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Research Article

Prediction of landslide hazard using LS-RAPID model: A case study in the Tia Dinh area (Dien Bien province, Vietnam)

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Abstract: Landslides represent a severe natural hazard, particularly in mountainous areas where steep slopes, intense rainfall, and unstable geological conditions frequently trigger destructive ground movements. This study focuses on assessing the potential landslides in Tia Dinh Commune, Dien Bien province, Vietnam, using the LS-RAPID model to simulate and predict potential hazards. By conducting extensive field surveys, geophysical measurements, and applying extreme-case scenario simulations, we identified three high-risk landslide zones (S1, S2, S3) alongside a larger area, zone S, which poses the most significant threat due to its potential for widespread and rapid material displacement. Despite challenges posed by limited geotechnical data in remote regions, the LS-RAPID model effectively predicted movement patterns, velocity, and impact zones of landslides, significantly improving our understanding of landslide dynamics. The results underscore the importance of integrating landslide risk assessments into local land-use planning to ensure safer community development. Additionally, we recommend the installation of groundwater monitoring devices at strategically identified locations within these high-risk zones to support early warning systems and enable timely preventive measures. Our findings highlight the need for a proactive approach to landslide risk management, combining prediction models with comprehensive monitoring strategies. This research provides a valuable framework for disaster preparedness, offering insights adaptable for regions facing similar landslide threats.

Keywords: Landslide hazard; LS-RAPID model; Tia Dinh commune.

1. Introduction

Landslides are among the most devastating natural disasters, particularly in mountainous regions where the convergence of steep slopes, heavy precipitation, and unstable geological conditions often triggers extensive ground movements [1, 2]. These events result in significant damage worldwide, affecting infrastructure, and agricultural lands, and posing severe threats to human safety [3, 4]. Notably, many landslides involve single mass movements characterized by long and wide flow paths, making them difficult to predict and leading to catastrophic consequences. A notable instance is the rock and ice avalanche from the north peak of Nevados Huascarán in Peru in 1970. This event resulted in a mass movement that traveled 16 kilometers, descending about 4,000 meters in elevation, with average speeds reaching 280 km/h, ultimately leading to the tragic loss of approximately

18,000 lives [5]. Similarly, on February 17, 2006, a rapid and long-runout landslide struck the southern part of Leyte Island, Philippines, where the debris flow extended over 1.5 kilometers, causing 154 confirmed fatalities and leaving 990 individuals missing [6].

In Vietnam, the risk of landslides is heightened by its rugged terrain, fractured geological structures, and intense seasonal rainfall, posing serious threats to communities and critical infrastructure [7, 8]. Many landslide incidents have combined with flash floods, impacting areas that extend over several kilometers. Examples include the events recorded in Phin Ngan Commune, Bat Xat District, Lao Cai Province in 2004 and 2016; in various communes of Phuoc Son and Nam Tra My districts, Quang Nam Province in 2020; and more recently in Lang Nu Village, Phuc Khanh Commune, Bao Yen District, Lao Cai Province. These occurrences underscore the destructive potential of landslides. Given landslides' sudden and volatile nature, developing robust prediction and risk management strategies is essential to mitigate their impact on vulnerable regions [9].

Engineering interventions, including retaining walls and slope reinforcements, are widely used to reduce landslide risks; however, these measures often come with significant financial and labor demands and are difficult to apply effectively over extensive areas. The repeated occurrence of landslides in Sichuan, China, highlights the limitations and challenges of structural mitigation approaches, especially in regions with complex and unstable geological landscapes. Despite considerable investments in preventative efforts, the area's vulnerability to seismic activity and variable weather patterns continue to fuel these recurring landslide events. Studies have shown that natural triggers such as earthquakes and intense rainfall are frequently responsible for initiating landslides, thereby complicating the efficiency of conventional engineering solutions in landslide control and management [10, 11].

Numerous dynamic models have been developed to simulate and analyze the runout behavior of landslide materials, including MADFlow [12], RASH3D [13], Particle Flow Code PFC3D [14], DAN3D [15], and the LS-RAPID model [16]. These models have proven to be highly effective in accurately predicting landslide initiation and progression when supported by comprehensive geotechnical data. However, their application is often limited due to the substantial requirement for extensive field data, detailed soil characterization, and meticulous model calibration, all of which can be resource-intensive processes [17]. Additionally, the variability of terrain in landslide-prone areas, marked by differing soil characteristics, rock formations, and hydrological conditions, presents a significant challenge in applying these models universally across diverse regions.

In situations where early indicators of instability, such as ground cracks or subsidence, are observed, the prompt use of predictive models becomes crucial in issuing early warnings and executing preventive measures. Extreme scenario modeling can effectively highlight high-risk areas, enabling timely interventions like evacuations or the enforcement of land-use regulations. The implementation of predictive models for assessing the impact of sliding material flows supports the generation of hazard maps, which play a key role in guiding land-use planning and enhancing disaster preparedness.

In this study, we employed the LS-RAPID model in Tia Dinh Commune to strengthen landslide risk management by simulating extreme-case scenarios. The LS-RAPID model is a 3D software capable of simulating the entire sequence of a landslide event (from identifying the initiation point to tracking the material flow's movement path). The LS-RAPID model has been applied extensively to simulate numerous landslide events worldwide [18–23], including in Vietnam [24, 25], helping to identify characteristics of landslide masses, such as triggering groundwater levels, material flow thickness, and affected areas. With its proven effectiveness, this model can accurately predict potential landslide movements, providing critical support for construction safety and preventive planning. By offering a rapid and cost-efficient approach to landslide forecasting, our research seeks to enhance the understanding of landslide dynamics in developing regions, ultimately contributing to the protection of lives and the reduction of economic losses in vulnerable communities.

2. Materials and Methods

2.1. Study area

Tia Dinh Commune, located in Dien Bien Dong district of Dien Bien province in northwestern Vietnam (Figures 1 and 2), lies within a mountainous area that has been identified as a paleo-landslide zone through geological and geomorphological studies, as well as remote sensing analysis. In recent years, the region (referred to as Area A) has shown signs of instability, with multiple ground cracks and subsidence occurring during heavy rainfall events, posing a significant threat to the safety of residents and their infrastructure. Some images of these cracks and subsidence were taken since 2019 and are presented in Figures 3-6. This includes critical structures such as the People's Committee office, health stations, schools, and more than 69 residential houses. Given the evident landslide risks, local authorities have begun the process of relocating the commune center to a safer, lower-lying area (area B) to mitigate potential hazards.

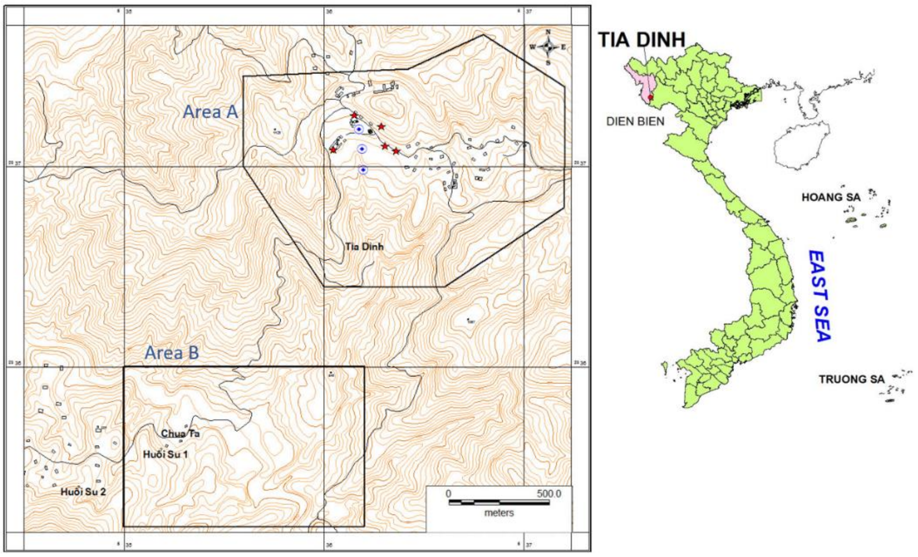

Figure 1. Study areas: The center of the Tia Dinh commune (Area A) and the proposed area for relocation (Area B).

The terrain of the study area is characterized by high mountains, with absolute peak elevations ranging from over 800 m to 1,200 m. In Area A, the terrain features a mixture of steep slopes and relatively rounded peaks. The central part of the commune exhibits distinct elevation levels, with the area above 960 m characterized by steep slopes, while the area below 960 m has significantly gentler slopes. Land cracking and subsidence phenomena are currently mainly observed within the boundaries of this terrain transition. In Area B, the terrain primarily consists of mountain ridges extending in a northeast-southwest direction, interspersed with short, gentle ravines forming part of the Na Hay stream valley. The mountain ridges in this area have relatively gentle slopes and peaks.

Concerning the geological characteristics, the area belonging to the Suoi Bang Formation (T_3n-rsb1) comprises sandstone, siltstone, mudstone, with minor sandstone-conglomerate, conglomerate, and breccia, showing a medium bedding structure. The formation dips southwest, with typical dip angles between 25 and 40 degrees. It belongs to the clastic sedimentary rock group, rich in aluminosilicates, characterized by weak cementation and high porosity. Near faults, the bedding orientation shifts to dip either southeast or northeast, with dip angles ranging from 60 to 80 degrees. Under humid tropical climate conditions, a thick weathering crust develops, resulting in significant thickness. An ancient landslide mass (Q) (Figure 2) was identified and delineated through topographic analysis combined with field investigation at a scale of 1:5,000, geophysical surveys, and borehole drilling. This landslide covers an area of approximately 15 hectares, extending about 800 meters in length and reaching a maximum width of 340 meters.

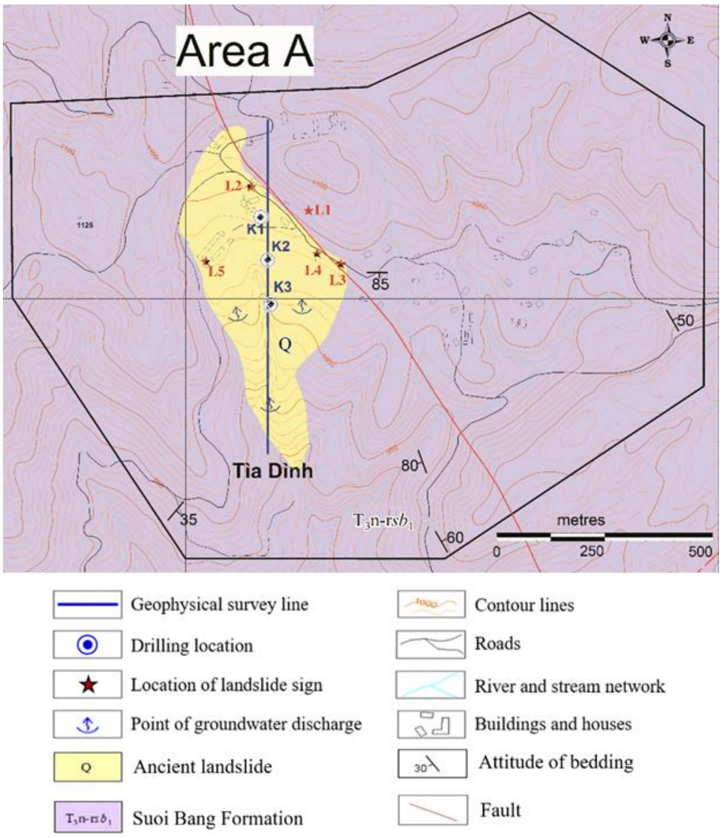

Figure 2. The center of the Tia Dinh commune (Area A).

Figure 3. Instability on the mountain slope (L1 in Figure 3) facing the office building of People's Committee.

Figure 4. Cracks appeared inside the office of the People's Committee (left) (L2 in Figure 3) and in a nearby house (right).

Figure 5. Cracks and subsidence on the foundations of Ms. Sung Thi Pa's house (left) (L3 in Figure 3) and Ms. Giang Thi Chu’s house (right) (L4 in Figure 3).

Figure 6. Damages at the primary school (L5 in Figure 3): In the classroom (left) and on the surrounding walls (right).

2.2. Methodology

The LS-RAPID model is a sophisticated tool designed to simulate and predict landslide-prone areas and assess their potential impact. It has demonstrated high accuracy in global applications, particularly when integrated with the undrained dynamic-loading ring-shear apparatus, yielding precise results in various regions. However, in Vietnam, where approximately 75% of the land consists of hilly or mountainous terrain, it is challenging to perform soil sample tests comprehensively across all landslide-susceptible zones due to constraints in resources and time.

Specifically, dealing with large and complex landslide masses poses difficulties, as combining parameters from different locations is often intricate. This complexity arises because physical models are generally more suitable for areas with uniform geological conditions. In regions already identified as at risk for landslides, it is crucial to explore simpler, more practical methodologies that can be rapidly deployed and adapted to predict hazardous zones effectively.

The fundamental concept behind this simulation approach can be visualized through Figure 1, which represents a vertical imaginary column within a moving landslide mass. The forces acting on this column include (1) its self-weight (W), (2) seismic forces (comprising vertical force Fv and horizontal forces Fx and Fy in the x-y direction), (3) lateral pressure on the side walls (P), (4) shear resistance at the base (R), (5) normal stress at the base (N) as a reaction from the stable ground due to the self-weight's normal component, and (6) pore pressure at the base (U). The landslide mass (m) experiences acceleration (a) due to the combined influence of these forces, which include the driving force (composed of self-weight and seismic forces), lateral pressure, and shear resistance.

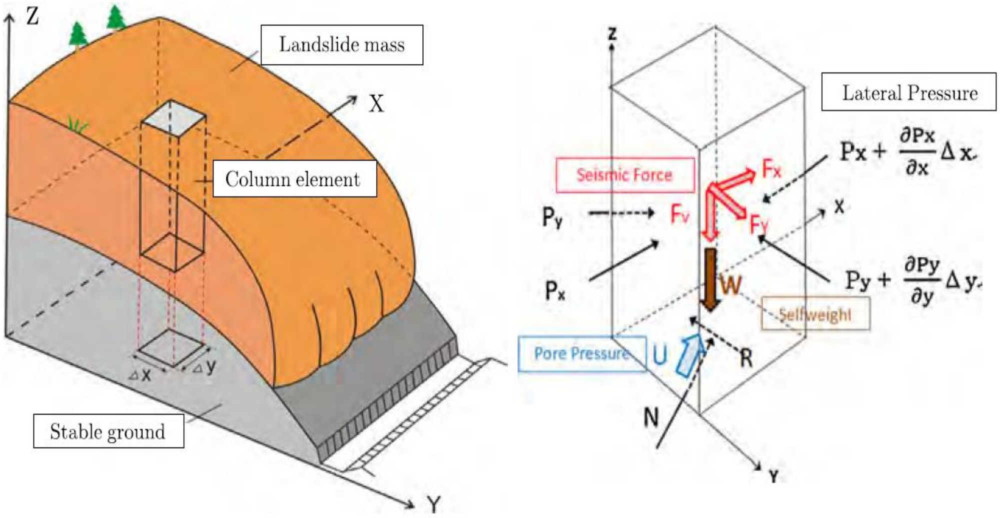

Figure 7. Core principles of the LS-RAPID model. On the left: a column element depicted within the moving landslide mass. On the right: the force equilibrium acting on the column is demonstrated [6].

In this study, the LS-RAPID model was utilized to predict potential landslide hazards, providing valuable insights for land-use planning and infrastructure development. Additionally, groundwater levels that could act as landslide triggers were assessed to enhance monitoring systems and enable early warnings before landslide occurrences. Several geotechnical parameters required for the LS-RAPID model were derived from soil sample analyses. However, due to the limitations in the available equipment in Vietnam, certain parameters could not be directly measured. In these cases, the extreme-case scenarios based on parameter suggestions from the model's developer or data from previous studies were employed to ensure a comprehensive risk assessment. The values of the model's key parameters are presented in Table 1, and detailed information about the parameters can be referred to in [16].

Table 1. The key parameters in LS-RAPID simulations were applied to the Tia Dinh area.

Parameters	**Value**	**Source**
Steady-state shear resistance (τ_{ss}, kPa)	5	Extreme value
Friction angle at peak (ϕ_p, degree)	20	Test data (average value)
Friction angle during motion (ϕ_m, degree)	20	Estimation based on ϕ_p
Cohesion at peak (c, kPa)	5	Extreme value
Shear displacement at the start of strength reduction (DL, mm)	6	Extreme value
Shear displacement at the start of steady state (DU, mm)	2500	Extreme value
Pore pressure generation rate (B_{ss})	0.8	Extreme value
Total unit weight of the mass (γ_t, kN/m^3)	20	Test data (average value)
Unit weight of water (γ_w, kN/m^3)	9.8	Standard value

The application process of the LS-RAPID model for predicting landslide hazards involves four key steps as follows:

(1) Data Collection and synthesize relevant information about the study area, including:

- Digital Elevation Model (DEM) data.
- Historical landslide traces and events, identified from satellite imagery and media reports.
- Previous measurement results conducted in the area.

- Research findings from previous applications of the LS-RAPID model, both within Vietnam and internationally.

(2) Field Survey:

- Identify and document visible signs of landslide activity.
- Investigate exposed sections to estimate the thickness of weathered layers (potential slip surfaces).
- Conduct geophysical measurements and drilling to determine the thickness of soil layers, if feasible.

The electrical resistivity sounding method was performed using a multi-electrode approach within a 2D model. Measurement points along each survey line were spaced 10 meters apart, following a dipole-dipole array configuration. Measurements were recorded using an electrical station equipped with a VIP 3000 transmitter and an Elrec Pro receiver by IRIS Instruments, delivering a transmission power of 3KW, with a maximum current of 10A and a peak output voltage of 1500V. For data analysis, we utilized Res2Dinv, a specialized software by Geotomo Software, which supports 2D quantitative analysis and includes terrain correction functions.

The results from the geophysical surveys reveal significant variations in geological units and structures, suggesting that geological features potentially influencing subsidence and landslide activities may extend to depths exceeding 20 meters. Accordingly, boreholes with depths of over 20 meters were drilled to further investigate these subsurface conditions

(3) Model Application: Implement the LS-RAPID model by delineating potential slip surfaces and simulating different scenarios using geotechnical parameters and groundwater levels. These scenarios should be based on both analytical results and data from previous studies.

In LS-RAPID model, the influence of groundwater levels on slope stability due to water rise is shown via the pore water pressure ratio r_u [6]:

$$r_u = \Delta u/\sigma \tag{1}$$

$$\Delta u = h \times \gamma_w \times \cos^2\alpha \tag{2}$$

$$\sigma = H \times \gamma_s \times \cos^2\alpha \tag{3}$$

where Δu: Pore water pressure exerted on the potential sliding surface (kPa); σ: Total normal stress exerted on the potential sliding surface (kPa); h, H: Water depth, soil depth (m); γ_w, γ_s: Unit weight of water, unit weight of soil (kN/m^3); α: Slope angle.

The value of r_u was incrementally adjusted to simulate scenarios of groundwater levels (from dry soil conditions to cases where groundwater levels are at ground level) and thereby predict the locations where landslides are most likely to initially occur.

(4) Report and Hazard Mapping:

- Develop a detailed report and forecast maps that include:
- Areas at risk of landslides and groundwater levels that could trigger such events (identifying locations where groundwater monitoring devices should be installed to support early warning systems).
- Predicted movement patterns of landslide materials (including impact range, average velocity, and thickness of the debris flow).

3. Results

3.1. Results of identifying potential high-risk landslides

Through comprehensive field surveys and analysis of drilling and geophysical data, the research team identified three high-potential landslide zones: S1, S2, and S3 (Figures 8 and 9), along with several other areas at risk. These zones together constitute the largest potential landslide, referred to as S. This extreme-case scenario envisions the simultaneous occurrence of landslides in all identified zones (S1, S2, S3) as well as other susceptible locations within Area A (Figure 10).

Landslide S1 (Figure 9a): This is the primary arc-shaped sliding surface that governs the movement of the central sliding block in Tia Dinh Commune. It originates from the mountain slope at an elevation of approximately 1070-1080 m. The arc's crest measures about 340 m in width, with the widest portion reaching nearly 400 m. The sliding surface aligns with the boundary between highly fractured rock layers and a significantly weathered zone or the old landslide material. The maximum thickness of the sliding surface in areas at high risk of landslides is estimated to be around 24 m. Cracks and subsidence features have been observed, with crack lengths ranging from a few meters to 30 m, widths up to 20 cm, and subsidence depths reaching up to 1.5 m in some locations.

Landslide S2 (Figure 9b): This large sliding surface is also located in the central area of Tia Dinh Commune. The crest of the sliding arc spans 300 m, with its widest section measuring 380 m. Landslide S2 lies entirely within the old landslide deposit, with its surface coinciding with the boundary between this material and either a highly weathered layer or fractured rocks. The sliding surface is situated approximately 12 m beneath the current terrain surface. Cracks and subsidence are frequently visible on both sides of the road, near the People's Committee office, and at the Primary School, with crack lengths ranging from a few meters to over 20 m and widths from a few centimeters to 10-15 cm. The observed subsidence varies between a few centimeters and up to 25-40 cm.

Landslide S3 (Figure 9c): This sliding surface is present in agricultural fields and around some fishponds, at elevations of 990-1015 m. The crest of this sliding surface measures 70 m, while its widest section reaches 130 m. It is situated within the old landslide material, with an estimated thickness of about 19 m. Signs of cracking and subsidence have been documented along the mountain slope, with lengths ranging from 15 to over 40 m and widths from a few centimeters to 10 cm. The subsidence depth mainly ranges from 20 to 80 cm, with some areas reaching depths of up to 150 cm. Groundwater discharge points are also observed near both the upper and lower sections of this sliding surface.

3.2. Result of LS-RAPID simulations

The LS-RAPID model has been applied to develop a comprehensive landslide risk map, highlighting areas vulnerable to landslide occurrence and their potential impacts by using extreme-case scenario parameters. The process involved generating a 3D model of the study area with a 5 m resolution digital elevation model, compiling detailed data from soil analysis, drilling results, and geophysical measurements, and determining the optimal parameter set

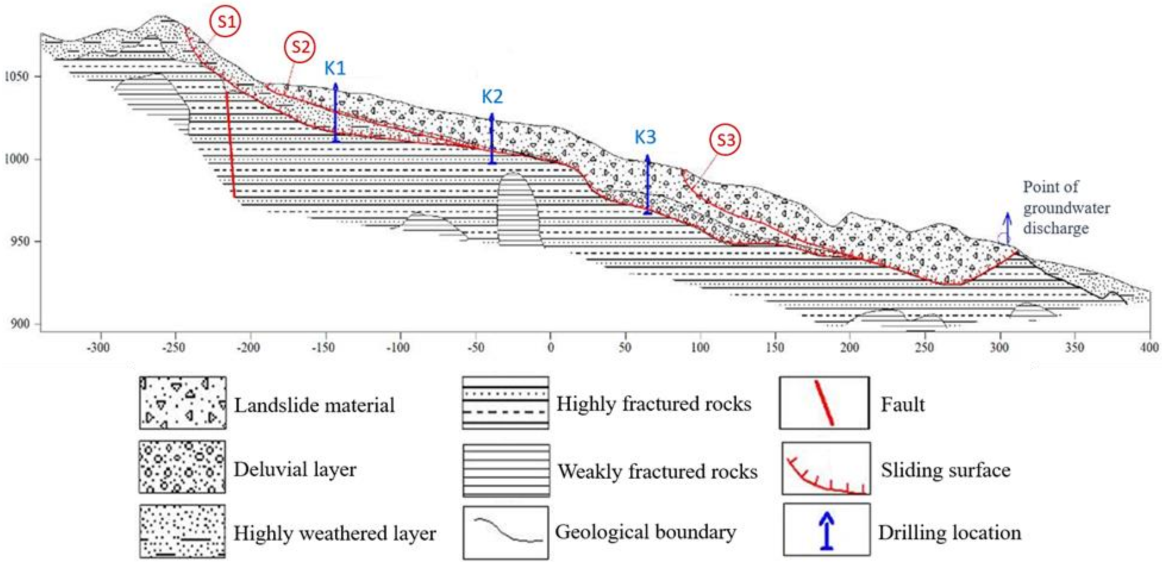

Figure 8. The potential landslides S1, S2, and S3 were determined based on the results of drilling, geophysical measurements, and field surveys.

for the model. The parameter set was based on either direct soil analysis results or extreme-case scenarios derived from recommendations provided by the model's author or from existing published studies. This approach ensures that the model is effectively calibrated to accurately predict landslide risks, taking into account the specific geotechnical conditions of the study area.

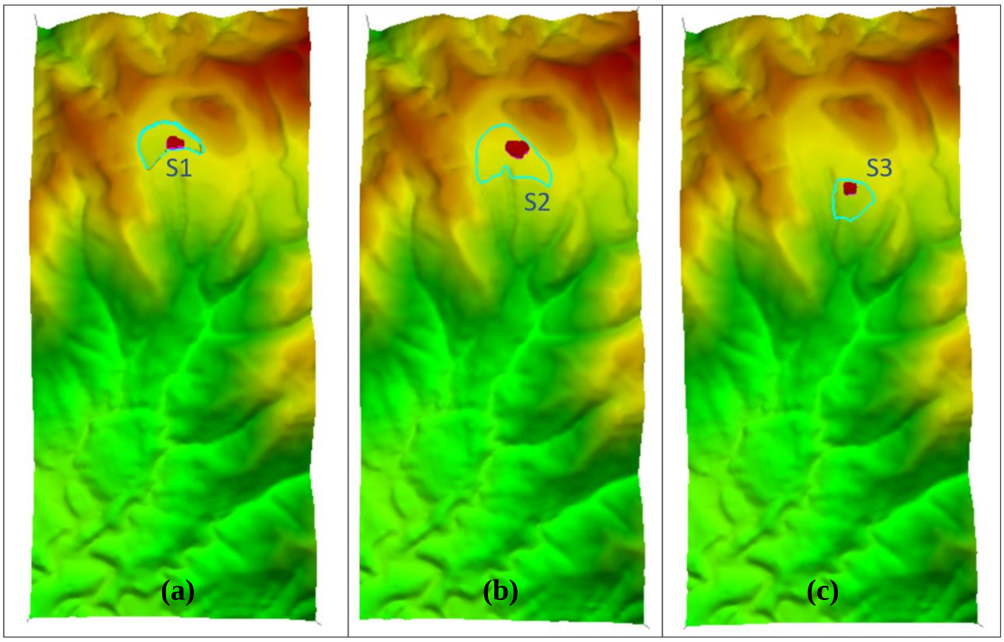

Figure 9. Predicted landslides (S1, S2, S3) (cyan color) and the locations with high potential for initiation (the red blocks inside). The area outside the cyan boundaries represents the elevation of the terrain, which ranges from green to red.

Figure 9 shows three predicted landslides (outlined in green lines) are S1 (a), S2 (b), and S3 (c), with high-risk locations where landslides could initiate (the red blocks inside).

The groundwater levels that are predicted to induce landslides S1, S2, S3 at the potential surfaces:

- Landslide S1 could occur when the groundwater level on the landslide surface is 4.9 m or higher (19.1 m or less from the ground).
- Landslide S2 could occur when the groundwater level on the landslide surface is 2.5 m or higher (9.5 m or less from the ground).
- Landslide S3 could occur when the groundwater level on the landslide surface is 5 m or higher (14 m or less from the ground).

The suggested sites for installing water level monitoring devices, to provide early warnings of landslides, are the locations where the initiation of landslides is predicted (indicated by the red blocks in Figure 9).

The potential hazard of the largest landslide, denoted as S, was simulated for the extreme-case scenario in area A (Figure 10). Figures 10 and 11 present the results of the LS-RAPID model simulations, illustrating the material movement of landslide S originating from area A. The model assumed an average sliding surface thickness of 22 m, consistent with the predicted potential landslides in the region. The simulation forecasted a possible flow path of the landslide material extending over 1.9 km, with a maximum thickness exceeding 40 m. The width of the material flow path progressively narrowed from 370 m at the top of the slope to 50 m at its terminus. Some of the landslide material can travel at high speeds, reaching Area B in just over 2 minutes. This highlights the immediate threat posed to Area B by the fast-moving debris, even as the landslide continues to unfold over a longer period. This indicates that the initial phase of the landslide is extremely fast, posing an immediate threat to area B, even while the rest of the landslide continues to move more slowly over a longer period.

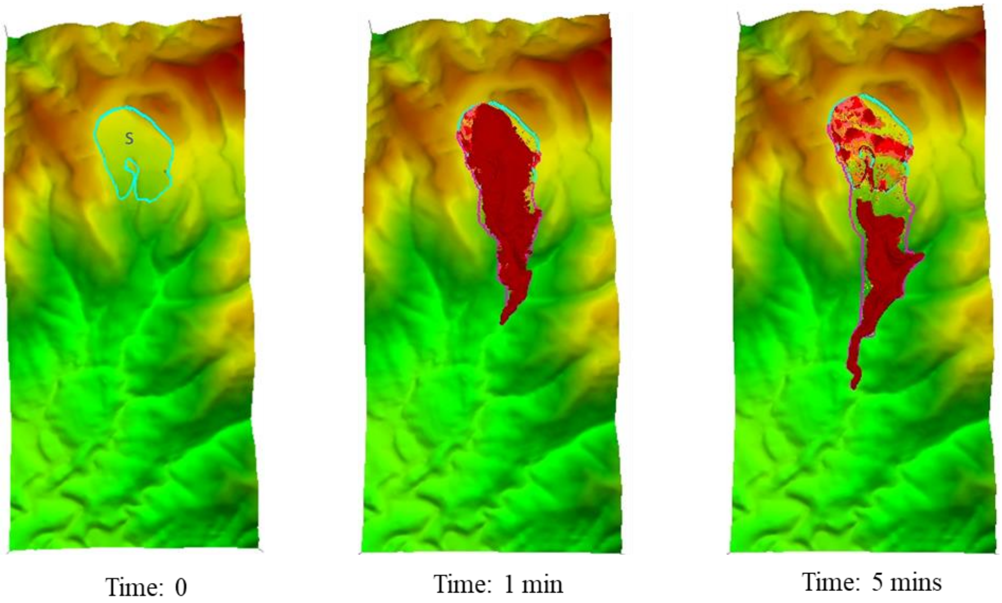

Figure 10. The simulation result of the LS-RAPID model for the movement of landslide S (the cyan color). The purple boundary indicates the range of impact of the sliding material over time, with the red blocks inside representing the masses of sliding material. The area outside the purple and cyan boundaries represents the elevation of the terrain, which ranges from green to red.

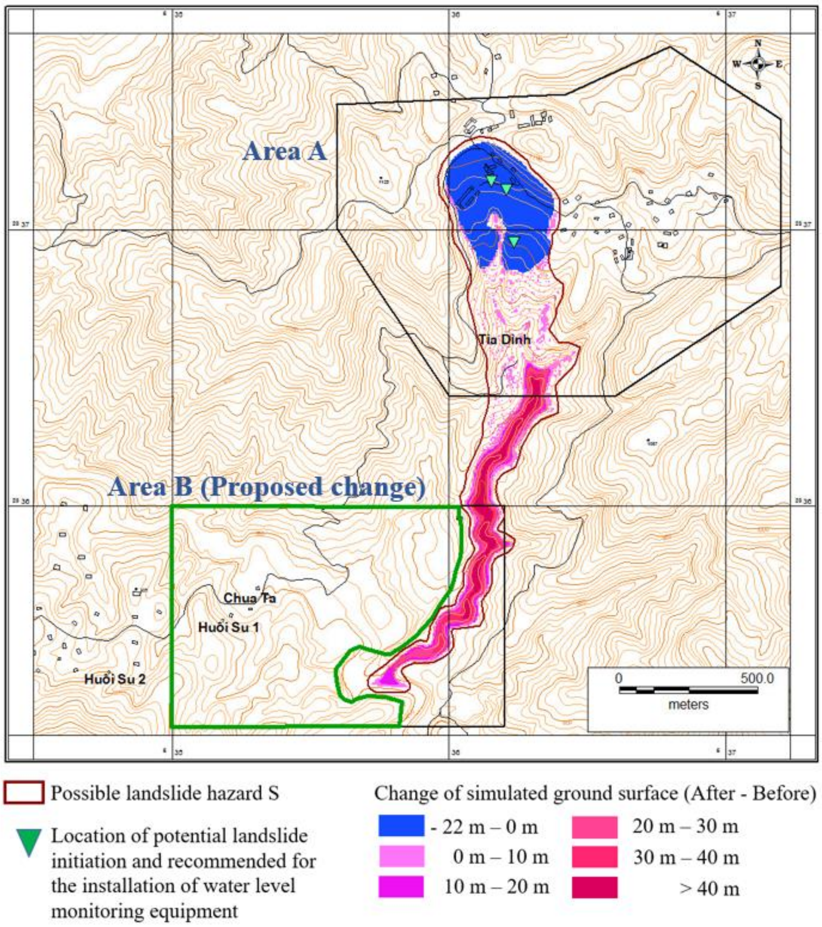

Figure 11. Map of possible landslide hazard S and proposed change for Area B. The red boundary area represents the range of impact from sliding materials, where changes in the topography (post-slide versus pre-slide) are indicated from blue (decreased) to red (increased).

Based on the simulation results, it is recommended to adjust the eastern boundary of area B to mitigate potential impacts from sliding material originating from area A. While the western boundary has been assessed as stable and suitable for further research and possible expansion of the resettlement area, the northern and southern regions appear currently safe from major landslide events. However, additional investigations are advised for these areas to ensure comprehensive risk assessment and mitigation in future developments. Furthermore, considering the potential risk from area A's landslide materials impacting Tia Dinh Commune, local authorities should adopt land-use strategies that prioritize safety. Specifically, high-risk areas might be more suitable for long-term tree planting or agricultural uses rather than residential or public infrastructure development.

Physical models, including the LS-RAPID model, are often praised for their precision in assessing landslide risks and impact extents. However, their applicability tends to be limited to smaller, geologically uniform areas. In larger regions with multiple potential landslide surfaces, geological parameters can vary significantly, which makes it challenging to select a representative sample for the entire area.

To better predict landslide-prone zones for effective land-use planning, the LS-RAPID model was employed using an extreme-case scenario approach for geological parameters. Although this method may not provide an exact simulation of hazard areas, it tends to overestimate the affected zones, thereby ensuring greater safety margins. This approach also offers significant cost and time savings, making it particularly suitable for application in remote mountainous regions of Vietnam. Additionally, if the thickness of the landslide mass can be estimated, the LS-RAPID model can be used to determine the minimum groundwater level required to trigger landslides. Identifying this critical activation level is essential for developing reliable landslide monitoring and early warning systems, thereby enhancing the region's preparedness against such natural hazards.

4. Conclusions

This study has demonstrated the effectiveness of applying the LS-RAPID model for landslide risk prediction in Tia Dinh Commune, Vietnam. Through comprehensive field surveys, soil analysis, and extreme-case scenario simulations, we identified three high-risk landslide zones (S1, S2, S3) within the study area, as well as the larger potential landslide zone S. The results indicate that the movement of landslide material in zone S could spread rapidly, posing immediate threats to both the existing resettlement area and the proposed relocation site, highlighting the need for urgent risk management measures.

The LS-RAPID model has proven to be a valuable tool in accurately simulating landslide dynamics, providing crucial insights into potential flow paths, velocities, and impact ranges of landslides. However, the accuracy of the model heavily depends on the availability of detailed geotechnical data. In regions like Vietnam, where data collection is often limited, there is a need for innovative approaches to estimate geological parameters more effectively.

To enhance early warning capabilities, this study recommends installing groundwater monitoring devices at critical locations identified in zones S1, S2, and S3. These positions were selected based on their potential to trigger landslides when groundwater levels reach specific thresholds. Continuous monitoring at these sites will be essential for issuing timely alerts, enabling preventive actions such as evacuations or structural reinforcements before landslide events occur.

The findings of this study also highlight the importance of incorporating landslide risk assessments into local land-use planning. High-risk areas, including the broader zone S, should be prioritized for non-residential uses, such as reforestation or agriculture, to minimize potential damage to infrastructure and human lives.

This study contributes significantly to the understanding of landslide dynamics in Tia Dinh Commune, providing a framework for effective risk management strategies that can be adapted to other landslide-prone regions in developing areas. Implementing these strategies, along with the establishment of a robust groundwater monitoring network, will be essential in enhancing community safety and mitigating the devastating impacts of landslides.

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