Roles of tectonic deformation, geological structures, petrography and topographic slope angle on the landslides susceptibility in mountainous provinces of Vietnam: implication for size, frequency and landside-prone areas

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***Abstract**: On the regional scale, landslide, a slope process, often occurs in monsoon in the high mountains in the tropical and high precipitation climatic zone. The occurrence of landslides was frequently assigned to the decisive role of intense or prolonged rainfall. However, on the local scale and in small geographic areas, where the same vegetation, duration and intensity of rain exist, rain often triggers landslides on only specific slopes and rocks. Apart from that, landslides can re-occur at the same location afterwards. The complicated and almost irregular nature of landslides requires a deep understanding of the endogenous and exogenous geological factors that can generate or play a significant role in the landslide process in a given area from which it is possible to delineate areas with a high risk of landslides. This research used the spatial statistical analysis of the relationship of 7855 historical landslides with tectonic factors, geological structures, litho-petrographic characteristics, and topographic slope. Our results indicated that fault zones and petrographic features are the most critical factors controlling the formation of landslides. Most landslides occur on the slope of 5 to 20 degrees. The areas where fault zones cut through magmatic and metamorphic rocks are likely to be more favourable for generating landslides of considerable size and volumes than the areas where the fault zones cut through the terrigenous rocks.*

1. Introduction

Landslide is one of many kinds of subsurface geological processes. When landslides threaten property and human life, they are considered a hazard. Many landslides resulted in casualties and devastating social and economic consequences like the catastrophic landslide of Rao Trang 3, Huong Hoa and Tra Leng in the mountain of Thua Thien Hue, Quang Tri and Quang Nam provinces of Vietnam, respectively, in October and November 2020. Landslide occurs mainly in the high mountain and is aggravated by humid tropical conditions characterised by high precipitation. It is a slope process related to a mass movement of residual weathering materials. In terms of physical mechanism, all landslides are the manifestation of gravitational collapse resulting from disequilibrium between shear stress and shear resistance of slope materials. Shear stress is induced by the weight of rock or soil mass on the slope, whereas stress resistance and properties of weathering materials vary depending on the specific regional conditions. When shear stress overwhelms the strength or shear resistance of slope materials, the balance states of the slope are broken down. Subsequently, the gravitational landslide process would be activated and resulting in a landslide with high speed or slow mass movement (Uyeturk et al., 2020). Although landslides have the nature of subsurface geological processes, or more precisely, slope processes, they intricately link to multi factors characterising the outermost part of the earth's crust. They can be classified into precondition, preparatory, triggering and sustaining factor groups (Glade and Crozier, 2005). These factors affect the specific areas differently. On the large region scale, landslide researchers invested their works on landslide susceptibility mapping by various GIS-based methods. Each layer stored a distinct attribute of the area interested in GIS software. They include the density of fracture and stream, slope angle, aspect, slope curvature, lithology, land use, soil type, rainfall, distance from roads, distance from the fault zone, and DEM layer (Bui et al., 2012; Guo et al., 2022; Liu and Wu, 2008; Ngọc et al., 2016; Pham et al., 2020; Tan and Tao, 2014; Tuan and Dan, 2012). They are often induced from remote sensing and imaging data. It is also notable that the number of input layers varies depending on the researcher and data availability. These layers are then assigned a weighted coefficient that is more or less subjective based on the researcher's experience and then converted to a pixel matrix by rasterisation operation.

Such landslide susceptibility index maps are helpful for sustainable development planning and hazard management. However, their predictive purpose is limited. Recent predictive research on landslides emphasised the climatic and hydrological factors. They are considered to play a key role in triggering landslides. These works focused on the identification of rainfall intensity-duration thresholds responsible for triggering landslides (An, 2012; Chang and Wang, 2022; Chang et al., 2017; Marin et al., 2021; Segoni et al., 2014; Shou and Yang, 2015; Wu et al., 2015; Zhao et al., 2022). However, the landslide is a result of a long-term process of accumulation of residual weathering materials and gravitational disequilibration occurring on the slope. The interaction of factors of geology (litho-petrography, geological structure, tectonic faults, fracture zones); geomorphology (topographic slope angle, relief curvature); meteorology (climatic, hydrological conditions), biology (vegetative state) and human activities (land use, road construction) controlled the producing weathering materials and their equilibrium state. Despite that, the tectonic, petrologic and structural factors were less taken into account in landslide predictive works. Careful analysis of relationships between these factors in a given region allows us to identify the role and extent they exert on the landslide susceptibility and how the landslide-prone areas will be delineated . The present paper analyses the role of tectonic deformation (faulting), geological structure, petrography and topographic slope angle on the landslide susceptibility based on the historical landslides inventory in some typical areas in Vietnam.

2. Outline of geology and landslides in Vietnam

2.1. Geological outline

The geology of Vietnam and its adjacent resulted from the amalgamation of several continental bocks in Paleozoic and followed by Mesozoic to Cenozoic overprinted tectonics. These blocks are marked by two well-acknowledged suture zones, namely Song Ma and Tam Ky-Phuoc Son (Faure et al., 2018; Tri, 1979) or regional-scaled major fault zones. The Song Ma suture zone separated North Vietnam from the Truong Son fold belt between Song Ma and Tam Ky Phuoc Son sutures. Southward of Tam Ky-Phuoc Son is Kon Tum block and Da Lat zone, and the Nam Bo plain. The boundary between the northeast and northwest parts of North Vietnam is marked by the Cenozoic Day Nui Con Voi shear zone.

2.1.1. Northeast part

This region is subdivided into inner and outer parts delimited by the Ha Giang fault. The inner part consisted mostly of metamorphosed Early Paleozoic sedimentary sequences and the Song Chay orthogneiss complex. A pervasive ductile deformation characterised by low angle foliation and N-S to NE-SW trending mineral and stretching lineation, and isoclinal folds coeval with a greenschist to amphibolite facies metamorphism dated at 246-234Ma (Faure et al., 2014; Maluski et al., 2001). The outer part consists of Late Paleozoic to Middle Triassic sedimentary rocks (mainly limestone) characterised by a series of N-E verging folds and thrust faults with a top-to-the-N-E sense of shear (Faure et al., 2014; Lepvrier et al., 2011).

2.1.2. Western part

This region can be subdivided into Song Da-Tu Le and Song Ma zones delineated by the Song Da fault. The Song Da-Tu Le zone consists of folded and ductile sheared Early Paleozoic, Devonian, Carboniferous, Permian and Triassic formations mainly formed by detrital rocks and carbonates and bimodal magmatic association with alkaline basalts, rhyolites, and volcanic-clastic rocks. The Neoproterozoic basement of these sequences was exposed in Hoa Binh and Yen Bai areas. The Song Ma zone corresponds to a mélange complex. It is composed of ultramafic-mafic and deep marine sedimentary rocks and Nam Co anticline consisting of Neoproterozoic and Paleozoic sandstone, siltstone, and limestone metamorphosed in 250-240 Ma (Lepvrier et al., 1997; Zhang et al., 2014).

2.1.3. Truong Son fold belt

Truong Son fold belt is located between two sutures, the Song Ma suture in the North and the Tam Ky-Phuoc Son one in the South. This belt composes mainly of Early Paleozoic volcano-terrigenous rocks, Middle Paleozoic limestone, sandstone, Late Paleozoic to Early Mesozoic basalt, rhyolite and sandstone, siltstone. These sequences are covered unconformably by Late Mesozoic coal-bearing sandstone to siltstone. Early-Middle Paleozoic and Late Paleozoic-Early Mesozoic granitoid intrusions are distributed in the axial zone of the belt in the NW-SE trend. Oligocene overprinted transtensional tectonics was recorded clearly in the North of the Song Ca fault.

2.1.4. Tam Ky Phuoc Son suture zone

This zone composing of metamorphosed Neoproterozoic to Early Paleozoic volcano-sedimentary sequences are intruded by granites formed in an arc setting. This sequence enclosed serpentinised ultramafic to mafic lenticular or body. The age obtained from zircon, monazite U Pb and micas Ar/Ar methods indicated a tectono-metamorphism occurred mainly in 255-245Ma.

2.1.5. Kon Tum massif

The high-grade metamorphic and igneous rocks are widespread in the Kon Tum massif. The metamorphic foliation attitude varies in the strike and the dip angle, but overall, they roughly delineated a vast dome structure. Cenozoic tectonics reactivated the Indosinian shear zones to generate a deep valley that coincided with fault zones. These fault zones crosscut the dome and limit the dome boundary. Most of them develop in N-S, E-W and NE-SW directions, while the NW-SE fault zone is less extended.

2.1.6. Da Lat zone

Da Lat zone extends in the NE-SW direction from the Song Ba fault. It consists of Cretaceous effusive and felsic magmatic rocks intruded into Jurassic sedimentary rocks.

2.1.7. Fault zones

Major fault zones in Vietnam resulted from the reactivation of ductile shear zones generated during four principal tectonics, including Late Paleozoic, Permian-Triassic, Jurassic-Cretaceous and Cenozoic. The Late Oligocene to Quaternary tectonics deformed strongly crust in the Indochina, resulting in strike-slip fault zones formation. These fault zones sliced the territory into narrow zones in the NW-SE direction. Apart from the main NW-SE fault direction, the N-S, NE-SW and E-W fault zones develop widely.

2.2. Data sources and methods

Landslide occurrences were collected from multiple sources, including technical reports of the project on the investigation, assessment and zoning for landslide warning in mountainous areas of Vietnam by (Hòa, 2017a, b, 2018; Hùng, 2014a, b; Vượng, 2016) and publications and updated to 2020 by field check in some areas. The position of landslide occurrences then was analysed by density distribution function in spatial correlation with the petrographic, tectonic deformation, and topographic features. Due to the tiny area of the polygon that delineated individual areas of landslides, therefore, they are treated as points.

2.3. Results and discussions

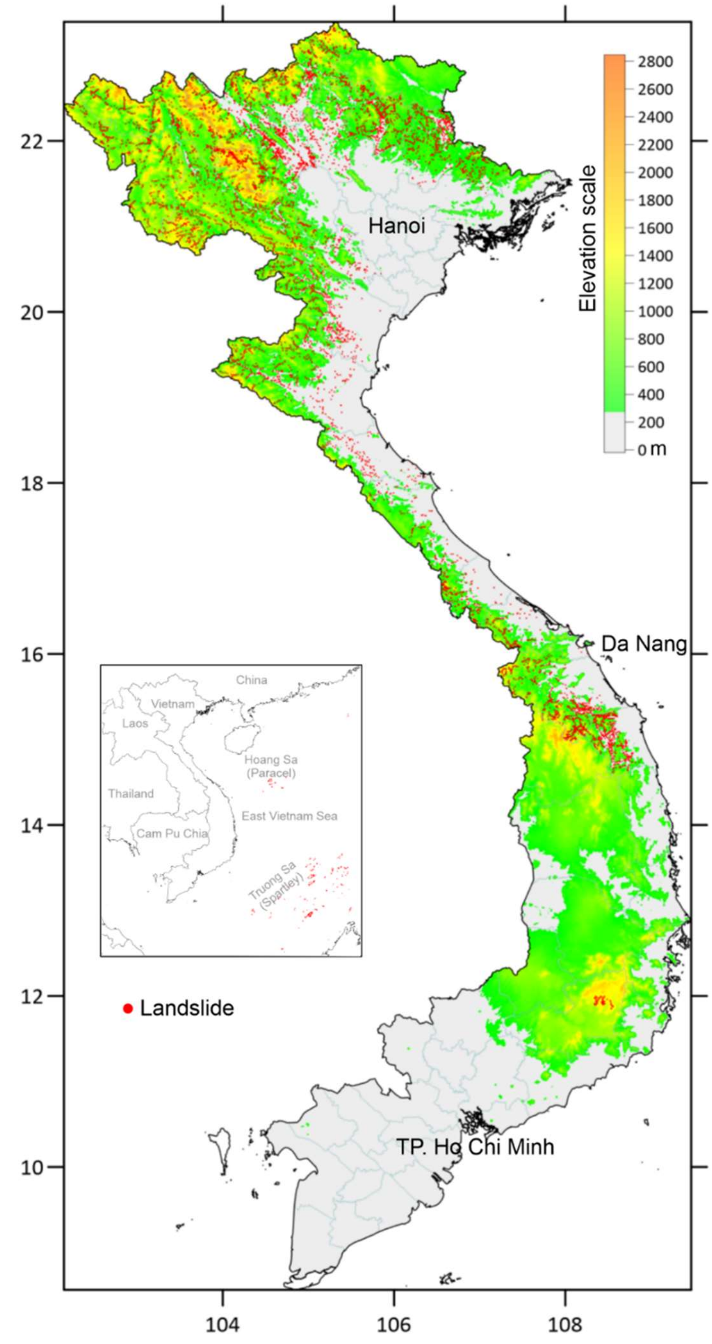

Figure 1. *Inventory of landslide occurrences in 20 mountainous provinces in Vietnam up to 2020*

2.3.1. Landslides inventory

Landslide occurrences in Vietnam were accounted for from published sources and digitalised into a database. A total of 7855 landslides in 20 mountainous provinces in Vietnam have been collected and updated to 2020. In this database, landslide size is not considered in operations of frequency statistical analysis and is treated equally without weighted values. These landslides then are analysed along with the litho-petrological, tectonic features and topological slope angle to identify individual feature's roles (Figure 1).

2.3.2. The relationship between petrology, geological structure and landslide occurrence

Stratigraphy units were reclassified into different categories in accordance with the main component of petrological characteristics. The petrological categories were identified based on the field check in conjunction with geological maps of 1:200.0000. They include the following i) limestone and carbonate rocks, ii) terrigenous sedimentary rocks with sub-horizontal attitude, iii) folded sedimentary rocks, iv) granitic rocks, v) gneiss and other metamorphic rocks with equivalent mineral composition, vi) other metamorphic rocks, vii) rhyolite and andesite, viii) basalts. The landslide occurrences density on the different types of rocks is given in Table *1*.

Table 1. *Landslide occurrences density vs different kinds of rocks*

No	Rock types	Landslide occurrences (case)	Area of formations containing landslide occurrence (km^2)	Percentage (%)	Approximate density (landslides/100km^2)
1	Limestone/Carbonate	333	11780	4,24	3
2	Folded terrigenous sedimentary rocks	3898	82960	49,62	5
3	Rhyolite	141	3086	1,8	5
4	Terrigenous sedimentary rocks with sub-horizontal attitude	642	11020	8,17	6
5	Basalt	175	3111	2,23	6
6	Gneiss	290	3021	3,69	10
7	Granite	1022	12028	13,01	9
8	Other metamorphic rocks	1354	21160	17,24	7

Statistical analysis of landslide occurrences in eight different groups of litho-petrography allows us to divide them into three categories based on the approximate and relative landslide density. The first category, including the carbonate rocks, has the most negligible landslide density of 3 events/100km^2. The second category, including the folded terrigenous sedimentary rocks, rhyolite and terrigenous sedimentary rocks with sub-horizontal attitude and basalt, has a landslide density of 5-6 events/100km^2. The third category has a value density between 7 and 10 events/100km^2, consisting of granitic, gneissic and metapelitic rocks. Obviously, the petrographic and mineral composition strongly influences the landslide susceptibility in the mountainous areas of Vietnam. The limestone/carbonate rocks possess a simple mineral composition and texture that can be dissolved easily. Therefore, they are challenging to gain enough material to produce a landslide. The group of terrigenous sedimentary rocks consist primarily of the Paleozoic to Early Mesozoic sandstone, coarse-grained siltstone or silicic rock. They also have simple mineral composition, including mostly quart, lithic fragments and minor micas, feldspars. These minerals with small grain sizes are almost resistant to exogenous conditions. The mineral composition of rhyolite and basalt is similar to granite and gabbro. However, microcrystal to glassy and more or less homogenous texture made them more difficult to alter than intrusions exited in the same conditions. Regarding the major mineral composition, the granite and orthogneiss share similarities and include alumosilicate minerals that are sensitive to weathering conditions. However, the foliated and banded texture of gneiss favoured the weathering that produces faster in gneiss than in granite which is more or less homogenous texture. These textures can explain the high density of landslide occurrences in areas of exposed gneiss compared to smaller densities in granite areas.

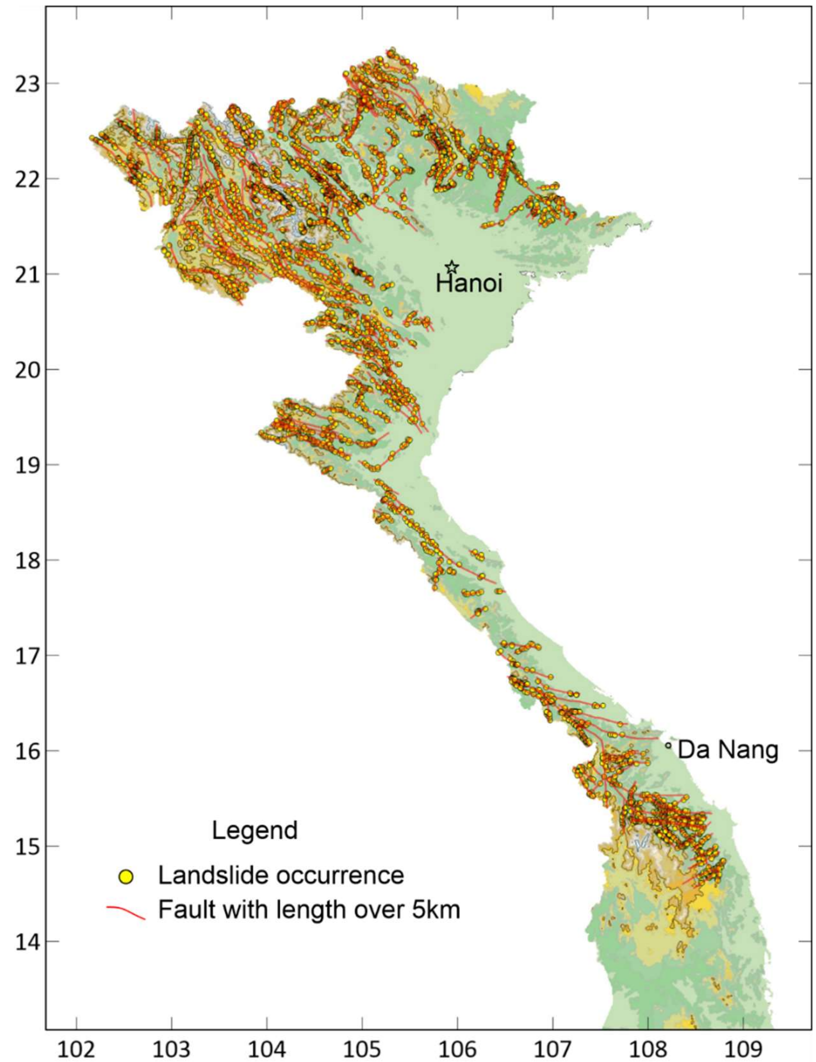

Figure 2. *Distribution of landslide occurrences controlled by fault zones*

2.3.4. The relationship between fault and landslide occurrence

The fault zone, fracture zone and shear zone are the results of multiple tectonic deformation phases (Chinh, 2000; Lepvrier et al., 1997; Trịnh et al., 2000; Vượng, 1998). These features are closely related to landslide occurrences. In this section, regardless of the petrology, the correlation of major faults of length over 5km and density of landslide occurrences was analysed. A total of 3507 and 5418 out of 7855 events, equivalent to 45% and 69% landslide occurrences, appeared in the fault dynamic zones with the active width of 1 km and 2 km, respectively. Thus the major fault zones over 5 km in length significantly influence the landslide occurrence. Two thousand four hundred thirty-seven landslide occurrences (31%) were distributed between major fault zones where minor faults and fractures exist. Among them, 46% occurred in folded sedimentary rocks compared to 9,9% in unfolded ones. This distribution implies that folded strata or strata attitude plays an important role in off fault landslide susceptibility. Folded strata are more sensitive than the sub-horizontal ones to the landslide. 16,6% and 15,3% of off fault landslide occurrences in the areas where granite and metamorphic rocks are exposed revealed the importance of petrographic features regarding landslide susceptibility. These areas are located at high elevations and are strongly weathered.

Table 2. *Number of landslide occurrences off fault and percentage*

No	Rock types	Landslide occurrences outside fault zones (case)	Percentage (%)
1	Folded terrigenous sedimentary rocks	1130	46,4
2	Granite	405	16,6
3	Other metamorphic rocks	372	15,3
4	Terrigenous sedimentary rocks with sub-horizontal attitude	242	9,9
5	Gneiss	112	4,6
6	Limestone/Carbonate	89	3,7
7	Rhyolite	47	1,9
8	Basalt	40	1,6

Table 3. *Relationship between topographic slope angle and off fault landslide occurrences*

No	Rock types	Slope angle range (degree)								
		3-6	6-9	9-12	12-15	15-18	18-21	21-25	25-28	Total
1	Folded terrigenous sedimentary rocks	562	333	144	57	29	2	3	-	1130
		49,7%	29,5%	12,7%	5%	2,6%	0,18%	0,27%		
2	Granite	56	100	120	65	49	11	4	-	405
		13,8%	24,69%	29,63%	16,05	12,01%	2,72%	0,99%		
3	Other metamorphic rocks	85	129	73	54	21	10	-	-	372
		22,8%	34,68%	19,62%	14,52%	5,65%	2,69%			
4	Terrigenous sedimentary rocks with sub-horizontal attitude	90	75	39	19	14	4	1		242
		37,19%	30,99%	16,12%	7,85%	5,79%	0,18%	0,99%		
5	Gneiss	16	36	27	25	6	2	-	-	112
		14,29%	32,14%	24,11%	22,32%	5,36%	1,79%			
6	Limestone/Carbonate	40	26	14	4	3	2	-	-	89
		44,94%	29,21%	15,73%	4,49%	3,37%	2,25%			
7	Rhyolite	10	15	10	8	3	1			47
		21,28%	31,91%	21,28%	17,02%	6,38%	2,13%			
8	Basalt	9	13	8	6	3	1	-	-	30
		22,5%	32,5%	20%	15%	7,5%	2,5%			

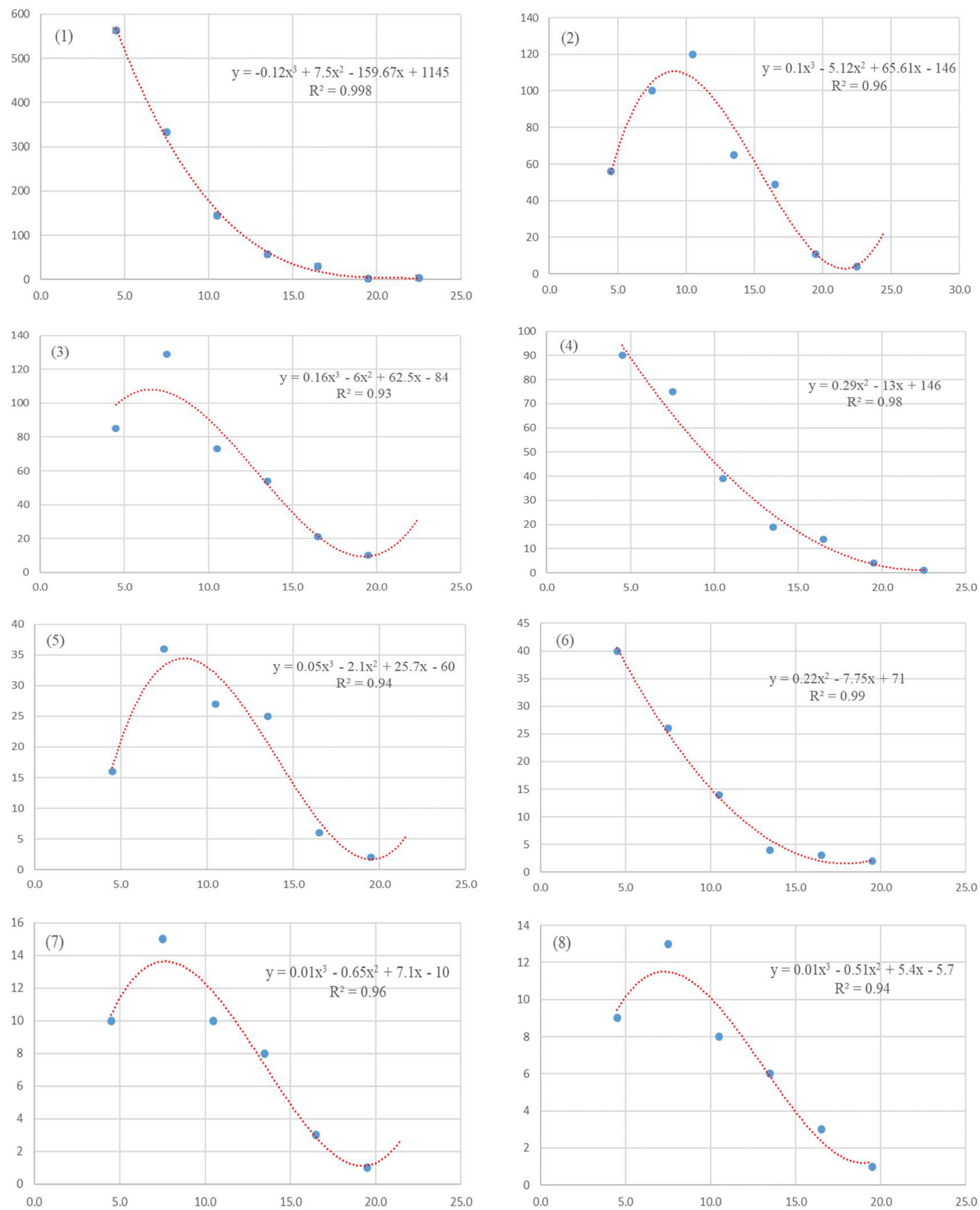

Figure 3. *Off fault landslides in (1) folded terrigenous sedimentary rocks, (2) granite, (3) metamorphic rocks, (4) terrigenous sedimentary rocks with sub-horizontal attitude, (5) gneiss, (6) limestone/carbonate rocks, (7) rhyolite, (8) basalt vs topographic slope angle.*

2.3.5. The relationship between topographical slope angle and off fault landslide occurrences

Topographic slope angle greatly influences the susceptibility of rainfall-induced landslides (Alkhasawneh et al., 2013; Çellek, 2020; Nakileza and Nedala, 2020; Zhang et al., 2012). However, statistical data on the relationship between two quantities of slope angle and landslide occurrences that accounted for different off fault kinds of rocks are rare. In this section, such a relationship was established and given in Table 3 and visualised in Figure 3. It represents the relation between landslide occurrences on the various kind of petrography vs topographic slope angles. These relations can be divided into two groups. The first group includes diagrams 1, 4 and 6 corresponding to landslides that occurred on the folded terrigenous sedimentary, terrigenous sedimentary with a sub-horizontal attitude and limestone/carbonate rocks. Notably, they are all sedimentary rocks. The maximum number of landslides on these rocks occurred mostly on topography with a moderate slope angle of about five degrees and gradually diminuation with respect to increasing slope angle. In contrast, the second group, including diagrams 2, 3, 5, 7 and 8, exhibited a different distribution. The landslides on these igneous and metamorphic rocks have trend maximisation and minimisation at the slope angle between 5 to 15 and 20 to 25 degrees, respectively. Thus, two trends of landslide distribution concerning topographic slope angle revealed the sedimentary rock's distinct behaviour compared to igneous and metamorphic rocks regarding landslide susceptibility. In the areas where the igneous and metamorphic rocks are exposed, landslides tend to occur mainly in areas with a slope angle of 5 to 15 degrees compared to less than 5 degrees for areas where the sedimentary rocks are exposed.

2.3.6. Implications for size, frequency and landslide-prone areas

Despite the complexity of soil and landslide, works on the slope stability documented that the occurrence of landslides is controlled by the Mohr-Coulomb criterion, which can be represented by the ratio between two quantities of shear strength and shear stress in a point of weathering materials (Zhu et al., 2017). When the ratio of materials shear strength upon shear stress induced by the weight of materials exerting on the slope exceeds one, theoretically, the landslide will not occur. Due to the slope angle being more or less proportional to the resistant force and inversely reciprocal with the stability of the slope, the topographic slope angle combined with the petrographic features can be used as an estimator for the size and volume of potential landslide susceptibility. Therefore, the difference between analysed trends for two different rock types revealed that the resistant stress required for the occurrence of landslides in the areas where sedimentary rocks crop out is smaller than that in igneous and metamorphic ones. This also implies that the volume of weathering materials derived from sedimentary rocks accumulated on slopes necessary for generating landslides is small. Consequently, the landslide size and volume in sedimentary rocks are also moderate. Conversely, weathering materials derived from igneous and metamorphic rocks required to generate potential landslides on a higher slope angle will be more voluminous. Therefore, the size and volume of landslides in igneous and metamorphic rocks will be more significant, subsequently leading to loss more severely. The topographic slope angles concerning landslides on the terrigenous rocks (57,8% of cases) are smaller than that of the igneous and metamorphic rocks areas. However, the total number of landslides on the terrigenous rocks is more significant than that in igneous and metamorphic rocks. This implies that the frequency of occurrences or reoccurrences of landslides on sedimentary is higher than on igneous and metamorphic rocks (33,9% of cases).

Combining bivariate analysis results obtained in this study allows us to identify that geological factors, including fault networks, petrographic features, and geological structures, play a decisive role in producing the weathering materials necessary for landslide generation. The areas where the fault zones cut exposed magmatic and metamorphic rocks tend to generate large size and voluminous landslides. Such landslides subsequently can cause damage to property and life loss. Typically like the case of deadly and damaged landslides occurred on 12th and 18th Oct 2020 and 28th Nov 2020 at Rao Trang 3 hydropower site of Phong Điền commune, Thon Cop (Tiger village) of Hướng Phùng commune, Hướng Hóa district and Tra Leng commune of Nam Tra My respectively. Major regional faults and granitic or migmatitic rocks coexist in all three areas. All three landslides occurred on the slope with a moderate angle but thick weathering crust. The Thon Cop landslide occurred on the biotite rich granodiorite damaged by a regional shear zone reactivated as a brittle fault, namely the Huong Hoa-Hue fault. The Rao Trang 3 landslide occurred on the foliated two micas gneissic granite and was damaged by another fault of Huong Hoa-Phu Loc. Both of these faults are branch faults of an important regional shear zone, namely the Da Nang-Tha Khet fault. Tra Leng landslide located at the high-grade metamorphic rocks area where the high density of branch faults extend in the E-W strike of the Tra Bong shear zone system.

3. Conclusions

Based on the analysing of the relationship of the distribution of 7855 historical landslide occurrences in 20 provinces in Vietnam with fault zones, litho-petrologic features and topographic slope angles, the following conclusions can be identified:

a. Landslide density is highest in the group of granite, gneiss and metapelite rocks. The most negligible density of landslide refers to the group of limestone/carbonate rocks, whereas the terrigenous rocks, rhyolite and basalt record an intermediate density.
b. The number of landslide occurrences on the folded and sub-horizontal attitude terrigenous rocks is the highest and corresponds to approximately 58%. In contrast, the total landslide occurrences on the igneous and metamorphic rocks hold 34%. The limestone/carbonate rocks, rhyolite and basalt rarely generate numerous landslides. Only approximately 8% of total landslide occurrences have been recorded on three kinds of such rocks.
c. A corridor of 2 km wide of shear and fault zones with a length of over 5km controls 69% of historical landslide occurrences, whatever the nature of litho-petrography in which the fault zones cut through them.
d. The off-fault landslide occurrences focus primarily on the topographic slope angle of 5 to 20 degrees. In the areas where the igneous and metamorphic rocks are exposed, landslides tend to occur mainly in areas with a slope angle of 5 to 15 degrees compared to less than 5 degrees for areas where the sedimentary rocks are exposed.
e. Areas with the simultaneous presence of fault zones that cut through magmatic and metamorphic rocks are likely to be more favourable for generating landslides with large sizes and significant volumes than areas with the fault zone that cuts through the terrigenous rocks.

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