not satisfy with their height and energy absorption capacity. The installed rockfall barriers definitely cannot retain bigger rockfall volumes, but for now successfully stops smaller running blocks.

6 CONCLUSIONS

This paper presents an analysis of the rock mass structure and causes of rockfall occurrences from the Raspadalica Cliff, Croatia, an almost vertical 100 m high limestone cliff located above the railway route in the foot, well-known by numerous rockfall occurrences in the past. The *in situ* traditional geological and geotechnical survey as well as remote sensing surveys were used to establish structural model of the cliff and to identify causes of numerous rockfall occurrences in the past that endangered railway route and caused significant damage as well as human injuries. Although the structural elements of the Raspadalica Cliff at first sight didn't indicate the causes of the frequent rockfall initiation that were reported in investigated area, the deeper analyses pointed to reasonable instability causes. Conducted kinematic stability analyses taking in account data obtained by *in situ* and remote sensing surveys showed importance of the joint influence of the two instability mechanisms (sliding and toppling) at rock blocks at the cliff face. These two joint mechanisms are associated with some other processes which had influences on weakening of joint friction forces caused by lateral stress relaxation, weathering and softening of joints infilling (coal interlayer) caused by freeze and thaw process, rock mass weathering processes, as well as caused by water and temperature impacts. Although there have been several attempts to protect the railway from landslides in the past, they do not provided adequate protection of the railway from falling rocks. The rockfall protection barriers installed in 2014 do not satisfy with their height and energy absorption capacity for relevant blocks determined by analyses described in this study. The adequate rockfall protection should be designed based on detailed identification of rockfall hazard and risk followed by 2D and 3D rockfall analyses to identify relevant trajectories of rolling blocks in accordance with the present conditions on the slope (shape of the blocks, restitution coefficients, impact of vegetation, etc.). It is likely that running blocks can be retained by rockfall protection barriers, but their height and energy absorption capacity must be significantly higher.

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