Journal of Integrated and Advanced Engineering (JIAE)
Vol. 4, No. 1, March 2024: 51-64
http://asasijournal.id/index.php/jiae
http://doi.org/10.51662/jiae.v4i1.127

Assessment of factors causing landslides using the Analytical Hierarchy Process (AHP) method

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Abstract
Landslides are Indonesia's second most common disaster in the last ten years. Landslides cause losses, reaching hundreds of billions and threatening human safety. For this reason, it is necessary to take action to reduce the negative impact of landslides. Physical and non-physical mitigation can occur before, during, and after a disaster. The most essential thing in disaster mitigation is knowing the major factors that cause landslides. This research aims to analyze the major and minor factors that cause landslides using the Analytical Hierarchy Process (AHP) and the Likert scale. Respondents in this research are experts in disasters, especially landslides—respondents from universities in Indonesia, practitioners, and people involved in disaster mitigation. Validity and reliability tests were carried out on each question used in the questionnaire. The research results show that the landslide disaster was caused by a disruption in balance that occurred due to internal and external disturbance factors. The major external factors that cause slope failures are the cutting of hills and changes in land use to built-up areas. In contrast, the major internal factors that trigger landslides are heavy rainfall and steep topographic conditions. The results of this research in the form of weight and scoring values for each factor causing landslides can be used as a reference for mapping landslide areas to identify areas with the potential for landslides.

Keywords:
AHP;
Expert;
Landslide;
Major factors;
Minor factors

Article History:
Received: November 29, 2023
Revised: February 14, 2024
Accepted: February 24, 2024
Published: March 3, 2024

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INTRODUCTION

A landslide is a movement down or off a slope by a mass of soil or rocks that make up the slope or a mixture of the two as debris due to disruption of the soil or rocks' stability [1]. Another definition of a landslide or ground movement is the movement of a mass of soil or rock, which causes displacement from its original position in a vertical, horizontal, or inclined direction [2, 3, 4]. Its occurs because the stability of the soil or rocks that make up the slope has been disturbed. Landslides are the second largest disaster, with 846 out of 2853 incidents after floods observed in the last ten years. There are around 733 locations in Indonesia that have the potential for landslides. Of the 733 areas, there are three provinces where landslides occur most frequently, namely, Central Java, West Java, and East Java, because most of these locations are mountainous and hilly [5][6]. Figure 1 shows the potential for landslides in Indonesia [7]. Landslide disasters cause losses reaching hundreds of billions and threaten human safety. For this reason, it is necessary to take action that can reduce losses arising from landslides. One method that can be used is to look for the major factors of landslides. The causes of landslides can vary greatly, including geological, hydrological, climatic, topographic, and anthropogenic factors [8, 9, 10].

Mapping areas with the potential for landslides is a form of mitigation before a disaster occurs. With a landslide hazard vulnerability map, it is hoped that people will be more alert to reduce negative impacts. To determine the weight and scoring value of each factor that causes landslides, an assessment is carried out, one of which is using the Analytical Hierarchy Process (AHP).

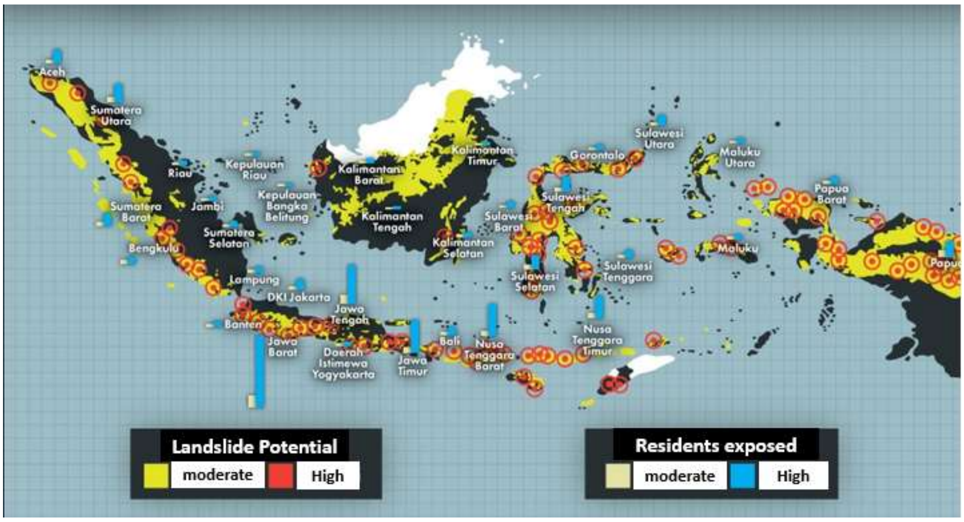


Figure 1. Indonesia's Disaster Landslide of Risk [7]

The AHP method is a decision analysis tool applied in various contexts, from business management to environmental science. AHP is a powerful method for measuring and grouping factors influencing a decision or complex phenomenon. The application of AHP in the context of research into landslide causal factors can contribute to a better understanding of the relative importance of these various factors. The analytic hierarchy process (AHP) method is used to determine the dominant factors in landslides. The AHP method was developed by Thomas L. Saaty and is used to make decisions using a hierarchical structure whose primary input is human perception [11]. The AHP method allows measuring factors causing landslides using a multicriteria approach, allowing researchers to consider many different factors simultaneously [12, 13, 14]. More knowledge extraction allows for ranking causal factors, and AHP can help identify the most significant factors in a particular area or condition [15][16]. The results of the AHP analysis can be used to assist decision-making in developing more effective landslide prevention and mitigation strategies. This research will adopt the AHP method to evaluate and prioritize factors causing landslides in certain areas [17][18]. AHP is a qualitative method used to determine the weight and scoring values of landslide-causing factors by involving people who are experts in their fields. This method provides a descriptive solution for landslide susceptibility mapping, and the assessment is subjective depending on the expert. It is the simplest technique because no historical data is needed regarding landslides. Meanwhile, the quantitative approach considers the mathematical relationship between the occurrence of landslides and the causal factors, and this method relies on the spatial distribution of landslides and their relationship with the causal factors [19, 20, 21].

METHOD

This research consists of several stages, namely:

1. Literature Study aims to collect data from written sources, books, archives, articles, magazines, and documents related to general factors causing landslides and the AHP method.
2. Creation and distribution of questionnaires
   The questionnaire was created using the AHP method, which was guided by literature studies that had been carried out previously. Questionnaires were distributed using Google

Forms and direct interviews with respondents. Questionnaires were distributed to experts with experience in landslides and came from universities in Indonesia.

3. Data processing

The data that has been obtained will then be processed using the AHP method and Likert scale using Mircosoft Excel. Primary data was obtained by distributing questionnaires to people with experience (experts) in landslide disaster problems. Respondents in the research were 20 experts from universities in Indonesia, practitioners, and landslide disaster mitigation experts.

3.a. Comparative analysis with AHP (Figure 2)

The use of the AHP method aims to provide an assessment of each factor that causes landslides by comparing each available alternative. Using this method will produce a weight value for each alternative. The following steps are taken to obtain a weight value for each alternative.

3. b. Establishment of Hierarchy

The formation of the hierarchy corresponds to the following levels:

Level 1: The target of the decision is placed at the top of the hierarchy. The target of this decision is the most dominant factor causing landslides. Level 2: At this level, we will be given what factors cause landslides. Level 3: Level three is a classification or sub-chapter of the second level.

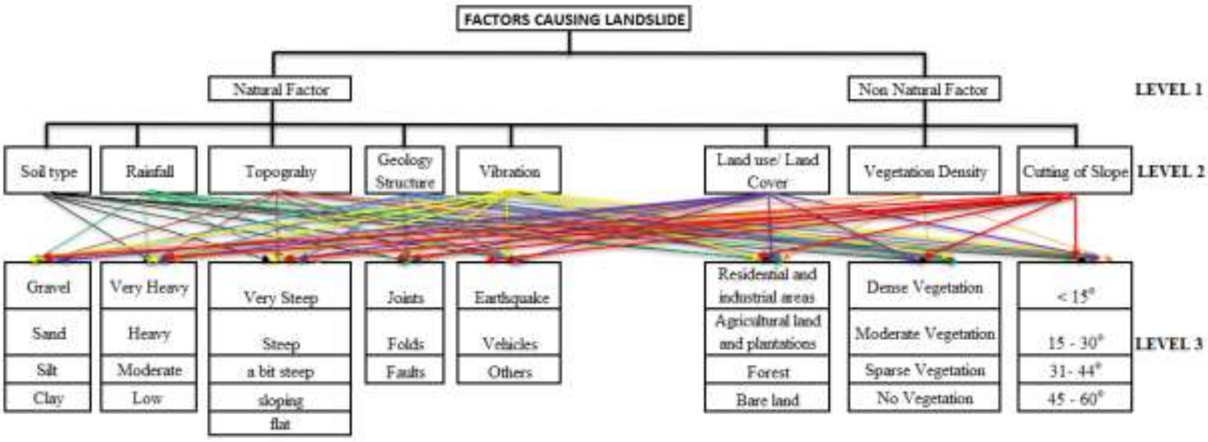


Figure 2. Landslide Disaster Factor Assessment Structure

Assessment Using Analytical Hierarchy Process (AHP)

In the AHP structure, each element is assessed, the assessment of each criterion follows the formulated AHP rules, and the level of importance of each alternative is determined based on expert assessment (survey). The assessment scale uses a scale from 1-9, where each scale has its meaning. Figure 3 shows the assessment flow chart using AHP.

Assessment Matrix

A pairwise comparison of all elements of the factors that cause landslides intends to produce a scale of the relative importance of each element; the results obtained are in the form of a rating scale in the form of numbers. When combined, pairwise comparisons in matrix form will produce a priority scale for the major factors causing landslides. Table 1 shows pairwise comparisons of each element causing landslide factors.

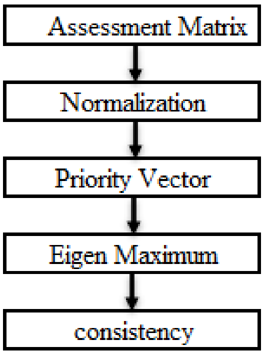


Figure 3. The Assessment Process Uses the AHP Method

Table 1. Comparison Matrix for Assessment of Landslide Causing Factors

Pairwise	**Rainfall**	**Soil type**	**Topography**	**Geology**	**Vibration**	**Cutting of Slope**	**Vegetation Density**	**Land use/ Land Cover**
Rainfall	a11	a12	a13	a14	a15	a16	a17	a18
Soil Type	a21	a22	a23	a24	a25	a26	a27	a28
Topography	a31	a32	a33	a34	a35	a36	a37	a38
Geology	a41	a42	a43	a44	a45	a46	a47	a648
Vibration	a51	a52	a53	a54	a55	a56	a57	a58
Cutting of Slope	a61	a62	a63	a64	a65	a66	a67	a68
Vegetation Density	a71	a72	a73	a74	a75	a76	a77	a78
Land Use/ Land Cover	a81	a82	a83	a84	a85	a86	a87	a88

Process Normalization

Normalization is carried out by dividing the value of each element in the matrix by the total value of each column. The following is the data normalization process.

$$\begin{pmatrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{pmatrix} \Rightarrow \begin{pmatrix} \frac{a11}{H} & \frac{a12}{I} & \frac{a13}{J} \\ \frac{a21}{H} & \frac{a22}{I} & \frac{a23}{J} \\ \frac{a31}{H} & \frac{a32}{I} & \frac{a33}{J} \end{pmatrix} \quad (1)$$

with:

H = a11 + a21 +a31
I = a12 + a22 +a32
J = a13 + a23 +a33

Priority Vector Calculation

Obtaining priority values requires a comparison of the total rows in the matrix, where the total rows are obtained from the sum of the total row values of the calculated matrix, which have been compared with the total matrix values in each column. Table 2 listed the Priority Vector used in this research.

Table 2. Priority Vector

Alternative	A	B	C	Total	Priority Vector
A	a11/ H	a12/I	a13/J	D	D/3
B	a21/H	a22/I	a23/J	E	E/3
C	a31/H	a32/I	a33/J	F	F/3
Total	1	1	1	3	1

Table 3. Maximum Eigen

Alternative	Matrix Product (MP)	Priority Vector (PV)	MP/ PV
A	K	D/3	(K) : D/3
B	L	E/3	(L) : E/3
C	M	F/3	(M) : F/3
Maximum Eigen (λmax)			Q

Calculate Maximum Eigen

To determine priorities and eigenvalues, use matrices and vectors. The priority value will be obtained by comparing the total rows in the matrix. To get the priority value, a comparison of the total rows in the matrix is required. The total number of multiplications of the priority values in the matrix compared to the priority values will produce the eigenvalues. The maximum Eigen is listed in Table 3.

$$\begin{pmatrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{pmatrix} x \begin{pmatrix} \frac{D}{3} \\ \frac{E}{3} \\ \frac{F}{3} \end{pmatrix} = \begin{pmatrix} K \\ L \\ M \end{pmatrix} \quad (2)$$

The formula was used:

$$\lambda_{max} = \frac{(K:\frac{D}{3}) + (L:\frac{E}{3}) + (M:\frac{F}{3})}{3} \quad (3)$$

Hierarchical Consistency

In contrast to other methods, the AHP method has absolute consistency requirements. The maximum eigenvalue determines this consistency. The following is the formula used to test consistency:

$$CI = (\lambda\ max - n)/(n-1) \quad (4)$$

Where:

CI : consistency deviation ratio.
λ max : largest eigenvalue of a matrix of order n
n : matrix order

The matrix is consistent if the CI value equals 0 (pairwise comparison). According to the formula, the inconsistency limit has been determined by saaty using the consistency ratio (CR), obtained by comparing the consistency index with the random index (RI) value.

$$CR= CI/CR \quad (5)$$

Where:

CR : Consistency Ratio
RI : Random index

The RI value is obtained from the Table 4.

Table 4. Random index value [16]

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.48

The paired matrix has a CR greater than 0.100, so the expert makes inconsistent decisions so that judgment cannot be used.

Geomean

Geomean or average equation is a consistent unification of opinions or assessments on questionnaires. To get the geomean value, all consistent data is multiplied and then taken to the square root by the amount of consistent data. With Formula:

$$GM = \sqrt[n]{(X1)\,(X2)\,\ldots\ldots\,(Xn)} \tag{6}$$

Where:

GM : Geometric Mean
X1 : 1^{st} Expert
X2 : 2^{nd} Expert
Xn : n^{th} expert

A hierarchical consistency test is still carried out for each respondent using the same formula. If the pairwise comparison matrix has a CR value of less than 0.1, the expert assessments that have been combined are consistent.

Assessment Using a Likert Scale

The Likert scale is an assessment using a widely used scale in questionnaires, developed by Likert in 1932. When responding to questions on this Likert scale, experts will be given several scales: the level of expert agreement with the questions asked. Assessment using Likert is used as an additional assessment of the classification of each factor causing landslides. When filling out the questionnaire, experts can choose a scale that is the level of expert agreement with the questions asked. The scale used is:

Very Not Dominant: 1
Not Dominant: 2
Dominant (D): 3
Very Dominant (SD): 4

RESULTS AND DISCUSSION

The research results are in the form of weight values and scores for each factor that causes landslides. The weight and scoring values will be used to map areas with potential landslides. Pairwise comparisons were carried out, then a hierarchical structure was arranged based on the factors causing landslides with guidance from previous studies, news, and annual data on landslides.

The results of this research are the results of a hierarchical structure that has been created into three levels. The comparison starts at the second level, which is the classification of the factors that cause landslides, and the third level is the division of each factor at the second level, which will be compared between the indicators.

Assessment of Factors Causing Landslide at Level 1

The results of the analysis show that, in general, landslide disasters occur due to a combination of natural and non-natural factors. Human activities will trigger landslides, which are naturally susceptible to landslides. At level one, natural and non-natural factors weigh the same as landslide triggers.

Assessment of Factor Causing Landslide at Level 2

At level two, eight factors cause landslides: rainfall, soil type, topography, geology, vibrations, hill cutting, vegetation density, and land use. By using pairwise comparisons and data processing using AHP, the weight values of the eight factors that cause landslides are obtained. Figure 4 shows the weight values at level two.

The assessment results show that the most dominant factor is hill cutting, with a weight of 0.193; the second highest weight is topography at 0.138; The third highest weight is the vegetation density factor of 0.136; and the lowest weight is vibration, with a weight of 0.081.

Hill cutting is one of the external disturbance factors that triggers the potential for landslides. Slope cutting that does not respect environmental rules and development that does not pay attention to soil stability are also triggers, such as changing the geometry of cliff contours or slopes that were initially gentle to steep; hill cutting also causes slope instability. It is caused by humans, such as mining, tunneling, and widening houses on the slope's edge [22]. Cutting the slope will disrupt the slope's stability, increasing the slope angle and thereby losing the holding force [23].

Assessment of Faktor Causing Landslide at Level 3

The assessment at Level Three is calculated for each type of classification of landslide factors. The assessment was carried out using the Likert scale method.

Rainfall

Rainfall with very high and prolonged intensity can trigger landslides due to increased water infiltration, which causes the soil to become saturated with water so that pores. Soil is easily destroyed, and soil aggregation becomes very weak so that the shear resistance of the soil decreases.

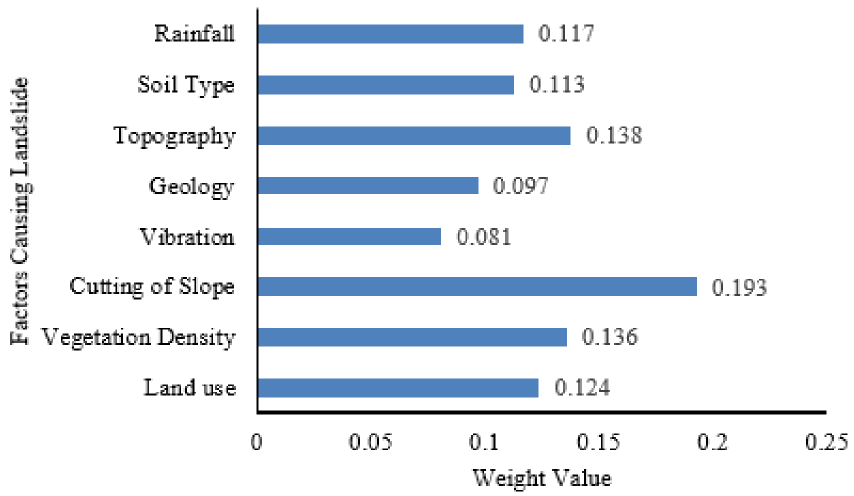


Figure 4. The Weight Value of Factors Causing Landslides with AHP Method

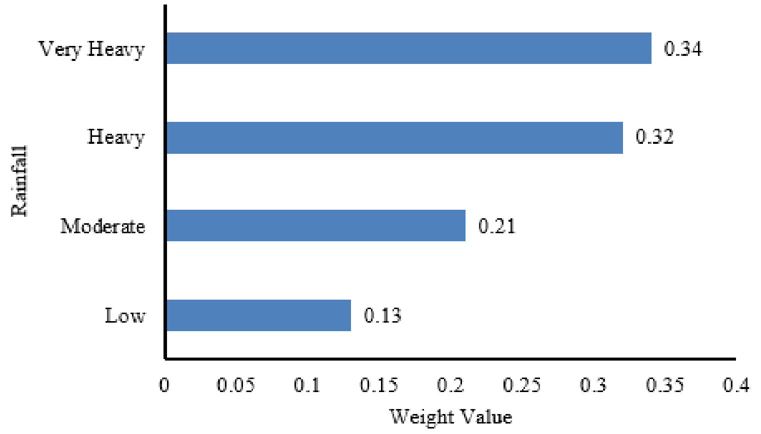
Saturated soil will also cause additional soil load, triggering landslides from higher places to higher places. The research results show that very high rainfall (weight = 0.34) is the major factor causing landslides, as shown in Figure 5.

Soil Type

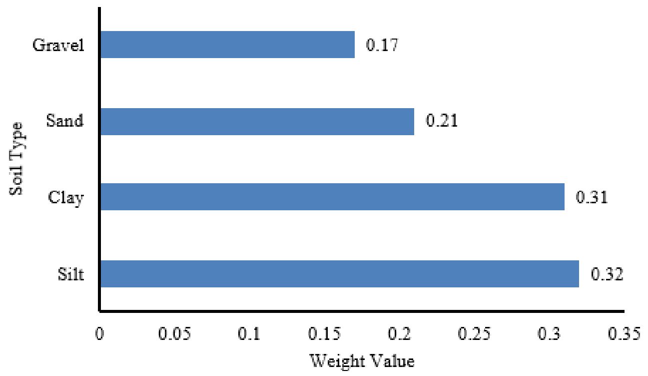
The result analysis shows that silt and clay soil types are soil types that are prone to landslides; this is because clay and silt soils have low shear strength (τ) and are very susceptible to water. High rainfall causes the water pressure (u) on clay and silt soil to increase while the effective stress (σ') becomes low; if the effective stress becomes zero (σ' = 0), the soil cannot support its overburden, so landslides occur.

Topography

The assessment results show that the steeper the topography, the greater the landslide potential, as depicted in Figure 6. The weight value for very steep topography gives a value of 0.29, and flat topography has a value of 0.11. Hilly and steep areas have a high risk of landslides. Steep and hilly areas will cause the driving force on the upper slope to be greater than the resisting force. On steep slopes, the soil volume is effortless to move or slide down, so landslides will occur.



(a)



(b)

Figure 5. (a) The Weight Value of Causing Landslide by Rainfall
(b) The Weight Value of Causing Landslide by Soil Type

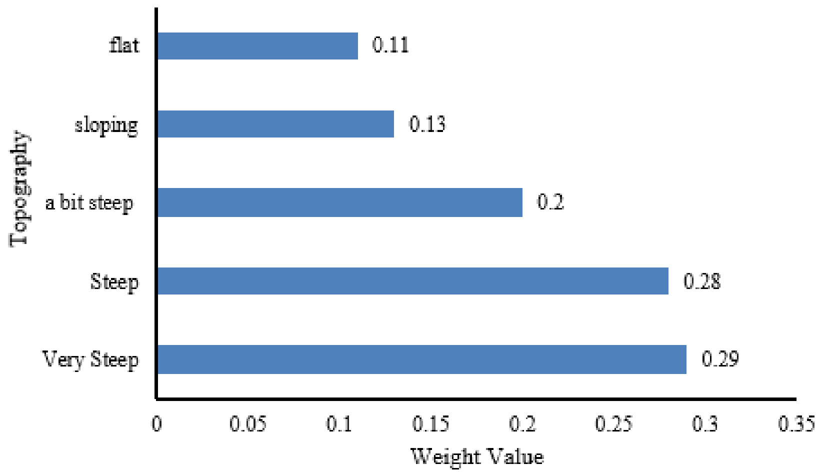


Figure 6. The Weight Value of Causing Landslide by Topography

Geology

The geological factor assessment shows that the highest weight is fault geology, with a weight of 0.41, and the lowest is joint geology at 0.11 as represented in Figure 7. The landslide disaster in Banjarnegara and Kebumen was caused by the geological structure in the form of faults in the area, which greatly influenced the landslides [24].

Vibration

Vibration is a dynamic factor that causes landslides. Vibrations can cause the balance of the soil to be disturbed so that the soil becomes unstable. Vibrations can come from earthquakes, vehicles, and others. The assessment results of the factors that cause slope failures show that earthquakes are the major factor that causes landslides with a weight value of 0.61, as shown in Figure 8. Earthquakes are one of the causes of landslides that often occur. Earthquakes cause vibrations, pressure on mineral particles, and weak areas in rock and soil masses. Landslides and earthquake disasters result from subduction activity, which causes landslides on cliffs or mountains [25].

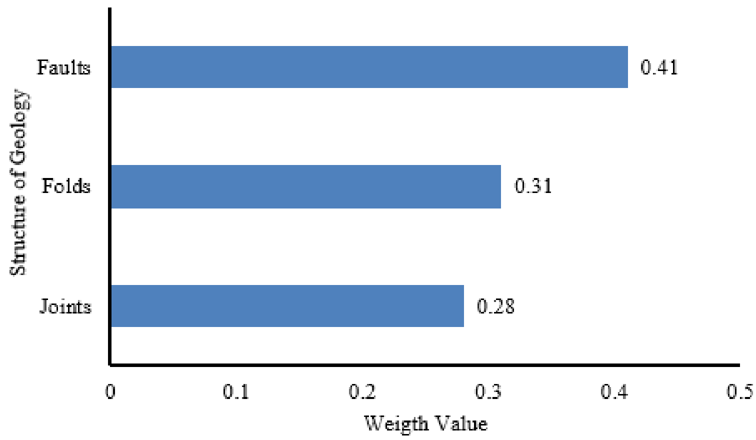
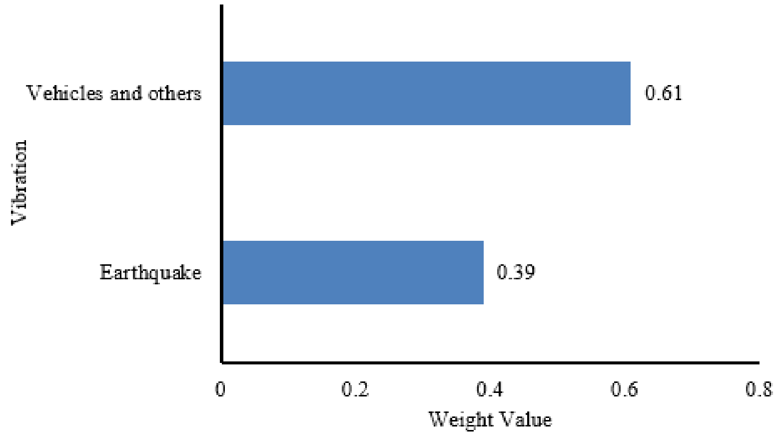
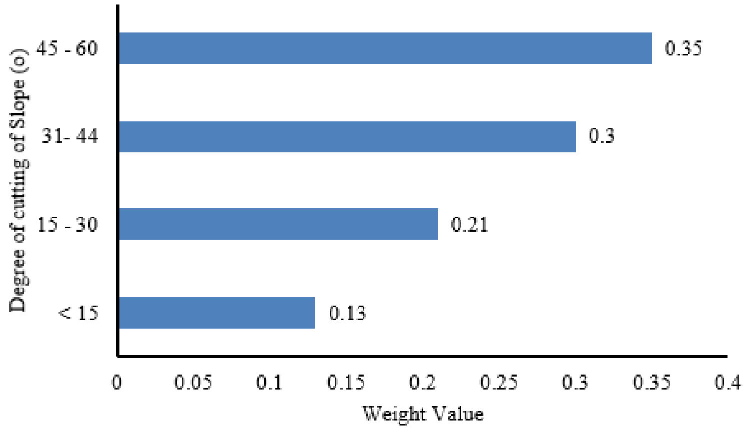


Figure 7. The Weight Value of Causing Landslide by Geology



(a)



(b)

Figure 8. (a) The Weight Value of Causing Landslide by Vibration
(b) The Weight Value of Causing Landslide by Cutting of Slope

Cutting of Slope

Cutting the slope will disrupt the balance of the slopes and trigger landslides because the opening of the surface layer of the soil and the increasingly vertical degree of cutting of the slopes cause the driving force to become more significant. In contrast, the holding force becomes lower. The results of the expert assessment show that the steeper the slope, the higher the potential for landslides as shown in Figure 8, because cliffs will increase the driving force.

Vegetation Density

Figure 9 shows that dense vegetation (weight value is 0.14) has a small potential weight value for landslides compared to non-vegetation areas (weight value is 0.37) because non-vegetation areas have large surface flow coefficient values, which trigger soil erosion and cause landslides. Dense vegetation consisting of trees can hold and control rainwater that enters the soil. However, when the trees disappear, the area becomes open land, and the plants cannot control the rainwater that enters the soil.

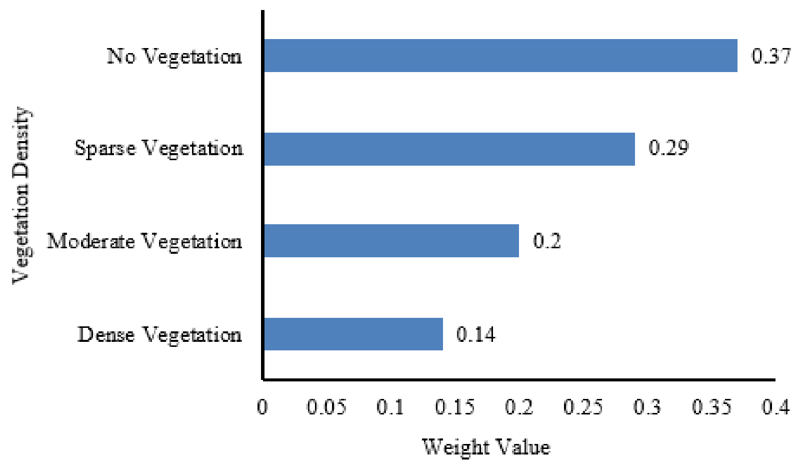


Figure 9. The Weight Value of Causing Landslide by Vegetation Density

Land Use / Land Cover

Changes in land use will disrupt the hydrological conditions of slopes; the carrying capacity of an environment dramatically influences the occurrence of landslides. If there is more bare land and a lack of trees, this will increase the risk of landslides. The research results show that bare land will have a high potential for landslides compared to forest or agricultural areas because of the high runoff coefficient on bare land and residential areas, which triggers soil surface erosion because there is no vegetation to hold water, causing landslides. The situation is depicted in Figure 10.

Table 5 shows the overall results of factors causing landslides using the AHP method. Figure 11 shows a landslide incident in the Gunung Sarik area, Padang. Observation results show that the landslide was caused by cutting slope activities for mining, exposing the top layer (no vegetation), and heavy rainfall with prolonged intensity. The balance of the soil is disturbed due to increased pore water pressure (u) while the effective stress (σ’) decreases so that it cannot withstand the load. Weathered soil on an impermeable rock on moderate to steep slopes has the potential for landslides during the rainy season due to high rainfall. If a hilly area does not have solid and deep-rooted plants, then the area is prone to landslides.

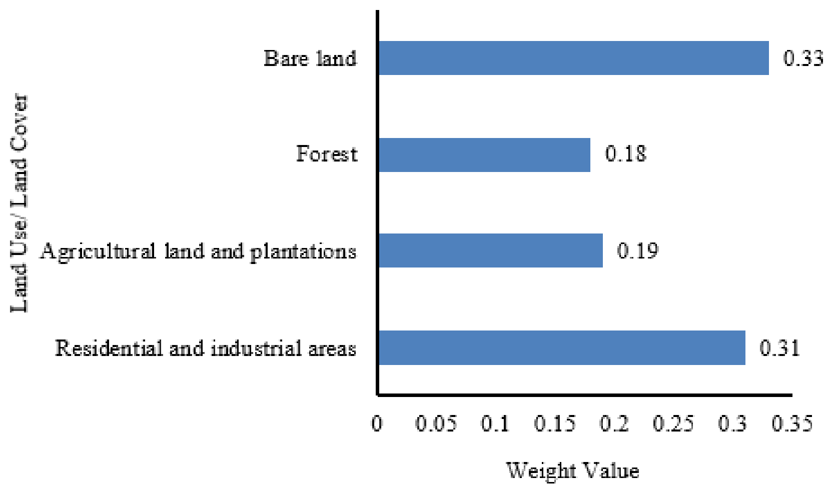


Figure 10. The Weight Value of Causing Landslide by Land Use/ Land Cover

Table 5. Assessment of All Levels of The Hierarchical Structure

No.	Factors	Weight 1	Weight 2	Total Weight
1	**Rainfall**	**0.117**		
	Very heavy		0.34	3.98
	Heavy		0.32	3.74
	Moderate		0.21	2.46
	Low		0.13	1.52
		Total	**1.00**	**11.70**
2	**Soil Type**	**0.113**		
	Gravel		0.17	1.939
	Sand		0.20	2.314
	Clay		0.31	3.440
	Silt		0.32	3.565
		Total	**1.00**	**11.30**
3	**Topography**	**0.138**		
	Very Steep (>45 %)		0.29	4.00
	Steep (25 – 45 %)		0.28	3.86
	A bit Steep (15-25 %)		0.20	2.76
	Sloping (8-15 %)		0.13	1.80
	Flat (0 – 8 %)		0.10	1.38
		Total	**1.00**	**13.80**
4	**Geology**	**0.097**		
	Joins		0.28	2.72
	Faults		0.41	3.98
	Folds		0.31	3.00
		Total	**1.00**	**9.70**
5	**Vibration**	**0.081**		
	Earthquake		0.61	4.94
	Vehicle and others		0.39	3.16
		Total	**1.00**	**8.10**
6	**Cutting of Slope**	**0.193**		
	$45^o – 60^o$		0.35	6.76
	$31^o – 44^o$		0.30	5.79
	$15^o – 30^o$		0.20	3.85
	$< 15^o$		0.15	2.90
		Total	**1.00**	**19.30**
7	**Vegetation Density**	**0.136**		
	Non-Vegetation		0.37	5.03
	Sparse Vegetation		0.29	3.95
	Moderate Vegetation		0.20	2.72
	Dense Vegetation		0.14	1.90
		Total	**1.00**	**0.136**
8	**Land Use/ Land Cover**	**0.124**		
	Bare land		0.33	4.10
	Forest		0.18	2.23
	Agriculture and Plantations		0.19	2.36
	Residential and Industry areas		0.31	3.85
		Total	**1.00**	**0.124**

Figure 11. Landslide incident on Gunung Sarik, Kuranji - Padang (November 15, 2021) [26]

CONCLUSION

Based on the Analysis Hierarchy Process (AHP) of the factors causing landslides, it can be identified that some factors contribute more significantly than others to landslide events. The analytical hierarchy process (AHP) produces weight values and scoring factors that cause landslides; from the assessment results, it is found that natural and non-natural factors have the same weight value as triggers for landslides. Slope cutting (weight value = 0.193), very steep topography (weight value = 0.138), changes in land use (weight value = 0.124), and very high rainfall (weight value = 0.114) are the major factors causing landslides. By knowing the weight and scoring value of each factor that causes landslides, mapping of potential landslide-prone areas in an area can be carried out so that areas with the potential for landslides can be identified. Mitigation can be applied to these areas to reduce negative impacts.

ACKNOWLEDGMENT

The author would like to thank all parties involved, especially experts and Universitas Andalas, for the support provided.

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