Hydraulic Fracturing in Earth Dam Monitoring by Dam Instruments

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ABSTRACT: The long-term safety and performance of earth dams are critical concerns for dam owners and maintenance authorities. While many dams are constructed with monitoring instruments for dam monitoring and safety, the comprehensive analysis of the data collected over time remains limited. After several years of operation, data collection is often terminated, assuming that the dam has passed its critical phase and safe. Most of the failures of earth dams are accounted for by internal erosion as the highest cause of geotechnical failures. Hydraulic fracturing (HF) is one of a phenomenon of internal erosion that caused by water pressures exceeding the stresses within the soil or rock mass. It can initiate the internal erosion. Detection and quantification of HF occurrence are essential for dam safety screening and long-term management. This research investigates the potential of HF, using data from piezometer responses. The findings provide a Hydraulic Fracturing Index (HFI) that formulated to quantify the degree of HF in different areas of the dam. This contributes to the understanding of HF behavior in earth dams. Three parameters T_L, P_R, and H_w from piezometer reading are proposed to evaluate the potential of HF. Analyses of HFI and these parameters evaluate the indicative of internal erosion progression, with implications for dam safety. The concepts can also extend to incorporate with dam monitoring database for continuous report on HF potential in dam.

KEYWORDS: Hydraulic fracturing, internal erosion, dam monitoring, earth dams

1. INTRODUCTION

Many existing dams had been installed dam instrument mainly for dam safety reasons. But only a few dams had been seriously analysed the data for long term dam behaviours. Seepage monitoring is usually monitored by piezometers, observation wells, seepage flow meters on the critical area or dam cross section(s). After five years from the first impounding, many reading was terminated, presumably the dam had passed the critical period and safe. Detailed analysis of piezometer responses not only tells the routine safety precaution, but it can reflect the progression of internal erosion or hydraulic fracturing. Three crucial parameters are proposed that can quantify levels of hydraulic fracturing occurrence. This interpretation is benefit for the dam owners or dam maintenance office to apply for the existing dam database system. The continuous report of hydraulic fracturing or internal erosion can be achieved for dam safety screening and long-term management.

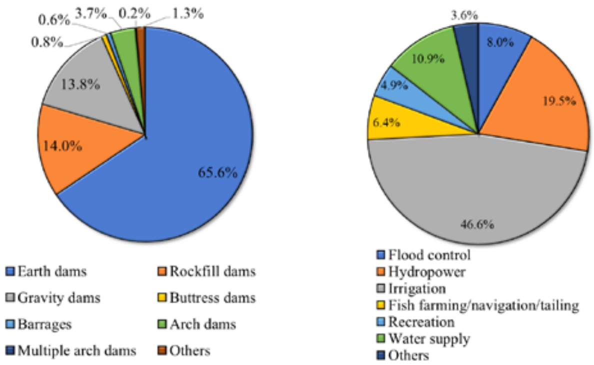
1.1 Failures of Earth Dams

Total number of registered dams according to ICOLD in 2020 are 61,988 dams around the world. China and USA are the leaders in number of dams of 24,089 and 10,158 dams respectively. The earth dams are accounted for about 67% of the total number of dams as indicated on Figure 1.

According to ICOLD incident database Bulletin 99 (ICOLD, 2019), statistical analysis of 311 dam failures by the continent has been reported as failed dams comparing to existing dams as given on Figure 2. Even though total numbers of existing dams are much more than the registered dam, but the overall ratio of dam failure reflects around 0.88 %. The failure ratio had the tendency to decrease from 2.20% before 1900 to 0.12% after 2000. This data is the reverse trend with the increased number of dams constructed from 1950 to 2000. The better performance results from the improving of investigation, design, construction, and maintenance techniques. It also due to the knowledge of dam engineering and risk management of dam projects.

The failure age of dam is other crucial factor for dam operation. During first 5 years of operation, the dams failed about 50% of total dam failures. On Figure 3 a) shows the distribution of dam failure on every period of ten years after construction. And the reducing every year of failure for the first 10 years is shown on Figure 3 b).

ICOLD (2020) reported that technical causes of dam failures could be from spillway capacity, geotechnical issues, hydro-mechanical issues, material ageing and structural issue. The geotechnical related cases are recorded to be the major causes of dam failures accounted for more than 58% as shown on Figure 4 a). The internal erosion is also contributed as the highest cause on geotechnical failures in earth-fill dam as shown on Figure 4b).



a) Dam Types b) Dam Purposes

Figure 1 Distribution of dams according to dam types and purposes reported by ICOLD (2020)

Continents	Existing dams	Failed dams	Ratio (%)
ASIA	11,335	56	0.49
NORTH AMERICA	11,118	130	1.17
EUROPE	7,713	61	0.79
AFRICA	2,330	30	1.29
SOUTH AMERICA	1,887	22	1.17
AUSTRALIA-ASIA	824	12	1.46
CENTRAL AMERICA	23	0	0.00
TOTAL	**35,230**	**311**	**0.88**

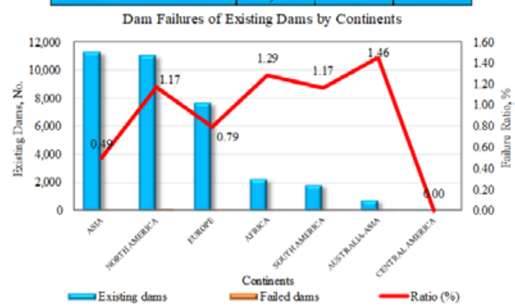
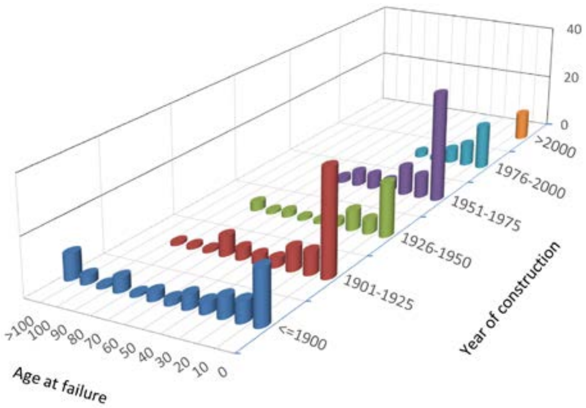


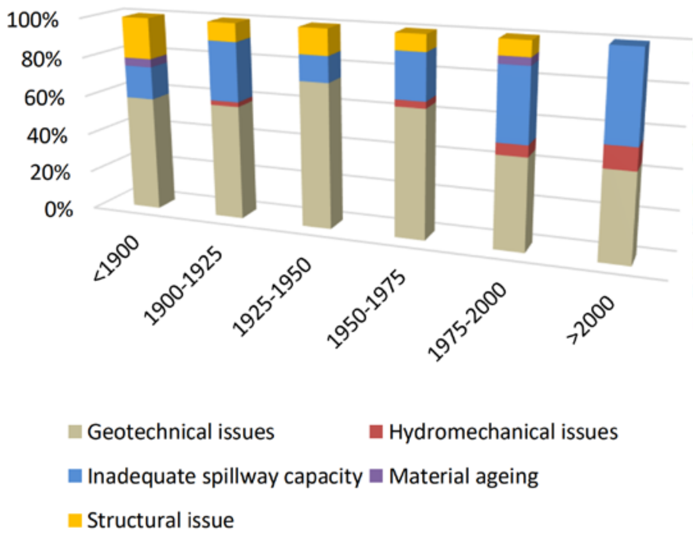
Figure 2 Ratio of dam failures by the continents



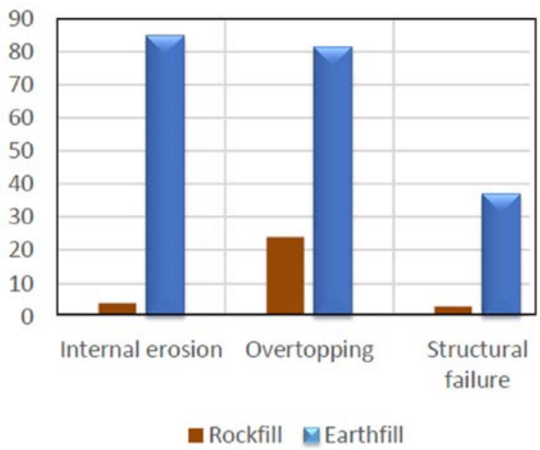
a) Failures by year of Construction

b) Failures by age after construction

Figure 3 Distribution of Failures by Periods of construction and age after construction



a) Ratio of failures per cause and failure period



b) Failures modes on embankment

Figure 4 Distribution of failure cause and mode on embankment dams

2. HYDRAULIC FRACTURING (HF) IN DAMS

2.1 Case Histories of Hydraulic Fracturing Failure in Dams

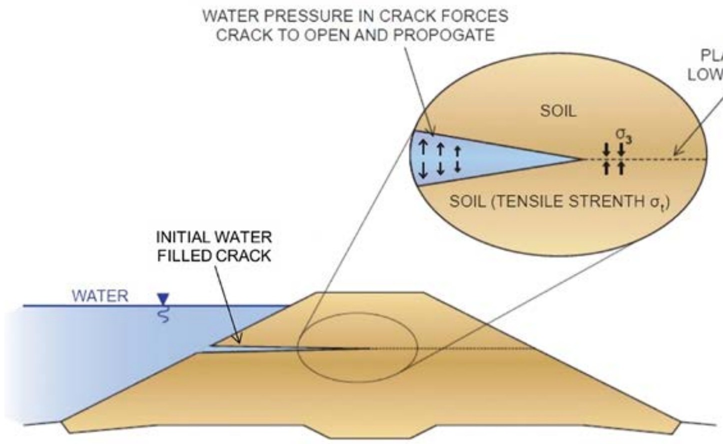
Hydraulic fracturing (HF) in earth dams is the conditions of crack propagation in any part of dam during dam reservoir rising. When the water pressures are higher than the stresses within the soil or rock mass (Mhach, 1991). It can create a new crack or enlargement of an existing crack. From the past records (Wang, 2014; Salari *et al.*, 2018), it causes dam internal erosion, especially during the first reservoir filling. In the narrow clay core or untreated dam foundations can be a main cause of initiating internal erosion in the dam. This phenomenon may result in concentrated leakage and progressive failure (Sherard, 1986; Wang, 2014).

Several case history dams have been suspected to have damages or failures as a result of hydraulic fracture (HF). Some examples are Dale Dyke Dam in UK (Binnie, 1978, 1983; Dounias *et al.*, 1996), Hytejuvet Dam in Norway (Kjaernsli and Torblaa, 1968; Ng and Small, 1999; Haeri and Faghihi, 2008), Balderhead Dam in UK (Vaughan, 1970). Teton Dam in USA (Independent Panel, 1976; Penman, 1977; Seed and Duncan, 1987).

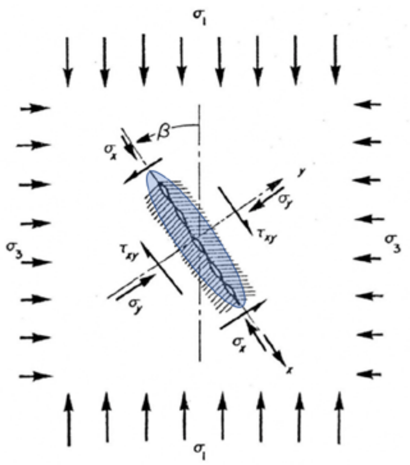
The most recent case is the failure of saddle dam of Xe-Pian- Xe-Namnoy Dam in Laos (Chraibi *et al.*, 2020). The saddle dam D of the large hydroelectric power project was failed during the first impounding on July 23, 2018. It claim more than 70 dead and 7095 loss their houses and properties. The cause of failure was concluded by Independent Expert Panel (2019) as the high permeability of the foundation causing interconnected path of flow and internal erosion. Early and correct interpretation of the monitoring data, would have allowed to take early actions to save the dam.

2.2 Mechanisms of Hydraulic Fracturing (HF)

When embankment dams deformed by their own weight or water storage, some differential settlement occurred. The regularity of foundation surface, rock joint, differential elastic modulus etc. can initiate the arching of the stresses. As the minor principal stress decrease and major principal stress is less than the unconfined compressive strength. The crack can be happened, enlarged and propagated in the low stress zones. The water from the reservoir can penetrate in soil or rock. This is the progressive process as the crack openning, then permeability of soil and rock will suddenly increase (Wang, 2014; Chalermpornchai *et al.*, 2021). Seepage water on this area will flow faster and the internal erosion can be started. The simple hydraulic fracture model and stresses around the crack can be illustrated on Figure 5.



a) Failures by year of Construction (Fell *et al.*, 2015)



b) Stress conditions around crack area (Hoek and Bieniawski, 1965)

Figure 5 Hydraulic fracturing initiation and stresses

The Independent Panel of Teton Dam Failure (1976) suggest the simple equation for the condition of hydraulic fracturing on Eq.1.

$$\mu_f > \sigma_3 + \sigma_t \tag{1}$$

When, μ_f = pore water pressure at hydraulic fracture state, σ_3 = minor principal stress, and σ_t = soil tensile strength.

Jaeger and Cook (1976) include the secondary principal stress (σ_2) for calculation of hydraulic fracturing pressure in rock as on Eq.2.

$$P > 3\sigma_2 + T_0 - \sigma_1 \tag{2}$$

When, P = Pore pressure in rock, $\sigma_{1,2}$ = Principal stresses, and T_0 = rock tensile strength.

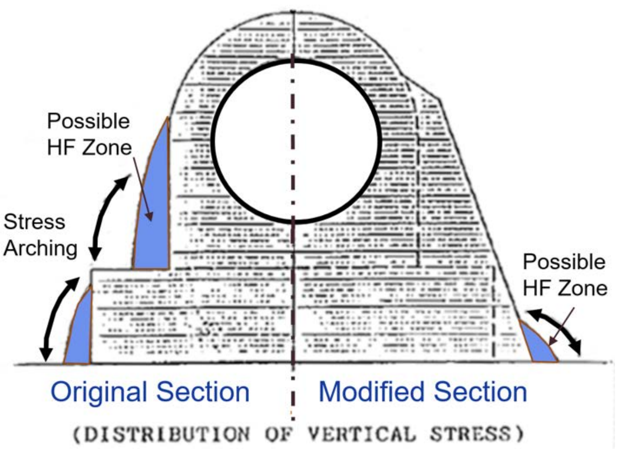
3. HYDRAULIC FRACTURING (HF) ANALYSES

3.1 Case Study of HF in Thailand

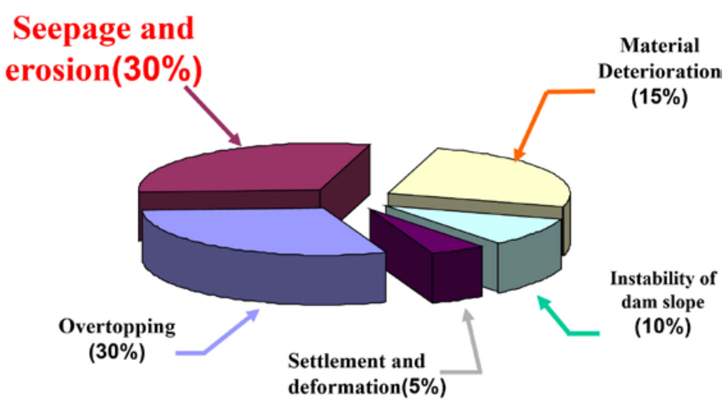
Hydraulic fracturing failures and damages in Thailand had not been clearly separated from the internal erosion. In 1985, Sanyu Consultants and TEAM Consulting Engineers, during design of Mae Kuang Dam in the northern Thailand, it is found that the original design of main outlet structure had stress arching area as shown on Figure 6 a) The hydraulic fracturing might be initiated at this zone. The section of outlet structure was modified after the detailed stress analysis. Dam safety project for Royal Irrigation Department, Regional Office Region 9, and the causes of dam damages was concluded that 30% from seepage and internal erosion as on Figure 6 b).

Case study of this paper is the earth saddle dam of a large hydropower project on the north of Thailand. The dam is homogenous earth filled dam of 33 m. high and 468 m. crest length. The dam was impounded in 1972 with no dam monitoring instrument. In 1994, the seepage points were observed on downstream toe. During that time, the reservoir water level was above the normal high water level (NHWL = 162 m MSL). Finally, the slip surface was observed above the wet area as shown on Figure 7. The emergency repaired work was commenced by construction of rock berm to about 1/3 of downstream slope. After the incident, piezometers with automatic reading system were installed. However, the high pore pressures are recorded when the reservoir water reaching 150 m MSL. The wet and potential boiling area was observed at about 150 m. downstream from the dam axis.

The study area is located on the metamorphic rocks of phyllite and quartzitic schist. The intrusive igneous rocks cause the tectonic movement and foliation of the foundation rock as shown on Figure 8.



a) Possible hydraulic fracturing zone



b) Internal erosion from field inspection

Figure 6 Previous information on internal erosion and hydraulic fracturing in Thailand

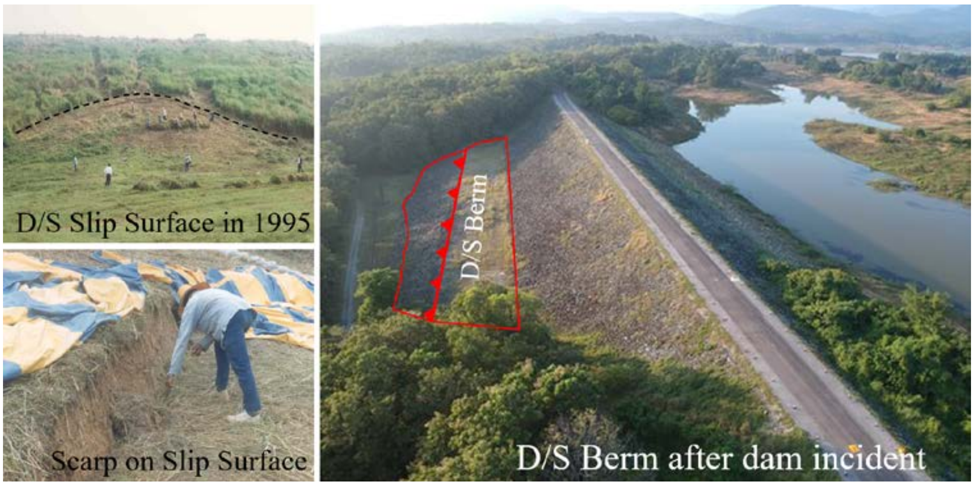


Figure 7 Dam indent on 1995 and stabilization of D/S slope by rock berm

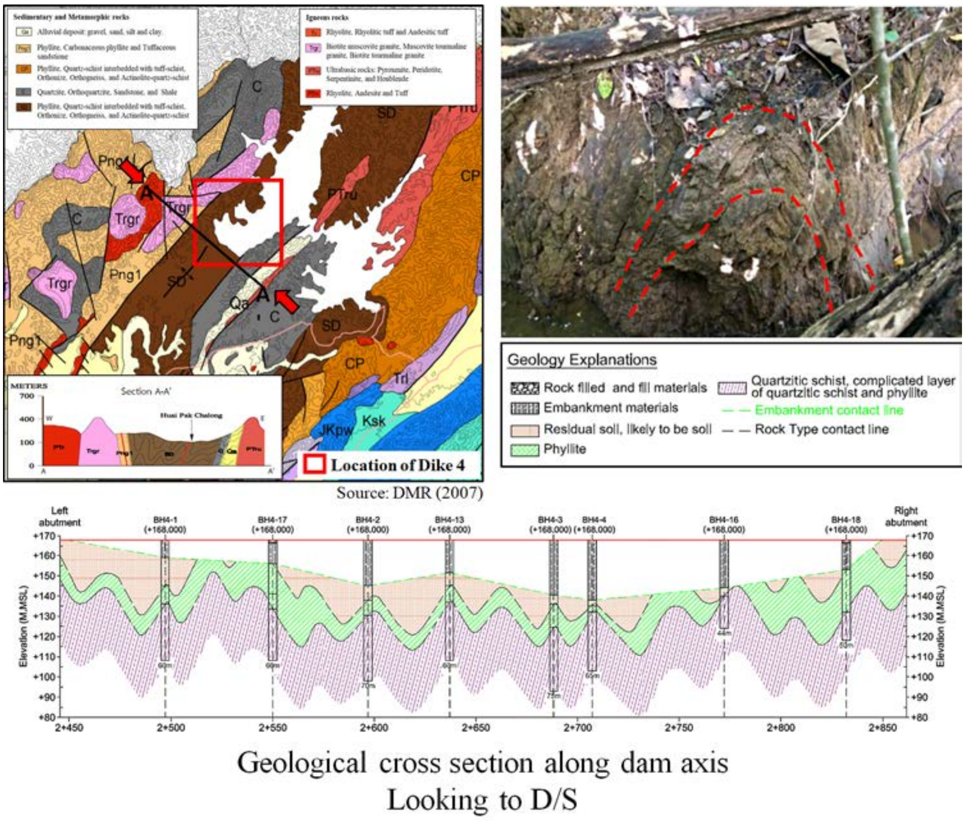


Figure 8 Geology of the study dam

3.2 Hydraulic Fracturing Modelling

Stress-deformation analyses were performed on longitudinal section along dam axis. The longitudinal section was analysed for the location and the area of possible hydraulic fracturing. While on dam cross section, the seepage and stability analyses was done. Material properties were obtained field boring, surface mapping and laboratory tests for several occasions. Table 1 shows the material properties for FEM analyses. The hydraulic fracturing zones are determined by minor principal stress level and pore pressure at the corresponding point as indicated on Eq.(1). The foliations are divided to 15 sections for the details analyses.

The distribution of minor principal stress along the dam axis is given on Figure 9. The stress arching is clearly seen at the syncline trough area between residual soil and weathered phyllite. These arching area or low stress zones that pore pressure can penetrate into the rock crack. When pore pressure is higher than minor principal stress, the new crack initiated and expanded.

Table 1 Material properties used in FEM

Material	$E_{modulus}$ (kPa)	γ (kN/m^3)	c (kPa)	ϕ (^{0})	ψ (^{0})
Embankment	22,000	21	30	22	0
Residual soil	25,000	21	30	22	0
Weathered Phyllite	500,000	23	700	28	5.6
Quartzitic Schist	1,000,000	25	1500	33	6.6

Notes: $E_{modulus}$ is Elastic Modulus, γ is unit weight, c is Cohesion, ϕ is Friction angle, and ψ is Dilatancy angle

As comparing to the possible pore pressure on the plan along dam axis, the difference between minor principal stress and pore pressure indicates the area of HF. The levels of HF can be simulated at the different reservoir water levels as shown on Figure 10. The calculation from Eq. 1, the tensile stresses of soil and rocks are considered to be every small (approximately = 0) since the materials are derived from cleavage rocks of phyllite.

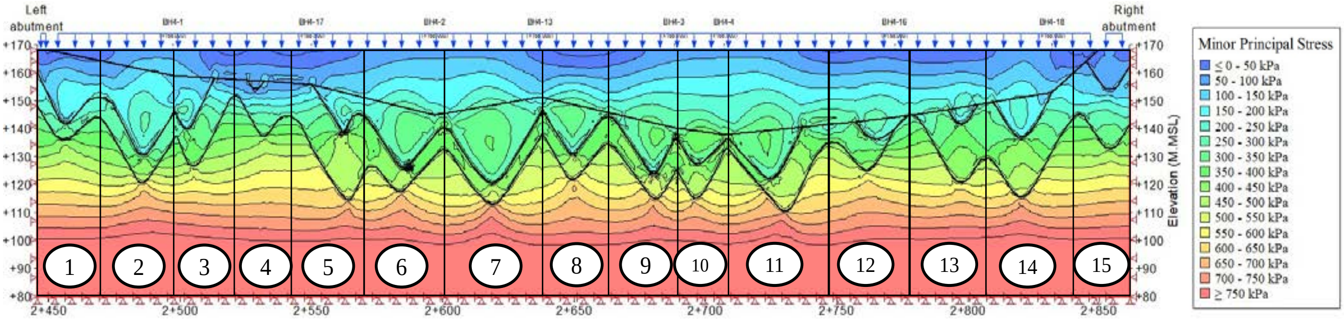
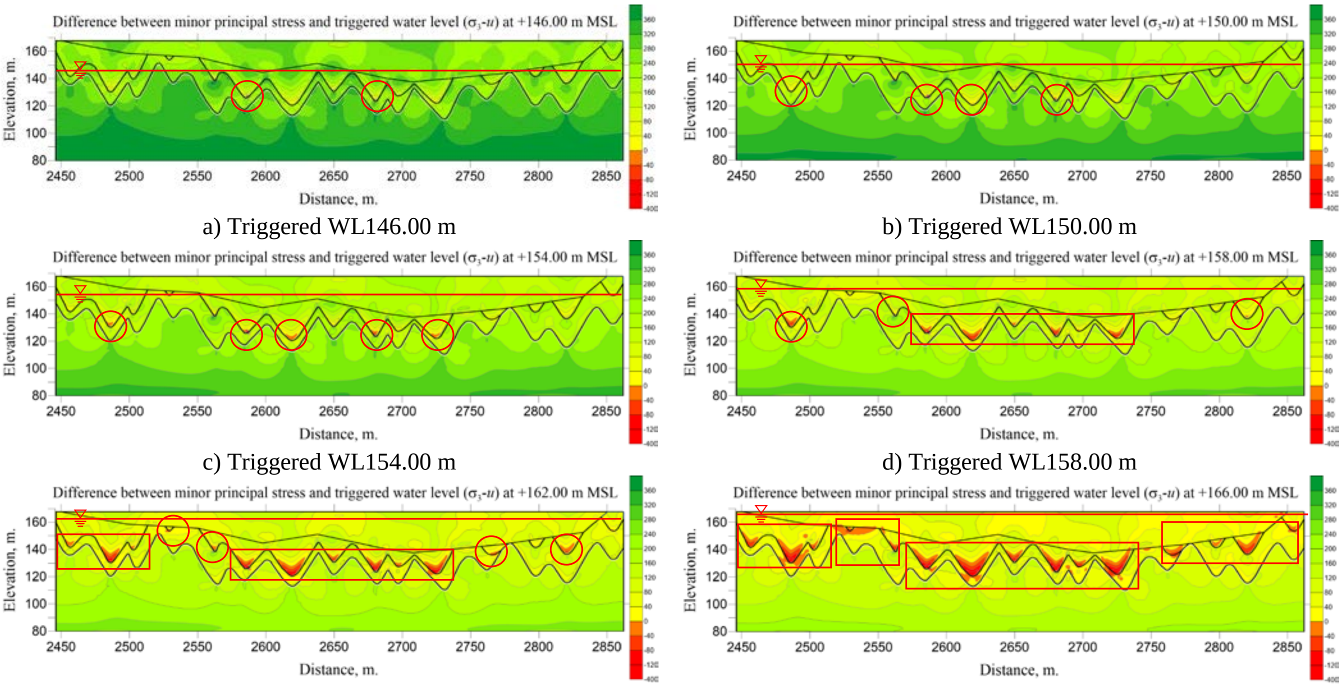


Figure 9 Minor principal stress distribution along dam axis



a) Triggered WL146.00 m

b) Triggered WL150.00 m

c) Triggered WL154.00 m

d) Triggered WL158.00 m

e) Triggered WL162.00 m (NHWL)

f) Triggered WL166.00 m (MFWL)

Figure 10 Progression of hydraulic fracturing zones

When the reservoir water level rises, the areas of HF zone are expanded. From FEM analysis, HF zones start to notice when water level above 150.00 m MSL. The HF areas are initiated on the lower part of syncline in residual soil. As the water level higher than 160.00 m MSL, the HF zones clearly occur on every syncline. These results quite agree with piezometer responses to be discussed later.

HF areas were expanded onto the foliation slopes, particularly folds 2, 7, and 11. These indicated that overburden stresses transfer to both foliation slopes, causing the stress arching. The low-stress zones are hydraulic fracturing areas on the syncline hinge on rock foundations. Kunsuwan *et al.* (2023) show the increasing of HF area are exponentially increased with reservoir water level.

3.3 Hydraulic Fracturing Index

Quantification of hydraulic fracturing can be done by the term "Hydraulic Fracturing Index" (HFI) as proposed by Chalermpornchai (2022) and Kunsuwan *et al.* (2023). All possible factors were assembled based on studies and theories developed by A (Ohta *et al.*, 2006; Fell *et al.*, 2007; Talebi *et al.*, 2013; Djarwadi *et al.*, 2017; Komasi and Beiranvand, 2020; Soroush and Pourakbar, 2022). that contributing to HF occurrence are included as in indicated on Figure 11 and Eq. (3).

$$HFI = \frac{H_{favg}}{B_{width}} \times \frac{H_w}{H} \times \left(\sqrt{\frac{E_2}{E_1}}\right) \quad (3)$$

When HFI = Hydraulic Fracturing Index, H_{favg} = average height of foliation, B_{width} = foliation width, H_w = water depth from triggered water level to reservoir level, H = water depth from syncline inverse to reservoir level, E_1, E_2 = elastic moduli of the upper and lower materials respectively.

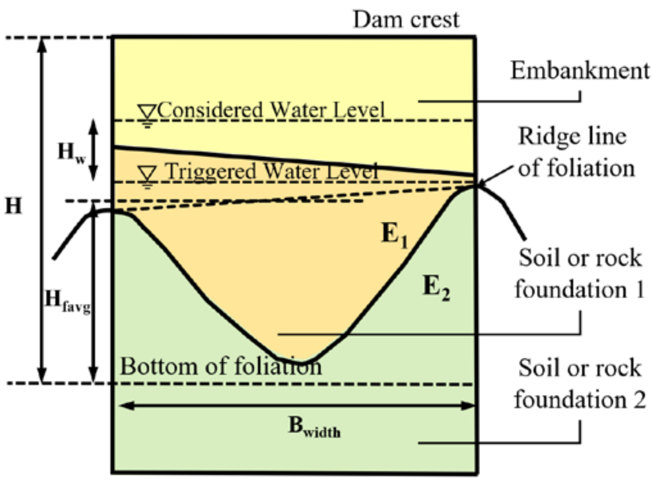


Figure 11 Geometry of foliation or foundation irregularity

The HFI can be calculated for every possible foliation or abrupt change of dam foundation interface. Those geometries can contribute to the stress arching, low stress zone, and hydraulic fracturing. Application of HFI can be used to classify the levels of possibility of HF occurrence as the example shown on Figure 12.

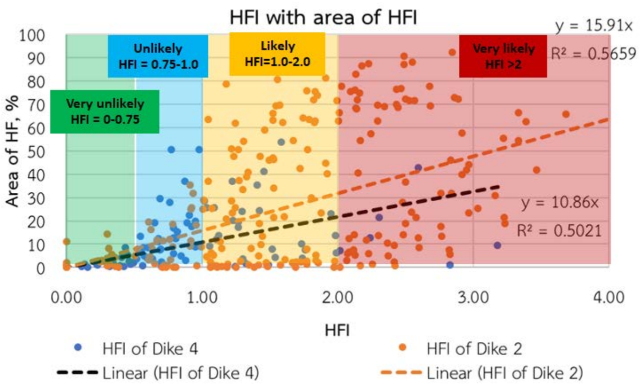


Figure 12 Classification of Hydraulic Fracturing Index from FEM analyses for study dams

4. DETECTION BY DAM INSTRUMENTS

4.1 Related Dam Instruments

Dam instruments are special sensors and measuring system for monitoring specific dam behaviours for dam safety warning and long-term dam performance. First group of dam instrument to monitor HF is similar to seepage monitoring as shown on Figure 13. Piezometers, observation wells and seepage flow meters should be installed on the critical locations in dam body and foundation. The specific locations are on rock fault, irregular foundation rock, thin clay core, interface area of dam structure etc. The drain or filter and seepage flow meter should be separated into some suspected region of HF. The large dam with complex foundation, the earth pressure cells might be the good choice for stress field measurement and stress arching.

4.2 Monitoring Parameters

Pore pressure measurement is the most important data to analyse the HF behaviour (Mairaing, 1999; FEMA, 2015; GERD, 2019). Generally, the pore pressure reading vs. time is called piezometer or pore pressure response (Wang *et al.*, 2018). In this study, the piezometer responses at the critical section are used for detail analyses of potential of HF. Three parameters are applied for response characteristics namely, time lag (T_L), pore pressure ratio (P_R) and reservoir trigger level (H_w).

Time lag (T_L) is the delay time from the reservoir rising to the piezometer reading. It essentially consists of 1) "traveling time", the time for reservoir pressure change to travels to the location of piezometer tip and 2) "activated time", the time for pressure change around the tip to flow into the reading system. Modern piezometer system, the activated time is very short and can be neglected as comparing to travelling time. Figure 14 shows the time lag for piezometer response.

Pore pressure ratio (P_R) is the ratio of piezometer head change to reservoir rising head. It reflects the head loss along the seepage path. When P_R = 1, the water can easily seep through the crack of erosion channel without any head loss. P_R can be calculated from the slope of plot between the piezometer head vs. reservoir level as shown on Figure 15 a). On the critical dam section, the contour of P_R can indicate the potential seepage erosion path as on Figure 15 b).

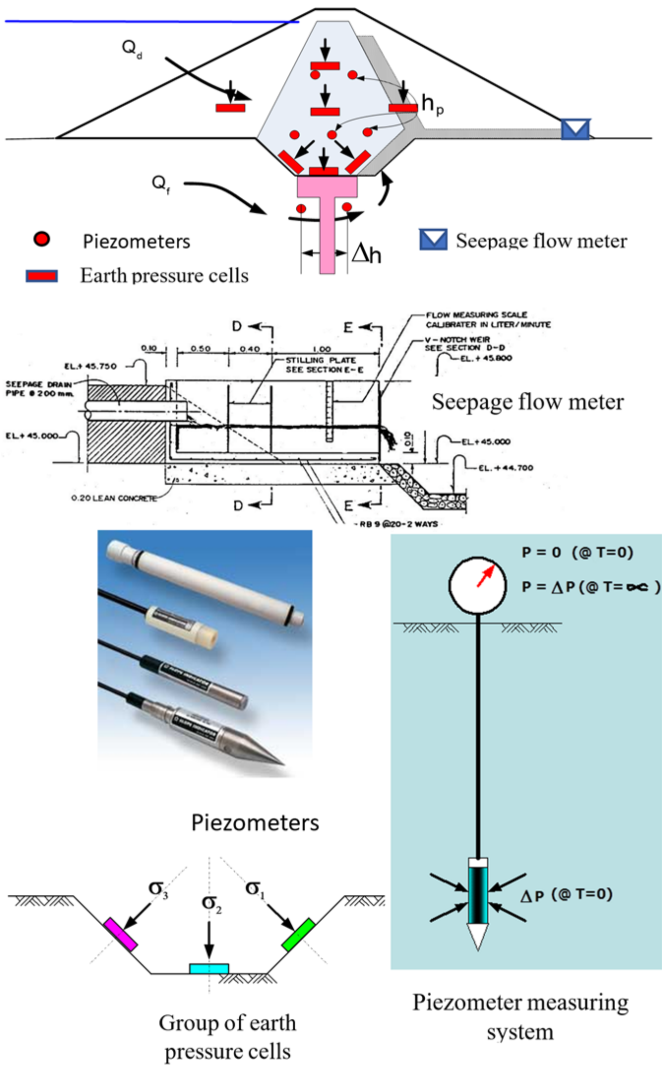


Figure 13 Dam instruments for HF monitoring

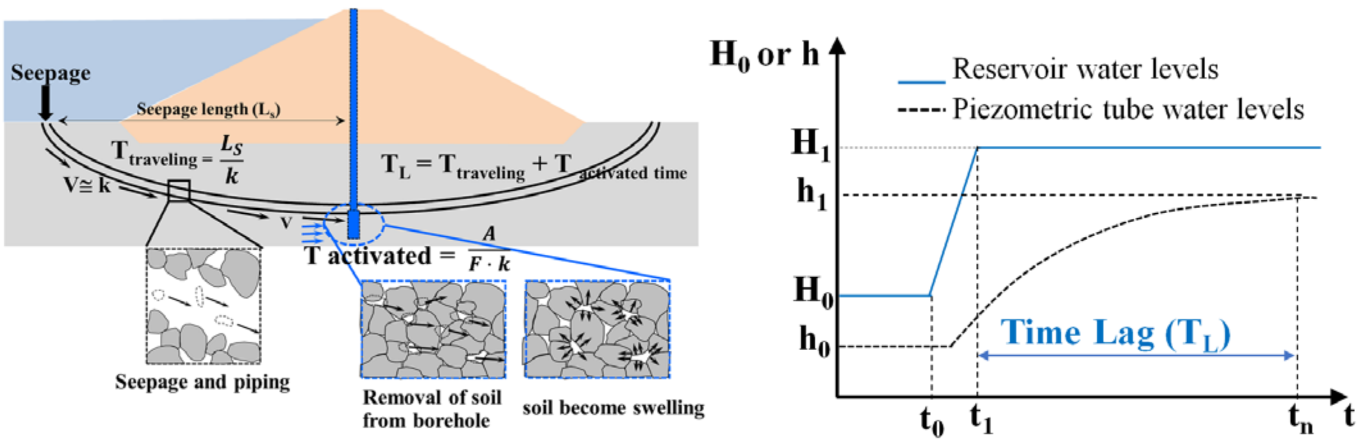
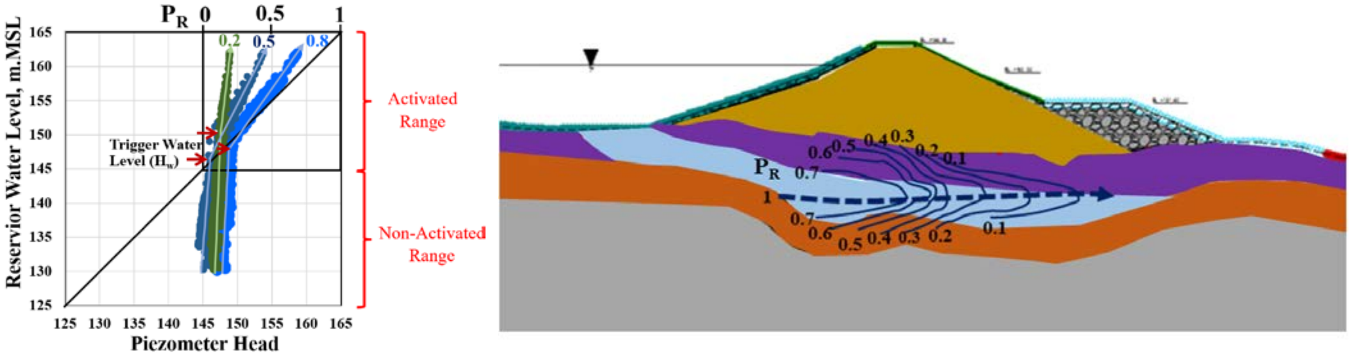


Figure 14 Time lag for piezometer response



a) Piezometer head vs reservoir rising

b) Contour of pore pressure ratio

Figure 15 Pore pressure ratio from piezometer reading

4.3 Variation of T_L

The fluctuation of T_L of piezometers on residual soil from 2003 to 2022 are shown on Figure 16. The behavior of T_L can be divided into period 1 (2003–2008), 2 (2008–2013), and 3 (2013–2022). The maximum T_L of OSP10 is a good example, it decreased from 50 to 20 to 0 days (No time lag) from period 1 to 3 respectively. This indicates potential of internal erosion increasing on that area. Where at the area of dam axis, T_L of OSP8 and 8/1 show very small time lags of less than 10 days. The erosion on this area toward upstream might happened before the time of first installation on piezometers.

The changes of T_L vs. reservoir water level on Figure 17 at the dam axis to downstream areas, show the alternate high and low time lags. These indicate the ongoing crack plugging and erosion. When the reservoir level is high enough (above 159 m MSL), the internal erosion is dominated and T_L become very low.

4.4 Pore pressure ratio vs internal erosion

Pore pressure ratios at various locations on dam foundation are shown on Figure 18. In the lower part of residual soil, P_R starting at 0.9–1.0 at the upstream area and slightly reducing to 0.7–0.8 at the middle area of the foundation. On the phyllite rock, P_R are ranging from 0.5 at the dam axis to below 0.2 on downstream area as usual phenomenon. The higher P_R in residual soil indicated the potential of internal erosion along the lower layer of residual soil but plugging on the downstream area.

Hydraulic fracturing or internal erosion is the progressive action depending material erodibility, arching stresses, reservoir level and operating time. The contour plots of P_R on plan view for three periods on Figure 19, show the invasion of the hydraulic fracturing zones. Distinctive zone is centred on Sta. 2+700 that is agreed with the wet spot and slip surface on 1995. Jotisankasa and Mahannopkul (2014) used Ground Aeration Sound (GAS) to detect the route of high seepage. The results show the higher seepage on Sta. 2+650 to 2+700.

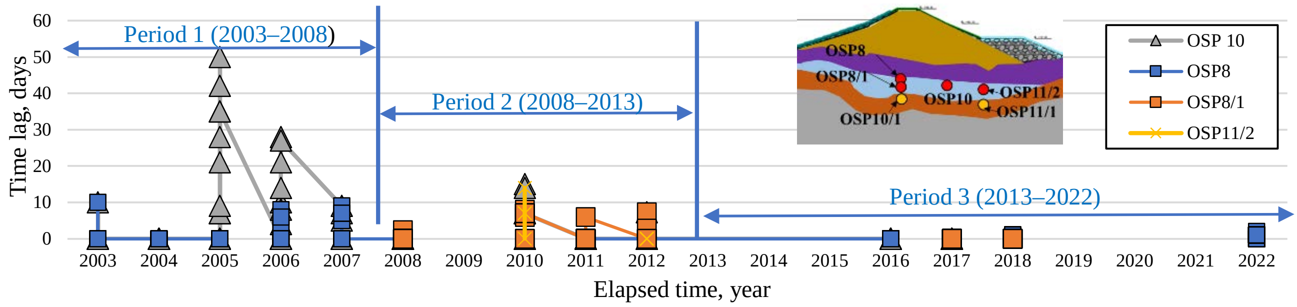


Figure 16 Time lag for piezometer response

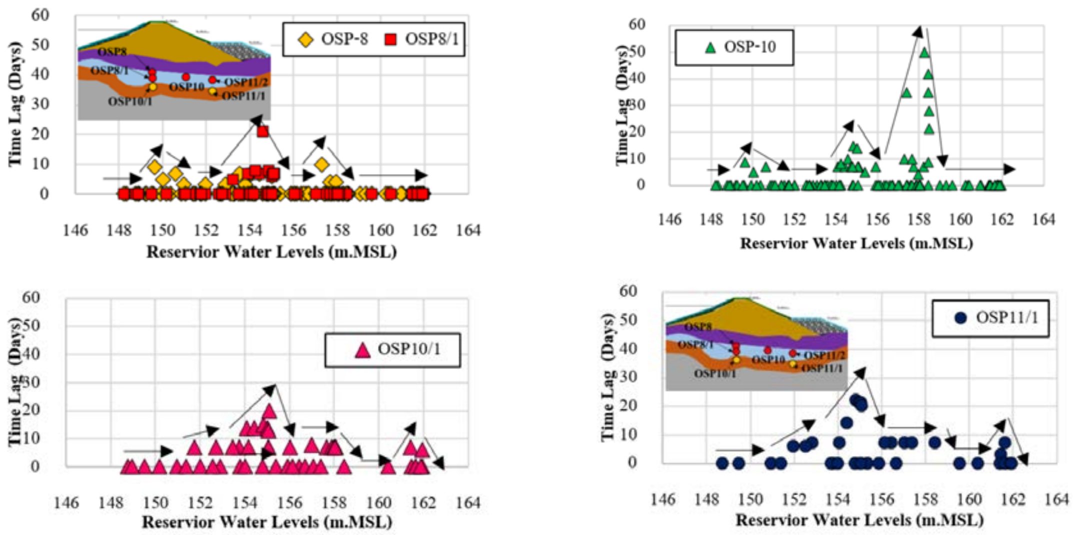


Figure 17 Time lags change with reservoir water levels

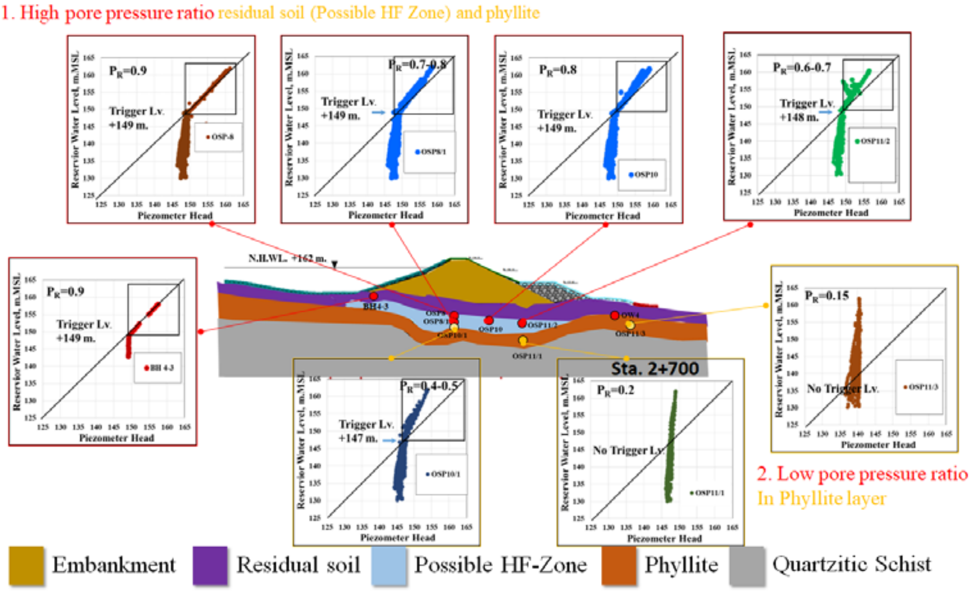
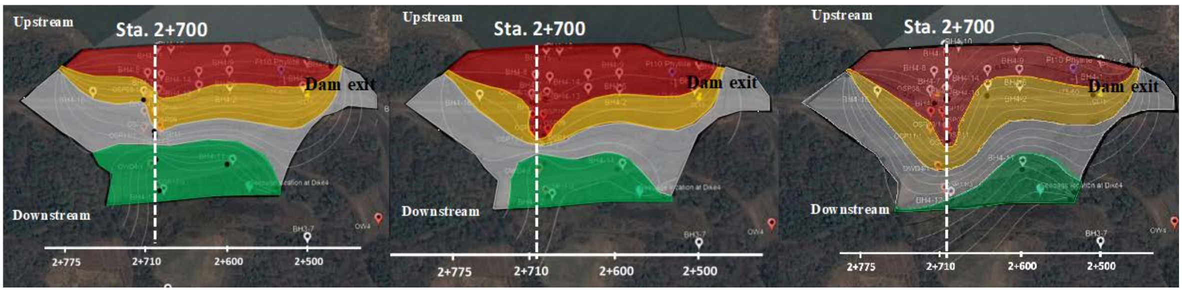


Figure 18 Pore pressure ratio on the dam foundation



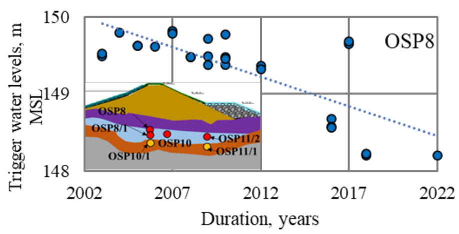
a) Period 1 (2003-2008) b) Period 2 (2008-2013) c) Period 3 (2013-2022)

P_R = 0.8–1.0 P_R = 0.6–0.8 P_R = 0.3–0.6 P_R = 0.0–0.3

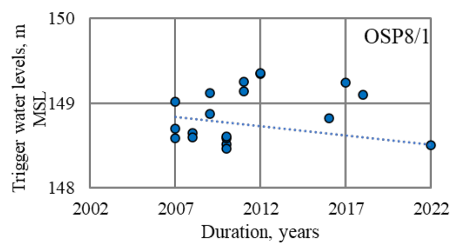
Figure 19 Progression of pore pressure ratio toward downstream area on plan view.

4.5 Reservoir trigger levels

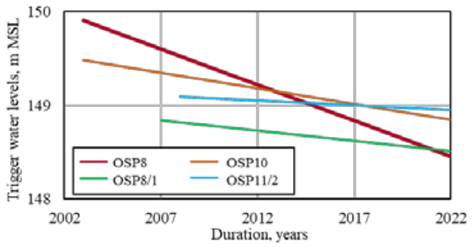
Reservoir trigger level (H_w) is the reservoir water level that activate the piezometer reading. The H_w as shown on Figure 18 are between 148–150 m MSL for all piezometers. However for individual piezometer in the zone of HF, the trigger levels change with time. The H_w for OSP8 on Figure 20 a) had changed from 150 to 148.5 m MSL from year 2002 to 2022. It is mean that for 20 years, the piezometer is progressively activated by the reservoir water. The flow from the reservoir seeps to the piezometer quicker with higher permeability and less seepage loss along the flow path. Figure 20 c) shows the trend line of decreasing of trigger level for a group of piezometers on the potential HF zone. When the trigger levels outside the HF zone on Figure 20 d) do not show any change with time.



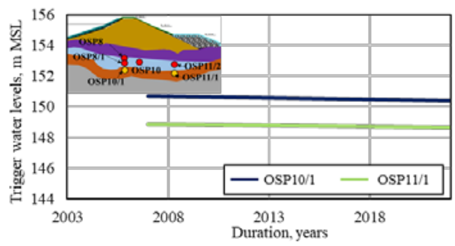
a) Trigger level change on OSP8



b) Trigger level change on OSP8/1

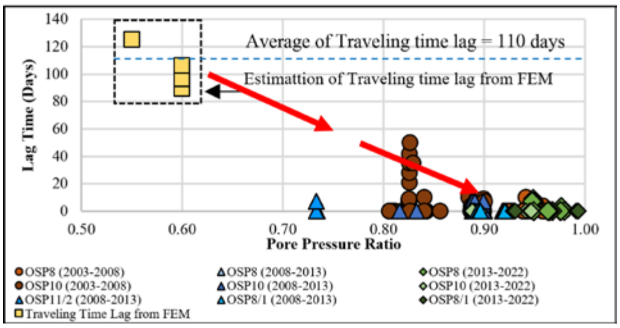


c) Trends of trigger levels change on HF area

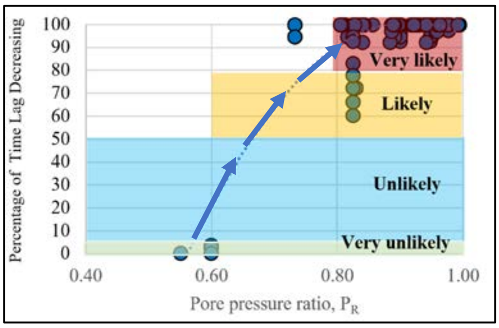


d) Trends of trigger levels change on non-HF area

Figure 20 Changes of reservoir trigger levels on piezometer responses



a) Pore pressure ratio vs time lags



b) HF risks by P_R vs T_L plot

Figure 21 Relationship of time lags with pore pressure ratio

4.6 Relation of pore pressure ratio and time lags

The attempted to combine 2 indices namely P_R and T_L for HF evaluation. On Figure 21 a), the plots of pore pressure ratio vs. time lags show the trend of more T_L with less P_R toward less T_L with moreP_R. The risk levels are also proposed on Figure 21 b) by using the time lag decreasing from the theoretical time lag from FEM.

4.7 Criteria for risk evaluation

Three parameters, T_L, P_R, and H_w derived from piezometer readings and interpretation from the field monitoring can be used to evaluate the risk levels. The ranges of T_L, P_R, and H_w are proposed by Saejiaw (2022) and Saejiaw *et al.* (2023) as shown on Table 2. This information is a guideline of dam owner and dam engineer who operates the dam to screen the risk level of instrumented dam. The values on Table 2 may be derived according to the study case. The application for other dam has to be customized by the characteristics of each dam.

Table 2 T_L, P_R, H_w Criteria for HF Risk (Saejiaw, 2022)

Risk Levels	T_L *	P_R	H_w **
Very unlikely	< 5%	0.0–0.3	Constant
Unlikely	5–50%	0.3–0.6	<0.25 m
Likely	50–80%	0.6–0.8	0.25–1 m
Very likely	>80%	0.8–1.0	>1 m

Notes: T_L * is percentage decreasing from analytical or first reading after construction. H_w ** is head decreasing from first reading after construction. The values are applied from study case only.

5. CONCLUSION

Dam instrument data especially piezometer responses can be applied for evaluation potential of hydraulic fracturing and dam internal erosion. Piezometer data and guideline analyses (FEM) need to be carefully interpreted during the dam operation. The main conclusion of this study can be drawn as follows.

1. Most of failure cases on earth dams are from internal erosion for more than 30% of total failures. Hydraulic fracturing, one of important phenomenon that high pore pressure can overcome the soil pressure and open the cracks.

2. Hydraulic fracturing (HF) is not well known among geotechnical and dam engineering until the failures of Hytejuvet, Balderhead, and Teton dams. Recent case of Xe-Pian- Xe-Namnoy Dam in Laos and case study dam in Thailand are experienced the HF phenomenon in this region.

3. Case study dam is the earth dam of 33 m. high and 468 m long. When it retained reservoir water more than NHWL of 162 m MSL, the slip circle occurred above the wet area at D/S toe. Geology of dam site is complex foliation of Phyllite and Quartzitic Schist.

4. The FEM analyses show the area of HF at the syncline of residual soil on top of phyllite layer. The HF areas are expanded according to the reservoir water level. The Hydraulic Fracturing Index (HFI) is proposed to quantify the degree of HF for each foliation.

5. Three parameters T_L, P_R, and H_w from piezometer reading are used to evaluate the potential of hydraulic fracturing (HF).

6. Time lag (T_L) from piezometers on potential HF zone decreased from 50 to 20 to 0 days at reading period 1 (2003–2008) to period 2 (2008–2013) to period 3 (2008–2022). They are indicated the internal erosion progress over the measuring time.

7. Pore pressure ratio (P_R) are very high at 0.9–1.0 on upstream foundation and slightly reducing to 0.7–0.8 at the middle foundation zones. These ranges of P_R are considered high with possible internal erosion and open cracks in foundation soil. On the downstream area and phyllite layer, P_R are from 0.5 to 0.2 which are the normal range without internal erosion.

8. Reservoir trigger levels (H_w) are about 148 to 150 m MSL. On the potential area of HF, the H_w's are gradually reduced with time from 2002 to 2022. While on non-HF area, the H_w's are constant.

9. Combination of T_L, P_R, and H_w behaviors, the ranges of HF risk can be proposed as very likely, likely, unlikely and very unlikely of HF occurrence.

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