

Designing conduit sabo dam series as a debris flow protection structure

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Abstract. A high potential area for landslides was identified upstream of the Air Beras River on Bukit Beriti Besar which was feared to generate debris flow through the Air Beras River. One of the preventive efforts that can be conducted for debris flow is the sabo dam. This study aims to design a series of conduit sabo dams and evaluate the structure stability according to SNI 2851:2015 and Technical Standards and Guidelines for Planning and Design of Sabo Structures (JICA, 2010). By using the design discharge of debris flow of 120 m³/s, the velocity of 5.06 m/s, and the inclination of the riverbed of around 6.16°, the spillway height of the Sabo Dam 1 was determined to be 3 m, while the spillway height of Sabo Dam 2 was 2 m. The Sabo Dam 1 has a height of 10 m and a width of 30 m with a total manageable volume of 49,600 m³ while the Sabo Dam 2 has a height of 10 m and a width of 45 m with a total manageable volume of 91,500 m³. The safety factors of the sabo dam in the debris flow condition were 2.14 for overturning, 1.50 for sliding, and 5.74 for bearing capacity. Based on the result, the conduit sabo dam series effectively controls the destructive power of debris flow.

1 Introduction

Debris flow typically consists of an unsteady, non-uniform surge of the mixture of muddy water and a high concentration of sediment. It attains large mobility from the enlarged void space saturated with water or slurry. It is a secondary disaster that can be initiated by a landslide, riverbed erosion, and natural dam breaching [1-2]. It has a high destructive power that makes it one of the most catastrophic hazards in mountainous areas [3].

A landslide is a form of mass movement that is influenced by several factors such as morphology, mechanics of rock/soil, hydro-geological, and land use. Many landslide occurrences are triggered by storm rainfall and earthquake. Slope stability depends on the form of interaction between the slope constituent material and triggering factors [4]. The excess pore water pressure in the soil causes interference in slope stability. The groundwater level will reach the slip surface so that the pore structure of the soil layer will be damaged, and the soil particles lose their shear resistance, causing deep landslides [5]. The soil particles are no longer bound to each other but stay on top of the liquefied layer as an earth block. If the water in the pore of the earth block has been used up to produce the liquefied layer or the earth block has reached a flatter area, it will stop. However, the debris

flow following the earth block will continue flowing down.

Referring to geological and geotechnical studies, the western area of the Air Beras River on Bukit Beriti Besar has a high potential for landslides that can trigger debris flow [6-7]. The rock lithology identified in this area has undergone alteration, resulting in brownish-white and grayish-white alterations. The debris flow in this area was predicted to flow through the Air Beras River. The upstream of this river has a characteristic of a V-shaped river valley with a narrow cross-section and steep river cliffs.

The debris flow disasters can be countered by structural and non-structural works. The structural work is intended to reduce the energy of debris flow, store sediment, or divert the flow, thereby preventing severe damage to the protected facility. In contrast, the non-structural work is aimed to increase the resilience of the environment-community and/or existing buildings against the risk of debris flow. The common structural protection works against debris flow are debris flow shed, deflection wall, and sabo dam. Several previous studies have shown that a sabo dam provides satisfactory performance in storing sediment [8-11]. Based on the construction function, sabo dams can be classified into slit sabo dams, breaker sabo dams, and barrier sabo dams. The

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slit type can be in the form of a conduit sabo dam has been revealed as the most effective structure to trap large boulders on debris flow [12]. The debris flow in 2016 in the Air Kotok River (the southern of the upstream of the Air Beras River) on Bukit Beriti Besar showed that the debris material was a combination of boulders with a maximum diameter of 1.5 m and trees [13]. Thus, in this study, the conduit sabo dam equipped with sub sabo dam and apron was selected to mitigate debris flow and decrease impact damage.

2 Conduit sabo dam

A Sabo dam is intended to reduce flowing sediment that is moving downstream to prevent the movement of unstable sediment on the riverbed and to control the sediment runoff. A Conduit sabo dam has an additional opening in the main body to drain flowing material and the crest of the main body may be used as a road or bridge (Fig. 1).

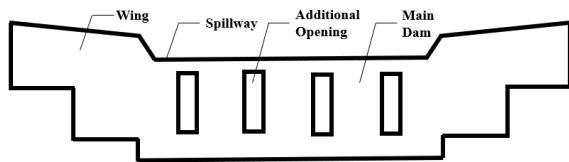


Fig. 1. The conduit sabo dam.

The structure location was selected by considering the result of the feasibility study, which included social, engineering, environmental, and economic aspects [14-15]. The location of the structure should comply with the following conditions:

- a. The structural placement is carried out in a location that should satisfy the geological condition and in straight river geometries.

- b. A hydraulic review is necessary when the structure is placed on a river bend to determine the runoff and scouring potential upstream and downstream of the structure.
- c. Structures and their utilities are placed in an area with large storage volumes, but not in a location where there are residential and productive areas.
- d. The structures are protected from the dangers of river degradation. The axis of the main body should be perpendicular to the downstream flow direction.

The use of conduit sabo dam series is intended to be able to manage more sediment volume and thus be more effective. In addition, the sabo dam series works effectively when placed between the end of the source area to the transport zone. Taking into several aspects of the foregoing, the selected location of the sabo dams was shown in Fig. 2.

3 Designing sabo dam

The design of the sabo dams for debris flows was in compliance with the SNI 2851:2015 on Designing Sediment Retaining Structures and Technical Standards and Guidelines for Planning and Design of Sabo Structures ratified by JICA (2010). The design work includes the design for the main sabo dam, sub sabo dam, and apron.

3.1 Main sabo dam

The dimensions of the sabo dam were designed to be favorable to catch sediment in the mixture flowing. The design is referred to SNI 2851:2015 and JICA (2010). The height of the sabo dam was determined by considering the storage volume sediment, while the width of the sabo dam was adjusted to the river width.

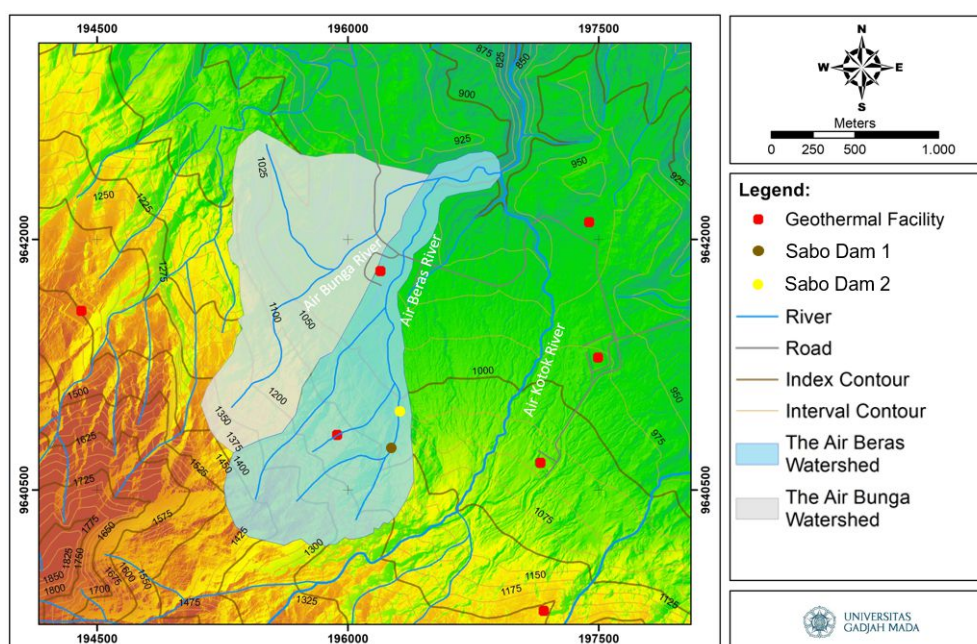


Fig. 2. The location of Sabo Dam

The manageable sediment volume that can be controlled by the sabo dam was calculated using Equation (1) and Equation (2).

$$V_p = nH^2B \quad (1)$$

$$V_c = 0.5nH^2B \quad (2)$$

where V_p is the potential storage volume (m³); V_c is the control volume (m³); n is the ratio of riverbed inclination ($1/D$); H is the height of sabo dam (m), and B is the width of sabo dam (m). The calculation result for the dimensions of the sabo dam and the sediment volume can be seen in Table 1.

Table 1. The dimension of the sabo dam and the sediment volume

Parameter	Sabo Dam 1	Sabo Dam 2
River width at structure location (B_{loc} , m)	33.1	61
Width of the dam ($B_{main\ dam}$, m)	30	45
Height of dam (H , m)	10	10
Potential storage volume (V_p , m ³)	33,100	61,000
Control volume (V_c , m ³)	16,500	30,500

The spillway of the sabo dam is designed to escape the stream which is perpendicular to the axis of the downstream river. The width of the crest spillway should be over 3 m and the inclination of crest spillway m_2 is 0.5. Furthermore, in the main body of the sabo dam, additional openings were also made to drain the debris flow. Therefore, if the overflow depth is h_1 (m) and the base width of the spillway is B_1 , the discharge of the spillway can be calculated using Equation (3).

$$Q_{co} = (0.71 \times h_1 + 1.77 \times B_1) \times h_1^{3/2} \quad (3)$$

The dimensions of the spillway were determined by a trial-error method to obtain the optimal height. The spillway has a trapezoidal shape, while the additional opening is rectangular. Using the design discharge of debris flow of 120 m³/s, the velocity of 5.06 m/s, and the inclination of the riverbed of around 6.16°, the dimensions of the spillway can be seen in Tabel 2, where the height of the freeboard is 0.6 m.

3.2 Sub sabo dam and apron

The sub sabo dam is a complementary building designed by considering the dimension of the river and the dimension of the main sabo dam. One of the functions of the sub sabo dam is to reduce the energy flow. Therefore, the height of the sub sabo dam was determined to be 1/3 of the main dam height and the width was adjusted to the width of the river [16]. The sub sabo dam and the main sabo dam were connected by an apron made of reinforced

concrete. The apron served to avoid local scour, maintain the stability of the sabo dam, and protect the sabo dam foundation from cliff collapse. The length of the apron was calculated by using Equation (4) and the thickness of the apron with Equation (5).

$$L_a = (1.5 \text{ until } 2.0) \times (h_1 + h_3) \quad (4)$$

$$t_a = 0.2(0.3h_1 + 0.6h_3 - 1.0) \quad (5)$$

where h_1 is the height of the water flow upper spillway and h_3 is the height from the apron's surface to the crest of the main body, respectively in m. The dimension of the sub sabo dam and apron is shown in Table 3.

Table 2. The dimension of the spillway and additional opening

Parameter	Sabo Dam 1	Sabo Dam 2
Flow height (h_1 , m)	1.7	1.3
Spillway height ($h_{spillway}$, m)	3.0	2.0
Spillway thickness (t_s , m)	3.0	3.0
The inclination of crest spillway (m_2)	0.5	0.5
Width of the base spillway (B_1 , m)	30.0	45.0
Width of crest spillway (B_2 , m)	33.0	47.0
Width of additional opening (B_{las} , m)	1.5	1.5
Height of additional opening (h_{las} , m)	3.0	3.0
Amount of additional opening	5	5

Table 3. The dimension of the spillway and additional opening

Parameter	Sabo Dam 1	Sabo Dam 2
Height of sub sabo dam (H_2 , m)	4.00	4.00
Width of sub sabo dam (B_{sub} , m)	30.00	45.00
Length of the apron (L_a , m)	15.00	15.00
Minimum thickness of apron (t_a , m)	0.90	0.92

4 Stability of main sabo dam

The main body should satisfy the stability requirements, including the stability against overturning, sliding, and bearing capacity. Based on SNI 2851:2015, the minimum safety factor for the dam structure is summarized in Table 4.

Table 4. Requirement for the safety factor

Parameter	Safety Factor
Stability against overturning	≥ 2
Stability against sliding	≥ 1.5
Bearing Capacity	≥ 1.5

4.1 Forces acting on sabo dam

The calculation of the safety factors of these parameters started with calculating the forces acting on the structure. These forces were such as a dead load from the weight of the structure, hydrostatic pressure, earth pressure, the weight of debris flow, debris flow hydro-force, and uplift force. The diagram force can be seen in Fig. 3.

These forces will invent moment with a point of view downstream of the structure. By using the unit weight of water (γ_w) of 9.81 kN/m³, the unit weight of concrete (γ_c) of 24 kN/m³, the unit weight of sediment (γ_s) of 16.7 kN/m³, and the sediment coefficient (C_e) of 0.27, the vertical force, the horizontal forces, and the moment acting on the structures can be seen in **Table 5**.

4.2 Overturning stability

The stability against overturning was evaluated by comparing the resisting moment M_r (kN.m) and the driving moment M_d (kN.m) with a base point downstream as Equation (6). The moment was obtained by multiplying the force by the moment arm length. Overturning failure can occur if the driving moment is greater than the resisting moment.

$$SF_{ot} = \frac{\sum M_r}{\sum M_d} \quad (6)$$

The stability against overturning also can be evaluated by a threshold of eccentricity. Eccentricity can occur due to the deviation of the center of resultant force from the center of mass. Eccentricity is acceptable if the resultant force acts within $b_2/3 < x < 2b_2/3$, where x is the length between the point of working resultant force at the main dam bottom and a downstream end. If the safety factor or eccentricity value does not comply with the requirements, the design of the sabo dam should be reviewed. The result is summarized in Table 6.

Based on Table 6, the resisting moment was greater than the driving moment. From the value of safety factor, it is known that the structure is qualified against overturning and fulfilling the safety requirement. In terms of eccentricity, the value of x was still within the allowed limits.

Table 6. The calculation result of stability against overturning

Parameter	Notation	Value
Resisting Moment	$\sum M_r$ (kN.m)	9,289.51
Driving Moment	$\sum M_d$ (kN.m)	4,350.77
Safety Factor	SF_{ot}	2.14
Length of Resultant Force	x (m)	5.27
The base width of the main body	b_2 (m)	10.00
Eccentricity	e (m)	0.27
Threshold	$b_2/3 < x < 2b_2/3$	OK

4.3 Sliding stability

The stability against sliding was influenced by the resultant of the resisting force and the resultant of the driving force. The resultant of the resisting force is a combination of soil shear strength and resistance from the mass structure while the horizontal force is generated by the external force. The stability against sliding may be evaluated using Equation (7).

$$SF_{sl} = \frac{\sum V_{fo} \tan \phi + c \times b_2}{\sum H_{fo}} \quad (7)$$

where V_{fo} is a vertical force (kN), ϕ is internal friction angle ($^\circ$), c is cohesion (kN/m²), b_2 is the width of the main body base (m), H_{fo} is a horizontal force (kN).

The principle of it is that the resultant of the resisting force should be greater than the driving force acting on the structure and as a result, the structure can maintain its stable position. The forces acting on the structure can be seen in Table 5. Using the cohesion (c) of subgrade equal to 51.22 kN/m² and the internal friction (f) equal to 35.25 $^\circ$, the calculation result of stability against sliding is shown in Table 7.

Table 7. The calculation result of stability against sliding

Parameter	Notation	Value
Resultant of resisting force	$\sum F_v$ (kN)	1,757.60
Resultant of the driving force	$\sum F_H$ (kN)	1,168.93
Stability against sliding	SF_{sl}	1.50

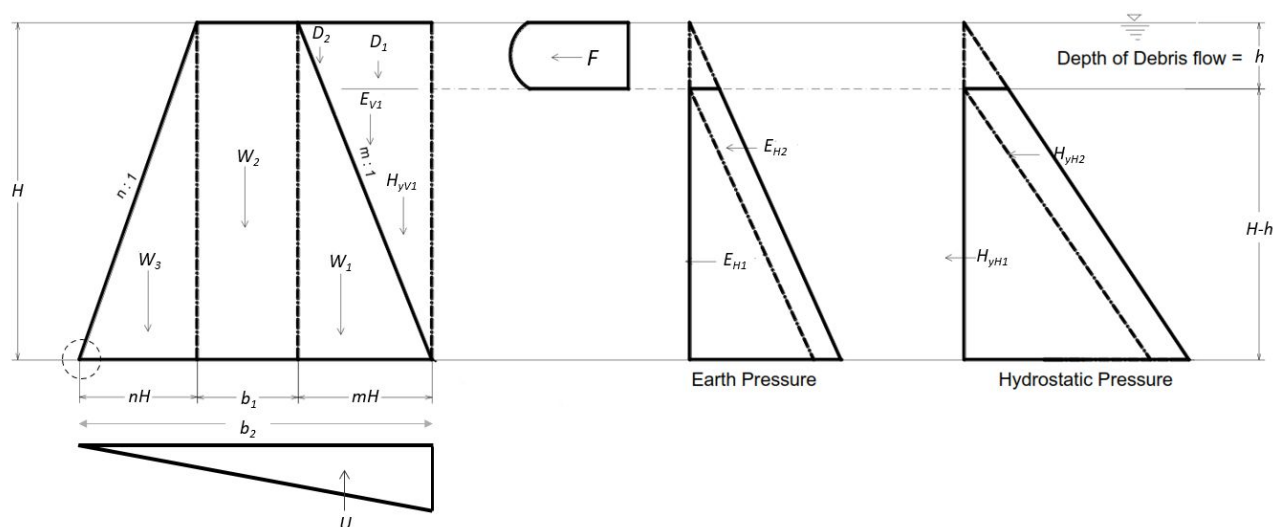


Fig. 3. The diagram force (modified from JICA, 2010).

Table 5. The calculation result of forces acting on sabo dam

Parameter	Formula	Force (kN)		Arm Length (m)	Moment (kN.m)	
		Vertical	Horizontal		Vertical	Horizontal
Dead Load (<i>W</i>)	$W_1 = 0.5\gamma_c mH^2$	600.00	-	6.67	4,000.00	-
	$W_2 = \gamma_c b_1 H$	720.00	-	3.50	2,520.00	-
	$W_3 = 0.5\gamma_c nH^2$	240.00	-	1.33	320.00	-
Hydrostatic Pressure (<i>H_y</i>)	$H_{yv1} = 0.5\gamma_w m(H-h)^2$	213.13	-	8.45	1,800.12	-
	$H_{yH1} = 0.5\gamma_w (H-h)^2$	-	426.25	3.11	-	1,324.51
	$H_{yH2} = \gamma_w h(H-h)$	-	62.00	4.66	-	288.96
Earth Pressure (<i>E</i>)	$E_{v1} = 0.5\gamma_s m(H-h)^2$	362.81	-	8.45	3,064.43	-
	$E_{H1} = 0.5\gamma_s m(H-h)^2$	-	362.81	3.11	-	1,127.39
	$E_{H2} = C_e \rho_f h(H-h)^2$	-	292.21	4.66	-	1,362.00
Weight of Debris Flow (<i>D</i>)	$D_1 = \rho_d hm(H-h)$	80.58	-	7.67	617.97	-
	$D_2 = 0.5\rho_d mh^2$	2.93	-	5.23	15.31	-
Debris Flow Hydro-Force (<i>F</i>)	$F = \frac{\rho_d}{g} h(v_d)^2$	-	25.66	9.66	-	247.90
Uplift (<i>U</i>)	$U = 0.5\gamma_w b_2 (H-h)$	-457.25	-	6.67	3,048.32	-
Total		1,762.19	1,168.93		9,289.51	4,350.77

The shear strength parameters of the subgrade gave a significant effect to the resisting force. The shear strength parameters had a linear relationship with shear stability, which was the greater parameters would increase the resisting force. The subgrade had very good shear strength parameters because the constituent bedrock was a compact andesite. Based on the result in Table 7, it can be stated that the structure fulfills the safety requirement, as the value of SF_{sl} is ≥ 1.5 .

4.4 Bearing capacity

The bearing capacity was evaluated with the ratio of the ultimate bearing capacity of the subgrade and the maximum normal stress acting on the structure. If q_u is the ultimate capacity of subgrade (kN/m^2) and σ_{max} is maximum normal stress (kN/m^2), a safety factor of bearing capacity is given by Equation (8).

$$SF_{bc} = \frac{q_u}{\sigma_{max}} \quad (8)$$

The ultimate bearing capacity can be calculated using the Terzaghi formula or using the recommended value by JICA (2010). The smallest value of the ultimate bearing capacity was used to obtain the conservative value in the safety factor calculation. While the normal stress was influenced by the vertical force, the base width of the main body, and the eccentricity. The calculation result of bearing capacity was summarized in Table 8.

Table 8. The calculation result of bearing capacity

Parameter	Notation	Value
Ultimate bearing capacity (Terzaghi)	q_u (kN/m^2)	6,840.38
Ultimate bearing capacity (JICA)	q_u (kN/m^2)	1,176.00
Maximum normal stress	σ_{max} (kN/m^2)	204.93
Minimum normal stress	σ_{min} (kN/m^2)	147.51
Safety factor for bearing capacity	SF_{bc}	5.74

The ultimate bearing capacity using the Terzaghi formula gave a greater value than the recommended value by JICA as the Terzaghi formula was addressed to calculate the bearing capacity on a shallow foundation with finite dimensions. The base width of the main body was 10 m; therefore, it will provide a great bearing capacity because the force is distributed on a large area while the ultimate bearing capacity was obtained by JICA recommendation with the assumption that the subgrade is classified as soft rock. Based on the calculation result in Table 8, the structure complies with the safety requirement as the safety factor is more than 1.5. The illustration of the main sabo dam is shown in Fig. 4.

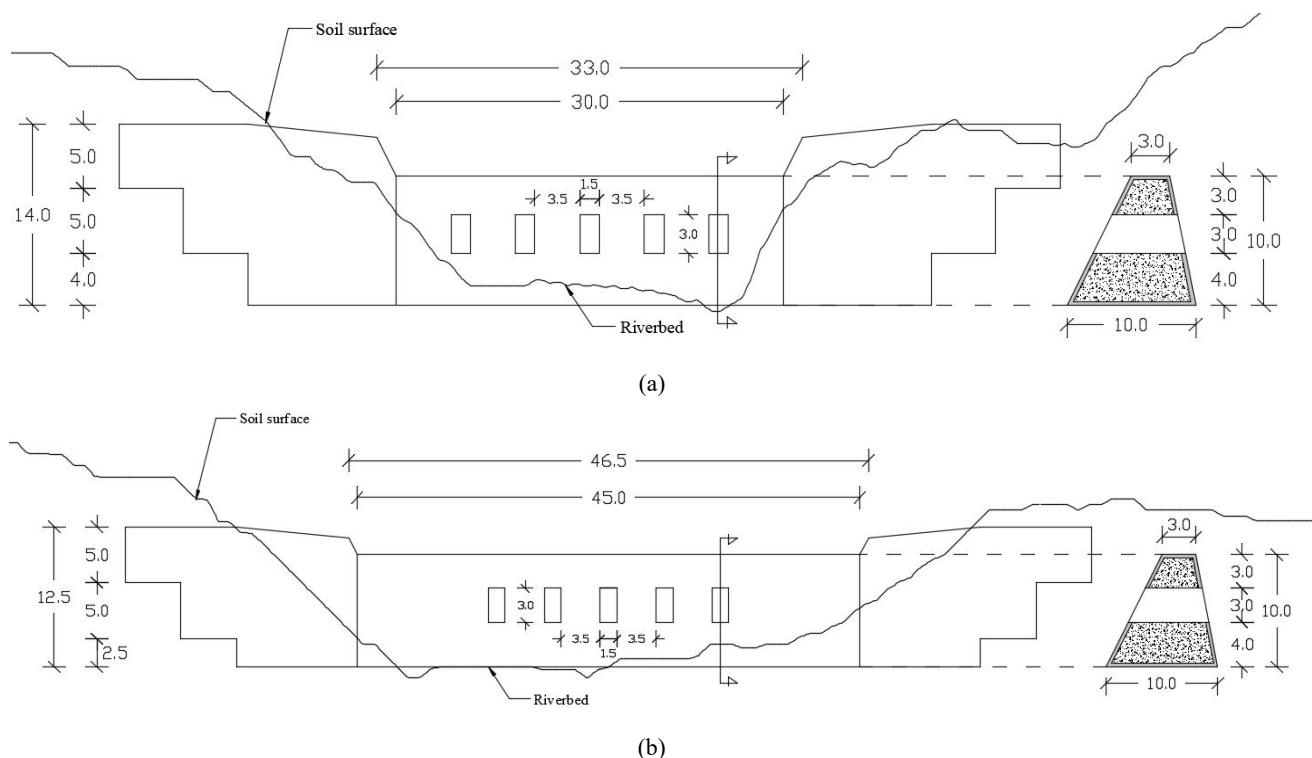


Fig. 4. The cross-section (a) Sabo Dam 1 and (b) Sabo Dam

5 Summary

The design of sabo dam in the Air Beras River was designed using two conduits sabo dams, which has a main dam height of 10 m. The width of the sabo dam was adjusted to the width of the river, i.e., 30 m for Sabo Dam 1 and 45 m for Sabo Dam 2. This conduit sabo dam series can accumulate the sediment with a total manageable volume of 141,100 m³.

The spillway is planned to escape the flow with the discharge of 120 m³/s. Consequently, it is determined that the spillway height is 3 m for Sabo Dam 1 and 2 m for Sabo Dam 2. In the body of the main dam, there are five additional openings, each has a height of 3 m and a width of 1.5 m.

The result of the stability evaluation for both conduits sabo dams indicates that the structures comply with the safety requirement of overturning, sliding, and bearing capacity. The safety factor of the sabo dam in the debris flow condition is 2.14 for overturning with the resisting moment equal to 9,289.51 kN.m and the driving moment equal to 4,350.77 kN.m. The safety factor for sliding is 1.50 with the resultant of resisting force of 1,757.60 kN and the resultant of driving force of 1,168.93 kN. The ultimate bearing capacity obtained is 1,176.00 kN/m² and the maximum normal stress is 204.93. Therefore, the safety factor for bearing capacity is 5.74.

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