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Evaluation of Sustainable Slope Stability with Anti-Slide Piles Using an Integrated AHP-VIKOR Methodology

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Abstract: The sustainable design of major civil engineering projects, such as landslide management and slope stability, provides new opportunities for our society regarding the global energy crisis. These sources offer an effective solution to environmental issues and human energy needs. Slope stability, as a critical aspect of ensuring public safety and protection of infrastructure, often leads to disastrous consequences, highlighting the significance of designing effective and sustainable measures to mitigate the risks associated with landslides. Although anti-slide piles have become a widely used method to enhance slope stability, this paper investigates how the Analytic Hierarchy Process (AHP) and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) methodologies can be combined to achieve a sustainable design for anti-slide piles, simultaneously considering environmental, economic, safety, and technical factors. Through the integration of AHP-VIKOR and a case study, this paper demonstrates an effective approach to prioritizing sustainability in the design process of anti-slide pile systems, evaluating five main criteria—slope stability, sustainability, anti-slide pile capacity, cost, and ease of construction—and five sub-criteria. The proposed methodology is validated through a case study, wherein various design alternatives for anti-slide piles are evaluated based on sustainable requirements. The results indicate that the slope stability criterion has the highest weight of 0.404, followed by anti-slide pile capacity (0.283), sustainability (0.129), and cost (0.146) criteria. The ease of construction has the lowest weight of 0.038. As a result of the evaluations, it has been seen that, if the sustainability criteria are included in the analyses, the anti-slide pile alternatives are determined in the range of ξ = 0.1–0.3 and s/D = 2.0–3.0, compared to the scenarios where only the economic and technical criteria are satisfied. A pile geometry of diameter, D = 1.00 m, is the most sustainable value within the selected pile spacing intervals, meeting the criteria of slope safety, pile capacity, cost, and ease of construction. This hybrid approach allows for a more balanced consideration of a multi-criteria decision, while considering the sustainability aspects of anti-slide pile selection.

Keywords: anti-slide pile; multi-criteria decision making; slope stability

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1. Introduction

For several decades, civil engineering has been a decisive instrument for addressing the externalities of traditional infrastructure and urban design, but it has overlooked nature's global limits. However, in the last two decades, a prevailing awareness of the environment-centered perspective has become important to conceptualizing 'sustainable civil engineering', which opposes strong industrialization, unhealthy human-centered urbanization, and overconsumption-oriented engineering [1–10]. With this conceptual change, the conflict between the effectiveness and multidimensional systemic view of sustainability and the one-dimensional view of conventional practices has been the subject of discussion and research in multiple disciplines [1–10].

Geotechnical engineering is becoming increasingly significant due to its integrative function in unifying civil engineering sub-disciplines. Landslides, as a major issue in geotechnical engineering, have a critical importance, which can lead to severe problems, including infrastructure damage and potential casualties. An efficient and reliable method to stabilize the slopes is of key importance to prevent social, economic, and sustainable vulnerabilities in regions affected by this phenomenon. In this context, researchers, policymakers, engineers, and designers all pointed out the relevance of the climate-change-related impacts of landslides. Therefore, it has become critical to evaluate the sustainability-based selection of each structural component to prevent geohazards. Laterally loaded piles, which are classified as one of the most cost-effective and time-efficient structural solutions for urban areas, become a suitable option. However, many solutions in geotechnical engineering are still approximate due to a lack of experimental information and dominant environmental conditions. As a result, there is an important need to make decisions at the strategic level of a suitable design process.

Multi-criteria decision making (MCDM), including approaches and methods to obtain the best possible suitable solution, involves multiple conflicting criteria for its sustainability-oriented decision process. MCDM is becoming more applicable and more popular for modeling the complex behavior of most geotechnical engineering problems, including foundation engineering, excavations and supporting soil structures, underground structures, dams, natural or artificial embankments, substructures, and landslide assessments, due to its superior predictive ability when compared to conventional methods [1,2,4,5]. Some experience-based knowledge involved in the selection of anti-slide piles has been recorded in the literature; however, it is not always possible to reach expert engineers to decide on the pre-design of geotechnical structures. Experts have identified sustainable anti-slide pile selection as a complicated process, comprising environmental, technological, economic, and safety aspects.

Basari et al. [11] utilized the AHP and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods to select the most suitable pile foundation based on various criteria, such as cost, constructability, and environmental impact. Josa et al. [12] focused on the sustainability-oriented multi-criteria analysis of different continuous flight auger piles (CFAPs). The study aimed to evaluate the environmental, economic, and social impacts of CFAPs and compare them with other foundation systems. Pons et al. [13] presented a sustainability-driven decision-making model for selecting the most suitable pile material for a specific construction project. The model considers the environmental, economic, and social factors associated with the production and use of fiber-reinforced concrete foundation piles. Golafzani et al. [14] proposed an optimized selection process that considers various criteria such as accuracy, reliability, and cost-effectiveness based on the criteria using TOPSIS. Muñoz-Medina et al. [15] applied Analytic Network Process (ANP) and TOPSIS to select the most suitable retaining wall type using different criteria, including aesthetic, cost, performance, and environmental impact. Adhikari et al. [16] proposed a multi-criteria decision support system to recommend slope repair methods by using AHP to prioritize the criteria that affect the decision-making process, including cost, time, safety, and environmental impact. Balasbaneh and Marsono [17] presented a comparative analysis of alternatives for earth-retaining walls using MCDM techniques, incorporating life cycle assessment (LCA). Dachowski and Gałek [18] used MCDM methods for selecting the best underpinning method for building foundations alternatives based on technical, economic, and environmental criteria. De la Fuente et al. [19] applied a multi-criteria decision-making model to evaluate the sustainability index of wind turbine support systems with environmental, economic, and social impacts. According to the analysis of the current literature review, although the integrated use of AHP and VIKOR is not common practice, combining sustainability criteria with ease of construction in terms of technical, economic, and safety criteria is a new approach. Classical MCDM methods such as the AHP have been widely used in the domain of sustainable approaches. As a significant multi-criteria evaluation method, VIKOR is utilized in sustainability-oriented design of civil engineering structures by giving compromise solutions and improving the limitations of the TOPSIS and PROMETHEE methods used in the literature [12,14,15].

In the present study [20], a new sustainability-oriented MCDM framework using an integrated AHP-VIKOR methodology was applied in the selection of a suitable anti-slide pile, addressing slope stability problem. With the increasing concern for environmental sustainability and the need to mitigate risks associated with slope failures, researchers have developed innovative methodologies to enhance the effectiveness and efficiency of anti-slide pile designs. This research aims to contribute to the existing knowledge by integrating AHP and VIKOR methodologies to enhance the sustainable design process for anti-slide piles. By leveraging both methodologies, this study aims to optimize the selection of design alternatives, considering complementary use of environmental impact, economic feasibility, and technical considerations. This research will provide valuable insights into sustainable design practices for anti-slide piles, ensuring slope stability while accommodating the principles of sustainability. The proposed methodology is a generalized model, which can be applied to a great variety of practical civil engineering problems also encountered in sustainable design, utilizing a robust methodological approach. AHP is used to rank the weights of the criteria and the VIKOR approach is used to select the suitable options for the anti-slide pile. This study will also consider and focus on the main conflicting criteria of the assessment and comparisons. In Section 2, we present the key steps of the AHP and VIKOR methodologies, as well as the multifarious structure of MCDM approaches. In Section 3, we introduce an integrated MCDM model with an AHP-VIKOR algorithm, which renders the decision-making techniques for achieving suitable selection of a sustainable anti-slide pile design. Then, the results obtained from the MCDM model are described, and the validation and subsequent implications of the case study are explained. Sensitivity analysis and presentation of the suitable anti-slide pile alternatives are carried out in Section 4. Finally, the key conclusions of the paper are presented in Section 5.

2. Materials and Methods

2.1. Multi-Criteria Decision Making (MCDM)

MCDM approaches and recent developments (e.g., Ordinal Priority Approach (OPA)), which are assumed to be useful and suitable for a multifaceted structure of contradictory evaluation, allow decision makers to find logical solutions to decision problems involving various criteria [21–25]. The Analytical Hierarchy Process (AHP) is a widely used multi-criteria decision-making method for a solution to complex decision problems that reaches the intended target, which determines the weights of the criteria. It is used in this study to select the suitable sustainability-oriented geotechnical structure in slope stability problems by determined hierarchy-including criteria, sub-criteria, and alternatives that constitute the consistency achieved. AHP is a method that involves comparing pairs to gather input data from decision makers to assess the consistency of their judgments on multi-criteria problems. This feature makes AHP well suited for studying slopes reinforced by anti-slide piles. Likewise, VIKOR (Vlse Kriterijumska Optimizacija Kompromisno Resenje) is a modest computational method that can be used to solve multi-criteria problems by measuring the proximity of feasible alternatives to both ideal and non-ideal options, considering conflicting aspects [21]. As the combination of different approaches with the inclusion of MCDM methods is not a rare phenomenon, an integrated AHP-VIKOR multi-criteria decision-making system was created for the selection of appropriate anti-slide piles in slope stability problems, according to the criteria determined based on experience and expert opinions.

2.1.1. AHP

AHP, first proposed by Thomas L. Saaty [26] to evaluate reasoning by decision makers, with its powerful, adaptable, dynamic structure, provides an appropriate collaborative strategy for the solution of complex decision problems. The AHP approach, which mainly assists in decision making in multi-criteria decision problems, is utilized to evaluate the multi-dimensional decision problem on both qualitative and quantitative scales by dividing up the multidimensional problems. The key steps include: (1) hierarchical modeling of the decision problem containing the goals; (2) establishing the priorities for the weights of criteria by the pairwise comparisons, via utilizing AHP scale of relative importance (Table 1); (3) synthesizing the outcomes by judging the overall priorities for the hierarchy; and (4) examining the consistency of the judgments. This was carried out.

Table 1. AHP scale of relative importance [26].

Scale	Definition	Explanation
1	Equally Important	C_1 and C_2 hold equal significance.
3	Weakly Important	C_1 surpasses C_2 slightly in prominence.
5	Strongly Important	C_1 significantly outweighs C_2 in prominence.
7	Very Strongly Important	C_1 holds a very strong advantage in prominence over C_2.
9	Extremely Important	C_1 holds an extreme advantage in prominence over C_2.
2, 4, 6, 8	Intermediate Values	Intermediate degrees of significance.

Since 'n' is the number of criteria, matrix 'X' is created for pairwise comparison (Equation (1)) and reciprocal value is assigned to inverse comparison, i.e., $a_{ji} = 1/a_{ij}$, where a_{ij} indicates importance of i'th element compared to j'th element:

$$X = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{a_{n1}} & \frac{1}{a_{n2}} & \dots & 1 \end{bmatrix} \quad (1)$$

Having obtained the aggregate judgement matrix to evaluate opinions formed in a pairwise comparison, the consistency index CI is determined using Equation (2).

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

where n is the matrix size and λ_{max} is the eigenvalue represented in Equation (3). Then, the pairwise comparison matrix is normalized as matrix A and the right eigenvector (W) corresponding to the largest eigenvalue (λ_{max}) is calculated using the following formula:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i} \quad (3)$$

Subsequently, judgement consistency is examined to obtain an acceptable judgement matrix providing a $CR \leq 0$ condition by seeing the value of the consistency ratio (CR) by utilizing Equation (4).

$$CR = CI/RI \quad (4)$$

where RI is the random consistency index obtained from Table 2.

Table 2. Consistency index (RI).

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.0	0.0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

2.1.2. VIKOR

VIKOR, a method developed by Opricovic and Tzeng [27] for the optimization of complex multi-criteria systems in dynamic processes, focuses on selecting and ranking alternatives to problems with conflicting criteria. In addition, it considers the multi-criteria ranking index as a partial measure of similarity to the compromise solution. The VIKOR technique provides a consensus-based solution to support the final decision. In this context, in order to create a reliable decision support system with the VIKOR method, there should be a linear relationship between each of the conflicting criteria and the benefit of the decision maker.

The VIKOR approach consists of the following steps: (1) development of decision matrix (*DX*) as shown in Equation (5), where A_i is ith alternative and C_{xj} is jth criteria with x_{ij} as the performance of ith alternative; (2) determination of positive ideal and negative ideal solution; (3) calculation of the utility measure and index value; (4) ranking of the order.

$$\begin{array}{cc} & C_{x1} \ldots C_{x3} \ldots C_{xn} \\ DX = \begin{array}{c} A_1 \\ \vdots \\ A_m \end{array} & \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{x1n} \\ \vdots & \vdots & \ldots & x_{2n} \\ \vdots & \vdots & x_{33} & \vdots \\ x_{ml} & x_{m2} & \ldots & x_{x1n} \end{bmatrix} \end{array} \tag{5}$$

Subsequently, the normalized decision matrix can be expressed as follows by using Equation (6):

$$F = [f_{ij}]_{mxn} \tag{6}$$

where $f = \frac{x_{ij}}{\sqrt{\sum_{i-1}^{n} x_{ij}^2}}$, the alternate values, denoted by x_{ij}, are associated with the j_{th} criterion and I = 1; 2; . . .; m; j = 1; 2; . . .; n.

In the first step of the VIKOR method, the positive ideal (f_i*) and negative ideal (f_i^-) solutions are determined for the criteria. The solution can be expressed as follows (Equation (7)): for i = 1, 2, . . ., n;

$$f_i{}^* = maxf_{ij} \text{ (for beneficial criteria) and } f_i{}^- = minf_{ij} \text{ (for non-beneficial criteria)} \tag{7}$$

In the opposite case, the values of (f_i*) and (f_i^-) are expressed as in equation (Equation (8)): for i = 1, 2, . . ., n;

$$f_i{}^* = minf_{ij} \text{ (for non-beneficial criteria) and } f_i{}^- = maxf_{ij} \text{ (for beneficial criteria)} \tag{8}$$

Utility measure S_j and regret R_j values for each alternative are calculated by the following expressions (Equations (9) and (10)).

$$S_j = \sum W_i(f_i{}^* - f_{ij})/(f_i{}^* - f_i{}^-)\ n_i = 1 \tag{9}$$

$$R_j = \max\,[W_i(f_i{}^* - f_{ij})\, f_i{}^* - f_i{}^-] \tag{10}$$

where W_i represents the weight of criterion and j = 1, 2, ..., m.

Then, the index values Q_j for each alternative are calculated using Equation (11):

$$Q_j = \nu(S_j - S^*)S^- - S^* + (1-\nu)(R_j - R^* R^- - R^*) \tag{11}$$

where $R^* = \min_j R_j$; $S^* = \min_j S_j$; $R^- = \max_j R_j$ $S^- = \max_j S$, ν is indicating the maximum group utility, and the (1 − ν) represents the minimum regret. It is usually set to 0.5. Once these Q_j, S_j, R_j scores are obtained, the smallest Q_j value of the alternative is considered the best solution and highest ranked among the suitable options if the following two conditions are satisfied.

The first of these conditions is defined as an acceptable advantage (A1), where the difference between the first most suitable option and the second most suitable option should be provided as the observed condition:

$$Q(P2) - Q(P1) \geq D(Q) \tag{12}$$

where P1 is the best ranked alternative by the measure Q (minimum), while P2 is the alternative with the second position and j is the number of alternatives (Equation (13)).

$$D(Q) = 1/j - 1 \tag{13}$$

The second condition (A2) is acceptable stability utilized to prove that the obtained compromise solution is stable. The alternative P1, with the minimum Q_j value, must have the best score in at least one of the S and R values. If either of the two specified conditions (A1 and A2) is not satisfied then the following set of compromise solutions are recommended:

- If A2 is not satisfied: P1 and P2 alternatives;
- If A1 is not satisfied: the inequality is expressed as follows, considering the P1, P2, ..., PM alternatives:

$$Q(PM) - Q(P1) < D(Q) \quad (14)$$

for maximum M regarding the position of these alternatives in closeness.

3. The Use of AHP-VIKOR Methods and Decision-Making Criteria for Sustainable Anti-Slide Pile Selection

3.1. The Use of Multi-Criteria Decision-Making in Sustainability-Oriented Geotechnical Engineering Problems

An AHP-VIKOR multi-criteria decision-making system has been established for the selection of geotechnical support structure types in slope stability problems, based on criteria determined by expert opinions and experiences acquired from experts [20]. Firstly, the criteria weights were evaluated using the AHP method in the established system. Then, the VIKOR method was utilized to rank the alternatives under the criteria. The aim of this study is to transfer expert knowledge based on experiences related to the selection of anti-slide piles. In this study, the problem of selecting the type of geotechnical support structure for slope stability and geotechnical support structure stability was evaluated based on environmental sustainability criteria, which consider energy consumption, environmental impact, and social benefit, in addition to construction ease and cost criteria. Based on a literature review, it was observed that all these criteria are not evaluated simultaneously when selecting geotechnical support structures for slope stability problems. This study contributes to the literature by simultaneously considering the criteria, such as environmental sustainability and ease of construction, which can be defined as contemporary, in addition to the traditionally considered cost and stability criteria in the decision-making process.

3.1.1. Anti-Slide Pile Appraisal Criteria

In this research, a set of criteria based on an expert's opinion [20] is required for the selection of the appropriate anti-slide pile alternatives in slope stability. The preferences and choices of decision makers have a great influence on the results. Survey research was undertaken to purify the criteria and criteria priorities from the individual preferences of the decision maker and to ensure that the criteria represent the problem objectively. Then, a questionnaire survey was conducted to determine the criteria to be considered and to determine the priorities of the criteria. The target group of the questionnaire survey was researchers and academicians with expertise in this field, geotechnical engineers, and experts in the construction industry. As a result of the survey research, five main criteria (Figure 1, shown as C1, C2, C3, C4) and five sub-criteria (Figure 1, shown as C3.1, C3.2, C3.3, C4.1, C4.2) were determined. To combine the opinions of experts who compared criteria, a geometrical average method has been used. The proposed AHP and questionnaire survey result was used to rank these anti-slide pile alternatives based upon the judgments of experts. Using the weight of the anti-slide pile alternatives in slope stability, VIKOR methodology was applied to prioritize the solutions.

The major criteria are slope stability, anti-slide pile capacity, cost, sustainability, and ease of construction. The framework of the decision-making problem of anti-slide pile planning formulated in this study is shown in Figure 1.

Slope Stability (C1)

This criterion defines the safety of slopes in existing geometric and geotechnical conditions to maintain slope stability in cases where slopes are forced to slide under influences such as their own weight, surcharge loads, earthquakes, and underground and surface water movements. More specifically, slope stability is defined by the factor of safety (FS), which is defined as the ratio of the soil shear strength to the average shear stress along the existing slip surface. The slope stability safety factors and internal forces in the piles were obtained using the Plane Deformation Approach with PLAXIS 2D [28] finite element software.

The finite element geometry is presented in Figure 2, where the slope stability of the anti-slide pile is computed in terms of FS values for each alternative.

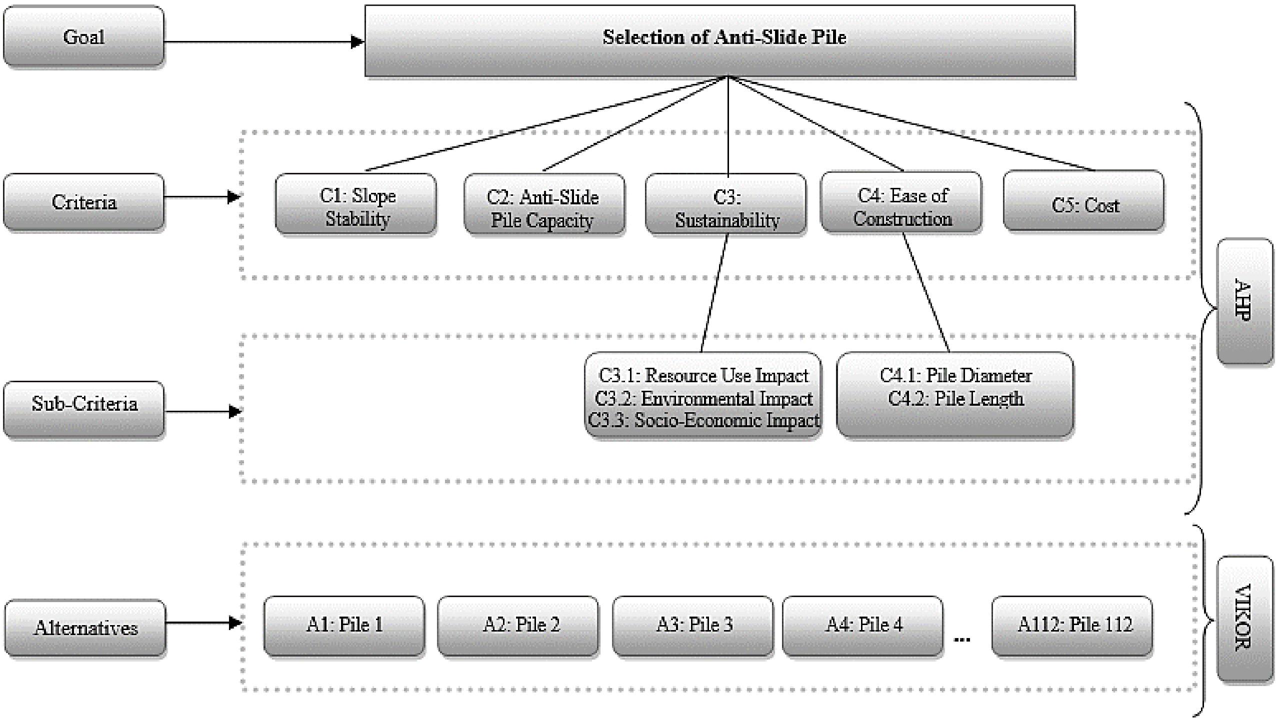


Figure 1. Integrated AHP-VIKOR flow chart of anti-slide pile selection in slope stability problem.

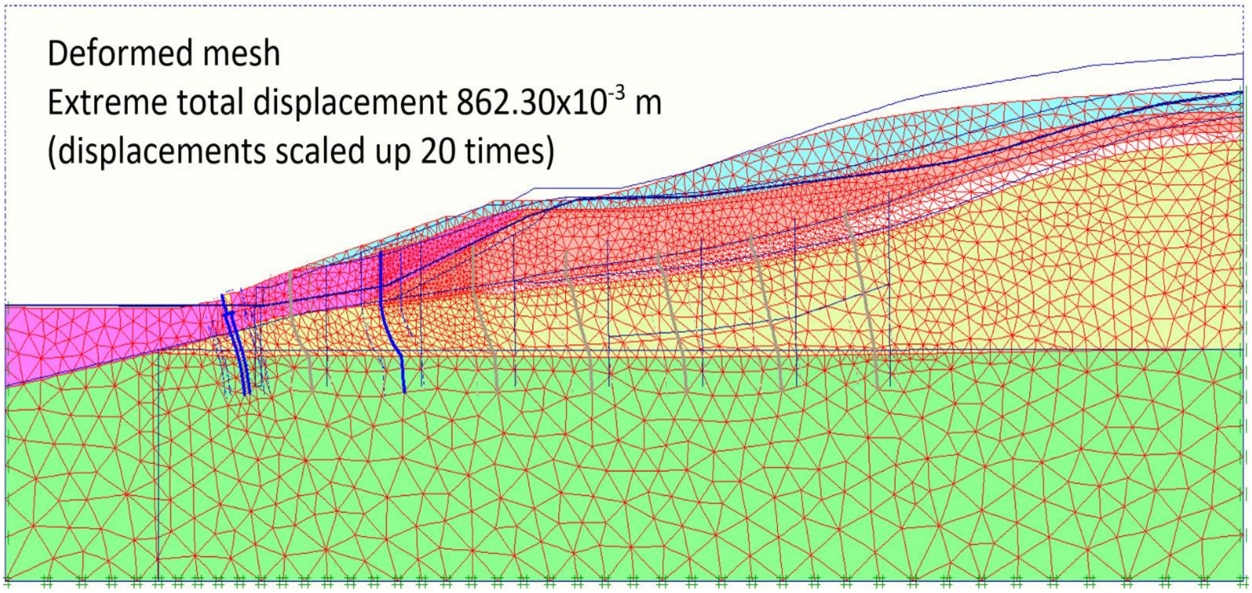


Figure 2. The finite element geometry in slope stability for the anti-slide pile.

Anti-Slide Pile Capacity (C2)

It is widely known that piles with different geometries and positions have sufficient capacity depending on the shear force and bending moment values obtained in the static condition using PLAXIS 2D [28]. The pile/anti-slide pile system design method represents a program procedure that uses a set of parameters that meet geotechnical and structural design requirements. The anti-slide pile capacity is represented by the safety factor (FS_{Pile}), considering geometry and location parameters such as the pile diameter (D), pile location (ξ), and the ratio of the pile spacing to the pile diameter (s/D) for all alternative pile arrangements (Figure 3).

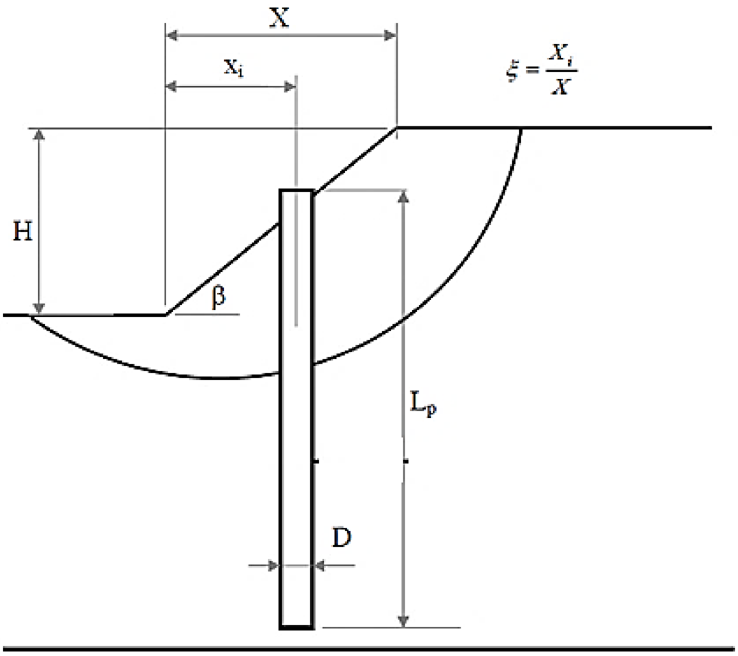


Figure 3. Anti-Slide pile geometry and location parameters.

Shear forces, bending moments, and displacements of piles are calculated with PLAXIS 2D software (Figure 4). The most critical result from the shear force, bending moment, and displacement results is considered as the anti-slide pile capacity (C2).

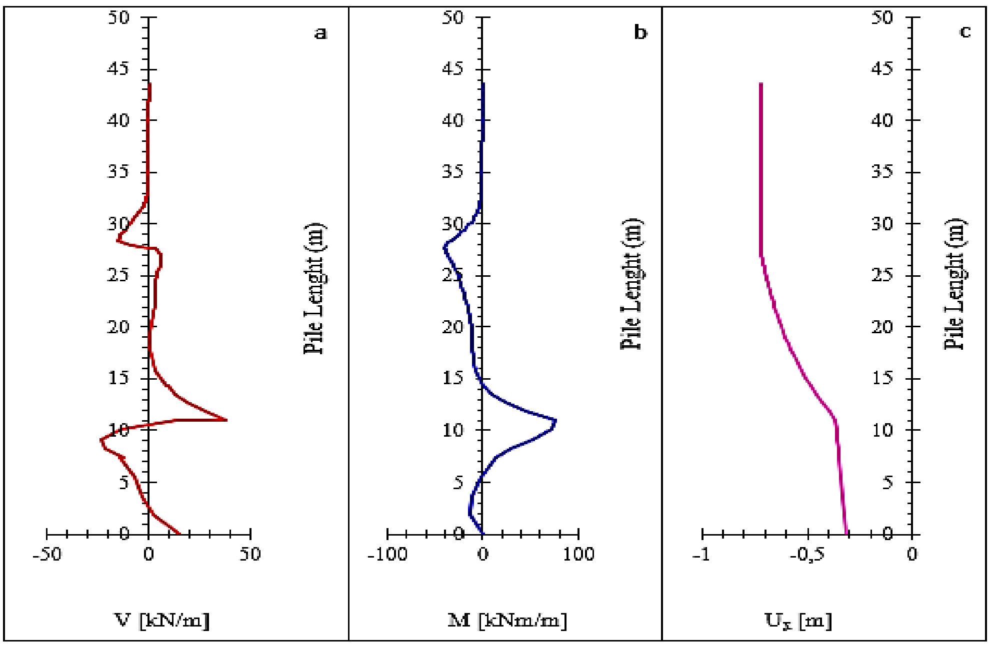


Figure 4. PLAXIS 2D (**a**) shear force, (**b**) bending moment, and (**c**) displacement graphics.

Sustainability (C3)

This criterion defines an integrated impact assessment that meets the preliminary objectives of life cycle assessment: (i) it determines the resource consumption and emissions of anti-slide piles from production to use through the life cycle database; and (ii) it measures the sustainability of anti-slide piles in terms of environmental, social, and resource use. The indicators used in the formulation of the sustainability criteria of anti-slide piles are defined as the sum of the resource use impact index ($I_{ResourceUse}$), socio-economic impact index ($I_{Socio\text{-}Economic}$), and environmental impact index ($I_{Environmental\ Impact}$). The resource use index ($I_{ResourceUse}$) is calculated by Equation (15). Exergy is defined as the maximum useful work that can be produced as the system is brought into equilibrium with its environment by an ideal process in thermodynamics. A_n and A_{total} denote the nth alternative and sum of all alternatives, respectively.

$$\text{Resources Usage} = (\text{Exergy} + \text{Embedded Energy})_{An}/(\text{Exergy} + \text{Embedded Energy})_{Atotal} \quad (15)$$

Input database analysis in life cycle evaluation [29–31] calculations was carried out in accordance with the life cycle database by using energy equations based on embedded energy and exergy. The outputs discussed in the study are emissions that affect air and water environments. The exergy per unit mass of a homogeneous system for a defined state is calculated by Equation (16):

$$b_{state1} = b_{state1,t} + b_{state1,c} + b_{state1,k} + b_{state1,p} + b_{state1,n} + \ldots \quad (16)$$

where, $b_{state1,t}$, $b_{state1,c}$, $b_{state1,k}$, $b_{state1,p}$, and $b_{state1,n}$ represent the thermodynamic, chemical, kinetic, potential, and nuclear exergy components of total exergy, respectively. For soil, steel, and cement, the total exergy [32–34] is obtained by multiplying the amount of material and unit exergy value (b_{soil} = 0.02, b_{cement} = 5.35, b_{steel} = 41.0) calculated in accordance with the ReCiPe [35] database.

Embedded energy values ($CERA_{soil}$ = 0.45, $CERA_{cement}$ = 4.60, $CERA_{steel}$ = 36.40), which constitute the resource use effect, were determined by cumulative energy [32–34] requirement analysis (CERA) in MJ/Kg using Equation (17) for soil, cement, and steel usage, respectively:

$$\text{CERA} = \text{CERAp} + \text{CERAu} + \text{CERAd} \quad (17)$$

where production (CERAp), (ii) operational phase (CERAu), and (iii) disposal (CERAd) [32–34].

Environmental impact subcategories were determined as acidification potential, global warming potential, and human health. The environmental impact index ($I_{Environmental\ Impact}$) was calculated as the sum of the indicator value of the acidification potential, global warming potential, and human health components, as specified in the ReCiPe database [35]. In the second phase of impact assessment, the relative contribution of each input and output was measured, and the contributions of all inputs and outputs were then aggregated within the various effect categories. The effect potential of certain substances, such as CO_2 and SO_2, was used to define the effects of inputs and outputs within impact categories [35]. The effect in each category was computed by first accumulating the emission amounts over the several impact categories and then multiplying the sums by the respective weights. The weights represent the relative relevance of the impact categories and define the percentage of an emission that is allocated to a certain category. The weights (indices) in the present research are based on the ReCiPe database [35], which uses the distance to objective approach. Impact assessment procedures comprise impact category structure, categorization, and characterization. The structure of an impact category outlines the environmental consequences that are considered important for the purpose of impact assessment. The details of the calculations are reported in a study by Tuskan [20].

Ease of Construction (C4)

This criterion describes the relative ease of construction of the anti-slide pile on site in terms of pile geometry ratio (normalized pile diameter/normalized pile length). The increase in pile diameter and pile length is inversely proportional to the ease of construction in the slope stability area.

Cost (C5)

This criterion defines all expenses related to the geotechnical support structure, including the cost of concrete, excavation (including disposal of all excavated material), and labor cost. The required machinery and manpower, such as drilling, assembly, loading, unloading, transportation, and the cost of the drilling machine, are all included, as well as the cost of ready-mixed concrete produced or purchased at the concrete plant and pumped at a pressure resistance class of C 25/30, and the wages of the skilled workers. All expenses are calculated based on the 2022 unit prices of the Ministry of Environment and Urbanization [36].

3.2. An Integrated AHP and VIKOR Method

3.2.1. The General Description of the Integrated Method

The selection of a reliable anti-slide pile alternative for slope stability is a complex decision-making process that involves evaluating multiple factors, such as planning horizons, irreversibility of options, product preferences, necessary slope safety, required pile bearing capacity, capital availability, and future growth due to sustainability. To address this complexity, this study examines anti-slide pile alternatives from various perspectives, including social, economic, quality, technical, and environmental considerations. To identify the most suitable anti-slide pile alternative for slope stability, an integrated method that combines AHP and VIKOR is proposed (Figure 5).

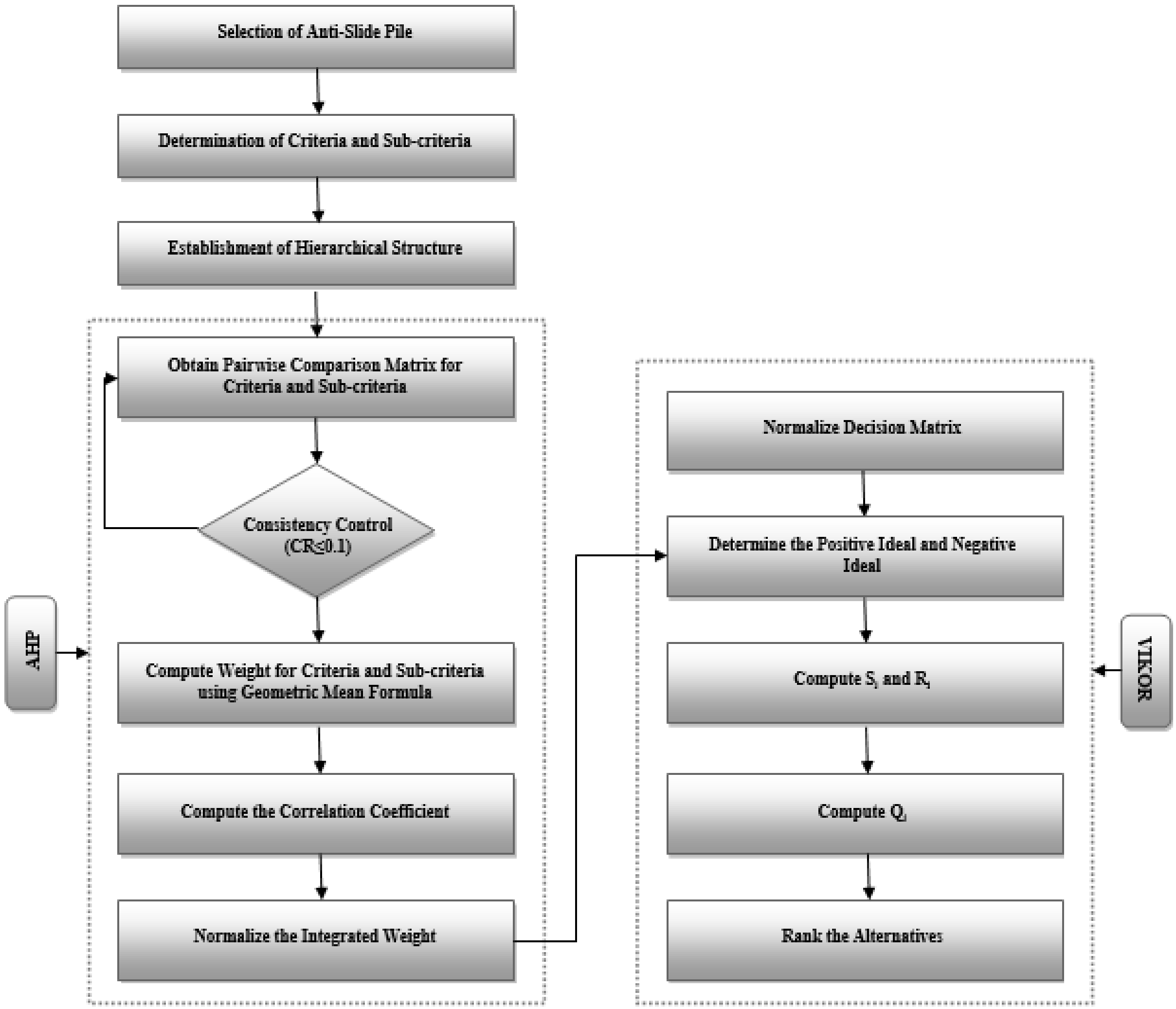


Figure 5. Structure of proposed methodology.

3.2.2. The Integrated Process for the Weights

The initial task in the decision-making process is to assign weights and arrange the decision matrix for each construct. This study follows a methodology that involves two procedures: the first procedure involves making weights using the Analytic Hierarchy Process (AHP). A questionnaire survey was conducted to provide forward-thinking judgments and speculations assigned to criteria, sub-criteria, and alternatives. Government, industry, and academic experts were invited to the questionnaire survey. The matrix coefficients used in the AHP analysis were created according to the questionnaire survey results. Government, industry, and academic experts were invited to provide insightful judgments and speculations assigned to the criteria, sub-criteria, and alternatives. A 1–9 scale is used in AHP for a pairwise comparison matrix between criteria and sub-criteria (Table 1). One way to calculate criteria weights in the AHP is to conduct a survey among relevant stakeholders, such as customers or employees, to elicit their preferences or judgments on the importance of the criteria. Responses from the questionnaire survey can be scored and analyzed to generate a pairwise comparison matrix, which captures the relative importance of the criteria in relation to each other. Once the pairwise comparison matrix is generated, the next step is to calculate the eigenvalues and eigenvectors of the matrix to determine the principal or characteristic vector, which represents the relative weights of the criteria. The questionnaire received responses from 32 experts with the following demographic characteristics (Table 3).

Table 3. Demographic characteristics of experts participating in questionnaire survey.

Age Range of Participants		
Average Age of Participants	Min Age of Participants	Max Age of Participants
43.3	35	54
Education Properties of Participants		
	Number	%
Bachelor's Degree	6	18.75
Master's Degree	17	53.13
Doctorate	9	28.12

Calculation parameters in the AHP and VIKOR methods are generally predicted and selected by an expert. These determined calculation parameters are also effective on the result, due to the nature of the method. Having an expert selecting the parameters can also alter the results according to the expert's preference and opinion. We aimed to remove the subjectivity of the AHP and VIKOR methods via a questionnaire. For this purpose, the questionnaire given in Appendix A was designed and implemented with the participation of a certain number of experts. To calculate the principal vector, one common method is to use the geometric mean formula, which involves taking the geometric mean of each row of the pairwise comparison matrix. The evaluation of the comparison between the i criteria and j criteria by the k experts is indicated by a_{ij}^{k}. In this case, the common decision of n experts is reduced to a single value represented by:

$$a_{ij}^{k} = \left[a_{ij}^{1} \times a_{ij}^{2} \times \ldots \times a_{ij}^{n}\right]^{\frac{1}{2}} \tag{18}$$

The geometric mean formula provides an accurate and robust way to calculate criteria weights as a powerful mathematical approach [37]. It allows decision makers to account for both the importance and the interdependence of the criteria, and to generate a set of weights that are consistent and rational [38]. In MCDM models, the weighting coefficients assigned to the criteria and sub-criteria have a significant effect on the comprehensive evaluation results and, therefore, they also have an effect on the decision-making process. As such, it is of utmost importance to establish a practical and effective weighting method. Due to the limited knowledge and incomplete information available, this paper adopts group evaluation techniques. Nonetheless, since different decision makers may assign varying weights, integrating group intelligence and obtaining final weights for the main criteria and sub-criteria poses a complex challenge.

3.3. Case Study

Landslides have occurred on different known dates (in 1996, December 2001, and December 2011) in the Kadifekale area. When the current situation in the landslide area is examined, the latest landslide, which is the subject of this case study and occurred on the north-facing slopes of Kadifekale in Izmir Province, covers an area of approximately 16.5 decares. The slope zoning map of the landslide area, extending by 201 m in the northwest-southeast direction and 117 m in the northeast-southwest direction, and the landslide impact area are shown in Figure 6.

Figure 6. Landslide impact area [20].

Slope failures may be caused by various triggering factors, such as surface loading, dynamic forces from artificial and natural sources, geological conditions, mechanical and physical properties of discontinuities, and groundwater condition. When slope instability affects a settlement, the situation becomes more complex and requires additional social measures for those living in the affected areas. As observed in the Kadifekale landslide region, which is within the active tectonic mechanism of the İzmir Fault, it requires considerable effort to persuade both the public and the authorized persons to settle in safer places. Slope stability and landslide prevention measures, which are considered in the decision support system, will ensure the safety of the site during earthquakes, which will create low surface accelerations in static conditions. However, it does not seem possible in engineering practice to provide slope safety under large-scale earthquake conditions, which both İzmir Fault and Tuzla Fault can produce, where the epicenter is close to the landslide area [20]. The existing residual failure surfaces and slopes and the proximity of active faults do not allow this. For this reason, it is highly recommended to expropriate the site and create a security zone. Due to its historical importance, it would be appropriate to preserve the Topaltı School building in the proposed area and preferably restore it as an education museum or a similar structure, opening it to public use by the relevant official authorities.

As stated in study [20], it was decided that measures needed to be taken in the examined case to ensure slope stability, which should consist of a reinforced concrete retaining wall with counterforts and embedded slope stability piles. At this stage, the damage mode of the reinforced concrete retaining wall with piles, which was constructed before the landslide occurred and performed its task to protect the route of 746th Street located at the northwest border of the landslide area, was investigated [20]. A total of 112 anti-slide pile alternatives (different pile spacing, pile diameter, and arrangement of pile) and five criteria concerning the economic, sustainable, social, safe, and technical dimensions of the problem (slope stability, anti-slide pile capacity, cost, sustainability, and ease of construction) were determined by the literature review and decision makers' experiences. To prevent such damage from occurring again, anti-slide piles were designed. Anti-slide pile properties in the case study were determined with the AHP and VIKOR methods. The anti-slide pile parameter range for the AHP and VIKOR methods is presented in Table 4.

Table 4. Anti-slide pile parameter range for AHP and VIKOR methods.

Anti-Slide Pile Parameters	Parameter Range
Pile Diameter (D, m)	1.0–1.2–1.5–2.0
Pile Spacing/Pile Diameter (s/D)	1.5–2.0–2.5–3.0
Pile Location Ratio (ξ)	0.1–0.2–0.3–0.4–0.5–0.6–0.7

The AHP-VIKOR design utilized in this study is structured with four levels [20]. At the highest level is the overarching goal, which is then broken down into criteria at level two and sub-criteria at level three. The fourth level is comprised of anti-slide piles, referred to as alternatives. The analysis process itself involves a two-step method, with the AHP and geometric mean weighting model applied to determine the weights for criteria and sub-criteria, and the VIKOR technique is utilized to select a suitable anti-slide pile. After determining the alternatives for selecting piles to be used in slope stabilization, selection criteria will be established by following solution-oriented steps within the framework of the problem's objective. In this study, evaluations of pile alternatives were conducted in terms of environmental sustainability, stability (slope stability and geotechnical support structure stability), ease of construction, and cost criteria.

3.3.1. The Weights of Criteria

A priority vector shows how important each component is relative to its parent level. Once the pairwise comparison is consistent, the proposed weighting model (Equation (18)) was applied to determine the final weights for the criteria, as explained in Section 2.1.1. To achieve this, we followed these steps: the matrix of correlation coefficient of main criteria is calculated as follows (Equation (19)),

$$\begin{pmatrix} 1 & 2 & 4 & 7 & 3 \\ & 1 & 4 & 7 & 2 \\ & & 1 & 3 & 2 \\ & & & 1 & 1/7 \\ & & & & 1 \end{pmatrix} \tag{19}$$

The model result shows that the stability aspect of slope is the most crucial criterion, with a weight of 0.404. This indicates that the experts attribute high importance to safety factors. Second, the capacity aspect of anti-slide pile is also significant, with a weight of 0.283, given the current state of safety factor against bending moment and shear capacity. The sustainability factor has a weight of 0.129; this value indicates that it should be considered as important as the cost criterion, which has a weight of 0.146. Finally, the ease of construction has the least weight among the main criteria. Figure 7 depicts the results for the criteria that align with the goal of the study. The Consistency Index (CI) was found to be 0.091 using Equation (2). The maximum eigenvalue (λ_{max}) was calculated as 5.37 for five criteria using Equation (3). The CR value was verified to be 0.082 using Equation (4) and Table 2.

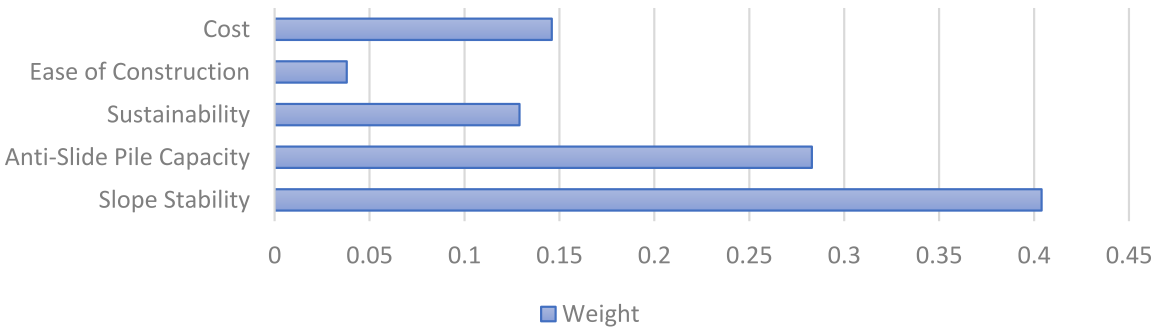


Figure 7. Main criteria weight.

3.3.2. The Weights of Sub-Criteria

After processing for the main criteria, the same process was applied for the sub-criteria. The normalized decision matrix obtained for the main and sub-criteria is given in Table 5. The sustainability criteria have three sub criteria, namely, the resource use impact index ($I_{ResourceUse}$), socio-economic impact index ($I_{Socio\text{-}Economic}$), and environmental impact index ($I_{EnvironmentalImpact}$), with an equal weight of 0.043. Similarly, the ease of construction criteria has two sub-criteria with an equal weight of 0.019.

Table 5. Normalized decision matrix.

	Criteria							
Alternative	**(C_1)**	**(C_2)**	**(C_{31})**	**(C_{32})**	**(C_{33})**	**(C_{41})**	**(C_{42})**	**(C_5)**
(A_1)	0.9090	0.6041	0.0313	0.2016	0.7351	0.1873	0.7356	0.1240
(A_2)	0.9090	0.6286	0.0308	0.1204	0.8364	0.1475	0.6543	0.0960
(A_3)	0.3367	0.0894	0.1994	0.2341	0.8352	0.1117	0.1342	0.1576

Table 5. *Cont.*

	Criteria							
Alternative	**(C_1)**	**(C_2)**	**(C_{31})**	**(C_{32})**	**(C_{33})**	**(C_{41})**	**(C_{42})**	**(C_5)**
(A_4)	0.3367	0.1156	0.0918	0.8361	0.4527	0.0874	0.2793	0.0828
⋮								
(A_{112})	0.8978	0.1917	0.0425	0.2471	0.9366	0.2868	0.3267	0.1328
Weight	0.404	0.283	0.043	0.043	0.043	0.019	0.019	0.146

3.3.3. The Composite Results for Alternatives

The VIKOR method is employed to determine the most suitable option. The values allocated to the main and sub-criteria are normalized using Equation (2) and the results of the normalized decision matrix are presented in Table 5.

In order to calculate the unity and regret measures, Equations (3) and (4) were utilized to normalize and identify the positive and negative ideal solutions as described in Section 2.1.2, and the values are determined as follows (Table 6).

Table 6. Unity measure and regret measure.

Ideal Solution	**(C_1)**	**(C_2)**	**(C_3)**	**(C_4)**	**(C_5)**
f^*	1.299	1.94	0.527	1.00	456,959
f^-	1.199	10.28	1.320	10.00	3,157,847

This process is then replicated for all attributes and alternatives, culminating in the presentation of the utility measure, S_j, and regret measure, R_j, and the Q_j values for each of the 121 alternatives were calculated [20] following the same procedure outlined in step five of Section 2.1.2. Table 7 illustrates S_j, R_j, and Q_j for the smallest value of Q_j for first five alternatives to consider the best solution and high Q_j rank.

Table 7. Alternative number, Sj, and Rj values for the least five values of Q_j.

Q_j	**Alternative**	**R_j**	**S_j**
0.0054	(A_{20})	0.0182	0.0581
0.0249	(A_4)	0.0220	0.0632
0.0258	(A_3)	0.0225	0.0709
0.0322	(A_{36})	0.0395	0.0676
0.0335	(A_{35})	0.0336	0.0753

4. Discussion

Based on the results, an anti-slide pile of arrangement s/D = 3.0, ξ = 0.20, and geometry of D = 1.00 m (A_{20}) with a low Qi value of 0.0054 received the highest ranking, followed by an anti-slide pile of arrangement s/D = 3.0, ξ = 0.10, and geometry D = 1.00 m (A_4) in second place. An anti-slide pile of arrangement s/D = 2.5, ξ = 0.10, and geometry of D = 1.00 m (A_3) with a decisive weight of 0.0258 ranked third. An anti-slide pile of arrangement s/D = 3.0, ξ = 0.30, and geometry of D = 1.00 m (A_{36}) ranked fourth, while an anti-slide pile of arrangement s/D = 2.5, ξ = 0.30, and geometry of D = 1.00 m (A_{35}) came in last with a final weight of 0.0335. Table 8 provides a figurative representation of the anti-slide piles, considering the Q_j values for each alternative [20].

Sensitivity Analysis

Sensitivity analysis is important in order to examine the relationship between inputs and outputs, to reveal the robustness of outputs, to measure uncertainty, and to determine the direction and range of the effect of parameter changes [39]. Sensitivity analysis demonstrates the effect of the weighting factors to assist decision makers (DM) in making more effective judgments [40]. It is believed intuitively that a change in the weight of the criterion that has the highest weight will have the greatest impact on the results. Sensitivity analysis was performed by changing the weight values of the main criteria according to the cases in Table 9, and how the ranking of alternatives was affected was examined.

Table 8. Figurative representation of the first five anti-slide pile alternatives for the smallest value of Q_j.

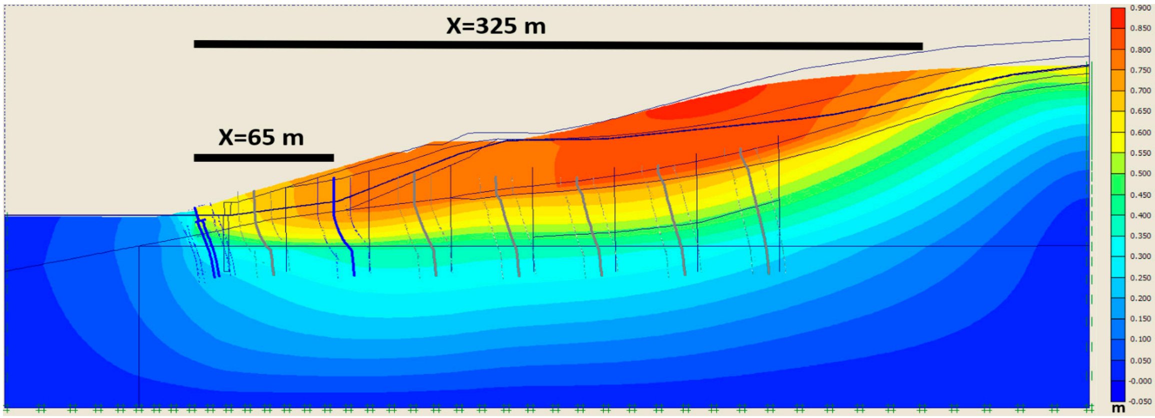
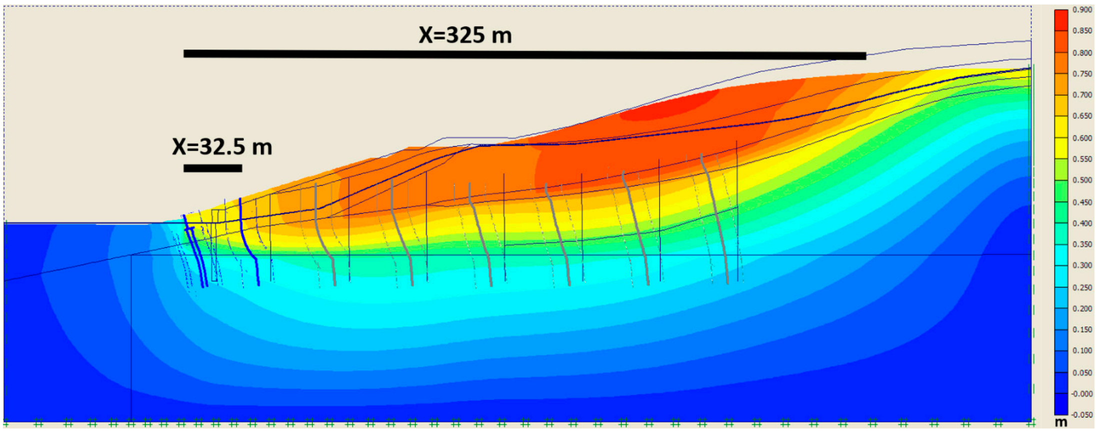
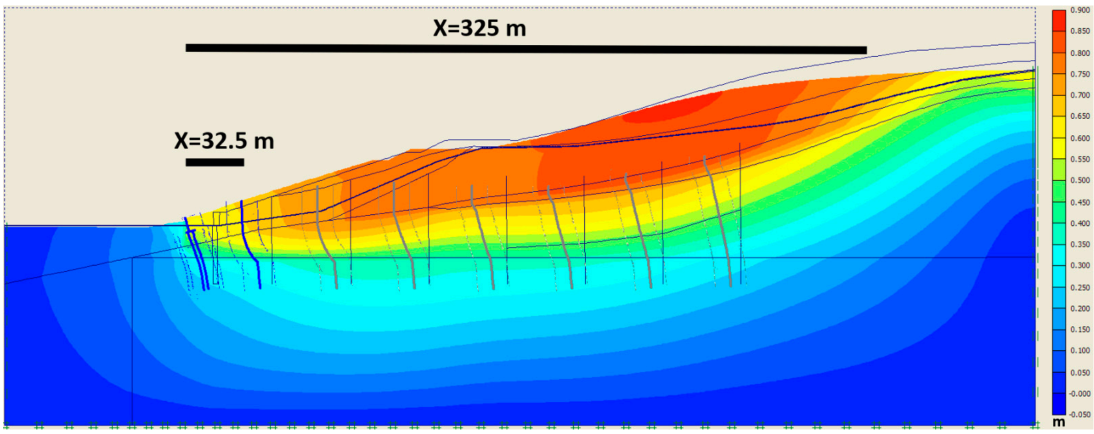
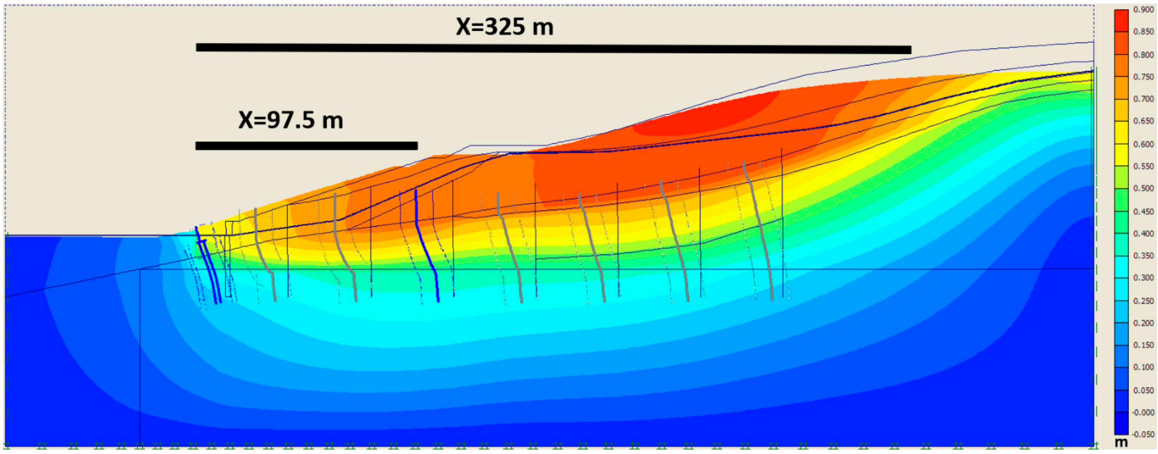
Anti-Slide Pile Alternatives	
(A_{20})	
	(A_{20}) Description: D: 1.00 m, s/D: 3.0, ξ = xi/X: 0.20 Criteria Value (C_1) = 1.277 (C_2) = 2.347 (C_3) = 0.591 (C_4) = 1.259 (C_5) = 492,287
(A_4)	
	(A_4) Description: D: 1.00 m, s/D: 3.0, ξ = xi/X: 0.10 Criteria Value (C_1) = 1.250 (C_2) = 2.647 (C_3) = 0.417 (C_4) = 1.000 (C_5) = 456,960
(A_3)	
	(A_3) Description: D: 1.00 m, s/D: 2.5, ξ = xi/X: 0.10 Criteria Value (C_1) = 1.253 (C_2) = 2.561 (C_3) = 0.424 (C_4) = 1.000 (C_5) = 541,321

Table 8. *Cont.*

Anti-Slide Pile Alternatives

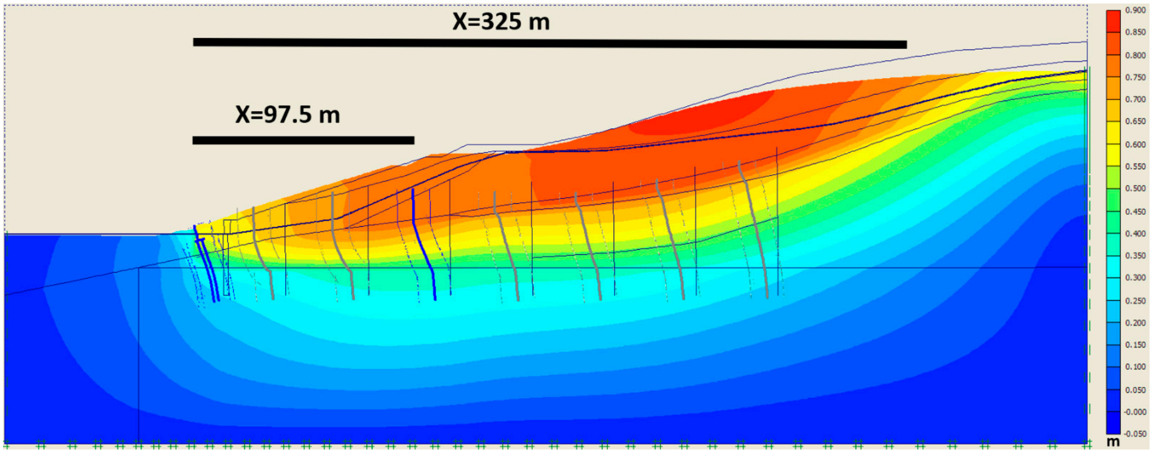
(A_{36})



(A_{36})
Description:
D: 1.00 m,
s/D: 3.0,
ξ = xi/X: 0.30

Criteria Value
(C_1) = 1.243
(C_2) = 2.247
(C_3) = 0.751
(C_4) = 1.349
(C_5) = 562,943

(A_{35})



(A_{35})
Description:
D: 1.00 m,
s/D: 2.5,
ξ = xi/X: 0.30

Criteria Value
(C_1) = 1.247
(C_2) = 2.161
(C_3) = 0.758
(C_4) = 1.349
(C_5) = 666,871

Table 9. Scenario matrix of sensitivity analysis.

	DMs Weights	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**
(C_1)	0.404	1	0	0	0	0	0.2	0.5
(C_2)	0.283	0	1	0	0	0	0.2	0.5
(C_3)	0.129	0	0	1	0	0	0.2	0
(C_4)	0.038	0	0	0	1	0	0.2	0
(C_5)	0.146	0	0	0	0	1	0.2	0

A weight value of one was assigned to only one main criterion for Scenarios 1–5. In Scenario 6, weights were distributed equally among the five criteria in the ranking and the VIKOR method was applied. In Scenario 7, the stability of slope inclination and geotechnical bearing capacity, which were identified as the two most important criteria by expert survey results, were assigned equal weight values of 0.5. The sensitivity analysis of the alternatives according to seven different scenarios was calculated and presented in Figure 8 through the Q_j-value results considering scenarios (Table 9).

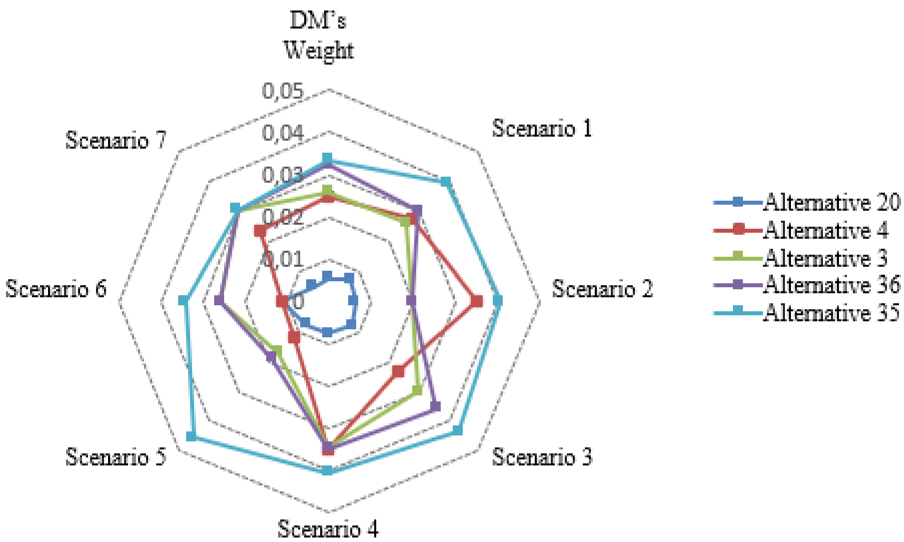


Figure 8. Q_j rank sensitivity radar chart.

Based on the VIKOR sensitivity diagram, and considering the weights assigned to all criteria for each scenario, Alternative 20 was identified as the most preferable alternative. Although Alternative 4 switched places with Alternative 3 in Scenario 2, it was still ranked as the second-best alternative following the most suitable alternative. When different scenarios were considered, Alternatives 35 and 36 had varying ranks. When ranked by Q_j-values, if the top two alternatives (Alternatives 4 and 20) were not selected, one of the three alternatives (Alternatives 3, 35, and 36) could still be a suitable choice based on their geotechnical bearing capacity. To select the optimal geotechnical bearing capacity for slope stability, the top five ranking alternatives were identified based on the 112 anti-slide pile alternatives, considering their arrangement and geometry. Alternative 35 was among the top five alternatives despite having the highest Q_j-value for Scenario 5. Many studies in the literature have based the AHP and VIKOR methodology on a single expert opinion [4,6,7,12,13]. In this study, criteria features and weights were determined via the consensus of more than one expert. A questionnaire study was conducted to distance the results of the AHP and VIKOR methods from subjectivity.

5. Conclusions

This study proposes a specific sustainability-oriented methodology for selecting an anti-slide pile in a slope stability problem using an integrated MCDM framework. This procedure involves using an AHP-VIKOR-based optimization technique that integrates five main criteria and five sub-criteria. The slope stability criterion holds the most significant weight (0.404), followed by the anti-slide pile capacity criterion (0.283). The sustainability factor has a weight of 0.129, indicating that it is considered as important as the cost criteria with a weight of 0.146. Finally, the ease of construction has the least weight among the main criteria. It was identified that resource use is a crucial sub-criterion from the embedded energy and exergy perspective, while the environmental impact and socio-economic impact are equally significant from the acidification potential, global warming potential, human health aspect, and construction noise components. It has been observed in this study that pile alternatives have the lowest Q values in the ξ = 0.1–0.3 and s/D = 2.0–3.0 range when sustainability criteria are included, compared to situations where only economic and technical criteria are met. A pile diameter of D = 1.00 m was found to be the most sustainable value within the selected pile spacing intervals, meeting the criteria of slope safety, pile capacity, cost, and ease of construction.

The integrated AHP-VIKOR methodology's computational requirements for large-scale landslide projects may impede its practical application in real-world scenarios, thereby limiting its usefulness in the design of anti-slide piles. The lack of comprehensive large-scale validation studies presents a further limitation of the integrated AHP-VIKOR methodology in the design of anti-slide piles, as the effectiveness and reliability of the methodology have been extensively verified for small-scale collapses. The integrated AHP-VIKOR methodology may not adequately address the uncertainties and variations associated with slope stability conditions, leading to potential challenges in achieving optimal design outcomes for anti-slide piles. Additionally, criteria weights, which can be used for similar anti-slide pile problems in the future, are suggested from the questionnaire survey results. These findings can support recommendations to future studies about the difficulties in applying integrated AHP-VIKOR to choose the suitable criteria for mitigating large-scale landslides.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Designed and implemented questionnaire with the participation of a certain number of experts.

Criteria A	Extremely more important	Intermediates value	Very strongly important **DÜZEYDE**	Intermediates value	Strongly more important	Intermediates value	Weakly important	Intermediates value	Equally important	Intermediates value	Weakly important	Intermediates value	Strongly more important	Intermediates value	Very strongly important **DÜZEYDE**	Intermediates value	Extremely more important	Criteria B
pairwise comparison questionnaire with AHP scale of relative importance [20]																		
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
(C1)																		**(C2)**
(C1)																		**(C3)**
(C1)																		**(C4)**
(C1)																		**(C5)**
(C2)																		**(C3)**
(C2)																		**(C4)**
(C2)																		**(C5)**
(C3)																		**(C4)**
(C3)																		**(C5)**

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