390
GEOME 2
Manuscript received: August 8, 2022
Accepted: October 10, 2022

Geologica Macedonica, Vol. **36**, No. 2, pp. 165–175 (2022)
On print ISSN 0352 – 1206
On line ISSN 1857 – 8586
UDC: 552.1:624.131.537]:[624.134:004.94
https://doi.org/10.46763/GEOL22362165i

Original scientific paper

ASSESMENT OF ROCKFALL DITCH EFFECTIVENES BY APPLICATION OF COMPUTER SIMULATIONS. AN PROBABILISTIC APPROACH

Simona Ivanovski[1], Igor Peševski[2], Milorad Jovanovski[2], Sead Abazi[2], Jovan Papić[2], Daniel Velinov[2]

[1]*Geohydroconsulting, Manapo St. 7, 1000 Skopje, North Macedonia*
[2]*Faculty of Civil Engineerin g, Ss. Cyril and Methodius University in Skopje,*
Blvd. Partizanski odredi no. 24, 1000 Skopje, North Macedonia
pesevski@gf.ukim.edu.mk

Abstract: Different types of geohazards frequently affect road and railway traffic. Among them, in the case of mountainous terrains, the rockfalls are considered to be most usual. They cause economic losses of different magnitude, in some cases even loss of human life. In order to improve the management of the rockfall hazard and risk, researchers had been developing many different methodologies for assesment and design of effective control, protection and preparedness measures. One of the approaches is to apply a structural measure along the road/railway line in the form of a rockfall catch ditch at the toe of the rock cuts. Experimental field tests and computer simulations by many authors have investigated the effectiveness of these ditches, with main goal being to design ditches that are as effective as possible. The paper presents application of computer simulation technique coupled with probabilistic analysis. The main idea is to test the effectiveness of rockfall catch ditches with different geometries, by simulating rockfall blocks of different geometrical shapes. Beside variation of the ditch and block geometry, also varied are the height and slope angle of the rock cut. Results from the probabilistic simulations show the different degree of ditch effectiveness in the investigated cases. The approach is considered useful for the goals in the design process, with main benefits being the improved management of the rockfall risk and economical rationalization of cuts design.

Key words: geohazards; rockfalls; catch ditch; geometry; simulation; design rationalization

INTRODUCTION

Rockfalls present the most common type of geological hazard (often called rockfall geohazard) that can threaten road and railway traffic and cause material damages and human losses. Besides the geological settings and geometrical properties of the road/railway alignment, the extend of the risk from rockfalls depends on various other factors, such as the vehicle speed and length, the available decision sight distance, the traffic volume, the length of the risk section, the number of occupants in a vehicle, and the type of vehicle.

Different methods have been developed to evaluate the rockfall risk, ranging from developing engineering rock classification systems (Harp and Noble, 1993); hazard and risk classification systems of unstable road cut slopes, based on visual observation, simple calculations and by estimating the rock mass properties through rock mass classification systems (Pantelidis, 2009). In terms of hazard rockfall analysis, one of the most widely used methods is the Rockfall Hazard Rating System, also known as RHRS (Pierson, 1991). RHRS is a standardized methodology, which sets rockfall project priorities. Russell (2008) proposed a modified RHRS method for Colorado region. Singh A. (2004) developed a different approach in order to determine an index, known as Falling Rock Hazard Index. The parameters taken into account and scored are the following: slope height, slope inclination, slope irregularities, rock condition, spacing of discontinuity, block size, volume of rockfall, excavation method and duration without remedy and rockfall frequency. The hazard level estimation is followed by the proposal of proper mitigation systems. Saroglou et al. (2012) proposed a rating system, which is slightly based on the RHRS system, but it is not limited on roadway and railway slopes. It refers also to the effect of rockfalls on inhabited areas and estimates the hazard and the risk levels of a potential rockfall.

Abbruzzese et al. (2009) developed a methodology using 2D or 3D trajectory models based on

Swiss case studies, in order to assess the hazard level. The hazard analysis is assessed by taking into account rockfall intensity, expressed by the total kinetic energy (translational and rotational) of the falling blocks.

Others have investigated methods for predicting the run outs paths of rockfalls, rock bounce heights, kinetic energy conditions, velocity of falling blocks, etc. (Paronuzzi, 1989; Pfeiffer and Bowen, 1989; Guzzetti et al., 2002). Arbanas et al. (2012) presented the Croatian experiences on rockfall hazard determination, rockfall analyses and applied protection designs at particular locations along the Adriatic coast of Croatia.

Rocfall and landslide risk mitigation measures in general encompas different approaches such as application of structural and non-structural measures (Bernardi et al., 2008; Hopkins et al., 1996). Yoon et al. (2020) introduced simple and new method to mitigate the rockfall hazard using the so-called sand pool, was made by ditching and then filling sand where the rock should be stopped or arrested, capability of the sand pool to stop or arrest the rockfall was examined. The proposed framework was applied to a case study by Lee et al. (2021) of rockfall along the highway network of South Korea, demonstrating how the rockfall occurrence rates can be systematically classified and how the risk reduction effects of different mitigation measures can be quantitatively estimated. This study also proposed an operation method to select an appropriate mitigation strategy for any given artificial cut slope based on available rockfall frequency rates.

In addition to other relevant numerous scientific researches, it is important to mention the work of Ritchie (1963), which is considered pioneering in terms of research related to rockfalls on steep hillside and slopes. Ritchie was the first who researched and developed criteria for designing slopes and rockfall catchment areas, and proposed a so called rockfall catch ditch. Ritchie pointed that there is a need to determine a way to predict the stability of the surface material after excavating the slope. Rolling over hundreds of test rocks he studied the movement and trajectory of "rockfalls" and tried to develop an analytical solution to rockfall based on the laws of motion (Pierson et al. 2001).

With development of information technology, researchers began to program softwares for simulation of rockfalls. The first known computer program for the simulation and analysis of rockfall on slopes was developed by Piteau and Clayton (1976). Other computer programs that have been developed are CRSP (Colorado Rockfall Simulation Program) developed by Pfeiffer and Bowen (1989); GeoStru's GeoRock 2D and GeoRock 3D products who use the Lumped Mass and GRSP model; Rockyfor3D (Dorren L.K.A., 2016); STONE software by the DEMOCLES European Project. All simulation programs use the equations of motion of a rigid body and the properties of the slope inclination to calculate the velocity and bounce characteristic of the block as it moves down the slope.

In this paper is presented a probabilistic approach of two dimensional rockfall computer simulations, in a case of existance of rockfall ditch below the road cuts. Several parameters of the rockfall process and geometrical conditions are varied, in order to forsee what are the most optimal combinations of geometry of both the rockfall ditch and the slope face of the rock cut, depending on the geometrical shape of falling rock block. For better representation and analysis of the obtained results, many respective graphs are generated.

MATERIALS AND METHODS

Contemporary computer programs in the field of geotechnics are proving to be an economical and reliable tool for slope failure analysis. All simulation programs use the equations of motion of a rigid body, the properties of the slope inclination to calculate the velocity and bounce characteristic of the rock block, as it moves down the slope. In order to reduce the number of parameters in the simulation of the fall rock blocks, the following general assumptions are made:

- The effect of gravity and friction during the rolling of the block is insignificant.
- Rockfall process is considered in a plane perpendicular to the slope.
- There is no weathering of the rock blocks during the rockfall process (Baishan, P., 2000).

Although the simulation algorithms of different computer programs differ from each other, the general algorithm is the same, it defines the rolling of the block (bouncing, sliding or rolling), calculating the movement speed at the end of each stroke and finding out where the block stops.

- Height and slope angle.

- Dimensions and shape of a rolling rock block.
- Coefficients of restitution (normal and tangential).

In the paper we have applied the rocfall simulaton program RocFall® product of Rocscience Canada. The program incorporates all of the above mentioned aspects for simulation of rockfalls. In order to investigate the different level of rockfall ditch effectivenes depending on variyng geometries, we have varied the following rockfall parameters: block dimensions and shape, unit weight of rock, restitution coefficients (adopted on the basis of research results on the A2 expressway in Macedonia, section Dlabochica – Chatal). According to the recommendations from the literature and our observations of the respective road section, slope heights of 10 m, 20 m and 30 m were applied. The adopted slopes inclinations are in the ranges: 1V:1H (45^o); 2V:1H (63^o); 3V:1H (72^o), 4V:1H (76^o), 6V:1H (81^o).

Dimensions of ditch (width and depth) are calculated from the diagram of Ritchie (1963), according to the height and the slope angle of the cut slope (Figure 1). Four different shapes of the ditch are simulated: circular, trapezoidal, triangular and V shape (Figure 2), and for three different block shapes: cubic, pentagonal and elliptical (Figure 3). A total of 180 simulations were performed.

Additional assumptions in performing of the rockfall simulations are the following:

- the statistical approach used in the simulation is Monte Carlo method (a mathematical technique, which is used to estimate the possible outcomes of an uncertain event) (Rubinstein, 1981);
- the number of simulated falling rocks is 100 in all tested variants;
- rocks are falling from the top of the slope;.
- the initial speed of the falling rocks is zero;
- the material of the slopes is a degraded schist rock (Table 1 shows the adopted parameters for the rock mass).

The effectiveness of the ditch is measured by its ability to stop the rockfall from reaching the edge of ditch, with the possibility of analyzing numerous dynamic indicators of the rockfall process.

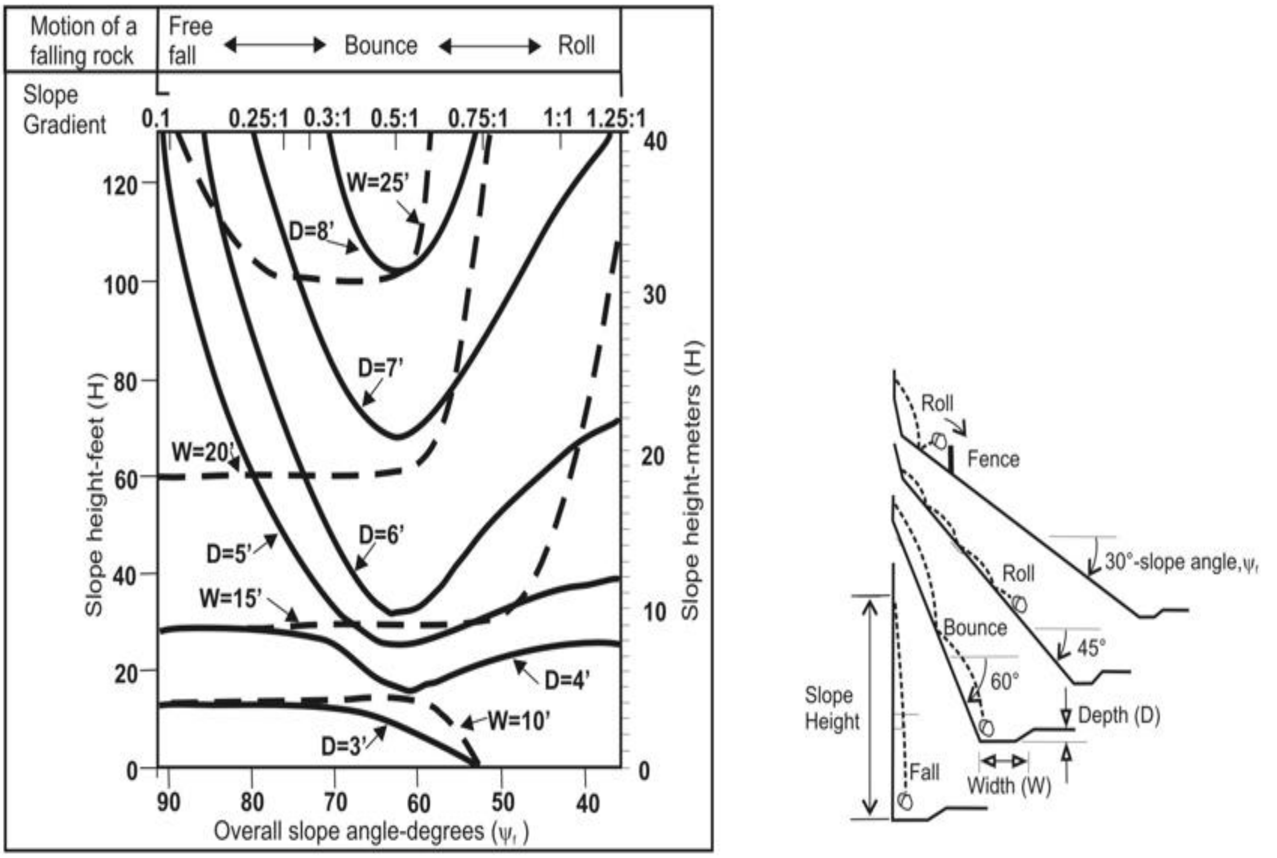


Fig. 1. Ritchie rockfall catch ditch design chart (Pierson et al., 2001)

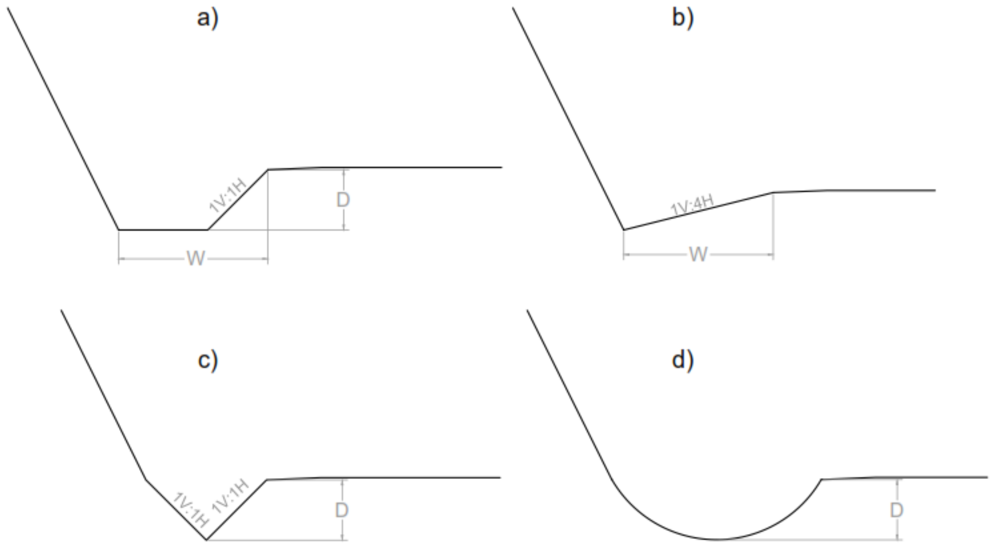


Fig. 2. Ditch shapes used in our case study

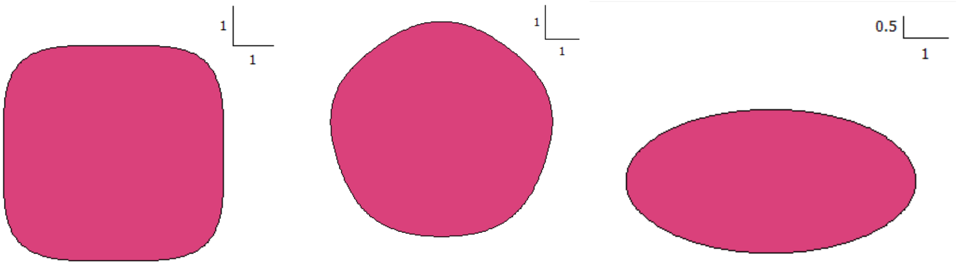


Fig. 3. Block shapes used in our case study

Table 1

Rock and slope material properties

Rock properties		Slope material properties	
Unit weight (kg/m^3)	Average block dimension (m)	Normal coefficient of restitution (Rn)	Tangenciall coefficient of restitution (Rt)
2732	0.5	0.35	0.85

The RocFall program simulates the behavior of rockfalls by applying the equations of parabolic trajectories of free-falling bodies and the principle of total energy conservation. Block dimensions are used as additional parameters for rockfalls modeling. It is assumed that the angle between the direction of rolling the block and the profile of the slope can be changed according to the parameters for the specific case of analysis. Therefore, the model considers combinations of motion during free fall, bounce, roll and slide, which may vary in relation to the size of the rock blocks (Figure 4).

A Data Collector in RocFall is a line segment that gathers information about the rocks that pass through the line on their way down the slope. Data collectors record the velocity, kinetic energy, vertical location, and horizontal location of all rocks that pass through it. The program has the ability to visually present the dynamic parameters of the rockfall process. For the purpose of the paper, the data collector is placed at the position where the ditch ends, i.e. at the edge of the roadway shoulder, which we consider as a border point from which no further blocks should pass (on the roadway). A view of the data collector in the software environment is given in Figure 5.

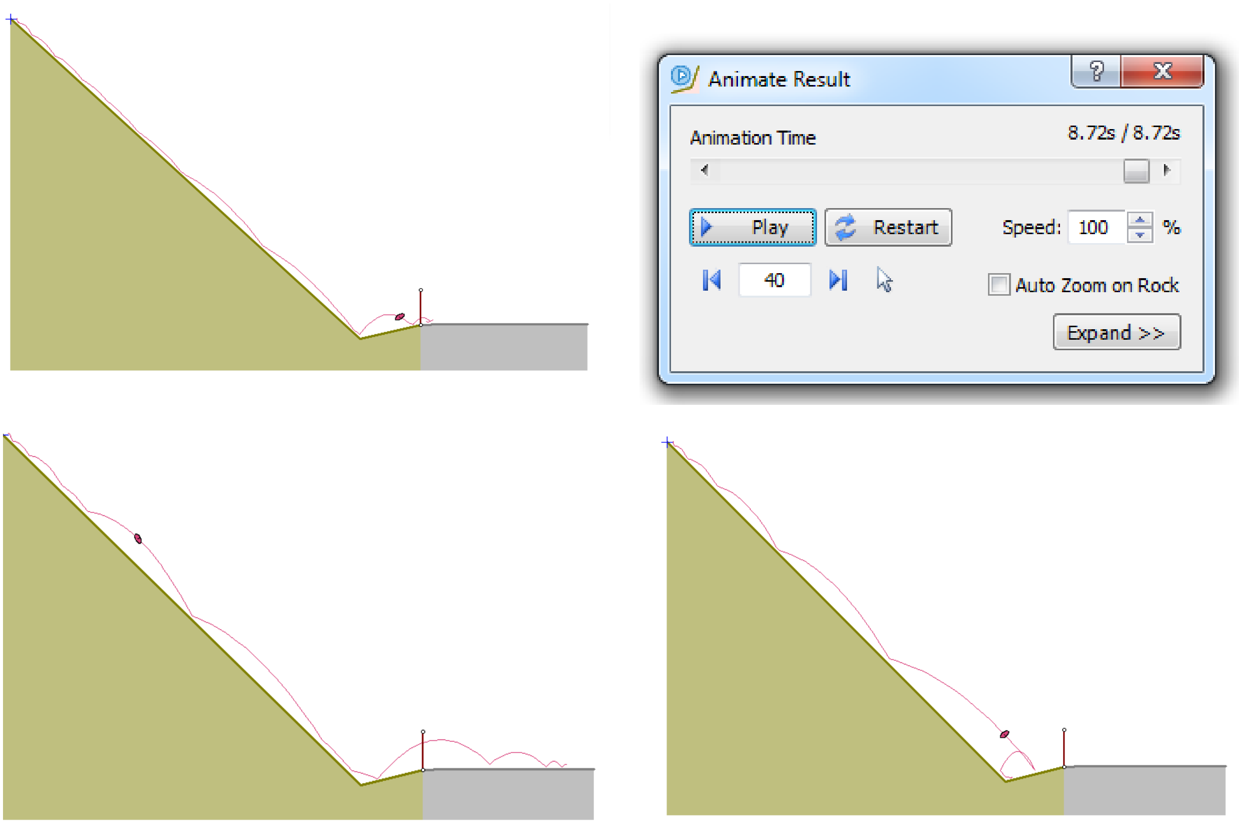


Fig. 4. Animated path results at several different positions along the cut slope

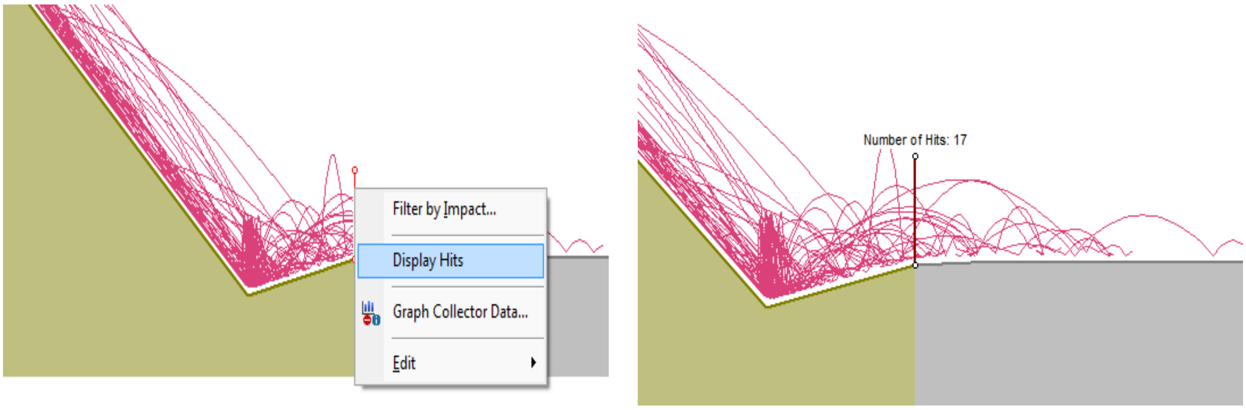


Fig. 5. View of animate path and position of "data collector"

RESULTS AND DISCUSSION

The graphs in Figure 6 show results of different ditch shapes and a pentagonal shape of falling rock block. It should be noted that for a slope with a height of 10 m, the ditch accepts rockfalls in all cases, except for the triangular shape of the ditch and the slope inclination of 45° where 10% of the blocks pass over the ditch edge. At a slope with a height of 20 m and a slope inclination of 45°, the blocks cross the edge in the range of 15–45%, except for V-shaped ditch, where total effectiveness is obtained (0%). The circular (rounded) shape of the ditch is shown to be the ineffective for slope heights of 20 and 30 m. Without further detailed analysis of these graphs, it can be concluded that for the pentagonal shape of a rockfall block, the most effective ditch is with V shape. The same analysis is shown in Figure 7, which refers to the square shape of the rockfall block.

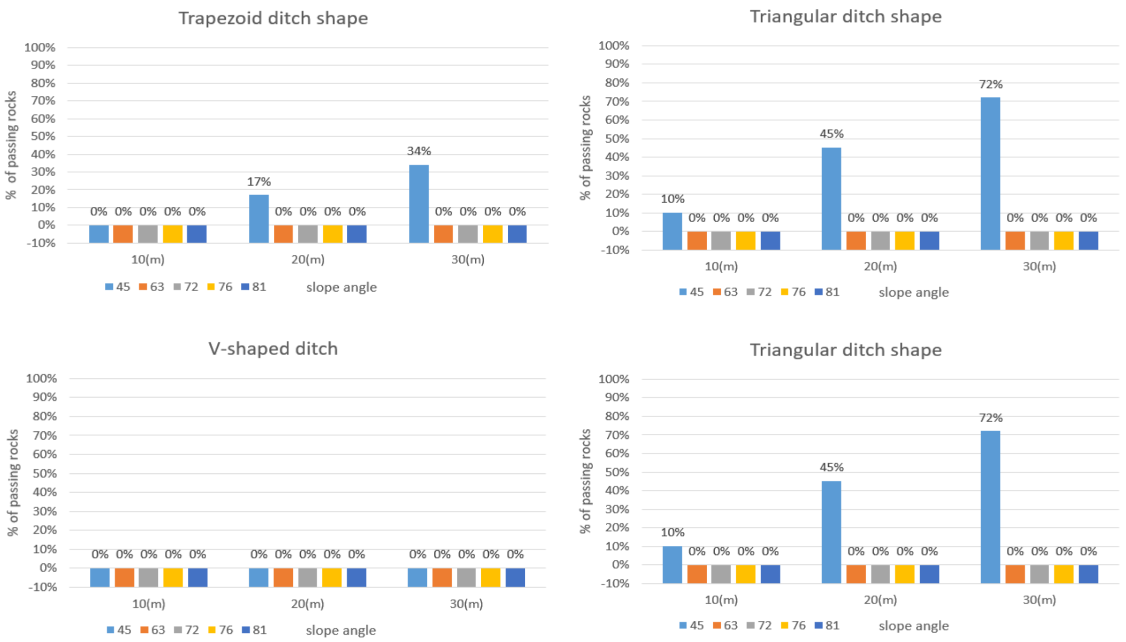


Fig. 6. Percentage of rockfall blocks (pentagonal shape) passing the edge of the catch ditch

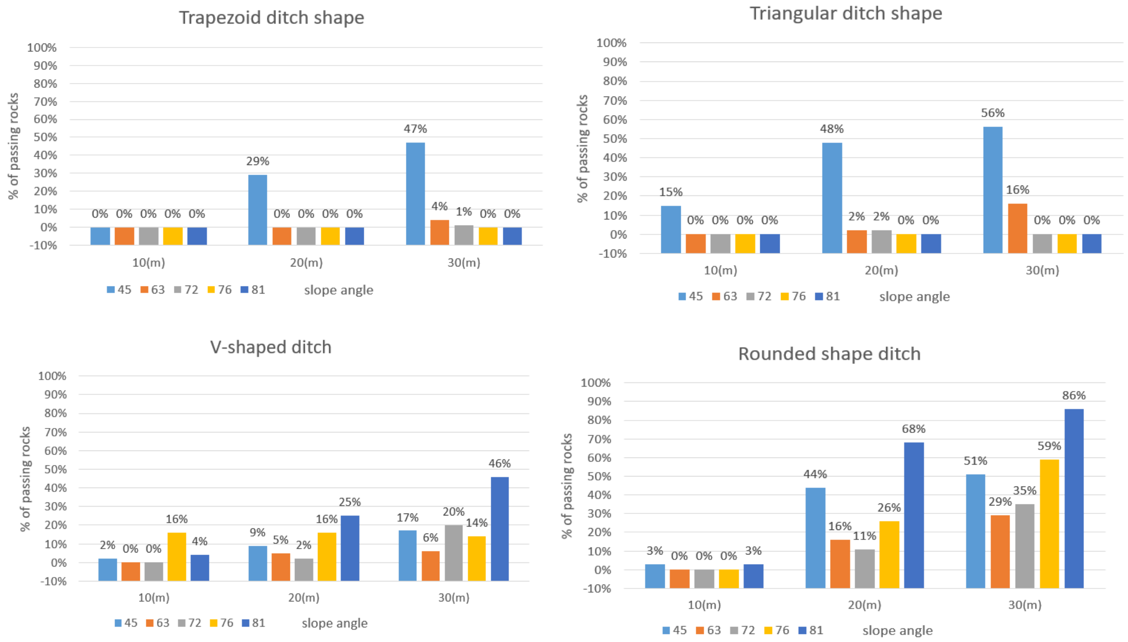


Fig. 7. Percentage of rockfall blocks (square shape) passing the edge of the catch ditch

The graphs in Figure 8 show the results for an elliptical block shape and for different ditch shapes. According to the analysis, the trapezoidal form gives the best results in most cases, except for slopes of 20 m and 30 m at an cut slope angle of 45°, where 1–5% of the rockfall blocks pass over the ditch. In the case of a triangular ditch, the angle of 45° is shown to be the most unfavorable cut slope angle at different slope heights, as well as the angle of 63° for slopes of 20 m and 30 m, and the angle of 72° for slopes of 20 m. The V-shape and the circular shape of the ditch with this block shape are considered to be unfavorable, except for some rare cases of slope / height combinations..

For additional analytical comparisons, on the graphs in Figures 9, 10, 11 and 12 are presented the results obtained with a different shape of block, while the shape of the ditch is kept the same. It is noted that in most of the assumed cases the effectiveness is significant, however the most unfavorable combinations can also be noticed very clearly. On the graphs in Figure 9, in the case of a trapezoidal ditch for slopes of 10 m, the ditch has a high effectiveness in all block shapes. At a height of 20 m and 30 m on a slope, a greater deviation occurs only at an angle of 45°, while with other slope geometries there is a smaller deviation of 2–16%.

For additional analytical comparisons, on the graphs in Figures 9, 10, 11 and 12 are presented the results obtained with a different shape of block, while the shape of the ditch is kept the same. It is

noted that in most of the assumed cases the effectiveness is significant, however the most unfavorable combinations can also be noticed very clearly. On the graphs in Figure 9, in the case of a trapezoidal ditch for slopes of 10 m, the ditch has a high effectiveness in all block shapes. At a height of 20 m and 30 m on a slope, a greater deviation occurs only at an angle of 45°, while with other slope geometries there is a smaller deviation of 2–16%.

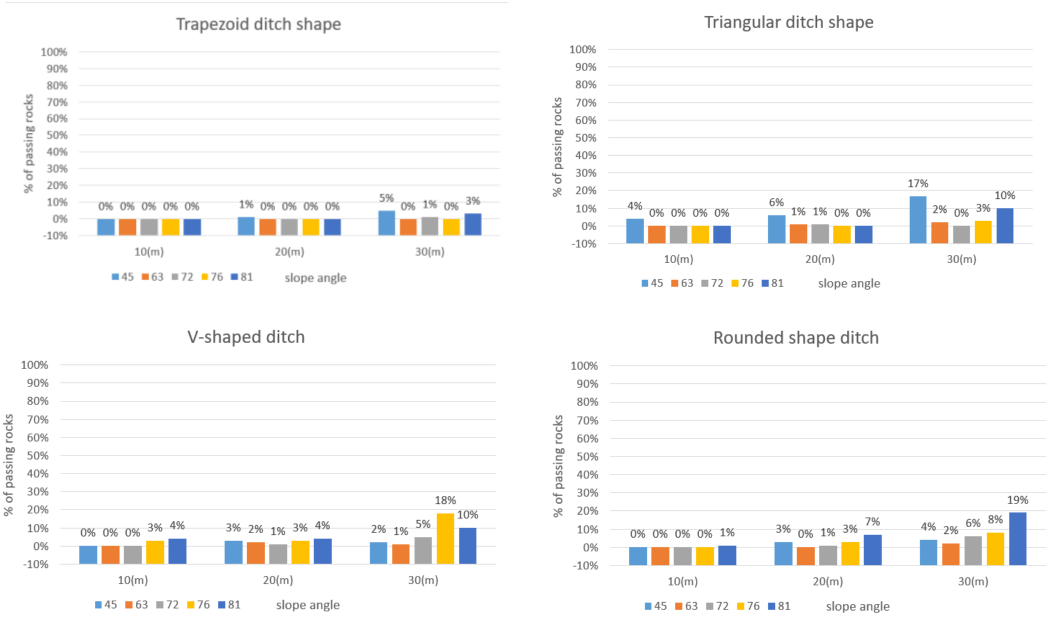
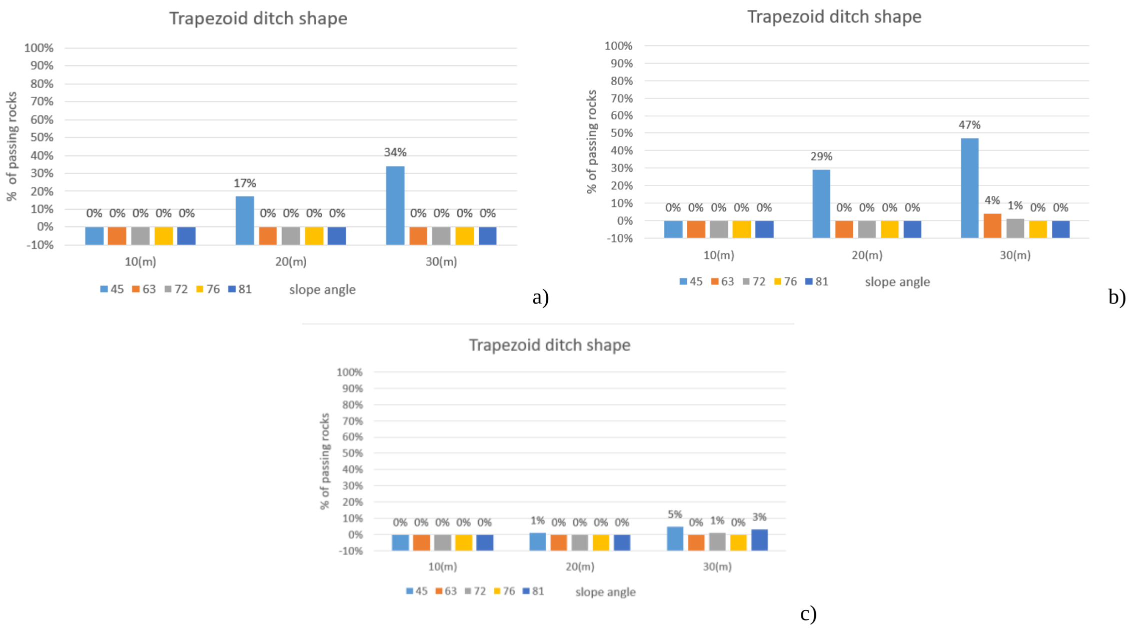


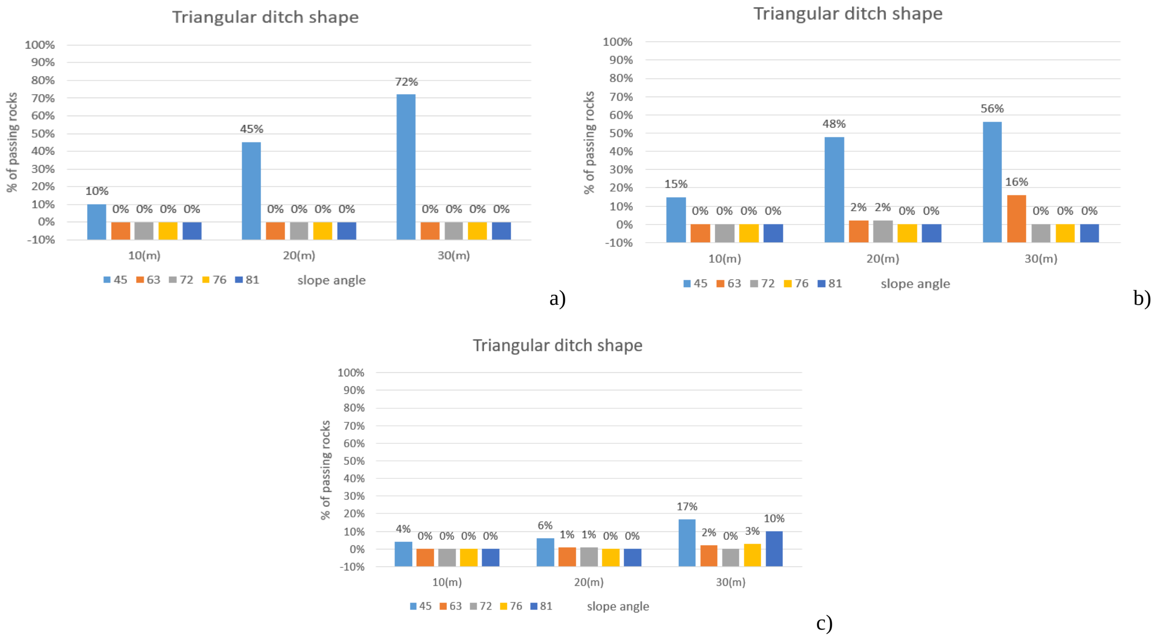
Fig. 8. Percentage of rockfall blocks (elliptical shape) passing the edge of the catch ditch



a) b) c)

Fig. 9. Percentage of block passing the edge of ditch (trapezoid) with the same ditch shape and different block shape a) pentagon, b) square, c) ellipse

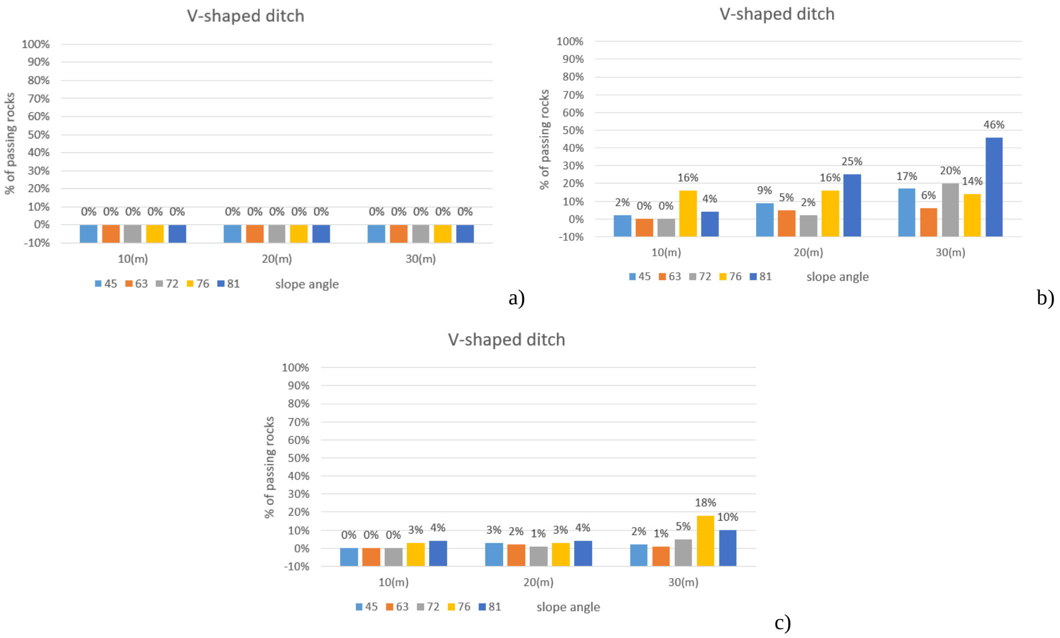
In Figure 10, for a triangular ditch and slopes of 10m, good results are obtained, except at an angle of 45°, where a deviation is observed (4–15%). For slopes of 20 m and 30 m, larger deviations are also seen at an cut slope angle of 45°, and the most unfavorable combination is a slope height of 30 m, an angle of 45° and a pentagonal block shape, where 72% of the blocks cross the edge of the catch ditch. Smaller deviations of 1–16% occur in other slope combinations.



a) b) c)

Fig. 10. Percentage of block passing the edge of ditch (triangular) with the same ditch shape and different block shape a) pentagon, b) square, c) ellipse

In Figure 11, with a V-shaped ditch and a pentagonal block shape, a great effectivenes of the ditch can be seen. If the blocks are square-shaped, the ditch with this shape at different combinations of angles and heights of slopes has a lower efficiency (and up to 46% in one of the combinations). If the blocks are elliptical shape, the percentage of blocks that cross the edge of the ditch are 1–18%.



a) b) c)

Fig. 11. Percentage of block passing the edge of ditch (V-schaped) with the same ditch shape and different block shape a) pentagon, b) square, c) ellipse

In Figure 12 for a circular ditch shape, the least favorable combination is with a square block shape, where a large number of blocks cross the edge of the roadway. The most unfavorable is the case with a cut slope angle of 81° and a height of 30 m (86%). For an elliptical block shape, the highest effectiveness is obtained, where the percentage of unretained blocks ranges between 1–19%.

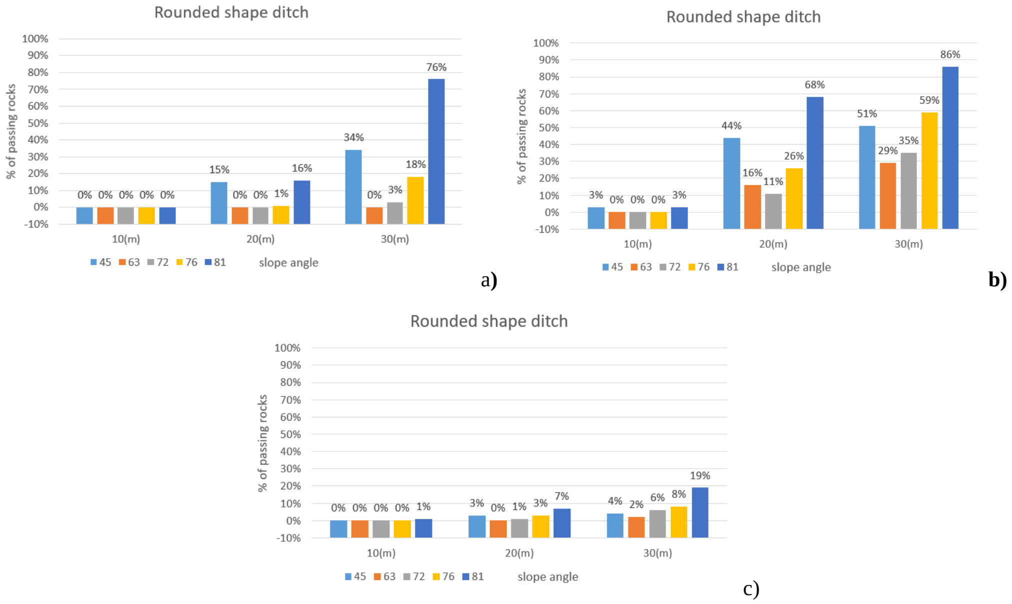


Fig.12. Percentage of block passing the edge of ditch (rounded) with the same ditch shape and different block shape
a) pentagon, b) square, c) ellipse

CONCLUSIONS

The paper analyzes computer simulated trajectories of possible rockfalls in case of slopes/cuts along road sections equipted with rockfall catch ditch as a protection measure. By statistical processing of the results it is concluded that for slopes with a height of 10 m can be recommended to design a trapezoidal ditch that satisfies the effectiveness in all tested variants, i.e. catches the rockfall blocks in all considered conditions of the rockfall event. With the V-shape of ditch, for all analyzed slope heights (10 m, 20 m, 30 m), different inclination and with a pentagonal block shape, a high effectiveness of the ditch is achieved, which also applies to slopes of 10 m with a circular ditch shape. For trapezoidal and triangular ditch shapes, for slope heights of 20 m and 30 m, the most unfavorable case is a slope angle of 45° and it is recommended not to apply these combinations of height/inclination/ditch shape, while for other combinations of slopes and heights, the blocks pass the edge of the ditch but with a lower percentages of 1–17%. With V and circular ditch shape and pentagonal blocks, in most cases with cut slopes of 10 m, satisfactory results would be obtained, but larger deviations should be taken into account at higher slopes. All ditch shapes show the lowest effectivness in the case of falling blocks with square shape. The applied approach makes it possible to perceive the degree of rockfall catch efficiency of ditches in different variants of cut slope and ditch geometry, thus can be recommended for practical design purposes. Depending on the project conditions, a combination with other possible rockfall protection measures is possible and desirable. Final desicion on the design would idealy be based on a respective cost-benefit analysis taking in consideration all direct and indirect influences to the proposed types/combination of measures. Authors stress that before performing these types of rockfall simulation analyses, it is of fundamental importance to collect the respective engineering geological data on the slopes and falling rocks, with searching rockfall databases for similar sections in order to determine the geometric shape of the expected rockfall blocks and appropriate restitution conditions of the cut slope surfaces. Other conditions of the environment should be also considered, such as natural or induced seismicity, vegetation cover, etc.

Acknowledgment: Authors would like to express special thanks to the Faculty of Civil Engineering in Skopje and the company Rocscience, who made it possible to use the RocFall software (Product Key: 8a8c8ac3-ccfa-45f8-8340-b900f166339a).

REFERENCES

Abbruzzese, J. M., Sauthier, C., Labiouse, V. (2009): Considerations on Swiss methodologies for rock fall hazard mapping based on trajectory modeling. *Natural Hazards and Earth System Sciences (NHESS)*, **9**, 1095–1109.

Arbanas, Ž., Grošić, M., Udovič, D., Mihalić, S. (2012): Rockfall hazard analyses and rockfall protection along the Adriatic Coast of Croatia, *Journal of Civil Engineering and Architecture*, ISSN 1934-7359, USA, Vol. **6**, No. 3 (Serial No. 52), pp. 344–355.

Baishan, P. (2000): *Rockfall Trajectory Analysis – Parameter Determination and Application*. A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Engineering Geology in the University of Canterbury.

Bernardi, A. R., Berti, M., Borgatti, L., Corsini, A., Fanti, R. (2008): Structural and non-structural mitigation of landslide risk in road connections: the integration of monitoring and early warning devices in the Scascoli Gorges (northern Apennines, Italy). *EGU General Assembly*, Vol. **10**, EGU 2008-A-08957, 2008.

Dorren, L. K. A. (2016): *Rockyfor3D (v5.2) revealed – Transparent description of the complete 3D rockfall model*. EcorisQ, International Association for Natural Hazards Risk Management.

Guzzetti, F., Crosta, G., Detti, R., Agliardi, F. (2002): STONE: A computer program for the three-dimensional simulation of rock-falls. *Computers & Geosciences,* **28**, 1079–1093. DOI:10.1016/S0098-3004(02)00025-0.

Harp, E. L., Noble, M. A. (1993): An engineering rock classification to evaluate seismic rock-fall susceptibility and its application to the Wasatch Front. *Bulletin of the Association of Engineering Geologists.* **30**, 3, 293–319.

Hopkins, T. C., Beckham, T. L., Puckett, W. A. (1996): *Rockfall mitigation measures*. Research Report KTC-96-9, Kentucky Transportation Center, College of Engineering University of Kentucky, Lexington, Kentucky, 40506-0043.

Lee, J., Barbato, M., Lee, D. K., (2021): Rockfall hazard analysis based on the concept of functional safety with application to the highway network in South Korea, *Rock Mechanics and Rock Engineering,* **54** (3–4).
DOI: 10.1007/s00603-021-02490-3

Pantelidis, L. (2009): Rock slope stability assessment through rock mass classification systems. Aristotle University of Thessaloniki, Thessaloniki, Greece. *International Journal of Rock Mechanics and Mining Sciences,* Vol. **46**, Iss. 2, pp. 315–325.

Paronuzzi, P. (1989): Probabilistic approach for design optimization of rockfall protective barriers. *Quarterly Journal of Engineering Geology and Hydrogeology,* **22** (3), 175–183. DOI:10.1144/GSL. QJEG.1989.022.03.02

Pfeiffer, T. J. Bowen, T. D. (1989): Computer simulation of rockfalls. *Environmental & Engineering Geoscience,* **xxvi** (1), 135–146.

Pierson L. A. (1991): The R*ockfall Hazard Rating System,* Oregon State Highway Division Engineering Geology Group.

Pierson, L. A., Gullixson, C. F., Chassie, R. G. (2001): *Rockfall catchment area design guide*. Final Report SPR-3(032) (Metric edition). Oregon Department of Transportation Research Group and Federal Highway Administration. Report no. FHWA-OR-RD-02-04m.

Piteau, D. R., Clayton, R. (1976): *Description of the slope model computer rockfall program for determining rockfall distribution.* D.R. Piteau Assoc.

Ritchie, A. M., (1963): *Evaluation of Rockfall and its Controll*. Washington State Highway Commission. Paper sponsored by Committee on Landslide Investigations.

Rubinsten, R. Y. (1981): *Simulation and the Monte Carlo Method*. John Wiley & Sons. New York, NY. United States. ISBN:978-0-471-08917-9. Pp:304

Russell, C., Santi, P., Higgins, J. (2008): *Modification and statistical analysis of the Colorado rockfall hazard rating system.* Colorado Department of Transportation, DTD applied research and innovation branch, Report No. CDOT-2008-7.

Saroglou, H., Marinos, V., Marinos, P., Tsiambaos, G. (2012): Rockfall hazard and risk assessment: An example from a high promontory at the historical site of Monemvasia. Greece. *Natural Hazards and Earth System Sciences,* **12** (6), 1823–1836. DOI:10.5194/nhess-12-1823-2012.

Singh, A. (2004): FRHI – A system to evaluate and mitigate rockfall hazard in stable rock excavations, *Journal of the Institution of Engineers (India). Civil Engineering Division.* Vol. **85** (5) 62–75.

Yoon, J., Ban, H., Hwang, Y., Par, D., (2020): Mitigation Method of Rockfall Hazard on Rock Slope Using Large-Scale Field Tests and Numerical Simulations. *Hindawi, Advances in Civil Engineering,* Vol. 2020 (3), pp. 1–6. https://doi.org/10.1155/2020/3610651

Резиме

ПРОЦЕНА НА ЕФЕКТИВНОСТА НА РОВОВИ ЗА ЗАФАЌАЊЕ ОДРОНИ СО РАЗЛИЧНИ ГЕОМЕТРИИ. ПРИМЕР СО ВЕРОЈАТНОСЕН ПРИСТАП

Симона Ивановски[1], Игор Пешевски[2], Милорад Јовановски[2], Сеад Абази[2], Јован Папиќ[2], Даниел Велинов[2]
[1]*Геохидроконсалтинг, ул. Манапо 7, 1000 Скопје, Северна Македонија*
[2]*Градежен факултет, Универзитет „Св. Кирил и Методиј“ во Скопје,*
бул. Партизански одреди 24, 1000, Скопје“, Северна Македонија,
pesevski@gf.ukim.edu.mk

Клучни зборови: ризици; одрони; ров за зафаќање; геометрија; симулација; рационално проектирање

Патниот и железничкиот сообраќај можат да бидат во голема мера засегнати од различни видови геоbecome ризици. Во случај на планински предели, одроните на карпи се сметаат за највообичаен тип на георизик. Тие предизвикуваат економски загуби од различни размери, за жал во некои случаи дури и загуби на човечки животи. Со цел да се подобри управувањето со опасноста и ризикот од одронување на карпи, истражувачите развиле многу различни методо-

логии за процена на опасноста од одроните и за воспоставување ефективна контрола, заштита и мерки за подготвеност. Еден од пристапите е да се примени структурна мерка по должината на патната/железничката линија, во форма на ров за зафаќање на одроните кој се поставува во подножјето на косините. Ефективноста на овие ровови е истражена со експериментални теренски тестови и компјутерски симулации од многу автори, со главна цел да се проектираат ровови колку што е можно поефикасни. Во трудот е претставена примена на компјутерска симулациска техника на одрони во комбинација со веројатносен пристап. Главната идеја е да се тестира ефективноста на рововите за зафаќање одрони при различни геометрии на косините, а при симулирање на одронети карпи со различни геометриски форми. Покрај варирањето на геометријата на ровот и карпата која се одронува, варирани се и височината и аголот на наклонот на косината која се анализира. Резултатите од симулациите со веројатносен пристап го покажуваат различниот степен на ефективноста на ровот во истражените случаи. Пристапот е предложен за употреба во процесот на проектирање, при што главни придобивки се подобреното управување со ризикот од одронување и рационализацијтаа на проектирањето од економска перспектива.