

A Review of Structural Dynamics, Multi-Hazard Effects, and Intelligent Monitoring

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Abstract: In this paper, the authors focus on the major impacts of rockfall hazards on the bridge and railway infrastructure in terms of dynamic structural responses and the efficacy of the present-day mitigation measures. The authors conducted a systematic literature review of the publications from the year 2020 to 2026 and explored the topics of high-end computational simulations, multi-hazard interaction methodologies, and the use of artificial intelligence. We synthesized data from well-validated numerical models, natural disasters case studies like the Kaikoura earthquake, and the analyses of failures of protective systems. The analysis indicates that structural resilience depends significantly on complex aspects such as strain-rate effects and the non-additive damage resulting from seismic-rockfall cascades, which might decrease the capacity of a pier by more than 80%. It is demonstrated that the performance of protection measures, such as flexible barriers and pier-targeted composites, depends to a large extent on connection detailing and the capability to withstand cascading geohazards. Nevertheless, some issues were noted, like the unavailability of general-purpose machine learning models, the oversimplification of rock fragmentation in computer simulations, and the absence of standardized performance protocols. These drawbacks may render the current design methods less trustworthy. The authors highlight the importance of physics-informed neural networks, thermal-hydraulic-mechanical coupling at the modeling stage, and resilience-based design codes, amongst others, which provide a coherent guide to the building of robust and adaptable transportation infrastructure in geologically unstable zones.

Keywords: Rockfall Impact, Flexible Barrier, Multi-Hazard, Machine Learning, Structural Resilience, Impact Mechanics

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1. Introduction

Rockfalls continue to pose serious risks to major transportation infrastructure, and this is a great concern for engineers worldwide. Bridges, viaducts, and rails in mountainous and hilly regions exposed to rockfalls are a potential source of heavy structural damage, long disruption of services, and even loss of life. Therefore, a modern structural engineer must have a thorough knowledge of how different types of bridge structures - from the simplest girders to those with complex twin-column piers - react to these variable impacts. This is becoming rapidly the case, given the threat of global warming and consequent more frequent extreme weather conditions. As a case in point, heavier rainfall and more cycles of freezing and thawing are leading to the weakening of rock faces. As a result, large boulders are more often breaking off. Also, modern infrastructure rarely faces only one hazard at a time. For instance, an earthquake can cause rockfalls in a very large area, or a bridge might get corroded by the natural environment before an earthquake can hit it. As these cascading,

multi-hazard events create complex failure modes that single-hazard models can hardly handle, it is actually the combination of all our current knowledge that will lead to the creation of safer and resilient infrastructure [1].

This article brings focus on the rockfall hazard and its exposure to a bridge and railway infrastructure, first discussing the general stability of a slope and later the high-speed impacts along with the main structural problems. Primarily, it deals with the literature of 2020 to 2026, which is a period of rapid technological development and, in particular, the crucial switch from simple analytical models to high-tech computational simulations [2]. Besides reviewing how digital technologies and machine learning are being deployed to detect structural vulnerabilities, create surrogate models, and assess damage at the moment of occurrence, the paper also discusses the development of new protective solutions such as flexible, ultra-high-capacity barriers and energy-absorbing sandwich structures made of ultra-high-performance concrete [3]. The exploration of these innovative concepts helps to point out major issues in the existing research. For instance, there is a need for standardized, performance-based design approaches, an enhanced understanding of structural failure under multi-hazard situations, and more dependable real-time monitoring systems [4]. In essence, this study aims to lead further research to find measures that would ensure the rapid restoration and adaptation of our transport systems to the changing environment.

This article conducts a thorough investigation of how rockfalls occur and the measures taken to prevent them to meet these goals. First, it investigates the physics behind rockfall impacts, their trajectories, and the problems of multiple hazard interaction. Afterwards, it discusses the structural response of various bridge parts, including the mechanisms of damage and the remaining strength capacity of a structure as a whole. Immediately after, the attention is on practical aspects, exposing modern protective structures such as hard sheds, flexible barriers, and composite shields, which are individually designed for each pier. The article also elaborates on how modern risk assessment methods can outperform numerical simulation techniques such as finite and discrete element methods for the purpose of understanding, experimenting, and predicting rockfall scenarios. Lastly, the article examines how AI, along with state-of-the-art monitoring systems, can change the whole industry by using real-world examples to demonstrate the concept. Illustrate these technological breakthroughs. It then outlines existing limitations and makes recommendations for building more resilient infrastructure in the future.

2. Rockfall Impact Mechanisms and Dynamics

2.1 Rockfall Trajectory and Kinematics

Understanding the trajectory and kinematics of a rock falling down a slope is a prerequisite to assessing the real hazard to bridge infrastructure. Impact energy, spatial distribution, and velocity vector at the point of collision are functions of initial release conditions, slope geometry, vegetation density, and surface features. Field observations and detailed three-dimensional discontinuous deformation analyses (3D-DDA) reveal that bounce height, translational velocity, and rotational kinematics respond very sensitively to changes in the slope angle and coefficients of normal and tangential restitution of the surface being impacted [5]. Typical generalized rockfall trajectory models use a tangential coefficient of restitution of approximately 0.85 and a normal coefficient of restitution of approximately 0.35. However, these values may vary significantly depending on whether the rock impacts bedrock, talus, or forested slopes.

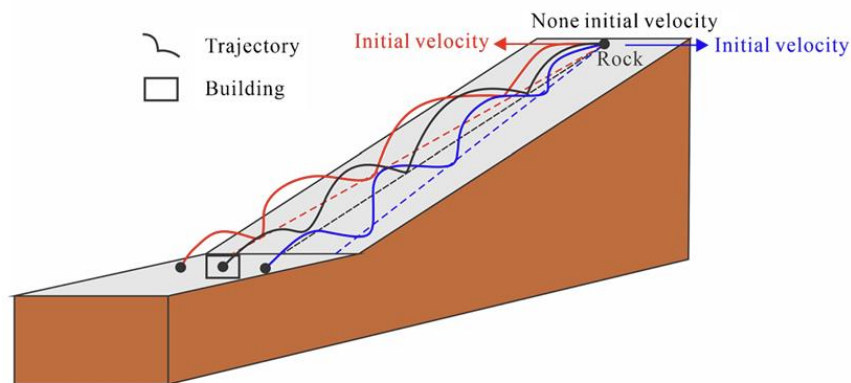


Figure 2-1: Influence of complex 3D topography on rockfall trajectories and velocity[6]

Changes in surface roughness or localized rock fragmentation cause variations in the trajectory, which result in uncertain impact sites and scattering effects [7]. In order to incorporate micro-topographical effects into the modelling of rockfall trajectories, 3D terrain models derived from UAV photogrammetry and LiDAR are now being used. Not only is this level of detail necessary for preparing bridge piers in complex canyon environments, but it also reveals that narrow landscapes can create a channelling effect, which leads to increased rockfall speeds. Furthermore, initial velocities induced by earthquakes strongly influence co-seismic rockfall events. Research shows that seismic acceleration can boost the initial horizontal velocity. Simulations in the Nujiang Bridge area revealed that raising the initial velocity from 0.06 m/s to 0.518 m/s in the horizontal plane greatly increases the chance of a

rock block hitting critical infrastructure at the valley bottom, leading to much longer travel distances.[6].

2.2 Impact Mechanics and Strain Rate Effects

When a rock hits something, like a wall or a beam, it is the way they touch that decides how much damage is done to the rock and the thing it hits. The way they touch is really complicated. Involves a lot of things, like the rock breaking the surfaces, rubbing against each other, and the thing it hits bending and changing shape. The force of the hit, how long the hit lasts, and the shock that goes through the thing that was hit all depend on the thing. These things are how hard the rock is compared to the thing it hits, the angle at which the rock hits, and how fast the rock is going. The first place the rock hits is really important. If the rock falls from high up, it can go a long way and hit really hard, which can cause a lot of damage to the thing it hits. The rock has a lot of energy from falling far, and when it hits, that energy is released and can cause a lot of shear forces, which are, like, really strong pushes that can break things.

The way concrete reacts when struck hard is crucial to understanding how it breaks. For example, concrete reinforced with metal and a special type known as ultra-high-performance concrete, or UHPC, becomes stronger upon fast impact. The compressive and tensile strength of both high-performance concrete and ordinary concrete wood increases remarkably when they are subjected to a high level of stress for a short duration only. This is exactly their improving power to withstand compressive and tensile forces. Ductile ultrahigh-performance concrete, along with normal concrete, illustrate their capability through dynamic increase factors, implying its strengths go up when subjected to higher strain rates [8]. For instance, radial strengthening is frequently simulated to demonstrate how the strength of a UHPC with a baseline quasi-static compressive strength of 120 MPa can be altered upon a drop-weight or rockfall impact. Low-velocity impacts, usually linked to smaller rocks or longer runout zones with high friction, typically cause localized concrete spalling, crushing, and flexural cracking. In contrast, high-velocity impacts can lead to serious punching shear, deep perforation, and brittle fracture of structural members. These impacts are marked by fast-moving fragments that create additional hazards [9]. The ultimate failure mode is determined by the mass of the rock block, the particular shape of the affected member, and the density of transverse reinforcement; velocity alone does not determine the transition between different failure regimes.

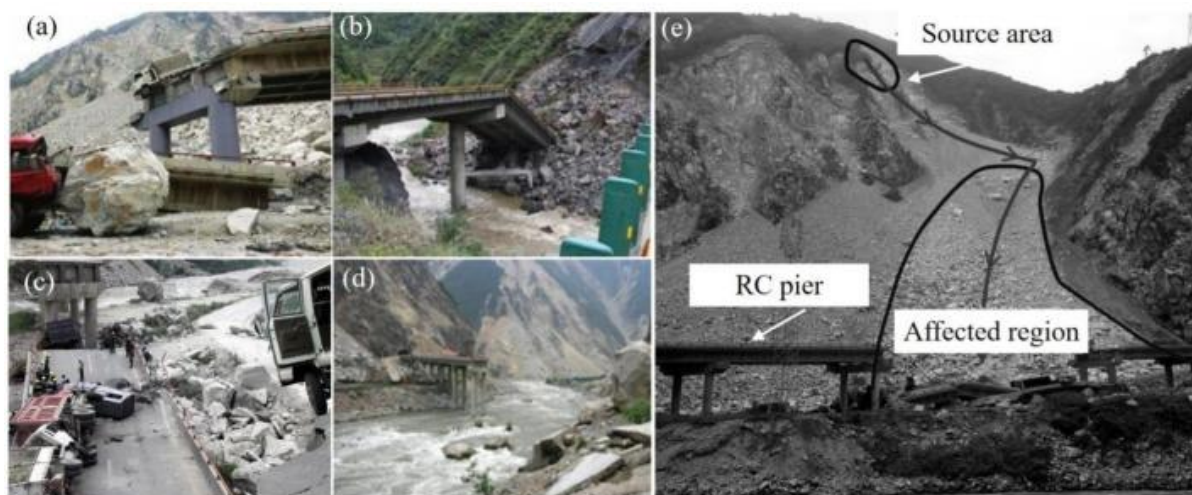


Figure 2-2 Comparative damage patterns under low and high-velocity rockfall impacts [10]

2.3 Multi-Hazard Interactions and Synergistic Degradation

The realization that rockfall impacts are rarely isolated occurrences and that transportation infrastructure is usually vulnerable to concurrent or cascading multi-hazard scenarios is a crucial development in recent literature. One of the most damaging episodes is the seismic-rockfall cascade. A structure that has already experienced seismic damage is frequently struck by the resultant rock mass when an earthquake causes a rockfall. Prior seismic damage, such as base cracking, yielding of longitudinal bars, and residual drift, significantly lowers the impact resistance of bridge piers, according to studies using hybrid simulation frameworks. The interaction is non-additive. For instance, the residual vertical load-carrying capacity drastically decreases under a maximum believable earthquake ground motion followed by a rockfall impact at a velocity of 20 m/s. The combination results in an 83% synergistic reduction in capacity, which reflects non-additive damage mechanisms where reduced confinement and cracking caused by earthquakes reduce the pier's capability to withstand subsequent shear and impact stresses in ways that cannot be simply superposed [11].

The joint effects of rockfall and environmental degradation are equally important. Steel corrosion caused by chloride is a serious problem for bridges in hilly coastal areas or those exposed to strong de-icing salts [12]. Corrosion reduces the pier's ductility and energy absorption capacity, weakens the concrete cover through rust expansion cracking, and deteriorates the reinforcing cross-section. Corroded RC piers have significantly reduced residual bearing capacity, according to recent numerical studies that monitor 90-year service life cycles. Because of the loss of confinement, the residual bearing capacity post-impact can drop by more than 47% after 60 years of service when compared to a newly built pier.

Additionally, the damage depth penetrates deeper into the core portion, and severe surface damage areas grow by hundreds of percent [12]. This multi-hazard certainty highlights the total inadequacy of single-hazard design codes and necessitates integrated, lifecycle vulnerability assessments.

Table 2-1 Synergistic effects of multi-hazard interactions

Hazard Interaction	Primary Structural Effect	Impact on Residual Capacity
Seismic + Rockfall	Pre-existing flexural cracking; loss of core confinement; yielding of reinforcement; amplified rock trajectory velocity.	Highly non-additive reduction (up to 83% capacity loss) due to synergistic damage mechanisms.
Corrosion + Rockfall	Reduced rebar cross-section; cover concrete spalling; severe loss of ductility; altered stress-strain profiles.	Progressive non-linear decay (up to 47.1% loss over 60 years); transition to brittle shear failure.
Extreme Weather + Rockfall	Increased freeze-thaw cycles weaken rock faces, increase debris flow fluidization, and cause foundation scour.	Increased impact mass and combined hydrodynamic/impact loading; massive debris entrainment.

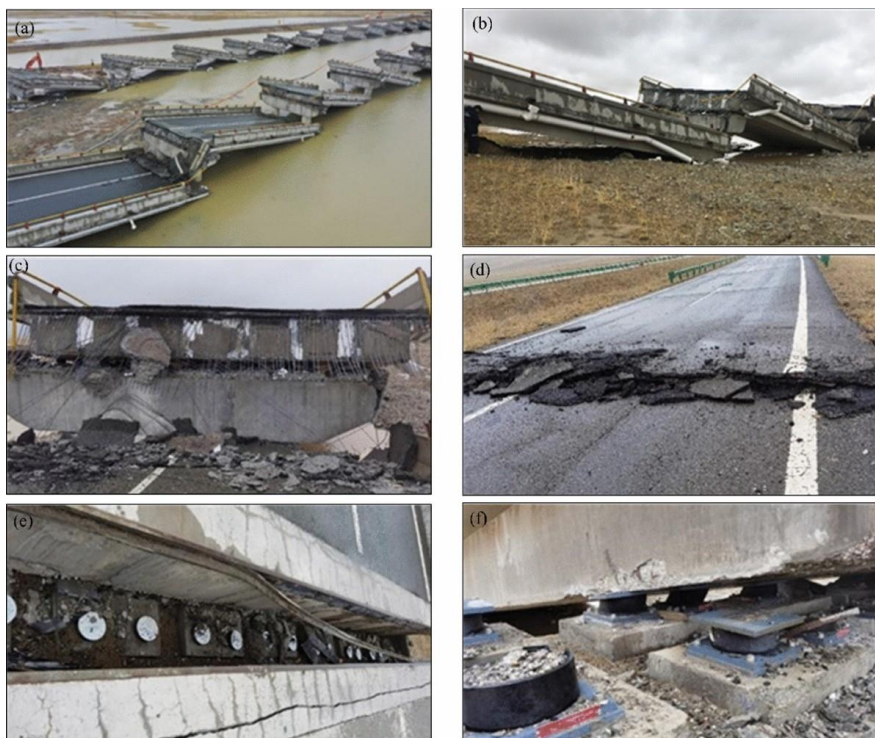


Figure 2-3 Synergistic degradation mechanisms in multi-hazard scenarios [13]

3. Structural Response of Bridge Piers to Rockfall Impact

3.1 Damage Mechanisms and Dynamic Strut-and-Tie Modelling

When a rockfall strikes a reinforced concrete bridge pier, it starts a fast chain reaction of stress wave propagation that causes both local and global damage mechanisms. Due to high localized contact stresses that are greater than the dynamic compressive strength of the

concrete cover, local damage mostly appears at the point of contact as concrete spalling, crushing, and penetration. As the kinetic energy of the rockfall converts into significant bending moments and shear forces that spread over the pier's length, global damage modes like flexural cracking and shear failure emerge.[14]. The shift between these failure types has been accurately explained by recent developments in dynamic strut-and-tie modelling. Tensile ties and compressive struts function as truss members connected by nodal zones in strut-and-tie modelling, which posits that internal stresses are conveyed via a truss-type mechanism [15]. Shear-dominated reactions predominate in near-support impact scenarios where rockfalls strike the lower third or quarter of the pier because stresses are transferred to the foundation quickly before significant flexural deformation can take place [16]. In many cases, the damage is characterized by extensive diagonal fissures that go straight from the impact point to the pier's base. On the other hand, flexure-dominated failure increasingly replaces shear-dominated failure as the impact height rises toward the mid-span or upper column, where the peak bending moment predominates.

3.2 Hollow Thin-Walled Pier Response

Compared to solid piers, hollow thin-walled bridge piers, which are frequently used in high-altitude and mountainous viaducts because of their superior stiffness-to-mass ratio and material efficiency, show complicated and very different reaction characteristics under rockfall impact. Stress propagation is significantly changed by the hollow section shape; upon impact, stress waves move from the front-side plate to the back-side plate via the webs, creating intricate multi-axial tensile and compressive fields [17].

These pier's thin walls are quite vulnerable to diagonal shear cracking and local buckling. At geometric discontinuities, such as internal fillets and section transitions, stress concentrations are significantly increased. A dual failure mechanism that is directly related to the rockfall diameter is shown by high-fidelity numerical calculations, radically changing the local failure mechanics with significant design implications [11]. Small-diameter rockfalls cause a very localized slab-action rupture with a typical failure width of about 947 mm. 33 by concentrating contact pressure only on the front panel. On the other hand, very large diameter rockfalls not only impact the side panel but also make simultaneous contact with the front panel. This causes catastrophic shear failure of the side panel with rupture widths extending to about 1388 mm. 33, thus fully involving the pier's lateral stiffness due to cross-section and altering the damage pattern. Since internal cracking can deeply compromise the pier's structural stability even when the external damage seems to be limited, hollow piers will need

highly specific design methods, for example, enhanced transverse reinforcement and the internally well-placed stiffening diaphragms to restrain rapid web collapse [17].

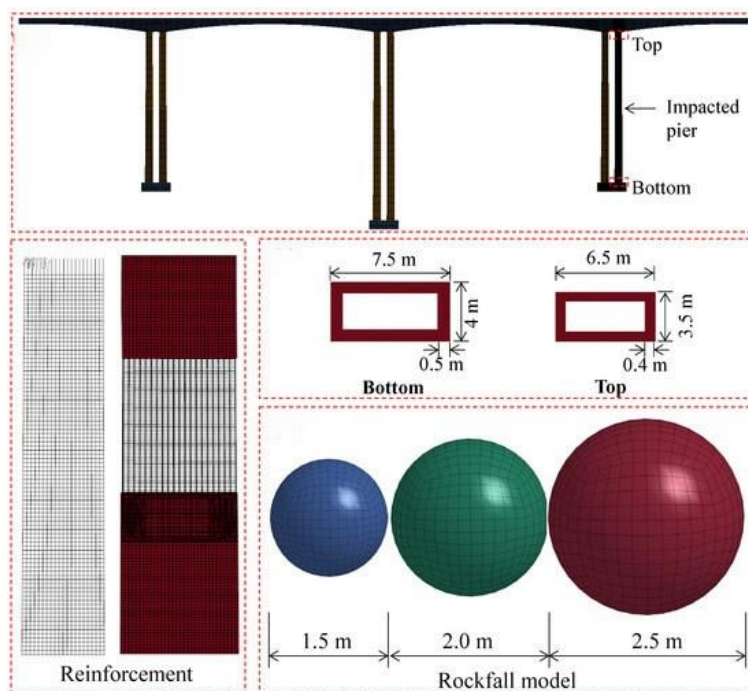


Figure 3-1 Hollow thin-walled piers under variable rockfall diameters [18]

3.3 Influence of Structural Parameters

Cross-sectional geometry, reinforcing details, and applied loads all have a significant impact on a bridge pier's resistance to rockfall impacts. Compared to rectangular or square columns, circular columns often dissipate impact energy more uniformly and show better resistance to local penetration, according to studies comparing cross-sectional shapes. The structural disadvantage of square columns in hilly regions is strongly supported by rectangular columns' severe stress concentrations at the corners, which make them more vulnerable to cover spalling and shear failure along the impact axis [19].

The longitudinal reinforcement ratio controls the global flexural capacity, but the spacing and detailing of transverse reinforcement (stirrups) play the most critical role in controlling concrete spalling and maintaining core confinement under high-strain dynamic loads. Closer stirrup spacing delays the onset of diagonal shear cracks and significantly improves post-impact ductility, preventing the premature buckling of longitudinal bars [14]. Furthermore, the presence of axial loads from the bridge superstructure acts as an initial pre-compression force. This axial load imposes a constraint on the pier that can temporarily delay the onset of tensile concrete cracking, resulting in less severe initial damage compared to unloaded experimental tests. However, during extreme impacts, heavy axial loads can also precipitate sudden P-delta instability once the core concrete is crushed.

4. Protection Systems and Mitigation Measures

4.1 Flexible Rockfall Barriers

Flexible rockfall barriers are the predominant passive mitigation strategy for protecting transportation corridors, favored for their high energy absorption capacity, adaptability to complex topographies, and relatively low environmental footprint. These highly engineered systems typically comprise interlocking steel wire ring nets, support ropes, energy dissipating devices (such as friction brakes or deformation tubes), and supporting steel posts [20].

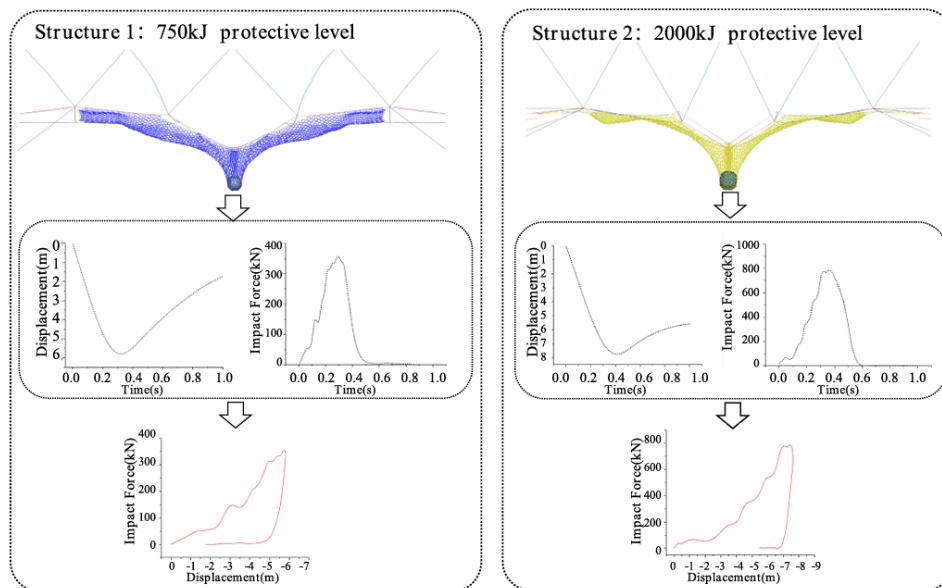


Figure 4-1 Rockfall displacement and impact force of the established two flexible barrier systems [21]

Energy dissipation in flexible barriers relies heavily on large inelastic deformation. While friction brakes release significant energy as heat as the support ropes slip, the barrier transforms the kinetic energy of the rockfall into strain energy when it is impacted by the tremendous elongation of the ring net [22]. Current systems bring about to withstand extreme impact energies ranging from 500 kJ to over 10,000 kJ [23]. However, either component incompatibilities or installation errors, structural breakdowns in the field frequently occur much below design capacity. Steel post buckling, insufficient anchor pull-out resistance, and critical connection failures are common failure modes. The incapacity of shackles to move freely along support ropes hinders the required large-scale net deformation in many forensic analyses. The net itself remains intact, but the stiff locking transmits enormous instantaneous loads to the base anchors and steel supports, resulting in a catastrophic system collapse. However, it has been pointed out that to truly enable the system to reach its full ductile capacity, free-sliding connections and strong anchor foundations are indispensable [23]. Besides, the studies draw analogy with wildlife fences, which, while relying more on plastic

deformation than friction brakes, also explain the underlying low-energy barrier mechanics [24].

4.2 Rockfall Shed Tunnels and Galleries

Rigid rockfall shed tunnels offer permanent overhead shielding for roads and railroads in high-frequency, high-energy rockfall routes when flexible barriers are inadequate or physically impracticable [25]. The effectiveness of these structures, which are made of heavily reinforced concrete, depends solely on the performance of an energy-absorbing cushion layer that sits on top of them. This layer distributes the concentrated point load evenly across the roof slab, prolongs the impact duration, and reduces peak impact forces [26].

Conventional single-layer dirt or sand cushions work well, but they put enormous dead loads on the building, requiring large foundations. Recent geotechnical research has concentrated on composite systems using expandable polyethylene (EPE) geofoam and expanded polystyrene (EPS) to address this. In comparison to slabs, multi-impact experimental investigations show that adding EPE or EPS geofoam to a sand cushion can lower peak impact forces and slab accelerations by as much as 80%. EPE foam is exceptionally good at reducing several consecutive impacts because of its exceptional durability and elastic recovery. On the other hand, dense EPS is quite successful in permanently crushing plastic to dissipate a single, high-energy impact. The best load distribution is achieved by sophisticated three-layered systems that combine geogrid-reinforced soil over an EPS core, greatly lowering the necessary thickness and dead weight of the roof structure while retaining outstanding protection against energies greater than 2000 kJ [17]. Additionally, compared to conventional rigid designs, innovative flexible shed tunnel designs with fully enclosed circular steel arches and 9-cm-thick rubber cushion layers have been demonstrated to attenuate peak forces transmitted to bridge decks by almost 60% [27].

4.3 Pier-Specific Protection Devices

Localized pier-specific protection systems have been designed to protect bridge piers against direct, high-velocity attacks since they are crucial single points of failure. Steel shell-rubber composite protectors, which have a thick rubber core for impact cushioning and an exterior steel casing for puncture resistance, are a common method [19]. This arrangement reduces the equivalent plastic strain in the pier to insignificant levels and successfully stops concrete spalling. A rubber thickness of 0.3 m has been demonstrated to totally avoid internal damage to the RC pier at impact velocities up to 20 m/s, allowing the kinetic energy to be fully dissipated within the hyperelastic composite [19]. Sandwich structures are the state-of-the-art

in protective design for situations with more severe hazards. These multi-module systems mix metallic foam, ceramic balls, or unique lightweight concrete cores with ultra high-performance-fiber-reinforced concrete (UHPFRC) face sheets, which offer remarkable tensile strength and puncture resistance [3]. The internal core stabilizes the progressive crushing behaviour, allowing the device to absorb huge kinetic energy without transferring critical shear forces to the original structural pier [28]. Additionally, flexible crashworthy devices utilizing ribbed steel tubes or aluminium honeycombs act as sacrificial layers, deforming plastically to protect the pier and allowing for rapid, cost-effective replacement post-impact without requiring full structural closure [29].

Table 4-1 Performance characteristics and limitations of pier-specific rockfall protection devices

Mitigation System	Primary Energy Dissipation Mechanism	Structural Advantages	Known Limitations
Flexible Ring-Net Barriers	Large-scale elastic-plastic elongation; friction brakes.	Lightweight; highly cost-effective; massive energy capacity (>10,000 kJ).	Requires extensive spatial deflection zones; highly susceptible to connection binding and corrosion.
Rigid Shed Tunnels (EPS/Sand)	Plastic crushing of geofoam; load distribution through soil/geogrid matrices.	Permanent overhead protection; zero traffic disruption during minor to moderate events.	Extremely high initial construction cost; massive dead loads require robust foundational support.
Steel-Rubber Pier Composites	Elastomeric compression and hysteretic damping; steel puncture resistance.	Directly protects critical nodes; easily retrofittable; highly effective for low/mid-velocity strikes.	Limited volumetric capacity against massive rock blocks; rubber degrades over time via environmental exposure.
UHPFRC Sandwich Shields	Compression and hysteretic damping; steel puncture resistance.	Exceptional penetration and shear resistance; withstands extreme multi-mass energies; highly durable.	Expensive specialized materials; complex fabrication and attachment; difficult to inspect post-impact.

5. Artificial Intelligence and Machine Learning Integration

5.1 ViReal Sensing and Deep Learning Architectures

Combining Artificial Intelligence and Machine Learning with traditional simulation means a great enhancement in predictive power, making it possible to avoid large computational delays of non-linear dynamic analyses, which are common [30]. Currently, deep learning methods are used fairly regularly to understand complicated input-output relations in

structural impacts, and they have led to the creation of virtual sensing methods. One of such methods includes using a new network type called the Kolmogorov-Arnold Network (KAN) Transformer for virtual sensing of internal forces in flexible rockfall barriers. Standard Multi-Layer Perceptron (MLP) based vision or sequence Transformers have problems with parameter disorganization and no interpretability. KAN-Transformers get rid of these MLPs and introduce group rational learnable stimulation functions directly placed on the network edges [31]. Such a change in the architecture significantly improves a model's understanding of complex, non-linear, time-evolving data. Thanks to KAN-Transformers, professionals are now capable of monitoring and predicting dynamic and highly transient internal forces of wire ropes and foundation anchors just through sparse, remotely collected external displacement data, which dramatically lessens the use of fragile physical strain gauges [32].

5.2 Vulnerability Quantification and Rapid Prediction

Based on stochastic inputs (mass, velocity, diameter, impact height) in fractions of a second, surrogate models employing sophisticated machine learning algorithms can precisely forecast impact forces and residual capacity for bridge piers. In order to produce extremely precise peak shear demands, frameworks that combine Convolutional Neural Networks with Support Vector Machines (CNN-SVM) specifically account for the stochastic properties of rockfall parameters [1]. Similarly, Bayesian-optimized Long Short-Term Memory (LSTM) networks, frequently used in parallel hydraulic applications for predicting bridge pier scour depth, are being adapted to predict the sequential, time-history degradation of impacted pier [33]. Additionally, multi-fidelity data-driven prediction models have incorporated the Random Forest (RF) and Extreme Gradient Boosting (XGBoost) algorithms, which have successfully classified structural health states and localized damage with average accuracies above 93%. Engineers may do real-time, probabilistic risk assessment over large, regional infrastructure networks by avoiding the need to run multi-day simulations by training these ML surrogate models on large, high-fidelity FEM databases [30].

5.3 Noncontact Optic Flow and Smart Aggregates

The arrangement of smart monitoring systems represents a transformative approach to real-time infrastructure protection. A significant advancement is the utilization of deep learning-based visual flow algorithms for the noncontact, full-field spatial-temporal deformation measurement of protective structures [34]. By tracking surface features across high-speed video sequences, these algorithms can reconstruct the dynamic impact force and precise deformation topography of a rockfall barrier without any physical sensors attached to the mesh [35].

Piezoelectric smart aggregates (SAs) embedded inside RC and UHPC elements provide unmatched diagnostic capabilities. SAs send and receive stress waves via the concrete matrix while acting as both actuators and sensors. The precise impact position, the start of internal micro-cracking, and the general deterioration of structural stiffness can all be quickly and accurately determined by changes in the signal amplitude, wave velocity, and frequency spectrum [36]. This facilitates a transition from reactive, schedule-based inspections to continuous, condition-based predictive maintenance.

6. Case Studies and Field Applications

6.1 Mountainous Highway and Railway Projects

The Modern infrastructure mega-projects provide a striking example of the effective use of improved rockfall mitigation. A prime example of extremely difficult viaduct foundation design in the face of severe, crossing geohazards is the Kicking Horse Canyon Phase 4 project in British Columbia, Canada. Engineers used deep pile foundations deeply socketed into bedrock to navigate extremely steep terrain that was vulnerable to active landslides, debris flows, avalanches, and rockfalls [37]. Strategic hazard avoidance is the ultimate form of mitigation, as evidenced by the deployment of a massive 155-meter cantilever roadway structure that eliminated the need for extremely vulnerable bridge crossings and moved the vital infrastructure away from the highest-risk runout paths [38].

Similarly, the China-Pakistan Economic Corridor (CPEC) and the Xi'an-Chongqing High-Speed Railway demonstrate the critical role of pre-construction geohazard modelling [39]. Along the CPEC, ensemble machine learning frameworks integrating climatic and seismic factors achieved predictive accuracies exceeding 0.885 in mapping massive landslide and rockfall susceptibilities over a 940,000 square km area.³ In the Daba Mountain district for the high-speed railway, predictive 3D DEM simulations modelled the initiation, acceleration, and catastrophic disintegration of massive tower-shaped rock formations [39]. The resultant mapping of potential kinetic energy zones directly influenced geological line selection, allowing the railway alignment to bypass lethal trajectories. 94, where railway piers could not be relocated, targeted rigid shielding and flexible barriers were systematically deployed. [40]

6.2 Post-Earthquake Rockfall Events

Observations from major seismic events provide invaluable, if highly destructive, field validation for multi-hazard modelling. The 2016 M_w 7.8 Kaikōura earthquake in New Zealand triggered tens of thousands of massive landslides and rockfalls across 10,000 square km, completely severing State Highway 1 and the South Island main trunk railway. The

incident brought to light the enormous amount of rockfall produced in Lower Cretaceous greywacke sandstones as well as the severe vulnerability of transportation routes that cross narrow valleys. Field reconnaissance showed that many slopes experienced deep internal fracturing rather than rapid failure, making them extremely vulnerable to eventual rainfall-induced failure. This is evidence of the critical need for dynamic, temporal risk assessments [41]. The 2024 M_w 7.5 Noto Peninsula earthquake in Japan and the 2015 M_w 7.8 Gorkha earthquake in Nepal demonstrated the extensive, catastrophic reach of co-seismic rockfalls. In Nepal, massive remote sensing campaigns mapped over 4,300 triggered landslides, noting that peak ground acceleration directly correlated with specific metamorphic lithologies to dramatically exacerbate rockfall density along critical infrastructure routes [42]. In Japan, the cascading effects of massive fault rupture induced up to 4.4 meters of uplift and systematic mountain slope movements, resulting in immediate structural impacts to bridges and prolonged access disruptions [43].

6.3 Lessons from Failures

Analysing catastrophic failures is critical for advancing protective engineering design codes. The 2017 Xinmo landslide in Sichuan, China, provided a stark lesson in the transition from rockfall to high mobility debris flow [44]. Initiated as a massive 4.3 million cubic meter rock collapse due to historical seismic failure from the 1933 Diexi and 2008 Wenchuan earthquakes, the rock mass struck the lower slope. This damaged ancient deposits and transformed the event into a high-speed avalanche that overwhelmed all topographical barriers, burying an entire village. This tragedy explicitly highlights that rigid protection designs based solely on isolated rock block impacts are, in essence, insufficient when geohazards force into massive, highly fluid entrainment flows [45].

Extensive field investigations of flexible rockfall barriers in Western China often reveal catastrophic failures that occur significantly below the system's designated energy capability at the individual component level. According to forensic engineering assessments, connection failures, more especially, the incapacity of shackles to move freely along support ropes because of corrosion, improper installation, or geometrical binding, are the primary cause of these early collapses. The required large-scale inelastic deformation of the net is totally prevented by this strict locking. Because of this, enormous instantaneous forces are passed straight to the steel posts and base anchors, avoiding the friction brakes and resulting in catastrophic buckling and anchor pull-out even when the wire mesh itself is completely

intact. The most recent analytical design codes, which emphasize flexible connection details and require routine maintenance, are directly influenced by these real-world failures.

6.4 Research Gaps and Future Directions

Current predictive models for rockfall impacts still have substantial limitations, despite the significant advancements in computational techniques. The absence of simplicity in machine learning (ML) surrogate models is a major problem. While CNN-SVMs and LSTMs provide great accuracy for some predetermined geometries, they frequently have trouble adapting to alternative forms, like rectangular or T-shaped sections, without requiring costly retraining. Additionally, numerical models frequently rely on idealized rigid-sphere assumptions for impactors. This approach neglects the complex destruction, internal deformability, and surface irregularities of natural rock masses, which significantly alter contact stress distributions and impact durations. Moreover, the field lacks coordinated international testing methodologies and established quantitative damage indices, which makes it challenging to compare novel protection solutions or effectively capture strain-rate effects. An interdisciplinary strategy is necessary to close these gaps. A promising approach to overcoming the generalization limitations of solely data-driven models is to incorporate basic conservation laws into machine learning frameworks using Physics-Informed Neural Networks (PINNs), allowing for more reliable predictions across a variety of structural geometries. Furthermore, thermal-hydraulic-mechanical (THM) connections should be included in computational models more and more. As climate change permanently alters thermal regimes, it is essential to understand how freeze-thaw cycles and water infiltration affect both rockfall triggers and the long-term degradation of protection systems. Finally, future engineering practices must shift toward resilience-based design codes. By moving beyond prescriptive, force-based criteria to probabilistic functional recovery objectives, engineers can design adaptive, modular protective systems focused on the rapid restoration of transportation networks following severe impact events.

7. Conclusions

To summarize, this detailed review compares many cases of how rockfall protection systems are implemented in real-life outside of the controlled environment. By looking at major infrastructure projects, severe earthquakes, and past system failures, we have obtained very useful insights. When done after the disaster analyses and remote sensing, a large discrepancy between the model behavior and actual field behavior was unveiled. We noticed that the advanced protections - flexible barriers and rigid rock sheds perform well only under perfect conditions, and their real success is greatly dependent on high-quality installation and strong

structural connections. Besides that, these systems are being frequently surprised by a series of unexpected events. For example, a rockfall turns into a massive debris flow, as in the case of the Xinmo landslide.

This paper provides a better understanding of the practical weaknesses of our transportation networks, but at the same time, it is not without faults. Earthquakes as a trigger remain very unpredictable, and the lack of common, public data concerning the capacity of protective systems under extreme stress is the second largest problem. As a result, it is almost impossible to obtain universally valid conclusions that can be applied in any environment and climate. To solve this problem, further studies ought to aim to develop uniform guidelines for real-time monitoring and post-disaster reporting. These will allow us to analyze the degradation of different systems over time caused by environmental stress, thus enhancing the reliability of hazard prediction models.

In the end, this research provides practical learning for geotechnical engineering and structural engineering areas. It emphasizes: (1) strong structural connections as a critical need, (2) the importance of being prepared for a series of natural disasters, and (3) the benefits of avoiding high-risk areas when planning new infrastructures. By bridging advanced numerical simulation and field evidence, this research supports the design of safer and more resilient infrastructures capable of withstanding an increasingly unpredictable world.

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