

Erosion risk assessment: A case study in Lam Dong province, Vietnam

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Abstract: In recent years, landslides have increasingly become a pressing issue in Vietnam for many causes, in which erosion is that which promotes landslides occurrence. Therefore, this paper examined the erosion level in Lam Dong province using an empirical equation of the particle size distribution named as “ROM scale”. Based on the categories of “Critical”, “Very high”, “High”, “Moderate” and “Low” range, the erosion risk in various areas was identified. Laboratory analysis results showed that most samples were sandy clay loam, clay, clay loam, and silty clay. Combined with site investigation results, this paper clarified the linear relationship between soil texture and the erosion level as well as the influence of vegetation cover on the erosion level. From there, early forecasts can be made and solutions to reduce landslides can be proposed, aiming at socio-economic development. The results of this study can also serve as a basis and premise for further studies in the whole Lam Dong province.

Keywords: Erosion level; ROM scale; critical shear stress; soil texture; vegetation cover

1. Introduction

Landslide is a natural disaster, not only affecting the regional economic development, but also threatening the daily livings of human being. Landslide occurs mainly in mountainous areas, or even in low relief areas due to geological structure, climate change and human activities. Recent years, it has become more frequent at severe consequences. With a diverse topography, Vietnam is naturally predisposed to landslide occurrences in both high mountains and steep hills. The situation is exacerbated by the country's tropical monsoon climate, which brings heavy rainfall, especially during the rainy season from May to October. These climatic conditions, combined with rapid socio-economic development, deforestation, and infrastructure expansion, have significantly heightened the risk and impact of landslides across the nation. “Landslides, also known as landslips, or rockslides, are several forms of mass wasting that may include a wide range of ground movements, such as rockfalls, mudflows, shallow or deep-seated slope failures and debris flows” [1]. Landslides occur primarily in highland area, but they can also occur in low relief areas because of human activities such as construction (roadway and building excavation, deforestation), mining (coal, quarries and open-pit mines) [2]. For mountainous areas, there have been many studies worldwide and in Vietnam on the factors causing landslides, in which the main factors include geological structure, heavy rainfall [3-7], climate change [8-11] and human activities [12].

Located in the highland area, Lam Dong province faces a high risk of landslide disaster. Mass movement contains economical and fatal consequences. For example, a catastrophic landslide on June 17th 2023, with a 8-rock talus unexpectedly collapsed in Loc Chau Commune, Bao Loc City, resulting in one death and four injuries. Following this, on June 29th, Dalat City witnessed 13 landslides, leading to two deaths, three injuries, and substantial damage to numerous houses. The most severe incident occurred on Hoang Hoa Tham Road, where a talus collapse caused two deaths and five injuries (Fig. 1b). On July 30th, a soil talus behind the Madagui Traffic Police Station collapsed, burying three traffic police officers and one civilian, completely cutting off traffic through Bao Loc Pass (Fig. 1a).



Fig. 1. (a) A fatal landslide at Bao Loc Pass, occurred on July 30th 2023; (b) a landslide at Hoang Hoa Tham street, occurred on June 30th 2023 [21]

For geological structure, sand, silt and clay contents play an important role in the soil structure which results in landslides. Therefore, the purpose of this paper is to calculate the erosion index using the “ROM” scale based on the sand, silt and clay content. From there, predict areas at risk of landslides to provide early warning and propose preventive and mitigation measures.

2. Methods

2.1. Site investigation

The authors carried out a preliminary field survey and took soil samples at a depth of 1.5 m below the natural ground surface at 11 locations, that have experienced or are at risk of future landslides (Fig. 2). At each sampling point, parameters such as terrain elevation, vegetative structure, and weather conditions were recorded to serve the analysis and correction of more accurate results.

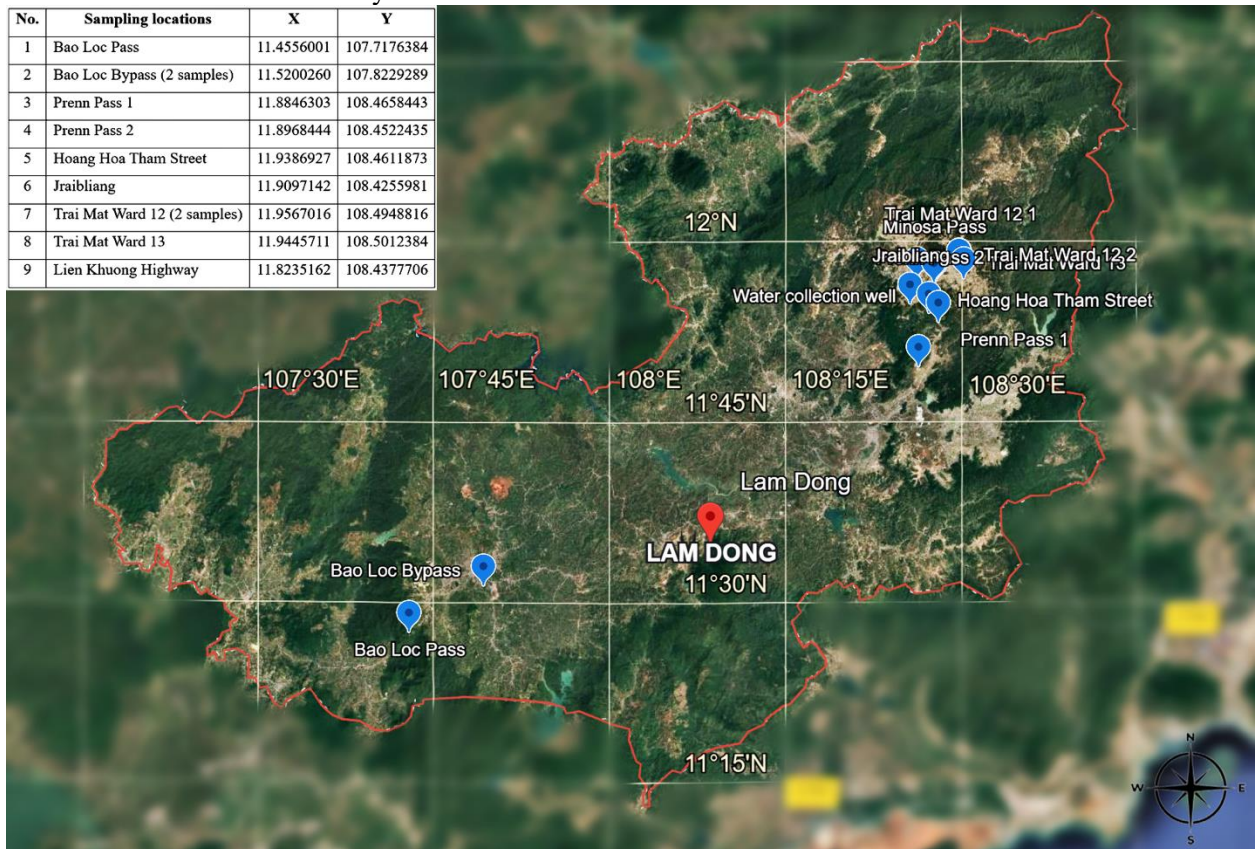


Fig. 2. Sampling locations

The hand auger sampling method was used to took the soil samples at a depth of about 1.5 m compared to the natural ground. The procedure is as follows: The sampling location is selected, and the surface is cleared of debris such as leaves, grass, or stones. The hand auger is then positioned at the designated spot and rotated clockwise to penetrate the soil. The auger is driven down continuously until it reaches the desired depth of 1.5 m. Periodically, the auger is removed to collect the soil sample and stored

in the sample container. Once the target depth is achieved, the soil sample is carefully extracted from the auger, labeled, and preserved for subsequent analysis. Proper preservation of the sample is essential to maintain its original properties, avoiding exposure to direct sunlight and high temperatures.

2.2. Laboratory analysis

Soil samples were brought to the laboratory to analyze geotechnical properties including grain size analysis, moisture content, liquid limit, plastic limit, density, void ratio, shear strength determination. Grain size was analyzed according to the norm TCVN 4198: 2014 [13] using dry sieving method for grain size larger than 0.5 mm, wet sieving method for grain size larger than 0.1 mm, both methods used sieve set with mesh sizes: 10, 5, 2, 1, 0.5, 0.25 and 0.1 mm, and hydrometer method for grain size smaller than 0.1 mm using hydrometer, desiccator and some chemicals such as NH₄OH 25%, HCl 10%, HNO₃ 10%, Na₂P₂O₇ 4%. For soil analysis, liquid limit and plastic limit were determined according to the norm TCVN 4197: 2012 [14] using Casagrande apparatus, moisture content according to the norm TCVN 4196: 2012 [15], shear strength according to the norm TCVN 4199: 1995 [16] with shear box apparatus. These tests were all performed under standard conditions in the laboratory.

2.3. Assess the level of geological erosion

Sand, silt and clay contents are factors affecting soil erosion. Therefore, from the results of grain size distribution, the erosion index is calculated based on the sand, silt and clay contents, with 5 levels of low, moderate, high, very high and critical. Bouyoucos (1962) [17] used formula (1) to calculate the Bouyoucos erosion index.

$$\text{Bouyoucos erosion index} = \frac{\% \text{ sand} + \% \text{ silt}}{\% \text{ clay}} \tag{1}$$

This index was extended into the “ROM” scale by Zainal Abidin and Mukri (2002) [18] (Julian and Torres (2006) [19]) according to formula (2).

$$EI_{ROM} = \frac{\% \text{ sand} + \% \text{ silt}}{2. \% \text{ clay}} \tag{2}$$

In Table 1 there are compared the “ROM” scale and the Erosion level.

Table 1. Five erosion levels based on “ROM” scale

"ROM" scale	Erosion level
<1.5	Low
1.5÷4.0	Moderate
4.0÷8.0	High
8.0÷12.0	Very high
>12	Critical

The critical shear stress, τ_c is estimated using empirical formulas based on the percentage of silt - clay particles (SC%) from results presented by Dunn (1959) [20] and Vanoni (1977) [21] (equation 3). Additionally, Smerdon and Beasley (1961) [22] developed empirical relationships between soil properties such as the plasticity index (I_w), mean particle size (D_{50}), and percentage of clay by weight (P_c)—and the critical shear stress (refer to equations 4 to 6).

$$\tau_c = 0.1 + 0.1779(SC) + 0.0028(SC)^2 - 2.34E - 5(SC)^3 \tag{3}$$

$$\tau_c = 0.16(I_w)^{0.84} \tag{4}$$

$$\tau_c = 3.54 \times 10^{-28.1D_{50}} \tag{5}$$

$$\tau_c = 0.493 \times 10^{0.0182P_c} \tag{6}$$

3. Results

3.1. Grain size distribution

Soil samples were taken at 11 locations, and described as follow (Table 2):

Tab. 2. Summary of soil samples

No.	Name of sample	Description
1	Lien Khuong Highway	Basaltic clay, reddish brown – yellowish brown, semi-rigid state
2	Hoang Hoa Tham Street	Sandy clay, yellowish brown – ash grey, rigid plastic state
3	Trai Mat Ward 12 S1	Basaltic clay, reddish brown – yellowish brown, semi-rigid state
4	Trai Mat Ward 12 S2	Basaltic clay, reddish brown, rigid plastic state

5	Trai Mat Ward 13	Basaltic sandy clay with
6	Jraibliang	Basaltic sandy clay, yellowish brown, rigid plastic state
7	Bao Loc Bypass S1	Basaltic clay, reddish brown, rigid plastic state
8	Bao Loc Bypass S2	Basaltic clay, reddish brown, rigid plastic state
9	Bao Loc Pass	Basaltic clay with laterite grit, reddish brown, yellowish brown, rigid plastic state
10	Prenn Pass S1	Basaltic sandy clay with laterite grit,
11	Prenn Pass S2	Weathered basaltic clayey, whitish gray, yellowish brown, rigid plastic state

Fig. 3 shown that the soil samples from the research locations span a range of soil texture classes, with most samples are within the sandy clay loam, clay, clay loam, and silty clay categories. Notably, Trai Mat Ward 12 S2 and Prenn Pass S2 are situated in the clay loam region, indicating a balanced mixture of sand, silt, and clay. This texture is known for good nutrient retention and moderate drainage properties, which can contribute to soil stability in these areas. Lien Khuong Highway, Bao Loc Pass and Bao Loc Bypass are situated in the clay region, but they're quit balanced mixture. Bao Loc Bypass S1 and Trai Mat Ward 12 S1, on the other hand, is classified as silty clay, characterized by higher clay content and relatively low sand content. Soils with a higher clay content are generally more cohesive, providing higher shear strength, but they are prone to swelling and shrinking. In contrast, Jraibliang, Prenn Pass S1, Hoang Hoa Tham Street and Trai Mat Ward 13 are identified as sandy clay loam, where the sand fraction is higher. Sandy clay loams offer good drainage but are less cohesive than pure clay soils.

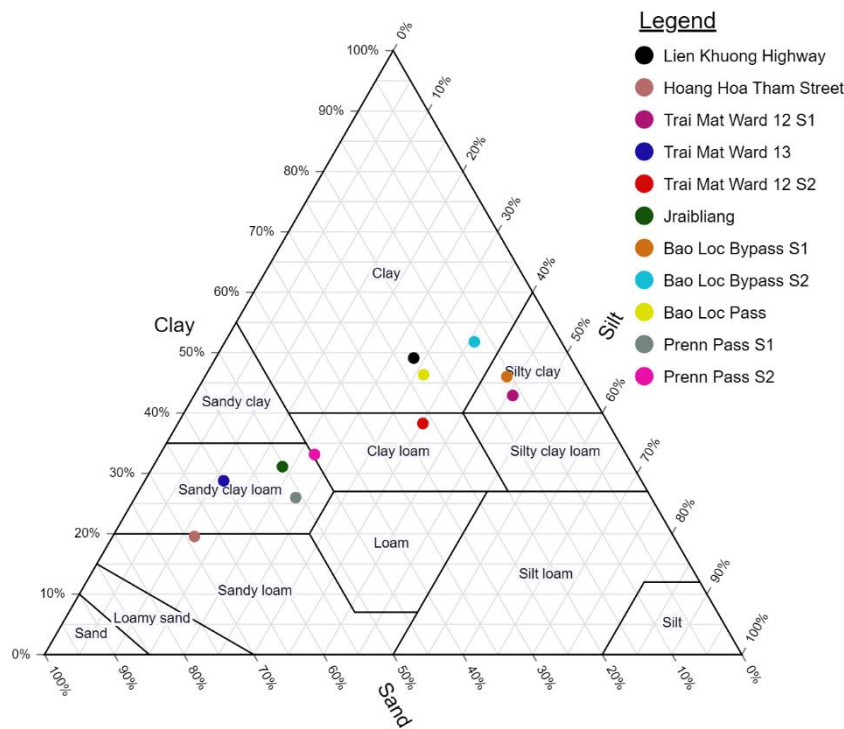


Fig. 3. Grain size distribution [Source: USDA]

3.2. Evaluating the erosion index of geological structures

The result of erosion level assessment shown that most of the locations had low erosion levels, with EI_{ROM} values typically below 1.0 (Table 3). Notably, Lien Khuong Highway, Trai Mat Ward 12 (both S1 and S2), Bao Loc Bypass (both S1 and S2), and Bao Loc Pass have EI_{ROM} values ranging from 0.47 to 0.81, indicating relatively stable conditions with minimal erosion risk.

However, two locations stand out due to their moderate values: Hoang Hoa Tham Street and Prenn Pass S1. Hoang Hoa Tham Street, with an EI_{ROM} value of 2.06, is categorized as having a moderate erosion level. This finding suggests that this area is more susceptible to erosive forces. On the other hand, Prenn Pass S1, with an EI_{ROM} value of 1.42, is classified as having a low erosion level, but it is on the higher end of the low level.

Tab. 3. Evaluation index of erosion level

Location	EI_{ROM}	Erosion level
Lien Khuong Highway	0.52	Low
Hoang Hoa Tham Street	2.06	Moderate
Trai Mat Ward 12 S1	0.67	Low
Trai Mat Ward 13	1.24	Low
Trai Mat Ward 12 S2	0.81	Low
Jraibliang	1.11	Low

Location	EI_{ROM}	Erosion level
Bao Loc Byass S1	0.59	Low
Bao Loc Byass S2	0.47	Low
Bao Loc Pass	0.58	Low
Prenn Pass S1	1.42	Low
Prenn Pass S2	1.01	Low

3.3. Evaluating the critical shear stress using empirical equations

Among the locations assessed, Trai Mat Ward 12 S1 and Bao Loc Byass S2 exhibit the highest τ_c values related to silt-clay contents, at 21.567 Pa and 21.182 Pa respectively, indicating that these locations possess relatively strong soil resistance to shear stresses. In contrast, Hoang Hoa Tham Street shows the lowest τ_c value (6.763 Pa), signifying a potential vulnerability to shear failure and thus a higher risk for erosion or landslides.

The τ_c values calculated from plastic index (eq. (4)), which account for the influence of water content on soil shear strength, are generally lower than τ_c calculated from silt-clay contents (eq. (3)) across all locations (Table 4). This difference suggests that the presence of water considerably reduces the soil's shear resistance, a critical factor in regions with high rainfall.

When considering τ_c with percentage of clay, which reflects the influence of particle cohesion on shear strength, the results show a broad range of values, with Bao Loc Byass S2 showing the highest value at 4.127 Pa and Hoang Hoa Tham Street the lowest at 1.026 Pa. This variation highlights the differing soil compositions across the locations, with some areas having more cohesive, and therefore more resistant, soils.

Finally, the τ_c values related to the median grain size of the soil, show that the particle size distribution plays a substantial role in the overall shear strength (Table 4). The data reveal that locations such as Trai Mat Ward 12 S1 (3.4742 Pa) and Lien Khuong Highway (3.5081 Pa) have soils with larger particle sizes contributing to their shear strength, compared to smaller particle-sized soils at Prenn Pass S2 (1.2093 Pa).

Tab. 4. Evaluation the critical shear stress (Pa)

Location	$\tau_c (SC)$	$\tau_c (I_w)$	$\tau_c (P_c)$	$\tau_c (D_{50})$
Lien Khuong Highway	19.812	2.331	3.859	3.5081
Hoang Hoa Tham Street	6.763	1.305	1.026	2.2623
Trai Mat Ward 12 S1	21.567	2.223	2.976	3.4742
Trai Mat Ward 13	7.467	1.411	1.234	1.8535
Trai Mat Ward 12 S2	18.755	2.179	2.393	3.4207
Jraibliang	12.017	1.720	1.662	3.1569
Bao Loc Byass S1	20.596	2.275	2.890	3.4585
Bao Loc Byass S2	21.182	2.432	4.127	3.5240
Bao Loc Pass	15.642	2.136	2.182	3.2167
Prenn Pass S1	10.140	1.393	1.194	2.8910
Prenn Pass S2	6.959	1.286	1.014	1.2093

4. Discussion

4.1. Relationship between soil texture and erosion risk

The distribution of soil textures across these locations has direct implications for erosion risk and land management strategies. Locations with a higher clay content, such as Hoang Hoa Tham Street and Lien Khuong Highway, might experience lower immediate erosion risk due to the cohesive nature of clay. However, these areas require careful management to prevent issues related to water retention and soil swelling, which could compromise infrastructure and lead to gradual erosion.

On the other hand, areas classified as sandy clay loam, such as Prenn Pass S2 and Trai Mat Ward 13, might face higher erosion risks due to the lower cohesion of sandier soils. These locations would benefit from soil conservation practices, such as vegetation cover or engineered structures, to reduce the impact of surface runoff and prevent soil loss.

Tab. 5. The correlation between erosion level and soil texture

Erosion level	Min / Max	% Sand	% Silt	% Clay	τ_c (Pa)
Moderate		61.5	10.5	17.5	6.76
Low	Min	9.8	8.6	17.2	6.96
	Max	46.9	39.7	50.7	21.18

Data in Table 5 suggests that soils with higher clay content tend to exhibit greater resistance to erosion, as indicated by the higher τ_c values observed in the low erosion category. Clay particles are known for their high cohesion and ability to bind together, forming a more stable soil structure that resists erosion. This characteristic is crucial for soil conservation efforts, particularly in regions prone to heavy rainfall or other erosive forces.

On the other hand, the moderate erosion observed in sandy soils underscores the need for targeted erosion control measures in areas with high sand content. Such soils may benefit from interventions such as the addition of organic matter, which can enhance soil cohesion, or the implementation of physical barriers to reduce the impact of surface runoff.

Fig. 4 shows the relationship between the "ROM" erosion index and soil moisture, where the ROM index generally decreases as soil moisture increases. This suggests that soils with lower moisture content are more susceptible to erosion, potentially due to reduced cohesion in drier soils. Drier soils often have fewer binding forces between particles, making them more vulnerable to shear forces that contribute to erosion.

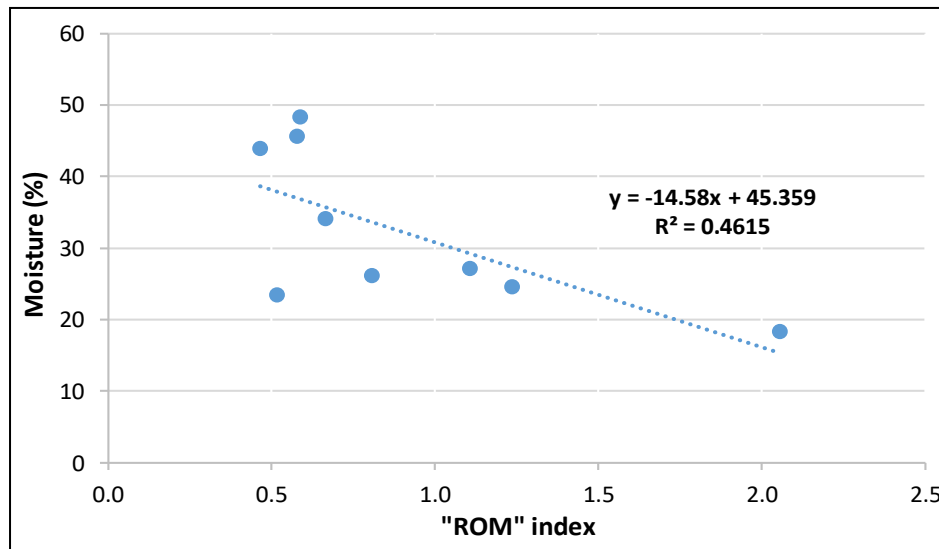


Fig. 4. Relationship between "ROM" index and soil moisture

However, there are some outliers in the data. For instance, certain points with high moisture exhibit relatively low ROM index, while some points with lower moisture content do not correspond to high erosion risk. These irregularities could stem from differences in soil composition, particularly the proportions of clay, silt, and sand, which influence how moisture affects cohesion. Soils with a high clay content retain moisture well and typically resist erosion better, while sandy soils, even with some moisture, may remain prone to erosion due to their larger particle sizes and lack of cohesion. These observations suggest that, while moisture is an important factor, it interacts with soil texture to affect erosion susceptibility.

4.2. The influence of vegetation cover on erosion levels

Tab. 6. The relationship between erosion level and vegetation cover

Location	Erosion Risk	Vegetation cover
Lien Khuong Highway	Low	Grass
Hoang Hoa Tham Street	Moderate	No

Location	Erosion Risk	Vegetation cover
Bao Loc Byass S1	Low	Grass
Bao Loc Byass S2	Low	Grass

Trai Mat Ward 12 S1	Low	Grass
Trai Mat Ward 13	Low	Grass + Pine Tree
Trai Mat Ward 12 S2	Low	Grass
Jraibliang	Low	Grass

Bao Loc Pass	Low	Grass
Prenn Pass S1	Low	Pine Tree
Prenn Pass S2	Low	Pine Tree

Most of the locations where grass is the dominant vegetation cover, such as Lien Khuong Highway, Trai Mat Ward 12 S1, Trai Mat Ward 13, Bao Loc Bypass S1, Bao Loc Bypass S2, and Bao Loc Pass, exhibit low erosion levels. Moreover, Hoang Hoa Tham Street is the only location with moderate erosion levels, and notably, it lacks any vegetation cover (Table 6). These suggests a direct link between the absence of vegetation and higher susceptibility to erosion. Without vegetation, the soil is exposed to the full impact of environmental forces, leading to greater soil loss and degradation. The absence of roots also means there is no organic matter to bind the soil particles, resulting in higher erosion rates.

4.3. Relationship between ROM index and estimated critical shear stress

Fig. 5 illustrates the relationship between the "ROM" index and estimated critical shear stress values, τ_c derived from different soil parameters: plasticity index (I_w), clay content (P_c), median particle diameter (D_{50}), and combined silt - clay content (SC). Overall, the data show a decreasing trend in critical shear stress as the ROM index increases, suggesting that as the soil's resistance to shear forces tends to decrease, the erosion potential grows.

For most parameters, data points are clustered relatively close to the trend lines, indicating a consistent relationship with critical shear stress. However, the critical shear stress based on SC exhibits notable outliers, where certain data points lie further from the trend line. This deviation may indicate that the combined silt - clay content does not uniformly influence shear strength, as variations in clay-to-silt ratios could lead to unpredictable soil behavior. Soils with higher clay proportions generally show stronger cohesion and greater resistance to shear stress, whereas silt-dominant mixtures may lose structural integrity more easily, particularly under drying or stress conditions.

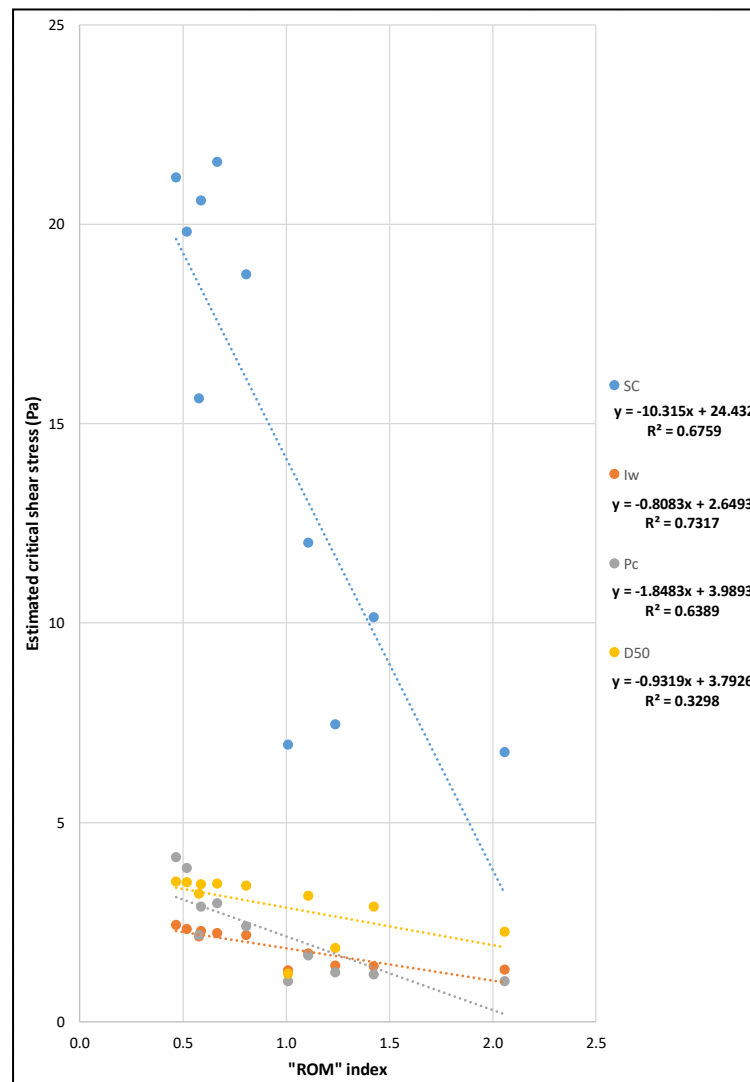


Fig. 5. Relationship between ROM index and estimated critical shear stress

5. Conclusion

This paper assessed the erosion level at 11 locations that have been and are at risk of landslides in Lam Dong province based on the ROM scale and estimated the critical shear strength using empirical formulas. From there, the following conclusions are drawn:

- The soil samples from the research locations span a range of soil texture classes, with most samples falling within the sandy clay loam, clay, clay loam, and silty clay categories. The clay loam is a balanced mixture of sand, silt and clay, is known for good nutrient retention and moderate drainage properties, which can contribute to soil stability in these areas. The silty clay with a higher clay content are generally more cohesive, providing higher shear strength, but they are also prone to swelling and shrinking, which can lead to structural instability in the presence of moisture changes. The sandy clay loam offer good drainage but are less cohesive than pure clay soils. This makes them more susceptible to erosion, especially under heavy rainfall, although their shear strength remains significant due to the presence of clay.
- The observed variability in τ_c estimates reflects the complex nature of soil behavior and the influence of different empirical approaches. This highlights the need for careful consideration when selecting empirical formulas for estimating critical shear strength, particularly in diverse and complex landscapes.
- The results emphasize the importance of maintaining and enhancing vegetation cover, particularly in erosion-prone areas. Grass, due to its wide coverage and dense roots, plays a vital role in minimizing soil erosion, especially on slopes and areas exposed to runoff. Meanwhile, the introduction or maintenance of tree species, such as pine, can provide deeper root systems that further stabilize the soil, particularly in areas where grass alone may not suffice.

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