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Physical Slope Stability: Factors of Safety Under Static and Pseudo-Static Conditions

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Abstract: Evaluating physical slope stability is essential to prevent landslides and damage to infrastructure located on sloping terrains. This study analyzes how static and pseudo-static conditions affect slope safety, considering the magnitude and location of the loads exerted. A total of 2394 simulations were carried out on 399 terrain profiles, using the Spencer method to calculate factors of safety (FSs). The results reveal that uniformly distributed loads placed at the center of the slope increase stability under static conditions. However, in pseudo-static scenarios, the action of dynamic forces, such as seismicity, drastically reduces the FS, especially on slopes greater than 15%. This analysis allowed the identification of critical zones of high susceptibility, promoting the implementation of reinforcement techniques, such as retaining walls and drainage systems. In addition, zoning maps were developed that prioritize safe areas for urban development, aligned with the international standards. The findings underscore the importance of integrating predictive models into design and planning processes, considering both static and dynamic factors. In conclusion, this study provides practical tools for risk mitigation and resilient infrastructure design in sloping terrains.

Keywords: slope stability; static analysis; pseudo-static analysis; seismicity; risk mitigation

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1. Introduction

The physical stability of a slope depends on all the forces that intervene in the system. Thus, the construction of buildings on a slope alters the natural equilibrium of a slope, so a rigorous analysis must be carried out considering all the conditioning factors and susceptibility to landslides, which, when interacting, generate different scenarios.

Mass movements occur in different ways, associated with factors that condition the stability of the slope, so it is necessary to identify and recognize possible areas of failure, through techniques to reduce or eliminate the risk [1].

For the evaluation of seismic risk, it is essential to observe the local soil conditions, which can drastically modify the movement transmitted to the structure [2]. The impact between adjacent structures during earthquakes can depend considerably on the effects of the interaction between the soil, foundations, and structures [3]. Therefore, seismic risk mitigation is a crucial aspect for most cities characterized by a high seismic risk. This can be addressed with the modeling of sections of a building, based on geotechnical characterizations, and carried out using a static and dynamic approach [4].

The evaluation of seismic, geotechnical, and structural risks is essential for the stability of infrastructures on sloping terrains and the prevention of landslides. The interaction between the soil, foundations, and structures, especially in seismic scenarios, is key to ensuring safety.

Seismic, geotechnical, and structural risks in sloping terrains depend on the soil–structure interaction (SSI), which can affect nearby structures during an earthquake [5]. It is crucial to consider soil–structure interaction (SSI) in the seismic evaluation of infrastructures on sloping terrains. Evaluating SSI is important for a better understanding of seismic effects and their impact on structures, which contributes to designing safer and more resilient infrastructures [6].

In seismic areas with historic buildings, such as the churches in Sicily, soil–structure interaction (SSI) plays a key role. The study of the 1980 earthquake and its impact on these churches highlights how dynamic soil effects can increase the seismic risk, emphasizing the need for proper seismic renovations. Advanced numerical models provide tools to improve structural safety and mitigate seismic risks in historic infrastructures [7] (Table 1).

Table 1. Technical aspects.

Aspect	Description	Key Indicators
Seismic risk assessment	It is essential to guarantee the stability of infrastructures on an inclined terrain and prevent gradual advances of land.	Structural stability. Identification of areas prone to landslides. Evaluation of seismic impact. Use of predictive models.
Soil–structure interaction (SSI)	SSI is crucial for infrastructure safety, especially during an earthquake, as it can affect the stability of nearby buildings.	Impact of SSI on structure safety. Simulation of dynamic soil effects. Evaluation of soil deformability and structural flexibility.
Advanced 3D numerical models	Use of 3D numerical models to simulate the interaction between the soil, the foundation, and the structures, considering non-linear mechanisms.	Non-linear soil modeling. Accurate assessment of soil deformability and structural response. 3D models for soil–structure interaction simulation.
Zoning and mitigation measures	Parametric analysis allows identifying critical areas to implement mitigation measures, such as retaining walls and drainage systems.	Identification of critical areas. Implementation of mitigation measures. Analysis of soil types and their impact on stability.

A case study of the San Jeronimo de Yuste buildings in Bogota, Colombia. The objective was to determine a diagnosis of the main causes of the displacements that occurred in the San Jerónimo de Yuste building and of the structural affectations observed, thus establishing the level of risk of the slopes under gravity and seismic loads. The investigation was of a cross-sectional type. The methodology employed encompassed a series of studies (GPS monitoring, topographic surveys, geotechnical analysis, and seismic simulations), all of which were coordinated to determine the safety coefficient in light of the NSR-10 standard and to establish whether the buildings were safe for occupation and use. It was concluded that the theoretical results are consistent with what was observed and agree with the fact that the soil on which the residential complex is located has clayey levels. Under static conditions, the finite element models show that the stabilization measures implemented (drainage system and pile barrier) increased the safety factor of the slope, while under the effect of an earthquake, in a pseudo-static analysis, the safety factor was close to that required by the standard. The triggering factor of the landslide was water [8].

The method used in the analysis of slope stability in limit equilibrium was Spencer. It was concluded that, to generate hazard maps, the initial geometric (slopes) and geological data of the material to be slid were accurate, which would be fundamental in urban developments to avoid construction in these unstable areas. To carry out specific infrastructure works, slopes must be analyzed in detail using the limit equilibrium method, to consider the infiltration of rainwater into the slope [9].

For all these reasons, the importance of this research lies in the sustainable construction of hillside housing considering the appropriate factors for the physical stability of the slope, duly articulated to the study variables proposed and taking into account the reference regulations.

This study addresses the analysis of slope stability through the evaluation of the factor of safety (FS) in various scenarios, comparing this methodology with advanced numerical simulations that require considerable time and effort [10]. Different loads applied to the head, body, and foot of the slope were analyzed, representing loads from various buildings located in these areas. A crucial aspect was the influence of earthquakes, which generate critical scenarios for slope stability. To tackle this challenge, a pseudo-static analysis was chosen, considering the locations and loads of buildings on the slope, allowing for a more complete and precise risk assessment. Regarding the slope stability, 2394 simulations were performed on 399 soil profiles using the Spencer method, revealing that uniformly distributed loads at the center of the slope increase stability under static conditions, while seismic forces drastically reduce stability in slopes greater than 15%. This analysis helped identify critical areas with a high susceptibility to landslides, proposing mitigation measures, such as retaining walls and drainage systems. Additionally, zoning maps were developed to prioritize safe areas for urban development, aligned with the international standards. The findings highlight the importance of integrating predictive models in design and planning processes, promoting more resilient and safer infrastructures in sloping terrains, considering both static and dynamic factors, such as seismicity and rainwater infiltration, key elements in landslide-prone areas.

1.1. Topographic Slope

The average slope of a terrain according to the RNE-G.040 [11] standard is a percentage that indicates the measured inclination of a terrain concerning the horizontal plane, calculated based on the maximum and minimum levels of the terrain. To balance the forces of the soil, it is possible to consider the abatement of the slope. The slope conformation has the purpose of balancing the mass of the soil, reducing the forces that generate the movement of the slope.

1.2. Load Exerted by Dwellings

Houses exert loads on the ground, which are forces that are represented quantitatively using vectors. The magnitude of the stress depends on the magnitude of the force and the size of the surface on which it acts. The buildings as a whole with all their elements must have the capacity to resist the loads to which they will be subjected as a consequence of the use and service conditions for which they were designed. The service loads are those that act directly on the building; these loads are made up of static loads and seismic loads, which generate a uniform pressure (kg-f/m^2). There are innovative methods for analyzing slope stability in urban environments, where slopes are more exposed to the influence of human activities, such as construction, excavation, and alterations in drainage. Among these are advanced computational modeling, real-time sensors for monitoring slope conditions [12].

1.3. Slope Stability

Stability is the property of a body to recover after suffering a disturbance or to remain in equilibrium. It is considered physical stability since the internal structure, composition, and physical processes that occur are studied. Stability is the slope's capacity to maintain its equilibrium in the face of external effects that try to modify it, such as earthquakes and rainfall, among others. The factors that trigger instability in a slope are: precipitation, the seismic effect, and the anthropic factor, the same factors that generate the increase in shear stresses and the decrease in the resistance of the material [13].

2. Materials and Methods

A slope stability analysis requires a failure model, as well as the following components: slope geometry, geologic model, and loads exerted. The stability analysis consists of determining whether there is sufficient strength in the slope soils to withstand the shear stresses that tend to cause failure or sliding. Most of the equilibrium limit methods have in common the comparison of the resisting and acting forces or moments on a given failure surface. The main variations in the various methods are the type of failure surface and the way the forces act internally on the failure surface. For the slope stability analysis, reference was made to the Manual of Roads, Soils, Geology, Geotechnics, and Pavements of the Ministry of Transport and Communications. The height of the slope was 134.90 m, where V > 10 m, and according to the Manual de Carreteras, Suelos, Geología, Geotecnia y Pavimentos del MTC, a stability analysis was required. For the slope stability analysis, the Spencer method was considered, taking into account that this method applies to any failure surface and evaluates the forces and moments in slopes whose inclination is between (0–34°). Likewise, this method obtained good results as it is a method that fully satisfies the equilibrium of both moments and forces [14].

It is essential to consider the factors that influence landslides, such as rainwater infiltration, seismic force, and particularly the presence of geological faults. In the study area, the presence of the Cusco fault stands out, which requires special consideration with historical factors, added to this, aspects such as altitude and the frequency of seismic movements. These elements must be evaluated together, since their interaction can increase the risk of landslides and affect the stability of the terrain.

The behavior of slopes under the influence of dynamic forces, such as earthquakes, vibrations, or heavy machinery, affects the stability of slopes, considering factors such as the nature of the material, the geometry of the slope, and seismic conditions [15].

The methodology applied in this research focuses on solving immediate problems by applying general theories to analyze and evaluate the determining factors in the sustainable construction of homes, considering geomechanical soil parameters and slope stability. An experimental approach was used, manipulating independent variables to determine the appropriate factors for construction and the physical stability of slopes, with a longitudinal analysis that allowed information to be gathered across different scenarios. To evaluate slope stability, the Spencer method, based on limit equilibrium, was used to calculate the factor of safety (FS) of the slopes and determine the forces that could trigger landslides. This analysis involved identifying stabilizing and destabilizing forces and was carried out through iterative procedures to calculate the normal force and the location of the forces. The FS calculation considers both static and dynamic forces, concluding that a FS greater than 1 indicates stability, while a FS less than or equal to 1 indicates instability. This highlights the importance of evaluating both static and dynamic factors in the design and analysis of slope stability.

Additionally, one of the critical factors influencing landslides is rainwater infiltration, alongside seismic forces. In particular, the presence of the Cusco fault in the study area makes rain a triggering factor that must be considered in previous studies, as altitude and seismic movements, especially due to the San Ramón–Chile fault, increase the likelihood of landslides. This research focused on expanding urban areas in the foothills of the mountains and in the Piedmont region, where these geological and climatic factors play a crucial role in slope stability.

2.1. Methodology According to the Orientation: Applied

Also called utilitarian, this poses problems that require immediate solutions, puts general theories into practice, and directs its efforts to solve the needs posed by society and mankind. The applied research can integrate a previously existing theory. This research focuses on analyzing and evaluating the determining factors for the sustainable construction of homes, considering the geomechanical parameters of the soil, as well as the study of slope stability, identifying the action of the load associated with construction on sloping land.

2.2. Methodology According to the Technique of Contrasting: Experimental

In the experimental research, the independent variables are intentionally manipulated at different levels of experimentation. In this research, the independent variable was manipulated to determine the appropriate factors for the sustainable construction of houses and to preserve the physical stability of the slope, taking into account the intervening variable [16].

2.3. Methodology According to the Evolution of the Studied Phenomenon: Longitudinal

The longitudinal type of research is common in the experimental research, obtaining information in different scenarios, to make inferences about the change, its causes, and effects on certain variables or the relationship between them. In the present research, information was collected considering different scenarios where the independent variable was intentionally manipulated.

2.4. Spencer Method

It is a general method of cuts made based on the limit equilibrium, which is required to satisfy the equilibrium of forces and moments acting on each segment. This method not only satisfies the calculation of the intervening forces, but also the balance of moments. The Spencer procedure is based on the assumption that the forces between voussoirs are parallel to each other, i.e., they have the same angle of inclination [17]. The specific inclination of the forces between voussoirs is the same as the specific inclination of the forces between the voussoirs.

The specific inclination of the forces between the slices is calculated as an unknown in the equilibrium equations and Spencer assumes that the normal force acts at the center of the base of each slice. Two equilibrium equations are solved.

The equation for force equilibrium can be written as:

$$\sum Qi = 0$$

where Qi is the resultant of forces of the cuts Zi and $Zi + 1$.

$$Qi = Zi - Zi + 1$$

Assuming that the forces are parallel, Qi, Zi, $Zi + 1$ exhibit the same direction, where Qi is only the difference [18].

By summing the forces in directions perpendicular and parallel to the base of the voussoir, the following equilibrium equations are obtained:

$$N + F_v \cos\alpha - F_h \sin\alpha - Q\sin(\alpha - \theta) = 0$$

$$S + F_v \sin\alpha + F_h \cos\alpha + Q\cos(\alpha - \theta) = 0$$

The quantities F_h and F_v represent all known horizontal and vertical forces on the shear, including the shear weight, seismic loads, forces due to surface loads, and reinforcement forces, distributed and concentrated.

Likewise, consider the normal that is given by ($u\Delta l$) whose force represents the effect of pore pressure water on the base of the shear [19].

In this way, we obtained the shear force:

$$Q = \frac{-F_v \sin\alpha - F_h \cos\alpha - (\frac{c'\Delta l}{F}) + (F_v \cos\alpha - F_h \sin\alpha + \mu\Delta l)(\tan\phi / F)}{\cos(\alpha - \theta) + [\sin(\alpha - \theta)\tan\phi' / F]}$$

The procedures through this method are iterative, assuming values for the factor of safety and the inclination until both equations are satisfied. Once these unknowns are calculated, the values of the normal force, the force between cuts, and the location of the forces can be calculated [20].

2.5. Factor of Safety

The analysis of the factor of safety in the stability of steep slopes must consider the forces that could cause earth displacement, such as the weight of the soil, external loads and environmental conditions; applying geotechnical methods that indicate the ability of a slope to resist failure [21].

To determine the factor of safety, the shear strength properties of the soils and other soil and slope properties were previously determined.

$$FS = \frac{\text{Stabilizing forces}}{\text{Destabilizing forces}}$$

In circular surfaces where there is a center of rotation and resistant and acting moments, the *FS* is given by:

$$FS = \frac{\text{Available resisting moment}}{\text{Acting moment}}$$

In equilibrium limit methods, the factor of safety is assumed to be equal for all points along the failure surface; therefore, this value represents an average of the total value over the entire surface. If failure occurs, the shear stresses would be equal at all points along the entire failure surface [20].

The conceptual stability condition is detailed in the research by:

FS > 1: Stable slope.

FS $\leq$ 1: Unstable slope.

If the FS is slightly greater than 1, even a small imbalance in the slope can cause failure.

The stability of slopes is influenced by both static factors, such as the weight of the soil, the resistance of the material, and the characteristics of the terrain, and by dynamic factors, such as earthquakes, vibrations, or heavy traffic loads. Both types of factors have a considerable impact on the stability of slopes, which makes it essential to consider both aspects to carry out a complete and adequate evaluation [22].

3. Results

For the analysis of the results, it is necessary to present adopted soil parameters such as DH: Thickness of the stratum; γ: Specific weight; γ_{sat}: Saturated specific weight; ϕ: Angle of internal friction; ϕ_{corr}: Angle of internal friction corrected according to Terzaghi; c: Cohesion; c_{corr}: Cohesion corrected according to Terzaghi; c_u: undrained cohesion; and μ_s: Poisson's coefficient of the soil (see Table 2). The same values that were obtained by making three pits in the study area (see Tables 3 and 4), which were arranged in a staggered manner, as presented in Figure 1.

Table 2. Mechanical resistance parameters: pits 01, 02, and 03.

Pit 01							
DH (m)	γ (Kg/m^3)	ϕ (°)	ϕ_{corr} (°)	c (Kg/cm^2)	c_{corr} (Kg/cm^2)	c_u (Kg/cm^2)	μ_s
0.5	1410.0	28.6	20.07	0.02	0.0134	0.0	0.0
4.0	1520.0	29.27	20.58	0.0	0.0	0.0	0.0
Pit 02							
DH (m)	γ (Kg/m^3)	ϕ (°)	ϕ_{corr} (°)	c (Kg/cm^2)	c_{corr} (Kg/cm^2)	c_u (Kg/cm^2)	μ_s
0.7	1900.0	15.0	10.18	0.02	0.0134	0.0	0.0
4.3	1730.0	0.0	0.0	0.74	0.4958	0.0	0.0
Pit 03							
DH (m)	γ (Kg/m^3)	ϕ (°)	ϕ_{corr} (°)	c (Kg/cm^2)	c_{corr} (Kg/cm^2)	c_u (Kg/cm^2)	μ_s
1.8	1430.0	28.74	20.17	0.0	0.0	0.0	0.0
2.2	1540.0	29.42	20.7	0.0	0.0	0.0	0.0

Table 3. Location of pits.

Pit	**Coordinates**		**Altitude**
	East	**North**	
C1	183,688.50	8,500,237.50	3355.10
C2	183,798.00	8,500,162.25	3445.72
C3	183,857.25	8,500,096.25	3490.05

Figure 1. Location of pits.

This study describes the topographic profiles considering representative cross-sections of the terrain, which allow analyzing the morphology of the study area, as presented below (Figures 1 and 2).

Table 4. Slope flattening.

Slope	β	Horizontal Distance (m)	Topographic Relief (m)
Slope natural	29.72°	236.26	134.90
Slope 1	27.72°	236.26	125.62
Slope 2	25.72°	236.26	115.23

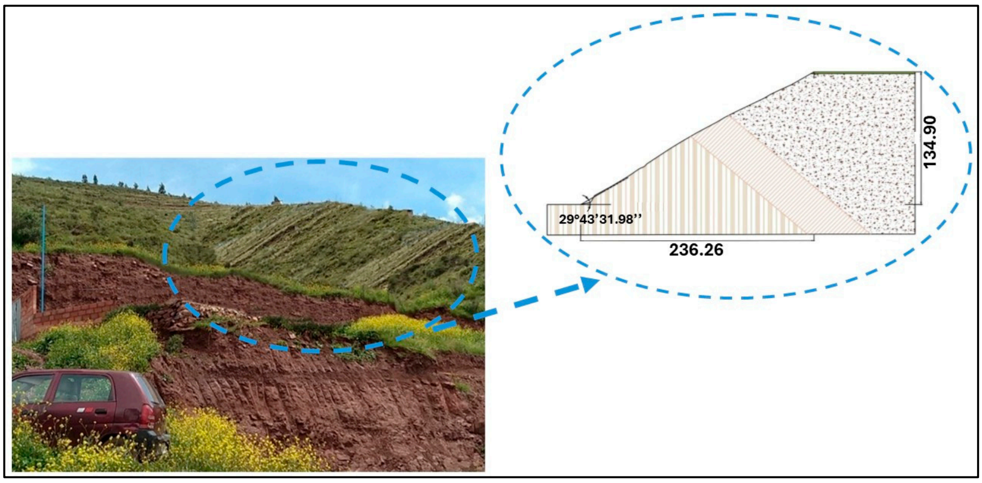

Figure 2. Slope flattening.

Likewise, the factors that influence the climate are atmospheric humidity and temperature. The month that registers the highest humidity in the study area is February (66%), while in August it is only recorded (46%) [23].

3.1. Analysis and Interpretation of Load Location

For hypothesis testing, the Chi-square test statistic (X2) was used, proposing the following hypotheses:

Ho: The location of the load exerted on the slope does not noticeably affect the factors of safety under static and pseudo-static conditions.

Ha: The location of the load exerted on the slope has a significant effect on the factors of safety under static and pseudo-static conditions.

3.1.1. Statistical Contrast: Load Location and Static FS

The significance value of the X2 statistic according to the analysis resulted in 0.001, as can be seen in Table 4, lower than the significance level ($\alpha = 0.05$); therefore, the null hypothesis (Ho) was rejected and the alternate hypothesis (Ha) was accepted, affirming with a confidence level of 95% that the variables of the vertical location of the load and the static FS were not independent.

Considering a significance level of 5% and 258 degrees of freedom, the critical value of X2c is 296.5, while the theoretical X2t value is 1833.549, as can be seen in Table 4. The latter value is within a range that is called the rejection zone of the Ho.

Therefore, the physical stability of the slope would increase by determining the proper vertical location of the load under static conditions.

The association between these variables was determined through the V-Cramer, whose result was 0.505 (see Table 5). There is a large effect or high strength of association between both variables.

Table 5. Chi-square tests: vertical load location and static FS.

Test X2	Value	Gl	Asymptotic Sig.
Pearson's Chi-square	1833.549	258	0.000
Likelihood ratio	826.284	258	0.000
Linear-by-linear association	8.553	1	0.003
N of valid cases	1197		

3.1.2. Vertical Load Location and Pseudo-Static FS

The significance value of the X2 statistic according to the analysis resulted in 0.001, as can be seen in Table 6, lower than the significance level ($\alpha = 0.05$). Therefore, the null hypothesis (Ho) was rejected and the alternate hypothesis (Ha) was accepted (Tables 6 and 7).

Table 6. Symmetric measure: vertical load location and static FS.

Symmetric Measure	Value
Cramer's V	0.505
N of valid cases	1197

Table 7. Chi-square tests: vertical location of load and pseudo-static FS.

Test X2	Value	Gl	Asymptotic Sig.
Pearson's Chi-square	1782.182	210	0.000
Likelihood ratio	830.039	210	0.000
Linear-by-linear association	11.375	1	0.001
N of valid cases	1197		

Therefore, the physical stability of the slope would increase by determining the proper vertical location of the load under pseudo-static conditions. The association between these variables was determined through the V-Cramer, whose result was 0.498 (see Table 8). There is a medium or moderate effect between both variables, which represents an association of 49.80%.

Table 8. Symmetric measure: vertical load location and pseudo-static FS.

Symmetric Measure	Value
Cramer's V	0.498
N of valid cases	1197

The degree of dependence to predict the FS in the pseudo-static condition from the vertical location of the load on the slope was 0.199 and in agreement. This indicates that the location of the load would help to predict 19.90% of the FS, while the latter only helps to predict 4.10% of the vertical location of the load.

In pseudo-static conditions, the highest FS analysis interval was in the range of 1.321–1.340, which is recorded when the load is located vertically at the head, foot, or head–feet of the slope, while there is no record in this interval when the load is located in the body of the slope.

The minimum FS interval was in the range of 0.960–0.980, in which the highest frequency (81 profiles) is recorded when the exerted load is located at the head–body–foot of the slope.

3.1.3. Stability Analysis According to Load Location Slope—Natural Slope

For the stability analysis according to the location of the load on the slope with a natural slope (29°43′31.98″), three slopes were considered showing the variation according to the characteristics mentioned in Table 9, which can be observed as follows.

Table 9. Stability analysis according to load location—natural slope.

N° Profile	Applied Load (KN/m^2)			Vertical Location			Horizontal Location (m)			Factor of Safety	
										Static	**Pseudo-Static**
Initial										1.399	1.063
2		10			Body			1		1.287	0.975
23	10	10	10	Head	Body	Foot	1	1	1	1.287	0.975

Static Condition

Profiles 2 and 23 consider the horizontal location of the load at 1 m from the slope. This similarity allows recognizing the conditioning parameter in the variation in the FS in comparison to the analysis standard profile, as shown in Figures 3–5.

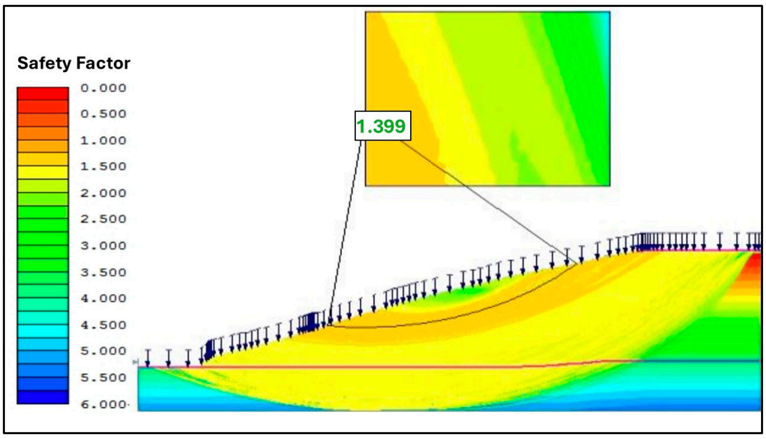

Figure 3. Initial condition: natural static slope.

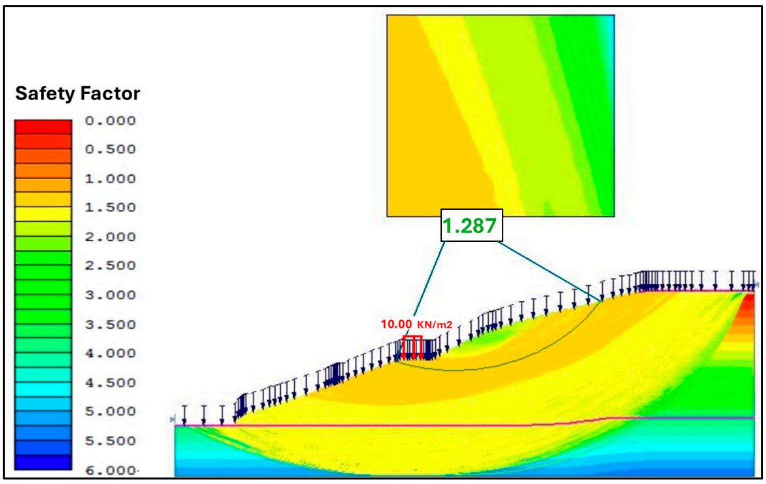

Figure 4. Profile 2—natural static slope.

It can be observed that profiles 2 and 23 register a FS equal to 1.287 and present a load of 10 KN/m^2 in the body of the slope, which is the factor that statically conditions the stability behavior.

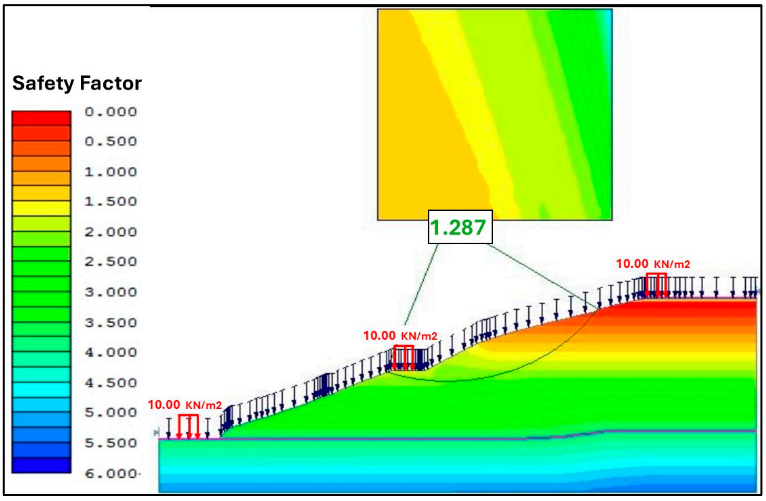

Figure 5. Profile 23—natural static slope.

Pseudo-Static Condition

The FS in pseudo-static conditions recorded in the standard profile was 1.063 and in profiles 2 and 23 it was 0.975 (see Figures 6–8), there being a difference with respect to the values achieved in static conditions, this due to the seismic force.

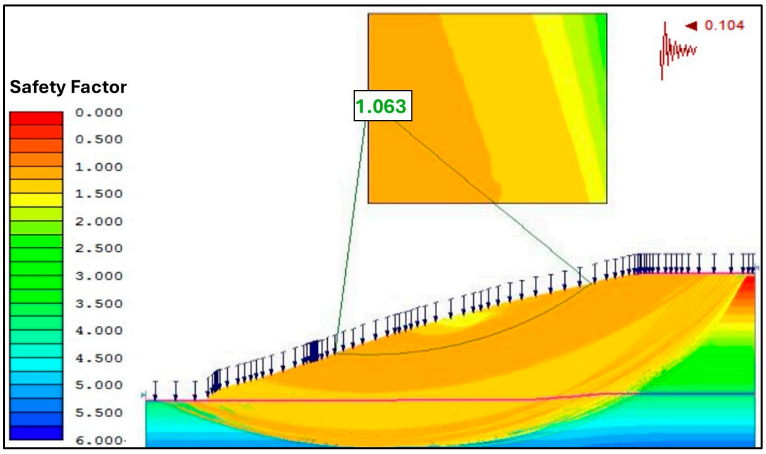

Figure 6. Initial condition: natural pseudo-static slope.

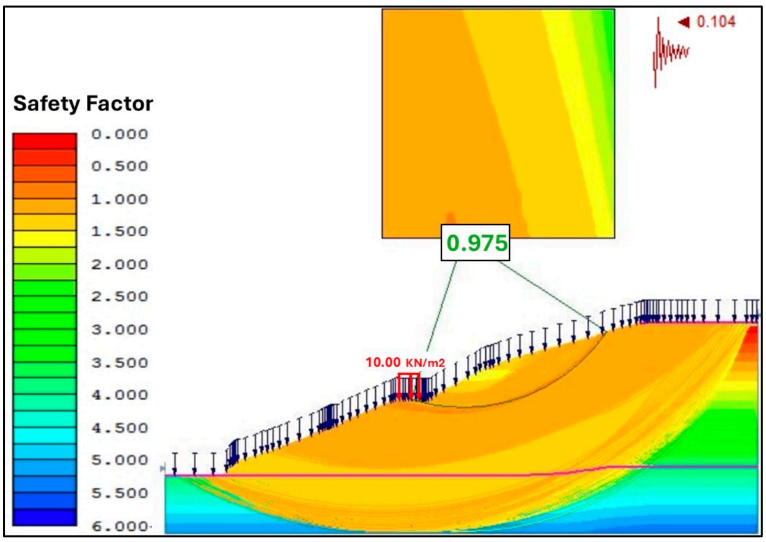

Figure 7. Profile 2—natural pseudo-static slope.

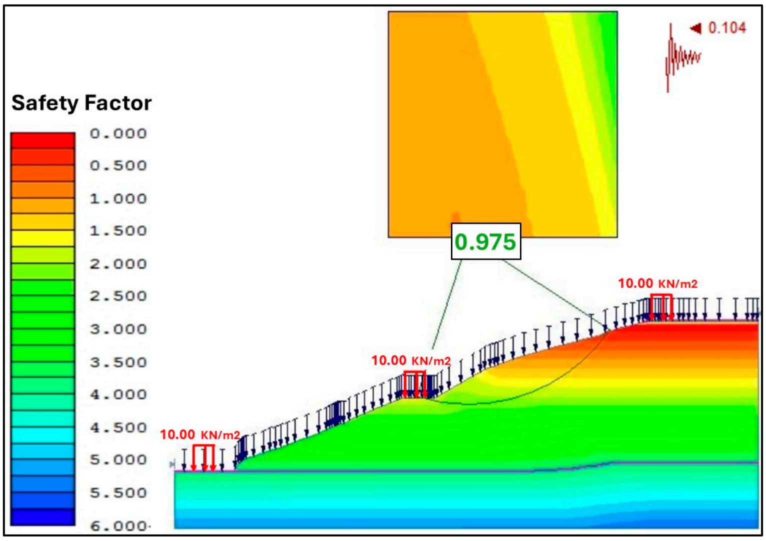

Figure 8. Profile 23—natural pseudo-static slope.

3.1.4. Stability Analysis According to the Load Location—Slope 1

For the stability analysis according to the load location on the slope with slope 1 (27°43′31.98″), three slopes were considered to show a variation according to the mentioned characteristics (Table 10).

Table 10. Stability analysis according to the load location: slope 1.

N° Profile	Applied Load (KN/m^2)			Vertical Location			Horizontal Location (m)			Factor of Safety Static	Factor of Safety Pseudo-Static
Initial										1.622	1.190
15	10	10		Head	Body		1	7		1.456	1.068
173	20	10	20	Head	Body	Foot	4	7	1	1.456	1.068

Static Condition

The FS in static conditions recorded after the analysis was 1.622, see Figure 9, while in profiles 15 and 173 it was 1.456. This variation is due to the characteristics of each analysis unit (Figures 9–11).

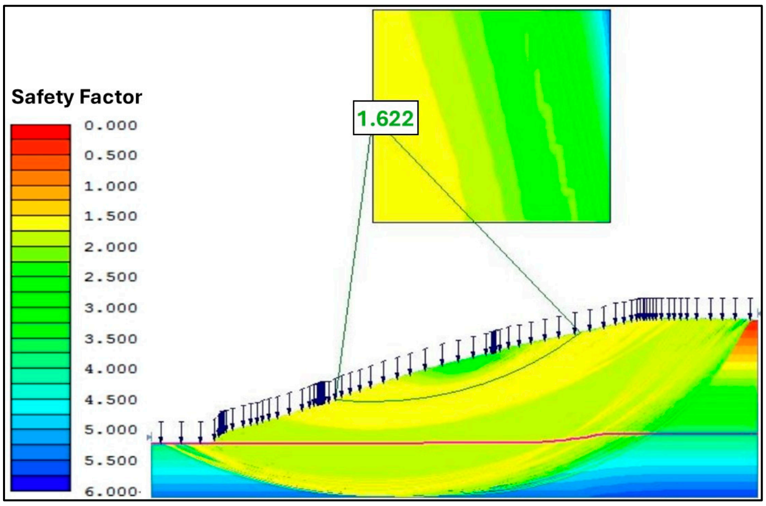

Figure 9. Initial condition: slope 1—static slope.

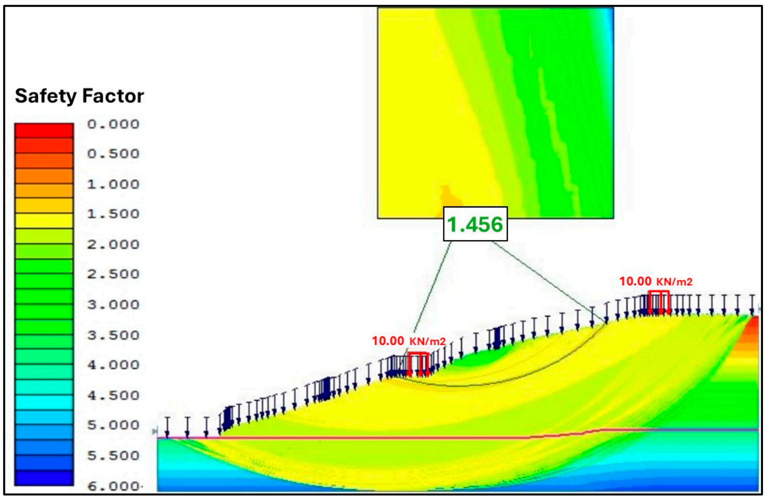

Figure 10. Profile 15—slope 1: static slope.

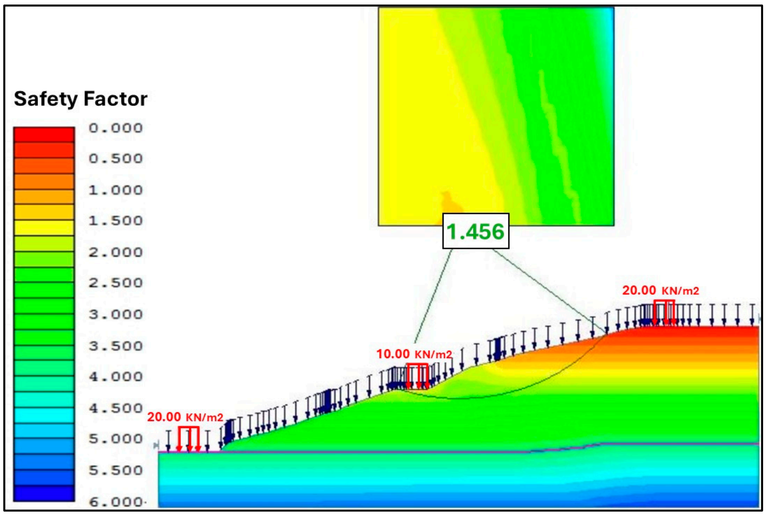

Figure 11. Profile 173—slope 1: static slope.

In profiles 15 and 173, the horizontal location and the load considered are different at the head and foot of the slope, while the existing characteristics in the body of both profiles are kept uniform. This to identify the parameter that influences the instability of the slope. The load applied on the body of the slope is the parameter that conditions the stability.

Pseudo-Static Condition

The FS in pseudo-static conditions recorded in the standard profile was 1.190 (see Figure 12) and in profiles 15 and 173 it was 1.068, there being a difference with respect to the values reached in static conditions, this due to the seismic force (Figures 12–14).

3.1.5. Stability Analysis According to the Load Location: Slope 2

For the stability analysis according to the location of the load on slope 2 (25°43′31.98″), three slopes were considered showing the variations according to the mentioned characteristics shown in Table 11.

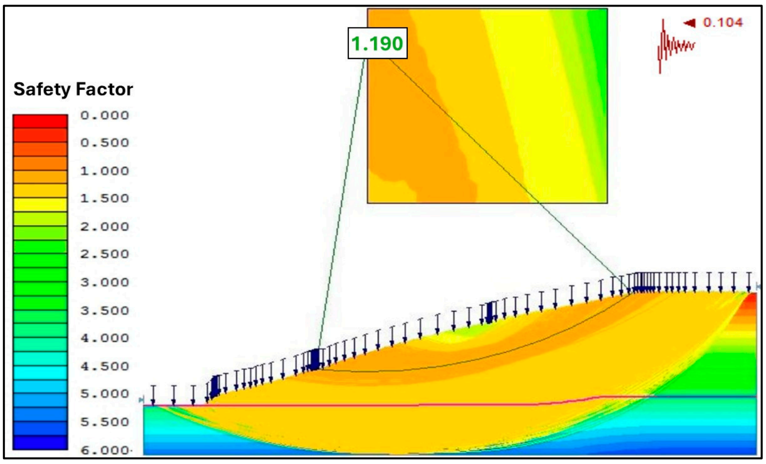

Figure 12. Initial condition: slope 1—pseudo-static slope.

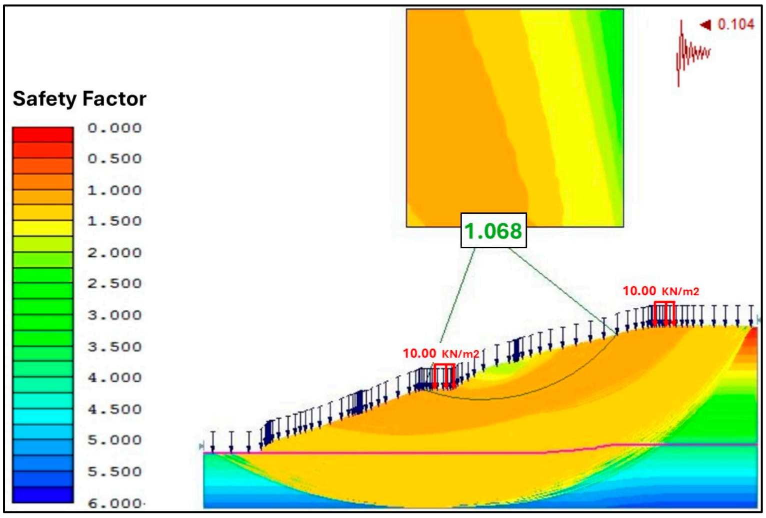

Figure 13. Profile 15—slope 1: pseudo-static slope.

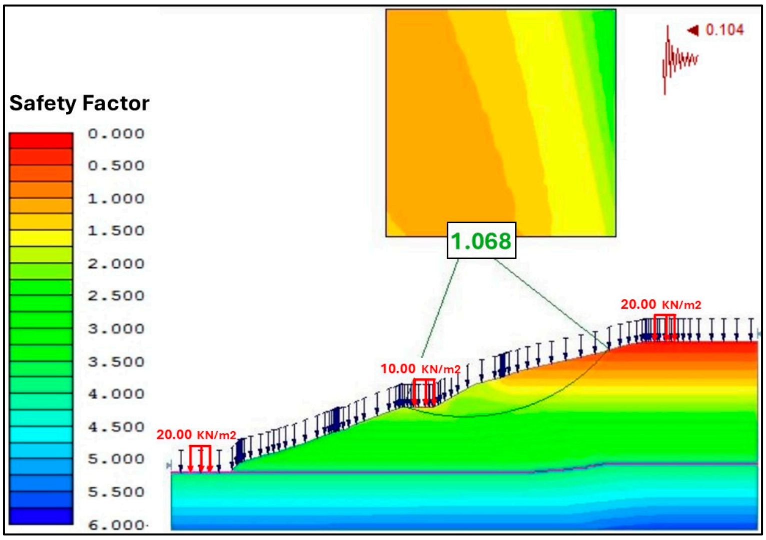

Figure 14. Profile 173—slope 1: pseudo-static slope.

Table 11. Stability analysis according to the load location: slope 2.

N° Profile	Applied Load (KN/m^2)			Vertical Location			Horizontal Location (m)			Factor of Safety	
										Static	Pseudo-Static
Initial										1.859	1.325
10		10	10		Body	Foot		1	1	1.719	1.246
91	30	30	30	Head	Body	Foot	7	1	1	1.719	1.246

Static Condition

The FS in static conditions was 1.719 in the analysis of profiles 10 and 91, unlike the standard profile that recorded a FS equal to 1.859, as shown in Figures 15–17.

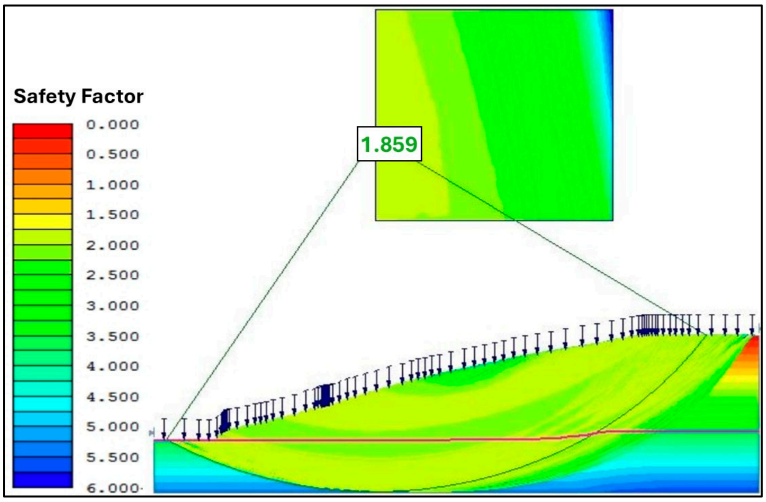

Figure 15. Initial condition: slope 2—static slope.

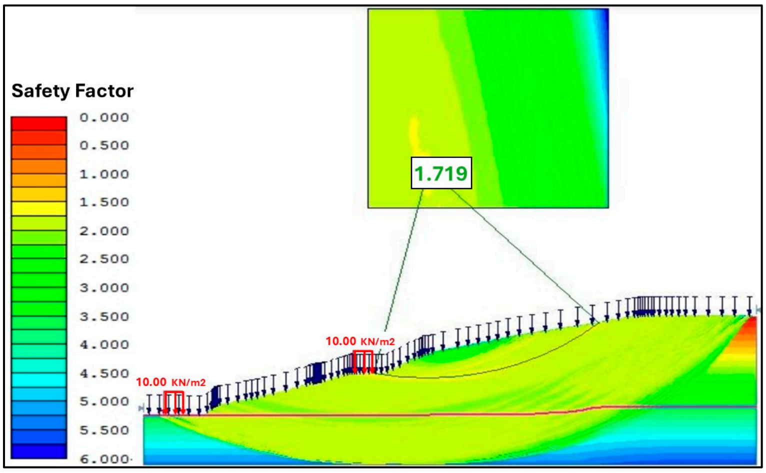

Figure 16. Profile 10—slope 2: static slope.

It could be observed in the stability analyses performed above that the stability conditioning parameter is the load exerted on the body of the slope. Thus, the stability is analyzed in profiles 10 and 91, which consider different characteristics at the head and foot of the slope, while in the body there is a variation in the load exerted, but the horizontal location of the load is kept uniform.

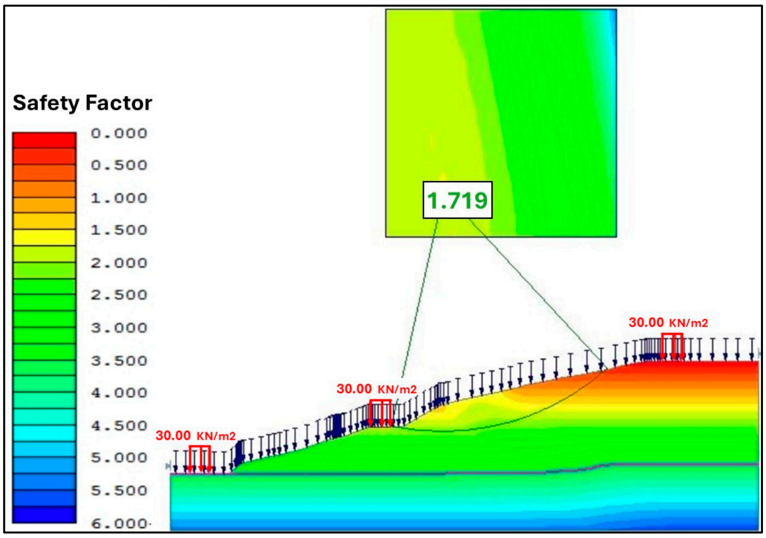

Figure 17. Profile 91—slope 1: static slope.

Pseudo-Static Condition

The FS in pseudo-static conditions recorded in the standard profile was 1.325 (see Figure 18), and in profiles 10 and 91 it was 1.246, there being a difference with respect to the values reached in static conditions, this due to the seismic force (Figures 18–20).

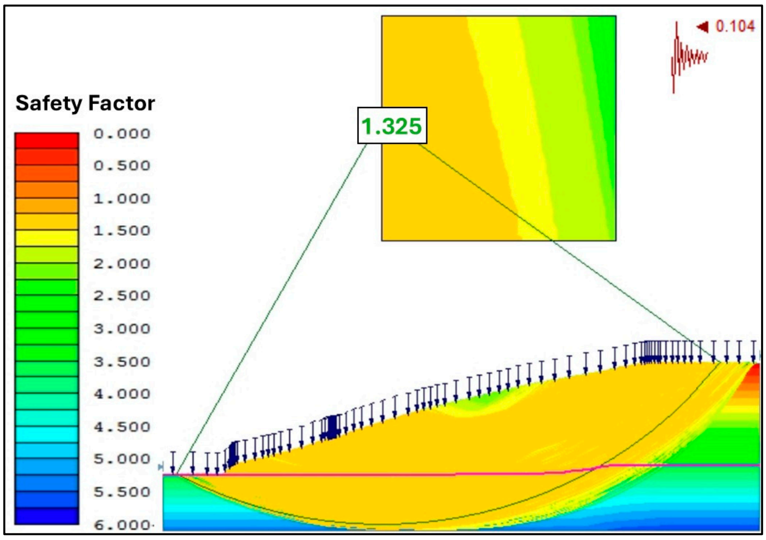

Figure 18. Initial condition: slope 2—pseudo-static slope.

3.1.6. Incidence of the Load Location Factor in the Static Condition

The location of the load exerted on the slope has a significant impact on the safety factor in static conditions. As the horizontal distance increases, the FS increases, shifting from 1.719 to 1.730 when it was evaluated on slope 2, as shown in Table 12.

Likewise, the FS increases as the topographic slope decreases, reaching a difference of 34.63% between slope 2 and the natural slope.

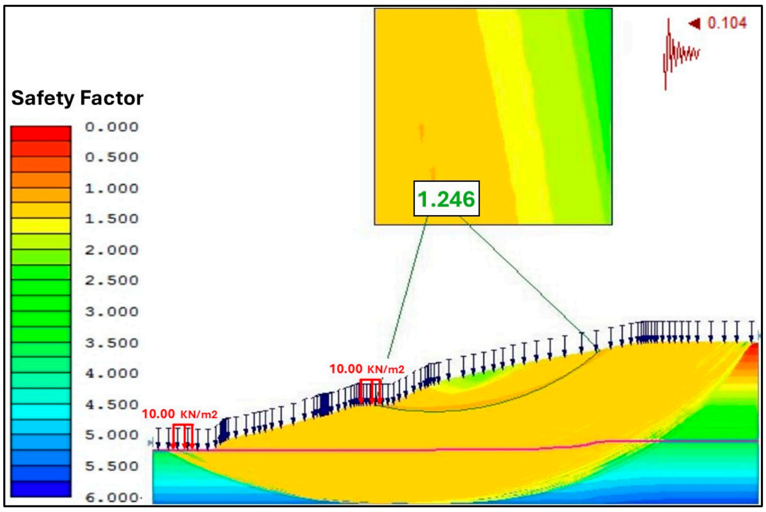

Figure 19. Profile 10—slope 2: pseudo-static slope.

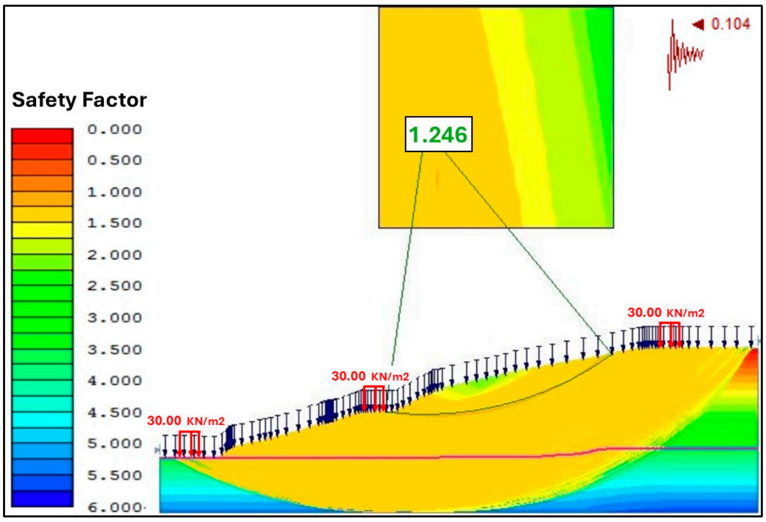

Figure 20. Profile 91—slope 2: pseudo-static slope.

Table 12. Variation in the FS in the static condition according to the location of the load and the reduction in the slope.

N° Profile	Load (KN/m^2)			Vertical Location			Horizontal Location			Natural Slope		Slope 1			Slope 2		
										N° Simulation	Static Factor	N° Simulation	Static Factor	Variation	N° Simulation	Static Factor	Variation
23	10	10	10	Header	Body	Foot	1	1	1	23	1.287	422	1.459	13.36%	821	1.719	33.57%
26	10	10	10	Header	Body	Foot	4	4	1	26	1.286	425	1.458	13.37%	824	1.725	34.14%
27	10	10	10	Header	Body	Foot	7	7	1	27	1.285	426	1.456	13.31%	825	1.730	34.63%

3.1.7. Incidence of the Location of the Load: Safety Factor in the Pseudo-Static Condition

The location of the load exerted on the slope has a significant impact on the factor of safety in pseudo-static conditions. As the horizontal distance increases the FS increases, shifting from 1.246 to 1.249 when it was evaluated on slope 2, as shown in Table 13.

Table 13. Variation in FS in the pseudo-static condition depending on the location of the load and the reduction in the slope.

N° Profile	Load (KN/m²)			Vertical Location			Horizontal Location			Natural Slope		Slope 1			Slope 2		
										N° Simulation	Static Factor	N° Simulation	Static Factor	Variation	N° Simulation	Static Factor	Variation
23	10	10	10	Header	Body	Foot	1	1	1	1220	0.975	1619	1.069	9.64%	2018	1.246	27.79%
26	10	10	10	Header	Body	Foot	4	4	1	1223	0.977	1622	1.068	9.31%	2021	1.248	27.74%
27	10	10	10	Header	Body	Foot	7	7	1	1224	0.982	1623	1.068	8.76%	2022	1.249	27.19%

Likewise, the FS increases as the topographic slope decreases, reaching a difference of 27.79% in slope 2 and the natural slope.

3.2. Analysis and Interpretation of the Magnitude of the Load Exerted on the Slope

For the contracting of hypotheses, the Chi-square test statistic (X2) was used, proposing the following hypotheses:

Ho: The magnitude of the load exerted on the slope does not noticeably affect the safety factors under static and pseudo-static conditions.

Ha: The magnitude of the load exerted on the slope has a significant effect on the factors of safety under static and pseudo-static conditions.

3.2.1. Test Statistic: Load Exerted on the Slope and Static FS

The significance value of the X2 statistic according to the analysis was 0.001 lower than the significance level (α = 0.05); therefore, the null hypothesis (Ho) was rejected and the alternative hypothesis (Ha) was accepted, affirming with a confidence level of 95% that the variables of load exerted on the slope and static FS were not independent.

Considering a significance level of 5% and 774 degrees of freedom, the critical value of X2c is 839.8, while the theoretical X2t value is 1716.722, as shown in Tables 14 and 15. The latter value is within a range that is called the rejection zone of the Ho.

Table 14. Chi-square tests—load exerted on the slope and static FS.

Test X2	Value	Gl	Asymptotic Sig.
Pearson's Chi-square	1716.722	774	0.000
Likelihood ratio	1326.000	774	0.000
Linear-by-linear association	6.847	1	0.009
N of valid cases	1197		

Table 15. Symmetric measure: load exerted on the slope and static FS.

Symmetric Measure	Value
Cramer's V	0.282
N of valid cases	1197

Therefore, the factors of safety under static conditions would increase, determining the appropriate magnitude of the load exerted on the slope.

The association between these variables was determined through V-Cramer, whose result was 0.282. There is a small effect between both variables, which represents an association of 28.20%.

The highest FS analysis interval in static conditions is 1801–1900, which is recorded when 1 or 2 loads are exerted on the slope, while in combinations of 3 loads, there is no record.

The FS records in the 1701–1800 range show an increase of up to 54 analyzed profiles, being the most frequent in the table, and are only present with the combination of the three loads of analysis (10, 20, and 30 KN/m^2).

3.2.2. Test Statistic: Load Exerted on the Slope and Pseudo-Static FS

The significance value of the X2 statistic according to the analysis was 0.001, as shown in Table 16, lower than the significance level (α = 0.05); therefore, the null hypothesis (Ho) was rejected and the alternative hypothesis (Ha) was accepted, affirming with a confidence level of 95% that the variables of load exerted on the slope and pseudo-static FS are related.

Table 16. Chi-square tests: load exerted on the slope and pseudo-static FS.

Test X2	Value	Gl	Asymptotic Sig.
Pearson’s Chi-square	1761.890	630	0.000
Likelihood ratio	1292.761	630	0.000
Linear-by-linear association	9.379	1	0.002
N of valid cases	1197		

Considering a significance level of 5% and 630 degrees of freedom, the critical value of X2c is 689.5, while the theoretical X2t value is 1761.89. The latter value is within a range that is called the rejection zone of Ho.

Therefore, the factors of safety under pseudo-static conditions would increase by determining the appropriate magnitude of the load exerted on the slope.

The association between these variables was determined through V-Cramer, whose result was 0.286, as shown in Table 17. There is a small effect between both variables, representing an association of 28.60%.

Table 17. Symmetric measurement: load exerted on the slope and pseudo-static FS.

Symmetric Measure	Value
Cramer’s V	0.286
N of valid cases	1197

The highest FS analysis interval in pseudo-static conditions was in the range of 1.321–1.340, which is recorded when 1 or 2 loads are exerted on the slope, while in combinations of 3 loads, there is no record.

The FS records in the interval of 1.241–1.260 present an increase of up to 54 analyzed profiles, this being the one with the highest frequency in the table, and is presented only with the combination of the three analysis loads (10, 20, and 30 KN/m^2)

3.2.3. Distribution of the Sample Variation in the FS in Static Conditions According to the Load Exerted

Natural Slope

The FS under static conditions calculated on the natural slope (29°43′31.98″) suffered a decrease due to the load exerted. Initially, this slope registered a FS equal to 1.399. When applying a load of 10 KN/m^2, it decreased by 3.46%; when applying a load of 20 KN/m^2, it decreased by 5.36%; and finally, when applying a load of 30 KN/m^2, it decreased by 5.90%, as shown in Figure 21.

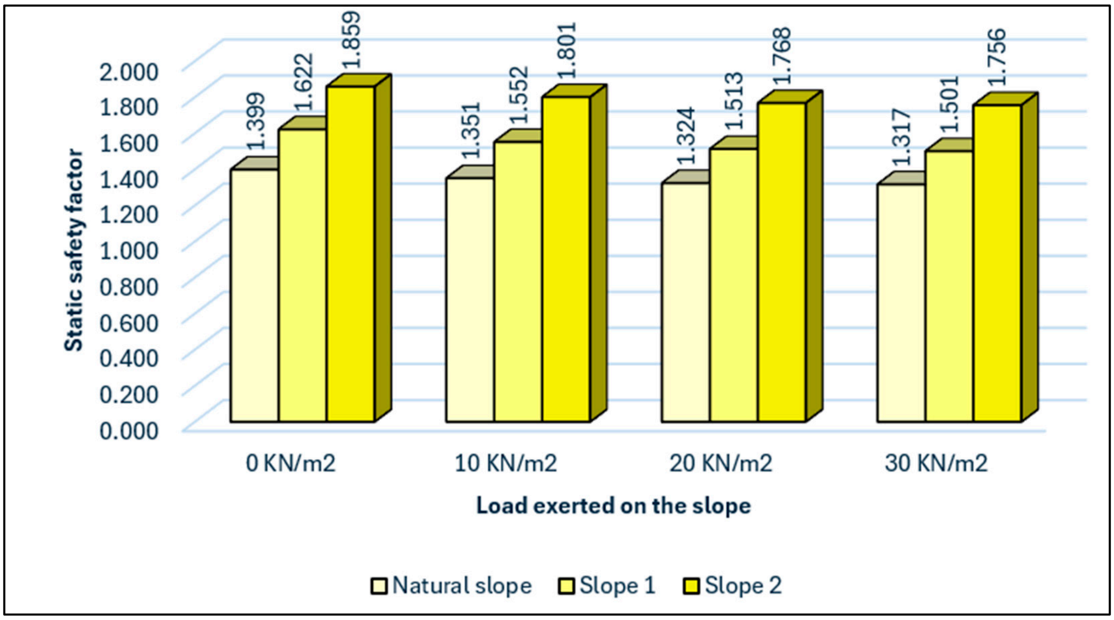

Figure 21. Variation in FS in the static condition according to the load exerted—natural slope, slope 1, and slope 2.

Slope 1

The stability analysis under static conditions of a slope 1 slope (27°43′31.98″) showed the decrease of the FS due to the load exerted. However, when considering a load of 10 KN/m^2, it decreased by 4.34%; when applying a load of 20 KN/m^2, it decreased by 6.72%; and finally, when applying a load of 30 KN/m^2, it decreased by 7.43%, as shown in Figure 21.

Slope 2

The FS in static conditions calculated for slope 2 (25°43′31.98″) suffered a decrease due to the load exerted. Initially, this slope registered a FS equal to 1.859. When applying a load of 10 KN/m^2, it decreased by 3.11%; when applying a load of 20 KN/m^2, it decreased by 4.89%; and finally, when applying a load of 30 KN/m^2, it decreased by 5.55% (see Figure 21).

3.2.4. Effect of the Magnitude of the Load Exerted on the Slope Safety Factor in the Static Condition

The magnitude of the load exerted on the slope has a significant impact on the safety factors in static conditions in the analysis of the natural slope, slope 1, and slope 2, where the SF decreased to 5.90%, 7.43%, and 5.55%, respectively.

Likewise, the FS in static conditions is related to the reduction in the slope (see Table 18), where there is an increase up to 33.53% considering the load of 20 KN/m^2 in initial conditions and slope 2 (see Table 19).

3.2.5. Magnitude of the Load Exerted on the Slope: Safety Factor in the Pseudo-Static Condition

The magnitude of the load exerted on the slope has a significant impact on the safety factors in pseudo-static conditions in the analysis of the natural slope, slope 1, and slope 2, where the SF decreased to 5.90%, 7.56%, and 4.55%, respectively.

Table 18. Variation in the static safety factor according to the applied load—natural slope, slope 1, and slope 2.

The Load Exerted on the Slope (KN/m^2)	Static Safety Factor	Percentage Difference
	Natural Slope	
Inicial	1.399	0.00%
10	1.351	3.46%
20	1.324	5.36%
30	1.317	5.90%
	Slope 1	
Inicial	1.622	0.00%
10	1.552	4.34%
20	1.513	6.72%
30	1.501	7.43%
	Slope 2	
Inicial	1.859	0.00%
10	1.801	3.11%
20	1.768	4.89%
30	1.756	5.55%

Table 19. Variation in FS in the static condition according to the magnitude of the load exerted and the slope abatement.

The Load Exerted on the Slope (KN/m^2)	FS-Static Variation
Initial	32.88%
10	33.31%
20	33.53%
30	33.33%

Likewise, the FS in pseudo-static conditions is related to the lowering of the slope, as shown in Table 20, where there is an increase up to 26.50%, considering the load of 30 KN/m^2 in initial conditions and slope 2 (see Table 21).

Table 20. Variation in the pseudo-static safety factor according to the applied load—natural slope, slope 1, and slope 2.

The Load Exerted on the Slope (KN/m^2)	Pseudo-Static Safety Factor	Percentage Difference
	Natural Slope	
Inicial	1.063	0.00%
10	1.027	3.37%
20	1.007	5.31%
30	1.000	5.90%
	Slope 1	
Inicial	1.190	0.00%
10	1.138	4.38%
20	1.109	6.80%
30	1.100	7.56%

Table 20. *Cont.*

The Load Exerted on the Slope (KN/m^2)	Pseudo-Static Safety Factor	Percentage Difference
	Slope 2	
Inicial	1.325	0.00
10	1.292	2.51
20	1.272	3.98
30	1.265	4.55

Table 21. Variation in FS in the pseudo-static condition according to the magnitude of the load exerted and the slope abatement.

The Load Exerted on the Slope (KN/m^2)	Variation FS-Pseudo-Static
Initial	24.65%
10	25.80%
20	26.32%
30	26.50%

4. Discussion

The presence of the Cusco geological fault affects the scenario in the displacement zone as well as the research that was carried out in expanding urban areas in the foothills of the mountain and Piedmont [24,25], which considers the infiltration of rainwater, seismic force, and in particular the presence of the San Ramón–Chile geological fault, which triggered mass movements. Therefore, the analysis from previous years must be considered, since the altitude and the incidence of seismic movements condition these events [8,26].

The methodology used was based on a comprehensive approach that included topographic surveys in the field and laboratory tests, among other procedures. From these data, safety factors were calculated through slope stability analysis, which made it possible to evaluate the behavior of the terrain under different conditions. This provided a robust comparative framework to validate the accuracy and reliability of the results generated. In contrast, there is the analysis that began by dividing the basin into units of similar geomorphological, geological, and geotechnical conditions, among other parameters, followed by a quantitative calculation [27,28]. This methodology considers the weighted sum of the evaluation assigned to a list of conditioning factors (slope, height, soil type, shear resistance, saturation, and vegetation) [29,30]. Susceptibility values have a scale of 0 to 100 and depend largely on local geology and slopes [31]. This comparison reinforces the validity of the geotechnical stability results. The greater the susceptibility, the more likely that area will be the source of a landslide event.

The stability of the slope was analyzed in terms of housing construction and intervening variables. However, the safety factor on the Urubamba–Cajamarca slopes is calculated in terms of the surface degradation and rotational failure [32].

The safety factor in natural slope and static conditions was 1.399, and in seismic condition it was 1.063 (obtained using Slide v 9.0 software). On the other hand, using the Slide v 8.0 software, they were found to be below the RNE requirements, whose results were 0.362 in the static condition and 0.167 seismically, and considered unstable and unsafe slopes [33,34].

To identify the factors that contribute to the instability of mass movements, various thematic maps are superimposed, including lithological, slope, geomorphological, vegetation cover, hydrogeological, and tectonic maps [17,24]. In the present investigation, 399 modeling profiles were analyzed that consider different variations in the load exerted on the slope, as well as the analysis of safety factors in static and pseudo-static conditions.

In a slope stability analysis, all the indicators triggering mass removal events are considered [13,26]. Likewise, alternative solutions are proposed, such as the construction of retaining walls, these being economical and viable for slope stabilization [16,33]. In addition to this, in the present investigation, it is ensured that the problems are also due to unfavorable factors, such as seismicity, and to mitigate the exposure of the population to risk areas, the geometric modification of the terrain is proposed based on the slope.

The premature deterioration of civil works located on slopes is one of the consequences of seismic behavior. The stability of the structures in the crown of the Malecón Costanera, San Miguel, Lima, was analyzed through field studies, geological mapping, and mathematical calculations [9,14]. In conclusion, the admissible capacity of the soil would increase if it is dosed with clay soil, affirmed, cultivated, or injected with lime oxide slurry or cement [14,29]. In the present investigation, it was considered convenient to geometrically modify the slope to increase the confinement and consequently the bearing capacity of the land.

The stability analysis of the María Reiche slope, located on the Costa Verde cliff in Miraflores, Lima, was carried out by applying an acceleration coefficient of 0.2 g for the pseudo-static study, under the equilibrium limit criterion [35]. It is concluded that the rockfall is caused by wind erosion on the non-revegetated face of the slope, which leaves gravel and boulders exposed. For this reason, a slope stability analysis should have been carried out prior to any building [36]. Similarly, in the present investigation, an acceleration coefficient of 0.2 g was used, and it is recommended to evaluate the slope in static and pseudo-static conditions before exerting loads on it.

5. Conclusions

Most of the buildings in Cusco have been built on the San Sebastian geological formation. The same area where the research was developed, geotechnically has bad behavior due to the origin of lake sediments. The study area is framed within a rugged terrain, where the strata are arranged at N45°2′2′2.10″ E and a dip of 40° to the SE. This geological reconnaissance allowed us to locate three diagonally arranged and staggered pits for exploration and to define the stratigraphic profile for simulation through Slide v 9 software. The maximum acceleration in the pseudo-static analysis was 0.104 g and the infiltration was 14.07 mm/h, which was calculated based on the rainfall records of the last 50 years from four meteorological stations, provided by SENAMHI. After evaluating the intervening variables, it can be generalized that Cusco is unstable in the face of landslide events and the factors for the sustainable construction of hillside housing have a significant impact on the physical stability of the slope.

The results of the simulation of 2394 profiles through Slide v 9.0 software show that the highest FS in static conditions (1.867) is located in the range of 1.801–1.900, when 1 or 2 loads are exerted on the slope, while in combinations of 3 loads, there is no record. Similarly, this happens in pseudo-static conditions whose highest FS interval (1.322) is in the range of 1.321–1.340. The exerted load and safety factor data in static and pseudo-static conditions show a distribution different from normal, and the significance value of the X2 statistic according to the analysis is 0.001, lower than the significance level (α = 0. 05). Therefore, the load exerted on the slope and the factor of safety were not independent. The association between both variables calculated by V-Cramer indicates that there is an effect between both variables; therefore, the magnitude of the load exerted on the slope has a significant influence on the factors of safety in static and pseudo-static conditions, and consequently on the physical stability of the slope.

To determine the appropriate location of the load in static and pseudo-static conditions, the X2 statistical test was performed, which was the most appropriate since there was no normal distribution of the data. The significance value in static and pseudo-static conditions of the vertical and horizontal locations of the load was 0.001 lower than the significance level ($\alpha = 0.05$), so these variables are related. In both static and pseudo-static conditions, in the highest interval, the profiles are only recorded when the load is located vertically at the head, foot, or head–foot, while there is no record in this interval when the load is located in the body of the slope. Likewise, in sections 15 and 173, the FS in static conditions was 1.456 and in pseudo-static conditions 1.068, with only a variation in the characteristics in the body of the slope. As described above, the load applied on the body of the slope is the one that conditions the stability; therefore, it is concluded that the location of the load exerted has a significant influence on the safety factors in static and pseudo-static conditions.

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