Research Paper

International Journal of Research and Review
[Indexed, Peer-Reviewed Journal]
Volume 12; Issue: 3; March 2025
Website: www.ijrrjournal.com
E-ISSN: 2349-9788; P-ISSN: 2454-2237

Landslide Vulnerability Mapping using Dominant Frequency and HVSR Spectral Amplification Data at MAN Insan Cendekia Central Bengkulu

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DOI: https://doi.org/10.52403/ijrr.20250317

ABSTRACT

This study aims to map landslide vulnerability in the MAN Insan Cendekia Bengkulu Tengah area using the Horizontal to Vertical Spectral Ratio (HVSR) method. This method analyzes two main parameters, dominant frequency (f_0) and spectral amplification (A_0), which are then used to calculate the seismic vulnerability index (K_g). The results reveal varying levels of soil vulnerability in the studied area. Points with high A_0 and low f_0 values were found to be more prone to landslides, characterized by soft soils with high susceptibility to disruptions from earthquakes or heavy rainfall. Conversely, points with low A_0 and stable f_0 values indicate harder, more stable soils. Areas with high K_g values, such as Points l, m, n, and o, require special attention through mitigation interventions like soil structure reinforcement and drainage management. Areas with low Kg values are relatively stable but still necessitate periodic monitoring. This study produced distribution maps of A_0, f_0, and K_g, which provide essential information for disaster mitigation planning. This approach enables the design of targeted mitigation measures to reduce landslide risks, such as restricting construction in high-risk zones and reinforcing structures in vulnerable areas.

Keywords: Vulnerability, Landslide, HVSR Spectral Amplification, Central Bengkulu

INTRODUCTION

Tectonically, Indonesia is located at the confluence of three main plates, namely Indo-Australia, Eurasia, and the Pacific (Fahrurijal *et al.*, 2020); (Rahman, 2016). Bengkulu Province is one of the regions in Indonesia with a high level of vulnerability to natural disasters, especially landslides (Rozi Wahyudi, 2020). Geographically, Bengkulu is located on the west coast of Sumatra Island which is dominated by mountainous topography with steep slopes and high rainfall throughout the year. This condition is exacerbated by massive land use changes, such as the conversion of forests into agricultural land, plantations, and settlements. As a result, the land's ability to absorb water decreases, increasing the potential for landslides, especially during the rainy season. Based on data from the National Disaster Management Agency (BNPB), several regencies in Bengkulu, such as Central Bengkulu, are among those with a very high risk of landslides.

Landslides are one of the natural disasters that often occur in Indonesia. Landslides occur when masses of soil, rock, or other debris move down a steep slope due to natural influences or human activities (Waladani *et al*., 2022); (Naryanto et al., 2019). Trianda Obrin (2018) mentioned that landslides can occur through falling, rolling, sliding, spreading, or flowing movements from the slope. Some of the main causes of landslides include: 1) High Rainfall: prolonged heavy rainfall can infiltrate water into the soil, increasing its weight and reducing cohesion between soil particles thus triggering landslides; 2) Earthquakes: ground tremors caused by earthquakes can shake the ground and trigger landslides; 3) Slope Erosion: water flow or human activities that cause erosion on slopes can reduce their stability, triggering landslides; 4) Human Activities: uncontrolled development, logging, and agricultural activities can cause slope instability; 5) Steep Slopes: Steep slopes are prone to landslides, especially if affected by external factors such as vibration or additional loads..

Disaster risk reduction efforts are very important, considering that Indonesia has a high potential for various types of natural disasters (Annisa & Setyowati, 2019). Therefore, priorities in disaster risk reduction need to be effectively implemented in the education sector (Sukamto *et al*., 2021). The approach to disaster management in Indonesia has evolved with the enactment of Law No. 24/2007 on disaster management. This law was strengthened by a number of related regulations, including Presidential Regulation No. 08/2008 on the National Disaster Management Agency, Government Regulation No. 21/2008 on the Implementation of Disaster Management, Government Regulation No. 22/2008 on Disaster Relief Funding and Management, and Government Regulation No. 23/2008 on the Participation of International Institutions and Foreign Non-Governmental Organizations in Disaster Management.

The formulation of the problem in this research is how to map landslide risk areas in MAN Insan Cendekia Central Bengkulu using dominant frequency data and HVSR spectral amplification? The purpose of this research is to analyze dominant frequency data and HVSR spectral amplification to map landslide risk areas with low to high risk categories. Then describe landslide mitigation efforts at MAN Insan Cendekia Bengkulu Tengah.

MATERIALS & METHODS

This research was conducted in November 2024 at MAN Insan Cendekia school in Bengklu Tengah, Bengkulu Province. The measurement was conducted by taking data of dominant frequency and HVSR (Horizontal to Vertical Spectral Ratio) spectral amplification. The dominant frequency (f0) and amplification (A0) obtained from HVSR are used to find the susceptibility index and thickness of the sediment layer.

The processing method used in this research is the Horizontal to Vertical Spectral Ratio (HVSR) method, which is a general analysis of earthquake motion in the horizontal direction compared to the vertical direction. The HVSR analysis is then connected to the type of sediment and sediment thickness at the measurement location to further analyze the influence of sediment and geological conditions of the region when an earthquake occurs. This method is one of the initial methods that is quite good in describing the condition of soil vulnerability of an area. Using this method, a map of the distribution of soil vulnerability in the research area can be obtained which can be used as a reference material and development consideration (Wachidah, S. F., dan Agsutin, 2021). It was continued by (Shaleha et al., 2016) hat the HVSR method is an indicator of the subsurface structure of the soil.

The HVSR (Horizontal to Vertical Spectral Ratio) method is a method that can be used in residential areas because it is very affordable effective, and environmentally friendly. The use of HVSR method will show the dominant frequency value and the amplification factor value. The relationship between dominant frequency and amplification factor can express the value of soil susceptibility index (Handayani et al., 2024).

The dominant frequency (f0) is the most frequent frequency value in the interval. This value can be used to indicate the type and thickness of sedimentary layers in an area (Winardi et al., 2023). The classification of the value of this dominant frequency can be seen in Table 1.

Tabel 1. Classification of Dominant Frequency Values against Sediment Layer Thickness

Soil Classification Type	**Dominant Frequency (Hz)**	**Kanai Classification**	**Description**	**Character**
IV	6,66 – 20,00	Tertiary or older rocks. Consists of Hard sandy gravel.	Very thin thickness of surface sediments dominated by hard rock	Hard
	4,00 – 6,66	Alluvial rocks with a thickness of 5 meters. Consists of sandy-gravel, sandy hard clay, loam, etc	Surface sediment thickness falls into the medium category 5-10 meters.	Moderate
III	2,50 – 4,00	Alluvial rocks are almost the same as type IV (4.00 - 6.66), distinguished only by the presence of bluff formations.	Surface sediment thickness falls into the medium category 10-30 meters.	Soft
II	1,00 – 2,50	Alluvial rocks formed from delta sedimentation, top soil, mud, etc. With a depth of 30 meters or more.	The thickness of surface sediments is very thick.	Very soft

(Kanai, 1983., dalam Siregar, 2017).

The amplification factor is a factor related to wave amplification (Laduni, 2020). The amplification factor is affected by wave speed. The smaller the wave speed, the greater the amplification factor. This shows that the amplification factor is related to the level of rock density (Sitorus et al., 2017). So, the softer the soil rock, the higher the amplification and the risk of landslides.

Table 2. Classification of Amplication Factor Values

Zone	**Classification**	**Amplification Factor Values**
1	Low	A < 3
2	Medium	3 < A < 6
3	High	6 < A < 9
4	Very High	A > 9

(Setiawan, 2009., dalam Handayani, 2024).

The seismic vulnerability index (K_g) according to Nakamura (1998) measures the vulnerability of an area to earthquake impacts using HVSR. High Kg values are more susceptible to earthquake impacts, while low values indicate lower susceptibility. This index helps in disaster mitigation planning by identifying areas with higher potential damage from earthquakes (Kartiko & Sunardi, 2024).

Table 3. Classification of Soil Susceptibility Index Values

No	**Classification**	**Value k_g**
1	Low	< 3
2	Medium	3 - 6
3	High	> 6

(Handayani *et al.*, 2024)

RESULT AND DISCUSSION

Identifying the characteristics of landslide prone areas also requires mapping the risk of landslide prone areas, as a form of disaster mitigation efforts. An area that is threatened by disaster does not necessarily have the same level of disaster risk. Mapping can be done by clustering or by identifying each building in the vulnerable area based on the level of risk to landslides.

Amplification Value (A_0) and Dominant Frequency (f_0)

Table 4 is the value of HVSR acquisition results at MAN IC Bengkulu Tengah. The acquisition value is then processed into a frequency distribution map and amplification map presented in Figures 1 and 2. Then, to see the frequency (hz) of each point can be seen and presented in Figure 4.

Table 4. A_0 and f_0 values of HVSR acquisition results at MAN IC Central Bengkulu

No	Point Code	A_0	f_0	Description (Risk/soil characteristics)
1	Point a	3,33	5,13	Medium
2	Point b	3,53	6,18	Medium
3	Point c	3,29	6,18	Medium
4	Point d	4,50	5,07	Medium
5	Point e	3,58	5,45	Medium
6	Point f	2,00	7,49	Low, Hard
7	Point g	3,14	7,21	Medium, Hard
8	Point h	2,60	8,67	Low, Hard
9	Point i	3,92	4,48	Medium
10	Point j	2,64	6,49	Low, Medium
11	Point k	1,63	1,25	Low, Very Soft
12	Point l	3,43	1,29	Medium, Very Soft
13	Point m	3,73	1,47	Medium, Very Soft
14	Point n	5,37	1,61	Medium, Very Soft
15	Point o	4,50	1,60	Medium, Very Soft
16	Point p	3,45	5,40	Medium
17	Point q	3,16	6,23	Medium
18	Point r	2,41	4,79	Low, Medium
19	Point s	2,90	6,63	Low, Medium
20	Point t	1,61	5,34	Low, Medium

The higher the A_0 value, the greater the potential for ground vibration amplification, indicating that the area is more prone to landslides (in the event of an earthquake). Areas with high A_0 values, such as at points k, l, m, n, and o tend to have a higher risk of landslides, especially if they are located on slopes or have weak soil structures. Meanwhile, lower values of f_0 characterize strong soils (as shown in Table 1). f_0 describes the natural resonance of the soil to a particular seismic wave (Candraningtyas & Susanti, 2024).

In general, relevant f_0 values indicate that the soil can resonate with certain vibrations, potentially increasing the risk of soil vulnerability (Utami, 2024). The combination of high A_0 and f_0 in the medium to low range usually indicates unstable soil conditions that are prone to landslides. Land susceptibility to landslides as seen from Points l, m, n, and o shows moderate susceptibility because the A_0 value is moderate but f_0 is in the very soft soil character, indicating poor soil stability and requires attention. Furthermore, Point k (A_0: 1.63; f_0: 1.25) has a low A_0 risk of landslides but f_0 is characterized by very soft soil. So soil stability still needs attention. So far, there is no area that has high risk of landslide based on A_0 and f_0.

Table 5. K_g Value of HVSR Acquisition Results at MAN IC Central Bengkulu

No	Point Code	A_0	f_0	K_g
1	Point a	3,33	5,13	2,16
2	Point b	3,53	6,18	2,02
3	Point c	3,29	6,18	1,75
4	Point d	4,50	5,07	4,00
5	Point e	3,58	5,45	2,35
6	Point f	2,00	7,49	0,53
7	Point g	3,14	7,21	1,37
8	Point h	2,60	8,67	0,78
9	Point i	3,92	4,48	3,43
10	Point j	2,64	6,49	1,07
11	Point k	1,63	1,25	2,12
12	Point l	3,43	1,29	9,11
13	Point m	3,73	1,47	9,47
14	Point n	5,37	1,61	17,90
15	Point o	4,50	1,60	12,66
16	Point p	3,45	5,40	2,20
17	Point q	3,16	6,23	1,60
18	Point r	2,41	4,79	1,21
19	Point s	2,90	6,63	1,27
20	Point t	1,61	5,34	0,49

Based on the results of the seismic vulnerability index (Kg) calculation, points with high Kg values, such as Point n (17.90) and Point o (12.66), show a very high level of seismic vulnerability. This is due to the combination of large amplification values with low dominant frequencies, indicating very soft soil characteristics that are easily disturbed by vibrations. These areas require special attention as they are more vulnerable to damage in the event of an earthquake and subsequent landslides. Overall, the results of this analysis show that the MAN Insan Cendekia area of Central Bengkulu has significant variations in seismic vulnerability levels. Areas with high Kg values require interventions such as strengthening soil structure, installing retaining walls, or good drainage management to reduce disaster risk. While areas with low Kg values only require regular monitoring to maintain soil stability. This analysis provides important information for disaster mitigation planning, so that development can be carried out by considering the level of vulnerability at each point.

Map of Amplification Distribution (A_0), Dominant Frequency (f_0), and Seismic Vulnerability Index (Kg)

In making the landslide risk map, several stages were carried out, namely threat map modeling, vulnerability modeling, capacity modeling, and risk modeling. Hazard modeling is generated from weighting using overlay. Vulnerability and capacity modeling is generated referring to document review with vulnerability assessment using weighting. Meanwhile, the risk map modeling is processed by using the formulation of the Regulation of the Head of the Natural Disaster Management Agency (PERKA BNPB) No. 2 Year 2012 and modified VCA (Vulnerability Capacity Analysis) to determine the risk classification of landslides (Faizana et al., 2015).

This map provides important information to identify mitigation priority zones, such as slope strengthening or development restrictions in areas with high A0 values. The combination of this map with other data, such as dominant frequency (f0) and seismic vulnerability index (Kg), will provide a more comprehensive picture of potential landslide vulnerability in the region.

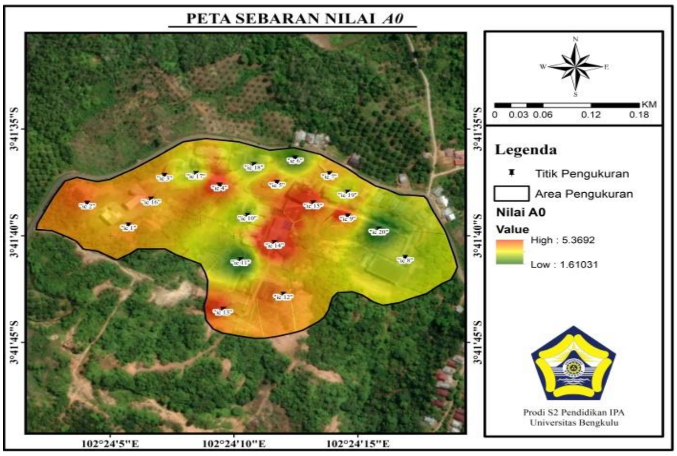


Figure 1. A_0 Distribution Map in MAN IC Central Bengkulu

Figure 1 shows the distribution of A_0 values in the MAN Insan Cendekia Bengkulu Tengah area. The A_0 values range from 1.61 to 5.36 with color gradations from green (low value) to red (high value). Areas with red color indicate locations with high A_0 values, which means that the soil in the area has a greater ability to amplify seismic waves.

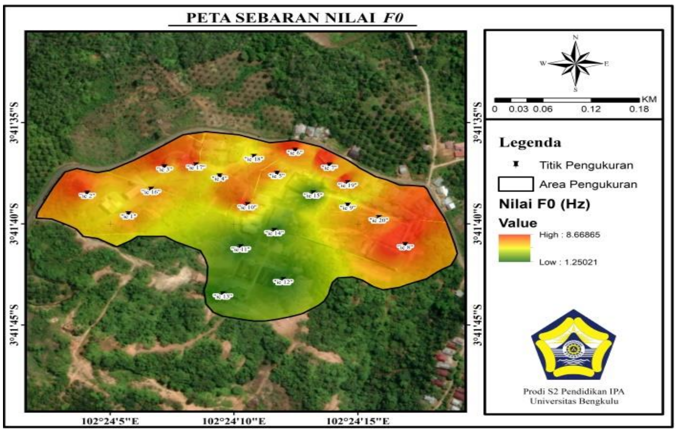


Figure 2. f_0 Distribution Map in MAN IC Central Bengkulu

Figure 2 scatter map illustrates the distribution of f0 (Dominant Frequency) values with a range of values between 1.25 and 8.66 Hz. The color gradation from green (low frequency) to red (high frequency) indicates the resonance characteristics of the soil at the site.

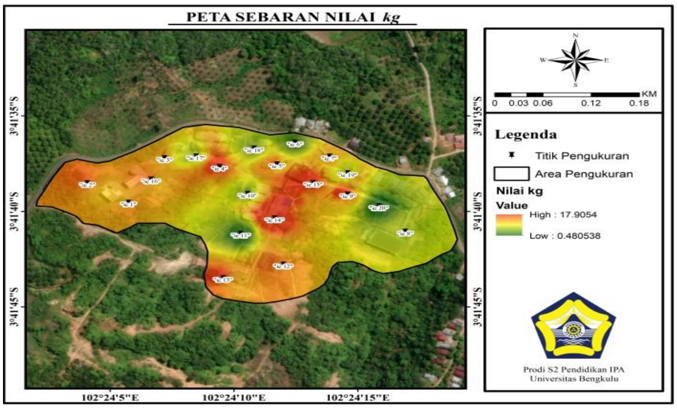
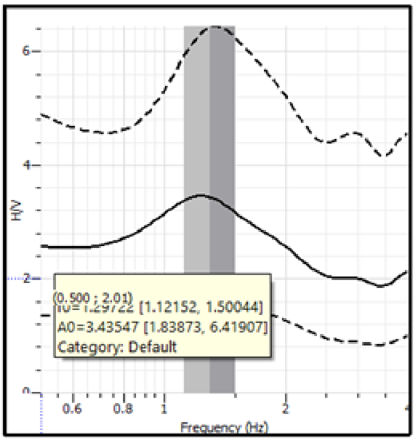


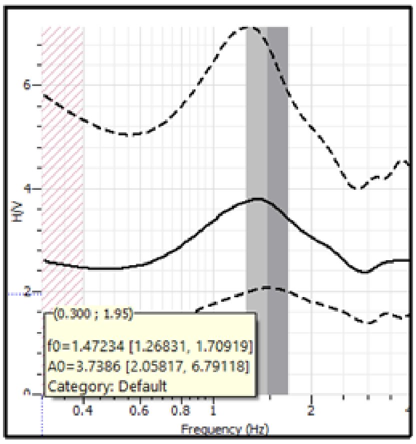
Figure 3. K_g Distribution Map in MAN IC Central Bengkulu

Figure 3 of the scatter map shows the distribution of Kg (Seismic Vulnerability Index) values, which is a combination of A0 and f0 values. Kg values range from 0.48 to 17.90, with color gradations from green (low values) to red (high values). Areas with high Kg values (red) indicate locations with significant seismic vulnerability risk.

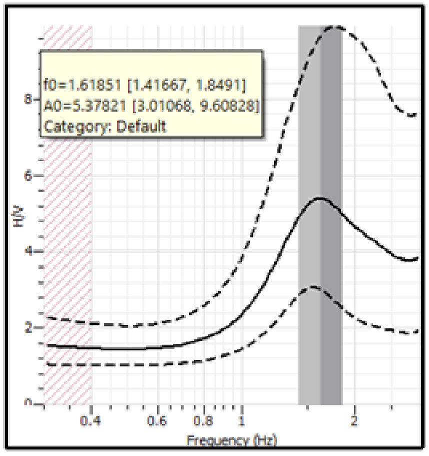
Point Spread of Amplification (A0) and Dominant Frequency (f0)



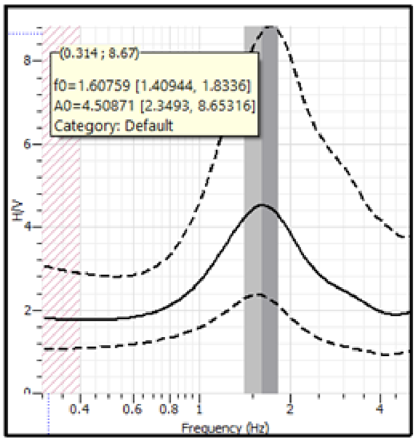
Titik l



Titik m



Titik n



Titik o

Figure 4. Results of Soil Vulnerability Waveform Analysis

Based on 20 measurement points conducted at MAN IC Bengkulu Tengah, the HVSR method produces two main parameters, namely dominant frequency and amplification factor. These values are used to calculate the soil susceptibility index in the area. The analysis results show significant variations in soil susceptibility between measurement points. In general, points with low dominant frequency values and high amplification factors indicate areas with higher susceptibility to landslides (Wibowo & Huda, 2020). This indicates that the area has soft geological characteristics. Conversely, points with high dominant frequency tend to be more stable and show a low level of vulnerability. The distribution of measurement results from each point provides an overview of the heterogeneity of soil characteristics in the MAN IC Central Bengkulu area. Some areas appear to require more attention for earthquake risk mitigation due to their higher vulnerability index. The HVSR method proved to be effective in identifying vulnerability zones in an efficient, economical and environmentally friendly way, so it can be used as a reference for disaster risk management in the region.

CONCLUSION

Based on this research, it can be concluded that the value of soil vulnerability in the MAN IC Central Bengkulu area can be concluded that:

1. MAN IC Bengkulu Tengah is located in a zone with an amplification factor of 1-8 with very soft soil characteristics and is easily disturbed by vibrations at Points l, m, n, and o. This area requires special attention because it is more vulnerable to damage in the event of an earthquake and subsequent landslides. This area requires special attention because it is more vulnerable to damage in the event of an earthquake and continues to landslides.
2. MAN IC Bengkulu Tengah has a small seismic vulnerability risk at Points t, f, and h. These areas typically have harder soils and are easily disturbed by tremors. These areas typically have harder soils and do not amplify vibrations significantly.
3. Other points such as a, b, c, d, e, g, i, j, k, p, q, r, and s are at safe risk from landslides.
4. Risk management for high risk areas are: strengthening the soil structure such as installing retaining walls or stabilization techniques. Then, apply vegetation to reduce the risk of erosion in areas with soft soil. In low risk areas, periodic monitoring is still needed to maintain soil stability.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: No conflicts of interest declared.

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How to cite this article: Yudi Maulana, Afrizal Mayub, Henny Johan, Muhammad Farid, Endah Lestari. Landslide vulnerability mapping using dominant frequency and HVSR spectral amplification data at MAN Insan Cendekia Central Bengkulu. *International Journal of Research and Review*. 2025; 12(3): 119-127. DOI: *https://doi.org/10.52403/ijrr.20250317*

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