INTEGRATED DYNAMIC RISK ASSESSMENT MODEL FOR BANK STABILIZATION WORKS

A. MOISE - National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania, moise_adrian89@yahoo.com
A. TRIFU - National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania,
M. GHEORGHE - National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania
C.I. ENACHE - National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania
L.F. RADU - National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania

Abstract: *Bank stabilization works represent one of the most hazardous activities in the construction sector, particularly in the context of deep excavations and variable geotechnical conditions. Although effective technical solutions exist, accidents continue to occur due to the complex interaction between technical, organizational, and human factors. In this context, the paper proposes an original dynamic risk assessment model – MIP-SM (Integrated Prevention Model – Bank Stabilization). The model integrates three main risk components and introduces a dynamic component based on changes in site conditions. In addition, a simplified digital implementation method is proposed, based on an Excel/Google Sheets calculator, which allows rapid risk assessment and continuous updating. The results highlight the usefulness of the model in accident prevention and in supporting the decision-making process on construction sites.*

Keywords: risk assessment, bank stabilization, occupational safety and health, dynamic model, accident prevention

1. INTRODUCTION

The construction sector is characterized by a high level of occupational risk, particularly in excavation and bank stabilization works. Slope collapses represent one of the main causes of serious accidents, with direct consequences for workers' health and safety. In practice, risk assessment is often conducted in a static manner, without accounting for continuous changes in site conditions, such as water level variations, technological modifications, or worker behavior. This limitation reduces the effectiveness of preventive measures. This paper proposes an integrated and dynamic risk assessment model, referred to as MIP-SM, which enables a multidimensional and adaptive approach to accident prevention.

Bank stabilization works and excavations are considered among the most dangerous activities in the construction sector due to soil instability and the complex interaction between technical and human factors. Studies in the field indicate that this type of activity is associated with a high number of serious and fatal accidents worldwide [1].

According to the scientific literature, the main risks involved in excavation works include slope collapses, exposure to hazardous atmospheres, machinery-related accidents, and human errors [2]. These risks are exacerbated by variable geotechnical conditions and the lack of adequate monitoring and control systems [3].

A significant number of studies emphasize the importance of correct soil classification in accident prevention, as excavation stability depends directly on the mechanical properties of the ground [4]. Factors such as moisture content, vibrations, and stratification structure can substantially reduce slope stability and lead to unexpected collapses [4].

From an occupational safety perspective, research shows that the construction sector remains one of the most hazardous fields, mainly due to the complexity of activities and the diversity of hazards present on construction sites [5]. Among the primary causes of accidents are insufficient training, inadequate supervision, and improper implementation of safety measures [5].

Recent studies on geotechnical works highlight that most accidents are generated by combinations of factors rather than by a single isolated cause, thus justifying the need for integrated risk assessment models [6]. This approach is also supported by research on risk modeling in construction, which shows that human factors and environmental conditions significantly influence accident probability [7].

The literature also emphasizes the essential role of regulations and legislative compliance in reducing occupational accidents. Non-compliance with safety regulations is frequently identified as a major cause of incidents in excavation works [8].

In recent years, research has increasingly focused on the use of modern technologies for real-time risk monitoring. Studies demonstrate that integrating sensors and monitoring systems can significantly improve accident prevention capabilities [9]. These technologies allow continuous updating of risk levels and support timely decision-making.

At the same time, modern approaches to risk assessment emphasize the use of mathematical models and simulations to quantify accident probability and severity. Statistical and probabilistic models are applied to analyze relationships between factors and to identify critical scenarios [7].

The literature also highlights the importance of organizational culture and worker behavior. Lack of training and unsafe behaviors contribute significantly to accident occurrence, even in the presence of adequate technical systems [3].

In conclusion, the literature review indicates that accident prevention in bank stabilization works requires an integrated approach that combines technical, organizational, and human factors. However, there is a lack of simple, dynamic models that can be applied directly on construction sites, which justifies the development of the MIP-SM model proposed in this paper.

2. CONCEPTUAL FRAMEWORK

Risk assessment in bank stabilization works must go beyond a strictly technical approach focused solely on soil stability and geotechnical characteristics and explicitly integrate organizational and behavioral factors. In practice, many accidents are not caused only by unfavorable technical conditions, but by the way these conditions are managed within the work process. Thus, even in the presence of adequate technical solutions—such as properly designed support systems or modern construction methods—the lack of effective organization or a strong safety culture can lead to hazardous situations.

The model proposed in this paper is based on the idea that accidents result from the dynamic interaction of three main categories of factors: technical work conditions, activity organization, and worker behavior. Technical conditions include elements such as soil type, presence of groundwater, excavation depth, and the influence of vibrations, all of which have a direct impact on slope stability. Organizational factors relate to work planning, the frequency and quality of inspections, access control to risk areas, and the existence of emergency response procedures. At the same time, human factors are essential and include worker training level, compliance with safety rules, fatigue, and risk-taking tendencies.

The interaction of these factors generates a complex system in which risk is not static but evolves according to actual site conditions. For example, an apparently minor change—such as the onset of rainfall or an increase in work pace—can simultaneously amplify technical and human risks, leading to a significant increase in accident probability. Therefore, the proposed integrated approach allows not only more accurate identification of potential causes but also the implementation of adaptive preventive measures aimed at both technical control and optimization of work organization and behavior.

3. THE MIP-SM RISK ASSESSMENT MODEL

3.1 Model Structure

The MIP-SM model defines global risk as a combination of three components:

$$R_{MIP-SM} = w_T \cdot R_T + w_0 \cdot R_0 + w_U \cdot R_U \qquad (1)$$

where:

R_T – technical risk
R_O – organizational risk
R_U – human risk

The weighting coefficients are as follows: $w_T = 0.45$, $w_O = 0.30$, $w_U = 0.25$

The selection of these weights is not arbitrary but is based on an analysis of the specific characteristics of bank stabilization works and on conclusions drawn from the scientific literature regarding the causes of accidents in construction. The highest weight is assigned to technical risk (wT=0.45w_T = 0.45wT=0.45), as the physical stability of the support system represents the determining factor in preventing collapses. In excavation works, failure of the ground or of the support system often occurs suddenly and results in severe consequences, largely independent of worker behavior. Parameters such as soil type, excavation depth, and the presence of water directly influence geotechnical equilibrium, which justifies the dominant role of this component.

Organizational risk (wO=0.30w_O = 0.30wO=0.30) is assigned an intermediate weight, reflecting the fact that poor work organization can either amplify or reduce technical risk. Inadequate planning, lack of inspections, or the absence of emergency response procedures frequently lead to situations in which existing risks are not properly identified or managed. Thus, the organizational component acts as a control factor over technical risk.

Human risk (wU=0.25w_U = 0.25wU=0.25) completes the model, having a lower but still significant weight. Although worker behavior may contribute to accident occurrence, in bank stabilization works it generally represents an aggravating rather than a triggering factor. For example, failure to use personal protective equipment or non-compliance with work instructions may increase the severity of consequences but does not directly determine ground instability.

The distribution of weights therefore follows the principle that risk in geotechnical works is dominated by physical factors, while being significantly influenced by work organization and human behavior. At the same time, the model remains flexible, as the coefficients can be adjusted according to project-specific characteristics, type of work, or the maturity level of the occupational health and safety management system. This approach enables a realistic and adaptive risk assessment, facilitating the prioritization of preventive measures based on the impact of each component.

3.2 Technical Risk Assessment

$$Rt = \frac{S+H+A+V}{4} \tag{2}$$

where:
S – soil stability
H – excavation depth
A – influence of water
V – vibrations

3.3 Organizational Risk Assessment

$$Ro = \frac{P+I+C+E}{4} \tag{3}$$

where:
P – work planning
I – inspections
C – access control
E – emergency procedures

3.4 Human Risk Assessment

$$Ru = \frac{F+O+D+N}{4} \tag{4}$$

where:
F – training
O – fatigue
D – use of personal protective equipment (PPE)
N – risky behavior

3.5 Dynamic Component of the Model

A key innovative feature of the MIP-SM model is the introduction of the dynamic risk component, which allows the assessment to be adapted according to the evolution of real site conditions. Unlike classical risk assessment methods, which provide a static snapshot of risk at a given moment, the proposed model integrates contextual variations that may influence excavation stability and worker safety.

Accordingly, the dynamic risk is defined by the following relationship:

$$R_d(t)=R_{MIP\text{-}SM}+K_c \tag{5}$$

where the correction coefficient $K_c$reflects the impact of external and operational factors:

$$K_c = C_p+C_m+C_v$$

C_p – influence of meteorological conditions
C_m – changes in work methods
C_v – additional vibrations

The coefficients included in $K_c$were selected based on an analysis of real construction-site conditions and of factors responsible for rapid variations in risk:

- C_p– **Influence of meteorological conditions.**

Meteorological conditions, particularly rainfall, have a direct impact on slope stability. Increased soil moisture leads to reduced cohesion and higher pore-water pressure, favoring slope failures. In addition, infiltration may affect support systems and generate local instabilities. For these reasons, this coefficient plays a critical role in updating the risk level.

- C_m– **Changes in work methods.**

Technological changes occurring during execution (e.g., modification of excavation sequences, use of different equipment, or variation in the support solution) may introduce additional risks that were not anticipated during the design phase. These changes affect both the technical and organizational components, justifying the inclusion of a dedicated coefficient.

- C_v– **Additional vibrations.**

Vibrations generated by heavy machinery, road traffic, or driving and vibration activities can reduce soil stability, particularly in non-cohesive or saturated soils. These effects are often underestimated, yet they can significantly contribute to the initiation of local slope failures.

By introducing the correction coefficient K_c, the MIP-SM model becomes sensitive to temporal variations in working conditions. Risk assessment can therefore be updated periodically or in real time, depending on:

- meteorological changes;
- work progress;
- the emergence of disturbing factors.

This approach enables a shift from reactive to proactive risk management, whereby preventive measures can be implemented before the occurrence of an incident.

Integrating the dynamic component into the MIP-SM model provides several benefits, including increased accuracy of risk assessment, adaptability to real site conditions, decision-making support for occupational health and safety management, and the possibility of implementation using simple digital tools. In conclusion, the correction coefficient $K_c$transforms the MIP-SM model into a flexible and practical instrument capable of reflecting the complexity and variability of bank stabilization works.

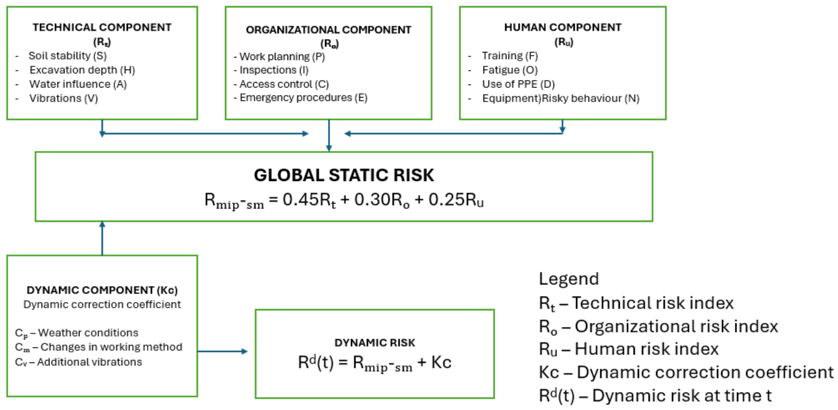
4. DIGITAL IMPLEMENTATION METHOD

4.1 The MIP-SM Digital Calculator

For the practical application of the proposed model, a simplified digital tool was developed in the form of an MIP-SM calculator implemented in a spreadsheet file (Microsoft Excel).

This tool enables rapid risk assessment and continuous risk updating based on actual site conditions (Fig. 2). The tool provides the following functionalities: automatic risk calculation; risk level classification; instant updating when input data are modified; graphical representation of risk components; and decision-making support for the occupational health and safety (OHS) manager.

Fig. 1. Structure of the MIP-SM model



Legend
R_t – Technical risk index
R_o – Organizational risk index
R_u – Human risk index
Kc – Dynamic correction coefficient
$R^d(t)$ – Dynamic risk at time t

Fig.1 Structure of the MIP-SIM Model

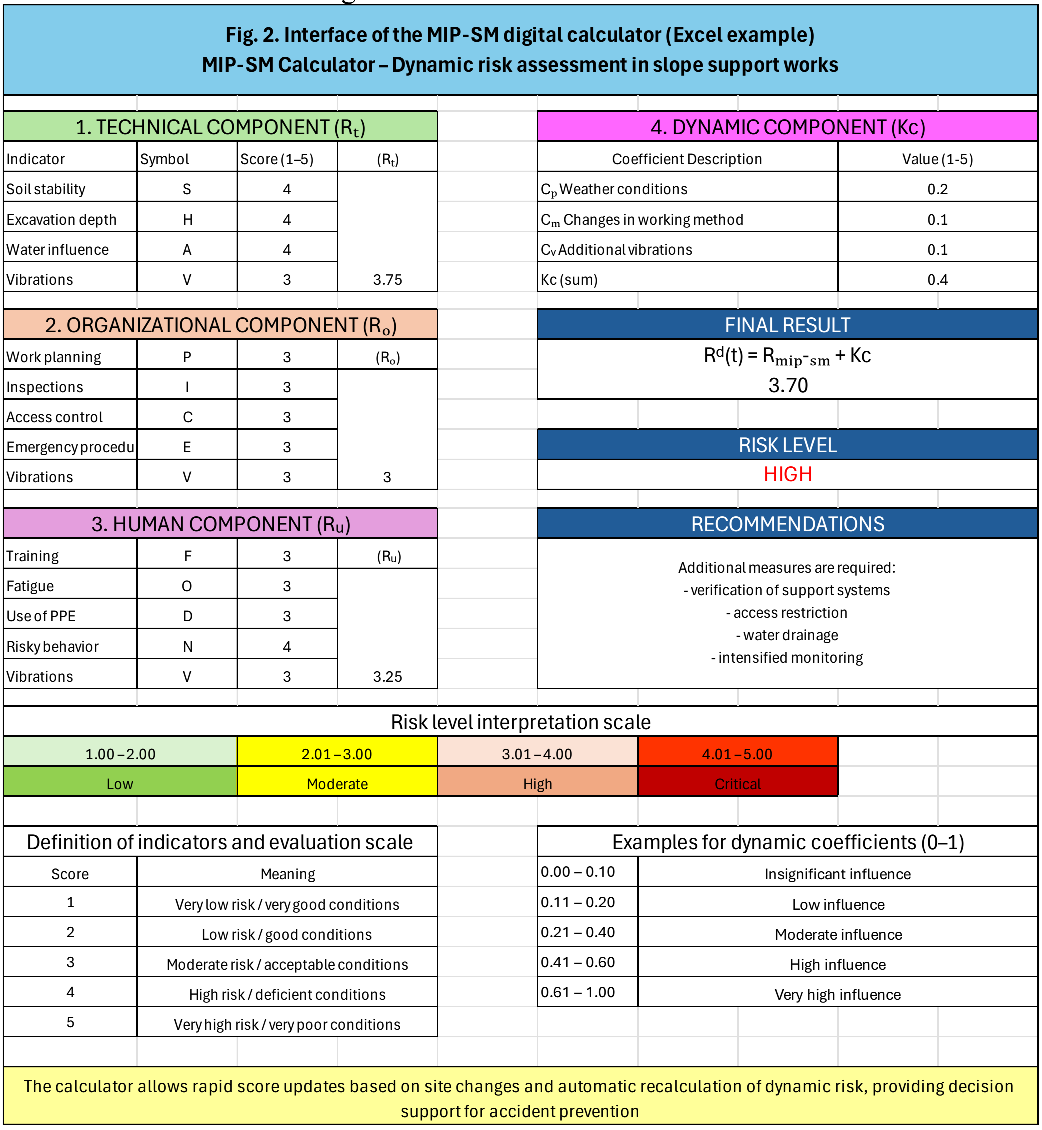


Fig. 2. Interface of the MIP-SM digital calculator (Excel example)
MIP-SM Calculator – Dynamic risk assessment in slope support works

1. TECHNICAL COMPONENT (R_t)

Indicator	Symbol	Score (1–5)	(R_t)
Soil stability	S	4	
Excavation depth	H	4	
Water influence	A	4	
Vibrations	V	3	3.75

2. ORGANIZATIONAL COMPONENT (R_o)

Work planning	P	3	(R_o)
Inspections	I	3	
Access control	C	3	
Emergency procedu	E	3	
Vibrations	V	3	3

3. HUMAN COMPONENT (R_u)

Training	F	3	(R_u)
Fatigue	O	3	
Use of PPE	D	3	
Risky behavior	N	4	
Vibrations	V	3	3.25

4. DYNAMIC COMPONENT (Kc)

Coefficient Description	Value (1-5)
C_p Weather conditions	0.2
C_m Changes in working method	0.1
C_v Additional vibrations	0.1
Kc (sum)	0.4

FINAL RESULT

$R^d(t) = R_{mip\text{-}sm} + Kc$

3.70

RISK LEVEL

HIGH

RECOMMENDATIONS

Additional measures are required:
- verification of support systems
- access restriction
- water drainage
- intensified monitoring

Risk level interpretation scale

1.00 – 2.00	2.01 – 3.00	3.01 – 4.00	4.01 – 5.00
Low	Moderate	High	Critical

Definition of indicators and evaluation scale

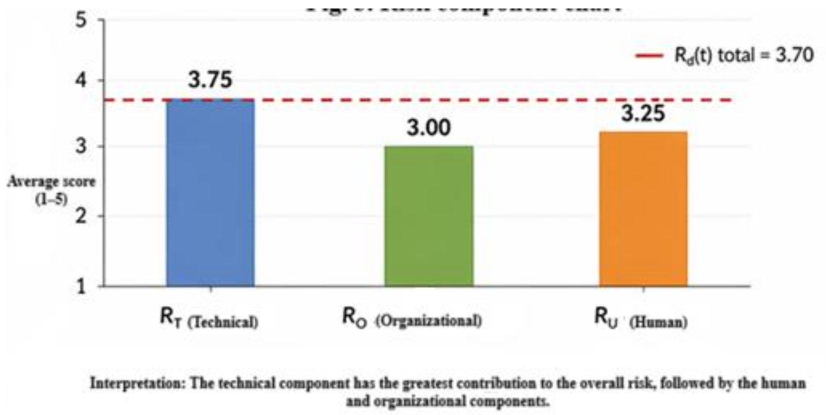
Score	Meaning
1	Very low risk / very good conditions
2	Low risk / good conditions
3	Moderate risk / acceptable conditions
4	High risk / deficient conditions
5	Very high risk / very poor conditions

Examples for dynamic coefficients (0–1)

0.00 – 0.10	Insignificant influence
0.11 – 0.20	Low influence
0.21 – 0.40	Moderate influence
0.41 – 0.60	High influence
0.61 – 1.00	Very high influence

The calculator allows rapid score updates based on site changes and automatic recalculation of dynamic risk, providing decision support for accident prevention

Figure 2. Interface of the MIP-SIM



Interpretation: The technical component has the greatest contribution to the overall risk, followed by the human and organizational components.

Fugure 3 Risk component chart

The graphical representation of the risk components highlights the relative contribution of each dimension to the overall risk (Fig. 3). In the analyzed case, the technical component has a dominant weight, confirming the critical importance of geotechnical stability in bank stabilization works. At the same time, the organizational and human components contribute significantly to the final risk level, demonstrating the need for an integrated approach.

The tool allows for: entry of scores (1–5) for each indicator; automatic risk calculation; risk level classification; and generation of prevention and protection measures.

5. CASE STUDY

To validate the proposed MIP-SM model, a representative case study for bank stabilization works in an urban environment was analyzed, characterized by variable geotechnical conditions and high operational constraints. The case involves the execution of an excavation for the installation of a utility pipeline in a densely built-up urban area. The main characteristics of the project are as follows:

- excavation depth: 4 m;
- soil type: clayey–sandy soil, with reduced cohesion in a saturated state;
- presence of groundwater: variable, influenced by precipitation;
- use of heavy machinery: excavator and compaction equipment;
- proximity to urban infrastructure (roads and buildings).

These conditions result in an initial moderate-to-high risk level, requiring careful and continuous assessment.

Based on on-site observations, the following scores were assigned:

- soil stability: S = 4 (moderate to high instability);
- excavation depth: H = 4;
- influence of water: A = 4;
- vibrations: V = 4.

Technical component: $R_T = (4+4+4+4):4 = 4.00$

(6)

Organizational component: $R_O = (3+3+3+3):4 = 3.00$ (7)
(where: work planning $P = 3$; inspections $I = 3$; access control $C = 3$; emergency procedures $E = 3$)
Human component: $R_U = (3+3+3+3):4 = 3.00$ (8)
(where: training $F = 3$; fatigue $O = 3$; PPE use $D = 3$; risky behavior $N = 3$)
Static global risk calculation $R_{MIP-SM} = 0.45 \cdot 4 + 0.30 \cdot 3 + 0.25 \cdot 3 = 3.45$ (9)
Interpretation: moderate-to-high risk, but manageable under normal conditions.
Introduction of the Dynamic Component
During execution, an episode of heavy rainfall occurred, resulting in increased soil moisture, reduced cohesion, and infiltration within the excavation area.
The following values were considered:

$$Cp = 0.3,\ Cm = 0.1,\ Cv = 0.1,\ Kc = 0.5 \quad (10)$$

Dynamic risk calculation:: $Rd(t)=3.45+0.5=3.95$ (11)
The obtained value indicates a high risk level.

This reflects the major impact of dynamic factors on work stability. It can be observed that, although the initial risk was manageable, changes in environmental conditions led to a significant increase in the overall risk level.

6. DISCUSSION

The results obtained through application of the MIP-SM model highlight the need for an integrated and dynamic approach to risk assessment in bank stabilization works. Unlike traditional methods, which treat risk as a static value determined during design or planning stages, the proposed model demonstrates that risk levels are strongly influenced by the evolution of site conditions and by interactions among technical, organizational, and human factors.

A key finding of the case study is the significant impact of the dynamic component on global risk. Although the initial assessment indicated a moderate-to-high risk (RMIP-SM=3.45R_{\text{MIP-SM}} = 3.45RMIP-SM=3.45), the introduction of the correction coefficient driven by meteorological and operational conditions increased the risk to a critical intervention level (RD(t)=3.95R_D(t) = 3.95RD(t)=3.95). This confirms that ignoring dynamic factors may lead to underestimation of real risk and, implicitly, to insufficient preventive measures.

Analysis of the contribution of each component shows that technical risk has a dominant influence, which is consistent with the nature of geotechnical works, where ground stability is the determining factor. However, the results also indicate that organizational and human risks cannot be neglected, as they may amplify technical hazards or prevent early identification of dangerous situations. For example, inadequate planning or lack of inspections may allow instabilities to develop without intervention, while unsafe worker behavior increases exposure to hazards.

Another important aspect is the sensitivity of the model to variations in the dynamic coefficient KcK_cKc. Even relatively small changes can shift the risk level from one category to another, highlighting the importance of continuous monitoring of site conditions. While this sensitivity represents an advantage by enabling rapid detection of critical situations, it also constitutes a limitation, as assessment accuracy depends on the quality of the input data.

Implementation of the digital method based on the MIP-SM calculator significantly enhances the model's practical applicability. The use of a simple spreadsheet-based tool allows OHS managers and site supervisors to perform rapid assessments and update risk levels in real time, without requiring advanced modeling expertise or complex equipment. This facilitates integration into routine site activities and supports decision-making by providing clear and easily interpretable results.

Nevertheless, the model also has certain limitations. First, indicator scoring is semi-quantitative, introducing a degree of subjectivity. Second, the weighting coefficients were established based on a general analysis of the field and may require adjustment depending on the specific type of work or local conditions. Additionally, the model does not explicitly account for nonlinear interactions between factors, which could be addressed in future research using probabilistic approaches or artificial intelligence-based systems.

Despite these limitations, the MIP-SM model provides a coherent and applicable framework for dynamic risk assessment in bank stabilization works. The integration of multiple risk factors and the use of a simple digital tool contribute to improved accident prevention and support the development of a proactive safety culture.

7. CONCLUSIONS

This study highlights the complexity of risk assessment in bank stabilization works, emphasizing that occupational accidents cannot be explained solely by technical factors. In this context, the MIP-SM model (Integrated Prevention Model – Bank Stabilization) was proposed, introducing a multidimensional and dynamic risk assessment approach that integrates technical, organizational, and human components.

One of the main findings is that excavation-related risk is a dynamic phenomenon, significantly influenced by changing site conditions. The introduction of the correction coefficient $K_c$enables continuous updating of risk levels based on factors such as weather conditions, technological changes, and external influences. This approach overcomes the limitations of traditional static assessment methods and provides a more realistic tool for real-time risk analysis.

The case study results confirmed the usefulness of the MIP-SM model in identifying critical situations and supporting the decision-making process. The increase in risk from a moderate level ($R_{\text{MIP-SM}} = 3.45$) to a high level ($R_D(t) = 3.95$) following environmental changes demonstrates the model's sensitivity and its ability to reflect real-risk evolution. As a result, preventive measures can be implemented before accidents occur, reducing worker exposure to hazards.

Another significant contribution is the development of a simple digital implementation method in the form of an Excel-based MIP-SM calculator. This tool facilitates practical application on construction sites, providing rapid and accessible decision support for occupational health and safety personnel. By automating calculations and graphically representing results, the method improves assessment efficiency and enhances risk communication.

The proposed model makes notable contributions both theoretically and practically. From a theoretical perspective, it offers an integrated risk analysis framework linking geotechnical, organizational, and behavioral factors. From a practical standpoint, it is easy to implement and adaptable to various types of works, without requiring advanced technological resources.

However, certain limitations must be acknowledged. The use of semi-quantitative scoring may introduce subjectivity, and the weighting coefficients are generalized and may require project-specific calibration. Future extensions may include integration of probabilistic methods, historical databases, or real-time monitoring technologies to improve assessment accuracy.

In conclusion, the MIP-SM model represents an effective tool for dynamic risk assessment in bank stabilization works, supporting the development of a proactive occupational safety and health approach. Its implementation has the potential to significantly reduce workplace accidents, optimize work processes, and enhance overall safety levels within the construction sector.

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