National road cliff protection analysis in Malibau Anai after Anai River flood, West Sumatra

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Abstract. Scouring of the riverbed can lead to landslides and erosion of the river bank. Landslides on river cliffs are a type of slope failure caused by the swift flow of rivers which can be worse during flash floods events. In this discussion, cliff protection is analyzed at the location 0°29'36 "S 100°20'20" E on the Padang-Bukittinggi national road, which suffered significant damage due to the Anai River flood. With a road elevation of +373 m and a river bed elevation of +317 m, the 56 m high escarpment, which is only 3 m from the edge of the national road, is highly vulnerable to erosion and landslides. This study used field surveys for geotechnical measurements, and hydrological analysis to assess the stability of the cliff and the effectiveness of proposed protection measures, such as reducing river flow velocity, shifting the road, and improving drainage channels. The results show that although natural protection methods have shown positive results, they are insufficient and ineffective when facing of large flood pressures. Recommendations for improvement include the construction of ground-sills and flow diverters in the Anai River, road drainage, planting stronger vegetation, shifting the road body, and regular monitoring.

1 Introduction

The Padang-Bukittinggi national road is one of the main transportation routes connecting the West Sumatra region with various surrounding areas. It plays a crucial role in the local economy by facilitating the movement of goods and people between economic centers. At the coordinate of 0°29'36"S 100°20'20" E, this route encounters a particularly challenging feature: a steep cliff with road elevation of +373 m and a river bed elevation of +317 m. This 56 m high cliff is only 3m from the edge of the asphalt road, making it highly susceptible to erosion and landslides, especially after flooding in the Anai River [1].

The Anai River, which flows along the base of the cliff, has a steep river bed and experience high discharge, particularly during the rainy season. Flooding at certain times results in increased water pressure on the cliff structure, leading to erosion of the river bed and weakening the cliff's foundations. Such events often trigger landslides that damage the cliffs and pose a significant threat to the safety of the nearby national road. This condition is exacerbated by the high intensity of rainfall in the region, which further increases the likelihood of landslide events [2, 3]. The condition of the cliff before the landslide in Malibau Anai can be seen in Fig. 1.

Fig. 1. Cliff condition before the landslide (source: google earth, february 23, 2024)

The cliffs' vulnerability at this location not only affects the physical stability of the road infrastructure, but also negatively impacts road users' safety [4-6]. Any landslide event can result disrupt transportation routes, leading to considerable economic and social disruption for the communities that rely on this road [7]. Therefore, protecting the road is critical to ensure the safe and sustainable operation of the Padang-Bukittinggi national road.

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Effective cliff protection at this site requires a comprehensive approach that includes geotechnical and hydrological analysis, as well as the application of protective technologies suited to local conditions. In addition, periodic monitoring is required to anticipate changes in cliff conditions due to external factors such as rainfall and seismic activity. This research aims to analyse the protection measures of implemented after the Anai River flood and evaluate their effectiveness in maintaining cliff stability and national road safety at this location. It is expected to provide recommendations for improving road bed protection in the future.

2 Method

This research aims to analyse and evaluate the effectiveness of cliff protection measure on the Padang-Bukittinggi national road at coordinates 0°29'36"S 100°20'20"E, which is in critical condition following the Anai River flash flood. This research employed a comprehensive methodological approach using field survey techniques. These surveys were conducted to obtain a clear understanding of the physical condition of the cliff and its surrounding environment.

The direct observations included hydrological mapping, cliff topography, measuring the cliff's distance from the road edge, and identifying landslide prone areas. The visual and descriptive data collected during this survey were used to model the actual condition of the cliff and its surrounding, which were further analysed. Geotechnical measurements were conducted to assess the physical and mechanical characteristics of soil and rock in the cliff, including sieve analysis to determine the soil structure composition and to evaluate the cliff's stability against potential landslides.

The implemented natural cliff protection measures were evaluated using the survey data and stability analysis results. This evaluation included assessing various protection techniques, such as the installation retaining walls, creating road drainage channels to control surface water flow, and planting vegetation to strengthen the soil structure.

3 Results and discussion

3.1 Anai river hydrological analysis

The hydrological analysis of Anai River is crucial for understanding its water flow characteristics and its impact on cliff stability at the study site. Historical rainfall and stream flow data from local hydrological stations form the main basis for this analysis [6, 7]. Using the Nakayasu synthetic unit hydrograph method, it was calculated that the peak flood discharge reaches 1,073 m^3/s. How ever the unusual runoff coefficient of 3 hours seems unrealistic, as it normally ranges from 0 to 1. The analysis results indicate that for the area upstream of the Pasar Usang bridge, the Nakayasu method produces a peak flood discharge ranging from 780 m^3/s to 1,211 m^3/s. In contrast, for the area upstream to the estuary, the peak flood discharge ranges from 853 m^3/s to 1,327 m^3/s as shown in Fig. 2.

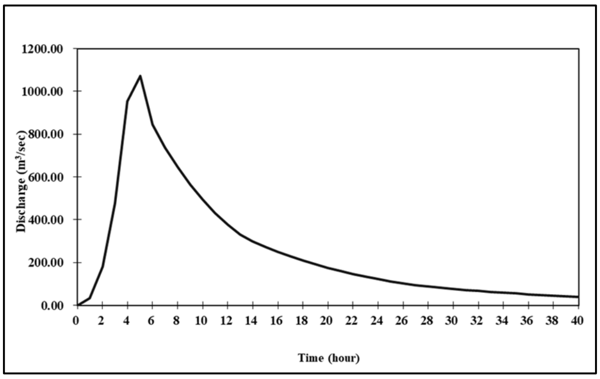


Fig. 2. Flood discharge graph

This difference reflects the complexity of hydrological dynamics from upstream to downstream of the river. Hydrological model simulations were also conducted to predict the impact of flooding on river bed erosion and cliff stability [8-10]. The simulations suggest that these hydrological fluctuations may increase erosion patterns and landslide risks [11].

Floods in the region significantly impact riverbed erosion and weaken cliff foundations. Flooding accelerates lateral erosion, eroding the cliff's base and reducing overall slope stability. These impacts are exacerbated by unpredictable river discharge changes, increasing hydraulic stress on the cliff structure. The condition of the Anai River is illustrated in Fig. 3.

Fig. 3. The condition of one of the points in the Anai River

3.2 Anai river geological analysis

The Anai Valley features a distinctive river valley morphology, with varied shapes resembling the letters "V" and "U", particularly in the river meanders. The river is approximately 40 meters wide, with a depth ranging from 10 to 56 meters below the road. The geology of this area is dominated by alluvial deposits consisting of weathered and eroded materials from Mount Marapi, including igneous rock fragments ranging in size from sand to boulders.

Based on the results of the sieve analysis, the disturbed soil sample from the Malibau Anai location contains 10.43 percent gravel/rock, 78.87 percent sand, and 10.70

percent fine-grained soil (clay/silt). With the gravel/rock percentage of below 15 percent, this soil is categorized as sand type (Fig. 4).

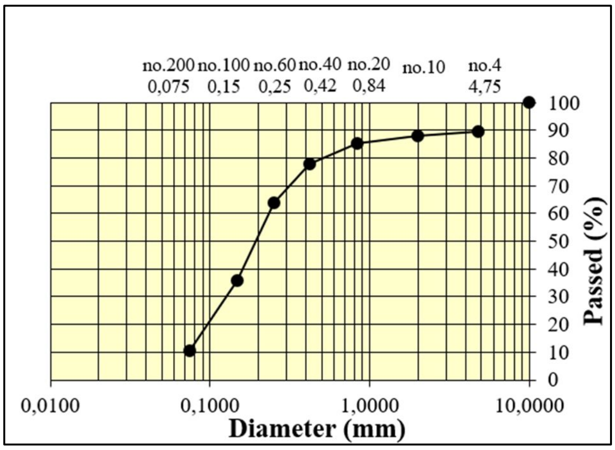


Fig. 4. Grain size distribution of the Anai River sediment filter test

The soil composition has significant implications for protecting the cliffs along the National Road in Malibau Anai, particularly following the flooding of the Anai River. The soil in these areas is w predominantly sand, which has lower stability compared to coarse grained soils such as gravel. Sand is more susceptible to erosion, especially when exposed to strong water flow, during and after flood events.

The high sand content (78.87 percent) indicates that the cliffs around the national road are at significant risk of erosion, especially during heavy water flows after floods. This can reduce the stability of the cliffs, thereby increasing the risk of landslides and damage to the road infrastructure [4]. Therefore, implementing effective cliff protection measures, such as structural reinforcement and efficient drainage systems, is crucial for reducing the risk of landslides and ensuring the safety of national roads in Malibau Anai.

3.3 Cliff condition after flood

Fig. 5. Cliff condition after flash flood (may 11, 2024)

The results of the field survey conducted after the flood in the Anai River showed significant morphological changes to the cliff, located at 0°29'36"S 100°20'20"E along the Padang–Bukittinggi national road. The flood caused severe erosion at the base of the cliff, leading to the loss of soil and rock material. This erosion resulted in slope instability which was further exacerbated by the extremely steep slope of the cliff (Fig. 5).

After the flood, several new cracks were observed in the middle to upper section of the cliff, indicating an increased risk for landslides. These cracks resulted from the pressure of water entering the soil through its pores during the flood, which increased pore water pressure and reduce the soil's shear strength [2, 11, 12]. In addition, the cliff section adjacent to the river flow experienced a reduction in height due to the lateral erosion process, which further weakened the cliff foundation. Meanwhile, the road cliff collapse at the Malibau Anai location still needs to be repaired.

The soil test using standard penetration has been conducted in the cliff as shown in Fig. 6. Based on that test, the soil parameter then is calculated as written in Table 1.

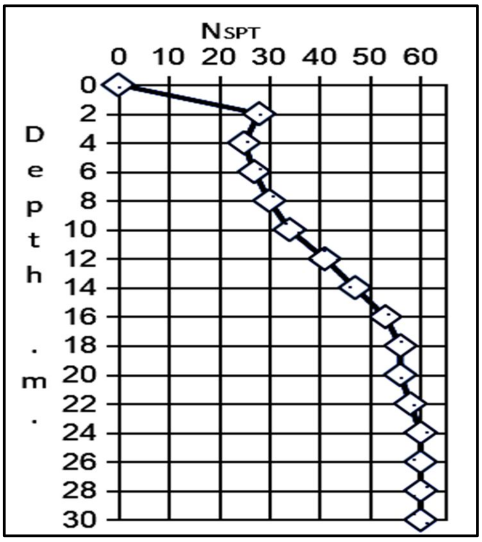


Fig. 6. Nspt test result (source: redrawn after National Road Office West Sumatra)

Table 1. Soil parameters for cliff stability analysis

Depth (m)	NSPT (blows)	ϕ (degree)	Unit Weight (t/m^3)	Unit Weight (kN/m^3)	EAVE (kN/m^2)
2	28	41.3	1.9	18.6	12000
4	25	40.3	1.7	16.7	11000
6	27	41.0	1.9	18.6	11000
8	30	42.0	1.9	18.6	12000
10	34	39.6	1.9	18.6	13000
12	41	42.4	1.9	18.6	16000
14	47	44.8	1.9	18.6	17000
16	53	47.2	1.9	18.6	19000
18	56	48.4	1.9	18.6	20000
20	56	48.4	1.9	18.6	20000
22	58	48.4	1.9	18.6	21000
24	60	49.2	1.9	18.6	21000
26	60	50.0	1.9	18.6	21000
28	60	50.0	1.9	18.6	21000
30	60	50.0	1.9	18.6	21000

The slope stability of the cliff then was analyzed using the test result. The stability analysis in the terms of factor of safety with the results in Fig. 7. The cliff has safety factor (SF) less than 1 for the distance about 8 m from the edge of the cliff.

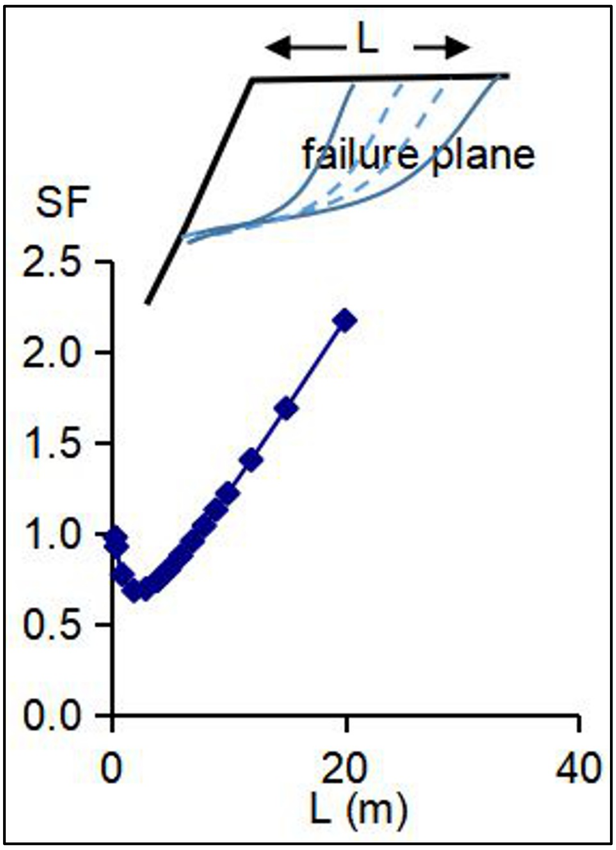


Fig. 7. The reduced stability of the cliff increases the risk of landslides.

Meanwhile, the road cliff collapse at the Malibau Anai location still needs to be repaired. Table 2 shows several locations that are being repaired.

Table 2. Landslide points and handling type plans (source: National Road Office West Sumatra)

No	Location/KM	Types of Damage, height, and length of damaged road	Handling Type Plan
1.	62+700	partial road collapse, H 10m and L 120m	Secant pile
2.	64+100	Road collapse, H 5m and L 60m	Secant pile
3.	64+200	Road collapse, H 8m and L 120m	Secant pile+DPT
4.	64+600	Road collapse, H 12m and H 60m	Secant pile+EPS Geofoam
5.	64+900	Road collapse, H 12m and L 20m	Secant pile+EPS Geofoam
6.	65+000	Road collapse, H 12 and L 100m	Secant pile+EPS Geofoam
7.	65+400	partial road collapse, H 12m and L 40m	Secant pile+EPS Geofoam
8.	66+000	partial road collapse, H 12m and L 100m	Secant pile+EPS Geofoam
9.	67+100	Partial road collapse, H 7m and L 60m	Secant pile

3.4 Impact on national roads and road user safety

Changes in the cliff's morphology after the flood have directly impacted the national road, located only 3 meters from the cliff (Fig. 8). The reduced stability of the cliff increases the risk of landslides (Fig. 7), potentially damaging this vital transportation route due to river water erosion. Minor deformation had been observed on the road surface in some areas, indicating potential soil movement beneath the asphalt layer.

Fig. 8. Cliff Condition with road shoulder 3 meters away.

This risk raises serious concerns for the safety of road users. The Padang–Bukittinggi national road is a major transportation route, connecting various regions in West Sumatra so that any disruption can have significant economic and social impacts. In addition, the possibility of landslides during heavy rains or subsequent floods heightens the need for urgent precautions.

The installation of guardrails along the road shoulder would be an effective temporary solution to prevent motorists from getting to close the cliff and to safeguards vehicles from failing off the edge.

3.5 Effectiveness of cliff protection measures that have been implemented

An evaluation of the implemented cliff protection measures been showed mixed results. The installation of retaining walls in several areas has successfully reduced erosion rates at the base of the cliff and enhanced local stability. However, these walls have not fully restrained strong water flows during major floods, leading to vortex formation upon water impact, which has caused some parts of the structure to be damaged or displaced.

Drainage channels built to control surface water flow have also shown positive results in reducing water pressure on the cliffs. However, their capacity is insufficient to handle large volumes of water during extreme flooding, resulting in waterlogging at several points and the instability of the cliffs.

Natural vegetation along the cliffs has achieved moderate success in stabilizing the soil. While vegetation roots help reinforce the topsoil layer, they are insufficient to withstand deeper soil movements, particularly during water saturated conditions. This highlights the need for more robust vegetation or a combination of engineering methods to improve effectiveness

3.6 Recommendations for cliff protection improvements and enhancements

Based on the results of this evaluation, several essential recommendations can be made for future enhancement to cliff protection:

a. Ground-sill Development and Flow Director

The Anai River at this location is a sediment transportation zone characterize by a steep and winding slope. The foundation needs to be strengthened to prevent erosion of the river bank wall by flood flows. This requires the construction of river slope control structures, such as a ground-sill and cliff base reinforcement, along with flow directing structures. In addition, a ground-sill should be constructed to protect the main dam from local downstream erosion (scouring), maintain the stability of the Sabo-dam foundation, and prevent the collapse of the cliffs [13]. The surface of the ground-sill should be flat (Fig. 9). The thickness of the ground sill is determined based on the erodibility of the riverbed and the size of the boulders present. In thick, soft rock layers, the apron should be set between 0.70 – 1.0 meters. If the river bed consists of sand and gravel, the thickness of the apron should be determined according to Table 3.

Table 3. Ground sill thickness for sand and gravel base layer (sources: technical standard and guideline for planning and design Sabo, march 2002).

Main dam height (H_m)	6 m	7 m	8 m	9 m	10 m
Apron thickness (t_a)	1,0 m	1,0 m	1,2 m	1,2 m	1,5 m
Main dam height (H_m)	11 m	12 m	13 m	14 m	15 m
Apron thickness (t_a)	1,5 m	1,5 m	1,5 m	1,5 m	2,0 m

On both cliffs, ground sills are built with side walls to protect the cliffs from erosion and maintain the stability of the Sabo-dam. The following considerations determine the height of the side walls:

1) The elevation of the upstream side wall should be 1.0-1.50 meters higher than the elevation of the wing face sub-dam.
2) The elevation of the side walls should match the height of the wing face of the sub-dam or the upright wall for the dam with the energy absorbing pool.

b. Increasing Drainage Capacity

Existing road drainage channels need to be upgraded to cope with larger volumes of water, especially during extreme rainfall events. Additional channels or emergency water diversion systems may be necessary to prevent water accumulation on the cliffs.

c. More Effective Uses of Vegetation Engineering

Vegetation with a deeper and stronger root system can improve soil stability, especially in deeper soil layers. Additionally, combining vegetation and other soil strengthening techniques, such as the use of geotextile netting, can help reduce the risk of landslides.

d. Road Body Shifting

In the medium term, the road which currently has a width of 2 x 3.60 meters, should be realigned to move it away from the landslide prone area (Fig. 10).

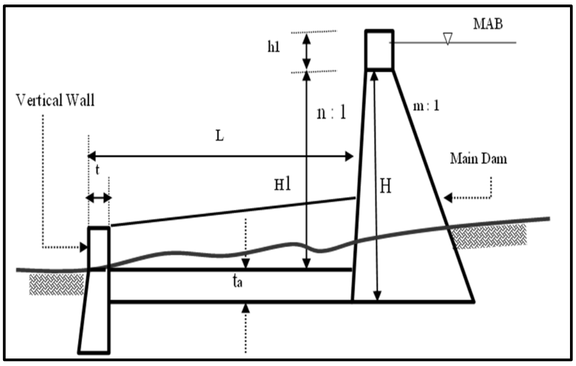
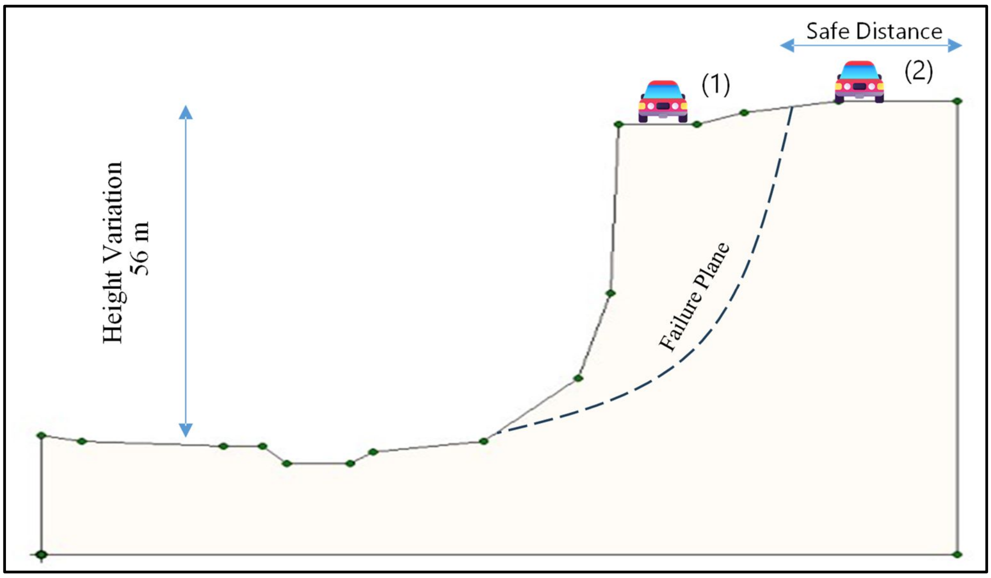


Fig. 9. Ground sill length on flat type



Information: (1) Existing; (2) Safe distance road

Fig. 10. Illustration of the condition of the cliff with the shoulder of the road

e. Periodic Monitoring and Maintenance

An automated monitoring system that detects soil movement and changes in pore water pressure should be implemented to provide early warning of potential landslides. In addition, regular maintenance of retaining structures and drainage channels must be carried out to ensure their continued effectiveness.

By implementing this recommendation, it is expected that the protection of cliffs on the Padang–Bukittinggi national road can be improved, so that the risk of landslides can be minimized and the safety and sustainability of this transportation route can be maintained.

4 Conclusion

This study analyzed the cliff conditions at the location of 0°29'36 "S 100°20'20"E on the Padang–Bukittinggi national road, located above the Anai River, and evaluated the effectiveness of cliff protection measures implemented after the flood. The results of field surveys and geotechnical measurements show that the cliffs at the research site have a very steep slope, with the road just about 3 meters away. The soil structure on this cliff is dominated by materials that are prone to erosion and landslides, especially at the cliff's base, due to the impact of the Anai River flow. Increased pore water pressure during floods and high groundwater content after intense rainfall leads to a reduction in soil shear strength, thereby increasing the risk of landslides.

A Hydrological analysis of the Anai River revealed that the flooding in this region had a significant impact on riverbed erosion and weakened the cliff foundations. Flooding accelerates the lateral erosion, eroding the cliff's base and further reducing the overall stability of the slope. These effects are exacerbated by unexpected changes in river discharge, which increases hydraulic pressure on the cliff structure.

The implemented cliff protection measures had a positive impact on reducing the risk of landslides. However, their effectiveness varies depending on the location and specific conditions of the cliffs. Although these measures were successful in the short term, the evaluation shows that some areas still experienced decreased stability, particularly in sections of the cliffs directly affected directly affected by erosion from the Anai River.

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