UAV-Based Photogrammetry and Geophysical Methods for Rockfall Hazard Assessment in Karst Terrain (Thung Nham, Vietnam)

Huynh The Pham [1*], Dung Van Le[2]
[1] Hanoi University of Mining and Geology, 18 Vien street, Hanoi 100000, Vietnam; ORCID https://orcid.org/0009-0009-8794-148X
[2] Institute of Geophysics, VAST, A8/18 Hoang Quoc Viet Road, Hanoi 100000, Vietnam; ORCID https://orcid.org/0009-0004-6374-8603
* Corresponding author: phamthehuynh@humg.edu.vn

doi: 10.29227/IM-2026-01-01-016

ABSTRACT

Rockfall is a hazardous geological phenomenon frequently occurring in steep limestone cliff terrains, posing significant risks to infrastructure and human safety. In the Thung Nham heritage area of Ninh Binh province, the expansion of transportation networks through mountain-slope cutting, combined with natural geological anomalies, has exacerbated the instability of rock masses. This study aims to decode the complex five-stage rockfall mechanism and quantify the scale of potential sliding masses to provide a scientific basis for mitigation. An integrated research methodology was employed, combining traditional field investigations with modern non-contact and penetrating technologies, specifically Unmanned Aerial Vehicle (UAV) photogrammetry for high-resolution terrain modeling and Natural Electric Field (Self-Potential) profiling using the S150 instrument. The geophysical results successfully delineated an extensive subterranean karst system characterized by large-scale cavities and deep-seated fractured zones infilled with water-saturated clay and poorly consolidated debris. The study quantifies a significant potential sliding mass with a high kinematic tendency to obstruct the transport corridor. These findings facilitate the proposal of four specialized engineering solutions, ranging from geotechnical reinforcement to protective galleries, ensuring a balance between absolute safety and the preservation of the original natural landscape.

KEYWORDS: *Unmanned Aerial Vehicle (UAV), rockfall hazard, self-potential profiling, Karst mechanism*

1 INTRODUCTION

Rockfall is a hazardous geological phenomenon characterized by both its latent nature and its potential for immediate disaster [1]. Known for occurring rapidly and unexpectedly, this type of hazard causes severe damage to infrastructure and the economy, and poses a direct threat to human life [2]. Globally, rockfalls from steep cliffs have become a major research focus in numerous countries with mountainous terrain and developed tourism industries, such as Italy [3], Switzerland [4], China [5], and Canada [6]. Previous studies have shown that rockfalls account for a considerable proportion of geological hazards and lead to significant annual economic losses to transportation infrastructure

globally [7]. Particularly in natural heritage sites, a critical challenge arises: ensuring absolute safety for tourists while preserving the original state of the natural landscape [8].

In Vietnam, this hazard occurs frequently in mountainous provinces, especially in areas with steep limestone cliff topography [9]. This terrain is typically characterized by intense fracturing due to weathering processes and long-term tectonic activities. Ninh Binh Province, specifically Nam Hoa Lu Ward, is a typical karst region with numerous vertical limestone cliffs [10]. Amidst economic and tourism development, the expansion of transportation routes and public infrastructure often requires cutting into mountain slopes to create steep cut-slopes (talus). These anthropogenic activities have altered the natural stress state of the rock masses. When combined with topographical anomalies such as "undercuts" (toe erosion), these factors create favorable conditions for rock blocks to collapse or fall to the base of the slope [11].

In recent years, the transport route from Ninh Binh city center to the Thung Nham Ecotourism Zone (Hai Nham Village, Hoa Lu District) has experienced rockfall events at several critical locations. Rock fragments of various sizes falling directly onto the road pose a constant danger to tourists and passing vehicles. However, identifying latent risks within the rock mass the primary drivers of instability remains a significant challenge when relying solely on traditional surface survey methods [11].

Following current international research trends, the application of non-contact and penetrating technologies has become an optimal solution. The use of Unmanned Aerial Vehicles (UAVs) in combination with photogrammetric techniques allows for the construction of high-resolution Digital Elevation Models (DEMs) to evaluate topography [12, 13]. Furthermore, modern geophysical methods, such as Natural Electric Field sensing, are prioritized by scientists to detect underground anomalies and hollow karst caves the 'invisible' factors that cause roof collapse and rock mass failure [14]. Although rockfall hazards in karst areas have received research attention, most previous studies in the Ninh Binh region have mainly focused on status statistics or qualitative assessments based on surface surveys. These studies often face limitations in accurately identifying subsurface anomalies such as voids and fractured zones deep within the mountain the core causes of sudden rockfalls. Additionally, quantifying the scale of pfotential sliding masses on steep cliffs using traditional measurement methods not only poses safety risks to surveyors but also results in significant errors due to topographical complexity. To date, no research in the Thung Nham area has integrated high-precision surface modeling data from UAVs with penetrating geophysical exploration data to provide a detailed explanation of the rock mass failure mechanism [11].

Based on that practical context, this study was conducted with the objective of applying a combination of modern technologies, including Unmanned Aerial Vehicles (UAVs) and Natural Electric Field profiling (S150 instrument), to decode the five-stage rockfall mechanism in the Thung Nham heritage area, Ninh Binh. By penetrating the subsurface structure to define the boundaries of the karst cave system (41m in length and 57m in depth), the research accurately quantifies the potential sliding mass at up to 2,160 m³. Consequently, a system of specialized engineering solutions is proposed to ensure absolute safety for the transportation corridor while preserving the original landscape of the heritage core zone. The research results not only address local safety issues but also contribute to confirming the effectiveness of integrating modern survey methods in geological hazard management.

2 STUDY AREA

The investigated rockfall site is located on the positive cut-slope (talus) of the access road to the Thung Nham Ecotourism Zone, in Hai Nham Village, Ninh Hai Commune (Nam Hoa Lu Ward), Ninh Binh Province, within the Trang An Landscape Complex. The center coordinates of the rockfall mass are identified at 20°12’52.460” N and 105°53’54.359”. Spanning a core area of 334.2 hectares, the region is characterized by intensely dissected limestone (karst) topography, featuring jagged "karren"

peaks and closed valley systems, most notably the 1,500m-long Thung Nham depression, which houses interconnected subterranean caves such as But Cave and Chua Cave [11].

Geologically, the area is primarily composed of limestone from the Dong Giao Formation (T2a dg), which has been severely fractured due to its position at the intersection of three major fault systems (NW-SE, NE-SW, and sub-meridional). Field surveys at the positive cut-slope revealed a 22m-high mushroom-shaped dry karst cave filled with loose, poorly consolidated debris. Hydrogeological characteristics include a well-developed river network with a NW-SE flow direction; during the rainy season, surface water infiltrates through fractures, creating groundwater veins that emerge at the "lubricated" siltstone layers [11].

The convergence of fractured rock structures, the presence of subterranean voids, and construction of transportation infrastructure cutting through the mountain base has created steep cut-slopes, disrupting the natural equilibrium and directly accelerating the rockfall process, which poses an immediate threat to the lives of local residents and tourists traveling through this heritage site [11].

3 METHODOLOGY

The study employs an integrated approach combining traditional field surveys with modern exploration technologies to address the challenge of rockfall hazard assessment in complex karst geological conditions. The research process was conducted through the following steps:

(1) Field Investigations: Conducted to establish the regional geological framework. Emphasis was placed on measuring the structural attitudes (dip and strike) of the Dong Giao limestone formation (T2a dg) and analyzing the density and orientation of fracture systems and tectonic faults. Lithological characteristics, particularly the intercalation of weathered calcareous clay layers, were recorded in detail to serve as a basis for identifying potential sliding surfaces.

(2) UAV Technology Application: To overcome the limitations of steep and hazardous terrain, Unmanned Aerial Vehicles (UAVs) were deployed to collect high-resolution aerial imagery. From this data, Digital Elevation Models (DEMs) and 3D models were constructed to analyze slope morphology in detail, identifying "undercut" (toe erosion) areas and unstable "isolated blocks" on the positive cut-slopes. The UAV platform and field data acquisition process are illustrated in Figure 1a.

(3) Natural Electric Field (Self-Potential - SP) Profiling: Utilized as a key tool for determining deep subsurface structures. The research team established four survey lines with a 1-meter station spacing, using the specialized PQWT-S150 instrument (Figure 1b) to probe depths up to 100 meters. This step aimed to locate and size hollow karst caves or caves filled with secondary materials (water-saturated clay) situated behind the exposed rock face. Electric field anomalies were analyzed to construct structural cross-sections, defining the boundaries of fractured zones and subterranean cave systems.

(a)

(b)

Figure 1. Equipment used in the study: (a) DJI Phantom 4 RTK; (b) PQWT-S150

Rys. 1. Sprzęt użyty w badaniu: (a) DJI Phantom 4 RTK; (b) PQWT-S150

(4) Mechanism Modeling and Quantification: Based on the integration of geological and geophysical data, a model for the rockfall development mechanism across various deformation stages was developed. The volume of potential rockfall material was calculated based on geometric parameters (length, width, depth) of the karst cave systems and fractured blocks identified from the electric field survey results.

(5) Integrated Assessment and Mitigation Proposals: Finally, the study applied a comprehensive assessment method considering endogenous, exogenous, and anthropogenic factors. Mitigation solutions were proposed based not only on technical safety standards but also optimized for the specific conditions of the heritage site, ensuring harmony between structural stability and natural landscape preservation.

4 RESULTS AND DISCUSSION

4.1 Characteristics of Rockfall in the Thung Nham Area, Nam Hoa Lu, Ninh Binh Province

4.1.1 Factors Influencing Rockfall

The results of field investigations and rapid analysis of soil and rock samples in the study area indicate that rockfall occurs due to several primary factors:

- Climatic Factors: Prior to the rockfall events, prolonged rainfall occurred over many days. Weathered soil within the infill layers and karst caves became highly saturated, with some locations reaching a state of full saturation. This reduced cohesive strength and friction, disrupting the natural equilibrium and leading to the collapse of soil and rock masses.

- Geological Factors: The rock composition primarily consists of gently dipping bedded limestone. Extensive faulting and fracturing have caused severe fragmentation of the rock mass, while simultaneously creating conduits for vertical and horizontal water circulation within fractured zones, weakening the structural integrity of the rock mass.

- Lithological Composition: The rockfall mass contains layers of plastic-flow clay and angular boulders with very weak bonding.

- Anthropogenic Factors: The slopes exhibit "undercut" (mushroom-shaped) morphologies resulting from human activities, specifically the cutting of mountain slopes to create steep-angled talus.

4.1.2 Analysis of Hazard Causes

The rockfall phenomenon in Thung Nham is the result of a complex interaction between endogenous, exogenous, and anthropogenic factors:

- Endogenous Causes: Neotectonic activities and fault systems have fractured the rock mass, accelerating deep-seated chemical and physical weathering. These processes create prerequisites for the formation of subterranean karst cave systems. Such structures increase slope gradients and create unstable voids within the mountain core.
- Exogenous Causes: Heavy rainfall acts as the direct triggering factor. The processes of erosion, washout of fine materials, and saturation of the weathered overburden cause local gravitational imbalance, leading to the collapse of individual rock blocks or complex rock clusters.
- Anthropogenic Causes: This is the decisive factor regarding the timing and scale of hazards in the survey area. Road construction using blasting methods not only increased the fracture density of the bedrock but also created vertical cut-slopes that intersect the bedding planes. Specifically, when the slope inclination is nearly perpendicular to the dip direction of the limestone bedding (Northeast), the risk of rockfall escalates due to the formation of "undercut" morphologies, facilitating the free fall of isolated boulders onto the roadway (Figure 2).

Figure 2. Slope morphology exhibiting a basal undercut (overhang) structure

Rys. 2. Morfologia stoku z podcięciem u podstawy (nawis)

Based on the analysis and assessment of the current status, influencing factors, and causes of instability, the mechanism and evolution of the rockfall process are identified as follows:

Initially, following the formation of karst caves, soil and rock debris from roof collapses or surrounding areas gradually infill these voids. Subsequently, during rainfall events, surface and subsurface runoff washes away fine-grained materials through deeper conduits or subterranean channels. Simultaneously, the infiltration of water saturates the clay components within the cave infill, significantly reducing cohesion and disrupting the natural equilibrium of the rock mass. Furthermore, as karst caves develop along inclined bedding planes, the surrounding walls often evolve into concave or "undercut" profiles, further exacerbating the susceptibility to collapse.

Anthropogenic activities, specifically slope excavation for road construction, expose these karst caves and create a facilitated "discharge zone," allowing materials to escape more easily and rapidly.

Once the binding strength is lost, the infilled debris and fragmented rocks are discharged from the cave, rolling down the man-made talus slope and onto the roadway as boulders.

The mechanism and evolution of this rockfall process are illustrated through a five-stage model (Figure 3).

4.2 Assessment and Prediction of Rockfall Hazards

4.2.1 Natural Electric Field Profiling

The layout of the survey lines established at the site is illustrated in Figure 4, while the detailed technical specifications, including the number of stations and the investigation depth for each transect, are summarized in Table 1. These survey lines were strategically positioned to intersect the primary fracture zones and delineate the boundaries of the suspected karst system. The integration of data from these profiles reveals a complex subsurface architecture characterized by a large-scale karst cavity system. Beyond defining the physical boundaries (41 m in length and 57 m in depth), the geoelectric analysis indicates that these voids are not entirely hollow but are predominantly infilled with a heterogeneous mixture of water-saturated clay and poorly consolidated debris. This infill significantly reduces the internal shear strength and increases the hydrostatic pressure against the rock walls during rainfall events. The spatial distribution of these anomalies confirms that the karst system creates a major structural discontinuity within the mountain core, acting as the primary driver for roof collapse and the subsequent discharge of material toward the roadway. These findings provide the essential empirical basis for the volumetric estimation and the five-stage failure mechanism model discussed in the following sections.

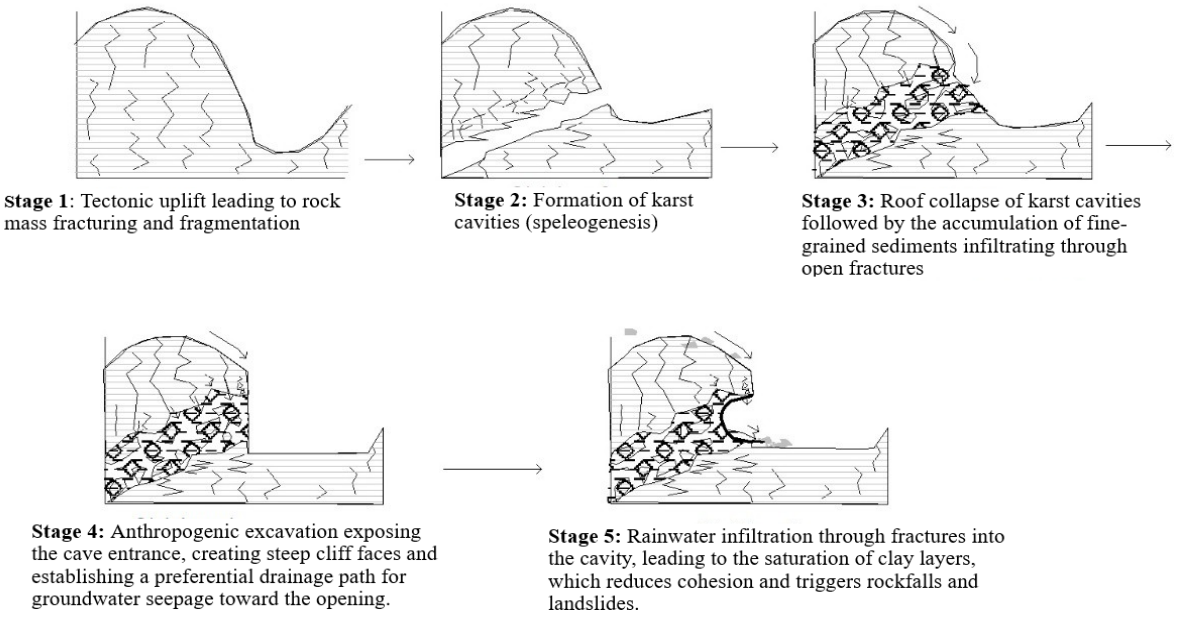

Figure 3. Schematic model of the developmental stages of the rockfall mechanism

Rys. 3. Schematyczny model etapów rozwoju mechanizmu obrywu skalnego

Table 1. Coordinates of the Natural Electric Field profiling lines

Tab. 1. Współrzędne linii profilowania naturalnego pola elektrycznego

No.	Survey Line Name	Number of Stations	Measurement Depth (m)	Self-potential instrumentation
1	L810S150	67	100	S150
2	L811S150	61	100	S150
3	L812S150	47	100	S150
4	L813S150	39	100	S150

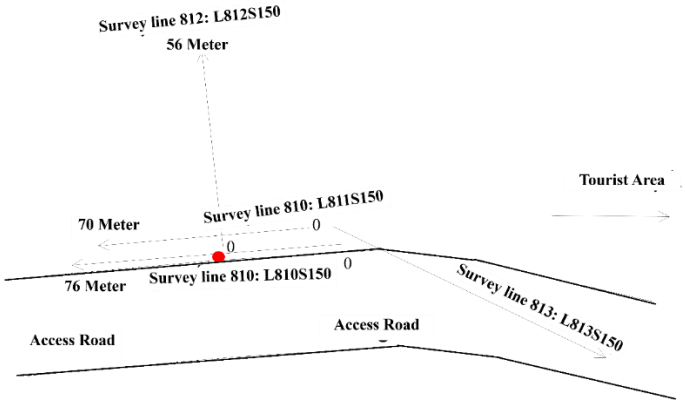

Figure 4. Schematic map of SP survey lines at the Thung Nam landslide area

Rys. 4. Schematyczna mapa linii pomiarowych SP w obszarze osuwiska Thung Nham

4.2.2 Geophysical Interpretation of Self-Potential (SP) Data

a) Profile L812S150

The SP profile L810S150 (Figure 5) was established along a 76-meter transect comprising 67 survey points at a 1-meter interval. The survey was positioned at the toe of the landslide, extending along the right side of the access road from the resort toward the entrance gate. Based on the stratigraphic cross-section derived from the self-potential data, several anomalies were identified: Within the depth range of -3 m to -15 m relative to the surface topography, a series of micro-karst caves (2.0-3.0 m in dimension) were detected, with vertical extensions varying from 2.0 to 6.0 m. Infilled materials, primarily water-saturated clay, were observed at specific intervals (Points 9, 13, 15, 19, 39, 49–52, and 55-67). Of particular tectonic significance are two deep-seated fracture zones identified at Point 19 (23 m) and Point 31 (35 m), which exhibit high water-bearing capacity. Furthermore, between Points 29 and 32, two distinct cavities containing water-saturated sandstone were located at depths of -6 m to -12 m and -17 m to -24 m. From Point 54 (58 m) to the end of the profile, the data indicates a highly fractured and crushed zone with significant water content, likely compounded by the presence of anthropogenic fill materials from road construction.

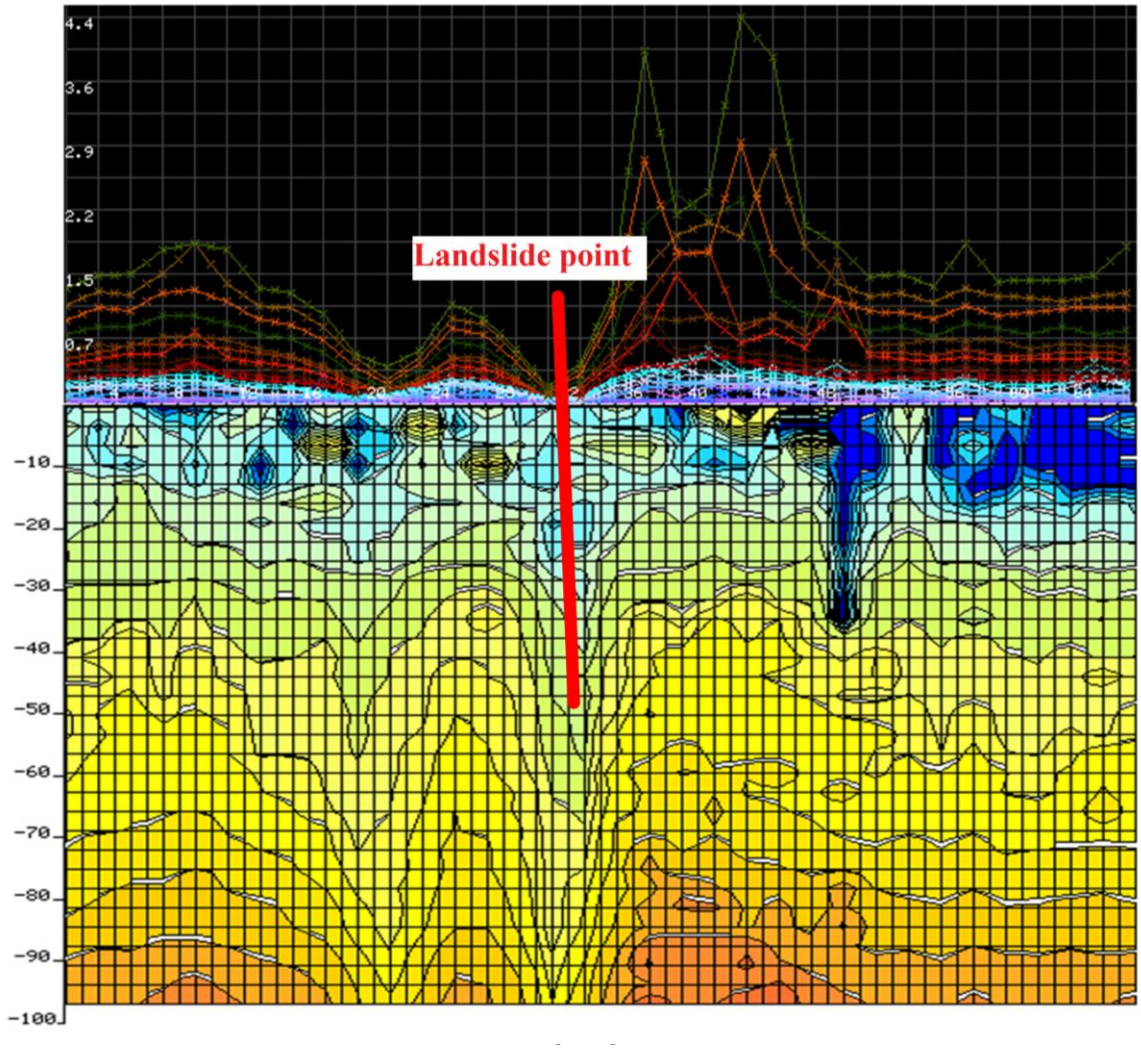

Figure 5. Geoelectric structural cross-section based on self-potential profiling results for line L810S150

Rys. 5. Przekrój strukturalny na podstawie wyników profilowania dla linii L810S150

b) Profile L811S150

The SP profile L811S150 (Figure 6) extends over a 70-meter transect with a 1-meter electrode spacing (61 survey points). This profile was conducted on the mountain slope, positioned 5 meters from the road edge (offset 5 meters from the cliff face), following the same orientation as profile L810S150 (from the resort toward the main entrance). The geoelectric structural analysis (Figures 3 and 10) reveals the following characteristics: A significant karst cavity system was identified between survey points 08 and 50 (distance 12 m to 54 m), spanning depths from -6 m to -57 m. This system is subdivided into three smaller chambers. Notably, the central chamber located between points 18 and 31 (distance 22 m to 35 m) is infilled with water-saturated clay, extending to a maximum depth of approximately -57 m. The chamber width varies from 2 m at its narrowest point to 13 m at its widest, with an average width of 8–9 m and a mean depth range of -6 m to -40 m (effective cavity height of 34 m). Additionally, another clay-filled cavity was detected between 40 and 50 at a depth of -13 m to -26 m. At points 19 and 20 (distance 23 m to 24 m), a deep-seated foliated saturated clay zone was observed, extending from -87 m to depths exceeding -100 m.

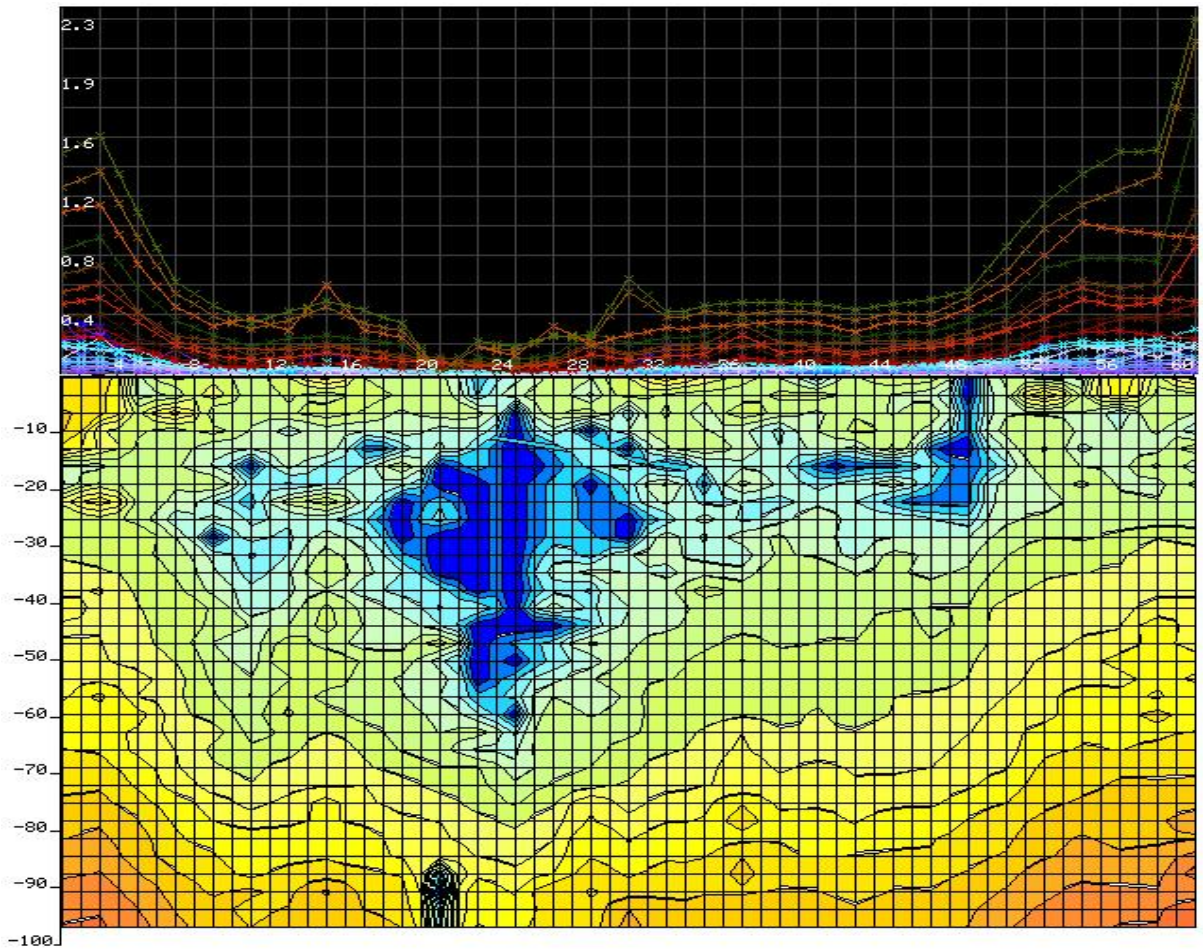

Figure 6. Geoelectric structural cross-section based on self-potential profiling results for line L811S150

Rys. 6. Przekrój strukturalny na podstawie wyników profilowania dla linii L811S150

c) Profile L812S150

The SP profile L812S150 (Figure 7) consists of a 56-meter transect with 47 survey points spaced at regular 1-meter intervals. This profile is located on the mountain slope and oriented perpendicular to profile L811S150, with the main purpose of defining the longitudinal boundary and overall extent of the karst cavity system. According to the geoelectric structural interpretation, a prominent karst cavity is identified extending from the beginning of the profile to survey point 36. This cavity occurs within a depth range from approximately -3 m to -30 m, indicating a relatively shallow but continuous void zone. Notably, the cavity shows strong vertical development, reaching a maximum depth of about -47 m at survey point 29 (equivalent to 33 m along the transect). The total interpreted length of this karst feature is approximately 41 meters, suggesting a large and laterally continuous subsurface cavity. In addition, the profile reveals a distinct bedrock partition at the end of the cavity, which appears to act as a natural boundary separating it from an adjacent karst structure. However, the morphology, connectivity, and further extension of this neighboring cavity are not clearly resolved and should be investigated in future studies.

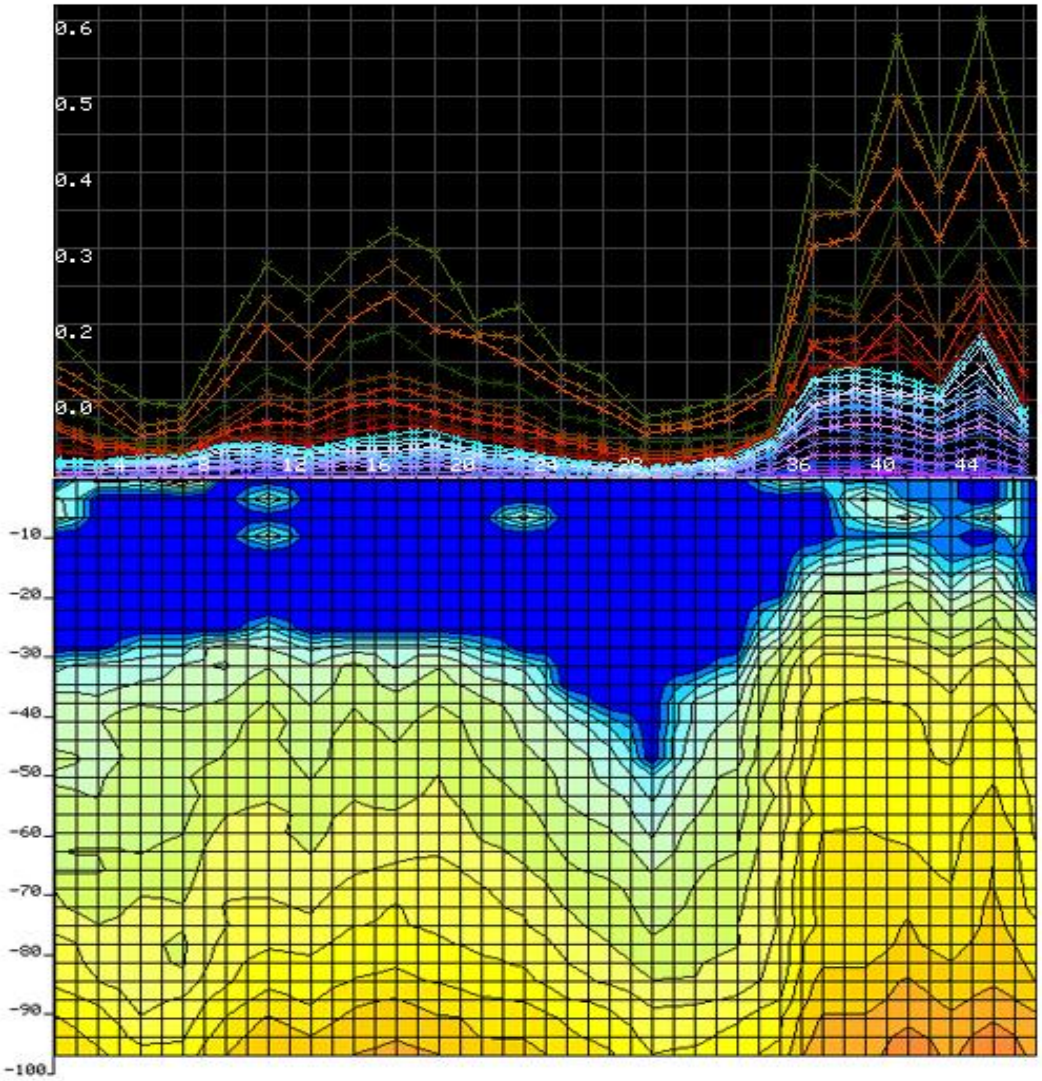

Figure 7. Geoelectric structural cross-section derived from self-potential profiling data for line L812S150

Rys. 7. Przekrój strukturalny geoelektryczny opracowany na podstawie danych dla profilu L812S150

d) Profile L813S150

The SP profile L813S150 (Figure 8) comprises a 48-meter-long transect with a total of 39 survey points spaced at regular 1-meter intervals. The profile begins at the margin of the mountain, located adjacent to the resort area, and continues outward across the main road, thereby covering both natural and modified terrain. Based on the interpreted geoelectric structural cross-section, several notable geological characteristics were identified along this line. A significant fractured zone, interpreted as being infilled with water-saturated clay, was identified between survey points 22 and 33, corresponding to a distance range from 26 m to 37 m along the transect. Field-based topographic observations indicate that this segment likely coincides with a major fault-related fracture system. This structural weakness may have been further influenced or expanded by anthropogenic activities, particularly the placement of fill materials during road construction, which could contribute to increased heterogeneity and water retention. In addition to this major zone, a secondary, smaller fractured feature was detected between survey points 10 and 12 (approximately 14 m to 16 m). This localized structure shows clear evidence of active groundwater seepage, suggesting ongoing subsurface water movement and possible hydraulic connectivity with surrounding formations.

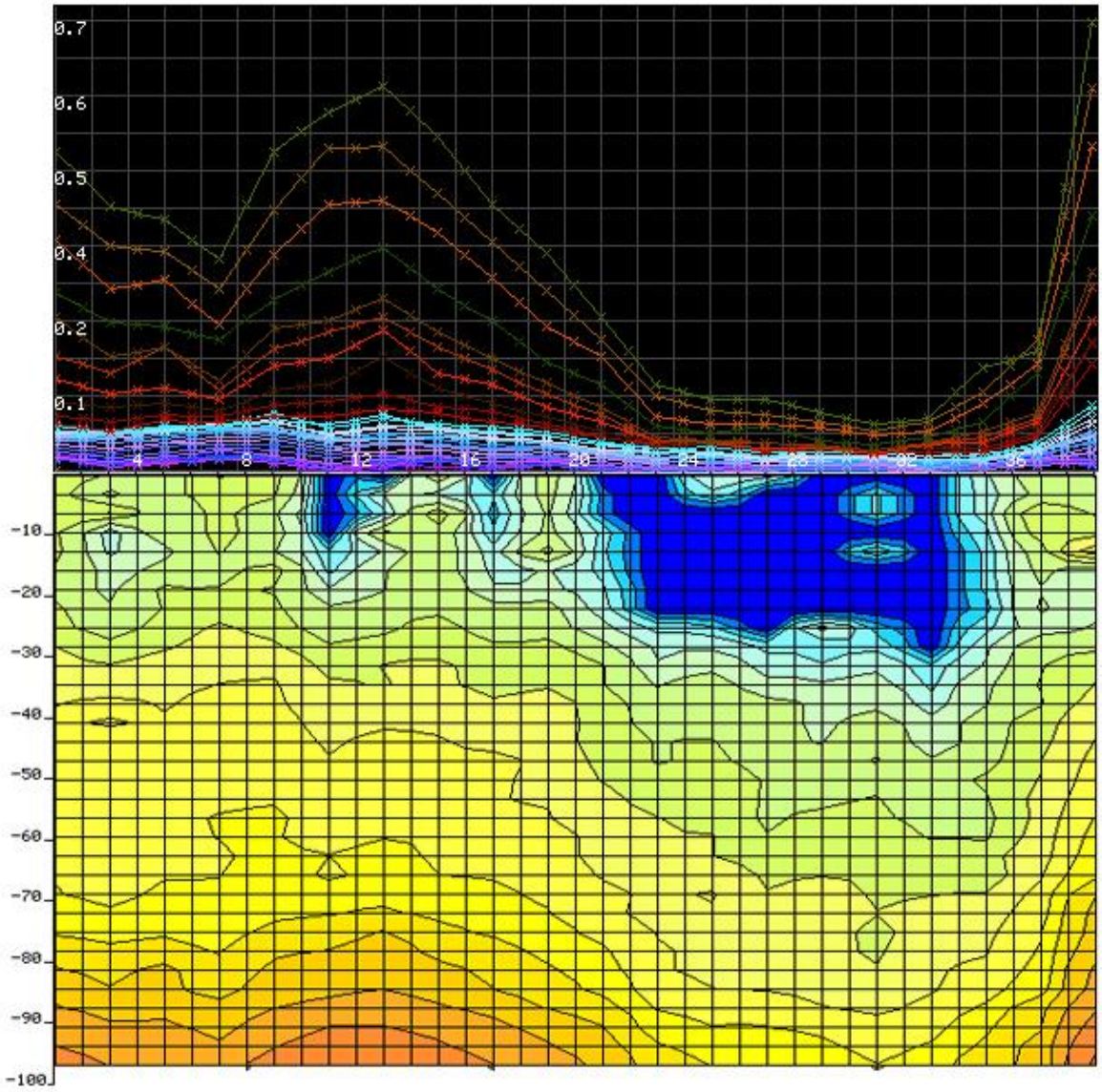

Figure 8. Geoelectric structural cross-section derived from self-potential profiling data for line L813S150

Rys. 8. Przekrój strukturalny geoelektryczny opracowany na podstawie danych dla profilu L813S150

4.2.3 Geophysical Analysis and Volumetric Estimation of the Karst Cavity System

The self-potential (SP) profiling results reveal a significant karst cavity infilled with a heterogeneous mixture of water-saturated claystone, sandstone, and isolated limestone boulders (erratic blocks). This infilled structure is primarily located at depths ranging from -3 m to -27 m relative to the surface topography, with localized vertical extensions reaching a maximum depth of -57 m. The interpreted morphology of the cavity indicates an average width of 8–9 m and a longitudinal extent of approximately 40–41 m. Based on these geometric parameters, the estimated volume of the unstable infill material is approximately 8,640 m³ (Figure 9).

The identified landslide mass exhibits a kinematic tendency to slide toward the adjacent roadway. Due to the previous loss of toe support from prior rockfall events, the slope stability is severely compromised. Under conditions of prolonged and high-intensity rainfall, the internal friction is significantly reduced. Given the slope inclination of 30° to 35°, it is estimated that approximately 25% of the total unstable volume equivalent to 2,160 m³ could potentially fail and obstruct the transport corridor. Immediate remediation measures are highly recommended to mitigate this imminent risk. Analysis of the self-potential (SP) data along both quasi-meridional and quasi-latitudinal transects yields the following insights:

Quasi-meridional orientation: The karst cavity system shows significant southward lateral extension, reaching up to 40 m from the current failure scarp, with vertical development extending to a depth of 47 m.

Quasi-latitudinal orientation: Profiles conducted at the toe of the slope (aligned with the roadway) reveal no major cavities. Instead, the subsurface is characterized by micro-cavities and several fracture zones with widths ranging from 1.0 to 1.5 m. These features correspond to the meridional fault and joint systems previously identified in the structural geological analysis.

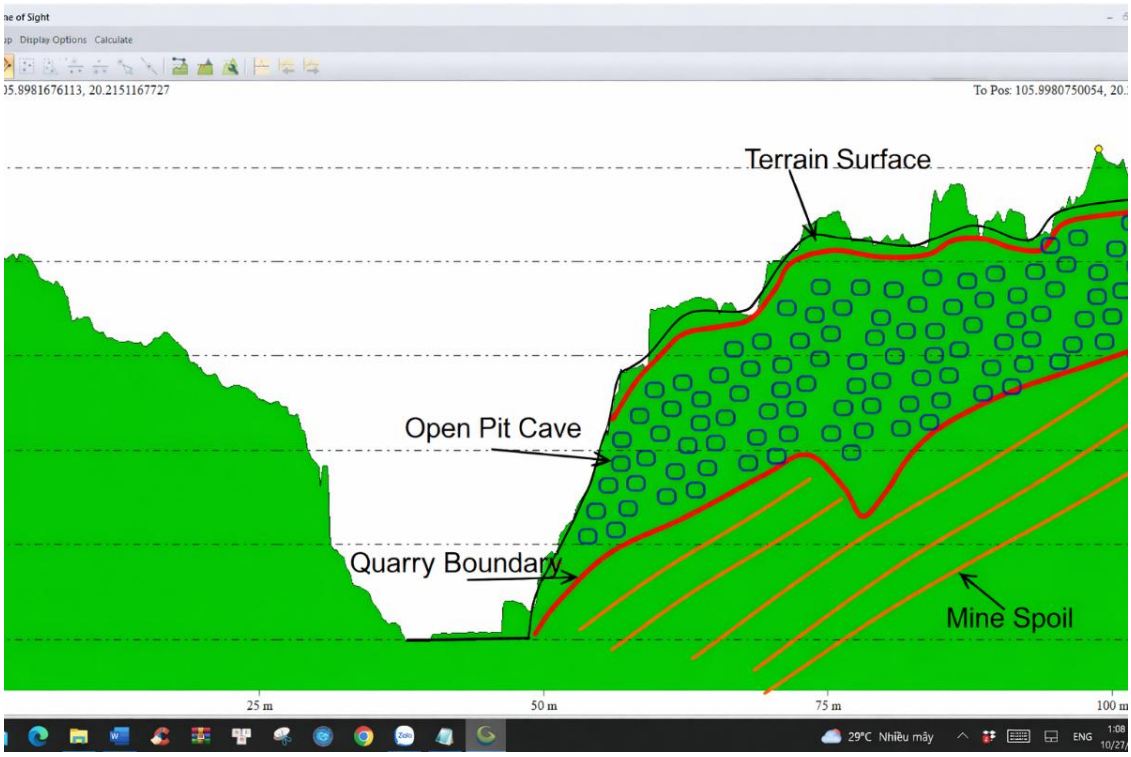

Figure 9. Failure mechanism model at the landslide location

Rys. 9. Model mechanizmu zniszczenia w miejscu osuwiska

4.3 Assessment of Landslide and Rockfall Hazards

The risk of geohazards within the study area remains significant, characterized by two primary mechanisms:

Residual sliding within the failure scarp: The internal face of the existing landslide scarp still retains a substantial volume of clayey materials interspersed with rock fragments and small boulders (ranging from 10–20 cm to several meters in diameter). During the rainy season, the infiltration of surface water leads to the saturation of these clay layers. Given that the underlying limestone bedrock is impermeable and possesses a distinct inclination, this creates a preferential slip surface. Consequently, localized sliding processes rather than catastrophic rockfalls are expected to persist, although the scale of these events is predicted to be relatively minor.

Potential for secondary rockfalls and gravitational instability: A considerable volume of poorly consolidated and weakly cohesive debris remains perched above the previous failure zone, resting on a sub-horizontal limestone ledge. The presence of a pronounced basal undercut (undermining/overhang) directly beneath this mass significantly compromises its structural equilibrium. This configuration poses a high risk of spontaneous rockfalls onto the roadway, a process that could be accelerated by seismic vibrations or anthropogenic disturbances.

Furthermore, the upper crest of the slope is characterized by large unstable boulders situated on steep, stepped terrain, presenting a constant threat of rockfall toward the toe of the embankment. On the opposite cut slopes, the presence of micro-karst cavities and highly fractured rock masses, some in precarious, metastable positions further elevates the hazard level. These findings necessitate the immediate implementation of mitigation strategies to minimize potential structural damage and ensure public safety.

4.4 Proposed Mitigation Strategies and Engineering Solutions

Based on the integrated results of geological surveys, self-potential (SP) profiling, and rockfall kinematic modeling, four technical strategies are proposed to mitigate landslide risks while balancing structural safety and environmental preservation:

Option 1: Slope Geometrical Modification and Retaining Structures

This approach involves re-profiling the cliff face to eliminate immediate hazards. The procedure entails the removal of highly weathered or unstable rock masses to establish a stable slope gradient inclined toward the mountain core. Subsequently, high-pressure shotcrete is applied to seal fractures, supplemented by the construction of reinforced concrete retaining walls at the slope toe. While providing high structural durability and maximum corridor safety, this method significantly alters the natural aesthetic and local ecosystem of the limestone cliff.

Option 2: Deep Anchoring and Geotechnical Mesh Reinforcement.

This modern engineering intervention aims to maintain the mountain's original morphology while ensuring structural integrity. The process involves localized treatment of fragmented rock patches, followed by the installation of high-strength steel anchors drilled deep into the stable bedrock. A high-tensile steel or geogrid mesh is then draped over the entire face to contain potential rockfalls. This solution effectively balances safety requirements with the preservation of the natural geological structure.

Option 3: Subsurface Cavity Grouting and Structural Support.

Prioritizing the conservation of the site's unique karst landscape, this method focuses on internal structural reinforcement. The primary stages include infilling existing undercuts (basal notch) and karst cavities with high-grade concrete, followed by the installation of reinforced concrete pillars to provide direct vertical support for overlying massive rock blocks. Protective wire meshing is used as a secondary measure for smaller fragments. This approach preserves the primordial silhouette of Vai Gioi mountain, aligning with regional eco-tourism and cultural heritage objectives.

Option 4: Protective Gallery (Rockfall Shed) Construction

In scenarios where direct intervention on the cliff is restricted by strict forest protection regulations, a protective gallery is considered the optimal bypass solution. A reinforced concrete arched structure is constructed over the roadway to shield the transport corridor from falling debris. The gallery is subsequently backfilled and landscaped with native vegetation to simulate a natural tunnel. This ensures absolute safety for commuters and tourists without infringing upon the protected forest area or the natural geological integrity of the cliff.

5 CONCLUSION

This research successfully achieves the objective of modeling the rockfall failure mechanism in the Thung Nham area by synthesizing surface and subsurface exploration data. The integration of UAV technology and Natural Electric Field (SP) profiling proves to be an optimal approach for karst environments, overcoming the limitations of traditional surveys in detecting "invisible" drivers of instability such as deep-seated voids and saturated fracture zones. The study confirms that rockfall events at this site are the cumulative result of neotectonic fracturing, heavy rainfall inducing clay saturation, and anthropogenic slope excavation that disrupts natural equilibrium. By establishing a detailed geoelectric structural framework, the research not only identifies the core causes of sudden rockfalls but also provides a precise volumetric estimation for hazard prediction. Looking forward, the integration of high-precision survey data into real-time monitoring systems and AI-driven early warning models represents a promising direction for managing geological hazards in complex terrains. Furthermore, future engineering interventions should prioritize "green" structural solutions to minimize visual impacts on the core zones of world natural heritage sites while maintaining rigorous safety standards for tourism development.

Acknowledgements

Thanks to two reviewers for their valuable comments on the earlier version, which helped us to improve the quality of the manuscript.

.

6 REFERENCES

1. Wang, X., et al., Dynamic rockfall risk analysis. Engineering Geology, 2020. 272: p. 105622.
2. Ferrari, F., A. Giacomini, and K. Thoeni, Qualitative rockfall hazard assessment: a comprehensive review of current practices. 2016, Springer.

3. Pignalosa, A., et al., Topographic amplification and debris remobilization as a cause for increasing rockfall hazard in seismic areas: A case study in Central Italy. Geomorphology, 2022. 403: p. 108160.
4. Galletti, M., Moosfluh, towards a rock slope failure? 2018.
5. Ji, Z.-M., et al., Assessment and prevention on the potential rockfall hazard of high-steep rock slope: a case study of Zhongyuntai mountain in Lianyungang, China. Natural Hazards, 2023. 115(3): p. 2117-2139.
6. Thapa, P., Controls on Rockfall-Talus Process-Response Systems, Kananaskis, Canadian Rockies. 2017, University of Calgary (Canada).
7. Congress, S.S.C. and A.J. Puppala, Geotechnical slope stability and rockfall debris related safety assessments of rock cuts adjacent to a rail track using aerial photogrammetry data analysis. Transportation Geotechnics, 2021. 30: p. 100595.
8. Zhan, J., et al., Rockfall hazard assessment in the Taihang grand canyon scenic area integrating regional-scale identification of potential rockfall sources. Remote Sensing, 2022. 14(13): p. 3021.
9. Tien, P.V., et al., Initial insights of the first documented earthquake-induced landslides in limestone areas in Vietnam. 2025, Springer.
10. Tran, T.T., Traditional culture of Van Lam village (Ninh Hai commune, Hoa Lu district, Ninh Binh province). http://thuvien.hluv.edu.vn:8080/jspui/handle/DHLH123/370, 2015.
11. Mining Electro-Mechanical Research Center, Consultation on surveying and assessing landslide risk at Vai Gioi mountain in quen dau area, Ninh Hai commune, Hoa Lu district, and proposing safety measures. Scientific research contract, 2022.
12. Jiménez-Jiménez, S.I., et al., Digital terrain models generated with low-cost UAV photogrammetry: Methodology and accuracy. ISPRS International Journal of Geo-Information, 2021. 10(5): p. 285.
13. Leitão, J.P., et al., Assessing the quality of digital elevation models obtained from mini unmanned aerial vehicles for overland flow modelling in urban areas. Hydrology and Earth System Sciences, 2016. 20(4): p. 1637-1653.
14. Hussain, Y., et al., The potential use of geophysical methods to identify cavities, sinkholes and pathways for water infiltration. Water, 2020. 12(8): p. 2289.

Fotogrametria UAV oraz metody geofizyczne w ocenie zagrożenia obrywami skalnymi w terenie krasowym (Thung Nham, Wietnam)

Obrywy skalne stanowią niebezpieczne zjawisko geologiczne, często występujące na stromych wapiennych ścianach, stwarzając poważne zagrożenie dla infrastruktury oraz bezpieczeństwa ludzi. Na obszarze dziedzictwa Thung Nham w prowincji Ninh Binh rozwój sieci transportowej poprzez przecinanie stoków górskich, w połączeniu z naturalnymi uwarunkowaniami geologicznymi, zwiększył niestabilność mas skalnych. Niniejsze badanie ma na celu wyjaśnienie złożonego, pięcioetapowego mechanizmu obrywów skalnych oraz oszacowanie objętości potencjalnych mas osuwiskowych w celu dostarczenia podstaw naukowych dla działań zapobiegawczych. Zastosowano zintegrowaną metodologię badawczą, łączącą tradycyjne obserwacje terenowe z nowoczesnymi technologiami bezkontaktowymi i penetracyjnymi, w szczególności fotogrametrię z wykorzystaniem bezzałogowych statków powietrznych (UAV) do tworzenia modeli terenu wysokiej rozdzielczości oraz profilowanie naturalnego pola elektrycznego (Self-Potential) przy użyciu aparatury S150. Wyniki badań geofizycznych pozwoliły na identyfikację rozległego podziemnego systemu krasowego, charakteryzującego się dużymi pustkami oraz głębokimi strefami spękań wypełnionymi nawodnioną gliną i słabo skonsolidowanym materiałem rumoszowym. Oszacowano znaczną objętość potencjalnej masy osuwiskowej o wysokiej tendencji kinematycznej do zablokowania korytarza transportowego. Uzyskane wyniki umożliwiły zaproponowanie czterech specjalistycznych rozwiązań inżynieryjnych, od wzmocnienia geotechnicznego po konstrukcje ochronne, zapewniających równowagę pomiędzy maksymalnym bezpieczeństwem a zachowaniem naturalnego krajobrazu.

Słowa kluczowe: bezzałogowy statek powietrzny (UAV), zagrożenie obrywami skalnymi, profilowanie potencjału własnego, mechanizm krasowy