

Development and field evaluation of a UAV-based supervision framework for rope-access operations in rockfall mitigation projects

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Abstract

Rockfall mitigation projects involve high occupational health and safety (OHS) risks due to steep topography, hard-to-access work zones, rope-access operations, and environmental uncertainties. In such projects, conventional supervision and communication practices may be limited by blind spots, restricted visibility, and difficult terrain conditions. This study develops and field-evaluates an unmanned aerial vehicle (UAV)-based supervision framework to support OHS planning and operational coordination in rope-access operations carried out within rockfall mitigation projects. A descriptive and exploratory field-based research design was adopted. Questionnaire data were collected from 128 Rope Access Technicians (RATs) working in 16 active rockfall mitigation projects in different regions of Türkiye. The survey examined participants' professional profiles, accident experiences, safety checks, communication and supervision practices, UAV awareness, UAV-related training status, and perceptions regarding UAV-supported monitoring. Field observations were also used to document the physical and operational characteristics of rope-access worksites. Based on the survey findings and field observations, a UAV-based supervision framework was structured around real-time visual monitoring, blind-spot reduction, communication support, hazard observation, and operational coordination. The proposed framework was then examined through a single-site pilot implementation in an active rockfall mitigation project. The findings indicate that RATs generally perceive UAV-supported monitoring and communication as potentially useful for improving situational awareness and supporting field coordination. The pilot implementation provided observational evidence that UAVs can assist supervisors by extending visual access to hard-to-observe work areas. However, the study does not claim to demonstrate quantitative reductions in accident rates, work duration, or costs. The proposed UAV-based framework should therefore be considered a complementary decision-support and supervision tool rather than a replacement for trained rope-access supervision.

1. Introduction

Rockfall is a natural hazard that occurs when detached rock blocks move downslope under the influence of gravity, posing serious threats to transportation corridors, infrastructure systems, settlements, and human life [1-3]. Therefore, rockfall mitigation projects play an important role in disaster risk reduction and public safety. However, these projects differ from conventional construction activities because they are generally carried out on steep, unstable, and hard-to-access slopes where geological, topographical, and environmental uncertainties directly affect both construction operations and worker safety.

Rockfall mitigation works involve several site-specific engineering activities, including drilling, anchorage

installation, surface cleaning, scaling of unstable blocks, wire mesh placement, shotcrete application, and the installation of energy-dissipating barriers [4-6]. In many cases, these activities are performed by Rope Access Technicians (RATs), who carry out construction tasks while suspended on ropes or positioned on steep slope surfaces. Accordingly, RATs are not only responsible for accessing difficult locations but also for implementing critical construction operations under physically demanding and hazardous site conditions.

The occupational health and safety (OHS) risks encountered in rope-access operations are multidimensional. RATs may be exposed to falls from height, sudden rock detachments, unstable ground conditions, slippery surfaces, rope or equipment failures, falling objects, adverse weather conditions, and limited opportunities for rapid emergency

response [7-10]. This concern is also relevant in the Turkish construction context, where national occupational accident statistics indicate that approximately 30% of occupational accidents in 2024 were associated with working at height [11]. These risks show that safety management in rockfall mitigation projects cannot be limited to the use of personal protective equipment (PPE) alone. Effective OHS planning also requires continuous supervision of work areas, monitoring of rope lines and anchor zones, early recognition of hazardous conditions, reliable communication, and coordination between RATs, supervisors, and site management.

From a construction management perspective, rope-access-based rockfall mitigation projects create specific challenges for field supervision and operational coordination. The size and irregular geometry of slope surfaces, restricted visibility from ground level, and the dispersed positioning of workers may create blind spots for supervisors. In addition, conventional communication tools such as two-way radios, mobile phones, shouting, or hand signals may become insufficient in noisy, rugged, or visually obstructed environments. These limitations may delay the identification of unsafe conditions, reduce situational awareness, and negatively affect the continuity of work processes. Therefore, there is a need for complementary supervision tools that can support OHS planning, communication, and field coordination in such high-risk construction environments.

Unmanned aerial vehicles (UAVs) have increasingly been used in the construction sector for visual inspection, photogrammetry, progress monitoring, site documentation, logistics planning, and safety-related observation [12-15]. UAVs can provide visual access to areas that are difficult or unsafe for workers to reach and can support decision-making by supplying real-time or near-real-time site information. These capabilities make UAVs potentially valuable for construction activities conducted in complex and hazardous environments. However, most existing studies have focused on conventional construction sites, infrastructure inspection, or general safety monitoring practices.

Despite the growing body of research on UAV applications in construction, limited attention has been given to UAV-supported continuous supervision in rope-access operations performed within rockfall mitigation projects. In particular, the combined use of UAVs for blind-spot reduction, real-time visual support, communication assistance, hazard observation, and operational coordination in active rockfall mitigation works remains underexplored. This gap is important because the working conditions of RATs on steep rock slopes differ substantially from those of workers on conventional construction sites, and the supervision needs of these operations require a more context-specific approach.

In response to this gap, this study aims to identify current supervision, communication, and OHS-related challenges in rope-access operations within rockfall mitigation projects and

to develop a UAV-based supervision framework that can support visual monitoring and field coordination. The study adopts a descriptive and exploratory field-based approach. Questionnaire data were collected from 128 RATs working in 16 active rockfall mitigation projects in different regions of Türkiye, and field observations were used to document the operational characteristics of rope-access worksites. Based on these findings, a UAV-based supervision framework was developed and examined through a single-site pilot implementation in an active rockfall mitigation project.

Accordingly, this study addresses the following research questions:

RQ1: What are the main OHS, supervision, and communication challenges encountered by RATs during rope-access operations in rockfall mitigation projects?

RQ2: How do RATs perceive the potential usefulness of UAV-supported monitoring, communication, training, and operational coordination in such projects?

RQ3: How can a UAV-based supervision framework be structured to support visual monitoring, blind-spot reduction, communication, and supervisor decision-making in rope-access operations?

The contribution of this study is fourfold. First, it provides field-based evidence on the supervision, communication, safety, and UAV-related perceptions of RATs working in active rockfall mitigation projects. Second, it frames UAV use not only as a visual inspection tool but also as a complementary support mechanism for OHS planning and operational coordination. Third, it proposes a UAV-based supervision framework structured around real-time visual monitoring, blind-spot reduction, communication support, hazard observation, and decision support. Fourth, it evaluates the field applicability of the proposed framework through a pilot implementation. The study does not position UAVs as a replacement for trained rope-access supervision; rather, it considers them as complementary tools that may assist supervisors and RATs in improving situational awareness and coordinating high-risk field operations.

2. Methodology

This study was designed as a descriptive and exploratory field-based research to evaluate OHS, site supervision, communication, and operational coordination challenges encountered during rope-access operations in rockfall mitigation projects and to develop a UAV-based supervision framework in this context. The research process consisted of field observations conducted in active rockfall mitigation sites, a questionnaire survey administered to RATs, content analysis of open-ended responses, development of the UAV-based supervision framework, and a single-site pilot implementation to examine the field applicability of the proposed framework.

2.1. Research design

The study adopted a descriptive and exploratory approach rather than an experimental or causal effect-measurement design. Accordingly, the purpose of the research was to identify existing field conditions and worker experiences, rather than to produce statistically generalizable or causal findings. The results are therefore interpreted as field-based evidence reflecting the experiences, perceptions, and current practices of RATs working in active rockfall mitigation projects, rather than as representative findings for all RATs or all rockfall mitigation projects in Türkiye.

Three complementary sources of evidence were used in the study: field observations, questionnaire data, and pilot implementation observations. Field observations were used to document worksite conditions, topographical constraints, rope-access practices, and supervision and communication limitations in rockfall mitigation projects. Questionnaire data were used to identify RATs' individual experiences, safety practices, communication methods, and perceptions regarding UAV use. The pilot implementation was conducted to observe the field applicability of the proposed UAV-based supervision framework under active site conditions.

2.2. Project selection and sample

Within the scope of the study, 16 active rockfall mitigation projects located in different cities of Türkiye were included at the time of data collection. The selection of these projects was based on three main criteria: the presence of ongoing rockfall mitigation works, the use of rope-access operations within the project, and the active involvement of RATs on site. In addition, only the sites for which the researchers were able to establish communication, obtain verbal acceptance, and collect data were included in the study.

Since no comprehensive and accessible data were available on the total number of active rockfall mitigation projects or the total number of RATs working in such projects in Türkiye during the study period, probability-based sampling could not be applied. Therefore, the study was conducted using a purposive and accessible sampling approach. Accordingly, the sample should be interpreted as an accessible field-based sample rather than a statistically representative sample of all RATs or rockfall mitigation projects in Türkiye.

The regional distribution of the 16 sites was as follows: nine sites were located in the Black Sea Region, one site in the Marmara Region, two sites in the Mediterranean Region, and four sites in the Southeastern Anatolia Region. Although this distribution indicates that data were collected from active projects carried out under different geographical conditions in Türkiye, it does not imply a regionally balanced or statistically representative sample.

2.3. Field observations

Field observations were carried out in the same 16 active rockfall mitigation projects in which the questionnaire survey

was administered. During these observations, the topographical characteristics of the sites, slope surfaces, locations where RATs were positioned, rope lines, anchorage zones, work surfaces, equipment used, visibility limitations, and on-site communication practices were examined. These observations provided contextual information for interpreting the questionnaire findings and for developing the UAV-based supervision framework.

The visual materials obtained during the field observations were used to document the physical conditions of rope-access works, steep and hard-to-access work surfaces, the positioning of RATs in the field, and the risk context of rockfall mitigation projects. In this regard, Fig. 1. presents the field conditions and rope-access operations observed in active rockfall mitigation projects.

The questionnaire respondents consisted of RATs working in the same 16 projects where the field observations were conducted. However, the observation records were not linked to individual questionnaire responses. Therefore, field observations and questionnaire data were treated as complementary but distinct sources of evidence.

2.4. Questionnaire structure and survey administration

The questionnaire survey was conducted with a total of 128 RATs working in the 16 active rockfall mitigation projects. Participation was voluntary, and survey responses were collected anonymously. Depending on site conditions and participant accessibility, the questionnaire was administered both online and face-to-face.

The questionnaire consisted of closed-ended, multiple-choice, yes/no/partially structured, and open-ended questions. It addressed participants' demographic and professional profiles, rope-access experience, certification levels, PPE use, accident and health problem experiences, pre-work and in-work safety checks, existing supervision and communication methods, UAV awareness, UAV-related training status, and perceptions regarding UAV-supported monitoring and communication systems.

The open-ended questions allowed RATs to describe, in their own words, possible accident types encountered in the field, routine safety checks, how they monitor and protect one another against hazards, communication practices, and factors affecting work efficiency. Thus, the descriptive findings obtained from closed-ended questions were supported by more detailed field experiences derived from open-ended responses.

2.5. Data analysis and content analysis procedure

Quantitative data obtained from the questionnaire were analyzed using frequencies and percentages. Since the study was based on a purposive and accessible sampling approach, no comprehensive data were available on the total RAT population in Türkiye, and the research was descriptive and exploratory in nature, inferential statistical tests were not used.



Fig. 1. Field conditions and rope-access operations observed in active rockfall mitigation projects

Therefore, the findings were interpreted as descriptive results reflecting the field experiences and perceptions of the RATs included in the study, rather than as causal or statistically generalizable outcomes.

Responses to open-ended questions were analyzed using an inductive content analysis approach. In the first stage, the responses were read repeatedly to identify meaningful expressions. Similar expressions were then grouped under initial codes. These codes were subsequently combined into broader themes according to semantic similarity. Ambiguous, repetitive, or multi-theme statements were re-evaluated, and the final themes were organized in line with the research aim. As a result of this process, main themes were developed concerning occupational accident risks, routine safety checks, supervision and communication practices, factors affecting work efficiency, and perceptions of UAV use. The open-ended responses were coded by a single coder. Therefore, inter-coder agreement statistics were not calculated. To improve coding consistency, the responses were reviewed iteratively, initial codes were refined through repeated comparison, and overlapping codes were grouped under broader themes.

2.6. Development of the UAV-based supervision framework

Based on the findings obtained from the field observations and questionnaire survey, a UAV-based supervision

framework was developed to support rope-access operations in rockfall mitigation projects. The main components of the framework were defined as real-time visual monitoring, blind-spot reduction, hazard observation, monitoring of rope lines and anchorage zones, on-site communication support, operational coordination, and decision-support processes.

The proposed framework does not aim to replace trained rope-access supervision. Instead, it is intended to provide complementary visual monitoring and coordination support to existing supervision and OHS planning practices. In this context, UAV use is considered an auxiliary tool that can support the decision-making process of responsible site personnel, make hard-to-observe work areas more visible, and strengthen communication between RATs and site management. The overall research workflow and the development process of the UAV-based supervision framework are summarized in Fig. 2.

2.7. Pilot implementation

The proposed UAV-based supervision framework was pilot-tested in one active rockfall mitigation site among the 16 projects included in the study. The RATs working at the pilot site were also part of the overall survey sample of 128 participants. This indicates that the pilot implementation was carried out in one of the active projects evaluated within the survey and field observation stages, rather than in a separate or unrelated site.

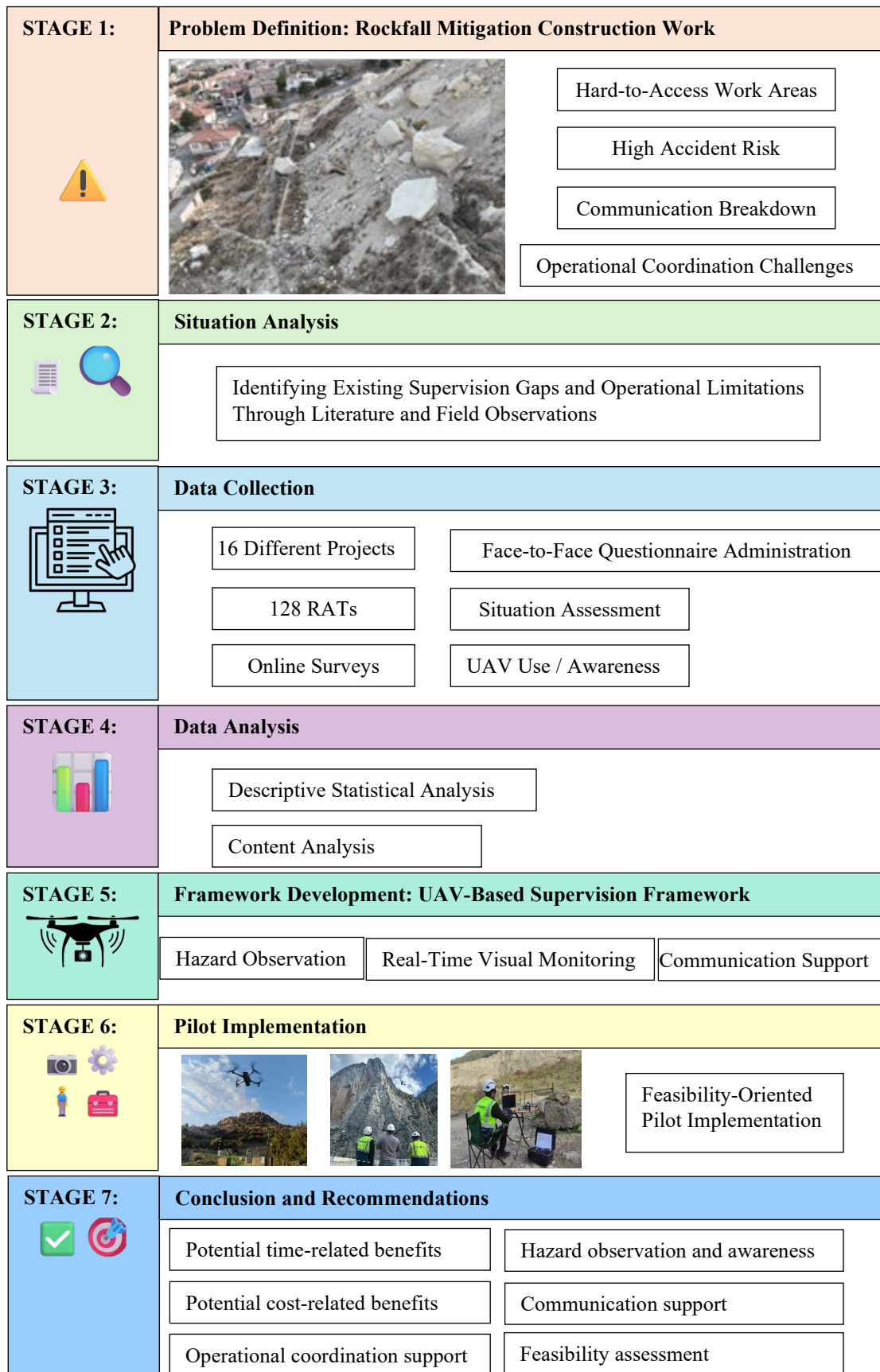


Fig. 2. Research workflow and development process of the UAV-based supervision framework

The pilot site was selected because it was an active rockfall mitigation project where site access and permission for UAV-supported observation could be obtained. The site

included active rope-access operations, steep and hard-to-access work zones, rope-access routes, anchorage areas, and restricted ground-based visibility conditions. These

characteristics made the site suitable for observing the field applicability of the proposed UAV-based supervision framework. The pilot implementation was conducted within one working day, and the researchers observed the rope-access and construction activities that were being carried out on site during that day. Due to site management restrictions, detailed project-specific information and detailed production records are not reported in the manuscript.

The pilot implementation was conducted as a feasibility-oriented field application rather than a controlled effectiveness experiment. During the implementation, the UAV was used to visually observe work surfaces, rope lines, anchorage zones, rope-access routes, and field conditions that could require additional safety attention. The visual information provided by the UAV enabled responsible site personnel to assess the work area from a broader perspective.

Within the scope of the pilot implementation, the UAV was observed to support the monitoring of areas with restricted visibility, recognition of potential hazards along work lines, understanding of worker positioning in the field, and coordination of site activities. However, quantitative performance indicators such as accident rates, work duration, cost advantages, or risk reduction were not systematically measured during the pilot implementation. Therefore, the pilot findings were interpreted as observational evidence regarding the field applicability of the proposed framework, rather than as quantitative evidence demonstrating the effectiveness of UAV use.

3. Findings

This section presents the findings obtained from the questionnaire survey conducted with 128 RATs working in 16 active rockfall mitigation projects and the field observations carried out in the same projects. The findings are organized under six main themes: participant profile, risk profile and accident experience, safety checks and PPE use, existing supervision and communication practices, UAV awareness and perceived usefulness, and thematic results derived from open-ended responses. In line with the descriptive and exploratory nature of the study, the results are reported using frequencies, percentages, and thematic interpretations. The findings related to UAV use are interpreted as worker perceptions and field-based observations rather than as measured evidence of accident reduction, time savings, or cost savings.

3.1. Participant profile

Table 1 summarizes the demographic and professional profile of the RATs included in the study. The age distribution shows that most participants were between 26 and 40 years old, indicating that the surveyed workforce was largely composed of physically active field personnel. In terms of education

level, half of the participants were high school graduates, while associate degree, bachelor's degree, and postgraduate graduates were also represented. This distribution indicates that the RAT profile in the surveyed rockfall mitigation projects was heterogeneous in terms of educational background.

Regarding rope-access experience, most participants had between 1 and 10 years of experience, while a considerable proportion had more than 10 years of field experience. Certification levels also showed a multi-layered structure: L1-certified RATs constituted the largest group, while L3-certified RATs represented more than one-quarter of the sample. In the rope-access certification system, L1 refers to entry-level technicians who perform rope-access tasks under supervision; L2 refers to intermediate technicians with more advanced access and rescue skills; and L3 refers to senior technicians responsible for supervision, rescue planning, risk assessment, and OHS oversight. Both Industrial Rope Access Trade Association (IRATA) and Society of Professional Rope Access Technicians (SPRAT) define rope-access competence through a three-level certification structure, although IRATA was the dominant certification body among the RATs included in this study [16, 17].

3.2. Risk profile and accident experience

Fig. 3. presents the occupational accident history of the RATs during rope-access operations. Although most participants reported that they had not experienced an occupational accident, a notable proportion stated that they had experienced at least one accident during their professional practice. This finding indicates that accident exposure remains an important concern in rope-access operations carried out within rockfall mitigation projects.

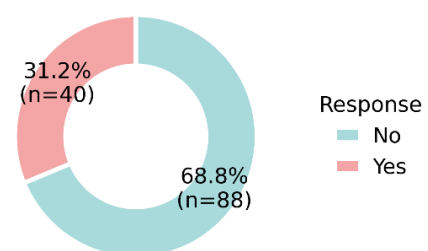


Fig. 3. Occupational accident history of RATs during rope-access operations

Fig. 4. shows the reported causes of occupational accidents among RATs who had accident experience. The responses indicate that accident causes were not limited to fall-related events. Wet or slippery surfaces, rockfall, slope failure, and tool or equipment drops were also reported as important sources of risk. These findings suggest that OHS planning in rockfall mitigation projects should address not only individual PPE use but also environmental, geotechnical, and equipment-related hazards.

Table 1. Demographic and professional profile of the surveyed RATs

Variable	Category	n	%
Age	20–25	9	7.0
	26–30	30	23.4
	31–35	34	26.5
	36–40	28	21.9
	41–45	17	13.3
	46–50	8	6.3
	51–60	2	1.6
Education level	Primary school	8	6.2
	High school	64	50.0
	Associate degree	24	18.8
	Bachelor's degree	28	21.9
	Postgraduate	4	3.1
Rope-access experience	Less than 1 year	8	6.3
	1–5 years	44	34.4
	6–10 years	40	31.3
	11–15 years	22	17.2
	16 years and above	14	10.9
Certification level	L1	72	56.3
	L2	20	15.6
	L3	36	28.1
Certification body	IRATA	120	93.8
	SPRAT	8	6.2

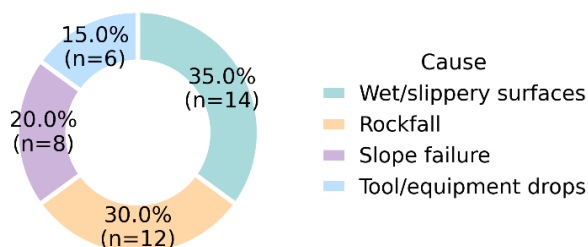
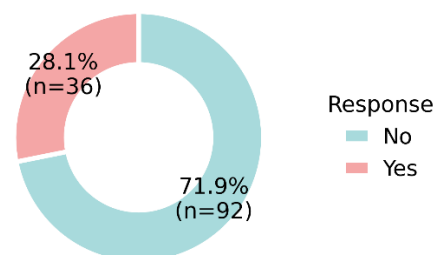
**Fig. 4.** Reported causes of occupational accidents during rope-access operations

Fig. 5. presents the health problems experienced by RATs during rope-access operations. While most participants reported no health problems, some RATs indicated issues such as dizziness, cramps, heat- or cold-related discomfort, and nosebleeds. These findings show that rope-access operations should also be considered in terms of physical strain and health-related risks arising from demanding field conditions.

The open-ended responses further supported this multidimensional risk profile. RATs identified possible accident scenarios such as rock or stone fall, rope damage, falling from height, falling objects, improper anchorage, pendulum effect, slope failure, injuries during heavy material handling, and lack of attention. Overall, the findings indicate that rope-access operations in rockfall mitigation projects

involve environmental, mechanical, human-related, and organizational risk factors.

**Fig. 5.** Health problems experienced by RATs during rope-access operations

3.3. Safety checks, PPE use and visibility

The responses regarding routine safety checks indicate that safety control in rope-access operations is not limited to a single pre-work inspection. Before starting work, RATs emphasized the importance of checking PPE, ropes, carabiners, descenders, ascenders, anchor points, weather conditions, ground conditions, sharp rock surfaces, and the overall work area. During work, the main checks focused on rope positioning, locked carabiners, rope contact with sharp surfaces, loose stones, falling-object risks, worker positioning, and teammate safety. These findings show that

safety control in rope-access operations is a continuous and dynamic field practice.

Table 2 summarizes the PPE categories reported by RATs during rope-access operations. The responses show that RATs use basic protective equipment such as helmets, safety harnesses, gloves, lanyards, shock absorbers, lifelines, anchors, carabiners, and fall-arrest systems. In addition, eye and face protection, hearing protection, respiratory protection, and auxiliary rope-access equipment are used depending on the task and site conditions.

Fig. 6. presents the use of high-visibility clothing by RATs during rope-access operations. Visibility-related clothing practices are relevant not only for worker detectability in complex terrain but also for UAV-supported visual monitoring. However, some RATs stated that reflective vests may interfere with harnesses and other rope-access equipment, limiting comfort and freedom of movement. Therefore, visibility practices should be considered together with ergonomic suitability and task-specific equipment requirements.

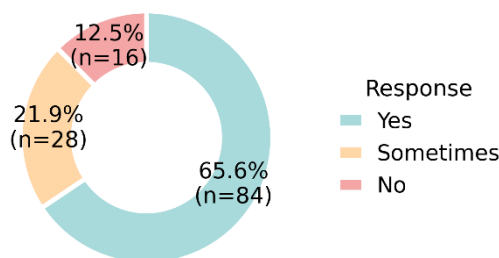


Fig. 6. Use of high-visibility clothing during rope-access operations

3.4. Existing supervision and communication practices

The findings related to existing supervision and communication practices show that rope-access operations in rockfall mitigation projects require continuous coordination between RATs, supervisors, and ground personnel. Field observations indicated that work areas were generally located on steep slopes, unstable rock surfaces, and hard-to-access zones where direct visual supervision was limited. In such conditions, supervisors may not always be able to observe all

workers, rope lines, anchor points, and potential hazard zones simultaneously.

The questionnaire responses and field observations also showed that communication during rope-access operations is carried out through a combination of verbal communication, hand signals, radios, mobile phones, and direct visual contact where possible. However, the effectiveness of these communication methods may be reduced by terrain conditions, distance between workers and supervisors, noise, limited visibility, and the physical separation of work teams across the slope. These limitations are particularly important in tasks involving scaling, drilling, mesh installation, anchorage works, and material handling.

From an OHS and construction management perspective, these findings suggest that supervision in rockfall mitigation projects should not be considered only as a compliance-based safety control process. Instead, it should be evaluated as a field coordination mechanism that supports hazard observation, task sequencing, worker positioning, communication continuity, and rapid response to changing site conditions. Therefore, the need for a complementary visual monitoring tool becomes more evident in work environments where conventional ground-based supervision is restricted by topography and access limitations.

Overall, the findings indicate that current supervision and communication practices provide a necessary basis for managing rope-access operations; however, they may remain limited in terms of blind-spot reduction, real-time visual awareness, and continuous observation of high-risk work zones. This forms the practical basis for proposing a UAV-based supervision framework as a complementary support tool for rope-access operations in rockfall mitigation projects.

3.5. UAV awareness, training status and perceived usefulness

Fig. 7. presents the views of RATs regarding the usefulness of a UAV-based monitoring and voice communication system during rope-access operations. The findings show that most RATs considered such a system beneficial, while a smaller group evaluated its usefulness as partial.

Table 2. PPE used by RATs during rope-access operations

PPE Category	Equipment Reported by RATs
Head Protection	Helmets
Hand and Arm Protection	Work gloves, cut-resistant gloves, arm protectors / forearm guards
Body Protection	Safety harnesses, work-positioning harness, coveralls / protective overalls
Fall Arrest / Safety Equipment	Lanyards, shock absorbers, work-positioning lanyards, horizontal lifeline, retractable fall arresters, fall-arrest devices, anchors / anchorage points, carabiners
Foot and Leg Protection	Safety boots, work boots, protective kneepads
Eye and Face Protection	Safety goggles, face visor
Hearing Protection	Earmuffs, ear plugs
Respiratory Protection	Gas masks, dust masks / particulate respirators
Environmental Safety and Auxiliary Equipment	Accessory ropes, webbing slings, mechanical rope pulleys, descenders, ascenders, rig devices, jumars, pantin, podium

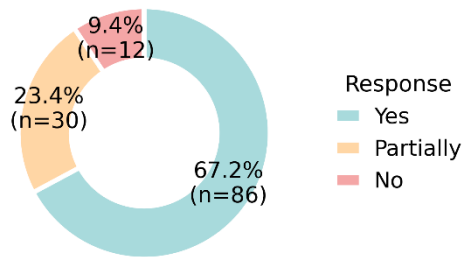


Fig. 7. Responses of RATs to the usefulness of a UAV-based monitoring and voice communication system

This result indicates that RATs generally perceive UAV-supported monitoring and communication as a promising complementary tool for improving visual awareness, communication continuity, and field coordination. However, the “Partially” and “No” responses also indicate that the perceived usefulness of such systems may depend on site conditions, technical accessibility, operational costs, and the practical integration of UAVs into existing work routines.

Fig. 8. shows the views of RATs regarding whether rope-access work is formally recognized in national legislation. The dominance of “No” responses indicates that RATs perceive a lack of clear professional recognition and legal definition for rope-access work. This finding is important because regulatory ambiguity may affect not only the professional status of RATs but also the standardization of training, supervision, and OHS practices in rockfall mitigation projects.

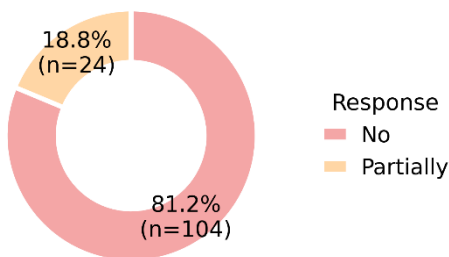


Fig. 8. Responses of RATs regarding the recognition of rope-access work in national legislation

Fig. 9. presents the UAV-related training status of RATs. The results show that the vast majority of participants had not received any training related to the use of UAVs in rope-access operations. This finding reveals a clear training gap between the perceived usefulness of UAV-supported monitoring and the current level of UAV-related competence among RATs. Therefore, the integration of UAVs into rope-access operations should be supported by structured training programs covering UAV operation, field communication, visual monitoring, emergency response, data interpretation, privacy, and site-specific safety protocols.

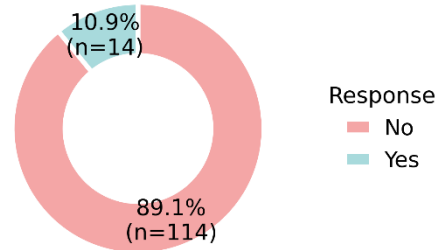


Fig. 9. UAV-related training status of RATs

Fig. 10. presents the views of RATs regarding whether UAV training would contribute to OHS awareness. Most participants stated that UAV training could improve safety awareness, while some participants considered this contribution partial. This result suggests that UAV training is not only a technical requirement but also a potential component of safety culture development. However, such training should be adapted to real field conditions and should not remain limited to theoretical or device-oriented instruction.

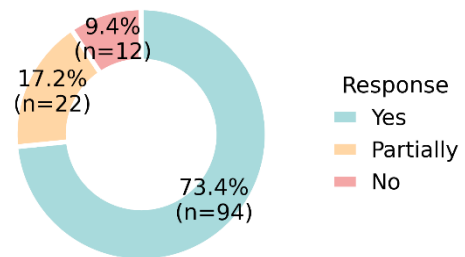


Fig. 10. Views of RATs on the contribution of UAV training to OHS awareness

Fig. 11. presents the views of RATs regarding whether UAV use could reduce work duration and provide cost advantages in rope-access operations. The results indicate that many RATs perceive UAVs as potentially useful for improving operational efficiency. Participants associated possible benefits with faster site inspection, quicker identification of hazardous areas, improved task monitoring, and better coordination between field teams. However, these findings should be interpreted as worker perceptions rather than measured evidence of time or cost reduction. The present study does not provide controlled quantitative data demonstrating reductions in work duration, cost, or accident frequency.

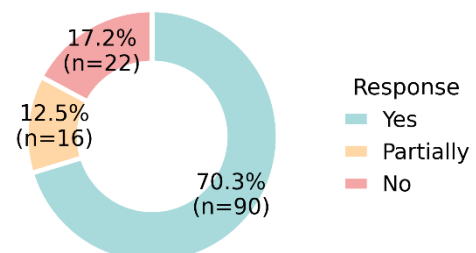


Fig. 11. Responses of RATs regarding the perceived time and cost benefits of UAV use

3.6. Thematic results from open-ended responses

The open-ended responses were analyzed through inductive content analysis in order to identify recurring risk factors, supervision needs, and expectations regarding UAV-supported field practices. The responses were first reviewed repeatedly, then similar expressions were grouped under initial codes. These codes were subsequently organized into broader themes related to accident risk, safety control, communication, monitoring, training, and operational efficiency. Table 3 presents the thematic summary of the open-ended responses.

The thematic results show that RATs define rope-access operations as a dynamic and high-risk work process shaped by changing terrain conditions, environmental hazards, equipment reliability, and communication continuity. These responses also indicate that UAVs are not perceived merely as recording devices but as potential support tools for field supervision, visual awareness, and operational coordination. However, the responses also underline that UAV use requires training, clear responsibilities, and integration with existing rope-access safety procedures.

Overall, the content analysis supports the development of a UAV-based supervision framework by identifying the main field needs that such a system should address: blind-spot reduction, real-time visual monitoring, communication support, hazard observation, and decision support for supervisors. At the same time, the findings suggest that UAVs should be positioned as complementary tools within the

existing OHS and rope-access supervision system rather than as substitutes for trained RATs, supervisors, or established safety procedures.

4. UAV-Based Supervision Framework for Rope-Access Operations

Based on the questionnaire findings, field observations, and thematic analysis of open-ended responses, this section proposes a UAV-based supervision framework for rope-access operations in rockfall mitigation projects. The framework is designed to support OHS planning, visual monitoring, communication, and operational coordination in steep and hard-to-access work environments. It should be emphasized that the proposed framework does not replace trained RATs, L3 supervisors, or established rope-access safety procedures. Instead, it provides a complementary supervision and decision-support mechanism by extending the visual access of site supervisors to areas that are difficult to observe from the ground.

4.1. Rationale for the framework

The findings of the study indicate that rope-access operations in rockfall mitigation projects involve a combination of environmental, geotechnical, equipment-related, and organizational risks. RATs reported accident scenarios associated with rockfall, slope failure, falling objects, rope damage, improper anchorage, pendulum effect, slippery surfaces, and loss of balance.

Table 3. Thematic summary of open-ended responses

Theme	Main codes identified from responses	Interpretation
Accident and hazard scenarios	Rockfall, stone fall, slope failure, falling from height, falling objects, rope damage, improper anchorage, pendulum effect, loss of balance	RATs perceive risk as a combination of geotechnical, environmental, equipment-related, and human-related factors.
Safety checks before work	PPE control, rope inspection, anchor-point control, carabiner locking, weather control, terrain control, sharp rock surfaces, loose stones	Safety preparation is understood as a multi-step process that includes both personal equipment and site-specific hazard checks.
Safety checks during work	Rope position, rope contact with sharp edges, teammate position, falling-object risk, anchor stability, worker movement, changing slope conditions	Safety control continues during work and requires constant observation of both workers and the surrounding terrain.
Supervision limitations	Blind spots, limited visibility, difficult terrain, distance between workers and supervisors, inability to observe all work zones simultaneously	Conventional ground-based supervision may remain limited in complex and steep work environments.
Communication challenges	Voice limitation, distance, noise, hand signals, radio/mobile phone use, delayed information transfer	Communication is critical for coordination, but its effectiveness may decrease under difficult field conditions.
Expected contribution of UAVs	Visual monitoring, observation of inaccessible areas, hazard observation, coordination support, faster site inspection, improved situational awareness	UAVs are perceived as complementary tools that may support supervisors by extending visual access to hard-to-observe areas.
UAV-related concerns	Cost, technical competence, training need, weather sensitivity, operational integration, device limitations	UAV integration requires training, planning, and site-specific protocols rather than simple equipment deployment.
Training and awareness needs	UAV operation, OHS awareness, communication procedures, emergency response, field coordination, equipment compatibility	RATs emphasize that UAV-supported supervision should be supported by structured training and practical field adaptation.

In addition, field observations showed that work areas are commonly located on steep slopes, unstable rock surfaces, and visually complex terrain conditions.

Under such conditions, conventional ground-based supervision may remain limited. Supervisors may not always be able to observe worker positions, rope lines, anchor points, loose rock blocks, equipment placement, and changing surface conditions simultaneously. These limitations become more critical when workers are distributed across different elevations or when the topography creates blind spots between RATs and supervisors.

The survey findings also showed that RATs generally perceived UAV-supported monitoring and communication as useful for improving visual awareness and field coordination. However, UAV-related training was limited among participants. This contrast suggests that UAVs may offer practical potential for supporting supervision, but their integration into rope-access operations requires a structured framework, clearly defined roles, and site-specific safety procedures.

Therefore, the proposed framework is based on three main assumptions. First, UAVs can improve visual access to hard-to-observe work zones. Second, UAV-supported visual information can support communication and coordination between RATs, supervisors, and ground teams. Third, UAVs should be used as complementary supervision tools rather than as autonomous decision-making systems or substitutes for rope-access expertise.

4.2. Main components of the UAV-based supervision framework

The UAV-based supervision framework consists of six interrelated components: pre-work site observation, real-time visual monitoring, blind-spot reduction, hazard observation, communication support, and supervisor decision support.

Pre-work site observation refers to the use of UAVs before the start of rope-access operations to visually examine the work area. This component includes the observation of slope geometry, rock surfaces, access routes, loose blocks, potential falling-object zones, anchorage areas, and material storage locations. The purpose of this stage is to support the supervisor's preliminary assessment of site conditions and to contribute to safer work planning.

Real-time visual monitoring refers to the use of UAVs during rope-access operations to support continuous observation of workers, rope lines, working surfaces, and surrounding terrain conditions. This component is particularly relevant in rockfall mitigation projects where direct ground-based visibility may be restricted by slope angle, distance, vegetation, or topographic irregularities.

Blind-spot reduction is one of the central functions of the framework. UAVs can provide additional viewing angles for areas that cannot be easily observed by supervisors from the ground. This may help supervisors maintain better situational awareness, especially when RATs are working at different

elevations or behind rock projections, mesh systems, or uneven slope surfaces.

Hazard observation refers to the visual identification of potentially unsafe field conditions through UAV imagery. These may include loose stones, unstable surface areas, unsafe material placement, rope contact with sharp edges, falling-object risks, or equipment left in hazardous locations. In this framework, hazard observation should not be interpreted as automated hazard detection. The UAV provides visual information, while the interpretation and decision-making responsibility remain with trained supervisors and OHS personnel.

Communication support refers to the contribution of UAV-supported visual information to field coordination. UAV imagery may help supervisors communicate more clearly with RATs and ground teams by referring to visible locations, work zones, or risk areas. This is particularly important in work environments where voice communication, hand signals, or radio communication may be limited by distance, noise, or terrain conditions.

Supervisor decision support refers to the role of UAVs in assisting, but not replacing, field decisions. UAV-supported visual information can help supervisors decide whether to continue work, request additional checks, warn workers, modify task sequencing, or temporarily stop operations. Therefore, the UAV is positioned as a decision-support tool within the existing rope-access supervision system.

4.3. Operational workflow and decision protocol

The proposed UAV-based supervision framework follows a three-stage operational workflow: pre-work observation, during-work monitoring, and post-work review. Each stage has a different function within the supervision process and should be integrated with existing rope-access safety procedures.

In the pre-work observation stage, the UAV is used to visually examine the work area before RATs begin rope-access operations. The UAV operator, under the coordination of the site supervisor or L3 technician, observes the slope surface, access routes, anchorage zones, loose rock blocks, material placement areas, and possible falling-object zones. The visual information obtained at this stage supports the preliminary risk assessment and helps the supervisor identify areas that may require additional inspection, cleaning, protection, or restriction before work starts.

In the during-work monitoring stage, the UAV provides visual support for observing RAT positions, rope lines, work surfaces, anchorage areas, and surrounding terrain conditions. The aim is not to continuously control workers in a surveillance-oriented manner, but to support situational awareness and coordination in areas where ground-based visibility is limited. UAV-supported monitoring may be particularly useful when RATs work at different elevations, behind slope irregularities, or in zones that cannot be directly observed by the supervisor.

In the post-work review stage, UAV images or videos may be reviewed for documentation, training, and improvement of future work planning. This stage can support the identification of recurring field risks, communication problems, equipment placement issues, and areas where additional OHS measures may be required. However, the use of UAV records should comply with relevant privacy, data protection, and site management procedures.

The decision protocol of the framework is based on a simple escalation logic. Under normal conditions, UAV-supported visual monitoring continues without interrupting rope-access operations. If a potential hazard is visually observed, the supervisor evaluates the situation and communicates with the relevant RATs or ground team. If the hazard is minor and controllable, the supervisor may request an additional check or adjustment, such as repositioning equipment, checking a rope contact point, or moving away from a loose surface area. If a serious hazard is observed, such as unstable rock movement, unsafe rope contact, anchor-related concerns, falling-object risk, or communication loss, the supervisor may temporarily stop the operation and request a field reassessment.

The decision-making responsibility remains with the rope-access supervisor, L3 technician, site manager, or OHS personnel according to the project organization. The UAV operator provides visual information but does not independently make rope-access safety decisions unless also authorized within the project safety hierarchy. Therefore, UAV-supported supervision should be implemented through clear communication protocols, predefined stop-work criteria, and coordination with existing emergency response procedures.

This workflow positions the UAV as a complementary supervision tool that supports visual access, communication, and decision-making. It does not create a separate safety system independent from rope-access procedures; rather, it strengthens the existing supervision process by providing additional visual information from hard-to-observe areas.

4.4. Roles and responsibilities

The effective implementation of the UAV-based supervision framework requires clearly defined roles and responsibilities. Since rope-access operations involve high-risk work at height and complex terrain conditions, UAV-supported supervision should be integrated into the existing safety hierarchy rather than introduced as an independent monitoring practice.

The UAV operator is responsible for conducting the flight safely and in accordance with site-specific procedures, technical limitations, weather conditions, and applicable regulations. The operator should maintain safe flight distances from RATs, ropes, anchorage zones, equipment, and unstable rock surfaces. The UAV operator is also responsible for providing stable visual information to the supervisor but should not make independent rope-access

safety decisions unless formally assigned such authority within the project organization.

The rope-access supervisor or L3 technician has the primary responsibility for interpreting UAV-supported visual information in relation to rope-access safety. This role includes evaluating worker positioning, rope lines, anchorage areas, equipment placement, work sequence, and potential field hazards. If UAV images indicate an unsafe condition, the rope-access supervisor or L3 technician should decide whether additional inspection, corrective action, temporary work suspension, or emergency response is required.

RATs are responsible for carrying out rope-access tasks in accordance with existing safety procedures, supervisor instructions, and project-specific risk assessments. UAV-supported supervision does not reduce the responsibility of RATs to check their own PPE, ropes, anchor points, carabiners, positioning systems, and surrounding work area. Instead, UAV monitoring provides additional visual support that may help identify risks that are difficult to observe from the worker's immediate position.

The ground safety team supports communication between the UAV operator, rope-access supervisor, RATs, and other site personnel. This team may assist in maintaining exclusion zones, controlling pedestrian or vehicle access, managing falling-object risks, and transmitting supervisor instructions to the field team when direct communication is limited.

The site manager and OHS personnel are responsible for integrating UAV-supported supervision into the broader project safety management system. Their responsibilities include preparing UAV use procedures, defining authorization levels, ensuring compliance with OHS requirements, coordinating training, managing documentation, and evaluating whether UAV use is appropriate under specific site and weather conditions.

The framework also requires predefined communication rules. Before UAV use, all team members should know who will observe the UAV feed, who has authority to issue warnings, which communication channels will be used, and under which conditions the work will be paused. This is particularly important because UAV-supported visual information may reveal risks that require rapid but coordinated decision-making.

Overall, the role distribution in the framework is based on a clear principle: the UAV provides additional visual information, while safety interpretation and operational decisions remain under the responsibility of trained and authorized personnel. Therefore, UAV-supported supervision should strengthen, not replace, the existing rope-access supervision structure.

4.5. Pilot implementation and observational evidence

The proposed UAV-based supervision framework was examined through a single-site pilot implementation in an active rockfall mitigation project. The pilot implementation was conducted to evaluate the field applicability of UAV-

supported visual observation in rope-access operations. It was not designed as a controlled experiment to measure accident reduction, time savings, or cost reduction. Therefore, the pilot findings should be interpreted as observational evidence regarding feasibility and supervision support.

Fig. 12. illustrates the field conditions in which rope-access operations are commonly carried out in rockfall mitigation projects. The images show steep rock surfaces, rope-access routes, anchorage zones, surface cleaning activities, and difficult terrain conditions. These examples demonstrate why ground-based supervision may be limited in such environments. In particular, slope geometry, elevation differences, vegetation, rock projections, and restricted access may reduce the supervisor's direct visibility of RATs, rope lines, and potential hazard zones.

Fig. 13. presents examples of UAV-supported visual observation of rope-access activities and equipment-related field conditions. These images show how UAV-supported visual information may assist supervisors in observing worker positioning, active work zones, unused equipment, and potentially unsafe material placement. However, the figure

should be interpreted as an example of visual support for field supervision, not as evidence of automated hazard detection or measured risk reduction.

Prior to the pilot implementation, the work area was visually assessed to identify suitable UAV take-off and landing zones and to avoid interference with rope-access operations. The UAV flight was planned according to terrain constraints, visibility conditions, and the position of RATs on the slope. The operational flight altitude ranged approximately between 80 and 150 m above the working level, depending on visibility and topographic conditions. The reported 80–150 m range refers to the approximate elevation difference between the UAV take-off / ground control station level and the rope-access work zones observed on the slope. It does not represent absolute altitude above sea level. Since the pilot site had a steep and irregular topography, this vertical difference varied according to the location of RATs and the observed work area. The UAV platform used in the pilot implementation was a DJI Mavic 3 Enterprise-class system equipped with 4K dual optical zoom sensors and an RTK positioning system.



Fig. 12. Rope-access routes, anchorage zones, and surface cleaning stages in rockfall mitigation projects



Fig. 13. Examples of UAV-supported visual observation of rope-access activities and equipment-related field conditions

The UAV operation was planned in accordance with the applicable Directorate General of Civil Aviation (SHGM) framework and UAV requirements for UAV registration and operational compliance in Türkiye [18]. The UAV and the pilot/operator were registered in the SHGM system, and the pilot observation was conducted after the relevant operational permissions and site-level approvals were obtained. The flight area was checked before the operation, and no flight was conducted in restricted or prohibited airspace without authorization.

During the pilot, safe flight distances were maintained from RATs, rope lines, anchorage zones, equipment, and unstable rock surfaces. No fixed numerical separation distance was tested as an experimental variable. However, operational separation was applied as a safety criterion: the UAV was not flown directly above RATs, between active rope lines, or close to anchorage points, and the operator maintained a conservative visual distance from workers, ropes, equipment, and rock surfaces throughout the flight. The UAV operator provided visual information to the ground control station, while safety interpretation and operational decisions remained under the responsibility of the authorized field personnel. The UAV imagery was monitored at the ground control station through a live visual feed, allowing authorized field personnel to observe work zones without physically approaching hazardous or hard-to-access areas. Fig. 14. shows the pilot implementation setup, including the ground control station and UAV-supported field observation conditions.

During the pilot implementation, UAV-supported observation helped extend the visual access of supervisors to work areas that were difficult to observe from the ground. The UAV provided additional viewing angles for slope surfaces, rope-access routes, and equipment locations. This visual support may contribute to improved situational awareness, especially when workers are distributed across different elevations or when the supervisor's line of sight is restricted.

The pilot implementation also highlighted several practical considerations. UAV use in rope-access operations requires suitable weather conditions, adequate battery management, trained operators, clear communication channels, safe flight distances from ropes and workers, and compliance with site-specific safety procedures and applicable UAV operation requirements. In addition, UAV-supported visual monitoring should be coordinated with the rope-access supervisor or L3 technician, who remains responsible for interpreting the visual information and making safety-related decisions.

Overall, the pilot implementation suggests that UAVs can provide useful visual support for supervision and coordination in rope-access operations. Nevertheless, the findings remain limited to a single-site observational implementation. Further studies are required to evaluate the framework across different project types, terrain conditions, UAV configurations, and operational scenarios using measurable indicators such as inspection time, communication delays, near-miss reporting, supervisor response times, and documented hazard-control actions.

5. Discussion

The findings of this study indicate that rope-access operations in rockfall mitigation projects are not limited to work-at-height risks alone, but represent a complex field process shaped by environmental, geotechnical, equipment-related, communication-related, and organizational risks. Therefore, supervision in rope-access operations should not be considered only as a conventional OHS practice focused on checking the use of PPE. It should also be understood as a construction management process that involves task sequencing, field coordination, worker positioning, rope lines, anchorage zones, equipment placement, and changing terrain conditions. This perspective becomes particularly important in rockfall mitigation sites where slopes are steep, access is difficult, and direct visual control is limited.



Fig. 14. Pilot implementation setup showing the ground control station and UAV-supported field observation conditions

The literature on rockfall mitigation indicates that such projects are commonly carried out on steep, unstable, and hard-to-access slopes, where activities such as drilling, anchorage installation, wire-mesh placement, surface cleaning, shotcrete application, and barrier installation expose workers to multiple hazards [4, 5, 7-9, 19]. The findings of the present study are consistent with this literature. The RATs identified risks such as rockfall, slope failure, slippery surfaces, falling from height, falling objects, rope damage, improper anchorage, and pendulum effect. These findings show that risk in rockfall mitigation projects cannot be explained only by individual worker behavior or equipment use. Instead, it should be evaluated through the interaction of

terrain morphology, geotechnical uncertainty, equipment reliability, worker positioning, and the effectiveness of field supervision.

The use of UAVs in construction has been widely discussed for site exploration, progress tracking, photogrammetric data acquisition, safety monitoring, logistics planning, and visual documentation of hard-to-access areas [12-15, 20-22]. However, many of these studies focus on general construction monitoring, digital data acquisition, or site management processes. The contribution of the present study is to position UAV use within the specific context of rope-access operations in rockfall mitigation projects, as a supervision framework supporting OHS

management and field coordination. In this respect, the UAV is not treated merely as an imaging or recording device, but as a complementary support tool that may extend supervision capacity in sites characterized by restricted visibility, blind spots, and communication difficulties.

Previous studies have shown that UAVs and related imaging technologies can support slope observation, topographic documentation, terrain analysis, and preliminary risk assessment processes [23-26]. These studies demonstrate that UAVs can provide additional visual information in complex and difficult terrain conditions. In the framework proposed in this study, the pre-work observation component similarly relies on the visual examination of slope surfaces, loose blocks, access routes, anchorage zones, and possible falling-object areas. However, this study does not claim that UAV use provides automated hazard detection. UAV images should be interpreted as visual support data provided to supervisors and OHS personnel for professional evaluation.

UAV-supported real-time monitoring and construction safety supervision have also received increasing attention in the construction safety literature. Previous studies have examined the use of UAV images for monitoring PPE use, identifying unsafe behaviors, observing work areas remotely, or supporting computer vision-based safety applications [27-32]. However, the scope of the present study does not include automated image processing or AI-based hazard detection. For this reason, the proposed framework defines the UAV as a visual support tool that can extend the supervisor's field of view and may help reduce blind spots, rather than as an automated safety inspection system. This distinction is important because the responsibility for safety interpretation and operational decisions should remain with the authorized L3 technician, site supervisor, and OHS personnel, rather than with the UAV operator or the system itself.

Communication is a critical component in the safe execution of rope-access operations. Studies on UAV-supported communication and temporary communication infrastructures suggest that UAV-based systems may support field communication in hard-to-access areas or areas with limited signal coverage [33, 34]. In the present study, RATs' positive perception of UAV-supported monitoring and voice communication is consistent with this potential. However, the technical performance of the UAV as a communication relay node was not tested in this study. Therefore, the communication-related findings should be interpreted as RATs' perceptions regarding field coordination and visual communication support, rather than as measured communication performance.

Previous studies have also discussed the use of UAVs for construction progress tracking, measurement verification, field reporting, and schedule control [35, 36]. In this context, UAV-based visual documentation may assist site managers in evaluating work progress and observing specific field conditions more efficiently. In the present study, many RATs perceived UAV use as potentially beneficial in terms of time

and cost. However, this finding should not be interpreted as measured time savings, cost reduction, or productivity improvement. The study did not include before-and-after measurements of work duration, cost performance, rework rates, or productivity indicators. Therefore, these findings should be evaluated as perceived operational potential related to UAV use.

Another important finding of the study is that, despite the positive perception of UAV-supported supervision, most RATs had not received UAV-related training. This indicates that UAV integration should not be limited to the provision of technological equipment. Studies on safety training, simulation-based learning, worker-UAV interaction, visual and auditory warning protocols, and UAV-related secondary risks emphasize the importance of training and procedural development when new technologies are introduced into construction sites [37-40]. In this regard, training programs for UAV-supported rope-access supervision should include UAV operation, flight safety, field communication, data interpretation, emergency coordination, and safe distances from rope systems. Such training should support existing rope-access safety procedures rather than replace them.

A considerable proportion of participants stated that rope-access work is not sufficiently defined in national legislation. This finding indicates a need for clearer regulations regarding professional recognition, training standards, certification processes, and supervision responsibilities in rope-access work. At the international level, IRATA and SPRAT provide widely used frameworks for personnel competence, certification levels, and safe working principles. In addition, ISO 22846-1 and ISO 22846-2 [41] provide references for the safe use and application of rope-access systems. The findings of this study indicate a need for clearer alignment between national OHS regulations and internationally recognized rope-access standards in the Turkish context. UAV-supported supervision should not be evaluated independently from this standardization need, because its effective use depends on clearly defined authority, responsibility, training, and site procedures.

The UAV-based supervision framework proposed in this study was structured around pre-work observation, real-time visual monitoring, blind-spot reduction, hazard observation, communication support, and supervisor decision support. The pilot implementation provided observational evidence regarding the field applicability of this framework. UAV images may support supervisors' visual awareness in situations where slope surfaces, rope-access routes, anchorage zones, worker positions, and equipment placement are difficult to observe from the ground. However, this contribution should not be presented as a measured improvement in accident frequency, work duration, or cost performance. The contribution of the study lies in proposing a structured UAV-based supervision framework for rope-access operations in rockfall mitigation projects and

discussing this framework through field observations and a single-site pilot implementation.

This study has several limitations. Although the sample included 128 RATs working in 16 active rockfall mitigation projects in different regions of Türkiye, it was not selected using a probabilistic sampling method. Therefore, the findings should not be generalized to all RATs or all rockfall mitigation projects in Türkiye. The questionnaire data were based on self-reported responses and may therefore include response bias or recall bias. The open-ended responses were analyzed through inductive content analysis by a single coder; therefore, inter-coder agreement statistics were not calculated. The pilot implementation was conducted in only one active project and did not include a controlled experimental design. In addition, objective performance indicators such as accident frequency, near-miss events, inspection time, communication delays, cost performance, or productivity were not measured. Therefore, the findings should be interpreted at the level of framework development, field applicability, and perceived potential, rather than as evidence of the quantitative effectiveness of UAV-supported supervision.

Future studies should test the proposed framework in different rockfall mitigation projects, terrain conditions, and UAV configurations. Further research should also examine the effects of UAV-supported supervision on measurable indicators such as work duration, supervisor response time, communication delays, hazard observation records, near-miss reporting, and OHS decision-making processes. Such studies would allow the contribution of UAV-supported supervision to rope-access operations to be evaluated not only through perceptions and observations, but also through comparative and measurable field data.

6. Conclusions

This study developed and field-examined a UAV-based supervision framework for rope-access operations in rockfall mitigation projects. The framework was developed based on questionnaire data obtained from 128 RATs working in 16 active rockfall mitigation projects, field observations conducted in the same project context, thematic analysis of open-ended responses, and a single-site pilot implementation. The study focused on the potential role of UAVs in supporting OHS planning, visual supervision, communication, and operational coordination in steep and hard-to-access work environments.

The findings showed that rope-access operations in rockfall mitigation projects involve a multidimensional risk profile. RATs reported risks related to rockfall, slope failure, falling objects, rope damage, improper anchorage, slippery

surfaces, pendulum effect, and limited visibility. These findings indicate that supervision in such projects should not be limited to PPE control or worker-level safety checks. Instead, supervision should be considered as a broader field coordination process involving worker positioning, rope lines, anchorage zones, equipment placement, terrain conditions, and communication continuity.

The proposed framework structures UAV-supported supervision around pre-work observation, real-time visual monitoring, blind-spot reduction, hazard observation, communication support, and supervisor decision support. In this framework, UAVs are not positioned as autonomous safety inspection systems or substitutes for trained rope-access supervision. Rather, they are defined as complementary visual support tools that may assist authorized personnel in observing hard-to-access areas and making field decisions within the existing rope-access safety hierarchy.

The pilot implementation provided observational evidence regarding the field applicability of the proposed framework. UAV-supported observation helped extend visual access to slope surfaces, rope-access routes, anchorage zones, worker positions, and equipment locations that were difficult to observe from the ground. However, the study did not measure accident frequency, near-miss events, inspection time, communication delays, work duration, cost performance, or productivity indicators. Therefore, the findings should not be interpreted as evidence of quantitative reductions in accidents, time, or costs. The pilot results should be considered as feasibility-oriented observational evidence.

The study also showed a gap between the perceived usefulness of UAV-supported supervision and the current level of UAV-related training among RATs. This indicates that the integration of UAVs into rope-access operations requires more than the use of technological equipment. Clear role definitions, UAV-specific training, safe flight procedures, communication protocols, data-use rules, and coordination with existing OHS and rope-access procedures are necessary for practical implementation.

The main contribution of this study is the development of a structured UAV-based supervision framework tailored to rope-access operations in rockfall mitigation projects. The framework provides a basis for integrating UAV-supported visual observation into OHS and construction management practices without overstating its effectiveness. Future studies should test the framework in different project types, terrain conditions, and UAV configurations. Further research should also examine measurable indicators such as supervisor response time, communication delays, inspection duration, hazard observation records, near-miss reporting, and documented OHS decision-making processes.

Declarations

Conflict of Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Author Contributions

B. A. Temel: Conceptualization, Methodology, Data curation, Investigation, Writing - Original draft preparation, Visualization, Investigation, Validation, Analysis, Writing - Reviewing and Editing.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Ethics Committee Permission

The study was approved by the Institutional Review Board / Ethics Committee of Karadeniz Technical University (Protocol No. E-82554930-050.01.04-119482; approval date: 4 November 2025). Participation in the questionnaire was voluntary, and all participants were informed about the purpose of the study before data collection. Survey responses were collected anonymously, no personally identifiable information was reported, and the collected data were used only for academic research purposes.

Use of Generative AI and AI-assisted Technologies

The author used ChatGPT-4.5 solely for language polishing (e.g., grammar check) and have reviewed and take full responsibility for the final content.

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