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Multicriteria Selection of Slope Stabilization Alternatives for Railway Infrastructure Using the Analytic Hierarchy Process

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Abstract. Slope instability in railway infrastructure means a technical problem associated with rainfall, surface runoff, weathering, erosion, and progressive degradation of exposed soil or rock masses. This study applies the Analytic Hierarchy Process (AHP) to prioritize slope stabilization alternatives using four evaluation criteria: geological conditions, slope geometry, instability or risk level, and hydraulic conditions. Four alternatives were assessed: geomat with hydroseeding, shotcrete with previous surface trimming, a mixed system with geomat, mesh and anchors, and an integral stabilization system with drainage and structural treatment. The criteria comparison matrix showed acceptable consistency, with a consistency ratio of 0.044. Results indicated that the integral stabilization system obtained the highest global priority, with 51.2 %, followed by shotcrete, the mixed system, and geomat with hydroseeding. The proposed approach provides a structured decision-support tool for selecting technically justified slope stabilization measures.

Keywords: Analytic Hierarchy Process, slope stabilization, railway infrastructure, multicriteria decision making, hydraulic conditions, geotechnical risk.

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1 Introduction

Transportation infrastructure requires the construction of linear works that modify the natural conditions of the terrain, creating cuts or embankments that leave soil or rock surfaces exposed. These elements are directly subjected to the actions of rainfall, surface runoff, weathering, erosion, and infiltration. These processes promote a progressive degradation of the material, which manifests through soil loss, sediment generation, and a reduction in the hydraulic capacity of cross and longitudinal drainage works. Furthermore, rainfall infiltration increases pore water pressure and reduces soil shear strength, thereby increasing the likelihood of slope instability and mass movements (Niyomukiza et al., 2023).

In the field of railway engineering, the geometric alignment imposes severe restrictions compared to other transport infrastructures, such as limited longitudinal gradients and wide curvature radii. These technical demands significantly reduce the design degrees of freedom, which usually results in larger excavation volumes, high embankments, and slopes with a considerable exposure surface (Campos e Matos et al., 1998). Additionally, the extensive length of these projects increases the probability of crossing heterogeneous geological formations, complicating the implementation of uniform stabilization solutions throughout the entire section.

Railway operation also introduces dynamic solicitations that influence the geotechnical behavior of slopes and support structures. Train loads are transmitted to the ground through a system composed of the rail, sleeper, ballast, subgrade, and embankment body, configuring a highly complex soil–structure interaction (Campos e Matos et al., 1998). In this context, the stability of cuts and embankments does not depend exclusively on their geometric characteristics or the index properties of the material, but also on combined static and dynamic loads, vibrations, and accidental actions associated with train traffic. Therefore, Gao et al. (2025) highlight that evaluating the dynamic response of railway subgrades under train loading is essential for understanding infrastructure behavior and ensuring the long-term safety and operational performance of railway systems.

Several studies point to water as one of the main triggering factors of slope instability. Failures can originate from a reduction in the shear strength of the material or from an increase in the solicitations required to maintain hydromechanical equilibrium. The mechanisms involved include increased pore water pressure, cracking, swelling, accelerated weathering, progressive softening, and the effect of cyclic loads (Assefa et al., 2016). In this sense, the implementation of drainage systems constitutes a fundamental stabilization measure, especially during prolonged or intense precipitation events; however, their long-term performance depends on an adequate design and a constant maintenance program, given that catchment and conveyance structures can lose functionality due to clogging or sedimentation processes.

On the other hand, surface erosion on slopes is controlled by soil properties, the presence of vegetative cover, topography, and local climatic conditions. Vegetation reduces the kinetic energy of raindrop impacts, enhances infiltration, decreases surface runoff velocity, and reinforces the soil through its root system, thereby contributing to erosion control and slope stability (Niyomukiza et al., 2023). Under this scenario, geotechnical solutions such as hydroseeding, organic blankets, and turf reinforcement mats (geomats) are appropriate when the predominant deterioration mechanism is limited to surface erosion and a significant structural instability condition does not coexist. Nevertheless, in the presence of intensely fractured materials, unfavorable discontinuities, cavities, or zones of low mechanical competence, these superficial measures are usually insufficient. In such circumstances, the design of rigid or flexible retention or reinforcement systems is required, such as high-strength wire meshes, cable net systems, and anchored reinforcement, which increase the energy absorption capacity of the protection system, improve rock mass confinement, and reduce the likelihood of block detachment (Buzzi et al., 2014).

In this same regard, geosynthetics have demonstrated effectiveness in controlling settlements and increasing the overall stability of railway infrastructure. Recent numerical studies on railway subgrades have shown that train loading and soil conditions significantly influence vertical displacement and the overall mechanical response of railway embankments, highlighting the importance of evaluating subgrade performance under different operating conditions (Gao et al., 2025). These findings confirm that stabilization alternatives must be evaluated by simultaneously considering the governing failure mechanism and the specific operating conditions of the track.

In civil engineering practice, the selection of these stabilization alternatives is not always performed through structured procedures. Frequently, the final decision is based on the empirical experience of the designer, general construction criteria, or the immediate availability of resources and materials on site. Although these factors are valuable during project execution, they can lead to simplified analyses when variables of a different nature interact. For instance, a slope exclusively affected by surface erosion can be remediated using vegetative protection or geomats; conversely, a cut exhibiting local failures, cavities, active runoff, or representing a direct risk to railway operations will require robust solutions such as shotcrete, anchoring systems, major drainage works, or combined integral treatments.

Thus, the most adequate solution does not necessarily correspond to the alternative with the highest rigidity, execution speed, or economic cost, but rather to the one that responds most precisely to the dominant failure mechanism. This highlights the need for methodological tools that integrate technical, geological, geometric, hydraulic, and risk criteria in a systematic, transparent, and structured manner.

To address this type of problem, multicriteria decision-making methods offer an appropriate framework to evaluate alternatives against heterogeneous variables, some of which are quantifiable and others subject to expert judgment. Within this group of tools, the Analytic Hierarchy Process (AHP) stands out for its ability to decompose a highly complex problem into a hierarchical structure composed of a central objective, evaluation criteria, and alternative solutions. This characteristic is ideal for transportation infrastructure engineering, where decisions depend on the interaction of physical, functional, and safety factors.

The AHP, conceived as a measurement theory based on ratio scales, allows the integration of quantitative and qualitative factors through a process of pairwise comparisons, starting from the assumption that the formal knowledge and experience of specialists possess a value comparable to that of the available physical data (Vargas, 1990). Its operational foundation relies on the fundamental scale proposed by Saaty (1980), which transforms qualitative preference judgments into reciprocal and consistent numerical values. Furthermore, compliance with its axioms of reciprocity, homogeneity, and independence ensures that the decision problem is structured coherently.

Recent scientific literature confirms the utility of the method in solving real-world problems oriented toward the management and design of complex processes. Subramanian and Ramanathan (2012) highlight that the AHP is frequently used in alternative selection, resource allocation, and performance evaluation in environments involving multiple criteria of a technical or operational nature.

Similarly, in scenarios requiring group decisions, the AHP offers formal mechanisms to aggregate the opinions of different specialists through the use of geometric means, a procedure that is fully consistent with the ratio scale and the reciprocity principle of the method's matrices (Forman and Peniwati, 1998). This condition is of particular relevance in linear infrastructure projects, where the selection of a technically pertinent stabilization measure benefits from the technical convergence among experts in geotechnics, hydraulics, construction, and railway operation.

In this study, the AHP method is applied to evaluate slope stabilization alternatives in railway infrastructure. The decision model considers four technical criteria: geological conditions of the material, slope geometry, risk and instability level, and hydraulic conditions. Simultaneously, four distinct intervention alternatives are analyzed: surface protection with geomat and hydroseeding, shotcrete with prior preparation, a mixed system with geomat, mesh, and anchors, and an integral system with drainage and structural treatment.

The objective of the present work is to develop a structured decision-making procedure to support the identification of the most adequate alternative according to the specific site conditions. This seeks to offer a methodological support tool that complements field experience and strengthens the technical substantiation of the selected solution for railway infrastructure.

2 Analytic Hierarchy Process Method

The Analytic Hierarchy Process (AHP) is a multicriteria decision-making tool designed to compare alternatives in scenarios where selection depends on multiple technical criteria. The method organizes the problem through a hierarchical structure that links a general objective, a set of evaluation criteria, and the solution alternatives.

In this study, the AHP is used to select the most adequate slope stabilization alternative in railway infrastructure. This decision cannot be based on a single parameter, given that the stability of a cut responds to the interaction between the geological conditions of the material, the geometry of the excavation, the observed instability level, and the presence of surface or infiltrated water. Under this approach, the method provides a technical evaluation and reduces subjectivity when choosing constructive solutions.

The proposed hierarchical structure is organized into three levels. The first level establishes the objective of the analysis: to select the most adequate stabilization alternative for slopes in railway infrastructure. The second level defines the evaluation criteria, corresponding to the geological conditions of the material, slope geometry, risk and instability level, and hydraulic conditions. The third and final level incorporates the intervention alternatives, classified as surface protection with geomat and hydroseeding; shotcrete with prior trimming; a mixed system with geomat, mesh, and anchors; and integral stabilization with drainage and structural treatment. These alternatives represent the engineering solutions considered to mitigate surface erosion, rockfalls, local failures, and distresses associated with runoff on the slopes.

The comparison between criteria and alternatives is performed using pairwise comparison matrices. In each matrix, one element is contrasted against another to establish its relative importance with respect to the decision objective. Saaty's fundamental scale is used to quantify these judgments: a value of 1 represents equal importance; 3, moderate importance; 5, strong importance; 7, very strong importance; and 9, extreme importance. The intermediate even values (2, 4, 6, and 8) can be employed when a gradual assessment between two levels of the scale is required.

If a criterion located in the row is considered more important than the one in the column, the corresponding integer value is assigned; otherwise, its reciprocal value is introduced. For example, if the instability level is assessed as having strong importance against the slope geometry, a 5 is recorded in that matrix cell, and a 1/5 is entered in the inverse cell. This reciprocal property ensures the mathematical coherence of the matrix.

The general pairwise comparison matrix for the criteria is represented by the expression:

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \tag{1}$$

where aij represents the relative importance of criterion i with respect to criterion j, and n corresponds to the total number of evaluated criteria. In this investigation, four criteria are considered; thus, the main matrix has a dimension of 4×4.

Data processing begins with the normalization of the matrix, dividing each value by the sum of its respective column, which generates a normalized matrix where each column sums to unity. The relative weight of each criterion is calculated by averaging the normalized values in each row; this weight represents the contribution of each criterion to the final decision.

Once the criteria weights are determined, the evaluation of the alternatives with respect to each criterion is carried out. To achieve this, specific pairwise comparison matrices are constructed, in which the stabilization alternatives are contrasted by considering the geological conditions, geometry, risk level, and hydraulic conditions separately. This procedure allows for the identification of which alternative presents the best technical performance within each individual criterion.

For the geological conditions, the compatibility of each solution with the type of material, fracturing degree, weathering, and the presence of friable materials is analyzed. For slope geometry, the height, inclination, and configuration of the cut are taken into account. In the risk and instability level, signs of failure, rockfalls, active erosion, cavities, and proximity to the exposed infrastructure are evaluated. Finally, under hydraulic conditions, the presence of runoff, moisture, seepage, and water accumulation is analyzed, since this element constitutes one of the main factors that accelerate erosion and reduce the performance of superficial solutions.

The global priority of each alternative is obtained by multiplying the weight of each criterion by the relative performance of the alternative within that specific criterion. The sum of these products defines the final priority value.

To verify that the judgments established in the matrices are acceptable, the consistency of the analysis is calculated. First, the principal eigenvalue λmax is obtained from the product of the original matrix and the weight vector. Subsequently, the Consistency Index (CI) is calculated using:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

Then, the Consistency Ratio (CR) is obtained as:

$$CR = \frac{CI}{RI} \quad (3)$$

Where RI corresponds to the Random Index proposed by Saaty according to the matrix size. For a matrix with four criteria, the reference value used is RI=0.90. The matrix is considered to present an acceptable consistency when CR<0.10. If this value is exceeded, the judgments must be reviewed to correct the contradictions in the comparisons made.

The application of the AHP in this study allows to the structuring of an orderly methodology to select slope stabilization solutions. Unlike a selection based solely on field experience, the proposed procedure integrates technical criteria in an explicit and quantifiable manner. This facilitates the comparison of alternatives with different constructive complexities and allows for the substantiation of the final selection based on the expected behavior of the slope, the dominant failure mechanism, and the specific site conditions.

In synthesis, the method is developed through the following stages: definition of the decision objective, selection of criteria, identification of alternatives, construction of pairwise comparison matrices, calculation of weights, evaluation of alternatives, consistency verification, and final ranking of the solutions. This sequence establishes a replicable methodological framework for decision-making in slope stabilization projects for railway infrastructure.

3 Application of the AHP Model to Railway Slope Stabilization Alternatives

The case study focuses on the evaluation of stabilization alternatives for slopes in railway infrastructure. In this type of linear infrastructure, cuts are generated as a result of adapting the longitudinal grade to the natural terrain, leaving materials exposed with varying degrees of competence, fracturing, weathering, and susceptibility to erosion.

The model is developed taking as a reference the stabilization needs observed in railway cuts associated with Section 7 of the Tren Maya project, with the purpose of mitigating their deterioration due to erosive processes. This condition responds both to the surface exposure of the material and the risk of degradation progressing into high-severity problems, such as rockfalls, localized mass loss, or landslides. Therefore, the selection of a stabilization measure must not depend solely on the availability of materials, equipment, or constructive ease, but rather on the interaction among the geological, geometric, hydraulic, and risk conditions present in each slope.

The main problem is associated with cuts in natural materials that may exhibit surface erosion, cavities, discontinuities, persistent moisture, active runoff, and zones of low mechanical competence. When these factors are not analyzed in an integrated manner, there is a risk of proposing oversized, inefficient, or insufficient solutions for the dominant deterioration mechanism. This can translate into higher maintenance costs, adverse effects on the durability of the work, and potential restrictions on the safe operation of the infrastructure.

Based on this condition, the application of the Analytic Hierarchy Process (AHP) is proposed as a tool to support the selection of the most adequate stabilization alternative. The decision model is organized around a central objective, four technical criteria, and four intervention alternatives. The objective is to select the most pertinent solution for the slopes in the railway infrastructure, considering the geological conditions of the material, the cut geometry, the hydraulic conditions, and the associated risk level.

3.1 Evaluation Criteria

The selected criteria correspond to the factors that condition slope behavior and the feasibility of each constructive solution. Each criterion reflects a dimension of the problem that affects the efficacy of the chosen treatment.

Geological conditions of the material: The type of material forming the slope, along with its fracturing degree, weathering, presence of friable materials, cavities, and loss of cohesion, influences the predominant deterioration mechanism and the compatibility of the stabilization system. A fine, highly erodible material usually responds favorably to surface protection; a fractured rock mass, conversely, may require retention meshes, anchors, or shotcrete. Incompatibilities at this point can compromise the long-term functionality of the structure.

Slope geometry: The height, slope angle, cut configuration, and surface exposure define the magnitude of stresses acting on the slope, runoff velocity, and rockfall potential. Low slopes with moderate inclinations generally allow for lightweight solutions. High or steeply inclined cuts usually require more rigid treatments or combined systems acting both at the surface and at depth.

Level of instability or risk: This criterion encompasses the presence of scarps, rockfalls, local failures, block dropping, cavities, active erosion, and proximity to the exposed infrastructure. It is assigned the highest weight within the model because it shows the condition most directly related to operational safety and slope stability. In the presence of greater observed instability, the need to opt for structural or integral solutions that do not rely solely on surface protection is anticipated.

Hydraulic conditions: The presence of runoff, moisture, seepage, surface flow concentration, or water accumulation conditions the performance of the treatments. Water can accelerate erosion, reduce material shear strength, and decrease the effectiveness of superficial protections that would operate correctly under dry conditions. Therefore, the convenience of incorporating ditches, interceptor ditches, and downspouts is recognized in the presence of active runoff or slope saturation. It is recommended that the dimensions and slopes of ditches and interceptor ditches comply with the specifications of the executive project or be adjusted according to technical area recommendations. It must also be verified at all times that outlets or downspouts exist to prevent water accumulation on the benches. This criterion serves to unify the conditions that may arise; however, they can change according to the accessibility of the bench, a situation to be considered by the engineer in charge of each cut.

3.2 Evaluated Stabilization Alternatives

Four intervention alternatives were evaluated, considered as representative solutions for different conditions of erosion, rockfalls, fracturing, and water presence.

A1. Surface protection with geomat and hydroseeding: Consists of placing a geomat or geosynthetic on the slope surface, complemented with hydroseeding to promote vegetative cover (Fig. 1). It is primarily oriented toward surface erosion control on slopes with fine materials, moderate inclinations, and low instability levels. The performance of geosynthetics in erosion control can be quantified using the Revised Universal Soil Loss Equation (RUSLE), which allows to the selection of the appropriate product based on site conditions (Rimoldi, 2010). Rimoldi (2021) documents that three-dimensional geomats and organic blankets are especially effective on slopes with moderate gradients where vegetative cover can establish and complement the protective function.

Fig. 1. Geomat and hydroseeding, Section 7 of the Maya Train. Source: Author's own.

A2. Shotcrete with prior trimming: Includes cleaning and removing loose material, followed by the application of shotcrete (Fig. 2). It is considered adequate for zones with cavities, local failures, rockfalls, or intense erosion. It exhibits high strength and durability, although it may require surface drainage or sub-drainage systems if the main problem is of hydraulic origin. When fiber-reinforced shotcrete is used, its mechanical performance, crack resistance, and durability may be improved due to the crack-bridging effect provided by the fibers and the enhanced interaction between the reinforcement and the cement matrix (Chen & Wen, 2024).

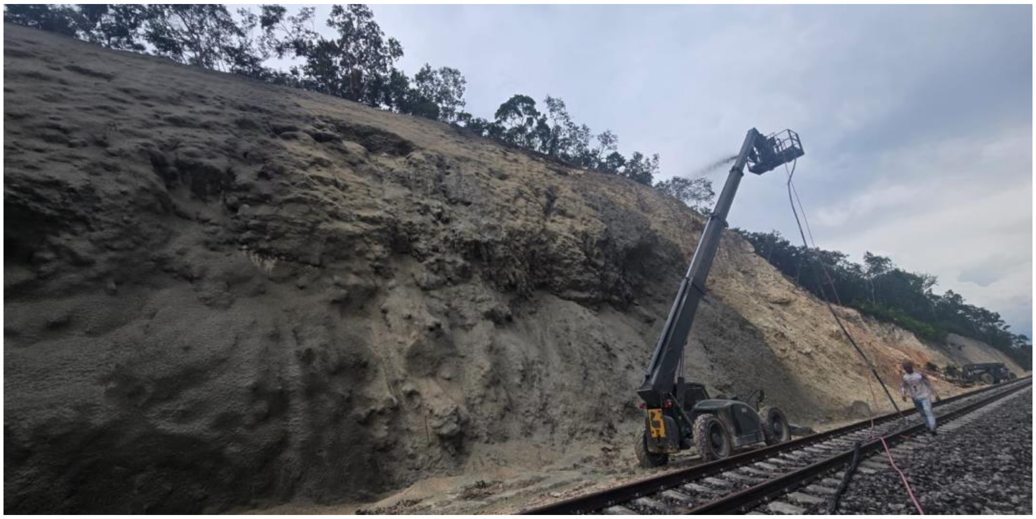

Fig. 2. Shotcrete with prior trimming, Section 7 of the Maya Train. Source: Author's own.

A3. Mixed system with geomat, mesh, and anchors: Composed of a geosynthetic reinforced with metallic mesh and anchored to the slope (Fig. 3). It is recommended for fragmented materials, mixtures of rock and fines, or areas with a risk of small block drops, combining erosion control with superficial mechanical retention. Rimoldi (2021) points out that three-dimensional geosynthetics allow for the integration of erosion control and surface retention functions when combined with metallic meshes, expanding their applicability to fragmented slopes. The use of anchors is consistent with the principles of the soil nailing system, which has demonstrated effectiveness in the stabilization of cuts with moderate strength materials (Byrne et al., 1996; Lazarte et al., 2015).

Fig. 3. Geomat with mesh and anchors, Section 7 of the Maya Train. Source: Author's own.

A4. Integral stabilization with drainage and structural treatment: This alternative allows for simultaneously addressing the failure mechanism and the effect of water as a triggering factor for deterioration. It integrates surface drainage works (ditches, interceptor ditches, and downspouts) with structural or superficial treatments depending on site conditions (Fig. 4). It can combine shotcrete, geomats, meshes, or anchors, addressing both the failure mechanism and the hydraulic triggering factor. Byrne et al. (1996) and Lazarte et al. (2015) document that soil nail systems combined with active drainage constitute an integral solution for slopes with multiple failure mechanisms, allowing for the reduction of pore pressure and the improvement of shear strength simultaneously. This logic is directly applicable to alternative A4, where the integration of drainage works and structural treatment responds to both the hydraulic trigger and the mechanical failure mechanism.

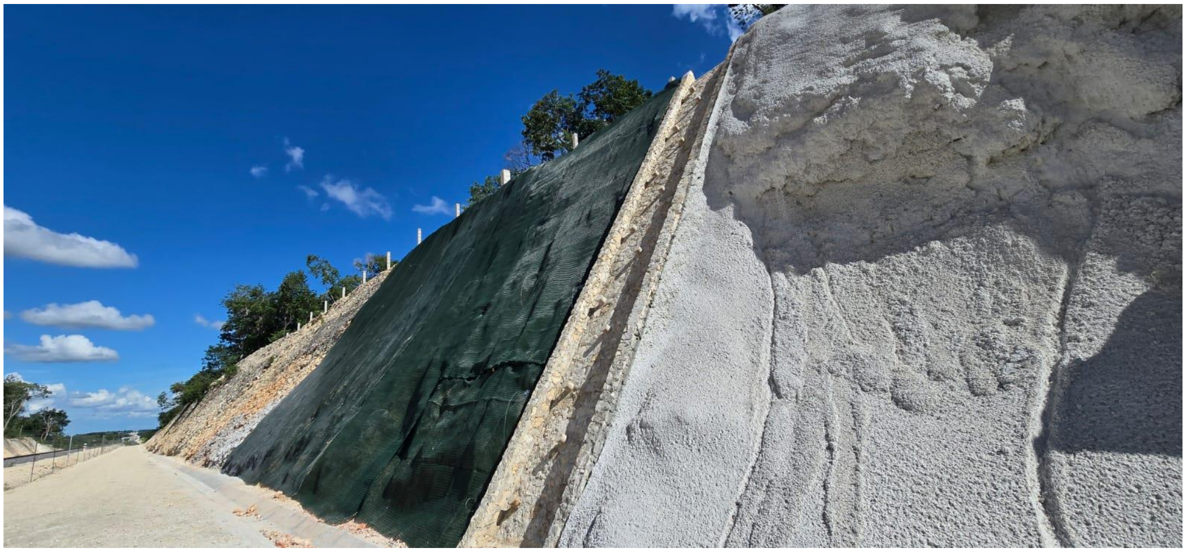

Fig. 4. Integral stabilization with drainage and structural treatment, Section 7 of the Maya Train. Source: Author's own.

3.3 Pairwise Comparison Matrix for Criteria

To define the relative importance of the criteria, a pairwise comparison matrix was constructed based on Saaty's scale (Table 1). A higher weight was assigned to the risk and instability level due to its direct relationship with slope and infrastructure safety. In second place, hydraulic conditions were evaluated, considering that water constitutes a triggering factor for erosion and progressive degradation. The geological conditions of the material were placed in third place, and geometry was considered a conditioning criterion with less relative weight compared to risk and water.

The pairwise judgments were established by consensus among the expert panel using Saaty's fundamental scale. During the evaluation session, the relative importance of each criterion was discussed before assigning the comparison values. For example, the risk and instability criterion received a strong preference over slope geometry because active landslides, rockfalls, and progressive degradation have a more direct influence on railway safety than geometric configuration alone. Likewise, hydraulic conditions were prioritized over geometry since infiltration, surface runoff, and water accumulation are recognized as the main triggering factors of erosion and slope instability. Similar technical reasoning was applied during the evaluation of the stabilization alternatives. For instance, the integral stabilization system with drainage and structural treatment was considered superior to the geomat with hydroseeding under the risk and hydraulic criteria because it simultaneously incorporates water control and structural reinforcement capable of addressing more complex failure mechanisms. Conversely, the geomat with hydroseeding was assigned higher ratings only for slopes dominated by superficial erosion and low instability levels, whereas shotcrete with prior trimming was preferred over the mixed system for localized cavities, surface deterioration, and intense erosion.

Since the obtained Consistency Ratio is CR=0.044 (less than 0.10), the matrix exhibits an acceptable consistency.

Table 1. Criteria comparison matrix

CRITERIA COMPARISON MATRIX									
CRITERIA	Geology	Geometry	Risk	Hydraulic	NORMALIZED MATRIX				WEIGHING
Geology	1	3	1/3	1/2	0.16	0.25	0.18	0.10	0.172
Geometry	1/3	1	1/5	1/3	0.05	0.08	0.11	0.07	0.078
Risk	3	5	1	3	0.47	0.42	0.54	0.62	0.512
Hydraulic	2	3	1/3	1	0.32	0.25	0.18	0.21	0.238
TOTAL	6.3	12.0	1.9	4.8					

The pairwise comparison weights were established during an evaluation session conducted with a multidisciplinary panel of specialists, including experts in hydraulic engineering and drainage systems, geotechnical engineering and soil mechanics, structural engineering, surveying and highway engineering, railway slope stabilization with direct field experience, and mathematical optimization and algorithm development. The composition of the panel ensured that the decision-making process incorporated the different technical perspectives involved in slope behavior and stabilization, combining design expertise, field experience, and mathematical modeling to reduce the subjectivity inherent to expert judgment.

The pairwise judgments were defined through consensus among the panel members after evaluating the expected performance of each stabilization alternative with respect to the dominant failure mechanisms, as well as the geological and hydraulic conditions of the site. The panel also considered the technical experience accumulated from linear infrastructure projects to support the decision-making process. This approach enabled the construction of pairwise comparison matrices based on engineering judgment and technical criteria rather than on the opinion of a single evaluator.

3.4 Alternative Evaluation Matrices per Criterion

For each criterion, a comparison matrix among alternatives was structured. The assigned values respond to the estimated technical pertinence for each alternative regarding the evaluated criterion.

3.4.1 Matrix for C1. Geological conditions of the material

In this criterion, alternative A4 shows a high valuation due to its flexibility to adapt to different geological conditions through the combination of drainage and structural treatment. Alternative A3 also shows an adequate performance in fragmented materials or with small blocks, while A2 is oriented toward addressing cavities or local failures (Table 2).

Table 2. Geological conditions of the material

Geology									
CRITERIOS	Geomat and hydroseeding	Shotcrete	Mixed system	Drainage and structural treatment	NORMALIZED MATRIX				WEIGHING
Geomat and hydroseeding	1	1/3	1/4	1/5	0.08	0.05	0.07	0.10	0.07
Shotcrete	3	1	1/2	1/3	0.23	0.16	0.13	0.16	0.17
Mixed system	4	2	1	1/2	0.31	0.32	0.27	0.25	0.28
Drainage and structural treatment	5	3	2	1	0.38	0.47	0.53	0.49	0.47
TOTAL	13.00	6.33	3.75	2.03					

3.4.2 Matrix for C2. Slope geometry

Regarding geometry, shotcrete (A2) and the integral system (A4) show a favorable performance on steeper slopes or cuts with significant exposure. The mixed system (A3) is viable on inclined slopes, provided that conditions allow for anchor installation. The geomat with hydroseeding (A1) is considered more adequate for moderate slopes and lower heights (Table 3).

Table 3. Matrix for the slope geometry criterion

Geometry									
CRITERIOS	Geomat and hydroseeding	Shotcrete	Mixed system	Drainage and structural treatment	NORMALIZED MATRIX				WEIGHING
Geomat and hydroseeding	1	1/4	1/3	1/5	0.0769	0	0	0.0741	0.08
Shotcrete	4	1	2	1	0.3077	1/3	3/8	0.3704	0.35
Mixed system	3	1/2	1	1/2	0.2308	1/5	1/5	0.1852	0.20
Drainage and structural treatment	5	1	2	1	0.3846	1/3	3/8	0.3704	0.37
TOTAL	13.00	2.75	5.33	2.70					

3.4.3 Matrix for C3. Level of instability or risk

For the instability level, alternative A4 stands out as a robust option because it allows to combining drainage, concrete, mesh, or anchors according to the specific failure mechanism. Shotcrete (A2) shows an adequate behavior against local failures and rockfalls, while the mixed system (A3) is suitable for the superficial retention of fragmented material. Alternative A1 is considered limited for moderate to high risk scenarios (Table 4).

Table 4. Matrix for the criterion Level of instability or risk

Risk									
CRITERIOS	Geomat and hydroseeding	Shotcrete	Mixed system	Drainage and structural treatment	NORMALIZED MATRIX				WEIGHING
Geomat and hydroseeding	1	1/5	1/4	1/7	0.0588	0	0	0.0723	0.06
Shotcrete	5	1	2	1/2	0.2941	1/4	1/3	0.253	0.28
Mixed system	4	1/2	1	1/3	0.2353	1/7	1/6	0.1687	0.17
Drainage and structural treatment	7	2	3	1	0.4118	1/2	1/2	0.506	0.48
TOTAL	17	3 5/7	6 1/4	1.9762					

3.4.4 Matrix for C4. Hydraulic conditions

In this criterion, alternative A4 obtains the highest weight because it explicitly incorporates drainage works for the control of runoff, moisture, and flow concentration. Alternative A1 can contribute to reducing surface erosion but does not resolve concentrated runoff. Option A3 protects the slope superficially, although it does not control water flow on its own. Finally, alternative A2 possesses an adequate structural performance, but its application without associated drainage can conceal or aggravate pressure or moisture problems (Table 5).

Table 5. Matrix for the Hydraulic Conditions criterion

Hydraulic									
CRITERIOS	Geomat and hydroseeding	Shot crete	Mixed system	Drainage and structural treatment	NORMALIZED MATRIX				WEIG HING
Geomat and hydroseeding	1	2	2	1/5	0.1 429	1/ 6	1/ 5	0.1 325	0.16
Shotcrete	0.5	1	1/2	1/7	0.0 714	0	0	0.0 946	0.08
Mixed system	0.5	2	1	1/6	0.0 714	1/ 6	1/ 9	0.1 104	0.11
Drainage and structural treatment	5	7	6	1	0.7 143	3/ 5	5/ 8	0.6 625	0.65
TOTAL	7.00	12	9.50	1.51					

3.5 Global Weighting of Alternatives

The global priority of each alternative was obtained through the weighted sum of the alternative scores across all criteria. The consolidated result is presented in the following matrix (Table 6).

Table 6. Overall weighting of alternatives

	Geology	Geometry	Risk	Hydraulic	
Geomat and hydroseeding	0.07	0.08	0.06	0.16	8.6%
Shotcrete	0.17	0.35	0.28	0.08	22.1%
Mixed system	0.28	0.20	0.17	0.11	18.1%
Drainage and structural treatment	0.47	0.37	0.48	0.65	51.2%
	0.17	0.08	0.51	0.24	100%

4 Results and Discussion

The results obtained through the Analytic Hierarchy Process show a clear ranking among the evaluated stabilization alternatives. The integral drainage and structural treatment system achieved the highest global priority (51.2%), followed by shotcrete with prior trimming (22.1%). In third place was the mixed system with geomat, mesh, and anchors (18.1%), while surface protection with geomat and hydroseeding obtained the lowest weight (8.6%).

This distribution reflects that, for the critical slopes in the analyzed railway infrastructure, the most adequate solution is not limited to surface protection, but rather to an option that integrates hydraulic control and structural support. This result shows direct correspondence with the weighting of the criteria: the risk and instability level was the criterion with the highest relative weight (0.51), followed by hydraulic conditions (0.24). Together, both criteria represent approximately 75% of the decision, indicating that the final selection within the model was dominated by the need to address the physical safety of the slope and the effect of water as a triggering factor for erosion or progressive degradation.

Under the risk criterion, the integral drainage and structural treatment system obtained a local weight of 0.48, which is superior to shotcrete (0.28), the mixed system (0.17), and the geomat with hydroseeding (0.06). This behavior is technically consistent, as an integral solution has a greater capacity to respond to diverse instability mechanisms, such as active erosion, cavities, rockfalls, or direct impacts on the exposed infrastructure. Conversely, superficial solutions have a more restricted field of application and are less adequate when the slope exhibits moderate to high risk conditions.

Hydraulic conditions were also a determining factor in the overall result. Within this criterion, drainage and structural treatment obtained the highest local weight (0.65), reflecting its relative advantage over the other alternatives. This value is explained because this option explicitly incorporates surface drainage works (such as ditches, interceptor ditches, and downspouts), in addition to the possibility of being combined with superficial coatings or structural elements. In contrast to a solution based solely on a surface coating, the integral treatment reduces runoff concentration, controls surface moisture, and decreases the probability of water acting as a degradation agent on the slope.

Shotcrete with prior trimming positioned itself as the second most favorable alternative. Its global priority of 22.1% is mainly due to its good performance against the risk criterion (0.28) and the geometry criterion (0.35). This suggests that shotcrete is an adequate solution for cuts with demanding geometries, irregular surfaces, or areas with localized rockfalls. However, its low valuation under the hydraulic criterion (0.08) shows a relevant limitation: if it is not accompanied by adequate drainage, it may not properly resolve the problems associated with runoff or moisture accumulation behind the rigid facing.

The mixed system with geomat, mesh, and anchors obtained a global priority of 18.1%. Its best performance was observed under the geological criterion (0.28), suggesting that this alternative is convenient in fragmented materials, zones with small blocks, or slopes where combining surface protection with mechanical retention is required. Nonetheless, its performance was lower under the risk and hydraulic criteria, with values of 0.17 and 0.11, respectively. This indicates that, although it is a technically useful alternative, it can be insufficient when the dominant mechanism is associated with concentrated runoff or active instability of greater magnitude.

For its part, the geomat and hydroseeding alternative recorded the lowest global priority (8.6%). This result does not imply that it is an inadequate solution in all cases, but rather delimits its applicability against the predominant criteria in this model. Its performance is more favorable under conditions of superficial erosion, low-criticality slopes, moderate gradients, and materials that allow for the establishment of vegetative cover. However, when the analysis incorporates higher risk and the need for structural treatment, this alternative loses competitiveness against more robust solutions.

The overall outcome confirms the utility of the AHP in ranking stabilization alternatives based on differentiated technical criteria. The criteria pairwise comparison matrix presented a consistency ratio of 0.044, which is below the recommended limit of 0.10. This indicates that the judgments used exhibit an acceptable internal consistency within the comparison model, validating the transitional coherence of the assigned preferences.

The technical discussion also allows for the identification that no alternative should be interpreted as a universal solution. Although the integral drainage and structural treatment system obtained the highest priority in the model, its real-world application must be justified on slopes where risk conditions, water presence, or progressive deterioration actually exist. On slopes with low heights, moderate gradients, and purely superficial erosion, a solution like geomat and hydroseeding could be sufficient and more efficient from an environmental and economic standpoint. Similarly, shotcrete or the mixed system may be more convenient in localized zones where the problem is mainly structural or related to superficial retention, rather than hydraulic.

The results suggest that slope stabilization in railway infrastructure should be approached with a differentiated intervention logic. For zones of high criticality due to risk and hydraulic conditions, the integral drainage and structural treatment system is the most robust alternative. For areas with cavities or localized material loss, shotcrete can be a technically pertinent solution. For slopes with superficial fragmentation or the potential for small block drops, the mixed system with mesh and anchors offers an intermediate performance. Finally, for areas with surface erosion and low risk, geomat with hydroseeding remains a viable alternative.

The application of the AHP allowed for the establishment of a technical hierarchy of solutions, in which the integral alternative with drainage and structural treatment presented the highest priority due to its capacity to simultaneously address risk and hydraulic conditions. This result reinforces the utility of complementing technical experience and constructive criteria through structured decision-making procedures, promoting a selection of solutions sustained by explicitly traceable criteria.

5 Conclusions

The application of the Analytic Hierarchy Process allowed for the structuring of the selection problem for slope stabilization alternatives through an ordered sequence of analysis. The procedure began with the definition of the objective, continued with the selection of criteria and alternatives, and subsequently incorporated the construction of pairwise comparison matrices, the determination of weights, and the calculation of the global priority. This structure facilitated the transformation of a technical problem with qualitative and quantitative components into a traceable, comparable, and methodologically verifiable decision process.

The criteria pairwise comparison matrix presented a consistency ratio of 0.044, a value below the acceptable limit of 0.10; therefore, the emitted judgments can be considered consistent. This result indicates that the judgments used exhibit an acceptable internal consistency within the comparison model. The criteria with the highest weights were the risk and instability level (0.51) and hydraulic conditions (0.24). To a lesser extent, geological conditions (0.17) and slope geometry (0.08) were ranked. This distribution shows that the analysis was not oriented solely toward the slope configuration or the type of material. The decision within the model was dominated by factors that can compromise infrastructure safety and accelerate the degradation of the cut, especially the presence of active instability and the effect of water.

The AHP also facilitated the differentiation of each alternative's performance across each criterion. This allowed the evaluation to be structured in an explicit and comparable manner among alternatives, as each solution was independently evaluated against the geological, geometric, hydraulic, and risk conditions considered in the study. In this regard, the method provided a useful tool to technically substantiate the final selection within the framework of the model, reducing the reliance on less systematized approaches.

The alternative with the highest global priority was integral stabilization with drainage and structural treatment, with a value of 51.2%. This result suggests that, within the developed evaluation model, alternatives integrating hydraulic control and structural treatment present a higher priority when facing scenarios of greater complexity in the analyzed railway infrastructure. Its advantage was mainly observed under the risk and hydraulic criteria, where it obtained the highest local weights. This is relevant because a slope with these characteristics does not only require a surface coating; it also needs to control runoff, reduce moisture accumulation, and treat sectors where the material exhibits a loss of stability.

Shotcrete with prior trimming occupied the second position, with a global priority of 22.1%. This alternative is technically adequate in zones with cavities, rockfalls, local failures, or exposed surfaces that require confinement and rigid protection. Nonetheless, its performance decreases when the dominant problem is of hydraulic origin. Shotcrete, applied as an isolated measure, does not guarantee the control of runoff, seepage, or water pressures behind the lining. Therefore, its use must be accompanied by drainage works when moisture or concentrated surface flow is present.

The mixed system with geomat, mesh, and anchors reached a global priority of 18.1%. Its main advantage relates to its compatibility with fragmented materials or slopes with a risk of small block drops. This alternative represents an intermediate solution. It combines surface protection and mechanical retention, making it useful on slopes where the problem does not reach a generalized instability condition, but where superficial material loss or minor rockfalls do exist. Even so, its efficiency can be limited if it is not accompanied by adequate measures for water management.

The geomat and hydroseeding alternative obtained the lowest global priority value (8.6%). This result does not imply that it is a discardable solution, but rather delimits its applicability against the predominant criteria in this model. Its application is pertinent on slopes with surface erosion, moderate gradients, low risk levels, and conditions that allow for the establishment of vegetative cover. However, on slopes with active instability, concentrated runoff, or direct impacts on railway infrastructure, this alternative is insufficient as a standalone measure.

Taken together, the results show that the selection of a stabilization alternative must respond to the dominant deterioration mechanism. For slopes with high risk and water presence, the integral option with drainage and structural treatment is the most rob

ust. For localized distresses, shotcrete can be adequate. For fragmented materials, the mixed system is a technically viable solution. For surface erosion of lower complexity, the geomat with hydroseeding remains a functional alternative.

The AHP demonstrated its applicability to railway infrastructure projects because it allows for the integration of criteria of different natures into the same evaluation procedure. In this type of work, the selection of stabilization solutions usually involves geotechnical, hydraulic, constructive, and operational information; therefore, a multicriteria method facilitates ordering the decision and justifying the selected alternative.

The proposed methodology can be used as a support tool in stages of diagnosis, preliminary design, or technical review of solutions for railway cuts. Its utility increases when multiple technically feasible alternatives coexist, each possessing distinct advantages and limitations. In these cases, the AHP provides comparison of alternatives without reducing the decision to a single criterion, such as cost, material availability, or constructive ease. It can also be useful for documenting decisions before technical teams, construction supervision, or entities responsible for maintenance. By presenting criteria, weights, and priorities, the method explains why one alternative is more suitable than another under specific slope conditions. This strengthens technical traceability and can contribute to grounding decisions on explicit criteria.

However, its application must be understood as a decision-support tool, not as a substitute for detailed geotechnical, hydraulic, or structural analysis. The AHP results must be complemented with field inspections, material characterization, runoff reviews, stability analyses, and specific constructive designs.

For future work, it is recommended to incorporate a sensitivity analysis to evaluate how the ranking of alternatives changes when the weights of the criteria are modified. This analysis would identify whether the selected alternative remains stable against variations in the importance assigned to risk, hydraulic conditions, or material geology. Another important aspect would be to integrate economic and constructive criteria; although this work prioritized the technical pertinence of the alternatives, in executive projects it is necessary to consider cost, construction time, material availability, maintenance, environmental impact, and ease of implementation.

Finally, it is recommended to apply the method by tramps or homogeneous sections, so that each slope is evaluated according to its particular condition and not through a generalized solution applied to the entire infrastructure.

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