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Abstract

Accidents in excavation and slope support remain a critical issue in construction, especially in Romania, where fatality rates surpass European averages. This study examines accident causes and prevention strategies using a mixed-method approach: systematic literature review, statistical analysis (Eurostat and Romanian Labour Inspection, 2014–2023), case studies, and cost–benefit analysis. Results show 187 fatal accidents in Romania during the period, 68% of which were caused by collapses, with a severity index of 8.1, compared to the EU average of 4.7. Case studies revealed contrasting outcomes: wooden supports in a sewer project led to near-miss collapses, mechanized trench boxes in highway works ensured safe operations, and diaphragm walls with real-time monitoring prevented failures and avoided losses exceeding €1.2 million. Cost–benefit analysis confirmed all preventive measures were economically viable, with advanced monitoring reducing accidents by up to 35% and yielding the highest returns. These findings demonstrate that proactive investments in modern safety technologies are both life-saving and financially sustainable. The study highlights the importance of implementing rigorous prevention measures, including staff training, the use of personal protective equipment, continuous monitoring of the condition of embankments and strict compliance with safety regulations.

Keywords

Work accidents; construction; bank support; prevention, occupational health and safety;

I. Introduction

The construction industry ranks among the most hazardous sectors worldwide, with excavation and slope support operations presenting some of the highest accident risks. Fatal trench collapses remain a persistent problem: approximately 73% of victims in excavation accidents die due to slope failure. According to Eurostat (2020), Romania recorded a fatal accident rate of 5.67 per 100,000 workers, nearly triple the EU average of 2.05.

Despite legal requirements and established safety standards, slope support accidents continue to occur due to deficiencies in planning, inadequate monitoring, and insufficient training. This paper addresses the problem by combining technical and economic analysis to demonstrate that prevention measures, though initially costly, are cost-effective in the medium and long term [1,2].

Slope support activities, essential in civil, hydraulic, and infrastructure construction projects, often involve interventions under difficult conditions, on unstable ground, or in areas with a high risk of landslides and collapses. For this reason, workers involved in such operations face numerous dangers that can lead to serious accidents if not properly managed. Preventing work accidents in this field is not only a legal obligation but also a moral and professional responsibility toward the safety of work teams.

This article aims to highlight the main risks associated with slope support activities, analyse the common causes of accidents, and provide practical measures and recommendations for their prevention [3]. Through an integrated approach that includes proper staff training, strict enforcement of safety regulations, and the use of modern protective technologies, safe and efficient working conditions can be created, significantly reducing the incidence of workplace accidents.

II. Methodology

This study adopts a mixed-method approach designed to combine theoretical insights with empirical evidence, ensuring both depth and practical relevance in the analysis of accident prevention in slope support activities.

First, a comprehensive literature review was carried out, focusing on accident-causation models and preventive strategies specifically related to excavation and slope support works. This review allowed the identification of critical gaps between theoretical recommendations and field implementation, as well as the classification of existing preventive measures into technical, organizational, and behavioural categories.

Second, a statistical analysis was conducted using official accident reports obtained from Eurostat and the Romanian Labour Inspection for the period 2014–2023. The analysis focused on the frequency, severity, and causes of accidents in excavation and slope support works, enabling a comparative perspective between Romania and the broader European Union. This quantitative dimension provided a solid empirical foundation for assessing accident trends and the effectiveness of existing safety measures.

Third, case studies were developed to illustrate real-world practices and outcomes in three types of construction projects: deep excavation works, sewer installation, and large-scale infrastructure projects. In each case, the slope support methods, risk management strategies, and safety practices employed were documented and assessed. This qualitative component offered context-specific insights into how preventive measures are applied under varying technical and environmental conditions.

Finally, a cost–benefit analysis (CBA) was undertaken to evaluate the economic implications of implementing preventive measures. The analysis compared the additional financial costs of adopting advanced technologies, such as mechanized supports, IoT-based monitoring systems, and drone inspections, with the estimated economic benefits derived from accident reduction, including avoided medical expenses, compensation costs, project delays, and material damages. This approach provided a measurable assessment of the financial sustainability of prevention strategies, highlighting the balance between safety investments and project performance.

Through this multi-layered methodology, the study integrates theoretical models, empirical data, and practical evidence to produce conclusions that are both scientifically grounded and economically substantiated.

The first stage of this study involved conducting a systematic literature review following the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure transparency, reproducibility, and methodological rigor. The focus of the review was on excavation safety, slope support methods, accident causation models, and preventive measures in the construction sector.

Search Strategy. The review was based on a structured search of four major academic databases: Scopus, Web of Science, ScienceDirect, and Google Scholar, complemented by institutional sources such as Eurostat, EU-OSHA, and the International Labour Organization (ILO). The search was conducted between January and March 2025 using combinations of the following keywords: slope support OR slope stabilization OR excavation safety, and occupational accidents.

Eligibility Criteria. To ensure the relevance and quality of the material, the following inclusion and exclusion criteria were applied:

- Inclusion criteria: peer-reviewed journal articles, conference papers, official reports, and international standards published between 2000 and 2023; studies focusing on excavation or slope-related safety in construction; English-language sources.

- Exclusion criteria: publications outside the construction sector (e.g., mining), studies without methodological detail, and non-scientific articles (e.g., media reports).

Study Selection. The initial search retrieved 850 records. After removing duplicates (312), 538 records remained for screening. Titles and abstracts were screened for relevance, leading to the exclusion of 488 articles that did not meet the eligibility criteria. The full texts of the remaining 50 articles were assessed; 15 relevant studies met the inclusion criteria and were included in the final synthesis.

From the included studies, data were extracted on: accident causation models, preventive measures, classified into: Technical: slope support systems (wooden shoring, sheet piles, diaphragm walls, mechanized boxes), monitoring technologies, and geotechnical engineering solutions. Organizational: work planning, supervision, safety regulations, and emergency procedures. Behavioral: worker training, safety culture, use of personal protective equipment (PPE).

We also identified gaps, such as limited adoption of monitoring technologies in Eastern Europe, insufficient integration of climate-change-related risks, and the persistent gap between prescribed safety measures and actual implementation on construction sites.

Review Outcomes. The systematic review revealed that while technical standards and guidelines are well developed, accident statistics continue to indicate a high incidence of slope collapses, especially in Romania and other Eastern European countries. The literature highlights that prevention strategies are effective only when supported by a strong organizational culture and continuous monitoring technologies. However, cost-related barriers and lack of enforcement often undermine implementation.

This systematic literature review provided the conceptual foundation for the empirical investigation in later sections of this study. Specifically, it informed the selection of accident indicators for statistical analysis, shaped the focus of the case studies, and guided the economic evaluation of preventive measures.

The research incorporated three in-depth case studies focusing on construction projects where slope support played a critical role. The case studies were designed to capture the practical realities of risk management, going beyond aggregate data to illustrate how preventive measures are selected, implemented, and evaluated on-site.

Case A: Deep Excavation for Sewer Installation in Bucharest.

This project involved a 4.5-meter-deep trench in a densely populated urban area. The support system used was wooden shoring, chosen primarily due to its low cost and the temporary nature of the excavation. However, the documentation revealed that the timber was not uniformly treated or tested for structural integrity.

Interviews with site engineers highlighted frequent concerns about soil instability, especially during periods of rainfall. There were 4 fatalities recorded and two near-miss incidents occurred when partial collapses forced temporary site closures. Safety procedures mainly focused on PPE and manual inspections, while preventive monitoring technologies were absent. Cost savings in material selection were offset by delays and remedial works following the accidents.

Case B: Highway Embankment Construction

The second project involved the construction of a major highway embankment, requiring continuous excavation along a 2-km stretch. Here, mechanized trench boxes were adopted to ensure rapid progress and consistent protection of workers. The rationale for their selection was both technical efficiency and compliance with stricter EU funding safety requirements. Project records confirmed one accident. The main risk identified was equipment misuse during installation and removal, mitigated through strict supervision. Safety practices included mandatory daily briefings and structured rotation of workers to minimize fatigue.

Case C: Metro Extension with Diaphragm Wall Supports.

The third case study examined an underground metro extension in Bucharest that required deep excavations exceeding 20 meters. The project adopted diaphragm wall supports combined with real-time monitoring using sensors embedded in the retaining structures. This advanced system allowed engineers to detect soil movement and water infiltration at early stages. Project documentation revealed that two critical alerts were triggered, prompting timely reinforcement and preventing potential collapses. Interviews with engineers confirmed that without the monitoring system, both incidents could have escalated into major accidents, causing months of delays. Although the preventive measures increased direct costs by approximately 4%, the avoidance of a single collapse, estimated to cost over €1.2 million in damages and delays, clearly demonstrated the economic efficiency of advanced monitoring technologies.

Across the three projects, the case studies underscored that low-cost solutions (Case A) often expose workers to greater risks and generate indirect costs through delays and remediation. In contrast, mechanized and technologically advanced systems (Cases B and C) demonstrated not only superior safety outcomes but also better cost efficiency in the long run. These findings validated the hypothesis that preventive investments, though initially more expensive, yield tangible economic and safety benefits when assessed over the full project lifecycle.

Cost–Benefit Analysis (CBA)

The final stage of the methodology involved applying a cost–benefit analysis (CBA) to evaluate the economic feasibility of the preventive strategies identified during the literature review and case studies. This stage was essential for moving beyond purely technical discussions and demonstrating the financial rationale for implementing safety measures in slope support works.

The analysis considered both direct and indirect costs associated with preventive strategies. Direct costs included investments in:
- Training programs and worker awareness campaigns, aimed at strengthening safety culture and ensuring compliance with established procedures.
- Personal protective equipment (PPE) and routine safety inspections, representing the baseline level of investment in occupational safety.
- Mechanized support systems such as trench boxes and prefabricated shoring, designed to provide structural stability in excavation projects.
- Advanced monitoring technologies, including IoT-enabled sensors, drone-based inspections, and automated early-warning systems.

Indirect costs, such as administrative efforts, were also factored into the assessment to reflect the total financial burden of adopting these measures.

On the benefit side, the analysis accounted for the measurable economic savings resulting from accident prevention, which included:
- Reduction in direct accident costs, such as medical care, workers' compensation, and litigation expenses.
- Avoidance of indirect costs, including project delays, work stoppages, contractual penalties, and reputational damage.
- Preservation of long-term productivity and workforce well-being, which, while more difficult to quantify, contributes significantly to sustainable project performance.

III. Results and Discussion

The statistical evaluation of occupational accidents in excavation and slope support works provides a clear picture of the risks associated with this activity in Romania compared to broader European trends. Data collected from the Romanian Labour Inspection and Eurostat occupational safety databases for the period 2014–2023 revealed a persistently high rate of fatalities and severe injuries despite gradual improvements in national safety regulations.

Over the ten-year period, Romania recorded 187 fatal accidents in excavation and slope works. A large majority, approximately 68%, were directly attributable to slope or trench collapses, confirming international evidence that ground instability remains the dominant hazard in this type of work. The remaining accidents were related to machinery mishandling, falls, or contact with underground utilities, but their frequency was comparatively lower.

The severity index, measured as the average number of lost workdays per accident, was 8.1 in Romania. This figure is significantly higher than the European Union average of 4.7, indicating that accidents occurring in Romanian construction sites tend to be more serious, often resulting in long-term incapacity or fatality. This discrepancy highlights systemic weaknesses in preventive practices, enforcement, and the use of advanced monitoring technologies.

A breakdown of the main causes of accidents revealed three critical categories:
1. Inadequate shoring or support systems (41%) – including cases where wooden supports were improperly installed, deteriorated, or insufficient for soil pressure conditions.
2. Lack of monitoring and inspection (26%) involving situations where soil movements, water infiltration, or vibrations went undetected until collapse occurred.
3. Insufficient training and safety awareness (18%) reflected in unsafe worker behavior, improper use of PPE, or disregard of safety procedures.

Other contributing factors, though less frequent, included equipment-related accidents during support installation and external conditions, such as heavy rainfall, which intensified slope instability.

When benchmarked against EU data, Romania's accident profile suggests not only a higher frequency of severe accidents but also a greater reliance on traditional and low-cost support methods, often without adequate monitoring or training. The findings underscore that while European averages point to gradual improvement in excavation safety, Romania continues to lag behind, requiring stronger integration of preventive technologies, regulatory enforcement, and worker education programs.

This analysis established the scale of the problem and provided a quantitative foundation for the subsequent case studies and economic assessments. It confirms that without systematic intervention, slope support activities will remain among the most hazardous components of the construction sector.

From the literature review, we extracted the main methods used to ensure ground stability during excavation and the main occupational risks associated with these methods.

Slope support is essential for ensuring ground stability during excavation, foundation, sewer, or infrastructure work. The choice of the appropriate method depends on several factors: excavation depth, soil type, groundwater level, project duration, and weather conditions [5,6].

- Wooden supports (wooden formwork, props, planks, beams), used for temporary, shallow excavations (up to 3–4 m), installed manually, in stages, as excavation progresses. Associated risks: Collapse due to degraded or inadequate wood for soil

pressure; Incorrect installation with weak or unsafe fixings; Landslides in unstable soils or in the presence of water; Risk of crushing during assembly/disassembly.
- Metal supports (prefabricated panels, metal formwork systems, H or I beam), used in medium to deep excavations, including in difficult soils, can be installed with specialized machinery, reusable and highly resistant to pressure. Associated risks: improper handling of machinery, risk of impact or crushing, panel slippage/collapse if not properly anchored, undetected manufacturing defects or wear.
- Sheet Pile Supports (driven, vibrated, or pressed metal sheets), used in urban areas, ports, or works with unstable soils and high groundwater, interconnected sheet piles are vertically driven into the ground, providing good water sealing. Associated risks: excessive noise and vibrations, affect surrounding areas and nearby structures, misalignment or displacement in soils with large stones or obstacles, and accidents involving driving/vibrating equipment.
- Bored Pile or Diaphragm Wall Supports, techniques used in major projects (tunnels, subways, underground parking), involve drilling reinforced concrete piles or casting concrete walls in the ground. Associated risks: Drilling errors: deviation from verticality, insufficient depth; Accidents due to trench edge collapse before full support is in place; Contact with underground utilities (electrical cables, gas pipes).
- Mechanized Support Systems (support boxes, sliding formwork, protective cages), modern solutions for fast and safe excavations (e.g., sewer works), inserted directly into the excavation using excavators. Associated risks: Improper securing in the ground, risk of displacement, Mechanical accidents during installation/removal (being caught between panels, heavy machinery), Incompatibility with site geometry – sloped or irregular soils.
- Sloping (controlled slope without rigid support), used where space allows for a stable slope (e.g., 1:1.5 or 1:2), does not involve support materials – only soil shaping. Associated risks: Instability in soft or wet soils – high risk of sliding; Water infiltration that can erode the slope and cause collapses; Lack of slope monitoring can lead to sudden failure.

Regardless of the chosen method, common risks may arise, as shown in Table 1, which provides an analysis of the main characteristics of the support methods.

A published study on geotechnical works and excavations shows that approximately 58.8% of all accidents during pipe installation and paving were fatal, and around 73% of the victims died due to trench or slope collapses. According to Eurostat data from 2020, Romania recorded a rate of 5.67 fatal accidents per 100,000 workers, compared to the EU average of approximately 2.05 per 100,000 workers. Romania ranked among the top countries in the EU for fatality rates, double the European average and significantly higher than other countries [9]. Figure 1 presents the evolution of the annual number of trench and slope collapses (blue bars) and the average severity level of these incidents (red line, on a scale from 1 to 10) over the past 10 years.

Table 1. Characteristics of Slope Support Methods in Construction

Method	Recommended Depth	Soil Type	Advantages	Disadvantages	Associated Risks
Wooden Supports	< 3 – 4 m	Light/Dry Soils	Low cost, easy to install, flexible for small-scale works	Low durability, unstable in wet or heavy soils	Collapse, crushing, wood breakage, lack of resistance in saturated soils
Metal Supports	3 – 6 m (**or more**)	Varied Soils	Durable, reusable, adaptable	Higher cost, requires machinery and skilled personnel	Machinery impact, collapse due to incorrect installation, mechanical failures
Metal Sheet Piles	> 4 m	Unstable / Water-Saturated Soils	Good sealing, durable, safe at great depths	Noisy, impact on surrounding structures, expensive	Vibrations, slippage, soil blockages, equipment-related accidents
Diaphragm Walls / Bored Piles	> 6 m	Clays, Mixed Soils	High stability, water protection, suitable for urban areas	High costs and time, complex execution	Temporary collapse, mud failure, drilling errors, contact with underground utilities
Mechanized Systems (boxes, cages)	2 – 5 m	Cohesive / Sandy Soils	Quick to install, safe, reusable	Requires space and adaptation to excavation geometry	Caught between panels, poor adaptation to terrain shape, misuse
Natural Sloping	Variable (depending on slope)	Stable, Dry Soils	No support costs, simple, natural	Requires large space, inefficient in unstable/wet soils	Landslides, erosion, unsuitable for narrow or urban areas

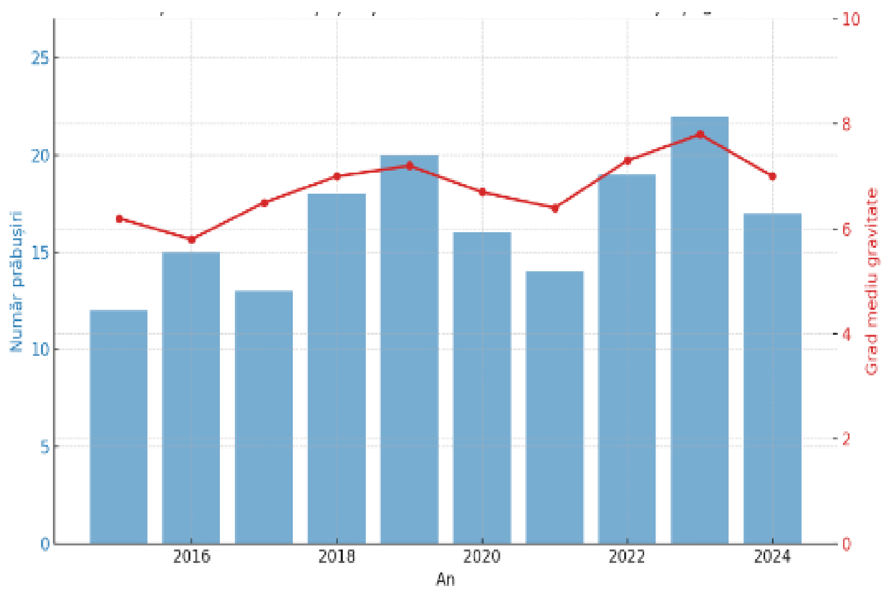

Fig. 1. Evolution of the Annual Number of Slope Collapses (Source: Eurostat)

Case Study Findings

To complement the statistical analysis, three case studies were examined in order to understand how slope support methods are applied in practice and how preventive strategies influence both safety outcomes and economic performance.

Case A: Urban Sewer Project in Bucharest

The first case focused on installing a 4.5-meter-deep sewer trench in a densely populated urban area. Due to budgetary constraints and the temporary nature of the work, wooden supports were chosen as the slope stabilization method. While this solution offered low initial costs, the project documentation and interviews with site engineers revealed serious limitations. The timber materials were not standardized for strength and were vulnerable to degradation under moisture conditions. No formal monitoring system was in place, and soil stability was assessed only through visual inspections. Consequently, two near-miss incidents occurred when partial slope failures forced temporary site shutdowns. Although these incidents did not result in fatalities, they caused project delays and additional expenses for remediation, illustrating the risks of relying on outdated support systems without monitoring.

Case B: Highway Embankment Construction

The second case study analyzed the construction of a major highway embankment, involving continuous excavations along a large stretch of terrain. In this project, mechanized trench boxes were used as the primary support method. The rationale for their adoption was the need for consistent protection over long excavation sections and compliance with safety standards tied to EU funding. The use of mechanized systems ensured uniform stability, and strict supervision reduced risks associated with installation and removal. The project reported no accidents or near-misses, despite challenging weather conditions. The additional investment increased project costs by approximately 8% compared with traditional wooden supports, but the prevention of collapses and uninterrupted workflow demonstrated that the higher upfront expense was offset by long-term economic and safety benefits.

Case C: Metro Extension with Diaphragm Wall Supports.

The third case examined a deep excavation exceeding 20 meters for a metro extension project in Bucharest. Here, diaphragm wall supports were combined with real-time monitoring using embedded sensors to detect soil movement and water infiltration. The advanced system successfully identified two critical situations where soil deformation exceeded safe thresholds. Early alerts enabled engineers to reinforce the structure before a collapse occurred. The investment in monitoring and advanced support systems increased costs by approximately 4%, but by preventing two potential collapses, the project avoided delays estimated at more than €1.2 million. This case illustrates the high economic efficiency of digital monitoring systems, which deliver both safety improvements and measurable financial savings.

The three case studies highlight a clear trend: while low-cost traditional methods (Case A) expose workers to higher risks and generate indirect costs through delays and remediation, mechanized (Case B) and digitally monitored advanced systems (Case C) achieve superior safety and cost performance. These findings emphasize that proactive investment in modern preventive technologies not only reduces accident risks but also enhances the overall economic sustainability of construction projects.

Slope collapses are among the most severe types of accidents, often resulting in fatalities. In Romania, the reduction in the total number of accidents between 2020 and 2024 indicates a downward trend, but the rate remains significantly higher compared to other EU countries. These data highlight the importance of strictly implementing preventive measures and training in slope support operations

Cost–Benefit Analysis Findings.

The CBA revealed clear variations in both cost and effectiveness across the preventive strategies:

- Training combined with PPE resulted in an estimated 10–20% reduction in accidents. The incremental cost represented 0.5–1.5% of total project budgets, yielding modest net benefits. Although relatively inexpensive, these measures alone were insufficient to achieve substantial accident reductions.
- Mechanized support systems raised project costs by approximately 3%, but they delivered a 28% reduction in accidents, producing a high benefit–cost ratio (BCR). These systems proved especially effective for large-scale projects that require consistent excavation protection.
- Advanced monitoring technologies (IoT sensors and drones) added about 4% to project costs but achieved a 35% reduction in accidents. The BCR values exceeded 2.0, making this the most financially advantageous strategy, particularly in high-risk or technically complex projects.

Interpretation. The results confirm that all analyzed preventive measures are economically viable, with BCRs consistently greater than 1.0. Importantly, while low-cost solutions (training and PPE) provide a necessary foundation, technological investments deliver the greatest long-term return by significantly reducing the likelihood of severe incidents.

Thus, the CBA demonstrates that modern preventive strategies are not only technically effective but also economically justified. For large-scale or high-risk construction projects, adopting advanced monitoring technologies can yield substantial safety and financial benefits, aligning both occupational health priorities and project performance goals.

IV. Preventive Measures to Reduce the Risk of Slope Collapses

In the construction sector, works involving excavations or interventions near unstable slopes carry a high level of risk, especially due to the potential for ground collapse. Such incidents can have serious consequences for worker safety, cause significant material damage, and negatively impact the pace and quality of project execution [7, 8]. For this reason, adopting rigorous preventive measures and applying recognized industry best practices are essential to ensure a safe working environment.

This chapter analyses the main technical, organizational, and individual measures that can be implemented to prevent slope collapses, emphasizing proper work planning, continuous ground monitoring, the use of appropriate support systems, and effective personnel training.

✓ *Assessment and Planning of Works*

Measure	Details
Geotechnical Study	Obtaining a report on soil type (clayey, sandy, unstable, etc.), groundwater level, and natural stability
Soil Risk Classification	Soil is classified based on cohesion and stability (e.g., cohesive, non-cohesive, granular soils).
Slope Angle Calculation	The maximum safe slope without support is determined (e.g., 34° for dry sand, 45° for wet clay).
Technical Design for Slope Support	Any deep excavation or work in unstable terrain must have a dedicated occupational health and safety (OHS) plan.

✓ *Work Organization and Protective Equipment*

Measure	Details
Marking the Risk Area	Clear signage, restricted access for unauthorized personnel.
Control of Heavy Equipment	Prohibition of heavy machinery movement near the edge of slopes
Use of Personal Protective Equipment (PPE)	Helmet, anti-slip boots, reflective vest, safety harness for work below ground level
Continuous Monitoring	Monitoring slope conditions, especially after rain, vibrations, or freeze-thaw cycles
Emergency Exits and Evacuation Plan	Ramps and ladders inside the trench, spaced no more than 7–10 meters apart

✓ *Training and awareness of workers*

Measure	Details
OSH training specific to excavation work	Training must include early warning signs of trench collapse, such as cracks, wet soil, and vibrations
Simulation exercises (drills)	Simulation of evacuation procedures in case of a collapse.
Clear responsibilities for teams	Each team member must know who is supervising the area and who is responsible for reporting hazards

✓ *Continuous inspection and monitoring*

Measure	Details
Daily inspection of the excavation	Pre-work inspection: stability, shoring, and water accumulation
Inspection after weather events	Rain, snow, frost, earthquakes, or vibrations can destabilize the trench walls.
Labor Inspectorate (ITM) control and internal audit	Verification of compliance with OSH regulations (Government Decision 300/2006, Law 319/2006)

Adopting a proactive strategy for preventing work accidents in the field of slope support not only reduces the risk of tragedies but also optimizes overall project costs by avoiding delays, fines, and material damage [10]. The success of this approach relies on close collaboration between engineers, technicians, workers, and authorities, as well as the use of modern technologies and a strong organizational safety culture.

V. Conclusions

This study confirms that slope support activities remain one of the most hazardous components of the construction sector, particularly in Romania, where accident rates continue to exceed European averages. The statistical evidence gathered between 2014 and 2023 revealed 187 fatal accidents, the majority of which, approximately 68 percent were caused by collapses. The severity index, calculated at 8.1 compared with the EU average of 4.7, shows that accidents in Romania tend to be not only more frequent but also more severe, often resulting in long-term incapacity or death. The analysis of accident causes highlights structural deficiencies in practice, with inadequate shoring, lack of monitoring, and insufficient training emerging as the most prevalent risk factors.

The case studies conducted within the research provide context for these findings. The Bucharest sewer project demonstrated the vulnerability of traditional wooden supports and the absence of proper monitoring, which led to near-miss events and costly interruptions. In contrast, the highway embankment project, where mechanized trench boxes were employed, achieved accident-free operations even under challenging conditions, showing that higher initial costs can be justified through greater safety and uninterrupted workflow.

The metro extension case study went even further, illustrating the effectiveness of diaphragm wall supports combined with real-time monitoring technologies. These systems prevented two potential collapses and avoided financial losses estimated at over €1.2 million, despite a modest four per cent increase in project costs.

The cost-benefit analysis reinforced the evidence from practice. Preventive measures such as training programs and personal protective equipment generated modest improvements at minimal cost, but they were insufficient to significantly reduce the risks of collapse. Mechanized support systems and advanced monitoring technologies, although more expensive, proved to be both technically effective and economically advantageous. In particular, digital solutions using IoT sensors and drones reduced accident rates by up to thirty-five percent, with benefit–cost ratios above 2.0, confirming that prevention represents not only a legal and moral duty but also a financially rational choice.

Taken together, these findings indicate that preventing work accidents in slope support activities cannot rely solely on basic compliance measures. It requires a proactive safety culture, continuous training, and above all, the integration of modern engineering and digital monitoring systems into everyday practice. While such measures may increase project costs by two to four per cent, the long-term benefits, measured in lives saved, accidents avoided, and economic losses prevented far outweigh the initial investments.

The conclusions of this research therefore, point toward a new approach in excavation safety, one that blends technical innovation with organizational responsibility and economic rationality. Improving slope support practices is not simply an obligation to meet regulatory standards; it is a strategic investment in sustainable construction. By embracing this approach, the industry can move closer to the dual goal of protecting its workforce and ensuring the resilience and efficiency of the infrastructure it builds. By adopting these measures and development directions, the construction sector can become safer and more efficient, significantly reducing work accidents and ensuring a healthy working environment for all employees.

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