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Risk Analysis of the Prijetan Dam in Lamongan Regency

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Abstract

The Prijetan Dam in Lamongan, East Java, has been in operation for over a century, making it one of the oldest dams in Indonesia. This study aims to assess the risks associated with the aging structure of the dam, including potential failures and safety concerns. The analysis was conducted using the ICOLD modified risk scoring system and the Failure Mode Effects Analysis (FMEA) method, taking into account physical deterioration, climate change impacts, and possible failure modes. The results provide insights into the current physical condition, risk levels, and necessary mitigation strategies to enhance the dam's safety and functionality. The study also prioritizes maintenance and rehabilitation actions based on risk levels, ensuring long-term operational safety and security for the surrounding areas.

Introduction

Dam construction in Indonesia has experienced very rapid development. The rapid construction of the dam aims to support one of the Indonesian Government's programs in order to realize national food and water security (Tamim et al., 2023). The Government of Indonesia through the Ministry of Public Works and Public Housing (PUPR) has programmed the construction of 61 dams in the 2014-2024 period and 11 new dams in the 2021-2027 period (Ministry of PUPR, 2023). These dams will later increase the number of existing dams in Indonesia. Based on the List of Dam Registration Numbers in Indonesia in 2023, the number of existing dams in Indonesia is 259 dams (Ministry of PUPR, 2023).

Dams can provide great benefits to the community such as providing water for irrigation, meeting the needs of raw water for industry and households, power generation, flood control and others (Alfin et al., 2022); (Sutrisno & Hamdani, 2019). In addition to providing enormous benefits, dams also hold a potential risk of great danger if they collapse because the impact they produce covers a large area in the downstream area of the dam (Wang et al., 2023). Dam failure can cause disasters in downstream areas resulting in the fall of many lives, property and objects (Rachmanto et al., 2024).

Law of the Republic of Indonesia Number 24 of 2007 concerning Disaster Management Article 40 mandates that "every development activity that has a high risk of causing a disaster is equipped with a disaster risk analysis as part of disaster management efforts". The obligation of disaster risk analysis is detailed in Government Regulation Number 21 of 2008 concerning the Implementation of Disaster Management article 12. Considering that dams have a high risk of danger, the Directorate General of Water Resources, Ministry of Public Works has established Guidelines for Dam Risk Assessment in 2017. According to this guideline, risk assessments are carried out on dams that are in the planning stage and existing

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dams or those that have been built. In the dams under construction, the risk assessment aims to set criteria and improve the design so that the risk of dam hazards can be minimized (Pramudawati, 2020), while in existing dams, risk assessment aims to find out whether the existing hazard risk is tolerable and if the hazard risk cannot be tolerated, it is necessary to plan actions to reduce the risk. In addition, risk assessment of existing dams also aims to determine the priority or ranking of repair or rehabilitation work needed to improve safety based on the risks in these dams (Firmansyah & Sriyana, 2022).

Risk analysis is a part or element of risk management. Risk management includes the process of measuring or assessing risks and developing their management strategies (Ostrom & Wilhelmsen, 2019; Landoll, 2021). Risk management strategies that can be taken include transferring risks to other parties, avoiding risks, reducing the negative effects of risks and accommodating some or all of the consequences of certain risks (Ardiyanto, 2023). Therefore, it is very important to identify the risks that exist in dams. It should be noted that dams have their own uniqueness or specificity so that the risks in one dam may be different from another. Identification of risks to dams can be done with the help of opinions from experts. Several dams in Indonesia were built during the Dutch East Indies rule (Rospriandana et al., 2023; Minkman et al., 2019). One of these dams is the Prijetan Dam. The Prijetan Dam was built from 1910 to 1917. Thus, this dam has been in operation for 107 years and makes it the oldest dam in East Java. Administratively, the Prijetan Dam is located in Sumbergempol Village and Tenggerejo Village, Kedungpring District, Lamongan Regency, East Java Province.

Over time, dams can deteriorate in quality (deterioration) that can threaten the safety of the dam (Herawanto et al., 2023). Changes in climate conditions can also affect the amount of planned flood discharge that can be secured by dams (Qin et al., 2022; Buldan et al., 2021). Therefore, it is necessary to conduct a risk analysis on the Prijetan Dam which aims to prevent or at least reduce the risk of dam failure and maintain the sustainability of the function and safety of the dam for as long as possible. The report aims to analyse the risks to the Prijetan Dam, which has been in operation for 107 years. The formulation of the problem includes the physical condition of the dam, its risk assessment, risk reduction plan, and the priority of necessary rehabilitation (Ribas & Pérez-Díaz, 2019; Eslami et al., 2021). The goal is to assess the physical condition of the dam, determine the level of risk, and develop a risk reduction strategy and priority of repair work. This report is limited to the analysis of dam safety risks, carried out at the operation and maintenance stages, with a focus on the Prijetan Dam located in Lamongan Regency, East Java.

Methods

The stages or processes that will be carried out in the research are presented in the form of a flow chart as shown in Figure 1.

The data and reports collected for the risk assessment of the Prijetan Dam are as follows Feasibility study report, Design report, Construction/repair/rehabilitation implementation report including implementation photos, As-built drawing, Full details about the modifications to the dam, Dam safety monitoring and inspection reports (routine, annual, comprehensive), Dam OP Guidelines, Dam safety study report, Emergency action plan (RTD) document, Special incident reports. The risk assessment of the Prijetan Dam was carried out by 2 (two) methods, namely the ICOLD Index Score method and the dam failure probability method (Event Tree Analysis).

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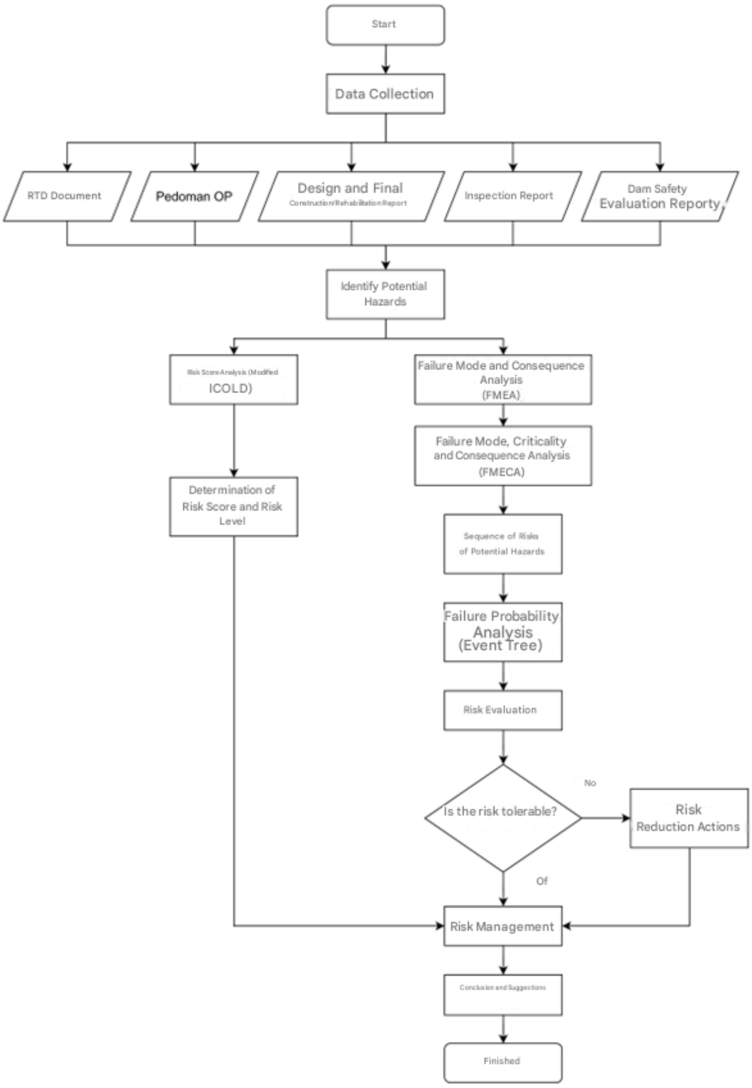

Figure 1. Research Flow Chart

Results and Discussion

Evaluation of Dam Safety on Structural Aspects

The stability analysis of the dam body was carried out under static and dynamic loading conditions (earthquakes). The parameters of the pile and foundation materials are as follows.

Table 1. Parameters of Pile and Foundation Materials

Soil Type	Volume Weight (g) kN/m3	Cohesion (c) kN/m2	Sliding Angle (º)	Permeability Coefficient (k) m/s
Clay	16,67	24,54	23,5	4.89 x 10-8
Concrete	24	0	0	10-10
Foundation	19,02	29,02	25	6.56 x 10-8
Riprap	23	0	40	*Free drain*

Source: Data Processed by Researchers, 2024

The geometry used as a reference for seepage analysis and slope stability is *as built drawing* of the Prijetan Dam Rehabilitation Work by PT Adhi Karya, 1999 and Topographic Measurements (2020).

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Identify Potential Hazards

Table 2. Identification of Potential Hazards at the Prijetan Dam

Component	Loading Conditions	Identify the Source of Danger	Cause	Failure Mode
Dam body	Usual	The possibility of seepage through the dam body is uncontrollable	Deterioration in the core zone of concrete	Bamboo erosion (*piping*)
Dam body	Usual	Possible instability of the downstream slope of the dam	Increased pore water pressure in the downstream dam body due to rock *toe blockage*	Runoff through the top of the dam (*overtopping*)
Dam body	Earthquake	Possible reduction in care height	Subsidence at the top of the dam and/or avalanche on the slope of the dam	Runoff through the top of the dam (*overtopping*)
Focus Hill	Usual	Seepage on the right platform when the water level of the reservoir is + 48 meters above sea level	The contact between the concrete core zone and the foothill is not good and/or there is a weak zone on the foothill in the form of limestone and napal stone intersection	Bamboo erosion (*piping*)
Major overflow	Usual	Cracks and peeling of the upstream landmark concrete surface and damage to the downstream floor	Degradation of concrete quality and water erosion	The collapse of the spillway landmark
Major overflow	Flood	Inadequate overflow capacity	The flood discharge that occurred exceeded the planned flood discharge	Runoff through the top of the dam (*overtopping*)
Primary overflow and auxiliary overflow	Flood	No *trashboom* on the overflow face	Not installed	The possibility of overflow can be blocked by garbage, wood, etc., thereby reducing the overflow capacity which results in runoff through the top of the dam (*overtopping*)
Additional overflow	Flood	Inadequate overflow capacity	The overflow door cannot be operated	Runoff through the top of the dam (*overtopping*)
Instrumentation	Usual	The piezometer readings cannot be evaluated because the location of the piezometer installation is unknown	*As built* piezometer installation drawing not found	The pore water pressure behavior in the dam body cannot be evaluated and cannot be used to evaluate the safety of the dam

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Instrumentation	Usual	Seepage originating from the dam body cannot be monitored	The floor of the V-notch building has cracks that cause water to leak through the floor. As a result of this condition, secretions cannot be accommodated and measured	Seepage behavior cannot be analyzed and cannot be used to evaluate the safety of dams

Source: Data Processed by Researchers, 2024

Table 2 illustrates the identification of potential hazards found at the Prijetan Dam. The main hazards include uncontrolled seepage, downstream slope instability, and structural damage to the dam body and overflow. One of the significant potential failures is reed erosion (piping) caused by deterioration in the concrete core zone, as well as seepage on the right platform due to imperfect contact between the concrete core and the pivot hill (Talalay, 2023; Broderick, 2020). In addition, there is a risk of runoff through the top of the dam (*Overtopping*) during floods due to inadequate overflow capacity or clogged by garbage. This condition is exacerbated by the lack of effective monitoring, such as piezometer results that cannot be evaluated due to unknown installation locations, as well as damage to the V-notch resulting in seepage water leakage.

Analysis of Dam Failure Models and Their Consequences

The failure mode effects analysis (FMEA) model analysis is carried out after potential hazards in dam components are identified. In this analysis, it can be known the influence of failure that will occur on the system/dam as a whole. Each of the potential hazards that have been identified will trigger different effects of failure. The results of the analysis of the dam failure model and its consequences are presented in table 3.

Table 3. Analysis of the Prijetan Dam Failure Model

Identified Parts	**Function**	**Failure Mode**	**Consequences of Failure**		**Hazard Opportunities**
			Local Influence	**Final Influence**	
Downstream soil	As a stockpile material	Bamboo erosion on downstream slopes (*piping*)	Increased uncontrolled secretion discharge	Dam collapse	Low
Downstream soil	As a stockpile material	Avalanches on downstream slopes	Overtopping due to reduced guard height	Dam collapse	Very low
Dam body	As a stockpile material	Reduced guard height	Runoff through the top of the dam (*overtopping*)	Dam collapse	Very low
Hill right focus	As the foundation of the dam	Bamboo erosion on downstream slopes (*piping*)	Increased uncontrolled secretion discharge	Dam collapse	Keep
Main overflow control building	Controlling or regulating the discharge of water that comes out through the overflow	Damage or collapse of the control building	Former ruins can reduce overflow capacity causing *overtopping*	Dam collapse	Low
Main overflow control building	Controlling or regulating the discharge of water that comes out through the overflow	Significant rise in reservoir water levels	Runoff through the top of the dam (*overtopping*)	Dam collapse	Very low

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Main and auxiliary spillway buildings	Drain flood water so that it does not overflow through the top of the dam	Possible overflow clogged by logs	Runoff through the top of the dam (*overtopping*)	Dam collapse	Very low
Additional overflow	Drain flood water that exceeds the main overflow capacity so that it does not overflow through the top of the dam	Doors cannot be operated during floods	Runoff through the top of the dam (*overtopping*)	Dam collapse	Low
Vibrating wire piezometer instrument	Measuring and monitoring pore water pressure in the dam body	The behavior of pore water pressure in the dam body cannot be evaluated	Dam safety evaluation cannot be done accurately	The safety of the dam against the structural aspect cannot be accurately evaluated	Very low
Secretion measuring instrument (V-notch)	Measuring and monitoring seepage discharge originating from the dam body	Seepage behavior in the dam body cannot be evaluated	Dam safety evaluation cannot be done accurately	The safety of the dam against the aspect cannot be accurately evaluated	Low

Source: Data Processed by Researchers, 2024

Table 3 shows the results of the analysis of the failure model of the Prijetan Dam which identifies various failure modes and their impacts. The downstream part of the soil drainage has the potential to experience reed erosion (piping) and landslides, which can lead to increased seepage and runoff discharge, with a low to very low chance of danger (Reed & Kite, 2020; Nakamura & Shimatani, 2021; Şen, 2020). In the dam body, a decrease in guard height can result in runoff (overtopping), but the chance of danger is also considered very low. Meanwhile, the foundation on the right foothill has a moderate chance of experiencing reed erosion, which has the potential to cause the dam to collapse. Overflow control buildings are also at risk of damage, which can reduce overflow capacity and trigger runoff, although the chance of danger remains low. Monitoring instruments, such as piezometers and V-notchs, if not functioning properly, can hinder the accurate evaluation of dam safety. Overall, although some parts have the potential for failure, the chance of danger is generally low, but it still needs attention to maintenance and supervision.

Model Analysis of Failure, Criticality and Aftermath

Failure mode effect and criticality analysis (FMECA) was carried out to estimate the risk and criticality level of potential hazards in dams. The results of the model analysis of failure, criticality and consequences at the Prijetan Dam are presented in Table 4.

Table 4. Model Analysis of Failure, Criticality and Consequences at the Prijetan Dam

Component	**Likelihood (P)**	**Consequences (I)**	**Belief (C)**	**Risk (R) = (P) x (I)**	**Criticality (Cr) = (R) x (C)**
Dam body	2	5	2	10	20
Dam body	1	5	2	5	10
Dam body	1	5	2	5	10
Focus Hill	3	5	3	15	45
Major overflow	2	5	2	10	20
Major overflow	1	5	2	5	10
Primary overflow and auxiliary overflow	1	5	2	5	10
Additional overflow	2	5	2	10	20
Instrumentation	1	2	2	2	4

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Instrumentation	1	2	2	2	4

Source: Data Processed by Researchers, 2024

Table 4 presents an analysis of the model of failure, criticality, and consequences in the Prijetan Dam by taking into account the probability (P), consequence (I), belief (C), as well as risk (R) and criticality (Cr). The component with the highest criticality level is the fulcrum hill, with a criticality value of 45, because it has a high probability (P = 3) and major consequences (I = 5), indicating that failure in this component will have a great impact on the stability of the dam. The dam body and the main and auxiliary overflow have lower criticality values, ranging from 10 to 20, although it is still worth noting because the potential for failure can cause a large impact (I = 5). Instrumentation, such as piezometer monitoring devices, showed a low level of risk and criticality, with a value of 4, because although the probability of failure was low, the impact on the safety of the dam was not as large as the main structural components. These results highlight the importance of risk management, especially on the foothills and dam bodies.

Risk Sequence of Potential Hazards of the Prijetan Dam

The determination of the risk sequence of potential hazards is carried out to determine the priority of potential hazards that need to be further analyzed by analyzing the probability of dam failure or event tree analysis. The selected potential hazard is the potential hazard with the most critical and most risky condition (Rathi et al., 2021; Hallek, 2019). Potential hazards with low or low risk and criticality values are considered non-priority and may not need further analysis. Each risk and criticality value is sorted by system *Ranking*. The results of the analysis of the sequence of potential hazard risks at the Prijetan Dam can be seen **Error! Reference source not found.**5.

Table 5. Risk Sequence of Potential Hazards of the Prijetan Dam

Component	Loading Conditions	Danger	Risk		Criticality	Order		Action
			Value	Description	Value	Risk	Criticality	
Dam body	Usual	The possibility of uncontrolled seepage through the dam body	10	Keep	20	2	2	Analyzed
Dam body	Usual	Possible instability of the downstream slope of the dam	5	Low	10	3	3	Not analyzed
Dam body	Earthquake	Possible reduction in care height	5	Low	10	3	3	Not analyzed
Focus Hill	Usual	Seepage on the right platform when the water level of the reservoir is + 48 meters above sea level	15	Tall	45	1	1	Analyzed
Major overflow	Usual	Cracks and peeling of the upstream landmark concrete surface and damage to the downstream floor	10	Keep	20	2	2	Analyzed
Major overflow	Flood	Possible inadequate overflow capacity	5	Low	10	3	3	Not analyzed
Primary overflow and auxiliary overflow	Flood	No *trashboom* on the overflow face	5	Low	10	3	3	Not analyzed
Additional overflow	Flood	Possible inadequate overflow capacity	10	Keep	20	2	2	Analyzed
Instrumentation	Usual	The piezometer readings cannot be evaluated because the	2	Very low	4	4	4	Not analyzed

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		location of the piezometer installation is unknown						
Instrumentation	Usual	Seepage originating from the dam body cannot be monitored	2	Very low	4	4	4	Not analyzed

Source: Data Processed by Researchers, 2024

Based on the results of the analysis of the sequence of potential hazard risks, the priority of potential hazards that need to be further analyzed with the analysis of the probability of dam failure is as follows: (1) The possibility of uncontrolled seepage through the dam body; (2) Seepage on the right platform when the reservoir water level is at an elevation + 48 meters above sea level; (3) Cracks and peeling of the concrete surface of the upstream spillway landmark and damage to the floor of the downstream part of the spillway landmark; (4) Possible inadequate additional overflow capacity.

Dam Failure Probability Analysis

Table 6. Recapitulation of the Probability of Failure of the Prijetan Dam

Cases / Conditions	Consequences					Total	Order
	Annual Probability						
	E	H	M	L	N		
The possibility of uncontrolled seepage through the dam body	1,10E-08	1,09E-06	0.00E+00	9,90E-04	9,99E-01	1,00E+00	4
Seepage on the right platform when the water level of the reservoir is + 48 meters above sea level	5,05E-05	4,99E-03	0.00E+00	4.50E-02	9,50E-01	1,00E+00	1
Cracks and peeling of the upstream landmark concrete surface and damage to the downstream floor	4.50E-07	4,05E-06	4.05E-05	4,95E-02	9,50E-01	1,00E+00	3
Possible inadequate overflow capacity	9,58E-06	5,40E-06	8.99E-05	4.99E-01	5.00E-01	1,00E+00	2
Annual probability	6,05E-05	5,01E-02	1.30E-04	5,95E-01	3.40E+00		

Source: Data Processed by Researchers, 2024

The results of the event tree analysis show that the cumulative probability of several cases of the Prijetan Dam failure model with extreme consequences is 6.05E-05. The highest probability of failure is obtained in the case of seepage on the right pedestal while the lowest probability of failure is in the case of the possibility of uncontrolled seepage through the dam body

Risk Evaluation

In order to evaluate the acceptance of the risk of failure of the Prijetan Dam, the results of the probability analysis using the ETA method are included in the f-N graph. Based on the analysis of the dam collapse, the loss of life due to the collapse of the Prijetan Dam is estimated at 20,905 people. By including the annual probability value of the dam failure and the number of lives lost due to the dam collapse, the risk status of the Prijetan Dam is within the "tolerated limit for existing dams". The status of risk acceptance of the probability of failure of the Prijetan Dam can be seen in Figure 2.

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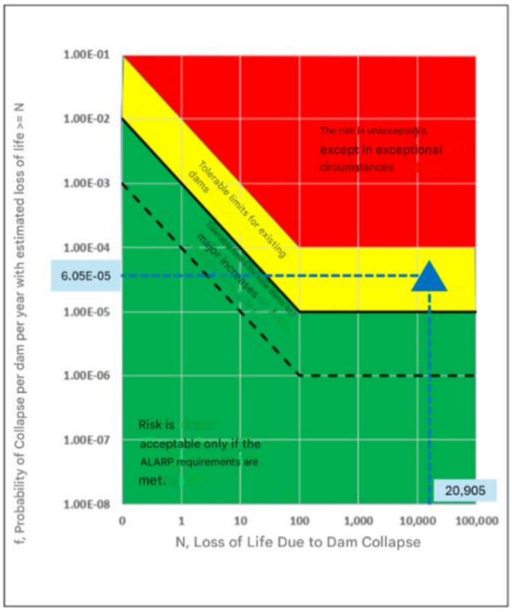

Figure 2. Acceptance of the risk of failure of the Prijetan Dam

ICOLD Method Risk Index Assessment

Table 7. Summary of Prijetan Dam Scores and Risk Categories

S.N.	Risk Index	Weight	Level of Risk/Importance	
1	Reservoir Capacity (ML m3)	4	40 > C > 2.0	*High*
2	Dam Data (m)	3	200 < L < 500 meters	*Moderate and strong importance*
3	Evacuation Requirements	10	10,000 < PAR < 100,000	*Very high*
4	Potential Downstream Damage	13	Major national highways / inter-regional / power plants	*High and strong importance*
5	Availability of Construction and Maintenance documents	3	Periodic inspections & repairs as needed	*Low importance*
6	Availability of Instrumentation and Supervision documents	1	60% < I < 80%	*Moderate importance*
7	Effort level in previous safety evaluations	2	*Only most important deficiencies addressed*	*High*
8	Downstream Regional Development Plan	0	RTDs are available and implemented	*Low importance*
9	Flood Capacity (deficiency)	3	*Masonry*	*Moderate and strong importance*

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10	Static Stability (deficiency)	3	No signs of *sinkholes*	*Weaker importance*
11	Earthquake Resistance (deficiency)	8	APT > 0.25g & no fracture within 10 km	*High*
Total Score		50		
Dam Risk Level		Tall		

Source: Data Processed by Researchers, 2024

Table 7 provides a summary of the risk scores and categories of the Prijetan Dam, with a total risk score of 50, indicating a high level of risk. Some of the factors that contribute significantly to this high level of risk include large reservoir capacity ("High risk category"), significant downstream damage potential due to the presence of critical infrastructure such as national highways and power plants ("High and strong importance" category), and very high evacuation requirements with more than 10,000 people at risk ("Very high" category). In addition, resistance to earthquakes is also a concern with high values in areas that have the potential to experience earthquakes ("High" category). Meanwhile, other factors such as construction and maintenance documentation, as well as downstream development plans, are considered to have a lower level of importance (Handayani et al., 2019; Kuriqi et al., 2021). Overall, a combination of these various indicators puts the Prijetan Dam at a high level of risk, which requires further attention and evaluation to minimize potential hazards.

Risk Reduction Action Plan and Implementation Priorities

The recommendations for risk reduction actions (TPR) of the Prijetan Dam and their implementation priorities are as follows:

For individual problems/risks identified and analyzed, TPR proposals and implementation priorities can be seen in table 8.

Table 8. Risk Mitigation Measures and Implementation Priorities

It	Location	Issue / Case	Annual Probability for Very High Consequences	Priority	Proposed Risk Mitigation Actions
1	Dam body	The possibility of uncontrolled seepage through the dam body	1,10E-8	Low	Regular monitoring of pore and secretion water pressure
2	Right focus	Seepage on the right platform when the water level of the reservoir is + 48 meters above sea level	5,05E-05	Keep	Installation of foot drainage channels and V-notches around the seepage area, then routine monitoring of seepage discharge. In addition, it is necessary to install a waterproof layer, for example with *a clay blanket* on the upstream slope or the installation of a barrier wall

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3	Overflow building	Cracks and peeling of the upstream landmark concrete surface and damage to the downstream floor	4.50E-07	Low	Repair of cracks and peeling of concrete surfaces on upstream spillway landmarks and repairs on downstream floors
4	Additional spillway buildings	Possible inadequate overflow capacity	9,58E-06	Low	Conduct regular spillway door operation tests to ensure the door is always in good working order

Source: Data Processed by Researchers, 2024

For cumulative problems/risks/communities that fall into the "unacceptable" category, the improvement/creation of flood warning systems, emergency action plans including flood inundation maps are high priorities.

For problems that are not identified, it needs to be handled as a routine obligation for the maintenance and implementation of dam safety.

Conclusion

The conclusion of the risk analysis of the Prijetan Dam shows that although it has been in operation for more than a century, it requires repair and rehabilitation to reduce existing risks, especially related to structural safety and disaster risk. Several risk reduction measures, such as physical repairs, improved maintenance procedures, and strengthening early warning systems, are indispensable to maintain the sustainability and safety of dams. As a suggestion, the management should immediately prioritize the repair work that has been identified in this analysis, as well as increase regular monitoring efforts to ensure that the dam remains safe and functioning optimally for the long term.

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