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Analysis of The Impact of River Discharge on Embankment Stability and Nature-Based Solutions: A Case Study at The CS-9 Cibingbin Site

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Keywords:
River Discharge; Embankment Stability; HEC-RAS; GeoStudio; Nature-Based Solution (Gabion).

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Abstract

River embankments constructed from granular materials excavated during river channel normalization, including gravel, stone, and sand, are particularly susceptible to erosion, seepage, and instability under high-flow conditions. This study examined the effects of river discharge on embankment stability at the CS-9 Cibingbin cross-section in Kuningan Regency, Indonesia, and assessed a hybrid nature-based solution (NBS) incorporating gabion structures and riparian vegetation as a potential stabilization measure. A quantitative numerical case study approach was employed, integrating annual maximum rainfall data from 2018 to 2024, hydraulic simulations using HEC-RAS, and slope stability analyses using GeoStudio SLOPE/W with Bishop's simplified method at station STA 1+875. The results indicated a mean annual maximum rainfall of 139.43 mm and a standard deviation of 35.20 mm, with estimated design flood discharges ranging from 423.2 to 828.0 m^3/s along the Cisanggarung–Cijangkelok river reach. The simulated water surface elevation at STA 1+875 increased from 66.84 ft for the two-year return period (Q2) to 67.10 ft for the 25-year return period (Q25). The calculated factor of safety (FoS) decreased substantially from 5.968 under dry conditions to 0.976 under the modeled inundation condition, indicating potential embankment instability. These findings suggested that changes in hydraulic loading and seepage conditions could reduce embankment stability by increasing pore water pressure and decreasing effective shear strength. A hybrid stabilization approach combining permeable gabion structures for toe protection and erosion control with riparian vegetation for potential root reinforcement was recommended as a sustainable mitigation strategy, subject to further geotechnical and hydraulic evaluation.

INTRODUCTION

Flood mitigation in Indonesia has traditionally relied heavily on structural measures, including the construction of river embankments and river channel normalization. However, these approaches may present challenges in terms of long-term sustainability, maintenance costs, and environmental impacts (Chiu et al., 2022; Quagliolo et al., 2022). Although nature-based solutions (NBS) have increasingly been proposed as strategies for flood risk reduction and climate change adaptation, their implementation and quantitative assessment remain limited, particularly for stabilizing embankments along inland rivers (Bestari et al., 2023; Griffiths et al., 2024; Herawati et al., 2026; Hill et al., 2023). Without comprehensive modeling that accounts for extreme river discharge, hydraulic loading, seepage conditions, and interactions between soil and

riparian vegetation, embankment stability may remain vulnerable under high-flow conditions (Zhao et al., 2022).

The CS-9 Cibingbin site in Kuningan Regency represents a relevant location for investigating embankment stability because its contributing watershed may experience substantial increases in river discharge during periods of intense rainfall (Haris et al., 2022). Elevated water levels and associated hydraulic forces can threaten embankment stability through toe erosion, seepage-induced changes in pore water pressure, and potential slope failure (Ilham, 2025; Upomo et al., 2022). However, site-specific hydrological monitoring and integrated assessments of embankment stability at locations such as CS-9 remain insufficiently documented. Furthermore, nature-based interventions, including riparian revegetation and bioengineering techniques, have not been systematically incorporated into embankment protection strategies at the study site (Moreau et al., 2022). These conditions highlight the need for an integrated hydrological, hydraulic, and geotechnical assessment to identify potential instability mechanisms and evaluate sustainable embankment stabilization alternatives (Aprizal & Swandewi, 2026; Nuraeni & Permana, 2026; Nurnawaty et al., 2024).



Figure 1. The existing condition of the Cibingbin River embankment at the research site

Previous studies have provided relevant insights into river embankment stability and erosion mitigation. Aminulloh et al. (2025) investigated slope stability and embankment design along the downstream reach of the Jatiroto River using GeoStudio, incorporating flood discharge estimates obtained through HEC-RAS simulations. Their findings indicated that embankments may experience shear failure under elevated flood discharge conditions. Similarly, Triarso and Dwipurwanto (2021) examined the stability of gabion structures used for coastal embankment protection in residential areas, highlighting their potential as flexible and permeable retaining structures for mitigating erosion and improving slope stability. Although both studies addressed the structural performance of embankments, neither comprehensively integrated the contribution of riparian vegetation as a nature-based stabilization measure. Furthermore, their findings provided limited insights into embankment behavior in relatively small inland watersheds, such as the Cibingbin area of Kuningan Regency, where hydraulic conditions and granular embankment materials may present distinct geotechnical challenges.

Embankment stability requires comprehensive assessment of potential slope failure, seepage, and erosion, particularly during periods of elevated river water levels. Increased hydraulic loading and seepage infiltration may raise pore water pressure within the embankment, reducing effective stress and, consequently, the available shear strength of the soil (Upomo et al., 2022). Under unfavorable hydraulic and geotechnical conditions, these processes may decrease the factor of safety (FoS) below the acceptable stability threshold. Such mechanisms are particularly relevant to embankments composed predominantly of granular materials, including sand and gravel, as observed at the CS-9 Cibingbin site. Riverbank bioengineering using riparian vegetation may enhance soil reinforcement through root tensile resistance and additional apparent cohesion, depending on root distribution, soil characteristics, and moisture conditions (Ahmed & Hussain, 2023; Capobianco et al., 2021; Kamath et al., 2025; Pisano & Cardile, 2023; Świtała, 2023). Meanwhile, gabion structures provide flexible, permeable protection against toe erosion and localized soil displacement (Al-Awadi et al., 2025; Triarso & Dwipurwanto, 2021). Their ability to accommodate limited deformation without immediate structural failure makes them potentially suitable for embankment stabilization when appropriately designed and installed.

This study aimed to address these research gaps by developing an integrated quantitative modeling framework incorporating hydrological, hydraulic, and geotechnical analyses to investigate the effects of river discharge on erosion susceptibility and embankment stability at the CS-9 Cibingbin site. Particular attention was given to embankments constructed from granular materials excavated during river channel normalization. The study also examined the potential application of a hybrid stabilization approach combining gabion structures and riparian vegetation to improve embankment resistance to erosion and enhance slope stability. The findings were expected to provide practical recommendations for sustainable embankment protection in comparable inland river environments, particularly those characterized by granular embankment materials and limited hydrological monitoring data.

METHOD

This study employed a quantitative numerical modeling approach focusing on Cross Section 9 (CS-9), particularly station STA 1+875 along the Cisanggarung–Cijangkelok River in Cibingbin District, Kuningan Regency, West Java, Indonesia. The study site was selected because the embankment consisted primarily of granular materials, including sand and gravel, excavated during river channel normalization, making it potentially susceptible to erosion and seepage under fluctuating river discharge conditions.

The research was conducted as a numerical simulation-based case study to evaluate the effects of design flood discharges on embankment stability under the modeled conditions. Hydraulic simulations were performed using HEC-RAS to estimate flow velocities and water surface elevations, while geotechnical stability analyses were

conducted using GeoStudio SLOPE/W to calculate the factor of safety (FoS) under the specified hydraulic and soil conditions.

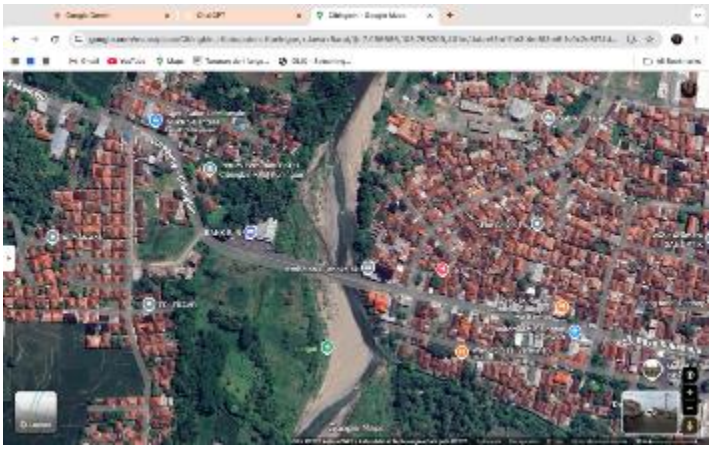


Figure 2. The location of the research on the cross-section of the CS9 of the Cibingbin River

The study used annual maximum daily rainfall data recorded at the Cibogo Rainfall Station from 2018 to 2024, river geometry and cross-sectional data obtained from the Detailed Engineering Design (DED) documents for the Cisanggarung River normalization project, and design flood discharge data from the Hydrology Report of the Cimanuk–Cisanggarung River Basin Authority (BBWS Cimanuk–Cisanggarung). Geotechnical parameters, including soil unit weight, cohesion, internal friction angle, and permeability, were obtained from subsurface investigations at borehole GT CS-9.

Table 1. Primary and secondary data of the study

Data Collected	Data Source	Remarks
River geometry data	Field measurements	DED 2022
Cross section	Copyright © 201	Working Drawings
Soil data	Laboratory tests	DED 2022
Rainfall data	Cibogo Rain Post	2018–2024

The research was conducted in four stages. First, primary and secondary data were collected. Second, hydrological analysis was performed to estimate design flood discharges for return periods of 2, 5, 10, and 25 years (Q2, Q5, Q10, and Q25) using rainfall frequency analysis and goodness-of-fit tests. Third, hydraulic simulations were conducted using HEC-RAS by incorporating the CS-9 cross-sectional geometry and estimated design flood discharges to determine water surface elevations under each flow scenario. Finally, geotechnical stability analysis was performed using GeoStudio SLOPE/W and Bishop's simplified method. Embankment geometry and soil parameters were incorporated into the model, while the simulated water surface elevations obtained from HEC-RAS were used to define the assumed piezometric conditions. The factor of safety (FoS) was calculated for each discharge scenario to assess embankment stability and provide a baseline for evaluating potential stabilization measures involving gabion structures and vegetative reinforcement.

RESULT AND DISCUSSION

Hydrological Analysis

Hydrological analysis uses annual maximum daily rainfall data for the 2018–2024 period. The results of the analysis show that the highest maximum rainfall of 203.5 mm occurred in 2023, while the minimum rainfall of 98 mm occurred in 2020. The average annual maximum rainfall was 139.43 mm with a standard deviation of 35.20 mm, which indicates considerable annual rainfall variation at the study site.

Table 2. Relationship of planned rainfall to re-period

Return Period	Planned Rainfall (mm)
2 years	145,06
5 years	169,00
10 years	185,19
25 years	211,24

The results of the frequency analysis showed that the larger the re-use period, the greater the planned rainfall value obtained. The planned flood discharge in this study refers to the Hydrology Report DED Normalization of the Cisanggarung River, with a biannual discharge (Q2) in the upstream part of Cisanggarung of 423.2 m^3/s, at the Cijangkelok junction of 645.7 m^3/s, and downstream of Cisanggarung of 828.0 m^3/s. The discharge used in the HEC-RAS simulation in this study was taken from the Cijangkelok junction point because STA 1+850 and STA 1+875 are in this segment.

Hydraulic Analysis with HEC-RAS

The hydraulic analysis aims to obtain water surface elevation in the cross-section of STA 1+850 and STA 1+875 of the Cisanggarung River. The simulation is carried out in stages as follows.

First, river geometry data in the form of cross sections STA 1+850 and STA 1+875 from AutoCAD data were entered into the HEC-RAS Geometric Data module, equipped with station-elevation data, bank station, Manning's coefficient of roughness n, and downstream reach length.

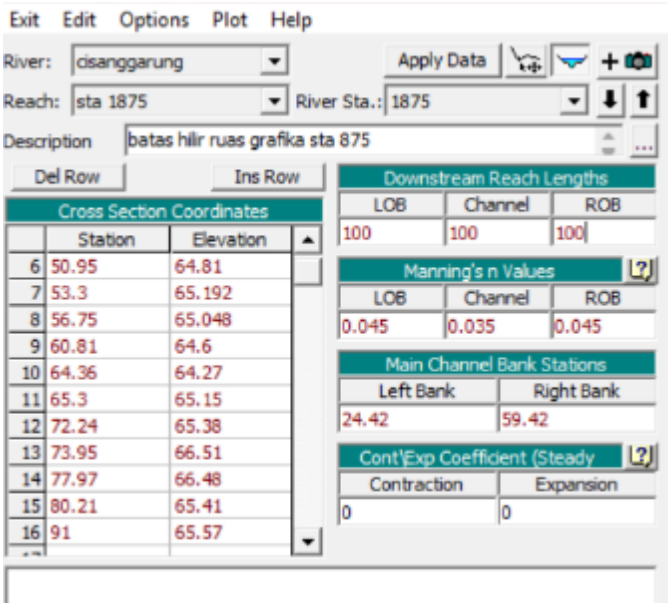


Figure 3. Geometric data input in HEC-RAS

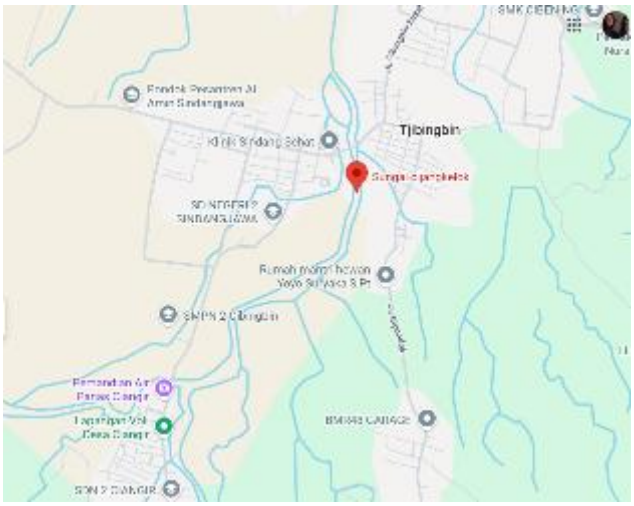


Figure 4. Cross section of STA 1+875 on HEC-RAS

Second, the planned flood discharge for the Q2, Q5, Q10, and Q25 reruns is entered as steady flow data in the Steady Flow Data menu. The larger the flood discharge that is entered, the higher the water level level produced in each river cross-section.

Table 3. Plan flood discharge data (Q2, Q5, Q10, Q25) as Steady Flow Data input

Periode	Debit
Q2	423,2 m³/s
Q5	472,4 m³/s
Q10	503,9 m³/s
Q25	538,2 m³/s

Third, after the running steady flow analysis process, HEC-RAS produces a water surface elevation profile (W.S. Elev) for each repetition, as well as displaying an

illustration of the transverse cross-section along with the depth of the water table at the STA 1+875 location.

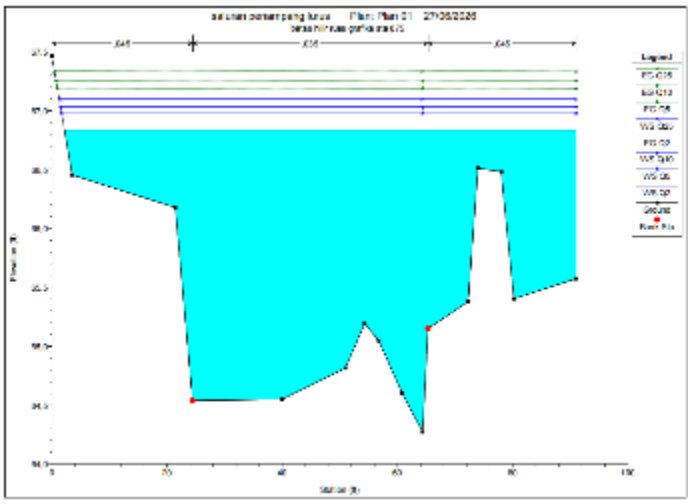


Figure 5. Illustration of the water level profile resulting from the HEC-RAS steady flow simulation at STA 1+875

The simulation results showed that the elevation of the water level at STA 1 + 875 increased with the increase in flood discharge, namely Q2 = 66.84 ft, Q5 = 66.98 ft, Q10 = 67.03 ft, and Q25 = 67.10 ft. This increase in water level shows that the higher the flowing flood discharge, the greater the hydrostatic pressure acting on the embankment body, which has the potential to increase the pore water pressure and become a determining factor in the analysis of slope stability at the next stage. These results indicate that increased flow velocity and volume during extreme discharge can raise the shear stress at the river–embankment boundary, making riverside erosion a likely mode of embankment failure during flooding.

Table 4. Results of HEC-RAS simulation of water level elevation (W.S. Elevation) at STA 1+875

Repeat Time	Discharge (Cijangkelok Junction)	W.S. Elevation STA 1+875
Q2	according to DED 2021	66.84 ft
Q5	according to DED 2021	66.98 ft
Q10	according to DED 2021	67.03 ft
Q25	according to DED 2021	67.10 ft

Slope Stability Analysis with GeoStudio SLOPE/W

The water level elevation from the HEC-RAS simulation was then used as a pore water pressure limit condition in the slope stability modeling of the GeoStudio 2025 SLOPE/W module using the Bishop method, which was chosen because it had accuracy for both homogeneous and layered soil slope conditions. The geotechnical data used were obtained from the results of drilling at the GT CS9 point, with the groundwater level at a depth of about 2.3 m from the ground level.

Table 5. Soil parameters (fill weight, cohesion, depth sliding angle) for the Mohr-Coulomb model

Material	Unit Weight (kN/m³)	Cohesion (kPa)	Friction Angle (°)
Rock Fill	22	0	43
Gravel	19,64	2	29
Claystone 1	25,66	68,63	18
Claystone 2	22,29	231,11	16,89

Table 6. Permeability data of Claystone and Gravel layers from field tests

Material	Unit Weight (kN/m³)	Cohesion (kPa)	Friction Angle (°)
Rock Fill	22	0	43
Gravel	19,64	2	29
Claystone 1	25,66	68,63	18
Claystone 2	22,29	231,11	16,89

The test results showed that the Claystone layer has a greater permeability value than the Gravel layer, so seepage flow is easier to occur in the gravel layer and has the potential to increase the pore water pressure when the river water level rises. The modeling steps in GeoStudio are carried out in stages as follows.

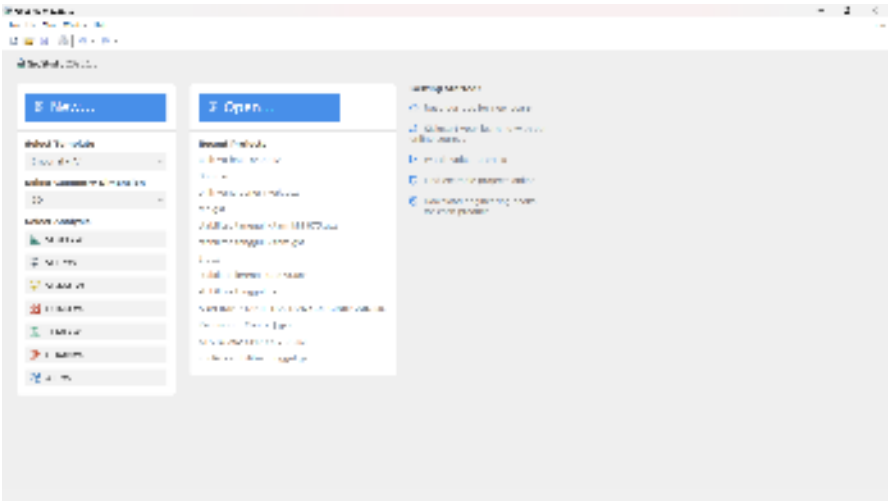


Figure 6. Stage 1 – Unlock the GeoStudio 2025 software

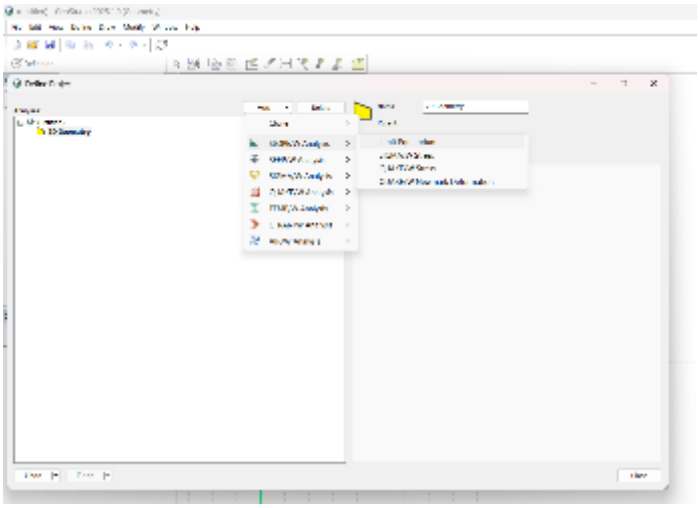


Figure 7. Phase 2 – Define Project and add Slope/W analysis with the Limit Equilibrium method

The analysis was then cloned into five scenarios to distinguish the Dry Condition and the four flood face conditions (Q2, Q5, Q10, Q25).

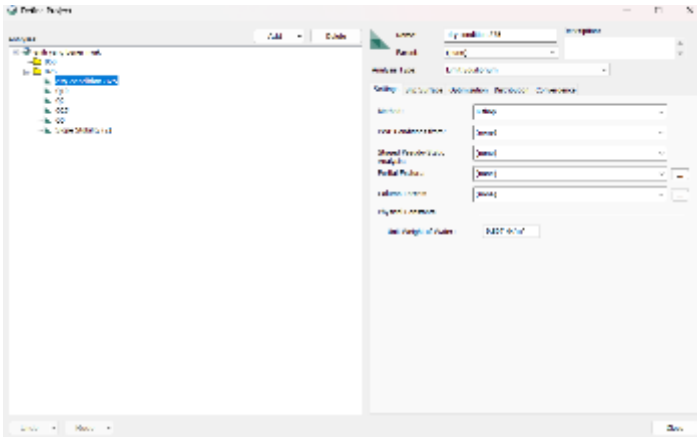


Figure 8. Stage 3 – Cloning the analysis into five modeling scenarios

Furthermore, the elevation and distance axes are set according to the X and Y coordinates of the cross-section of the embankment and gabion based on AutoCAD data, then the cross-sectional geometry is drawn using the Draw Regions feature according to the STA coordinate point 1+875.

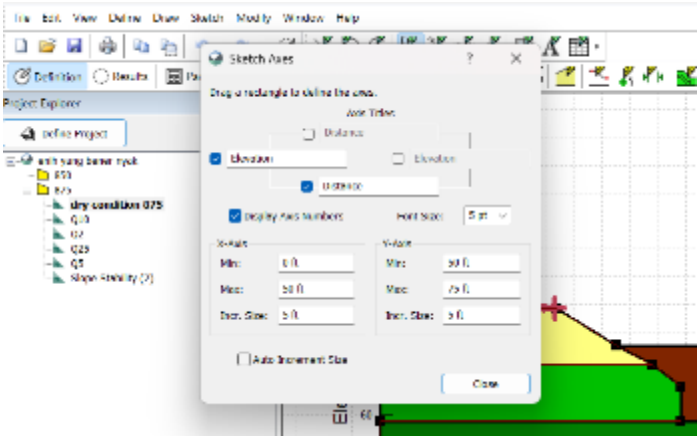


Figure 9. Stage 4 – Setting the axes of elevation and cross-sectional distance

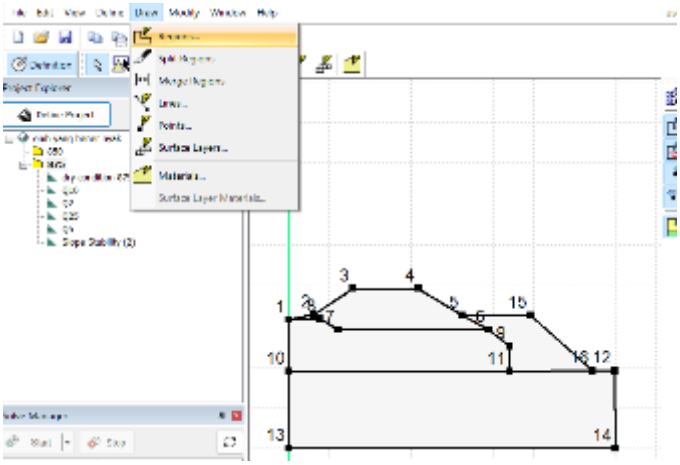


Figure 10. Stage 5 – Drawing Regions of STA 1+875

The soil material is then defined using the Mohr-Coulomb model in the Material Properties menu with the parameters of fill weight, cohesion, and inner sliding angle according to the results of laboratory tests, and given a different color code for each layer so that it is easy to distinguish when drawing (Draw Material).

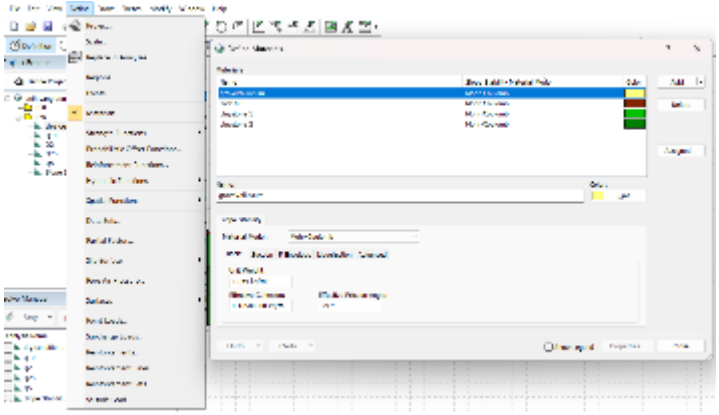


Figure 11. Stage 6 – Definition of Material Properties of the Mohr-Coulomb model

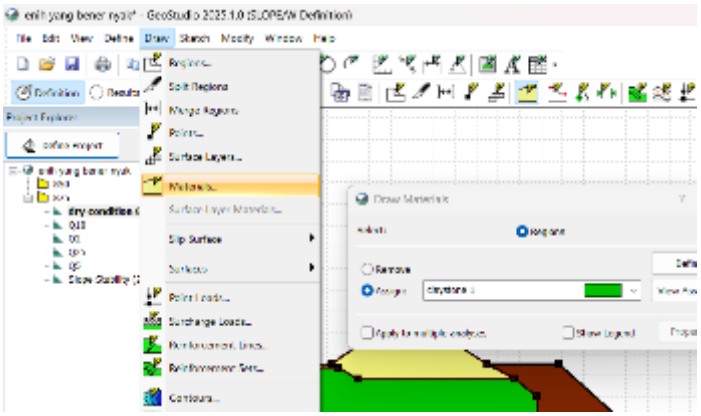


Figure 12. Stage 7 – Drawing of Material according to the soil layer

The slip surface is determined through the Entry and Exit menu to limit the location of the entry and exit of the landslide field that will be automatically searched by the software, then the analysis is carried out through the Solve Manager.

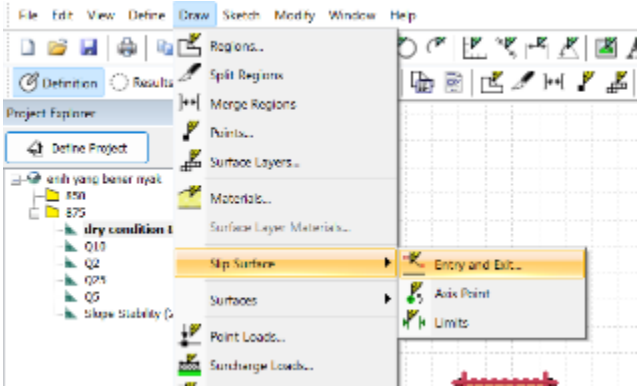


Figure 13. Stage 8 – Determination of slip surface (Entry and Exit) slip surface

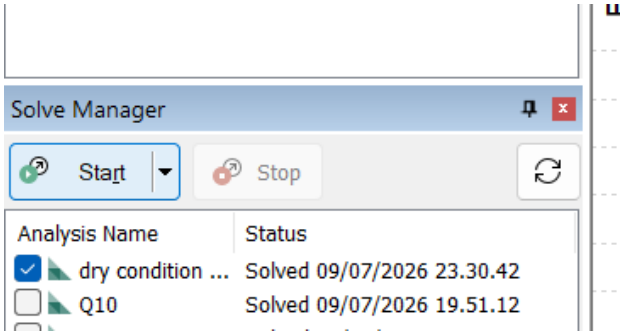


Figure 14. Stage 9 – Running the analysis via Solve Manager

The results of the analysis on Dry Conditions (without the influence of river water level) show a Factor of Safety (FoS) value of 5.968 through the View – Mass Information menu. This value is much greater than the recommended minimum FoS limit (FoS ≥ 1.50), which indicates that the levee in dry conditions is very stable and does not have the potential for landslides.

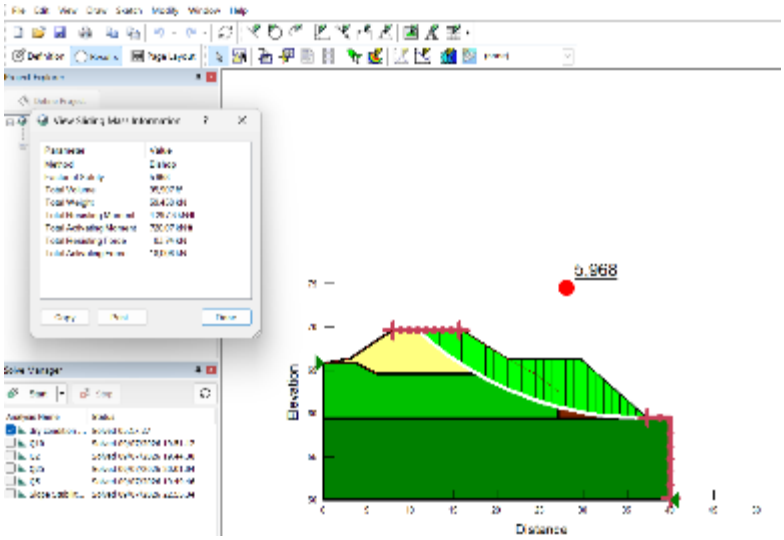


Figure 15. The result of the Factor of Safety (FoS) of Dry Condition was 5.968

To simulate the influence of flood water levels, the Pore Water Pressure (PWP) condition is changed to Piezometric Surface, then the elevation points of the water level resulting from HEC-RAS are entered in columns X and Y according to the width of the river cross-section (40 ft). For example, for the Q2 profile, the W.S. Elevation of 66.84 ft is included.

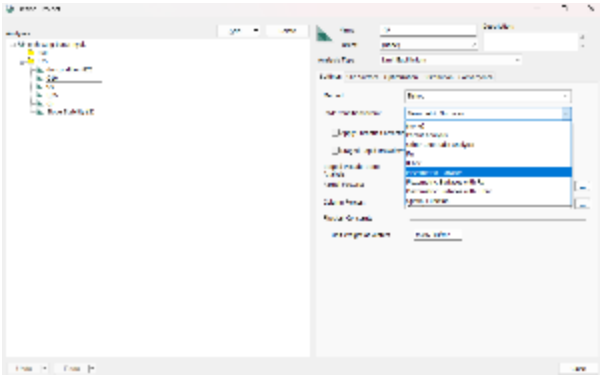


Figure 16. Stage 10 – Converting PWP Condition to Piezometric Surface

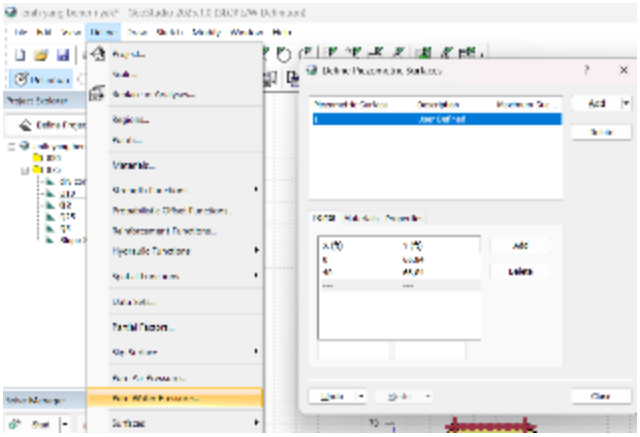


Figure 17. Stage 11 – Input of the Pore Water Pressure point from HEC-RAS

Once the piezometric surface data for the Q2 profile is entered, the analysis is run again through the Solve Manager by checking the Q2 profile. The same procedure was repeated for Q5, Q10, and Q25 profiles with different water level elevation values according to the HEC-RAS results.

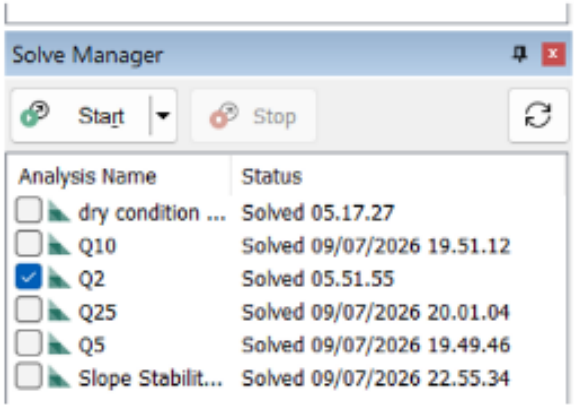


Figure 18. Stage 12 – Running Q2 profile analysis in Solve Manager

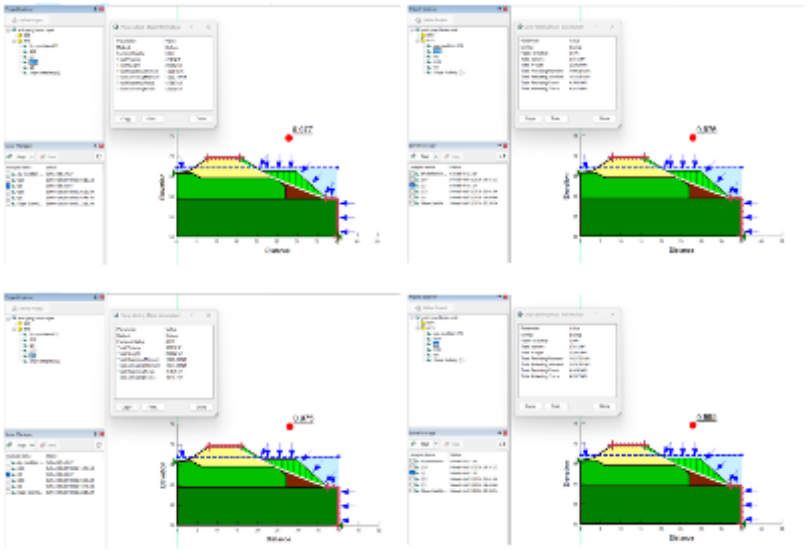


Figure 19. Results of Factor of Safety analysis on Q2, Q5, Q10, and Q25 profiles

The simulation results showed that the safety factor of the embankment decreased drastically once the flood water table load was included in the model, from 5.968 in dry conditions to reach 0.976 in critical conditions. This value shows that the slope of the embankment is in an unstable condition and is at high risk of landslides, even in flood discharges with a two-year anniversary (Q2) which is relatively frequent.

Table 7. Recapitulation of Factor of Safety (FoS) on each water level profile

Profil STA 1+875	FoS (Factor of Safety)
Dry Condition	5,968
Q2	0,995
Q5	0,975
Q10	0,976
Q25	0,977

Effect of Discharge on Embankment Stability

The results of the linkage between HEC-RAS and GeoStudio show that the increase in river discharge causes an increase in the elevation of the water level, which further increases the pore water pressure on the body of the embankment. This increase in pore water pressure lowers the effective tension of the soil, so that the shear strength of the soil is reduced and the slope Safety Factor decreases significantly, from 5.968 in dry conditions to 0.976 in conditions affected by flood water levels. These findings are consistent with the principle of soil mechanics which states that rising water levels will raise the water pressure so that the effective stress of the soil is reduced and reduces the holding force against the driving force of the landslide.

The results of this study also show that floods with a two-year anniversary (Q2) alone have caused critical conditions on the embankment. Hydrologically, the two-year anniversary is a flood event with a relatively frequent frequency so that it should still be anticipated by the river protection system. This condition indicates that the capacity of existing embankments has decreased in performance, which can be influenced by changes in land use in watersheds, sedimentation that reduces cross-sectional capacity, degradation of embankment materials due to service life, and increased rainfall intensity as a result of climate change.

Effectiveness of Nature-Based Solutions (Gabions and Vegetation)

Based on these critical conditions, the handling that has been implemented by BBWS consultants and contractors PT Bumi Karsa is the application of Nature-Based Solution (NBS) in the form of adding or renovating gabions combined with riparian vegetation. Nature-Based Solution is an action of managing and restoring natural ecosystems that are integrated with vegetation to effectively answer societal challenges, while providing benefits for the environment and human welfare.



Figure 20. Application of gabions from the normalization of the excavation of the Cijangkelok River combined with riparian vegetation

From a geotechnical aspect, gabions do not increase soil shear strength parameters such as content weight (γ), cohesion (c), or deep sliding angle (φ), but increase the stability of the slope system through adding weight to the slope legs as a counterweight, reducing erosion due to river flow, and releasing water pressure through permeable rock cavities. With this mechanism, gabions help maintain the effective tension of the soil so that the potential for landslide field development can be reduced. Gabions can also maintain a high Safety Factor in intensive seepage conditions due to their ability to deform minor without experiencing total structural failure, in contrast to rigid concrete structures.

In addition to these technical benefits, the use of gabions has advantages over conventional concrete structures because it is able to utilize normalized local stones as filler materials, is more flexible to soil deformation, has good drainage, is easy to maintain, and can be combined with vegetation to support the ecological function of riverbanks. The root system of riparian plants also increases the effective cohesion of the soil (Δc) through natural tensile reinforcement, thereby increasing the slope Safety Factor and resistance to surface erosion. Therefore, the application of gabions combined with riparian vegetation in STA 1+875 is considered urgent and recommended as a preventive mitigation measure to increase the resilience of the embankment to increase the discharge of the Cisanggarung River in the future.

CONCLUSION

Based on hydraulic simulations using HEC-RAS and slope stability analyses using GeoStudio SLOPE/W with Bishop's simplified method at station STA 1+875 along the Cisanggarung River, the findings indicated that increasing flood discharge was associated with higher water surface elevations and reduced embankment stability. The HEC-RAS simulations showed that water surface elevations increased progressively across the design flood scenarios, reaching 66.84 ft, 66.98 ft, 67.03 ft, and 67.10 ft for the 2-, 5-, 10-, and 25-year return periods (Q2, Q5, Q10, and Q25), respectively. These simulated elevations were subsequently used to establish hydraulic boundary conditions for the slope stability analysis. The GeoStudio SLOPE/W results indicated that the calculated factor of safety (FoS) decreased substantially from 5.968 under dry conditions to 0.976 under the modeled inundation conditions, suggesting potential embankment instability

and an increased risk of slope failure. The reduction in stability was consistent with the potential effects of increased pore water pressure, reduced effective stress, and decreased available shear strength within the granular embankment materials at the CS-9 Cibingbin site. A hybrid stabilization approach incorporating gabion structures and riparian vegetation was recommended as a potential mitigation measure to improve toe protection, reduce erosion susceptibility, and support riverbank ecological functions. However, its structural effectiveness, economic feasibility, and long-term sustainability require further evaluation through site-specific hydraulic, geotechnical, and environmental assessments.

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