SEEPAGE AND SLOPE STABILITY ANALYSIS FOR SAFETY EVALUATION OF PIDEKSO DAM

Ika Sakti Octaviarini[a*], Teuku Faisal Fathani[a]

***Abstract**: The Pidekso Dam is one of the National Strategic Projects. The dam is located in Pidekso Village, Giriwoyo District, Wonogiri Regency, Central Java Province. The dam was designed as an earth-fill dam of zonal type with random fill and an upright core. Although the construction of a dam provides huge benefits, it may pose a potential hazard if collapses. Therefore, it is necessary to conduct a study to determine the safety of the Pidekso Dam in various conditions, including during an earthquake occurrence. The study analyzed the seepage on the main dam construction using Seep/W and dam-slope stability using Slope/W by reviewing the cross-section of the dam body and its foundation. The data used as the input in the analysis include the coefficient of soil permeability, soil cohesion, internal friction angle, and soil density based on field investigations and laboratory analysis. For the seepage analysis, manual calculations were also carried out using the Schaffernak and Casagrande method compared to the Seep/W results. From the results of the seepage analysis with Seep/W, the Pidekso Dam is safe against leakage with the largest discharge of 6.480×10^{-4} m^3/s at maximum water level. The safety factor against piping showed safe results with the lowest safety factor of 6.295 at the end of the filter drainage. In the dam stability analysis with Slope/W, several unsafe conditions have the lowest safety factor of 0.926 on the upstream slope at the minimum water level with MDE (Maximum Design Earthquake) of 0.25. In Makdisi-Seed analysis, the highest slope displacement value is 0.862 m with an earthquake magnitude of 8.25; Y/H (Y is the depth from the top of the dam and H is dam height) of 0.25. This value is smaller than the maximum limit of 2.00 m, hence the dam is still in a safe condition.*

Keywords: *Earth fill Dam, piping, safety factor, stability, seepage*

INTRODUCTION

Indonesia is an agrarian country where the main source for the most population is farming. According to the Ministry of Agrarian and Spatial Planning / National Land Agency of the Republic of Indonesia (ATR/BPN) in 2019, Indonesia has 7,463,948 million hectares of rice fields. However, only about 11% of the area is supplied with dam water. Therefore, the government developed a program to construct 65 dams as stated in the 2014-2019 Medium-Term Development Plan (RPJMN). The Pidekso Dam, whose construction began in 2015 and is planned to be completed by the end of 2021, is one of the National Strategic Projects (PSN).

The location of the Pidekso Dam construction project is in Pidekso Village, Giriwoyo District, Wonogiri Regency, Central Java Province. The satellite imagery and a top view of the Pidekso Dam are shown in Figure 1. The Pidekso Dam was designed as an earth-fill dam of zonal type with random fill and upright core. This dam has a peak length of 383 m which stretches from Southeast to Southwest with a maximum dam height of 31 m from the riverbed and 44 m from the bottom of the excavation. The Pidekso Dam is planned to have a storage capacity of up to 25 million m^3.

The Pidekso Dam is expected to be able to water an irrigation area of 15,000 ha and is targeted to increase the cropping intensity from 2,000 ha to 3,000 ha. The Pidekso Dam was designed for supplying water with a capacity of 300 liters/second for Wonogiri, Sukoharjo, Solo City, and surrounding areas, and for other purposes such as flood control, land conservation, tourism, and the generation of hydroelectric power with a capacity of 0.5 MW.

Dams are very complex infrastructures with various components that support each other to withstand large loads. A dam must be ensured that it is always stable and safe during its operation to prevent the dam from collapsing which can cause a potential hazard.

Based on these problems, it is necessary to carry out an analytical study related to the safety of the Pidekso Dam including the analysis of dam slopes stability, seepage, and safety including in the event of an earthquake to provide alternatives if the analysis shows that the Pidekso Dam design is not safe.

This study aims to determine the seepage discharge through the dam body, the safety of the dam against piping, and the stability of the upstream and downstream slopes of the dam by considering earthquake loads. Many studies on the stability and safety of dams have been carried out, including the analysis of the stability of the embankment dam with modelling tests in the laboratory [1], the analysis of the stability and deformation of the Jatigede Dam [2], the safety evaluation of the Situ Gintung Dam after comprehensive rehabilitation [3], the Leuwikeris Dam safety analysis on geotechnical aspects [4], the Tukul Dam stability analysis due to reservoir water level changes [5], the Bener Dam safety analysis on geotechnical aspects [6], and slope stability analysis and erosion control in the Leuwikeris Dam spillway [7].

This study is different from the studies previously mentioned. In this study, the seepage analysis was carried out on the body and the foundation of the dam as well as the stability of the upstream and downstream slopes of the Pidekso Dam [8].

EARTH DAM

A dam is a structure built across a stream or river to hold water back for various purposes. An embankment dam is a type of dam that is built by piling up materials in a certain composition with the function of lifting the surface of the water contained in the reservoir [9].

The Pidekso Dam reviewed in this study was designed as a zonal type embankment dam with random fill and upright core with a filter zone. An embankment dam zone generally consists of several zones, namely an impervious

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Figure 1 (a) The Pidekso Dam construction project location map (Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community) [1];
(b) Top view of the Pidekso Dam

zone, a filter, a transition or semi-permeable zone, a permeable zone, and a foundation [10].

A dam must be designed according to some predetermined or required criteria. A dam must qualify the basic and general criteria. The basic criteria include safety against structural failure, safety against seepage and leakage, and safety against hydraulic failure [11]. An embankment dam must have a stable slope to prevent slope failure or landslides. It is necessary to analyze the safety factor to determine the potential collapses of the dam slopes in several conditions which are construction period, steady flow, operational, and emergency [12].

The parameter that needs to be considered is the earthquake factor. There are several earthquake conditions that need to be used as a reference in the dam design, namely Maximum Design Earthquake (MDE), Operating Basis Earthquake (OBE), and Reservoir Induced Earthquake (RIE) [13].

A slope is categorized as safe and stable if it has a safety factor greater than that required by SNI 8064:2016 regarding the method of static slope analysis of the fill type. Seepage in the dam body is also one of the important factors in dam analysis [14]. Seepage can be defined as the movement of water or water flow from a reservoir through bodies and foundations which is a function of time and includes the flow through the permeable soil.

METHODOLOGY

Problem identification was carried out as the first step of this research to determine the problem to be studied. Then, secondary data was collected from the final Report of the Pidekso Dam design including general technical data, dam engineering geological drawings, and dam material design parameters. A literature study was carried out in order to obtain information from various sources relevant to the problems to be studied in this study. The dam geometry parameter used refers to the DED Pidekso Dam STA 0+200, while the material parameters used include the coefficient of permeability, internal friction angle, soil cohesion, and soil density.

The seepage analysis was performed using Seep/W and the slope stability analysis was performed using Slope/W. The review scenario for the seepage analysis is shown in Table 1 and the review scenario for the slope stability analysis is shown in Table 2. In the dam stability analysis, earthquake loads were reviewed under 2 conditions, namely conditions allowed without damage and without collapse (OBE) and conditions that allowed non-collapse failure (MDE). If the safety factor of the Slope/W is smaller than the minimum safety factor, then further analysis will be carried out using the Makdisi-Seed method. At the last step, conclusions were drawn from the analysis that was carried out regarding the safety condition of the Pidekso Dam and some suggestions were given in accordance with the conditions obtained from the results of the analysis.

Table 1 Scenario for the seepage stability analysis

Case	Description
R1	Steady state analysis at normal water level (+185.00 m)
R2	Steady state analysis at maximum water level (+186.85 m)
R3	Steady state analysis at minimum water level (+174.50 m)
R4	Rapid drawdown transient analysis from normal to minimum water level
R5	Rapid drawdown transient analysis from maximum to minimum water level

Table 2 Scenario for the slope stability analysis

Case	Description	Earthquake	
		OBE	MDE
S0	Slope stability analysis after constructions	50%	50%
S1	Slope stability analysis at normal water level	100%	100%
S2	Slope stability analysis at maximum water level	100%	100%
S3	Slope stability analysis at minimum water level	100%	100%
S4	Slope stability analysis during rapid drawdown from normal to minimum water level	100%	-
S5	Slope stability analysis during rapid drawdown from maximum to minimum water level	-	-

THE PIDEKSO DAM DESIGN

The Pidekso Dam is an embankment dam with a zonal type consisting of several zones as its constituent layers. Based on the final report of the Pidekso Dam, the body parts of the Pidekso Dam consist of zone 1 impervious core, zone 2 filters, zone 3 transition, zone 4 and 4R random soil in the

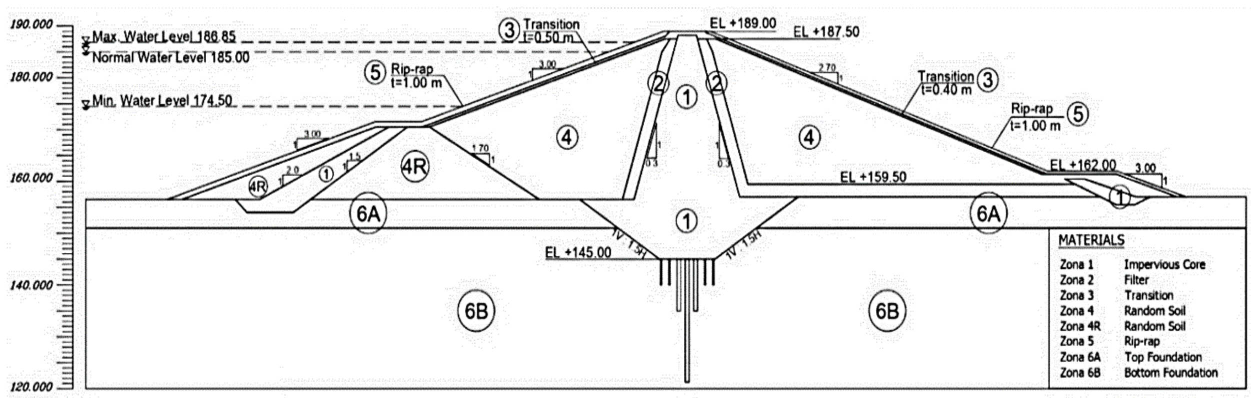

Figure 2 The geometry of Pidekso Dam STA 0+200 based on sections A-A´ in Figure 1

form of weathered rock, zone 5 rip-rap, and a foundation consisting of two layers of soil (river alluvial and talus).

In this study, the reviewed analysis was only on the dam body and the foundation layer below it. Technical data regarding the dimensions of the dam can be seen in Table 3. The design parameters for each material used in this study are shown in Table 4. Related to the seepage analysis, the water level of the reservoir used is based on the Pidekso Dam Design Final Report, including the water level. normal (+185.00 m), maximum water level (+186.85 m), and minimum water level (+174.50 m) with an average inflow of Pidekso Dam of 1.435 m3/s.

The seepage and slope stability analysis only reviews the cross-section of the dam body and foundation at STA 0+200. This profile is the profile of the dam body with the maximum height. In this analysis, simplification of the dam geometry was carried out to facilitate the modeling of the software used. The geometry of the dam at STA+200 with reference to sections A-A´ in Figure 1 can be seen in Figure 2.

Table 3 The Pidekso Dam technical data

Parameter	Value	Unit
Maximum height above the bottom of the excavation	44,00	m
Peak elevation	+189.00	m
Peak length	383.00	m
Peak width	10.00	m
Upstream slope	1:3	
Downstream slope	1:2.7	

Table 4 The Pidekso Dam material design parameters

Zone	Material	Effective soil cohesion	Effective internal friction angle	Permeability
		c'	φ'	k
		(kN/m²)	°	(m/det)
1	Impervious core	17	19	6.78×10^{-6}
2	Filter	0	35	9.25×10^{-4}
4	Random soil	28	23	2.4×10^{-4}
4R	Random soil	28	23	2.4×10^{-4}
6A	Foundation (alluvial)	10	40	
6B	Foundation (semi-consolidated talus)	40	40	

ANALYSIS AND DISCUSSION

A. SEEPAGE ANALYSIS

The seepage analysis was carried out under two conditions, namely steady-state and transient. Steady-state is a condition commonly carried out in seepage analysis on dams when seepage is constant, namely at normal water level conditions, maximum water level elevation, and minimum water level elevation. The conditions reviewed by steady-state analysis include cases of R1, R2, and R3. Seepage flow can change with time, commonly called transient flow. This condition generally occurs when there is a change in the water level of the reservoir. The conditions reviewed in the transient analysis include rapid drawdown from normal water level to minimum water level (R4) and rapid drawdown from maximum water level to minimum water level (R5) where there is a gradual decrease in water level in the reservoir.

The seepage analysis with Sepp/W began with determining the type of analysis to be used according to the conditions to be reviewed, namely steady-state and transient. This is followed by a geometric drawing referring to the simplified design drawing of the Pidekso Dam, a cross section of STA 0+200. The dam geometry modeling on Seep/W which refers to the cross-section of STA 0+200 is shown in Figure 3. The material parameters used as input to the Seep/W are shown in Table 5 and Table 6. Then the boundary conditions were determined on the upstream slope and downstream of the dam.

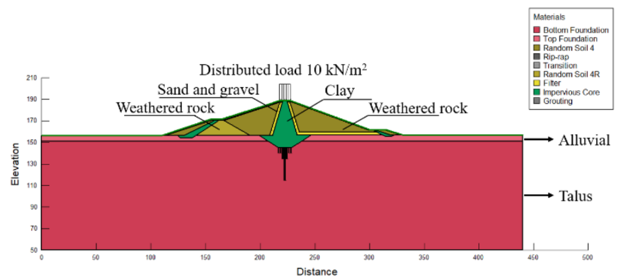

Figure 3 Seepage analysis modeling at Seep/W

B. STEADY STATE ANALYSIS

The results of the seepage analysis using the software Seep/W at normal water level conditions (R1) with the output pore water pressure distribution can be seen in Figure 4. Different color gradations in the analysis results describe the pore water pressure values with different values. Towards the bottom then the resulting color is getting darker.

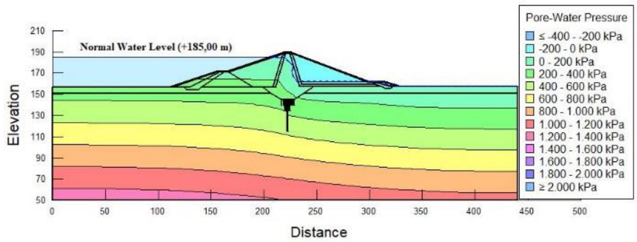

Figure 4 Pore water pressure distribution at normal water level

This shows the value of the larger pore water pressure. The blue dotted line in Figure 4 represents the phreatic line that occurs. The phreatic line is an imaginary line that separates the saturated zone and the capillary zone. The value of the pore water pressure right on the phreatic line is zero. The area above the phreatic line has a negative pore water pressure, while the area below the phreatic line has a positive pore water pressure. The negative value is caused by the presence of capillary attraction. The distribution of pore water pressure at maximum water level (R2) and minimum water level (R3) can be seen in Figure 5 and Figure 6.

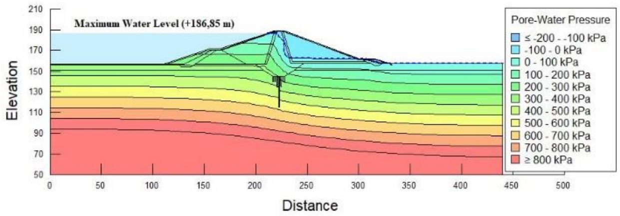

Figure 5 Pore water pressure distribution at maximum water level

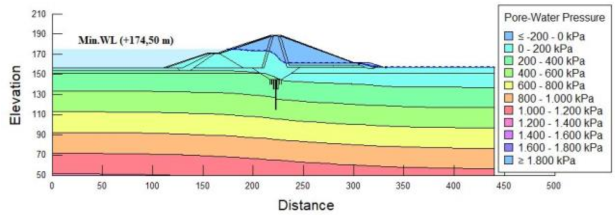

Figure 6 Pore water pressure distribution at minimum water level

Another output produced besides pore water pressure is the distribution of the total head that occurs in the dam body. The distribution of the total head can be seen in Figure 7, Figure 8, and Figure 9.

Table 5 Material input parameters in Seep/W (1)

Volumetric Water Content Function					
Material	Material Model	Type	Method	Saturated WC	Sample Material
Impervious core	Saturated/ Un-saturated	Vol. WC Data Point Func.	Sample Function	0.162	Clay
Filter				0.238	Sand
Transition				0.238	Sand
Random Soil				0.293	Gravel
Rip-rap				-	Gravel
Top foundation	Saturated Only	-	-	-	-
Bottom foundation		-	-	-	-

Table 6 Material input parameters in Seep/W (2).

Hydraulic Conductivity Function					
Material	Type	Method	VWC Function	Saturated kx (m^3/s)	ky/kx Ratio
Impervious core	Hyd. K. Data Function	Fredlund & Xing	Impervious core	8.37×10^{-8}	1
Filter			Filter	9.25×10^{-4}	1
Transition			Transition	1.00×10^{-2}	1
Random Soil			Random Soil	2.62×10^{-6}	1
Rip-rap			Rip-rap	1.00	1
Top foundation	-	-	-	8.34×10^{-7}	1
Bottom foundation	-	-	-	1.92×10^{-7}	1

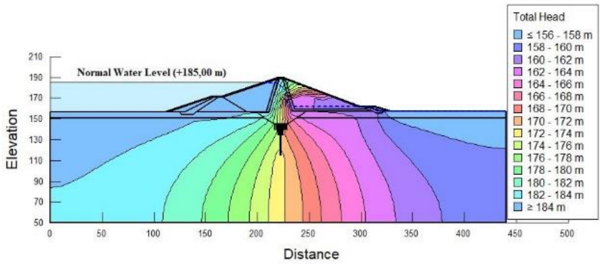

Figure 7 Total head distribution at normal water level

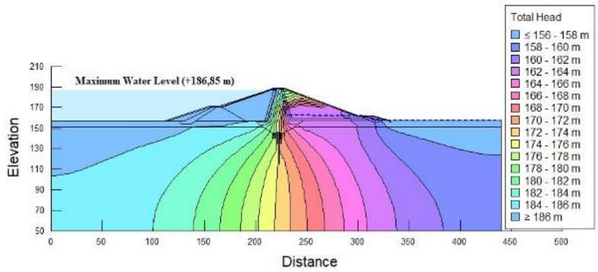

Figure 8 Total head distribution at maximum water level

In 1993, Soedibyo [15] proposed that the maximum allowable seepage discharge from the dam is 2% - 5% of the inflow. The inflow at the Pidekso Dam in this study refers to the average inflow discharge based on the hydrological analysis of the Pidekso Dam, which is 1.435

m^3/s. 2% of the dam inflow (0.029 m^3/s) was used as the maximum allowable seepage discharge.

The total seepage discharge of the dam by an analysis using the software Seep/W can be seen in Table 7. Manual calculations were also carried out using the Schaffernak and Casagrande method compared to the results of Seep/W. The results of the analysis of seepage discharge on the body of the Pidekso Dam can be seen in Table 8.

Table 7 Seepage discharge based on Seep/W

Case	Flux	Dam Width	Seepage Discharge
	(m^3/s)	(m)	(m^3/s)
Maximum Water Level	1.6743×10^{-6}	387	6.480×10^{-4}
Normal Water Level	1.0755×10^{-6}	387	4.162×10^{-4}
Minimum Water Level	2.1178×10^{-7}	387	8.196×10^{-5}

Based on the three analytical methods used, the method that is considered to provide the most accurate value is seepage analysis with Seep/W. There were two parameters used as input In Seep/W, i.e., volumetric water content and hydraulic conductivity. Volumetric water content function describes the volume of the pore voids in the soil that remain filled with water when the soil is drying, while the hydraulic conductivity function describes the soil's ability to carry or drain water in saturated or unsaturated condition. The seepage analysis with the method of Schaffernak and Casagrande only used the value of permeability as input in the calculation, so it is considered unable to produce the accurate value.

Based on the results of the seepage discharge analysis presented in Table 8, it can be seen that the largest seepage discharge in all analytical methods occurred at the maximum water level (R2). The largest seepage discharge used as a reference is the seepage discharge produced by Seep/W which is equal to 6.480×10^{-4} m^3/s. This value is still smaller than the allowable seepage discharge of 0.029 m3/s. Consequently, it can be said that the Pidekso Dam was still in the safe category against the leakage.

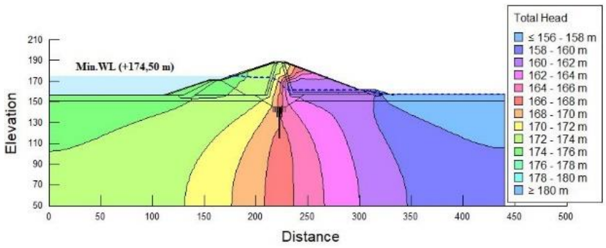

Figure 9 Total head distribution at minimum water level

Another condition that needs to be considered is the occurrence of piping. The factor of safety against piping can be expressed as the ratio between the critical gradient (i_c) and the exit gradient (i_e). In SNI 8065:2016 regarding the analysis method and how to control water seepage for embankment type dams, the minimum safety factor value against piping erosion has been set at 4. To determine the

Table 8 The results of the Pidekso Dam seepage discharge analysis

Case	Analysis Method			Maximum Seepage Discharge (m^3/s)
	Seep/W	Schaffernak	Casagrande	
	(m^3/s)	(m^3/s)	(m^3/s)	
Max. Water Level	6.480×10^{-4}	1.228×10^{-3}	1.071×10^{-3}	0.029
Normal Water Level	4.162×10^{-4}	1.011×10^{-3}	1.057×10^{-3}	0.029
Min. Water Level	8.196×10^{-5}	3.067×10^{-4}	9.880×10^{-4}	0.029

Table 9 Safety factor of piping at the end of filter drainage

Parameter	Unit	Water Level Condition		
		Maximum	Normal	Minimum
γ_{sat}	kN/m^3	20	20	20
γ_w	kN/m^3	9.81	9.81	9.81
γ'	kN/m^3	10.19	10.19	10.19
i_c	-	1.039	1.039	1.039
i_e	-	0.091	0.091	0.091
Safety factor of piping	-	6.295	6.789	10.184
Allowed safety factor of piping	-	4	4	4
Description	-	Safe	Safe	Safe

Table 10 Safety factor of piping at the downstream foot of the foundation.

Parameter	Unit	Water Level Condition		
		Maximum	Normal	Minimum
γ_{sat}	kN/m^3	21	21	21
γ_w	kN/m^3	9.81	9.81	9.81
γ'	kN/m^3	11.9	11.9	11.9
i_c	-	1.141	1.141	1.141
i_e	-	0.091	0.085	0.070
Safety factor of piping	-	12.535	13.420	16.295
Allowed safety factor of piping	-	4	4	4
Description	-	Safe	Safe	Safe

safety factor of the dam against piping hazards, a safety analysis was carried out by reviewing the end of the filter drainage and the downstream foot of the foundation. The results of the safety factor analysis for piping at the end of the filter drainage and the downstream foot of the foundation are shown in Table 9 and Table 10.

Based on Table 9 and Table 10, the lowest safety factors for each review are 6.295 and 12.535. These values are larger than the maximum allowable value of 4, hence it can be said that the dam is safe against piping.

C. TRANSIENT ANALYSIS

The parameter reviewed in the transient analysis is the condition when the seepage occurs is not constant as a function of time due to rapid drawdown. The analysis of R4 was reviewed at 50 days and R5 was reviewed at 60 days. The non-constant seepage due to rapid drawdown can be seen through the transformation of the phreatic line upstream of the dam as shown in Figure 10 and Figure 11.

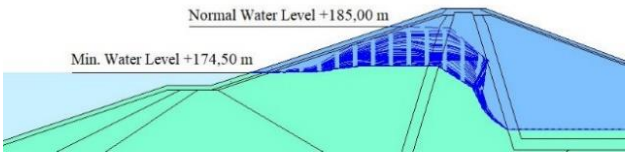

Figure 10 Seepage conditions during rapid drawdown from normal to minimum water level

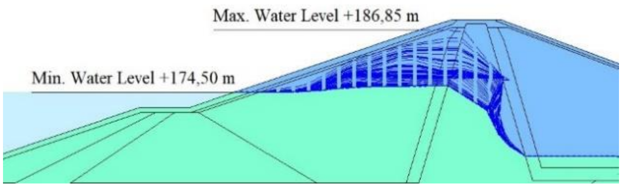

Figure 11 Seepage conditions during rapid drawdown from maximum to minimum water level

D. SLOPE STABILITY ANALYSIS OF DAM

The slope stability analysis of the dam was carried out by reviewing the safety factor on the upstream and downstream slopes under various conditions as shown in Table 2. If the slope safety factor does not reach the minimum requirements, then the analysis will be continued with the Makdisi-Seed analysis to determine the stability of the dam. The analysis type used in the analysis of dam slope stability with Slope/W is the limit equilibrium using the Morgenstern-Price (MP) method. The dam geometry used refers to the geometry in the selected parent analysis, namely the dam geometry in the previous seepage analysis.

The analysis of slope stability in the event of earthquake loads needs to include the value of the seismic load. In this study, the seismic load entered is the design earthquake coefficient (K). An earthquake coefficient at depth (Y) from the top of the dam have different values with a review carried out on $Y = 0.25H$; $0.50H$; $0.75H$; and H (H is the height of the dam). An illustration of the term Y/H can be seen in Figure 12. The design earthquake coefficient values for each depth can be seen in Table 11.

The input parameters for each material that make up the dam body can be seen in Table 12. The slip surface is described using the entry and exit method. The direction of movement is adjusted to the location of the slope to be reviewed. The output of slope stability analysis using Slope/W is the slope safety factor.

A slope that is categorized as safe if it has a safety factor greater than the allowable safety factors required by SNI 8064:2016. The allowable safety factors for after construction condition are 1.3 (without seismic load) and 1.2 (with seismic load). The allowable safety factors for normal water level are 1.5 (without seismic load) and 1.2 (with seismic load). The allowable safety factors for maximum and minimum water levels are 1.3 (without seismic load) and 1.1 (with seismic load). The allowable safety factors for normal water level have a greater value than the maximum and minimum water level conditions. This is intended to anticipate the effects of uncertainty on the shear strength of the material, pore water pressure in the impervious core, long-term loading, the downstream slope collapse, and emergency water release.

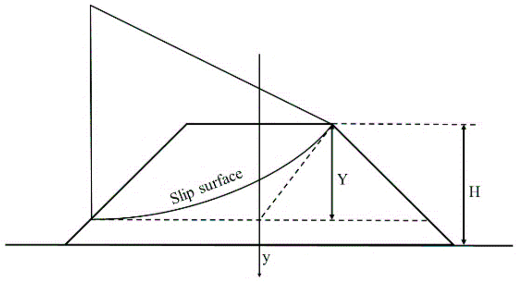

Figure 12 Illustration of the term Y/H

Table 11 The design earthquake coefficient.

(Y/H)	Earthquake return period	
	100 Years (OBE)	5000 Years (MDE)
0.25	0.156	0.245
0.50	0.130	0.204
0.75	0.119	0.186
1.00	0.107	0.168

Table 12 Material input parameters in Slope/W.

Material	Parameter			
	Material model	Unit Weight kN/m^3	Cohesion kPa	Phi °
Impervious core	Mohr-Coulomb	17	17	19
Filter	Mohr-Coulomb	19	0	35
Transition	Mohr-Coulomb	19	0	35
Random soil	Mohr-Coulomb	18	28	23
Top foundation	Mohr-Coulomb	20	10	40
Bottom foundation	Bedrock	-	-	-

E. CONDITION AFTER CONSTRUCTION (CASE S0)

Referring to SNI 8064:2016 regarding the method of static slope stability analysis of embankment dams, the earthquake coefficient used in the slope stability analysis for conditions after construction is 50% of the design earthquake coefficient as shown in Table 13.

The results of the analysis using Slope/W show that the most critical safety factor on the downstream slope is 1.389 which occurred in MDE earthquake conditions with a depth of $0.25H$. The landslide field for this condition can be seen in Figure 13. On the upstream slope, the most critical factor of safety is 1.488 which occurred in MDE

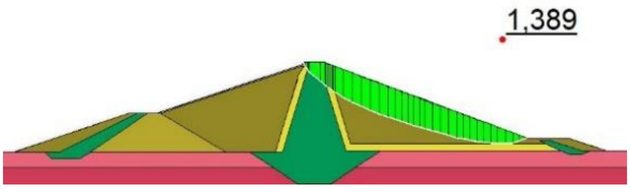

Figure 13 Downstream slope slip surface conditions after construction (MDE 0.25H)

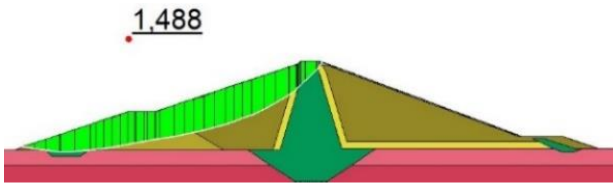

Figure 14 Upstream slope slip surface conditions after construction (MDE 0.25H)

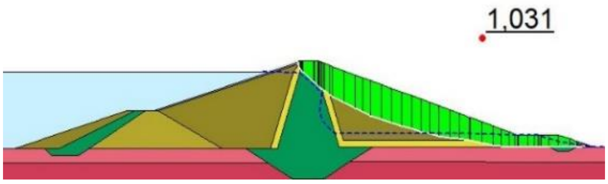

Figure 15 Downstream slope slip surface at normal water level (MDE 0.25H)

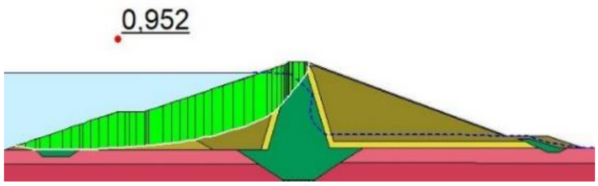

Figure 16 Upstream slope slip surface at normal water level (MDE 0.25H)

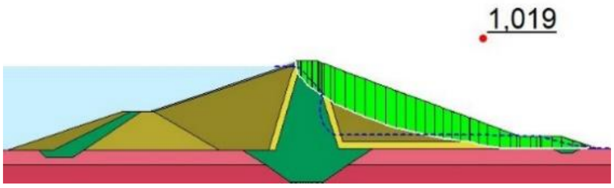

Figure 17 Downstream slope slip surface at maximum water level (MDE 0.25H)

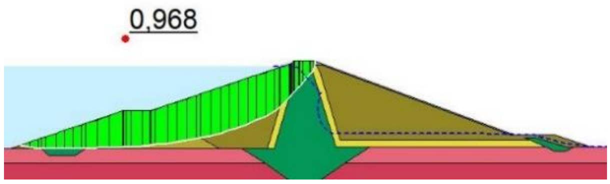

Figure 18 Upstream slope slip surface at maximum water level (MDE 0.25H)

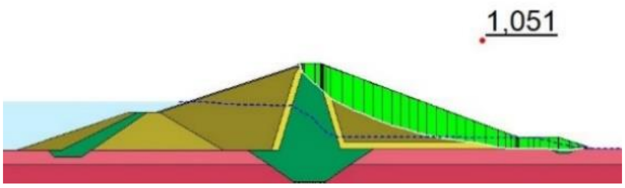

Figure 19 Downstream slope slip surface at minimum water level (MDE 0.25H)

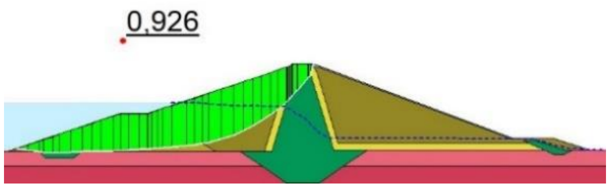

Figure 20 Upstream slope slip surface at minimum water level (MDE 0.25H)

conditions with a depth of 0.25*H*. The landslide field for this condition can be seen in Figure 14. These values were still larger than the minimum safety factor required for MDE earthquake conditions, which is 1.00, so the upstream slope of the dam can be categorized as safe. The safety factor for the upstream and downstream slopes of the dam with various seismic conditions after construction conditions can be seen in Table 14.

Table 13 The design earthquake coefficient for dam condition after construction.

Y/H	Earthquake return period	
	100 Years (OBE)	5000 Years (MDE)
0.25	0.078	0.122
0.50	0.065	0.102
0.75	0.059	0.093
1.00	0.054	0.084

F. NORMAL WATER LEVEL CONDITION (CASE S1)

On the downstream slope of the dam, the most critical safety factor is 1.031 which occurred in the MDE 0.25*H* earthquake conditions. This value is still larger than the minimum allowed safety factor, which is 1.00. The slip surface for this condition can be seen in Figure 15.

On the upstream slope, the most critical safety factor also occurred in the MDE 0.25*H* earthquake condition with a safety factor value of 0.952. In this condition, the upstream slope was not safe because the resulting safety factor was smaller than the required safety factor of 1.00. The slip surface for this condition can be seen in Figure 16. The value of the safety factor for the upstream and downstream slopes at normal water level conditions can be seen in Table 15.

G. MAXIMUM WATER LEVEL CONDITION (CASE S2)

On the downstream slope of the dam, the most critical safety factor is 1.019 which occurred in the MDE 0.25*H* earthquake conditions. This value is still larger than the minimum allowed safety factor of 1.00. The slip surface for this condition can be seen in Figure 17.

On the upstream slope, the most critical safety factor also occurred in the MDE 0.25*H* earthquake condition with a safety factor value of 0.968. In this condition, the upstream slope was not safe because the resulting safety factor was smaller than the required safety factor, which is 1.00. The slip surface for this condition can be seen in

Table 14 Safety factors after construction

Case	*Y/H*	Earthquake coefficient	Downstream	Upstream	Allowable safety factors	Description	
						Downstream	Upstream
Without seismic loads	-	-	1.891	2.101	1.3	Safe	Safe
OBE	0.25	0.078	1.539	1.665	1.2	Safe	Safe
	0.50	0.065	1.586	1.725	1.2	Safe	Safe
	0.75	0.059	1.608	1.757	1.2	Safe	Safe
	1.00	0.054	1.628	1.782	1.2	Safe	Safe
MDE	0.25	0.122	1.389	1.488	1.0	Safe	Safe
	0.50	0.102	1.446	1.568	1.0	Safe	Safe
	0.75	0.093	1.480	1.602	1.0	Safe	Safe
	1.00	0.084	1.522	1.641	1.0	Safe	Safe

Table 15 Safety factors at normal water level

Case	*Y/H*	Earthquake coefficient	Downstream	Upstream	Allowable safety factors	Description	
						Downstream	Upstream
Without seismic loads	-	-	1.891	2.101	1.5	Safe	Safe
OBE	0.25	0.156	1.232	1.244	1.2	Safe	Safe
	0.50	0.130	1.307	1.365	1.2	Safe	Safe
	0.75	0.119	1.339	1.416	1.2	Safe	Safe
	1.00	0.107	1.380	1.480	1.2	Safe	Safe
MDE	0.25	0.245	1.031	0.952	1.0	Safe	Unsafe
	0.50	0.204	1.117	1.070	1.0	Safe	Safe
	0.75	0.186	1.158	1.132	1.0	Safe	Safe
	1.00	0.168	1.202	1.198	1.0	Safe	Safe

Table 16 Safety factors at maximum water level

Case	*Y/H*	Earthquake coefficient	Downstream	Upstream	Allowable safety factors	Description	
						Downstream	Upstream
Without seismic loads	-	-	1.886	2.101	1.3	Safe	Safe
OBE	0.25	0.156	1.228	1.276	1.1	Safe	Safe
	0.50	0.130	1.297	1.401	1.1	Safe	Safe
	0.75	0.119	1.341	1.461	1.1	Safe	Safe
	1.00	0.107	1.370	1.529	1.1	Safe	Safe
MDE	0.25	0.245	1.019	0.968	1.0	Safe	Unsafe
	0.50	0.204	1.105	1.089	1.0	Safe	Safe
	0.75	0.186	1.144	1.151	1.0	Safe	Safe
	1.00	0.168	1.194	1.226	1.0	Safe	Safe

Table 17 Safety factors at minimum water level

Case	*Y/H*	Earthquake coefficient	Downstream	Upstream	Allowed safety factors	Description	
						Downstream	Upstream
Without seismic loads	-	-	1.891	2.098	1.3	Safe	Safe
OBE	0.25	0.156	1.262	1.171	1.1	Safe	Safe
	0.50	0.130	1.333	1.271	1.1	Safe	Safe
	0.75	0.119	1.367	1.320	1.1	Safe	Safe
	1.00	0.107	1.408	1.366	1.1	Safe	Safe
MDE	0.25	0.245	1.051	0.926	1.0	Safe	Unsafe
	0.50	0.204	1.137	1.020	1.0	Safe	Safe
	0.75	0.186	1.182	1.071	1.0	Safe	Safe
	1.00	0.168	1.229	1.119	1.0	Safe	Safe

Figure 18. The value of the safety factor for the upstream and downstream slopes at normal water level conditions can be seen in Table 16.

H. MINIMUM WATER LEVEL CONDITION (CASE S3)

On the downstream slope of the dam, the most critical safety factor is 1.051, which is larger than the minimum safety factor that occurred in the MDE 0.25*H* earthquake conditions. The downstream slip surface in this condition is shown in Figure 19. On the upstream slope, the most critical safety factor also occurred in the MDE 0.25*H* earthquake condition with a safety factor value of 0.926. In this condition, the upstream slope was not safe because the resulting safety factor was smaller than the required safety factor. The upstream slip surface in this condition is shown

Table 18 The results of the Makdisi-Seed analysis

Slope	M_s	Y/H	U_{maks} (g)	K_{maks}/U_{maks}	K_{maks} (g)	K_y	K_y/K_{maks}	Uk	U (m)
Upstream	6.5	0.25	1.281	0.842	1.079	0.236	0.219	0.106	0.125
		0.50	1.281	0.600	0.769	0.217	0.282	0.075	0.124
		0.75	1.281	0.432	0.554	0.198	0.358	0.026	0.060
	7.5	0.25	1.281	0.842	1.079	0.236	0.219	0.452	0.534
		0.50	1.281	0.600	0.769	0.217	0.282	0.266	0.441
		0.75	1.281	0.432	0.554	0.198	0.358	0.035	0.081
	8.25	0.25	1.281	0.842	1.079	0.236	0.219	0.730	0.862
		0.50	1.281	0.600	0.769	0.217	0.282	0.476	0.789
		0.75	1.281	0.432	0.554	0.198	0.358	0.069	0.160

in Figure 20. The overall value of the safety factor at normal water level conditions can be seen in Table 17.

I. RAPID DRAWDOWN FROM NORMAL TO MINIMUM WATER LEVEL (CASE S4)

Based on the results of the analysis with Slope/W, the most critical safety factor in conditions without seismic load on day 1 is 1.556. This value is larger than the required minimum safety factor of 1.3. The slip surface for this condition can be seen in Figure 21. However, when the OBE seismic load is applied, the analysis results show that the most critical safety factor is 0.854 which occurred during the 0.25*H* OBE earthquake on day 1. This value did not reach the required minimum safety factor value, which is 1.1. As a result, the upstream slope of the dam was in an unsafe condition at rapid drawdown from minimum to normal water level with the OBE earthquake. The slip surface for this condition can be seen in Figure 22.

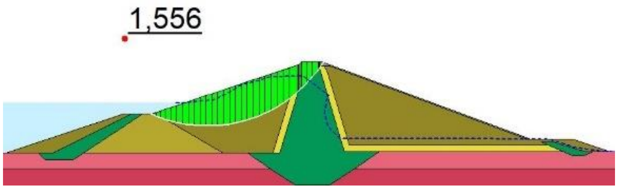

Figure 21 Upstream slope slip surface at rapid drawdown from normal to minimum water level without seismic load (day 1)

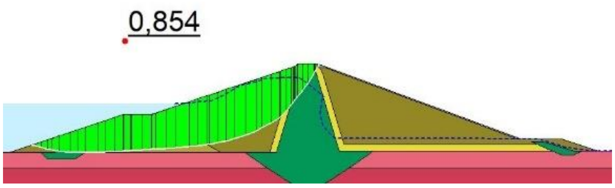

Figure 22 Upstream slope slip surface at rapid drawdown from normal to minimum water level with OBE 0.25H earthquake (day 1)

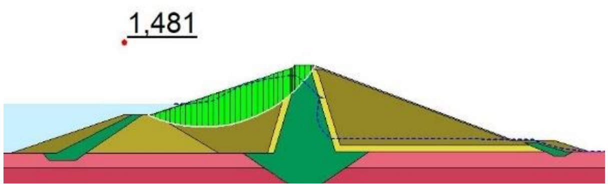

Figure 23 Upstream slope slip surface at rapid drawdown from maximum to minimum water level without seismic load (day 1)

J. RAPID DRAWDOWN FROM MAXIMUM TO MINIMUM WATER LEVEL (CASE S5)

Based on the results of the analysis using Slope/W, the most critical safety factor is 1.480 which occurred on day 1. This value is larger than the minimum allowed safety factor, which is 1.3 hence it can be said that the upstream slope was safe. The slip surface of the upstream slope in this condition is shown in Figure 23. The overall safety factor for the upstream slope under rapid drawdown conditions from maximum to minimum water level with a review period of 60 days has shown that all conditions are safe.

K. MAKDISI-SEED ANALYSIS

Based on the results of the slope stability of the dam, there were several reviews that indicate the condition is unsafe because the resulting safety factor did not reach the minimum safety factor required in SNI 8064:2016. Therefore, further analysis was needed to determine the stability of the dam using the Makdisi-Seed analysis method [16]. The results of the Makdisi-Seed analysis for the upstream slope of the dam can be seen in Table 18.

Based on the results of the Makdisi-Seed analysis in Table 18, the largest fixed displacement value (*U*) is 0.862 m which occurred on the upstream slope with an earthquake magnitude of 8.25 at a *Y/H* depth of 0.25. The maximum fixed displacement for an embankment dam is half of the guard height. The fixed displacement for Pidekso Dam is 2.00 m. The largest fixed displacement was still smaller than the maximum allowable value, accordingly, it can be said that the Pidekso Dam is still in a stable condition.

CONCLUSIONS

Based on the seepage analysis using Seep/W, the largest seepage discharge, which is 6.480×10^{-4} m^3/s, occurred at maximum water level (R2). This value was smaller than the maximum allowable discharge, which is 0.029 m^3/s. This means that the Pidekso Dam is safe against the danger of leakage due to seepage. The results of the analysis show that the overall safety factor for piping is greater than the minimum safety factor in all review conditions. The lowest safety factor against piping at the downstream foot of the foundation is 12.535 and at the end of the filter drainage was 6.295 which occurred at the maximum water level. This has shown that the Pidekso Dam is safe against piping.

In the slope stability analysis of the dam, there were several analysis results that indicate the slope conditions were not safe because the resulting safety factor value is smaller than the minimum safety factor. The lowest safety factor was found at 0.926 which occurred on the upstream slope with minimum water level conditions with an MDE earthquake of 0.25*H* (S3). This value is smaller than the minimum safety factor, which is 1.00, and therefore, the slope was not safe. However, when the further analysis was carried out using the Makdisi-Seed method, the largest fixed displacement value is 0.862 m, which occurred under M_s = 8.25 earthquake conditions with a depth of 0.25*H*. This value was still smaller than the required maximum value allowed, which is 2.00 m, in consequence the slope of the dam was still in a safe and stable condition.

Suggestions that can be taken into consideration for further research include the need for further analysis of the safety factor for the possibility of hydraulic cracking, analysis of reservoir water fluctuation conditions by considering the duration of the rapid drawdown conditions adjusted to the Pidekso reservoir rule curve (for inflow under normal year flow conditions, wet, and dry) and analysis of the dynamic load of earthquake using finite elements so that the amplification effect on the dam body can be evaluated accurately. Further analysis of the Pidekso Dam stability can also be carried out after the construction is completed by considering the safety of its complementary buildings.

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