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Rockfall simulation on a rock slope along E75 road at km 890+725 to 891+093

ABOLMASOV Biljana[1], MARJANOVIĆ Miloš[1], MILENKOVIĆ Svetozar[2], PEJIĆ Marko[3], BERISAVLJEVIĆ Zoran[4]

[1] PhD, University of Belgrade, Faculty of Mining and Geology, Đušina 7, Belgrade, Serbia; biljana.abolmasov@rgf.bg.ac.rs
[2] M.Sc., Highway Institute Belgrade, Kumodraška 257, Belgrade, Serbia;
[3] PhD, University of Belgrade, Faculty of Civil Engineering, Bul. Kralja Aleksandra 73, Belgrade, Serbia;
[4] PhD, Koridori Srbije d.o.o., Kralja Petra 21, Belgrade, Serbia

Abstract. The section of E75 motorway under construction was subjected to simulation of potential rockfall hazard. 3D point-cloud surface model of the rock slope, obtained by a combination of LiDAR and UAV techniques, was used for mapping of discontinuities, their orientation and spacing. These were inputs for appropriate slope stability analyses, which were further used do delineate potential depletion zones or rockfall block sources. Once delineated, source zones were used to simulate 3D rock trajectories over 3D surface slope model, for various block sizes. All trajectories were compared and evaluated for their potential impact on the viaduct setting, based on their spatial propagation, kinetic energies and forces, bouncing heights etc. Finally, according preventive measures for rockfall hazard mitigation were proposed.

Keywords: Rock slope, Rockfall simulation, RAMMS, LiDAR scanning, UAV photogrammetry

1 INTRODUCTION

The detailed 3D characterization of the site topography is critical to many geotechnical studies of slope stability. The brief review of on-site characterization of rock slopes by 3D laser scanning technology that is followed herein, is well presented in Feng and Röshoff (2015). Terrestrial LiDAR measurements have been used for numerous slope and rock cut stability assessments as discussed in Abellan et al. (2010), Armesto et al. (2009), Baldo et al. (2009), Dunning et al. (2009), Lato et al. (2009a), Lato et al. (2009b), Sturzenegger and Stead (2009) and Sturzenegger et al. (2011). Nowadays, this is a well-recognized technology for rock slope stability analysis.

Route E75 is one of the main European corridors (Corridor 10), which traverses Serbia from Hungarian border on the north, to Macedonian border on the south. The most of the E75 rout through Serbia is a full profile highway, except for about 25 km in Grdelica gorge (the southern Serbia). Full profile construction along this part is currently underway, and one of the critical points is certainly zone of fomer Momin Kamen quarry. In this paper, results of TLS and UAV survey and rockfall simulation in RAMSS software package of the Momin Kamen site is presented

2 METHODOLOGY

2.1 Field investigation

Geodetic survey of the study area was performed by two methods: Terrestrial Laser Scanning (TLS) and photogrammetric survey by Unnamed Automatic Vehicle (UAV). Two types of TLS were used: mid-range Leica P20 and long-range Leica Nova. Recordings and additional information were geo-referenced to the official coordinate system of the motorway based on the total of 13 orientation points. The rock slope was scanned from 8 basic and 5 auxiliary positions and more than one billion points within the resulting point cloud were collected. Photogrammetric survey was performed from drone platform Leica Aibot X6. Total of 1712 digital recordings in 16 Mpix resolution, taken by calibrated Coolpix A camera and 18.5 mm lenses were collected. Digital Terrain Model (DTM) and orthophoto were created based on 56 million generated 3D points.

Engineering geological field mapping was performed in section that was physically accessible. The mapping encompassed defining of the joint system, i.e. parameters of joint sets and individual joints, as well as the mode and degree of fracturing. Also, in-situ determination of axial compression strength of joint walls was performed on physically accessible slopes by use of Schmidt hammer.

2.2 Geotechnical characterisation of rock mass

Geotechnical characterization of the rock mass included engineering geological model of discontinuities according to the geometric and kinematic joint parameters, geotechnical classification of rock mass within engineering-geological homogenous zones and kinematic analysis, in order to ascertain possibility of block sliding, wedge sliding or toppling. At the same time, the classification of the rock mass according to RMR (Bieniawski, 1989) and Geological Strength Index (GSI) was done and was given for each assigned engineering geological homogenous zone. Kinematic analysis was performed to determine possibility for block sliding, wedge sliding or toppling, within the COLTOP 3D software package, over point clouds obtained by TLS. Orientation of joint sets have been defined directly on the point cloud, semi-automatically, per separate sections. The sections were separated vertically in relation to the azimuth of certain facets of the slope.

2.3 Slope stability modelling

Slope stability analysis was done for the three representative cross-sections. Numerical modelling was performed by Finite Element Analysis using Phase2 8.008 software. Shear Strength Reduction (SSR) method was used to determine Strength Reduction Factor (SRF) of the slope which is equivalent to safety factor (F_s) in traditional limit equilibrium methods. Analysis was done with 500 element mesh, whereas the state of stress was simulated with tolerance of 0.001, with maximum iteration number 1000. Non-linear empiric Hoek-Brown failure criterion was used in calculations.

2.4 Rockfall analysis in RAMMS®

Rockfall simulations were performed in RAMSS Rockfall 1.6.43 software (Christen et al., 2012), based on the physics of a rigid body with hard unilateral constraints and necessary spatial data layers were produced in GIS environment. Input data were based on the survey performed by Leica Aibot X6 drone and appropriate camera and data from DTM with 11 cm resolution, obtained by decimating original point cloud.

Starting point for simulation set-up were data obtained by engineering geological field mapping and 2D stability analyses, which relate to possible rockfall source areas in which the kinematic status (spatial position of joint sets) and/or degradation of rock mass are indicative of possible instabilities. By measuring the block sizes within each individual section (measuring was performed on the point cloud from TLS, with 5 cm resolution) and assessing the degree of weathering, the four cube-shaped blocks dimensions were identified: small (side a=0.1-0.3 m), medium (a=0.5 m), large (a>1 m) and extremely large (a>2 m).

For all groups of blocks separate simulations were done and the following was adopted:

- Rock mass has been separated to: hard base rock, medium hard detritus on slope shoulders of old quarry, and medium soft fill material in the viaduct construction stage, so that possible ground damping during block rebound can be taken into account

- The block shape is cuboid
- Vegetation was delineated in parts which have a density of 20 m/ha, to account for its effect on deceleration of blocks
- Sampling for simulation within individual zones is done every 3 m in a squared grid.

Each simulation included determination of trajectory, kinetic energy along the trajectory as well as rebound height and velocity of detached block along the trajectory, i.e. at each 0.1 ms time increment of its path. As previously stated, simulation could not be used to determine eventual fragmentation of rock mass after ground contact, but it can be assumed that it should be on the safe side, as somewhat more favorable scenario is when a bigger blocks shatter into smaller fragments (the reach is longer but it has considerably less energy).

3 CASE STUDY

Study area is located on the south of Serbia, approx. 320 km from Belgrade, close to the Macedonian border in the zone of the former Momim Kamen quarry. The study area is currently in the zone of intense construction activities for E75 motorway. Site morphology changes daily because of excavation and filling. Local morphological characteristics of the study area are mainly the result of dacite quarry excavation works from the end of XIX century (1883) until recently. Terrain altitude varies from 310 m.a.s.l. to 450-540 m.a.s.l. Height of the rock slopes locally exceed 150 m and slope gradient varies from sub-vertical (km 890+725 to km 890+900) to 45^{o} in lower parts of the rock face.

A geological setting of the investigated area has relatively simple lithological composition represented by a biotite-dacite and subordinately dacite-andesite of the Džep River (Basic Geological Map 1:100 000, sheet Vlasotince K34-45). Dacites are the result of tertiary volcanism and were most probably intruded along the axis of south Morava sinclinorium, as a dominant regional tectonic structure. North and south borders are in tectonic-fault contact with Serbian-Macedonian Paleozoic shales. From the geotechnical point of view, structure of the Momin Kamen dome is important for understanding of the paleo stress axes and genesis of the dome itself, which had a consequence of specific local structural composition, i.e. primary fracturing of rock mass – radial and spherical joint sets distribution.

4 RESULTS AND DISCUSSION

Several engineering-geological homogenous zones (which were subsequently subjected to geotechnical classification of rock mass) were identified in the study area. Estimated values of basic physical-mechanical parameters, RMR and GSI classifications for Zone 1 (as an example) are given in Tables 1, 2, and 3 respectively.

Table 1. Adopted values of basic physical-mechanical parameters

Unit weight γ (kN/m^3)	Monolith compressive strength σ_p (MPa)	Angle of internal friction φ (^{o})	Cohesion c (MPa)	Elasticity module E (MPa)
26	80	55	1.5	12000

Table 2. RMR Classification of rock mass

Classification parameters	σ_p (MPa)	RQD (%)	Joint spacing	Joint characteristics	Groundwater	Joint orientation
	100-250	90-100	0.6-2.0		Completely dry	Good
Number of points	12	20	15	25	15	-25

Table 3. RMR and GSI classification

Total RMR points	Excavation class	Description	GSI
62	II	Favorable rock	60-70

Kinematic analysis was performed on the point cloud obtained by scanning in required resolution (5 cm). First, the vegetation was removed from the point cloud by CANUPO filter in Cloud Compare software package. Semiautomatic and automatic mapping of joint planes was done separately per each section, and sections were separated vertically, depending on the slope face orientation (Fig. 1). Five sections were separated in the study area. Results of kinematic analysis for individual sections and positions of potentially unstable blocks satisfying any of the kinematic failure conditions (block sliding, wedge sliding, toppling) is given on the point cloud obtained by photogrammetric survey with RGB values. Slope stability analysis was performed for representative cross section (Fig. 2).

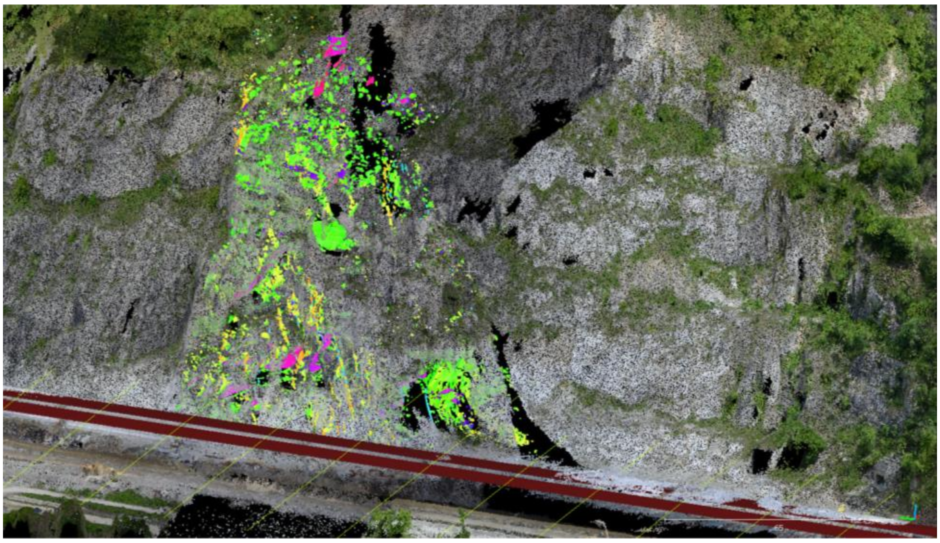

Figure 1. Screen shot of the joint sets and their planar daylights on point cloud with RGB values, section 4

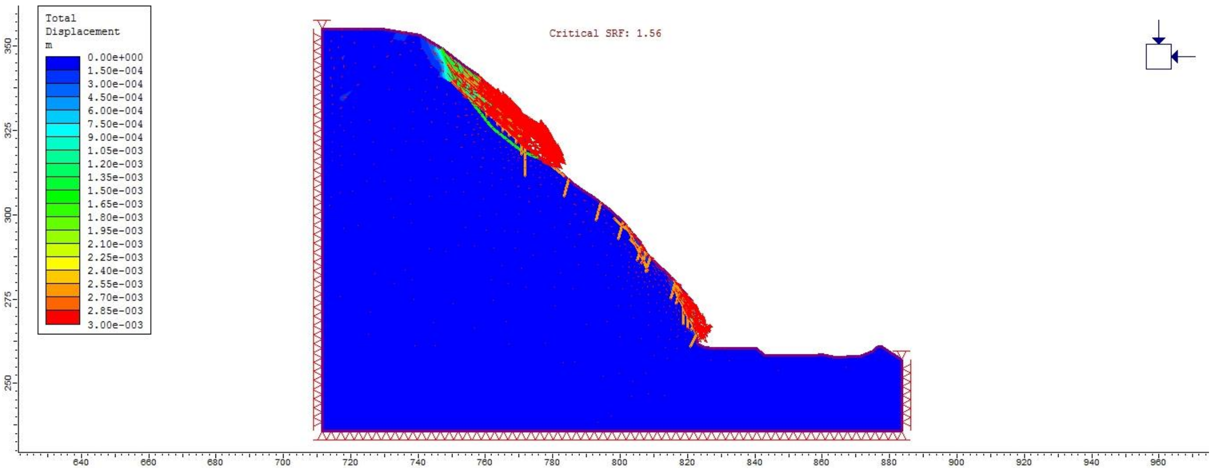

Figure 2. Slope stability analysis for cross section 202

Based on the stability analysis of three characteristic cross-sections (Fig. 2), it was concluded that the slopes are generally stable. However, there is a possibility of detaching of individual blocks (sliding or toppling) along registered joint sets.

a selection of computer simulations from potential source areas was performed to determine the rockfall vulnerability. Fifteen source areas were identified in the study area. Each simulation included determination of trajectory, kinetic energy along the trajectory, as well as rebound height and speed of blocks along the trajectory. Example in Figure 3 shows plan simulation for rockfalls of blocks >1 m^3 from appropriate source areas on 2.5D terrain model (DTM). Based on the performed analyses it can be concluded that smaller cuboid blocks 0.001 to 0.03 m^3 (a=0.1-0.3 m) from hypsometrically highest source areas, and which are relatively close to the viaduct route have the potential to reach the viaduct. However, the rebound heights at the level of the viaduct are small, i.e. superficial rolling of the blocks is prevalent. Similar relations are kept in the case of medium blocks (a=0.5 m, 0.125 m^3). Simulation was also performed for block sizes > 5 m^3 (a=2 m), only from the source areas which are closest to the viaduct line, primarily for the purpose of analysis of potential vulnerability of viaduct pillars. The analysis shows that, as expected, the reaches are shorter, as well as the rebounds, meaning that rolling is prevalent in the viaduct zone.

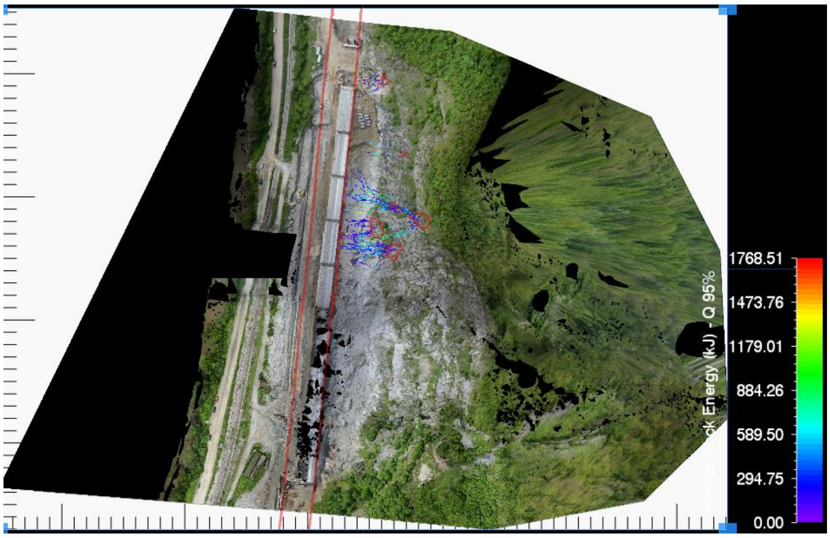

Figure 3. Simulation of potential kinetic energy of blocks >1 m^3 from potential source areas

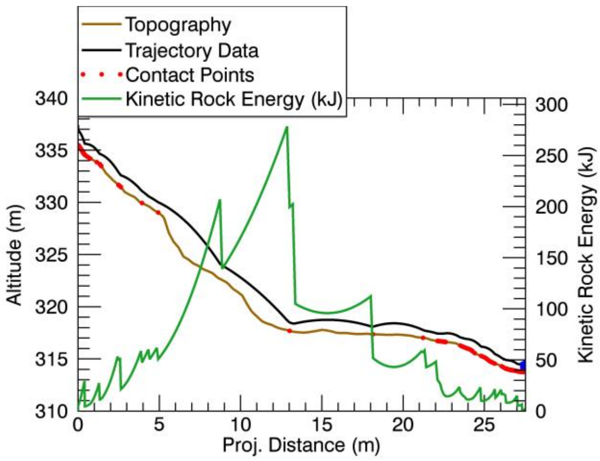

Figure 4. Illustration of trajectory 73 and kinetic energy of potentially unstable block >1 m^3 (pillar 1)

5 CONCLUSION

This article examples the application of LiDAR and UAV data in rockfall analyses in combination with conventional geotechnical approach. Simulations from potential detachment source areas for various dimensions of cuboid blocks have shown that even for the greatest volume blocks, the energy dissipation completes outside of the level of the already built viaduct, while the rebound heights in the structure zone are below the level of the viaduct, meaning that rolling under the viaduct prevails in the zone of the structure. Critical trajectories of blocks greater than 1 m^3 which reach viaduct pillars at the part of the route where the structure is physically closest to the rock face have been additionally analyzed.

It is recommended to erect protective netting which would guide potential downhill-moving fragments in cases of block detachment, which would reduce their rebound potential. This would apply to blocks of smaller dimensions as well as block which would probably emerge as secondary ones – by fragmentation of blocks of larger dimensions following their first contact (impact) with the ground. It is also recommended to construct an embankment of local quarry material with gradient towards the slope along the entire viaduct section as a protective system for viaduct pillars.

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