# Lake Cliff Landslide Mitigation – A Case Study of Lut Tawar Peusangan Lake, Aceh, Indonesia

Ulil Amri[1], Cut Azizah[1,2]*, Ernawita[1], Sarif Robo[3], Nuraida[4],
Romaynoor Ismy[2], Halus Sastriawan[1]

[1] Environmental and Natural Resources Management Master Program, Al Muslim University, Bireuen, Aceh, Indonesia

[2] Civil Engineering Study Program, Al Muslim University, Bireuen, Aceh, Indonesia

[3] Soil Science Study Program, Khairun Gambesi University, South Ternate, Maluku Utara, Indonesia

[4] Forestry Study Program, Al Muslim University, Bireuen, Aceh, Indonesia

* Corresponding author's e-mail: cutazizah@umuslim.ac.id

**ABSTRACT**

Landslide is one of the most common natural disasters in Indonesia. In Lut Tawar Lake, specifically the cliff side, the landslide event occurs almost daily. Mitigation effort becomes a necessity following the fatality cases it causes. This study aimed to identify landslides and suitable mitigation for the case of Lut Tawar's lake cliff. A combined approach of landslide survey and image interpretation with field validation was used. In addition, local vegetation surrounding the case area was identified from the survey and interview process. The results showed there are in total 37 landslide points in the study area. The conducted analysis showed the landslide was mainly caused by land use change from forest to a plantation, slope, particularly in the cliff area that was carved for road development, the volcanic geology of Bukit Barisan mountain, rainfall intensity, and the equatorial rainfall characteristic of the study area. The results also suggest the finest solution for landslide mitigation, namely the eco-engineering approach, a revegetation method using the local vegetation. Local vegetation comprises multiple strata, of which grass in the below strata, shrubs in the middle strata, and trees in the upper strata, constitute a shield for the lake cliff. Within this structure, government and community can cultivate these plants in the surrounding lake area.

**Keywords:** cliff, eco-engineering, lake, landslide, mitigation, vegetation, volcanic.

## INTRODUCTION

Landslides are extremely dangerous for the area below the cliff. Any movement from stones, soil, and debris down the slope can cause mortality and damage (Highland, 2008; Ilyas, 2016). The fatality caused by landslides reached approximately 55.997 persons from various events (Froude Melanie. 2018). The damages from landslides affect the economy, road infrastructure, settlement, and environment. The people affected by the landslide were highly prone to have short-term and long-term mental health issues, following the loss of relatives, assets, livestock, and plantations. Landslides also have an enormous impact on the health system and public services,

for instance, water, electricity, and communication network (Perera et al., 2018; Šilhán, 2021; Chalov et al., 2016).

Landslide is one of the most common natural disasters in Indonesia (Yuniawan et al., 2022). Over time, the event showed an increasing trend, estimated to be 18 percent in the last few years (BNPB, 2022). This was due to the country's humid tropic characteristic with high rainfall (Azizah et al., 2022; Lee, 2015), an extensive area with a steep slope (Ilyas, 2016), soil vulnerable to movements (BNPB, 2014), and land use change (Pagiola, 2000).

According to (Highland, 2008; Tyagi, Tiwari and James, 2022), a landslide was caused by erosion, slope failure, earthquake, and volcanic

eruption. In some cases, landslides were highly connected to another phenomenon. For instance, earthquakes trigger a landslide, causing a clogged river stream that is vulnerable to collapse; hence, leading to flash floods (Azizah et al., 2022; Gonda et al., 2014). Referring to Christenson et al., (2015); Maturidi et al., (2021), erosion and slope failure are triggered by extreme rainfall, floods, deforestation, and steep terrain. The steep terrain is mainly located in the high cliff area (e.g., volcanic lake cliff).

High cliff in volcanic lake is unsafe for human activity due to a high landslide potential (Barbano et al., 2014). Any disturbance to the volcanic lake cliff or anthropogenic activity (i.e., construction of road, settlement, and public facility) should be equipped with a cliff protection strategy to hinder slope failure that causes landslides (Masannat, 2014).

Protection of the lake cliff includes the construction of the cliff protection, such as embankment construction (Masannat, 2014; Kimura, Nagata and Kan, 2020); however, this option demands a high cost for the case of a high and extensive cliff (Chakrabarti and Cheenikal, 2013; Zhang and Chen, 2019). Eco-engineering concept is one of the feasible solutions (Bergen, Bolton and Fridley, 2001; Zhang et al., 2021).

Eco-engineering is a manipulated design to predict, construct, develop or recover, and manage an ecosystem by integrating humans with the natural environment for mutual interest (Bergen, Bolton and Fridley, 2001). In the case to support land cliff, eco-engineering is a construction design that uses the vegetation from the natural ecosystem to prevent landslide (Genet et al., 2008; Lu, 2014; Chen, Wu and Lin, 2014; Zhang et al., 2021; Spiekermann et al., 2022). Vegetation roots will strengthen and enhance the soil movement in the surface layer. Vegetation helps to maintain soil cover from the strong and extended root, increasing the cohesive capacity and effectively maintain the formation to the vulnerable foundation; therefore, increase the soil stability (Spiekermann et al., 2022; Genet et al., 2008).

Lut Tawar is a volcanic lake in the Gayo highland, part of Bukit Barisan's ridge on Sumatra island (Ifani, 2019; Iriadi et al., 2015). The lake has become a national and international tourist attraction due to its exquisite landscape, Gayo tribe culture, ecosystem, Gayo coffee, and endemic fish (Muchlisin, Musman and Azizah, 2010; Ifani, 2019; Iswanto and Suryana, 2020; Adhar, 2005). The number of visitors in the last five years amounted to 150 thousand people per year (Disparpora, 2021). The lake is surrounded by a



**Figure 1.** Lut Tawar Lake with its public building surrounding the area, like roads (c) (yellow arrow), hotel (d), and settlement (e). Landslides block the road area and cause fatality (a) and in a few locations, the cliff has no land cover/vegetation (b)

cliff with roads lengthening on the edge. Land use in the perimeter of the lake is dense with hotel, settlement, prayers building, restaurant, and camp site (Figure 1).

The steep and high cliff surrounding the lake has led to landslide events in multiple locations, causing death and damage (Ardi, 2012; Warsidi, 2017; Nisak, 2022; Yunus, 2022). The area becomes vulnerable to falling with gigantic stones hanging to the cliff (Figure 1). The landslide in Lut Tawar Lake has been a concerning issue for the local community and government. Therefore, this study aimed to identify the landslide location and to formulate mitigation activity for the landslide in Lut Tawar Lake cliff.

## METHODOLOGY

### Study area

The study was conducted in Lut Tawar Lake, part of Krueng Peusangan watershed (Figure 1), Central Aceh District. Lut Tawar is upstream of Krueng Peusangan watershed, a cross-district watershed in Aceh Province, which includes Central Aceh, Bener Meriah, North Aceh, and Bireuen. Geographically, Lut Tawar Lake is located at 04°34'43" N dan 96°55'25" E. The lake extended for 57.8 km², with a periphery of around 46.12 km. The water catchment of the lake is around 246.5 km² with a height of 1.205 m above sea level.

### Data preparation and analysis

This study used Digital Elevation Model (DEM) data with 30 m of resolution from the US Geological Survey (USGS) to analyze the slope. In addition, the land use data from the remote sensing interpretation approach using the 2022 data year, calibrated and validated were employed. The land use data were referred to the Sentinel 2 image, with an acquisition date of June 13, 2022 (T47NKF). Ground checks were employed at 55 coordinate reference points in the field to verify the image interpretation. During the field verification process of the land use data, the coordinate points of
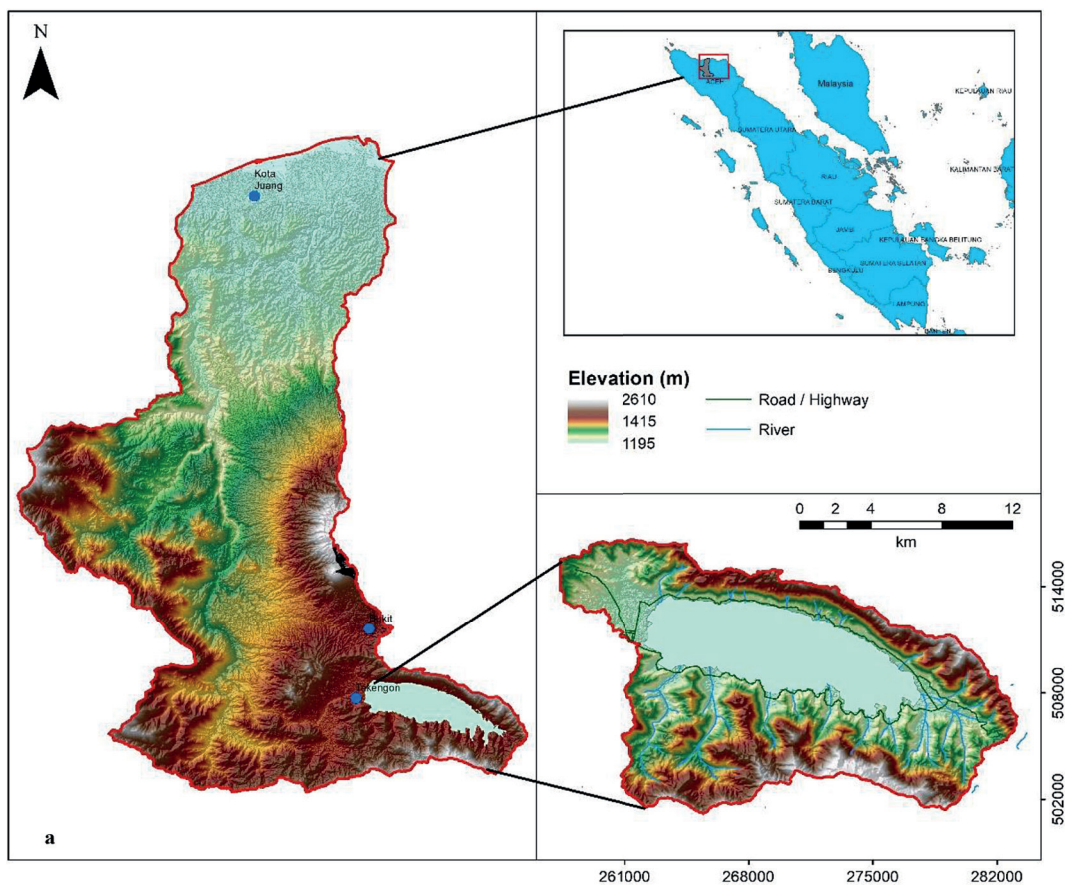


**Figure 2.** Lut Tawar Lake is one of the largest lakes on Sumatra island, Indonesia. The lake is the upper stream of the Peusangan watershed (a) that crosses four districts in Aceh Province

landslide events for the entire study area were also marked. Land slope and land use analysis were estimated using ArcGIS 10.5 tool (geographical information system).

The land use map is also used to determine the location for vegetation identification. A vegetation survey surrounding the cliff area of Lut Tawar Lake was conducted. The cliff area was explored for the purpose of finding indigenous vegetation. In this case, includes an intact ecosystem with no anthropogenic disturbance as the location for identification. Vegetation was identified by examining the flower, leaves, and roots. Vegetation as a protection to the cliff should fill the criteria in terms of life survival and physical condition of the vegetation, specifically the root's shape that should be strong enough to hold soils and stones in the lake cliff. Vegetation identification also considers local knowledge of the Gayo tribe to the native vegetation. In addition, the Google Lens tool was used to obtain additional information during the identification process.

## RESULTS AND DISCUSSION

### Landslide area

The results from field identification of the landslide in the study area in early August 2022 revealed 37 landslide points surrounding the lake (Figure 3). The right side of the lake (in Figure 3, bottom side) showed 23 landslide points and for the left side 13 landslide points. The landslide was located on the edge side near a busy road, frequently used by the local community and tourists. More landslide points are found on the right side compared to the left side, due to the different land use, of which plantation (e.g., coffee and pine) and agriculture dominate the right side of the study (Figure 3).

The land use change in the Lut Tawar land cliff from intact forest to coffee and pine plantation has increased the cliff landslide intensity. The result resonates with the study by Glade (2003); Chen and Huang (2013); Karsli et al. (2009), stated that vegetation cover is the most important factor influencing the occurrence and the rainfall
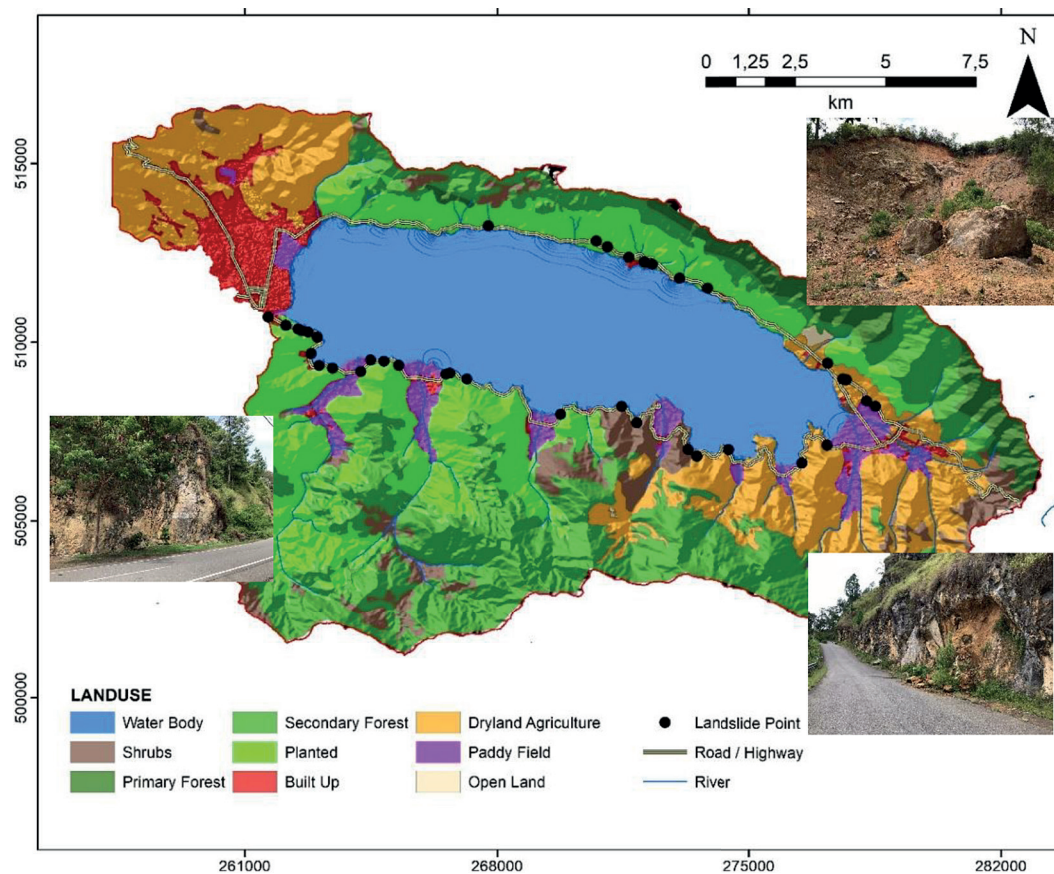


**Figure 3.** Landslide points in Lut Tawar Lake, specifically in the road surrounding the lake area. Visual images were captured in early August 2022. The figure also shows the land use in the water catchment area of the Lut Tawar Lake

movement that further trigger landslide event, and that the dynamic of the vegetation cover alters the landslide pattern.

Landslides are also triggered by the slope factor. Steeper slopes have less friction; hence, increasing the likelihood of landslide (Çellek 2022). The obtained results from slope analysis of the water catchment area in the study area have uncovered that the surrounding area of the lake was categorized as rather steep (29%), steep (16%), and very steep (2.6%). Flat and tilt area (33% and 19.6 %) mainly located in the downstream floodplains and the area where river stream to the lake. The steep area is indeed rather small; however, the location indicates the danger potential, where the cliff's slope was carved for the road surrounding the lake area (as visualized in Figure 3). These steep slopes were extremely dangerous for human activity, considering it is frequently crossed by drivers.

Landslides were caused by high-intensity rainfall. Referring to the studies on landslides globally (Polemio and Petrucci, 2000; Ferardi, Wilopo, and Fathani 2018), the statement is an undeniable scientific fact. Frequent landslide in Lut Tawar Lake was found to occur during high rainfall intensity. The results on the past five years landslide events show that the event was more frequent during April and November. This was due to an equatorial rainfall pattern in Aceh Province (Azizah, Nuraida, and Robo, 2022). The equatorial rainfall pattern has two peak periods of the rainy season; hence, causing two landslide occurrences in a year. The information on the peak rainfall is fundamental to receive more recognition as part of the prevention action of landslide disasters for both community and government (Caloiero, 2018).

The abundant cases of landslide in Lut Tawar Lake were also affected by the geological condition of the Gayo upland area that was part of Bukit Barisan ridge, extended along the Sumatra island. These ridges were known as the Great Sumatran Fault or *Patahan Semangko*. Lut Tawar Lake which was formed by both tectonic and volcanic activity was the main cause for the cliff to be highly vulnerable to landslide events (Alif, Fattah, and Kholil 2020; Alif, Fattah, and Kholil 2020).

## Revegetation as part of landslide mitigation

There was a saying that nature provide the solution for every problem they had. It is a suitable solution to overcome frequent landslides in Lut Tawar Lake by conducting revegetation under the eco-engineering approach. Planting a new tree in
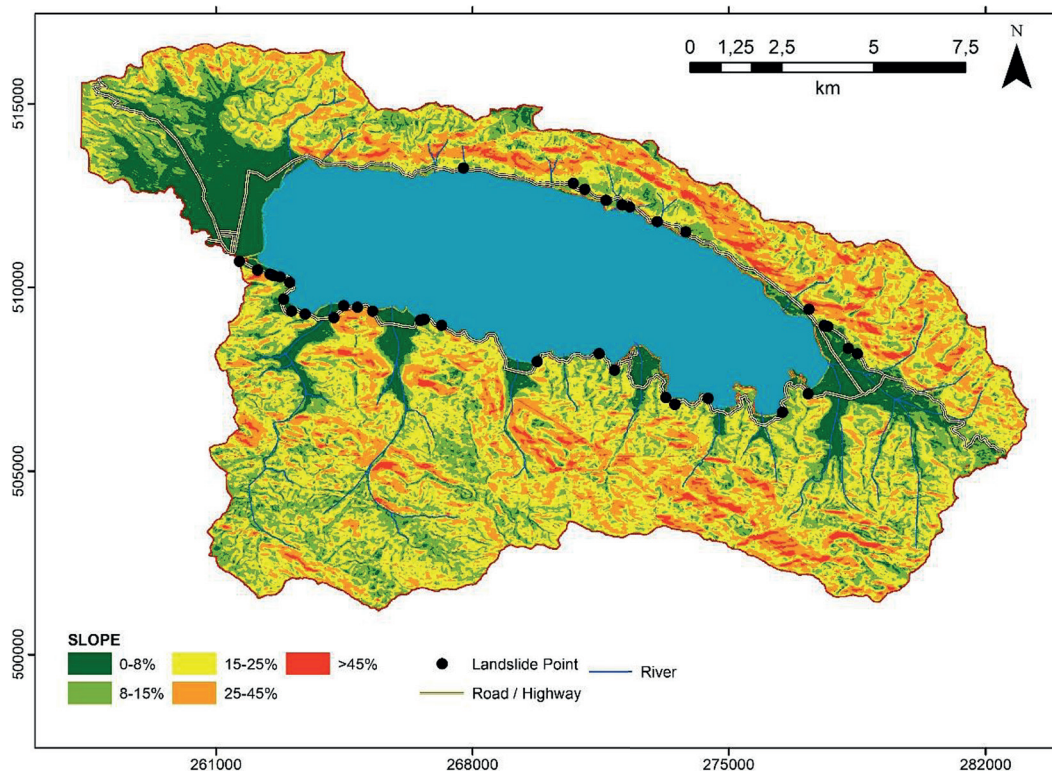


**Figure 4.** Slope of the catchment area in Lut Tawar Lake

the unvegetated area of the lake cliff become an efficient method to strengthen the cliff (Freschet et al., 2018). The embankment provided by the vegetation is sustainable yet economically acceptable compared to the concrete one.

One way to protect the lake cliff from slope failure is to construct cliff protection like an embankment (Masannat, 2014; Kimura, Nagata and Kan, 2020); however, this will demand a costly investment if the cliff were high and extensive (Chakrabarti and Cheenikal, 2013; Zhang and Chen, 2019). Embankment construction in some landslide points has been constructed and elevated; therefore, it requires huge spending. For the future, the option is not viable as Lut Tawar's perimeter could reach 46,12 km. In this case, the vegetation approach becomes one of the applicable solutions.

Franklin et al., (2013) stated that vegetation is a group of several trees growing together in a given space that forms one integrity, of which each species were in co-dependency to each other, known as a plant community. According to Forbes et al., (2013); Lu (2014); Widjaja, (2018); (Phillips et al., 2021) the most appropriate vegetation for cliff protection is the local one. Local vegetation has been adapted and is suitable for its endemic; thus, capable to function in its growing space. In this case, if they grow in the cliff area, they already functioning to protect the space and environment (Freschet et al., 2018).

The observation of the local vegetation in Lut Tawar Lake that could reduce the landslide impacts has a land cover feature of grass in the below strata; shrubs in the middle strata; and trees in the upper strata. These three strata worked together to hold the soils firmly and provide optimum protection to the lake cliff area. The vegetation type for each stratum were provided in Table 1 below.

The conducted study showed that the most common vegetation in the lake cliff area, dominated by stone texture, has its uniqueness. *Agave sp*, a native species from Mexico and Central America, is a vegetation that proved to have remarkable adaptation capacity in a dry environment, like the rocky surface of the Lut Tawar Lake. In its native country, *Agave* plays important roles to anchor soils and providing structural support for landforms (Matthew et al., 2018). Bamboo trees also took part in preserving the land structure and have been reported in studies due to their extensive root system (Tardio et al., 2018). *F. ceilanica*, which was discovered on the lakeside, was reported previously as a lithophyte that was grown on rocks (Widodo and Luthfi, 2018). The three levels of plants were then all together to provide support to the cliff of Lut Tawar Lake. The local vegetation can be cultivated by the government as part of a landslide mitigation strategy.

## CONCLUSIONS

The identification results show 37 landslide points on the cliff of Lut Tawar Lake. Landslide occurs due to the land use change from forest to a plantation, and slope, particularly in a cliff area that was carved for road development purposes. Other factors include the volcanic geology of the soil that was part of Bukit Barisan's ridge. The rainfall factor is the main cause of the landslide in the study

**Table 1.** Description of the vegetation identified at the edge of Lut Tawar Lake

| No. | Family | Scientific name | Local name* |
|-----|--------|-----------------|-------------|
| Below strata | | | |
| 1 | *Poaceae* | *Brachiaria* sp. | Rumput bede (Ind.) |
| 2 | *Asparagaceae* | *Agave* sp. | Agave, century plant (Ind.) |
| Middle strata | | | |
| 1 | *Verbenaceae* | *Lantana camara* | Tembelekan (Ind.) |
| 2 | *Piper umbelatum* | *Piper umbelatum* | Sirih-sirihan (Ind.) |
| 3 | *Poaceae* | *Bambusa* sp. | Uluh regen, uluh kuning (Gy), Bambu (Ind.) |
| 4 | *Melastomaceae* | *Melastoma malabathricum* | Senduduk (Ind.) |
| Upper strata | | | |
| 1 | *Muntingiaceae* | | Temung (Gy). |
| 2 | *Ficus sp.* | | Kayu kol (Gy). |
| 3 | *Bignoniaceae* | | Sakura (Gy). |
| 4 | *Gentianaceae* | *Fragraea ceilanica* | Kayu Pirak (Gy). |

**Notes:** *(Ind.) = name in Bahasa; (Gy.) = name in Gayo (local language).

area. The equatorial pattern of the rainfall also affects the landslide intensity to be twice a year.

Mitigation for the landslide in the lake cliff area can be done under the eco-engineering approach through revegetation using local/native species. Local vegetation for the below strata is grass (*Poaceae*; *Asparagaceae*), the middle strata is a shrub (*Verbenaceae*; *Piper umbelatum*; *Poaceae*; *Melastomaceae*), and for the upper strata is trees (*Muntingiaceae*, *Ficus sp*, *Bignoniaceae*, *Gentianaceae*) that could provide protection for the lake cliff. The government and local community can plant these species surrounding the lake area.

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