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Piezometer Time-Lag and Pore Pressure Ratio for Identification of Dam Internal Erosion

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Abstract

Earth dams on complex geology without proper foundation treatment often face the risk of seepage problems. Sufficient installation and interpretation of field instruments are essential for monitoring dam behavior. Three indicators are introduced for assessment of seepage behavior: time lag (T_L), pore pressure ratio (P_R), and trigger water level (H_W). The normalized T_L reflects the washing out and plugging of rock cracks, as well as the progression of internal erosion. The foundation of the studied dam consisted of foliated rocks that were highly fractured, with the axis of the foliations aligned almost in the upstream-downstream direction, with a possible low-stress zone on the syncline axis. The existing crack easily opened in the concave section of the syncline when the reservoir had risen to a certain elevation, resulting in increased permeability and a higher flow to the downstream area, known as "hydraulic fracturing" (HF). The piezometer T_L clearly indicated a shorter response time as the operating period progressed. The study dam showed the possibility of HF in the foundation, as observed during 2003–2024. The progression of HF was also confirmed by the increase in P_R levels toward downstream. This revealed that the ongoing progression of HF had occurred at sta.2+700, which agreed well with the location of the slip zone that had occurred in 1993. H_W was activated by the reservoir water level response also decreasing with time from 2003 to 2024, confirming that water infiltration through the rock crack progressed with time. These three indicators could act as good warning indices for seepage problems. This compiled knowledge could be transformed into a flowchart to identify the possible risks of hydraulic fracturing in the dam. If the three indices all showed the same trend, the potential for hydraulic fracturing and internal erosion would be very high.

Keywords: Time Lag; Pore Pressure Ratio; Hydraulic Fracturing; Internal Erosion.

1. Introduction

Piezometer response is important monitoring data to assess the possible dam internal erosion. Unusual high pore pressures, fast time lags, and low trigger levels observed by piezometer may indicate serious seepage erosion [1-3]. When combined with visual inspection and seepage modeling, the seepage behavior can be evaluated. This approach can provide proactive dam monitoring for long-term safety [4, 5]. Information and statistics [6-9] showed that about 30–50% of earth dam failures are the result of piping and internal erosion. However, internal erosion may reach an advanced

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stage before it shows the visible signs. Proper interpretation of instrument data can be the first evidence of dam risks. [10-13] Furthermore, good interpretation can predict the level of dam defects and the estimated time to failure [14-16].

Research on dam monitoring and internal erosion has made significant progress, focusing on the application of artificial intelligence (AI) [17-19]. Predictions of piezometric level and seepage flow can be done by AI [20, 21]. The numerical modeling (FEM, FDM) is usually employed to compare with measurement results [22-24]. These are dependent on piezometer readings and seepage flow measurements to evaluate the seepage behavior [25-27].

However, the seepage evaluation gaps still exist for simple piezometer responses. That is the selection of reasonable indexes to indicate the critical levels of internal erosion. The erosion may gradually progress over many years without a distinctive sudden pore pressure change. This study offers the basic seepage evaluations from time lag, pore pressure ratio, and trigger level, which are the effective tools to quantify the levels of internal erosion.

Among the various methods used for leakage evaluation [28, 29], seepage monitoring techniques [30-34] have been widely applied and interpreted over time [35-37[. These methods typically rely on parameters such as time lag [31, 32] and seepage length, which provide insights into the flow characteristics of water within the dam [38, 39]. However, few studies have focused on evaluating the long-term behavior of dams using more refined parameters, such as piezometer time lag, pore pressure ratio, and trigger levels.

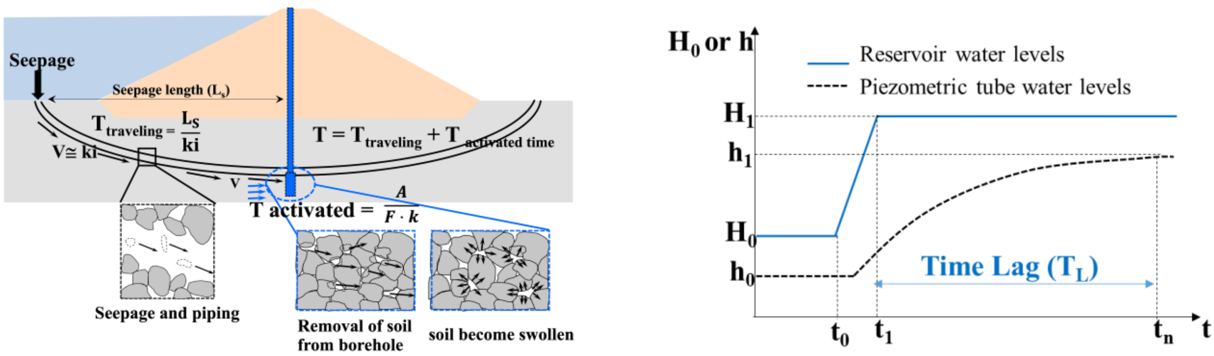
An earth dam in northern Thailand was used in this case study. This dam had been evaluated based on semi-quantitative risk assessments (SQRA) in 2020 [40]. The results indicated there was a possible risk of concentrated seepage and internal erosion. Previously, a concentrated leak in the downstream area was observed in a period of high reservoir water levels. [41-44], reported that the seepage problems were due to the complex geology of the dam foundation, where stress arching in rock foliation had initiated hydraulic fracturing (HF) and internal erosion. The HF was triggered when the reservoir water level reached the curtain level. As the water pressure started to open the rock crack and the seepage flow increased [42, 45-47]. This behavior was detected based on piezometer readings in the dam foundation on highly weathered rocks.

Hydraulic fracturing (HF) initiates the progressive flow path, resulting in more rapid seepage velocities. The time lag (T_L) from the reservoir water rising to the piezometer response became shorter. The total head loss along the seepage path decreased as a result of increasing permeability. Then the ratio (P_R) of the piezometer head as compared to the reservoir rising is increased. Variation in these two parameters can be used as indices for the evaluation of seepage erosion in the dam [29, 34]. T_L, P_R and the trigger level (H_W) can then be used for evaluating the potential of internal erosion. When a dam instrument database is established by the dam owner, then the systematic seepage evaluation for a group of dams can be done. These results are the more effective maintenance program for the dam owner's safety management.

2. Background

2.1. Time Lag

The piezometer response normally shows a time lag from the rise of the reservoir water level. It takes longer for the piezometer head to sense the peak of water level, as shown in Figure 1. This delay period is called "time lag" [3].

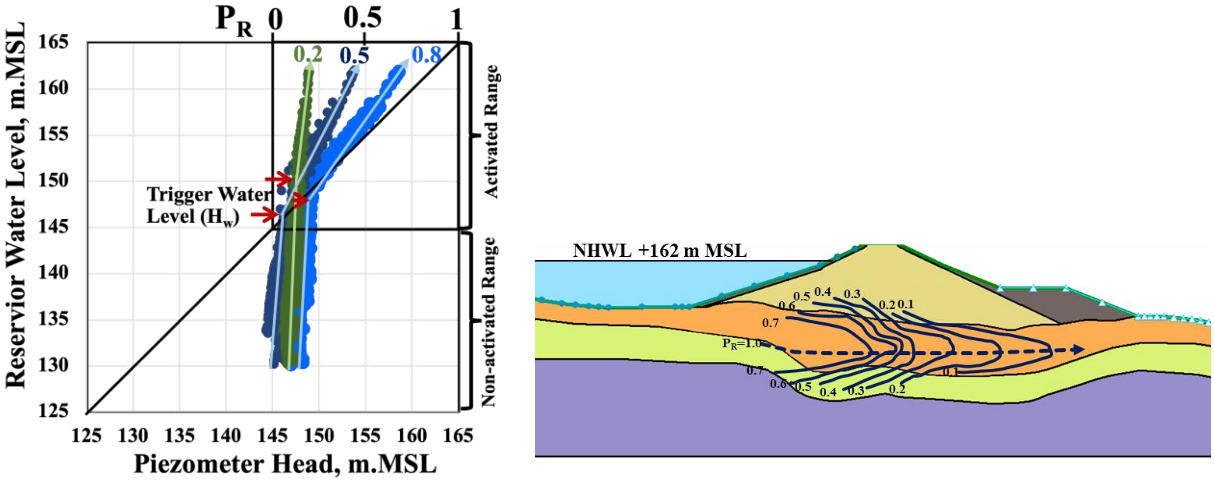


a) Travelling time of seepage flow b) Basic time lag on piezometer reading

Figure 1. Piezometer Time Lag [3, 31, 48]

The two components of time lag in Figure 1-a are: 1) "traveling time", which is the time for the pressure change in the reservoir to travel to the area surrounding the piezometer tip; and 2) "activated time", which is the time for the water pressure change around the tip flow into the piezometer measuring system. The traveling time is dependent on the seepage distance and the soil permeability along the seepage path. The activated time lag is dependent on the intake area of the filter element and the volume of water required to flow in or out of the tip to register a pressure change.

The basic equations for the determination of time lag are based on Darcy's Law. Basic traveling and activated time lags for a standpipe piezometer, as shown in Figure 2, can be defined using Equations 1 and 2 [31].



(a) Determination of P_R (b) Pore pressure ratio distribution

Figure 2. Determination of Pore Pressure Ratio (P_R)

Refer to Figure 1 a), when change of pressure head in the reservoir happen, the flow starts to seep from upstream to the location of piezometer. According to the Darcy's law, the flow velocity can be written as

$$Flow\ velocity;\ V = ki \tag{1}$$

Seepage path along the flow line can be estimated by flow-net or FEM analysis as, L_S. Then the travelling seepage time for each dam and foundation material will be, L_S/ki. The summation of travelling time for every dam and foundation section will be;

$$T_{traveling} = \sum \frac{L_s}{k} \tag{2}$$

$$T_{activated} = \frac{V}{q} = \frac{AH}{FkH} = \frac{A}{Fk} \tag{3}$$

where L_s is the seepage length, k is the soil permeability of each soil, F is a factor which depends on the shape and dimensions of the filter, and A is the cross-sectional area of the standpipe. A long seepage length result in a long traveling time, while the activated time is very short for the new version of piezometer so that for simplification, $T_{activated}$ can be ignored.

2.2. Pore Pressure Ratio

Pore pressure ratio, or P_R is the proportion of the piezometer head to the reservoir water level (RWL). It reflects the remaining total head after head loss along the seepage path. If P_R = 1, then water can easily seep through the cracks or erosion channel to the piezometer tip without any head loss. The pore pressure ratio can increase with time as internal erosion progresses [34, 41, 44]. P_R can be calculated based on the slopes of the plots between the piezometer reading and the rising reservoir water level, as shown in Figure 2-a. [40]. The contour of P_R to indicate the possible route of seepage from upstream to downstream is shown in Figure 2-b.

2.3. Study Dam

The study dam is a saddle dam in a large hydropower project that was constructed during 1968 to 1972. The dam was placed directly on stripping ground with practically no foundation treatment. The upstream residual soil was assumed to act as a natural blanket. The crest elevation and maximum dam height were 168 and 30 m MSL, respectively. The geology of the dam consisted of quite complex metamorphic rocks. The intrusion of nearby igneous rocks had created lateral tectonic forces, resulting in rock foliation, as shown in Figure 3. The foliation structures were aligned in a northeast-southwest direction and almost perpendicular to the dam axis. The dam foundation consisted of residual soil, phyllite, and quartz schist [41, 49]. The longitudinal profile along the dam axis using boreholes and field investigation is illustrated in Figure 4. The current study compiles geological information from previous investigations, outcrop inspection and mapping, regional geology, and a core log.

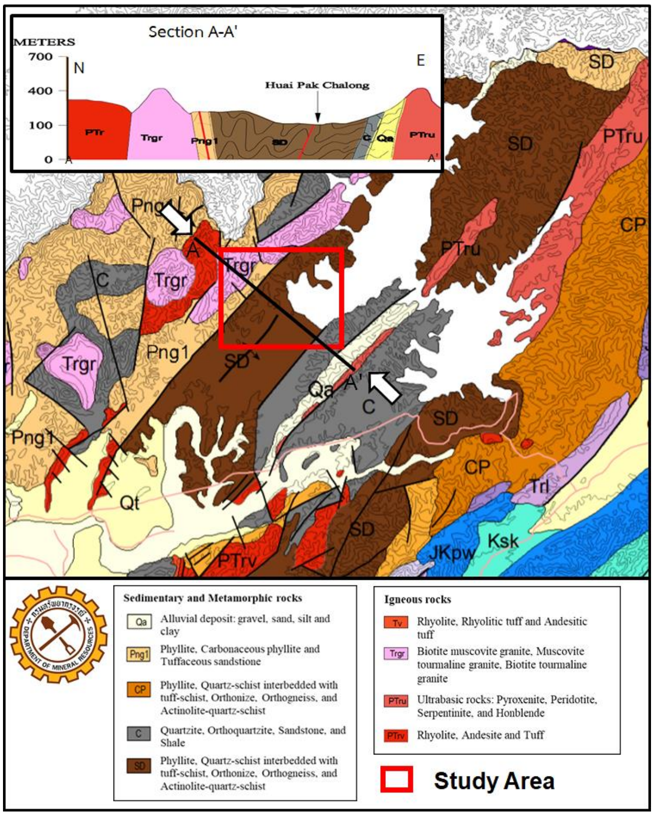


Figure 3. Geology of case study area [43]

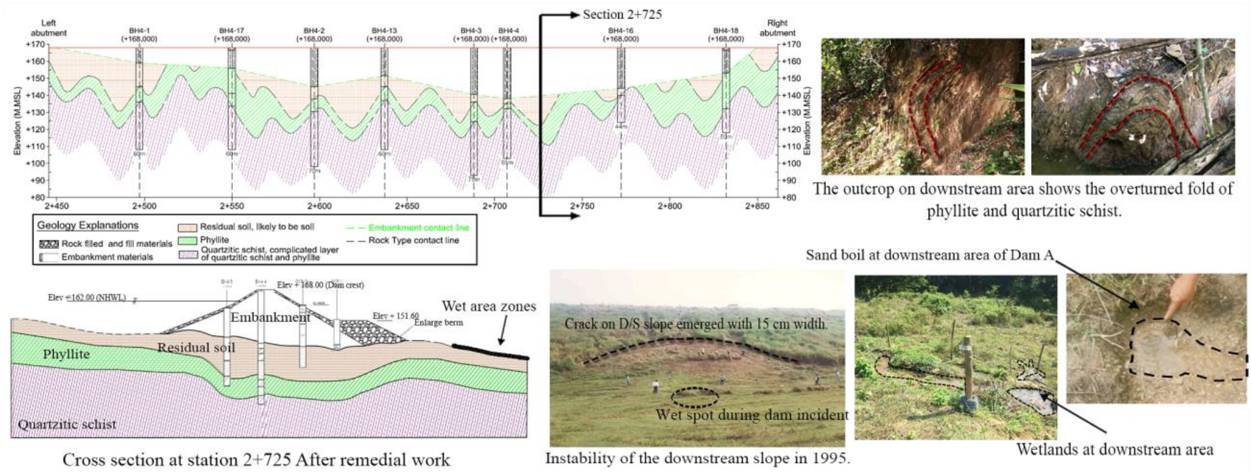


Figure 4. Geotechnical investigations, geological profiles, and dam incidents for study dam [43]

The previous FEM analyses of stresses, rock crack opening, and possible hydraulic fracturing (HF) indicated that HF might occur on the lower ridge of the syncline rock [43]. This HF can encourage the internal erosion from US to DS of the dam when foliation axes were aligned almost perpendicularly to the dam axis. [33, 49]. The typical cross section at sta. 2+700 were considered as the deepest foliation, as indicated in Figure 5.

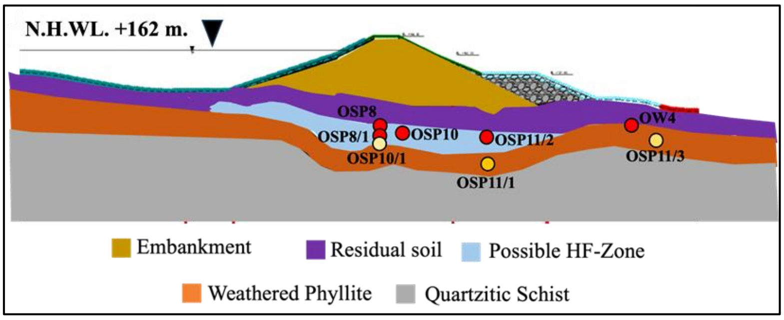


Figure 5. Location of piezometer installed in cross section at station 2+700

3. Methodology

The sequences of the study can be illustrated by the flowchart given on Figure 6. Starting with the acquisition of piezometer reading until the summarized of possible HF and internal erosion from T_L, P_R and H_W.

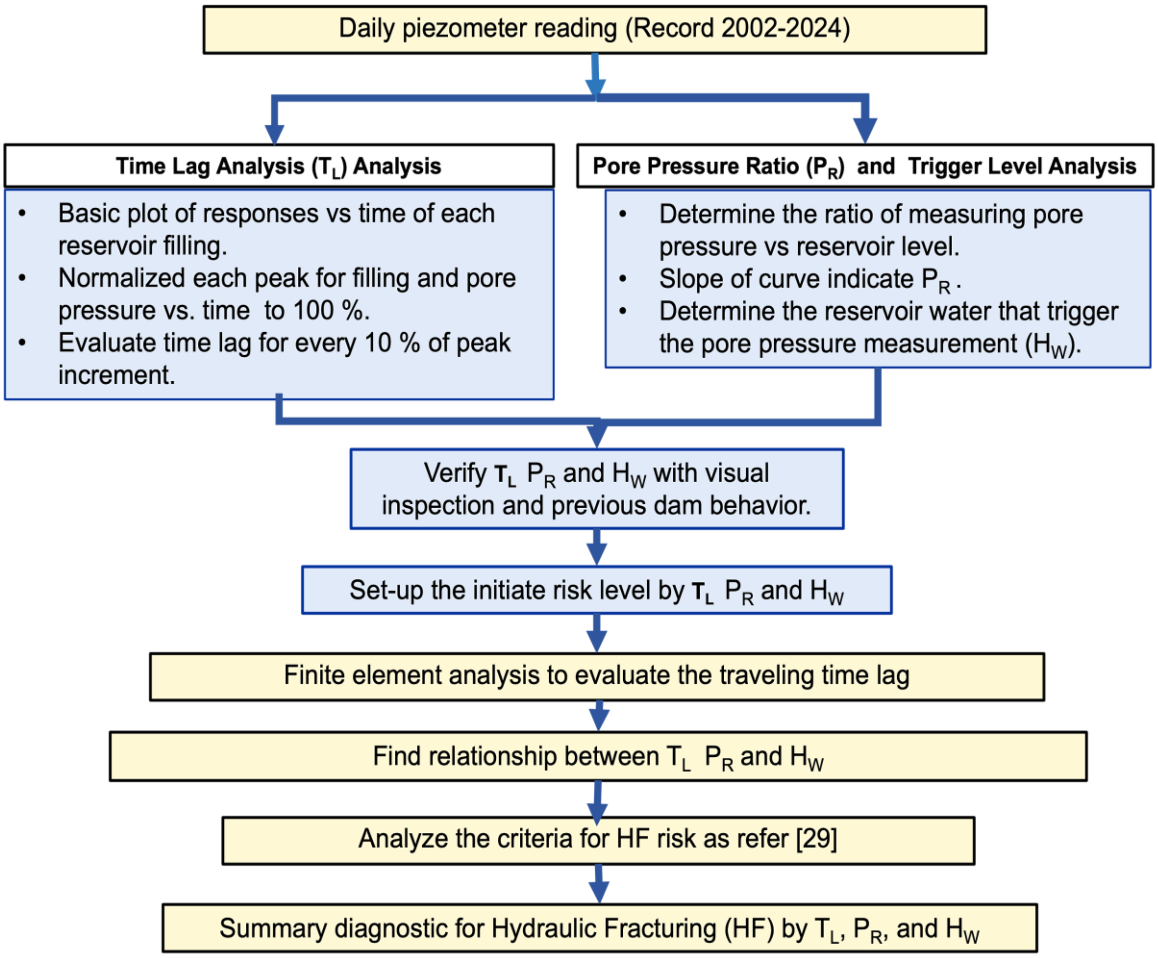
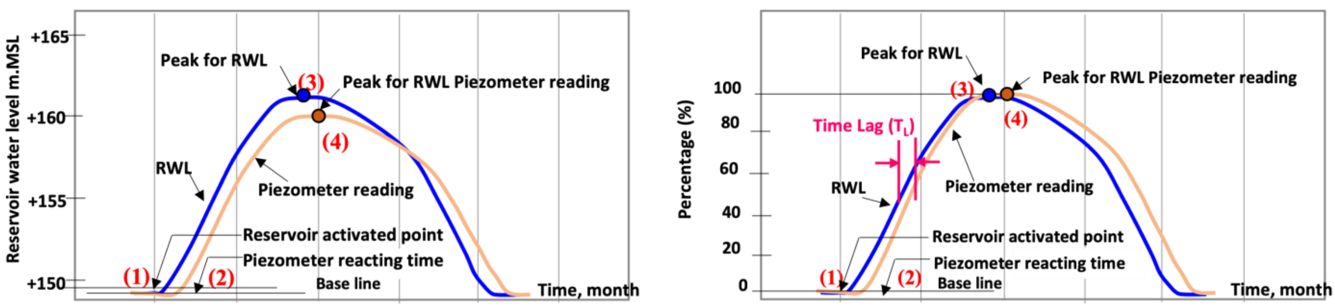


Figure 6. Flow Chart of the Study

3.1. Time Lag Evaluation

The RWL and piezometer response for every peak flood are plotted in Figure 7-a. From the initial time at which the reservoir level rising or falling, the piezometers response at delay time (time lag). When RWL reached the peak pressure first, and the piezometer records the peak later at the lower pressure. The two graphs were normalized by assigning both peaks as 100% of the pressure increment. Then every level of 10% increments of both graphs is evaluated time lag (T_L) as shown in Figure 7-b.



(a) Piezometer response

(b) Normalized piezometer response

Figure 7. Time lag evaluation

3.2. Analysis of Pore Pressure Ratio

P_R was calculated as the ratio of the piezometer level to RWL. A statistical trend line was fitted to each part of graph based on regression equations. The slope of the linear fit after the trigger point (Hw) is P_R, as shown in Figure 8.

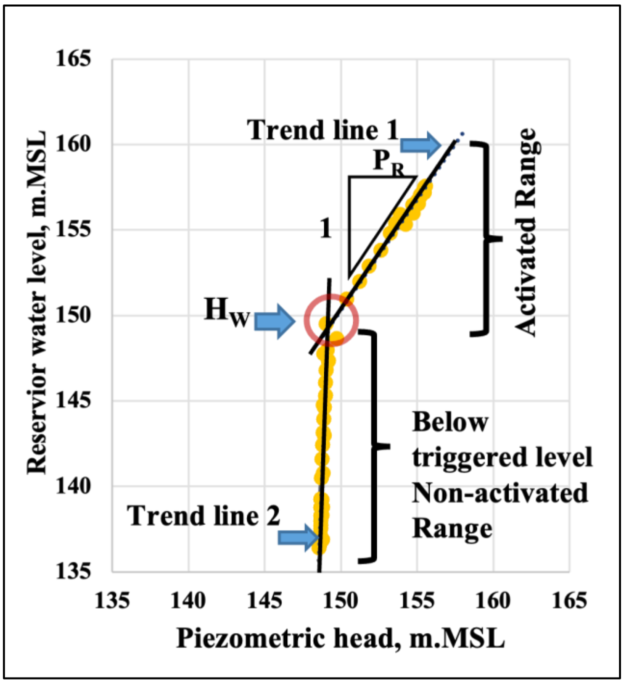


Figure 8. Pore pressure ratio evaluation

Then, decision rules from monitoring data can be applied according to the previous study by [42-44]. These rules can serve as partial decision factors for risk assessment of internal erosion and HF for the foundation of an earthen dam. However, an existing dam with sufficient piezometer readings and T_L, P_R, and H_W data can be initially evaluated for internal erosion and HF.

4. Results and Discussion

4.1. Time Lag Versus Internal Erosion

Several piezometers were installed in the dam foundation on critical cross sections from 2002. The time lags (T_L) in the residual soil above the phyllite layer are shown in Figures 9 and 10. The results from 2003 to 2024 indicated the progression of erosion as T_L gradually decreased, which could be divided into three periods: 2003–2008, 2008–2013, and 2013–2024. The maximum T_L of OSP10 at the offset distance 15 m. to the downstream area provides a good example—it decreased from 50 to 20 to 0 days for periods 1–3 respectively. These values indicated that rock/soil cracks had gradually opened up, resulting in high permeability and possible internal erosion. In addition, in the area below the dam axis the T_L values of OSP8 and 8/1 indicated very shorter time lags of less than 10 days. The erosion in this area toward upstream might have occurred before the first installation of piezometers.

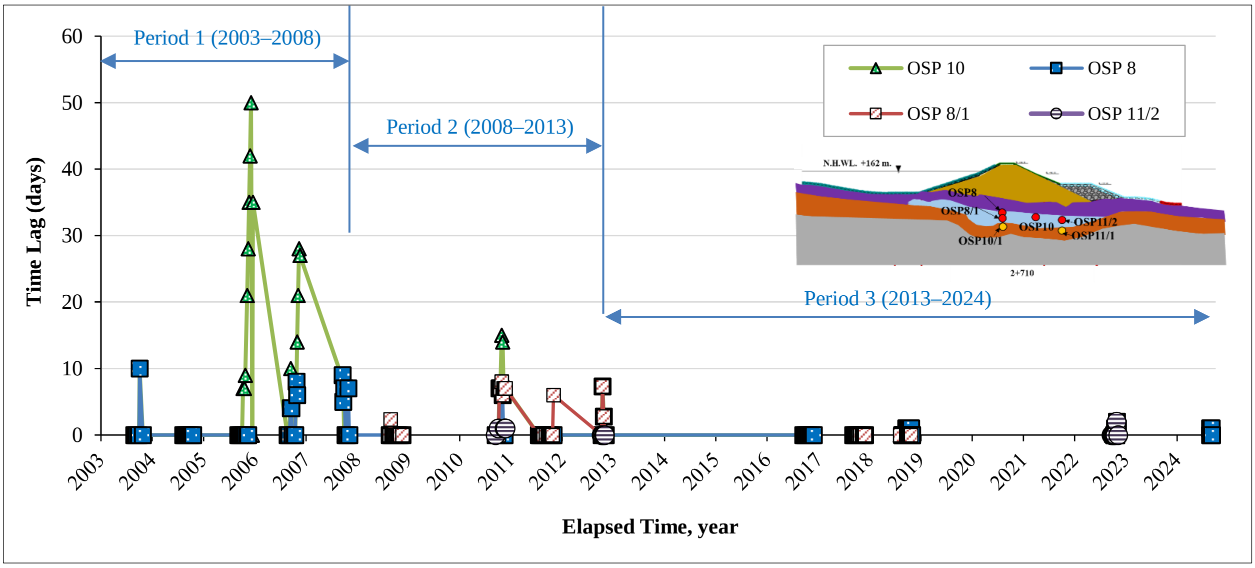
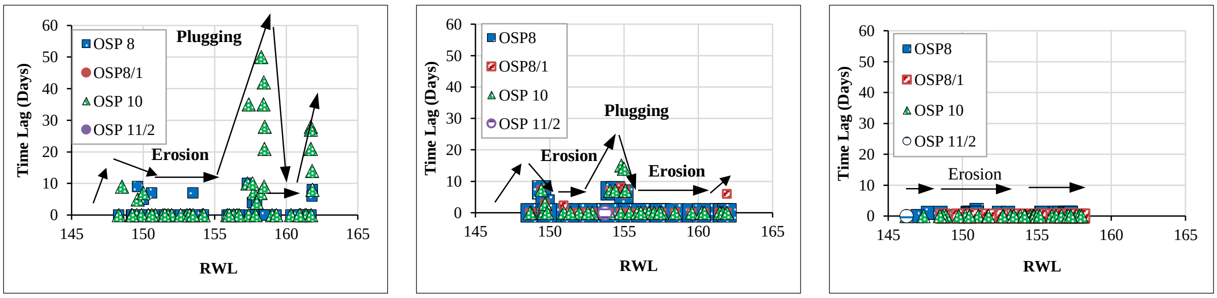


Figure 9. Time Lag Decreasing in Residual Soil



a) Period 1 (2003–2008) b) Period 2 (2008–2013) c) Period 3 (2013–2024)

Figure 10. Time lag versus RWL in residual soil

The potential for erosion and plugging was detected along the seepage paths in the residual soil layer, as shown in Figure 10. The first period of erosion and plugging behavior is shown in Figure10-a. Especially, on OSP10 at the offset distance 15 m. to downstream, there was plugging as T_L increased up to 50 days. Then, during the second period (Figure 10-b), the maximum T_L reduced from 50 to 14 days. Finally, in the third period, T_L was nearly 0 days, with no sign of the plugging area (Figure10-c). These results indicated that soil cleavages could open with increasing seepage pressure, known as "hydraulic fracturing" (HF). Subsequently, internal erosion occurred through the seepage path. However, T_L in the phyllite layer (Figure 11) showed no decreasing trend related to internal erosion.

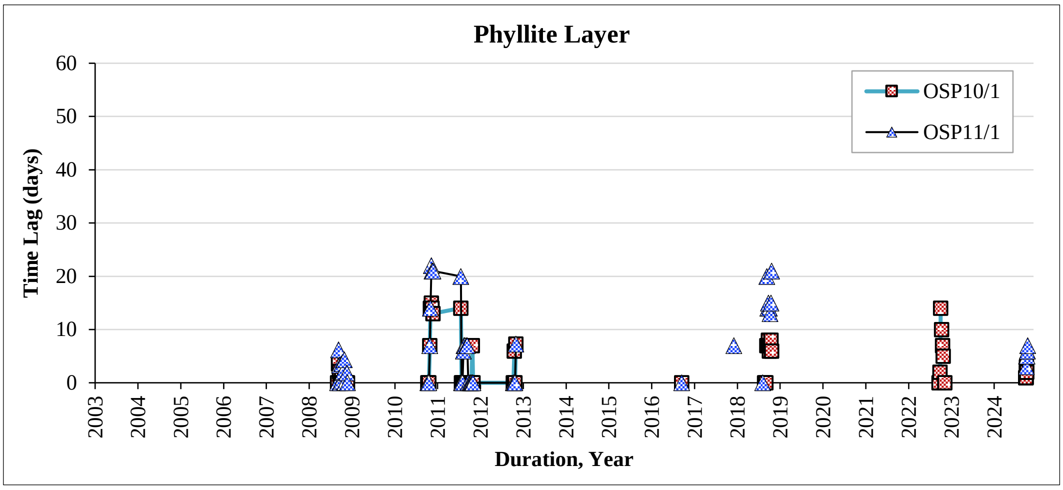
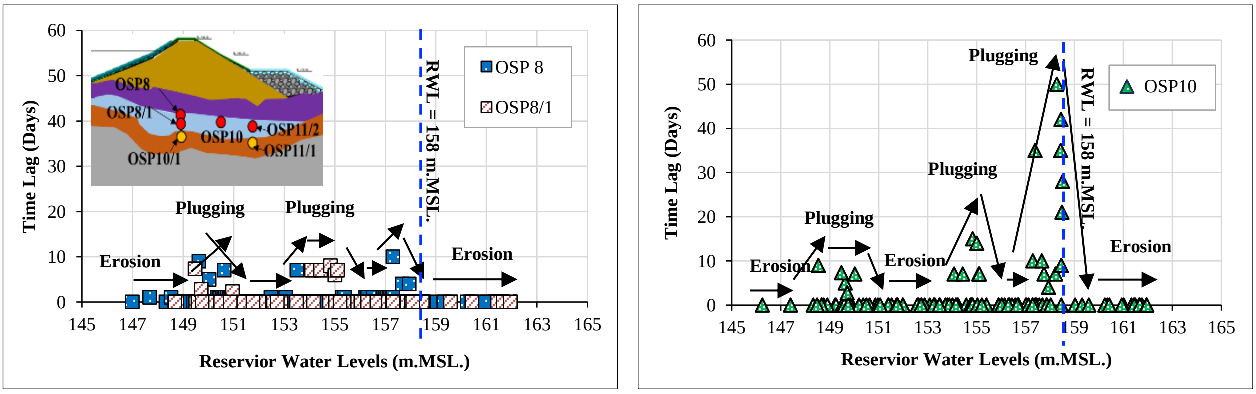


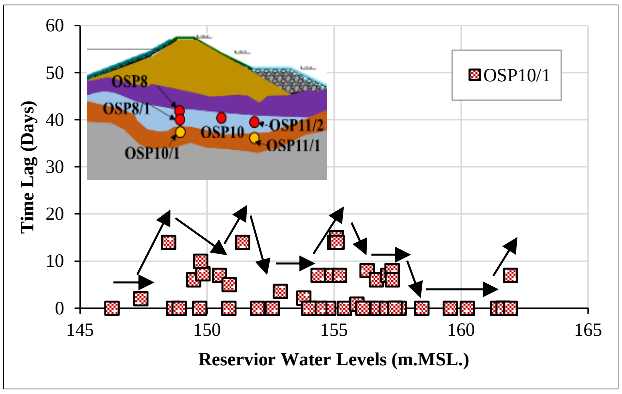
Figure 11. Time Lag Decreasing in Residual Soil

The T_L values at different locations fluctuated with the reservoir water level. Figure 12 shows the T_L values at OSP8, OSP8/1, and OSP10 in the residual soil. During the RWL increase from +148 to +162 m. MSL, T_L presented alternate high to low time lags, revealing the alternate plugging and erosion of the surrounding soil. These phenomena proceeded until all the crack filler material eroded out, resulting in a continuous increase in permeability. In the phyllite layer (Figure 13), because the permeability was higher than in the residual soil. A reduction in the time lag is not clearly shown, with the except on the lower part of the residual soil, where T_L is very low when RWL exceeds +158.5 m. MSL, indicating the erosion progression. At OSP 10/1 and OSP11/1, as shown in Figure13, there was no apparent internal erosion until the RWL increased to +160.0 m. MSL. These results agreed with [42, 43] who reported that the HF on a study dam started from the lower hinges of the residual soil in the syncline area.

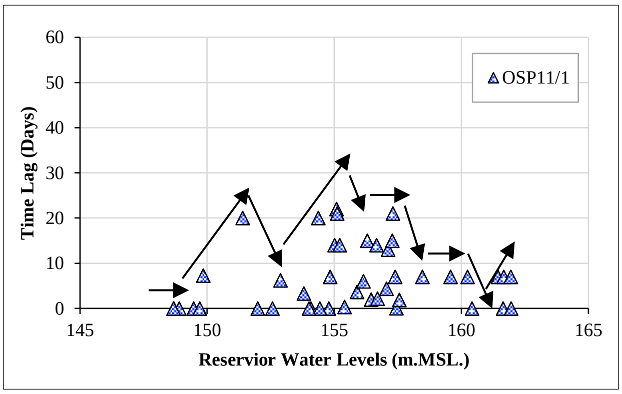


(a) OSP8 and OSP 8/1 installed in dam axis area (b) OSP 10 offset distance 15 m to downstream area

Figure 12. Time Lag Changes with Reservoir Water Levels in Residual Soil



(a) OSP8 and OSP 8/1 installed in dam axis area

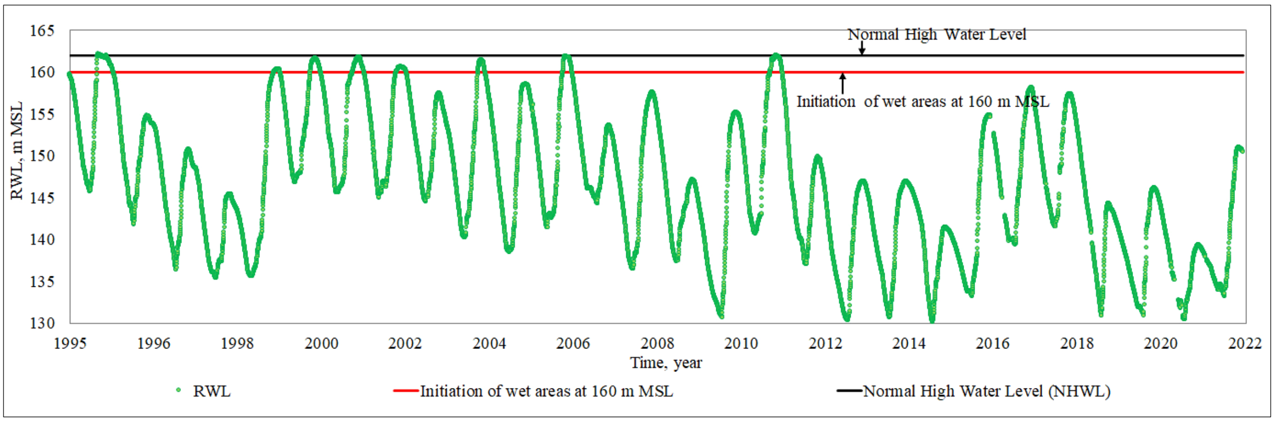


(b) OSP 10 offset distance 15 m to downstream area

Figure 13. Time Lag Changes with Reservoir Water Levels in Phyllite

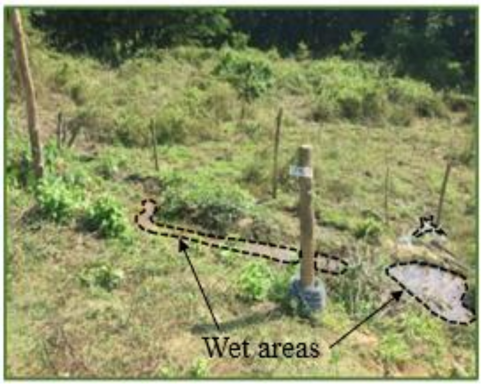
4.2. Time Lag Relate to The Actual Physical Progression of Erosion

T_L are directly related to the progression of internal erosion. Inadequately treated dam foundations can lead to HF, which increases seepage as pore pressure exceeds soil stress, causing cracks to open and flow increasing. This phenomenon is reflected by piezometric pressure increasing and shortening of T_L. Without erosion, as water level drops then cracks can be elastically closed by surrounding soil pressure. Then T_L remains high as shown in periods 1 and 2 of Figure 9. On the opposite, if cracks are opened by sustained pressure, the crack filler will be wash away. The cracks will be permanently opened. This causes continuous internal erosion and high permeability. Advanced erosion stage shows near-zero T_L, as in Figure 9, period 3. On Figure 12. when RWL exceeds +158 meters, T_L reaches zero values. The rock cracks are fully opened and allowing water to infiltrate easily. As RWL reaching +160 m. MSL, the wet areas are visible as shown in Figure 14. This is agreed with the evidence of high pressure on 4 m. extended standpipe as shown in Figure 15.



(a) Relationship of initiation of wet areas and reservoir water level with time

b) wet Area at 1995



c) wet Area at 2021

Figure 14. Wet areas appearing when the RWL above +160 m.MSL at different time intervals

Figure 15. The solving of measurement due to high water pressure at downstream area

FEM analysis by Kunsuwan et al. [43] and Nhu et al. [43, 24] reveals that HF begins when the water level reaches +148 m.MSL, initially occurring at narrow area. As the water level rises, the number of affected points and the area expand, with HF spreading significantly above +160 m.MSL. This behavior contributes to the appearance of seepage (wet areas) in downstream areas.

4.3. Pore Pressure Ratio Versus Internal Erosion

Figure 16 shows a plot of P_R in the foundation layer. The highest P_R values were located mostly on the upstream and lower parts of the residual soil. The pressures had no impact until reaching the trigger level of +148 to +149 m. MSL. The high range for P_R was 0.95–0.70, indicating. These indicated hydraulic fracturing and internal erosion phenomena. In the phyllite layer at a distance of 45 m. from the dam axis to downstream, the P_R values were lower (0.50–0.15), which are considered as normal seepage, compared to the analyses reported by Chalermpornchai et al. [42].

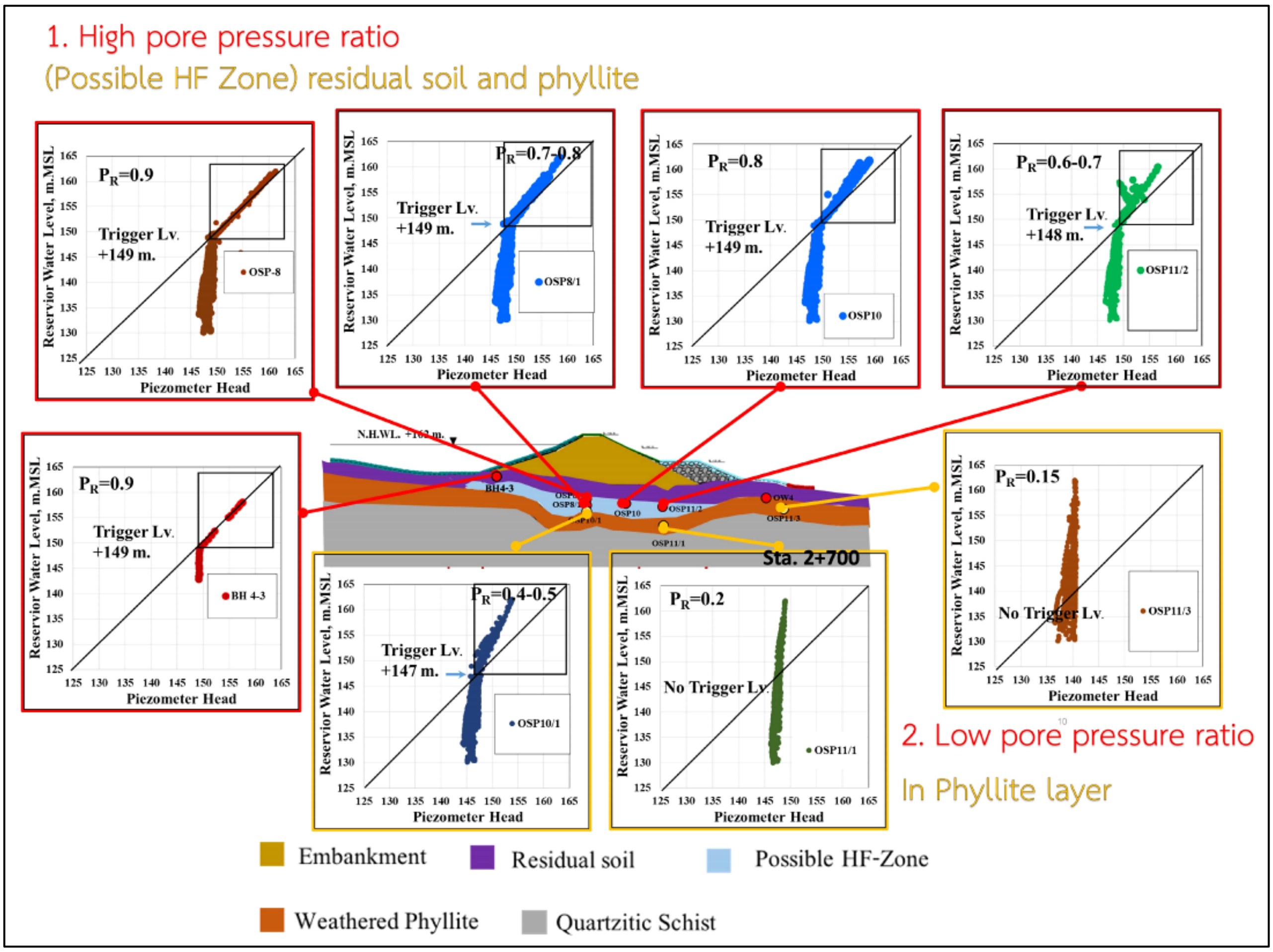


Figure 16. Pore Pressure Ratios for Study Dam [44]

This article continues the study using the data from Saejiaw et al. [44], who proposed risk levels of internal erosion using P_R, by supplementing the P_R data obtained from piezometer measurements up to 2024., as shown in Figure 17. The contour maps of estimated internal erosion indicated by P_R levels show the progression with time in Figure 18.

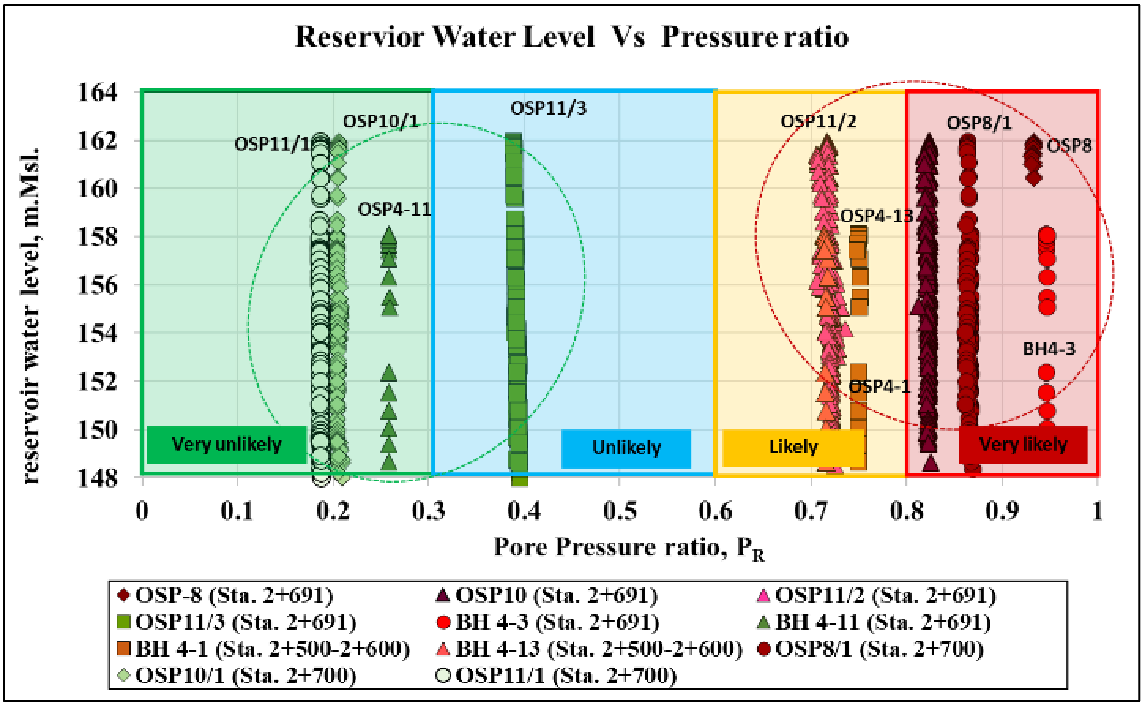
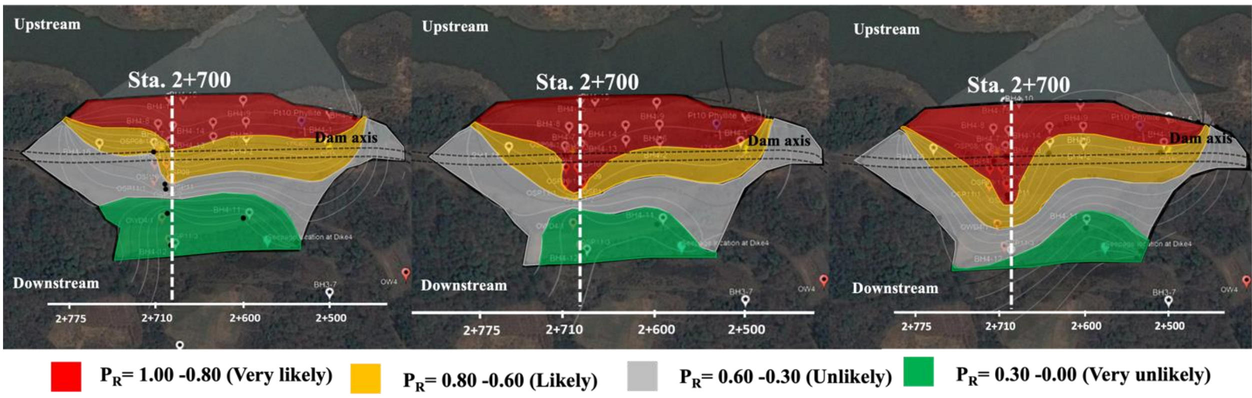


Figure 17. Risk Levels of Internal Erosion Classified Using P_R modified from [44]



a) Period 1 (2003-2008). b) Period 2 (2008-2013) c) Period 3 (2013-2024)

Figure 18. Progression of Hydraulic Fracturing Area 2003–2024

During the first monitoring period from 2003 to 2024, the level of internal erosion of the very likely (red-shaded) area located upstream to about the dam axis is shown in Figure 18-a. The advancement proceeded to the downstream area during the second and third periods (Figures 18-b and 18-c). The greatest increase in HF was at Sta. 2+700, where the rock fractures gradually opened and erosion developed along this path, which corresponded to the old stream channel. In addition, the field observations showed that the downstream area at sta.2+650 to 2+700 had wet areas when the reservoir level rose above 160 m. MSL. This result was in agreement with the use of ground aeration sound, showing the possibility of a high seepage flow zone.

The trend in internal erosion can be observed in Figure 19. Piezometer OSP8 had P_R values in the range 0.9–1.0 from 2003 to 2024. Seepage from upstream to the dam axis had almost no head loss. The P_R values at OSP 8/1 and OSP 10 from 2003 to 2024 increased from 0.7 to 0.8 (OSP 8/1) and from 0.6 to 0.8 (OSP 10). In contrast, at OSP11/2 located near downstream, the P_R value remained constant at 0.6, indicating no erosion. Soil particles could migrate from the upstream area to downstream and at the curtain distance in the downstream area, resulting in plugging and self-filtering. This blocking area was temporary and tended to move downstream as time increasing.

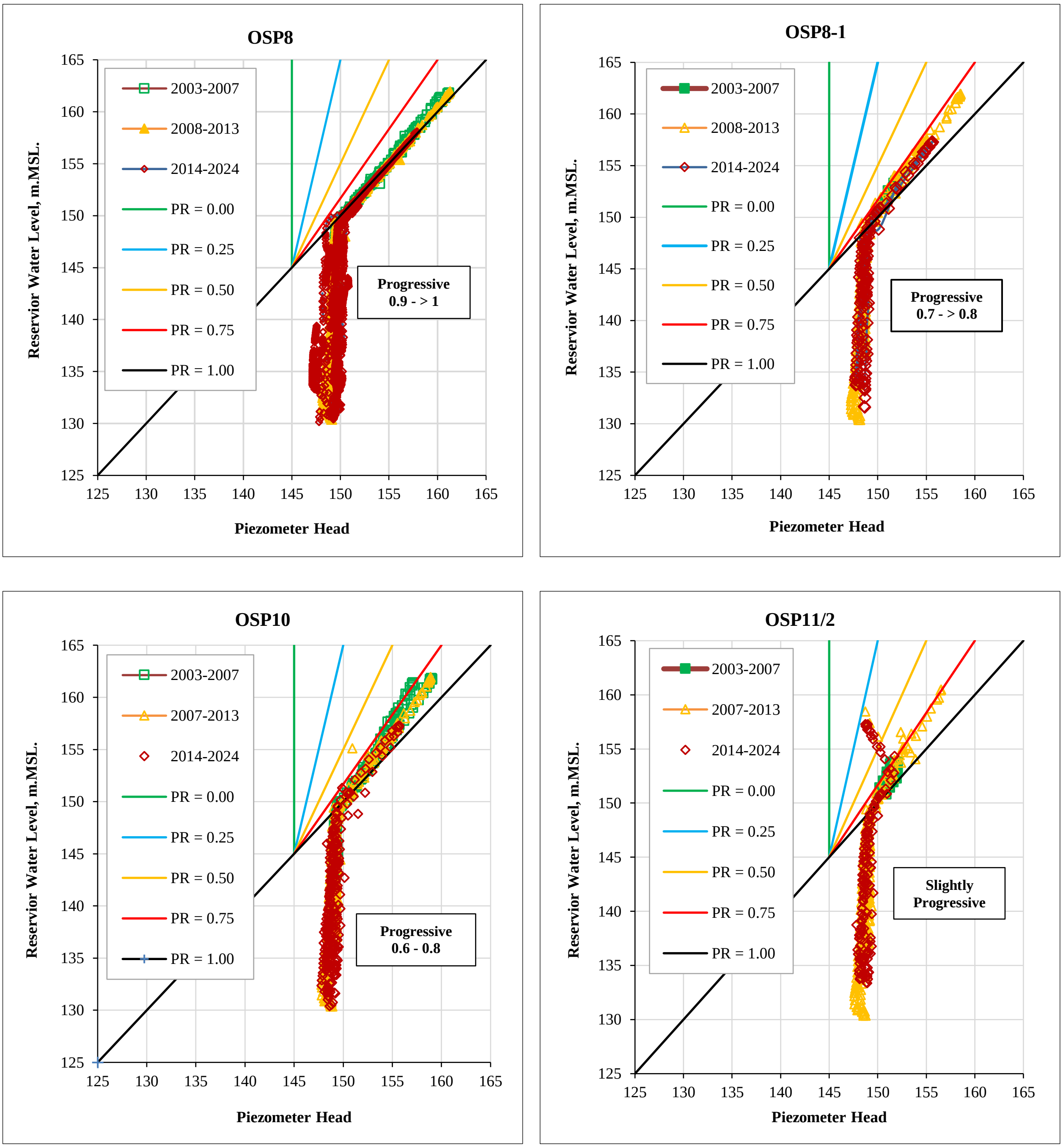
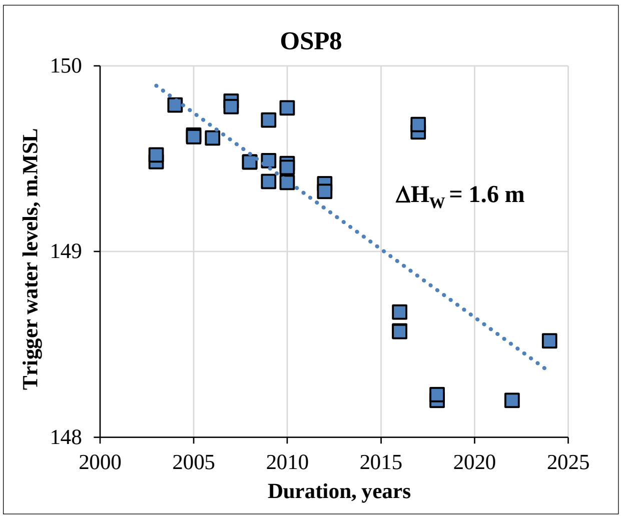


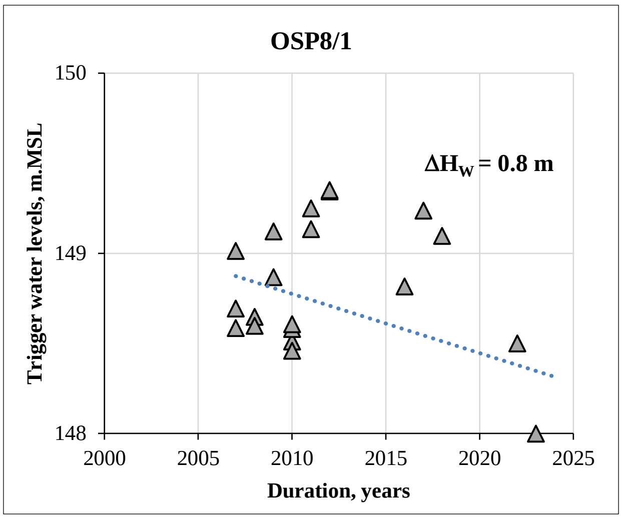
Figure 19. Progression of Pore Pressure Ratio 2003–2024

4.4. Triggered Water Levels Versus Internal Erosion

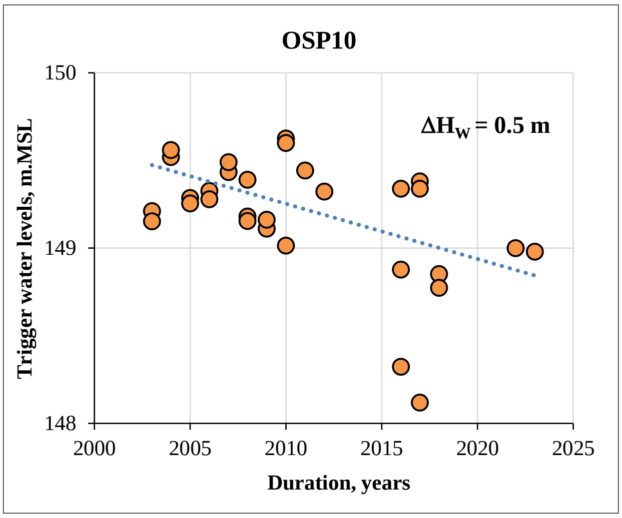
Linear regression was used to evaluate the yearly triggered water levels (H_W). In general, the piezometer readings showed triggered levels at 148.00–150.00 m. MSL, as shown in Figure 20. The H_W values from the dam axis to about 45 m downstream presented a decreasing trend with time, as shown in Figures 21 and 22. The decreasing of ΔH_w = 1.6 m, 0.8 m, 0.5m, and 0.2m for OSP8, OSP8/1, OSP10, and OSP11/2, from 2003 to 2024 respectively. The H_w of the piezometers located in the phyllite (Figure 22) did not decrease with time, indicating less erosion in the phyllite. OSP 8 show the highest decreasing of trigger level about 1.6 m., as shown on Figure 20-a.



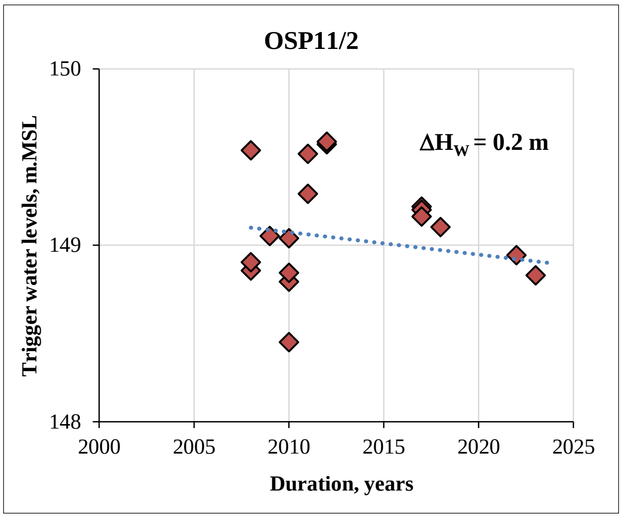
(a) Triggered water levels at OSP 8



(b) Triggered water levels at OSP 8/1

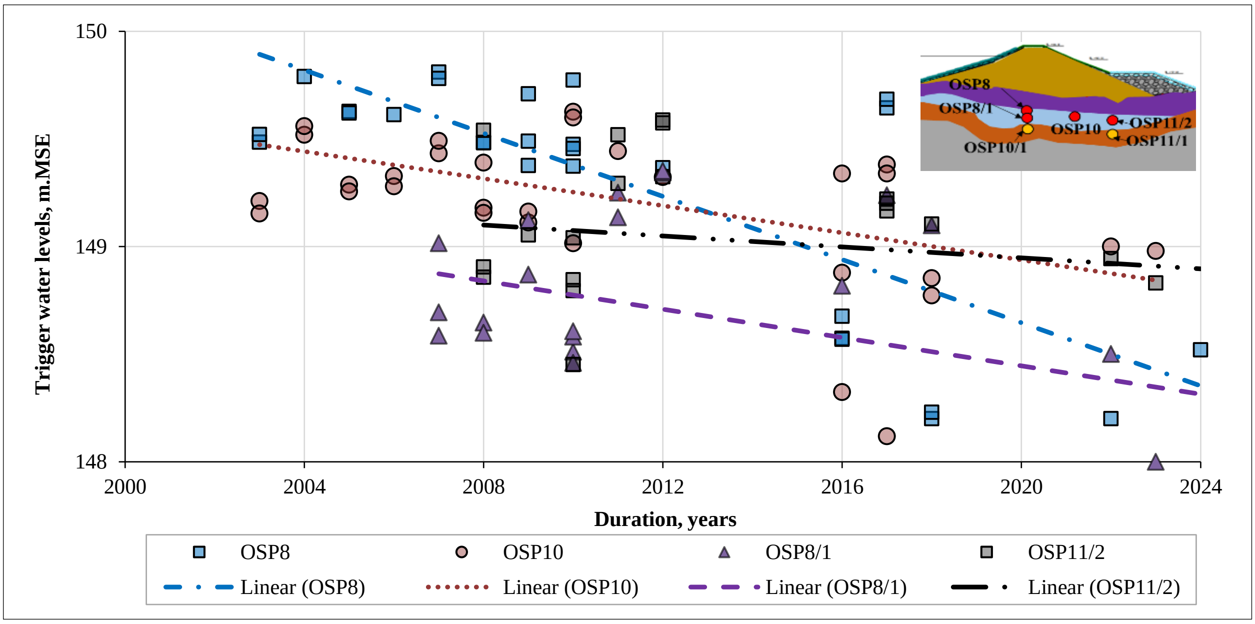


(c) Triggered water levels at OSP 10



(d) Triggered water levels at OSP 11/2

Figure 20. Triggered Water Levels in Residual Soil



The decreasing of triggered water levels (ΔH_W)	OSP8	OSP8/1	OSP10	OSP11/2
	1.6 m	0.8 m	0.5 m	0.3 m

Figure 21. Trend Lines of Trigger Water Level in Residual Soil from 2003 to 2024

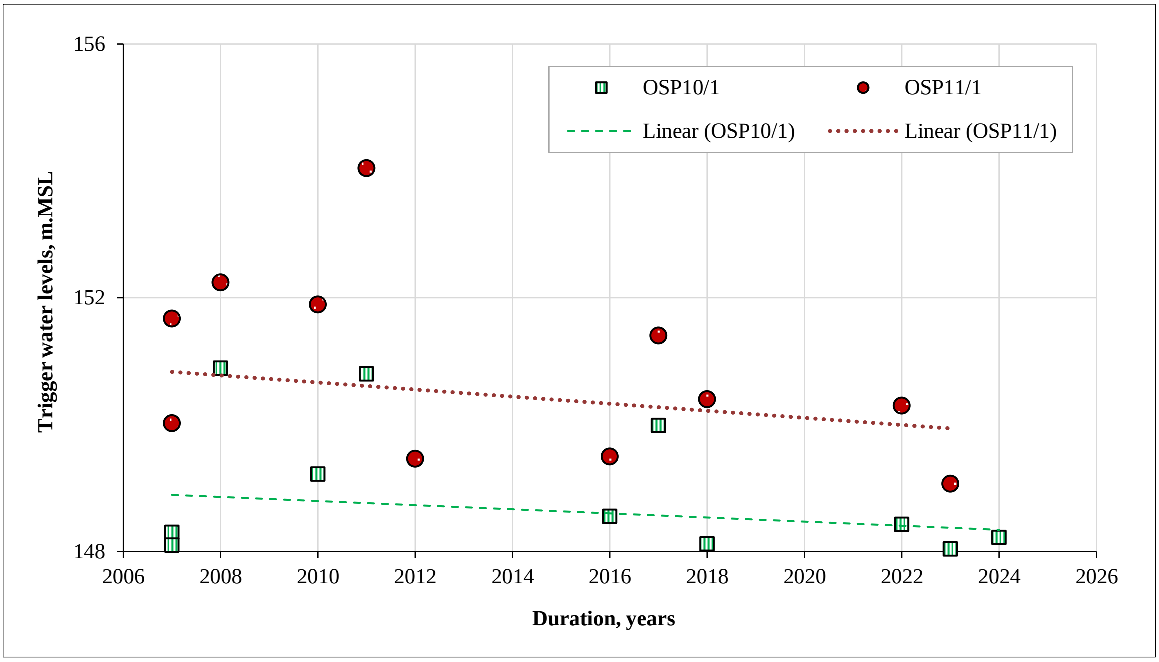


Figure 22. Trend Line of Trigger Water Levels (HW) in Phyllite from 2007 to 2024

For this study, changes of H_W can be in cooperated as criteria for HF occurrence. Four levels of HF are suggested as: H_W decreasing: >1 m. (very likely), 0.25–1 m. (likely), <0.25 m. (unlikely), and constant (very unlikely).

The relationship between H_W and P_R is presented in Figure 23. The residual soil layer had more seepage problem than the phyllite layer, since it had a lower H_W with a higher P_R. In the residual soil, the range in H_W was from +148 to +150 m. MSL. with a P_R range from 0.7 to 1.0, whereas in the phyllite layer, H_W is the range from 149 to +156 m. MSL, with low P_R values in the range from 0.2 to 0.6.

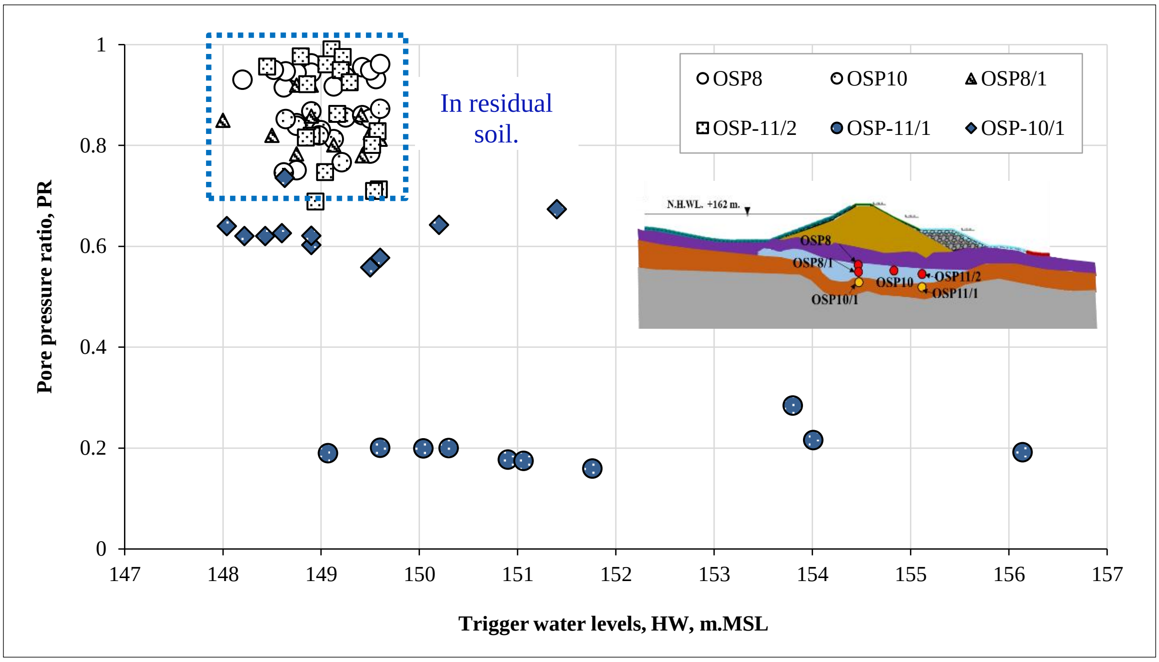


Figure 23. Relationship of Pore Pressure Ratio (PR) and Trigger Water Levels (HW) in Dam Foundation

4.5. Criteria for Internal Erosion

The criteria are considered FEM for normal seepage without internal erosion as references for T_L and P_R. The results are shown in Figure 24, where the average T_L piezometer value near the dam axis was 100 days and the P_R values were in the range 0.53–0.62. When comparing to the records between 2003 and 2024, T_L are 0 to 55 days much lower than FEM. And P_R are between 0.73–1.00 higher than the references. Those are indicated the internal erosion occurrence.

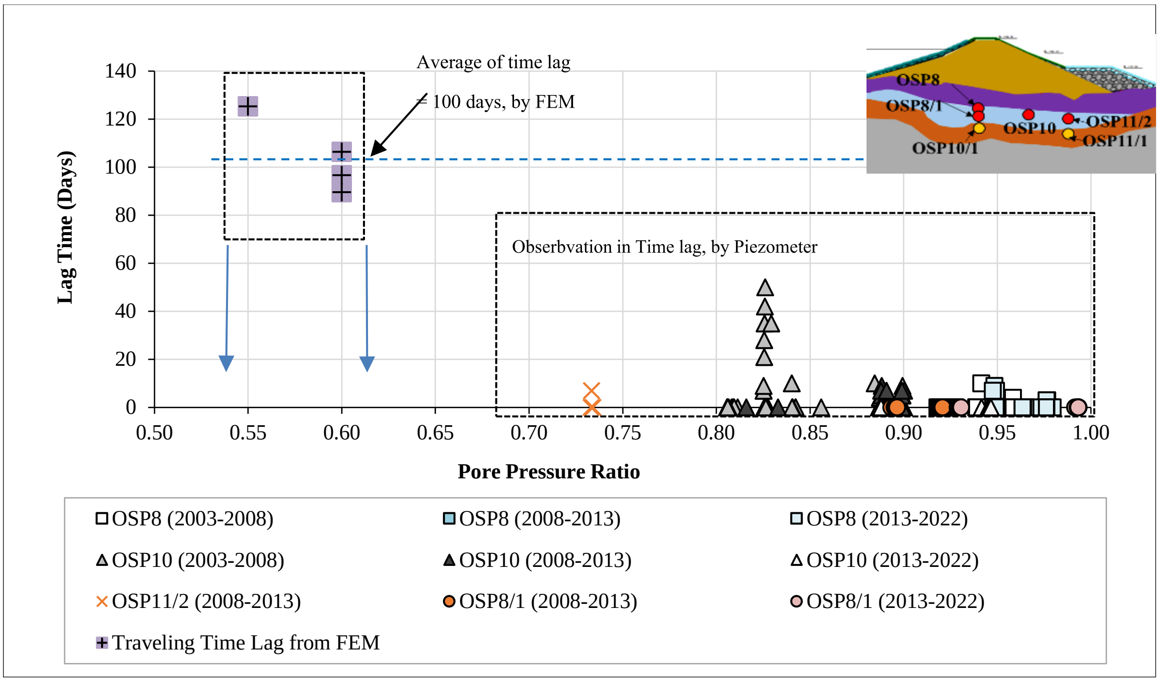


Figure 24. Comparison of TL from FEM Analyses with TL from Monitoring Data

The changes of T_L and P_R are plotted in Figure 25. The risk levels for HF occurrence were proposed for the very likely, likely, unlikely, and very unlikely scenarios, according to Saejiaw et al. [44]. The risk criteria are presented in Table 1, classified according to the three main indicators (P_R, T_L, and H_W).

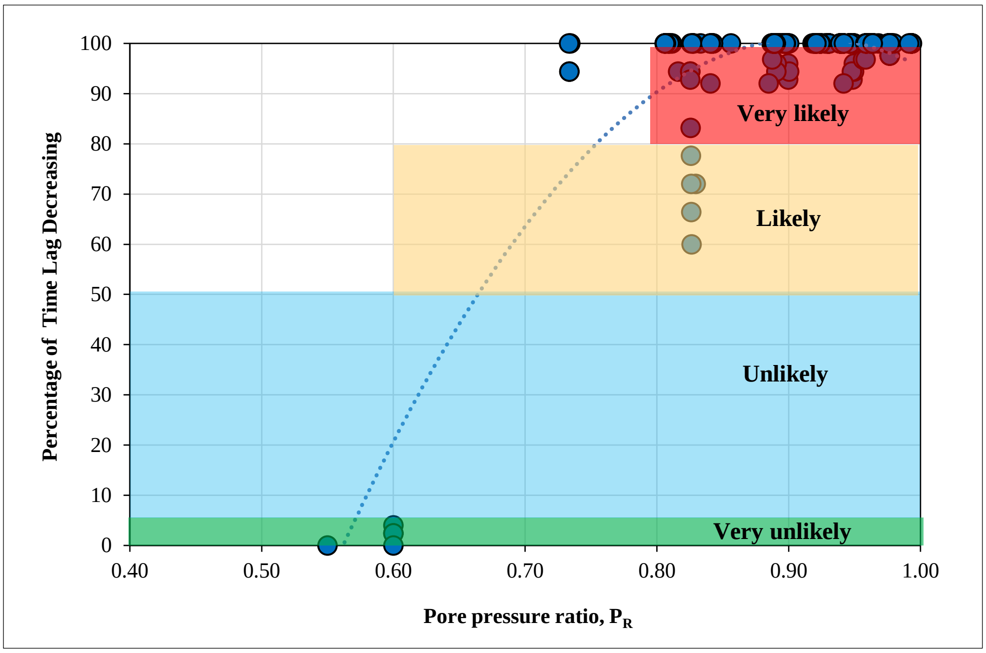


Figure 25. Normalization of TL Data Based on Regression Equation

Table 1. T_L, P_R, H_W criteria for HF risk assessment

Risk Level	P_R [44]	T_L^* Decreasing	H_W^{**} Increasing
Very unlikely	0.0–0.3	< 5%	Constant
Unlikely	0.3–0.6	5–50%	<0.25 m.
Likely	0.6–0.8	50–80%	0.25–1 m.
Very likely	0.8–1.0	>80%	>1 m

Note: T_L^* is percentage decrease from analytical or first reading after construction. H_W^{**} is head decrease from first reading after construction. The values are applied from study case only.

The criteria in Table 1 can be used to construct a decision tree for an expert system, which would benefit for dam owner in monitoring a large number of dams. The decision tree could also combine with the dam database for the evaluation of internal erosion risk of each dam.

4.6. Limitations of Proposed Internal Erosion Criteria for Long-Tern Monitoring

The internal erosion criteria as monitoring by time lag, pore pressure ratio and reservoir trigger level (T_L, P_R, H_W). It is the newly proposed approach to evaluate the internal erosion risk level for embankment dams. The risk levels of this study are based on 21 years of previous piezometer records from the study dam. They are intended to be the guide line for other dam that might face the same problem. However, the limitations of proposed criteria are still existed as follows.

a) Curtain period of past piezometer and reservoir water level records is required (more than 10 years).

b) Reasonable sufficient geology data should be available.

c) Past dam field investigations and records of dam incident would be the good verification of the criteria.

d) Numerical seepage analyses may be needed to cross checking with the criteria.

e) Each dam will have the individual characteristic of seepage behavior depending on the physical dimension of dam, dam zoning, foundation geology etc. Then the criteria should be set and verify according those factors.

Mainly, the criteria are suitable of existing dam during operation with the sufficient past record. In case of the future dam during design stage, the criteria might give the idea for the designer to plans for seepage instrumentation location, the data collection, the interpretation of data.

4.7. Risk Reduction of Study Dam

After the evidences lead to possible HF and internal erosion of the study dam. More detail geological investigation was done and analyses and designs for the rehabilitation were commenced during 2020. Then the construction of slurry cut-off wall was start on 2023. The design based on the grab and hydromill excavators from the dam crest to the maximum depth of 73 m. The cut-off wall passed through embankment, residual soil, highly weathered phyllite, and rest on the moderately quarzitic schist. The backfill material is the plastic concrete of less than 1×10^{-7} cm/sec. The profile along dam axis is shown on Figure 26. The required seepage reduction was set at 75 % of the original estimation. The construction will provide new 20 piezometers, 3 seepage measuring weirs in addition to the existing monitoring instruments the long-term seepage behavior.

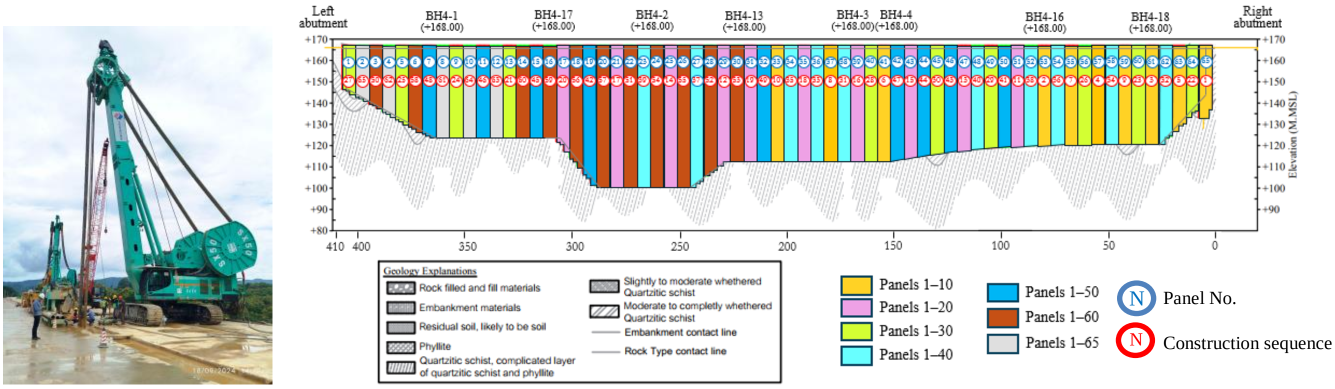


Figure 26. Construction plan along longitudinal section of cutoff wall

5. Conclusions

Based on this study, the following conclusions can be drawn:

- Dam piezometer readings can be used for interpretation of potential for internal erosion and hydraulic fracturing. Three parameters from piezometer readings were analyzed: time lag (T_L), pore pressure ratio (P_R), and reservoir trigger level (H_W).
- The study dam was a saddle dam of a large hydropower project and was constructed during 1968–1972. After 22 years of operation, the dam experienced a sliding mass above the dam toe with high pressure and wet areas. During this period, no piezometer was installed and no record of pore pressure in the dam.
- After emergency repairs using a downstream rock berm, piezometers were installed to monitor the pressure in the dam foundation. High pressure readings were observed in the lower part of the residual soil just above the underlying phyllite.

- The time lag (T_L) behavior could be divided into three periods. During the first period from 2003 to 2008, T_L values remained high (up to 50 days). During the second period from 2008 to 2013, the T_L values reduced substantially to less than 12 days. During the third period from 2013 to 2024, the T_L values were close to 0 days, indicating that along the seepage path, the rock/soil cracks were continuously open, resulting in greater permeability and possible internal erosion.
- The T_L values at the different locations fluctuated with the reservoir water level, reflecting the potential of material erosion and plugging along the seepage paths.
- The pore pressure ratio (P_R) was very high in the residual soil from upstream to 15 m. downstream. There was a high range in the P_R values (0.7–0.95) compared to the FEM analytical range (0.5–0.6), indicating that the seepage resistance had reduced and internal erosion may be progressing.
- The expansion of the hydraulic fracturing zone plotted using P_R-contours showed advancement toward the downstream direction. The greatest advancement was close to the old buried stream channel at about Sta. 2+700.
- The values for the trigger water level (H_W) in the potential internal erosion risk zone tended to decrease with time. On risk zone of study dam the decreasing of 1.5 m. was founded.
- The time lag decrease (in days) using the analytical time lag versus the pore pressure ratio could be applied to establish the risk zones of internal erosion/hydraulic fracturing. This process indicated that the study dam shows likely to very likely hydraulic fracturing occurrence.
- T_L, P_R, and H_W can be compiled to provide HF risk criteria for decision tree. The decision tree could be applied in expert system for monitoring a group of dams. The dam owners who operate many dams can benefit by making real-time judgments of the risk each dam.

6. Declarations

6.1. Author Contributions

Conceptualization, W.M. and W.T.; methodology, W.M., B.K., and W.T.; software, M.J. and T.C.; validation, B.K., W.T., and W.M.; formal analysis, W.T.; writing—original draft preparation, B.K. and W.T.; writing—review and editing, W.T. and W.M.; visualization, T.C. and M.J.; supervision, W.T and B.K.; project administration, W.M.; funding acquisition, W.T and B.K. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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