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Deep-seated rainfall-induced landslides on a new expressway: a case study in Vietnam

Abstract In Vietnam, landslides frequently occur on cut slopes along the road system during the rainy season. An understanding of the contributing factors and triggering mechanisms is essential so that effective measures can be taken to stabilize cut slopes and mitigate impacts caused by landslides. This study uses as a research subject the largest deep-seated landslide triggered by heavy rainfall on July 21, 2018, and the subsequent sliding induced by 5-day continuous rainfall events on the Halong–Vandon expressway. We examined the causative factors, failure mechanisms, and characteristics of the landslides through detailed geological investigation, unmanned aerial vehicle (UAV) surveys, and analysis of data from geology, geomorphology, well-prepared documents of rainfall events, and the expressway project. Results show that the heavy rainfall was the triggering factor for both events while slope cutting was the main landslide causative factor. The slump-type landslides occurred on weathered limestone layers that were parallel to the dip-slope direction of the strata. Geological settings of highly fractured and weathered sandstone, siltstone, and limestone combined with the development of karst caves favored the buildup of groundwater levels in deep layers, thereby causing deep-seated landslides. The analysis shows that in addition to geological factors, the landslide occurrences resulted from anthropogenic effects including the improper design of the calculation method for safety factors in road construction and quarrying activities. Site evidence and UAV photos also reveal that the July 21 landslide body on the lower slope was reactivated to travel downward due to the dynamic effect of the subsequent sliding on July 31. Based on numerical analysis using the Plaxis 2D model, an estimated sliding surface similar to the actual plane was simulated for the entire slope. Furthermore, the study presents an appropriate solution that has been applied to slope stabilization.

Keywords Causative factors · Cut slopes · Landslides · Limestone · Mechanism · Plaxis model · Rainfall

Introduction

Landslides are one of the most common disasters occurring along mountain roads, which cause economic and human losses. These phenomena have been reported in many countries such as Italia, Scotland, China, Taiwan, and Nepal (Liu et al. 2012; Winter et al. 2013; Lo et al. 2014; Marco et al. 2017; Ma et al. 2019). Previous studies also warned that the occurrence of landslides can pose a great level of risk to the operation of transportation networks (Winter et al. 2016). Therefore, various stabilization solutions have been applied for the slope stabilization and protection against landslides, for example, slope reinforcements by stabilizing piles combined with soil nails and anchors (Kang et al. 2009), deep drainage and the gravity wall (Galuf and Vojkan 2017), and anchored pile retaining wall and deep drainage (Frangov et al. 2017; Katarina et al. 2017). So far, the stability of slopes is often estimated

using the limit equilibrium methods (Spencer 1967; Morgenstern and Price 1965), at which the limit equilibrium state of slopes is taken into account. These methods firstly assume the failure surface of slopes and then calculate the safety factor, which is defined as the ratio between the resisting forces to the driving forces. Although these methods are quite simple and can be performed by manual calculation, the assumption of the failure surface requires the full understanding of the slope stability. Most recently, the finite element method, particularly the Plaxis 2D computer software coupled with the strength reduction technique, has been developed to assess the safety factor of slopes (Rawat and Gupta 2016; Fawaz et al. 2014; Ashour and Ardalán 2010). The greatest advantage of this method is that the failure surface of slopes is formed naturally among the yielding or large displacement points of the soil so that no assumption is required. Furthermore, the complicated geometry of slopes and the retaining system can be fully modeled. In the slope stability analysis, the shear strength of soils, as represented by c and ϕ values, will be reduced successively until numerical solutions could not converge in analysis, which is defined as the failure of slope. The factor of safety is then determined as the maximum reduction in soil shear strength, which is indicated by the ratio $\Sigma M_{s,r}$ between the original soil shear strength and the reduced one. Many studies have demonstrated that the use of the finite element method with the aid of Flaxis 2D can help geotechnical engineers in defining appropriate mitigating measures (Galuf and Vojkan 2017; Katarina et al. 2017; Schweiger et al. 2018).

Located in the tropical monsoon region and affected by the environmental impact of deforestation, mining, and slope cutting for construction of houses and roads, Vietnam is vulnerable to the risk of landslides (Duc 2013; Tien Bui et al. 2017). Every year, landslides claim lives and cause property losses estimated at nearly US\$100 (Tam 2001). Extensive landslides often occur during tropical cyclones, and rainfall is of the main triggering factors (Duc 2013; Tien et al. 2016a, b; Tien Bui et al. 2017). Most of the landslides in Vietnam occur on cut slopes along the national North–South railway and national highways, particularly on the Ho Chi Minh (HCM) route (Tam et al. 2008; Binh 2009; Duc 2013; Tien et al. 2016a, b; Luong et al. 2016). On the HCM route, which connects the North to the South of Vietnam, there were 1539 landslides along the road until the year 2012 (Lo et al. 2014). Previous studies on landslides along the HCM highway presented that the geological conditions play an important role in the occurrence of landslides and the spatial distribution is very likely to get involved in geological periods, especially most of the landslides that occurred in the areas of Mesozoic geology (Miyagi et al. 2016; Tien et al. 2016a, b; Luong et al. 2016). In Vietnam, three structural solutions are used to prevent and mitigate landslide impacts. These include temporary measures (such as rock gabions and temporary structures), semi-permanent measures (e.g., low/gravity retaining walls, slope surfacing with concrete structures

combined surface/groundwater drainages, and vegetation), and permanent measures (e.g., reinforced concrete wall, anchored retaining walls, and anchor piles combined with cutting slopes, protective nets, or anchors). Although countermeasure works against landslides have been applied to sites, landslides still occur or reactivate year by year. This might be due to (1) the use of improper geological investigation and design solutions, and (2) the increasing impact of extreme meteorological events.

In recent years, severe landslides have occurred on newly built roads, including the Ha Noi–Lao Cai, Bac Giang–Lang Son, and Halong–Vandon expressways. The 60-km Halong–Vandon expressway, as a key transport project in Quang Ninh province, was put into service in February 2019 to connect the Hanoi–Hai Phong–Quang Ninh economic triangle, thereby boosting the development of Quang Ninh and the Northern Key Economic Region. The road operation was delayed several months due to extensive damage from numerous landslides during rainy season since 2017. In July 2018, a deep-seated landslide triggered by heavy rainfall in Thong Nhat commune, Hoanh Bo district in Quang Ninh province, attracted much public attention. The landslide site is located at $21^{\circ}3'2.20''\text{N}$ and $107^{\circ}7'55.30''\text{E}$, approximately 12.5 km northeast of Halong city (Fig. 1). The landslide occurred on an excavated slope where excessive mining and slope cutting for road building were conducted in 2017 (Fig. 2a). The landslide area consisted of the main mass movement and a subsequent sliding triggered by heavy rainfall on July 21 and July 31, 2018, as shown in Fig. 2b and c, respectively. However, the exact time and formation process of the landslides are still unknown. This landslide destroyed the slope protection system in Thong Nhat and buried about 70% of the expressway's width (Fig. 2d). For the implementation of urgent countermeasures against landslides, geological and topographical surveys and soil testing were conducted in October 2018. A comprehensive slope stabilization solution is due for completion in June 2019.

The current study aims to investigate the contributing factors and triggering mechanisms of landslides along the Halong–Vandon expressway by using the case study of the Thong Nhat landslide, which not only is the largest landslide to occur on this new road but also has typical features in terms of geology, topography, triggering factors, and failure characteristics. Furthermore, this study aims to answer an important question: Despite all of the cut slopes being designed on the basis of national standard specification, why do landslides still occur after construction? Based on the study findings, a comprehensive slope stabilization solution, which is analyzed to examine slope stability using the Plaxis 2D model (Brinkgreve et al. 2010), is proposed for remediation of the landslide on the expressway. An improved understanding of the failure mechanism is imperative in proposing suitable measures to mitigate causative factors and reduce landslide risk in future constructions on the road system in Vietnam.

Regional settings

The study area is located northeast of Halong city, where the topography is hilly with low-relief mountains. The average altitude is in the 150–250-m range with slope angles at 15–25°. In terms of geological characteristics, the Thong Nhat landslide involved the Hon Gai and Bac Son formations with limestone, sandstone, siltstone, conglomerates, gritstones, shale, and thin lenses of coal

(Fig. 1). The faults, including those along the Halong–Vandon expressway (DGM 1999), are strongly active and form large destructive zones, which result in the occurrence of numerous landslides.

The landslide area is situated in a tropical coastal climate with two separate seasons: (1) hot and rainy during summer from May to October and (2) cold and dry during winter from November to April. Approximately 70–85% of the annual average rainfall occurs from June to September, and approximately 45–50% occurs in July and August (Fig. 3). Heavy rain occurs continuously for 2–3 days. In the study area, heavy rainfall is considered as the main trigger that has caused several disastrous events, including the fatal July 28, 2015, rapid landslide, killing 8 people (Loi et al. 2017).

Geological drilling and soil properties

The geological cross section A–A' of the landslide was estimated from the geological drilling and resistivity survey in the landslide body area (Fig. 4). The results of the resistivity survey along the A–A' line are presented in Fig. 5. The results from boring holes and the electrical resistivity survey showed that the initial landslide and its subsequent failures slid on limestone layers. Drilling and standard penetration tests (SPTs) were conducted by Vietnam–Japan Engineering Construction Company to explore the geological structure of the landslide strata (BC 2018). In these tests, boreholes BH1 and BH2 were used to predict the sliding surface on the lower slope whereas BH3 and BH4 helped to estimate the sliding plane of the subsequent landslides on the upper slope. For a detailed investigation of geological boundaries, the SPTs were performed for drill-core samples at various depths along the boreholes during drilling. The boundary of the limestone bedrock and upper sedimentary blocks, i.e., sandstone and siltstone, are visible in the drilling cores (Fig. 5). Borehole data and field observation show that the limestone presents highly irregular fractures (Figs. 4, 6, and 7). The limestone layer is covered by clayey loam. This layer consists of highly weathered limestone, siltstone, and claystone with grayish–reddish brown color and thickness ranging from approximately 3 m on top of the slope to approximately 32 m on the lower part of the slope.

The sandstone and siltstone are highly to completely weathered from the bedrock to the surface. The slope strata consist of four material layers: (1) residual soil, less plastic clay, clayey sand, and vegetable products (layer 1); (2) medium to highly weathered sandstone and siltstone (layer 2); (3) dominated sandstone mixed with less plastic clay (layer 3a) or dominated less plastic clay mixed with sandstone (layer 3b); and (4) medium weathered limestone (layer 4). The geological cross section of the landslide is presented in Fig. 4b. For BH1 and BH2, disturbed layers of completed weathered sandstone and siltstone are found at depths of 24.2 m and 32.5 m, respectively. These materials also form a chaotic layer at 26–31 m in BH3 and at 22.4 m in BH4. At these elevations, SPT values are less than 10 (BC 2018). Based on the drilling investigation, the sliding surface of the lower and upper slope failures was roughly drawn. The sliding surface had a maximum depth of approximately 32 m, presenting a large-scale landslide on the new expressway.

Samples for laboratory tests, including S_{11} and S_{12} from BH1, S_{21} and S_{22} from BH2, S_3 from BH3, and S_{41} and S_{42} from BH4, were obtained from different layers of boreholes to measure soil properties. The grain-size distribution and geotechnical properties of

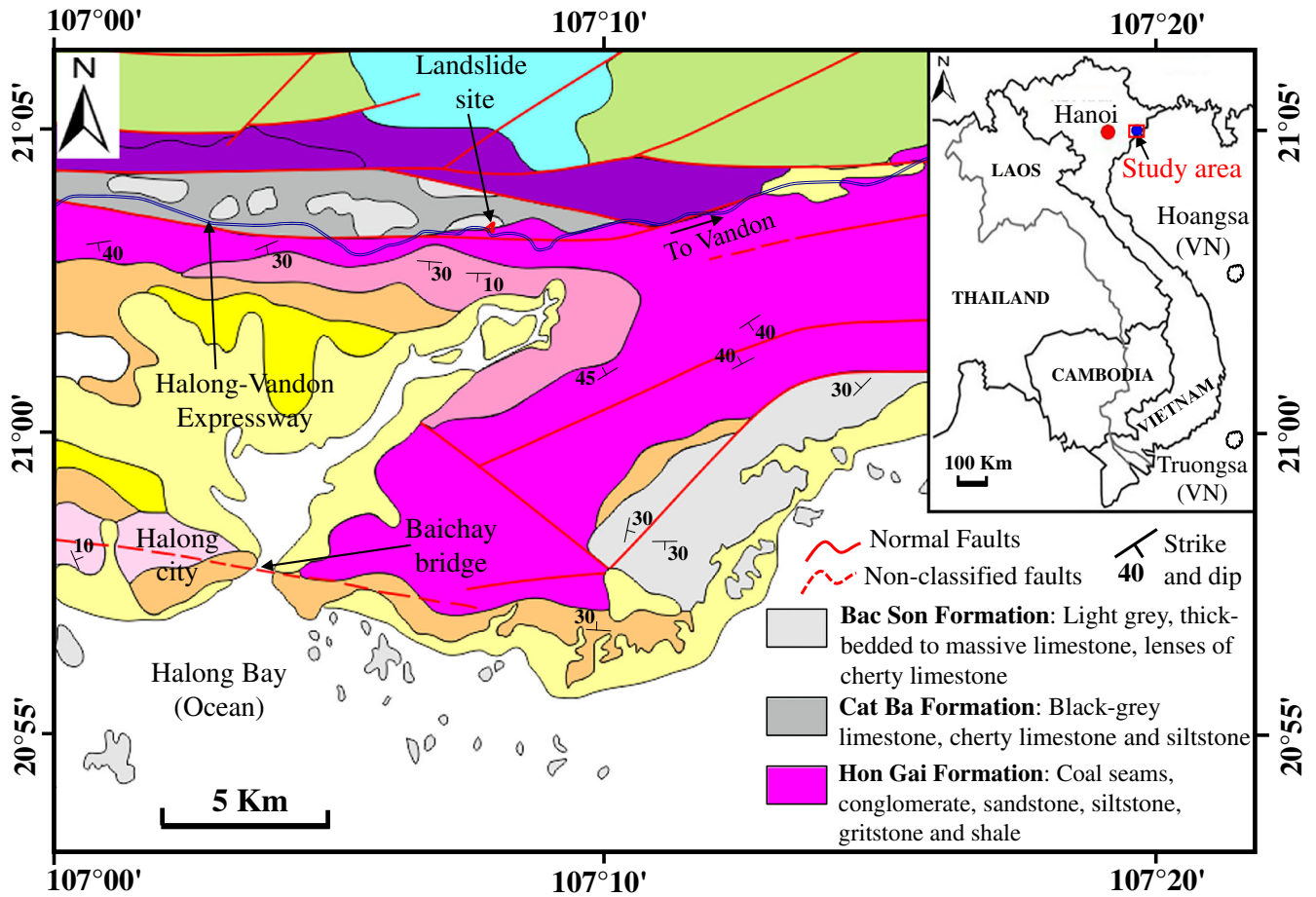


Fig. 1 Geological map (DGM 1999) and location of Thong Nhat landslide

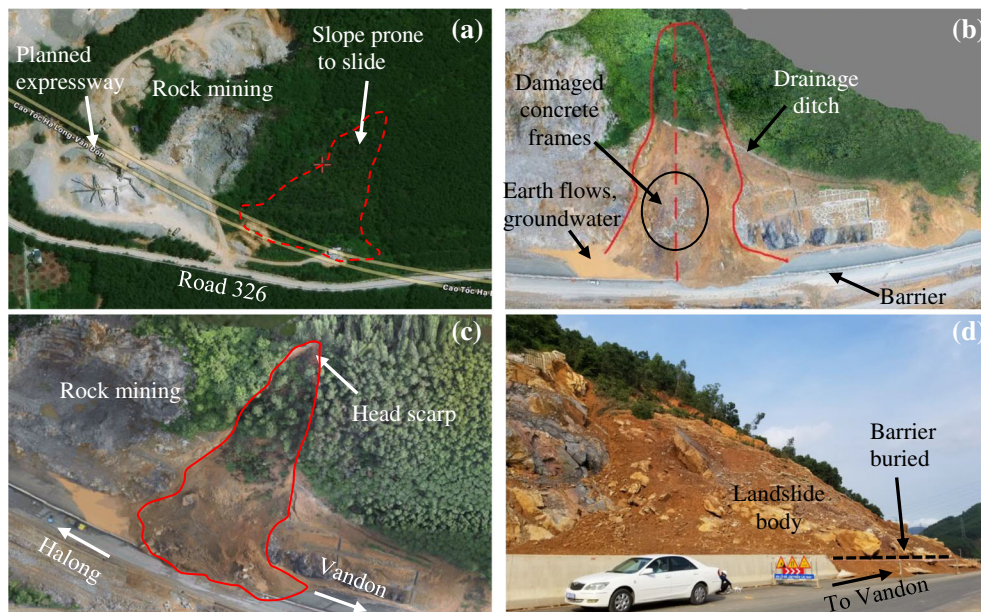


Fig. 2 Morphological changes of the slope by time and landslide views: a slope in October 2017 from Google Earth; b initial landslide on July 21, 2018 (taken by Vietnam–Japan Engineering Construction Company, BC 2018); c subsequent landslide on July 31, 2018; and d the entire landslide body viewed from the right direction

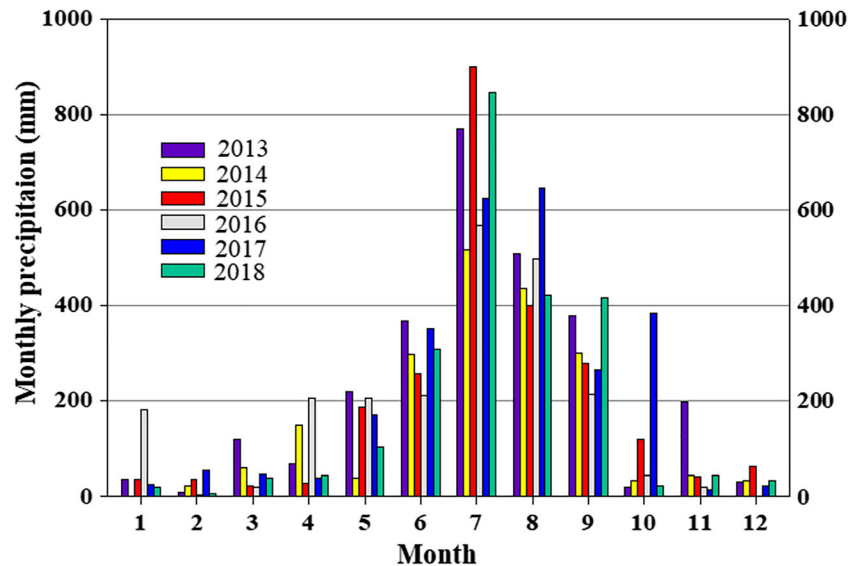


Fig. 3 Monthly rainfall by year from 2013 to 2018

the drilling samples, which are summarized from the reports of the Halong–Vandon project (BC 2018), are present in Fig. 6 and Table 1. The grain size analysis indicates that the samples contain much clay and silt-sized grains.

Method and data

To study the geological and hydrological conditions and characteristics of the sliding surface and weathering crust, we conducted site surveys at several days after the main and subsequent landslides. The geological structures of the slope, which were exposed after landslide deposits were removed and borehole drilling was conducted to set ground anchors, were also carefully examined during the construction of slope stabilization measures. In particular, a large slope area was surveyed using an unmanned aerial vehicle (UAV) to examine topographical features and generate a 1-m-mesh digital elevation model (DEM) of the landslide. The model was used to create cross sections of the landslide for 2D numerical analysis and stability design for the affected landslide slope.

Then, various data including rainfall, geological cross section, boreholes, and design documents from relevant authorities were collected to further investigate the contributing factors of the landslides. To characterize the correlation between rainfall and landslide occurrences, we analyzed daily rainfall data monitored from 2013 to 2018 at Bai Chay Hydro-meteorological Station, approximately 12.5 km from the landslide area.

Furthermore, a numerical analysis using Plaxis 2D computer software (Version 2010) was conducted to examine the sliding surface along a central cross section of the entire landslide body and study the behavior of the new cut slope with and without reinforced structures so that an effective solution against landslides could be proposed. In the model, in order to simulate behaviors of subsoil layers, the elastic perfectly plastic Mohr–Coulomb model was employed, which required parameters, including Young’s modulus (E), Poisson’s ratio (ν), friction angle (ϕ), and cohesion (c). The safety factor of the slope was estimated

using the ϕ – c reduction technique (Rawat and Gupta 2016; Fawaz et al. 2014; Ashour and Ardanal 2010; Brinkgreve et al. 2010). The soil properties were determined from physical tests on samples obtained from the boreholes. The input parameters of soil and rock are summarized in Table 2.

Landslide characteristics from site investigations

Landslide characteristics

The landslide characteristics were investigated through site surveys after the subsequent event on July 31. Figure 8 presents an overview of the Thong Nhat landslide and its geological features. The landslide occurred on a southwest-facing slope covered by a forest of *Acacia mangium* Willd. The landslide body was formed by mass movements of the lower and upper slopes on July 21 and 31, respectively. The failures were characterized by a deep-seated slump type with observable scarps on the head and flanks (Fig. 8b and c). The head scarp had a maximum height of 10 m while scarps on the flanks were approximately 1.0–3.0 m high. The landslide occurred on bedrock layers of limestone with an average sliding surface angle of 39° . The angle of repose of the deposit for the whole landslide body (the inclination connecting the top and the toe of the landslide) was about 22° .

The entire landslide volume is over $150,000 \text{ m}^3$ in volume with a maximum depth of approximately 32 m, length of 135 m, and width ranging from 40 m at the head to 80 m at the toe (Figs. 2d and 4b). The first slide was 35 m wide and 76 m long. The total fall height was 77 m from the top of the head scarp at elevation 175 m to the road where the landslide deposited at elevation 98 m. The landslide deposits consisted of weathered and loose materials of sandstone and black-gray siltstone mixed by conglomerate. As a result of rainfall, the weathered sandstone and siltstone became soft and prone to breakage. Thus, landslide deposit largely expanded on the road surface under the impact of groundwater that flowed out through fissures of the slope. Spring water coming out of the slope was observed during the post-landslide site investigations, thereby proving the abundance of groundwater in the landslide body.

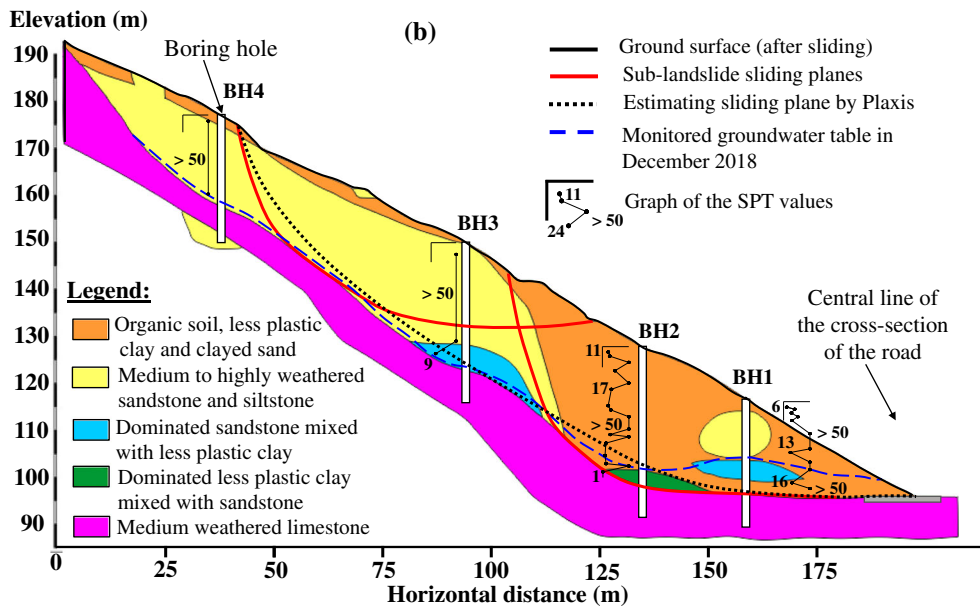
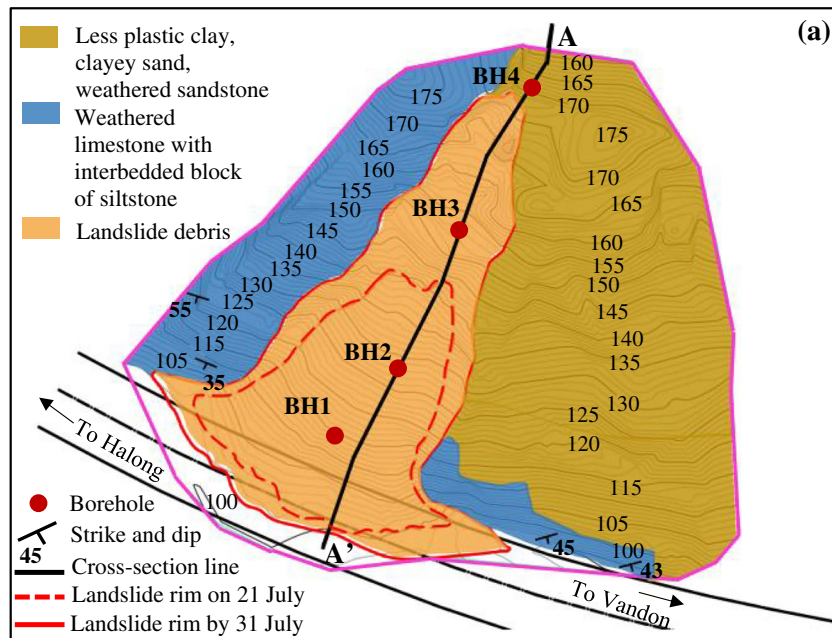


Fig. 4 a Topographic map and b geological cross section A–A' of Thong Nhat landslide (modified from engineering drawings provided by the BOT Bien Cuong Joint Stock Company, BC 2018)

Geological features

The major geological features of the landslide area were highly fractured and weathered crust of sandstone, siltstone, and limestone. The geological structure presented exhibited dipping strata; bedding planes parallel to the slope; and interbedded formations of limestone, sandstone, and siltstone (Fig. 9). The landslide was mainly formed along the dip-slope direction of the strata (Fig. 9b and d). Interbedded sandstone and shale layers were found near the left and right flanks of the landslide (Fig. 9c). Based on the detailed data analysis and geological drill cores, the sliding surface was deduced to be on weathered limestone layers with a depth of 24–32 m. The geotechnical properties of the drilling samples are reported in Fig.

7 and Table 1. Test results show that shearing resistance is equal to 6.02° – 19.2° , and cohesion is equal to 5.7–32.1 kPa. The samples have a high natural degree of saturation ranging from 67.19 to 96.88% and a high void ratio of 0.642–1.125. These parameters imply that rainwater can easily infiltrate the slopes, increase the saturation degree of the soils, and reduce slope stability.

Karst and weathering process

Due to the geological structure consisting of limestone, the landslide strata are characterized by underground drainage systems with caves. The site evidence was observed at an outcrop on the right side of the landslide toe (Fig. 10a) and through drillings (Fig. 10b). For the

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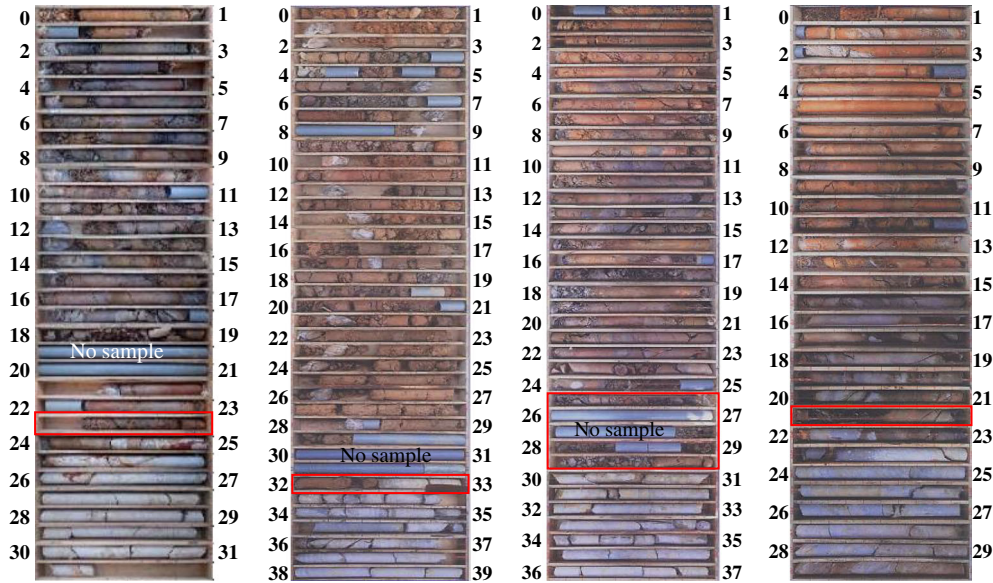


Fig. 5 Lithological description of four Thong Nhat landslide boreholes (Note: the red rectangle indicates the disturbed layers of completely or strongly weathered sandstone and siltstone, BC 2018.)

setting of the end of the cable anchor to hard bedrock, the borehole at an elevation of 143.0 m was drilled through a large cave where many bats are nesting and living. Figure 10b displays a view inside the cave during the construction of the ground anchor system. The image shows that karst topography commonly developed in this area as a result of the limestone dissolution. The karst process might occur only beneath the limestone bedrock and at subsurface levels because the limestone blocks were covered by the non-soluble rock of weathered sandstone and siltstone. Although this study was conducted in February 2019 during the dry season, images and videos revealed the existence of groundwater inside the cave. This condition implied the possible existence of an underground spring system that

may form beneath the slope strata in tropical regions. The areas where karst caves were detected during the construction phase are presented in Fig. 13a.

Determination of sliding surface using Plaxis 2D model

A model of the Thong Nhat slope was analyzed on the Plaxis 2D program (Brinkgreve et al. 2010) to predict the sliding surface of the landslide. Soil properties corresponding to each material layer obtained from the laboratory tests were inputted in the model. The sliding plane was then automatically determined among the large displacement points of soil by numerical analysis (Fig. 11). It can be seen that the total displacement plot at the time numerical

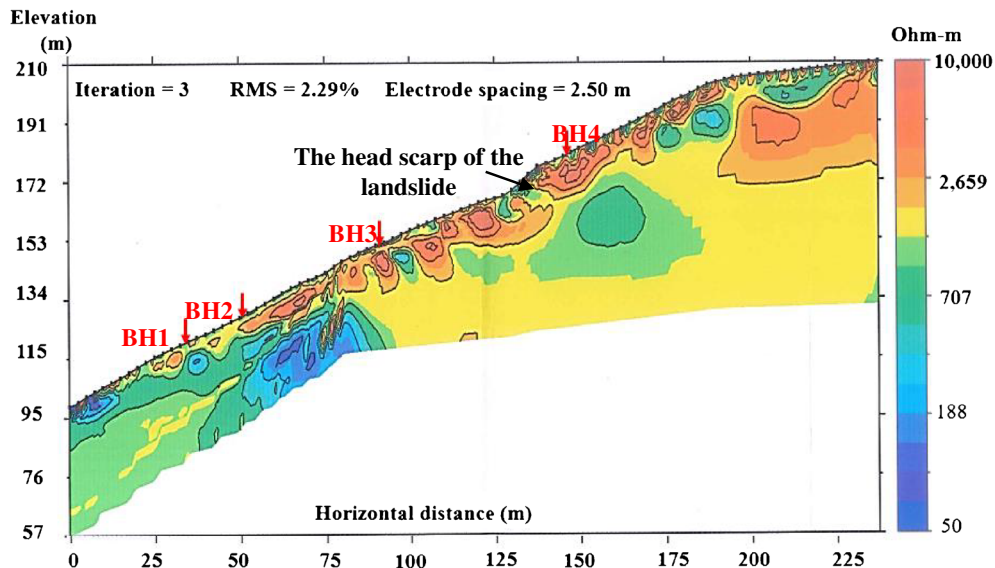


Fig. 6 Results of the resistivity survey along the central line A-A' (BC 2018)

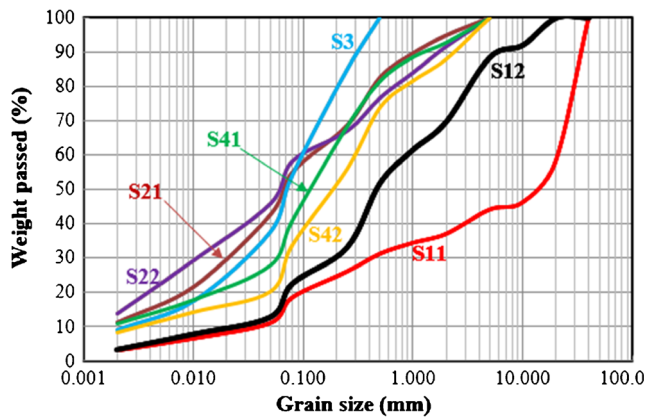


Fig. 7 Grain-size distribution of samples from boreholes (based on test results, BC 2018)

solutions could not converge in stability analysis and the predicted failure surface. As the figure indicates, the failure surface determined by numerical analysis was almost coincident with the geological boundary between the weathered sedimentary layers and underlaid bedrock (Fig. 4).

Discussion

Mechanisms and formation process of landslide

Under heavy rainfall, the initial landslide as the main event occurred at the top elevation at 143.0 m at the lower slope on July 21.

The landslide moved downward, swept away the drainage ditch system and concrete frames, collided with the concrete median barrier, and deposited on the road surface. The debris mass not only blocked the lanes of 70 m length toward Vandon city but also spread over the barrier of 0.65-m height and laid on the opposite lanes. After the sliding, no temporary countermeasure was applied to stabilize the slope. The upper slope continued to move down not only because of ongoing heavy rainfall on July 27–31 but also due to loss of support at the base (lower part). Site evidence and UAV photos showed that the mass movement of the subsequent landslide partly overrode the surface of the initial landslide after the upper slope failed. As a result, the middle part of the entire slope was largely covered with upper-slope sedimentary materials and tilted trees from the top. Notably, damaged concrete frames topped the surface of the initial landslide (Fig. 2c), which was not covered by the subsequent deposit (Fig. 2d). This evidence implied that the run-up to the subsequent event could not reach the toe of the deposit mass of the initial landslide. Furthermore, because the landslide deposit area expanded to the road surface, the deposit mass of the initial landslide was pushed away by the downward movement of the upper slope. This condition means that the lower debris mass continued to move to that extent due to the dynamic effects of the subsequent sliding.

No evidence of liquefied materials on the site and the high apparent friction angle (22°) of the energy line indicate that the mass movements traveled with low landslide mobility. It is because the materials of the sliding zone are fine as clayey (Fig. 7) that are not highly susceptible to grain crushing and excess pore water pressure generation under shearing. Hence, the sliding surface

Table 1 Geotechnical properties of soil samples

Properties	Samples (from the boreholes at different elevations)						
	BH1 S ₁₁ (1.6–1.9 m)	S ₁₂ (21.6–21.8 m)	BH2 S ₂₁ (26.5–26.7 m)	S ₂₂ (31.8–32 m)	BH3 S ₃ (2.6–2.8 m)	BH4 S ₄₁ (5.3–5.5 m)	S ₄₂ (10.4–10.6 m)
Water content (%)	20.89	17.02	23.93	40.07	23.81	29.87	35.09
Natural unit weight (kN/m ³)	20.0	18.8	19.5	17.9	18.5	18.9	17.8
Dry unit weight (kN/m ³)	16.5	16.1	15.7	12.8	15.0	14.6	13.2
Saturated unit weight (kN/m ³)	20.4	20.2	19.9	18.1	19.5	19.3	18.4
Specific gravity (kN/m ³)	27.1	27.2	27.2	27.2	27.3	27.3	27.4
Porosity (%)	39.1	40.79	42.26	52.94	45.05	46.52	51.83
Void ratio	0.642	0.689	0.732	1.125	0.820	0.870	1.076
Saturated degree (%)	88.18	67.19	88.92	96.88	77.61	93.73	89.36
Liquid limit (LL, %)	32.56	22.82	36.3	42.53	34.31	51.15	54.89
Plastic limit (PL, %)	16.53	14.93	19.53	24.06	19.27	28.10	28.31
Plasticity index (PI)	16.03	7.89	16.77	18.47	15.04	23.05	26.58
Liquidity index	0.27	0.26	0.26	0.87	0.27	0.08	0.26
Cohesion (kPa)	20.2	19.8	21.0	5.7	20.9	32.1	22.0
Angle of internal friction (degree)	16.3	17.05	16.5	6.02	16.35	19.2	17.11

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Table 2 Input parameters for the Plaxis 2D model

Parameters	Symbol	Unit	Layer 1	Layer 2	Layer 4	Ground anchor
Lithology	–	–	Less plastic clay and clayed sand	Medium to highly weathered sandstone and siltstone	Weathered limestone	–
Type of model	–	–	Mohr–Coulomb Undrained	Mohr–Coulomb Drained	Mohr–Coulomb Undrained	Elastic
Thickness	–	m	(*)	(*)	(*)	–
Natural unit weight	γ_{unsat}	kN/m^3	18.7	25.5	27.1	–
Saturated unit weight	γ_{sat}	kN/m^3	19.4	25.7	27.2	–
R_{inter}	R_{inter}		0.5	0.67	0.67	–
Cohesion	c'	kPa	24.6	0	0	–
Internal frictional angle	ϕ'	°	18.2	33	35	–
Poisson's ratio	ν	–	0.31	0.3	0.3	–
Elastic modulus	E_{ref}	kN/m^2	$1.05E + 04$	$7.0E + 04$	$1.0E + 05$	–
EA		kN/m				$7.25E + 4$

*Values correspond to depths on geological cross section (as shown in Fig. 4b).

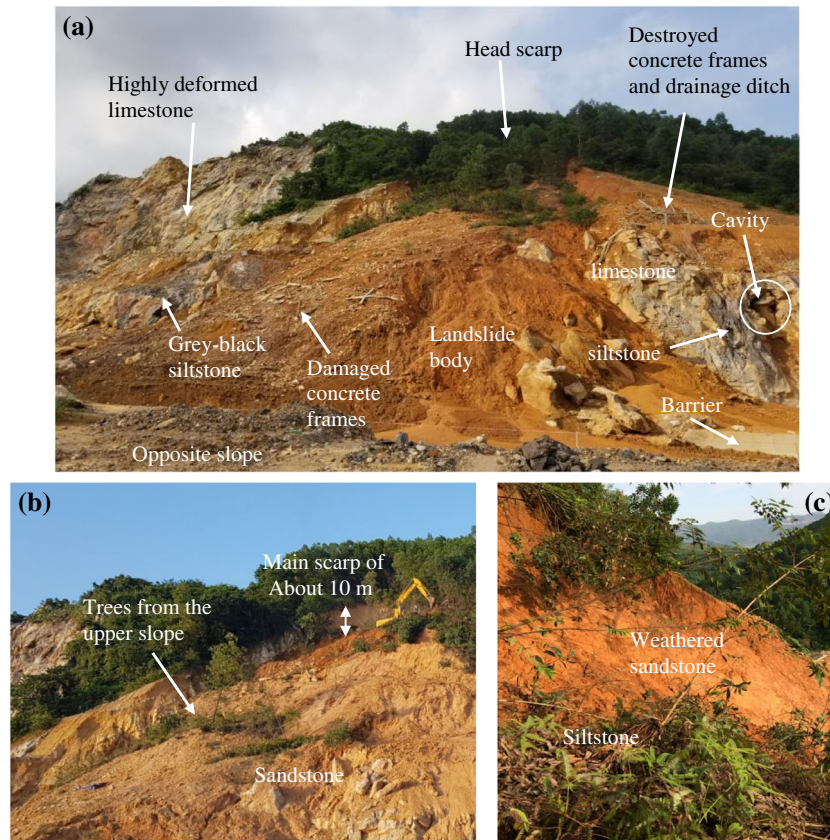


Fig. 8 Lithological characteristics of landslide

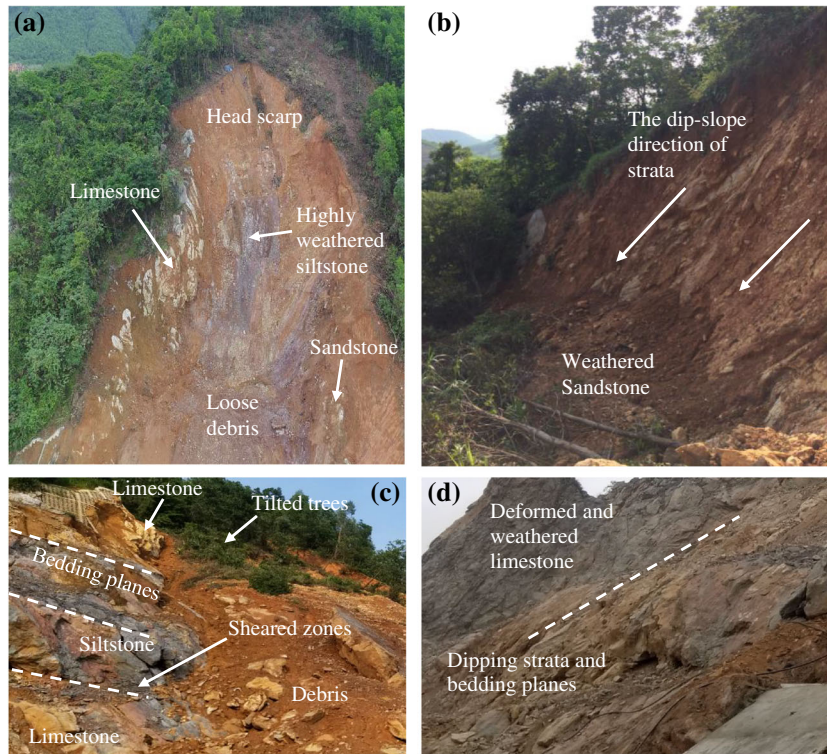


Fig. 9 Geological structure of landslide: **a** head scarp and upper part of landslide after soil removal to construct slope-stabilizing solution, **b** sliding surface on right flank near head scarp, **c** interbedded layers of weathered sandstone and siltstone, and **d** the dip-slope direction and bedding planes at an outcrop on right flank and adjacent to landslide boundary

liquefaction presenting high landslide mobility would not take place because of the lack of excess pore water pressure generation (Sassa 1996; Fukuoka et al. 2006; Tien et al. 2018); the landslide therefore moved a short distance.

Triggering factor

Rainfall data before and after the landslide occurrences are shown in Fig. 12. As indicated, rainfall with moderate to high intensity was the main trigger for the Thong Nhat landslide including the main movement on July 21 and the subsequent sliding on July 31, 2018. On these dates, daily rainfall exceeded 100 mm, reaching 165.8 and 105.5 mm in total. Landslides were induced by the continuous 5-day rainfall with accumulative amounts of 320.8 mm and 303.0 mm on July 18–22 and July 27–31,

respectively. Owing to the highly fractured and weathered level of limestone strata, rainwater not only induced the soil saturation but also deeply infiltrated the slope layers, resulting in an increase in groundwater level that triggered the failures. For both events, the precipitation presents the same pattern of rainfall with moderate to high intensity in a short time period that triggered many landslides in Quang Ninh province in the typhoon seasons (Tien et al. 2019).

Geological causes of landslide

The Halong–Vandon expressway runs along the active west–east-trending fault system (Fig. 1), which has suffered from many landslides after the construction. The location of the landslide near the fault zone and its geological features of broken formation and fractured rocks

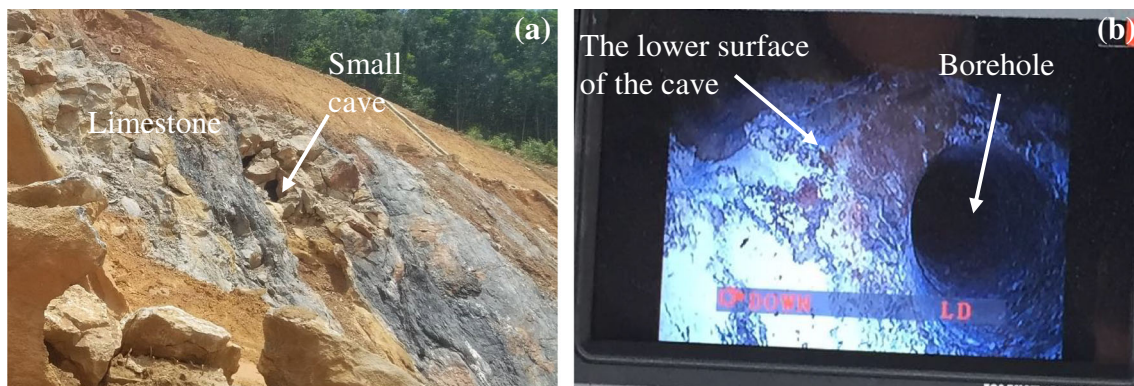


Fig. 10 **a** A small cave at an outcrop on the left flank of the landslide. **b** An image of a cave formed inside the limestone bedrock

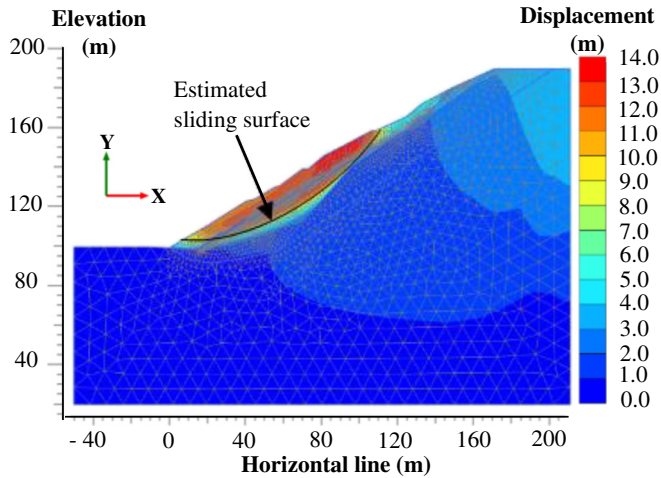


Fig. 11 Predicted sliding surface of landslide based on the Plaxis 2D model

indicate that the landslide occurrence is strongly affected by active faults. The geological morphological features of the slope are among the important preparatory factors that strongly influence the occurrence of the Thong Nhat landslide. First, the fractured and weathered limestone, sandstone, and/or siltstone materials and their deep weathering crust are a favorable condition for the water to deeply infiltrate the rock mass to build up the groundwater table. Weathered materials are extremely soft and highly permeable, and are therefore prone to slope saturation and erosion process, whereas slope materials are heterogeneous and loose and slide easily due to low shear strength when heavy rainfall occurs. The underground spring system and karst caves within the slope present a good condition for providing groundwater to build up the excess pore water pressure to trigger the landslide. On the other hand, water containing in caves and waters coming out from fissures suggested the abundant condition of groundwater sources that exacerbated the weathering level in the slope. Furthermore, the geological structure is in the dip-slope direction that favors the landslide formation. Consequently, the slope slid along the bedding planes of limestone and on the southwest-facing direction that is the main direction of the dip slope.

Anthropogenic factors contributing to failures

In the study area, a contributing factor to the landslide is the improper design of slope cutting and stabilization. In Vietnam,

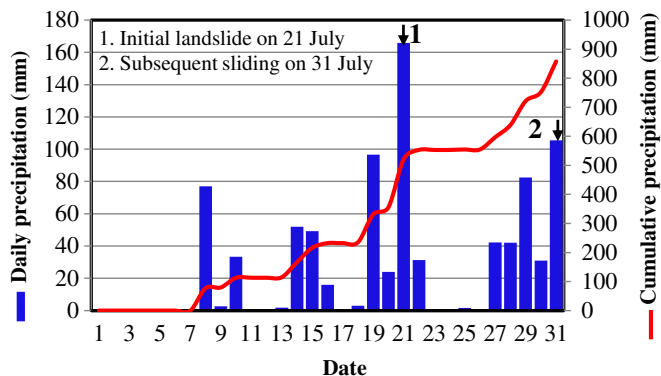


Fig. 12 Daily rainfall and its accumulative precipitation in July 2018

two specification standards govern geological surveys for landslides; these are 22 TCN263-2000, which applies to new roads at risk of landslides, and TCVN 9861-2013, which applies to active landslide routes. Both standards set detailed procedures and contents of the landslide survey. However, most of the road building projects, including this expressway, were only conducted with a geological survey and slope stability design for (1) landslide risk areas at the stage of technical design and (2) failed slopes with a reinforcement design. The updated design has not been implemented in the construction phase for potential landslide areas because no monitoring and additional survey for updating geological conditions are applied in practice. Under this situation, typical geological data are commonly used to represent the unknown conditions of a landslide location for slope stabilization. Consequently, this problem often leads to slope failures immediately or after the road is put into service, as in the case of the Hanoi–Laocai, Bacgiang–Langson, and Halong–Vandon expressways. The fact mentioned above is likely to be one of the answers to the given question: despite all of the cut slopes applying remedial measures based on the standard specification, why do landslides continue to occur during and after construction? Thus, applying geologically and morphologically supplemental surveys is strongly recommended in proposing construction solutions appropriate to actual locations for deep-cutting slopes and open excavation under complex geological conditions.

Regarding the Halong–Vandon project, although geological conditions along the road are highly complex, the technical design for slope stabilization had used the preliminary results of the geological survey. At the location of the Thong Nhat landslide, input parameters were strength values of weathered rocks, which were larger than that of completely weathered sandstone and siltstone on the actual slope. From this point of view, the safety factor was calculated to be larger than 1.3 to meet the current specification standards, whereas the actual value of the safety factor for this cutting slope was less than 1.2 (BC 2018). The design solution to stabilize the slope after cutting was uncertain on the technical aspect. Consequently, the slope failed one month after slope cutting.

In addition to the examined causative factors, very strong ground vibrations, such as those generated by quarrying activities and explosions in the production of construction, aggregate in areas adjacent to the right flank of the landslide indirectly contributed to instability slope. Such ground vibrations resulted in a large number of fractures in rock masses and a loss of connection forces and soil strength properties.

Proposals for countermeasures

Due to the extensive impact and project operating progress, the Thong Nhat landslide was considered an urgent countermeasure by the Quang Ninh government. Based on findings on the causative factors and landslide mechanism, a comprehensive slope stability solution was proposed to stabilize the failed slope and prevent future landslides. The slope stability analysis was conducted on the Plaxis 2D model to examine the appropriate solution. In this case, the failed slope was cut to form a new design cross section, which was stabilized by a complex technical solution (Fig. 13a).

The new design cross section included a total of 10 blocks (N1 to N10 from the toe to the top of the slope), with each block having a height of approximately 10 m. The combination of a reinforced concrete retaining wall and ground anchor was employed at the toe of the

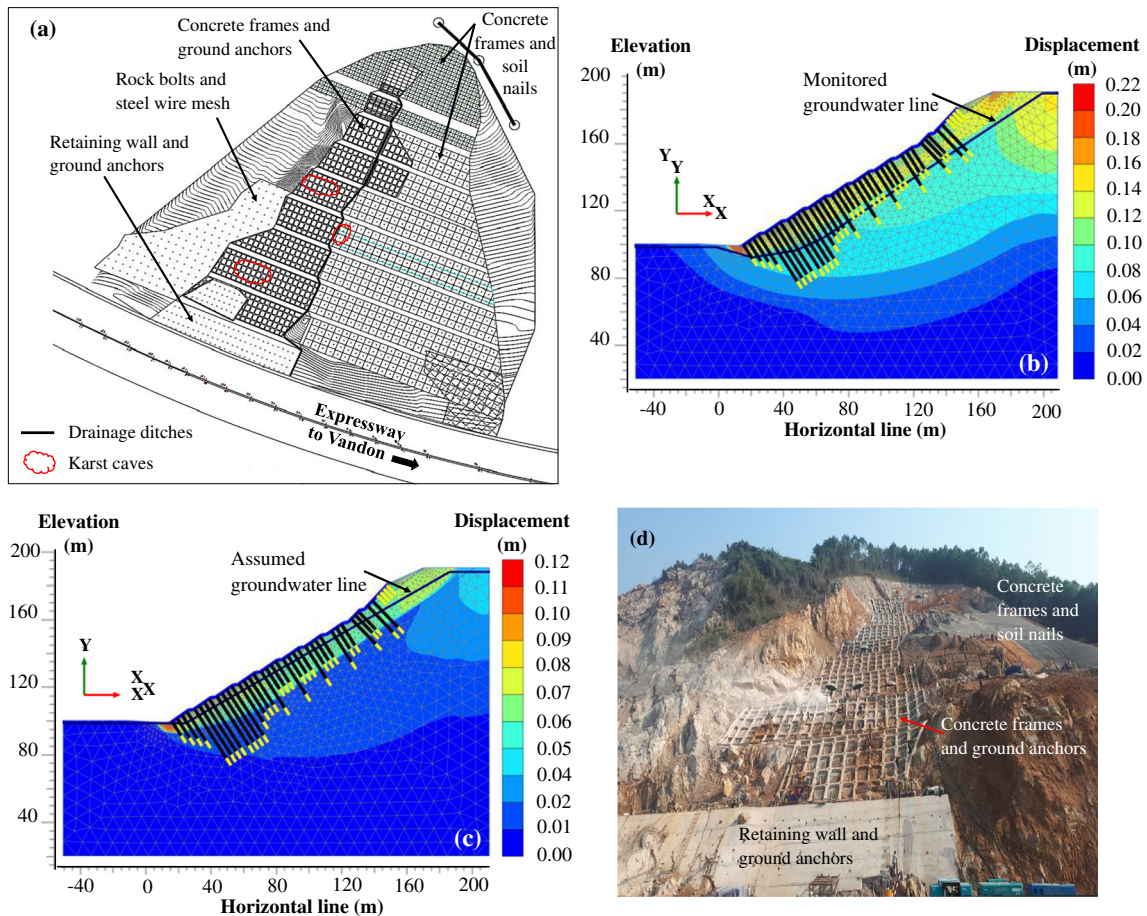


Fig. 13 Design and construction of engineering measures: a overview of technical solution to the failed slope, b, c total displacement on designed slope after applying reinforcement solutions, and d remedial solution under construction as of May 2019

slope (block N₁). The next seven blocks (N₂ to N₈) were designed by the reinforced concrete frame and ground anchor system. The ground anchors, soil nails, and reinforced concrete frame were set up at the last two blocks at the top of the slope (N₉ and N₁₀). Moreover, rock bolts and PVC-coated steel wire mesh were applied on both sides of the main slope to prevent rockfalls.

In the Plaxis model, the total displacement on the designed slope after applying the reinforcement solutions is presented in Fig. 13b and c. This compound remedial solution is reliable for application to the site, which is under construction (Fig. 13d).

Conclusion

This paper presented a preliminary study on the causative factors, sliding mechanisms and characteristics of the Thong Nhat landslide on the Halong–Vandon expressway. The heavy rainfall with 5-day accumulation of 320.8 mm and 303.0 mm is the triggering factor of two sequential slope failures. The slope cutting under the highway construction is an important preparatory factor causing the landslide. Both mass movements on the lower and upper slopes slid on the bedrock layers of limestone as the slump type. The landslide occurred on the southwest-facing slope, which was parallel to the dip-slope direction of the limestone, sandstone, and siltstone layers. Bedding planes, strata fracture, and karst phenomena were observed in the landslide

area. The geological structure was characterized by completely and highly weathered sandstone and siltstone overlaid limestone blocks that are highly prone to landslides. These intrinsic geological features favored the buildup of groundwater levels in deep layers of the slope, thereby contributing to the deep-seated landslide. Besides, the landslide was affected by active faults that run west–east along the expressway.

The detailed analysis showed that in addition to the geological and topographical causes of the landslide, the anthropogenic factors were also a significant contributing factor, including the uncertainty in the use of soil properties, improper design for slope cuttings, and mining in the area on the right flank of the landslide body. In the case of the Thong Nhat landslide, slope stability design for remedial measures employed soil parameters measured in the stage of technical design, which was not reliable to be applied to the construction phase that requires updating geotechnical properties in detail. Notably, there was no examination of the actual geological conditions and karst topography that completely affect the construction. Thus, additional surveys at landslide sites stipulated by the two current standards should be conducted for the construction phase instead of using the representative soil properties. In this critical point of view, remedial measures against landslides can effectively work after the building.

The time and motion process of both slidings have not been recorded and described to date. However, site evidence and UAV photos prove that the subsequent landslide on the upper slope overrode the surface of the lower slope landslide but could not reach the toe of the initial sliding mass. The expansion of the landslide debris on the road surface resulted from the reactivated movement of the lower landslide body due to a pushing force from the upper slope sliding. Since sliding materials are not highly susceptible to grain crushing to generate excess pore water pressure, the landslide did not show the high mobility to travel in a long runout. As a result, the landslide traveled at a short distance with the apparent friction angle of the energy line of 22°. For an improved understanding of the formation of the Thong Nhat landslide, a numerical simulation using the 3D LS-Rapid model, which integrates the initiation and motion processes of landslides triggered by rainfall, should be performed (Sassa et al. 2010; Tien et al. 2018).

A numerical analysis using the Plaxis 2D model was conducted to examine the sliding plane of the entire landslide body and the behavior of the cut slope with and without reinforcement. For the central cross section, the sliding surface defined by the numerical model was similar to the geological boundary line between the limestone and sedimentary rock layers. Thus, the study shows that the Plaxis model allow us to well predict the sliding surface of landslides based on measured parameters of soil layers. Based on our understanding of the causative factors, failure mechanisms, and characteristics of the Thong Nhat landslide, a comprehensive measure was designed and applied on the site to stabilize the failed slopes and prevent landslide risk in the future. To date, compound solutions including retaining wall, ground anchor, and soil nail have been firstly applied in Vietnam for this case study. The findings not only provide a good case study on manmade slope landslides but are also a useful reference in solving practical problems regarding slope remedy along roads in Vietnam.

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