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RESEARCH ON THE CHARACTERISTICS OF SHALLOW LANDSLIDES AND THEIR EFFECTS ON ROAD EMBANKMENT STABILITY IN THE NORTHWESTERN MOUNTAINOUS REGION.

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SUMMARY OF DOCTORAL DISSERTATION

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INTRODUCTION

1. Research rationale

In the context of climate change, with heavy and extreme rainfall becoming increasingly frequent, landslides are becoming a common and dangerous geological hazard in the mountainous areas of Vietnam. Under prolonged rainfall, the weathered soil layer becomes saturated, which reduces its shear strength and causes slope instability, leading to the formation of shallow landslides. In the Northwest mountainous region (NWMR), with its steep terrain, complex geology and well-developed network of ephemeral gullies, shallow landslides frequently damage the roadbed and pavement and the drainage system, and disrupt traffic.

Although numerous studies on landslides have been conducted, in-depth studies on the characteristics of shallow landslides and their influence on the roadbed stability of mountain roads remain limited. Therefore, the research topic "*Study on the characteristics of shallow landslides and their influence on roadbed stability in the Northwest mountainous region*" is of high scientific and practical significance.

2. Research objectives

To clarify the characteristics and mechanisms of shallow landslides and to assess their direct and indirect influences on the roadbed stability of roads in the NWMR. On this basis, to propose engineering solutions to reduce the likelihood of roadbed damage and failure during heavy rainfall.

3. Research subject and scope

3.1. Research subject

The research object is shallow landslides, as defined by the classification systems currently in common use worldwide, occurring on the cut slopes of roads in the NWMR.

3.2. Research scope

The spatial scope is the NWMR (according to the Vietnam Geographical Atlas 2024, comprising the former Hoa Binh province, Son La, Dien Bien, Lai Chau, Lao Cai and the former Yen Bai province), with a focus on existing national highways (QL) and provincial roads (DT). The typical study route is Provincial Road DT128, Lai Chau province, within which the 20-km-long Chan Nua – Sin Ho section is investigated in detail.

4. Research content

(1) Survey and analysis of landslide characteristics along selected roads in the NWMR; (2) development of a landslide susceptibility zonation map along Road DT128; (3) analysis of the characteristics and mechanisms of shallow landslides along the section studied in detail; (4) analysis of the direct and indirect influences of shallow landslides on roadbed stability along the typical section, and proposal of engineering mitigation measures.

5. Research methods

The dissertation employs an integrated set of research methods, comprising: collection, processing and analysis of geological and landslide data; field investigation and surveying; application of GIS and remote sensing, and of AI using deep learning models evaluated by statistical metrics; laboratory testing (physico-mechanical properties, chemical composition and mineral composition of soils); GeoStudio (SEEP/W and SLOPE/W modules) for the seepage–slope stability problem, and RAMMS for debris flows along ephemeral gully channels; and the expert method.

6. Scientific and practical significance

Scientific significance: The dissertation supplements the general database on shallow landslides and an AI-based approach to landslide susceptibility zonation for the existing road network of the NWMR. It also clarifies the characteristics and mechanisms of shallow landslides and evaluates the relationships among shallow landslides, heavy rainfall and roadbed stability under terrain conditions where ephemeral gullies cross the road.

Practical value: The dissertation provides scientifically grounded material to support the management and maintenance of roads in the NWMR with similar topographic and geological conditions, and to serve their upgrading and rehabilitation; it also proposes engineering solutions that can be applied in practice to reduce the damage caused by shallow landslides.

7. Dissertation structure

In addition to the Introduction and the Conclusions, the dissertation consists of four chapters:

Chapter 1: Review of Shallow Landslide Research

Chapter 2: Theoretical basis of the research

Chapter 3: Landslides along roads in the Northwest mountainous

region and characteristics of shallow landslides along the typical study route

Chapter 4: Shallow landslides and roadbed stability along the typical study section

CHAPTER 1
REVIEW OF RESEARCH ON SHALLOW LANDSLIDES

1.1. Landslides and their classification

1.1.1. Concept and causative factors of Landslides

According to Varnes (1978, 1984) [178, 179], Cruden (1991) [65] and Cruden and Varnes (1996) [66], a landslide is a phenomenon in which a mass of soil, rock or a mixture of both loses stability and moves from the slope towards its toe under the action of gravity; it occurs when the equilibrium between the resisting forces and the driving forces is disrupted.

According to Le Duc An (2008) [1], landslide causative factors are divided into two main groups: permanently acting factors, such as geological, topographic and climatic conditions and human activities; and instantaneous factors, such as earthquakes, extreme heavy rainfall, blasting or reservoir flood releases.

1.1.2. Classification of Landslide

Landslides vary in mechanism, scale and conditions of occurrence and are therefore classified according to various criteria, such as the depth of the slip surface, the size of the sliding mass, the material involved and the movement mechanism. In this dissertation, the classification by slip surface depth proposed by Xavarenxky (1934) [190] is used as the main basis for studying shallow landslides (with depths of approximately 1–5 m) along roads in the NWMR.

1.2. Overview of research on Shallow Landslide

1.2.1. Research on Shallow Landslide worldwide

Worldwide, landslide susceptibility mapping has been conducted since the early stages of geotechnical research, employing a variety of methods that have progressively advanced with the support of GIS, remote sensing, and artificial intelligence. Machine learning and deep learning models such as SVM, RF, ANN, CNN, and RNN have been widely applied owing to their ability to effectively process spatial data and improve landslide susceptibility prediction accuracy.

Numerous studies have confirmed that heavy rainfall and infiltration processes are the primary triggering mechanisms of shallow landslides. Prolonged rainfall increases pore-water pressure, reduces soil shear strength, and leads to slope instability. Studies by Wang and Sassa (2003)

[163] and Li et al. (2022) [105] have clearly demonstrated the role of rainfall in shallow landslide triggering mechanisms. In addition, topographic, geological, and vegetation cover factors also exert significant influence on the formation and development of shallow landslides.

Beyond susceptibility assessment, some recent studies have also focused on predicting landslide volume. Tuganishuri et al. (2025) [156] demonstrated that an XGBoost model is capable of predicting rainfall-induced shallow landslide volumes with high accuracy ($R^2 \approx 0.88$).

1.2.2. Research on Shallow Landslide in Vietnam

In Vietnam, landslides along roads have been studied in Quang Nam and Quang Binh, and along QL4D, the Ho Chi Minh Road, QL6, QL32, etc.; recently, many research groups have applied machine learning and deep learning to susceptibility zonation. Huynh Thanh Binh (2023) [2] conducted flume tests under rainfall intensities exceeding 100 mm/h lasting several days and divided the development of shallow landslides into five stages according to the evolution of pore-water pressure.

1.3. Outstanding issues in research on shallow landslides along roads in the mountainous areas of Vietnam

Regarding shallow landslides on the existing mountain road network of Vietnam, the dissertation identifies the following issues that have not yet been clarified: (i) the region-specific nature of the relationships among shallow landslides, topography, geology and roadbed stability; (ii) the direct and indirect influences of shallow landslides on the stability of the roadbed and of structures along the route have not been quantitatively considered, particularly in terrain dissected by ephemeral gullies that carry temporary flows during heavy rainfall; (iii) prevention and mitigation solutions have not been considered holistically in relation to the topographic, geological, hydrological and economic conditions of each region; (iv) there is a lack of a database on shallow landslides on the mountain road network; (v) there is a lack of integrated studies combining susceptibility zonation with modern tools for spatial screening and in-depth studies of shallow landslide characteristics and mechanisms, whereas selecting the section for detailed study on the basis of subjective experience entails the risk of overlooking high-susceptibility areas.

On this basis, the dissertation uses AI-based landslide susceptibility zonation as a route-scale spatial screening step, providing an objective basis for selecting the section for detailed study. Two main tasks are then carried out: analysis of the characteristics and mechanisms of shallow landslides, and assessment of the influence of shallow landslides on roadbed stability.

CHAPTER 2
THEORETICAL BASIS OF THE RESEARCH

2.1. Landslide hazard zonation using artificial Intelligence (AI)

2.1.1. Theoretical basis of the AI models used in the research

The dissertation uses four deep learning models. The convolutional neural network (CNN) exploits the local spatial structure of the stack of multi-channel raster map layers; the deep neural network (DNN) models the global nonlinear relationships among the features at each pixel; the recurrent neural network (RNN) and the long short-term memory (LSTM) network were originally designed for sequential data, with LSTM adding a gating mechanism to retain information over long sequences. The analysis indicates that CNN is suited to the raster nature of the data in the spatial zonation problem, whereas RNN and LSTM are better suited to time series such as rainfall series.

2.1.2. Performance evaluation of the AI models

he performance of the AI models is evaluated using statistical metrics, including TP, TN, FP, FN, PPV, NPV, sensitivity (SST), specificity (SPF), accuracy (ACC), Kappa, RMSE, the ROC curve and the area under the curve (AUC). To interpret the predictions, SHAP analysis based on Shapley values [182] is used. SHAP values quantify the contribution of each factor to the model prediction; they reflect the statistical relationships learned by the model and are not equivalent to a direct physical causal role in slope instability.

2.2. Simulation of ephemeral flow intensity with loose materials from Shallow Landslides

2.2.1. Nature of water flows carrying loose debris

After a landslide occurs, the loose debris, together with rainwater, forms a debris flow with high velocity, high kinetic energy and great destructive potential.

2.2.2. Models for simulating the intensity of water flows carrying loose debris

Commonly used simulation models include depth-averaged hydraulic models, the Herschel–Bulkley model, the Voellmy–Salm model and two-phase models. Among these, the Voellmy–Salm model is widely applied owing to its ability to simulate the motion of debris flows well through two friction parameters, μ and ξ.

2.2.3. Simulation of flow Intensity with loose materials using RAMMS

The RAMMS software is based on the Voellmy–Salm model and simulates the motion of debris flows using the system of depth-averaged

mass and momentum conservation equations. In this model, the flow resistance comprises two main components, the basal friction μ and the turbulent–viscous friction ξ, which allows the effects of both the solid and fluid phases during debris flow propagation to be represented simultaneously.

2.3. Slope stability analysis using numerical modelling

2.3.1. Theoretical basis of seepage analysis using SEEP/W

The SEEP/W module is based on the extended Darcy's law to simulate unsaturated seepage. The model uses the finite element method to analyse the spatial and temporal changes in pore-water pressure and in the seepage field under rainfall, thereby assessing the influence of the seepage process on slope stability.

2.3.2. Soil–Water characteristic curve (SWCC)

The SWCC describes the relationship between the soil water content and matric suction in unsaturated soil. As no direct tests were available, the SWCC was determined indirectly from the grain-size distribution curve following Arya and Paris (1981) [37].

2.3.3. Limit equilibrium theory and Bishop's method for slope stability analysis

To assess slope stability under rainfall and time-varying saturation conditions, the Bishop limit equilibrium method is used to calculate slope stability in terms of the factor of safety FS, which represents the ratio of the resisting forces to the driving forces. A slope is stable when $FS > 1$ and unstable when $FS < 1$.

2.4. Theoretical basis for analyzing the effects of Shallow Landslides on Roadbed stability

2.4.1. Effects of Shallow Landslides on pavement quality

The dissertation systematizes three typical types of pavement distress associated with shallow landslides: localized depressions (caused by accumulated landslide debris, impact, and water infiltration when side ditches are blocked, leading to subsurface erosion of the roadbed), pavement edge cracking (when the valley-side slope becomes unstable) and surface ravelling (caused by water ingress, which weakens the bond between the bitumen and the aggregate).

2.4.2. Effects of Shallow Landslides on drainage systems

With respect to the drainage system, shallow landslides fill side ditches and block cross culverts, causing water to overflow across the pavement, subsurface erosion and erosion of the valley-side slope; when the flow additionally carries loose debris from shallow landslides upslope, its dynamic impact can crack and displace culvert structures and destroy the

roadbed. These impacts form a cascading chain from the loss of drainage efficiency to damage to the pavement and roadbed and sliding of the valley-side slope.

CHAPTER 3
LANDSLIDES ALONG ROADS IN THE NORTHWEST MOUNTAINOUS REGION AND CHARACTERISTICS OF SHALLOW LANDSLIDES ALONG THE TYPICAL STUDY ROUTE

3.1. Landslides along roads in the NWMR of Vietnam

3.1.1. Natural characteristics of the NWMR of Vietnam

The Northwest is the mountainous region in the northwest of Vietnam, comprising the former Hoa Binh province, Son La, Dien Bien, Lai Chau, Lao Cai and the former Yen Bai province, with high, strongly dissected terrain and many large mountain ranges. The region has a tropical monsoon climate with a long rainy season and high rainfall, commonly about (2,400–3,000) mm/year and exceeding 4,000 mm/year in many places.

3.1.2. Investigation of the current state of landslides along roads in the NWMR

The NWMR is a high, rugged mountainous area with steep, strongly dissected slopes. It has a tropical monsoon climate, with mean annual rainfall commonly of (2,400–3,000) mm, reaching up to 4,692 mm at the rainfall centres of Lai Chau and Dien Bien; 24-hour rainfall may exceed 100 mm. A field survey of the current state was conducted from March to June 2023 on eight routes: QL12, QL4H and DT128 (Lai Chau); QL4G, QL37 and QL6 (Son La – Hoa Binh); and QL4D and QL279 (Lao Cai), with a total length of 397 km. The locations and dimensions of the landslides were determined using handheld GPS, laser rangefinders and measuring tapes, and were cross-checked against the DEM. The survey recorded 643 landslides of various types, of which 594 were shallow landslides (Table 3.1).

Table 3.1. Landslide density and proportion of shallow landslides along the surveyed routes

Province	Route	Length (km)	No. of landslides	No. of shallow landslides	Density (landslides/km)	Proportion of shallow landslides (%)
Lai Chau	DT128	90.0	294	284	3.27	96.6
	QL4H	40.6	101	95	2.49	94.1
	QL12	52.0	48	42	0.92	87.5
	Total/Mean	*182.6*	*443*	*421*	*2.23*	*92.73*
Son La	QL4G	45.6	31	29	0.68	93.5

Province	Route	Length (km)	No. of landslides	No. of shallow landslides	Density (landslides/km)	Proportion of shallow landslides (%)
	QL37	30.5	50	47	1.64	94.0
	QL6	50.8	34	26	0.67	76.5
	Total/Mean	*126.9*	*115*	*102*	*0.99*	*88.0*
Lao Cai	QL279	44.0	38	31	0.86	81.6
	QL4D	43.7	47	40	1.08	85.1
	Total/Mean	*87.7*	*85*	*71*	*0.97*	*83.35*

Landslide density ranges from 0.67 landslides/km (QL6) to 3.27 landslides/km (DT128), and the proportion of shallow landslides ranges from 76.5% (QL6) to 96.6% (DT128). By province, the mean proportion of shallow landslides is 83.35% (Lao Cai), 88.0% (Son La) and 92.73% (Lai Chau). Road DT128 in Lai Chau province has the highest density and the highest proportion of shallow landslides (3.27 landslides/km; 96.6%). The route has steep slopes of (30–45)° and elevations above 900 m, and lies close to the Lai Chau – Dien Bien fault zone. Its geological setting, with strongly foliated rock formations and interbedded schist, limestone and argillaceous limestone, closely resembles that of the main landslide-prone areas of the NWMR. Road DT128 was selected as the typical study route.

3.2. Landslide susceptibility zonation along Road DT128, Lai Chau province, using artificial intelligence

3.2.1. Natural Conditions of the Study Area

Road DT128 passes through an area of steep, strongly dissected terrain that is typical of the NWMR. The study area is underlain mainly by the Ben Khe, Sinh Vinh, Bo Hieng, Nam Pia and Yen Chau formations, composed mainly of schist, sandstone, quartzite and limestone, and is affected by major fault zones such as the Song Da and Dien Bien – Lai Chau fault zones.

The mean annual rainfall over the period 2010–2024 is approximately 2,271.8 mm/year, concentrated mainly in June and July. Together with the dense network of rivers, streams and ephemeral gullies and the steep terrain, these are favourable conditions for the occurrence of shallow landslides.

The vegetation along the route comprises natural forest, shrubs, grassland and agricultural land; however, the reduction in forest area due to logging and cultivation has increased landslide susceptibility in the study area.

3.2.2. Database used for landslide susceptibility zonation along the typical study route

Landslide data were collected within a 500-m-wide strip along the route from the survey in March 2023, records of the transport management agency

of Lai Chau province, and supplementary surveys in 2024 and 2025, yielding a total of 294 landslides along the entire route (Figure 3.1). Fourteen conditioning factors were selected: elevation, slope, curvature, aspect, topographic wetness index (TWI), stream power index (SPI) and flow accumulation (derived from the 12.5-m USGS digital elevation model, DEM); the vegetation index NDVI (Sentinel-2 imagery); mean annual rainfall and maximum 24-hour rainfall; geology and distance to faults (1:200,000-scale maps); and distance to roads and distance to rivers and streams. All layers were brought to a common 12.5-m grid. Pearson correlation analysis with a threshold of ±0.7 led to the removal of the distance-to-roads factor, leaving 13 factors as model inputs.

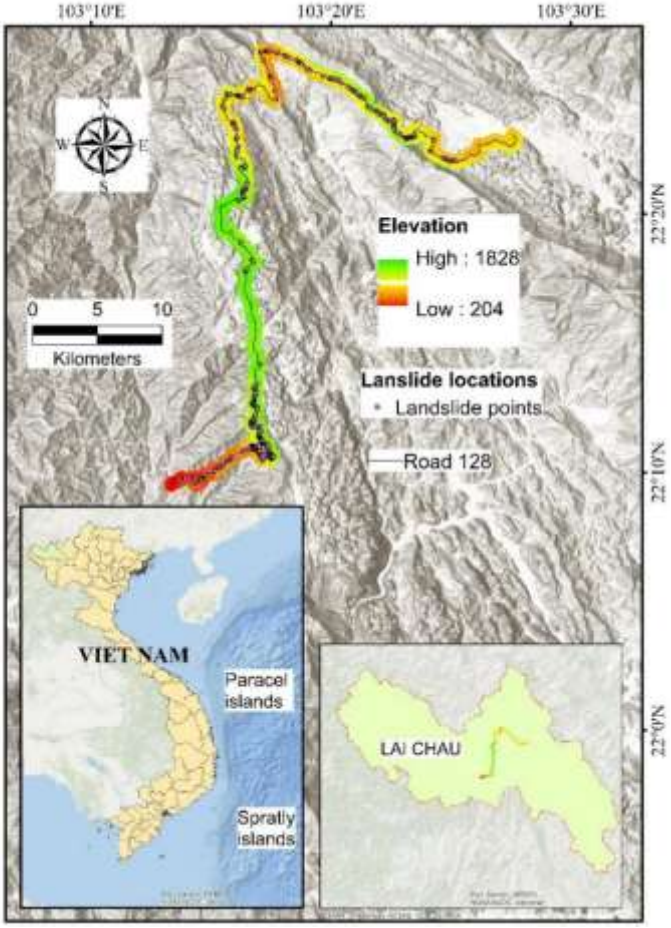


Figure 3.1. Location of the area and landslide points

3.2.3. Methodology of Landslide susceptibility mapping of the study area

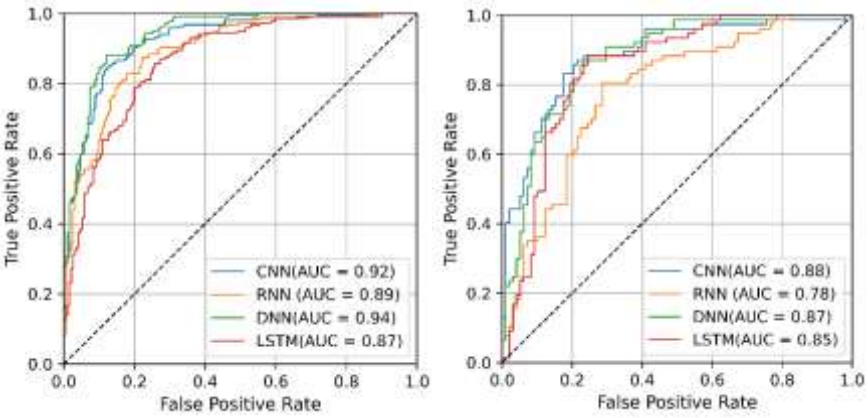
The research procedure comprises six steps: (1) compilation of data on the 294 landslides and 13 factors, harmonized to a (12.5 × 12.5) m grid in ArcGIS; (2) division of the landslide points into 70% (206 samples) for training and 30% (88 samples) for validation, together with 294 non-landslide points as control samples; (3) construction and training of the four models CNN, DNN, RNN and LSTM; (4) performance evaluation using the metrics described in Section 2.1; (5) production of a five-class susceptibility map using the best-performing model; and (6) validation of the map using landslide points not used in training.

3.2.4. Results of Landslide susceptibility mapping of the study area

Table 3.2. Prediction performance of AI models

Metric	Training Phase				Validation Phase			
	CNN	**RNN**	**DNN**	**LSTM**	**CNN**	**RNN**	**DNN**	**LSTM**
TP	165	175	166	134	82	84	78	64
TN	181	104	190	189	58	34	61	68
FP	26	16	25	57	16	14	20	34
FN	35	112	26	27	19	43	16	9
PPV (%)	86.39	91.62	86.91	70.16	83.67	85.71	79.59	65.31
NPV (%)	83.80	48.15	87.96	87.50	75.32	44.16	79.22	88.31
SST (%)	82.50	60.98	86.46	83.23	81.19	66.14	82.98	87.67
SPF (%)	87.44	86.67	88.37	76.83	78.38	70.83	75.31	66.67
ACC (%)	85.01	68.55	87.47	79.36	80.00	67.43	79.43	75.43
Kappa	0.700	0.386	0.748	0.582	0.592	0.310	0.585	0.518
RMSE	0.148	0.310	0.125	0.206	0.200	0.326	0.206	0.245

In the training phase, DNN achieved the highest ACC (87.47%), Kappa (0.748) and AUC (0.94) and the lowest RMSE (0.125); CNN ranked second (ACC 85.01%, Kappa 0.700, AUC 0.92). In the validation phase, CNN achieved the highest ACC (80.00%), Kappa (0.592) and AUC (0.88) and the lowest RMSE (0.200); DNN achieved an ACC of 79.43% and an AUC of 0.87; LSTM achieved an ACC of 75.43% and an AUC of 0.85; and RNN performed worst, with an ACC of 67.43%, a Kappa of 0.310 and an AUC of 0.78 (Table 3.2, Figure 3.2).



(a) Training phase *(b) Validation phase*

Figure 3.3. AUC analysis of the models used in the study

Considering both phases, CNN provides balanced and stable performance and was selected for producing the zonation map.

SHAP analysis (Figure 3.3) shows that the vegetation index (mean SHAP value 0.23) and slope (0.11) make the largest statistical contributions to the model predictions, followed by geology (0.06) and curvature (0.03); the remaining factors, including maximum rainfall and mean annual rainfall (0.02), make low contributions when considered individually. These values reflect statistical correlations between the input factors and the predictions and are not equivalent to a direct physical causal role in slope instability. The low contribution of the rainfall factors arises mainly because the rainfall data represent long-term climatic conditions, are divided into few classes (2–4 classes) and exhibit little spatial variation within the narrow route corridor; it does not imply that rainfall plays a minor triggering role. The vegetation index and slope are predisposing factors, whereas prolonged heavy rainfall is the triggering factor that determines the timing of landslides.

The CNN-based zonation map is divided into five classes: very low (0–0.121), low (0.121–0.293), moderate (0.293–0.519), high (0.519–0.742) and very high (0.742–1). The analysis shows that approximately 42% of the length of the study route lies in zones of very low landslide susceptibility. Of the remainder, 29%, 11%, 10% and 8% of the route length are classified as low, moderate, high and very high susceptibility, respectively (Figure 3.4).

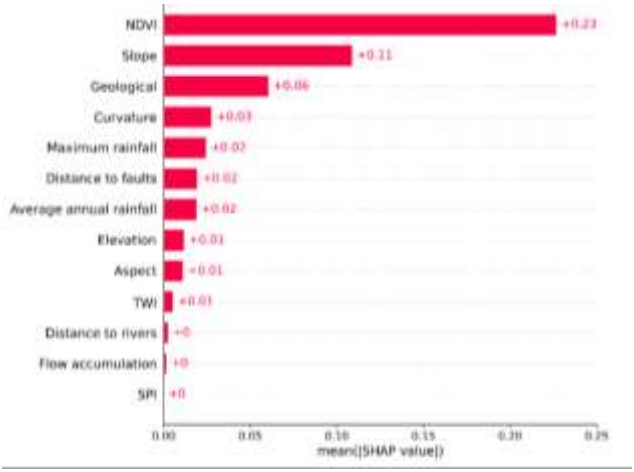


Figure 3.3. SHAP factor importance

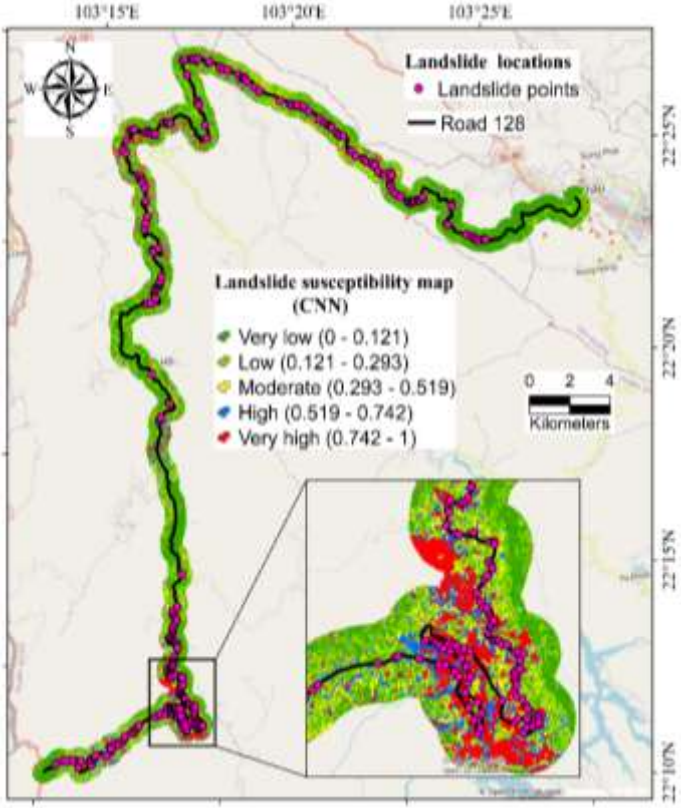


Figure 3.4. Landslide susceptibility map for route DT128

3.3. Shallow Landslide characteristics of the Chan Nua – Sin Ho segment of Route DT128

3.3.1. Current status of Shallow Landslides on the Chan Nua – Sin Ho segment

The field survey conducted in March 2024 recorded 74 landslides. According to the Xavarenxky classification, these comprise 2 surficial landslides, 69 shallow landslides (slip surface depth < 5 m) and 3 deep-seated landslides, with shallow landslides accounting for 93.25%.

Shallow landslides are distributed across most of the geological formations along the route, with a mean density of 3.45 landslides/km. The Bo Hieng Formation hosts the largest number of shallow landslides (34, or 49.3%), whereas the lower subformation of the Ben Khe Formation has the highest density, at 5.5 landslides/km.

The landslides are mainly small (29.0%) to medium (50.7%) in size. The most common type is planar (translational) sliding, accounting for 76.81%, whereas rotational sliding accounts for 21.74% and typically occurs in areas with a thick weathered overburden.

The landslide masses are predominantly arc-shaped (68.1%) and are concentrated in the Bo Hieng and Ben Khe formations. Landslides higher than 10 m account for the majority (66.7%) and occur on slopes of (30–40)°, reflecting the close relationship among steep terrain, intensely weathered geology and the occurrence of shallow landslides.

The slip surfaces are mainly near-planar (76.81%). Some landslides have curved or stepped slip surfaces, but these account for an insignificant proportion.

Within the Bo Hieng Formation (10.7 km along the route), the survey recorded six outcrops (TD1–TD6) marking lithological changes among limestone, marl, shale, sandstone and siltstone, with a weathered layer of clayey siltstone material containing rock fragments; these variations are not shown on the 1:200,000-scale map. On this basis, the dissertation compiled a 1:20,000-scale engineering geological sketch map showing the 69 shallow landslides and selected eight representative locations for constructing detailed cross-sections.

3.3.2. Relationship between rainfall and Shallow Landslides

Statistics of shallow landslide events over the period 2019–2024 show that shallow landslides are closely associated with the rainy season. Landslides recur at many locations, typically at km17+250 (approximately 25,000 m^3 on 28 August 2019 and 15,500 m^3 on 8 August 2023). Most events occurred when daily rainfall ranged from moderate to heavy, within

(30–100) mm; the dissertation proposes this range as the rainfall threshold range for triggering shallow landslides in the study area.

3.3.3. Characteristics of Shallow Landslides on the Chan Nua – Sin Ho segment

Of the 69 shallow landslides, overburden soil was sampled at 32 sites for testing of physico-mechanical properties, and samples from six locations representative of the formations were analysed for chemical and mineral composition. The overburden consists mainly of clay and loam containing fragments of weathered clayey siltstone or schist together with gravel, with a hard to semi-hard consistency. It is of residual (eluvial) origin, locally colluvial; its layering is indistinct, and it is heterogeneous both vertically and along the route.

In terms of mineralogy, mica (muscovite + illite + phlogopite) accounts for (43–65)%, quartz (19–36)% and kaolinite (5–17)%. Chemically, SiO_2 accounts for (44.5–61.8)%, Al_2O_3 for (19.8–23.5)% and Fe_2O_3 for (5.9–10.2)%. These results were compared with studies on the effect of mica on shear strength [159], [131], according to which the reduction in shear strength already becomes pronounced at mica contents above (10–20)%, particularly when the soil is saturated.

The fines content ($D < 0.08$ mm) ranges from 54.4% to 82.2% (mean 65.1%), comprising clay-size particles ($D < 0.002$ mm) of (10.6–38.0)% (mean 19.3%) and silt-size particles of (33.8–56.0)% (mean 45.8%). The grain-size distribution curves are relatively uniform in shape, reflecting in situ weathering origin. The liquid limit WL, plastic limit WP and plasticity index IP lie within (25–60)%, (14–32)% and (11–28)%, respectively. The saturated hydraulic conductivity at the three locations DT128-22, DT128-37 and DT128-60 is 1.10×10^{-5}, 0.97×10^{-5} and 0.83×10^{-5} m/s, respectively. The overburden soil is dominated by fines, is clay-rich, has a high water-retention capacity and readily loses shear strength upon saturation; these properties are consistent with the high density of shallow landslides and the recurrence of landsliding in the Bo Hieng Formation.

CHAPTER 4

SHALLOW LANDSLIDES AND ROAD STABILITY ALONG THE TYPICAL STUDY SECTION

4.1. Current state of the Chan Nua – Sin Ho section of Route DT128

The 20-km-long section is a Grade IV mountain road (TCVN 4054-2005), with a roadbed width of 7.5 m, a pavement width of 5.5 m and shoulders of at least 1.0 m (of which 0.5 m is hardened). The cut slopes have slope ratios of m = 0.75 and m = 1, and the pavement consists of asphalt

concrete on a graded crushed-stone base course. The drainage system comprises concrete or masonry side ditches, catch pits and cross culverts; (1.5 × 1.5) m box culverts are installed at the drainage gullies at km14+100 and km11+800. The ditches are frequently silted up and broken, and culvert inlets become blocked when landslide debris is deposited. The measures implemented to date (a gabion wall at km17+250, dredging and repair of ditches, and pavement patching) are mainly short-term restoration measures.

4.2. Analysis of Shallow Landslides by numerical modelling

Three cross-sections, DT128-22, DT128-37 and DT128-60, were selected because they represent the geological–geotechnical conditions of the Bo Hieng and Ben Khe formations, have morphological data, UAV-derived topographic data and soil samples, and lie within high or very high susceptibility zones according to Section 3.2. The 2D cross-sections were constructed from a UAV-derived DEM and consist of layer 1 (residual soil) and layer 2 (rock); the overburden thickness is (6–8) m. The main assumptions are as follows: (i) as no tests to determine the effective parameters (c′, φ′) were available, the c and φ values from direct shear tests were used as representative shear strength parameters, and the results are therefore used mainly to analyse trends in stability; (ii) the parameters of layer 2 were adopted with reference to TCVN 11823-2017; (iii) the SWCC and the hydraulic conductivity function were determined indirectly from the grain-size distribution; (iv) owing to the lack of monitoring data, the initial groundwater table was assumed to be deep, near the bottom of the cross-section. The boundary condition is the continuous rainfall series from 2 to 7 August 2023 based on GPM satellite data, with rainfall of (16–37) mm/day, immediately preceding the landslide event of 8 August 2023.

Table 4.1. Summary of the physico-mechanical properties of the soils

Cross-section	Soil layer	γ (kN/m^3)	c (kPa)	φ (^{0})	K (m/s)
DT128-22	Lớp 1	18	5.0	34.0	1.10 x 10^{-5}
	Lớp 2	25	50	18.8	
DT128-37	Lớp 1	17	5.0	34.0	0.97 x 10^{-5}
	Lớp 2	25	50	18.8	
DT128-60	Lớp 1	17.5	10	26.0	0.83 x 10^{-5}
	Lớp 2	25	50	18.8	

Slope stability was calculated for two cases: the initial condition before the rainfall series, i.e. before any rainfall, and the condition after the rainfall series, i.e. after the soil had been subjected to the rainfall series. The results for cross-section DT128-37 are presented in Figures 4.1 and 4.2. The calculated factors of safety FS are summarized in Table 4.2.

Table 4.2. Summary of the calculation results

Cross-section	Case	FS	Assessment
DT128-22	Initial condition before the rainfall series	1,038	Stable
	Condition after the rainfall series	0,941	Unstable
DT128-37	Initial condition before the rainfall series	1,034	Stable
	Condition after the rainfall series	0,969	Unstable
DT128-60	Initial condition before the rainfall series	1,048	Stable
	Condition after the rainfall series	0,991	Unstable

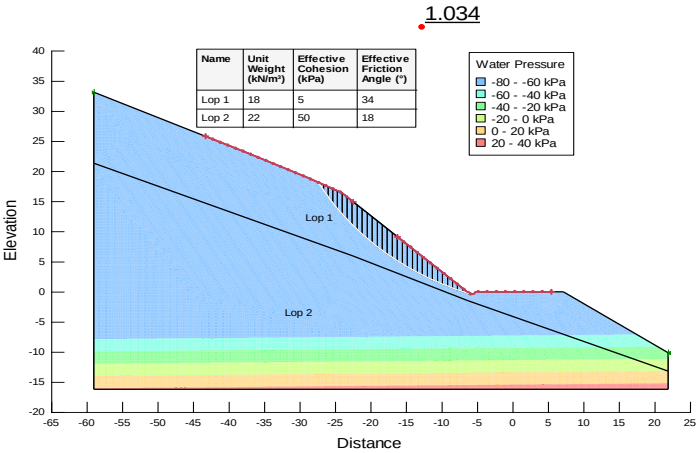


Figure 4.1. Factor of safety under the initial condition before the rainfall series, cross-section DT128-37

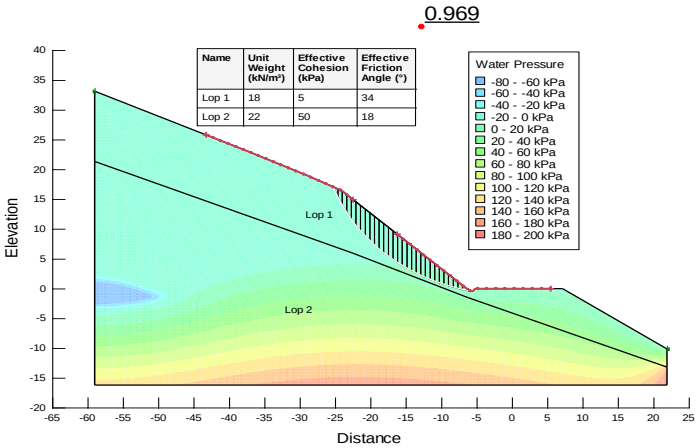


Figure 4.2. Factor of safety under the condition after the rainfall series, cross-section DT128-37

Before the rainfall series, the overburden was mainly unsaturated, with the degree of saturation Sr commonly (0.4–0.6); negative pore-water pressures of (−80 to 0) kPa, corresponding to matric suction of (0–80) kPa, contributed to maintaining shear strength. After the rainfall series, Sr increased to commonly (0.90–0.98), locally ≥ 0.995; the negative pore-water pressure zone contracted, the uw = 0 boundary rose, and positive pore-water pressures in the deeper zone increased, reaching (160–180) kPa in some areas of cross-section DT128-37. The factor of safety decreased from FS = (1.034–1.048) to FS = (0.941–0.991) (Table 4.2, Figure 4.1, Figure 4.2); the critical slip surface lies within the weathered overburden at a depth of approximately (2–5) m, which is consistent with the shallow landslides observed in the field. At DT128-22 and DT128-37, FS fell below 1 when Sr had commonly reached only (0.95–0.98); that is, failure may occur before the entire overburden becomes fully saturated. At DT128-60 (with a gentler slope), some zones reached Sr ≥ 0.995 when FS < 1. The simulation results indicate that the shallow landslide mechanism is mainly attributable to prolonged rainfall reducing matric suction and increasing the degree of saturation and pore-water pressure, which leads to a reduction in shear strength; this trend is consistent with the studies of Huynh Thanh Binh (2023) [2] and Luong Nguyen Hoang Phuong et al. (2023) [24].

4.3. Effects of Shallow Landslides on pavement condition and the drainage system

4.3.1. Effects of Shallow Landslides on pavement condition

When shallow landslides bury the pavement and side ditches, rainwater ponds on or overflows across the pavement, increasing damage to the pavement structure. The survey recorded 45 locations of pavement damage associated with the 69 shallow landslides, among which surface ravelling accounts for the largest proportion (65.2%), while depressions and edge cracking each account for 2.9%.

4.3.2. Effects of Shallow Landslides on the drainage systems

Shallow landslides cause siltation of side ditches, blockage of cross culverts and destruction of ditch structures. The investigation at the 69 shallow landslides found that 100% of them buried the side ditches and 35 (50.7%) damaged the ditch structures.

4.4. Numerical simulation of surface flow in the ephemeral gully with loose debris from Shallow Landslides

4.4.1. Characteristics of ephemeral gullies along the typical study route

The studied ephemeral gully crosses Road DT128 at four locations: No. 1 (km17+250), No. 2 (km14+100), No. 3 (km11+800) and No. 4

(km10+300, where the roadbed was destroyed and replaced by a bridge). From the gully head to the bridge, the gully channel is approximately 1.29 km long, with the elevation decreasing from 1,495 m to 965.5 m, and comprises four segments with lengths of 202.04 m, 522.72 m, 355.75 m and 210.09 m and average gradients of 65%, 25%, 50% and 98%, respectively. Along the catchment, there are more than 10 locations that have experienced landslides or are prone to further sliding; the shallow landslides in the upper reaches (km17+250) are regarded as the source of loose debris.

4.4.2. Heavy rainfall and Shallow Landslides in the studied gully catchment

Analysis of the rainfall evolution (GPM data, cross-checked against stations in the region) over the month preceding the four shallow landslide events at km17+250 (28 August 2019, 17 August 2020, 5 May 2021 and 8 August 2023) shows that all four events were preceded by a period of antecedent rainfall before the triggering rainfall: cumulative rainfall of approximately (80–300) mm, typically over a period of more than (12–14) days, with the landslide occurring on the day of, or immediately after, a sudden heavy rainfall. None of the events was caused by an isolated heavy rainfall alone. This result is consistent with the matric suction reduction mechanism obtained from the SEEP/W simulation in Section 4.2, in which the event of 8 August 2023 was used as the boundary condition.

4.4.3. History of road instability at km10+300 on the ephemeral gully flow path

At km10+300, the roadbed and cross culvert (completed at the end of 2006) operated normally until December 2017, while the vegetation cover of the catchment was still dense and the km17+250 shallow landslide had not yet occurred. From the rainy-season floods of 2018 onwards, shallow landslides developed in the upper reaches and vegetation cover declined; satellite images from 2017–2023 show that the landslide area evolved from a fan shape (elevation 1,495–1,580 m) into a branched landslide system with numerous erosion rills. The debris-laden flow destroyed the roadbed at km10+300, leading to the construction of a reinforced concrete (RC) bridge, which was put into service in December 2021.

4.4.4. Numerical analysis of roadbed stability on the ephemeral gully flow path with loose debris from shallow landslides

The topography was represented by a 2.0-m-resolution DEM acquired by UAV in January 2024. The release zone was defined as the zone where material from successive shallow landslides converges at the gully head (slope of approximately 45°), with two scenarios of material thickness, H

= 10 m and H = 15 m. The initial values $\mu = 0.1$ (estimated from $\mu \approx \tan 6° \approx 0.105$ for the deposition zone) and $\xi = 200$ m/s² (viscous mud flow, consistent with a fines-rich overburden) were calibrated using a trial grid ($\mu \pm 0.05$; $\xi \pm 50$ m/s²) against the deposition heights observed at location No. 3 (3–4 m) and at the bridge (2–3 m). The best-fitting parameter sets are $\mu = 0.15$, $\xi = 200$ m/s² (H = 10 m) and $\mu = 0.2$, $\xi = 250$ m/s² (H = 15 m). A sensitivity analysis with H = 10 m, $\mu = 0.10$–0.25 and $\xi = 200$–350 m/s² yielded velocities at the bridge of (7.5–9.1) m/s and pressures of (190–221) kPa, i.e. variations of (14.0–17.6)% over the entire parameter space examined and (2.0–3.8)% in the vicinity of the calibrated parameter set.

Table 4.3. RAMMS simulation results at the four locations where the ephemeral gully crosses Road DT128

Parameter	Unit	No. 1		No. 2		No. 3		No. 4 (Bridge)	
		H=10m	H=15m	H=10m	H=15m	H=10m	H=15m	H=10m	H=15m
Maximum deposition height	m	8	10	5.6	8.5	3.5	4.5	2.5	3.5
Maximum velocity	m/s	18	16.5	7.5	4.6	10	6	8	7.5
Maximum pressure	kPa	674	560	70	30	161	130	200	184
Time	s	15	15	70	75	135	170	175	210

To evaluate the results, the dissertation refers to pressure thresholds reported in other studies: the roadbed begins to be damaged at pressures of 30 kPa, and the probability of local failure increases significantly above 50 kPa [137]; 100 kPa has been proposed as the failure threshold for roadbeds without protection measures [114] and as the critical threshold for severe damage to robust structures such as box culverts and bridge abutments [182]. The dissertation adopts approximately 100 kPa as the critical reference threshold. Comparison with Table 4.3 shows the following. At location No. 1, the pressures of 674 kPa and 560 kPa and velocities of 18 m/s and 16.5 m/s far exceed the threshold, consistent with the repeated destruction of the roadbed observed since 2018. At location No. 2, the pressure is only (30–70) kPa; field observations show that this location is less affected because the segment between locations No. 1 and No. 2 (gradient 25%) dissipates the kinetic energy. At location No. 3, the pressures of 161 kPa and 130 kPa exceed the threshold; blockage of the cross culvert, partial damage to the roadbed and burial of the pavement have been recorded in practice. At the km10+300 bridge, the pressures of 200 kPa and 184 kPa, velocities of (7.5–8) m/s and deposition heights of (2.5–3.5) m are sufficient to destroy the protective soil and rock layer

around the abutment and pier foundations and to cause channel bed erosion, consistent with the erosion observed since 2022.

4.4.5. Shallow Landslides, ephemeral gully flows during heavy rainfall and the stability of the km10+300 bridge

After the bridge was put into service, the km17+250 shallow landslide continued to reactivate (particularly on 8 August 2023), supplying material to the channel flow and causing erosion, slumping of the slope beneath the bridge and of the downstream valley-side slope, damage to the protection structure of abutment M1, and settlement and cracking of the pavement behind the abutment. A survey in November 2024, following the floods of August–September 2024, recorded deep channel erosion, exposure of the base of the retaining wall in front of abutment M1, exposure of the pile cap of pier T1 and a transverse crack in a bored pile of pier T1. Since February 2024, traffic on the bridge has been restricted during the rainy and storm season; since August 2025, according to a notice issued by the Lai Chau Department of Transport, the bridge has been closed to cars and is open only to motorcycles and pedestrians.

4.5 Analysis of damage to typical structures caused by ephemeral flows carrying loose debris from shallow landslides within the typical study area

The assessment is based on the actual events associated with a single shallow landslide (km17+250). At location No. 1, the roadbed was destroyed and buried over a length of approximately 60 m, with approximately 10,000 m^3 of soil and rock to be cleared; at location No. 2, approximately 3,000 m^3; and at location No. 3, approximately 2,000 m^3, with ravelling of the pavement. The km10+300 bridge is assessed as difficult to repair because the cost would be equivalent to new construction; it would need to be replaced by a new bridge with approximately 2 km of approach roads, or the road would need to be relocated to a new alignment (15–17) km long. Based on the construction investment unit costs (Decision No. 816/QĐ-BXD dated 22 August 2024) and current regulations, the total damage is estimated at approximately VND 180 billion, of which construction costs account for VND 153.6 billion. Human casualties, vehicle losses and losses due to traffic disruption are not considered in the dissertation.

4.6. Proposed solutions to mitigate the impact of shallow landslides on the stability of mountain roadbeds in characteristically dissected terrain

4.6.1. Group of solutions for preventing Shallow Landslides

Given that instability is caused by increased pore-water pressure and reduced matric suction, solutions for preventing shallow landslides should

integrate drainage (crest ditches, stepped chutes, inclined drainage boreholes), deep reinforcement and surface protection. The dissertation proposes eight solutions divided into two groups. The conventional structural group comprises soil nails combined with an RC frame, with a surface anti-erosion layer consisting of: (1) masonry; (2) shotcrete; (3) precast concrete panels with or without grass-planting holes; or (4) conventional grass planting. The eco-engineering new-technology group comprises: (5) soil nails and an RC frame, with or without steel mesh, with sprayed mud mixed with grass seeds; (6) the same as (5), but with a sprayed mixture of grass seeds and binder (hydroseeding); (7) soil nails, an RC frame, steel mesh and a high-strength polymer 3D erosion-control mat; and (8) soil nails combined with high-strength steel mesh integrated with a 3D erosion-control mat, replacing the RC frame. Reference parameters: borehole diameter of approximately 110 mm, ribbed steel bars of (25–40) mm with cement grout injection, a nail length of 7.5 m, and frame cells ranging from (2 × 2) m to (3 × 3) m.

4.6.2. Group of measures for retaining loose debris from Shallow Landslides in the gully catchment to reduce the kinetic energy of ephemeral flows

To reduce the kinetic energy of ephemeral flows in the gully, the dissertation proposes two measures for retaining loose debris: (1) gabion walls with drainage openings, using PVC-coated, zinc–aluminium-coated steel gabions, with the gabion tiers arranged discontinuously, leaving a 50-cm gap every 2 m to drain water and retain coarse particles; this structure has been implemented in segments 2 and 3 of the studied gully since October 2024, has shown initial effectiveness in reducing the impact of the channel flow on the roadbed, and has been widely applied; and (2) high-strength steel wire mesh fences (minimum ultimate tensile strength of 1,770 MPa), placed behind the gabion walls to retain smaller-sized material. These solutions remain at the level of conceptual proposals and the identification of the basis for design loads.

4.7. Chapter 4 remarks

Shallow landslides affect the roadbed through two mechanisms: directly, through burial and damage to the pavement and the drainage system; and indirectly, by supplying loose debris that increases the kinetic energy of flows in ephemeral gullies. Within the scope of the stated assumptions, the results of the SEEP/W–SLOPE/W and RAMMS simulations are consistent with the observed damage and provide the basis for the proposed groups of solutions.

CONCLUSIONS AND RECOMMENDATIONS

1. Main Conclusions

Based on statistics of 643 landslides along national highways and provincial roads (397 km) in the NWMR, shallow landslides were identified as the predominant type of instability of roadway cut slopes, accounting for 88.02%. Road DT128 (Lai Chau) has the highest density and the highest proportion of shallow landslides (3.27 landslides/km; 96.6%) and is representative of the topographic, geological, tectonic and vegetation characteristics of the NWMR; it was therefore selected as the typical study route.

On the basis of 294 landslides and 13 conditioning factors along Road DT128, four deep learning models (CNN, RNN, DNN, LSTM) were developed to predict landslide susceptibility. CNN achieved the highest performance in the validation phase (AUC 0.88; ACC 80%; training AUC 0.92) and was used to produce the zonation map. Of the route extent, 18% falls into the high and very high susceptibility classes; the 20-km-long Chan Nua – Sin Ho section was selected for detailed study.

Along the typical section, 69 of the 74 landslides are shallow landslides (93.25%), concentrated in the Bo Hieng Formation (49.3%); medium-sized landslides account for 50.7%; landslide heights commonly exceed 10 m (66.7%); landslides occur mainly on slopes of (30–40)° (58.0%); and the slip surfaces are mainly near-planar (76.81%). The overburden soil is a weathered, mica-rich clay (mica content (43–65)%), with a fines content of (54.4–82.2)% and a plasticity index IP = (11–28)%.

Coupled SEEP/W and SLOPE/W simulations show that shallow landslides are mainly caused by prolonged rainfall reducing matric suction and increasing the degree of saturation and pore-water pressure in the weathered overburden, which results in a reduction in shear strength.

Shallow landslides on the upslope cut slopes both directly damage the roadbed and pavement (surface ravelling 65.2%; ditch damage 50.7%; burial by soil and rock at 100% of the landslides) and act as a source of loose debris that increases the kinetic energy of flows in drainage gullies. RAMMS simulations yield flow pressures at location No. 1, location No. 3 and the km10+300 bridge that exceed the reference threshold of 100 kPa, consistent with the damage and destruction recorded.

The dissertation proposes eight engineering solutions for preventing shallow landslides and two measures for retaining loose debris. According to the dissertation, these solutions have a scientific basis for wider

application to roads in the NWMR with conditions similar to those of Road DT128, after detailed design and further verification.

2. New contributions of the dissertation

Based on the landslide inventory established through field surveys and statistical analyses along several major transportation routes in the Northwestern mountainous region of Vietnam, shallow landslides were found to account for 83.35% - 92.73% of the recorded landslides.

The causes and characteristics of shallow landslides were clarified in relation to geological and geotechnical factors.

The direct and indirect effects of shallow landslides on pavement damage and road embankment stability were analyzed, with particular emphasis on the Chan Nua–Sin Ho section of Provincial Road 128.

3. Limitations of the dissertation

The conclusions are specific to Road DT128 (Lai Chau). Compared with studies of rainfall-induced shallow landslides in regions with a similar climate (Durmaz et al., 2023), the two-stage mechanism of antecedent rainfall followed by triggering rainfall shows similarities; however, the fines-rich and heterogeneous overburden is a distinguishing feature, so the results require calibration and verification when applied to other areas. The zonation model uses a 12.5-m DEM and a 1:200,000-scale geological map, which do not fully reflect the detailed conditions along the narrow route corridor; the sample size of 294 landslides over 90 km is limited and entails a risk of local overfitting. The SEEP/W–SLOPE/W model is simplified to 2D and uses daily rainfall; the c and φ parameters obtained from unconsolidated quick direct shear tests (TCVN 4199:1995) reflect total stresses and are not c′ and φ′; and the initial groundwater table is assumed. The RAMMS model is based on two field verification locations and assumes homogeneous material, without considering material layering. The proposed solutions remain at the conceptual level and have not yet undergone detailed engineering design or structural verification.

4. Recommendations

Integrate landslide susceptibility zonation maps into route planning and the design of new roads; give full consideration to engineering geological factors, the weathered overburden and drainage gullies in investigation, design and route alignment selection; strengthen inspection and maintenance of the drainage system, slope reinforcement and control of loose debris in ephemeral gullies in areas of high shallow landslide susceptibility along Road DT128, especially during the rainy season; establish a monitoring and early warning system based on multi-day

cumulative rainfall; and invest in upgrading baseline data (high-resolution DEMs from LiDAR and UAV, and detailed engineering geological maps).

5. Directions for further research

Extend the survey and assessment of shallow landslides to other mountain roads with similar conditions to verify the results; incorporate hourly rainfall data and simulate multiple rainfall intensity–duration scenarios to establish threshold curves for early warning; incorporate high-resolution DEMs and large-scale engineering geological maps to improve the reliability of the zonation maps; conduct consolidated slow direct shear tests or CD triaxial tests to determine c′ and φ′, and install piezometers to monitor the groundwater table; and test the field performance of the proposed solutions and integrate a shallow landslide monitoring and early warning system.

LIST OF PUBLISHED SCIENTIFIC WORKS

1. **Nguyen Viet Tiep***, Nguyen Duc Manh, Mai Sy Hung, Some characteristics of shallow cut slope sliding on mountain road embankments in the Northern mountainous region, Proceedings of the National Scientific Conference VIETGEO 2023, 574–582, 2023.

2. **Tiep Nguyen Viet**, Dam Duc Nguyen, Manh Nguyen Duc*, Cong Cao Trong, Mai Sy Hung, Hiep Van Le, Indra Prakash, Binh Thai Pham*, Exploring deep learning models for roadside landslide prediction: Insights and implications from comparative analysis, *Physics and Chemistry of the Earth*, 2024, https://doi.org/10.1016/j.pce.2024.103741

3. Duc-Dam Nguyen, **Nguyen Viet Tiep***, Quynh-Anh Thi Bui, Hiep Van Le, Indra Prakash, Romulus Costache, Manish Pandey, Binh Thai Pham, Landslide Susceptibility Mapping Using RBFN-Based Ensemble Machine Learning Models, *Computer Modeling in Engineering & Sciences*, 2024, DOI: 10.32604/cmes.2024.056576

4. Dam Duc Nguyen, Manh Duc Nguyen*, **Tiep Viet Nguyen**, Cong Trong Cao, Tran Van Phong, Dao Minh Duc, Tran Xuan Bien, Indra Prakash, Hiep Van Le & Binh Thai Pham*, Enhanced Landslide Spatial Prediction Using Hybrid Deep Learning Model and SHAP Analysis: A Case Study of the Tuyen Quang – Ha Giang Expressway, Vietnam, *Indian Society of Remote Sensing*, 2024, https://doi.org/10.1007/s12524-024-02055-1

5. **Nguyen Viet Tiep***, Nguyen Duc Manh, Mai Sy Hung, Effects of shallow landslides on road embankment stability in mountainous regions — A case study of route ĐT128, Chan Nua to Sin Ho segment, Lai Chau Province, Proceedings of the National Scientific Conference VIETGEO 2025, 145–153,