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Stability Evaluation of Diversion Tunnel Portal Slopes at Lau Simeme Dam Site, Indonesia, using Limit Equilibrium Method

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ABSTRACT. The construction of the Lau Simeme Dam used a tunnel as a diversion channel. Slopes at the diversion tunnel portals were prone to failure due to the tunnel excavation and earthquake. Earthquake load was not considered in the designs of the inlet and outlet portal slopes. This research evaluated the stability of the tunnel portal slopes under static and earthquake loads using limit equilibrium methods of the Bishop Simplified and Morgenstern-Price. Input material properties for the slope stability analyses were obtained from evaluations of soil and rock cores, including determination of lithology type and rock mass quality based on Geology Strength Index (GSI) and laboratory testing. Evaluations of soil and rock cores indicated that the inlet portal slope consisted of residual soil and good quality tuff breccia and sandstone. The outlet portal slope consisted of residual soil, poor quality sandstone, poor quality tuff breccia, fair quality sandstone, fair quality tuff breccia, and good quality tuff breccia. The seismic analyses determined the earthquake load coefficient based on the peak ground acceleration map for 10% probability exceedance in 50 years was 0.125 g. The slope stability analyses showed that the inlet and outlet portal slopes were stable under static and earthquake loads. The Bishop Simplified and Morgenstern-Price showed relatively similar Fs values. The inlet and outlet portal slope's Fs values decreased with the earthquake load application. Although Fs values of the outlet slope under static and earthquake loads met the requirements of the SNI 8460:2017, the rock mass conditions, particularly the poor rock masses of layers 2 and 3, required special attention. Application of slope reinforcement methods, such as shotcrete, is suggested to protect the slope integrity.

Keywords: Diversion tunnel · Lau Simeme Dam · Limit equilibrium method · GSI · Slope stability.

1 INTRODUCTION

Lau Simeme Dam site is located at Sibiru-biru Sub-district, Deli Serdang, North Sumatera, with a distance ±50 km from Medan City (Figure 1). The earth-fill dam is planned to use a diversion tunnel as the river flow switcher during construction. The diversion tunnel was designed by Balai Besar Wilayah Sungai (BBWS) Sumatera II through PT. Wahana Adya KSO in 2016. The Lau Simeme Dam site is located in an active seismic region, so that the earthquake may affect the tunnel portal slopes. Unfortunately, earthquake load was not considered in the slope design.

Slope stability on the tunnel portal is an important factor in building the tunnel since the portal slope potentially slides when excavation is performed. The stability of the portal slope is highly determined by geological engineering conditions, namely rock and soil conditions on the slope, the depth of water surface around the tunnel, and earthquake load factor in the loca-

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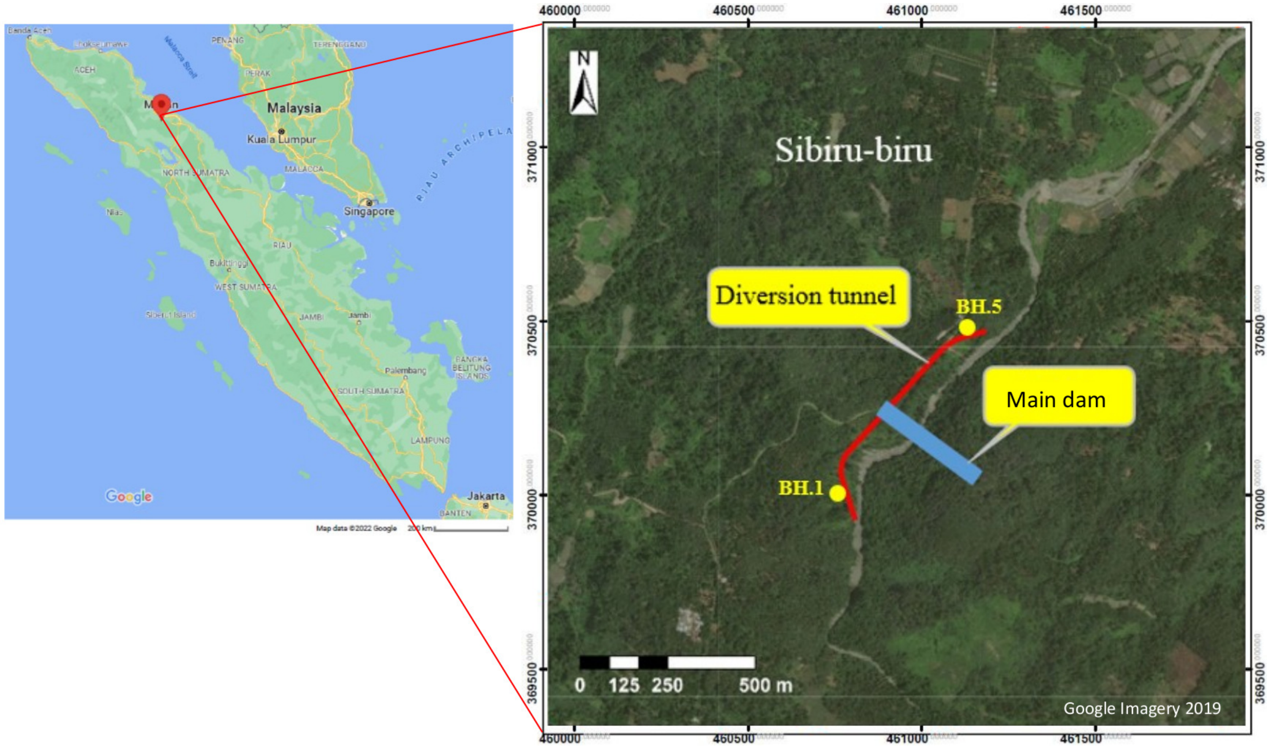

FIGURE 1. Locations of diversion tunnel and borehole 1 (BH.1) and borehole 5 (BH.5) at Lau Simeme Dam site.

tion. Factors controlling and analyzing methods of soil and rock slope stability are described in a number of literature (e.g., Abramson *et al.*, 2002; Wyllie, 2018).

This research aims to evaluate the stability of the tunnel portal slopes at the Lau Simeme Dam site that was designed by PT. Wahana Adya KSO is based on the geological engineering conditions of the slopes. The engineering geological investigations are presented, and the slope stability analyses under static and earthquake loads, performed using limit equilibrium methods of the Bishop Simplified and Morgenstern-Price methods, are discussed.

2 GEOLOGICAL SETTING

Based on the Regional Geological Map Sheet of Medan and the Surroundings developed by Cameron et al. (1982), the Lau Simeme Dam site and the surrounding area mainly consists of Quartenary Mentar Unit, Tufa Toba Unit, and Alluvium sediment (Figure 2). Huda (2020) indicated that lithologies found in the dam area are tuff breccia and tuffaceous sandstone, part of the Mentar Unit.

National Earthquake Research Center (2017) describes that Sumatera consists of 3 active fault segments, namely north, south, and the southernmost sections. The Lau Simeme Dam site is located in the north section of the active fault segment. The tectonic setting likely influences rock mass quality at the Lau Simeme Dam site. In addition to the major fault segment, Cameron et al. (1982) also describe the existence of estimated NW-SE-oriented faults in the Lau Simeme Dam site and the surrounding area (Figure 2).

3 METHOD

Slope stability analyses were performed based on geological engineering conditions of the inlet and outlet portal slopes. Engineering geological conditions of materials comprising the slopes were determined by evaluations of soil and rock cores drilled by BWS Sumatera II (2016). Locations of the two boreholes BH.1 and BH.5 are shown in Figure 1. The soil and rock core evaluations include determining lithology type and rock mass quality based on the Geology Strength Index (GSI) and laboratory testing.

According to Hoek *et al.* (2013), the GSI of rock cores could be determined from the value

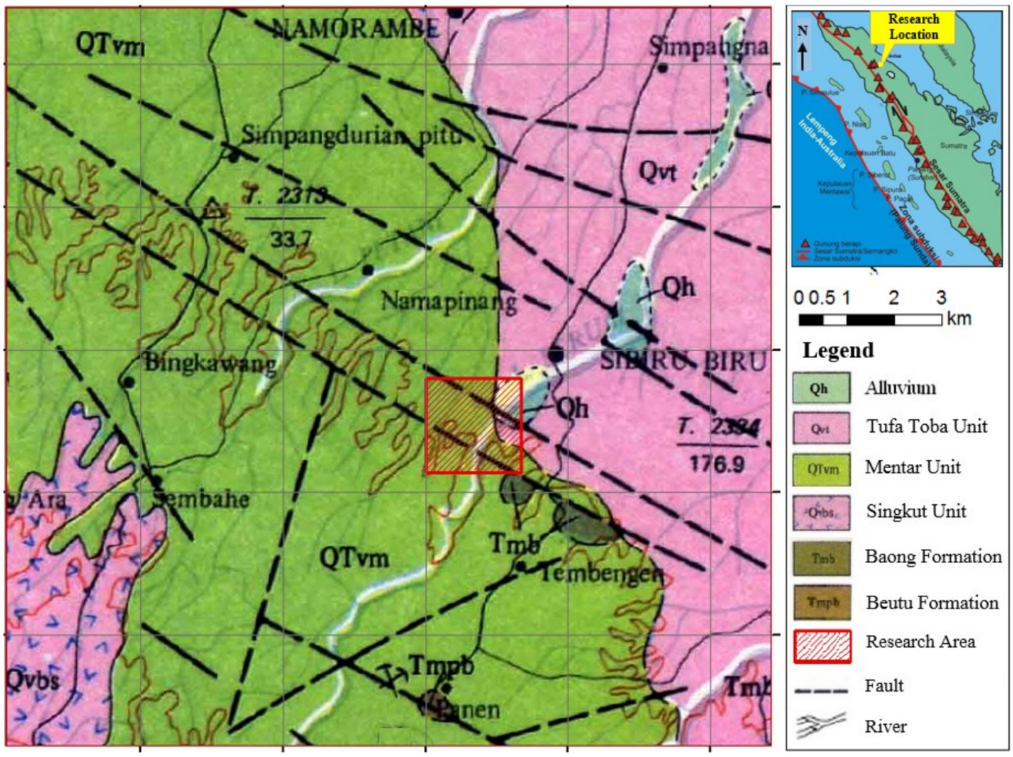

FIGURE 2. Research location in the part of the Geological map of Medan sheet produced by Cameron *et al.* (1982).

of Joint Condition (Jcond89) and Rock Quality Designation (RQD), as expressed in Equation 1:

$$GSI = 1.5\,J_{\text{cond89}} + RQD/2 \quad (1)$$

Joint Condition (J_{cond89}) referred to the Joint Condition in the rock mass classification developed by Bieniawski (1989), while RQD value referred to the rock mass quality table by Deere (1966). Sivakugan *et al.* (2013) classified rock mass quality based on the GSI into 5 groups, as shown in Table 1.

Laboratory testing was performed on 5 surface soil samples and 20 surface rock samples near the inlet and outlet portal slopes. Soil and rock laboratory testing included index properties (*e.g.*, unit weight) and mechanical properties (*i.e.*, shear strength and uniaxial compressive strength, UCS) of the soil and rock samples, which were then used as material parameters input in the limit equilibrium stability analysis. The slope stability analyses under earthquake load were performed using the pseudo-static method. The method is commonly used to simulate the effect of earthquake load on slope stability. The seismic coefficient used in the pseudo-static slope stability analyses was determined following procedures described in SNI 8460:2017 (BSN, 2017). The earthquake load factor coefficient used (k_h) was 0.5 times the peak ground acceleration (PGA) value in the location (Equation 2). In the slope design, earthquake load was designed using the PGA on bedrock for a 10 % probability of exceedance in 50 years. The PGA value was provided by National Earthquake Research Center (2017).

$$k_h = 0.5 \times Fa \times PGA \quad (2)$$

where k_h = earthquake load coefficient; Fa = amplification factor in the location; PGA = PGA value in the location.

Slope stability analyses were performed using Bishop Simplified and Morgenstern-Price methods. The Bishop Simplified method is popular because it is simple. The result obtained from this method is similar to that of other more rigorous methods, such as the Morgenstern-Price method (*e.g.*, Duncan, 1996; Fredlund *et al.*, 2019). In the slope stability analyses, the slope was divided into several small slices, and afterward, the force on each slice with the equilibrium method was calculated. The Bishop Simplified method calculates balancing

TABLE 1. GSI rock mass quality classification (Sivakugan *et al.*, 2013).

GSI	95–76	75–56	55–41	40–21	< 20
Rock mass quality	Excellent	Good	Fair	Poor	Very Poor

vertical force and moment worked on each slice but ignores shear force between slices. The Morgenstern-Price method considered 6 criteria of equilibrium, namely moment equilibrium, vertical and horizontal force equilibrium, normal force between slices (X), the shear force between slices (E), inclination from resultant (X/E), and the relationship between X-E (Krahn, 2004).

This research performed limit equilibrium analyses using Slide 6.0 software (Rocscience, Inc.). Geometries of the inlet and outlet portal slopes designed by PT. Wahana Adya KSO and soil and rock layers determined from core analyses in this study are shown in Figure 4. The inlet and outlet portal slopes were designed to have a 63° bench face inclination, 2 m bench width, and 5 m bench height. The bench configurations resulted in a 52° overall slope inclination. Because the rock discontinuity orientation is unknown, the slope was assumed to have circular failure surfaces. Slope stability was determined based on the safety factor (F_s) value obtained from the limit equilibrium analyses. Design criteria specified in the SNI 8460:2017 (BSN, 2017) were adopted, where the slopes were designed to have SF >1.1 without earthquake load (static load) and SF >1.5 with earthquake load (pseudo-static load).

4 RESULTS AND DISCUSSION

Qualities of the rock masses comprising the inlet and outlet portal slopes determined from rock core analyses based on the GSI values are shown in Table 2 and Table 3, while photographs of typical rock cores are shown in Figure 3. Detailed analyses of the rock mass qualities are described in Huda (2020). Input material properties of each soil and rock layer determined from laboratory tests are shown in Table 4.

Standard Penetration Test (SPT) conducted by PT. Wahana Adya KSO during the soil and rock drilling indicated that the Lau Simeme Dam site area had average SPT values of more than 50 (BBWS Sumatera II, 2016) and, therefore, the ground could be classified as a hard rock. Based on the peak ground acceleration map for 10 % probability exceedance in 50 years (National Earthquake Research Centre, 2017), the research location has a PGA of 0.25, and the Fa value is 1. Therefore, the seismic load coefficient (kh) applied in the pseudo-static slope stability analyses was 0.125.

Stability analysis results of the inlet and outlet portal slopes are shown in Figure 5 and Figure 6, respectively, and summarized in Table 5. In general, Fs values of the inlet and outlet portal slopes met the requirement specified by the SNI 8460:2017 (BSN, 2017).

Slope stability analyses of the inlet portal slope under static load (Figure 5) show that the analysis with the Bishop Simplified method results in an F_s value of 14.45, while the analysis with the Morgenstern-Price method results in an F_s value of 14.67. The F_s values decreased under the earthquake load, whereas the Bishop Simplified and Morgenstern-Price methods resulted in Fs values of approximately 12.18. Figure 5 shows that the critical slip surfaces cut the inlet slope until the tunnel portals. However, since the Fs values are relatively high, the slope failures will likely not occur.

Slope stability analyses of the outlet portal slope under static load (Figure 6) show that the Bishop Simplified method results in an F_s value of 4.39, while the Morgenstern-Price method results in an F_s value of 14.67. Under earthquake load, the Fs value based on the Bishop Simplified method is 3.71, while the Morgenstern-Price method is 3.74. Figure 5 shows that the critical slip surface is located in the 5^{th}th layer of the materials (*i.e.*, poor quality tuff breccia), Although F_s values of the outlet slope under static and earthquake loads meet the requirements specified by SNI 8460:2017 (BSN, 2017), the poor rock masses of layers 2 and 3 need special attention as they are easily eroded by rainwater. Application of slope reinforcement

TABLE 2. Rock mass quality determined by GSI at borehole BH.1 (near inlet slope).

Layer	Material	Thickness (m)	J_{cond89} Average	RQD Average (%)	GSI	Quality
1	Residual soil	3	-	-	-	-
2	Tuff breccia	5	24	78	75	Good
3	Tuffaceous sandstone	7	24	78	75	Good
4	Tuff breccia	8	24	78	75	Good
5	Tuff breccia	6	23	74	72	Good
6	Tuff breccia	18	25	77	75	Good

TABLE 3. Rock mass quality determined by GSI at borehole BH.5 (near outlet slope).

Layer	Material	Thickness (m)	J_{cond89} Average	RQD Average (%)	GSI	Quality
1	Residual soil	2	-	-	-	-
2	Tuffaceous sandstone	2.5	9	20	24	Poor
3	Tuff breccia	10	9	20	24	Poor
4	Tuffaceous sandstone	2.5	17	43	47	Fair
5	Tuff breccia	11	17	43	47	Fair
6	Tuff breccia	11.5	22	85	75	Good

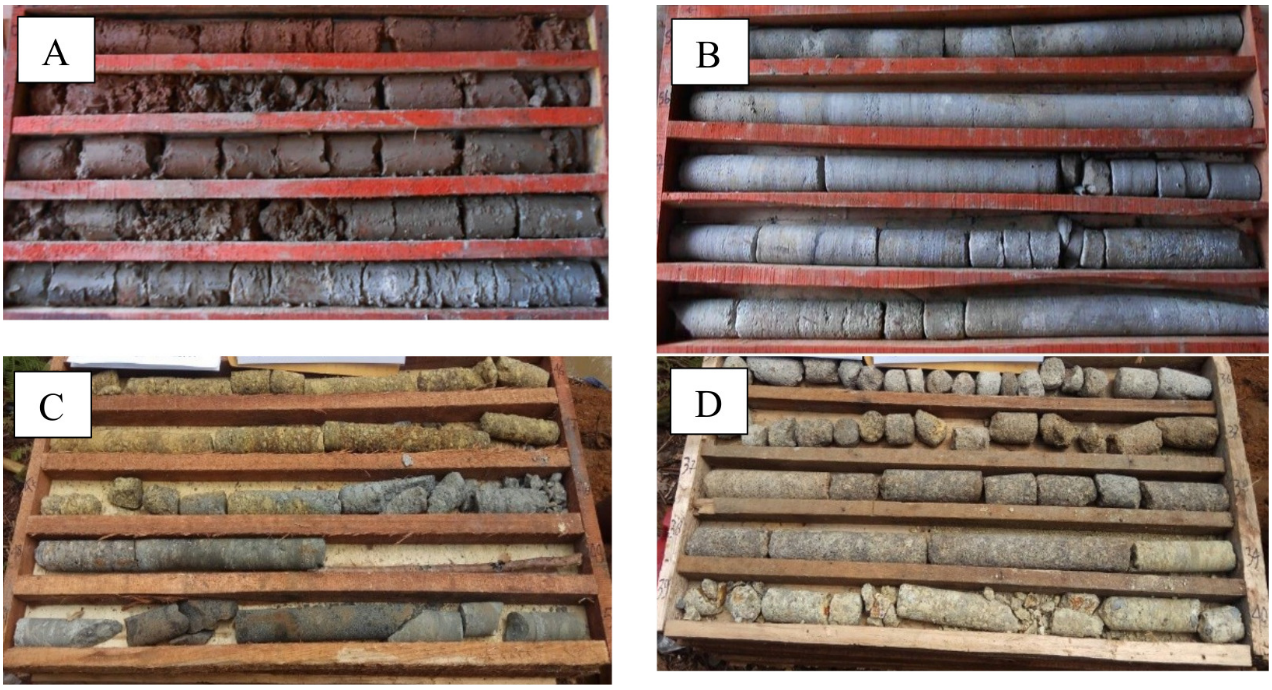

FIGURE 3. Photographs of typical soil and rock cores: (a) residual soil; (b) good rock mass quality of tuff breccia; (c) fair rock mass quality of tuff breccia; (d) poor rock mass quality of tuffaceous sandstone.

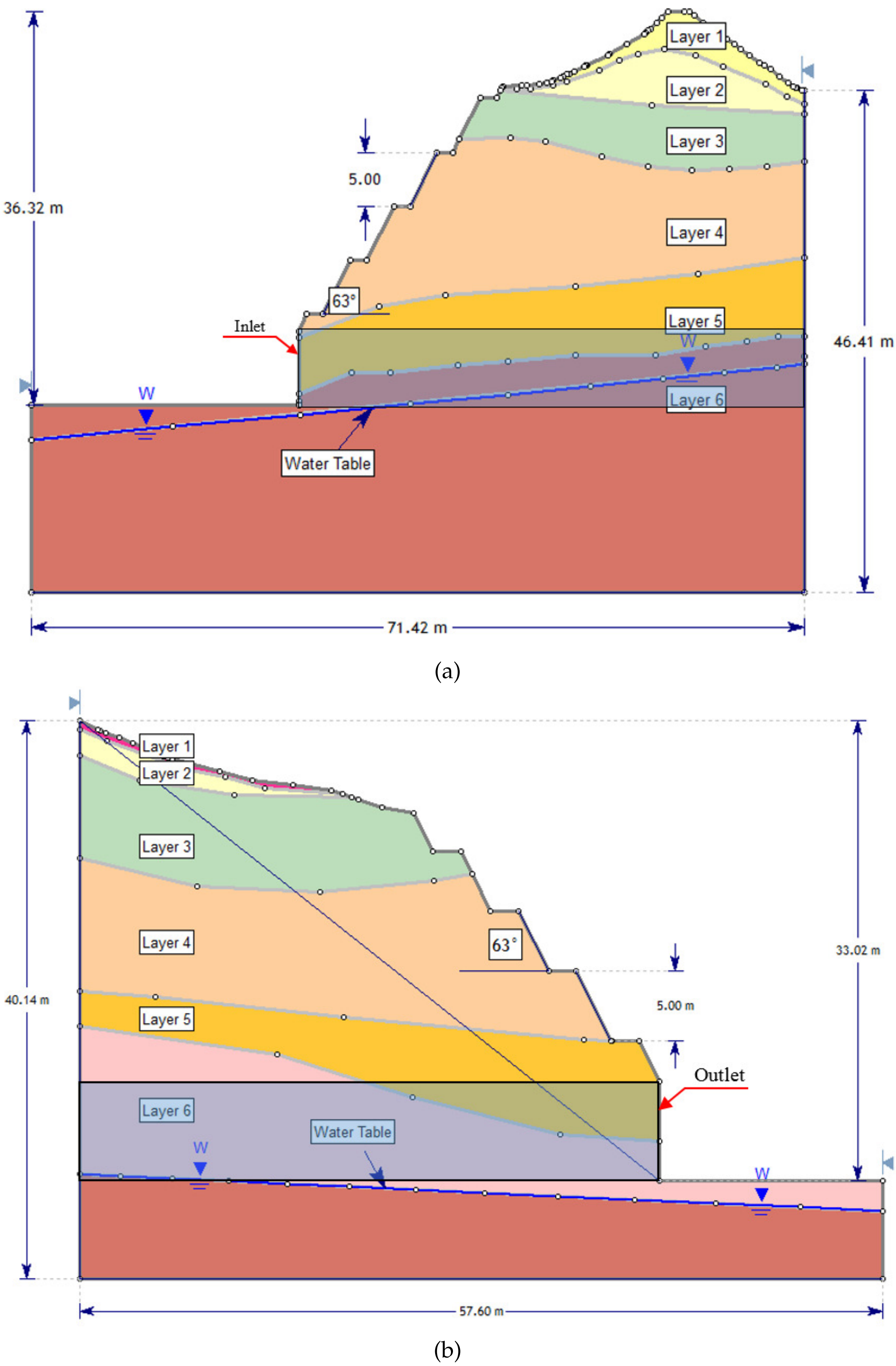

FIGURE 4. The geometry of the portal slopes: (a) inlet; (b) outlet.

TABLE 4. Input material properties for slope stability analyses.

Inlet

Layer	Lithology	GSI	γ (kN/m^3)	UCS (kPa)	c (kPa)	ϕ (°)
1	Residual soil	-	15.14	-	56.43	17.39
2	Tuff breccia	75	15.65	44456	-	-
3	Tuffaceous sandstone	75	20.71	80442	-	-
4	Tuff breccia	75	15.65	44456	-	-
5	Tuff breccia	72	19.46	37940	-	-
6	Tuff breccia	75	15.65	44456	-	-

Outlet

Layer	Lithology	GSI	γ (kN/m^3)	UCS (kPa)	c (kPa)	ϕ (°)
1	Residual soil	-	15.5	-	55.72	8.59
2	Tuff sandstone	24	16.23	60331	-	-
3	Tuff breccia	24	17.06	13345	-	-
4	Tuffaceous sandstone	47	12.87	64053	-	-
5	Tuff breccia	47	19.46	37940	-	-
6	Tuff breccia	75	15.65	44456	-	-

Note: γ = unit weight; UCS = uniaxial compressive strength; c = cohesion; ϕ = internal friction angle.

TABLE 5. Summary of slope stability analysis results.

Slope	Analysis Method	Safety Factor (F_s)	
		Static load	Earthquake load
Inlet	Bishop Simplified	14.45	12.18
	Morgenstern-Price	14.67	12.18
Outlet	Bishop Simplified	4.39	3.71
	Morgenstern-Price	4.40	3.74

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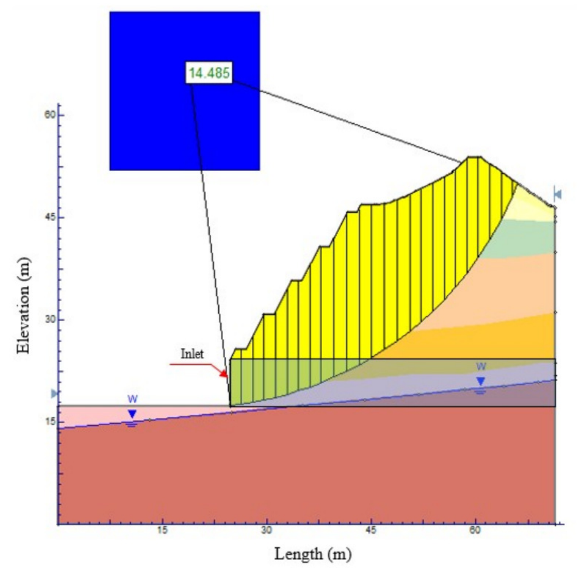
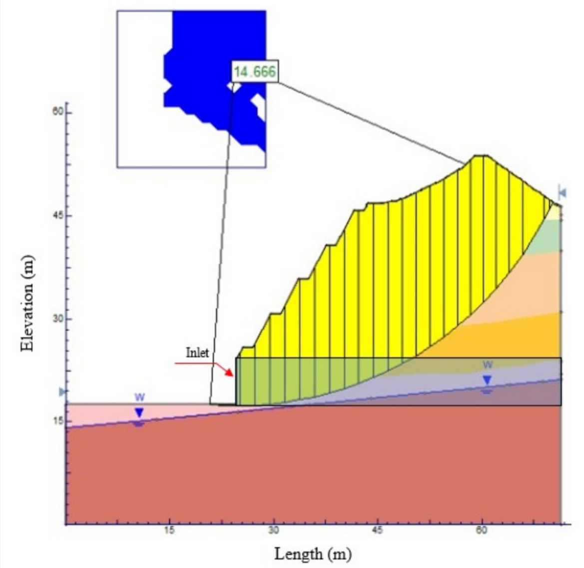
<tr><td>Static load</td><td>
</td><td>
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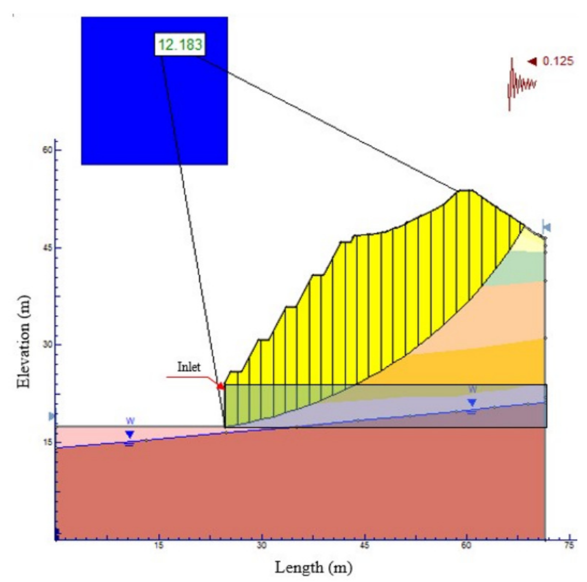
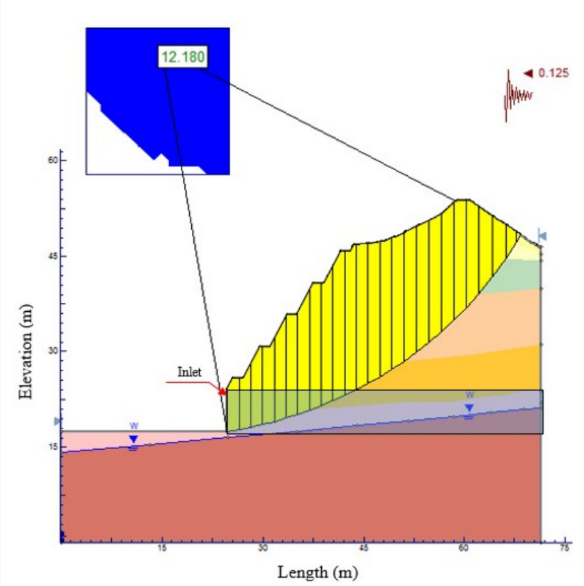
<tr><td>Earthquake load</td><td>
</td><td>
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<tr><td colspan="3">Note: the color of each material layer refers to Figure 4(a); the yellow shaded area indicates the slip surface area; the blue area surrounding the F_s value indicates the F_s contour.</td></tr>
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FIGURE 5. Results of inlet slope stability analyses. Note: the color of each material layer refers to Figure 4(a); the yellow shaded area indicates the slip surface area; the blue area surrounding the F_s value indicates the Fs contour.

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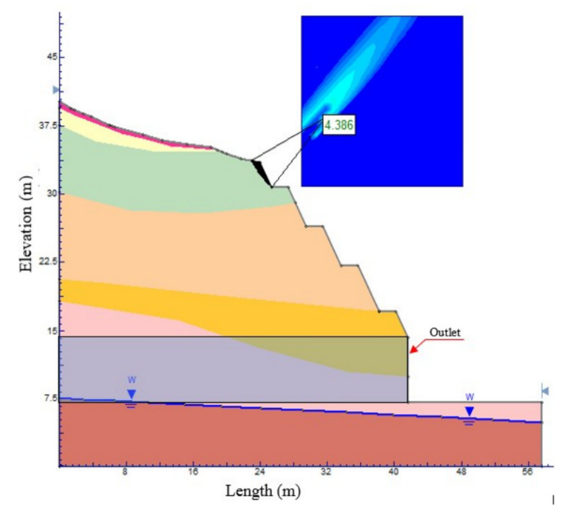
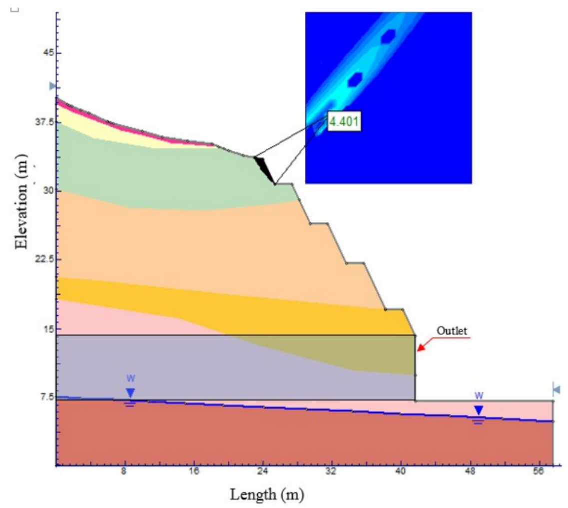
<tr><th></th><th>Bishop Simplified</th><th>Morgenstern-Price</th></tr>
<tr><td>Static load</td><td>
</td><td>
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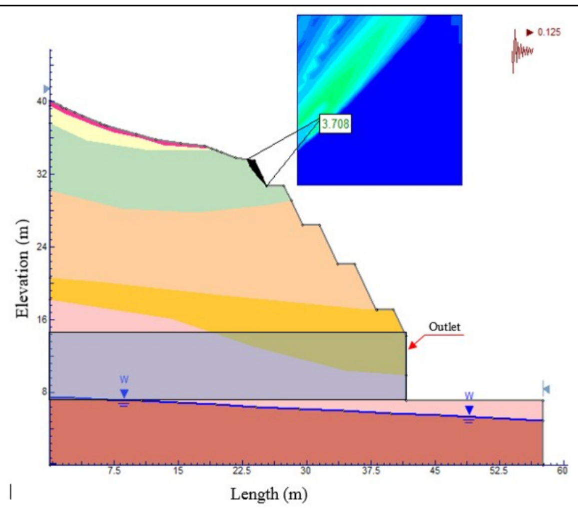
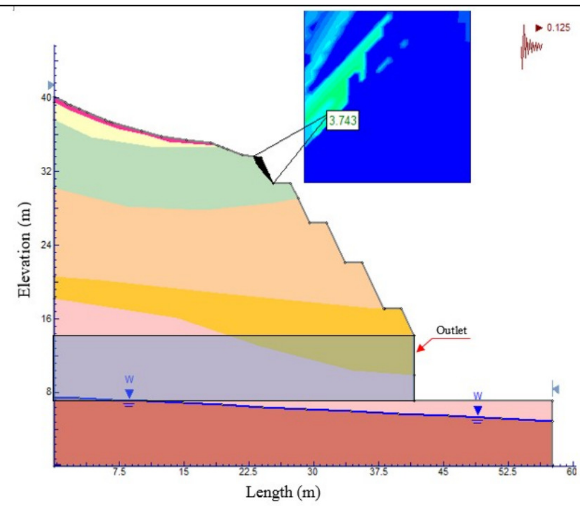
<tr><td>Earthquake load</td><td>
</td><td>
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FIGURE 6. Results of outlet slope stability analyses. Note: the color of each material layer refers to Figure 4(a); the yellow shaded area indicates the slip surface area; the blue area surrounding the F_s value indicates the F_s contour..

methods, such as shotcrete, is suggested to increase the slope stability.

5 CONCLUSION

Evaluations of soil and rock cores indicated that the inlet portal slope consisted of residual soil, good quality tuff breccia, and tuffaceous sandstone. The outlet portal slope consisted of residual soil, poor quality sandstone, poor quality tuff breccia, fair quality tuffaceous sandstone, fair quality tuff breccia, and good quality tuff breccia. The seismic analyses determined the earthquake load coefficient based on the peak ground acceleration map for 10% probability exceedance in 50 years was 0.125 g. Under the assumption of a circular slip surface, the slope stability analyses showed that the designed inlet and outlet portal slopes were stable under static and earthquake loads. The Bishop Simplified and Morgenstern-Price resulted in relatively similar F_s values. The inlet and outlet portal slope's F_s values decreased with the earthquake load application. Although F_s values of the outlet slope under static and earthquake loads met the requirements specified by SNI 8460:2017, the rock mass conditions, particularly the poor rock masses of layers 2 and 3, required special attention. Application of slope reinforcement methods, such as shotcrete, is suggested to further increase the slope stability, particularly from rainwater erosion.

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