Journal of Brilliant Engineering 2 (2023) 4832
Brilliant Engineering
journal home: www.acapublishing.com/journals/4/ben
Research Article

Rainfall Infiltration Impact on Road Embankment Stability

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Keywords

Infiltration,
Pore water pressure,
Slope stability,
Limit equilibrium,
Safety factor.

Abstract

This study evaluates the stability of a widened road embankment slope by considering the effect of rain infiltration, which is often ignored in practical design. Rainfall infiltrates the soil and alters pore water pressure, reducing its shear strength and potentially causing slope failure. The Phi Index method is used to determine rain infiltration values, using rainfall data from four nearby rain stations over 10 years. The changes in pore water pressure resulting from rain infiltration are incorporated into the slope stability analysis by the limit equilibrium concept using the Spencer method. Back analysis is used to determine the soil shear strength parameters since the CPT test results provide a correlation with values within a certain range. Soil parameters resulting in a safety factor value close to 1.25 (critical condition) were considered representative field conditions. The analysis shows a decrease in the safety factor from 1.50 to 1.31 (12%). These findings emphasize the importance of accounting for rain infiltration in road embankment stability analyses, particularly in areas with high rainfall where the safety factor may fall below the minimum required by Indonesian geotechnical code. When an infiltration effect analysis is not conducted, the safety factor should be increased at least 12% from normal conditions.

1. Introduction

Road widening is a government initiative aimed at enhancing road performance to facilitate efficient distribution activities and drive the economy. However, such projects often encounter obstacles due to factors such as topography and land use conditions. One of such example is the road widening project in Anduna Village, located in the Konawe Selatan Regency of Southeast Sulawesi Province. The existing land use conditions necessitated expanding the road towards a ravine, which required extensive filling to the bottom of the ravine, approximately 10 meters deep, and implementing slope angle adjustments to prevent slope failure on the road embankment.

Slope stability is influenced by several factors, including slope geometry, additional loads resulting from human activities, and a decrease in shear strength due to changes in pore water pressure in the soil [1,2]. In Indonesia, particularly in the Konawe Selatan regency, the tropical climate with an annual rainfall of 4,600.3 mm in 236 rainy days [3] is one of the significant triggers of slope instability. Rainwater infiltration increases the slope load due to the increased unit weight of the soil and reduces soil shear strength by increasing pore water pressure.

In the Southeast Sulawesi region, rainwater infiltration is frequently disregarded in practical design, despite its capacity to reduce the safety factor of slopes [4]. Therefore, this study aims to analyze the safety factor of road embankments and investigate the impact of infiltration on slope stability. The findings of this studies are intended to serve as a reference for road embankment design, drawing from the approach employed in this study.

2. Research Methodology

Topographic surveys and soil investigations are conducted in the first phase of road embankment design. Topographic surveys assess the existing slope geometry, while soil investigations are performed to determine the subsurface conditions. In this case, three Cone Penetrometer Tests (CPT) were conducted in the vicinity of the road embankment area.

The analysis process consists of two stages, namely, hydrological analysis and slope stability analysis. A hydrological analysis was conducted to estimate infiltration based on design rainfall analysis, and the calculated infiltration value is then utilized in slope stability analysis. Infiltration refers to the process of water entering the soil from the surface. The Phi Index method is employed to calculate the infiltration value, which is a function of rainfall intensity determined using the mononobe equation [5].

$$I = \frac{R_{24}}{24}\left(\frac{24}{t}\right)^{\frac{2}{3}} \tag{1}$$

Where

I = Rain intensity (mm/h)
t = Rain duration (h)
R_{24} = Daily maximum rainfall (mm)

This study determined infiltration by calculating the maximum rainfall from rainfall station data over the past ten years. The rain stations considered in the analysis were the Moramo, the Onembute, and the Tanea rain stations, all located near the study site.

The slope stability analysis was performed to determine slope stability with and without the impact of rainfall. The soil stratigraphy for the analysis was determined based on the results of soil investigations using CPT. The limit equilibrium method was employed for slope stability analysis, specifically the Spencer method [6]. Compared to other methods such as [7]-[9], the Spencer method utilized the equilibrium of force and moment in the analysis process [10]. This

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Received 29 Apr 2023; Revised 04 Jun 2023; Accepted 04 Jun 2023
https://doi.org/10.36937/ben.2023.4832

method is essentially an extension and modification of the simplified method of Bishop, which defines the factor of safety as the ratio of total available strength S at the slip surface to the total shear strength mobilized S_m.

$$F = \frac{S}{S_m} \tag{2}$$

In Spencer's analysis, the derived resultant Q of pair of interslice forces:

$$Q = \gamma H b \left[\frac{\frac{c'}{F\gamma H} + \frac{h \tan\phi'}{2HF}(1 - 2r_u + \cos 2\alpha) - \frac{h \sin 2\alpha}{2H}}{\cos\alpha \cos(\alpha - \theta)\left[1 + \frac{\tan\phi'}{F}\tan(\alpha - \theta)\right]} \right] \tag{3}$$

Where

Q	= Resultant of pair of interslice forces
b,h	= width and height of slice
γ	= Bulk density
H	= height of the embankment
c'	= cohesion (effective stress)
F	= Safety factor
ϕ'	= Internal skin friction (effective stress)
r_u	= Pore-pressure coefficient
α	= Slope of base slice
θ	= Slope of resultant pair of interslice forces

The moment of the internal interslice forces Q is zero, therefore:

$$\sum[Q \cos(\alpha - \theta)] = 0 \tag{4}$$

The same principle applies to a force equilibrium, where the vertical and horizontal forces sum is zero. Therefore:

$$\sum[Q \cos(\theta)] = 0 \tag{5}$$

$$\sum[Q \sin(\theta)] = 0 \tag{6}$$

Due to the magnitude of the interslice force being constant, equations (5) and (6) will be identical:

$$\sum[Q] = 0 \tag{7}$$

The safety factor value is determined by iteratively solving equations (4) and (7) until a single value of θ is obtained, yielding the same safety factor value from both equations. Various soil parameters such as unit weight, cohesion, internal friction angle, and soil permeability coefficient were determined to conduct the analysis by correlating them with the CPT data proposed by Look [11]. Stability analysis was conducted under different conditions, including existing conditions, embankment completion, and embankment completion with the effect of rain infiltration. The resulting safety factor value was then compared to the minimum safety factor criteria set by the Indonesian geotechnical code [12] to assess its compliance.

3. Result and Discussion

3.1. Field investigation results

The study was conducted in Anduna Village, located in the hilly area of Konawe Selatan Regency. On the right side of the road embankment plan lies a residential area, while the left side features a 10-meter deep ravine with the presence of the Laeya River. A topographic survey was conducted along a 380-meter stretch following the main road, as illustrated in Figure 1. The survey results yielded contour maps, as shown in Figure 2.

Figure 1. Site location

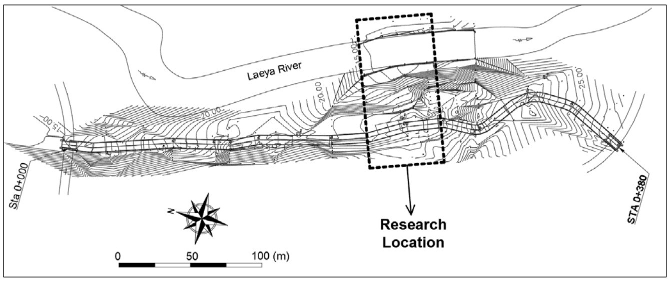

Figure 2. Contour map of site location

Three CPT tests were performed near the road embankment plan, as shown in Figure 3. The soil types at the study site were determined using the soil classification chart proposed by Robertson [13]. The results of the CPT tests revealed the presence of dense sand and bedrock (q_c> 150 kg/cm^2) at a depth of 2 meters. Figure 4 illustrates the stratigraphy of the soil layer.

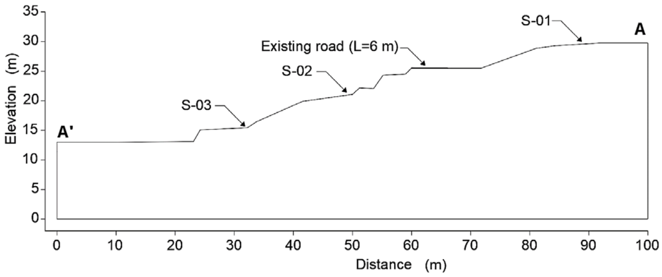

Figure 3. CPT test location

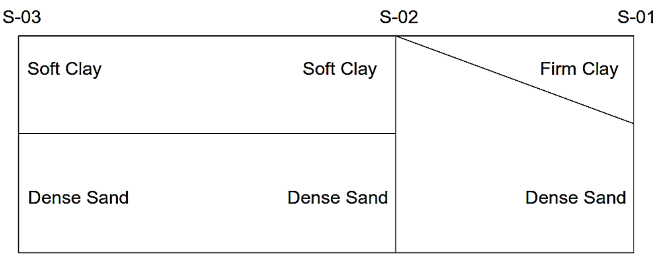

Figure 4. Simplify stratigraphy

3.2. Hydrological analysis

As stated in the research methodology, the average rainfall was determined using corrected rainfall data. The calculated results for the mean watershed rainfall, employing the arithmetic mean method, are shown in Table 1.

Table 1. Average watershed rain

No	Year	STA. Moramo (mm)	STA. Onembute (mm)	STA. Tanea (mm)	Average rainfall (mm)
1	2017	138.5	56.0	31.0	75.2
2	2016	62.0	33.0	31.0	42.0
3	2015	72.6	34.0	31.0	45.9
4	2014	92.0	54.0	31.0	59.0
5	2013	203.0	120.0	86.4	136.5
6	2012	95.0	44.0	31.0	57.0
7	2011	148.6	56.0	31.0	78.5
8	2010	179.9	63.0	48.5	97.2
9	2009	156.4	59.0	17.1	77.5
10	2008	164.3	67.0	19.0	83.4

The data required for slope stability analysis was the infiltration value corresponding to the maximum rainfall with a 10-year return period. The process involved selecting an appropriate distribution type for the rainfall data and conducting compatibility tests using the Smirnov-Kolmogorov test and the Chi-Square test [5], [14]. Furthermore, the analysis results indicated that the Log Normal distribution is suitable for calculating the rainfall design. This rainfall design value was then used to determine the rain intensity, facilitating the computation of the infiltration value using the phi index method [5]. Figure 5 shows the outcomes of the rainfall intensity analysis. The phi value is estimated to fall within the $0.4 < \varphi < 0.8$ range. The histogram area above the red line in Figure 5 represents the runoff depth. The calculated infiltration index value is 0.542, affirming the accuracy of the estimated range of $0.4 < \varphi < 0.8$. The analysis concludes that the infiltration value is 0.542 cm/h.

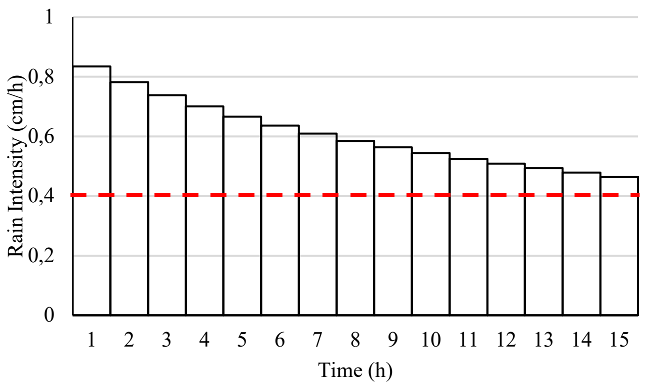

Figure 5. Rainfall intensity

3.3. Slope stability analysis

The purpose of conducting slope stability analysis was to evaluate the safety factor of the slope in response to infiltration. Slope stability is defined as the ratio between the resisting force and the driving force acting on the slope, or alternatively, the ratio between the shear stress and the shear force along the potential sliding plane. The analysis was carried out using the Spencer method within the framework of the limit equilibrium method [6].

3.3.1. Analysis of existing condition

This analysis aimed to derive soil parameters for each soil layer. As mentioned earlier, the only available soil investigation conducted was the Cone Penetration Test (CPT), which provided data on cone resistance and friction resistance. However, parameters such as cohesion, internal friction angle, and unit weight were required for the analysis. Due to the obtained values for each parameter falling within a specific range, a back-analysis method was employed to approximate the soil parameter values [1]. The soil parameters resulting in a safety factor close to 1.25 were considered representative of field conditions when a slope safety factor of 1.25 under critical conditions [12]. The soil properties obtained after the back-analysis process are shown in Table 2.

Table 2. Soil properties

Soil layer	Cohesion (c) (kPa)	Internal friction angle (ϕ) (°)	Unit weight (γ) (kN/m³)
Dense sand	5	30	18
Medium clay	20	8	17
Soft clay	8	5	16
Fill material	5	30	18

3.3.2. Analysis of road embankment

The construction of a road embankment involves placing the fill material directly on top of the existing ground surface, with a slope ratio of 1V:2H. The geometry of the embankment slope is illustrated in Figure 6, and the properties of the road embankment are shown in Table 2. It is assumed that proper compaction measures are implemented during the construction process to achieve favorable shear strength parameters for the analysis. The load acting on the slope is represented by a traffic load, which, according to the Indonesian code, is simplified as a uniform load applied over the width of the road. A load magnitude of 15 kPa was utilized for this study [12]. The analysis results employing the Spencer method indicate a safety factor 1.504 for the road embankment under traffic loads, with a slip surface illustrated in Figure 7. This value satisfies the minimum required safety factor.

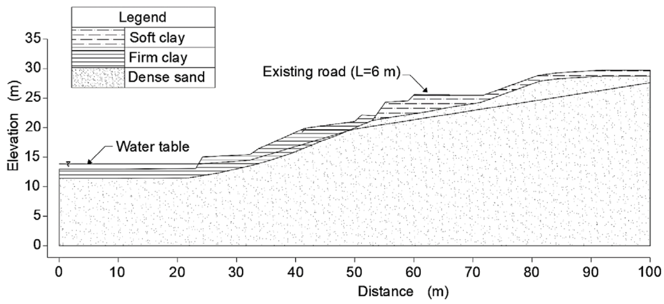

Figure 6. Road embankment design

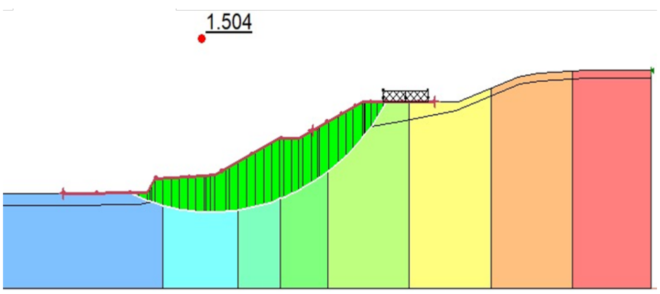

Figure 7. Safety factor of road embankment

3.3.3. Analysis of road embankment with infiltration

This analysis aimed to evaluate the influence of infiltration on the stability of road embankments. The previously determined infiltration value was incorporated into the model, as infiltration alters the pore water pressure and subsequently impacts the safety factor of the slope.

The analysis results indicate that the safety factor of the road embankment is 1.309, as illustrated in Figure 8. This value is very close to the critical safety factor value of 1.25. Notably, there is a significant disparity between the slip surfaces with and without the influence of infiltration, as shown in Figures 6 and 7. Due to infiltration, the original deep slip surface becomes shallow, even approaching the surface. This phenomenon occurs because infiltration primarily affects the pore water pressure near the slope surface.

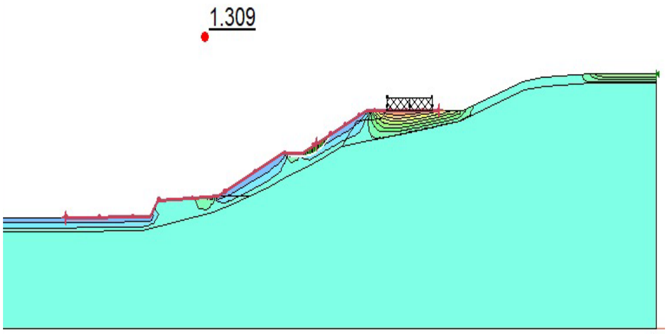

Figure 8. Safety factor of road embankment with infiltration effect

Although the slip surface resulting from the slope failure may be shallow and classified as a small landslide, it is crucial to remain vigilant. This is because even a minor failure can trigger a more significant subsequent failure on slopes. Moreover, even though the impact of infiltration on the safety factor is still greater than the safety factor value in critical conditions, it can reduce the safety factor significantly. This means it is necessary to incorporate it into every analysis or increase the safety factor criteria without considering the effects of infiltration.

4. Conclusions

An alternative solution for road widening near the ravine involves adjusting the slope of the road embankment to reach the bottom of the ravine. Analysis results indicate that a 1V:2H slope configuration yields a safety factor of 1.504, meeting the minimum safety requirements according to the Indonesian code. However, it is important to consider the impact of rainfall on the stability of embankment slopes during the planning phase. The analysis reveals that rain infiltration significantly affects slope stability, resulting in a reduction of approximately 12% in the safety factor. The analysis also demonstrates changes in pore pressure around the slope surface, which can potentially trigger small landslides leading to larger failures. This risk can be mitigated by planting vegetation on the slope surface or applying a waterproof material like shotcrete to minimize water infiltration into the soil. Another approach involves increasing the safety factor criteria by at least 12%. This ensures that even when water infiltrates the soil, causing a decrease in the safety factor, the resulting value will still comply with the safety factor criteria.

Nomenclature

I : Rain intensity
t : Rain duration
R_{24} : Daily maximum rainfall
Q : Resultant of pair of interslice forces
b,h : width and height of slice
γ : Bulk density
H : height of embankment
c' : cohesion (effective stress)
F : Safety factor
ϕ' : Internal skin friction (effective stress)
r_u : Pore-pressure coefficient
α : Slope of base slice
θ : Slope of resultant pair of interslice forces

Declaration of Conflict of Interests

The authors affirm that no conflicts of interest are associated with this study. They assert that they have no competing financial interests or personal relationships that could have influenced the work reported in this study.

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How to Cite This Article

Ngii, E., Minmahddun, A., and Kudus, F.N.R., Rainfall Infiltration's Impact on Road Embankment Stability, Brilliant Engineering, 2(2023), 4832.
https://doi.org/10.36937/ben.2023.4832