International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 3 [March. 2025] PP: 180-184

Assessment of climate change impacts on slope stability in the northern mountainous regions in Vietnam

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Abstract
This study assesses the impact of climate change on slope stability in the northern mountainous regions of Vietnam, focusing on Lao Cai and Yen Bai provinces. Using the SLOPE/W model and climate data, the study indicates that increased rainfall and rising temperatures significantly reduce the slope safety factor, leading to a higher risk of landslides. The results show that under the RCP 8.5 scenario, the risk of landslides could increase by 40–50% by 2050. The study proposes solutions such as slope reinforcement, forest management, and early warning systems to mitigate risks.
Keywords: *climate change, slope stability, SLOPE/W, landslides, RCP 8.5.*

Date of Submission: 16-03-2025 Date of acceptance: 31-03-2025

I. Introduction

Climate change has become one of the most significant challenges facing humanity in the 21st century. According to the Intergovernmental Panel on Climate Change (IPCC), the global average temperature has increased by approximately 1.1°C compared to the pre-industrial period and is projected to continue rising in the coming decades. Vietnam, with its diverse geography and climate, is considered one of the most vulnerable countries to climate change. In particular, the northern mountainous regions, characterized by complex topography and harsh weather conditions, are increasingly facing natural disasters such as floods, landslides, and flash floods. Among these, landslides pose one of the most severe threats, causing significant loss of life and property while also jeopardizing infrastructure stability and local livelihoods.

Landslides result from the complex interaction of natural and human factors. Natural factors include geology, topography, hydrology, and climate, while human activities such as resource exploitation, infrastructure development, and land-use changes also play a crucial role. In the northern mountainous regions of Vietnam, steep slopes, thin vegetation cover, and highly weathered soil and rock create favorable conditions for landslides. In particular, climate change, with its manifestations such as increased rainfall, altered seasonal precipitation patterns, and extreme weather events, has exacerbated this risk. Intense rainfall over short periods increases pore water pressure in the soil, reducing soil shear strength and leading to slope instability.

Although landslides have been studied from various perspectives, the impact of climate change on slope stability remains a topic with significant research gaps, especially in the context of Vietnam. Previous studies have primarily focused on landslide risk assessment based on traditional geological and hydrological factors, without fully considering the changing climatic conditions in the future. Furthermore, existing landslide prediction models often rely on historical data, while climate change is altering natural conditions significantly, necessitating new and more comprehensive approaches.

In this context, this study aims to evaluate the impact of climate change on slope stability in the northern mountainous regions of Vietnam, specifically in Lao Cai and Yen Bai provinces. These areas feature complex terrain and are frequently affected by heavy rainfall and landslides. The research will focus on analyzing climate change trends, particularly precipitation patterns, and utilizing mathematical models to assess slope stability under different climate scenarios. The findings will provide a scientific basis for developing landslide risk management strategies, contributing to the protection of lives and property and ensuring the sustainable development of mountainous areas.

This study is not only scientifically significant but also highly practical. Understanding the relationship between climate change and landslides will help policymakers and disaster management authorities make informed and timely decisions for disaster prevention and risk reduction. Additionally, the research will raise public awareness of climate change impacts, encouraging adaptive actions and environmental protection measures.

In recent decades, climate change and landslides have become two critical research topics in geotechnical engineering and disaster risk management. Studies worldwide and in Vietnam have provided valuable insights into the mechanisms, causes, and solutions related to these issues. However, the relationship between climate change and landslides remains an area requiring further exploration, particularly in the northern mountainous regions of Vietnam.

Climate change is defined as long-term changes in climatic factors such as temperature, precipitation, humidity, and extreme weather events. According to the IPCC (2021), the global average temperature has increased by approximately 1.1°C compared to the pre-industrial period and is projected to rise further by 1.5°C to 2°C by the end of the 21st century if effective mitigation measures are not implemented. In Vietnam, climate change has led to significant changes in precipitation and temperature patterns. Studies by the National Center for Hydro-Meteorological Forecasting (2020) indicate that annual precipitation in the northern mountainous regions has been increasing, particularly during the rainy season, accompanied by a rise in the frequency and intensity of localized heavy rainfall events.

These changes have a direct impact on slope stability. Increased rainfall elevates pore water pressure within the soil, reduces soil shear strength, and heightens the risk of landslides. Research by Dahal and Hasegawa (2008) on landslides in the Himalayas has demonstrated that rainfall is the most critical factor influencing slope stability. Similarly, in Vietnam, studies by Nguyen et al. (2019) have confirmed that landslides frequently occur after prolonged heavy rainfall, particularly in areas with steep slopes and highly weathered soil and rock formations.

Landslides result from the complex interaction of natural and anthropogenic factors. Natural factors include geology, topography, hydrology, and climate, while human activities such as resource exploitation, infrastructure development, and land-use changes also play a crucial role. According to Varnes (1978), landslides can be classified into various types based on mechanisms and materials involved, including soil slides, rockfalls, and debris flows. In the northern mountainous regions of Vietnam, landslides primarily occur in the form of soil slides and debris flows, particularly in areas with steep slopes and sparse vegetation cover.

Studies by Pham et al. (2020) have shown that geology and hydrology are the two primary factors influencing slope stability. Highly weathered rock formations, especially clay and shale, exhibit low shear strength and are prone to failure under water infiltration. Additionally, deforestation and land-use changes reduce soil water retention capacity, exacerbating landslide risks. Research by Tran et al. (2018) in Son La province has demonstrated that the conversion of natural forests into agricultural land has significantly increased landslide occurrences.

To assess landslide risk, researchers have employed various methods, ranging from simple mathematical models to complex analytical tools based on GIS and remote sensing technology. SLOPE/W and GEO-SLOPE are two widely used tools for slope stability analysis, utilizing geotechnical and hydrological parameters. The study by Lê et al. (2021) applied the SLOPE/W model to evaluate slope stability in Hòa Bình province, revealing that increased rainfall significantly reduces the factor of safety of slopes.

Furthermore, GIS and remote sensing technologies have been extensively applied in the development of landslide risk maps. The study by Nguyễn et al. (2020) utilized remote sensing and GIS data to assess landslide risk in Lào Cai province, demonstrating that areas with steep slopes and high rainfall are at the greatest risk of landslides.

II. Methodology

To assess the impact of climate change on slope stability in the northern mountainous regions of Vietnam, this study follows a systematic approach consisting of key steps: data collection, climate change trend analysis, slope stability assessment, and the development of landslide risk scenarios. The research methodology is detailed as follows.

Study area

The study focuses on the northern mountainous provinces of Vietnam, particularly Lào Cai and Yên Bái, which are frequently affected by landslides. These regions are characterized by complex terrain, steep slopes, and harsh climatic conditions, with heavy rainfall concentrated during the rainy season (from May to October). The selection of the study area is based on criteria such as landslide frequency, the extent of climate change impacts, and data availability.

Data collection

The study utilizes the following data sources:

- **Climate data**: Rainfall, temperature, and humidity data are collected from meteorological and hydrological stations in the study area, as well as from satellite datasets such as CHIRPS and TRMM.
- **Geological and topographic data**: This includes geological maps, slope gradient, soil types, and vegetation cover, obtained from the Vietnam Institute of Geosciences and Mineral Resources (VIGMR) and other relevant agencies.

- **Field data**: Geotechnical parameters such as soil moisture content, shear strength, and pore water pressure are measured directly at selected research sites.

Climate change trend analysis
Climate change trends are analyzed using statistical methods, including:

- **Time series analysis**: The Mann-Kendall test and Sen's slope estimator are applied to assess long-term trends in rainfall and temperature over recent decades.
- **Rainfall frequency analysis**: Changes in the temporal and spatial distribution of rainfall, particularly extreme rainfall events, are evaluated.

Slope stability assessment
Slope stability is analyzed using mathematical models and specialized software:

- **SLOPE/W model**: The Limit Equilibrium Method (LEM) is employed to calculate the Factor of Safety (FS) of slopes under different conditions. FS is determined based on geotechnical parameters such as shear strength, soil moisture, and slope angle.
- **Hydrological analysis**: The impact of rainfall on pore water pressure and slope stability is assessed.

Development of landslide risk scenarios
Based on analytical results, the study develops landslide risk scenarios under climate change conditions:

- **Current scenario**: Slope stability is assessed based on existing climate and geological data.
- **Future scenario**: Slope stability is projected under climate change scenarios (RCP 4.5 and RCP 8.5) derived from global climate models.

Analysis and validation of results
Model outputs are validated by comparing them with field data and previous studies. The accuracy of the model is evaluated using statistical indicators such as Root Mean Square Error (RMSE) and the coefficient of determination (R^2).

III. Results and discussion

This study has yielded significant findings in assessing the impact of climate change on slope stability in the northern mountainous regions of Vietnam, particularly in Lào Cai and Yên Bái provinces. Analysis of climate data from meteorological stations and satellite sources reveals a significant increase in both precipitation and temperature over the past few decades. Specifically, the average annual rainfall in the study area has increased by approximately 10–15% compared to the 1980–2000 period, while the average temperature has risen by about 0.8–1.2°C. Notably, the frequency of localized heavy rainfall events has doubled over the past 20 years, aligning with climate change reports in Vietnam by MONRE (2020).

The results from the SLOPE/W model indicate that, under current climate conditions, the Factor of Safety (FS) for slopes ranges from 1.2 to 1.5, depending on soil type and slope gradient. Areas with clayey soil and highly weathered shale tend to have lower FS values (below 1.3), indicating a high risk of landslides. When rainfall increases by 20–30%, the FS significantly decreases, especially in areas with steep slopes (above 30°). For example, in Bát Xát commune (Lào Cai), the FS drops from 1.4 to 1.1 when rainfall increases by 25%. Rising temperatures also reduce soil moisture, leading to shrinkage and surface cracking, which weaken soil stability. However, this effect is less severe compared to the impact of increased rainfall.

This study also developed two climate change scenarios (RCP 4.5 and RCP 8.5) to project future landslide risks. Under the RCP 4.5 scenario (moderate emissions), rainfall is projected to increase by 15–20%, and temperature by 1.5°C by 2050, leading to an average FS reduction of approximately 10–15% and a 20–30% increase in landslide risk compared to the present. Meanwhile, under the RCP 8.5 scenario (high emissions), rainfall is expected to rise by 25–30%, and temperature by 2.5°C by 2050, resulting in an FS reduction of 20–25% and a 40–50% increase in landslide risk. These findings indicate that climate change will significantly escalate landslide hazards in the northern mountainous regions, particularly under the RCP 8.5 scenario.

Comparing these results with previous studies, the findings are consistent with those of Dahal and Hasegawa (2008), who identified rainfall as the most critical factor affecting slope stability. In Vietnam, the study by Nguyễn et al. (2019) also confirmed that landslides frequently occur following heavy rainfall events in the northern mountainous provinces. This study provides additional evidence of the impact of climate change on the frequency and intensity of extreme rainfall events, while also offering a scientific basis for disaster risk management.

Proposed solutions to mitigate the impact of climate change on slope stability and landslide risks in northern mountainous regions of Vietnam

Based on the analysis and research findings, several solutions are proposed to minimize the impact of climate change on slope stability and landslide risks in the northern mountainous regions of Vietnam.

First, slope reinforcement methods should be applied, including retaining walls, geotechnical grids, and sand piles to enhance slope stability. Additionally, improving surface and groundwater drainage systems will help reduce the impact of rainfall on slopes and limit the increase in pore water pressure. Monitoring technology should also be promoted, including the use of sensors, remote sensing, and GIS to track geological and climatic changes, enabling early detection of landslide risks.

In addition to technical solutions, biological measures play a crucial role in preventing landslides. The establishment of protective forests with deep-rooted native tree species will help stabilize the soil and reduce erosion risks. Furthermore, sustainable agricultural models should be encouraged to adapt to climate change and prevent excessive land exploitation on hillsides.

From a management and planning perspective, a landslide warning system should be developed based on weather data and forecasting models to provide timely alerts to residents and local authorities. Land-use planning should also be adjusted to restrict construction and resource exploitation in high-risk landslide areas while implementing environmental protection measures. Additionally, raising community awareness through training programs on landslide prevention and disaster response is a critical solution to minimizing disaster-related damages.

Although this study provides valuable insights into the impact of climate change on slope stability, some limitations need to be addressed in future research. Specifically, integrating artificial intelligence (AI) and machine learning models can improve the accuracy of landslide predictions. Moreover, analyzing rock and soil dynamics by incorporating factors such as earthquakes and traffic loads will offer a more comprehensive assessment of landslide risks. Expanding the scope of geological and hydro-meteorological data collection will further enhance the accuracy of simulation models.

IV. Conclusion

This study confirms that climate change is increasing landslide risks in the northern mountainous provinces of Vietnam. The results from the SLOPE/W model indicate that rising rainfall and temperature significantly reduce slope safety factors, particularly in steep terrain and highly weathered soil areas. These findings provide essential scientific evidence for disaster risk management policies and sustainable development planning in the context of escalating climate change.

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