Regional rockfall exposure assessment, experience from Serbia

Miloš Marjanović, Biljana Abolmasov, Uroš Đurić, Jelka Krušić, Snežana Bogdanović

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5TH REGIONAL SYMPOSIUM ON LANDSLIDES
IN ADRIATIC-BALKAN REGION

Landslide Modelling & Applications

Proceedings of the 5th ReSyLAB

Editors

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5th Regional Symposium on Landslides
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Croatian Landslide Group
University of Rijeka, Faculty of Civil Engineering
University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

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Foreword

The Regional Symposium on Landslides in the Adriatic-Balkan Region (ReSyLAB), organized under the auspices of the International Consortium on Landslides (ICL), has reached its fifth edition. This is an important milestone for ICL and for its Adriatic-Balkan Network (ABN).

Ten years ago, the ICL has encouraged the establishment of thematic and regional networks in the framework of its ten-year strategic Plan. The ABN was promptly launched in 2012, gathering together scientists, researchers, engineers, professionals and decision-makers, from the Adriatic and Balkan region and elsewhere, concerned with landslide hazard and risk, their reduction and impact on society.

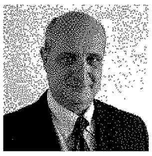
Today we can say that this has proved to be a successful strategy and the ABN is perhaps the best example of successful regional network. Since its foundation in the year 2012, the ABN has regularly organized its regional symposium every two years, dedicated to specific issues, in various countries of the Adriatic-Balkan area: Croatia, Serbia, Slovenia, Bosnia and Herzegovina and Croatia again.

Participation has gradually expanded to other countries, throughout Europe and elsewhere. This year the Symposium sees the participation of scientists from ten countries, providing an effective platform to achieve fruitful cooperation among landslide researchers.

The ReSyLAB represents a successful contribution to the Kyoto Landslide Commitment (KLC2020) launched by ICL in the year 2020 for the global promotion of understanding and reducing landslide disaster risk. The main purpose of the KLC2020 is to build a common platform for sharing ideas, good practices and policies with key actors and stakeholders concerned with landslide risk at the global level. One of the main priority actions of KLC2020 is to facilitate and assess progresses through the organization of meetings at the regional and national level, to take place in respective countries, in order to show deliveries and performances made towards the achievement of objectives for landslide risk reduction on a global scale.

The general theme of the 5th ReSyLAB is "Landslide Modelling & Applications", which clearly shows the close interplay between scientific research and its application in the engineering practice and for supporting risk reduction policies.

For these reasons, I am convinced that the example of the ABN and the ReSyLAB should be valued and exported in other geographical contexts.



Nicola Casagli
President of the International Consortium on Landslides
Florence, Italy

Foreword

The International Consortium on Landslides (ICL) was established in January 2002 in Kyoto, Japan, to promote landslide research for the benefit of society and the environment, and capacity building, including education, notably in developing countries.

In January 2005, the second UN World Conference for Disaster Reduction was organized in Kobe, Japan. ICL, UNESCO, WMO, UNU, IAHS etc. jointly organized a thematic session on Landslides (IPL) and Floods (IFI). The Letter of Intent on Earth System Risk Analysis and Sustainable Disaster Management was agreed in the session and signed by global partners (ICL, UNESCO, WMO, FAO, UNU, UN-ISDR, ICSU, WFEO within 2005. Participants included Professors Ognjen Bonacci from Croatia, Kyoji Sassa, Hideaki Marui, and Kaoru Takara from Japan.

In January 2006, ICL and its global partners (UNESCO, WMO, FAO, UNU, UN-ISDR, ICSU, WFEO etc.) organized the Round Table Discussion for the IPL and adopted the 2006 Tokyo Action Plan strengthening research and learning on landslides and related earth system disasters for global risk preparedness. In 2007, Science and Technology Research Partnership for Sustainable Development (SATREPS) program to promote international joint research for global issues based on the needs of developing countries was founded by the Government of Japan. This programme was very timely to promote the 2006 Tokyo Action Plan. The Croatia-Japan Joint SATREPS Project "Risk identification and land-use planning for disaster mitigation of landslide and floods in Croatia" was proposed in 2007 and accepted as one of the initial SATREPS projects in 2008.

In order to support this SATREPS project, the Ministry of Foreign Affairs of Japan organized a workshop in Tokyo aiming at regional cooperation in South-Eastern Europe on disaster management by inviting Professors Željko Arbanas, Matjaž Mikoš, Snježana Mihalić, Biljana Abolmasov, Sabid Zekan and others from Adriatic-Balkan Region on 14-17 December 2010. This workshop contributed to the establishment of the Adriatic-Balkan Network of International Consortium on Landslides (ICL ABN) in January 2012 and also its biannual regional symposium; the 1st ReSyLAB in March 2013 in Zagreb (Croatia), the 2nd in May 2015 in Belgrade (Serbia), the 3rd in October 2017 in Ljubljana (Slovenia) and the 4th in October 2019 in Sarajevo (Bosnia and Herzegovina), and 5th in March 2022 in Rijeka (Croatia). The ICL has launched the Open Access Book Series "Progress in Landslide Research and Technology" for Kyoto Landslide Commitment 2020 which is published twice a year. I wish to invite all participants of this symposium to contribute articles to this new open access book series. The target readers of the book series are practitioners and other stakeholders who apply in practice the most advanced knowledge of science and technology for landslide disaster risk reduction. Articles must be written in a simplified way easily understandable by practitioners and stakeholders.

The Adriatic-Balkan Network of International Consortium on Landslides (ICL ABN) is the most successful network of the ICL and its biennial symposium and its publication contributed to boost the regional potentials for reducing landslide disaster risk. I am very grateful for this tremendous effort to organize the fifth regional symposium of the International Consortium on Landslides. I wish the Adriatic-Balkan network a very successful meeting and a very good publication.

Kyoji Sassa
Secretary-General of the International Consortium on Landslides
and the Kyoto Landslide Commitment 2020
Editor-in-Chief of the Open Access Book Series of the ICL
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Preface

The 5th Regional Symposium on Landslides in Adriatic-Balkan Region (ReSyLAB) will be held in the year of two important anniversaries: 20 years of establishing of International Consortium on Landslides (ICL) and 10 years of establishing regional and thematic networks of ICL. The regional Adriatic-Balkan Network (ABN) is one of the most active networks and this 5th ResyLab2015 will contribute to regional cooperation and widening the Network by the new members in the region. Just for reminder, the 1st ReSyLAB was held in Zagreb, Croatia, 2013; 2nd ReSyLAB in Belgrade, Serbia; 3rd ReSyLAB in Ljubljana, Slovenia and 4th ReSyLAB in Sarajevo, Bosnia and Herzegovina. The 5th ReSyLAB will be held three years after the last Symposium, disrupting the biannual schedule due to Covid-19 pandemic and will be held as hybrid event, but we believe that this will not diminish the significance of this Symposium.

This book contains peer-reviewed papers that will be presented at the 5th Regional Symposium on Landslides in the Adriatic-Balkan Region entitled "Landslide Modelling & Applications". The Symposium will be held in Rijeka, Croatia from March 23th to 26th, 2022. A wide range of landslide topics are presented in the Symposium sessions that include landslide monitoring, landslide investigation, landslide mapping, landslide susceptibility zonation, laboratory testing, physical and numerical modelling of landslides and landslide case studies. This collection of papers is beneficial to practitioners, researchers and other professionals dealing with landsides. The proceedings reflect the ongoing response of researchers and practitioners from 10 countries from the region and around the world. Unfortunately, the Covid-19 pandemic situation disables landslide scientists from Japan that were present at all previous ReSyLABs, to join us in Rijeka.

We would like to thank all authors and participants for sharing their ideas and research results in the area of landslide science and practice. We wish to acknowledge the help from all the reviewers in advising and refining the contributions to their final version published in this book.

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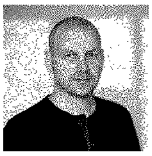

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Laboratory Testing, Physical and Numerical Modelling of Landslides

Landslide Case Studies

Regional rockfall exposure assessment, experiences from Serbia

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Abstract Rockfalls are common in hilly and mountainous areas, especially along roads with engineered slopes and cuts. Such is the case for most of the state and local road routes in Central, Serbia, which was the subject in this case study. A road network of 276 km covering roughly 1700 km^2 between the cities of Kraljevo, Čačak and Ivanjica is presented. Assessing of such wide areas needs to be conducted from large to site-specific scale, i.e., using GIS spatial tools and 2D-3D stability models, respectively. The regional scale of assessment using GIS tools was in focus. The primary input was the Digital Terrain Model, obtained from open data ALOS mission at 12.5 m resolution, as well as appropriate sheets of geological maps at 100k scale. The first step was to delineate areas that can host unstable blocks by inspecting planar sliding kinematic condition against available data. These included raster data (slope angle and azimuth) but also, point-based data (discontinuities' strike, dip and friction angle) which had to be estimated or interpolated across the area by various GIS operations. In total, there were nearly 5000 potential detachments delineated. Further step was to run the rockfall simulation by using these detachment zones as initiation sources in a simple kinetic model CONEFALL, standalone software. The output model simulated several thousands of rockfalls, with various runout distance (<650 m), velocity (<46.5 m/s) and energy (<540 kJ). When overlapped with the road network, this model revealed the road exposure to rockfall. Locations with runouts that reached the road lines make about 6.7 % of the total network length. Zones of estimated energies higher than serviceable threshold (300 kJ) occupy 0.9 % of the total and require additional remediation design. Presented analysis is a promising tool for supporting planning and decision making in the road management sector.

Keywords CONEFALL, exposure, GIS, rockfall, Serbia

Introduction

Rockfalls are common in hilly and mountainous areas, especially along roads with engineered slopes and cuts. Such is the case for most of the road routes in Central, Eastern, Western and Southern Serbia, especially on low-category state and local roads. Rockfalls can induce hazard of high magnitude (frequency, velocity, energy etc.), causing temporary or long-term effects. They impose constant problems to the road management enterprises, requiring frequent maintenance or mitigative activities. In addition, population growth and entailed urbanization, as well as climate change impacts (extreme weather conditions) all imply further emphasis on this type of hazard, together with all other climate-affected slope processes (Gariano and Guzzetti, 2016). Therefore, strategies that are including rockfall hazard assessment (as well as other road-threatening processes) are increasingly important in road management, but also in planning, engineering design and research (Davies et al., 2014), and such practice is in its beginnings in Serbia and throughout the region (Abolmasov, 2017; Marjanović et al., 2018; Marjanović et al., 2019, Marjanović et al., 2020).

State-of-the-art

Although the rockfall mechanism is precisely defined in the conventional landslide and mass movement classifications (Hungr et al., 2014, Dikau et al., 1996), it is rather common to assess mixed types of mechanisms, i.e. falling in combination with sliding and toppling, as well as bouncing, fragmenting etc., instead of solely free-falling rock. This is justified due to the actual. realistic events, which are always complex in this and many other aspects, but rock avalanches and large rockslides, as well as DSGSD (deep-seated gravitational slope deformation) are to be differentiated from rockfall mechanism, as perceived herein. Regardless of the scale and due to their different mechanism in comparison to other landslide types (high mobility and velocity), the assessment practice of rockfall hazard commonly includes (i) delineation of the release or detachment or source zones, (ii) characterization of the source material (block shape, size, strength, etc.) and the background (roughness, vegetation, deformability), and (iii) rockfall simulation with trajectory runout modelled per several parameters (reach distance, jump height, velocity, energy, etc.) (Dorren et al., 2011). The scale of assessment dictates the level of detail of input data, and complexity of the model. Obviously, regional scale models cannot be provided with site-specific level of input data, which is why they are usually confined to steps (i) and simplified step (iii) (Jaboyedoff and Labiouse, 2011).

Many authors have reported rockfall hazard case studies ranging from large to local scales, endangering roads, rails or hiking tracks. A full overview of the state-of-the-art would be beyond the topic and purpose of this paper, which is why only most relevant works, regarding regional scales and road network exposure context, will be addressed hereinafter. As step (i) requires delineation of sources, it is worth mentioning that such procedure for larger scales is commonly automated and GIS-based. Alternatively, there are procedures that integrate field and operative data for mapping of slopes and their classification specifically for the roads (Budetta, 2003). Inconveniently, they overlap procedures from (i), (ii) and (iii) in a single classification procedure, commonly subjective. Loye et al. (2009) reported a procedure based on high-resolution (airborne LiDAR) Digital Elevation Model (DEM) analysis. They have decomposed slope angle distribution to map cliffs and steep slopes as predominant rockfall sources in alpine regions and argue that such global criterion can be easily applied to any other mountainous area with slight adjustments. Since they have offered global criterion, they have not considered geological or kinematic conditions. Even though inspiring, their approach was not directly implemented in this research, as the principal intention herein was to include other important conditions. Similarly, Aksoy and Ercanoglu (2006) used rule-based fuzzy analysis over a set of morphological, but also structural (field) data for the city-wide assessment of rockfall source areas. Fanos and Pradhan (2019) performed comprehensive rockfall hazard assessment at city-wide scale but demonstrated how machine learning algorithms can extract potential source areas from high-resolution DEMs, which might be direction of our future research. Copons and Vilaplana (2008) have introduced a case of rockfall risk assessment at scales 1:5,000-25,000 for land use planning purposes, by calculating and statistically processing the exposure distribution at the foot of the designated large-scale slope of known dynamics, which has inspired our approach, too. Road and rail networks at regional scales were the subject of several researchers (Lato et al. 2009; Michoud et al., 2012; van Veen et al., 2018), wherein it is typical to adopt realistic scenarios using confirmed source areas, based on historical remote sensing and LiDAR monitoring data (static or mobile). These were further using various tools, usually simplified, for solving step (iii) and calculating the exposure of the target infrastructure.

Common for most of these studies is the use of high-resolution DEM from airborne LiDAR campaigns, which is not widely available in Serbia. Another conformity, with some exceptions, is the preference of morphological rather than integrated (geological and structural) criteria for delineating source zones. It is also apparent that the level of detail of the terrain surface model severely affects both, detection of potential source areas and propagation of the rockfall trajectories. Higher level of detail (1x1 m or less) commonly implies greater rockfall hazard than the coarse DEMs (10x10 m or more) over the same area, so optimization of inputs is also indicative suggestion in described works. It is also indicative that shifting from small-scaled and detailed to large-scaled and general rockfall assessment implies application of les complex simulation models at step (iii).

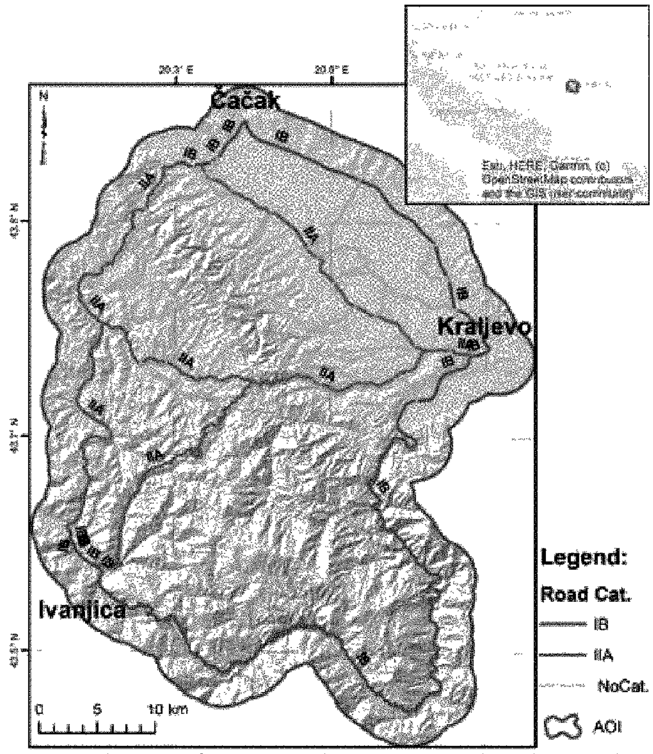

Figure 1 The area of interest with its categorized road network.

Area of interest

In this article, experience from a case study in Central Serbia, covering a road network 276 km long within an area of roughly 1700 km² will be presented (Fig. 1). It is situated between cities of Čačak, Kraljevo and Ivanjica within a mixed terrain configuration, from flat river valleys to the north, to hilly-mountainous terrain to the south. The wider investigation concept is defined in the World Bank project: Mainstreaming climate resilience in road transport management in Serbia, conducted in 2020-2021 for Public Enterprise Roads of Serbia. The presented analysis of rockfall exposure is just a fraction of all performed spatial and traffic modelling, which was targeted at developing and testing methodology for quantitative risk assessment in respect to relevant natural hazards including the current and future climates.

In brief, the project framework included several key tasks. Firstly, the area of interest was scoped for examples of instabilities, resulting with a database, used as input and validation data for hazard models, i.e., hazard maps. This subproject was named ClirTheRoads and contains digital repository (http://clirtheroads.rgf.rs/). The exposure of the network was analysed by overlapping road network over these maps while introducing quantified vulnerability parameters of the road assets. The next task was to detect critical locations and develop scenarios in respect to traffic and population distress. For each scenario a cost-benefit analysis was conducted to test the balance between the importance of the scenario and risk mitigation costs. Finally, this information was used to prioritize road sections which will be future investment candidates.

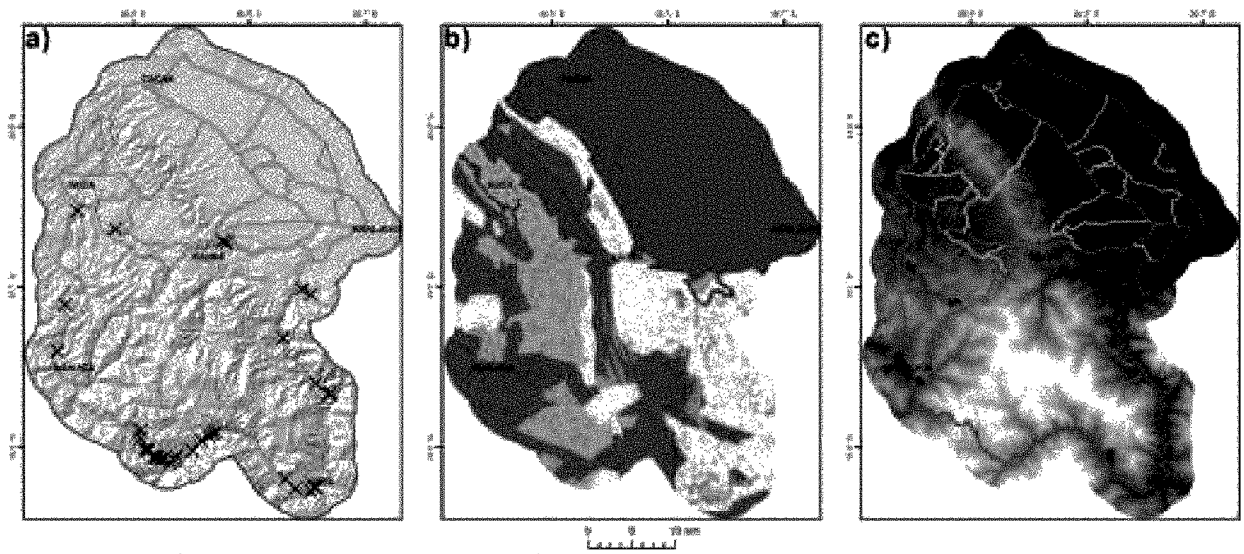

Figure 2 Raw inputs: a) field mapped rockfall examples; b) simplified engineering geological map in respect to rockfall susceptibility (more prone to rockfall from green to red) overlaid by planar discontinuity measurements (dip and dip direction); c) DEM (ranging from 231 to 1620 m a.s.l.) overlain by categorized road network (road category increases from light pink to violet).

Materials and Methods

As indicated before, the approach in this study is split into: step (i) source delineation, by using both morphologic and geologic/structural features, validated by field data, therein including free-fall but also block sliding mechanisms of detachment; and step (iii) which includes simplified kinetic trajectory simulation tool. Given that it represents a subtask in a larger project framework, only respective (rockfall assessment-related) data acquisition and methodology will be presented hereinafter.

Input data

The following base maps and resources were used for both task (i) and (iii) implementation (Fig. 2):

- Field locations database (subproject ClirTheRoads, http://clirtheroads.rgf.rs/)
- Engineering-geological and geological map 1:300,000 (Geological Survey of Serbia, https://geoliss.mre.gov.rs/karte/igk300.html)
- Digital Elevation Model (DEM) 12.5 m resolution (ALOS PALSAR mission open products, https://earthdata.nasa.gov/)
- Pilot road network (Public Enterprise Roads of Serbia, excerpt from the national road network vector, https://www.putevi-srbije.rs/index.php/)

These were used directly or for derivation of intermediate raster inputs such as:

- Aspect (derived from DEM at 12.5 m resolution using standard D8 GIS algorithm)
- Slope (derived from DEM at 12.5 m resolution using standard D8 GIS algorithm)
- Dip angle (nearest-neighbour-interpolated from planar features on geological map 1:300,000)
- Dip direction (nearest-neighbour-interpolated from planar features on geological map 1:300,000)
- Friction angle (assigned using experience-based values for formations defined on engineering geological map 1:300,000 and encountered during the field survey)

Modelling

Task (i) requires a delineation of potential rockfall sources, marking areas where blocks are easily detachable. Foremost, it was needed to mask all areas that do not consist of solid rocks, which was done by masking appropriate units, i.e. assigning zero values in the digitized engineering geological map (dark green in Fig. 2). Secondly, the remaining areas covered by solid rocks were scored according to their susceptibility to rockfall occurrence. The scoring factor F value was set arbitrarily, within the 0-1 interval, and relied on experience from the field surveys conducted in 2020. In general, loose, jointed, weak, tabular and schistose rocks had higher scores than fresh igneous or compact isometric sedimentary rocks. Subsequently, the block sliding conditions along planar discontinuities (Eq. 1-2) as defined by conventional Markland's kinematic criteria (Hoek and Bray, 1981), were tested against the intermediate raster layers: Aspect (ψ); Slope (β); Dip angle (α); Dip direction (ν) and Friction angle (φ) in a GIS environment.

$$\nu = \psi \pm 20° \qquad [1]$$

$$\varphi < \alpha < \beta \qquad [2]$$

Directional tolerance of ±20° corresponds to maximal probability which (1). The tolerance was successively enlarged while failure probability P of instances that meet such condition was proportionally reduced. The failure probability was subsequently normalized against all pixels that meet Markland's condition to 0–1 range. These were finally multiplied with scoring factor (0–1) F.

Next modeling step required solving of rockfall trajectory runout, velocity and energy. A standalone software CONEFALL was used (Jaboyedoff and Labiouse 2011), as it relies on a simple "dry friction" triangle (cross-section along the block's trajectory) between the source area, its vertical base and its horizontal reach, or the shadow angle (Fig. 3). In 3D setting the triangle is promoted to cone, and in both cases the shadow angle limit is arbitrary, but empirical evidence suggests using a range between 27-38°. It further relies on potential E_p to kinetic E_k energy proportion (energy conservation law), and suggests that at any point along the propagation axis X, the velocity v is proportional to the difference of topographic and cone surface dH by the power of 2 (Eq. 3). Knowing the gravitational constant g and assuming unit volume V, velocity and kinetic energy can be easily calculated along each trajectory.

$$E_p = E_k \Rightarrow g\frac{m}{V_{\to 1}}dH = \frac{mv^2}{2} \Rightarrow dH = \frac{v^2}{2g} \qquad [3]$$

The hazard map was generated by the adopting the distribution of the energy value, although velocity value or their combination are available as an output form. Since most of the protective measures refer to impact velocity thresholds (https://www.geobrugg.com/), the hazard map was kept in said values, split according to intervals that are more or less manageable by protective measures (0-100 kJ low; 100-300 kJ moderate; >300 kJ high).

Figure 3 Cone model (red rectangle is source, black line is topographic surface, blue line is cone surface, shade angle ~ 32°, green area is a trajectory domain) of 2020 event in the background (photo M. Marjanović).

The last step involves superimposing the spatially distributed rockfall hazard to a linear object, i.e., the road network vector. This has been completed by segmenting the entire road network into 500 m intervals and averaging the overlapping pixels (12.5 m resolution) per each segment of the hazard map using the zonal statistics tool in the GIS environment. Thereby, highly exposed segments of the road network are emphasized in contrast to low exposed ones visually, but also quantitatively.

Results and discussion

The results of the task (i) are indicating relatively low susceptibility to host rockfall, while the rockfall hazard in general seems to be limited to narrow sections of the road isolated in the southernmost regions of the area of interest (Fig. 4-5). Hereinafter, a more detailed review of these outcomes follows.

Source areas

Kinematic analysis rectified by an experience-based lithological criterion and with lateral limits expanded to ±45° suggests that there are few cases that comply with sliding block failure. In total, 34.5 km^2 or only about 2 % of the area is prone to such failure mode, while lateral tolerance is expanded to great extents (Fig. 4). However, evidence from the field suggests higher slope activity, but mainly along road cuts, which could not be represented with the current low-resolution DEM. In fact, its derived slope model shows that majority of the slope faces lie below 30° inclination, while the overall average is about 13°. Only 0.2 km^2 of the total is steeper than 50°, which reduces to isolated cases/pixels. Rough, steep faces, especially along the road cuts are presumably smoothened by 12.5 m resolution of the DEM, which is insufficient to capture greater level of detail.

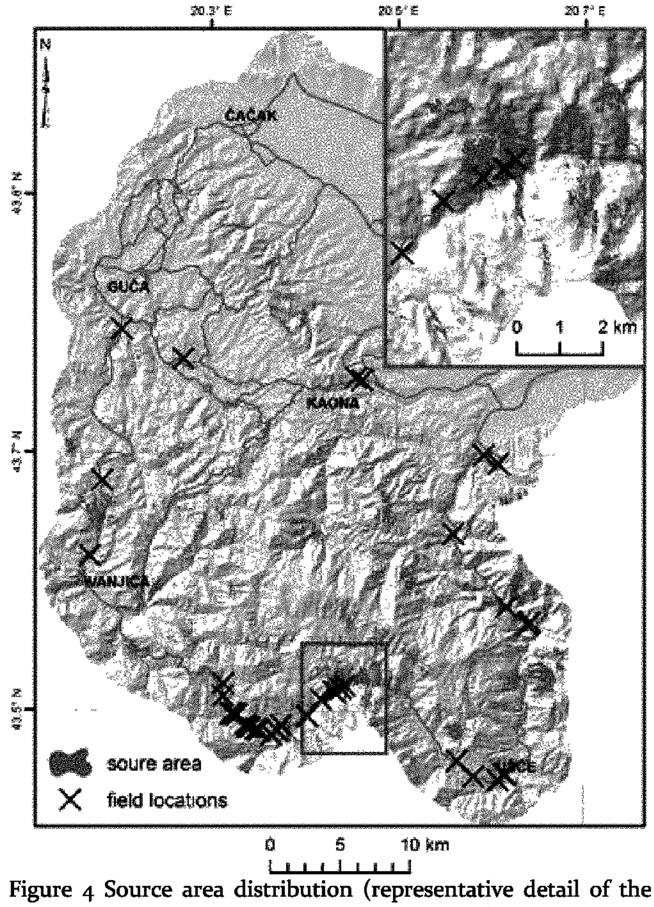

Figure 4 Source area distribution (representative detail of the southern rockfall hot-spot given in the top right).

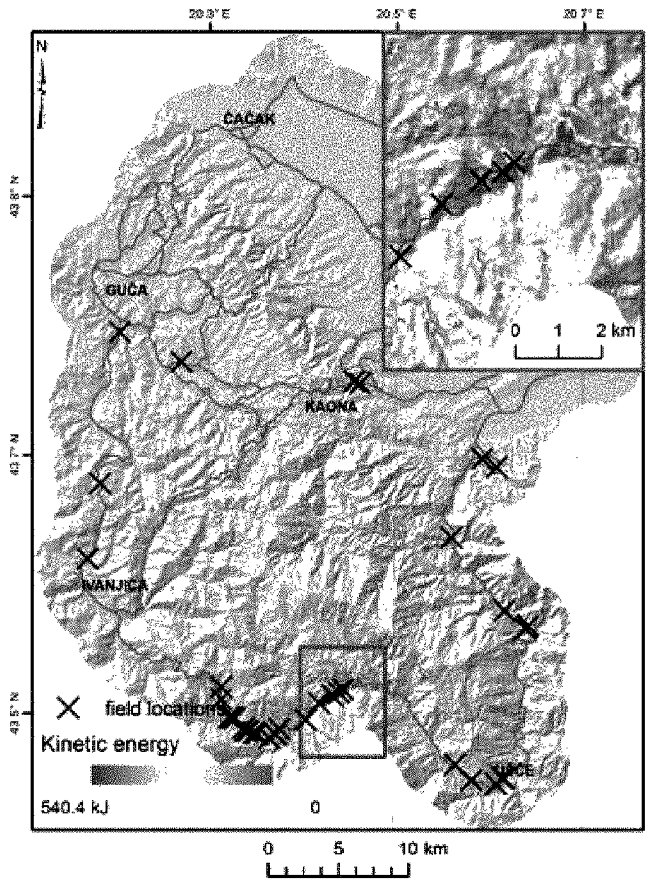

Figure 5 Rockfall kinetic energy distribution (representative detail of the southern rockfall hot-spot given in the top right).

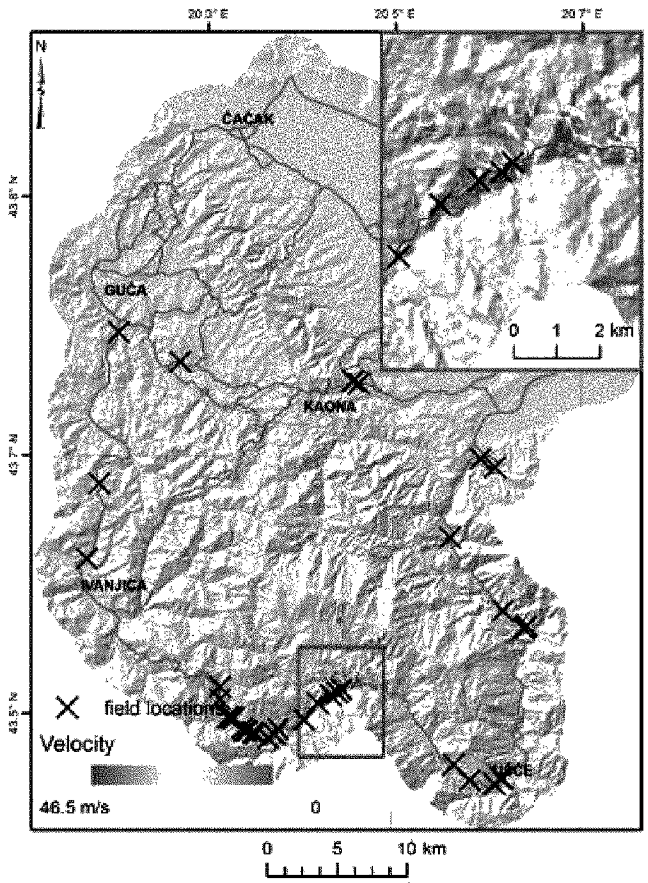

Figure 6 Rockfall velocity distribution (representative detail of the southern rockfall hot-spot given in the top right).

Rockfall hazard and road exposure

Cone model "trajectories", which are but per pixel calculations of Eq. 3, suggest rather a moderate rockfall hazard in both aspects, spatial and intensity-wise (energy and velocity). Reach distances were simulated by using the cone shadow angle of 32° which has been confirmed as the most realistic value during the field investigations in 2020 (ClirTheRoads subproject), blocks were assumed as cubical, while their average dimension was set to 0.5-0.7 m, meaning that average block mass was about 500 kg (assuming bulk density around 20 kN/m^3). By converting the raster output as a vector, the runouts were approximated, and their axial dimension was estimated to range between 50 and 650 m, wherein only 1 % is longer than 500 m.

Rockfall energy distribution (Fig. 5) can be divided into low hazard 0-100 kJ which occupies 88 % of the total area, moderate hazard 100-300 kJ which covers 11 % of the area, while the remaining 1 % is a high hazard with energies >300 kJ. This is a generally adopted threshold in respect to the serviceability limits of common road meshes and drapes used in practice. In addition, velocities are calculated, and their distribution seems more uniform (Fig. 6).

Overlapping road segmented (500 m) network over kinetic energy raster and using the same criteria for classifying low-high hazard and translating it to the exposure to rockfall, the following distributions are obtained (Fig. 7). Zero hazard is occupying most of the area, as well as most of the road length, i.e., 93.3 %, which is even more optimistic than 88 % for the areal distribution. Thus, 6.7 % is non-zero exposure, i.e., 18.6 km of 276 total network length. Moderate exposure covers 5.8 % of the total length of 16 km, which means that the remaining 0.9 % or 2.6 km is covered in high exposure to rockfall. It is located in the southernmost part of the area of interest, along the Ivanjica-Ušće route, as well as along the Ibar river valley to the east (Kraljevo-Ušće route), with some seldom occurrences in other parts of the network.

Clearly, the models do not comply with field data particularly well (35 wide-spread rockfall occurrences, few of which were indicated as critical for potential road closure and detouring), which means that the approach is more general than desired. The principal reason is the level of DEM detail available. LiDAR-based DEM (airborne) of a meter or sub-meter resolution would allow mapping of much steeper local cliffs, as well as shoulders, breaks etc. giving a more realistic source area delineation as well as better background for running simulations.

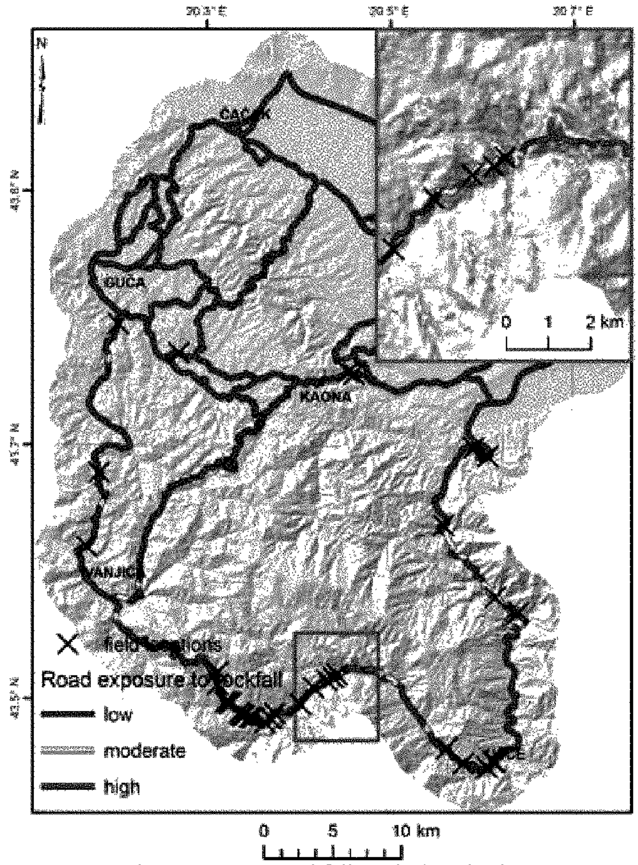

Figure 7 Road exposure to rockfall underlain by kinetic energy model (representative detail of the southern rockfall hot-spot given in the top right).

Conclusions

This work presents a quantitative approach for determining road exposure to rockfall hazards in a medium-sized area located in central Serbia. The terrain configuration is susceptible to rockfalls in the southern and eastern parts, which has been confirmed by a thorough field survey, conducted in 2020. Expert-driven and physical modelling are herein coupled to perform task (i) - rockfall source zones delineation, and (iii) - simulation of rockfall trajectories and their features. The results are considered appropriate for a general assessment level of planning and prioritizing but require some improvements. A major drawback is the lack of high-resolution DEM which would resolve most of the modelling issues in both tasks (i and iii). Further improvements are possible by including more realistic surfaces, but also, land use features (forests, and other surface fabric) which can be used as a correction factor in the postprocessing of energy and velocity calculations, as a task (ii). Even though mismatching in some aspects, the field validation and models are statistically speaking comparable (a relatively low level of hazard is present in both). The simplicity of the simulation model is also a source of error. However, one "hot-spot" area in the southern part is a very representative example where the model meets a realistic scenario.

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