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Slope reinforcement analysis using retaining structures: a case study in a heritage temple area in Yogyakarta

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ABSTRACT

Indonesia is home to numerous cultural heritage sites situated on sloping terrain, where geotechnical stability plays a crucial role in preservation and restoration efforts. One such site is a Buddhist stupa in Sambirejo, Prambanan, Sleman, located approximately 200 meters north of Barong Temple. The stupa lies on a slope with a 16.10% gradient underlain by lithosol and regosol soils of limited thickness, which raises potential risks of instability. This study aims to evaluate the slope stability conditions of the temple area and to propose suitable reinforcement designs to ensure structural safety. Field investigations, including cone penetration tests (CPT) and hand boring, revealed that the subsurface consists primarily of fine to medium-silty sand with a groundwater table at a depth of 2.5 m. Stability analyses were performed using both manual calculations based on SNI 8460:2017 and numerical modelling with PLAXIS. Two reinforcement alternatives were assessed: cantilever retaining walls and concrete sheet piles under static and pseudo-static (seismic) conditions. The results showed that the safety factor increased by 17.9% and 12.5% for cantilever and sheet pile walls, respectively, under static loading, and by approximately 8% under dynamic conditions. These findings confirmed that both methods effectively enhance slope stability, with cantilever retaining walls demonstrating better performance in minimizing deformation than concrete sheet pile.

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1. Introduction

Indonesia preserves numerous cultural heritage structures, including temples from the classical Hindu–Buddhist era. Many of these sites are located on hilly or sloping terrain, where geotechnical stability becomes a critical factor in preservation efforts. Slope instability not only threatens surrounding landscapes but can also endanger the integrity of heritage structures, particularly during restoration or reconstruction processes.

One such heritage site is a Buddhist stupa located in Sambirejo, Prambanan, Sleman, approximately 200 m north of Barong Temple. The location of the site can be seen in Fig. 1. Archaeological surveys conducted between 1987 and 2023 have revealed remnants of stone structures forming circular and angular layouts, with partial reconstruction carried out in recent years. A feasibility study in 2023 concluded that the temple is suitable for restoration. However, the site is situated on sloping ground with a gradient of 16.10%, which raises concerns regarding slope stability. The temple is positioned above the Semilir Formation, with an upper soil layer of lithosol measuring 1.0–2.5 m in thickness, underlain by a regosol layer of 0.4–0.6 m. The surrounding land is mainly used for agriculture, consisting of gardens and fields, which may influence surface water infiltration and slope conditions.

Several studies have investigated slope reinforcement methods using retaining structures under static and seismic loading conditions. The cantilever wall is commonly applied on steep slopes, such as hilly areas or road embankment with the height more than 5 to 6 m [1]. Their design considers sliding, overturning, and internal stability both static and seismic conditions [2]. Under seismic conditions, cantilever may experience increased stress and displacement, thus reinforcement strategies, such as anchor, can enhance their performance [3].

Meanwhile the concrete sheet pile is generally used in limited height which is less than 5m [2]. Concrete sheet piles are effective for slope reinforcement due to their strength and durability. Under seismic conditions, their performance is influenced by soil-structure interaction, with the pivot point near the toe playing a critical role in stability [4], [5] and [6].

However, previous studies mainly focused on transportation embankments and urban slopes areas [7] and [8], while limited attention has been given to slope stabilization in cultural heritage sites located on volcanic residual soils. In addition, comparative evaluations between cantilever retaining walls and concrete sheet piles under both static and pseudo-static conditions remain limited for archaeological restoration areas. Therefore, this study aims to evaluate the slope stability of a Buddhist stupa area in Sambirejo, Yogyakarta, and to compare the effectiveness of cantilever retaining walls and concrete sheet piles using both analytical and numerical approaches under static and seismic conditions.

Fig. 1. Sambirejo, Prambanan, Sleman, Yogyakarta [9]

2. Method

A slope is considered stable when the resisting forces exceed the driving forces, thereby preventing potential movement or failure. The slope at the temple was classified using a slope classification based on [4], and it can be categorised as a slightly steep slope with an inclination of 16.10%. Flat landslides with a lot of ground movement and erosion may happen to the slope.

2.1. Slope Stability

A slope is a soil surface that is inclined at a certain angle to the horizontal plane and is not protected [5]. A slope consists of two surfaces with different elevations, which creates driving forces causing the higher soil mass to tend to move downward. This condition, commonly referred to as gravitational potential force, significantly contributes to slope failure. The degree of slope inclination may vary and directly affects its stability, where steeper slopes are more susceptible to landslides [6]. The slope stability analysis was conducted using PLAXIS to know the initial stability. Then, the dimension of reinforcements was initially calculated based on SNI 8460:2017 [10].

The slope safety factor used as a reference in stability analysis was determined by considering the cost and potential slope failure against the uncertainties of the analysis conditions. Under static conditions, the required minimum safety factor is 1.25. Meanwhile, under dynamic conditions, the minimum safety factor for the pseudo static model is required to be greater than 1.1 (FK > 1.1), using the seismic coefficient derived from the peak ground acceleration (PGA), which was determined based on site classification and amplification factors in accordance with SNI 8460:2017 [11].

2.2. Cantilever Wall

A cantilever wall is a retaining system designed to resist lateral soil pressure and prevent soil movement or slope failure. Several types of retaining walls were evaluated in this study, including gravity walls, gabion walls, cantilever walls, and cantilever walls with mini piles. Based on the calculated safety factors, each wall type was analyzed to determine the optimal dimensions that satisfy the required stability criteria. The analysis results indicate that the cantilever retaining wall with mini piles provides the most effective performance, meeting all safety requirements under the given conditions [12].

The construction process of a retaining wall generally begins with determining the project site and the required wall dimensions. In the design stage, the dimensioning of the retaining wall is a critical step to ensure adequate stability. The retaining wall must be checked for stability against overturning, lateral sliding, and bearing capacity failure. The required safety factors are a minimum of 2.0 for overturning, 1.5 for lateral sliding, 3.0 for bearing capacity, 1.5 for global stability, and 1.1 for seismic stability. These criteria serve as design benchmarks to ensure that the retaining wall performs adequately under both static and dynamic loading conditions. These considerations form the basis of the engineering analysis to ensure that the structure effectively prevents soil displacement and slope instability. Preliminary design based on [10].

2.3. Piles

Piles are structural elements installed vertically into the ground to provide lateral support and prevent soil movement. The piles, such as steel sheet-piles, concrete sheet-piles, and soldier piles, are commonly used in waterfront structures, excavation support systems, and slope reinforcement projects. Compared to conventional retaining walls, piles require less space, making them suitable for areas with limited working conditions.

Based on [13], soldier-piles were used for slope reinforcement alternatives to address land limitation issues encountered during the construction. Therefore, the study explored the use of soldier pile walls, both with and without ground anchors, as a technical solution. The results indicated that the most efficient design alternative was the soldier pile system combined with ground anchors, which effectively improved slope stability while optimizing land use and construction cost.

Similarly, [14] examined urban construction conditions where limited land availability necessitates the development of underground spaces such as basements. Initial calculations determined the required penetration depth using conventional methods, followed by manual stability analysis and deformation modeling with PLAXIS V20. The results showed that the inclusion of ground anchors significantly reduced the required penetration depth and increased the safety factor against overturning. Moreover, deformation under shallow groundwater conditions decreased notably after the installation of ground anchors. These findings confirm that sheet pile retaining walls equipped with ground anchors are an effective reinforcement method, capable of enhancing slope stability and controlling deformation in limited-space environments.

In the design stage, the analysis of piles considers factors such as penetration depth, lateral earth pressure distribution, soil strength, and safety against sliding and overturning. The performance of the pile system is also influenced by groundwater conditions and surcharge loads from nearby structures. By incorporating these design aspects, piles can be effectively applied as an alternative reinforcement method for stabilizing the slope at the heritage site. In this study, concrete sheet-piles were used to reinforce the slope.

3. Soil Investigation

In this study, a subsurface investigation was conducted using cone penetration tests (CPT) at two locations and a hand boring test at one location to obtain soil samples, determine soil hardness, and identify the thickness of each soil layer. Several points were selected to provide a representative overview of the soil type, stratification, physical properties, and relative density at the site. The site layout of the temple area and the coordinates of the field investigation points are presented in Fig. 2.

Fig. 2. Soil investigation map

Based on grain size distribution, hand boring test indicated that the subsurface layers across all investigation points are predominantly composed of fine to medium silty sand with minor gravel content, exhibiting medium to dense consistency. However, due to the absence of Atterberg limit data, definitive USCS classification could not be established. The material is interpreted to consist mainly of silty clay to clayey silt." The groundwater table was encountered at a depth of approximately 2.5 meters below the ground surface. A summary of the soil parameters based on laboratory tests from the investigation is presented in the corresponding Table 1. These parameters were used as input parameters in the PLAXIS model.

Table 1. Soil parameters

No	Parameter	Unit	Results			
			HB 1 (1.00-1.50) m	HB 2 (1.00-1.50 m)	HB 3 (1.5-2.0 m)	HB 4 (0.0-0.5 m)
Soil properties	Water content	%	31.53	33.22	26.32	33.33
	Specific Gravity		2.638	2.550	2.623	2.578
	Saturated Unit weight	gr/cm^3	1.798	1.586	1.634	1.798
	Dry Unit weight	gr/cm^3	1.367	1.190	1.293	1.348
	Void ratio, e		0.93	1.14	1.03	0.91
	Degree of Saturation	%	89.44	74.17	67.15	94.21
Grain Size Analysis	Gravel	%	0.00	0.00	0.00	0.00
	Sand	%	12.39	26.27	27.57	24.92
	Clay	%	25.51	25.29	16.34	9.21
	D10 (mm)	mm	-	-	-	0.0023
	D30 (mm)	mm	0.0032	0.0251	0.0251	0.0129
	D60 (mm)	mm	0.0417	0.0512	0.0606	0.0519
	Passing #200	%	86.71	73.73	72.43	75.08
Engineering Properties	*Total friction angle*, φ		29.20	27.40	27.70	21.90
	Cohesion, c	kg/cm^2	0.21	0.47	0.34	0.38

3. Results and Discussion

3.1. Load analysis

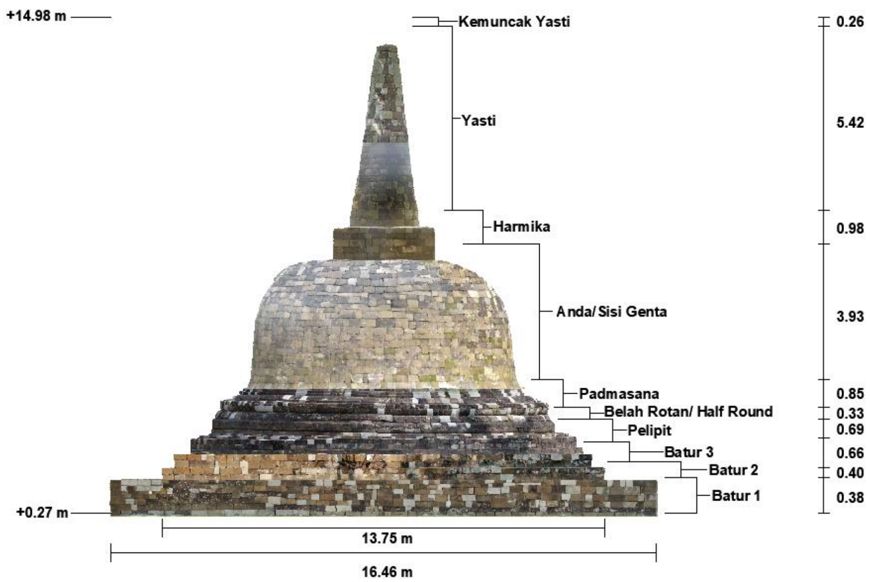


Fig. 3. South section of reconstructed temple

The calculation of the stupa load was carried out by determining the total volume of stone material in each layer and multiplying it by the unit weight of the corresponding material. The structure consists of two main components, natural andesite stone blocks forming the stupa body and river stone masonry used as supporting layers. Based on the reconstruction design as shown in Fig. 3, the total volume of natural stone was 655.54 m³, while the volume of river stone masonry is 256.08 m³.

By applying a unit weight of 2.771 kg/m³ for andesite stone and 2.200 kg/m³ for river stone masonry, the calculated dead load was 1,816,510.95 kg and 563,376.71 kg, respectively. In addition, a dynamic surcharge load of 100 kg/m² corresponding to 33,306.25 kg was applied. Including a safety margin of 10%, the total design load acting on the foundation was estimated at approximately 2,654,513.91 kg, or 78.16 kN/m² when distributed across the foundation area. The summary of the calculation is shown in Table 2.

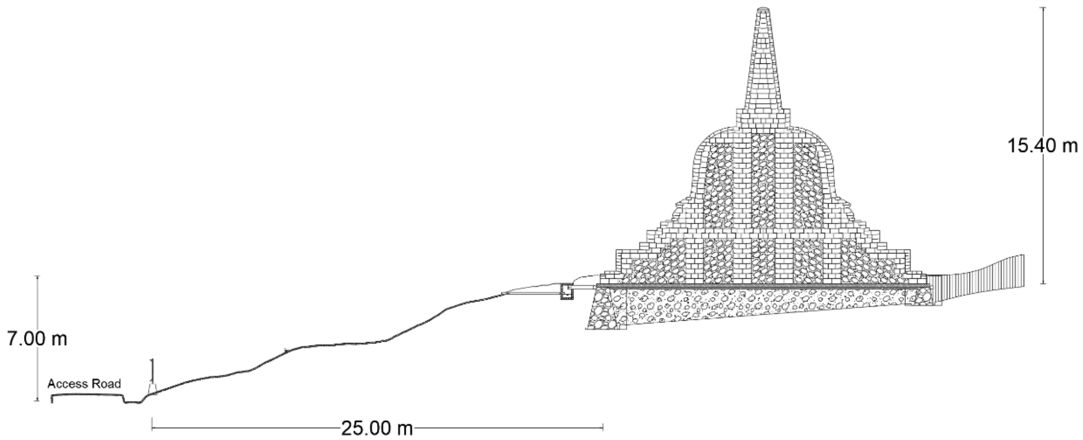
Table 2. Summary of the temple load

Component	Volume (m³)	Unit Weight (kg/m³)	Load (kg)	Load (kN)
Natural stone (andesite)	655.54	2.771	1.816.510,95	17.814,7
River stone masonry	256.08	2.200	563.376,71	5.525,1
Dynamic load (100 kg/m² × 333.06 m²)	–	–	33.306,25	326,7
Subtotal	–	–	2.413.193,91	23.666,5
Safety margin (10%)	–	–	241.319,39	2.366,7
Total Design Load	–	–	2.654.513,91	26.033,2

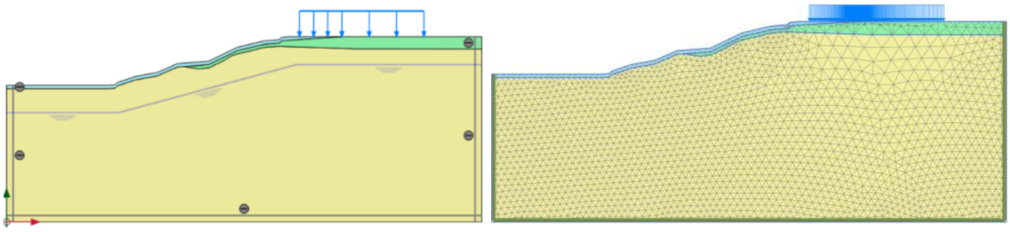
3.2. Slope stability analysis

The slope stability analysis was conducted under two conditions, static and dynamic. For the dynamic condition, a Peak Ground Acceleration (PGA) value of 0.426g was applied [11]. Meanwhile the horizontal coefficient (k_h) was 0.5PGA, which was 0.213g. In the PLAXIS model, the slope geometry and soil stratigraphy are shown in Fig. 4. The soil parameters used are listed in Table 1, with undrained (A) conditions applied to all soil layers. The temple load located above the slope was modelled as a uniformly distributed load, as shown in Fig. 4(a). The model boundaries and groundwater table are presented in Fig. 4(b), while the fine mesh distribution generated in the analysis is shown in Fig. 4(c).

The analysis began with evaluating the initial slope condition without reinforcement. The output from this analysis included the factor of safety (FS) and the critical slip surface, which served as a reference for determining the required slope reinforcement design. Under static conditions, the factor of safety indicated a stable slope. However, under dynamic conditions, the factor of safety was below the minimum allowable limit [14], indicating the need for reinforcement. The results of this analysis are summarized in Table 3.



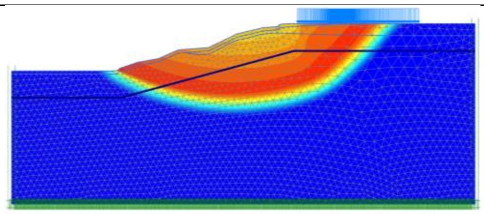
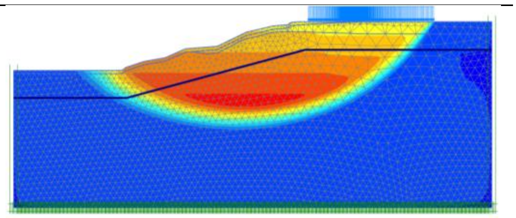
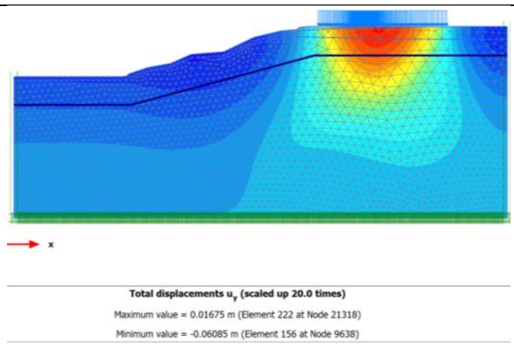
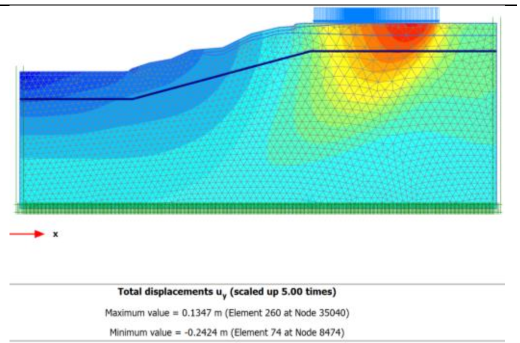
(a) Cross-sectional area of the slope and temple



(b) Boundary and groundwater table (c) mesh condition

Fig. 4. Cross-sectional area of the slope

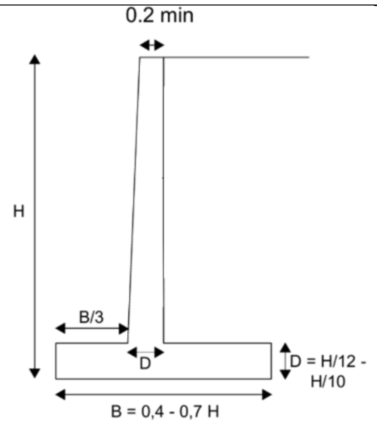
Table 3. Slope stability model without reinforcement

	Static condition	Pseudo static condition
Safety Factor	 SF = 1.865	 SF = 1.025
Total displacement, U_y (m)	 $U_y = 0.01675$	 $U_y = 0.134$

3.3. Slope reinforcement analysis

Based on the analysis results, two reinforcement alternatives were recommended for the temple area, which were a cantilever retaining wall and concrete sheet pile. For the cantilever retaining wall, a preliminary design was developed assuming a wall height of 6.5 meters, extending to the surface of the first soil layer. The proposed wall dimensions are presented in Table 4.

Table 4. Preliminary Design of Cantilever Wall

Design	Requirements	Dimension used
	H = 6 m	6.5 m
	B = 0.4 – 0.7 H	0.7 H = 4.55 m
	D = H/12 – H/10	D = H/10 = 0.65 m
	D	0.6 m
	B/3	1.5 m
	0,2 m (min)	0.5 m

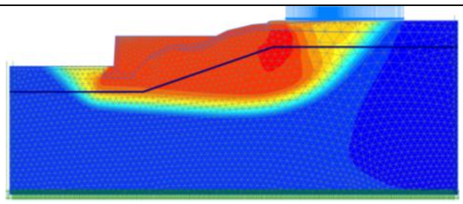
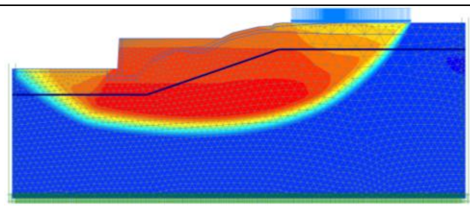
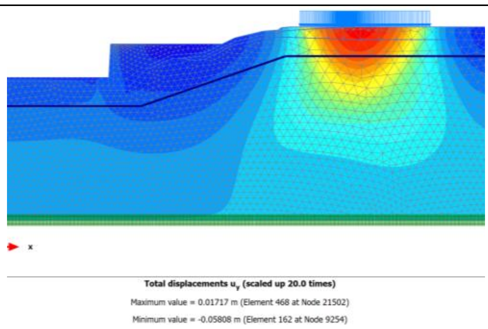
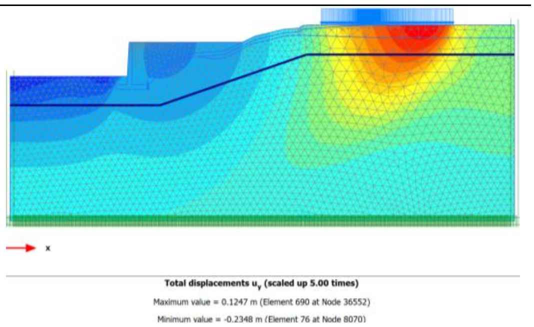
The stability analysis of the retaining wall at the temple site demonstrated that all safety criteria were satisfied. The factor of safety (FS) against overturning was calculated as 4.26, exceeding the minimum requirement of 2.0. The FS against sliding was found to be 2.62, which is also greater than the required minimum of 1.5. The eccentricity value was 0.177 m, remaining below the allowable limit of 0.758, thus meeting the criteria.

Table 5 Stability analysis of Cantilever Wall

Parameter	Formula	Result	Requirement	Status
FS against Overturning	ΣMr / ΣMo	4.26	> 2.00	OK
FS against Sliding	ΣFr / ΣFd	2.62	> 1.50	OK
Eccentricity (e)	B/2 - (ΣMr - ΣMo)/Σv	0.177 m	< 0.758	OK
Minimum Stress (σ_{min})	Σv/B (1 - 6e/B)	75.99 kPa		OK
Maximum Stress (σ_{max})	Σv/B (1 + 6e/B)	122.40 kPa		OK
Ultimate Bearing Capacity	cNc + qNq + 0.5γBNγ	3888.01 kPa		–
Safety Factor (Bearing)	Qult / σmax	31.76	> 3.00	OK

The stress distribution on the soil foundation was within safe limits, with a minimum stress of 75.99 kPa and a maximum stress of 122.40 kPa, both greater than zero. The ultimate bearing capacity (Q_{ult}) was obtained as 3888.01 kPa, significantly higher than the maximum applied stress. Consequently, the factor of safety for bearing capacity was calculated as 31.76, which far exceeds the minimum requirement of 3.0. Overall, these results confirm that the retaining wall design meets the required stability standards and can be considered structurally safe. Table 5 shows the analysis results. A subsequent global stability analysis was also conducted to assess the performance of the reinforced slope. The modelling results indicated an increase in the factor of safety under both static and dynamic conditions, as shown in Table 6.

Table 6. Slope Stability Analysis with Cantilever Wall

	Static condition	Pseudo static condition
Safety Factor	 SF = 2.199	 SF = 1.111
Total displacement, U_y (m)	 U_y = 0.01717	 U_y = 0.1247

For the concrete sheet pile reinforcement, the analysis focused on determining the embedded depth (d_o) of the pile required to achieve stability. The design considered the lateral earth pressures acting on the structure at the site. The loads contributing to the lateral earth pressure included the uniform load (σ_q) applied on top of the slope, the active lateral earth pressure (σ_{h2} and σ_{c2}), and the passive lateral earth pressure (σ_{h3} and σ_{c3}). The lateral earth pressure distribution diagram is illustrated in Fig. 5.

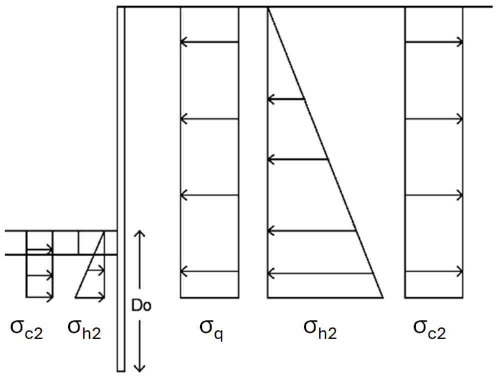


Fig. 5. Diagram of Lateral Earth Pressure

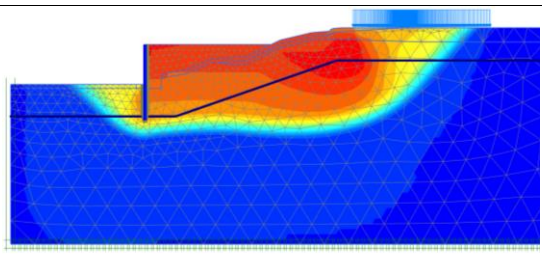
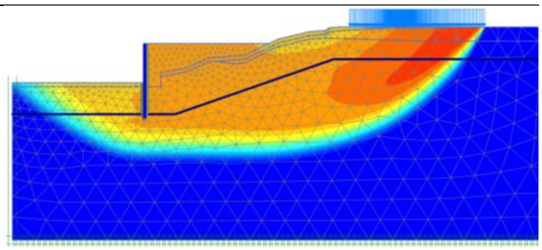
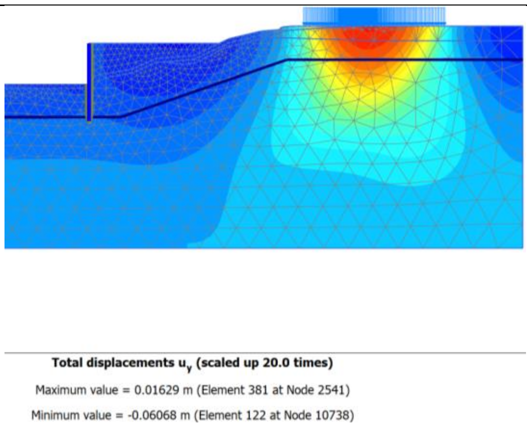
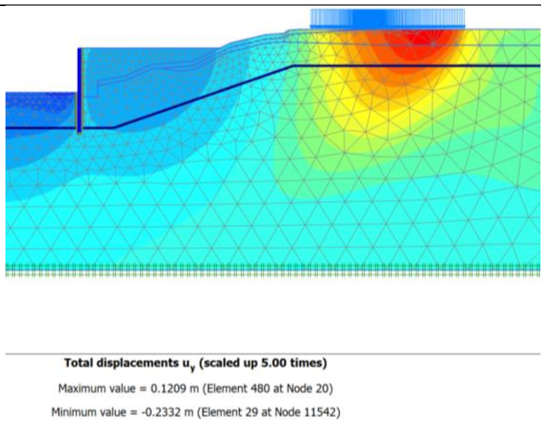
Based on the lateral active and passive earth pressure analysis using Rankine theory, the required theoretical embedment depth of the sheet pile was calculated as 3.46 m. By applying a safety factor of 1.2, the design embedment depth increased to 4.1 m, resulting in a total sheet pile length of 9.1 m. The analytical calculation produced a maximum bending moment of 294.52 kNm. Subsequently, the design was verified using PLAXIS 2D numerical analysis to evaluate the deformation behavior and bending moment distribution along the sheet pile. The numerical simulation indicated a maximum bending moment of 116.5 kNm, equivalent to approximately 13.05 ton·m. These values are summarised in Table 7.

Table 7. Parameter Values Summary

Parameter	Value
Retained soil height (h)	5 m
Active earth pressure coefficient (K_a)	0.344
Passive earth pressure coefficient (K_p)	2.905
Theoretical penetration depth (D_o)	3.46 m
Safety factor (SF)	1.2
Design embedment depth (D)	4.1 m
Total sheet pile length	9.1 m
Maximum bending moment (PLAXIS)	116.5 kNm (≈ 13.05 ton·m)
Selected sheet pile type	CCSP

This analysis provided a comprehensive evaluation of slope reinforcement performance, ensuring the structure remained stable under both static and seismic (dynamic) loading conditions. The concrete sheet-pile was also modelled to know the global safety factor. The results of the stability model is shown in 8.

Table 8. Slope Stability Analysis with Concrete Sheet-pile

	Static condition	**Pseudo static condition**
Safety Factor	 SF = 2.098	 SF = 1.110
Total displacement, U_y (m)	 U_y = 0.01629	 U_y = 0.01629

The analysis results indicated that the application of retaining structures, both cantilever walls and concrete sheet piles, significantly improved slope stability compared to the unreinforced condition. Under static loading, the factor of safety (SF) increased by approximately 17.9% for the cantilever wall and 12.5% for the concrete sheet pile relative to the unreinforced slope. Similarly, under pseudo static (seismic) loading, the SF improved by about 8.4% and 8.3%, respectively. The displacement values also exhibited a slight reduction after reinforcement, particularly under seismic conditions, indicating improvements not only in overall stability but also in deformation control.

These results were consistent with findings by [15], who reported that cantilever retaining walls significantly increased the safety factor to 1.567 above the minimum stability threshold of 1.3 and effectively reduced deformation in slope structures. Comparable trends were also observed by [16] in the reinforcement of slopes using cantilever retaining walls on the West Ring Road of the Sadawarna Dam, where pseudo static safety factors reached approximately 1.11, meeting the SNI criteria for seismic stability. The similarity in results suggested that cantilever retaining walls remain a reliable and efficient reinforcement method capable of maintaining equilibrium between enhanced stability and acceptable deformation under dynamic loading conditions.

Overall, the present study corroborated previous research by demonstrating that both cantilever and concrete sheet-pile systems effectively improve slope resistance against failure mechanisms induced by gravity and seismic excitation. Nevertheless, the slightly higher SF values obtained for the cantilever wall indicate a more favorable performance in resisting deformation, particularly for heritage or sensitive site applications where both structural integrity and minimal displacement are essential. The summary of the analysis can be seen in Table 9.

Table 9. Summary of the Reinforcement Analysis

Condition	SF		
	Without reinforcement	Cantilever wall	Concrete sheet-pile
Static	1.865	2.199	2.098
Pseudostatic	1.025	1.111	1.110
	Displacement (m)		
	Without reinforcement	Cantilever wall	Concrete sheet-pile
Static	0.01675	0.01717	0.01629
Pseudostatic	0.1347	0.1247	0.1209

4. Conclusion

The analysis reveals that the temple stupa, constructed from andesite blocks, exerted a foundation pressure of approximately 78.16 kN/m². The initial stability assessment of the natural slope yielded a safety factor of 1.025 under pseudostatic conditions, indicating a state close to failure. To improve slope stability, two reinforcement alternatives were evaluated: a cantilever retaining wall and a concrete sheet pile. Both methods demonstrated significant improvements in slope performance, achieving safety factors of 1.111 and 1.110 in pseudosatic conditions, respectively. Although the difference between the two methods was minimal, the cantilever retaining wall produced a slightly higher safety factor, indicating better overall effectiveness in improving slope stability within the heritage site. Meanwhile, the concrete sheet pile reinforcement was more effective in reducing slope displacement under both static and pseudostatic conditions. These results indicate that both reinforcement methods successfully improved the slope safety factor; however, the concrete sheet pile provided better performance in minimizing displacement under static and pseudostatic loading conditions.

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