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Integrated of Pore Water Pressure, Hydraulic Gradient and Time Lag for Early Warning System at Sindang Heula Dam

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ABSTRACT

Excessive pore water pressure (PWP) is a primary factor contributing to internal erosion and catastrophic failures in embankment dams, accounting for nearly 40% of dam-related incidents worldwide. Despite routine monitoring, current practices remain limited by the absence of integrated analytical frameworks that simultaneously evaluate multiple hydraulic parameters for early warning system. This study aims to design an early warning system based on PWP, hydraulic gradient, and time lag parameters. The research was conducted at Sindang Heula Dam with 1,696 daily observation data (2020–2025) from four upstream and four downstream piezometers. Linear regression analysis was employed to predict PWP at low (86.613 masl), normal (106.613 masl), and maximum (108.613 masl) reservoir water level (RWL) conditions. Hydraulic gradients were derived from upstream–downstream head differentials, while time lags were determined based on the delay between peak reservoir levels and corresponding piezometric responses. The results revealed that upstream piezometers exhibited rapid responses (7–14 days) with strong correlations RWL (R^2 = 0.71–0.81), while downstream piezometers show delayed responses (35–42 days) with weaker correlation RWL (R^2 = 0.31–0.44). Hydraulic gradients increased from 0.32 at low to 0.63 at maximum RWL, indicating intensified seepage potential. The proposed integrated framework introduces a three-tier (green–yellow–red) early warning system based on real-time RWL thresholds, thereby improving proactive risk mitigation and strengthening dam safety management.

1. Introduction

Sindang Heula Dam, located in the Cibanten River Basin in Banten Province, has a storage capacity of 9.26 million cubic meters and a height of 41 meters [1]. The dam provides raw water, irrigation, flood control, and potential micro-hydropower generation. However, dams have the potential to fail due to excessive pore water pressure building up within the soil layers, which threatens the structure's stability. Globally, internal erosion and seepage-related

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failures account for approximately 40% of all dam incidents, highlighting the critical importance of continuous monitoring [2]. Elevated pore water pressure can lead to progressive internal erosion, piping, and catastrophic failure. To keep the dam safe and ensure reliable operation, engineers must regularly monitor pore water pressure by installing an Embankment Piezometer in the dam body. Despite routine instrumentation, many existing monitoring practices lack integrated analytical frameworks that combine multiple hydraulic parameters to provide early warning of potential structural distress.

Pore water pressure (PWP) is defined as the pressure exerted by groundwater within pore spaces between soil and rock grains. The determination of PWP is essential in monitoring embankment dams because it directly affects stability and indirectly indicates the position of the phreatic surface, which is used to evaluate the effectiveness of the filter in the dam body[3]. PWP in dams varies over time, exhibiting complex distribution patterns, where reductions in PWP closely relate to dam material permeability and internal hydraulic gradients [4]. Elevated pore water pressure is a key factor that can lead to seepage, piping, and compromising dam stability [5]. The hydraulic gradient is a key parameter governing water movement through porous media, defining flow velocity and direction along the flow path as influenced by differences in water surface elevation and material permeability within dam cores [6]. Studies have shown that the hydraulic gradient drives leak flux via Darcy's law and is shaped by core geometry, with maximum gradients near core-cutoff walls indicating high-risk zones for internal erosion [7]. Extreme hydraulic gradients within dam cores may induce hydraulic fracturing and progressive internal erosion [8]. To evaluate the vulnerability of dams to pore water pressure, the time lag must be taken into account. Time lag is defined as the temporal delay between changes in reservoir water level and corresponding pore water pressure response at piezometer locations. It is influenced by the permeability characteristics of dam materials and the efficiency of hydraulic pressure transmission through the porous medium [9].

Early warning systems are crucial for preventing catastrophic dam failures that can result in loss of life and extensive property damage. Unlike reactive monitoring approaches that identify problems after they have become visible, early detection frameworks enable proactive intervention by recognizing anomalous trends in hydraulic behavior before critical conditions develop. Studies have shown that dams equipped with integrated early warning systems can reduce the impact of disasters by up to 85% through timely evacuation and emergency response [10]. The economic benefits of early detection far outweigh costs, as preventive maintenance

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based on early warnings is significantly less expensive than post-failure reconstruction and compensation.

Previous research has demonstrated that PWP at dams correlates strongly with water elevation, and shifts in PWP distribution patterns can provide early warning of potential internal dam failures [11]. PWP affects embankment dam safety by weakening the shear strength of sandstone and reducing effective stress and interparticle friction [12]. Upstream core piezometers respond faster and record higher pressures than downstream ones [13]. At the Eyvashan Dam, the difference in piezometer readings was recorded at 118% higher upstream than downstream [14], [15]. A hybrid FCM–k-means approach has been proposed to improve pore pressure forecasts across dam zones [16]. Additionally, Geostudio Seep/W models pressures at crest elevation during Tigadihaji Dam construction, demonstrating practical pore pressure monitoring in design [17]. Recent studies show that hydraulic gradient is a key indicator of potential seepage and internal erosion in dams. The hydraulic gradient exhibits a rise–fall–rise pattern, indicating that significant seepage forces are necessary to disturb the soil particle structure before seepage failure occurs [18]. Rapid pore-water pressure reduction is observed during seepage, indicating complex particle-structure variations with depth due to differences in cover-layer thickness [19]. Piping erosion in impermeable core dams and its interaction with downstream filters have been experimentally investigated, leading to the development of methods that clarify the mechanisms of piping erosion and its role in embankment dam failure [20]. Data parsing techniques are required to eliminate the effects of rainfall and time delays prior to performing regression analysis [21] [22]. The hydraulic gradient plays a vital role in dam safety monitoring through pore water pressure [23]. The comprehensive Swedish study shows that changes in reservoir water levels cause a delayed seepage response in piezometers [9]. In predicting dam seepage, incorporating time-lag parameters for water storage and rainfall of 14 and 16 days, respectively, significantly improves predictive accuracy [24]. Seepage lag relative to rainfall is approximately one day, while the lag relative to water level changes is about four days. This difference can be attributed to the shorter travel path of rainfall infiltration compared with that of upstream reservoir water [25]. Time lag characteristics based on field research results at Jatibarang Dam show that upstream piezometers provide faster responses, while downstream piezometers respond more slowly [26].

Most studies have examined pore water pressure, hydraulic gradient, and lag time parameters separately, without building an integrated framework that combines all three aspects to support better decision making. Research integrating these three parameters to build a

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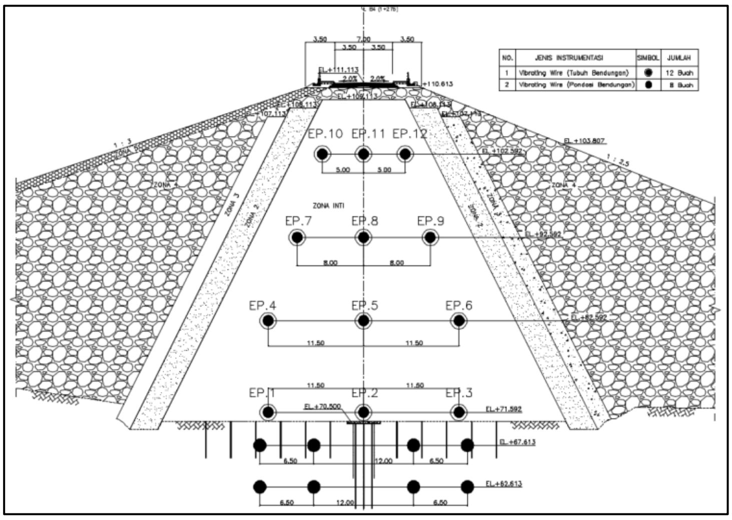
comprehensive early warning safety detection system remains scarce. This study aims to design an early warning system based on pore water pressure, hydraulic gradient, and time lag parameters. The study was conducted at the Sindang Heula Dam core using linear regression on rain-free daily data under low, normal, and maximum water level conditions during the 2020–2025 period. This research is expected to provide a systematic early detection framework that enables timely identification of abnormal seepage patterns, potential internal erosion, thereby supporting proactive risk mitigation and enhancing dam safety management.

2. Research Method

2.1 Location & Data Collected

This study was conducted at Sindang Heula Dam in Sindang Heula Village, Pabuaran District, Serang Regency, Banten. The zoned rockfill core dam has a height of 41 meters and a crest length of 250 meters. The dataset comprises 1.696 daily observations collected from January 2020 to June 2025. The data used include reservoir water level (RWL) elevation, based on Automatic Water Level Recorder (AWLR) measurements installed at the dam's upstream face, with daily recordings at 9 am. Pore water pressure (PWP) readings from embankment piezometers at upstream locations (EP.1, EP.4, EP.7, EP.10) and downstream locations (EP.3, EP.6, EP.9, EP.12) at sta 1 + 275. **Figure 1** presents the layout of the upstream and downstream piezometers. Piezometer readings were simultaneously collected using vibrating wire piezometers connected to an automated data acquisition system, ensuring temporal synchronization between RWL and pore water pressure measurements. Besides that, daily rainfall data from the Rain Gauge Station.



Source: As Built Drawing, (2018).

Figure 1. Layout of Embankment Piezometer Instrumentation.

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2.2 Data Analysis

The analysis of reservoir water surface elevation (RWL) and pore water pressure follows a systematic procedure to establish their relationship and assess seepage behavior. Piezometric head readings were converted to pore water pressure values using the standard hydrostatic Equation 1:

$$PWP = \gamma_w \times (h_{piezo} - h_{base}) \quad (1)$$

Where PWP represents pore water pressure in kPa, γ_w is the unit weight of water (9.81 kN/m³), h_{piezo} is the piezometric head elevation in meters above sea level, and h_{base} is the base elevation of the piezometer installation point.

Observations recorded during rainfall events were excluded from the analysis to obtain pristine pore water pressure values unaffected by precipitation infiltration. This parsing procedure reduced potential confounding effects and enhanced the accuracy of the regression relationship. Linear regression analysis was conducted to establish the functional relationship between reservoir water surface elevation for each piezometer. The regression equation used is shown in Equation 2.

$$y = mx + c \quad (2)$$

where y represents pore water pressure, x denotes reservoir water level elevation, m is the regression slope, and c is the intercept. Equation 2 was applied to predict pore water pressure at three operational reservoir conditions: low water level (86.613 masl), normal water level (106.613 masl), and maximum water level (108.613 masl). The coefficient of determination (R^2) was used to evaluate the strength of the relationship, with interpretation based on standards established in previous studies [27].

The hydraulic gradient between upstream and downstream piezometers was computed to assess seepage potential through the dam core [28]. The gradient was determined using Bernoulli's principle in Equation 3:

$$i = \frac{\Delta h}{L} \quad (3)$$

where i represents the hydraulic gradient (dimensionless), Δh is the head difference between upstream and downstream piezometers in meters, and L is the horizontal seepage path length between the piezometer locations in meters.

Time lag analysis quantified the temporal delay between peak RWL and corresponding peak PWP response at each piezometer location [29] [30]. For the period 2020–2025, annual peak reservoir elevations were identified, and the time interval (in days) between the date of peak reservoir level and the date of maximum pore water pressure at each piezometer was

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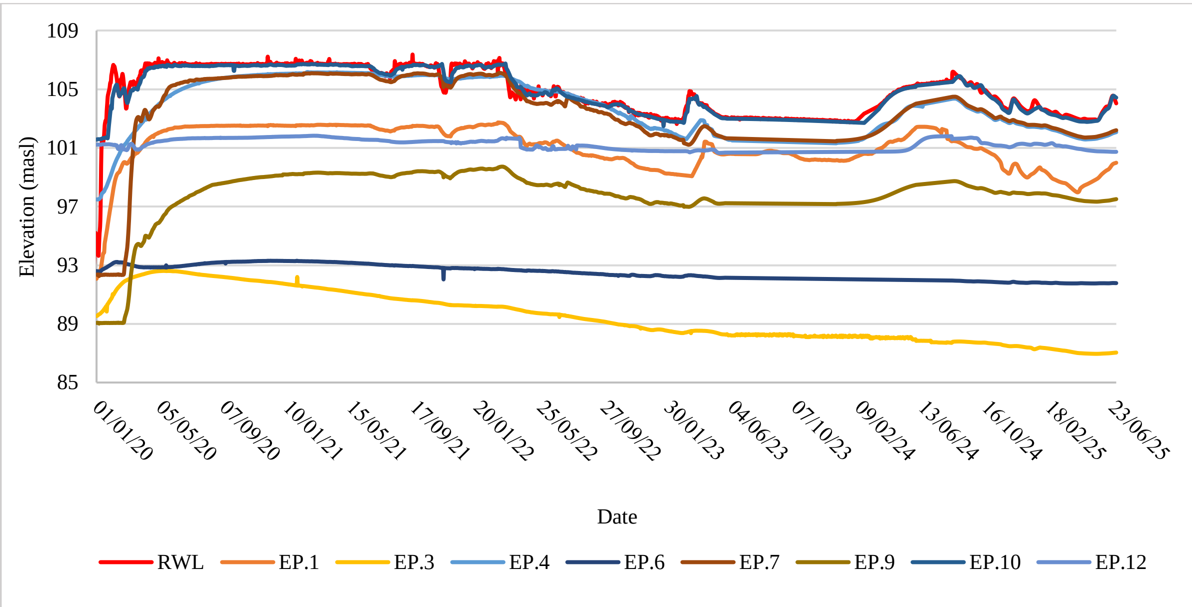
measured. The analysis was conducted to understand their implications for the permeability of the dam core and the seepage paths. The time lag analysis was conducted by comparing the time interval between the peak reservoir water level and the peak pore water pressure at two piezometers, EP.10 (upstream) and EP.12 (downstream).

The integration of pore water pressure regression, hydraulic gradient assessment, and time lag evaluation forms the basis for an early warning system framework. Threshold values for safe operation (green zone), early warning (yellow zone), and critical conditions (red zone) were established based on statistical analysis of the 2020–2025 monitoring dataset.

3. Results and Discussions

3.1 The Pore Water Pressure Behavior in the Upstream and Downstream

The piezometer data from the Sindang Heula Dam showed significant variations in response between the upstream and downstream locations in relation to changes in reservoir water level elevation. **Figure 2** presents the graph of piezometer readings and reservoir water level from January 2020 to June 2025. **Figure 3** illustrates the relationship between pore water pressure and reservoir water level as measured by the upstream and downstream piezometers.



Source: Author Research Results (2025).

Figure 2. Embankment Piezometer Readings from January 2020 to June 2025

Figure 2 presents the temporal trends in piezometric and reservoir water level data. The upstream base piezometer, EP.10 (elevation +102.592 masl), consistently registers the highest piezometric level readings, peaking at approximately 106 masl in response to elevated reservoir levels. This outcome reflects the direct hydraulic connectivity between the reservoir

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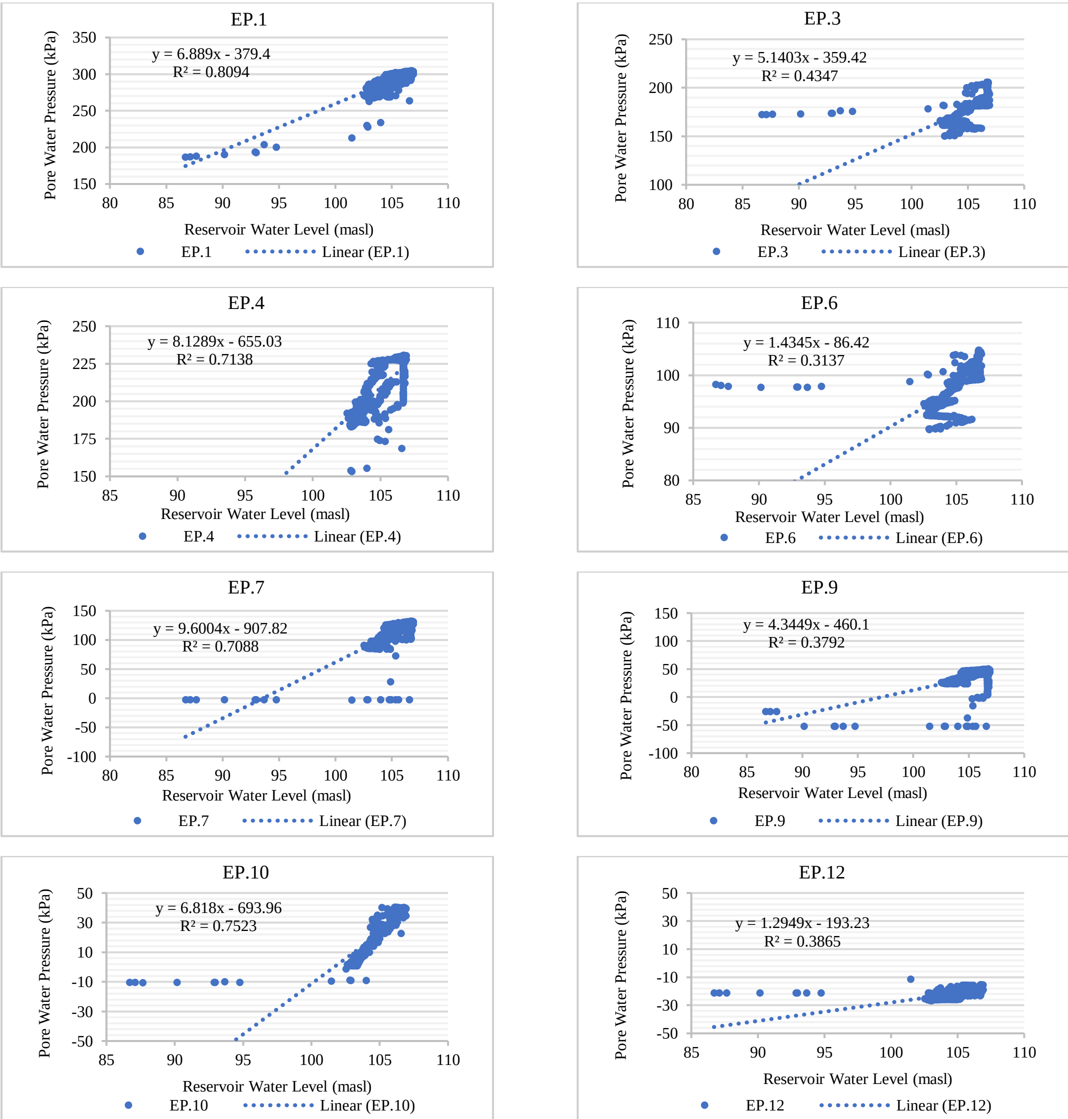
and EP.10, allowing for rapid transmission and limited dissipation of pressure. In contrast, the downstream piezometer EP.3 (elevation +71.592 masl) persistently exhibits substantially lower recorded values, most often below 90 masl, due to its separation from the reservoir by low-permeability core materials and a longer hydraulic path (23 m from EP.1), resulting in delayed and attenuated pressure signals. These results concretely demonstrate effective attenuation of hydraulic heads along the dam axis, with observed pressure gradients confirming the functionality of the zoned core design in managing seepage and pore pressure in line with established embankment dam theory.



Source: Author Research Results (2025).

Figure 3. Relationship between RWL and PWP at Upstream and Downstream Piezometers

Figure 3 demonstrates a marked distinction in hydraulic responsiveness between the upstream and downstream piezometers, as evidenced by higher coefficients of determination (R^2 = 0.71–0.81) for upstream sensors and lower values (R^2 = 0.31–0.44) downstream. The

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observed maximum R^2 value of 0.8094 at EP.1 indicates that fluctuations in reservoir levels exert a substantial influence on upstream pore water pressures. Conversely, the reduced correlation on the downstream side confirms the effectiveness of the dam's low-permeability core in attenuating reservoir-induced pressure variations, thereby contributing to slope stability and verifying the reliability of the upstream piezometers as early warning instruments. **Table 1** presents a summary of the regression equations and corresponding coefficients of determination (R^2) for each piezometer.

Table 1. Table of regression equation with R^2

Piezometer	Regression Equation	R^2	Desc.	Piezometer	Regression Equation	R^2	Desc.
EP.1	y = 6.889x - 379.4	0.8094	Very Strong	EP.3	y = 5.1403x - 359.42	0.4347	Moderate
EP.4	y = 8.1289x - 655.03	0.7138	Strong	EP.6	y = 1.4345x - 86.42	0.3137	Low
EP.7	y = 9.6004x - 907.82	0.7088	Strong	EP.9	y = 4.3449x - 460.1	0.3792	Low
EP.10	y = 6.818x - 693.96	0.7523	Strong	EP.12	y = 1.2949x - 193.23	0.3865	Low

Source: Author Research Results (2025).

Note: y = Pore Water Pressure (kPa); x = Reservoir Water Level (masl)

In the end, pore water pressure behavior in this research is crucial for maintaining downstream slope stability and preventing internal erosion, consistent with findings at other zoned embankment dams such as Eyvashan Dam, where upstream pressures reached 649 kPa versus 298 kPa downstream, and Jatibarang Dam which exhibits similar patterns [13] [15] [31].

3.2 Hydraulic Gradient

Table 2. Recapitulation of Hydraulic Gradient Values at Each Operating Water Surface

Reservoir Water Level	Piezometric level at Upstream		Piezometric level at Downstream		Δ *h*	*L*	*i*	Average of *i*
masl	EP	masl	EP	masl				
86.613 (LWL)	1	89.37	3	80.36	9.01	23.00	0.39	0.32
	4	87.60	6	86.46	1.15	23.00	0.05	
	7	84.79	9	84.03	0.76	16.00	0.05	
	10	99.02	12	91.24	7.78	10.00	0.78	
106.613 (NWL)	1	102.43	3	90.87	11.56	23.00	0.50	0.60
	4	104.22	6	89.39	14.83	23.00	0.64	
	7	104.42	9	92.91	11.51	16.00	0.72	
	10	105.96	12	102.06	3.89	10.00	0.39	
108.613 (MWL)	1	103.74	3	91.92	11.82	23.00	0.51	0.63
	4	105.88	6	89.68	16.20	23.00	0.70	
	7	106.38	9	93.80	12.58	16.00	0.79	
	10	107.35	12	102.33	5.02	10.00	0.50	

Source: Author Research Results (2025).

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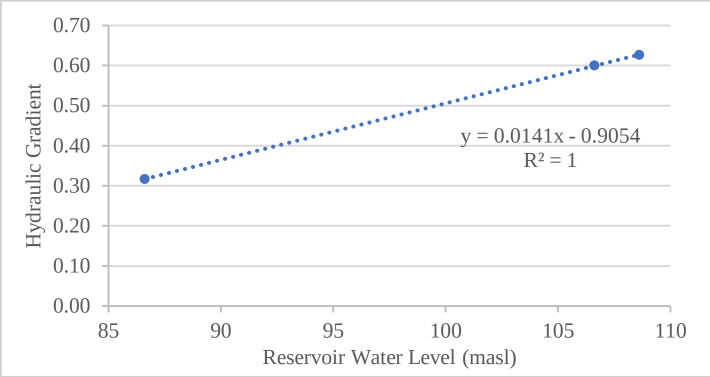

Source: Author Research Results (2025).

Figure 4. Relationship Between Reservoir Water Level and Hydraulic Gradient

The calculation results in **Table 2** and the regression in **Figure 4** indicate a clear positive correlation between the hydraulic gradient and the elevation of the reservoir water level. The average hydraulic gradient increases from 0.32 (LWL) to 0.60 (NWL) and 0.63 (MWL). As the reservoir water level rises. The pressure head difference between the upstream and downstream sides increases, driving a larger hydraulic gradient. A higher hydraulic gradient indicates an increased potential for seepage and a greater risk of internal erosion. The findings also emphasize a very strong R^2 value, indicating that the hydraulic gradient is highly associated with the reservoir water level. The comparison with previous studies at Kedung Ombo Dam shows a similar pattern, where the gradient increases from 0.66 at an elevation of 90 m to 0.72 at an elevation of 95 m, confirming the general trend that an increase in water surface elevation affects the rise in the hydraulic gradient [23].

3.3 Time Lag

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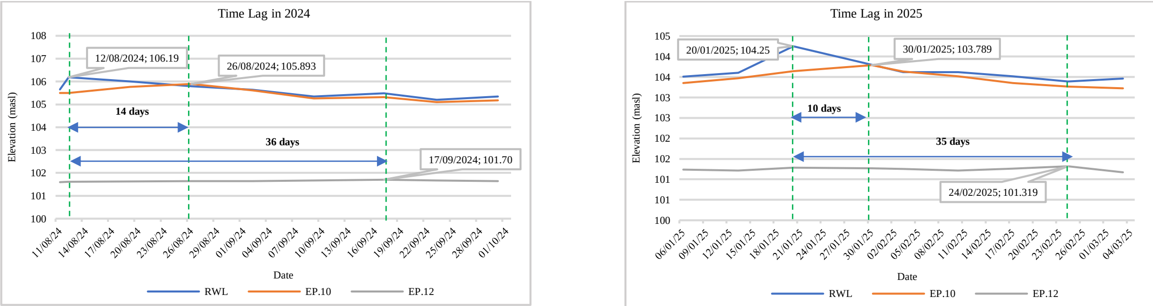

Source : Result of Analysis (2025)

Figure 5. Time Lag Graph from 2020 to 2025

From **Figure 5** we can understand that upstream piezometer EP.10 shows a shorter response time ranging from 7 to 14 days with the shortest duration of 7 days in 2020 and the longest duration of 14 days in 2024. In contrast, the downstream piezometer EP.12 exhibits a longer lag ranging from 35 to 42 days with the shortest duration of 35 days occurring in 2022 and 2025 and the longest duration of 42 days in 2021. The variability in time lag duration reflects the influence of several factors, including the permeability of the dam's core material, the distance of the piezometer from the seepage source (reservoir water surface) and fluctuations in reservoir water surface elevation.

The difference in time lag between the upstream and downstream piezometers illustrates the water flow mechanism through the zoned dam core. A shorter time lag at the upstream side indicates that changes in hydraulic pressure at that location are transmitted more quickly, as it is closer to the source of hydraulic load (the reservoir water surface). Conversely, a much longer time lag at the downstream side indicates that pore water movement through the dam core is slow, consistent with the function of a zoned core designed to limit permeability. This finding aligns with observations at the Jatibarang Dam, where the upstream piezometer showed a shorter time lag duration compared to the downstream piezometer located within the dam core [26]. Another study stated that piezometer time lag can be used to identify internal erosion within dams, reinforcing the relevance of these parameters in dam safety diagnostics [30].

3.4 Framework of Early Warning System

Based on the findings of the three parameters obtained from the research results, an early warning system framework for dam safety was developed by integrating these aspects. For pore water pressure elevation reduction, the green zone represents values exceeding the maximum observed head differential (safe condition), the yellow zone corresponds to the range between minimum and maximum observed values (caution) and the red zone indicates values

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below the minimum recorded differential (critical condition requiring immediate action). For hydraulic gradient thresholds, the green zone was set at values below the average gradient under normal operating conditions (i ≤ 0.32 for LWL. i ≤ 0.60 for NWL. i ≤ 0.63 for MWL), the yellow zone encompasses gradients between normal and maximum conditions, and the red zone represents gradients exceeding maximum safe operational levels, where internal erosion risk significantly increases based on critical gradient theory. Time lag thresholds were derived from historical response patterns, where the green zone represents time lags exceeding the maximum observed duration (indicating normal or slower seepage), yellow represents the range of typical variations observed during the monitoring period and red indicates time lags shorter than the minimum observed values, suggesting enhanced permeability or potential core deterioration. These statistically derived thresholds enable real-time anomaly detection by comparing current measurements against established operational norms as shown in **Table 3.**

Table 3. Early Warning System Framework Based on Research Results

RWL	Parameter	Green	Yellow	Red	Action
Low Water Level (+86.613)	PWP Elevation Reduction	≥ 9.01 m	0.76 - 0.91 m	≤ 0.76 m	**1. PWP elevation reduction:** • Yellow: Analyze increase of downstream PWP. increase reading frequency. • Red: Stop dam filling. emergency inspection. coordinate with Chief of Dam Operational Unit (Ka. UPB) **2. Hydraulic Gradient:** • Yellow: Lower reservoir water level. check core drainage. • Red: Lower water level immediately. geotechnical inspection **3. Time Lag at Upstream:** • Yellow: Inspect core condition. increase reading frequency. • Red: Emergency handling. structural evaluation. **4. Time Lag at Downstream:** • Yellow: Audit seepage paths. increase monitoring. • Red: Close flow. evacuate downstream. emergency mitigation
	Hydraulic Gradient	≤ 0.32	0.32 - 0.60	≥ 0.60	
	Time Lag at Upstream	≥ 42 days	21 – 42 days	≤ 21 days	
	Time Lag at Downstream	≥ 126 days	70 – 126 days	≤ 70 days	
Normal Water Level (+106.613)	PWP Elevation Reduction	≥ 14.83 m	3.89 – 14.83 m	≤ 3.89 m	
	Hydraulic Gradient	≤ 0.60	0.60 – 0.63	≥ 0.63	
	Time Lag at Upstream	≥ 17 days	9 – 17 days	≤ 9 days	
	Time Lag at Downstream	≥ 45 days	37 – 45 days	≤ 37 days	
Maximum Water Level (+108.613)	PWP Elevation Reduction	≥ 16.20 m	5.02 – 16.20 m	≤ 5.02 m	
	Hydraulic Gradient	≤ 0.63 m	0.63 – 1.00	≥ 1.0	
	Time Lag at Upstream	≥ 14 days	7 – 14 days	≤ 7 days	
	Time Lag at Downstream	≥ 42 days	35 – 42 days	≤ 35 days	

Source : Result of Analysis (2025)

Based on **Table 3**, the integration of three parameters, such as pore water pressure monitoring, hydraulic gradient, and time lag within this framework enables a holistic assessment of dam safety conditions. The reduction of pore water pressure serves as a key indicator of the core's effectiveness in limiting water penetration within a dam structure. A significant decrease in pore pressure may indicate potential seepage through the core or a malfunction of the filtration system. In contrast, the hydraulic gradient is highly sensitive to

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changes in reservoir water level elevation and can provide early warnings of increased seepage potential that may lead to internal erosion. The time lag reflects the characteristics of hydraulic pressure transmission through the porous medium, where a reduction in time lag suggests enhanced permeability, potentially signifying deterioration of the dam core material. By applying this framework, the Sindang Heula Dam Management Unit can take timely mitigation actions such as increasing monitoring frequency, lowering reservoir levels, conducting inspections or initiating emergency procedures.

This framework exhibits a strong correspondence with current developments in dam safety monitoring. Recent studies emphasize the use of predictive methodologies that compare empirical data with simulated outputs to facilitate early anomaly detection through an integrated monitoring approach [32]. This aligns with the tiered (Green–Yellow–Red) strategy adopted in the framework, where each color level represents a specific operational state that necessitates proportional and preventive actions. Research on dam instrumentation and monitoring further indicates that an effective system should be concise. clearly interpretable, adaptable to local site conditions and capable of providing dependable early warning functions [33]. By incorporating critical parameters such as PWP elevation, hydraulic gradient, and upstream–downstream time lag as primary indicators, the framework reflects global best practices in comprehensive dam safety and risk assessment.

4. Conclusion

This study shows that the pore pressure response in the upstream piezometer is faster and in the downstream piezometer is slower at the Sindang Heula Dam with respect to reservoir water level fluctuations. The increase in reservoir water level has been proven to enhance the hydraulic gradient and strengthen its relationship with pore pressure, indicating the effective role of the dam core in reducing pressure from upstream to downstream. The upstream piezometer has a shorter time lag duration, while the downstream piezometer shows a longer time lag. These findings emphasize the integration of pore pressure, hydraulic gradient and time lag as key indicators of dam stability. The integration of these three parameters provides a reliable basis for identifying the hydraulic behavior of the dam and can be used as an early warning detection design. The results of this study support the development of an early warning system capable of providing timely indications of potential leakage and hydraulic distress, thereby improving proactive risk mitigation and strengthening dam safety management.

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References

[1] BBWS Cidanau Ciujung Cidurian. “As Built Drawing Pembangunan Bendungan Sindang Heula. Kab. Serang. Prov. Banten.” Nov. 2018.

[2] R. Wang. G. Chen. and Y. Liu. “Internal Piping Erosion Evaluation of Embankment Dam Considering the Spatial Variability of Soil Properties.” *ASCE ASME J Risk Uncertain Eng Syst A Civ Eng*. vol. 10. no. 2. p. 04024006. Jun. 2024. doi: 10.1061/AJRUA6.RUENG-1218;ISSUE:ISSUE:DOI.

[3] F. Setiawan and I Sriyana. “Interpretasi Tekanan Air Pori sebagai dasar Pemeliharaan Piezometer di Bendungan Sermo.” *Wahana Teknik Sipil*. 2022.

[4] A. TM. “Dynamic Analysis of Pore Water Pressure Variation and Stability in Earth Dams During Rapid and Slow Drawdown: Khassa Chai Earth Dam as a Case Study.” *Eurasian Journal of Science and Engineering*. vol. 11. no. 1. 2025. doi: 10.23918/eajse.v11i1p2.

[5] L. Pagano. E. Fontanella. S. Sica. and A. Desideri. “Pore Water Pressure Measurements in the Interpretation of the Hydraulic Behaviour of Two Earth Dams.” *Soils and Foundations*. vol. 50. no. 2. pp. 295–307. Apr. 2010. doi: 10.3208/sandf.50.295.

[6] H. Mohammed Makkiyah. T. A. Mohammed. and R. I. Abdulridha. “Effect of Core Type on Zoned Earth Dams on Total Water Head and Flux.” *Pertanika J Sci Technol*. vol. 33. no. 1. Jan. 2025. doi: 10.47836/pjst.33.1.05.

[7] R. Norouzi. F. Salmasi. and H. Arvanaghi. “Uplift pressure and hydraulic gradient in Sabalan Dam.” *Appl Water Sci*. vol. 10. no. 5. p. 111. May 2020. doi: 10.1007/s13201-020-01195-2.

[8] Y. Shi. C. Zhao. Z. Peng. H. Yang. and J. He. “Analysis of the lag effect of embankment dam seepage based on delayed mutual information.” *Eng Geol*. vol. 234. pp. 132–137. Feb. 2018. doi: 10.1016/j.enggeo.2018.01.009.

[9] L. Olsson and J. Hellström. “Dynamic Warning Signals and Time Lag Analysis for Seepage Prediction in Hydropower Dams: A Case Study of a Swedish Hydropower

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

Plant." 2023. Accessed: Nov. 05. 2025. [Online]. Available: https://www.diva-portal.org/smash/record.jsf?pid=diva2:1778407

[10] F. Wiguna. "The Establishment of a Concept of an Early Warning System (EWS) for Dam Break Events in Indonesia." Parahyangan Catholic University. Bandung. 2022.

[11] S.-K. Yun. J. Kim. E.-S. Im. and G. Kang. "Behavior of Porewater Pressures in an Earth Dam by Principal Component Analysis." *Water (Basel)*. vol. 14. no. 4. p. 672. Feb. 2022. doi: 10.3390/w14040672.

[12] J. Cheng. Y. Liu. C. Xu. J. Xu. and M. Sun. "Study on the influence of pore water pressure on shear mechanical properties and fracture surface morphology of sandstone." *Sci Rep*. vol. 14. no. 1. p. 5761. Mar. 2024. doi: 10.1038/s41598-024-55834-8.

[13] R. H. Ardiansyah and N. D. Khurtumi. "Perilaku Tekanan Air Pori pada Bendungan Bajulmati mulai Pengisian hingga Tahun 2020." *FROPIL (Forum Profesional Teknik Sipil)*. vol. 9. no. 2. pp. 104–112. Aug. 2021. doi: 10.33019/FROPIL.V9I2.2553.

[14] B. Beiranvand and M. Komasi. "Monitoring and numerical analysis of pore water pressure changes Eyvashan dam during the first dewatering period." 2019.

[15] B. Beiranvand and M. Komasi. "An Investigation on performance of the cut off wall and numerical analysis of seepage and pore water pressure of Eyvashan earth dam." *Iranian Journal of Science and Technology - Transactions of Civil Engineering*. vol. 45. no. 3. pp. 1723–1736. Sep. 2021. doi: 10.1007/s40996-021-00613-y.

[16] B. Beiranvand. T. Rajaee. and M. Komasi. "Optimizing pore pressure prediction in earth dams through the integration of panel data and intelligent models." *Springer*. vol. 7. no. 8. Aug. 2025. doi: 10.1007/S42452-025-07516-X.

[17] R. M. S. Panggabean and W. Kresno Sadono. "Analisis Tekanan Air Pori Dan Rembesan Pada Proyek Pembangunan Bendungan Tigadihaji Sumatera Selatan." *Racic : Rab Construction Research*. vol. 10. no. 1. pp. 201–213. Jun. 2025. doi: 10.36341/racic.v10i1.5496.

[18] B. Wang. L. Chen. and Z. Niu. "Critical hydraulic gradient and fine particle migration of sand under upward seepage flow." *Sci Rep*. vol. 12. no. 1. p. 14440. Aug. 2022. doi: 10.1038/s41598-022-18720-9.

[19] L. Liang. D.-L. Tian. and Z.-C. Li. "Internal erosion process and its influence factors in widely graded loose soils due to rainfall infiltration." *Front Earth Sci (Lausanne)*. vol. 12. Aug. 2024. doi: 10.3389/feart.2024.1418293.

[20] C. H. Khor. S. P. Yap. and G. W. Leong. “Investigation of Piping Erosion in Embankment Dams with Downstream Filters.” *Journal of Geotechnical and Geoenvironmental Engineering*. vol. 150. no. 6. Jun. 2024. doi: 10.1061/JGGEFK.GTENG-11743.

[21] L. E. Orfa. “Perilaku Tekanan Air Pori pada Bendungan berdasarkan Data Instrumen Pneumatic piezometer.” *Jurnal Media Teknik Sipil*. vol. 20. no. 1. pp. 1–6. Feb. 2022. doi: 10.22219/jmts.v20i1.35931.

[22] I. Jung. M. Berges. J. G. Jr. B. P.-A. Engineering. and undefined 2015. “Exploration and evaluation of AR. MPCA and KL anomaly detection techniques to embankment dam piezometer data.” *ElsevierIS Jung. M Berges. JH Garrett Jr. B PoczosAdvanced Engineering Informatics. 2015•Elsevier*. 2015. Accessed: Aug. 19. 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1474034615001056

[23] R. Buldan. Suharyanto. N. Najib. and K. W. Sadono. “ANALISIS REMBESAN TERHADAP KEAMANAN BENDUNGAN KEDUNG OMBO DI GROBOGAN. JAWA TENGAH.” *JURNAL TEKNIK HIDRAULIK*. vol. 12. no. 2. pp. 79–92. Dec. 2021. doi: 10.32679/jth.v12i2.657.

[24] Y. Liu. D. Zheng. X. Wu. X. Chen. C. T. Georgakis. and J. Qiu. “Research on Prediction of Dam Seepage and Dual Analysis of Lag-Sensitivity of Influencing Factors Based on MIC Optimizing Random Forest Algorithm.” *KSCE Journal of Civil Engineering*. vol. 27. no. 2. pp. 508–520. Feb. 2023. doi: 10.1007/S12205-022-0611-6.

[25] S. wei Wang. Y. li Xu. C. shi Gu. and T. fei Bao. “Monitoring models for base flow effect and daily variation of dam seepage elements considering time lag effect.” *Water Science and Engineering*. vol. 11. no. 4. pp. 344–354. Oct. 2018. doi: 10.1016/J.WSE.2018.12.004.

[26] A. Setyadi. S. Suharyanto. and S. Edhisono. “Analisis Respon Tekanan Air Pori Terhadap Muka Air Waduk Pada Bendungan Jatibarang.” *Bentang : Jurnal Teoritis dan Terapan Bidang Rekayasa Sipil*. vol. 11. no. 1. pp. 67–80. Jan. 2023. doi: 10.33558/bentang.v11i1.5666.

[27] Sugiyono. *Metode Penelitian Kuantitatif dan Kualitatif*. CV. Alfabeta Bandung. 2017.

[28] L. Tanchev. *Dams and Appurtenant Hydraulic Structures*. vol. 2nd edition. Taylor & Francis Group: London. 2015.

[29] U.S. Department of Interior Bureau of Reclamation. “Embankment Dams Chapter 8: Seepage Phase 4 (Final).” 2015.

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

[30] W. Thepjunthra. W. Mairaing. M. Jinakulwipat. T. Chalermpornchai. and B. Kunsuwan. "Piezometer Time-Lag and Pore Pressure Ratio for Identification of Dam Internal Erosion." *Civil Engineering Journal (Iran)*. vol. 11. no. 3. pp. 1162–1179. Mar. 2025. doi: 10.28991/CEJ-2025-011-03-019.

[31] F. Terbouche. A. Hamza. and S. Gabi. "Analysis of pore water pressures in an earth dam under operating conditions (case of Taksebt Dam. Algeria)." *World Journal of Engineering*. vol. 19. no. 4. pp. 480–490. Jun. 2022. doi: 10.1108/WJE-07-2020-0330.

[32] A. El Bilali *et al.*. "Predicting daily pore water pressure in embankment dam: Empowering Machine Learning-based modeling." *Environ Sci Pollut Res Int*. vol. 29. no. 31. pp. 47382–47398. Jul. 2022. doi: 10.1007/S11356-022-18559-7.

[33] G. Dounias. "Monitoring and Instrumentation Strategies for New and Existing Dams." in *ICOLD Symposium on Sustainable Development of Dams and River Basins*. New Delhi: ICOLD. Feb. 2021.