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Regional Case Study

Analysis of Pore Water Pressure and Seepage During The Impounding Stage of Randugunting Dam

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Abstract

Piping induced by seepage poses a significant risk to the stability of Randugunting Dam, located in Blora Regency, Central Java. This study aims to assess the geological and engineering geological conditions of the study area and to analyze the behavior of pore water pressure and seepage during the impounding stage. The methodology includes geological and engineering geological mapping, as well as field monitoring using instruments such as vibrating wire piezometers, v-notch, and observation wells. These field results were then compared with Finite Element Method (FEM) analysis conducted in GeoStudio SEEP/W 2018. The pore water pressure values derived from FEM analysis were generally higher than the actual values recorded by the piezometers. Groundwater levels observed in the wells showed a strong correlation with rainfall intensity. The actual seepage discharge measured at the v-notch was 0.000118 m^3/sec, whereas the FEM analysis yielded a significantly higher discharge of 0.01271 m^3/sec. Despite this, the measured discharge remains within safe limits, being less than 0.016 m^3/s (2% of inflow) and below 0.14 l/min/m. Nevertheless, the higher discharge indicated by FEM analysis suggests a potential risk of piping that warrants attention.

Keywords: Actual instrumentation; finite element method; pore water pressure; Randugunting Dams; seepage

1. Introduction

Water is one of the most important renewable natural resources necessary to sustaining life. In Indonesia, water availability is abundant during the rainy season, but certain regions still experience drought during the dry season. Drought can adversely affect a region (Prasetyo et al., 2018). Droughts can significantly disrupt the balance between water demand and supply, impacting a wide range of needs. To maintain water availability and ensure food security, dam construction in Indonesia has steadily increased. The development of dams, including those in Central Java, supports the province's goal of becoming a national food production hub (Ministry of Public Works and Housing, 2019). Dams provide multiple benefits such as irrigation, raw water supply, flood control, tourism, and micro-hydropower generation. Among the various aspects of dam construction, the design phase is the most critical. Dams must be capable of withstanding the large volumes of water they contain while ensuring safety to prevent structural failure. Globally, seepage that leads to piping is one of the leading causes of dam failure (Setyawati et al., 2018). Seepage is closely related to pore water pressure, elevated pore pressure increases the potential for seepage, which may lead to piping and compromise dam stability (Huda et al., 2019).

Seepage into the dam body or foundation increases pore water pressure, which elevates shear stress and reduces soil's shear strength (Nofrizal et al., 2020).

Randugunting Dam, located in Central Java and was constructed as a central core fill-type dam. On November 29^{th}, 2021, the dam entered the impounding stage. This study aims to evaluate pore water pressure and seepage discharge during this stage to assess the dam safety against potential seepage and piping. The analysis will be carried out using instrumentation method and compared with Finite Element Method (FEM) analysis, considering subsurface lithological conditions, permeability values, and other geotechnical parameters. This study provides the first integrated evaluation of pore water pressure and seepage behavior during the initial impounding stage of the Randugunting Dam, one of Central Java's newest central core fill-type dams, by combining real-time instrumentation data with Finite Element Method (FEM) seepage modeling. Unlike previous Indonesian dam studies that rely predominantly on design assumptions or post-construction observations, this research explicitly incorporates the dam's detailed subsurface lithology, spatially variable permeability, and geotechnical parameters obtained from site investigation. The dual-method comparison enables a more accurate identification of seepage pathways and piping susceptibility during the most critical phase of dam operation. This approach provides a novel empirical–numerical framework for improving dam safety assessment in Indonesia, particularly for regions with complex stratigraphic units.

The study was conducted at the Randugunting Dam Construction Project, located in Kalinanas Village, Japah District, Blora Regency, Central Java. Geographically, the dam is positioned between latitude -6° 52' 22.77" S and longitude 111° 15' 27.359" E, spanning an area of approximately 17.98 km² by impounding the Banyuasin River. According to the Regional Geological Map of Rembang, Jawa (Kadar and Sudijono, 1993) and Ngawi, Java (Datun et al., 1996), the stratigraphic sequence of the research area, from oldest to youngest, includes the Bulu Formation (Tmb), Wonocolo Formation (Tmw), Ledok Formation (Tml), and Mundu Formation (Tmpm).

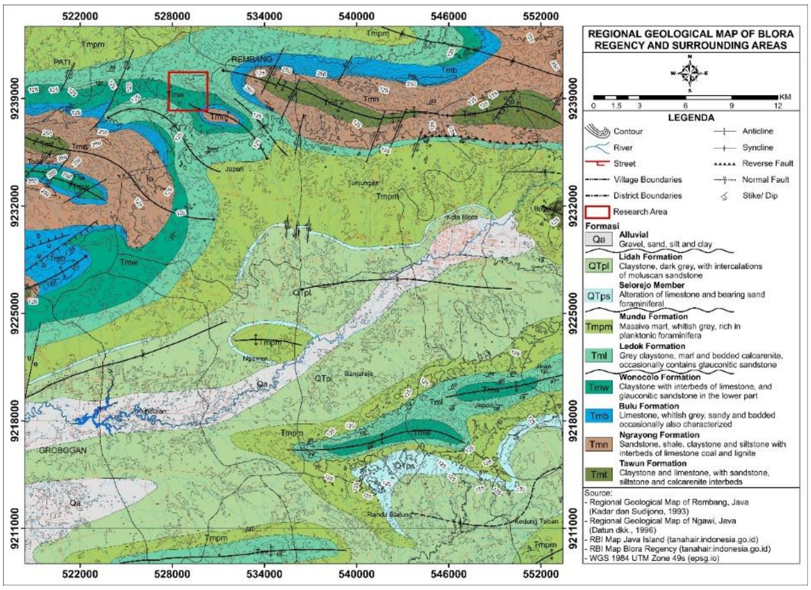


Figure 1. Regional geological map of Blora Regency and surrounding areas, research area on the red box in Kalinanas Village, Japah District (Modified from Kadar and Sudijono, 1993 & Datun et al., 1996)

2. Methods

This research employed both qualitative and quantitative methods. The qualitative approach consisted of a literature review, geological and engineering geological mapping, and the collection of core drilling data. Meanwhile, the quantitative approach involved the acquisition of field instrumentation data including vibrating wire piezometers, v-notch, and observation wells as well as numerical analysis using the Finite Element Method (FEM) in GeoStudio SEEP/W 2018. Additional data used included dam technical specifications and design parameters.

2.1. Geological and Engineering Geological Mapping

Geological mapping was conducted to obtain information on landform units, types, characteristics, distribution of lithology, and geological structures. The results were visualized through geomorphological and geological maps. Engineering geological mapping was used to identify the types, characteristics, and distribution of surface soils, which were compiled into an engineering geological map.

2.2. Actual instrumentation Monitoring

Vibrating wire piezometers data were recorded using a portable readout device. Seepage discharge at the v-notch was measured by reading the water elevation on a staff gauge. Meanwhile, groundwater in the observation wells were measured using a dip meter to determine water level elevations inside the pipe.

2.3. GeoStudio SEEP/W 2018

Numerical analysis of pore water pressure and seepage was performed using Finite Element Method (FEM) in GeoStudio SEEP/W 2018. Input parameters included permeability coefficients (Table 1), reservoir water level, and piezometer installation depths. These data enabled assessment of pore pressure and seepage across various reservoir levels to identify excessive seepage.

Table 1. Permeability coefficient of Randugunting Dam (River Basin Organization for Pemali Juana, 2017)

Materials	Permeability Coefficient
	cm/sec
Watertight core	4.59×10^{-6}
Fine filter	3.58×10^{-3}
Random	3.39×10^{-4}
Toe drain	1.00×10^{-2}
Horizontal drain	1.00×10^{-2}
Foundation depth 5 m	2.20×10^{-6}
Foundation depth > 5m	1.11×10^{-5}
Grouting	1.00×10^{-6}

2.4. Seepage Acceptance Criteria to Look 2007

The tolerance for seepage quantity is closely related to the level of seepage that can be considered safe. Seepage is deemed safe when it remains within normal limits and does not compromise the stability of the dam body (Look, 2007; Buldan et al., 2021). The maximum permissible seepage depends on the dam's height, length, and material permeability of core material.

Table 2. Seepage criteria on the dam body

Dam Height (m)	Seepage: liter/day/meters (liter/minutes/meters)	
	O.K	Not O.K
<5	<25 (0.02)	>50 (0.03)
5 – 10	<50 (0.03)	>100 (0.07)
10 – 20	<100 (0.07)	>200 (0.14)
20 – 40	<200 (0.14)	>400 (0.28)
>40	<400 (0.28)	>800 (0.56)

Source: Look, (2007); Buldan et al., (2021)

2.5. Seepage Acceptance Criteria to Soedibyo 2003

Seepage through the foundation and abutments must remain below the specified threshold to ensure efficient reservoir operation. The allowable seepage discharge is limited to 2%–5% of the average inflow rate (Soedibyo, 2003; Fallo, 2021), with higher inflow rates corresponding to lower permissible percentages.

2.6. Correlation Coefficient

The results of pore pressure analysis using the Finite Element Method (FEM) were compared with the actual instrumentation data. Calibration of these datasets established a correlation, which was evaluated using correlation coefficient interpretation criteria proposed by Sugiyono (2016), as shown in Table 3.

Table 3. Interpretation of the correlation coefficient

Interval Coefficient	Correlation Coefficient
0.00 – 0.199	Very low
0.20 – 0.399	Low
0.40 – 0.599	Medium
0.60 – 0.799	High
0.80 – 1.000	Very high

Source: Sugiyono, (2016)

3. Results and Discussion

3.1. Geomorphological Conditions

The study area comprises 3 (three) geomorphological units. The first unit is the floodplain, which includes river bodies and adjacent areas still influenced by fluvial processes. This unit occupies approximately 10% of the study area. The Banyuasin River, which traverses this region, exhibits characteristics of a mature river system, as indicated by the presence of meanders. The second unit is the Gaplokan Anticline Valley, a lowland plain characterized by relatively low elevation compared to the surrounding terrain. This unit covers about 40% of the study area, with slope ranging from 0 – 13% and elevation differences between 74 – 125 m (modified from van Zuidam, 1985). The third unit, the Gaplokan Anticline Hills, comprises hilly terrain surrounding the reservoir. It accounts for approximately 50% of the study area, with slopes ranging from 14 – 55% and elevation differences between 125 – 218 m (modified from van Zuidam, 1985). The geomorphological configuration of the reservoir area is illustrated in Figure 2.a.

3.2. Geological Conditions

The geological condition of the study area, based on mapping results, consists of 4 (four) lithological units: alluvial deposits, intercalated siltstone of calcareous sandstone, claystone, and calcareous sandstone. These units are part of Ledok and Wonocolo Formations. The descriptions of each unit are outlined below.

3.2.1 Alluvial Deposit

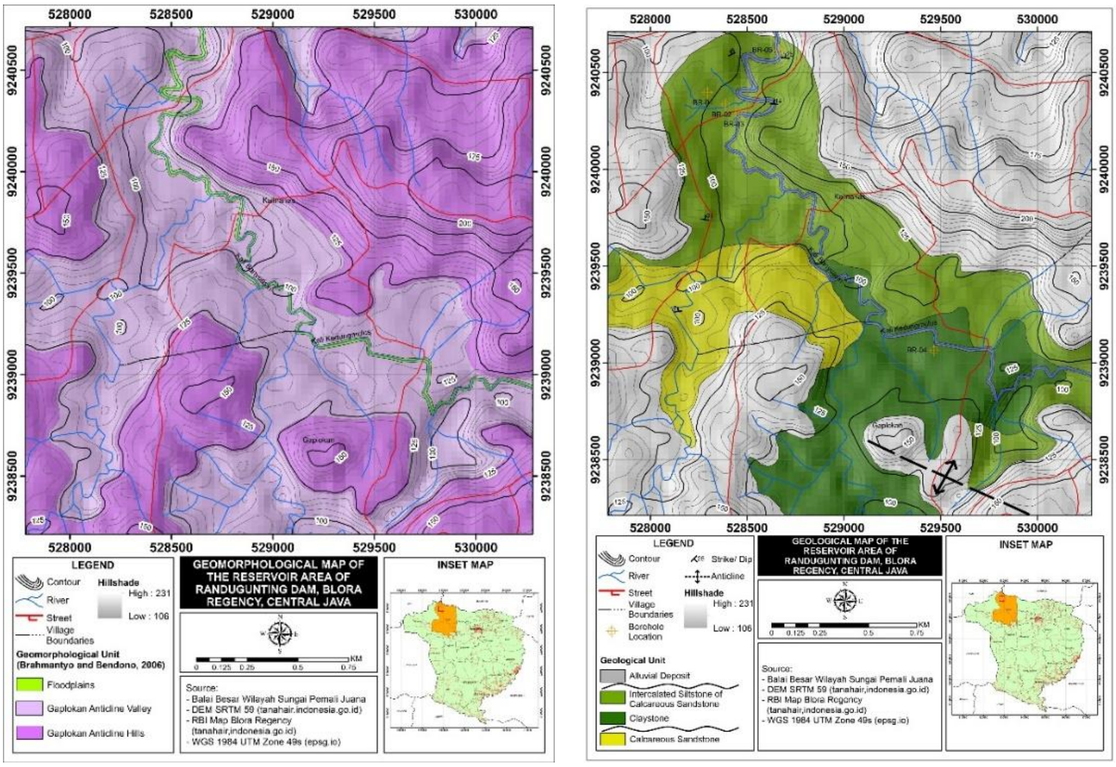
Composed of river sediment materials ranging in size from clay to gravel (Wentworth, 1992; Laksono, 2020), this unit is generally loose and exhibits sub-rounded grain shapes, predominantly consisting of sedimentary rock fragments such as calcareous sandstone. Additional deposits are found along riverbanks and meander bends, characterized by a brownish color and a sticky, slippery texture under wet conditions. Alluvial deposits are commonly distributed in riverbeds, meanders, channel bars, point bars, natural levees, and floodplains. This unit is estimated to have been deposited during the Holocene epoch.

3.2.2 Intercalated Siltstone of Calcareous Sandstone

Calcareous sandstone is found inserted in the siltstone. At the megascopic scale, the siltstone appears light gray in color, exhibits a laminated structure, has silt grain size with a clay matrix (Wentworth, 1992; Laksono, 2020), and contains whitish specks that suggest the presence of microfossils and carbonate cement. This unit exhibits medium hardness and tends to be loose. The calcareous sandstone is characterized by white to gray coloration, well-defined bedding, medium sand grain size, and a fine sand matrix (Wentworth, 1992; Laksono, 2020). The grains are sub-rounded, well-sorted, grain-supported, cemented with carbonate, and hard in texture. The intercalated siltstone of calcareous sandstone unit displays joint structures, particularly in the foundation areas of the main dam and diversion tunnel. This lithology dominates the foundation and supporting structures of the dam and is classified as part of the Ledok Formation, deposited during the Late Miocene epoch.

3.2.3 Claystone

At the megascopic scale, the claystone is characterized by a dark gray color, massive structure, brittle texture, grain size and clay matrix (Wentworth, 1992; Laksono, 2020), cemented with carbonate. It exhibits medium hardness and tends to be slightly loose. This unit also shows a high degree of weathering. The claystone is found in the southeastern section of the dam area, specifically upstream of the river, and is classified as part of the Ledok Formation, deposited during the Late Miocene epoch.



(a) (b)

Figure 2. (a) Geomorphological map of Randugunting Dam reservoir area (Modification by van Zuidam, 1985 & Brahmantyo and Bendono, 2006); (b) Geological map of Randugunting Dam reservoir area, Blora Regency

3.2.3 Calcareous Sandstones

The calcareous sandstone unit, observed at the megascopic scale, appears light brown coloration, bedding structures, fine sand grain size with a matrix of very fine sand (Wentworth, 1992; Laksono, 2020), and whitish spots that suggest the presence of microfossils. The grains are sub-rounded, well-sorted, grain-supported, cemented with carbonate, and exhibit a hard texture. This unit shows moderate weathering intensity and is located in the southwestern part of the reservoir area. It belongs to the Wonocolo Formation, which was deposited during the Late Miocene epoch. The geological distribution of this unit is illustrated in Figure 2.b.

3.3. Geological structure

Based on field data from Virama Karya, geological structures in the form of joints were identified within the intercalated siltstone of calcareous sandstone lithology. The joint planes exhibit a predominantly north–south orientation, with specific measurements recorded as N355°E/39°, N347°E/41°, N340°E/44°, N349°E/47°. These joints are interpreted as gash fractures, typically associated with an extensional tectonic regime. Structural analysis using a rosette diagram indicates that the principal stress axis (σ_1) is oriented N346°E, further supporting the dominant north–south orientation of the joints (Figure 3.a).

The Gaplokan Anticline, located in the southeastern part of the study area, is interpreted as the dominant fold structure responsible for the formation of joints due to its proximity to the site. To verify this assumption, fold structure analysis was performed using Dips software (Figure 3.b).

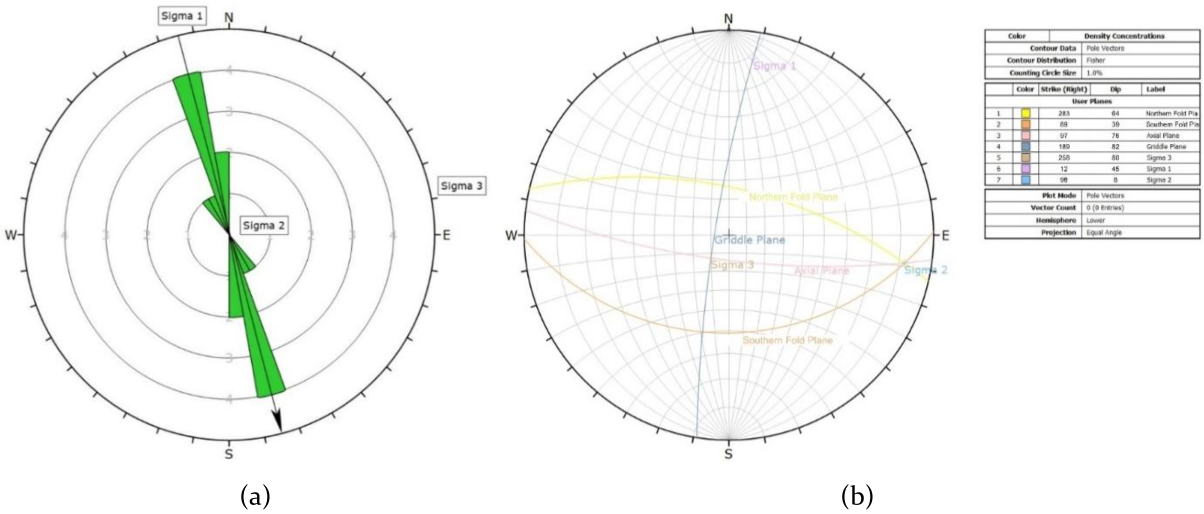


Figure 3. (a) Results of joint structure analysis using a Rosette Diagram; (b) Fold structure analysis results using Dips software

The results of the structural analysis indicate that the Gaplokan Anticline has a principal stress orientation (σ_1) of N12°E/45°, suggesting that the anticline's main stress direction is relatively aligned north–south. Therefore, it can be concluded that the gash fractures are structurally associated with the regional folding of the Gaplokan Anticline.

3.4. Engineering geological condition

Based on engineering geological mapping conducted for the Randugunting Dam Construction Project, the study area consists of 3 (three) engineering geological units: silty sand, sandy silt, and clay. The descriptions of each unit are outlined below.

3.4.1 Silty sand

The silty sand unit (Davis and Bennett, 1927) is grayish-brown in color and primarily composed of sandy grains mixed with some silt and calcareous sandstone fragments. This unit is unconsolidated with a very loose density. Laboratory test results show that 28.32% of the material passes through the No. 200 sieve, with a cohesion value of 14.9 kPa and an internal friction angle of 33.30°.

3.4.2 Sandy silt

The sandy silt unit (Davis and Bennett, 1927) is brownish-gray in color and composed mostly of fine-grained silt with some sand. It is characterized by a stiff to very stiff consistency and medium hardness, although it tends to be loose. Laboratory test results indicate that 48.36% of the material passes through the No. 200 sieve, with a cohesion value of 13.6 kPa and an internal friction angle of 31.79°.

3.4.3 Clay

The clay unit (Davis and Bennett, 1927) ranges in color from light brown to dark brown and consists of clay-sized particles derived from residual soil due to weathering. It is classified as slightly stiff to soft in consistency. Laboratory test results show that 69.22% of the material passes through the No. 200 sieve, with a cohesion value of 19.69 kPa and an internal friction angle of 22.78°. The engineering geological map of the reservoir area is shown in Figure 4.

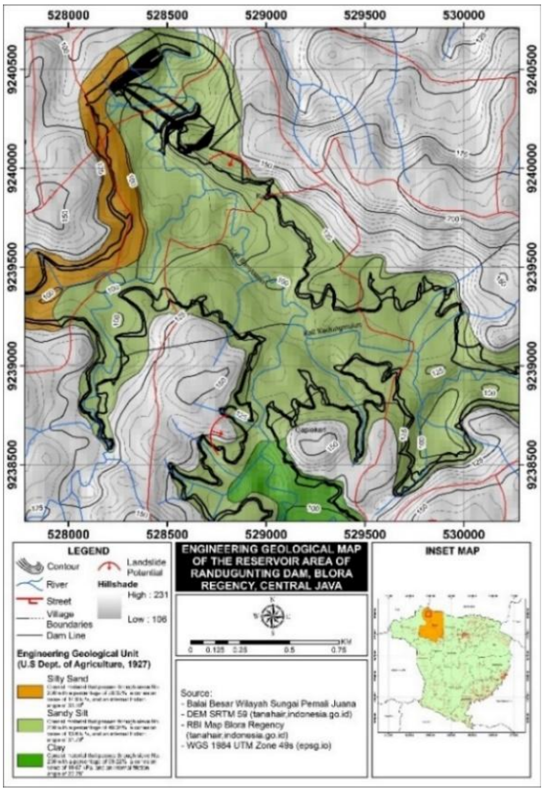


Figure 4. Engineering geological map of Randugunting Dam reservoir area, Blora Regency

3.5. Design Parameters

Geotechnical parameters of the embankment materials include saturated unit weight (γ_{sat}), cohesion (c), and internal friction angle (ϕ), which were obtained from laboratory tests on each material. These parameters, which correspond to the dam's geological conditions, are presented in Table 4. The impermeable core is composed of soft clay soil, based on its characteristics, clay soil is sticky (cohesive) and exhibits a very soft consistency under saturated conditions. The fine filter is composed of fine sand material, which is suitable as a filter material due to its permeability, it functions to protect the core zone from particle movement caused by water flow, random material consists of a mixture of free-draining materials that allow limited water flow. Rip-rap or rock toe is composed of solid andesite rock, the rip-rap functions to dissipate wave energy from the reservoir that may cause erosion of the embankment surface, it also contributes to preventing landslides on the upstream slope of the dam, the rock toe located on the downstream side, functions as part of the dam's drainage system. The horizontal drain is composed of coarse gravel and fine sand with a loose density, it functions as a drainage system that channels water from the fine filter to an outlet beneath the rock toe. In the foundation, the intercalated siltstone of calcareous sandstone unit exhibits soft to stiff characteristics with a loose to slightly dense consistency, making it suitable for preventing seepage through the dam foundation and reducing the potential for piping.

Table 4. Geotechnical parameters of Randugunting Dam embankment material (River Basin Organization for Pemali Juana, 2017)

Materials	γ_{sat}	c	ϕ
	KN/m³	KN/m²	°
Watertight core	17.8	15	20.5
Fine Filter	20	0	32
Random	14.6	5.3	32.6
Rip-rap/ Rocktoe	21	0	40
Horizontal Drain	22	0	32
Foundation depth 5 m	18.3	13.6	31.79
Foundation depth > 5 m	17.8	29.8	36.59

3.6. Reading Graph of Observation Well

In the monitoring graph shown in Figure 5, groundwater level elevations are correlated with increasing reservoir water levels (WL) and rainfall intensity (R). Observation wells are installed at six points downstream of the dam. Based on the monitoring results, the average groundwater level elevation remains below the reservoir water level, indicating no signs of seepage. The relatively stable groundwater conditions suggest that reservoir water is not entering the observation wells. A slight increase in groundwater level is likely due to rainfall infiltration into the wells. Conversely, a significant rise in groundwater level without concurrent rainfall or reservoir level increase may indicate seepage in the downstream area of the dam. Therefore, inspections should be carried out in downstream area that exhibit signs of increased moisture, such as denser vegetation compared to surrounding areas.

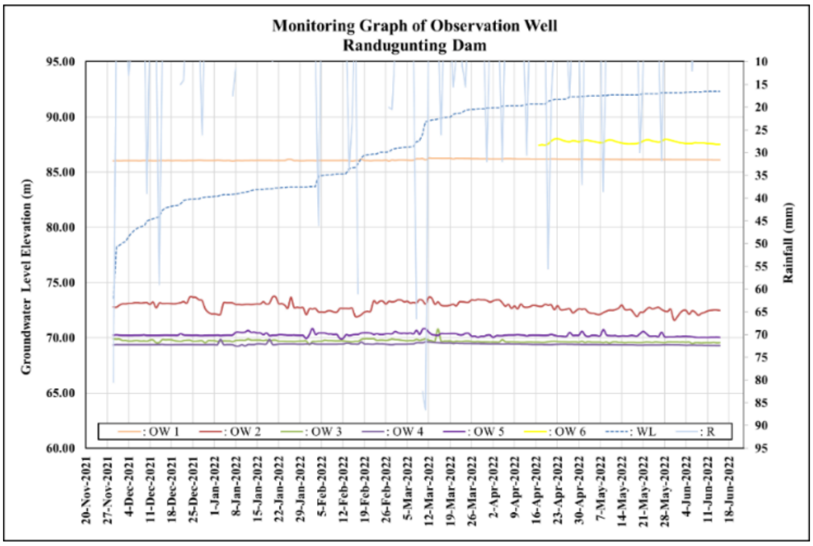


Figure 5. Randugunting Dam observation well monitoring graph

3.7. Calibration of Pore Water Pressure

Calibration of actual instrumentation data with FEM analysis results is conducted to evaluate the correlation between pore water pressure values. This aims to determine whether a strong or weak relationship exists between the actual instrumentation data and the FEM analysis results. A strong correlation indicates that the FEM analysis accurately reflects field conditions. The calibration was carried out at STA B12 during the peak reservoir water level recorded in the impounding period (+92.32 m).

Table 5. Pore water pressure calibration results at STA B12 with water level elevation +92.32 m

Code	Installation elevation	Actual PWP	FEM PWP	Deviation
	m	kPa	kPa	kPa
VWPE-11	+81.00	99.06	115.46	16.4
VWPE-12	+81.00	91.93	114.08	22.15
VWPF-13	+57.00	300.62	302.92	2.3
VWPF-14	+57.00	278.07	280.70	2.63
VWPF-15	+61.00	258.78	259.61	0.83
VWPF-16	+61.00	241.82	174.28	-67.54
VWPE-17	+69.00	174.81	197.11	22.3
VWPE-18	+69.00	132.31	94.66	-37.65
VWPE-19	+69.00	3.30	24.28	20.98
VWPE-20	+75.00	84.84	136.89	52.05
VWPE-21	+75.00	19.03	36.61	17.58
VWPE-22	+75.00	1.09	-34.31	-35.4
VWPE-23	+81.00	-6.19	73.84	80.03
VWPE-24	+81.00	-6,61	-20.94	-14.33
VWPE-25	+87.50	-5,37	-36.44	-31.07
VWPE-26	+81.00	92,33	111.45	19.12

Based on Table 5, the FEM analysis results show higher pore water pressure values compared to the actual instrumentation data. These elevated values are observed in VWPE-11, VWPE-12, VWPF-13, VWPF-14, VWPF-15, VWPE-17, VWPE-19, VWPE-20, VWPE-21, VWPE-23, and VWPE-26 resulting in positive deviations. A negative deviation in VWPF-16 is attributed to the influence of groundwater in the foundation, which causes the vibrating wire piezometer to register water flow as seepage, leading to elevated readings. In addition, the capacity of the vibrating wire piezometer, which can reach up to 500 kPa, may cause rapid increases in pore water pressure under saturated conditions. The negative deviations observed in VWPE-22, VWPE-24, and VWPE-25 are due to the high elevation of these instruments, where no water inflow is present. From the calculated pore water pressure deviations, an RMSE value of 35.26 was obtained. These findings are consistent with a study conducted at Raknamo Dam, East Nusa Tenggara (Kurniawan, 2021), which generally reported that pore water pressure values obtained through the finite element method are higher than those recorded by vibrating wire piezometers. According to the study, the FEM results can serve as a 'safe limit' for assessing the risks posed by excess pore water pressure. A significant rise in pore water pressure beyond this threshold, along with increasing reservoir water levels, may indicate the onset of piping within the dam embankment.

Based on the Figure 6, the relationship between pore water pressure values obtained from actual instrumentation and FEM analysis exhibits a positive correlation. This is indicated by the upward trend of the linear regression line, where pore water pressure values from both FEM and VWP increase concurrently. The results presented in Figure 6 show a correlation coefficient (R^2) of 0.89. According to Sugiyono (2016), this value falls within the 'very high' category, indicating a strong relationship between the two variables, with correlation range of 80–100%.

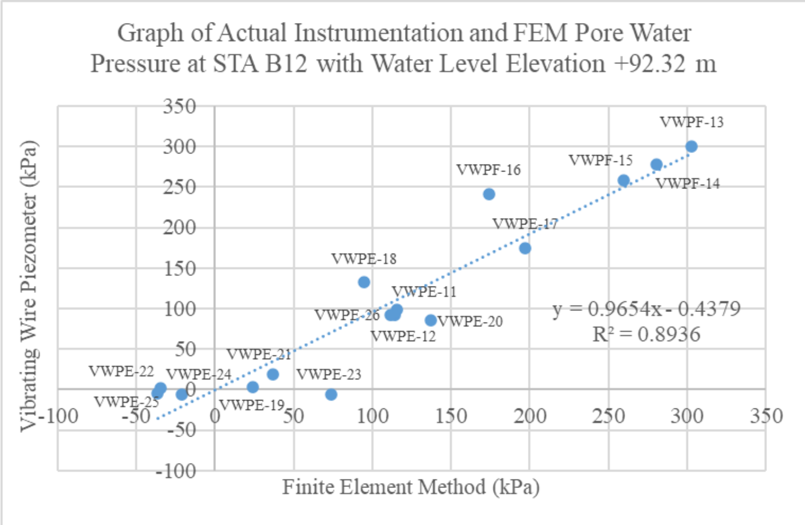


Figure 6. Graph of actual instrumentation and FEM pore water pressure at STA B12 with water level elevation +92.32 m

3.8. Seepage Calibration

Seepage discharge calibration was carried out at reservoir water level elevation of +92.32 m, based on both actual instrumentation data and FEM analysis results. The determination of the dam's seepage safety parameters refers to 2 (two) key sources.

Table 6. Seepage calibration at water level elevation +92.32 m

Parameters	Criteria		Actual	FEM
	Safe	Not Safe		
Look (2007)	0.14 l/min/m	0.28 l/min/m	0.01948 l/min/m	0.02098 l/min/m
Soedibyo (2003)	< 0.016 m³/sec	> 0.016 m³/sec	0.000118 m³/sec	0.01271 m³/sec

Based on the calculation results, the actual seepage discharge obtained from v-notch readings falls within the safe category, as it is less than 0.14 l/min/m (Look, 2007; Buldan et al., 2021) and below 0.016 m³/sec (Soedibyo, 2003; Fallo, 2021). Additionally, the seepage discharge value derived from the FEM analysis is also considered safe, remaining below the maximum allowable limits Qf < 1% of the average annual runoff (0.208 m³/sec) and Qf < 0.05% of the gross storage capacity of 0.0578 m³/sec (River Basin Organization for Pemali Juana, 2017). Therefore, both approaches are interrelated and crucial for accurately determining actual and relative seepage discharge in the dam.

3.9. Recommendations based on FEM analysis

Although the calibration results indicate that the seepage discharge falls within the safe category, the seepage estimated from the FEM analysis is relatively high, with a value of 0.01271 m³/sec, which may potentially lead to piping. Therefore, as a precautionary measure against the risk of excessive seepage as predicted by the model, 2 (two) technical recommendations are proposed for implementation in the event of an increase in actual seepage discharge.

3.9.1 Upstream Impermeable Layer

The installation of an upstream impermeable layer can extend the seepage flow, thereby reducing the seepage rate. Based on the FEM analysis results (Figure 7), such an installation can decrease seepage discharge by approximately 0.00661 m³/sec or 52%, from the original value of 0.01271 m³/sec at a reservoir water level elevation of +92.32 m in STA B12 to 0.0061 m^3/sec. This reduction is achieved when the permeability coefficient of the upstream impermeable layer is equal to the core zone, at 4.59×10^{-6} cm/sec.

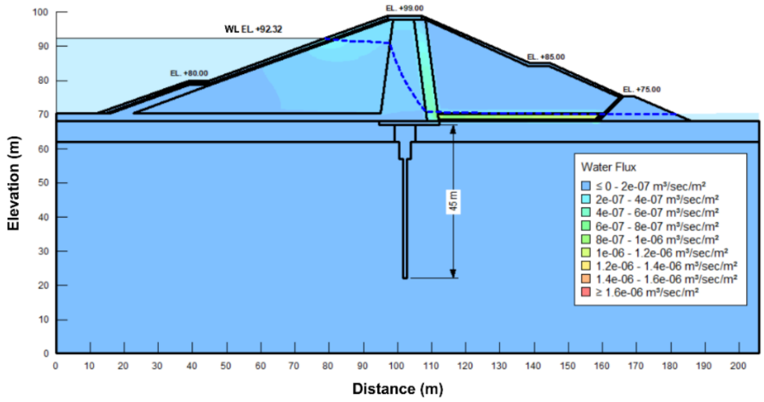


Figure 7. Modeling the addition of upstream impermeable layer

3.9.2 Downstream seepage berm

The installation of a downstream seepage berm can balance uplift pressure and reduce excessive seepage flow within the permeable foundation layer at the downstream toe of the dam. This berm can be constructed in the toe drain area. Based on FEM analysis results (Figure 8), such an installation can reduce seepage discharge by approximately 0.00547 m^3/sec or 43%, from the original value of 0.01271 m^3/sec at a reservoir water level elevation of +92.32 m in STA B12 to 0.00724 m^3/sec. This assumes a permeability coefficient for the downstream seepage berm of 2.00×10^{-2} cm/sec.

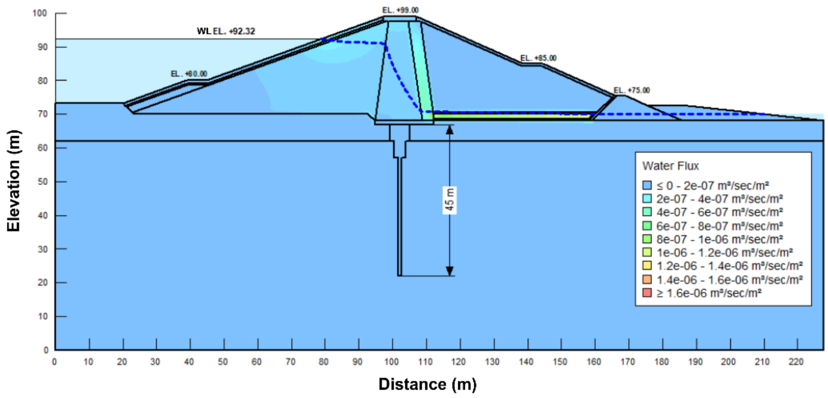


Figure 8. Modeling the addition of downstream seepage berm

4. Conclusion

The research area comprises 3 (three) geomorphological units such as Floodplains, Gaplokan Anticline Valley, and Gaplokan Anticline Hills. It also includes 4 (four) lithological units consisting of Alluvial Deposits, Intercalated Siltstone of Calcareous Sandstone, Claystone, and Calcareous Sandstone, as well as geological structures in the form of gash fractures trending in a north–south direction. Additionally, there are 3 (three) engineering geological units identified in the area such as Silty Sand, Sandy Silt, and Clay. Randugunting Dam is a central core fill-type dam that utilizes locally available materials. The permeability coefficients and geotechnical parameters of the embankment materials are consistent with the local geological conditions.

Based on the results of pore water pressure calibration, the correlation coefficient exceeds 60%, indicating a strong relationship between the actual instrumentation data and the FEM analysis results. The seepage analysis shows that all parameters fall within the safe category. However, the FEM analysis indicates that the estimated seepage discharge is relatively high, which could potentially lead to piping.

To mitigate this risk, engineering geological approaches may be applied, such as installing an upstream impermeable layer connected to the core zone to extend the seepage flow, or constructing a downstream seepage berm at the toe drain to balance uplift pressure and reduce the seepage rate.

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