DOI: https://doi.org/10.68732/b3ee141b80ba4ed1

ISBN: 978-9989-2053-7-8

Intelligent Landslide Early Warning Systems:Application on the Skopje–Veles Road Section

Z. Zafirovski
University Ss. Cyril and Methodius, Faculty of Civil Engineering, Skopje, North Macedonia
zafirovski@gf.ukim.edu.mk
0000-0003-2099-0710

S. Gjorgjevska
Civil Engineering Institute "Macedonia", Skopje, North Macedonia
0009-0002-1214-1030

Abstract

The transition from passive rockfall mitigation to proactive digital monitoring is critical for safeguarding highly vulnerable transport infrastructure under intensifying climate conditions. Along the Pan-European Corridor X near Katlanovo, the Skopje–Veles highway faces chronic hazards from sudden rockfalls due to the highly fractured and weathered nature of its Paleozoic schist formations.

This study proposes a conceptual engineering framework for an automated Intelligent Early Warning System (EWS). The perception layer utilizes a spatial grid of ten high-resolution MEMS digital inclinometers optimized in a dual-row configuration to detect real-time slope deformations. Data transmission is sustained via a low-power, long-range LoRaWAN network architecture, while decentralized Edge AI filtering is implemented within the sensor nodes to suppress mechanical traffic vibrations and mitigate false-positive alarms.

Kinematic modeling based on the corridor's design speed of 70 km/h and wet pavement friction criteria establishes a critical stopping sight distance of 130 m. Consequently, the system integrates upstream Variable Message Sign (VMS) portals positioned 300 m before the hazard zone to ensure safe vehicle cessation. Furthermore, the operational workflow adopts the international DATEX II standard to enable automated XML data dissemination across national Intelligent Transport Systems, accelerating emergency coordination with road maintenance units and traffic police.

The proposed IoT solution offers a highly cost-effective and scalable framework that minimizes capital expenditures compared to massive structural retaining walls. By validating the geomechanical and telecommunication feasibility of the sensor grid, this paper provides a replicable blueprint for smart transport corridors, drastically enhancing regional traffic safety and long-term infrastructure resilience against geohazards.

Keywords

IoT monitoring, MEMS inclinometers, LoRaWAN, DATEX II, Rock Engineering.

1 Introduction

Road traffic safety in mountainous and semi-mountainous regions presents a complex engineering and socio-economic challenge, particularly under the conditions of increasingly frequent extreme weather events. Among the natural phenomena that directly threaten the stability of road infrastructure, rockfalls and landslides stand out as some of the most unpredictable and hazardous occurrences, carrying severe consequences for both the safety of commuters and the continuity of traffic flow. The most reliable parameters for forecasting the time of failure at the slope scale are slope displacement and its derivatives (velocity and acceleration) (Intrieri et al., 2012; Intrieri et al., 2019). Rockfalls and landslides originate from various geodynamic processes and constitute a fundamental type of geo-hazard, causing substantial economic and social losses through structural damage to infrastructure and buildings.

The A1 highway in the Republic of North Macedonia, a vital segment of the pan-European Corridor X, serves as a strategic transit artery characteristed by high Annual Average Daily Traffic (AADT) volume. The specific road section near Katlanovo (coordinates: 41°45'15.5"N 21°44'36.3"E) constitutes a critical bottleneck where the alignment is excavated directly at the toe of steep, potentially unstable rock slopes.

The primary geological setting of the site is dominated by Paleozoic schists, exhibiting pronounced anisotropic schistosity and foliation planes. The kinematic behavior and rock slope failures are dictated by persistent systematic joint sets intersecting the foliation. This extensive jointing significantly reduces the mechanical cohesion and structural integrity of the rock mass. Driven by intensifying climate change, extreme temperature fluctuations, and freeze-thaw cycles, progressive mechanical degradation along these discontinuity joints leads to sudden rockfalls. The risk profile is further compounded by unfavorable road alignment geometry; sharp horizontal curves within the gorge create visual barriers that severely limit the stopping sight distance. At a design speed of 70 km/h, driver reaction time is critically restricted, and evasive maneuvers are highly constrained by the narrow right-of-way.

The traditional approach to the engineering protection of road slopes in Macedonia primarily relies on passive and semi-active stabilization methods (Zafirovski 2024). These measures include the installation of double-twisted steel wire meshes, the placement of heavy rockfall protection drapery systems made of steel wire ropes, the application of shotcrete, as well as the use of passive geotechnical rock bolts (Abramson et al., 2002). Their fundamental function is the mechanical retention of unstable blocks or the guidance of falling rock material toward a safe catchment zone alongside the roadway. Although these methods reduce immediate hazard exposure, they possess finite energy absorption limits and fail to provide pre-failure behavioral data regarding slope deformation. Consequently, unplanned closures along this international corridor trigger a socio-economic domino effect, resulting in inflated transport operational costs and logistics delays.

To address these limitations, this paper proposes a transition toward a proactive, digitized framework through the design of an intelligent Early Warning System (EWS) based on an IoT architecture. The proposed system integrates high-resolution MEMS digital inclinometers on the rock slope face, low-power LoRaWAN wireless telemetry, and variable message signs (VMS) for real-time traffic intervention, while maintaining full interoperability through the European DATEX II data exchange protocol.

2 Case study: Skopje–Veles

The community strongly requires an Early Warning System (EWS) to serve as a real-time data source for effective rockfall prevention and disaster management. Theoretically, if an early warning is delivered in a timely manner, the negative impact of a potentially catastrophic event can be entirely avoided or significantly minimized.

The Skopje–Veles road section, an integral part of the international E-75 highway corridor, represents one of the most structurally and geometrically complex transportation links in North Macedonia. The specific vulnerability of this alignment stems from its geomorphological setting within the Pčinja River gorge, near the Katlanovo locality, where the roadway is excavated directly into the steep slopes of the mountain massif. Historical data for this section record dozens of severe incidents where rock

masses with a volume of several cubic meters detached and landed directly on the driving lanes. These events are predominantly concentrated during early spring and late autumn, when intense temperature oscilla-tions and heavy rainfall trigger rapid joint propagation and hydraulic wedging within the rock mass.



Fig. 1 Overview of the analyzed critical rock slope section along the A1 highway (Skopje–Veles corridor).

The hazard profile of the section is further compounded by the presence of severe horizontal alignment geometry ("visual barriers")—sharp curves that restrict the stopping sight distance, preventing drivers from detecting fallen debris in time to execute a safe braking maneuver. The Annual Average Daily Traffic (AADT) volume along this corridor is among the highest in the country, featuring a substantial share of heavy goods vehicles (HGVs) engaged in international transit. Consequently, any unplanned closure of this section due to a rockfall event triggers a socio-economic domino effect. For these reasons, this specific corridor constitutes a primary candidate for the implementation of an intelligent monitoring and early warning system.

The specific 75-meter-long slope section investigated in this study was explicitly selected because it represents one of the most chronically unstable 'black spots' along the entire A1 highway corridor (Skopje–Veles section). Historical maintenance logs from the public enterprise indicate that this zone exhibits the highest frequency of rockfall events per kilometer annually. Geotechnically, the rock mass belongs to the Paleozoic metamorphic complex, consisting predominantly of highly weathered, anisotropic carbonaceous and sericite-chlorite schists.

In this metamorphic framework, the structural stability is governed entirely by the orientation of the schistosity planes (foliation) and intersecting systematic joint sets, rather than any sedimentary stratification. Kinematic analysis indicates that the primary failure mechanisms are planar sliding along the main schistosity planes (dipping unfavorably toward the roadway) and wedge failures formed by the intersection of two persistent joint sets. Due to continuous stress relief from historical blasting and ongoing traffic-induced cyclical vibrations, the shear strength parameters along these discontinuity joints are severely degraded. Under intense rainfall, the rapid rise in cleft water pressure triggers sudden kinematic mobilization, transforming isolated blocks into high-velocity rockfalls.

While multiple cutting sections exist along the gorge, the proposed IoT network is intentionally designed as a modular and scalable pilot system. By establishing the central LoRaWAN gateway and cloud server infrastructure at this most critical section, the architecture can dynamically accommodate additional sensor nodes on adjacent slopes in the future with negligible incremental capital cost, preventing system over-complexity.

3 System Architecture and Methodology

Conventional geotechnical measures along the Skopje–Veles section, including hexagonal wire meshes, shotcrete, and passive rock bolts, possess finite energy absorption limits and fail to provide pre-failure behavioral data regarding slope deformation. To overcome these limitations, a proactive three-layer IoT system architecture is proposed [Gubbi et al. 2013]:

- Sensor Layer (Edge Computing): Primary monitoring is executed using high-resolution digital MEMS inclinometers with an accuracy ranging from 0.001° to 0.01° [Mudarris & Munzir, 2024]. Utilizing edge computing, the nodes filter out micro-vibrations induced by heavy traffic, thereby eliminating false-positive alarms. Volumetric pore water sensors are integrated into this layer to monitor water saturation, which acts as the primary trigger for rockfalls during extreme rainfall events.
- Communication Layer (LoRaWAN Telemetry): Data transmission through the rugged gorge topography utilizes the LoRaWAN protocol, selected for its superior penetration through structural rock barriers and low energy consumption [Gamperl et al., 2021]. The central gateway aggregates telemetry data from the sensor nodes and forwards it to a cloud-based platform via an encrypted 4G/5G connection, ensuring robust communication redundancy.
- Information Layer (VMS Signaling): The final operational layer consists of Variable Message Signs (VMS) that display real-time speed restrictions or total road closures. A key engineering feature is the integration with the Katlanovo traffic junction, serving as the primary hub to alert drivers and divert traffic before they physically enter the hazard zone.

4 Engineering Calculations and Sensor Optimization

To accurately dimension the early warning system and establish the operational criteria for the VMS portals, a deterministic mathematical model was implemented to calculate the total stopping sight distance (D_{total}). The kinematic computation is based on the design speed of the Skopje–Veles road section (v = 70 km/h ≈ 19.44 m/s) using the following functional formulation:

$$D_{total} = D_{reaction} + D_{breaking} + D_{safety} \quad (1)$$

Where:

$D_{react} = v \cdot t_{react}$ represents the driver perception-reaction distance. Adopting a standard conservative perception-reaction time for complex road geometry (t_{react} = 2.5 s), yields:

$$D_{reaction} = 19.44\ m/s \cdot 2.5\ s = 48.6\ m \quad (2)$$

$D_{brake} = \frac{v^2}{2 \cdot g \cdot f}$ is the technical braking distance, where g = 9.81 m/s^2 is the gravitational acceleration and f = 0.35 is the longitudinal friction coefficient for wet asphalt conditions.

$$D_{breaking} = \frac{(19.44)^2}{2 \cdot 9.81 \cdot 0.35} = \frac{377.91}{6.867} \approx 55.0\ m \quad (3)$$

D_{safety} = 26.4 m is a design safety margin incorporated to compensate for longitudinal slope gradients and structural visual barriers within the gorge alignment.

Aggregating these components defines the minimum spatial threshold required for safe stopping:

$$D_{total} = 48.6 + 55.0 + 26.4 = 130.0\ m \quad (4)$$

Accounting for the latency induced by edge transmission, cloud-based data processing, and VMS activation relay (Δt = 5s), a vehicle travels an additional distance of D_{cloud}= 19.44 m/s · 5 s ≈ 97.2 m. Consequently, the optimal strategic positioning of the VMS portal is established at a distance of 300 m upstream from the hazardous zone.

For the spatial layout of the sensor network across the unstable slope face (L = 75 m), a grid configuration consisting of two parallel rows with 5 MEMS inclinometer nodes each was designed. The theoretical horizontal spacing (y) between adjacent nodes is governed by:

$$y = \frac{L}{n-1} = \frac{75}{5-1} = 17.5\ m \quad (5)$$

To account for the high jointing density and anisotropic nature of the Paleozoic schists, this spacing was structurally optimized to a refined step of 15 m, ensuring adequate redundancy and localized kinematics capturing before absolute structural collapse.

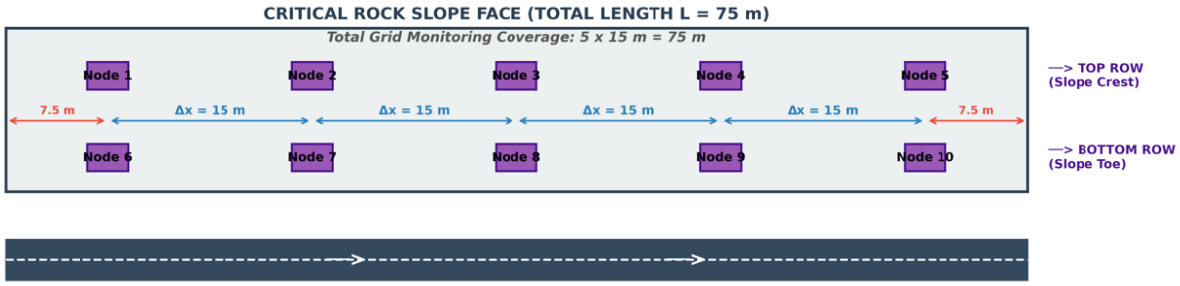


Fig. 2 Spatial grid configuration and geometric alignment of the 10-node IoT monitoring network across the critical slope face.

To ensure maximum clarity and rapid driver response, the proposed traffic signaling protocol on the VMS portal is differentiated into three distinct warning tiers (phases) based on the hazard severity level:

- Green Phase (Normal Operational Condition): No slope displacement is captured by the sensor network; traffic flows uninterrupted at the design speed.
- Yellow Phase (Alert / Cautionary Condition): The system detects initial kinematic displacements or critical soil moisture saturation thresholds. The VMS portal displays a rockfall hazard warning and automatically enforces a reduced speed limit of 40 km/h.
- Red Phase (Critical Hazard Condition): A structural slope collapse or active mass wasting onto the right-of-way is registered. The portal instantaneously triggers visual strobe alarms, enforcing a total road closure and dynamic detour routing.

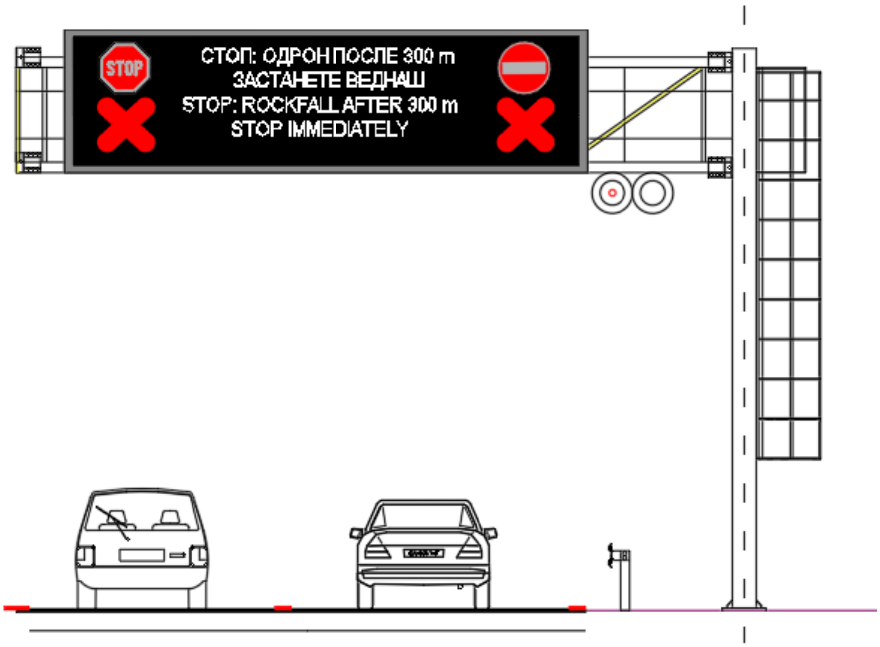


Fig. 3 Proposed layout of the Variable Message Sign (VMS) portal.

In addition to user dissemination via the three VMS operational phases, the integrated framework incorporates an automated emergency alerting network for relevant institutional authorities. The cloud-based software architecture is designed to dispatch instantaneous payloads to the Public Enterprise "Makedonijaroad", the traffic police, and emergency medical services. The transmitted telemetry includes precise incident GPS coordinates and an empirical volume estimation of the detached rock mass calculated from the total number of triggered sensor nodes. This synchronization drastically minimizes emergency response times, which is of paramount importance for mitigating traffic accidents within highly constrained and rugged gorge topographies.

5 Conclusion

This paper presents the conceptual design and feasibility assessment of an IoT-based intelligent rockfall Early Warning System (EWS) for the Katlanovo gorge section along the A1 highway (Skopje–Veles), identified as the highest-priority critical zone based on historical incident records, unfavorable slope geometry, and restricted stopping sight distance. The proposed framework addresses a documented gap between passive structural mitigation and proactive real-time monitoring along Pan-European Corridor X.

The core engineering contributions of this study are characterized by:

- A Robust Kinematic Model: Utilizing the section's design speed of 70 km/h and real-world friction criteria for wet pavement (f = 0.35), a critical stopping sight distance of 130 m was calculated, dictating the strategic placement of the VMS portal at 300 m upstream from the landslide hazard zone.
- An Optimized Sensor Grid: Spacing the high-resolution MEMS inclinometers at a structural interval of 15 m guarantees localized deformation monitoring within the highly jointed Paleozoic schists prior to catastrophic slope failure.
- Standardized Interoperability: Integrating the DATEX II data exchange standard allows for seamless integration into national and European Intelligent Transport Systems (ITS).

Several limitations of the current study must be acknowledged. The system has not yet been field-deployed; therefore, sensor performance under real traffic vibration loads and gorge-specific LoRaWAN signal attenuation conditions remains to be empirically validated. The kinematic thresholds defined for the three-phase VMS signaling protocol are based on deterministic modeling and conservative design criteria, and will require calibration against site-specific displacement monitoring data once the system is operational. Furthermore, the present study focuses exclusively on the Katlanovo pilot section; applicability to additional vulnerable zones along the corridor would necessitate independent geotechnical site assessments.

Future research will focus on field deployment and live data acquisition to validate the proposed thresholds, alongside the integration of Long Short-Term Memory (LSTM) networks and Bayesian belief networks for probabilistic time-to-failure forecasting under complex multi-variable environmental loads.

References

Mudarris M, Munzir (2024) Landslide Early Warning System Based on Multi Sensors and Artificial Internet of Things (AIoT): A Review. Journal of Engineering and Applied Sciences 19(2): 45–58. DOI: 10.3923/jeas.2024.45.58

Gamperl M, Singer J, Thuro K (2021) Internet of Things Geosensor Network for Cost-Effective Landslide Early Warning Systems. Rock Mechanics and Rock Engineering 54(8): 4125–4141. DOI: 10.1007/s00603-021-02495-w

Zafirovski Z, (2024) Road substructure, Faculty of Civil Engineering Skopje

Intrieri E, Gigli G, Mugnai F, Fanti R, Casagli N (2012) Design and implementation of a landslide early warning system. Engineering Geology 147–148: 124–136. DOI: 10.1016/j.enggeo.2012.07.017

Intrieri E, Carlà T, Gigli G (2019) Forecasting the time of failure of landslides at slope-scale: A literature review. Earth-Science Reviews 193: 333–349. DOI: 10.1016/j.earscirev.2019.04.017

Abramson LW, Lee TS, Sharma S, Boyce GM (2002) Slope stability and stabilization methods. 2nd edn. John Wiley & Sons, Inc., New York

Gubbi J, Buyya R, Marusic S, Palaniswami M (2013) Internet of Things (IoT): A vision, architectural elements, and future directions. Future Generation Computer Systems 29(7): 1645–1660. DOI: 10.1016/j.future.2013.01.010

DATEX II Organization (2020) DATEX II v3.1 Specifications and Standard for Traffic Information Exchange. https://www.datex2.eu/specifications. Accessed at 15.01.2026

European Committee for Standardization (2017) CEN/TS 16157: Intelligent transport systems - DATEX II data exchange specifications for traffic management and information. ReportSeriesName. CEN, Brussels