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Protection of the City of Omiš, Croatia, from rockfall threats

Željko Arbanas[1], Marin Sečanj[2], Martina Vivoda Prodan[1], Sanja Dugonjić Jovančević[1], Josip Peranić[1], Sanja Bernat Gazibara[2], Martin Krkač[2], Dalibor Udovič[3], Snježana Mihalić Arbanas[2]

1) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matejčić 3, zeljko.arbanas@gradri.uniri.hr

2) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Croatia

3) Monterra Ltd., Rijeka, Croatia

Abstract The City of Omiš, is situated in the middle part of the Croatian Adriatic coast, at the mouth of the Cetina River in the toe of high limestone cliffs and it is very exposed to high rockfall hazards. The old center of the City of Omiš was threatened by numerous rockfalls in the past that caused significant damages at residential structures and infrastructure. During the last decades several designs of rockfall protection structures were conducted, followed by installation of protection structures from 2016 to 2018. During the final design phase in 2016, the detailed field investigation was carried out using field and remote sensing methods to identify rockfall sources as well as endangered zones of the city. Based on field investigation data, 2D and 3D numerical modelling and rockfall simulations were performed to define adequate rockfall protection structures and their locations at the slope. Installed stabilization and protection structures (protection wire fences, wire meshes reinforced by steel ropes and rockbolts, and rockfall barriers) represent the first stage of mitigation measures, while the rockfall risk originating from rockfalls sources in upper parts of the slope should be mitigated in the future. In this paper the methods of field and remote sensing investigation of the slopes, identification of rockfall sources, modelling and simulation of rockfall propagation, as well as selection of protection measures and their positions at the slope above the City of Omiš will be presented. The necessity of further mitigation measures from possible rockfalls that can detach from the upper parts of the slope will be explained based on identified rockfall sources and carried out 3D simulations of rockfall propagation.

Keywords rockfall, rockfall hazard, modelling, rockfall protection, rockfall barriers

Introduction

Rockfalls are the most frequent and dangerous rock movements in mountainous zones, generating high economic and social damages (Emmer, 2018). The danger is mainly caused by the high speed of the falling rock blocks that is very difficult for any fast response (Dorren, 20103).

Figure 1 A view at the City of Omiš and limestone slopes above the town.

The City of Omiš, Croatia, was threatened by numerous rockfall occurrences in the past that caused significant damages at residential structures and infrastructure (Arbanas et al., 2019). The old town of Omiš, is situated in the middle part of the Adriatic coast, at the mouth of the Cetina River in the toe of high limestone cliffs (Figure 1) and it is very exposed to high rockfall hazards. The rockfall events along the limestone slopes were caused by unfavorable rock mass characteristics, rock mass weathering in combination with heavy rainfalls and the man-made influences (Arbanas et al., 2012).

During the last decade more rockfalls that damaged residential houses were registered, as well as numerous rockfalls that reached roads, streets in the town and courtyards without any significant consequence. Unfortunately, there is no rockfall inventory or statistical data about the rockfall volumes, but from the documented data it was found the most usual rockfall volumes were from 0.1 to 5.0 m^3. Although all of these rockfalls can be classified as a small, the risk caused by their direct impact on residential houses and infrastructure is very high. Several blocks of a volume of 1.0 to 3.0 m^3 fallen from the cliffs hit directly in the houses and came through the roofs and construction in the past (Figure 2) without any injured

Figure 2 Fallen rock block came through the roof in the house in January 2012 (www.24sata.hr).

and human victim. These occurrences pointed on necessary rockfall hazard and risk analyses and rockfall protection measures from rockfall threats.

The administration and government of the City of Omiš started with rockfall protection measures design in 2008. In period from 2008 to 2012 several preliminary and main designs for rockfall protection measures were completed for 22 identified potentially dangerous location that included several potentially unstable blocks (source zones) at the slopes above the town as well as the zones that could be reached by rockfall mass. Based on these analyses, rockfall protection measures were designed. Two design approaches (Arbanas et al., 2012) were adopted: (i) the prevention of rockfalls by installing rock mass support systems and (ii) the reduction of rockfall mass energy and suspension of running rockfall mass using rockfall protection barriers.

Study Area

The City of Omiš is a small historical town known form Roman time and started to develop at the mouth of the Cetina River in 12 and 13 century when most of old fortress were built. The old town is located in the toe of the mountain Omiška Dinara.

The Omiška Dinara Mountain is spreading over 15 km along the Adriatic coast with the highest peak at 865 m a.s.l. It is a part of a large nappe system and it is represented as an overturned anticline striking NW–SE that is the result of compressional tectonics occurred from Cretaceous to Miocene. The core of the anticline is built of Senonian rudist limestones, while the limbs of the anticline are built of Eocene breccia, limestones and flysch (Marinčić et al. 1977).

In the wider area of the City of Omiš, geological contacts between Cretaceous and Paleogene deposits are usually along steep reverse faults, striking E–W, with the tectonic transport top to south. Complexity of the geological-structural setting, caused by faulting and folding led to the formation of numerous discontinuities in rock mass. Progressive weathering of discontinuities led to the formation of unstable rock blocks with unfavorable orientation that are prone to rock falls (Sečanj et al., 2017; 2019).

The slopes directly above the City of Omiš spread over the area of around 0.15 km2, with the highest peak at app. 300 m a.s.l. Slopes in the area are very steep, with an average dip mostly over 60°, only locally transected by natural berms in the relief. Numerous sets of discontinuities with unfavorable orientation forming potentially unstable rock blocks were determined by field mapping. Due to high fracturing, detachments of rock blocks of various dimensions were determined, which are related to possible planar, wedge and toppling instabilities (Sečanj et al., 2017; 2019).

Main Design Settings

As it was noted before, the rockfall protection measures designing started in 2008, and till 2012 the main design was completed. The main design was set up on very poor preliminary data. Therefore, it is consequently resulted with a design which ensure only partially protection of the City of Omiš from rockfall hazard.

The designing didn't precede a rockfall hazard and risk analysis that would identify rockfall potential from the slopes above the City of Omiš and necessary data for rockfall run out analysis and protection measures design such as data about potential rockfall sources, potential rockfall volumes, probable trajectories of rockfalls and, finally, possible run out areas. Old topographic maps (in scale 1:5000) were used for designing that not enabled more accurate determination of rockfall source zones and potentially unstable rock block volumes. No engineering geological survey was done and no engineering geological map was created to identify rock mass structure and rock mass characteristics. Potential unstable rock blocks on the slope were visually determined from the toe of the slope and approximately located in the maps.

Based on identified potential unstable block position and their approximate volumes, prevention or protection measures were chosen. The prevention of rockfalls by installing rock mass support systems including rock bolts and rock anchors in combination with steel ropes, steel wire fences and steel wire meshes are designed to hold the rock blocks on. To protect the building and infrastructure from running rock mass blocks, the rockfall protection barriers were designed to reduce the rockfall energy and suspense running blocks. The necessary energy absorption capacity of rockfall protection barriers was defined based on 2D rockfall analysis.

In total 22 potentially dangerous location were chosen and for each location prevention or protection measures or their combinations (Volkwein et al., 2011) were designed. The main design included 8 locations of rockfall protection barriers with energy absorption capacity of 1.000 and 2.000 kJ as well as support measure for more than 30 potentially unstable blocks at the slopes above the City of Omiš.

Final Design Settings

The final design for rockfall prevention or protection measures above the old town of the City of Omiš was carried out as the first stage of construction works. According to the Croatian Construction Law, a final design should follow the basic construction and spatial elements from the main design, and has to define implementing details of constructions. In this way, a main design limits a final design to improve and/or designed rockfall prevention or protection measures.

Despite these limitations, the final design was carried out following the modern approaches and recent techniques in rockfall hazard analysis and rockfall structural protection (e.g. Sarro et al., 2018; Volkwein et al. 2011). Modern approaches include application of remote-sensing techniques enabled to ensure digital terrain models (DTM) from three-dimensional point cloud (3DPC) of the site surface; engineering geological mapping of the rock slopes using combination of remote-sensing techniques and field mapping; rockfall hazard and risk analysis; spatial analysis of rockfall initiating, propagation and run out (Li and Lan, 2015), as well as 3D rockfall simulation to identify trajectories, kinetic energy and run out of fallen rock block as an input data in rockfall protection barriers designing (Volkwein et al., 2011; Sarro et al., 2018).

DTM was derived from three-dimensional point cloud (3DPC) of the site surface provided by terrestrial scanning by light detection and ranging (LiDAR) in combination with topography models provided by structure from motion (SfM) digital photogrammetry. Terrestrial laser scanning (TLS) was used in the toe of the slope at the parts close to buildings, where was not possible to use SfM technique from unmanned aerial vehicle (UAV). TLS enables providing a 3DPC with high precision the scanned surface (Jaboyedoff et al., 2012), but this technique was too expensive to be used for overall area. The digital photogrammetry from SfM technique using high resolution digital camera (James and Robson, 2012) mounted on an UAV (Giordan et al., 2018) provided 3DPC (Figure 3) with precision of 1:1000 (i.e., centimeter precision for 10m distances). DTMs include vegetation and existing constructions (buildings, roads, electric poles, etc.). The analysis of rockfalls requires the use of DTM and the classification of the 3DPC is a key factor to determine the surface of the terrain (Sarro et al., 2018).

Detailed engineering geological mapping was carried out on the limited parts of the rock slopes at the parts where it was possible to physically access to the slopes. Because of very steep to vertical slopes, mapping and determination of rock mass characteristics was carried out by remote sensing on a high resolution 3DPC (Riquelme et al., 2016). Analysis of high resolution 3DPC enable the main characteristics of rock mass in a slope necessary for further analyses of rockfall source and rockfall mechanism such as discontinuity orientation (Lato and Vöge, 2012; Riquelme et al., 2014), discontinuity spacing (Riquelme et al., 2015), discontinuity persistence (Riquelme et al., 2018) as well as rock block volumes (Chen et al., 2017). All these data were combined with engineering geological mapping carried out in the field.

Figure 3 3DPC provided by TLS and SfM techniques. A view at the slope (down); a layout over the middle part of the town (left up).

Based on rock mass and discontinuities characterization data, spatial kinematic analysis were conducted to identify kinematic conditions of possible planar, wedge and toppling rock mass failure in different parts of the slope. The results of these analyses expressed indicated on zones on the slope as possible rockfall sources (Sečanj et al., 2017; 2019) that, with rock block volumes determination, gave quantitative and accurate input data for rockfall simulations.

RocPro3D and RockFall software were employed to conduct the rockfall simulation. RocPro3D is a software that enables 3D simulation of rockfall trajectories, using a probabilistic approach that considers a rock block volume and form, soil properties, irregularities of slope surface and restitution coefficient. RocPro3D for simulation uses DTM developed from 3DPC. RocPro3D was used to define and check precise locations, heights and energy absorption capacity of rockfall protection barriers. More than 1.000 simulation was conducted for each of 8 location of rockfall protection barriers, Additional check was carried out using RockFall software and 2D simulations for critical points identified by 3D simulations. Both 2D and 3D simulations enabled precise defining of rockfall protection barrier positions and their heights and energy absorption capacity. Conducted simulations pointed out on the need for installation of additional rockfall protection barrier at position where rock blocks can leap over a barrier. Position of each barrier pole was precisely determined and defined in high resolution DTM and 3DPC that enabled clear positioning of protection structures in construction stage (Figures 4 and 5). Stability analyses for potentially unstable rock blocks identified in the main design were conducted that defined necessary support system for each analyzed rock block and precisely determined and defined elements of support system in high resolution DTM and 3DPC.

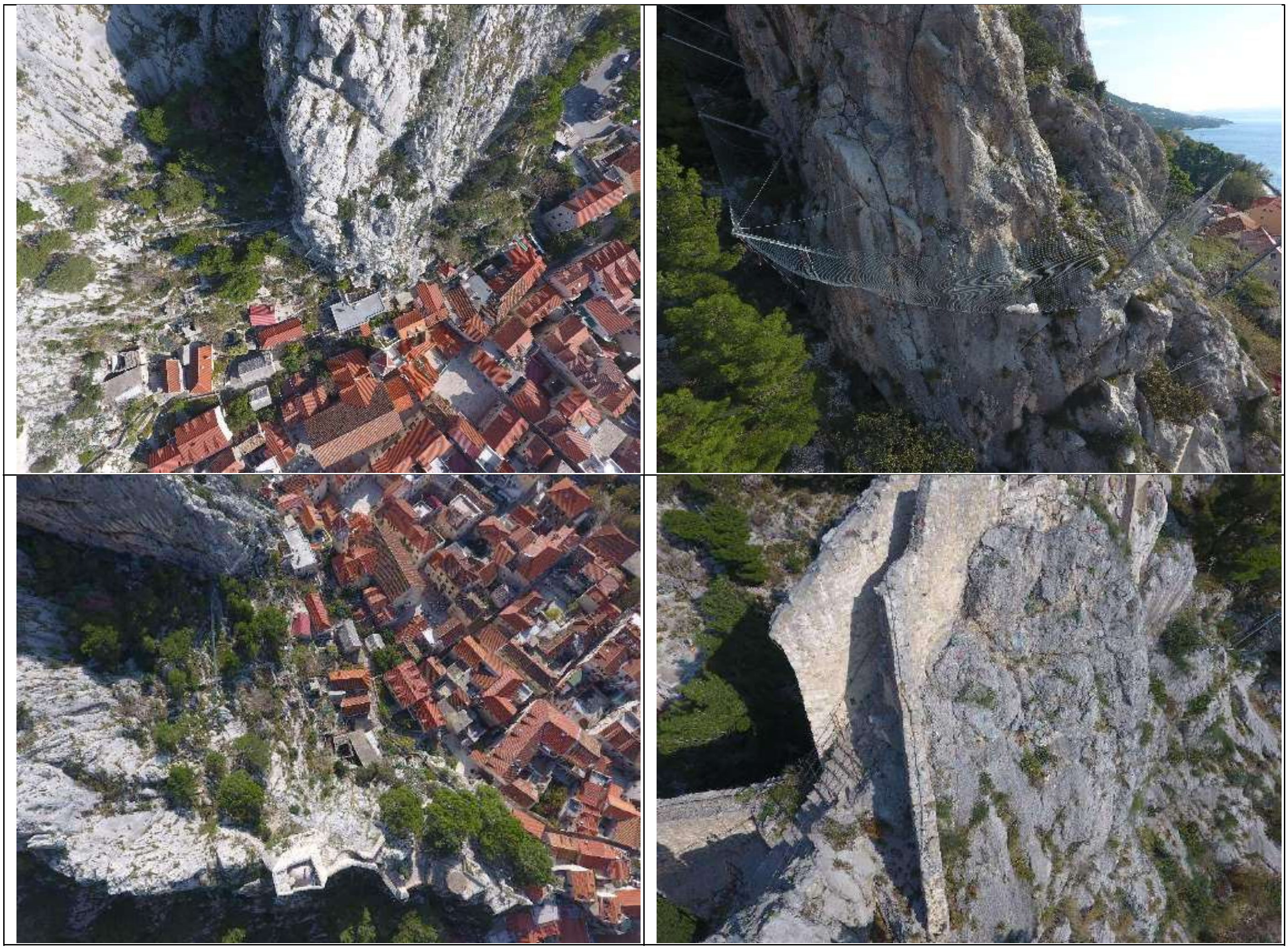

Figure 4 An aerial view at the rockfall protection barriers at limestone slopes above the City of Omiš (left up), a view at the rockfall protection barriers of 2000 kJ capacity at limestone slopes above the center of the City of Omiš (right up); an aerial view at the rockfall protection barrier of 2000 kJ capacity in the ravine above the City of Omiš (left down); a view at the rock mass support systems including rock bolts in combination with steel ropes and steel wire meshes at limestone slope below the Peovica Fortress (right down).

Conclusions

Construction of support systems and installation of rockfall protection barriers above the City of Omiš were completed in November 2018 according to the final design at 22 locations at the rock slopes. Conducted analyses of rockfall sources and run out areas provided by 2D and 3D rockfall simulations pointed out that the carried out protection constructions and measures will not ensure the residents and buildings in the City of Omiš from possible significant rockfall events in the future To ensure more comprehensive rockfall protection, it would be necessary to conduct a rockfall hazard and risk analysis (Arbanas et al. 2018) that would identify rockfall potential from the slopes above the City of Omiš, as well as better prediction of run out areas and associate rockfall hazard and risk. The results of this study should provide necessary data for the second stage of the rockfall protection project that will reduce the rockfall risk in the City of Omiš to an acceptable level.

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