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IoT-Based Smart Rock Fall Detection and Early Warning System for Mining and Hilly Regions: A Review

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Abstract. Rockfalls are a recurring hazard in mining areas, road corridors, and hilly regions. They are difficult to predict because they usually show very little pre-failure deformation and collapse within a short time. Internet of Things (IoT) technology, which combines low-cost field sensors, wireless communication, cloud processing, and automated alerting, offers a practical way to monitor such slopes continuously. This review synthesizes five selected scholarly works that cover vibration-based stability assessment of falling-type rock masses, 5G-IoT monitoring with a tangent-angle warning criterion, micro-seismic rockfall detection with failure forecasting, a multi-sensor rockfall early warning system in the Himalaya, and an IoT-based landslide early warning framework deployed in India. The literature suggests that displacement alone is a weak indicator for brittle rock failure, and that dynamic indicators such as dominant frequency and acceleration amplitude ratio, or event-based indicators such as accumulated seismic energy, can show instability earlier. Field deployments also show that communication reliability, power supply, seasonal environmental effects, and the absence of validated alert thresholds are major practical constraints. The paper compares the studies' methods and contributions, identifies cross-cutting challenges, and proposes directions for future investigation. Because the review is based on five selected papers rather than an exhaustive database search, it is presented as a focused narrative review and not as a systematic review.

Keywords: Rockfall, Internet of Things, early warning system, wireless sensor network, micro-seismic monitoring, tilt meter, crack meter, mining, hilly regions, failure forecasting.

I. Introduction

Rockfall is a common safety hazard on natural and engineered slopes, including those associated with mining, hydropower, and transportation projects. It is typically triggered by rainfall, earthquakes, blasting, or excavation, and it results from the growth of structural planes or a loss of rock mass strength. A defining characteristic of rockfall is the lack of pronounced pre-failure deformation combined with a very short collapse process (Lu et al., 2026). Manual surveys and periodic observation therefore cannot give reliable warning, and personnel working close to unstable faces are themselves exposed to risk.

IoT-based monitoring addresses this problem by placing sensors directly on or near unstable blocks, transmitting readings wirelessly to a server, and applying automated rules or models that can issue alerts without constant human supervision. In mining and hilly regions this approach is attractive because slopes are remote, power is limited, and conditions change quickly.

However, a working system needs more than sensors. It must also select indicators that actually respond to impending failure, keep data flowing in difficult terrain, separate genuine acceleration from seasonal fluctuation, and convert detections into warnings that people act upon.

The selected literature approaches these issues from different perspectives. Lu et al. (2026) investigate how acceleration amplitude ratio and dominant frequency evolve as a structural plane weakens. Li et al. (2021) describe a 5G-IoT monitoring platform with a four-level warning scheme. Feng et al. (2021) use a micro-seismic network to detect and classify rockfalls and to forecast larger failures. Dhiman et al. (2026) deploy tilt meters, crack meters, and a rain gauge at an active rockfall site in Manikaran, India. Ramesh et al. (2023) present an end-to-end IoT landslide early warning framework with two long-running deployments in India.

The objectives of this review are to: (i) summarize the selected studies and their findings; (ii) compare their sensing methods, communication architecture, warning logic, and scope; (iii) identify common challenges and potential gaps suggested by this set of literature; and (iv) propose research directions for a reliable IoT-based rockfall detection and early warning system. The review treats IoT monitoring as a tool that supports, but does not replace, engineering judgement and disaster-management decision making.

II. Review Methodology and Literature Selection Criteria

This paper uses a focused narrative review of five selected research works on the topic. They were selected for direct relevance to rockfall or landslide monitoring and early warning with sensor-based or IoT-enabled approaches: vibration and dynamic indicators of rock mass instability, 5G-IoT monitoring and warning criteria, micro-seismic detection and failure-time forecasting, multi-sensor field deployment in rockfall-prone terrain, and an integrated IoT early warning framework. The review compares each study's research focus, method, principal findings, and stated or inferable boundaries. Because the work is based on the five provided works and does not document a comprehensive database search or formal screening process, it is not presented as a systematic review.

The works were read and organized according to their research focus, method, principal findings, and relevance to the review objectives. Laboratory and numerical studies were considered in relation to their specimen scale and loading conditions. Field studies were considered in relation to their site, instrumentation, duration, and whether a failure event was actually observed. One of the five works is a book chapter reporting long-term operational deployments, and it was treated as a framework and case-study contribution rather than a controlled experiment.

The selection criteria for this focused synthesis were: (1) direct relevance to rockfall or landslide monitoring and early warning; (2) an identifiable research question, system description, or analytical objective; (3) publication in a scholarly journal or edited scholarly book; and (4) contribution to one or more of the review's main themes. No additional papers were added to the five-paper set. Since this project did not document a comprehensive search across multiple databases, search strings, or formal screening stages, it should not be described as a systematic review. No exhaustive-coverage or PRISMA claim is made.

III. Literature Review

1. Dynamic indicators for falling-type unstable rock masses

Lu et al. (2026) study a falling-type unstable rock mass held to the bedrock by a single dominant structural plane. They model it as a single-degree-of-freedom spring-mass-damper system, so that a loss of constraint changes stiffness and damping and therefore the vibration frequency and amplitude. A finite element simulation showed that the stress distribution changed mark-

edly as the crack deepened while deformation stayed negligible. At about 55.6% penetration, the maximum horizontal displacement rose by only about 1.7 mm and the crack width grew by roughly 8%. This supports the argument that displacement monitoring alone is a poor early warning signal for this failure type.

In contrast, the acceleration amplitude ratio between the rock mass and the bedrock rose from 1.11 to 2.6 in the simulation, and the dominant frequency fell from 27.34 Hz to 8.79 Hz. A laboratory test on a 20 cm gypsum-bonded cube, with the bond cut in 2 cm steps until failure at 14 cm, showed a similar pattern. The amplitude ratio grew slowly at first and about three times faster after roughly 30% of constraint was lost, while the dominant frequency declined gradually and then dropped at about ten times the earlier rate near failure. The authors used these two inflection points to propose a preliminary three-level (low, medium, high) risk classification. They state that the scheme comes from one specimen size and one model material and has not been validated with field data. They also note that the amplitude ratio depends on the reference and excitation location, whereas the dominant frequency is more stable, and that field use requires noise handling.

2.. 5G-IoT monitoring with a tangent-angle warning criterion

Li et al. (2021) describe a landslide monitoring and early warning system built on 5G and IoT technology and applied to creeping terraced slopes at Lianhe, Youxi County, Fujian Province, China. The system monitors three-dimensional surface displacement with GNSS stations, rainfall, ground cracks, and wall cracks. GNSS stations were installed along the front, middle, and back edges of the landslide, with a reference station on stable rock within 2 km and a co-located rain gauge. Data reach the indoor monitoring centre through a dual BeiDou satellite and GPRS link, and the sensor network supports both mesh and linear modes, so that the resilience of mesh and the range of linear networking complement one another. The authors report coverage of up to 100 km using low-power differential chirp modulation.

For warning, the system applies an improved tangent-angle criterion to the deformation–time curve and issues blue, yellow, orange, and red alerts. The tangent angle stays near 45° during uniform-velocity deformation; yellow applies between 45° and 80°, orange between 80° and 85°, and red at 85° or above. The monitored slope was in slow creep and had not entered accelerated deformation, so the scheme was demonstrated on real data but not tested against a failure. The criterion is deformation-based and therefore suits slow, creep-type behaviour better than the abrupt brittle failure typical of rockfalls.

3. Micro-seismic detection and failure forecasting

Feng et al. (2021) propose a framework for temporal and spatial rockfall early warning using a micro-seismic network at the Torgiovannetto quarry in central Italy. Four three-component stations recorded continuously at 200 Hz. An automatic program classifies events as earthquakes, tectonic tremors, or rockfalls; in a controlled release of 90 rocks it detected 88 (recall 98%), with precision estimated at no less than 81%.

For temporal warning, the accumulated relative seismic energy of rockfalls is used as the observable quantity. Its increment over a sliding one-hour window is computed, and an alarm time is declared when the increment passes a threshold (0.5 m^2/s^2 at this site). A modified Fukuzono–Voight inverse-rate method then extrapolates the inverse of accumulated energy to estimate a time of failure. For spatial warning, rockfalls from the preceding window are localized by seismic polarization on a topographic map, with errors of about 10 to 48 m in a test. In an ex post analysis of January 2013, the first alarm was declared at 11:12 on 15 January, and two relatively large events followed with lead times of 42 and 54 minutes. Six warnings were identified over six months, and the authors recommend resetting the cumulative energy periodically (monthly here). The result is an ex post validation at a single site with an empirically set threshold and window.

4. Multi-sensor field deployment in the Himalaya

Dhiman et al. (2026) report a Rockfall Early Warning System for an active rockfall-prone slope at Manikaran, Himachal Pradesh, where a rockfall in August 2015 killed more than ten people. After geological and structural mapping of the Left Rock Mass, Right Rock Mass, and critical blocks, they installed ten bi-axial MEMS tilt meters, four vibrating-wire crack

meters, and a tipping-bucket rain gauge. Sensors connect to four wireless nodes that send data by LoRa to a solar-powered gateway, which uploads files by GPRS and FTP to a server at Panjab University. Python scripts run every four hours to merge and clean data, display it on a Streamlit dashboard, detect the onset of acceleration with the Prospective Failure Time Forecasting (PFTF) model, and send SMS alerts to a nodal coordinator, who verifies the signal before informing district authorities. Data from November 2023 to April 2025 showed seasonal cyclic behaviour, with fracture opening in winter and closure in summer and monsoon, and permanent crack-meter displacements of about 0.8 to 1.8 mm. Tilt meters showed cyclic and, in some cases, permanent tilts. No onset of acceleration or rockfall occurred, so the authors describe the system as a demonstration framework and not a fully validated forecasting system. Site-specific thresholds have not been set, and the three alert levels (advisory, watch, warning) are preliminary. The relative effects of rainfall and temperature could not be separated, and rainfall was used for interpretation rather than as a forecasting input.

5. Integrated IoT landslide early warning framework

Ramesh et al. (2023) argue that a landslide early warning system must capture the sequence of sub-events specific to each landslide type, and present an integrated framework covering risk assessment, cost-benefit analysis, and risk communication and governance. For rock topple, slide, and fall, they identify crack initiation and propagation as precursors and list geophones, crack meters, tilt meters, extensometers, acoustic emission sensors, LiDAR, and drone imaging as measurements, noting that thresholds depend on material strength, mass size, and structure.

The framework is implemented in two long-running systems: Munnar (Western Ghats), operating since a 2008 pilot with about 20 deep earth probes and roughly 150 sensors, and Chandmari, Sikkim (Himalaya), with 11 probes over about 32 ha. Each probe is linked to embedded hardware, heterogeneous communication, and edge analytics. At Chandmari, geophone data showed micro-seismic activity indicating crack initiation and propagation before a rockfall at about 7:30 am on 17 June 2020. Regional and site-specific rainfall thresholds were derived for Sikkim, and the system issues four-level warnings. Warnings are reported for Munnar in several years between 2009 and 2022 and for Chandmari in 2022, including three evacuations in July and August 2018. The authors also describe wireless attenuation and solar shading under vegetation, which led to heterogeneous communication and power, and they add participatory sensing and mobile applications. The chapter is a framework and experience report and, in the sections reviewed, gives no formal statistics on false or missed alarms.

IV. Comparative Analysis of Existing Studies

The selected studies address connected problems but use different methods and units of analysis. Their findings are complementary rather than directly interchangeable. Table 1 compares the scope, main contribution, and boundary of each selected study.

Table 1. Comparative summary of the five selected studies

Study	Method / scope	Main finding and boundary
Lu et al. (2026)	Theory, finite element model, gypsum-block test with triaxial accelerometers	Amplitude ratio and dominant frequency respond to loss of constraint while displacement barely changes; laboratory scale only.
Li et al. (2021)	5G-IoT with GNSS, rainfall and crack sensors on creeping terraces, China	Four-level tangent-angle warning and dual-mode networking; slow creep, so no failure test.
Feng et al. (2021)	Four-station micro-seismic network, Italian quarry, six months	Accumulated energy with inverse-rate forecasting gave 42 and 54 min lead times ex post; single site, empirical threshold.

Study	Method / scope	Main finding and boundary
Dhiman et al. (2026)	10 tilt meters, 4 crack meters, rain gauge, LoRa/GPRS and PFTF, Manikaran	Automated pipeline works; seasonal cycles seen; no acceleration or failure, so forecasting not validated.
Ramesh et al. (2023)	Integrated IoT framework, two long-term deployments in India	End-to-end multi-level warning and community role; experience report, no controlled comparison.

A first theme is the choice of indicator. Lu et al. (2026) show that displacement changes very little before brittle failure while dynamic indicators change substantially. Feng et al. (2021) use the occurrence and energy of rockfall events, and Ramesh et al. (2023) combine geophones, crack meters, and tilt meters with rainfall thresholds. Li et al. (2021) and Dhiman et al. (2026) rely mainly on deformation, which suits creeping behaviour better than sudden failure. A second theme is architecture. The field systems share a chain of sensors, wireless node, gateway, long-range link, server, analysis, and alert, but differ in the link (5G with BeiDou and GPRS, LoRa with GPRS, or heterogeneous links) and in where analysis runs (server only, or partly at the edge). A third theme is warning logic: a tangent-angle scheme, an energy threshold with inverse-rate extrapolation, a PFTF onset-of-acceleration detector, and multi-parameter threshold models. Finally, none of the field studies reports validation against many real failures, and the longest-running deployments (Ramesh et al., 2023) provide experience reports rather than quantitative reliability metrics.

The methods also determine what each study can establish. Laboratory and numerical studies reveal how indicators behave under controlled conditions; the micro-seismic study validates detection and forecasting on recorded data; field deployments show what works under terrain, power, and communication constraints; and the framework chapter shows how monitoring connects to governance and community response. None alone covers all dimensions of the problem.

V. Research Challenges And Identified Gaps

The following are potential gaps suggested by the five selected works. They should not be interpreted as proof that no other research has addressed these topics.

1. Early indicators for brittle rock failure
Displacement-based criteria may not give enough lead time when little pre-failure deformation occurs. Dynamic indicators look promising but have been shown mainly in the laboratory (Lu et al., 2026) or at single sites (Feng et al., 2021). Further research is needed on whether they can be measured reliably in the field and combined with deformation and rainfall data.

2. Validated thresholds and false-alarm control
Dhiman et al. (2026) could not set site-specific thresholds because no acceleration occurred, Li et al. (2021) tested their scheme on a creeping slope only, and thresholds in Feng et al. (2021) are empirical. Studies are needed that report detection rates, false alarms, and missed events, and document how thresholds were calibrated.

3. Separating seasonal cycles from true acceleration
Cyclic opening and closure of cracks and tilting of blocks driven by temperature and moisture can resemble precursory movement and complicate automated detection. Methods are needed to distinguish reversible seasonal behaviour from progressive instability, including models for temperature and rainfall effects.

4. Reliability of power and communication in harsh terrain
Vegetation, steep terrain, and weather can attenuate wireless signals and reduce solar power (Ramesh et al., 2023). Long-term studies of node failure, data loss, battery life, and the benefit of mesh topologies or edge processing would help design systems for mines and hills.

5. Scale effects, ambient noise, and field transfer
Laboratory results use controlled excitation and small specimens, whereas field slopes have heterogeneous rock, ambient vibration, and larger blocks (Lu et al., 2026). Excitation-independent or passive-vibration methods and multi-scale testing are required before such indicators can be used operationally.

6. Human response, communication, and governance
Warnings are useful only if they are verified, communicated, and acted upon. The reviewed deployments rely on expert verification and coordination with disaster-management authorities (Dhiman et al., 2026; Ramesh et al., 2023). Research is needed on alert protocols, response times, and community trust, particularly at mining sites where workers, machinery, and haul roads are exposed.

VI. Proposed Research Directions

Based on the comparison, the following research directions may help address the identified challenges:

- **Multi-indicator sensing:** combine tilt, crack, vibration or micro-seismic, and rainfall sensors so that brittle failure signals and slow deformation are both captured.
- **Edge analytics:** run filtering, event detection, and basic threshold checks on the node or gateway to reduce latency and data volume and to keep working when the server link fails.
- **Resilient communication and power:** test hybrid links (for example LoRa with cellular or satellite backhaul), mesh topologies, and multiple power sources under vegetation and weather stress.
- **Adaptive thresholds:** develop site-specific thresholds updated as data accumulate, and evaluate machine learning for separating seasonal cycles from true acceleration.
- **Field validation:** run long-term, multi-site trials, report detection and false-alarm statistics, and compare indicator performance with laboratory predictions.
- **Multi-level alert protocols:** link alert levels to defined actions such as access restriction, evacuation planning, and stoppage of mining operations, with clear verification steps.
- **Cost-effective deployment:** study low-cost sensors and participatory monitoring to extend coverage to many slopes without prohibitive maintenance cost.

Future studies should distinguish measured findings from conceptual claims and avoid assuming that results from one site or specimen apply universally. They should also report trade-offs: a lower threshold may give earlier warning but more false alarms, and additional sensors may improve reliability while raising cost and maintenance.

VII. Conclusion and Future Scope

This review considered five studies on IoT-based and sensor-based detection and early warning of rockfalls and landslides. Together, they show that sensors, wireless communication, and automated analysis can support continuous monitoring of hazardous slopes, but that indicator choice, threshold validation, seasonal effects, communication reliability, and human response remain open problems. The selected literature highlights that displacement changes little before brittle failure, that dynamic and micro-seismic indicators are promising but mostly validated at laboratory scale or at a single site, that field systems can run automatically in remote terrain but have not been validated against many real failures, and that governance and community engagement are part of a working early warning system.

The review is limited by its small, selected set of five papers and is not an exhaustive account of the field. The studies use different methods, sites, and failure types, so their findings should not be treated as one uniform experimental result. A broader future review should search multiple scholarly databases, document search terms and screening decisions, and include additional work on mining-specific monitoring, radar and LiDAR, machine learning for event detection, and low-power wide-area networks.

In conclusion, an IoT-based rockfall early warning system is best treated as a decision-support tool rather than an automatic guarantee of safety. Future research should focus on reliable early indicators, validated and adaptive thresholds, robust communication and power, and clear alert and response protocols for mining and hilly regions.

References

1. Dhiman, R. K., Thakur, M., Habib, M. Z., Singh, S., & Aggarwal, N. (2026). Multi-sensor monitoring of an active rockfall site in Manikaran, Himachal Pradesh, India. Discover Applied Sciences, 8, Article 1130. https://doi.org/10.1007/s42452-026-09155-2
2. Feng, L., Intrieri, E., Pazzi, V., Gigli, G., & Tucci, G. (2021). A framework for temporal and spatial rockfall early warning using micro-seismic monitoring. Landslides, 18, 1059–1070. https://doi.org/10.1007/s10346-020-01534-z
3. Li, Z., Fang, L., Sun, X., & Peng, W. (2021). 5G IoT-based geohazard monitoring and early warning system and its application. EURASIP Journal on Wireless Communications and Networking, 2021, Article 160. https://doi.org/10.1186/s13638-021-02033-y
4. Lu, G., Xie, M., Li, S., Du, Y., & Zhang, L. (2026). Instability evolution and early warning of slope falling-type unstable rock masses based on acceleration and dominant frequency characteristics. Discover Applied Sciences, 8, Article 944. https://doi.org/10.1007/s42452-026-08951-0
5. Ramesh, M. V., Thirugnanam, H., Singh, B., Nitin Kumar, M., & Pullarkatt, D. (2023). Landslide early warning systems: Requirements and solutions. In I. Alcántara-Ayala et al. (Eds.), Progress in Landslide Research and Technology, Volume 1 Issue 2, 2022 (pp. 259–). Springer. https://doi.org/10.1007/978-3-031-18471-0_21