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REAL-TIME GEOTECHNICAL RISK MANAGEMENT IN CRITICAL URBAN INFRASTRUCTURE: MONITORING PROTOCOLS FOR SLOPE FAILURE PREVENTION

GESTÃO DE RISCO GEOTÉCNICO EM TEMPO REAL EM INFRAESTRUTURA URBANA CRÍTICA: PROTOCOLOS DE MONITORAMENTO PARA PREVENÇÃO DE RUPTURA DE TALUDES

GESTIÓN DE RIESGOS GEOTÉCNICOS EN TIEMPO REAL EN INFRAESTRUCTURA URBANA CRÍTICA: PROTOCOLOS DE MONITOREO PARA PREVENCIÓN DE FALLAS DE TALUDES

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ABSTRACT

Geotechnical instability in urban areas represents a critical risk to human life, residential occupation, and the operational continuity of road networks. Slope failures affecting highways, access roads, retaining structures, drainage systems, and densely occupied neighborhoods may occur suddenly, but they are frequently preceded by measurable physical processes such as displacement, moisture accumulation, surface tilting, cracking, pore-water pressure variation, and progressive deformation. This article discusses a protocol-oriented framework for geotechnical risk management in critical urban infrastructure, emphasizing real-time and near-real-time monitoring, remote sensing, sensor networks, numerical interpretation, and slope stabilization measures. Based on scientific literature on landslide detection, IoT-based geotechnical monitoring, UAV and satellite remote sensing, tilt sensors, acoustic emission systems, electrical resistivity imaging, road-slope warning systems, and structural mitigation, the article argues that effective prevention depends on the integration of monitoring data with engineering decision-making. The proposed approach is not limited to detecting slope movement; it seeks to transform geotechnical evidence into alert levels, inspection routines, containment priorities, traffic management, and emergency response protocols. In urban environments exposed to geological hazards, such integration can support the protection of human life and the resilience of critical road infrastructure.

Keywords: Geotechnical Risk. Critical Urban Infrastructure. Slope Monitoring. Landslide Early Warning. Slope Stabilization.

RESUMO

A instabilidade geotécnica em áreas urbanas representa um risco crítico à vida humana, à ocupação residencial e à continuidade operacional das redes de estradas. Rupturas de taludes que afetam rodovias, estradas de acesso, estruturas de contenção, sistemas de drenagem e bairros densamente ocupados podem ocorrer repentinamente, mas

frequentemente são precedidas por processos físicos mensuráveis, como deslocamento, acúmulo de umidade, inclinação da superfície, fissuras, variação da pressão de poro e deformação progressiva. Este artigo discute um marco teórico orientado por protocolos para gestão de risco geotécnico em infraestrutura urbana crítica, enfatizando monitoramento em tempo real e quase tempo real, sensoriamento remoto, redes de sensores, interpretação numérica e medidas de estabilização de taludes. Com base em literatura científica sobre detecção de deslizamentos, monitoramento geotécnico baseado em IoT, sensoriamento remoto por UAV e satélite, sensores de inclinação, sistemas de emissão acústica, imageamento de resistividade elétrica, sistemas de aviso de taludes de estrada e mitigação estrutural, o artigo argumenta que a prevenção efetiva depende da integração de dados de monitoramento com tomada de decisão de engenharia. A abordagem proposta não se limita a detectar movimento de talude; busca transformar evidência geotécnica em níveis de alerta, rotinas de inspeção, prioridades de contenção, gestão de tráfego e protocolos de resposta a emergências. Em ambientes urbanos expostos a hazards geológicos, tal integração pode apoiar a proteção da vida humana e a resiliência de infraestrutura crítica de estradas.

Palavras-chave: Risco Geotécnico. Infraestrutura Urbana Crítica. Monitoramento de Taludes. Aviso Antecipado de Deslizamentos. Estabilização de Taludes.

RESUMEN

La inestabilidad geotécnica en áreas urbanas representa un riesgo crítico para la vida humana, la ocupación residencial y la continuidad operacional de las redes viales. Los deslizamientos de taludes que afectan carreteras, caminos de acceso, estructuras de contención, sistemas de drenaje y barrios densamente ocupados pueden ocurrir repentinamente, pero frecuentemente están precedidos por procesos físicos medibles como desplazamiento, acumulación de humedad, inclinación de la superficie, grietas, variación de la presión de poro y deformación progresiva. Este artículo discute un marco orientado por protocolos para la gestión de riesgo geotécnico en infraestructura urbana crítica, enfatizando monitoreo en tiempo real y casi tiempo real, teledetección, redes de sensores, interpretación numérica y medidas de estabilización de taludes. Con base en la literatura científica sobre detección de deslizamientos, monitoreo geotécnico basado en IoT, teledetección por UAV y satélite, sensores de inclinación, sistemas de emisión acústica, imagen de resistividad eléctrica, sistemas de advertencia de taludes de carreteras y mitigación estructural, el artículo sostiene que la prevención efectiva depende de la integración de datos de monitoreo con la toma de decisiones de ingeniería. El enfoque propuesto no se limita a detectar movimiento de taludes; busca transformar evidencia geotécnica en niveles de alerta, rutinas de inspección, prioridades de contención, gestión del tráfico y protocolos de respuesta a emergencias. En entornos urbanos expuestos a peligros geológicos, tal integración puede apoyar la protección de la vida humana y la resiliencia de la infraestructura vial crítica.

Palabras clave: Riesgo Geotécnico. Infraestructura Urbana Crítica. Monitoreo de Taludes. Alerta Temprana de Deslizamientos. Estabilización de Taludes.

1 INTRODUCTION

Geotechnical risk management in urban environments requires more than the periodic inspection of slopes and retaining structures. In cities, unstable slopes may threaten residential areas, road corridors, drainage systems, utility networks, and emergency access routes. When slope failure occurs near highways or densely occupied neighborhoods, the consequences may include loss of life, traffic interruption, structural damage, isolation of communities, and delayed emergency response. For this reason, geotechnical risk should be understood as the interaction between physical susceptibility, triggering conditions, exposed people and infrastructure, vulnerability of built assets, and operational consequences. Landslide detection, monitoring, and prediction have increasingly relied on integrated methods that combine remote sensing, field instrumentation, engineering interpretation, and warning systems [1,2].

2 CRITICAL AREA IDENTIFICATION AND CLASSIFICATION

A technically consistent monitoring protocol should begin with the identification and classification of critical areas. In urban infrastructure, priority should be assigned to slopes located above or below roads, residential settlements, bridges, tunnels, retaining walls, drainage channels, and strategic access routes. This preliminary classification should consider geomorphology, geological structure, slope geometry, surface drainage, rainfall history, previous instability records, land use, and the potential consequences of failure. Geotechnical monitoring has been described as an important mechanism for reducing risks related to infrastructure works, especially when measured behavior is used to support preventive decision-making rather than merely document post-event conditions [3].

3 BASELINE CHARACTERIZATION AND MULTI-INSTRUMENTAL APPROACHES

The first stage of the protocol is baseline characterization. Before installing sensors or defining alert thresholds, engineers must understand the likely failure mechanisms. Surface failures, deep-seated landslides, riverbank instability, road-cut failures, and retaining wall distress may require different monitoring strategies. Multi-instrumental approaches are valuable because no single method can capture all relevant precursors of instability. Sestraș *et al.* demonstrated the usefulness of combining topo-geodetic survey, UAV three-

dimensional modeling, and ground-penetrating radar in a landslide-susceptible newly built-up area [4]. Similarly, integrated approaches using UAV and electrical resistivity imaging have been reviewed as relevant tools for earth infrastructure monitoring, particularly where both surface morphology and subsurface conditions must be interpreted together [5].

4 REMOTE SENSING FOR DEFORMATION MAPPING AND MONITORING

Remote sensing provides an essential layer for screening, mapping, and monitoring slope deformation across different scales. Satellite-based methods can identify slow ground displacement over broader areas, while UAV surveys can provide high-resolution topographic models, visual inspection of cracks, erosion features, drainage deficiencies, and changes in slope morphology. Spaceborne, UAV, and ground-based remote sensing techniques have been used for landslide mapping, monitoring, and early warning, showing that remote methods can support both regional surveillance and site-specific interpretation [2]. The integration of satellite InSAR with wireless networks of geotechnical sensors, as reported in the Pariana landslide case in Massa, Italy, illustrates the value of combining broad deformation detection with local instrumentation in urban areas [6].

5 PRECISION SENSOR SELECTION AND IOT-BASED MONITORING

The second stage of the protocol involves the selection of precision sensors according to the expected instability mechanism. IoT-based systems may include rain gauges, tilt sensors, extensometers, inclinometers, piezometers, moisture sensors, crack meters, acoustic emission sensors, and displacement monitoring devices connected to wireless transmission platforms. Abraham *et al.* proposed an IoT-based geotechnical monitoring system for unstable slopes in the Darjeeling Himalayas, demonstrating how connected sensors can support landslide early warning [7]. Broader reviews of landslide monitoring techniques also indicate that IoT integration creates opportunities for continuous observation, automated data transmission, and threshold-based warning [8]. In critical urban infrastructure, these systems are particularly relevant because warning delays may directly increase exposure of road users and residents.

Tilt sensors are useful for detecting surface deformation and shallow slope failure processes. Uchimura *et al.* showed that surface tilt monitoring can support precaution and

early warning of slope failures, particularly when rainfall-induced deformation develops progressively before collapse [9]. Acoustic emission monitoring also provides relevant information because internal deformation processes may generate measurable acoustic signals before visible failure. Dixon *et al.* developed an acoustic emission landslide early warning system aimed at communities in low- and middle-income countries, suggesting that monitoring strategies can be adapted to practical constraints while still supporting community protection [10]. These technologies are most effective when sensor data are interpreted within a geotechnical model of the slope rather than treated as isolated measurements.

Hydrological monitoring is central to landslide prevention because rainfall, infiltration, saturation, and pore-water pressure variation are frequent triggers of slope instability. High-resolution geophysical monitoring may detect moisture accumulation preceding slope movement, supporting improved early warning when subsurface hydrological conditions are difficult to observe directly [11]. Therefore, protocols for roads and residential zones should not rely exclusively on visual inspection or rainfall totals. They should integrate rainfall intensity, antecedent precipitation, soil moisture, resistivity variation, deformation velocity, and drainage performance. This is especially important in urban environments where drainage modifications, impermeable surfaces, and uncontrolled runoff may accelerate instability.

6 ANALYTICAL INTERPRETATION AND RISK ASSESSMENT

The third stage of the protocol is analytical interpretation. Monitoring data must be transformed into risk levels and operational decisions. Numerical analysis can support the evaluation of slope stability under rainfall or changing loading conditions. Nguyen *et al.* used numerical slope stability analysis to assess landslide prevention under rainfall impact, showing how modeling can inform engineering decisions [12]. Gu *et al.* proposed a road slope monitoring and early warning system integrating numerical simulation and image recognition, demonstrating the relevance of combining mechanical modeling with visual data for road infrastructure protection [13]. These studies reinforce that early warning systems should not merely collect information; they should connect data to predefined alert levels and intervention criteria.

7 PREVENTIVE INTERVENTION AND SLOPE STABILIZATION

The fourth stage involves preventive intervention and containment. Monitoring identifies abnormal behavior, but risk reduction depends on the capacity to act. Slope stabilization may include drainage improvement, retaining structures, anchored systems, slope regrading, erosion control, surface protection, soil reinforcement, vegetation measures, and sustainable techniques such as soilbag-based stabilization when suitable. Kamal *et al.* analyzed structural mitigation measures and community risk perception, emphasizing that landslide risk reduction involves both engineering performance and social acceptance [14]. Hong-In *et al.* evaluated soilbag-based slope stabilization for sustainable landslide mitigation in mountainous areas, indicating that stabilization methods must be selected according to engineering, environmental, and contextual constraints [15].

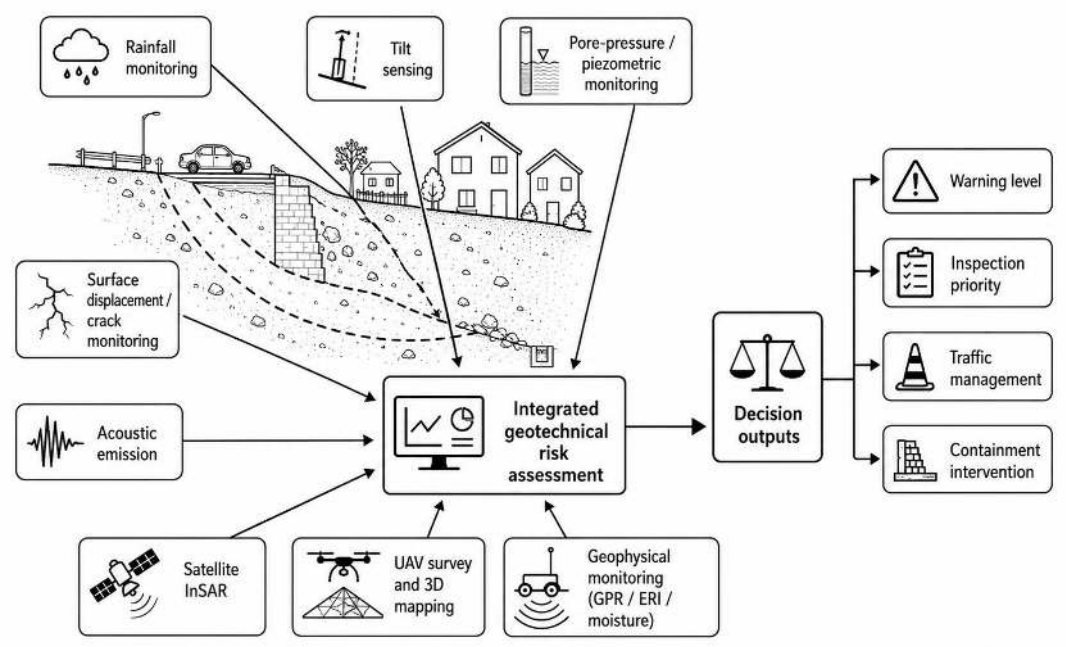
For infrastructure exposed to riverbank erosion or progressive soil failure, warning systems should be linked to asset protection and emergency response. Dang *et al.* discussed an early warning system for riverbank soil landslides and infrastructure protection, reinforcing the need to connect geotechnical monitoring with infrastructure management [16]. In urban settings, this connection may include traffic restriction, temporary closure of roads, evacuation of exposed dwellings, emergency drainage works, reinforcement of retaining structures, and mobilization of civil defense teams. Digital twin-based and knowledge graph-enhanced emergency response approaches also suggest that urban infrastructure risk management can benefit from structured integration of data, assets, and response procedures [17].

8 INTEGRATED MONITORING PROTOCOL FRAMEWORK

A geotechnical monitoring protocol for critical urban infrastructure should therefore operate as a continuous cycle. It begins with hazard mapping and exposure assessment, advances to baseline geotechnical investigation, incorporates sensor and remote sensing systems, defines alert thresholds, establishes operational response levels, and is recalibrated after inspections, events, false alarms, or interventions. The protocol must distinguish between periodic monitoring, near-real-time monitoring, and real-time sensor-based warning. It must also define institutional responsibilities, data validation procedures, maintenance routines for sensors, communication channels, and decision authority for emergency action.

Figure 1

Multi-source monitoring framework for slope instability in urban road corridors



Source: created by author.

9 CONCLUSION

In conclusion, the management of geotechnical risks in critical urban infrastructure requires the integration of engineering knowledge, monitoring technologies, containment techniques, and operational governance. Sensors, UAVs, satellite data, geophysical methods, numerical models, and warning systems are not independent solutions; their value depends on their incorporation into a technically coherent protocol. When properly designed, real-time and near-real-time monitoring can support early detection of instability, guide preventive stabilization, reduce exposure of residents and road users, and preserve the continuity of strategic road networks. The strategic value of this approach lies in applying geotechnical innovation to the protection of human life and the resilience of urban infrastructure against natural and anthropogenic slope hazards.

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