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CASE STUDY

ASSESSMENT OF THE HYDRAULIC BEHAVIOR OF AN EMBANKMENT DAM THROUGH THE SEEPAGE INSTRUMENTATION

CASE STUDY: HEULA DAM, INDONESIA

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ABSTRACT

Seepage conditions must be monitored regularly in embankment dams due to their vulnerability to seepage failure. The assessment of the seepage process can be performed by interpreting the data obtained from the monitoring works of seepage instrumentation. This study aims to assess the hydraulic behavior of embankment dams, represented by seepage conditions, in the Sindang Heula Dam, which is located in Serang Regency, Banten Province, Indonesia. Piezometer and V-notch monitoring data are interpreted through several analyses. The results show that the seepage monitoring instrumentation at the Sindang Heula Dam functions well according to its response to the reservoir water level. Moreover, evaluation of seepage is performed using seepage acceptance criteria and seepage index (QI) values. According to the calculation, seepage discharges occurring in the dam range from 1.28 l/min/m to 2.05 l/min/m, which are greater values than the requirement of 0.28 l/min/m. Meanwhile, the value of the seepage index (QI) was in the range of 0.1-1 (no QI >1), concluding that no excessive seepage occurred.

Keywords: Seepage, instrumentation, monitoring, piezometer, V-notch

INTRODUCTION

Monitoring seepage conditions in a dam must be carried out periodically to ensure that the seepage process is still within the range of acceptable safety criteria. Dam failure due to seepage may occur as a consequence of failure in monitoring seepage conditions. The seepage line that cuts the downstream slope may reduce dam safety due to releasing material that initially forms a small hole until it enlarges and eventually causes the dam to collapse (Huda et al., 2019). Dam safety instrumentation uses certain devices to measure certain dam safety parameters, carried out in conjunction with visual observations and other surveillance to evaluate dam performance and find early detection of abnormal behavior in the dam (Adamo et al., 2020). Seepage monitoring in dams can be carried out by monitoring dam instrumentation, which measures several parameters, namely, seepage rate, seepage quantity, flow velocity, phreatic conditions, and water quality, that occur in the foundation and body of the dam (FEMA, 2015). When analyzing the pore water pressure according to the recording data of the piezometer, it is usually done by plotting the data against time or conducting a correlation analysis. The correlation between hydrostatic height and reservoir water level can be found through piezometer data plots against a certain time unit (Jung et al., 2013). Three parameters must be monitored in the process of evaluating dam stability: (1) piezometric level, (2) pore water pressure, and (3) hydraulic loss (Seyed-Kolbadi et al., 2020). Reservoir water level monitoring is carried out to obtain a historical record of reservoir water level fluctuations because reservoir water level fluctuations directly affect the quantity of seepage or leaks in the dam body and dam foundation. Trends obtained from the monitoring data in instrumentation can be used to measure their performance, correlate them to reservoir water levels, detect anomalies in dam behavior or instrumentation, and be a tool for predicting future dam performance.

Figure 1: Location of Sindang Heula Dam

This study was conducted at Sindang Heula Dam, which is located in Sindang Heula Village, Serang Regency, Banten Province, as shown in Fig. 1. The purpose of dam construction is to supply water for domestic water demand in Serang Regency and Serang City and irrigation and to control flood discharge. Sindang Heula Dam is a rockfill dam with a clay core, and the elevation of the dam crest is El. +110.61 m. The dam crest length is 205.20 m, and the height of the dam is 37 m. The cross section of the Sindang Heula Dam is shown in Fig. 2.

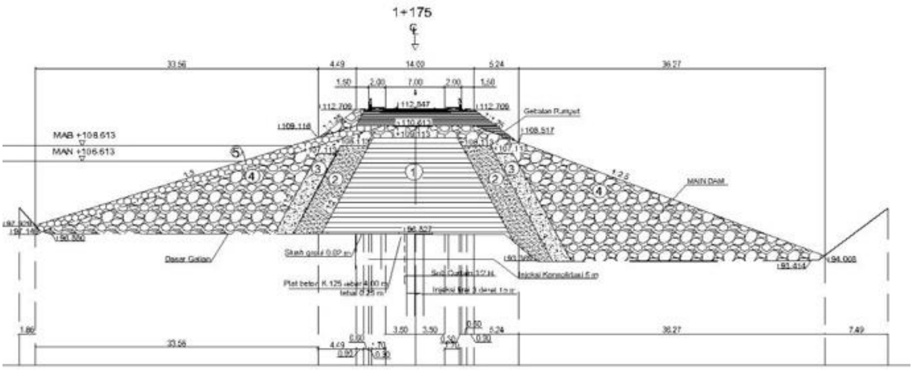


Figure 2: Cross section of Sindang Heula Dam

Several previous studies are collected to obtain a more comprehensive understanding regarding instrumentation monitoring and data interpretation along with seepage characteristics occurring in the dam. According to Aldulaimi (2021), U. C. Cita Sari et al. (2016), and Sharghi et al. (2018), instrumentation monitoring data are being used in the analysis of a dam and provide a satisfactory interpretation of the characteristics of dam seepage.

Previous studies performed by U. Cita Sari et al. (2017), Qiu et al. (2016), Rinaldi et al. (2004), Siswanto et al. (2019), Su et al. (2021), and Zhang et al. (2020) showed that the water level in the reservoir has a strong influence on the seepage discharge of the dam. These works have shown that the rise in water level causes an increase in the pore water pressure as well as the seepage discharge.

Previous studies have been performed by interpreting instrumentation monitoring data to analyze the seepage conditions occurring in a dam. This study displays the usage of seepage monitoring data to define the safety status of dam seepage using a different approach. In this case, multiple criteria are used by comparing the dam seepage with the typical seepage on a dam with a similar height and using the value of the seepage index (QI).

This study aims to analyze the hydraulic behavior of the Sindang Heula Dam using an interpretation of seepage instrumentation installed at the dam body, the piezometer and the V-notch to evaluate the seepage condition that is occurring. Additionally, the hydraulic behavior resulting from the instrumentation monitoring interpretation may display the proneness of the dam to seepage failure. The results of this study can benefit the dam operator in gaining a better understanding of the hydraulic behavior of the Sindang Heula Dam to execute the best-fitting procedure to control dam seepage to maintain dam safety.

METHODS

In this study, the data used are the instrument monitoring data of the vibrating-wire piezometers located in the embankment and the v-notch. The data period is from April 2018 to December 2021. This period covers the construction and impoundment phase of the dam. The placement layout of the vibrating wire-type piezometer installed on the Sindang Heula Dam is shown in Fig. 3.

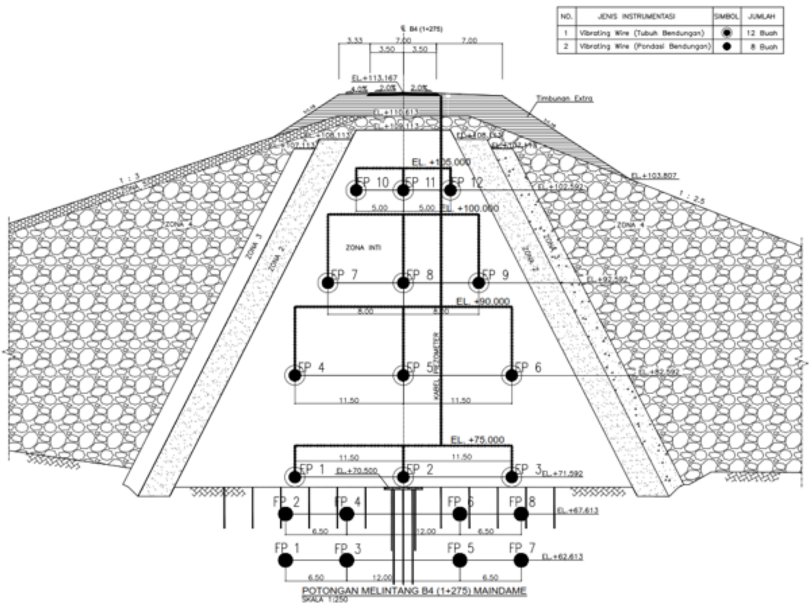


Figure 3: The placement layout of the piezometer in Sindang Heula Dam

The analysis in this study consists of (1) trend analysis in instrumentation data, (2) regression analysis of instrumentation monitoring data and the water level, (3) hydraulic gradient calculation, and (4) seepage evaluation analysis. The workflow of the study is shown in Fig. 4.

Trend analyses on instrumentation monitoring data are carried out in two ways: (1) plotting based on time, where piezometer data are connected with the reservoir water level to time, and (2) obtaining correlation by conducting correlation analysis on piezometer data versus water level reservoir. Correlation analysis is more appropriate to use in interpreting instrument data in conditions where the reservoir water level varies significantly (FEMA, 2015).

Empirically, the evaluation of the dam performance against seepage using instrumentation data can be done by analyzing the seepage condition and determining the dam seepage level based on the typical seepage losses and the seepage index (QI) assessment. The typical seepage level as the comparison in this study uses the guidance shown in Table 1. This guidance shows the typical seepage losses occurring at the dam with a certain height. A comparison will determine whether the seepage trend being monitored is within the range of the typical seepage at a dam with a similar height.

Table 1: Typical Seepage Losses of an Earth Dam (Look, 2007)

Dam Height (m)	Seepage, liters/day/metre (liters, minute/metre)	
	OK	Not OK
<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)

Another analysis is also performed by assessing the seepage discharge using the Seepage Index (QI). According to Novak et al. (2007), empirically, the QI value can determine the performance of a dam in terms of seepage behavior. QI can be calculated as follows:

$$QI = \frac{q}{(1000AKi)}$$

where q is the seepage discharge (lt/s) according to the V-notch data, A is the area of the element (m^2), K is the permeability of the core, and i is the hydraulic gradient across the core. Seepage is considered safe when QI <1. However, QI >1 may indicate that some leakage occurs, and further investigation is needed.

In this study, trend analysis was carried out on vibrating-wire type piezometer data placed in the dam body to determine (1) the piezometer response to reservoir water level fluctuations and (2) the hydraulic gradient that occurred in the dam body to calculate the QI value. Moreover, the V-notch data are used in comparison with the typical seepage shown in Table 1 and to calculate the seepage index.

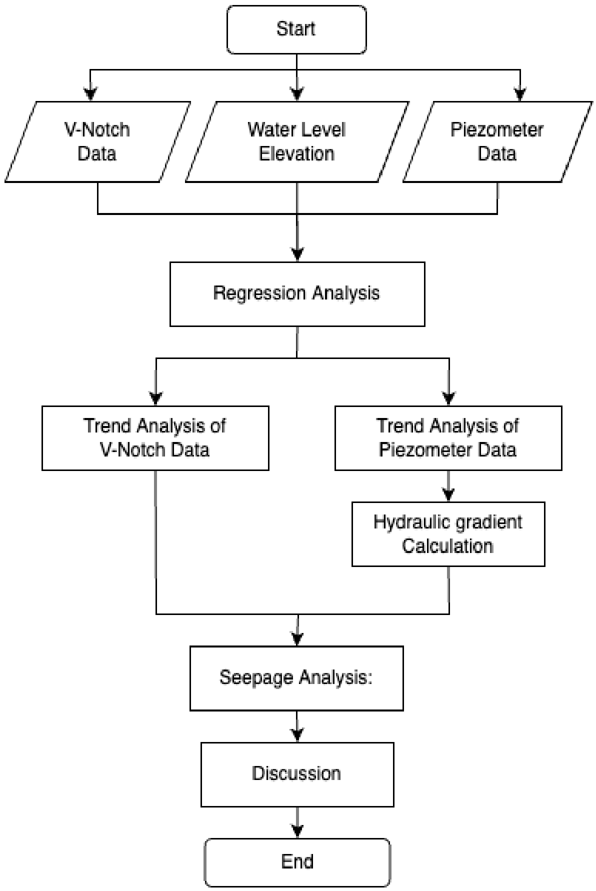


Figure 4: Workflow of the study

RESULTS AND DISCUSSION

Piezometer Data Trend in the Time-history Plot

Piezometer data are plotted with reservoir water level fluctuation data against time. The data used in this study are piezometer data from May 2018 to December 2021. The graphs showing pore water pressure in the time-history plot are presented in Fig. 5 to Fig. 8.

Piezometers EP1, EP2, and EP3 (Fig. 5) show an increase in pore water pressure as the result of an increase in the embankment level. Therefore, an increase in stress occurs. This occurred from April to October 2018. During this process, excess pore water pressure is formed at the clay core material. Identical characteristics also exist for piezometers EP4, EP5, and EP6 (Fig. 6). After the formation of excess pore water pressure, all piezometers showed a decreasing trend of pore water pressure, indicating the dissipation process. This condition took place from January to December 2019 until the beginning of dam impoundment.

The impoundment of the dam was performed from December 2019 to February 2020. Aldulaimi (2021), through modeling, found that there is a rapid increase in pore water during the initial reservoir filling period. The theory is applied to all piezometer data. The data show a trend of increasing pore water pressure at the beginning of reservoir filling (at the beginning of the graph, in December 2019) and continue to increase. Figs. 5 to 8 show that piezometers EP2 (Fig. 5), EP4, EP5 (Fig. 6), EP7, EP 8, EP9 (Fig. 7), EP10, and EP11 (Fig. 8) show a constant increase in the pore water pressure. In EP3 (Fig. 5), the trend in the data shows an increase during the reservoir filling period, but after the reservoir filling period is complete, the trend decreases. Meanwhile, in EP1 and EP6, the trend of the data increased during the reservoir filling period, but after that, the trend was flat. During this period, in general, the trend in the data shows an increase in pore water pressure. The increase in pore water pressure occurs simultaneously with the increase in the reservoir water level. Referring to the pattern, piezometer EP1 shows a faster increase in pore water pressure than piezometer EP3 (Fig. 5). Additionally, the increase that occurs on EP1 is more significant than the increase shown on EP3 (Fig. 5). The same condition is found on EP4 and EP6 (Fig. 6) and on EP7 and EP9 (Fig. 7).

All piezometers showing a faster response to the reservoir water level, namely, EP1, EP4, and EP7, are installed in the upstream position of the clay core material. Meanwhile, EP3, EP6, and EP9, which are piezometers installed in the downstream position of the core material, show a slower increase in pore water pressure. The difference in this response behavior is due to the very low permeability of the clay core material.

The piezometer instrument on the Sindang Heula Dam is generally confirmed to be performing well, according to the response shown by the piezometer to reservoir water level fluctuations.

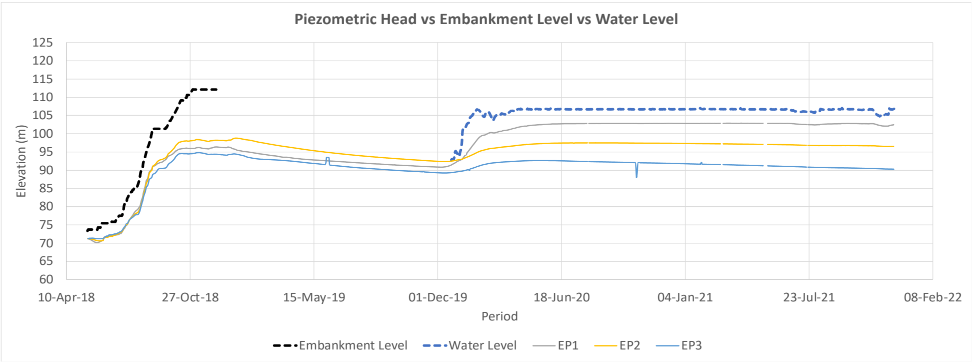


Figure 5: Piezometer monitoring data (piezometer elevation +71.59 m)

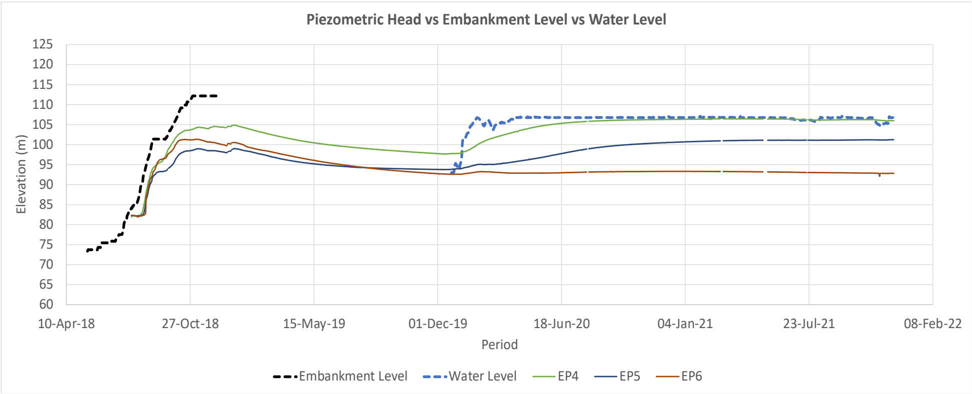


Figure 6: Piezometer monitoring data (piezometer elevation +82.59 m)

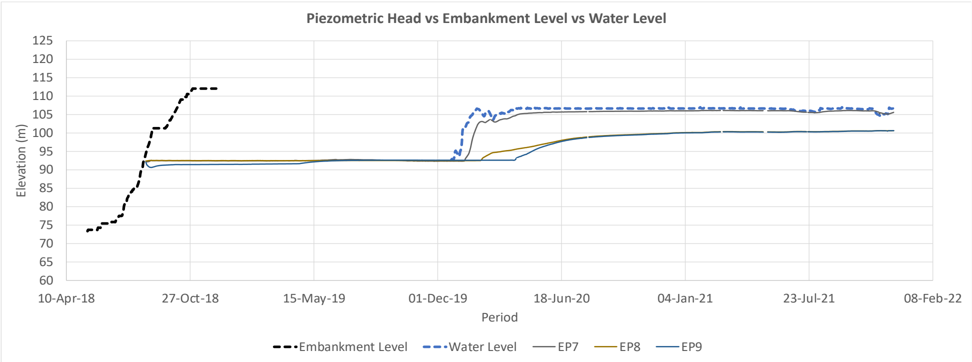


Figure 7 Piezometer monitoring data (piezometer elevation +92.59 m)

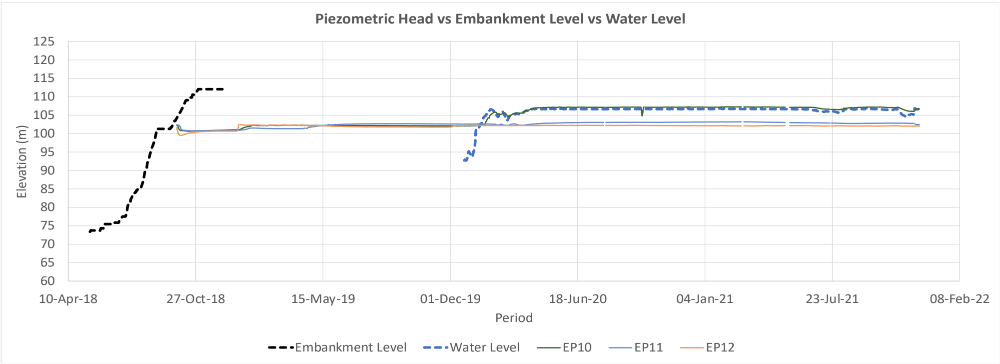


Figure 8 Piezometer monitoring data (piezometer elevation +102.59 m)

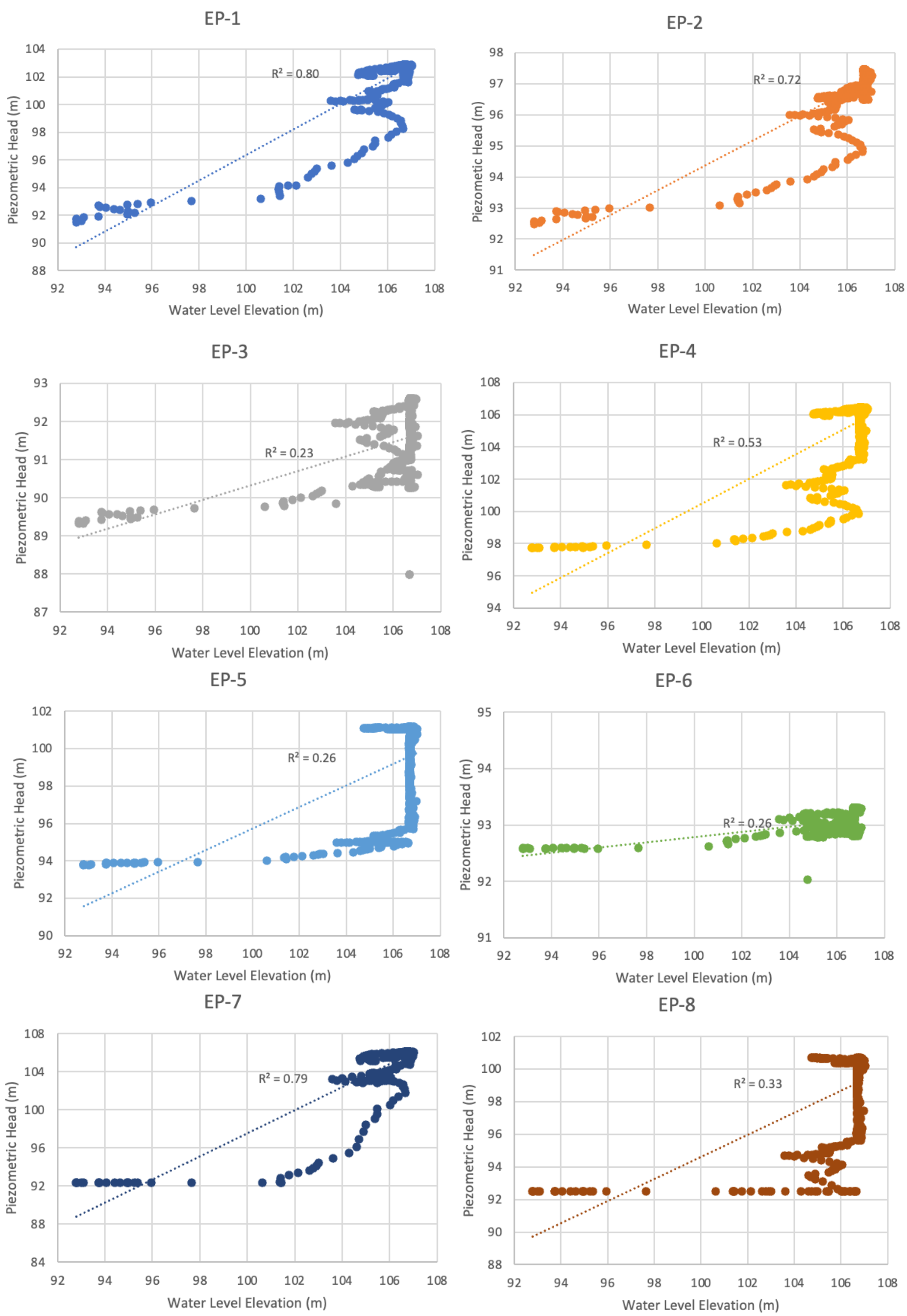
Piezometer Data Analysis

Previous studies by Buldan et al. (2021) and U. Cita Sari et al. (2017) stated that there is a strong correlation between pore water pressure and reservoir water level elevation. The rise in reservoir water level will cause an increase in pore water pressure. Variations in the rate of increase in the reservoir water level affect the time required for the pore water pressure to stabilize. When the water level rises, the pore water pressure will first increase and become stable. The higher the rate of increase in the water level in the reservoir is, the faster the pore water pressure becomes stable (Su et al., 2021).

To find the correlation between pore water pressure and reservoir water level, regression analysis was performed on each piezometer data series. The R^2 values obtained from the regression analysis are shown in Table 2.

Table 2: The R^2 Values

Piezometer	Elevation (m)	R^2	Correlation	Location (by the core)
EP1	71.59	0.80	Very Strong	Upstream
EP2	71.59	0.72	Strong	Center
EP3	71.59	0.23	Low	Downstream
EP4	82.59	0.53	Moderate	Upstream
EP5	82.59	0.26	Low	Center
EP6	82.59	0.26	Low	Downstream
EP7	92.59	0.79	Strong	Upstream
EP8	92.59	0.33	Low	Center
EP9	92.59	0.23	Low	Downstream
EP10	102.59	0.70	Strong	Upstream
EP11	102.59	0.16	Very Low	Center
EP12	102.59	0.04	Very Low	Downstream


EP-1
R² = 0.80
Piezometric Head (m)
Water Level Elevation (m)
EP-2
R² = 0.72
Piezometric Head (m)
Water Level Elevation (m)
EP-3
R² = 0.23
Piezometric Head (m)
Water Level Elevation (m)
EP-4
R² = 0.53
Piezometric Head (m)
Water Level Elevation (m)
EP-5
R² = 0.26
Piezometric Head (m)
Water Level Elevation (m)
EP-6
R² = 0.26
Piezometric Head (m)
Water Level Elevation (m)
EP-7
R² = 0.79
Piezometric Head (m)
Water Level Elevation (m)
EP-8
R² = 0.33
Piezometric Head (m)
Water Level Elevation (m)

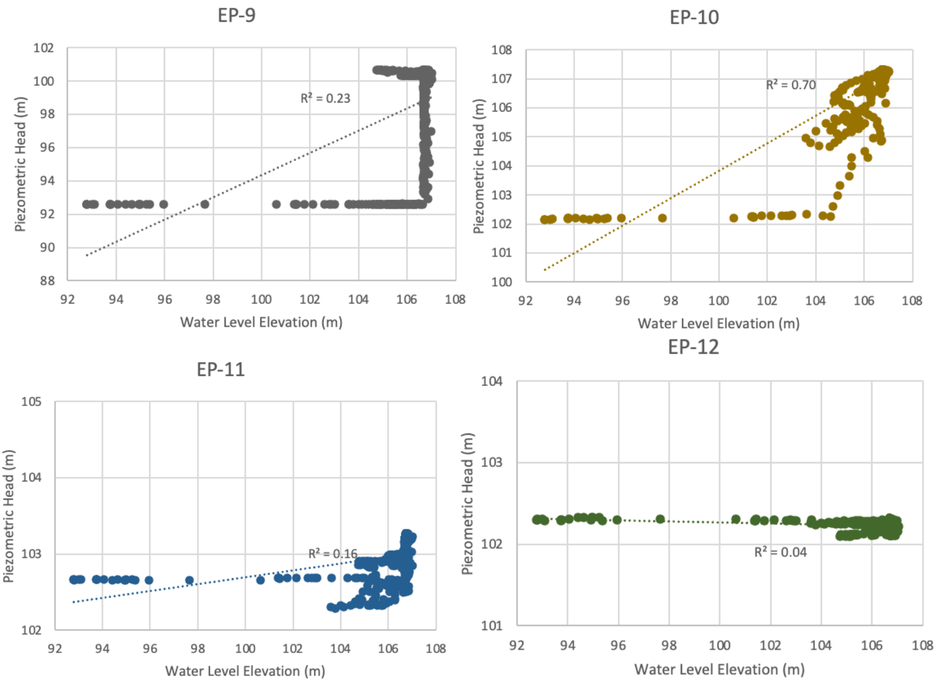


Figure 9: Regression Curves of Piezometer Data

The interpretation of the regression curves (Fig. 9) shows that in some piezometers, the distribution of the data plot does not form a correlation line. This condition occurs in the data distribution of several piezometers installed in the downstream area of the dam, where the data tend to be scattered around the trend line. This shows that the effect of the reservoir water level is also influenced by the lag/slower response time on the piezometer downstream. The results of the regression analysis in Table 2 indicate that the pore water pressure and the reservoir water level fluctuations at piezometers EP1, EP2, EP4, EP7, and EP10 have a strong correlation. Piezometers EP3, EP5, EP6, EP8, EP9, and EP11 show a low to moderate correlation. Piezometer EP12 shows a very low correlation. Depending on the location of the piezometer placement, in this case, the soil layer, the distance between the piezometer and the reservoir, and other parameters, the plot of the correlation analysis may vary due to differences in response times. The strong correlation obtained in this study represents a situation where reservoir water level fluctuations have a significant effect on piezometer data located more upstream of the dam (EP1, EP2, EP4, EP7, and EP10). Meanwhile, the influence of reservoir water level fluctuations on the monitored data at the location more downstream of the dam is smaller due to the lag/response time caused by the very low permeability of the dam core material.

V-Notch Data Analysis

The reservoir water level fluctuation and v-notch data used in the analysis are the data recorded from September 7, 2021, to December 6, 2021. This length of data may be considered short, but due to the unavailability of the data in the previous period, the analysis is performed by using the data available.

The V-notch monitoring data are represented in Fig. 10.

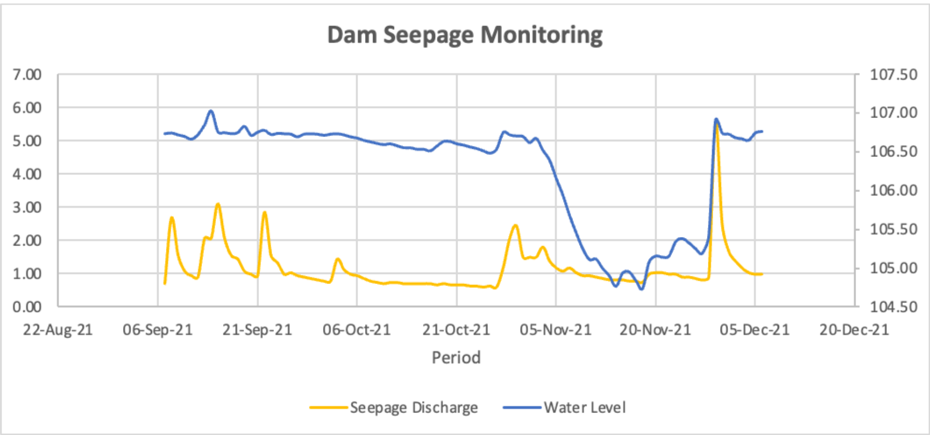


Figure 10: V-notch Monitoring Data

Seepage patterns in embankment dams or rockfill dams are generally related to the reservoir water level (Lee et al., 2018). An increase in reservoir water level will cause an increase in seepage discharge (U. Cita Sari et al., 2017 and Zhang et al., 2020). According to the interpretation of the graph in Fig. 10, the fluctuation pattern of seepage discharge is similar to the reservoir water level fluctuation. When the reservoir water level falls, the seepage discharge tends to decrease, and when the reservoir water level rises, the seepage discharge will also increase. It is necessary to interpret the V-notch data using acceptable seepage criteria and seepage index assessment so that the dam seepage safety level can be known.

Correlation analysis of V-notch data is also conducted to evaluate the seepage discharge according to v-notch data. The interpretation of the regression curve, as shown in Fig. 11, is that the distribution of the data plot is scattered when the water level reaches an elevation of +106.50 m. According to the theory, seepage discharge occurring in the dam will increase as the water level rises. This result, however, shows an inconsistency in the theory. At water level elevations of +106.50 m to +107.00 m, the data show that the seepage discharge of the dam fluctuated. Some conditions may cause this to occur. This analysis is done by using a relatively short period of recording data. Many situations may occur in the V-notch, so it is recommended to perform comprehensive monitoring in this instrument to ensure that the data obtained are reliable.

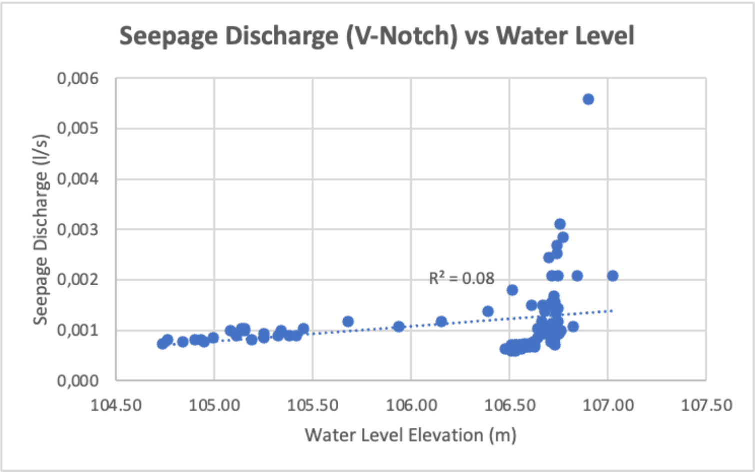


Figure 11: V-Notch Data versus Reservoir Water Level

Observation Well Data Analysis

The observation wells are also installed in the Sindang Heula Dam. This instrument installation aims to obtain a reference about the groundwater elevation in the surrounding area. This study includes observation well data interpretation to evaluate the seepage occurring in the downstream area.

The observation well installation layout is shown in Fig. 12. The observation well data used in this study are those recorded from December 2019 to December 2021. The interpretation is divided into two parts, consisting of the interpretation of the groundwater level at the left abutment and right abutment of the dam. The left abutment is represented by OW1, OW2, and OW3.

The observation well monitoring data in the left abutment are shown in Figure 13. The right abutment is represented by OW4, OW5, OW6, OW7, and OW8. The observation well monitoring data in the right abutment are shown in Fig. 14.

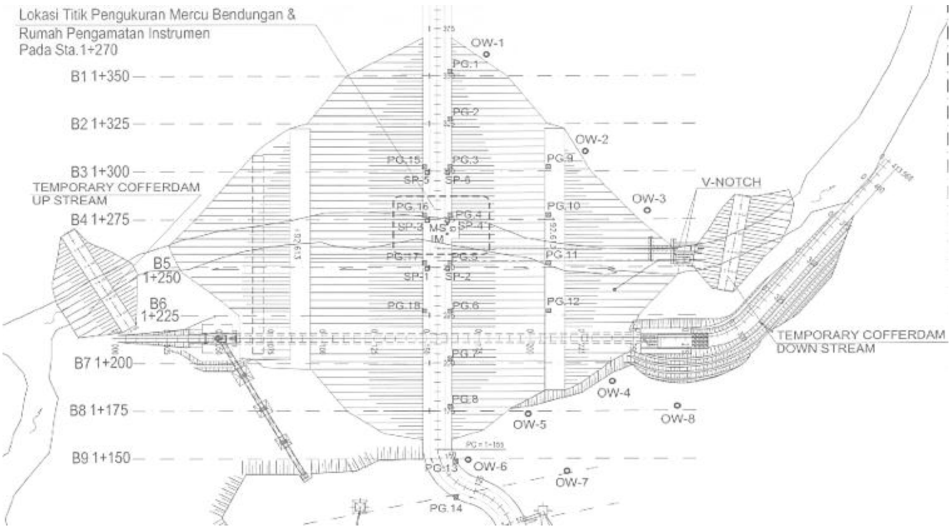


Figure 12: Installation Layout of Observation Wells (coded OW-)

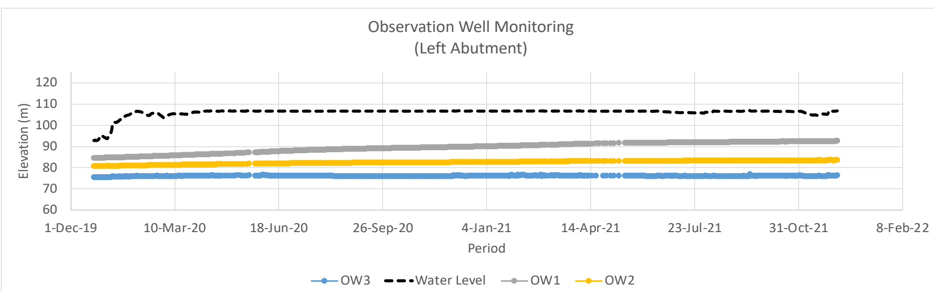


Figure 13: Observation Well Monitoring Data (Left Abutment)

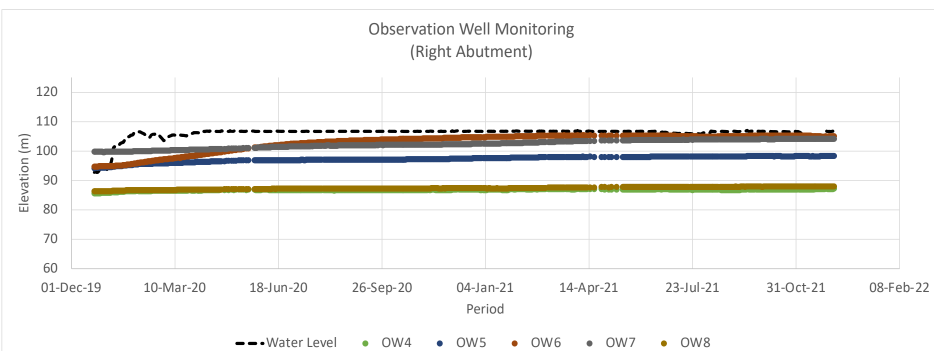


Figure 14: Observation Well Monitoring Data (Right Abutment)

Fig. 13 shows that the groundwater level remains constant after the impounding process. OW1, the observation well closest to the upstream slope of the dam, shows a slight increase in the groundwater level. Meanwhile, according to Fig. 14, OW6 shows a moderate increase in groundwater level. This shows that the seepage of the dam influences the area. Similar to OW1, OW6 is also the closest to the upstream slope.

The overall trend of the groundwater level shown by the observation well data is relatively constant. This indicates that the seepage occurring in the dam is considered normal, according to the monitoring of the downstream area that has not acquired the extreme increase in groundwater level after the impoundment of the reservoir.

Seepage Evaluation

The seepage evaluation was carried out by comparing the measured seepage quantity from the V-notch data with the typical seepage losses, as discussed in Table 1. The results of the analysis are shown in Table 3.

Table 3: Measured Seepage (V-notch) versus Typical Seepage Losses

	V-Notch seepage (liter/minute/meter)	Acceptable seepage Dam height = 41 m (liter/minute/meter)	Status
Sep-21	2.04	0.56	NOT OK
Oct-21	1.27	0.56	NOT OK
Nov-21	1.73	0.56	NOT OK
Dec-21	1.72	0.56	NOT OK

The results show that the seepage discharge in the period from September 2021 to December 2021 ranges from 1.27 to 2.04 liter/minute/meter (exceeding 0,56 liter/minute/meter). This shows that the seepage discharge trend at the Sindang Heula Dam is beyond the typical losses for a dam with a height >40 m.

To determine the level of seepage acceptance of the dam, it is recommended to conduct other types of seepage checking analysis to give a better understanding of the seepage condition.

An exit seepage area will form on the downstream slope of the dam, at which point a hydraulic gradient that is too large will cause piping. The hydraulic gradient value in that state is called a critical gradient. The value of the hydraulic gradient acting on that section should not exceed the critical gradient value to maintain dam safety (Siswanto and Suprapto, 2019).

The hydraulic gradient (i) value is computed using the piezometer monitoring data. The calculation is performed by dividing the difference between the pressure head between the upstream and downstream piezometers by the distance of both piezometers. The calculation of the seepage index (QI) value of the Sindang Heula Dam is shown in Table.4.

Table 4: Seepage Index (QI) Calculation

Period	q	i	QI	QI<1
7-Sep-21	0.003	0.49	0.118	OK
8-Sep-21	0.011	0.49	0.448	OK
9-Sep-21	0.006	0.49	0.260	OK
10-Sep-21	0.004	0.49	0.181	OK
11-Sep-21	0.004	0.49	0.158	OK
12-Sep-21	0.004	0.49	0.150	OK
13-Sep-21	0.008	0.49	0.345	OK
14-Sep-21	0.000	0.49	0.000	OK
15-Sep-21	0.012	0.49	0.516	OK
16-Sep-21	0.008	0.49	0.344	OK
17-Sep-21	0.006	0.49	0.259	OK
18-Sep-21	0.006	0.49	0.240	OK
19-Sep-21	0.004	0.49	0.179	OK
20-Sep-21	0.004	0.49	0.164	OK
21-Sep-21	0.004	0.49	0.157	OK
6-Oct-21	0.004	0.49	0.157	OK
22-Oct-21	0.003	0.49	0.112	OK
23-Oct-21	0.002	0.49	0.106	OK
24-Oct-21	0.002	0.49	0.106	OK
25-Oct-21	0.002	0.49	0.101	OK
26-Oct-21	0.002	0.49	0.107	OK
27-Oct-21	0.002	0.49	0.101	OK
28-Oct-21	0.005	0.49	0.198	OK
29-Oct-21	0.008	0.49	0.348	OK
30-Oct-21	0.010	0.49	0.410	OK
31-Oct-21	0.006	0.49	0.252	OK
1-Nov-21	0.000	0.49	0.000	OK
2-Nov-21	0.000	0.49	0.000	OK
3-Nov-21	0.007	0.49	0.303	OK
4-Nov-21	0.005	0.49	0.234	OK
5-Nov-21	0.005	0.49	0.200	OK
21-Nov-21	0.004	0.44	0.198	OK
22-Nov-21	0.004	0.44	0.190	OK
23-Nov-21	0.004	0.44	0.189	OK
24-Nov-21	0.004	0.44	0.172	OK
25-Nov-21	0.004	0.44	0.173	OK
26-Nov-21	0.003	0.44	0.165	OK
7-Nov-21	0.003	0.44	0.158	OK

Period	q	i	QI	QI<1
28-Nov-21	0.004	0.44	0.173	OK
29-Nov-21	**0.022**	**0.44**	**1.022**	**NOT OK**
30-Nov-21	0.010	0.45	0.454	OK
1-Dec-21	0.007	0.46	0.300	OK
2-Dec-21	0.005	0.46	0.246	OK
3-Dec-21	0.005	0.46	0.208	OK
4-Dec-21	0.004	0.47	0.182	OK
5-Dec-21	0.004	0.47	0.173	OK
6-Dec-21	0.004	0.47	0.171	OK

According to the results shown in Table 4, the largest QI is 1.02, occurring on November 29, 2021. In addition, the QI values range under 1. Fig. 15 shows that the hydraulic gradient has a constant trend. Nevertheless, the QI value fluctuates following the trend of the water level.

In general, it can be concluded that the Sindang Heula Dam is still safe from excessive seepage in the period September 2021 to December 2021 according to the absence of the trend of QI > 1.

Interpreting seepage monitoring data from instruments requires including the rainfall factor in the analysis. Rainfall can enter directly into the v-notch flow, making the measurement of seepage discharge difficult. It is necessary to separate the influence of rainfall in seepage analysis (Lee et al., 2018). Given the absence of rainfall recording data used in this study, rainfall-influenced data are not considered. However, the measured seepage shown by v-notch data may become too large when there is no effort made to eliminate the influence of rainfall.

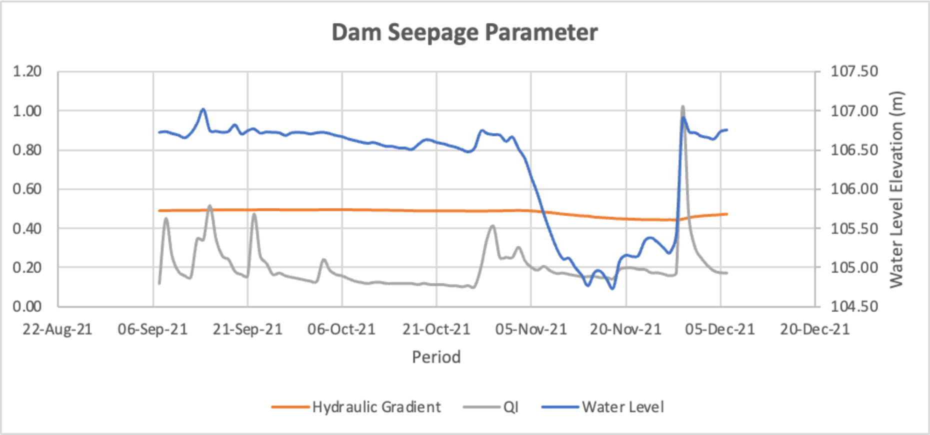


Figure 15: Dam Seepage Parameter versus Water Level

Further analysis is needed to determine the rainfall-unaffected seepage discharge by removing part of the data when there are rainfall data at the same monitoring time. Given the importance of collecting rainfall data in analyzing seepage, it becomes obligatory for the monitoring engineer to anticipate the event of rainfall when measuring seepage discharge. A long data series is crucial to detect the potential danger related to seepage in a dam, by which it is highly advised to collect data constantly to obtain the seepage characteristic of the dam in every weather condition throughout the dam service period.

The piezometric head changes over time in some periods. Determining the changes in the piezometric head is done by selecting the period in which some changes in the piezometric head may occur in that period. This is done by carefully partitioning the trend line in the piezometer monitoring data (shown in Fig. 5 to Fig. 8) into some sections. The sections are according to a period that is being used to monitor the piezometric head. The sections are as follows: (1) t1 represents the period from the beginning of monitoring, (2) t2 represents the period from t1 to the beginning of the consolidation process, (3) t3 represents the period from t2 to the end of the consolidation process/the beginning of reservoir impoundment, (4) t4 represents the period from t3 to when the reservoir water level reached the normal water level (NWL), and (5) t5 represents the period from t4 to the end of data. The piezometer monitoring from t1 to t5 is shown in Table 5.

Table 5: Piezometric Head Changes

Period	Piezometric Head (m)		
	EP1	**EP2**	**EP3**
t1	71.23	71.28	71.30
t2	96.38	98.20	94.32
t3	91.39	92.46	89.30
t4	98.25	94.81	91.03
t5	102.47	96.51	90.27

The piezometric head in each period is plotted in a graph to analyze the change, which may be in increasing or decreasing form. The graph is shown in Figure 16.

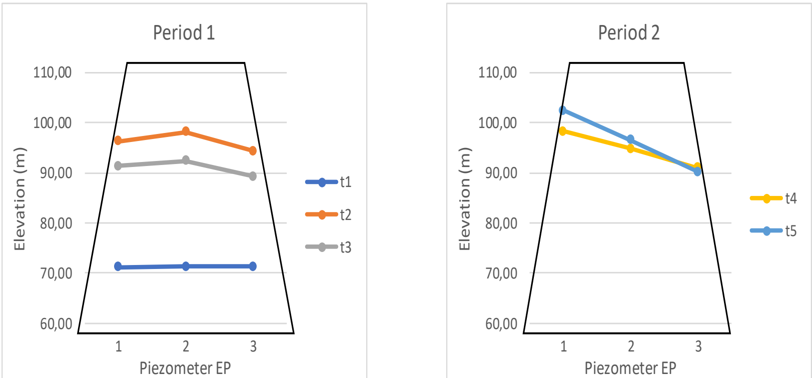


Figure 16: Piezometric Head Changes

The situation shown in Figure 16 explains that the pore water pressure acting on the piezometers has a downward trend from upstream to downstream. This follows the seepage theory in the dam, where the phreatic line on the dam will be down from upstream to downstream. When the embankment level is constant and the pore water pressure dissipation process occurs, the piezometric head is decreased. (t2 to t3). In the impoundment period, the increase in pore water pressure occurred slowly and not significantly (the trend from t5 to t6 did not change significantly). This entire process consistently matches the normal condition of the seepage process in an embankment dam. It can be concluded that the seepage condition in the dam is normal.

CONCLUSION

The results of the assessment in Sindang Heula Dam according to the seepage instrumentation data generally confirm that the hydraulic behavior of the dam can be considered normal. The piezometer data show that the instrumentation is working properly. This is confirmed by the result obtained from the regression analysis (the R^2 value), which shows that the piezometers in the upstream part of the core material respond to the water level fluctuation in a good manner. The results, however, also show that some piezometers in the downstream part of the core material are weakly correlated with the water level. This is due to the core material permeability, which is very low, making the pore water pressure acting in the surrounding area of the downstream part of the core less affected by the changes in water level.

The V-notch data show that from September 2021 to December 2021, the seepage discharge trend is greater than the criterion value of 0.56 l/minute/meter (for dam heights > 40 m). The values obtained from the analysis ranged from 1.28 to 2.05 l/minute/meter, concluding that the seepage condition does not meet the acceptance criteria. Meanwhile, the analysis using the seepage index (QI) calculation results in the status of normal conditions, where the QI value is in the range of 0.1 to 1. The trend from the result where QI<1 concluded that no excessive seepage endangers the stability of the dam. These two analyses show a sharp difference in the obtained result. To clarify the dam seepage status, this analysis also considers the observation well data. According to the results derived from the interpretation analysis, the groundwater level monitored by the observation well shows normal conditions. Additionally, according to the pore water pressure characteristic shown by the piezometric head changes, the seepage condition is consistent with the normal condition.

Early detection of hazards in dams can be obtained by regularly interpreting the results of instrumentation monitoring data. Additional monitoring must be provided as a control effort on the performance of the piezometer. It is necessary to ensure that the piezometers have sufficient sensitivity in describing the pore water pressure conditions acting on the dam. Additional analysis of the piezometer data can be performed in the future to predict the pore water pressure conditions that will occur when the water level elevation exceeds the water level elevation during the monitoring period. This analysis can be used in dam safety assessments when extreme conditions occur. Additionally, periodically, it is necessary to analyze the seepage that occurs against the tolerance limit of seepage acceptance using either the acceptance criteria or the seepage index parameter. Conducting further seepage analysis using the finite element method is recommended to obtain a more comprehensive result.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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