Seismic Disaster Study Based on Soil Vulnerability Index (Kg) and Peak Ground Acceleration (PGA) Values in Kokap and Surrounding Areas

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ABSTRACT

Kulon Progo region is one of the areas in Yogyakarta that often experiences natural disasters, especially landslides. With the morphology of mountains that are described as large domes with flat tops and steep wings (Van Bamelen, 1949), making the Kulon Progo area more prone to landslides. Earthquakes with great force can cause landslides in this area. To map areas that are prone to earthquakes and landslides, research using the microseismic method was used. The research is located in Hargorejo Village and Hargowilis Village, Kokap District and Karangsari Village, Pengasih District, DI. Yogyakarta consists of 9 measurement points. Data processing was performed using *Geopsy software* using the HVSR method. The results showed that the Kokap area and its surroundings had an amplification factor value range of 1-5 times, the natural frequency value was 1.2 Hz to 12.2 Hz, the dominant period value was 0.5-0.8 s, the soil vulnerability index value was , 1 s^2/cm to 2.7 s^2/cm and a PGA value of 64 cm/s^2 to 206.2 cm/s^2. Based on the research results, the area most vulnerable to the consequences of the earthquake is the village of Hargorejo. The village of Hargorejo which is composed of andesite intrusion has resulted in mineral alteration which produces clay minerals where clay minerals are impermeable so that they easily become sliding fields. When an earthquake occurs, this area will suffer significant damage.

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1. INTRODUCTION

Geographically, Indonesia is located between the meeting of three major plates in the world, namely the Eurasian plate, the Australian plate and the Pacific plate. The collision between these plates will cause the subduction zone to form undulations in the archipelago arc with steep to very steep slopes [15]. One of the major plate boundaries in Indonesia is located in the south of Java Island. The collision of the Eurasian plate with the Indo-Australian plate or known as subduction can trigger seismic activity. Earthquakes that occur can be caused by friction between the plates themselves or active faults on the island of Java which are triggered by subduction in the south of Java Island.

Large-scale earthquakes often cause damage that results in loss of life and material loss. One such earthquake occurred in Bantul, Yogyakarta in 2006, which is commonly known as the Bantul earthquake. The earthquake, which was periodically 5.9 SR or 6.2 Mw (USGS), did not only have an impact around Yogyakarta, but also in Central Java. The 2006 Bantul earthquake was caused by the active Opak Fault, which runs from the south to the northeast (along the Opak River). The active fault is caused by subduction activity south of Yogyakarta. Based on data recorded in the Catalogue of Significant and Destructive Earthquakes 1821-2018, the earthquake killed 5,782 people, injured 36,299, and damaged 390,246 houses.

Kulon Progo region is one of the areas in Yogyakarta that often experiences natural disasters, especially landslides. The morphology of the mountain range, described as a large dome with a flat top and steep wings [21], makes the Kulon Progo area more prone to landslides. Landslides can be caused by several factors such as physiography and geomorphology. However, in addition to these two factors, landslides can also be triggered by earthquakes that occur around the area. The impact of an earthquake will certainly be greater if an area has a high potential for landslides. If no further analysis is done, there will be huge losses both in terms of material and casualties. To reduce the negative impact caused by an earthquake, it can be done by mapping the soil characteristics. One of them is by calculating the value of soil susceptibility and maximum ground acceleration obtained from the use of microseismic methods.

This research aims to map the soil characteristics in the research area so as to identify areas that have high potential earthquake hazards based on the value of the soil susceptibility index and maximum ground acceleration. Soil susceptibility is a value that describes the level of susceptibility of the surface soil layer to deformation during an earthquake [11]. The maximum ground acceleration in a place caused by seismic vibrations depends on the propagation of seismic waves and the characteristics of the soil layer in that place [7]. From the mapping of soil characteristics, it is possible to anticipate the negative impacts that will arise in the event of an earthquake and can be useful for earthquake disaster mitigation.

1.1. The Geology of The Study Area

Astronomically, the research area located in Hargorejo Village, Hargowilis Village and Karangsari Village is located at coordinates 110˚5'59.46" - 110˚7'35.4‘ east and 07˚49'37.026’ - 07˚50'12.348" LS. Geologically, the research area is included in the Yogyakarta sheet. Where in the research area there are Old Andesite Formation (Old Andesite Bemmelen Formation), Sentolo Formation, Nanggulan Formation and andesite intrusion.

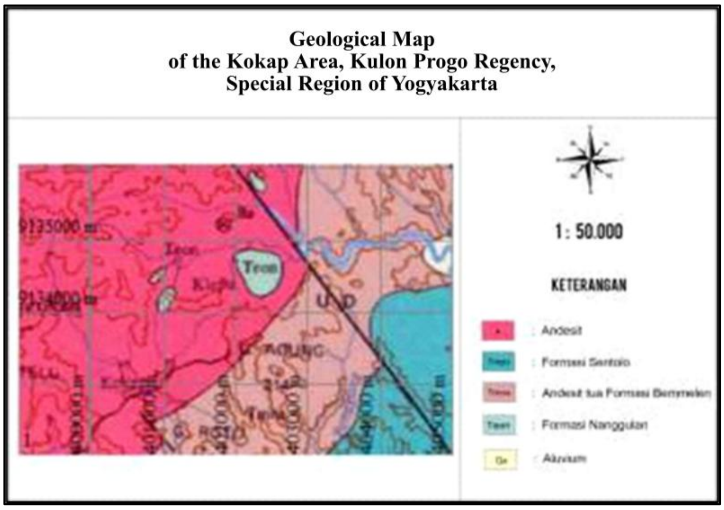

Figure 1.Geologic Map of the Research Area [14]

1.1.1. Nanggulan Formation (Teon)

The Nanggulan Formation occupies an area with a morphology of low to medium undulating hills evenly distributed in the Nanggulan area (eastern part of the Kulon Progo Mountains). Locally, this formation is also found in the Sermo, Gandul, and Kokap areas in the form of lenses or xenolith blocks in andesite igneous rocks. The Nanggulan Formation has a type locality in the Kalisongo area, Nanggulan. Van Bemmelen (1949) explained that this formation is the oldest rock in the Kulon Progo Mountains with its depositional environment being littoral in the sea flood phase. The constituent lithology consists of sandstone with lignite inserts, passive marl, claystone with limonite concretion, marl and limestone inserts, sandstone, tuff rich in foraminifera and mollusks, estimated to be 350 m thick. This formation type area is composed of shallow marine deposits, sandstones, shales, and interbedded marls and lignites. Based on the study of planktonic foraminifera, the Nanggulan Formation has an age range from Middle Eocene to Oligocene.

1.1.2. Old Andesite Formation (Tmoa)

This formation was deposited unconformably on top of the Nanggulan Formation. The lithology is volcanic breccia with andesite fragments, lapilli tuff, tuff, lapilli breccia, andesite lava flow inserts, agglomerates, and volcanic sandstones exposed in the Kulon Progo area. This formation is exposed in the central, northern and southwestern parts of the Kulon Progo area forming a moderate to steep undulating mountain morphology. The thickness of this formation is approximately 600 m. Based on planktonic foraminifera fossils found in the marl, the age of the Old Andesite Formation can be determined as Upper Oligocene.

1.1.3. Sentolo Formation

Above the Old Andesite Formation, the Sentolo Formation is deposited unconformably. The Sentolo Formation consists of limestone and tuffaceous sandstone. The lower part consists of conglomerate overlain by tuffaceous marl with glassy tuff inserts. These rocks towards the top gradually turn into well-layered limestones rich in Foraminifera. The thickness of this formation is about 950 m.

1.2. Microseismic

Microseismic is a ground vibration caused by natural or artificial factors such as wind, waves or vehicle activity that causes geological conditions on the surface [19]. Microseismic is one of the passive geophysical methods. The microseismic method basically records natural ground vibrations that reflect the geological conditions of an area. One of the techniques in microseismic is the HVSR (Horizontal to Vertical Spectral Ratio) technique.

1.2.1. Horizontal to Vertical Spectral Ratio (HVSR)

The HVSR method is a method used as an indicator of subsurface structure that shows the relationship between the comparison of the ratio of the fourier spectrum of the microtremor signal of the horizontal component to its vertical component [9]. The HVSR method is a method of comparing the spectrum of the horizontal component to the vertical component of microtremor waves. Microtremor consists of a basic Rayleigh wave variety, the peak period of the microtremor H/V ratio provides the basis of the S-wave period. The H/V ratio in microtremors is a two-component ratio that theoretically produces a value. The HVSR method is used to determine the amplification value and dominant period value of a location that can be estimated from the peak period of the microtremor H/V ratio [10].

1.2.2. Soil Vulnerability Index (Kg)

Earthquake susceptibility is a value that describes the level of susceptibility of the surface soil layer to deformation during an earthquake [12]. Earthquake vulnerability aims to measure the level of vulnerability of the soil or structure in receiving an earthquake [11]. Earthquake vulnerability is useful for predicting weak zones during an earthquake ([4][16]). According to Nakamura (2008), the value of earthquake vulnerability is obtained by squaring the amplification divided by its natural frequency, so it can be formulated as follows:

$$Kg = \frac{{A_0}^2}{f_0} \tag{1}$$

where Kg is the soil vulnerability index, A_0 is the amplification value, and f_0 is the dominant frequency.

1.2.3. Maximum Ground Acceleration (PGA)

The maximum ground acceleration (PGA) is the value of the largest ground vibration acceleration that has ever occurred at a place caused by earthquake waves. The maximum ground acceleration at a place caused by seismic vibrations depends on the propagation of seismic waves and the characteristics of the soil layer at that place [7].

The properties of the soil layer are determined by the natural period of the soil layer in the presence of seismic vibrations. The seismic vibration period (T) and the natural period of the soil (To) will affect the magnitude of rock acceleration in the bedrock layer and at the surface layer. While the difference in the speed of propagation of seismic waves in bedrock with the speed of propagation of seismic waves on the ground surface will determine the magnification factor G(T) [3]. According to Ozaki (1977), if the value of the seismic vibration period (T) and the natural period of the soil (To) are the same, resonance will occur, so that the ground acceleration will be strengthened, which is called the maximum ground acceleration. Based on this, Kanai (1966) formulated the empirical equation of maximum ground acceleration which is formulated as follows:

$$a = \frac{1}{T} 10^{(0,61M) - \left(1,66 + \frac{3,6}{R}\right) logR + \left(0,167 \frac{1,83}{R}\right)} \quad (2)$$

where a is the maximum ground acceleration (cm/s^2), T_0 is the dominant period (s), M is the source earthquake magnitude (SR), and R is the distance between the earthquake source and the measurement point (m).

2. METHODS

2.1. Data Acquisition

The research was located in Hargorejo Village and Hargowilis Village, Kokap District and Karangsari Village, Pengasih District, DI. Yogyakarta consisted of 9 measurement points. The research was conducted on Saturday 02 March 2013, which was measured from 08.42.42 WIB to 16.34.46 WIB. The research location covers an area of 3.3 x 1.1 km^2.

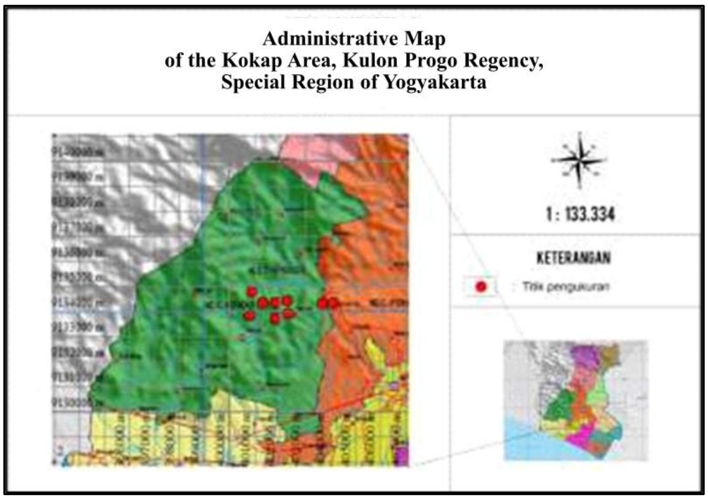

Figure 2. Administrative Map of the Research Area and Measurement Points

2.2. Data Processing

Data processing of 9 measurement points was carried out using Geopsy software with HVSR technique. Data processing is based on SESAME (2004). Picking waves is done based on their amplitude. The amplitude of microseismic waves is generally small, so when finding a drastic difference (from small amplitude to large amplitude), waves with large amplitude are ignored. After that, a spectrum graph of the H/V ratio against frequency will be obtained. From the HVSR processing, the amplification factor (A0) and natural frequency (f0) are obtained. The A0 and f0 data are then calculated to obtain the soil susceptibility value (Kg).

To calculate the PGA value, earthquake data is needed around the measurement point. The earthquake data used is the Yogyakarta earthquake in 2006 which had a magnitude of 5.9 SR at a depth of 11.8 km and was located at coordinates 8.03 LS - 110.32 BT. In addition to earthquake data, dominant period data is needed. The dominant period (T0) is obtained through calculations of the natural frequency. The PGA calculation method used is the Kanai method which uses the parameters of earthquake magnitude, dominant period and distance from the hypocenter to the measurement point. From the Kg and PGA values obtained, a map will be created with Surfer 13 and ArcGIS software by combining all Kg data from each measurement point.

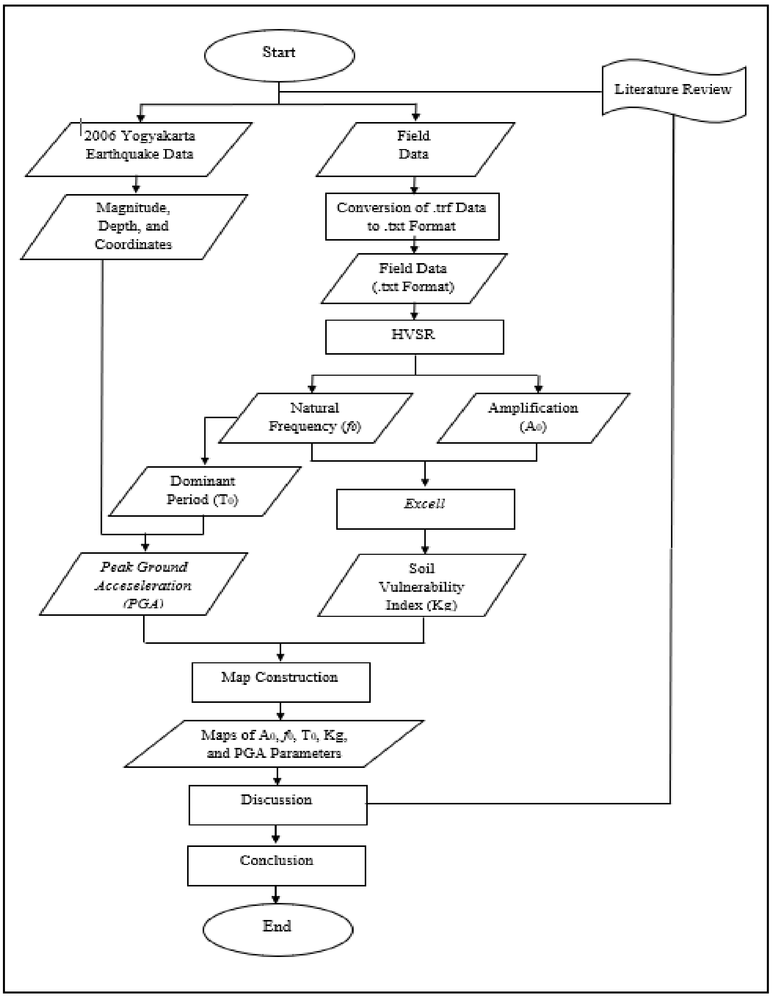

Figure 3. Research Flow Chart

3. RESULTS AND DISCUSSION

3.1. HVSR Curve

The H/V comparison spectrum is obtained from spectral analysis of microseismic data processed using Geopsy software. At each measurement point coordinate, the data obtained consists of three components, namely north-south (NS), west-east (EW) and up-down/elevation (UD). The three data are still in the time domain so that in the spectral analysis they will be converted into the frequency domain by applying the fast fourier transform (FFT) process. Before performing spectral analysis, a windowing stage is carried out to sort out the original data from noise. Noise is characterized by a sudden increase in amplitude [6]. This H/V comparison is carried out by combining the horizontal components (EW and NS) with their mean squares. Then the average ratio of the horizontal component to the vertical component (H/V) is calculated. The colors on the spectrum graph illustrate the H/V spectrum value against the frequency of each window. The window length used at each measurement point is always different depending on the recorded microseismic wave.

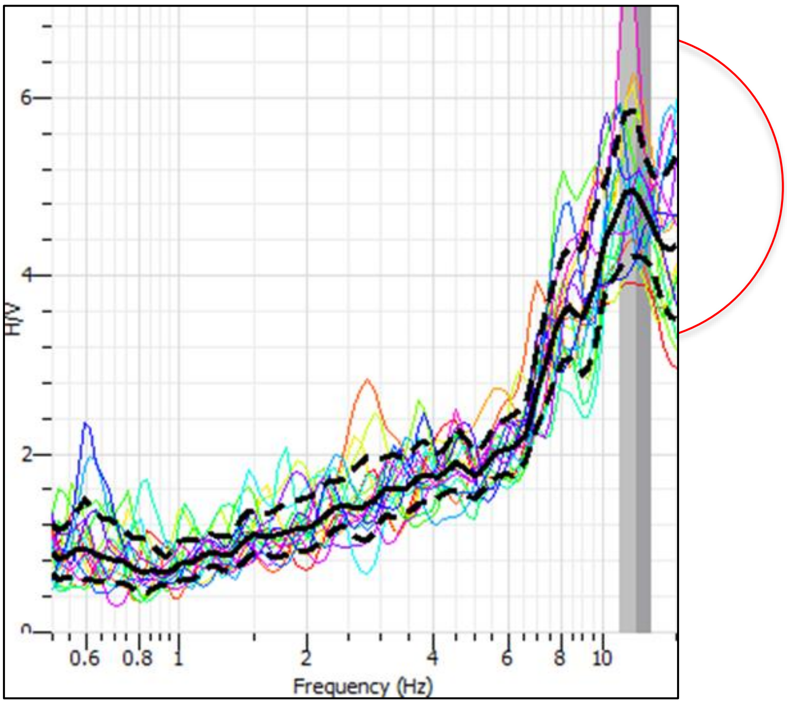

Figure 4. TA 28 Point

3.2. Amplification Map Analysis (A_0)

Amplification is the magnification of seismic waves that occurs due to significant differences between layers. From this, seismic waves will experience magnification if they propagate in a medium to another medium that is softer than the initial medium through which they travel [5]. The classification of amplification values is divided into 4, namely low classification (A<3), medium classification (3<A<6), high classification (6<A<9), and very high classification (A>9) [18].

The range of amplification values in the study area is 1 to 5. Seen on the map, low amplification values are the values that dominate the study area. This can be seen in Figure 5 where it is dominated by blue color which is classified as low amplification with a value of 1 to 3.1. The amplification value is related to the level of rock density, where reduced rock density will increase the amplification factor value. If the impedance contrast of the two layers is high, the amplification factor value is also high, and vice versa.

The southern part of Hargorejo village (TA point 28) has a medium amplification factor value. In contrast, the northern part of Hargorejo Village, Hargowilis Village and Karangsari Village have low amplification factors. Areas with low amplification on the map indicate that the impedance contrast between the overlying layers is small so that when earthquake waves propagate in the area, they will get a small magnification and the consequences will be small. This indicates that in this area the possibility of damage to the buildings standing on it is small in the event of an earthquake.

The research area is composed of Andesite intrusions of the Nanggulan Formation (Hargorejo Village and west of Hargowilis Village) and Old Andesite of the Bemmelen Formation (east of Hargowilis Village and Karangsari Village). The dominance of andesite rocks in the western part of the study area can be attributed to the amplification value of the study area which is included in the low to medium classification. Andesite rocks tend to have hard properties so that they can be classified as hard soil with a soft sediment layer above them that is not too thick. Hard ground when traversed by seismic waves or earthquake waves will not experience strong shaking due to the small magnification of the earthquake (amplification factor).

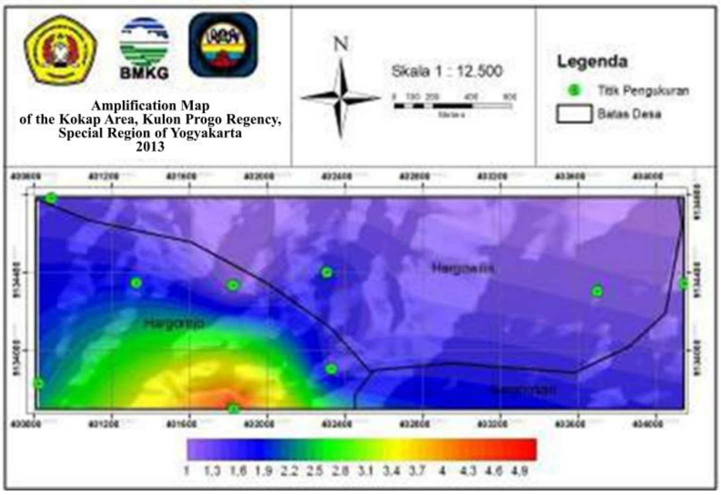

Figure 5. Amplification Map

3.3. Natural Frequency Map Analysis (f_0)

The natural frequency is the frequency that appears most often, so it is considered the average wave frequency at the measurement point. Analysis of the distribution of natural frequencies is carried out to determine the depth of the wave reflection field in the subsurface [6]. Nakamura (2000) provides a formulation of the natural frequency which is f0 equal to the wave speed S divided by four times the bedrock depth.

Based on Kanai's natural frequency classification, it is divided into 4 types. In type IV with a value of f0 < 2.5 Hz with a description of the rock is the thickness of the surface sediment layer is very thick about > 30 meters. Type III with a value of f0 2.5 - 4 Hz with a description of the rock is the thickness of thick category surface sediments, about 10-30 meters. Type II with a value of f0 4 - 10 Hz with a description of the rock is the thickness of the surface sediment layer of the middle category 5 - 10 meters. Type I with a value of f0 6.6 - 20 Hz with a description of the rock is a very thin surface sediment layer or even none at all [1].

The range of natural frequency values in the study area is from 1.2 Hz to 12.2 Hz. Hargorejo village which consists of 5 measurement points, namely TA 21, TA 22, TA 27, TA 28 and TA 29 is dominated by medium to high natural frequencies with values of 5.8-12.2 Hz. From the five measurement points, Hargorejo Village, especially in the southern part, can be classified into type IV, which has a very thin thickness of surface sediments, so that when earthquake waves pass through this area, there will be little impact on damage to buildings on it or damage to the soil in the area.

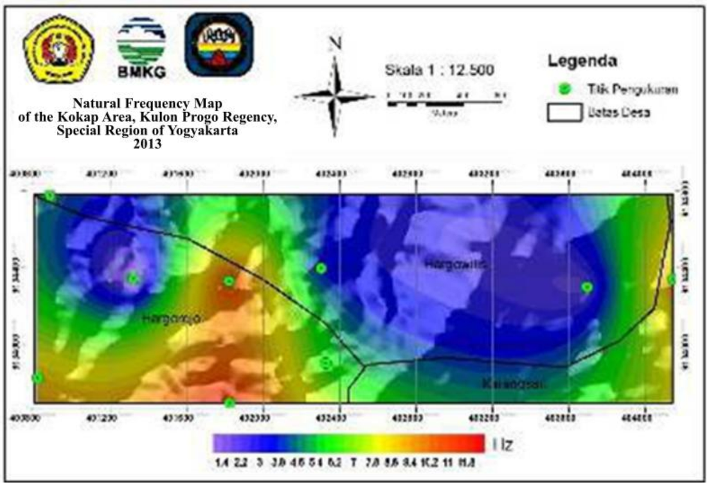

Figure 6. Natural Frequency Map

Hargowilis village, which consists of 3 measurement points, namely TA 15, TA 23 and TA 26, is dominated by low to medium natural frequencies with values of 2.02-4.6 Hz. From the three measurement points, Hargowilis Village can be classified into type II which is thought to have a surface sediment thickness of around 10-20 m. Karangsari Village, which consists of 1 measurement point, TA 20, is an area with a high natural frequency. The natural frequency value of point TA 20 is 9.98 Hz. Based on Kanai (1961) classification, it can be classified into type IV where this area is suspected to have a very thin sediment thickness.

3.4. Dominant Period Map Analysis (T_0)

The dominant period is the time it takes for micro-simic waves to propagate through the surface sediment layer. The dominant period value can indicate the character of the rock layers present in an area. Kanai-Omote-Nakajima classifies soils into 4 types based on their dominant period values. Type I with a value of 0.05-0.15 s has a hard soil character. Type II with a value of 0.10-0.25 s has a medium soil character. Type I and Type II can be classified as Type A. Type III with a value of 0.25-0.40 s has a soft soil character. This type III can be classified as Type B. Type IV with a value of >0.40 s has a very soft soil character. Type IV can be classified as Type C.

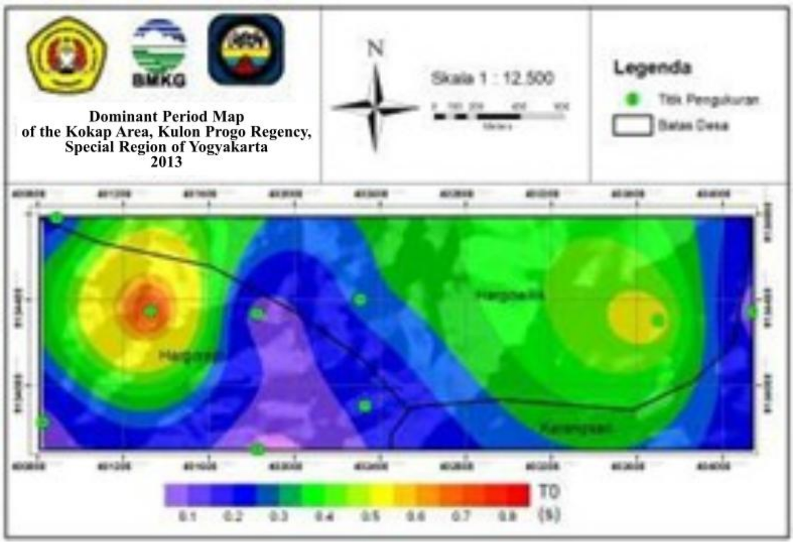

Figure 7. Dominant Period Map

Seen in Figure 7, the range of dominant period values in the study area is in the range of 0.08 s to 0.8 s. Hargorejo village in the northern part can be classified into type IV, which has a very soft soil character with a surface sediment thickness of more than 30 m, so that when earthquake waves pass through this area, it will have a major impact on damage to buildings on it and soil damage in the area. In contrast, the southern part of Hargorejo can be classified into type II with moderate soil characteristics. If earthquake waves pass through the area south of Hargorejo, the impact is quite small.

Hargowilis village can be classified into type IV which is thought to have a surface sediment thickness of about 30 m or more. Karangsari Village, which consists of 1 measurement point (TA 20), is an area with a low to medium dominant period of 0.1 s. Based on the Kanai-Omote- Nakajima classification, it can be included in types I and II (Type A) where this area is thought to have a very thin sediment thickness.

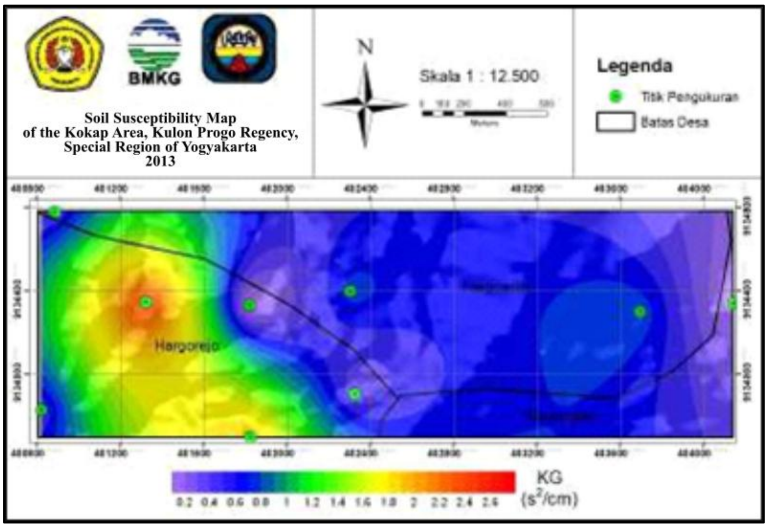

Figure 8. Soil Susceptibility Map

3.5. Soil Susceptibility Map Analysis (Kg)

The soil susceptibility map (Kg) is a map that identifies the vulnerability of a layer of soil that is deformed by an earthquake. The Kg value itself is found by the lithology of sedimentary rocks based on the hardness of the rock. A high Kg value indicates that the research area is prone to earthquake shaking. Vice versa, if the Kg value is low then the area will be less affected in the event of an earthquake.

Seen on the map, the soil susceptibility index values vary widely, but the more dominant ones are low values with a range of values from 0.1 s2/cm to 2.7 s2/cm. This indicates that the study area is largely safe from earthquake hazards and the potential for landslides is small. However, there are yellow to red colored clusters with increasing Kg values. The red clash is located in Hargorejo Village.

In terms of geology, Hargorejo Village is composed of andesite intrusions. The andesite intrusion causes alteration that converts primary minerals into altered minerals such as clay minerals. These clay minerals are impermeable, making it very easy to function as a slide zone that will trigger landslides. Therefore, with a high vulnerability index value, there must be consideration when building a building in the Hargorejo area to avoid severe damage during an earthquake because this area is the most vulnerable when an earthquake occurs.

The dominance of the Kg value in Hargowilis Village is quite low, making this area relatively safer when an earthquake occurs when viewed from its soil characteristics. However, Hargowilis Village is still at risk of damage when an earthquake occurs around the area. In this area, it is suspected that the sediment thickness is quite thick. Karangsari Village can be assumed to have a very thin sediment thickness, so Karangsari Village, Pengasih Subdistrict tends to be safer than other villages when an earthquake occurs.

3.6. Maximum Ground Acceleration Map Analysis (PGA)

The PGA value expresses the magnitude of the largest (maximum) ground acceleration when a location is passed by an earthquake. The PGA calculation used is the Kanai PGA calculation. The Kanai calculation method is used in this study because it takes into account the characteristics of the source earthquake such as magnitude (M) and distance (R) and also takes into account the dominant characteristics of the research location (T0). Variations in PGA values are influenced by overburden thickness, hardness and physical contrast between the overburden and bedrock.

Based on Kanai's calculation, the maximum acceleration value of Hargorejo Village and Hargowilis Village, Kokap Subdistrict and Karangsari Village, Pengasih Subdistrict ranges from 64 cm/s2 to 206.2 cm/s2. The maximum ground acceleration value of Kokap and surrounding areas can be classified into two according to the USGS, namely earthquake intensity VII with a PGA value of 50-100 cm/s2 and earthquake intensity VIII with a PGA value of 100-250 cm/s2. In the area of point TA 21 with a value of 64.5 cm/s2 is the measurement point with the lowest PGA value in Hargorejo Village and also the lowest in the entire research plot. Point TA 21 is classified as earthquake intensity VII. This indicates that this point responds more slowly to earthquake waves passing through point TA 21. The slow response is thought to be due to the formation of a fairly thick surface sediment layer. TA 28 is the area with the highest PGA value of all measurement points. With PGA values belonging to earthquake intensities VII and VIII, there should be consideration when building a building in the Hargorejo area in order to avoid severe damage during an earthquake because this area is the most vulnerable when an earthquake occurs. Also note that the area in Hargorejo has a fairly thick surface sediment layer.

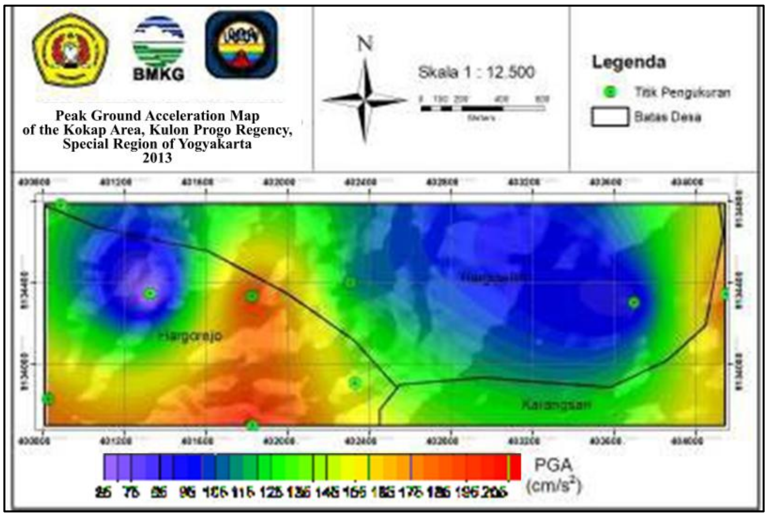

Figure 9. Maximum Ground Acceleration Map

Hargowilis village is dominated by lower maximum acceleration values than the Hargorejo area. The predominance of lower PGA values than Hargorejo Village makes this area relatively safer when an earthquake occurs when viewed from the characteristics of ground acceleration when an earthquake occurs. However, Hargowilis Village is still at risk of damage when an earthquake occurs around the area. This area is thought to have a fairly thick surface sediment thickness. From its geology, Hargowilis Village is composed of the Old Andesite Formation (Bemmelen Formation), Nanggulan Formation and andesite intrusions. Karangsari Village is an area with high maximum ground acceleration which is classified as earthquake intensity VIII. The soil susceptibility index value of point TA 20 is 195.84 cm/s2. Karangsari Village can be assumed to have a fairly thin sediment thickness, so that Karangsari Village, Pengasih District tends to be safer than other villages when an earthquake occurs.

4. CONCLUSION

From the research using microseismic method (HVSR) that has been done, conclusions can be drawn. The conclusion of the research conducted is as follows.

- The area most vulnerable to the consequences of an earthquake is Hargorejo village. The soil vulnerability index of Hargorejo village shows a fairly high value. This is supported by the high maximum ground acceleration value in the southern part of Hargorejo village (TA 28 = 206.12 cm/s2). Hargorejo village is composed of andesite intrusions resulting in mineral alteration that produces clay minerals where clay minerals are impermeable so that they easily become a sliding field. When an earthquake occurs, this area will experience severe damage.
- The potential seismic disaster that threatens Hargowilis and Karangsari villages is not as great as Hargorejo Village due to the low soil vulnerability index. However, with maximum ground accelerations that can be classified into earthquake intensities VII to VIII, which are thought to be composed of less thick layers of surface sediments, both villages are still vulnerable to the consequences of earthquake disasters.

DECLARATION

Author Contribution

Both authors contributed equally to the conception, design, data analysis, and writing of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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