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Evaluation of slope failure through the assessment of meteorological conditions and earthworks management

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Article

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Infrastructure damage
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Numerical analyses

Abstract

Slope failures due to erosion effect are a well-established cause of civil engineering structure disasters. Streams passing at the toe of a slope are a severe threat to geotechnical safety, especially in urbanized areas. To increase global safety, a retaining wall is usually proposed to limit the risk of failure. However, such works could also bring the high danger of a landslide during the construction works if not managed properly. The paper aims at investigating the collapse cause of residential buildings located at the edge of the slope at northwest part of Vietnam, where engineering works were performed to prevent failure due to soil erosion at the toe of the slope. During the retaining wall construction works, the applied excavation method caused significant vibrations and additional dynamic loads that could have affected the bearing capacity of the building foundations. Another cause of failure is associated with heavy precipitation recorded at the site just before the excavation works down the slope. The paper consists of numerical analyses allowing simulation of possible scenarios, including the effect of changing groundwater conditions using the meteorological data collected from the nearby monitoring weather station. The computations were performed using geotechnical software to reflect the in-situ conditions, and the entire process of earthworks performed at the site was carefully analyzed. The numerical analyses involved computations performed for a reinforced slope where a retaining wall was proposed to assure geotechnical safety of the remaining infrastructure after the failure.

1. Introduction

Slope stability is a critical safety concern in urban development planning, particularly in areas where construction activities alter the natural landscape. Landslides can occur due to both natural geological and climatic processes, as well as human-induced factors, such as poor site management and engineering practices. While natural processes—including extreme weather events, increased precipitation, flooding, earthquakes, and volcanic eruptions—are inherently difficult to control, implementing proper mitigation measures, such as groundwater and surface runoff management, can significantly reduce the risk of slope failure. In contrast, landslides triggered by human activities can often be prevented through comprehensive geotechnical assessments, well-planned construction practices, and effective site management (Kim et al., 2014). Key human-related causes include inadequate drainage systems, improper excavation techniques, unsuitable earthworks, and poorly executed construction works. Understanding these risks and implementing appropriate mitigation strategies are essential for ensuring the long-term stability of slopes and preventing damage to infrastructure.

The present study investigates the factors that contributed to the collapse of buildings located near the edge of a natural slope. The failure is primarily linked to extreme precipitation events recorded at the site, combined with the effects of retaining wall construction. The retaining structure was intended to enhance the geotechnical stability of the slope while preventing toe erosion caused by a nearby stream, which had previously inflicted seasonal damage on the supporting bank. However, despite its intended function, the wall's construction may have contributed to slope instability, ultimately leading to structural failure.

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Retaining walls are essential geotechnical structures designed to resist lateral earth pressures and control excessive slope deformation. Their effectiveness largely depends on the construction material and method used. Different types of retaining walls include gravity walls, masonry walls, gabion walls, diaphragm walls, and sheet pile walls (Lanzieri & Avesani, 2025; Look, 2022; Salgado, 2022; Raposo et al., 2017). More recently, Mechanically Stabilized Earth (MSE) walls, which utilize geotextile reinforcement to separate and strengthen soil layers (Kawalec et al., 2019), have become increasingly popular in engineering practice. In addition to their role in stabilizing slopes, retaining walls also serve as protective barriers against soil erosion along riverbanks and waterways, where undercutting at the slope's base can pose a serious threat to structural integrity. When implementing slope stability measures, particularly in areas with existing infrastructure, careful planning is essential to minimize the risks associated with reinforcement works. One of the most critical factors influencing slope stability is groundwater management. Continuous monitoring of groundwater levels is crucial, as fluctuations in water content can significantly impact soil behavior and slope stability (Wang et al., 2014). Properly designed and well-maintained drainage systems play a vital role in improving working conditions at sites undergoing reinforcement earthworks.

The method of reinforcement installation is especially crucial in high-risk areas, where slope failure could endanger surrounding infrastructure. Previous research has extensively examined rainfall-induced landslides (Benz & Blum, 2019; Lacroix et al., 2020; Lira et al., 2020; Maturidi et al., 2021) and failures caused by inadequate execution of earthworks during reinforcement installation. Engineering studies indicate that one of the most common triggers of slope instability is the increase in groundwater pressure, which reduces effective stresses along potential slip surfaces (Augusto Filho & Fernandes, 2019). This effect is particularly pronounced in developed areas, where changing groundwater conditions can alter soil properties, leading to failures that compromise both the ultimate and serviceability limit states of structures. Moreover, bearing in mind climate change predictions presented in Figure 1 after the Vietnamese governmental report (Thuc et al., 2016), estimating 80% increased torrential rainfalls by the end of 21st century the particular measures should be taken accordingly.

Rainfall plays a significant role in landslide initiation by increasing porewater pressure and reducing the shear strength of soil materials (Orense, 2004). As rainwater infiltrates the soil, it saturates upper layers, potentially triggering shallow slope failures. Prolonged precipitation, however, affects deeper layers of the slope profile, leading to much more severe collapses (Alsubal et al., 2019; Han et al., 2014; Patuti et al., 2017). One of the key factors influencing soil behavior under varying moisture conditions is soil suction, which develops in the unsaturated zone above the groundwater table. Changes in soil suction can have a substantial impact on the mechanical and hydraulic response of the soil, further exacerbating slope instability.

This paper aims to thoroughly investigate the root causes of slope failure in a site located in northwest Vietnam. A combination of natural and human-induced factors contributed to the failure, leading to extensive structural damage and the forced evacuation of local residents. To accurately reconstruct the sequence of events leading to the collapse, the study relies on comprehensive site investigation data, meteorological records, and documentation of earthworks executed during the retaining wall construction. By analyzing these factors, the authors seek to provide a detailed assessment of the mechanisms that contributed to the slope failure. One of the key objectives of this study is to propose effective restoration solutions for the site. The research focuses on re-engineering the failed slope by designing appropriate reinforcement strategies that ensure long-term geotechnical stability while minimizing risks to existing infrastructure. By considering past failures and evaluating alternative stabilization techniques, the study aims to offer insights that can be applied to similar high-risk construction projects in the future. Slope stability is a fundamental concern in urban development, particularly in areas where construction activities interact with complex geological and hydrological

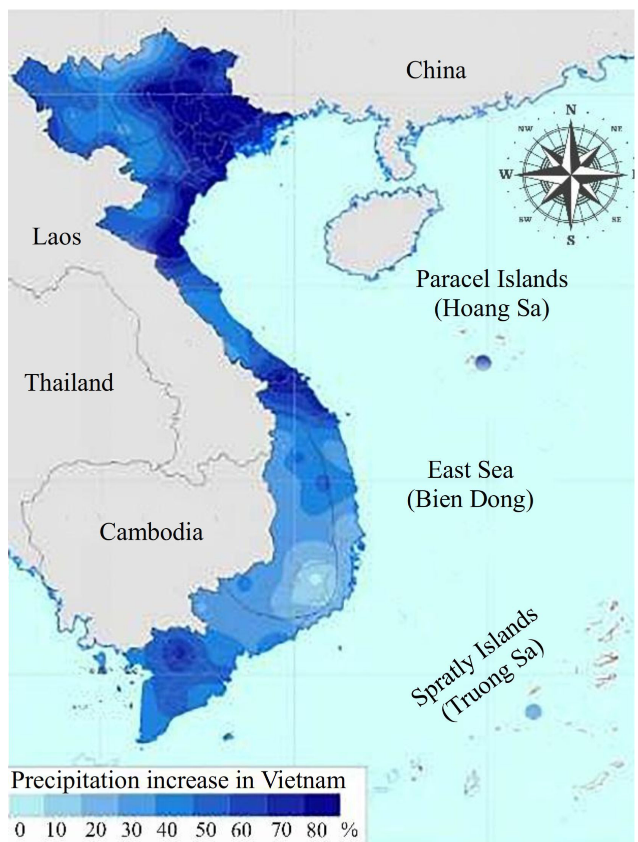

Figure 1. Average change in torrential precipitation (%) predictions for end of 21st century for Vietnam (modified after Thuc et al., 2016).

conditions (Osiński et al., 2020). While natural factors such as extreme precipitation can contribute to landslides, human activities—especially improper drainage and reinforcement techniques—can exacerbate instability and lead to structural failures. The findings of this study highlight the importance of integrating geotechnical assessments, effective drainage solutions, and appropriate construction methods to mitigate slope failure risks. By understanding the interplay between natural and anthropogenic factors, engineering practices can be improved to ensure safer and more sustainable urban development in landslide-prone areas.

2. Study site description

2.1 Geomorphology and climate conditions

The case study site is located in a mountainous district located in the center of Dien Bien province, in north-west part of Vietnam. The entire area is surrounded by high mountains reaching 450 m above the ground level. The district is divided into two landform zones where the terrain elevation ranges from 350-1000 m AMSL, and the zones where slopes reach up to 1500 m AMSL, with the slopes facing northwest-southeast. The study site location is presented on Figure 2.

The terrain is morphologically complex with a number of valleys and rivers crossing the entire region, where during the wet season, the meandering streams cut into the mountain's toes. What is important for the case study is the presentation of the local climate condition that has a major effect on the working conditions of the infrastructure and influences natural hazards like flooding and landslides. The climate conditions are typical of a tropical monsoon climate. The winter season is considered rather cold, with the lowest temperature at 2 °C, and the rainfall volume does not exceed 60 mm per month. The summer season is considered hot and rainy, with the highest temperatures reaching 40 °C and the monthly highest volume of rainfall up to 500 mm recorded in July. The average temperature during the year is between 18 °C and 25 ^{0}C. The average annual rainfall ranges from 1,600 to 2,400 mm. The rainy, hot and humid season starts in April and lasts for 6 months. The dry season starts from October to April, with low temperature and low rainfall volume (Luu et al., 2022). The average air humidity is from 83 to 85% with the lowest values recorded for springtime (March to May). According to data from the Vietnam Institute of Meteorology, Hydrology and Climate Change, the average annual rainfall, in the period from 1961 to 2018, was 1562 mm. In that same period, the average annual temperature was 22.17 °C, with an increase by 0.75 °C between 1961–1990 and 1991–2018. Dien Bien is expected to continue experiencing temperature increases (Tran-Anh et al., 2022). According to unpublished baseline data of the Agricultural Cooperative Strengthening (ACS) project run by humanitarian organization CARE in Vietnam, several adverse weather and climate events can be damaging to infrastructure development. These adverse conditions include floods, flash floods, landslides, early onset of the rainy season and extended rainy seasons.

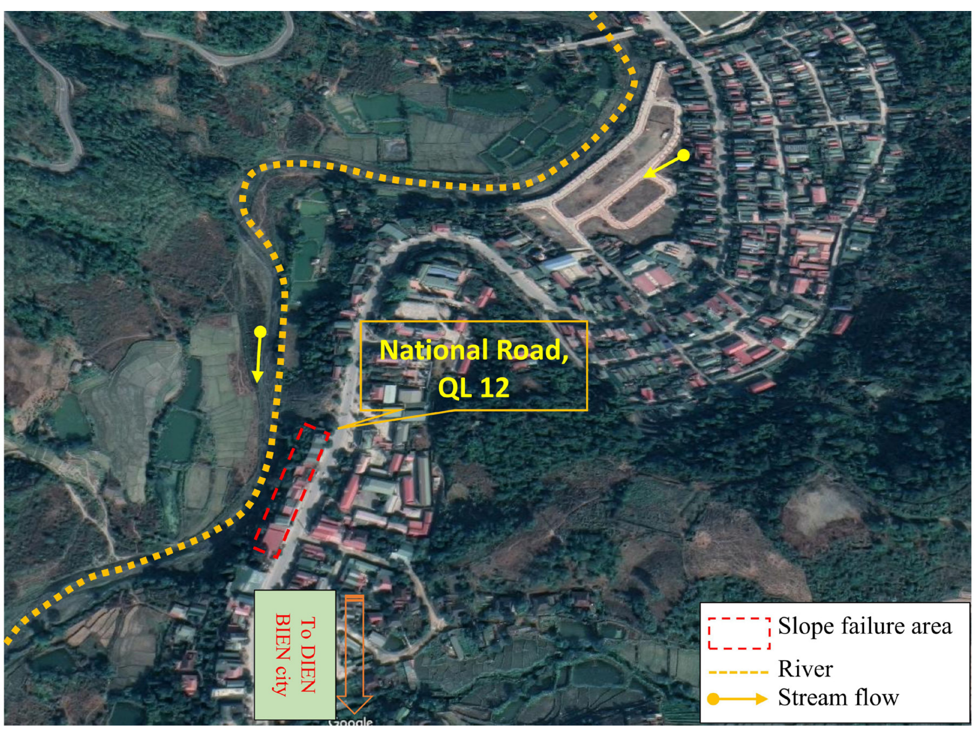

Figure 2. Location of study area.

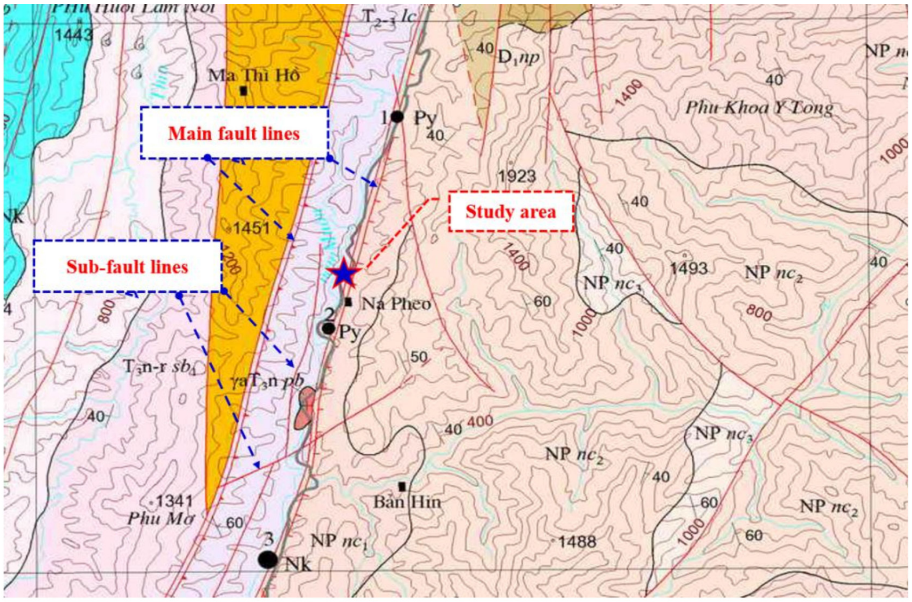

Figure 3. Geological map of the study area.

It is also important to highlight the fact that the area is seismically active. The most recent earthquake that took place at the site was recorded in 2018, of 4.3 magnitude (*M*). According to the geological map of Vietnam with a scale of 1:200000 (Figure 3) (DGMV, 2005), the study area is located on the main fault of the Dien Bien-Lai Chau fault zone.

The Điện Biên–Lai Châu fault zone is a sinistral strike-slip conjugate fault system of significant geological importance to the region. It consists of a main fault running through the center, accompanied by several subsidiary faults on either side. The main fault plane dips westward at an angle of 60°–70°, and is nearly vertical in the southern segment. This tectonic system results in highly jointed rock formations within the study area, which may expose the proposed structure to seismic risk. The fault cuts across formations dating from the Proterozoic, Paleozoic, and Mesozoic eras. In the territory of Vietnam, the fault zone is about 160 kilometers long (Nguyen, 2001). This is one of the most active fault zones in Vietnam where seismic activities have been recorded (Phuong & Truyen, 2015). A number of seismic events took place there along the main fault and the adjacent areas i.e., Dien Bien earthquake of *M* 6.75 in 1935, Na Pheo earthquake in 1980 of *M* 4.6; Lai Chau earthquake of *M* 4.2 in 2001 and Dien Bien earthquake of *M* 5.3 in 2001. Phuong and Truyen (2015) rated that the region of Dien Bien-Lay Chau could have experienced the maximum values of Pick Ground Acceleration (PGA) at 180 - 272 gals for 475 - 9975 years. According to the geological map (DGMV, 2005), the study area is located in Lai Chau formation (T2-3lc) which is characterized by fine-grained terrigenous sediments mainly of deep-water facies, distributed in a narrow band along the Lai Chau – Dien Bien fault. The site investigation revealed that the study area comprised light grey, fine-grained, thin to medium bedded (0.1 to 0.5m) sandstone interbedded with dark-grey, fine-grained thin bedded siltstone and argillaceous. According to the geotechnical investigation report, the bedrock is mainly composed of shale interbedded with sandstone which is in accordance with the descriptions in the geological map. The site survey (Figure 4) showed that the shales are strongly folded, and the surface condition was fractured due to a highly weathered surface with cracks and angular deposits.

Figure 4. Bedrock at the stream bank just beneath the reported failure.

The rock formations at the study site have two predominant joint sets, namely the bedding joints and near vertical set. Joints are mostly weathered and smooth with a spacing range from a few millimeters to 10 centimeters. Cracks less than 1 mm are usually filled with clay. The shale contains fissures due to shearing. Remarkably, the shale represents softening behavior due to water infiltration. Sandstone is whitish grey, fine grained and thinly bedded. The sandstone presents high uniaxial compressive strength. The bed rocks are randomly intersected by thin deposits of quartz. The presence of thin bedding joints and the tectonically induced discontinuities cause the rock mass to be highly fractured. The sandstone beddings are persistent, and the joint condition is rated to be fair with a moderately weathered and altered surface. Accordingly, the geological strength indices are estimated using Marinos (2019) classification as 15 and 25 for slightly weathered shale and slightly weathered sandstone, respectively.

2.2 Geotechnical site investigation and additional key data

For the purpose of detailed analyses of the conditions at the study site, the geotechnical investigation was performed to establish the geological and geotechnical soil profiles and the parameters necessary for further computations of geotechnical safety. The analyses of the geotechnical structures were based on the site investigation performed for two cross-sections involving 5 geological boreholes. The maximum depth of drilling was 30 m. The total depth for all the drillings was 100 m. The location of geological boreholes is presented in Figure 5. During the site investigation, 11 core samples were collected and transported to the laboratory, where physical and mechanical parameters were tested. During the field works Standard Penetration Tests (SPT) were also performed to determine the shear strength parameters. The investigation allowed distinguishing 4 major geotechnical layers. Starting from the ground level, these are:

- Layer 1 (Backfill): clay and gravel, inconsistent state from hard to soft of low SPT index. The thickness of the backfill layer varies from 1.8-4.7 m.
- Layer 2 (Strongly weathered shale): shale weathered into clay and gravel, thinly layered hard plastic state, of low SPT index. The thickness of the soil layer varies from 1.3 m to 5.8 m.
- Layer 3 (Lightly weathered shale): thin, fragile rock material. Thickness varies from 4.0 m to 9.2 m.
- Layer 4 (Sandstone): fine-grained sandstone, of high stiffness with interbedding of quartz particles. The thickness varies from 3.0 m to 3.4 m.

The experimental results of physicomechanical parameters from soil samples collected during site investigation are presented in Table 1.

To provide a better understanding of the geotechnical structure the slope profile is presented in Figure 6.

Since the rainfall events in the study were concerned with having a major effect on the failure, the precipitation data were also analyzed. To allow further understanding of the failure cause, the rainfall data was collected from the nearby monitoring station (Na Sang station, 10 km from the study area) and is presented in Figure 7. Important for the study is the accumulative rainfall recorded for October 2021, when 2000 mm of accumulative precipitation was reached.

Figure 5. Site investigation cross-sections and boreholes' locations.

Based on gathered data regarding geological, and geotechnical investigation and rainfall volume, the computations of geotechnical safety were performed to determine the failure mechanism and to reflect the sequence of the events.

Table 1. Physical and mechanical parameters of the investigated soil layers.

Parameter	Soil type			
	Fill	Shale*	Shale**	Sandstone**
w (%)	23.9	28.2	-	-
γ (kN/cm³)	19.6	19.0	22.0	25.0
e	0.69	0.8	-	-
Ip (%)	16.2	15.7	-	-
c' (MPa)	0.0167	0.174	0.09	0.18
φ' (°)	17	20	32	46

*highly weathered. **moderately weathered.

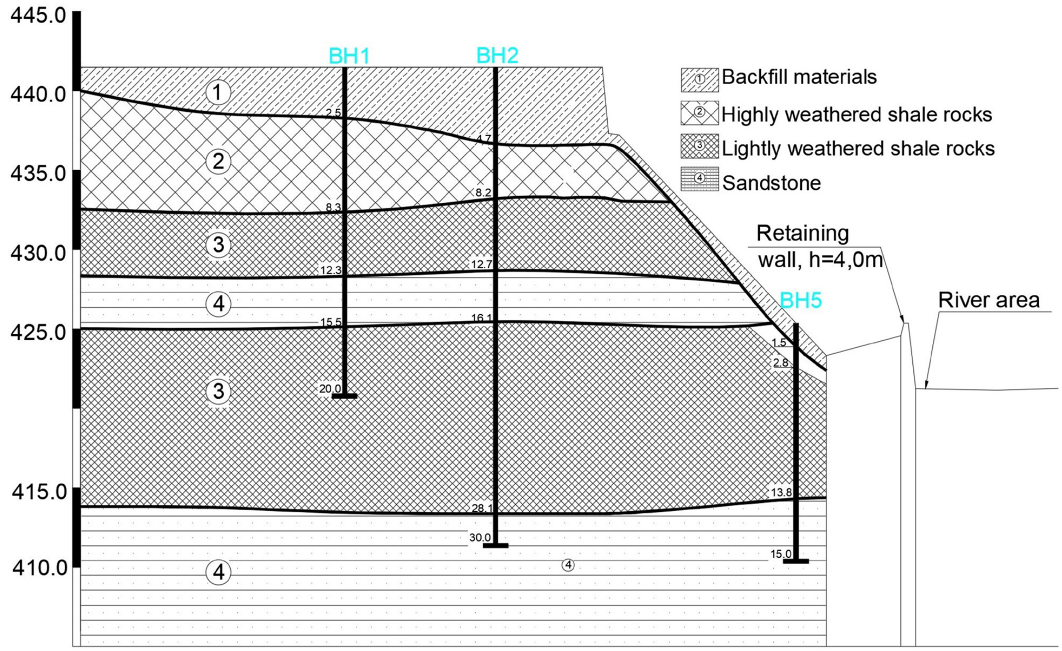

Figure 6. Geological cross-section I-I'.

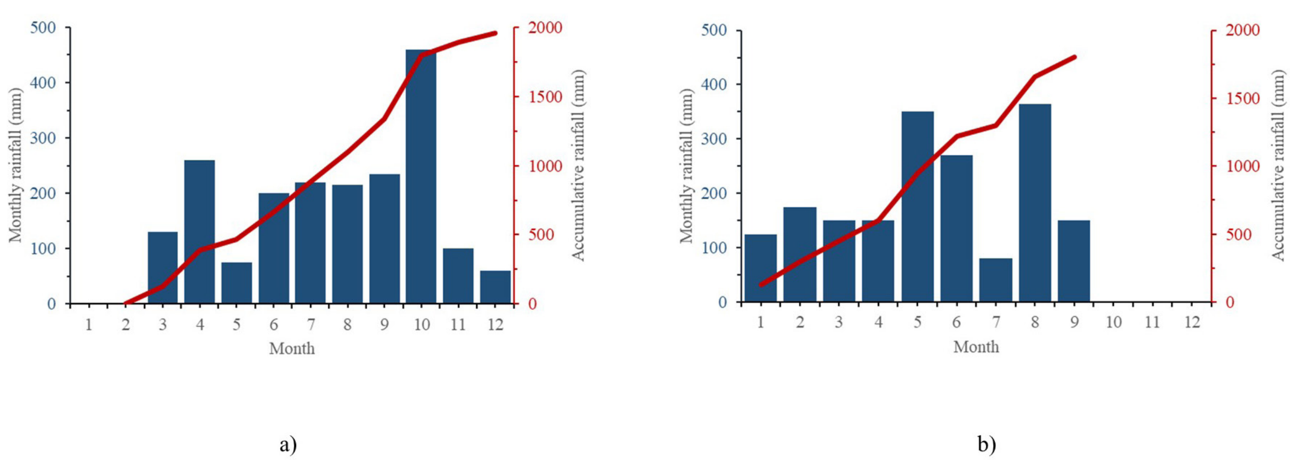

Figure 7. Rainfall data record for particular months a) in 2021 and b) in 2022 in Dien Bien district.

3. Results and discussion

3.1 Analyses of the events sequence

The case study concerns a natural slope with extensive infrastructure developed at the top edge. The infrastructure development started with the construction of a local road near the edge and the design of the drainage system, redirecting the runoff down the 25 m high slope. Following the road construction number of storey buildings were constructed in the section between the road and the slope's edge. At the toe of the slope, there is a natural stream passing with the flow changing depending on the rainfall volume. In recent years, the local community's major concern has been focused on the erosion effect due to the stream continuously cutting the toe of the slope. Thus, a retaining wall was constructed to control the water erosion and improve the slope's stability. After the works were accomplished, significant rainfall events took place. The finger pipe drainage was installed at the back of the wall. A few weeks later, the residents reported the first building cracking, which continued to develop until the next severe rainfall event that was followed by the slope failure and a collapse of buildings located at the study site. The damages to the infrastructure are presented in Figure 8.

The authors of the present paper aimed to investigate events and the processes contributing to the failure occurrence. Based on the data collected from the site investigation report, meteorological report and the information gathered during the site visits, the analytical study was performed to reflect the in situ conditions. The authors started their analysis by reconstructing the sequence of events leading to the slope failure. This involved a thorough examination of all relevant site conditions, including correlating recorded rainfall data with the timeline of the retaining wall construction, observing the development of cracks in residential buildings, and identifying the moment of the final slope failure. To provide a clearer understanding of the interplay between these factors, Figure 9 presents a chronological sequence of events, illustrating the possible causes that ultimately led to the collapse and the severe damage sustained by nearby structures.

In late 2021, following growing concerns about the deteriorating condition of the slope, local authorities decided to implement preventive stabilization measures. The primary intervention involved the construction of a concrete gravity retaining wall at the toe of the slope, intended to mitigate potential failure and reinforce the stability of the area. The excavation phase, which took place between October 7 and October 20, 2021, was reported to have caused significant ground vibrations. These vibrations were particularly noticeable to local residents living in the buildings situated at the crest of the slope. Complaints were raised regarding the intensity of the shaking, which raised concerns about its potential impact on the structural integrity of the buildings.

Despite these reports, the construction proceeded as planned. Shortly after the completion of the retaining wall, an extreme rainfall event occurred on October 22, 2021, with recorded precipitation levels reaching 30 mm in a single day. It is important to emphasize that the total accumulated rainfall for October 2021 was approximately 2000 mm, highlighting the exceptionally wet conditions in the region during that period. One week later, the first signs of structural distress appeared, as cracks were observed in the walls of residential buildings near the slope edge. Over the next two months, additional damage to the buildings became evident. The situation escalated dramatically on January 16, 2022, when a heavy rainfall event of nearly 45 mm in a single day occurred. Following this event, the slope experienced a catastrophic failure, resulting in the partial collapse of buildings and severe infrastructural damage. During the earthworks phase, the dynamic loads generated by excavation activities and construction-induced vibrations disturbed and loosened the soil structure at the building foundations.

Figure 8. Extensive damage to the residential buildings located on the study slope.

This disturbance likely compromised the shear strength of the soil layers, making it more susceptible to external environmental factors. Following this phase, heavy rainfall decreased the stability by infiltrating the loosened soil profile. The increase in pore water pressure within the soil layers led to a reduction in shear strength, thereby lowering the overall stability of the slope. Additionally, the inadequate drainage system failed to efficiently redirect surface and groundwater flow, causing excessive water retention within the slope mass. This progressive saturation contributed to the build-up of pore water pressure in the soil, further weakening its mechanical properties and increasing the likelihood of slope failure. Figure 10 presents a chronological sequence of events, providing a comprehensive overview of the factors contributing to the slope failure. By illustrating the circumstances including construction activities, recorded rainfall events, and the progressive development of structural damage the graphical interpretation helps to identify the potential interactions between these elements.

Understanding this sequence is crucial in determining the underlying causes of the slope's ultimate failure, which led to significant structural damage to residential buildings and posed serious safety risks to the affected community.

3.2 Restoration and slope stability improvements

Based on the geotechnical investigation data and recorded rainfall volume, computational analyses of geotechnical safety were conducted to determine the failure mechanism and reconstruct the sequence of events leading to the slope collapse. These analyses were crucial in understanding the contributing factors to instability and assessing the extent of structural damage. Following this assessment, restoration works were designed, and additional geotechnical safety

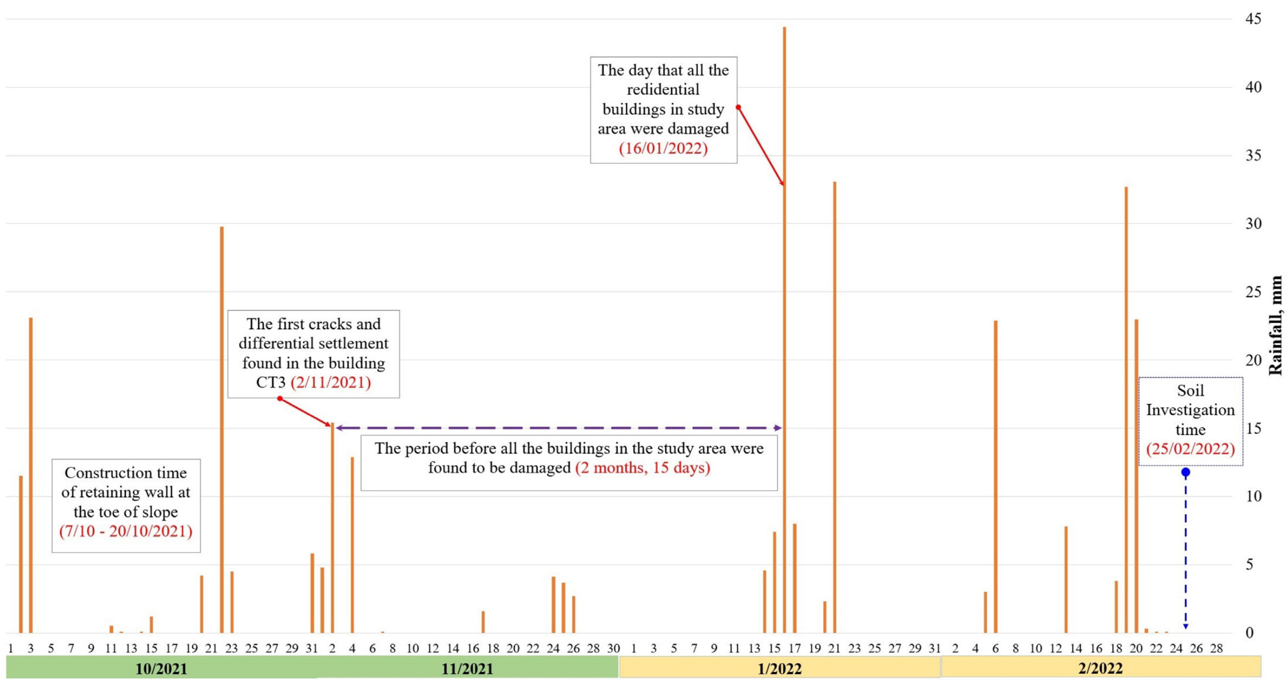

Figure 9. The sequence of events leading to a final failure with referencing rainfall data.

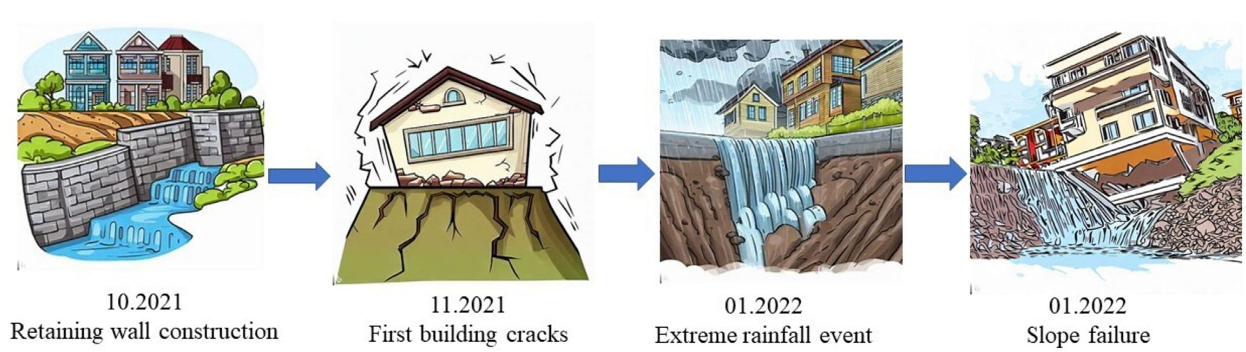

Figure 10. Graphical presentation of the sequence of events leading to a structural failure of residential buildings (AI generated).

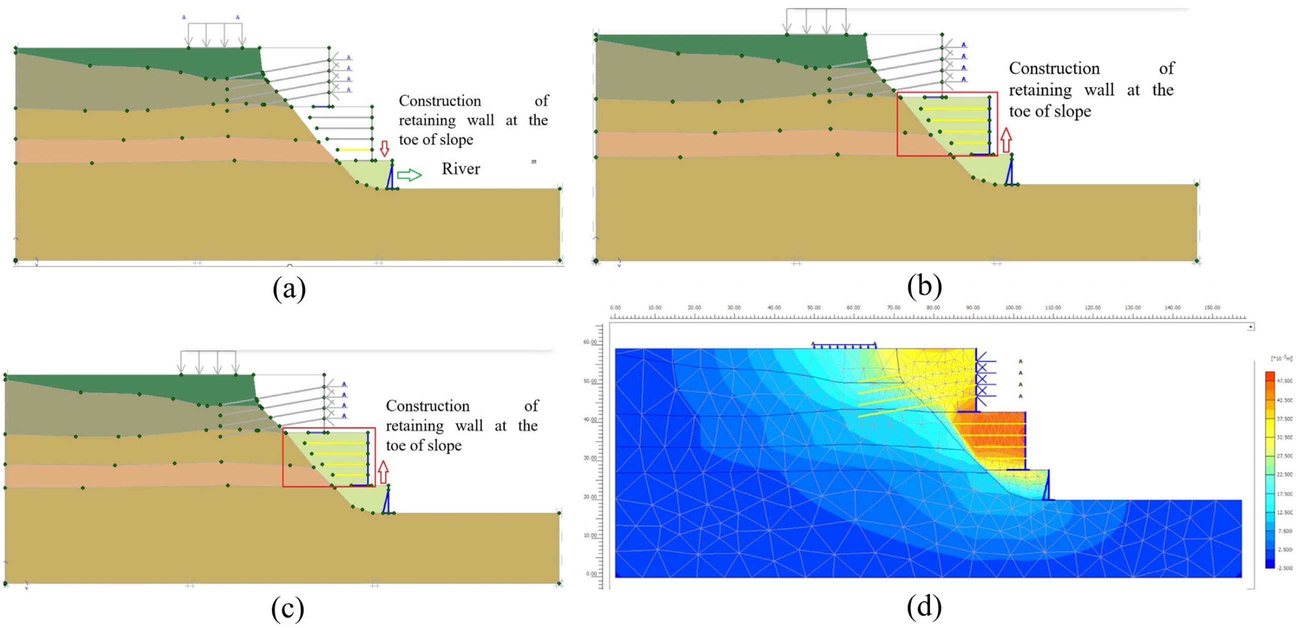

Figure 11. Sequence of slope stability improvement a) 1st stage-backfill with gabions, b) 2nd stage MSE, c) 3rd stage soil nails, d) displacements computations.

computations were performed to ensure the long-term stability of the slope and surrounding infrastructure. The slope stability analyses were carried out using the Finite Element Method (FEM), using commercial software Plaxis (Brinkgreve et al., 2016), incorporating geotechnical parameters obtained directly from site investigations. The Mohr-Coulomb soil model was applied to simulate soil behavior under different loading conditions, while the Factor of Safety (FoS) was computed using the Shear Strength Reduction (SSR) method to evaluate slope stability under various scenarios. To account for the hydrogeological influences on slope stability, multiple simulation scenarios were analyzed, considering the changing groundwater levels due to rainfall infiltration. These simulations provided insights into how excessive water infiltration reduced soil shear strength, increasing the likelihood of failure. To ensure long-term safety and prevent further instability, the entire slope was re-engineered using a combination of reinforcement techniques. The proposed stabilization system included: Mechanically Stabilized Earth (MSE) Wall – Implemented to provide additional lateral support and enhance slope resilience; Gabion Retaining Wall – Selected due to its flexibility, permeability, and ability to absorb dynamic loads, minimizing further deformation and reducing the impact of future precipitation events. This integrated reinforcement system was specifically designed to minimize excavation and earthwork disturbances to protect the remaining infrastructure and prevent further damage. The optimum stabilization solution was determined through numerical simulations, where deformation patterns and safety factors were analyzed. The results of these computations, presented in Figure 11, illustrate the effectiveness of the proposed stabilization measures in improving the overall geotechnical safety of the site. The obtained factor of safety was 1.34 > FoS= 1.25, and the maximum horizontal displacement did not exceed 4.25 cm < $\delta = H/200 = 7.5$ cm, where H is the total height of the wall.

4. Conclusions

The primary objective of this study was to investigate the on-site conditions and reconstruct the sequence of events that may have led to structural damage in residential buildings and ultimately caused the slope failure. A comprehensive analysis was conducted using site investigation data, meteorological monitoring reports, drainage assessments, and an evaluation of earthworks carried out during the construction of the retaining wall. This multidisciplinary approach enabled a thorough understanding of the key contributing factors to the slope's failure. Based on the collected data, a reclamation and stabilization plan were developed to mitigate further risks and restore geotechnical safety. The factor of safety (FoS) and total deformations of both the failed and newly engineered slopes were computed to validate the effectiveness of the proposed solutions. Advanced numerical modeling techniques were employed to assess different stabilization scenarios, ensuring that the remedial measures would prevent future failures while minimizing additional risks to the surrounding infrastructure. A critical takeaway from this case study is that earthworks intended to enhance safety can, under certain circumstances, have the opposite effect—particularly when executed in regions prone to extreme weather events. In this instance, the construction works, combined with heavy rainfall and inadequate drainage management, contributed to soil instability rather than preventing it. This underscores the importance of integrating climate-responsive geotechnical solutions, adopting real-time monitoring systems, and implementing proactive risk management strategies in similar high-risk environments. The findings suggest that the combination of intense construction activities and extreme meteorological conditions created a scenario where the slope became highly vulnerable to failure. While the retaining wall was intended to reinforce the area, the methods of excavation and drainage management likely played a significant role in destabilizing the slope rather than securing it. This case highlights the critical importance of incorporating advanced drainage solutions, real-time monitoring, and soil stability assessments in engineering interventions designed to mitigate landslides in high-risk areas. The findings from this study provide valuable insights into the interaction between construction-induced stress changes and hydrological effects on slope stability. Future research should focus on implementing early warning systems, improved geotechnical modeling, and resilient infrastructure designs to prevent similar failures in regions prone to heavy rainfall and complex topographical conditions.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Nguyen Quang Tuan, Duc Bui Van and Piotr Osinski: conceptualization, data curation, visualization, writing – original draft. Nguyen Van Manh, Ngoc Anh Do and Eugeniusz Koda: conceptualization, data curation, methodology, supervision, validation, writing – original draft. Piotr Osinski, Duc Bui Van and Eugeniusz Koda: formal analysis, funding acquisition, investigation, methodology, project administration, resources, software. Piotr Osinski, Ngoc Anh Do, Nguyen Van Manh: supervision, validation, writing – review & editing.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial inteligence

This work was prepared with the assistance of generative artificial intelligence (GenAI) DALL-E with the aim of creating the graphics in Figure 10. The entire process of using this tool was supervised, reviewed and when necessary edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

List of symbols

c'	Effective cohesion
e	Void ratio
w	Moisture content
ACS	Agricultural Cooperative Strengthening
AMSL	Above Mean Sea Level
FEM	Finite Element Method
FoS	Factor of Safety
H	Total height of the wall
I_p	Plasticity index
M	Magnitude
MSE	Mechanically Stabilized Earth
PGA	Pick Ground Acceleration
SPT	Standard Penetration Test
SSR	Shear Strength Reduction
γ	Unit weight
δ	Horizontal displacements
φ'	Effective internal friction angle

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