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COMBATING THE ROCKFALL HAZARD: A REVIEW OF APPROACHES AND TECHNOLOGIES USED FOR RISK ASSESSMENTS AND MANAGEMENT

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Abstract: Rockfalls pose a significant hazard in mountainous and hilly regions worldwide, threatening infrastructure, public safety, and ecosystems. Triggered by factors such as seismic activity, intense rainfall, erosion, and geomorphological instability, these events often result in severe consequences. Addressing rockfall risks effectively is essential for sustainable infrastructure planning and environmental protection. This review examines traditional and innovative approaches for assessing and managing rockfall hazards, drawing on advancements in geology, civil engineering, remote sensing, and artificial intelligence. Techniques such as terrestrial laser scanning (TLS), 3D modeling, geographic information systems (GIS), LiDAR, and machine learning algorithms have significantly enhanced the ability to detect, monitor, and evaluate these events. The review highlights the progress in understanding rockfall dynamics and developing effective strategies for risk prevention and mitigation. By integrating diverse methodologies, it underscores the importance of interdisciplinary collaboration in addressing the complex challenges posed by rockfall hazards.

Keywords: rock falls; risk assessment; risk management; traditional and innovative methods; advanced technologies

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INTRODUCTION

Rockfalls represent a persistent and significant hazard in mountainous and hilly regions around the world, posing serious risks to infrastructure, public safety, and environmental sustainability. These events are triggered by various factors, including seismic activity, intense rainfall, erosion, and geomorphological instability, often resulting in severe consequences. Effective assessment and management of rockfall risks are thus essential for sustainable infrastructure development and environmental protection.

In recent decades, interdisciplinary research across geology, civil engineering, remote sensing, and informatics has driven the advancement of innovative methods and technologies to detect, monitor, and assess rockfall hazards. While traditional approaches, such as field surveys and stability analyses, remain important, they have been complemented by cutting-edge tools, including terrestrial laser scanning (TLS), 3D modeling, geographic information systems (GIS), LiDAR, and machine learning algorithms. These technologies have significantly enhanced the understanding of rockfall dynamics and facilitated the development of more effective risk mitigation strategies.

This paper offers a comprehensive review of current methodologies and technologies for rockfall risk assessment and management. It examines both traditional and modern approaches, evaluates their efficiency and applicability in diverse geographical and geological settings, and explores their integration into comprehensive hazard assessment frameworks. The review emphasizes the role of advanced technologies in informed decision-making, particularly in relation to infrastructure planning and environmental management.

LITERATURE REVIEW

Seismic Monitoring for Early Warning

An innovative methodology for the early warning of rockfalls, based on the monitoring of microseismic data, was developed. The methodology was based on the observation that the frequency of rockfalls and small landslides increased progressively before larger collapse events. To achieve this, the authors used seismic data recorded by specialized instruments, which underwent a rigorous process of transformation and processing to detect and classify relevant seismic events. To calculate stored energy and forecast potential collapses, a complex algorithm was developed that was based on the analysis of crash frequency data and the use of a sliding time window model. For the precise location of rockfalls on topographic maps, the seismic polarization method was used, and as part of the process of detecting and classifying seismic events, the specialized software DESTRO was implemented. The latter was instrumental in grouping and categorizing seismic events such as earthquakes, rockfalls, and tectonic earthquakes. The obtained data were analyzed and interpreted, providing significant results regarding the distribution of seismic events and their behavior before major collapses. This methodology represented an important contribution to the field of geological risk monitoring and could be used to develop more efficient and reliable early warning systems (Feng, et al., 2020).

One article described the approach to rockfall impact study and the calculation of coefficients of restitution based on field data. Methods used included careful observation and documentation, analysis of impact mechanics, and laboratory testing. The datasets used included field data and laboratory tests on various surfaces, as well as geological attribute data (Wyllie, 2014). Another approach discussed the identification of small-scale rockfall incidents using the seismic signature. The authors proposed an algorithm for the detection of low-energy rockfall events, based on the analysis of seismic signals. They demonstrated the applicability of the algorithm in an experimental context, emphasizing the use of MATLAB software and seismography equipment (Tripolitsiotis, et al., 2015).

An analysis of rockfall monitoring using multichannel synthetic aperture radar (SAR) was also discussed by the authors. They described the methods used in their study, which included DPCA (Displaced Phase Center Antenna), ATI (Along-track Interferometry), and STAP (Space-Time Adaptive Processing). These methods were applied to suppress clutter in SAR data and detect rockfall targets. DPCA was used to suppress clutter from SAR data, and ATI was another method applied to detect rockfall targets. STAP was also used to remove clutter and interference from radar data (Liang, et al., 2019).

The authors presented an innovative methodology for rockfall and earthquake detection and association using multitask learning and transfer learning. RockNet was trained to perform several tasks simultaneously, including picking the arrival time of the seismic phase and masking the waveforms of earthquakes and rockfalls. The knowledge gained from the single-station detection model was transferred to improve the performance of the association model using dynamic weighted averaging (DWA) to estimate the weight of tasks in the loss function during training. Marching Mosaic Waveform Augmentation (MMWA) consisted of overlaying multiple earthquake samples and applying semi-synthetic waveform modifications. Earthquake Early Warning Augmentation (EEWA) involved the use of time-truncated earthquake waveforms with visibility only for P-waves in the receptive field of the model. The datasets contained records from multiple areas (Liao, et al., 2023).

Laser Scanning and GIS-Based Modeling

An approach for rockfall hazard assessment using laser scanning data and 3D modeling in GIS was developed by (Fanos & Pradhan, 2019). This hybrid methodology combines Gaussian mixture models and ensemble artificial neural networks to predict rockfall events. By using high-resolution LiDAR data and historical rockfall records, this study provides a robust framework for accurately assessing rockfall hazards and identifying vulnerable areas along transportation corridors.

Another method utilized for complete rockfall detection is, using machine learning algorithms and resampling techniques to analyze Terrestrial Laser Scanner (TLS) data. By optimizing model parameters, selecting relevant features, and evaluating model performance, this framework demonstrates the potential for automated rockfall detection and monitoring in diverse geological contexts (Zoumpekas, et al., 2021).

In Greece, researchers employed GIS techniques to create rockfall susceptibility zones. Using digital elevation models, geological maps, and precipitation data, this research proposed a matrix-based approach to risk assessment (Saroglou, 2019).

The paper proposed focuses on the key aspects of rockfall modeling, hazard and associated risk assessment, and identification of countermeasures required for rockfall protection. The methods used, such as 3D modeling, probabilistic risk analysis, and quantitative risk analysis, demonstrate a comprehensive and rigorous approach (Crosta, et al., 2015).

Another perspective is also demonstrated in the utility of LiDAR technology and geographic information systems in the assessment of rockfall hazard in different scenarios. The integration of 3D modeling and spatial analysis using the Analytic Hierarchy Process (AHP) provides a detailed approach to rockfall risk assessment (Fanos, & Pradhan, 2016). At the same time, researchers presented another approach that focuses on the use of terrestrial photogrammetry for monitoring the slope and detecting changes that could indicate impending rockfalls. The proposed method integrated remote sensing image analysis to improve the early detection of rockfall events. The use of software such as ArcGIS and Matlab enabled the efficient processing and analysis of photogrammetric data, helping to reduce false alarms and improve the reliability of the detection system (Panagiotis, Kallimani, & Tripolitsiotis, 2015).

This study introduced a new rockfall activity index (RAI) based on morphology and lidar data for rockfall hazard assessment. Using terrestrial laser scanning, they developed a high-resolution method for mapping rockfall activity and identifying risk areas (Dunham, et al., 2017).

This research focused on quantifying sediment transport caused by rockfalls and landslides in a mountain area in Austria. Using LiDAR and ALS data, researchers used DEM of Difference (DoD), which is a technique used to compare two or more digital elevation models (DEMs) and identify topographic changes that occurred in a certain area in time. This method involves subtracting the elevation values from one DEM from the corresponding values of another DEM in order to highlight the differences between the corresponding elevations in the two data sets, allowing authors to observe and analyze elevation changes and material movement patterns in the landscape over a specific time frame (Vehling, et al., 2017).

The investigation of rockfall threats has also interested other authors who propose an approach combining LiDAR technology with spatial modeling to assess and manage rockfall risk. Using high-resolution LiDAR data and digital elevation models, the authors were able to simulate rockfall trajectories and assess potential infrastructure damage. Spatial modeling and the use of specialized analysis tools allowed the identification of high-risk areas and the provision of recommendations for managing these risks. Integration of historical rockfall data and validation of simulated results ensured the accuracy and reliability of the rockfall hazard analysis (Lan, Martin, Zhou, & Lim, 2010).

This study demonstrates the effectiveness of change-based simulations for understanding and managing rockfall risks. The authors focused on the simulation of fragmented rockfalls detected using terrestrial laser scans from rocky slopes in south-central British Columbia, Canada. It thus used a change-based simulation approach, where the results of the simulations are compared to the changes observed in real rockfall events. The simulations are performed using a set of parameters that include dynamic friction coefficients, restitution, and viscoplastic soil strength. They used different sets of parameters for each location, and several simulations are performed to evaluate the rupture of the 24 m^3 wedge, considering various levels of fragmentation. To fragment source rockfall volumes, Voronoi fracturing is used, a method that divides the source mesh into disjoint convex polyhedra. The possibility of using resistance-based connections between simulated fragments as a potential method for simulating source volume rupture during depletion is discussed. In terms of datasets, Terrestrial Laser Scanning (TLS) data are essential because they provide high-resolution 3D grids that provide detailed information on the topography and geometry of areas of interest. Also, rockfall volumes extracted from TLS scans play a crucial role in the simulation. To perform the simulations and analyze the results, several software programs are used, including Blender for Voronoi fracturing and Unity Game Engine for using simulated fragmented 3D volumes. It is also implied that there is custom software or workflows developed for simulation and analysis, given the mention of a "rockfall modeling prototype" (Sala, Hutchinson, & Harrap, 2019).

The study focused on the use of drones to monitor, investigate, and design risk reduction measures on a rocky slope with multiple failure mechanisms. Rigid body methodology was used to model rockfalls. The shape of the falling block was simulated as a cube with rounded edges and specified as a "fourth-order superellipse". The study assumed a block with a diameter of 0.5 meters and a mass of 896 kg. The modeling did not take into account the disaggregation of the blocks, taking into account the largest dimensions found on the highway. Typical energy return coefficients for different slope materials were used, which were modified to match the material distribution observed on the highway. For data collection, digital photogrammetric techniques were used, including UAV surveys to obtain high-resolution point clouds. The point clouds were processed using digital photogrammetry software to reconstruct the topography. To improve the accuracy of the point cloud, ground control points (GCPs) were used. The Root Mean Square Error (RMSE) was used to evaluate the accuracy of the georeferencing process. The M3C2 (Model-to-Model Cloud Comparison) method was used to assess surface changes between different surveys. The drainage network was calculated using a digital elevation model (DEM) generated from the UAV point cloud. 2.5D rockfall analysis was performed with RocFall software to model rockfall trajectories of different sizes. Based on the analysis, risk mitigation strategies were proposed, including the use of catch nets, slope maintenance, and other measures (Rodriguez, et al., 2020).

Numerical and Probabilistic Modeling

This assessment of rockfall risk along roads is based on various methods, including a modified version of Ritchie's design diagram, the SMR method (SMR-Romana, 1985, 1988, 1991) for evaluating geological features, and Hoek's rock fall program for analyzing road cross sections. Data used in the assessment include climate data, traffic data, historical rockfall data, and datasets for numerical analysis. Software used in the evaluation process included Rockyfor3D, ST-Rate, and ROCKFALL (Budetta, 2004).

This work focused on the calibration and validation of rockfall modeling parameters in the Mallorca region, Spain. The methods used included statistical analysis, rockfall modeling, and reliability tests. Data sets used included geotechnical units, rockfall events, digital terrain models (DTMs), and specific road sections. Software used included Rockyfor3D, ST-Rate, and other applications for simulating rockfall trajectories (Mateos, et al., 2015).

Another study focused on three-dimensional numerical modeling of rockfalls, using probabilistic approaches to assess the associated risk. By integrating geologic, topographic, and climate data, this study provides a deeper understanding of rockfall dynamics (Agliardi, & Crosta, 2003).

Also, in this proposed article, the authors developed a tool for estimating the probability of rockfall events on transport networks. Using data on slope condition and past events, they implement a statistical-probabilistic approach to risk assessment and decision-making in geotechnical asset management (Mines, et al., 2018).

Another study presented compares deterministic and probabilistic approaches in risk assessment associated with several hazards, including rockfall. The use of specialized software for numerical simulation and probabilistic assessment provides a comprehensive and detailed insight into the multiple risks associated with road infrastructure (Oberndorfer, Sander, & Fuchs, 2020).

The authors presented a detailed analysis of rockfall hazards in the Sorrento Peninsula of Southern Italy. The methods used in this study encompass a wide range of geological, structural, and numerical techniques that have been applied to assess and manage rockfall risk in the area. As part of geological and structural surveys carried out between 2002 and 2007, detailed field surveys were carried out using alpine techniques to examine the vertical cliffs. These surveys included analysis of macro- and meso-scopic features, such as discontinuity type, orientation, spacing, and aperture. Estimates of the shape and size of unstable rock blocks were also made, and geo-mechanical classification was performed using the Slope Mass Rating (SMR) index. Through field experiments, a number of 24 unstable blocks were measured and artificially released, and the impact points and deposition locations were determined for each of these blocks. In terms of numerical modeling, several specialized techniques and software were used. GeoRock (2D) was used to estimate preliminary rockfall trajectories, maximum distance traveled, and energy dissipation. Rotomap (3D) was implemented to model trajectories in 3D, providing information on arrival points, maximum energy, and block height. GeoRock 3D allowed the modeling of fall trajectories in 3D, taking into account total energy conservation.

In addition, Stone (3D) was used for a physically based 3D kinematic distributed modeling of rockfall processes, taking into account the location of detachment zones, elevation data, and dynamic coefficients. The datasets used included geological and morphological information, obtained from existing topographic and geological maps, as well as data collected during field surveys. A digital elevation model (DEM) was created using terrestrial laser scanner data, providing high resolution for terrain analysis. Various specialized software, such as GeoRock (2D and 3D), Rotomap (3D), and Stone (3D), were used to implement these methods and analyze the data, which provided the necessary tools for rockfall risk assessment and management in the Sorrento Peninsula. Also, through modeling and probabilistic calculations, the authors identified the hazards and proposed risk management strategies to ensure the safety of rail traffic (Palma, Parise, Reichenbach, & Guzzetti, 2011; Macciotta, et al., 2017).

The authors examined rockfall risk assessment for people traveling in vehicles along the Amalfi Coast Road in Southern Italy. The methods used in this study include trajectory analysis, probabilistic risk assessment (PRA), the binomial theorem, spatiotemporal probability, and the standard normal cumulative distribution. Trajectory analyses are used to study the trajectory of falling rocks and their impact on vehicles. Probabilistic risk assessment (PRA) quantifies the probabilities of different rockfall scenarios. The binomial theorem is applied to calculate probabilities, and the spatiotemporal probability is evaluated to determine the probability of vehicles being affected by rockfall. The use of the standard normal cumulative distribution is mentioned for calculating the spatiotemporal probability. Various datasets were used to support these methods, including traffic volume data, road characteristics, rockfall class data, and historical information on rockfall events and their consequences. Spatial data was also used to identify road sections and their characteristics (Ferlisi, Cascini, Corominas & Matano, 2012).

Qualitative and Quantitative Risk Assessment

This article focused on the comparison between qualitative and quantitative rock fall risk assessment methods for a road section affected by severe rock falls. The authors discuss two main methods, the Modified Colorado Rockfall Hazard Rating System (mCRHRS) and Rockfall Risk Management (RO.MA.), highlighting both their advantages and limitations. They emphasize the importance of subjectivity in qualitative assessment and the need for a personalized approach in quantitative risk assessment (Budetta, & Nappi, 2015).

A comprehensive and detailed analysis of the methods used to assess the risk and hazards associated with rockfall in road infrastructure. The author explores three main hazard and risk assessment methods - the Evolving Rockfall Hazard Assessment (ERHA), the Modified Rockfall Hazard Rating System (mRHRS), and Rockfall Risk Management (RoMa) as well as their associated datasets. By presenting these methods, the author succeeds in providing a complete picture of the diversity of approaches available in rockfall risk assessment. The ERHA method is characterized as qualitative, focusing on the geostructural configuration of the area and the activity of the rock mass. The mRHRS is described as semi-quantitative, requiring detailed information on various factors such as block volumes and weather conditions. RoMa is presented as a quantitative method that provides reliable risk assessment through customizable event tree analysis (Mineo, 2020).

This assessment used the Tennessee RHRS to classify potential rockfall modes in road cuts. Methods used included rockfall hazard assessment and logistic regression analysis. Data sets used included data on geological attributes and dependent variables for logistic regression (Vandewater, 2005). This study focused on the quantitative analysis of rockfall risks and the identification of mitigation measures in a region with a high frequency of rockfalls. Using 3-D point cloud data and rockfall simulations, the authors assessed hazards and proposed hazard mitigation measures (Jiang, & Zhou, 2021).

Also, the rock slope evaluation procedure was implemented by the New York State Department of Transportation (NYSDOT), initially based on a procedure developed by Duncan C. Wyllie and later, a new evaluation system known as Total Relative Risk (TRR), which was developed internally as a risk assessment system. Using databases and GIS, researchers were able to effectively assess and manage the risks associated with rock slopes. They conducted field evaluations of the rock slopes, inspecting and evaluating them based on various criteria such as geology, block size, rock friction, presence of water/ice, rockfall history, and backslope above the cut, contributing to improving road infrastructure safety and human exposure to danger (Hadjin, 2002).

In this study the authors focused on the development and application of a rockfall hazard assessment system for the Poladpur-Mahabaleshwar highway in Western India. The method involves collecting and analyzing a diverse set of data, including topographical, climatic, geological, and traffic data, to assess the risk and consequences of rockfalls at various locations along the highway (Ansari, et al., 2015).

The authors focused on the assessment of rockfall susceptibility and vulnerability of the rural road network in the Harz Mountains of Germany. The methods used include a bivariate statistical approach and an indicator-based method, both applied to assess different aspects of rockfall risk and vulnerability of the road network. The bivariate statistical approach involved modeling rockfall susceptibility using several factors such as elevation, slope, material characteristics, road orientation, distance to faults, and weather conditions. These factors were evaluated and weighted using the information value method, and then a susceptibility index was calculated for each study area. The indicator-based method was used to assess the vulnerability of the road network, taking into account indicators such as average daily traffic volume, road type, speed reduction, and length of alternative routes. The weighting factors for these indicators were determined using the Analytic Hierarchy Process (AHP), and then a vulnerability index was calculated for each road section. Various datasets were used to support these methods, including rockfall information, thematic maps containing morphometric factors and material characteristics, and road network data in the study region. GIS-based analysis was performed using QGIS software, which was used for susceptibility modeling and spatial analysis. Receiver operating characteristic (ROC) analysis was used to validate the model, and AUC (Area Under the Curve) was calculated from the ROC plot to evaluate the performance of the susceptibility model. In addition, to determine the weighting factors in the indicator-based methodology, the Analytical Hierarchy Process (AHP) was used, which contributed to establishing the relative importance of different indicators in assessing the vulnerability of the road network (Wohlers, & Damm, 2022).

At the same time, the authors focused on the assessment of vulnerability to rockfalls in the Coziei Gorges of the Southern Carpathians, Romania, by using a mechanical Schmidt hammer with the aim of establishing the compressive strength of rock surfaces below the degree of weathering, the characteristics of cracks (density, width, orientation, continuity), and the dimensions of the fallen blocks. The data were mapped by GPS in order to establish their location, and scatter diagrams were used in order to identify the quantitative relationships between the variables (Ovreiu, et al., 2019).

Remote Sensing and Digital Tools

This article presents an integrated tool for assessing rockfalls along transport corridors. Through remote sensing techniques, morpho-structural analysis, and field surveys, this tool provides a comprehensive approach to rockfall risk assessment. By incorporating geological data, 3D terrain analysis, and rockfall simulations, it enables stakeholders to make informed decisions about risk mitigation strategies and infrastructure planning (Cloutier, et al., 2016).

Also, this article proposed the use of LiDAR technology for monitoring and early detection of deformations on rocky slopes. A detailed analysis of topographic changes and detected deformations demonstrates the technology's utility in identifying rockfall precursors (Kromer et al., 2015).

This paper proposed a modified Rockfall Hazard Assessment System method for hazard and associated risk assessment in a specific region of Pakistan. The authors proposed the integration of geostructural analysis and animal activity along highways, and in the hazard assessment system, it adds a new dimension to the understanding and management of rockfall risks (Tanoli, et al., 2022).

This study explored the benefits of using remote sensing in rockfall hazard assessment. By using optical imaging and UAV technology, the authors, were able to obtain high-resolution images for detailed assessment of the slope and associated risk factors (Bouali, et al., 2017).

This study explored the use of lidar and deep learning technologies for rockfall detection. By implementing deep learning architectures such as PointNet and PointNet++, the authors demonstrated the effectiveness of these models in rockfall detection and classification from 3D lidar data (Farmakis, et al., 2022).

The article presented by the researchers was a comprehensive approach to reducing the risks associated with road transport. Through a combination of methodologies, datasets, and potential software solutions, it aims to improve safety and efficiency in the transport sector. The methodologies used in the development of this system are based on risk assessment and quantification, bringing statistical and modeling approaches to the fore. An essential component of the system is the data sets used. These include data on various road transport risks, geospatial information, and real-time traffic data (Dobre, Ilie, Săvulescu, & Teodor, 2017).

The authors addressed rockfall susceptibility assessment and vulnerability assessment of the Italian railway network. Methods used included statistical modeling to assess rockfall susceptibility and the application of graph theory to railway network analysis. Statistical modeling for rockfall susceptibility assessment involves developing a mathematical model that can use various statistical techniques, such as logistic regression or machine learning algorithms. Using graph theory to analyze the railway network involves calculating edge betweenness and evaluating its variation when certain specific edges are removed. This approach allows the identification of vulnerable points of the railway network and the assessment of the risk of rockfalls in different sectors of the railway infrastructure. Various datasets were used to support these methods, including topographic units, the Italian National Landslide Inventory (IFFI) for validation, and railway network data. A digital elevation model (DEM) was also used to analyze terrain features and identify areas prone to rockfall (Alvioli, et al., 2021).

Regional Studies and Applications

Another article focused on rockfall risk assessment and management in the Kula Geopark region of Manisa, Turkey, was presented. To achieve this, detailed field surveys were carried out, including scan line surveys, determination of earth stake locations, and extensive geological descriptions. Furthermore, laboratory studies were conducted to determine the geomechanical properties of the rocks, such as water absorption by weight and uniaxial compressive strength. For numerical analyses, programs such as Rocfall and Conefall were used to evaluate the trajectories, flow distances, and velocities of basalt blocks in the case of rockfalls. Data sets used included field data, laboratory data, topographic data, and input data for numerical analyses (Binal, & Ercanoğlu, 2010).

This study focused on rockfall hazard assessment in a specific area of the Himalayas. The methods used, such as kinematic analysis and slope mass assessment, are adapted to the specific conditions of the region and provide a detailed understanding of the rockfall hazard in this area (Gupta, & Tandon, 2014).

Investigating the hazards and risks associated with rockfall in the Nera Valley of central Italy was also an interesting topic for researchers who assessed the rockfall hazard and identified high-risk road sections. Raster analysis and heuristic approaches were used to assess hazard, while overlap analysis and road network assessment were essential to assess road infrastructure risk. GIS software and simulation tools have enabled the generation of hazard maps and provided recommendations for risk management in an efficient and proactive manner (Guzzetti, Reichenbach, & Ghigi, 2004).

The study analyzed the threats posed by rockfall in the Swiss Alps region and proposed an integrated hazard and risk assessment method for road infrastructure. Using geological and topographical data, applied statistical analysis and spatial modeling to assess hazard and identify high-risk areas (Michoud, et al., 2012).

Also, the authors analyzed the hazards generated by rockfall in Hong Kong and proposed a method to assess these risks based on a detailed inventory of rockfall events. Using various statistical techniques and GIS software, the authors developed magnitude-frequency curves and analyzed correlations between collapse events and rainfall data to identify trigger conditions. Precipitation data and geological information were essential for hazard assessment and identification of areas at high risk of rockfall. Using software specialized in spatial analysis and geographic data management, the researchers were able to provide a detailed picture of the rockfall hazard in the densely populated urban region of Hong Kong (Chau, Wong, Liu, & Lee, 2003).

Focused on the spatial and temporal activity of rockfall in a forest stand in the Swiss Prealps, using a dendrogeomorphological approach. The research involved collecting tree cores or stem discs from trees in the study area. Analysis of tree rings and associated scars on trees allows researchers to reconstruct past rockfall events. The primary data set probably consists of three-ring data obtained from the sampled trees. Each tree ring can provide information about a particular year, and ring scars can be correlated with rockfall events. Information about rockfall events, including their location, magnitude, and timing, is likely included in the dataset. At the same time, a varied range of software was used for this study (Perret, Stoffel, & Kienholz, 2006).

The study carried out by the authors focused on the use of advanced dendrogeomorphology methods for the reconstruction of rockfall activity in the Cozia Massif. The dendrochronological samples were collected from 40 Picea abies trees. Growth rings were measured using digital methods, and growth disturbances caused by stone falls were identified, including impact scars, traumatic resin canals, compression wood, and sudden suppression of growth rings. The Conditional Impact Probability (CIP) was calculated to correct for any missed rockfall events in tree rings, with each tree covering an area of slope exposed to rockfall, defined as an “impact ring”. Growth disturbances from tree rings were interpolated to visualize the spatial distribution of rockfall activity, and rockfall trajectories were mapped based on these. Meteorological parameters were correlated with the reconstructed rockfall activity, with the Pearson correlation coefficient calculated to quantify the relationship between rockfall activities and meteorological variables (Ovreiu, Oprea, Topârceanu, & Pintilii, 2024).

Machine Learning Applications

This study examined the use of event tree analysis (ETA) for rock fall risk assessment on mountain transport routes. Through advanced simulations and probabilistic analyses, the researchers propose a method for modeling and managing the risk associated with these events (Mineo, Pappalardo, D'Urso, & Calcaterra, 2017).

The use of the machine learning technique is also discussed by the authors in this paper. They created a model for predicting the probability of rockfall presented as an innovative approach in this field. The K-Nearest Neighbors (KNN) method and cluster analysis are used to identify and classify the risks associated with rockfalls, providing a new and effective insight into this process (Regina, Milene & Barreto, 2022).

The study presented explores improved semi-automated processing for creating rockfall databases. Using an innovative approach, the authors developed and evaluated improved algorithms for the detection and classification of topographic changes associated with rockfalls. Through the M3C2 method, the authors introduced a modification of the M3C2 method to improve the detection of topographic changes. This change aims to reduce errors in the shift calculations by limiting the extent and direction of the cylinder projection. Machine learning algorithms, specifically a random forest classifier, were used to automatically classify point cloud clusters. This classifier was trained on specific parameters and features derived from the new point data. The study used synthetic data and real rockfall data to test the shift algorithm. Also, the Lidar scans collected for this area covered a significant period of 178 days (Schovanec, Walton, Kromer, & Malsam, 2021).

Multi-Method Approaches

The authors proposed to discuss the development of an operational methodology for the management of rockfalls on the road network, with an emphasis on a scenario-based approach and the use of an operational monograph tool. Thus, they highlight the importance of using geological data, web services, and GIS platforms in the risk management process (Giordan, et al., 2021).

The method introduced in this article focused on the evaluation and applicability of different rock slope assessment systems in Alberta, Canada, for geotechnical asset management. The authors presented an approach that involves field inspections, remote sensing data collection, and historical data analysis. They highlight the use of GIS and photogrammetry software for analysis and visualization (Wollenberg-Barron, et al., 2023).

The study explored methods for forecasting and managing rockfall risk in the Italian Alps. Using ground-based interferometric radar (GBInSAR) technology, they monitored ground movements and applied various analytical methods to assess rockfall risk and effectively manage these situations. One of the main methods of analysis is the "Inverse Velocity Method", which uses the extrapolation of the velocity trend over time to determine the likely time of fall. Another method, known as "Hao's Method", provides a new criterion for determining the time of fall, taking into account acceleration and velocity. These methods were applied to data obtained from GBInSAR technology, which provides high spatial resolution and optimal sampling frequency. In addition, the researchers integrated rainfall data to assess its impact on rockfall. By analyzing displacement patterns over time and predicting the time of fall, they were able to provide accurate risk estimates for the transport infrastructure in the Alpine region (Carlà, et al., 2019).

Another study proposed an edge detection-based registration algorithm for point cloud data collected by different platforms and in different epochs (Bolkas, Walton, Kromer, & Sichler, 2021). By using terrestrial laser scanning, terrestrial photogrammetry, and other technologies, the authors developed an effective method for monitoring rockfalls and assessing topographic changes over time. In addition to the risks associated with rockfalls on highways, it uses relative assessment methods and hierarchy analysis to determine the hazards and vulnerabilities associated with road infrastructure. With the help of comprehensive datasets and specialized software, the authors identified risk areas and proposed appropriate protective measures. This studio also went in this direction, using event tree analysis and other quantitative methods to assess the risks associated with the rockfalls on the railway (Li, Huang, Xue, & Yin, 2009).

Infrastructure and Risk Interaction

The method introduced in this article focused on the interaction of transport infrastructure with natural hazards such as rockfalls and landslides. Using an integrated and multidisciplinary approach, this study highlights the importance of effective natural risk management in the context of transport infrastructure (Verma, et al., 2019). In addition, other studies focused on the investigation of rockfall assessment methods in various geographic regions. By integrating field data, numerical modeling, and seismic analysis, these studies provide a deeper understanding of the factors that contribute to rockfalls and propose solutions to reduce the associated risks. Each article addresses different aspects of this field, such as three-dimensional modeling, kinematic analysis, the use of machine learning techniques, and associated risk assessment (Jirásko, Vaníček, & Vaníček 2018). Another perspective examined the analysis of rockfalls along transport corridors on high hillslopes. By using field inspections and 2D rockfall analysis, the authors assessed potential hazards and determined critical parameters of the fall process (Singh, Kainthola, Panthee, & Singh, 2016).

Another study presented a GIS extension for rockfall hazard modeling that used spatially distributed 3D data. Using distributed modeling and 3D techniques, the authors developed a tool for rockfall risk assessment and risk area identification in a GIS environment (Lan, Martin, & Lim, 2007).

The article presented refers to a detailed analysis of the railway infrastructure in Romania, with an emphasis on its improvement through a geomorphotechnical map. By combining analytical methods and varied data, the study provided a comprehensive insight into current conditions and possible improvements. The study methodology involved the use of cartographic analysis and quantitative analysis for assessing and understanding the geographical and geological features of the railway section. The study uses a variety of data sets, including geological and historical data, to gain a complete understanding of the environment and past challenges faced by rail infrastructures (Mihai, Dobre, & Săvulescu, 2014).

The authors bring to the fore a meticulous and detailed approach to the analysis of the railway infrastructure in Romania, focusing on its improvement through a geomorphotechnical map. With a particular focus on the Prahova River Gorge in the Curbura Carpathians, this study provided a broad view of the terrain conditions and possible improvements. The methods used in this study are varied and detailed. The field survey, using a classic 1:2,500 scale map and digital photographs, along with GPS surveying of key points, demonstrated a strong commitment to obtaining accurate data. In addition, the use of digital data sources such as digital elevation models and orthophotographs effectively complements the analysis. The study used a wide range of data sets, including geomorphic data and technical infrastructure data, to perform a comprehensive analysis (Dobre, Mihai, & Savulescu, 2011).

METHODOLOGY

This study systematically reviews 60 peer-reviewed articles to analyze the methodologies applied in rockfall risk assessment and management. The review examines both traditional approaches and advanced technologies, evaluating their effectiveness, limitations, and potential for integration within risk management frameworks. As a first step, a conceptual synthesis was developed by the author to summarize and organize the main research topics already addressed in the existing review literature (Figure 1). This overview identifies the thematic structure of current research and highlights the main methodological trends and topic interrelations in the field.

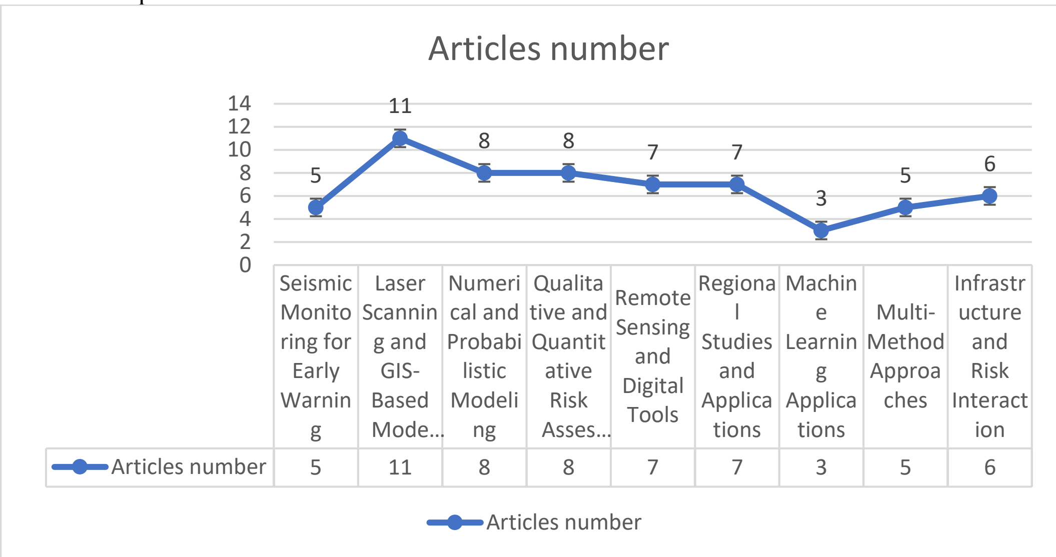

Figure 1. Overview of the topics and the number of respective articles in each category
(Source: Author's synthesis based on the 60 peer-reviewed articles;
data retrieved from Scopus & Web of Science, 2025)

To complement this synthesis, a bibliometric analysis was performed to explore publication dynamics and thematic distributions. The analysis included the annual evolution of publications related to rockfall risk assessment (Figure 2) and a categorization of reviewed papers by research domain, together with the number of publications in each category (Figure 3).

The bibliometric data used for Figures 2 and 3 were collected from the Scopus and Web of Science databases (2025), using the keywords "rock," "falls," "risk," and "assessment" in titles, abstracts, and keywords. These datasets provided quantitative insights into the evolution and structure of the research field.

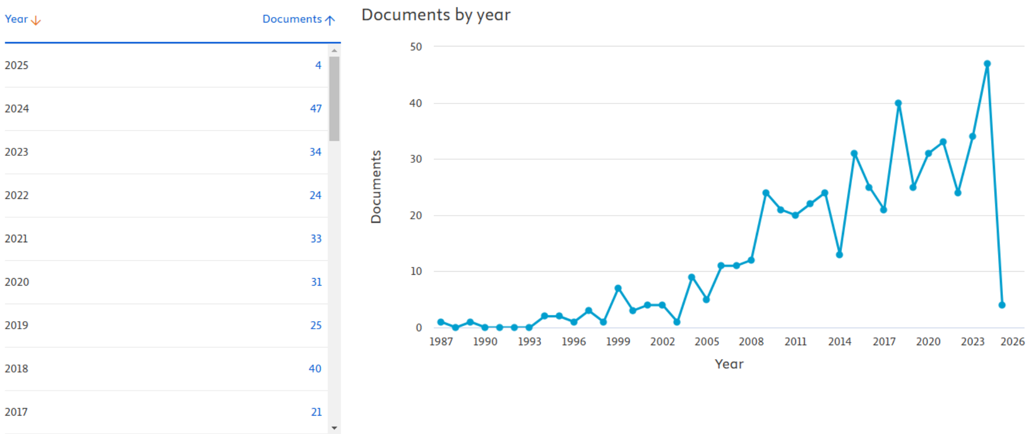

Figure 2. Overview of the number of respective articles published each year
(Source: Scopus bibliometric analysis, 2025)

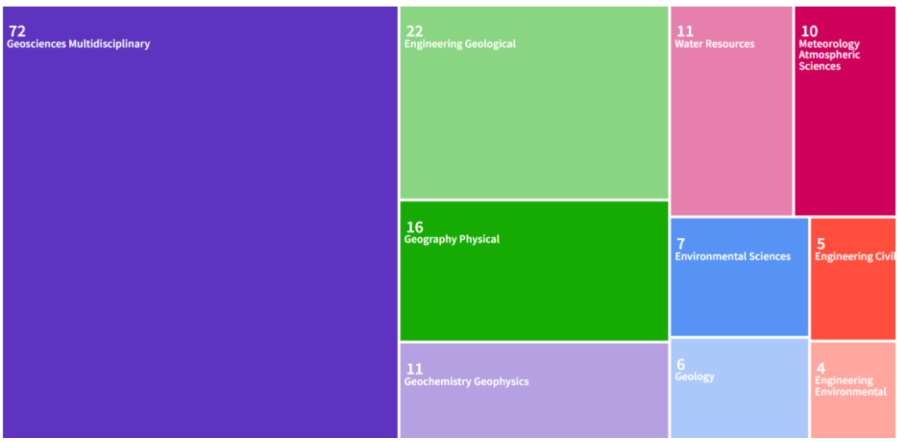

Figure 3. Overview of topic categorization based on research domain and the number of respective articles in each category
(Source: Clarivate bibliometric analysis, 2025)

RESULTS

Traditional rockfall risk assessment methods, such as field-based surveys and empirical models, continue to form the foundation of many rockfall studies. These approaches provide reliable initial evaluations of rockfall hazards, especially in regions with limited access to advanced technologies. However, their reliance on manual effort, local expertise, and the time-consuming nature of data collection pose limitations to scalability and the ability to assess large areas.

Key Outcomes of Traditional Approaches:

Accurate Geological and Geomorphological Characterization: Traditional methods enable detailed site-specific assessments, providing insights into the geological and geomorphological conditions that influence rockfall occurrence.

Baseline Data for Preventive Measures: Field surveys and empirical models yield valuable baseline data for initiating preventive actions, such as slope stabilization, rockfall barriers, or hazard zoning, that can mitigate risks in vulnerable areas.

Advanced Technologies

In recent years, the adoption of advanced technologies has significantly improved the accuracy, efficiency, and scalability of rockfall hazard assessments. The incorporation of tools such as Terrestrial Laser Scanning (TLS), Geographic Information Systems (GIS), LiDAR, and machine learning algorithms has revolutionized the field by enabling more detailed, dynamic, and large-scale assessments.

Terrestrial Laser Scanning (TLS): TLS enables the creation of high-resolution 3D models of slope surfaces, providing precise measurements of rockfall volumes, trajectories, and potential impact zones. This method is highly valuable in capturing detailed surface features that are critical for accurate hazard modeling.

Geographic Information Systems (GIS): GIS allows for the spatial modeling of rockfall susceptibility by integrating various datasets, including geological, climatic, and infrastructural information. This spatial analysis enhances decision-making, providing insights into areas of high vulnerability and enabling targeted interventions.

LiDAR: LiDAR provides extensive topographic data that can be used to create highly detailed susceptibility maps. The ability to collect data from large areas quickly makes LiDAR a powerful tool for assessing rockfall hazards in difficult-to-reach locations.

Machine Learning Algorithms: Machine learning enhances predictive modeling by identifying complex patterns within large datasets, such as historical rockfall events, weather patterns, and topographic features. These algorithms allow for dynamic risk assessments and provide forecasts that adapt to changing conditions.

Integration of Traditional and Advanced Approaches

The results indicate that a combined approach, integrating traditional field-based surveys with advanced technologies, offers the most comprehensive assessment of rockfall hazards. This hybrid methodology leverages the strengths of both approaches, improving data precision, validation, and predictive capabilities.

CONCLUSION

Rockfalls remain a persistent hazard in mountainous and hilly regions, posing significant risks to infrastructure, public safety, and the environment. This comprehensive review highlights the evolution of rockfall risk assessment and management approaches, encompassing traditional methods such as field surveys and stability analyses, as well as cutting-edge technologies like terrestrial laser scanning (TLS), 3D modeling, geographic information systems (GIS), LiDAR, and machine learning algorithms.

The findings underscore the pivotal role of advanced technologies in enhancing our understanding of rockfall dynamics and enabling effective hazard mitigation strategies. In particular, the integration of remote sensing, artificial intelligence, and GIS has facilitated the development of detailed susceptibility maps, real-time monitoring systems, and predictive models that significantly improve decision-making processes in infrastructure planning and disaster management.

Despite these advancements, the study identifies several challenges, including the need for interdisciplinary collaboration, region-specific customization of methodologies, and more robust validation techniques to ensure the reliability of results. Future research should prioritize combining traditional and innovative approaches, addressing data gaps, and improving accessibility to advanced technologies for local communities and policymakers.

Ultimately, this review emphasizes the importance of adopting a holistic and interdisciplinary approach to rockfall hazard assessment and management, paving the way for safer infrastructure development and enhanced resilience in vulnerable regions.

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