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Comprehensive Slope Stability Analysis: Floods and Rapid Drawdown Triggered Road Slope Instability (A Case Study)

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Abstract

The risks of erosion to road embankments due to increased river water volume, particularly during flood events, often disrupt economic activities such as food and clothing distribution between locations. Therefore, this research investigated the critical impact of rapid drawdown on slope stability for road infrastructure adjacent to the Laeya River in Southeast Sulawesi, Indonesia. To achieve this aim, a comprehensive two-stage method was adopted, and the first included hydrological analysis to simulate flood water levels and predict rapid drawdown scenarios. In the second stage, a detailed geotechnical analysis through finite element method (FEM) was used to assess the stability of the slopes. Consequently, the research findings showed essential safety factor (SF) values under various conditions. The initial SF for the existing condition was 1.20, but after implementing treatment measures, such as slope geometry modification and soil compaction, the value improved to 1.54. However, during flood water level conditions, SF decreased to 1.50 due to the submergence of the slope base. Observation showed that rapid drawdown conditions led to a critical reduction in SF to 1.22, signifying the need for further research on the implications of drawdown. This research provided valuable perceptions and engineering solutions for improving slope stability in river-adjacent road infrastructure.

Keywords: Geotechnical Assessment; Hydrological Analysis; Rapid Drawdown; Road Infrastructure; Slope Stability

1. Introduction

The primary challenge in road infrastructure development along rivers is the damage to the foundation of road embankments caused by erosion in the watershed [1]. This problem has a detrimental effect on road access, leading to disruptions in the distribution of food supplies and isolating the affected area due to road damage [2]. Various countries' research has identified, repaired, and simulated solutions for road areas along rivers. For instance, in United States (specifically Missouri River), Pakistan (Lahore Ring Road), and Vietnam (Vietnam National Highway 6 - NH6) have shown the severe impact of road infrastructure damage caused by erosion, particularly as a result of increased river water volume due to flooding in the watershed [3]–[5]. In addition, the research also plays a role in reporting a case that occurred in Indonesia, specifically on the Laeya River in Southeast Sulawesi Province. This area is distinctive for its hilly landscape and cliffs, with a river alongside the province. The affected road is a crucial infrastructure facility connecting Kendari City (the provincial capital) with South Konawe Regency. This road is essential in supporting economic activities such as distributing food and clothing between places [6], [7].

Slope stability in geotechnical engineering is affected by a range of geotechnical properties and hydrological and climatic factors, which are crucial for landslide risk assessment and mitigation. Geotechnical properties, such as soil type, rock

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composition, and structural features, are critical in slope stability. Moreover, expansive soils, due to plasticity and sensitivity to moisture, can significantly impact stability. Shear strength parameters, including cohesion and internal friction angles, impact slope resistance, with variations in these features affecting the safety factor (SF) [8], [9]. Hydrologically, water plays a significant role by increasing pore water pressure and reducing soil strength during rainfall infiltration, with groundwater fluctuations often leading to slope displacement and lower SF [10]–[13]. Additionally, soil-water characteristic curves are essential for understanding soil behavior under varying moisture conditions, affecting slope stability [14]–[16]. Climatic changes, particularly shifts in precipitation patterns, can aggravate slope vulnerabilities, with extreme weather events leading to rapid soil moisture changes and instability [17].

Rapid drawdown conditions are a crucial concern in slope stability analysis. The condition refers to the swift decrease in water levels in reservoirs or other bodies of water, which can significantly impact the stability of adjacent slopes [18], [19]. This phenomenon reduces stabilizing hydrostatic pressures, leading to undrained soil conditions and making the slope more susceptible to failure due to the activation of undrained shear strength. The drawdown rate plays a significant role, with faster rates causing greater displacements and an increased probability of slope failure [20]–[22]. During rapid drawdown, elevated pore water pressures may persist in the soil, further destabilizing slopes, particularly in earth-fill dams, where this loss of stabilizing pressure can critically reduce the firmness of the upstream slope and cause critical seepage pressures [23], [24]. Through finite element analysis, Zhou and Qin [25] showed a substantial reduction in SF during these conditions. Alonso and Pinyol [26] explained the effect of rapid drawdown on the safety of earth-fill dams. Soralump et al. [27] showed that recurrent events of this condition could have lasting impacts on slope stability. This research has extensively used numerical simulations and analytical methods to evaluate the stability of slopes under rapid drawdown conditions.

Despite extensive research on the rapid drawdown phenomenon, most research has focused on its impact in dam environments, where the water level recedes relatively slowly. However, there is a distinguished research gap in addressing the implications of rapid drawdown for road infrastructure, particularly those constructed adjacent to rivers. Unlike dams, river condition rates can be much faster due to sudden weather changes, flash floods, or unregulated water releases upstream. This accelerated drawdown can lead to more severe destabilization of slopes supporting roadways, increasing the risk of slope failure, road damage, or collapse, and understanding how specific conditions affect slope stability, particularly for road infrastructure in hilly areas near rivers. Moreover, current research does not adequately address the behavior of slopes in such environments, leaving a significant gap in understanding how to mitigate the risks of rapid drawdown in river-adjacent infrastructure. More focused research is needed to explore how to manage risks of rapid drawdown impacts specifically for roadways, where the speed of water level changes and the geotechnical responses of the slopes may differ from those observed in dam environments.

This research aimed to improve the stability of slopes prone to failure due to rapid drawdown, particularly for infrastructure located beside rivers. A comprehensive hydrological analysis will be conducted to simulate flood water levels and predict the condition scenarios to achieve the objective. In addition, a detailed geotechnical analysis using finite element method (FEM) will be used to understand how rapid drawdown reduces SF in slopes adjacent to rivers. The research will also focus on ensuring that slope designs remain safe under the conditions, providing engineering solutions that mitigate the risks associated with these environments.

This groundbreaking perspective aims to contribute valuable information for practitioners designing stable road slopes near river flows. By shedding light on the details of slope stability and water dynamics, the research is a practical reference for infrastructure development and management.

2. Laeya Watershed (Experimental Site)

The research focuses on a slope failure along Kendari – South Konawe roadway in Anduna sub-district, South Konawe Regency, Southeast Province, Indonesia, situated at a latitude of 4°15'47" South and a longitude of 122°29'31" East. The undulating terrain of the area contributes to frequent landslides originating from hilltops, worsened by the powerful river flow that weakens the support structures of the road [28]. Additionally, the research area covers a road segment with a length of 200 meters, as shown in Fig. 1. To address the issue, the responsible agency designed the slope embankment of the road on more stable ground. This new challenge is introduced, as the stable ground lies near the Laeya River, prone to recurrent flooding during the rainy season.

The Laeya River ecosystem has experienced degradation due to improvements in road infrastructure, deforestation, and the clearing of agricultural and plantation lands, leading to erosion and landslides. Additionally, population growth contributes to the transformation of watersheds into agricultural areas, impacting the watershed's integrity [29]. The watershed is extensively investigated due to its diverse land cover and role as a crucial water source for agriculture in South Konawe Regency. It is ranked as the fifth-largest watershed in Southeast Sulawesi Province. Moreover, the watershed covers an area of 68,978.79 hectares across eight sub-districts, including Wolasi, Baito, Laeya, Moramo, Kolono, Lainea, Palangga, and South Palangga. Laeya predominantly features secondary dryland forests and agriculture mixed with shrubs. Preserving the proper land use in the watershed is essential for sustaining its ecological functions [6].

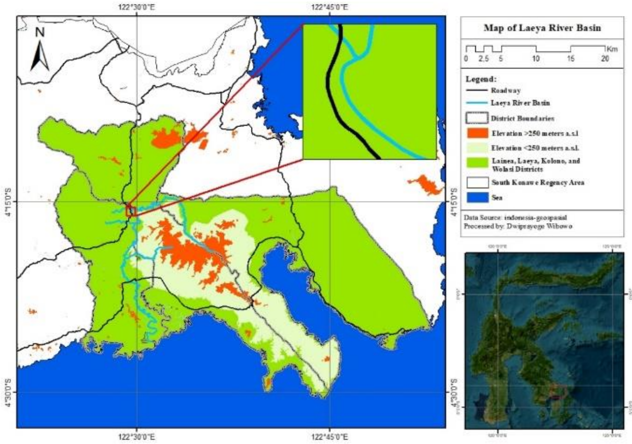

Figure 1. Map of Laeya watershed and experimental site

3. Research Methods

The research presented a two-stage method to identify road infrastructure damage. The first stage included identifying hydrological movement hazards originating from the Laeya watershed. This river was affected by multiple tributaries, including those from the Anggokomunu, Abari, and Haruri Rivers, as shown in Fig. 2. The second stage focused on slope stability identification to assess changes in slope SF during variations in river water flow, which aggravated road damage.

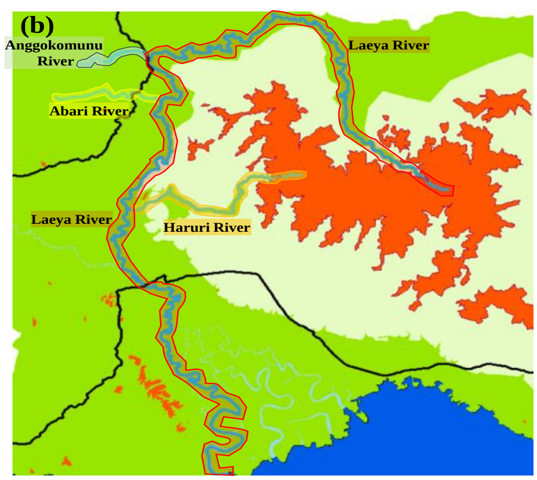

Figure 2. Identification of Laeya watershed

3.1 River Hydrology Analysis

The research revealed that the flow of the Laeya River was influenced by several tributaries, with the survey team delineating the Laeya watershed to cover an area of 647.54 km², including a designated control area of 190 km² and a main river length of 15.80 km; shown in Fig. 2. Rainfall analysis was a critical component, as it enabled the calculation of river discharge, which is essential for characterizing optimal river water levels. Increasing river levels also facilitated the identification of scouring along the riverside road slope. Nappo et al. highlighted that assessing road damage requires visualizing local factors such as rainfall, river conditions, and geotechnical characteristics [30]. To support this assessment, visualizations of geomorphological and environmental aspects—including landscape features, river flow states, and rainfall patterns—were created to inform geotechnical analyses.

In the initial identification phase, watershed maps were overlaid with the primary road, an essential regional distribution conduit to assess potential impacts on road stability. This approach improved the understanding of environmental factors contributing to potential landslides along the Laeya River.

Rainfall predictions were developed using ten years of annual rainfall data (2008-2017) from nearby stations, provided by Sulawesi River Basin Region IV. The arithmetic averaging method was employed to calculate rainfall trends across various stations within the Laeya watershed. Although unpredictable climate fluctuations posed challenges, this approach facilitated the simulation of average rainfall levels, a crucial factor in assessing landslide and flood impacts. The analysis utilized a 25-year return period (Qr_{25}) to determine annual flood discharge for major rivers. It is essential to note that Qr_{25} represents a statistical likelihood of a flood event occurring within that timeframe, rather than a guaranteed occurrence every 25 years [31].

Further analysis involved designing rainfall calculations, selecting appropriate distribution types for rainfall data, and conducting goodness-of-fit tests, including the Smirnov-Komogorov and Chi-Square tests. These analyses informed the rainfall intensity calculations needed for flood discharge estimation using the Nakayasu Synthetic Unit Hydrograph method [32], [33].

Floodwater levels were modeled with ArcScene version 10.8 and DEM data. Comparative flood simulations were conducted using HEC-RAS version 6.1 under unsteady flow conditions to generate precise data on flood peaks and inundation extents. To represent watershed topography, these simulations required river cross-section data, boundary conditions, channel slope, Manning's coefficient, and DEM data. Furthermore, the upstream flood discharge hydrograph was set based on return periods for the study area. To account for water loss beyond the study scope, the designated 2D model area was treated as a free boundary, allowing inflows to continue into non-modeled regions [34].

3.2 Geotechnical Analysis of Roadway Slope

The geotechnical analysis in this study aims to assess slope stability in a landslide-prone area, focusing on understanding the impacts of flooding and rapid drawdown on road infrastructure. The analysis begins with soil investigations conducted through three Cone Penetration Test (CPT) points within the landslide-prone area, as shown in Fig. 3. The CPT data provide initial insights into soil properties and stratigraphy, using empirical correlations proposed by Robertson to classify soil types and determine essential geotechnical parameters [35].

A model is then developed to conduct slope stability analysis by integrating the CPT results with topographic data. The finite element method (FEM), implemented using Plaxis 8.6 software, is employed for this analysis. It applies the Mohr-Coulomb criterion due to its straightforward relationship between shear strength, normal stress, cohesion, and internal friction angle, making it highly adaptable to numerical methods [36].

Safety Factor (SF) values are calculated using the shear strength reduction method, reducing strength parameters—tan φ (internal friction angle) and cohesion (c)—until slope failure occurs [37]. The model also incorporates a 15 kPa uniform traffic load according to Indonesian standards [38]. Additionally, the slope SF was analyzed under various conditions, including existing conditions, post-treatment, floodwater level, and rapid drawdown conditions.

3.2.1 Existing condition analysis

This analysis aimed to estimate the actual soil properties using a back-analysis method. The absence of soil shear strength data from laboratory test results necessitated using correlation data between CPT and other parameters in the analysis. For example, soil shear strength and modulus of elasticity were determined according to the correlation proposed by Look [39], while ratio values (v) of Poisson were determined according to Bowles [40]. Values of soil shear strength derived from correlations with CPT results (qc and fs) produced a range of values. Therefore, the back analysis method accomplished the selection of shear strength parameters.

Abramson et al. [41] asserted that the back analysis could be used for insufficient essential information. This method included using observed field data, such as slope failure, deformation, or pore water pressure measurements, to calibrate the parameters of a slope stability model [42]. Consequently, Deng and Xiang [43] used a back-propagation neural network and genetic algorithm to determine strength parameters. Nassirzadeh et al. [44] used probabilistic methods to understand uncertainties in shear strength, providing reliable estimates for slope stability. A novel displacement back-analysis method using geographically weighted regression improved the precision of geomechanical parameter estimation, showing high accuracy in modeling slope displacements [45]. Moreover, multi-layer analysis methods allow for a detailed reconstruction of landslide evolution, accommodating complex soil-structure interactions and understanding the effectiveness of retaining structures [46].

In this research, the existing slope condition method was adopted, considering the slope to be in a critical state, as explained by Popescu and Schaefer [47]. However, the research used the SF criterion SF<1.25 to define slopes in critical conditions [40], and a back-analysis process was conducted until the safety factor was achieved. When safety factor 1.20 is considered, soil properties are the slope's actual soil properties.

3.2.2 Post-treatment condition

This scenario simulated slope stability following treatment, where the slope configuration was modified to a 1V:2H ratio to mitigate potential landslides during slope widening. In addition, the soft clay at the slope base was replaced with compacted soil as seen in Fig. 4. The calculated safety factor was then compared to the Indonesian code requirements to assess slope safety after treatment. According to the Indonesian Code of Geotechnical Design [38], the minimum required safety factor is 1.50. This benchmark evaluated whether the post-treatment slope configuration met the necessary safety criteria.

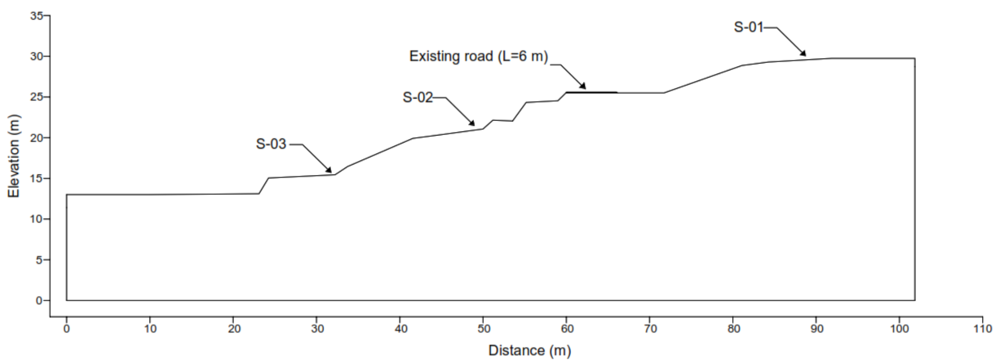

Figure 3. Cone Penetration Test location

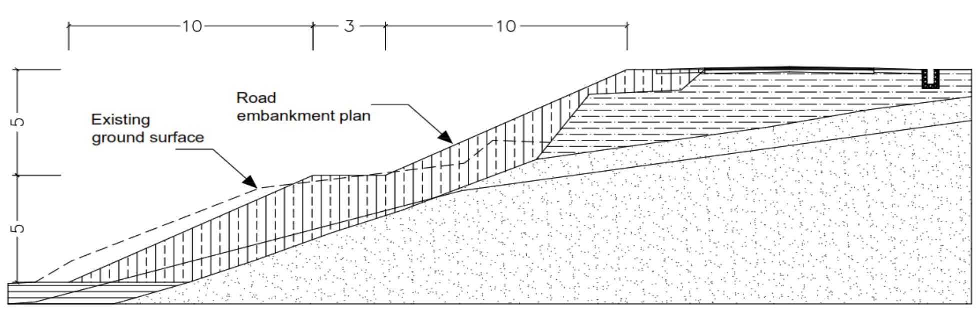

Figure 4. Landslide stabilization plan (unit in meters)

3.2.3 Flood and rapid drawdown condition

The objective of this analysis was to evaluate the slope stability under floodwater levels and rapid drawdown conditions, which are critical in flood-prone areas, such as riverbanks and embankments [48]. The rapid drawdown condition was simulated to replicate the effects of a quick water level recession after flooding, which typically occurs in saturated slopes. The safety factor was evaluated at this stage using a different criterion than in previous conditions, specifically applying the Indonesian Fill Dam Standard [49]. According to this standard, the minimum required safety factor is 1.30 under flood conditions and 1.20 under rapid drawdown conditions. This approach was chosen because the Indonesian Geotechnical Standard does not explicitly address slope safety factors in flood and drawdown conditions. Thus, the study adopts the Indonesian code for embankment dams as an appropriate alternative, given the phenomenon's similarity.

4. Results and Discussion

4.1. River Hydrological Analysis

The Laeya watershed area was identified as approximately 547.54 km², with control points covering 190 km² and a main river length of 15.80 km. As a first-order river, Laeya influences the flow patterns of second-order watercourses, such as Anggokomunu, Abari, and Haruri. Geographic Information System (GIS) data processing was utilized to identify water flow patterns, support repair decision-making, and understand damage factors affecting the Laeya River.

Flood control and structural reinforcement are critical for maintaining road stability along the Laeya River. Landslide identification using Bing satellite imagery, Fig. 5, indicated a road segment of up to 200 meters requiring attention due to slope instability. Reinforcing the road shoulder and improving the slope were essential measures to mitigate the impact of landslides from drawdown on Laeya River, thereby improving the general road structure's resilience and reducing the vulnerability of the main road to floods. The method of repairing through backfilling and leveling led to subsequent damage when done with improper materials [50], [51]. Therefore, workers used soil-hardening materials mixed with gravel to moderate the risk of road collapse. Fig. 5a shows a river buffer of 12 meters was established to simulate the river's width. A large buffer did not accurately represent the width of the main road. Following the discussion, workers built a simulated buffer of 6 meters to expand the road between its two sides. Fig. 5 b shows the theoretical Laeya River cross-section with an affected road, where the nature of the watercourse showed that the river's flow threatened the reinforcement wall of the road.

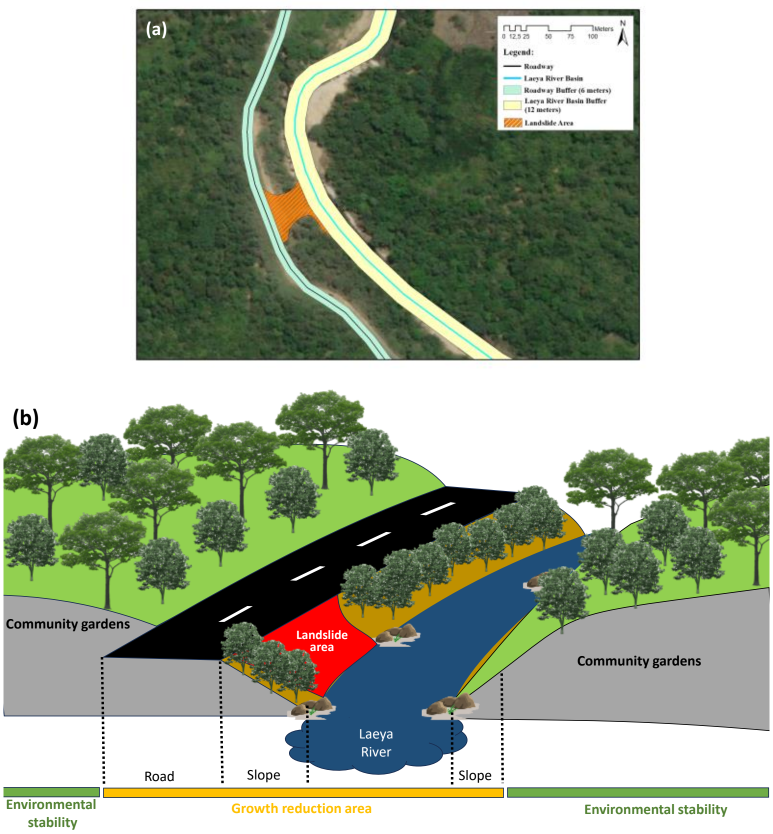

Figure 5. Landslide identification (a) Bing satellite imagery, and (b) Theoretical Laeya River cross-section with the affected road

Table 1 provides an overview of fluctuating rainfall intensities in the Laeya watershed, with the highest annual average rainfall observed in 2013 at 136.5 mm. This data underpins the design rainfall analysis and flood discharge calculations, as shown in Table 2, which correlates flood risk with flood discharge values across various return periods. Salas and Obeysekera [52] and Gumbel et al. [53] have established that an event's return period reflects the average interval between occurrences reaching or exceeding a specified value.

Table 1. Watershed rain average

Years	Rain Average (mm)
2017	75.2
2016	42.0
2015	45.9
2014	59.0
2013	136.5
2012	57.0
2011	78.5
2010	97.2
2009	77.5
2008	83.4

Table 2. Design rainfall distribution and results of planned flood discharge

Multiple Times (Years)	Prob. (%)	Design Rainfall Distribution (mm)				Flood (m^3/s)
		G	N	LN	LP	
2	50.0	71.5	75.2	71.1	70.2	275.39
5	20.0	104.6	98.4	95.6	95.2	366.89
10	10.0	126.3	110.6	111.6	112.5	426.82
25	4.0	153.9	118.6	123.7	135.2	471.72
50	2.0	174.5	131.9	146.5	152.7	556.92
100	1.0	194.7	139.6	161.7	170.7	613.71

Note: G was Gumbel, N represented Normal, LN was Log-normal, LP represented Log-person type III, and prob was probability.

The data in Table 2 introduced four types of rainfall distributions, each associated with planned flood discharge values for three distinct probability levels, including 50% possibility of a flood occurring in 1 year, 20% in 5 years, and 10% in 10 years. The rainfall distribution types included Gumbel, the commonly used distribution in flood planning, Normal, a distribution resembling Gumbel but with a flatter curve, Log-normal, characterized by an oval curve, and Log Pearson type III, showing a more pronounced oval curve than log-normal. For instance, the planned flood discharge for a 50% chance was 275.39 m^3/s under the Gumbel distribution. This result showed that a flood with a discharge of 275.39 m^3/s held a 50% probability of arising in 1 year. The significance of the Table was in its usefulness for planning drainage and flood control systems, providing an understanding of watershed size considerations to prevent or mitigate the impacts of floods.

Based on multiple times of finding versus flood discharge, shown in Table 2, the result showed a curve of increasing flood threat (y) due to increasing flood discharge (x) with an R^2 value of 0.80 with the equation $y = 2.9391x + 357.86$. As the time increased, the threat of flooding improved based on the analysis curve. This improvement raised the possibility of damage to the road slope, which could lead to sections of the road along the river being cut off.

The modeling outcomes were closely associated with the flood identification results in the research watershed when comparing the outcomes obtained from Arc Scene version 10.8 and HEC-RAS programs. During the simulation of unsteady flow with a flood discharge at a return period of 25 years, the modeling results showed data on the height and extent of the simulated flood. The flood inundation height at the specified review point was measured at 4.68 meters, as shown in Fig. 6. This flood inundation height served as a reference for evaluating changes relative to the normal flood height in slope stability analysis.

4.2 Geotechnical Analysis

The findings from each CPT point, describing the subsoil characteristics, were as follows.

- S-01: Bedrock was identified at a depth of 2.20 m from the ground surface, with a clay layer extending up to 1.60 m, followed by dense sand.
- S-02: Bedrock was discovered at a depth of 1 m from the ground surface, with a soft clay layer extending to 0.60 m, followed by dense sand.
- S-03: A hard soil layer was identified at a depth of 2.00 m from the ground surface, with soft clay found up to a depth of 1.40 m, followed by dense sand.

Fig. 7 shows the soil conditions at the landslide site categorized based on the three existing CPT data, as observed in the stratigraphic results.

4.2.1 Existing condition analysis

According to the Robertson chart, the topsoil layer primarily consists of clay, with average qc values at CPT points S-01 and S-03 recorded at 0.03 MPa and 0.31 MPa, respectively. Cohesion values for very soft to soft clay fall within the range of 0–25 kPa, based on Look [39]. A traffic load of 15 kPa, in line with road classification, was applied to the slope. Through back analysis, soil parameters were determined and are presented in Table 3, yielding a factor of safety (SF) of 1.20, as shown in Fig. 8.

Table 3. Soil parameters after back analysis

Soil Parameters	Soil properties			
	Soft Clay	Medium Clay	Dense Sand	Backfill
Material type	M-C	M-C	M-C	M-C
c (kPa)	10	35	1	10
ϕ (°)	2	2	30	35
γ_{unsat} (kN/m^3)	16	17.5	18	17
γ_{sat} (kN/m^3)	17	18.5	19	19
E (kPa)	1,678	2,411	30,000	50,000
υ	0.33	0.33	0.33	0.33

Note: M-C = Mohr – Coulomb criterion.

4.2.2 Post-treatment condition analysis

The analysis results show that using FEM analysis, the post-treatment safety factor (SF) improved to 1.54, primarily due to adjustments in slope geometry and material. This aligns with the general observation that slope stability is enhanced through slope shape and soil strength modifications. In this study, adjusting the slope geometry by creating steps to maintain a favorable gradient proved effective in increasing the SF. This finding is consistent with prior studies indicating that geometric factors, such as slope height and angle, substantially impact stability. For instance, increasing a slope's height and angle reduces stability, leading to a lower SF and a higher risk of failure. Additionally, the geometric shape affects failure modes, with lower slopes more prone to base failures. These observations underscore the crucial role of slope geometry in stability and the importance of careful design to prevent slope failure [54], [55].

In addition to geometry, previous studies highlighted the role of soil properties, such as cohesion and internal friction angle, in enhancing slope stability. Higher cohesion and friction angle values are associated with improved SF, consistent with the present study's finding that compacted soil replacement significantly enhanced stability by increasing shear strength [56]–[58].

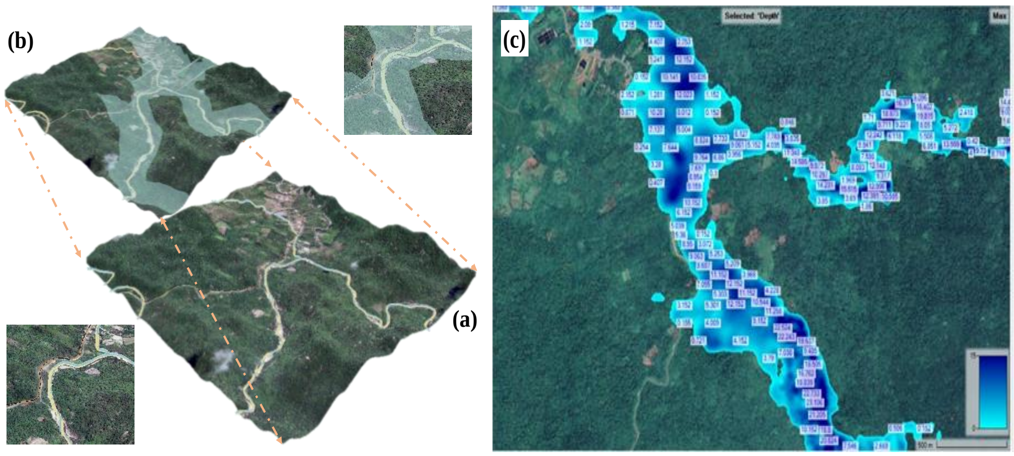

Figure 6. The floodwater level modeling (a,b), ArcScene version 10.8 program, and (c) HEC-RAS program

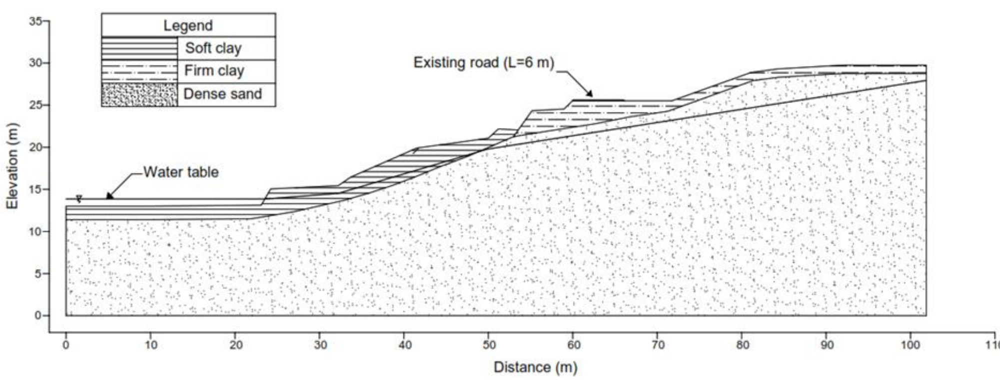

Figure 7. Slope stratigraphy

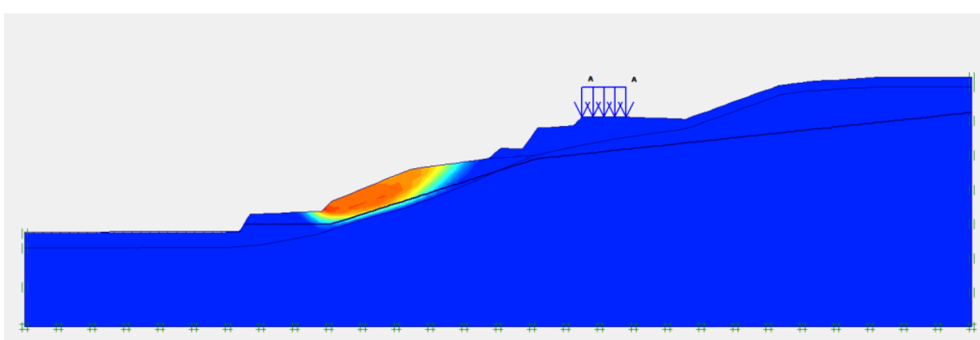

Figure 8. Slip surface in existing conditions

4.2.3 Flood and rapid drawdown condition analysis

Based on field survey data, the normal water level and riverbed elevation were established at +13.85 meters and +13.00 meters above sea level (a.s.l.), respectively. Hydrological analysis during a flood event indicated that the water level rose by 4.68 meters above the normal level, reaching +17.68 a.s.l. This rise caused submersion of a portion of the slope base, shown in Fig.

9, which altered the pore water pressure and affected the shear strength of the slope material [59], [60]. As a result, the safety factor (SF) under flood conditions decreased from 1.54 to 1.50, showing a slight reduction in slope stability due to submersion. Simultaneously, the increase in hydrostatic pressure on the slope surface provided additional resistance, partially counteracting the decrease in SF, though this effect was minimal [61].

Flooding affects slope stability through various mechanisms, including changes in pore water pressure, erosion, and scour at riverbanks. In this study, the increase in hydrostatic pressure helped counterbalance the reduction in SF caused by the submergence of the slope base. These findings align with previous studies, which highlight the role of increased pore water pressure in reducing slope stability. For example, flooding can destabilize slopes by altering subsurface water pressures and eroding the base of the slope, especially when floodwaters cause toe scour. The erosion of riverbanks during floods can lead to significant instability, particularly in slopes with vulnerable bases [62], [63].

Further studies on reinforced soil slopes indicate that flood-induced scour and hydrodynamic pressures can lead to shear failure, particularly at the base of the slope. These effects were observed where slopes were reinforced, but flood loading caused additional pressure, leading to the slope's base failure. Additionally, changes in flood wave characteristics—such as shape and volume—can influence pore water pressure dynamics, affecting slope stability estimates [64]. These findings emphasize the importance of considering both the immediate effects of flooding and the long-term consequences, such as gradual slope saturation [65].

Rapid drawdown, a critical condition often observed in waterlogged and fluctuating areas like dams and riverbanks, significantly impacts slope stability [18], [66]. This phenomenon was observed in the case of the road embankment in the Anduna sub-district. Here, a rapid increase in floodwater level led to the partial submergence of the slope, shown in Fig. 10, followed by a quick recession of water. Slope stability analysis under these rapid drawdown conditions revealed a marked reduction in SF to 1.22, which was attributed to the saturation of the slope's base during flooding. This saturation temporarily elevated pore water pressure, reducing the soil's effective shear strength [67].

Hydrostatic pressure initially exerted a resisting force on the submerged slope surface [68]. However, as floodwaters receded rapidly, this hydrostatic pressure dissipated, resulting in a significant SF decrease due to the internal water outflow from the slope. This finding aligns with studies by Fathani et al. (2019) and Hui (2015), which report similar stability trends: an initial increase in stability from hydrostatic pressure followed by a decrease as drawdown occurs [61], [69]. Since the slope remained saturated, the driving forces did not immediately change, given the time required for drainage [70]. This resulted in a 21% SF decrease during rapid drawdown, though the SF still met the minimum stability criterion of 1.20.[49]. As water levels normalized, the SF gradually improved as the slope drained.

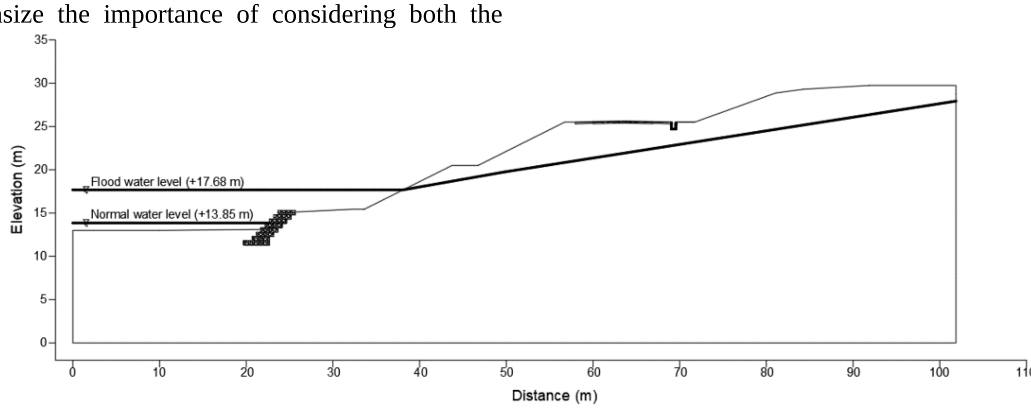

Figure 9. Water level during flood conditions

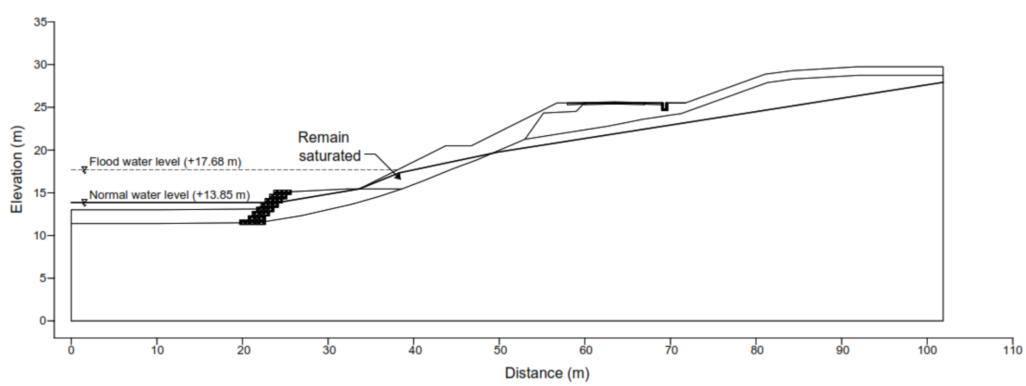

Figure 10. Rapid drawdown condition

This study highlights the importance of considering rapid drawdown conditions in slope stability assessments, beyond just analyzing flood levels. Neglecting rapid drawdown scenarios can lead to substantial stability risks, as evidenced by the notable SF reduction. These findings are consistent with research by Charrak et al. (2024), which highlights that SF for dam slopes decreases significantly during rapid drawdown, with the degree of impact depending on soil properties and drawdown rates [21]. Similarly, Ahsan et al. (2024) used finite element analysis to show that rapid drawdown exacerbates instability through abrupt pore water pressure changes that influence sliding surfaces [71]. Meng et al. [72] further noted that failure to consider rapid drawdown effects and stratigraphic and soil variability may lead to significant discrepancies in time-sensitive stability assessments.

The current analysis demonstrates that while SF under drawdown conditions met the minimum safety criterion, the significant decrease underscores the necessity of incorporating rapid drawdown scenarios into slope stability assessments to better anticipate critical conditions and manage slope stability proactively.

5. Conclusions

In conclusion, this research investigated the critical impact of rapid drawdown and flooding on the stability of road embankments adjacent to the Laeya River in Southeast Sulawesi, Indonesia. The study highlighted the importance of understanding and mitigating risks posed by water level fluctuations by combining hydrological analysis and geotechnical modeling. Key findings revealed that rapid drawdown significantly reduced slope stability, with safety factor (SF) values dropping to critical levels (1.22), emphasizing the need for comprehensive engineering measures. Post-treatment improvements, including slope geometry modifications and soil compaction, effectively increased the SF to 1.54, ensuring compliance with safety standards under normal conditions. These results underscore the importance of incorporating extreme hydrological events, such as rapid drawdown, into the design and maintenance of road embankments to enhance infrastructure resilience in river-adjacent areas.

Abbreviations

A list of symbols should be inserted before the references when a list is needed, and sorted in alphabetical order.

c	Cohession
E	Modulus of elasticity
φ	Friction angle
γ_{unsat}	Unit weight of unsaturated material
γ_{sat}	Unit weight of saturated material
ν	Poisson's ratio

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Edward Ngii: Proposed research idea, Investigation, Data Curation, and Funding Acquisition. Anafi Minmahddun: Project administration, Investigation, Software, Validation, and Writing – Original Draft. Suyuti Suyuti: Data Curation, Formal Analysis, and Methodology. Uniadi Mangidi: Validation, Methodology, and Investigation. Fathur Rahman Rustan: Software, Visualization, and Writing – Original Draft. Dwiprayogo Wibowo: Software, Validation, and Writing – Original Draft. Muhammad Nurdin: Supervision, Conceptualization, and Writing – Review & Editing.

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