Rockfall hazards – Risk assessment, benefit/cost analysis and the design of flexible rockfall protection systems.

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ABSTRACT: Rockfalls are a major threat to society and infrastructure in mountainous regions. The extension of settlement areas, linked with an increase in traffic combined with the people's need for safety while driving on roads, make rockfall risk assessments and the employment of technical rockfall protection solutions indispensable. However, it is impossible to eliminate all economic and social risks caused by rockfall in mountainous regions. Risk assessments combined with benefit/cost analysis aim to reduce the risk in a structured and transparent framework to an acceptable level while maintaining cost efficiency. Technical risk reduction solutions like flexible rockfall barriers, etc. are effective but costly considering the initial investment and maintenance. This paper discusses the methodology and elements of a conducted risk assessment along with a benefit/cost analysis and how the same was used in the decision-making process of a rockfall hazard mitigation project for a section of a federal road in Austria.

Keywords: Natural Hazards, Rockfall, Risk Concept, Risk Assessment, Benefit/Cost Analysis.

1 INTRODUCTION

Over 70 % of Austria's state territory are considered as mountainous region. In these parts rockfalls are a major threat to society and infrastructure. This paper discusses a pilot project carried out by the Austrian authority Amt der Steiermärkischen Landesregierung - A16 Verkehr und Landeshochbau, Referat Straßeninfrastruktur – Bestand (hereinafter Amt der Steiermärkischen Landesregierung) together with AFRY Austria GmbH aiming to reduce the rockfall risk using technical measures along a section of an Austrian federal road in a structured and transparent framework to an acceptable level while maintaining cost efficiency by employing a risk assessment combined with benefit/cost analyses.

2 THE RISK CONCEPT

The Risk concept for Natural Hazards is structured in three parts. Risk Analysis, Risk Assessment and Measure Studies (Figure 1). It is basically a fleshed-out, adopted variant of the ISO 31000 (2018), which provides a framework and process for managing risks in any sector.

In PLANAT (Nationale Plattform für Naturgefahren, 2009) these guidelines are adopted for Natural Hazards. It is also found within the ASTRA 89001 (Schweizerisches Bundesamt für Strassen, 2009) and applicable for roads and highways.

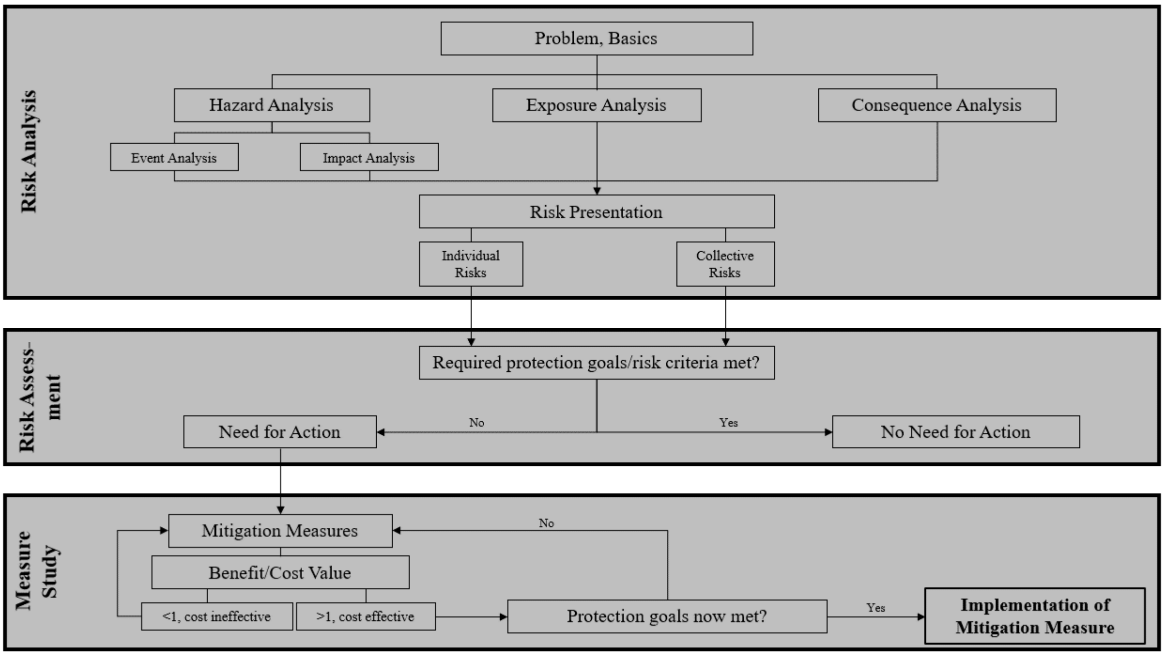

Figure 1. Explaining the Risk Concept, structured in Risk Analysis, Risk Assessment and Measure Study and its subdivisions.

2.1 Risk Analysis

2.1.1 Hazard Analysis

The Hazard Analysis for the discussed section of the federal road called for precise geological and geotechnical mapping of the source area, which is represented by triassic (dolomitic) limestones, the transition area and the deposition area. The bedding planes are moderately steep, mostly moderately and widely spaced and show foliation in some areas. Six different joint sets were found, whereas steep ones are dominating. Occasionally slickensides were found. Furthermore, the same included comprehensive documentation of so-called “silent witnesses”. The later are marks in nature or infrastructure resulting from natural hazards. Together with the documentation of recorded events in the project area (provided by the authority), a profound understanding of important hazard characteristics like block sizes, -shapes and frequency (≙ reciprocal of the return period) was attained. Moreover, the source areas along the 300 m section of the road were distinguished based on (geological) characteristics like the outcrop heights, tectonic deformation, foliation, present joints, natural boundaries, etc. into four separate homogeneous domains (HD). In other words, a HD clusters areas with similar characteristics. In the deposit and transition area of the project, three block sizes (Table 1) were found.

Table 1. Relevant block volume, present in all HD, proportionate occurrence, edge length, mass and density.

	Block volume [m³]	Proportionate occurrence [%]	Edge length [m]	Blockmass [kg]	Density [kg/m³]
Block 1	0.005	70	0.2	12	2700
Block 2	0.025	25	0.5	70	2700
Block 3	0.5	5	1	1400	2700

The information gathered in the course of the hazard analysis so far were harmonized and resulted in the so-called Event Scenarios (block sizes and their numbers, meaning more than one block can fall in one rockfall event). These event scenarios were thoroughly discussed with the client and verified existing documentation of past rockfall events. For every Intensity (Block Size ≙ Energy), the same provides a corresponding frequency (Table 2). The greater the block size, the lower the frequency.

Table 2. HD and their respective event scenarios (block numbers, volumes and the total edge length of those blocks in every scenario).

HD1 (Homogeneous domain 1)

Fequency [1/a]	Block 1 Numbers	Block 2 Numbers	Block 3 Numbers	Scenario Volume [m³]	edge lenght [m]
1/10	5	1	0	0.05	1.5
1/30	10	3	1	0.63	4.5
1/100	30	9	3	1.88	13.5

HD2 (Homogeneous domain 2)

Fequency [1/a]	Block 1 Numbers	Block 2 Numbers	Block 3 Numbers	Scenario Volume [m³]	edge lenght [m]
1/10	3	1	0	0.04	1.10
1/30	5	2	1	0.58	3.00
1/100	15	5	2	1.20	7.50

HD3 (Homogeneous domain 3)

Fequency [1/a]	Block 1 Numbers	Block 2 Numbers	Block 3 Numbers	Scenario Volume [m³]	edge lenght [m]
1/10	12	6	0	0.21	5.40
1/30	16	12	5	2.88	14.20
1/100	20	15	10	5.48	21.50
1/300	150	50	70	37.00	125.00

HD4 (Homogeneous domain 4)

Fequency [1/a]	Block 1 Numbers	Block 2 Numbers	Block 3 Numbers	Scenario Volume [m³]	edge lenght [m]
1/10	2	0	0	0.01	0.40
1/30	5	1	0	0.05	1.50
1/100	7	3	1	0.61	3.90

In the course of the Impact Analysis, the various block sizes of the Event Scenarios were modelled in Rockyfor3D, calculating trajectories of single individually falling rocks, in three dimensions (Dorren, 2016). The terrain parameters were gathered as previously described in the course of the field mapping campaign. To reflect the current local conditions the analyses have been performed considering the forestation and its protective impact. For analysis the Software FINT (Dorren, 2017) was used. The results of the 3D rockfall simulation are used to create intensity maps. The same consists of raster data that are visualized in a Geographic Information System (GIS). The corresponding maps provide information of rockfall intensities (energies in kJ) in the project area.

2.1.2 Exposure Analysis

The Exposure Analysis describes and quantifies lives and materials potentially at risk and monetizes those. In this case, people driving through the road segment and the road itself, as well as economic damages caused by people driving a detour. For evaluation purposes, a traffic count to define the probability of presence, the average daily traffic (ADT) value was carried out. Furthermore, the average speed of the cars (approximately 75 km/h) was recorded. At average, 1.15 people are sitting in a car (VCÖ, 2018) which is driving through the discussed road segment. Based on experience of the state government the costs to repair and maintain the road was defined with 1,000 €/m.

Furthermore, the marginal costs to save a human live was set and considered. The probability of car crashes and preventive road closures as well as road closures subsequently to a rockfall event was considered.

The probability of occurrences of rockfalls are given within each Event Scenario and is defined according to equation (1).

$$Probability\ of\ occurence = Frequency = \frac{1}{Return\ Period} \tag{1}$$

Considering previously discussed parameters and probabilities, a profound knowledge of monetized vulnerabilities was gained.

In order to add a so-called reach probability (equation 2), the rockfall trajectories actually reaching and intersecting the roads, defined in the 3D analyses, where taken into account.

$$Reach\ Probability = \frac{trajectories\ intersecting\ with\ the\ road}{all\ trajectories\ from\ the\ 3D\ rockfall\ simulation} \tag{2}$$

2.1.3 Consequence Analysis

Within the Consequence Analysis, the extent of damage is calculated. For this, the lethality and sensitivity to damage of each scenario is required. The lethality and sensitivity to damage is dependent on the intensity (result of the Hazard Analysis) of the natural hazard at the protection object and is a value/factor that ranges from 0-1. Furthermore, the spatial probability of rockfall has to be defined. The same is defined according to equation (3).

$$Spatial\ Probability = \frac{total\ of\ edge\ length\ of\ blocks\ per\ Scenario\ [m]}{lenght\ of\ homogeneous\ section\ [m]} \tag{3}$$

The spatial probability was multiplied by the reach probability to further reduce the probability, as not every simulation had blocks reaching the road. This takes into account, that rockfalls in reality also do not reach the road in all cases. This methodology is supported by and calibrated with the findings of the site mapping campaign, where blocks were found in the transition area as well as in the erosion channels of the slope. The mentioned three analyses result in risks, usually given in risk per annum or monetary risk per annum (Table 3).

Table 3. Collective personal risk, individual fatality risk, collective material risk and overall risk in all four homogeneous domains. For ADT (average daily traffic), two Scenarios are given (350 and 1300).

HS, corresponding length	HD1 120m		HD2 110m		HD3 165m		HD4 165m	
ADT	350	1,300	350	1,300	350	1,300	350	1,300

collective personal risk [€/a]	400	440	396	426	901	2.576	120	120
individual fatality risk [1/a]	1.1 x 10^{-6}	3.4 x 10^{-7}	1.1 x 10^{-6}	3.3 x 10^{-7}	2.8 x 10^{-6}	2.0 x 10^{-6}	3.4 x 10^{-7}	9.1 x 10^{-8}
collective material risk [€/a]	4,633	17,160	3,226	11,946	6,938	24,010	453	1,681
overall risk [€/a]	5,033	17,600	3,622	12,372	7,839	26,585	573	1,801

2.2 Risk Assessment

In Switzerland, a protection goal was proposed in PLANAT (Nationale Plattform für Naturgefahren 2009) in segments with “no” to “low” self-responsibility (e.g., residents, road users, rail passengers, etc.) and has been considered the standard value in the aforementioned areas since that time. For the maximum individual fatality risk per annum, a value of 1×10^{-5} (1:100,000) was employed in discussed analysis. The same is consequently applied in the online tool EconoMe (Schweizerisches Bundesamt für Umwelt 2022) as the limit value for compliance with the protection goal.

In Austria, the Swiss example was followed and a recommendation for the protection goal for gravitational natural hazards was issued by the Austrian Society for Geomechanics (2014). Here, a value of 1×10^{-5} is also recommended for the maximum individual fatality risk per annum. As shown in Table 3, considering discussed parameters, no mitigation measure has to be implemented as the individual fatality risk per annum is lower than the protection goal of 1×10^{-5}.

For roads in Switzerland, there are additional “soft” review criteria, which are used as a basis for risk assessment (Schweizerisches Bundesamt für Strassen, 2009). These are based on collective risks and are not subject to any protection goal. The review criteria were used as the basis for the action study in the present project:

Criterion 2: Overall Risk on the section > € 100 / m x annum.

Criterion 3: Overall Risk of the process area or ancillary facilities > € 10,000 / m x annum.

Table 3 shows, that the collective risks in HS1, HS2 and HS3 exceed Criterion 2 at an ADT of 1,300. This is caused by the high costs of road closures after a rockfall event leading to detours, which again have a massive impact on the economy. A one-day road closure leads to maximal 1,300 cars making a detour of 1 hour and 60 kilometers. Therefore, productivity is massively reduced.

2.3 Study on mitigation measures

The important part of this study is to find a cost effective however efficient mitigation measure. This can be done with the Benefit/Cost-Value (BCV), equation (4).

$$BCV = \frac{annual\ risk\ reduction}{annual\ cost\ of\ mitigation\ measure} \tag{4}$$

A mitigation measure is cost effective if the BCV≥1. A possible mitigation measure was discussed for the HD1. This section has a winding road layout, a tunnel entrance/exit with linked changing light conditions and short transition distances of falling rocks. According to the intensities, a flexible rockfall barrier with 2 m height and 100 kJ capacity was found to be sufficient (see section 3) to protect the area of interest from Block 1 and Block 2 (Table 1). The barrier cannot retain Block 3. The annual cost of the mitigation measure was calculated according to equation (5).

$$C_a = C_o + C_m + \frac{I_0 - Ln}{n} + \frac{I_0 - Ln}{2} x \frac{p}{100} \tag{5}$$

Whereas C_a: annual cost, C_0: operational cost, C_m: maintanance cost, I_0: Initial Investment, L_n: Residual value after n years, p: interest.

Following the defined parameters the annual cost resulted in 2,940 €/a. The annual risk reduction results in 2,991 €/a considering n=50 years and ADT=350. Therefore, the risk reduction is higher than the annual cost of the mitigation measure and to be judged as cost effective and efficient. This particular mitigation measure eliminates the outgoing risk of Blocks 1 and Block 2.

3 DESIGN OF A FLEXIBLE ROCKFALL BARRIER

Based on the results of the 3D rockfall analyses and field observations, dynamic rock fall barriers were designed for areas of interest. To validate the results gained from the 3D analyses and for barrier design purposes two sections along active erosion channels were selected for further 2D rockfall analyses. These sections represent the most unfavorable situation and common trajectories. All analyses were conducted with the program RocScience Rocfall 7.0. The relevant block sizes and shapes (Block 1 and Block 2) as well as the annually recorded events and consequence class were considered according to ONR 24810 (2021). The 2D simulations confirmed the results of the 3D analyses and the risk potential for the road in discussed section. Without considering rockfall barriers generally 2/3 of the simulated blocks reach the road with an overall low energy potential and low bouncing heights. In order to reduce the potential rockfall risk for the federal road a dynamic rockfall barrier with an adequate energy class (energy class 0, 100 kJ capacity and 2m height) was selected. Based on the analysis results (2D and 3D) and site findings the most suitable location and dimensions (parallel to the road) were defined. Considering the results and the local geological and geotechnical situation the dynamic rockfall barriers and it’s components have been designed according to ONR 24810 (2021).

4 CONCLUSION

The results of the carried out risk assessment combined with benefit/cost analyses showed good correlation with experience and Expert judgement. To further implement the discussed approach a clear legal situation is key, which is currently not the case in Austria. Therefore, many assumptions and uncertainties remain which have to be kept in mind when reading and interpreting this paper. It is not suitable or planned to employ mentioned approach systematically for the entire state road network but for preselected sections of interest.

REFERENCES

Dorren, L. 2016. Rockyfor3d (v.5.2) revealed - transparent description of the complete 3d rockfall model. ecorisQ paper

Dorren, L. 2017. FINT - Find individual trees. User manual. ecorisQ paper

ISO 31000. 2018. Risk management – Guidelines. The International Organization for Standardization

Nationale Plattform Naturgefahren (PLANAT) Schweiz. 2009. Risikokonzept für Naturgefahren – Leitfaden, Swiss Confederation

ONR 24810. 2021. Technischer Steinschlagschutz - Begriffe, Einwirkungen, Bemessung und konstruktive Durchbildung, Überwachung und Instandhaltung. Austrian Standards International

Österreichische Gesellschaft für Geomechanik, 2014. Empfehlung für das Schutzziel bei gravitativen Naturgefahren

Schweizerisches Bundesamt für Umwelt. 2022. EconoMe 5.1, Dokumentation Formelsammlung und Parameter.

Schweizerisches Bundesamt für Strassen. 2012. ASTRA 89001, Dokumentation Naturgefahren auf den Nationalstrassen: Risikokonzept, Schweizerisches Bundesamt für Straßen

VCÖ, 2018. Verkehrsclub Österreich. Durchschnittliche Personenbesetzung eines PkW’s in Österreich, Presseaussendung