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Methodology of Studies for Construction of Water Reservoir Dams in Countries Prone to Landslide Hazard

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Abstract

Construction of water reservoirs often has significant geomorphological and environmental impacts, particularly in regions prone to landslides. This study addresses the critical issue of slope stability in the context of the construction of a planned water reservoir in Astghadzor, Gegharkunik Marz, Armenia. The primary objectives are to investigate the stability of slopes, identify potential landslide triggers, and evaluate seismic impacts using advanced numerical modeling techniques. GeoStudio SLOPE/W software was employed, with calculations performed using the Morgenstern-Price and Spencer methods, which ensure rigorous equilibrium conditions for mountainous terrains. Field investigations and laboratory tests provided input data, forming an engineering-geology model for the analysis. The results reveal that the slopes remain stable under static loading conditions; however, seismic loading renders them unstable, particularly in soils related to Category III. Stability factors decrease by approximately 68% under adverse soil conditions. These findings underline the necessity for incorporating advanced stabilization measures and soil-specific interventions into the design of water reservoir dams. This study contributes to optimizing design methodologies, improving the safety of reservoirs, and guiding future research in landslide-prone and geologically challenging regions.

Keywords: Landslide; Water Reservoir; SLOPE/W; Morgenstern-Price Method; Spenser Method; Slope Stability; Seismic Resistance.

1. Introduction

Armenia faces diverse geological and hydro-meteorological hazards, including landslides, earthquakes, floods, and mudflows. The World Bank report (2005) ranked Armenia among the 60 countries most vulnerable to natural disasters. Landslides are particularly prominent due to steep slopes, complex geology, anthropogenic activities, and increasing climate-related precipitation extremes [1, 2]. More than 2,500 landslides included in the landslide catalogue of Armenia as of 2005 are affecting 4% of the country area and are posing significant risks to infrastructure and human settlements [3]. An inventory updated in 2019 identified approximately 3,500 landslides [4, 5]. However, research on how reservoir construction exacerbates landslide risks in such terrains has been still limited. This study strives to fill this gap by evaluating slope stability under static and seismic conditions at the site of the proposed Astghadzor reservoir. Key questions addressed by this study include the following:

- What are the critical factors influencing slope stability in the study area?
- How do seismic forces and soil properties affect stability margins?
- What methodologies are most suitable for accurate and reliable assessments in mountainous terrains?

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Recent studies on landslide risk assessment and slope stability analysis provide valuable insights into the factors influencing slope failure and the methodologies for assessing stability. Advanced numerical techniques, including limit equilibrium and finite element methods, have been widely adopted [6, 7]. The Morgenstern-Price and Spencer methods are particularly suitable for analyzing complex terrains due to their rigorous treatment of equilibrium conditions [8-12]. Several studies have explored the impacts of water reservoirs on landslide activation. Groundwater infiltration, rapid drawdown, and seismic forces are recognized as critical triggers [4, 13]. Recent research emphasizes the role of high-resolution modeling and field validation in assessing stability [14, 15].

The study by Zhang & Ding (2019) highlights the role of rainfall-induced instability in geotechnical areas, which can further inform slope stability assessments [16]. Havenith (2022) discussed landslide dynamics in the Lesser Caucasus, providing a valuable regional perspective [17]. Rotaru et al. (2022) critically reviewed sustainable slope stability methods, emphasizing advancements in integrating environmental and geotechnical factors [18]. Wang et al. (2023) proposed a comprehensive slope stability analysis combining limit equilibrium and finite element methods, showcasing the benefits of integrating multiple approaches for improved reliability [19]. Liu et al. (2015) examined slope stability using the limit equilibrium method and two finite element methods, contributing to the comparative understanding of these approaches in geotechnical contexts [20]. Liu et al. (2024) investigated the stability of loess slopes under varying rainfall intensities, underscoring the influence of rainfall on slope stability in diverse geotechnical contexts [21].

Cheng et al. (2007) critically reviewed two-dimensional slope stability analysis methods, highlighting the comparative effectiveness of discontinuity layout optimization, limit equilibrium, and strength reduction methods for different scenarios [22]. Lalicata et al. (2024) introduced an efficient slope stability algorithm with physically consistent parameterization of slip surfaces, providing enhanced computational accuracy and practical applicability in challenging terrains [23]. Despite these advancements, there remains a lack of region-specific studies addressing the combined effects of seismic and hydrological factors in mountainous terrains of Armenia. This study builds on these findings, incorporating recent methodologies and data to address the unique challenges posed by the Astghadzor site.

1.1. Description of the Study Area

The study area is located in southeastern Geharkunik Marz, approximately 3 km southwest of the Astghadzor village (Figure 1).

Figure 1. Location of the study area

The terrain is characterized by highly dissected mountainous relief, with elevations ranging from 2116 m to 2136 m. The Vardenis Mountains, with peaks exceeding 3500 m, dominate the southern landscape. The hydrography of the area is characterized d by rapid-flow rivers, including the Vardenik and the Astghadzor, which discharge into Lake Sevan. The geological setting includes rocks ranging by age from the Middle Eocene to the Quaternary. These strata comprise volcanic and sedimentary formations, including basalts, andesites, and dacites, as well as alluvial and deluvial deposits. Active tectonic structures, such as the Pambak-Sevan-Syunik Fault, traverse the region, amplifying the seismic risks [14, 15].

2. Research Methodology

2.1. Method for Slope Stability Analysis

There are many methods of slope stability calculation that can be subdivided into two groups.

The first group includes the methods applying the theory of the limit equilibrium of soils. According to this concept, the limit state within the entirety of the considered domain develops simultaneously. In the general case, application of the limit equilibrium theory for slope stability calculation as a plane problem requires concurrent solution of the two equilibrium equations [6, 7].

$$\left.\begin{aligned}\partial\sigma_x/\partial x + \partial\tau_{xy}/\partial y = X\\ \partial\tau_{xy}/\partial x + \partial\sigma_y/\partial y = Y\end{aligned}\right\} \tag{1}$$

and consideration of the limit equilibrium condition formulated as:

$$\frac{\left(\sigma_x+\sigma_y\right)^2+4\tau_{xy}^2}{\left(\sigma_x+\sigma_y+2c\cdot ctg\varphi\right)^2} = sin^2\,\varphi \tag{2}$$

where c and φ are the specific cohesion and the internal friction angle of a soil, respectively, while X and Y are the mass forces (including the filtration forces). This way of slope stability prediction, taking into account the filtration flow as well, was developed by Sokolovskiy [6] and Sokolovskiy [7] and in other studies. These techniques have not been applied largely as the solutions are very complex. Moreover, the assumption of the limit state developing at all points of the observed domain is not realistic from the standpoint of physics.

Methods related to the second group assume that the limit equilibrium is disrupted along a sliding surface. The pre-selected surface is assumed to be round-cylindrical or composed of straight lines or a combination of both forms. Safety factor for stability is determined by correlating the actual value of shear stress on the sliding surface to the limit stress according to the Coulomb-Mohr theory [13, 14], which is described as follows:

$$\tau_s = \sigma tg\phi + c \tag{3}$$

The equation below is used commonly to determine values of safety factor F:

$$F = \frac{\tau_s}{\tau} = \frac{tg\varphi}{tg\varphi\prime} = \frac{c}{c\prime} \tag{4}$$

where φ and c are the actual values of the internal friction angle and specific cohesion of a soil, respectively, φ' and c' are the values of the same characteristics of soil shear strength in case of which the limit state is generated within the entirety of the observed sliding surface. There are plenty of techniques related to this group. Among the early ones is the method of Stewart & Peterson (1917) [24] later used by Fellenius [25] for cylindrical slip surfaces and improved further by Bishop [26] (the simplified method). In this and other techniques, the slip (sliding) surface is pre-set. By speculation, the sliding soil mass is assumed being split into individual slices. Acting (driving) forces and mass forces are exerted on each slice facet. These approaches can be all grouped under the three subgroups depending on the number of equilibrium equations used. The Fellenius method designated for cylindrical slip surfaces considers the general equilibrium of the moments only, while forces exerted on the facets are disregarded. In the simplified Bishop's technique, conditions of the equilibrium of the total moments and the vertical forces are met. For each block, however, neither the condition of total moments, nor the condition of horizontal forces is met. The second subgroup includes the methods of Krey [27] and Florin [28] and Terzaghi [29]. The method of Krey applies the condition of zero-equal sum of the projections of all forces on the vertical axis, while by the technique of K. Terzaghi forces for each block are projected along the normal onto the slip surface. The third subgroup includes the approaches that meet the conditions of moment equilibrium, as well as the equilibrium of the vertical and horizontal forces. The methods of Morgenstern-Price [8-10] and Spencer [11, 12] are related to this subgroup. Therefore, they are theoretically more stringent than the methods described above.

Taking into account that the study area is characterized by highly dissected mountainous relief and active faults, to estimate stability this study applies the techniques related to the third subgroup, considering any potential impact on each soil block. The methods of Morgenstern-Price and Spenser are different in regarding the inclination angle of the interslice forces generated among the blocks as a constant value in each block.

The safety factor is calculated by the relation of the limit moment ($M_{\text{lim.react.}}$) of all reactive forces acting on the pre-set center to the moment of active forces ($M_{\text{act.}}$) exerted onto the same center [8-11]:

$$F_m = \frac{M_{\text{lim.react.}}}{M_{\text{act.}}} \tag{5}$$

In the meantime, the safety factor on the horizontal axis is determined by the relation of the projected reactive ($T_{\text{lim.react.}}$) and active ($T_{\text{act.}}$) forces:

$$F_f = \frac{\sum T_{\text{lim.react.}}}{\sum T_{\text{act.}}} \tag{6}$$

In the case of cylindrical slip surface, we get:

$$F_m = \frac{R\sum[c\beta+(N-u\beta)tg\varphi]}{\sum Wx-\sum Nf+\sum kWe\pm[Dd]\pm Aa} \tag{7}$$

$$F_f = \frac{\cos\alpha\sum[c\beta+(N-u\beta)tg\varphi]}{\sin\alpha\sum N+\sum kW-[D\cos\alpha]\pm A} \tag{8}$$

where c is the effective cohesion; φ is the effective angle of friction; u is the pore-water pressure; N is the slice base normal force; W is the slice weight; D is the concentrated point load; $\beta, R, x, f, d, \omega$ are the geometric parameters, and α is the inclination of the slice base (Figure 2a).

Equations 7 and 8 are nor linear, as the force normal to the block base (N), placed in the right part of the equation, depends on the safety factor F:

$$N = \frac{W+(X_R-X_L)+[D\sin\varpi]-\frac{\sin\alpha(c\beta-u\beta tg\varphi)}{F}}{\cos\alpha+\frac{\sin\alpha tg\varphi}{F}} \tag{9}$$

The method of iterations is used to estimate the safety factor (the technique of iterative approximations). For this purpose, safety factor is determined by the first approach setting the value of F by Equation 7 or by Equation 8. Placing the produced F value in Equation 9 the magnitude of N is validated and new F value is estimated by Equations 7 or 8 and so on. The process of iterations is terminated in case the desired rate of accuracy is achieved. This technique is quite convenient in making software-aided computerized calculations. It is noteworthy that similar formulas and methods are applied also when slip surface is not cylindrical, but composed of individual straight-line sections (broken-line) (Figure 2b).

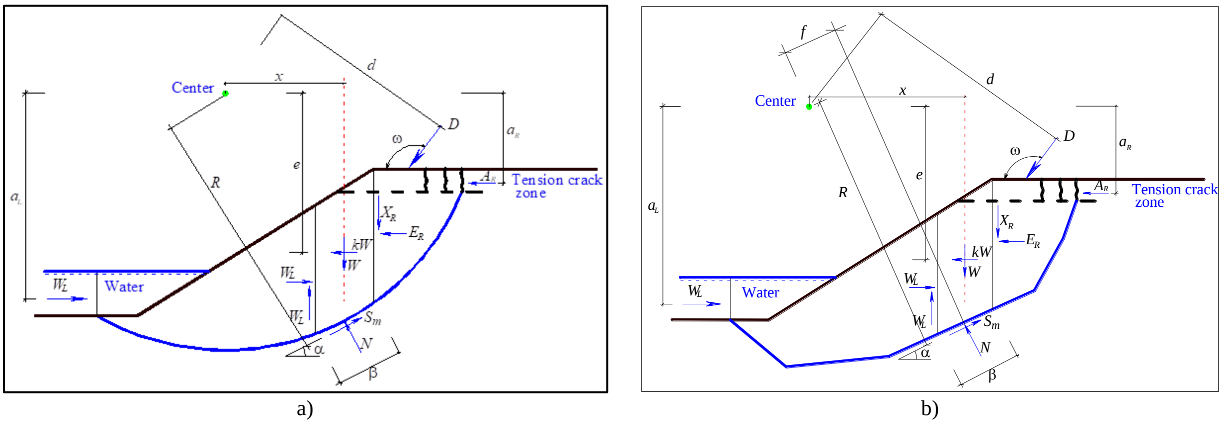


Figure 2. Slip surface calculation layouts: a) cylindrical and b) broken line

The approaches indicated above are used also in case of pseudo-static analysis accounting for seismic impacts on slope stability, when earthquake impact is modeled by placing an additional inertia force in the centre of gravity of the soil mass.

2.2. Seismic Impacts Calculation

Seismic impacts were incorporated using pseudo-static analysis, where seismic forces are modeled as equivalent static forces. These forces account for both horizontal and vertical accelerations. According to Armenian Building Code RABC 20.04-2020 [30], the seismic acceleration is defined as:

$$a = Ak_0k_1k_2g \tag{10}$$

where A is the abstract coefficient of seismic intensity, which demonstrates the relation of the ground acceleration in the considered settlement to the acceleration of free oscillations, k_0 is the coefficient allowing for soil conditions in a construction site, k_1 is the coefficient of permissible damages, k_2 is the coefficient for the rate of criticality of a structure, and g is the acceleration of gravity.

When estimating the vertical seismic load, coefficient A is multiplied by the factor of 0.7.

As per Clause 26 of RABC 20.04-2020 [30], in case of construction of buildings and structures at individual high-elevation sites (hills, mountain ridges and other) or on slopes with gradients steeper than 15°, the adopted design values of seismic ground acceleration must be multiplied by the factor of 1.2. Meanwhile, according to the Armenian Building Code RABC 20.04-2020, values of seismic loads are estimated taking into account the reducing coefficients k_1 and k_2, which consider the rate of permissible damage of buildings and structures. Coefficient k_0 allowing for the soil conditions of a construction site was set for both crushed-stone and gruss (Category II) and for loamy soils (Category III) [15]. Therefore, as provided for in RABC 20.04-2020 [30], relative design acceleration value is equal to:

- ***For Category II soils***
  - $(a/g)_{hor}$= 0.144 in the horizontal direction,
  - $(a/g)_{ver}$ = 0.101 in the vertical direction;
- ***For Category III soils***
  - $(a/g)_{hor}$= 0.436 in the horizontal direction,
  - $((a/g)_{ver}$= 0.305 in the vertical direction.

2.3. Standards for Slope Stability

Slope stability is assessed using the following condition [31]:

$$k = R/F \geq \Psi\gamma_n/\gamma_c \tag{11}$$

In this formula, k is the stability factor, F is the generalized estimated value of sliding forces, R is the generalized estimated value of limit strength forces, Ψ is the coefficient of the combination of loads, γ_c is the work condition factor and γ_n is the credibility factor.

Stability factor (k_{st}) values range from 1.25 to 1.10 in case of the principal combination of loads and from 1.20 to 1.05 in case of specific combination of loads, depending on the criticality of the slope and load combination:

- ***Principal Combination:* 1.25;**
- ***Specific Combination:* 1.20.**

Seismic forces are incorporated into the analysis by adding equivalent static forces to account for earthquake impacts. These forces ensure the structure can withstand certain damages and remain stable even under seismic conditions.

2.4. Methodology

To analyze slope stability, extensive field and laboratory studies were conducted. The field studies involved drilling operations with 17 boreholes drilled to depths ranging from 5.0 m to 50.0 m using Atlas Copco CS-14 drilling rigs. The drilling diameter was set at 151-100 mm and rotary core technique was applied. A total of 66 samples of soils, including both disturbed or undisturbed structure specimens, were collected for laboratory testing [14, 15]. The tests determined the physical-mechanical and filtration properties of the soils as required for slope stability calculations.

As summarized in Table 1, laboratory analyses established the following physical-mechanical characteristics for the soil samples:

Table 1. Adopted estimated values of the physical-mechanical characteristics of the soils

Layer №	Name of Soil Layer	Specific weight, γ kN/m^3	Internal friction angle, $\varphi°$	Specific cohesion, c, kPa
1	Black soil	17.65	-	-
2	Loam	18.00	16.2	25.7
3	Crushed-stone and gruss soil	18.63	34	1.0

Based on the analysis of field studies and laboratory results, an engineering-geology calculation model was created in GeoStudio (Figure 3).

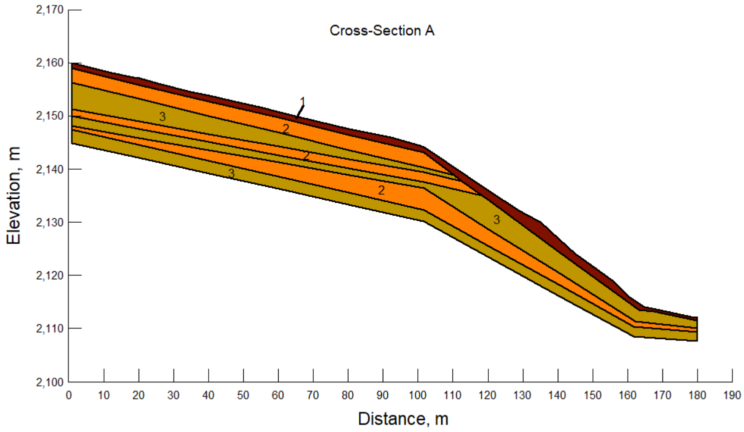


Figure 3. Calculation model – Section A

3. Results and Discussion

3.1. Results

Results of slope stability calculations are summarized in Table 2, with safety factors computed for both cylindrical and broken-line slip surfaces. Under principal load combinations, all calculated safety factors exceeded the standard limit of 1.25, indicating stable conditions. However, for specific seismic load combinations, safety factors fell below the required threshold of 1.20, especially in areas with Category III soils.

Table 2. Produced values of slope stability factors

Form of Surface	Stability Factor Values				
	Principal combination of loads (k_{sf})	Standard Limit Value (k_{st})	Specific combination of loads (k_{sf})		Standard Limit Value (k_{st})
			Category II	Category III	
Spenser					
Broken-line	1.473	1.25	1.085	0.751	1.20
Cylindrical	1.446		1.065	0.733	
Morgenstern-Price					
Broken-line	1.456	1.25	1.076	0.740	1.20
Cylindrical	1.447		1.066	0.731	

Figures 4 to 11 illustrate the safety factors and the slip surface geometries. Figures 4 to 7 comprehensively present the results of minimum safety factor calculations using the Spencer method for different slip surface geometries and load combinations, with an emphasis on soil categories and loading conditions. For broken-line slip surfaces, as shown in Figures 5 and 6, the results reveal that the safety factor for Category II soil is significantly higher compared to the one established for Category III soil under primary load combinations. However, under special load combinations, a reduction in the safety factor is observed, particularly for weaker soils, highlighting the impact of varying load scenarios on slope stability.

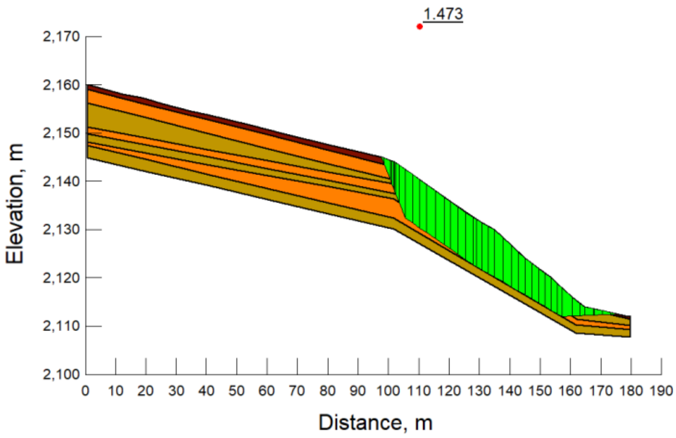
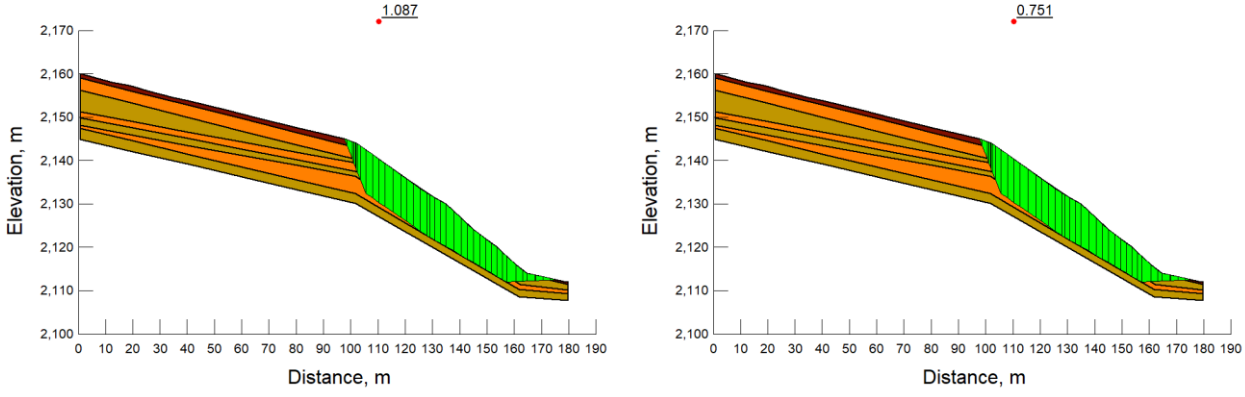


Figure 4. Minimum value of the safety factor derived by the Spenser method: broken-line surface. Principal combination of loads



a) b)

Figure 5. Minimum value of the safety factor derived by the Spenser method: broken-line surface. Specific combination of loads a) Category II soil, b) Category III soil

For cylindrical slip surfaces, presented in Figures 6 and 7, the results indicate that the safety factor for Category II soil remains substantially higher, demonstrating greater stability. In contrast, for Category III soil, the safety factor values show the lowest stability levels, reflecting the critical role of soil properties in slope behavior. Collectively, these findings underline the effectiveness of the Spencer method in capturing the variability in stability across different slip surface geometries, soil categories, and loading scenarios, providing a robust framework for geotechnical stability assessments.

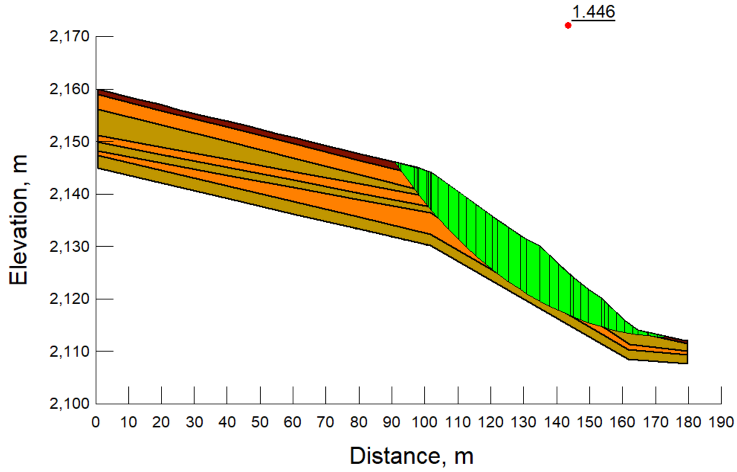
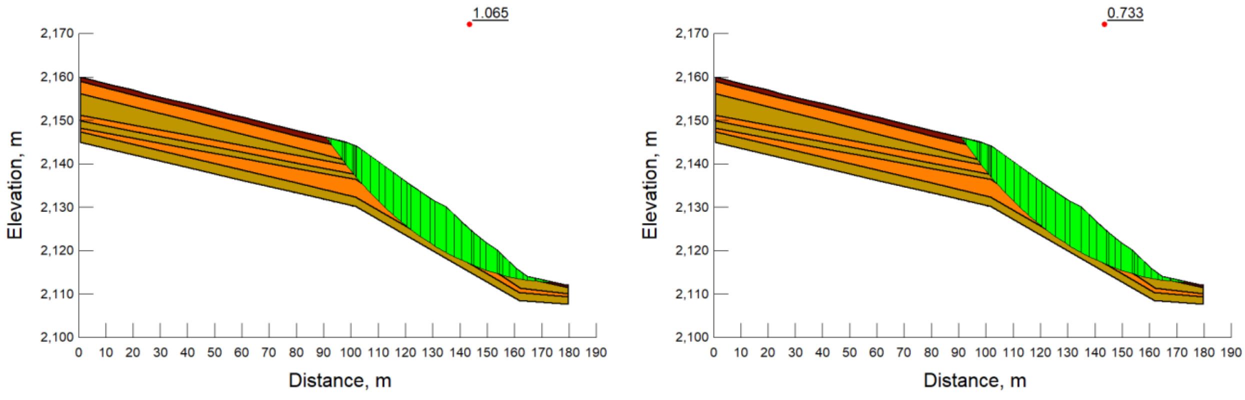


Figure 6. Minimum value of the safety factor derived by the Spenser method: cylindrical surface. Principal combination of loads



a) b)

Figure 7. Minimum value of the safety factor derived by the Spenser method: cylindrical surface. Specific combination of loads: a) Category II soil, b) Category III soil

Figures 8 to 11 provide a comprehensive analysis of slope stability using the Morgenstern-Price method for both broken-line and cylindrical slip surfaces under primary and special load combinations. Figure 9 establishes a reference point by presenting the minimum safety factor for a broken-line slip surface under the primary load combination, capturing the baseline stability.

Figure 9 expands on this by evaluating the safety factor for the same surface under special load combinations, accounting for the variability of Category II and Category III soils. For cylindrical slip surfaces, Figure 10 illustrates the minimum safety factor derived from the primary load combination, while Figure 11 highlights the influence of special load combinations on the safety factor for Category II and III soils.

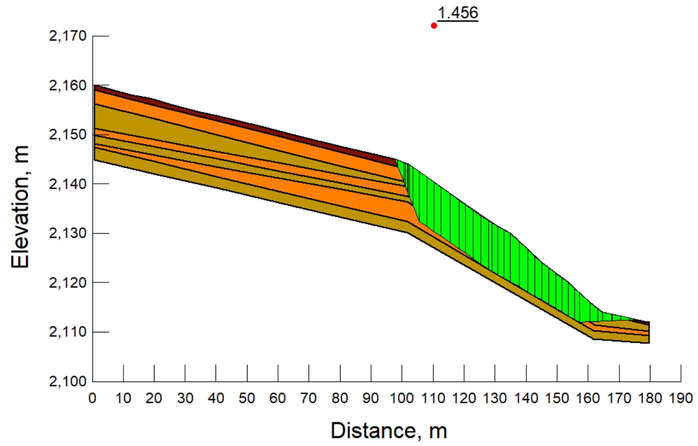
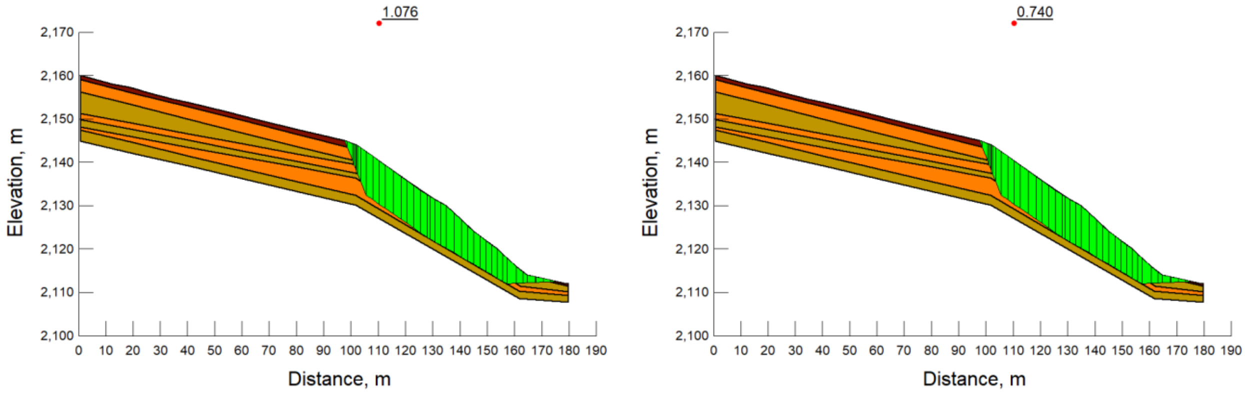


Figure 8. Minimum value of the safety factor derived by the Morgenstern-Price method: broken-line surface; principal combination of loads



a) b)

Figure 9. Minimum value of the safety factor derived by the Morgenstern-Price method: broken-line surface; specific combination of loads: a) Category II soil, b) Category III soil

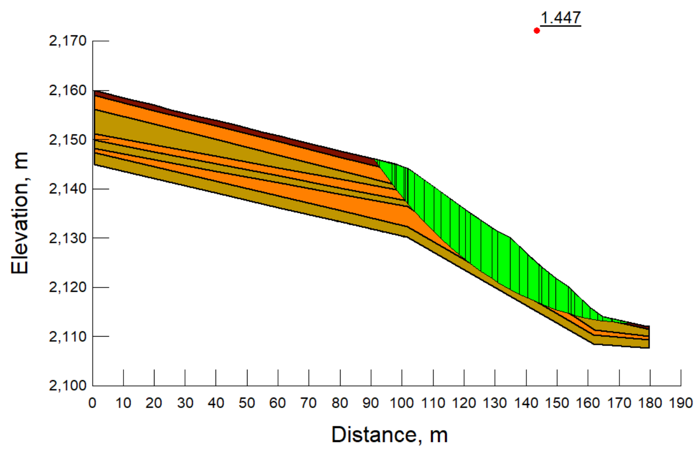


Figure 10. Minimum value of the safety factor derived by the Morgenstern-Price method: cylindrical surface; principal combination of loads

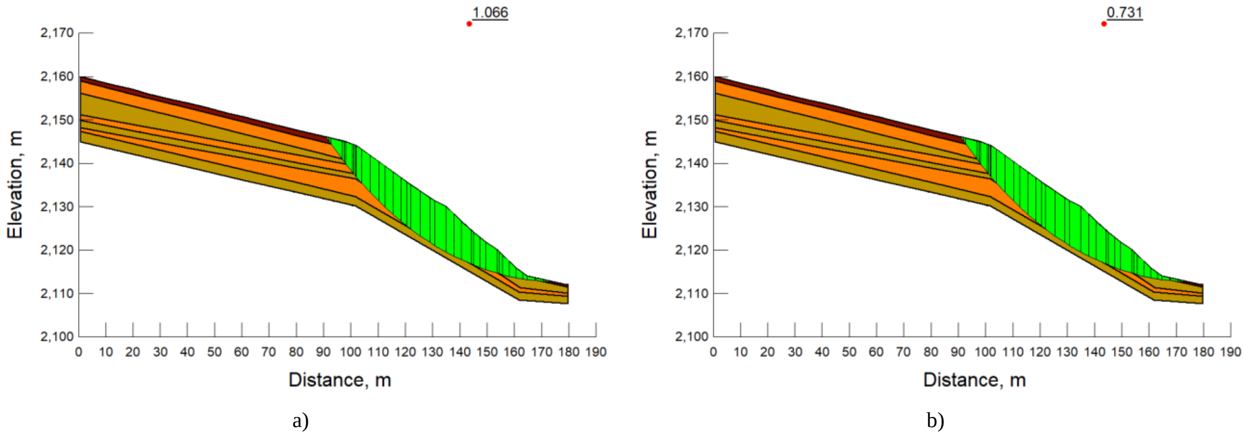


Figure 11. Minimum value of the safety factor derived by the Morgenstern-Price method: cylindrical surface; specific combination of loads: a) Category II soil, b) Category III soil

The analysis reveals that for broken-line slip surfaces, the Morgenstern-Price method produces results comparable to those of the Spencer method under primary load combinations, ensuring consistency and reliability. However, under special load combinations, minor deviations in safety factors are observed, reflecting the inherent flexibility and adaptability of the Morgenstern-Price method in addressing complex loading scenarios. Similarly, for cylindrical slip surfaces, the results indicate a stable trend in safety factors, demonstrating the robustness of the method in handling varying geometries and soil conditions.

3.2. Discussion

The findings of this study provide valuable insights into slope stability, particularly under the influence of seismic forces and variable soil conditions. By integrating localized field data with advanced numerical modeling, this research offers a more context-specific perspective compared to previous studies. The alignment of the results with established works, such as those by Spencer and Morgenstern and Price, emphasizes the critical role of pore-water pressure and seismic forces in slope stability analysis. However, this study distinguishes itself by combining empirical data with robust computational techniques, enabling a nuanced understanding of site-specific conditions.

The sensitivity of stability factors to soil type and seismic acceleration underscores the importance of targeted evaluations. The observed reduction in stability-by up to 68% for Category III soils under seismic conditions—highlights the critical need for careful assessment in areas prone to earthquakes. These findings not only reinforce the need for incorporating soil mechanics principles, as suggested by Sobhan & Das (2012) [13], but also extend the understanding by providing detailed parametric analyses for mountainous terrains.

A comparative review of previous studies reveals a trend of seismic stability reductions, often analyzed using either limit equilibrium or finite element methods. This study builds on the methodologies of Wang et al. (2023) [19] by integrating both approaches to achieve a more comprehensive evaluation. Additionally, the emphasis on hydrological impacts, as explored by Liu et al. (2024) [21], further enriches the context by acknowledging the role of rainfall intensity in slope stability. The inclusion of advanced algorithms, such as those introduced by Lalicata et al. (2024) [23] demonstrates the potential for improving computational efficiency and accuracy in stability assessments.

This study also validates the use of Morgenstern-Price and Spencer techniques, which adhere to stringent theoretical requirements and ensure equilibrium in horizontal and vertical forces. Notably, the comparison of cylindrical and broken-line surface calculations highlights the variability in safety factor values, with the latter yielding relatively lower stability measures under certain conditions. The findings confirm that slopes, while stable under principal load combinations, may become unstable under specific seismic conditions, especially for weaker soil categories. This observation underscores the necessity of seismic-resistant designs in construction activities.

In conclusion, the integration of advanced modeling with field-specific data provides critical insights for improving slope stability analyses. By addressing the limitations of prior studies and offering detailed parametric evaluations, this research sets a foundation for more effective methods in assessing and mitigating slope stability risks, particularly in seismically active and hydrologically sensitive regions.

4. Conclusion

This study presents a comprehensive methodology tailored for the construction of water reservoir dams in landslide-prone regions, using the Astghadzor reservoir site as a representative case. The findings underscore that while slopes remain stable under static conditions, they are highly susceptible to failure under seismic loading, particularly in Category III soils. Advanced analytical methods, such as Morgenstern-Price and Spencer, proved reliable for assessing complex terrains and identifying critical failure mechanisms. The study highlights that seismic impacts significantly reduce stability margins, emphasizing the importance of incorporating enhanced stabilization measures into dam design. These include considerations for soil category-specific interventions and the adoption of advanced engineering solutions to mitigate risks associated with landslides and seismic activity. Future research should focus on innovative stabilization techniques, their feasibility, and cost-effectiveness, especially for highly vulnerable soil types. This methodology contributes to the broader understanding of dam construction in geologically complex regions, offering practical guidance for achieving safer and more resilient water reservoir infrastructures. Furthermore, the findings provide a framework for addressing similar challenges in other regions prone to landslides and seismic hazards, ensuring both structural safety and long-term operational reliability.

5. Declarations

5.1. Author Contributions

Conceptualization, A.G., H.I., E.E., H.H., V.P., and R.K.; methodology, A.G.; software, A.G.; validation, A.G., H.I., E.E., H.H., V.P., and R.K.; formal analysis, A.G. and H.I.; investigation, A.G., H.I., E.E., H.H., V.P. and R.K.; resources, A.G., H.I., E.E., H.H., V.P., and R.K.; data curation, A.G. and H.I.; writing—original draft preparation, A.G.; writing—review and editing, A.G.; visualization, A.G., H.I., E.E., H.H., V.P., and R.K.; supervision, A.G. and H.I.; project administration, H.I.; funding acquisition, H.I. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding and Acknowledgements

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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