Design of the rockfall protection at the Špičunak location, Gorski kotar, Croatia

Maroje Sušac[(1)], Mirjana Vugrinski[(1)], Dalibor Udovič[(1)], Davor Marušić[(2)], Željko Arbanas[(3)]

1) Geolog savjetovanje Ltd, Samobor, Pod borom 3, Croatia, +385 91 4294 008 (maroje.susac@geolog.hr)

2) Terraforming Ltd., Rijeka, Croatia

3) University of Rijeka, Faculty of Civil Engineering, Rijeka, Croatia

Abstract The Špičunak location at the state road D3, near the Lokve settlement in the Gorski kotar region, Croatia, is well – known by numerous traffic interruptions caused by slide and rockfall occurrences. The rockfalls at the Špičunak location are mostly predisposed due to geological setting and heavy jointed rock mass in the road cut of approximately 180.0 m length and 23.0 m height. Structural and kinematic analysis of possible future rockfall were carried out following the modern approaches and recent techniques in rockfall hazard analysis. These 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 rock cut surface; engineering geological mapping using combination of remote-sensing techniques and field mapping. The three-dimensional high-resolution point cloud (3D HRPC) were established based on terrestrial laser scanning (TLS) and photogrammetry survey employing unmanned aerial vehicle (UAV) using *Structure form Motion* (SfM) technique. Based on established 3D models, the cut was analysed 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. 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 Rock Mass Rating (RMR) system and Geological Strength Index (GSI). Detailed analyses of field survey and remote sensing data pointed to three different zones, based on their properties and rock block standings according to the general orientation and dip of the cut face. To identify possibility of failures associated with the present joint sets and their orientations, the kinematic analyses of plane, wedge and toppling failure mechanisms 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. Based on the kinematic analyses results, adequate protection measures to prevent further brock block detachments and rockfalls were selected and designed. In this paper we will describe field investigation, establishing of the rock cut model based on remote sensing and traditional geotechnical investigations, stability analysis, as well as design element necessary for ensuring of stability of the rock mass in the cut and safety of the traffic along the road.

Keywords rockfall, rockfall protection, remote sensing, 3D modelling, kinematic analysis

Introduction

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

The Špičunak rock slope is located at the route of the State road DC3 (Rijeka – Zagreb), about 5 km south from the Lokve settlement, Fig. 1. The rock slope extends in the northeast-southwest direction and it was formed by cut excavation during the road construction in 1950's. The length of the investigated part of the cut is approx. 180.0 m, while its height at the highest part is up to 23.0 m, Fig. 2. The existing surrounding terrain has a general elevation of approx. 865.0 m a.s.l.

Problems due to sliding and rockfalls at the Špičunak location existed more than 50 years and caused numerous traffic interruptions. The road construction was repaired several times while the slide remediation was completed in 2021. Rockfall protection measures were applied to the rock cut several times, last time in 2005, according to then available techniques (Arbanas et al. 2012) and only to one part of the cut. Due to further rock mass weathering as well as freezing and thawing process, numerous rockfalls were triggered during winters followed by fallen blocks at

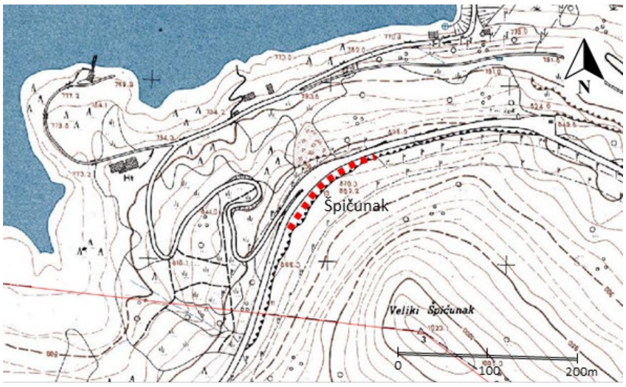

Figure 1 The map of the Špičunak location.


Figure 2 A view at the rock cut at the Špičunak location.

the road, indicating the need of new rockfall protection design and implementation which started in 2021.

Geological settings

The Špičunak rock slope is situated in the Gorski kotar region, south of the Lokve settlement, and the wider area of the investigated slope belongs to the structure of the Lokve Lake Dome, within the Gorski Kotar Structural Unit (Savić and Dozet 1989). The Lokve Lake Dome is built of Upper Cretaceous and Lower to Middle Permian clayey and sandy-conglomerate deposits, while the flanks are built of Upper Triassic dolomite and clastic deposits.

The slope at the location is composed of well-layered Upper Triassic dolomites of general north-south to northwest-southeast orientation, with a continuous dip of layers of 15-30 (40) ° to the west-southwest. Dominant joint systems are steep to subvertical, oriented N-S, NW-SE and W-E. One 30 m wide subvertical (108/87) shear fault zone (108/87) without pronounced vertical displacement was determined in the middle part of the slope. In the south-western part of the slope, a local steep fault (52/73) with approx. 0.5-2.0 m wide fault zone is registered.

Field investigation

In determination of the detailed geological structure of the rock cut at the Špičunak location, several campaigns of field investigations were carried out during the last decades. The last one carried out for the remedial measures and rockfall protection design was conducted using traditional methods of engineering geological survey and mapping combined with the remote sensing techniques based on Unmanned Aerial Vehicle (UAV) photogrammetry data (Froideval et al. 2019; Giordan et al. 2020; Antoine et al. 2020) and terrestrial laser scanning (Jaboyedoff et al. 2012)in combination with data collected by traditional survey (Francioni et al. 2019).

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 rock cut. Field investigations were combined with the study at the orthophoto (in scale 1:500) and 3D HRPC of about 35.6 million of points (Fig. 3) 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 rock cut, as well as to carry out a rock mass classification using Rock Mass Rating system (RMR) (Bieniawski 1989) and Geological Strength Index (GSI) (Marinos and Hoek 2000). In this study a combination of traditional geological and geotechnical field survey (Bolla and Paronuzzi, 2020) and remote sensing techniques are employed to geotechnical model of the Špičunak rock cut including 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 as well as representative block volumes for each of discontinuity sets (Palmstrom 2001).

Detailed analyses of field survey and remote sensing data pointed to three different zones, based on their properties and rock block standings according to the general orientation and dip of the rock cut face. These zones (Zone I to III) are presented at the 3D HRPC (Fig. 3) while the borders that separate zones were determined analysing changes in orientation and dips of the main joint sets as well as changes in rock block volumes. The *Cloud Compare* software (CloudCompare 2015) was employed to identify discontinuity sets. The rock cut face was divided in three zones (Fig. 3), 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 set necessary to determine block volumes was determined using the *Cloud Compare Distances* tool, while the persistence of joints in accessible rock cut face zones were measured *in situ*. The other discontinuity features (separation, infilling, discontinuity wall roughness and weathering grade) were obtained by *in situ* traditional geological and geotechnical surveys.

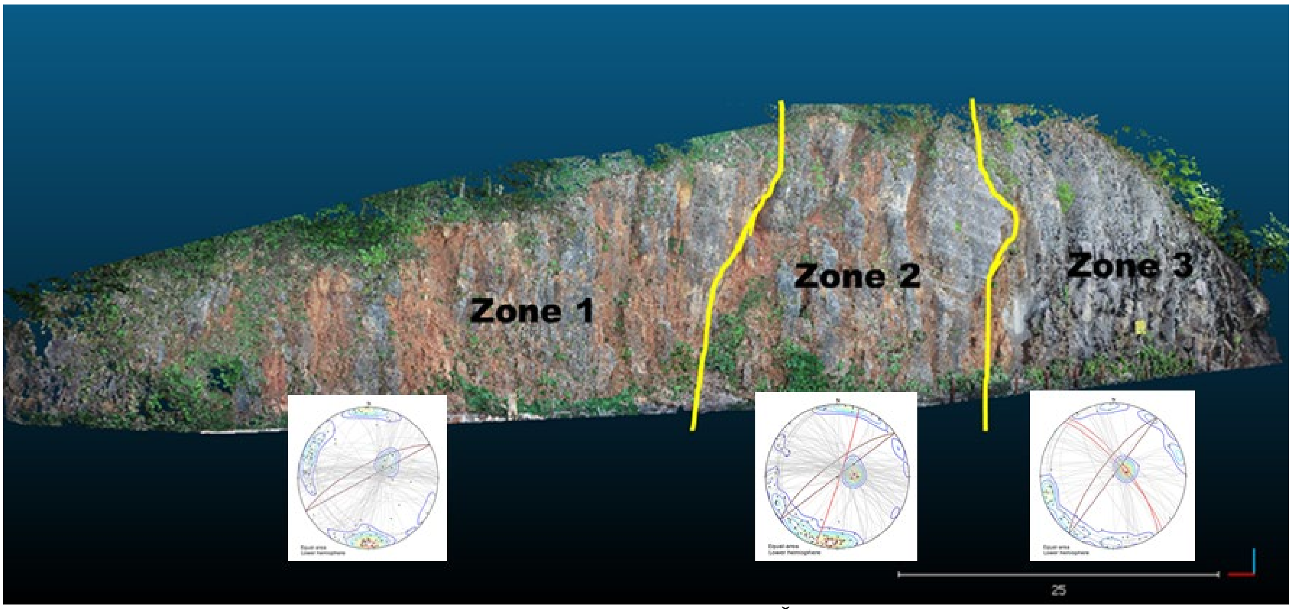

Figure 1 The three-dimensional high-resolution point cloud (3D HRPC) of the Špičunak rock cut with different zones and stereonet plots for each zone.

Geotechnical model

Based on previously described field and remote sensing investigations and analyses, a geotechnical model for each of determined geotechnical zones was established in order to conduct the necessary kinematic and slope stability analyses. In all of determined three geotechnical zones, three different geotechnical units (GU) were identified and presented in Tab. 1.

Talus deposits (GU 1) are present at the foot of the part of the rock cut, as a result of weathering of the dolomite rock mass. Significant accumulations of talus, which cover the toe of the investigated part of the cut, are up to 2.0 m, and are represented below the fault zones with pronounced shedding of highly weathered rock mass.

Highly to moderately weathered (HW/MW) dolomites (GU 2) are present along the slope within the fault zones, and extend from the bottom to the top of the cut due to subvertical faults extension. Within highly to moderately weathered (HW/MW) dolomites, the distance between discontinuities is usually small; from 6 to 20 cm. The roughness of the discontinuity walls is smooth. The discontinuity separation is open to medium wide (0.5-10.0 mm), in places wide (up to 10 cm), mostly filled with clay filling, while the interlayer separations are narrow (<0.25 mm) to partially open (0.25-0.50 mm). Persistence of discontinuities is long, >20m. The discontinuity systems represented mainly form polyhedral, rarely and equidimensional blocks, mostly small to medium in size (0.1-0.5 m³). The rock structure of highly to moderately weathered (HW/MW) dolomites is disintegrated (D) to blocky/disturbed (B/D) (Marinos and Hoek 2000). The RQD value as an indicator of the rock mass quality is estimated as 0-25% (very poor to poor). Laboratory tests determined a wide range of uniaxial compressive strength of intact rock mass; the interval of 45.0-53.0 MPa was adopted as representative value.

Table 1 Description of geotechnical units (GU).

Geotechnical unit	Geotechnical description
GU 1	Talus, gravelly clay and poorly graduated clayey gravel with pebbles and blocks.
GU 2	Highly to medium weathered (HW/MW) dolomites, medium to high compressive strength, layered, disintegrated to a blocky/disturbed structure.
GU 3	Slightly weathered (SW) dolomites, medium to high compressive strength, layered, blocky/ disturbed to very block-like structure.

Slightly weathered (SW) dolomites (GU 3) are present along the slope at the initial (Zone 1) and final part (Zone 3) of the investigated rock cut and are locally interrupted by fault zones with highly to medium weathered (HW/MW) dolomites. Within the slightly weathered (SW) dolomites, the distance between discontinuities is usually small to medium, 6-60 cm. The roughness of the rock discontinuity walls is predominantly smooth. The discontinuity separation is mostly partially open to medium wide (0.5–10.0 mm), predominantly fulfilled with clay filling and partially without infilling, while the interlayer separations are narrow (<0.25 mm). Persistence of discontinuities is long, >20m. The discontinuity systems represented mainly form polyhedral to equidimensional blocks; small to large in size (0.2-1.0 m³). The rock structure of weakly dilapidated dolomite is blocky/disturbed (B/D) to very blocky (B)(Marinos and Hoek 2000). The RQD value as an indicator of the rock mass quality is estimated as 25-50% (poor). The uniaxial compressive strength of intact rock mass is identical for

GU 2 and GU 3; interval of 45.0-53.0 MPa was adopted as representative value.

Based on the results of the traditional geological and geotechnical field surveys, as well as the remote sensing survey and data analysis, the geotechnical model of the Špičunak rock cut was established, which presented the main recognized joint sets, their orientations, and all other discontinuity features that are important for conducting stability analyses and identification of the causes of rockfall occurrences. For each of the identified zones, the mean values of joint set orientations and dip directions, as well as other discontinuity features were determined. According to the identified discontinuity features, the Geotechnical rock mass classification (Rock Mass Rating, RMR) (Bieniawski 1989) was determined and the mean RMR values were calculated for each cut zone. The mean descriptions and values of weathering grade, block volumes and RMR for each cut zone are presented in Tab. 2.

Stability analyses

After establishing of the geotechnical model of the Špičunak rock cut, as well as determination of geotechnical parameters necessary for slope stability analyses (RMR and uniaxial compressive strength), slope stability and kinematic analyses were conducted for each zone of the cut. Stability analyses of the cut in all three zones conducted using *RocScience Slide2* software (Rocscience 2021) pointed on acceptable values of factors of safety (FoS) in all three zones of the cut (FoS > 1.7) that is confirmed with the fact that the Špičunak rock cut has been globally stable during the last 70 years, while the instabilities mostly occurred as local detachments of individual rock blocks or several blocks from the cut caused by local planar, wedge or topple failures. This fact implied on necessary kinematic analyses to identify present rockfall susceptibility.

Kinematic analysis

Once the geotechnical model of the Špičunak rock cut was established based on the traditional geological and geotechnical field surveys and remote sensing analysis, it was possible to analyze the causes of instability and detachment of rock blocks from the cut face and the initiation of rockfall occurrences. To identify possibility of failure associated with the existing joint sets and their orientations, kinematic analyses of plane, wedge and toppling failure mechanisms (Wyllie and Mah 2004) were performed based on the data of the joint set discontinuity features collected along the rock cut. Kinematic analyses were performed for each rock cut zone employing the *RocScience Dips* software (Rocscience 2021). For each cliff zone, the exported discontinuity plane (facets), orientation (dip and dip directions) data extracted using the *Cloud Compare Facet* plugin (CloudCompare 2015)

Table 2 Description of zones of the Špičunak rock cut with descriptions and values of weathering grade, block volumes and RMR.

Rock Cut Zone	Weathering Grade	Block Volume	RMR
Zone 1	SW/MW	0.2-1.0 m^3	41
Zone 2	HW/MW	0.1-0.5 m^3	37
Zone 3	SW/MW	0.2-1.0 m^3	40

were imported into the *RocScience Dips* software, and kinematic analyses were performed for each type of failure mechanism. The results of kinematic analyses are presented in Fig. 4.

The analyses were conducted for each cut zone as it follows:

In Zone 1, analyses were conducted for 296 discontinuities that daylighting in the rock face analyses at dip and dip orientation of 76/330°. The results pointed on probability of 45.27% for planar failure, 51.16% for wedge failure and 53.38% for toppling.

In Zone 2, analyses were conducted for 515 discontinuities that daylighting in the rock face analyses at dip and dip orientation of 82/315°. The results pointed on probability of 31.65% for planar failure, 47.66% for wedge failure and 41.94% for toppling.

In Zone 3, analyses were conducted for 364 discontinuities that daylighting in the rock face analyses at dip and dip orientation of 88/275°. The results pointed on probability of 16.15% for planar failure, 33.41% for wedge failure and 33.33% for toppling.

The results of kinematic analyses are expressed as probability occurrence for any of possible failure mechanisms (planar sliding, direct toppling and flexural toppling; wedge failure was excluded because of very low probability of occurrence). Probability is expressed as the ratio of number of planes (or combination of planes) meeting the conditions for a failure related to the number of all planes (or combination of planes). An expression of probability of failure occurrence was presented as kinematic hazard index (KTI) by Casagli and Pini (1993), as a number of failures meeting kinematic conditions of failure relative to total number of possible failures. Here is applied the same approach, but the probability is related to each failure mechanism separately. As the temporal component of rockfall occurrences is not included, the calculated probabilities indicate on rockfall susceptibility rather than rockfall hazard.

The results of the analyses indicated a nearly high probability of all three failure mechanisms, that it was expected according to hard jointed rock mass and relatively small volumes of rock blocks at the cut face. The results and rock mass structure in all three zones of the cut, indicate on an approach that will include protection of the entire rock cut face and does not consider measures to support individual blocks at the slope, except in Zone 3, where bigger rock blocks are present.

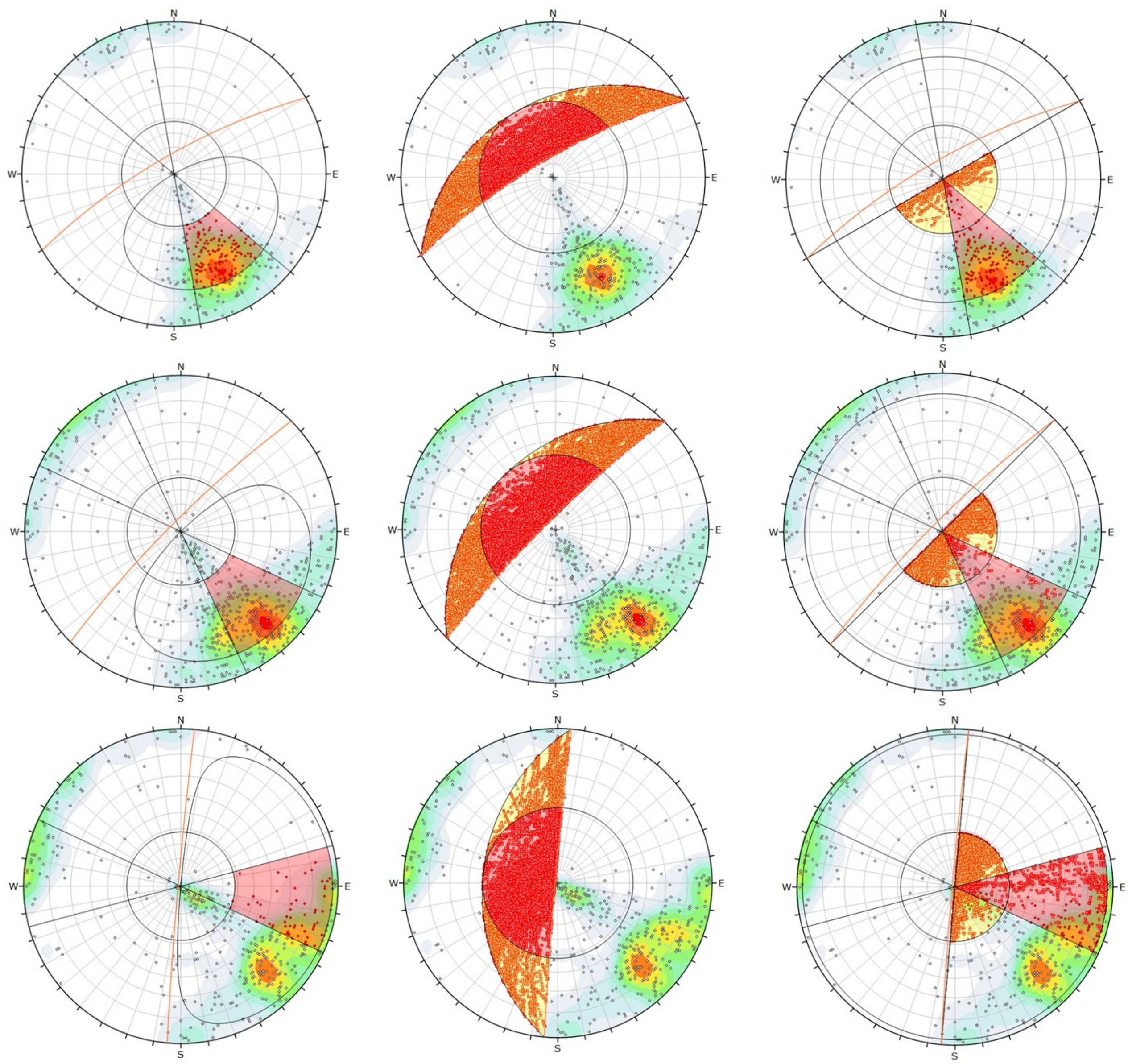

Figure 4 Kinematic analyses of the Špičunak rock cut by cut zones according to planar sliding, wedge and direct toppling, conducted using *Rocscience Dips* software. The results are presented in rows for each zone (e.g., Zone Z1 is in the first row). The results of planar sliding are in the first column, wedge failure in the second column, and direct toppling in the third column.

Slope protection systems

According to the results of slope stability and kinematic analyses, as well as rock mass structure in the cut, rockfall protection measures were designed. Two design approaches were considered (Arbanas et al 2012): (i) the prevention of rockfalls by removing potentially unstable rock mass or by installing rock mass support systems and (ii) the reduction of rockfall mass energy and suspension of running rockfall mass using rockfall protection diches, walls or barriers (Volkwein et al 2011). After analyses of technical and economic aspects of possible remedial and protection measures, application of rock mass support system in combination with rockfall protection walls in the foot of the cut was selected.

In Zone 1, with the lowest cut heights and relatively distant from the road, the rock cut protection is designed using rockfall protection fences that enable detachment of small blocks and their fall to the slope toe, but without reaching the road. In Zone 2, where the rockfall hazard and a possibility that detached running blocks reach the road and endanger vehicles, the support system consisted of rockbolts and multi-layered reinforced shotcrete that will cover overall cut face was designed. Rockbolts designed on a raster of 3.0 x 3.0 m, lengths of 6.0 and 9.0 m, and bearing capacity of 240 kN in combination with two-layered shotcrete lining will have significant impact on complete prevention of further rockfall occurrences as well as an increasing of global slope stability, Fig. 5.

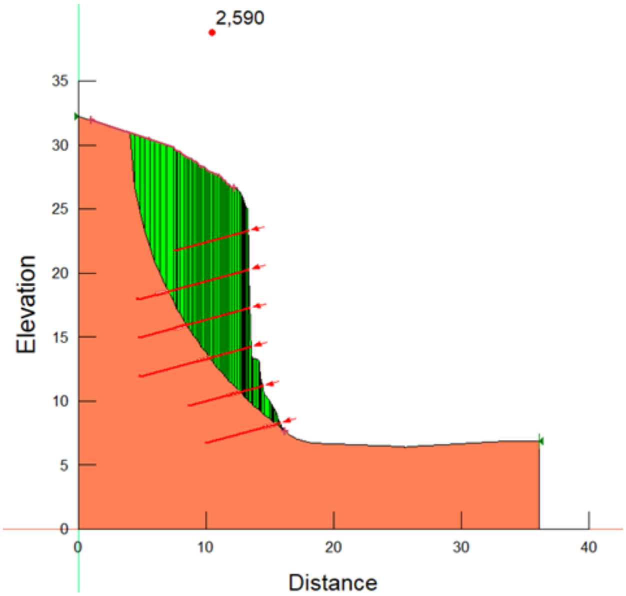

Figure 5 Results of global rock cut stability analysis with applied slope protection measures in Zone 2, conducted using *RocSlide* software.

In Zone 3, where the kinematic analyses indicate the lowest probability of rockfall occurrences, but with the biggest rock blocks in the cut and closest to the road, a combination of individual rock blocks support by rockbolts, support system consisted of rockbolts and multi-layered reinforced shotcrete and protective gabion wall along the road edge was designed.

Application of these rockfall measures at the Špičunak rock cut will practically completely eliminate further rockfall hazard in Zone 2 and 3, while the further rockfall processes associated with rock mass weathering process, rinsing of the discontinuity infilling related to freezing and thawing processes as well as temperature effects on rock mass, will take place in Zone 1. Anyhow, engineering judgment and analyses indicated on acceptable rockfall risk and rockfall protection using protection fences was adopted as an adequate and economically justified protection measure.

Acknowledgments

The part of this research is carried out in the frame of the UNIRi Project uniri-tehnic-18-276-1448 Research of Rockfall Processes and Rockfall Hazard Assessment supported by University of Rijeka, Croatia. This support is gratefully acknowledged.

References

Antoine R, Lopez T, Tanguy M, et al (2020) Geoscientists in the Sky: Unmanned Aerial Vehicles Responding to Geohazards. Surv Geophys 41:1285–1321. https://doi.org/10.1007/s10712-020-09611-7

Arbanas Ž, Grošić M, Udovič D, Mihalić S (2012) Rockfall Hazard Analyses and Rockfall Protection along the Adriatic Coast of Croatia. JCEA 6:344–355. https://doi.org/10.17265/1934-7359/2012.03.008

Bieniawski ZT (1989) Engineering Rock Mass Classifications A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering. Wiley-Interscience, New York

Casagli N; Pini G (1993) Analisi cinematica della stabilità di versanti naturali e fronti di scavo in roccia. Geologia Applicata e Idrogeologia. 1993, 28 223–232 (in Italian).

CloudCompare (2015) User manual. (http://www.cloudcompare.org) (last accessed 30 January 2022)

Dewez TJB, Girardeau-Montaut D, Allanic C, Rohmer J (2016) Facets: A CloudCompare plugin to extract geological planes from unstructured 3D point clouds. Int Arch Photogramm Remote Sens Spatial Inf Sci XLI-B5:799–804. https://doi.org/10.5194/isprs-archives-XLI-B5-799-2016

Dorren LKA (2003) A review of rockfall mechanics and modelling approaches. Progress in Physical Geography: Earth and Environment 27:69–87. https://doi.org/10.1191/0309133303pp359ra

Francioni M, Calamita F, Coggan J, et al (2019) A Multi-Disciplinary Approach to the Study of Large Rock Avalanches Combining Remote Sensing, GIS and Field Surveys: The Case of the Scanno Landslide, Italy. Remote Sensing 11:1570. https://doi.org 10.3390/rs11131570

Froideval L, Pedoja K, Garestier F, et al (2019) A low-cost open-source workflow to generate georeferenced 3D SfM photogrammetric models of rocky outcrops. Photogram Rec 34:365–384. https://doi.org/10.1111/phor.12297

Giordan D, Adams MS, Aicardi I, et al (2020) The use of unmanned aerial vehicles (UAVs) for engineering geology applications. Bull Eng Geol Environ 79:3437–3481. https://doi.org/10.1007/s10064-020-01766-2

Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide types, an update. Landslides 11:167–194. https://doi.org/10.1007/s10346-013-0436-y

Jaboyedoff M, Oppikofer T, Abellán A, et al (2012) Use of LIDAR in landslide investigations: a review. Nat Hazards 61:5–28. https://doi.org/10.1007/s11069-010-9634-2

Marinos P, Hoek E (2000) GSI: A Geologically Friendly Tool For Rock Mass Strength Estimation. ISRM International Symposium, Melbourne, Australia, November 2000 19

Nagendran SK, Mohamad Ismail MA, Wen YT (2019) Photogrammetry approach on geological plane extraction using CloudCompare FACET plugin and scanline survey. BGSM 68:151–158. https://doi.org/10.7186/bgsm68201916

Palmstrom A (2001) Measurement and Characterization of Rock Mass Jointing. In: Sharma, V.M. and Saxena, K.R., Eds., In-Situ Characterization of Rocks, A.A. Balkema Publishers, London, 97

Ritchie AM (1963) Evaluation of Rockfall and Its Control. Highway Research Record 17:13–28

Rocscience (2021) (http:// www.rocscience.com/software) (last accessed 30 January 2022)

Savić D, Dozet S (1989) Basic geological map scale 1:100 000, (Sheet Delnice). Institute for geological research, Zagreb.

Siddique T, Pradhan SP, Vishal V (2019) Rockfall: A Specific Case of Landslide. In: Pradhan SP, Vishal V, Singh TN (eds) Landslides: Theory, Practice and Modelling. Springer International Publishing, Cham, pp 61–81

Volkwein A, Schellenberg K, Labiouse V, et al (2011) Rockfall characterisation and structural protection – a review. Nat Hazards Earth Syst Sci 11:2617–2651. https://doi.org/10.5194/nhess-11-2617-2011

Wyllie DC, Mah CW (2004) Rock Slope Engineering: Civil and Mining, 4th Edition. Spon Press 456