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Foundation repair for Earthfill dams to mitigate piping and boiling phenomenon

[1]Kuntjoro, [2]Nafik Nurlaila and [3]Deris Faisa Ralindra

[1, 3]Vocational Faculty, Department of Civil Infrastructure Engineering, Sepuluh Nopember Institute of Technology, Surabaya, Indonesia
[2]Fresh Graduate from Department Teknik Infrastruktur Sipil, Sepuluh Nopember Institute of Technology, Surabaya, Indonesia

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Corresponding Author: Kuntjoro

Abstract

Embankment dams are highly susceptible to collapse due to hydrostatic pressure, water pressure, and geometric factors. This study aims to identify and analyse the potential risks of collapse and the impact of seepage on embankment dams. Crucial factors in maintaining dam stability include the selection of dam-forming materials and a stable foundation, particularly in addressing erosion due to seepage. The analysis was conducted using the SEEP/W program, focusing on three observation locations (STA) representing Normal Water Level and Flood Water Level conditions. In the initial phase, the analysis was performed under conditions without foundation repair to understand the extent of potential collapse risks. Subsequently, an analysis was conducted on several foundation repair alternatives, including grouting, cut off wall, and upstream blanket. The results of the analysis are presented in terms of safety factors against symptoms of piping and boiling for each STA under Flood Water Level conditions. The main findings indicate that safety factors can be significantly improved through the implementation of alternative foundation repair methods, where grouting, cut off wall, and upstream blanket each provide different levels of enhancement. A summary of these analysis results provides insight into potential risks and the effectiveness of foundation repair solutions, serving as valuable guidance in enhancing the safety of embankment dams. Presenting this information is expected to contribute to a deeper understanding of factors influencing dam stability and adopted foundation repair strategies to reduce the risk of collapse.

Keywords: Embankment dams, collapse risk, seepage, foundation repair safety factors

Introduction

Dams are vital structures constructed to control the flow of water from the upstream to downstream of rivers. They play a crucial role in flood control, preventing excessive overflow that could pose hazards. Additionally, dams regulate and store water during rainy seasons, providing a valuable resource for various purposes, including agriculture and serving as a water source for communities. The Bagong Dam, an earthfill dam, serves multiple purposes such as flood control, water supply, agriculture, and tourism. With a reservoir capacity of 17.4 x 10^6 m³ under Normal Water Level (NWL) conditions [1], the Bagong Dam faces the inherent risk of collapse due to hydrostatic pressure, pore water pressure, and geometric factors.

It is imperative to meticulously plan dams, ensuring that the materials constituting the dam body are of high quality and stand on a stable foundation. The foundation, a critical support for the dam body, must adhere to specific requirements. Comprising layers of soil or natural rock, the foundation is chosen to support the dam body and its accompanying structures. To maintain the stability of the dam foundation, remedial measures can be undertaken if the foundation fails to meet specified criteria. One crucial criterion for foundation stability is its resistance to erosion caused by seepage [2].

Seepage from the dam and foundation is a pivotal factor in dam stability. Seepage involves the continuous flow of water from the reservoir through permeable materials, traversing both the dam body and the foundation [3]. The flow of seepage in the dam foundation can lead to the entrainment of fine particles, causing erosion or piping phenomena. This study aims to analyse the influence of piping and boiling phenomena, considering various foundation repair alternatives as solutions. The analysis employs Geostudio SEEP/W and SLOPE/W software, along with manual calculations. The research questions addressed in this study are:

1. Piping and boiling phenomena.
2. Foundation repair alternatives to address piping and boiling phenomena, including: a. Grouting b. Cut off wall c. Upstream Blanket
3. Selection of the appropriate foundation repair alternative to mitigate piping and boiling phenomena.

The study site is located at the Bagong Dam, situated in the Semurup and Sengon villages, Bendungan District, Trenggalek Regency, East Java Province, as depicted in Figure 1.

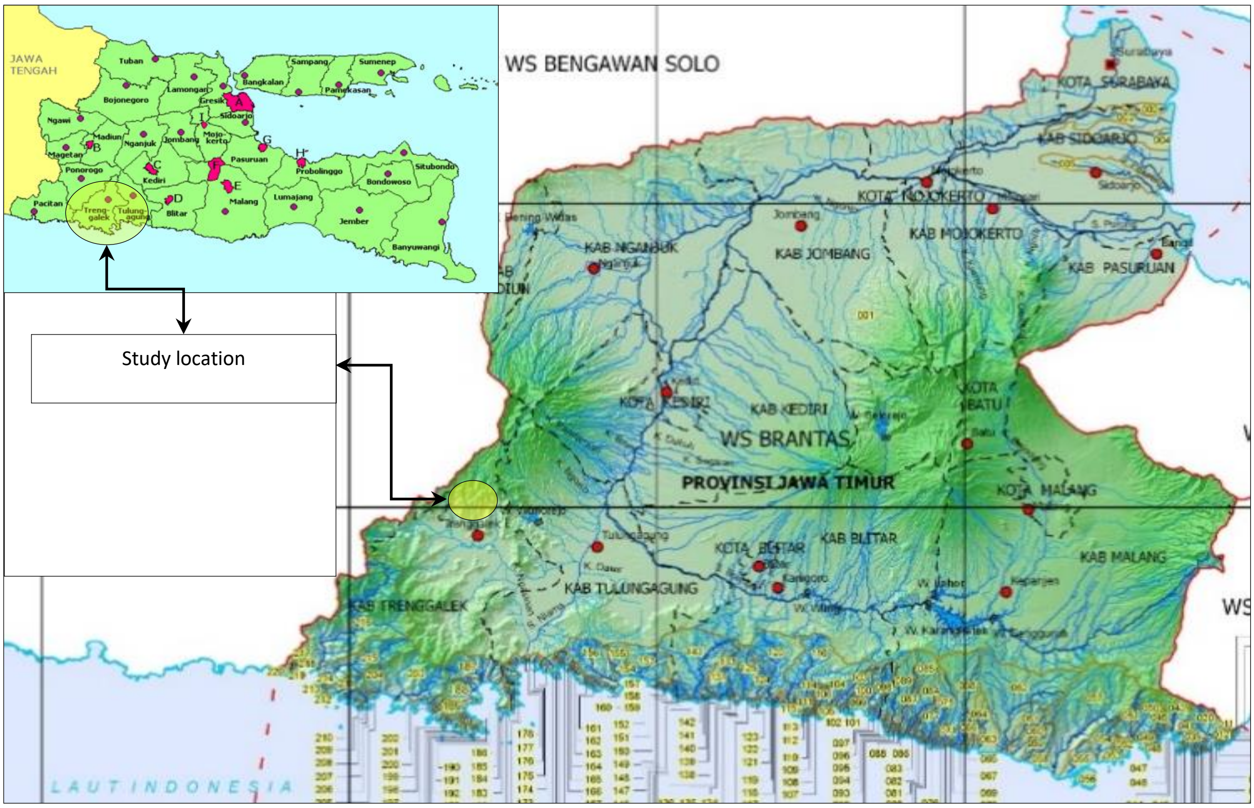

Fig 1: Location of Bagong dam construction site as the study area

Materials and Methods

Materials formation for main dam

The analysis of seepage to determine the safety factors for piping and boiling in this study utilizes the Geostudio software, specifically the SEEP/W sub-program. Additionally, slope stability analysis is conducted using the SLOPE/W sub-program, incorporating material data relevant to formation embankment body, as depicted in Figure 2. The seepage and slope stability analyses are performed for three STA (Station) models: STA +575, STA +425, and STA +225. The analyses are carried out in multiple stages as follows:

1. Alternative 1: Foundation repair using grouting.
2. Alternative 2: Foundation repair using cut off wall.
3. Alternative 3: Foundation repair using upstream blanket.

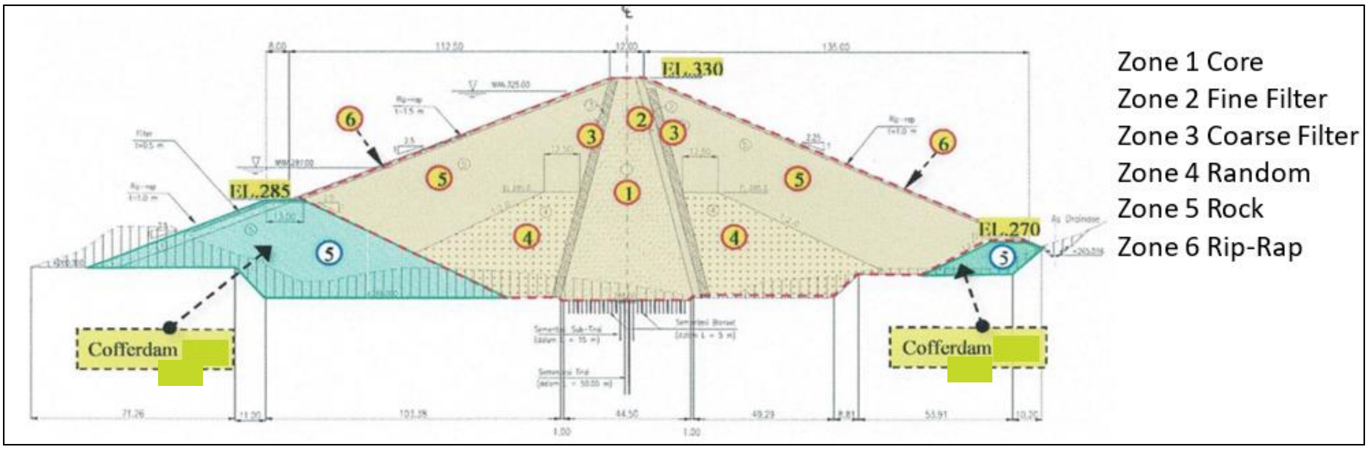

Fig 2: Cross-Sectional View of the Main Dam

Table 1: Analysis of availability of earth fill materials for the dam body

No	Material Type	Volume (m3)	Quarry Location
1	Zone I - Core (Clay)	1,394,496	Flooded area and dam foundation excavation
2	Zone II - Fine Filter	660,330	Badak River, Sidodadi Village, Nglegok and Garum, Blitar, approximately 90-110 km from the site
3	Zone III - Coarse Filter	269,561	Crushing results from river deposits and quarry rock material, maximum distance of 0-2 km.
4	Zone IV - Random Stone	954,262	Excavation from tunnel, spillway, foundations, right and left abutments, within 0-2 km distance
5	Zone V - Stone Fill	6,046,648	Quarry 1,2,3 and expansion area on the right side of the flooded area, within 0-2 km distance
6	Zone VI - Rip Rap		Quarry 1,2,3 and expansion area on the right side of the flooded area, within 0-2 km distance

Seepage Analysis

The theoretical foundation for the analysis of seepage in dam foundations employs Darcy's equations, as illustrated by Equation 1, Equation 2, and Equation 3 below:

$$Q = kiA \tag{1}$$

$$Q = \frac{k(h_1 - h_2)}{L} A \tag{2}$$

$$i = \frac{\Delta h}{L} \tag{3}$$

Where,

Q = Volume of water flow per unit time
k = Permeability coefficient
i = Hydraulic gradient
A = Cross-sectional area of the soil through which seepage occurs
$h1-h2$ = Difference in water surface elevation
L = Length of the soil layer through which seepage occurs

Piping Phenomenon is a rapid erosion occurring due to concentrated seepage through the body and/or foundation of an earthfill dam. To assess the indication of piping and boiling hazards, the safety factor for piping is calculated using the following equation:

$$SF = \frac{I_c}{I_e} \geq 4 \tag{4}$$

$$I_c = \frac{\gamma}{\gamma_w} = \frac{G_s - 1}{1 + e} \tag{5}$$

Where,
SF = Safety Factor (dimensionless)
I_c = Critical Exit Gradient (dimensionless)
I_e = Exit Gradient from Seepage Analysis or Piezometer Instrument Readings (dimensionless)
γ' = Effective weigh (submerged) (t/m^3)
γ_w = Water density (t/m^3)
G_s = Specific weight (dimensionless)
e = Porosity (dimensionless)

The safety factor for piping in both the body and foundation of the dam is ≥ 4 [4]. If the safety factor for piping falls below 4, foundation repair is necessary. The following are several foundation repair alternatives that can address piping and boiling:

a. **Grouting:** A displacement process involving the replacement of a fluid, typically water and air, in the voids within an in-situ mass with another fluid more suitable for improving the mass properties [4].
b. **Cut-off wall:** One foundation repair method to control seepage in the body and foundation of the dam. The barrier wall functions to reduce the discharge and energy of seepage, commonly placed upstream of the dam axis to prevent adverse effects from high water pressure and hydraulic gradients [5].
c. **Upstream blanket:** A foundation repair method aimed at extending the seepage flow to reduce leakage. The effectiveness of this upstream impermeable blanket depends on its length, thickness, vertical permeability coefficient, and the layering and permeability of the foundation material [6].

Stability analysis

Dam stability is a critical requirement in dam construction. Slope stability is influenced by various factors such as slope inclination, foundation layers, dam body material, and others. The determination of slope stability is synonymous with the Safety Factor (SF), which is the ratio of resisting forces to the driving forces acting on the soil. In the planning of earthfill dams, slope stability is designed with a safety factor of 1.5. The safety factor can be expressed by the equation:

$$SF = \frac{shear\ strength}{shear\ stress} \tag{6}$$

The commonly used method for slope stability analysis is the simplified Bishop slice method. The Bishop method employs a slice approach, where forces acting on each slice are utilized to analyse the circular slip surface. To calculate the force equilibrium, the safety factor in the Bishop method can be determined using Equation 7.

$$FS = \frac{\sum_{i=1}^{i=n} [cb_n + W\tan\varphi] \frac{1}{m_{a(n)}}}{\sum_{i=1}^{i=n} W_n \sin a_n} \tag{7}$$

In addition to slope stability, it is essential to consider the bearing capacity of the dam foundation soil. The soil must be capable of supporting and sustaining the planned load of the dam body without failure. Several theories proposed by previous researchers analyse the soil's bearing capacity. Among them is the bearing capacity theory proposed by Terzaghi [7]. This theory can be expressed as follows in

Equation 8:

$$qu = C\ x\ N_c + \gamma_t\ x\ D\ x\ N_q + 0.5\ x\ \gamma_t x\ Bx\ N_\gamma$$

Where,
Qu = Foundation Bearing Capacity
g = Unit weight of soil
D = Depth of foundation base
B = Width or diameter of the foundation
Nc, Nq, Nγ = capacity factors according to Terzaghi [6].

Results and Discussion

Seepage analysis under unrepaired foundation conditions: The seepage analysis results, conducted using the Geostudio Sub-program SEEP/W, were based on the Normal Water Level (NWL) conditions obtained from the Bagong Dam planning data, which is +325, and the Flood Water Level (FWL) determined through hydrological analysis at +329.4. The analysis was performed at various STA, as illustrated in Figure 3 for STA +575, Figure 4 for STA +425, and Figure 5 for STA +225.

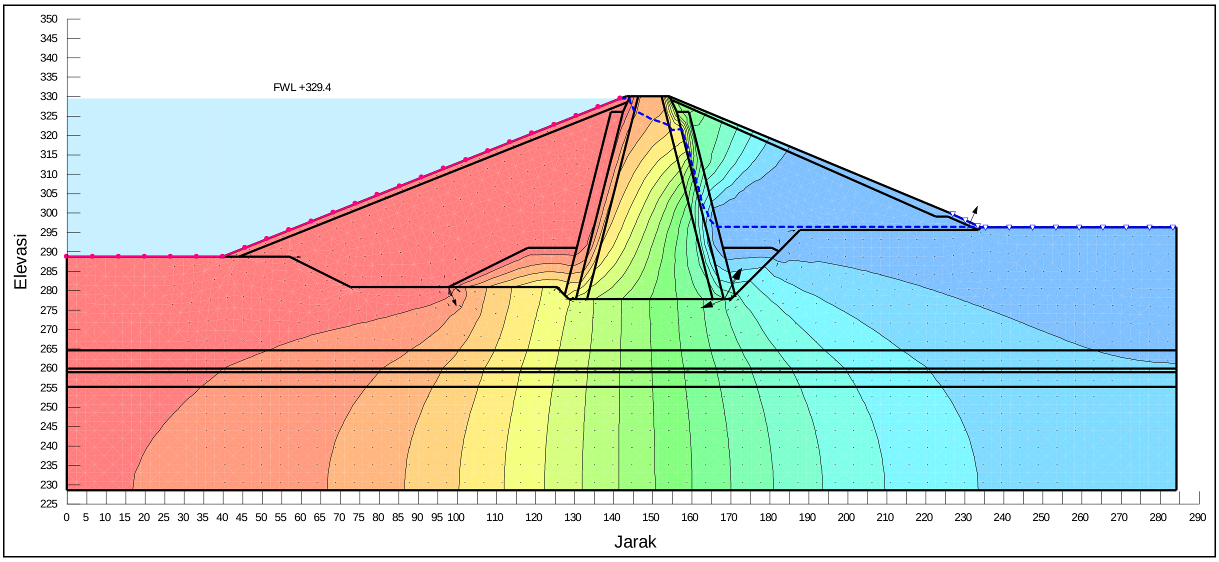

Fig 3: SEEP/W Results for STA +575 under Unrepaired Foundation Conditions at Flood Water Level (FWL)

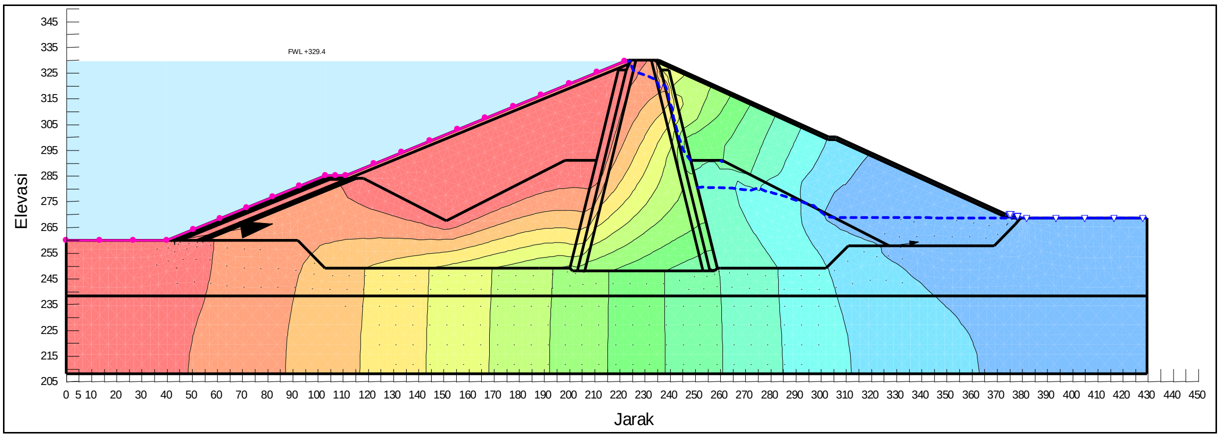

Fig 4: SEEP/W Results for STA +425 under Unrepaired Foundation Conditions at Flood Water Level (FWL)

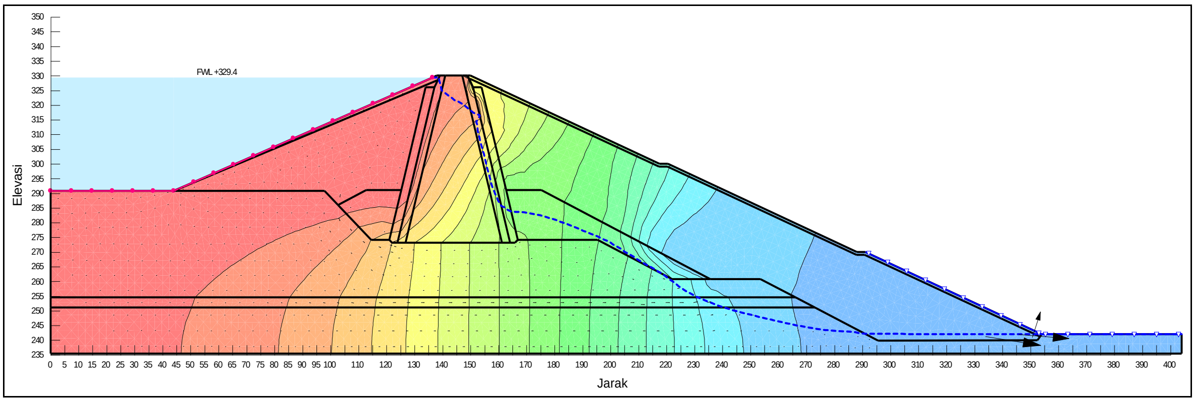

Fig 5: SEEP/W Results for STA +225 under Unrepaired Foundation Conditions at Flood Water Level (FWL)

The seepage analysis using the SEEP/W sub-program yielded hydraulic gradient values, which were then utilized to calculate the piping safety factor using Equation 4. The calculated results are presented in Table 2, showcasing the safety factor values for piping under both Normal Water Level (NWL) and Flood Water Level (FWL) conditions across several analyzed STA.

Table 2: Piping Safety Factor Values under Unrepaired Foundation Conditions

Analysis on		Point	Piping		
			I max	Icr	SF
STA +575	NWL	Q1	0.2515	0.662	2.6
		Q2	0.2347	0.662	2.8
		Q3	0.2044	0.662	3.2
	FWL	Q1	0.5136	0.662	1.3
		Q2	0.2709	0.662	2.4
		Q3	0.2111	0.662	3.1
STA +425	NWL	Q1	0.6227	1.548	2.5
		Q2	0.425	1.548	3.6
		Q3	0.3992	1.548	3.9
	FWL	Q1	0.7921	1.548	2
		Q2	0.5187	1.548	3
		Q3	0.4861	1.548	3.2
STA +225	NWL	Q1	0.5307	0.81	1.5
		Q2	0.499	0.354	0.7
		Q3	0.3436	0.81	2.4
	FWL	Q1	0.529	0.81	1.5
		Q2	0.5	0.354	0.7
		Q3	0.3441	0.81	2.4

Based on Table 2, it is evident that the safety factor for piping under unrepaired foundation conditions is ≤ 4. This indicates that under these conditions, the structure is not safe against piping and, consequently, is not safe against boiling as well. Given the inadequate piping safety factor, foundation repair planning is undertaken for the Bagong Dam, followed by subsequent analyses.

Regarding seepage discharge, according to regulations, the permissible seepage discharge should not exceed 1% of the average river flow entering the reservoir [1]. With the average flow of the Bagong River being 6.7964 m³/sec, the allowable seepage discharge is 6.76 x 10^{-3} m³/sec. Consequently, the seepage discharge values from the conducted analysis are deemed safe as they fall below the permissible seepage discharge limit, as observed in Table 3.

Table 3: Seepage Discharge Values Relative to Permissible Seepage Discharge under Unrepaired Foundation Conditions

Analysis on		Point	Seepage Discharge	Permissible Seepage Discharge	CHECK
STA +575	NWL	Q1	5.18 x 10^{-5}	6.79 x 10^{-3}	good
		Q2	4.27 x 10^{-5}		good
		Q3	3.85 x 10^{-6}		good
	FWL	Q1	6.08 x 10^{-5}		good
		Q2	5.96 x 10^{-5}		good
		Q3	3.86 x 10^{-6}		good
STA +425	NWL	Q1	2.51 x 10^{-4}	6.79 x 10^{-3}	good
		Q2	3.60 x 10^{-4}		good
		Q3	1.17 x 10^{-5}		good
	FWL	Q1	3.25 x 10^{-3}		good
		Q2	3.89 x 10^{-3}		good
		Q3	1.26 x 10^{-5}		good
STA +225	NWL	Q1	5.18 x 10^{-5}	6.79 x 10^{-3}	good
		Q2	4.27 x 10^{-5}		good
		Q3	3.85 x 10^{-6}		good
	FWL	Q1	6.08 x 10^{-5}		good
		Q2	5.69 x 10^{-5}		good
		Q3	3.86 x 10^{-6}		good

Seepage analysis with foundation repair using grouting

The depth of curtain grouting is determined based on the characteristics of foundation seepage. If the crack pattern is highly irregular and rational analysis is not feasible, then the depth into the rock is often established through empirical procedures [8].

$$D = \frac{1}{3}H + C \quad (9)$$

Where,
D = Grouting depth
H = Dam height
C = Constant

The results of the seepage analysis after foundation repair using grouting can be observed in Figure 6 for STA +575, Figure 7 for STA +425, and Figure 8 for STA +225. The values for the piping safety factor and seepage discharge in the analysis with grouting foundation repair are depicted in Figure 6 for STA +575, Figure 7 for STA +425, and Figure 8 for STA +225.

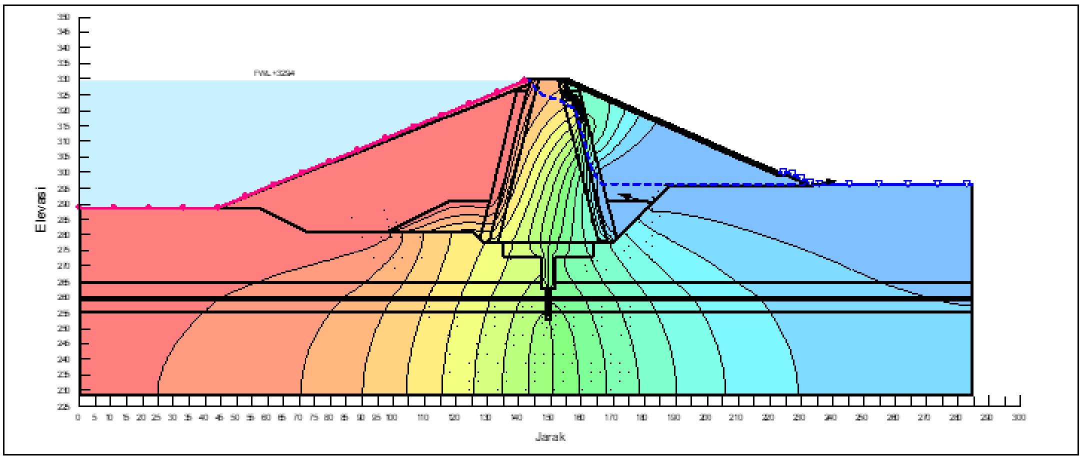

Fig 6: SEEP/W Results for STA +575 with Grouting Foundation Repair at Flood Water Level (FWL)

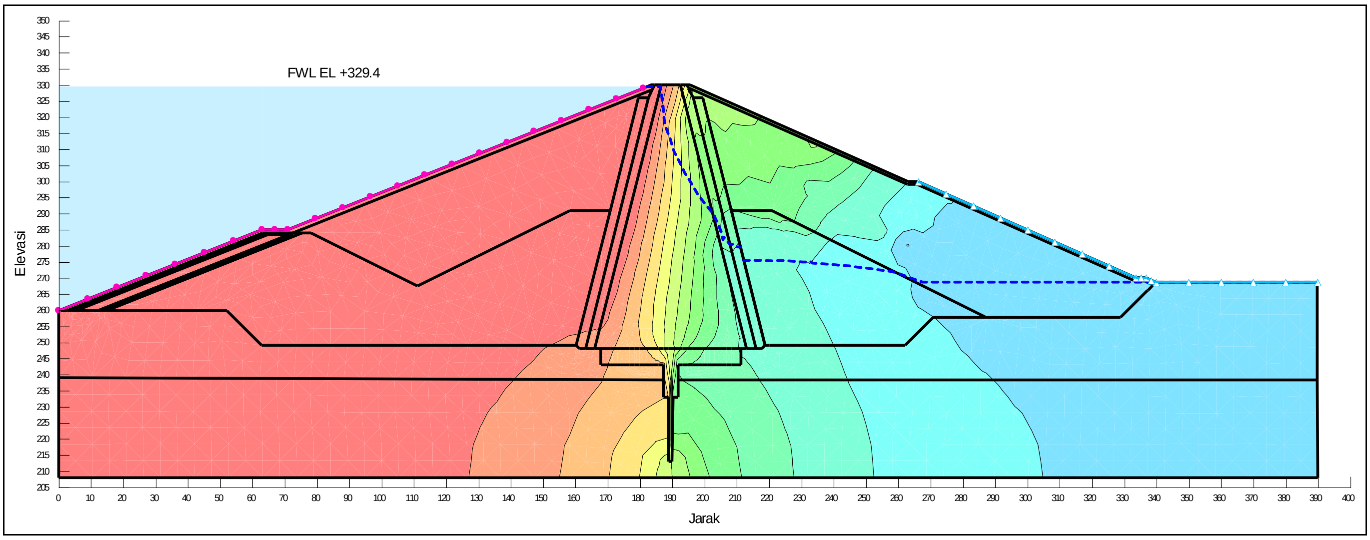

Fig 7: SEEP/W Results for STA +425 with Grouting Foundation Repair at Flood Water Level (FWL)

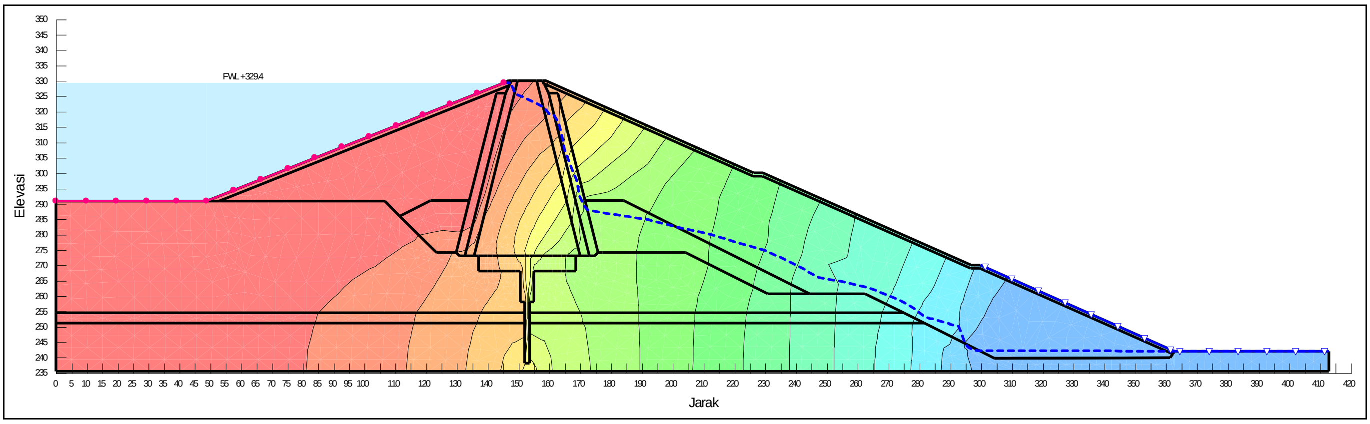

Fig 8: SEEP/W Results for STA +225 with Grouting Foundation Repair at Flood Water Level (FWL)

Table 4: Piping safety factor values with grouting foundation repair

Analysis on		Point	Piping		
			I max	Icr	SF
STA +575	NWL	Q1	0.1604	0.662	4.1
		Q2	0.2463	1.440	5.8
		Q3	0.0633	0.662	10.5
	FWL	Q1	0.1662	0.662	4.0
		Q2	0.2627	1.440	5.5
		Q3	0.0758	0.662	8.7
STA +425	NWL	Q1	0.3048	1.548	5.1
		Q2	0.2757	1.548	5.6
		Q3	0.0474	1.548	32.7
	FWL	Q1	0.3667	1.548	4.2
		Q2	0.2973	1.548	5.2
		Q3	0.0511	1.548	30.3
STA +225	NWL	Q1	0.1774	0.810	4.6
		Q2	0.2697	1.202	4.5
		Q3	0.160	1.202	7.5
	FWL	Q1	0.0849	0.810	9.5
		Q2	0.2518	1.202	4.8
		Q3	0.169	1.202	7.1

Table 5: Seepage Discharge Values Relative to Permissible Seepage Discharge with Grouting Foundation Repair

Analysis on		Point	Seepage Discharge	Permissible Seepage Discharge	Check
STA +575	NWL	Q1	5.18×10^{-5}	6.79×10^{-3}	good
		Q2	4.27×10^{-5}		good
		Q3	3.85×10^{-6}		good
	FWL	Q1	6.08×10^{-5}		good
		Q2	5.96×10^{-5}		good
		Q3	3.86×10^{-6}		good
STA +425	NWL	Q1	2.51×10^{-4}	6.79×10^{-3}	good
		Q2	3.60×10^{-4}		good
		Q3	1.17×10^{-5}		good
	FWL	Q1	3.25×10^{-3}		good
		Q2	3.89×10^{-3}		good
		Q3	1.26×10^{-5}		good
STA +225	NWL	Q1	5.18×10^{-5}	6.79×10^{-3}	good
		Q2	4.27×10^{-5}		good
		Q3	3.85×10^{-6}		good
	FWL	Q1	6.08×10^{-5}		good
		Q2	5.69×10^{-5}		good
		Q3	3.86×10^{-6}		good

The results of the seepage analysis, as seen in Table 4, indicate that the piping safety factor values with grouting foundation repair are ≥ 4. This implies that with the grouting foundation repair, the structure is secure against piping.

3. Seepage analysis with cut-off wall foundation repair

The material used for this alternative is a bentonite-cement slurry, with a seepage value based on the permeability of this selected material, $K=1.0\times10^{-8}$ m/sec [5]. The cut-off wall is constructed by excavating a trench with a width of 0.5 – 1.5 m [9]. According to the Guidelines for the Construction of Cut-off Walls in Embankment Dams, there are no practical regulations limiting the depth of this bentonite-cement slurry trench cut-off wall; however, this type of cut-off wall is typically constructed to a depth of up to 50 m [5]. The results of the seepage analysis using the cut-off wall foundation repair can be seen in Figure 9 for STA +575, Figure 10 for STA +425, and Figure 11 for STA +225, representing the seepage analysis under Flood Water Level (FWL) conditions.

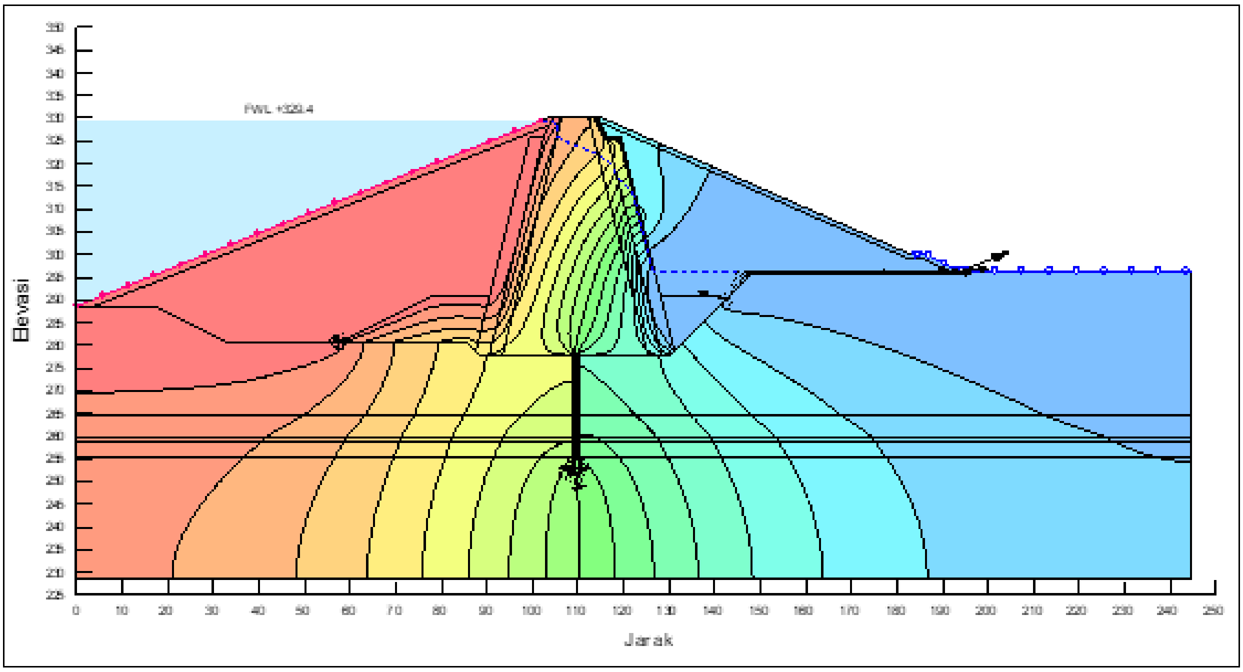

Fig 9: SEEP/W Results for STA +575 with Cut-off Wall Foundation Repair at Flood Water Level (FWL)

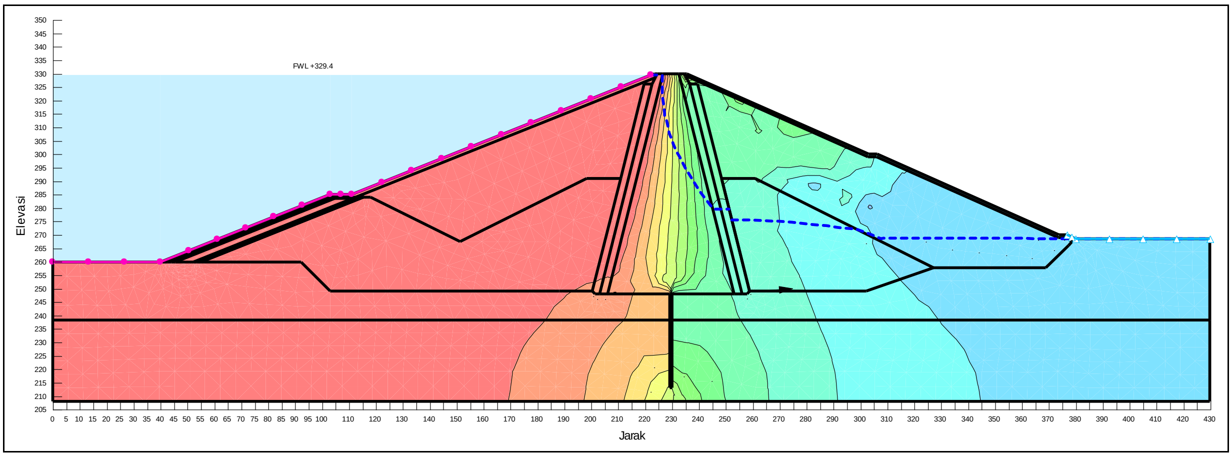

Fig 10: SEEP/W Results for STA +425 with Cut-off Wall Foundation Repair at Flood Water Level (FWL)

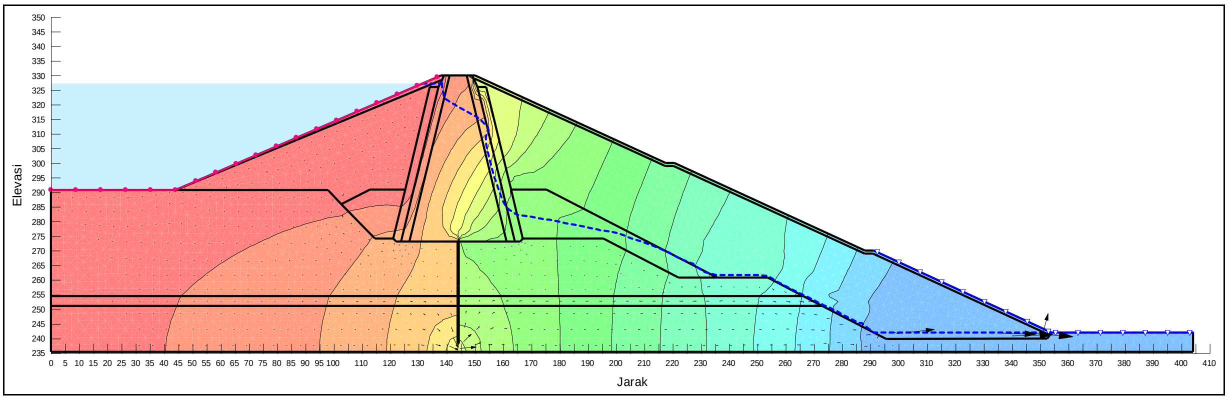

Fig 11: SEEP/W Results for STA +225 with Cut-off Wall Foundation Repair at Flood Water Level (FWL)

Table 6: Piping safety factor values with cut-off wall foundation repair

Analysis on		Point	Piping		
			I max	Icr	SF
STA +575	NWL	Q1	0.1622	0.662	4.1
		Q2	0.1950	1.440	7.4
		Q3	0.0614	0.662	10.8
	FWL	Q1	0.1644	0.662	4.0
		Q2	0.2594	1.440	5.5
		Q3	0.0706	0.662	9.4
STA +425	NWL	Q1	0.3807	1.548	4.1
		Q2	0.3779	1.548	4.1
		Q3	0.1216	1.548	12.7
	FWL	Q1	0.2762	1.548	5.6
		Q2	0.2760	1.548	5.6
		Q3	0.0789	1.548	19.6
STA +225	NWL	Q1	0.0731	0.810	11.1
		Q2	0.2923	1.202	4.1
		Q3	0.0224	1.202	53.7
	FWL	Q1	0.0738	0.810	11.0
		Q2	0.2783	1.202	4.3
		Q3	0.0239	1.202	50.4

The results of the seepage analysis, specifically the piping safety factor values as shown in Table 6, indicate that the piping safety factor values with the cut-off wall foundation repair are ≥ 4 for STA +575, STA +425, and STA +225. This implies that with the cut-off wall foundation repair, the structure is secure against piping and, consequently, is also secure against boiling. As for other seepage analysis results, such as the seepage discharge values shown in Table 7, they indicate that the seepage discharge values are below the permissible seepage discharge limit.

Table 7: Seepage discharge values with cut-off wall foundation repair

Analysis on		Point	Seepage Discharge	Permissible Seepage Discharge	Check
STA +575	NWL	Q1	2.68×10^{-5}	6.79×10^{-3}	good
		Q2	1.04×10^{-4}		good
		Q3	2.28×10^{-5}		good
	FWL	Q1	3.16×10^{-5}		good
		Q2	1.26×10^{-4}		good
		Q3	2.63×10^{-5}		good
STA +425	NWL	Q1	1.25×10^{-5}	6.79×10^{-3}	good
		Q2	4.07×10^{-4}		good
		Q3	8.06×10^{-6}		good
	FWL	Q1	7.25×10^{-5}		good
		Q2	3.97×10^{-4}		good
		Q3	1.38×10^{-5}		good
STA +225	NWL	Q1	1.15×10^{-5}	6.79×10^{-3}	good
		Q2	8.02×10^{-5}		good
		Q3	2.27×10^{-6}		good
	FWL	Q1	1.79×10^{-5}		good
		Q2	9.15×10^{-5}		good
		Q3	3.42×10^{-6}		good

Seepage analysis with upstream blanket foundation repair

Foundation repair using an upstream blanket or impermeable layer in the upstream part connected to the core zone. The efficiency of this upstream blanket depends on the length, thickness, and coefficient of permeability of the material used [8]. The calculation of the length of the upstream blanket is determined by equation 10 as follows:

$$Xt = \sqrt{\frac{Zb \text{ x } Kf \text{ x } Zf}{Kb}} \quad (10)$$

The results of the seepage analysis using the SEEP/W program after the upstream blanket foundation repair can be observed in Figure 12 for STA +575, Figure 13 for STA +425, and Figure 14 for STA +225.

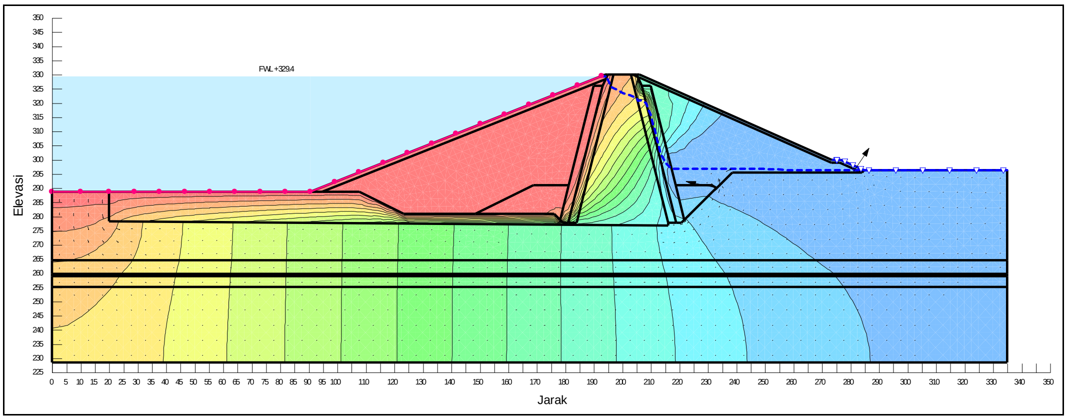

Fig 12: SEEP/W Results for STA +575 with Upstream Blanket Foundation Repair at Flood Water Level (FWL)

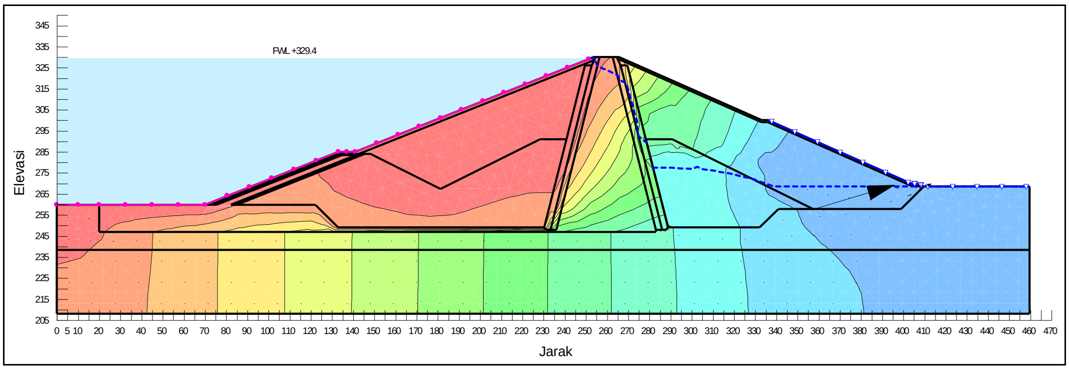

Fig 13: SEEP/W Results for STA +425 with Upstream Blanket Foundation Repair at Flood Water Level (FWL)

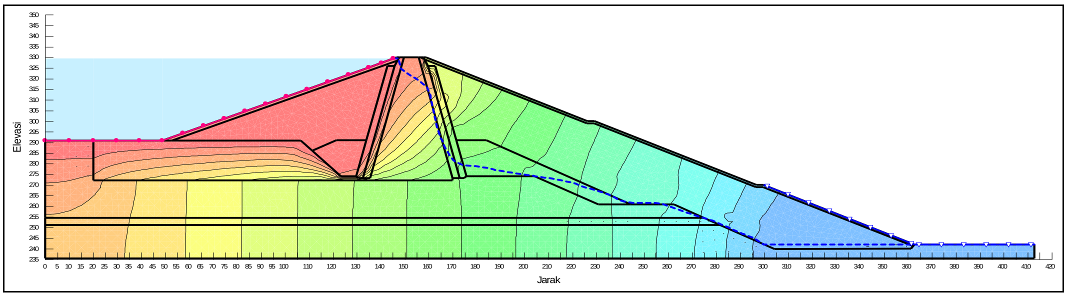

Fig 14: SEEP/W Results for STA +225 with Upstream Blanket Foundation Repair at Flood Water Level (FWL)

Table 8: Piping Safety Factor Values with Upstream Blanket Foundation Repair

Analysis on		Point	Piping		
			I max	Icr	SF
STA +575	NWL	Q1	0.1279	0.662	5.2
		Q2	0.1020	1.440	14.1
		Q3	0.0335	0.662	19.8
	FWL	Q1	0.1587	0.662	4.2
		Q2	0.1140	1.440	12.6
		Q3	0.0400	0.662	16.5
STA +425	NWL	Q1	0.1935	1.548	8.0
		Q2	0.1544	1.548	10.0
		Q3	0.0678	1.548	22.8
	FWL	Q1	0.2293	1.548	6.8
		Q2	0.1140	1.548	13.6
		Q3	0.0726	1.548	21.3
STA +225	NWL	Q1	0.2821	1.202	4.3
		Q2	0.2109	1.202	5.7
		Q3	0.0266	1.202	45.1
	FWL	Q1	0.2807	1.202	4.3
		Q2	0.2112	1.202	5.7
		Q3	0.0293	1.202	41.0

The results of the seepage analysis, based on the piping safety factor values as shown in Table 9, indicate that the piping safety factor values after the upstream blanket foundation repair are ≥ 4 for STA +575, STA +425, and STA +225. This implies that with the upstream blanket foundation repair, the structure is secure against piping and, consequently, is also secure against boiling.

Table 9: Seepage Discharge Values with Upstream Blanket Foundation Repair

Analysis on		Point	Seepage Discharge	Permissible Seepage Discharge	Check
STA +575	NWL	Q1	6.42 x 10^{-5}	6.79 x 10^{-3}	good
		Q2	2.91 x 10^{-5}		good
		Q3	8.57 x 10^{-6}		good
	FWL	Q1	9.73 x 10^{-5}		good
		Q2	4.73 x 10^{-5}		good
		Q3	1.37 x 10^{-6}		good
STA +425	NWL	Q1	1.77 x 10^{-4}	6.79 x 10^{-3}	good
		Q2	2.39 x 10^{-4}		good
		Q3	5.71 x 10^{-6}		good
	FWL	Q1	7.74 x 10^{-5}		good
		Q2	4.73 x 10^{-5}		good
		Q3	1.11 x 10^{-5}		good
STA +225	NWL	Q1	1.06 x 10^{-5}	6.79 x 10^{-3}	good
		Q2	4.23 x 10^{-5}		good
		Q3	9.06 x 10^{-7}		good
	FWL	Q1	8.08 x 10^{-5}		good
		Q2	4.95 x 10^{-5}		good
		Q3	7.54 x 10^{-7}		good

Based on Table 9, it can be observed that the seepage discharge values for the dam after the upstream blanket foundation repair are smaller than the permissible seepage discharge value of 6.7964 m^3/s. Therefore, the seepage discharge values for the dam with the upstream blanket foundation repair are considered safe.

Conclusion

Seepage Analysis for Piping and Boiling Safety Factors at Bagong Dam without Foundation Repair

a. Piping safety factor in the downstream section without foundation repair for STA +575, STA +425, STA +225 is unsafe for piping and boiling phenomena.
b. Seepage discharge values from the SEEP/W program for the conditions without foundation repair for STA +575, STA +425, STA +225 are considered safe.

Seepage Analysis for Piping and Boiling Safety Factors at Bagong Dam with Foundation Repair

Alternative 1: Grouting

- **a.1. Piping Safety Factor:** After the foundation repair using grouting, the piping safety factor for STA +575, STA +425, STA +225 is considered safe against piping and boiling phenomena.
- **a.2. Seepage Discharge:** The seepage discharge values from the SEEP/W program with grouting foundation repair for STA +575, STA +425, STA +225 are deemed safe.

Alternative 2: Cut Off Wall

- **b.1. Piping Safety Factor:** Following the foundation repair using a cut-off wall, the piping safety factor for STA +575, STA +425, STA +225 is considered safe against piping and boiling phenomena.
- **b.2. Seepage Discharge:** The seepage discharge values from the SEEP/W program with the cut-off wall foundation repair for STA +575, STA +425, STA +225 are deemed safe.

Alternative 3: Upstream Blanket

- **c.1. Piping Safety Factor:** After the foundation repair using an upstream blanket, the piping safety factor for STA +575, STA +425, STA +225 is considered safe against piping and boiling phenomena.
- **c.2. Seepage Discharge:** The seepage discharge values from the SEEP/W program after the foundation repair with an upstream blanket for STA +575, STA +425, STA +225 are deemed safe.

Based on the safety factors for piping, seepage discharge, and considering ease of implementation in the field, the author has selected Alternative 3, which is the upstream blanket foundation repair.

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