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Design and Planning of Riverbank Protection in Ledok Kulon Village, Bojonegoro

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ABSTRACT

In Ledok Kulon Village, Bojonegoro, unstable riverbanks pose a direct threat to local infrastructure. Preliminary GEO5 assessments found existing slopes to be critically unsafe, with factors of safety consistently below 1.50 and hitting a dangerous 0.90 at section P3. To address this, a protection system was developed using soil investigations and numerical simulations. The design integrates gabions, Flat Concrete Sheet Piles (FCSP), and mini piles to withstand normal, flooding, and rapid drawdown conditions. Findings show that the rapid drawdown phase (C3) is the most critical for stability. Nevertheless, the FCSP components performed satisfactorily, maintaining structural integrity with a maximum displacement of only 14.6 mm. This design is technically sound and fully compliant with SNI 8460:2017 standards.

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INTRODUCTION

Riverbank stability is a critical concern for water infrastructure development. This challenge is particularly acute in regions like Bojonegoro, where extreme fluctuations in water levels create unstable conditions along riverbanks. In Ledok Kulon Village, the current state of the riverbanks shows a high vulnerability to slope failure. Initial assessments using the Bishop method confirm that the stability across the observed sections (P1 to P6) is critically low, with Factor of Safety (FoS) values failing to meet the minimum safety requirement of 1.50. This instability poses a direct threat to local settlements and infrastructure along the river's edge, necessitating an effective technical solution through the design of proper bank protection structures (Udomchai et al., 2018).

Figure 1. Drone Visualization of the Research Area

Previous studies have demonstrated that the rate of pore water pressure dissipation plays a critical role in the reliability of slope stability predictions. Eduardo E. Alonso and colleagues reported that a fully coupled hydro-mechanical analysis provides more accurate pore water pressure estimations under rapid drawdown conditions than simplified analytical approaches (Alonso & Pinyol, 2016). Furthermore, slope stability is strongly influenced by the rate and magnitude of reservoir drawdown, as well as the permeability characteristics of the slope material. Similarly, a study by Pandey et al. (2023) found that the Finite Element Method (FEM) generally produces more conservative slope safety factor estimates than the Limit Equilibrium Method (LEM) when evaluating slope stability during the drawdown phase.

The complex interaction between soil and structural systems necessitates the use of advanced numerical modeling tools during the design process. Accordingly, this study employed the GEO5 software to perform geotechnical verification and evaluate the stability and performance of the proposed design (Sari et al., 2024). The proposed system integrates three primary structural components: a counterfort retaining wall, a mini-pile foundation, and slope reinforcement using a Flat Concrete Sheet Pile (FCSP). The design procedures adopted in this study were carried out in accordance with the requirements of SNI 1727:2020 and SNI 8460:2017.

This study seeks to design and validate a riverbank protection system for Ledok Kulon Village that can provide reliable long-term stability under critical loading conditions (Ezzeldin et al., 2026). The proposed system was verified through three loading scenarios, namely the normal condition (C1), flood condition (C2), and rapid drawdown condition (C3) (Zhou et al., 2022). By combining advanced numerical analysis with field-derived geotechnical data, the proposed design is anticipated to meet the required technical safety standards and effectively reduce the risk of slope failure at the project site (Sajwan & Ramana, 2024).

LITERATURE REVIEW

Slope Stability Analysis under Rapid Drawdown Conditions

The stability of slopes in embankment dams and riverbanks is highly influenced by fluctuations in the external water level. The most critical condition generally occurs during the rapid drawdown (RDD) phase, when a sudden decline in the water level removes the lateral hydrostatic support acting on the slope while excess pore water pressure within the soil mass has not yet dissipated. This transient condition significantly reduces the effective stress of the soil, thereby increasing the likelihood of slope failure. Norbert Morgenstern (1963) pioneered the development of stability charts for earth slopes subjected to rapid drawdown by assuming that no pore water pressure dissipation occurs during the water-level recession. Subsequent studies by Berilgen (2007) and Pinyol et al. (2008) further demonstrated that slope stability under rapid drawdown conditions is strongly governed by the drawdown rate, the drawdown ratio, and the hydraulic permeability of the soil. In particular, low-permeability soils exhibit a more pronounced reduction in the factor of safety (FoS) because pore water pressures dissipate more slowly than the external water level declines.

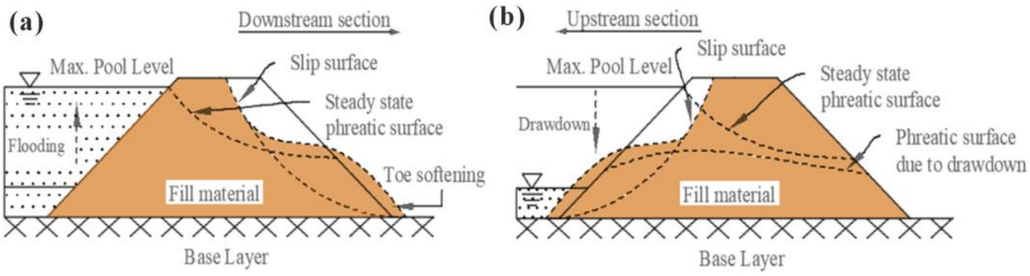
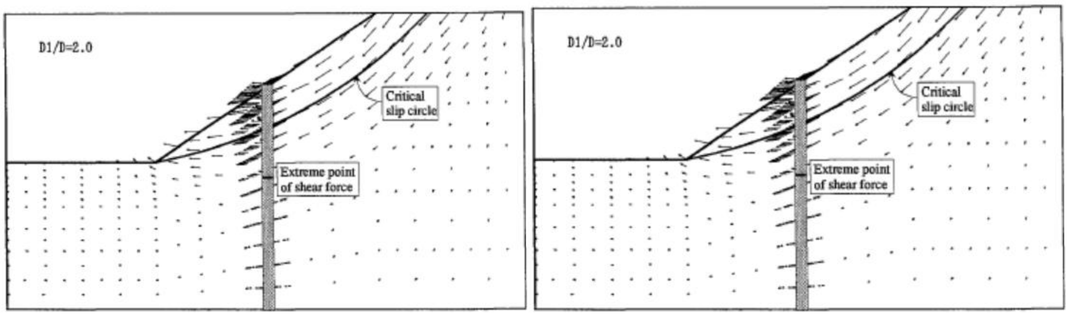


Figure 2. Mechanisms of Slope Instability under Groundwater Level Fluctuations: (a) Downstream Instability, (b) Upstream Instability (Chimere & Liu, 2025)

Design of Riverbank Reinforcement Systems

The application of hybrid structural systems that combine gravity-based retaining structures with foundation reinforcement has emerged as an effective solution for enhancing the global stability of complex slopes. Ramli et al. reported that gabion walls offer significant advantages owing to their structural flexibility and free-draining characteristics, which effectively reduce hydrostatic pressure behind the retaining structure (Ramli et al., 2013). In the context of riverbank stabilization, optimization of systems integrating gabion walls with embedded piles has demonstrated superior resistance to lateral shear forces compared with conventional gravity retaining structures alone (Wang & Smith, 2021). In the present study, conducted at the Ledok Kulon Village site, a composite reinforcement system consisting of Flat Concrete Sheet Piles (FCSP) and mini piles was adopted to provide resistance against bending moments and improve overall structural stability, while the gabion wall functions as a protective surface layer to minimize erosion caused by river flow.

Figure 3. Various Gabion Configurations Developed for Experimental Testing (Ramli et al., 2013)



(a) (b)

Figure 4. Illustration of Nodal Vector Displacements Using the Bishop Method: (a) Critical Circular Slip Surface, (b) Induced Nodal Vector Displacements (Ramli et al., 2013)

Table 1. Depth of the Critical Slip Surface (Ramli et al., 2013)

Pile Spacing D_1/D	**FEM Shear Strength Reduction Values**		**Bishop Method**
	Free Hand	**Hinged Head**	
2,0	6,27	6,27	2,84
3,0	4,98	6,27	3,18
4,0	4,18	6,27	3,34
6,0	4,18	4,98	3,50

Numerical Analysis Using the Limit Equilibrium Method

In this study, the Limit Equilibrium Method (LEM) implemented in the GEO5 software was employed using the Bishop method to evaluate the stability of the riverbank slope in Ledok Kulon Village. This method was selected because of its proven reliability in analyzing circular slip surfaces, particularly in fine-grained soils such as silty clay, which constitutes the predominant soil type at the study site. According to Sari et al. (2024), hydrogeological characteristics and conventional geotechnical soil parameters often indicate critical conditions in slopes that exhibit a high susceptibility to ground movement. Therefore, the Bishop method provides a robust analytical framework for assessing slope stability by incorporating the mechanical behavior of the soil under representative field conditions.

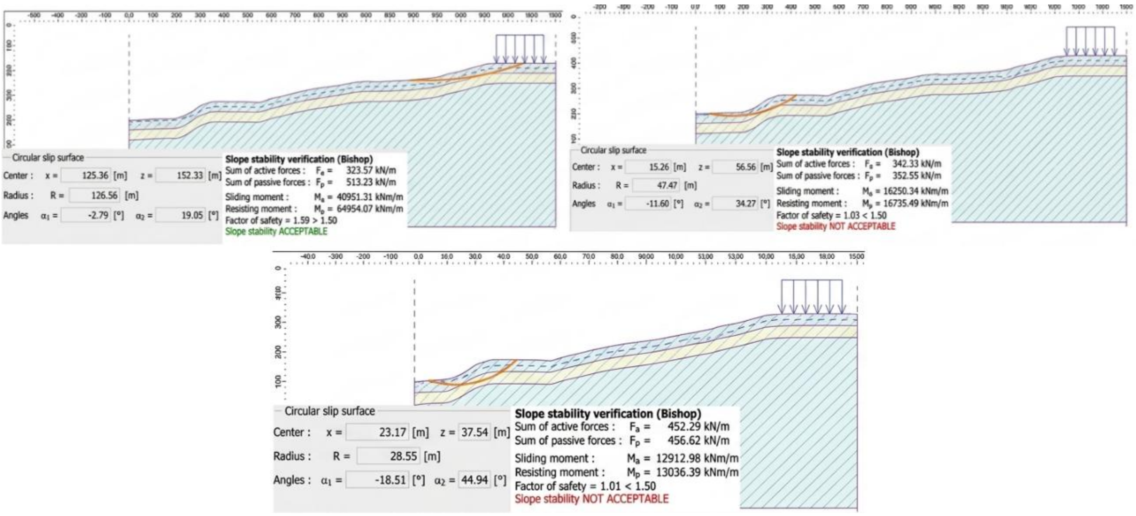


Figure 5. Slope Stability Analysis Results Obtained Using GEO5 Software at KM 8.5 (Sari et al., 2024)

METHODOLOGY

A comprehensive geotechnical investigation was conducted at the Ledok Kulon Village study site through a series of field and laboratory tests to characterize the subsurface stratigraphy and determine the engineering properties of the soil. Based on deep borehole investigations at three locations (BH-1, BH-2, and BH-3), the subsurface profile is predominantly composed of dense silty clay with brown to gray coloration. Undrained triaxial compression tests (ASTM D2850-87) yielded a shear strength characterized by a cohesion (c) of 0.250 kg/cm² and an internal friction angle (φ) of 8.34°. Furthermore, permeability testing in accordance with the applicable Indonesian National Standard indicated an exceptionally low hydraulic conductivity (k) of 0.0001560 cm/s, reflecting the soil's low permeability and limited drainage capacity. Consequently, pore water pressure dissipates slowly, making the slope particularly susceptible to instability under transient hydraulic conditions such as rapid drawdown. The geotechnical data obtained from the field investigation, including borehole exploration and Cone Penetration Test (CPT) results, were integrated as input parameters for the numerical slope stability analysis.

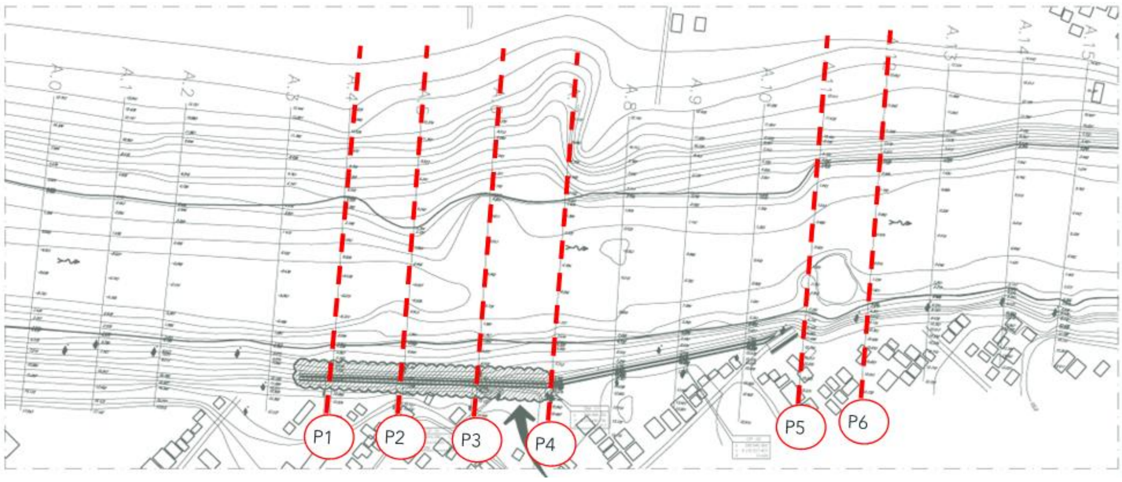


Figure 6. Layout of the Study Area and Investigation Points

The structural design analysis consisted of two main stages, namely the evaluation of the superstructure and the substructure. Both analyses were performed using the GEO5 software to assess the geotechnical stability and structural performance of the proposed riverbank protection system incorporating a gabion wall, Flat Concrete Sheet Piles (FCSPs), and a mini-pile foundation. The loading conditions adopted in the analysis were defined in accordance with the Indonesian National Standard (Badan Standardisasi Nasional, 2020) and comprised the following load components:

a) Dead load
b) Live load
c) Wind load
d) Quake load

The substructure analysis and slope stability verification were performed using the GEO5 software by evaluating three representative environmental loading scenarios, as follows:

a) Normal Condition (C1): This scenario evaluates the stability of the existing slope under static loading conditions and the natural distribution of pore water pressure.
b) Flood Condition (C2): This scenario assesses the effects of rising river water levels, which increase both hydrostatic pressure and pore water pressure, thereby potentially reducing the shear strength of the soil.
c) Rapid Drawdown Condition (C3): This scenario examines the most critical hydraulic condition, in which a rapid decline in the river water level causes a sudden redistribution of pore water pressure within the soil mass. Because pore water pressure cannot dissipate immediately, the reduction in effective stress may significantly compromise slope stability.

RESULTS AND DISCUSSION

Existing Slope Stability Analysis

An initial assessment of the existing riverbank conditions at the Ledok Kulon Village study site was conducted using the Bishop method across six representative cross-sections (P1–P6). The results indicate that nearly all cross-sections are classified as unstable (not acceptable), with Factor of Safety (FoS) values below the minimum recommended criterion of 1.50 [19]. At Cross-section P3, the calculated overturning moment (MA) was 419.61 kN·m/m, exceeding the corresponding resisting moment (MP) of 376.24 kN·m/m. This imbalance demonstrates that the stabilizing capacity of the existing riverbank has been exceeded, indicating an inadequate margin of safety against slope failure. Therefore, structural reinforcement is required to enhance the overall stability of the riverbank and effectively mitigate the risk of landslides.

Figure 7. Existing Slope Stability Verification at Cross-Section P3 (GEO5)

Table 2. Summary of Existing Slope Stability Analysis (GEO5)

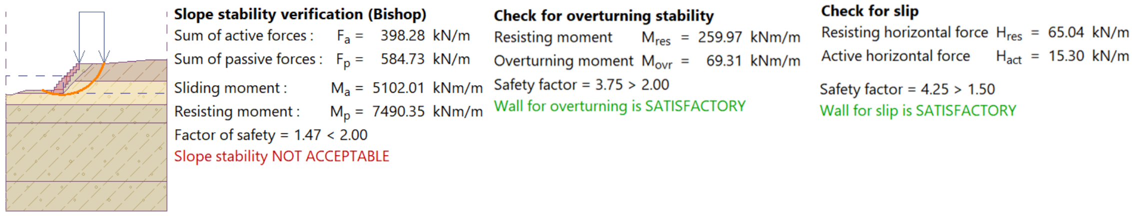
Section	F_A	F_P	M_A	M_P	Result
P1	657,28	1185,67	17812,27	32131,62	Satisfactory
P2	746,82	1064,58	16213,41	23111,93	Not Acceptable
P3	72,10	64,65	419,61	376,24	Not Acceptable
P4	89,02	113,55	619,61	790,29	Not Acceptable
P5	366,39	465,36	6258,00	7948,29	Not Acceptable
P6	260,71	289,71	3324,12	3693,82	Not Acceptable

Gabion Wall Stability Analysis

The gabion retaining structure was designed to evaluate the performance of a gravity-type retaining wall subjected to lateral earth pressures and overturning moments acting on the riverbank slope at the Ledok Kulon Village study site. The design verification included a comprehensive assessment of the structural stability against overturning, sliding, and bearing capacity failure in accordance with the requirements of SNI 8460:2017 (Indonesian National Standard, 2017). All numerical modeling and analyses were performed using the GEO5 software to accurately simulate the interaction between the gabion structure and the underlying silty clay soil, thereby providing a reliable evaluation of the geotechnical behavior and overall stability of the proposed riverbank protection system.

Based on the numerical simulation under the Normal Condition (C1), the gabion retaining structure demonstrated satisfactory performance in resisting static earth loads. For example, Cross-section P1 achieved a Factor of Safety (FoS) against overturning of 3.74, which exceeds the minimum design requirement of 2.00. The GEO5 analysis also yielded a FoS against sliding of 4.22, well above the minimum acceptable value of 1.50, indicating adequate resistance to lateral displacement. Furthermore, the verification of load eccentricity and foundation bearing capacity confirmed that the structure satisfies the required stability criteria under normal loading conditions, with a bearing capacity FoS of 5.50, significantly exceeding the minimum recommended value of 3.00. In addition, the evaluation of the joints between gabion blocks demonstrated satisfactory structural performance, with all calculated safety factors remaining well within the acceptable design limits.

However, a substantial reduction in structural stability was observed when the gabion system was evaluated under more severe hydraulic loading scenarios. Based on the GEO5 simulation results, the gabion retaining structure without additional reinforcement failed to satisfy the required safety criteria under both the Flood Condition (C2) and the Rapid Drawdown Condition (C3). At Cross-section P4 during the Rapid Drawdown Condition (C3), the Factor of Safety (FoS) against overturning decreased markedly to 0.54, while the FoS against sliding was reduced to 0.26, indicating a highly unstable condition. This loss of stability was primarily attributed to the accumulation of excess pore water pressure within the soil mass, resulting from the extremely low hydraulic conductivity (0.0001560 cm/s), which significantly delayed pore pressure dissipation. The instability was further aggravated by the rapid loss of hydrostatic support provided by the river water, leading to a substantial reduction in the stabilizing forces acting on the riverbank slope.



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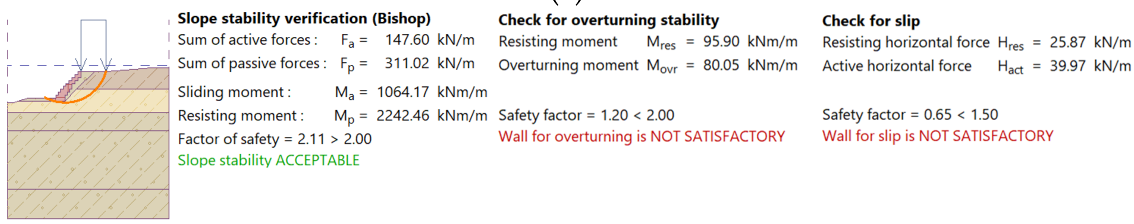

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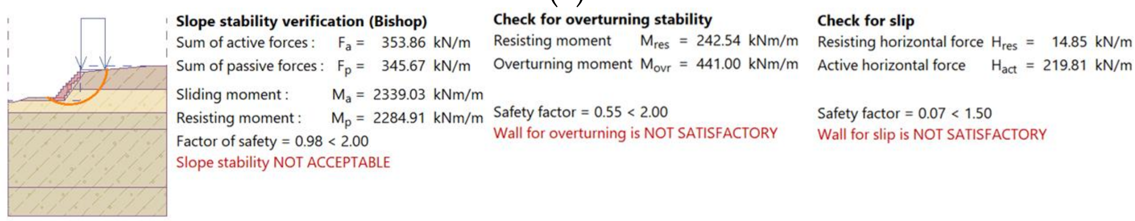

(c)

Figure 8. Analytical Results under Three Loading Scenarios: (a) Normal Condition (C1), (b) Flood Condition (C2) and (c) Rapid Drawdown Condition (C3) (GEO5)

Table 3. Summary of Numerical Analysis Results for the Gabion Wall (GEO5)

Section	Load Case	F_A	F_P	M_A	M_P	Result
P1	Normal	317,70	613,67	5006,99	9671,38	Not ok
	Flood	164,87	335,64	1236,54	2517,31	Ok
	Rapid drawdown	347,64	344,28	2308,35	2286,00	Not ok
P2	Normal	398,28	584,73	5102,01	7490,35	Not ok
	Flood	333,84	524,67	4082,90	6416,67	Not ok
	Rapid drawdown	500,24	435,12	4377,10	3807,34	Not ok
P3	Normal	398,28	584,73	5102,01	7490,35	Not ok
	Flood	147,60	311,02	1064,17	2242,46	Ok
	Rapid drawdown	353,86	345,67	2339,03	2284,91	Not ok
P4	Normal	127,43	308,14	843,57	2039,89	Ok
	Flood	126,13	311,55	885,41	2187,05	Ok
	Rapid drawdown	271,70	306,90	1670,93	1887,41	Not ok
P5	Normal	191,73	353,37	1526,18	2812,86	Not ok
	Flood	265,35	514,30	3383,15	6557,27	Not ok
	Rapid drawdown	354,73	246,22	2334,14	2278,11	Not ok
P6	Normal	219,17	374,34	1757,77	3002,23	Not ok
	Flood	265,35	514,30	3383,15	6557,27	Not ok
	Rapid drawdown	350,97	345,59	22298,85	2263,64	Not ok

Substructure Verification and Reinforcement Design

The structural integrity and geotechnical stability of the Flat Concrete Sheet Piles (FCSPs) were verified to ensure that the primary reinforcement system can effectively withstand lateral earth pressures and environmental loading acting on the riverbank slope at the Ledok Kulon Village study site. The analysis was performed using the GEO5 software, which integrates the geotechnical properties of the silty clay obtained from the field investigation with the technical specifications of the precast concrete sheet pile system. The FCSPs were designed to function as a rigid retaining structure that limits lateral slope deformation, thereby enhancing the overall stability of the riverbank under critical loading conditions.

In this study, the riverbank reinforcement system was designed using Flat Concrete Sheet Piles (FCSP) with dimensions of 500 × 320 × 6000 mm. The GEO5 numerical analysis predicted a maximum bending moment of 26.95 kN·m/m and a maximum sheer force of 22.06 kN/m. These results indicate that the proposed FCSP reinforcement system possesses a substantial structural capacity reserve, enabling it to safely withstand the design loads without approaching its structural resistance limits or experiencing material failure. Consequently, the FCSP system provides an effective and reliable solution for enhancing the stability of the riverbank under the prescribed loading conditions.

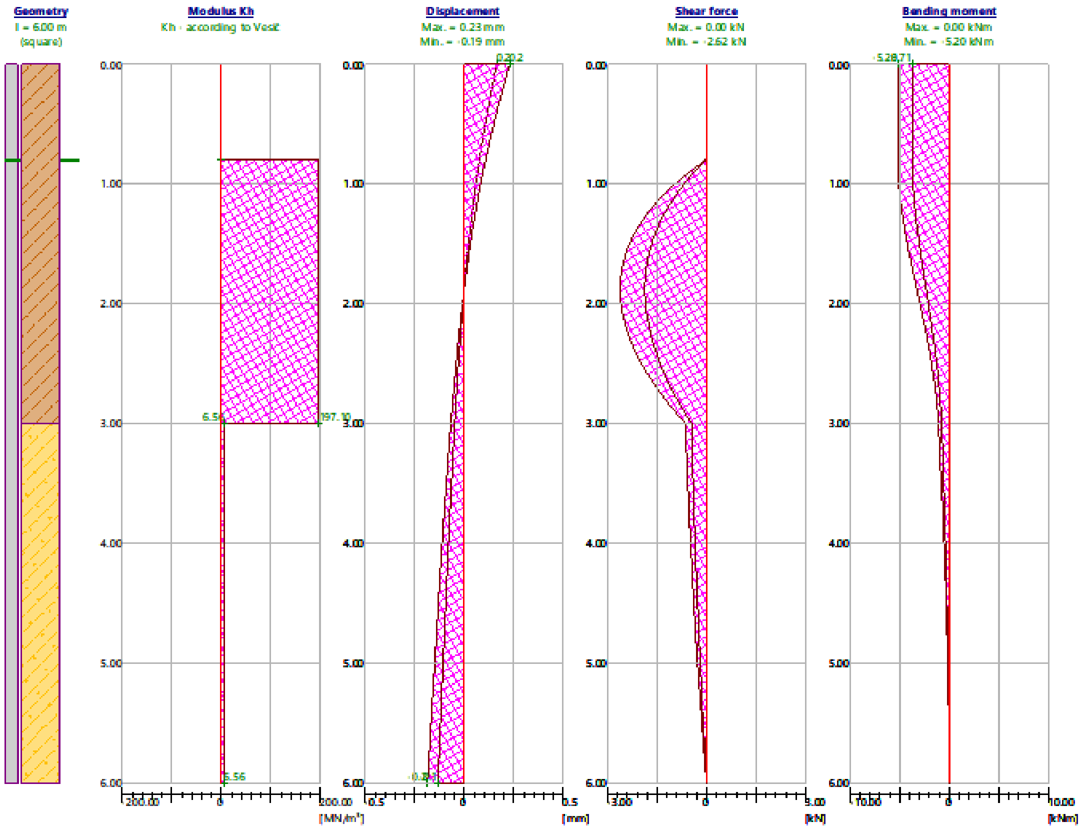

Figure 9. Structural Analysis Results of the Flat Concrete Sheet Pile (FCSP) System Obtained Using GEO5

The substructure verification of the proposed riverbank reinforcement system incorporating Flat Concrete Sheet Piles (FCSPs) was performed using the GEO5 software to evaluate its geotechnical stability and structural performance. The analysis confirmed that the system satisfies the required design criteria, with a Factor of Safety (FoS) against passive earth pressure failure of 9.18, substantially exceeding the minimum acceptable value of 1.50. Based on the overall design evaluation and verification, the integrated riverbank protection system comprising a gabion wall, mini-pile foundation, and Flat Concrete Sheet Piles (FCSPs) is considered the most reliable and effective engineering solution for stabilizing the riverbank at the Ledok Kulon Village study site, Balen District, Bojonegoro Regency.

CONCLUSIONS AND RECOMMENDATIONS

Based on the comprehensive analysis and discussion presented in this study, the following conclusions can be drawn:

a) The stability assessment of the existing riverbank slopes across six representative cross-sections (P1–P6) at the Ledok Kulon Village study site, Bojonegoro Regency, revealed that all sections were in an unstable condition, with Factor of Safety (FoS) values below the minimum acceptable criterion of 1.50. These findings confirm the urgent need for structural reinforcement to prevent or substantially reduce the risk of slope failure that could threaten nearby residential areas.

b) The proposed integrated riverbank protection system, consisting of a gabion retaining wall, a 25 × 25 cm mini-pile foundation, and Flat Concrete Sheet Piles (FCSPs), was demonstrated to be both technically reliable and structurally effective. Numerical verification indicated that all structural components possess sufficient load-carrying capacity to safely resist the design loads acting under the investigated site conditions.

c) Among the three loading scenarios considered, the Rapid Drawdown Condition (C3) was identified as the most critical, exhibiting significantly lower stability than both the Normal Condition (C1) and the Flood Condition (C2). At Cross-section P1, the FoS against overturning decreased dramatically to 0.54, while the FoS against sliding was reduced to 0.26. This severe instability was primarily attributed to the accumulation of excess pore water pressure within the soil mass, resulting from the extremely low hydraulic conductivity (0.0001560 cm^3/s), which delayed pore pressure dissipation following the rapid decline in river water level.

d) The design verification of the Flat Concrete Sheet Pile (FCSP) reinforcement system using the GEO5 software demonstrated satisfactory structural performance, with a Factor of Safety (FoS) against passive earth pressure failure of 3.82, substantially exceeding the minimum design requirement of 1.50. These results confirm that the proposed FCSP system provides a safe, reliable, and effective solution for reinforcing the riverbank under the analyzed loading conditions.

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