

Identification of Ground Vulnerability Based on Kg, PGA, And GSS Assessment by Single Station Microtremor in Gombel Village, Semarang

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ABSTRACT

Gombel Village, located in the southern region of Semarang City, Central Java, is one of the areas prone to land subsidence and localized slope instability. These geohazards are frequently exacerbated by anthropogenic activities, including uncontrolled development, heavy traffic, and infrastructure construction, which contribute dynamic loading to the already fragile geological setting. According to the United States Geological Survey (USGS), the last recorded earthquake in this region occurred in 1996. Although seismic activity appears relatively infrequent, the potential for seismic wave amplification due to site effects remains significant, particularly in zones underlain by thick alluvial or weathered sedimentary deposits.

This study aims to assess seismic site vulnerability in Gombel Village through the analysis of Ground Shear Strain (GSS), Peak Ground Acceleration (PGA), and the Seismic Vulnerability Index (Kg). Primary data were acquired through microtremor measurements conducted using a single-station approach across 65 strategically distributed points. The Horizontal to Vertical Spectral Ratio (HVSr) method was employed to extract the

dominant frequency (f_0) and amplification factor (A_0) from ambient seismic noise.

Results indicate that the seismic vulnerability index (Kg) in the study area ranges from 3.26×10^{-3} to 22.74 cm/s. PGA values are relatively stable, ranging from 5.22 to 5.24 Gal, while GSS values vary between 6.16×10^{-5} to 16.66×10^{-3} strain units. High seismic vulnerability zones are identified at measurement points D2, D3, E2, E3, F2, and F3, which coincide with areas undergoing active subsidence. These zones are characterized by high amplification factors (A_0) and low dominant frequencies (f_0), indicating the presence of thick soft sediment layers that are prone to amplify ground motion and facilitate ground deformation during seismic events.

The findings underscore the necessity for detailed microzonation and the incorporation of seismic risk mitigation strategies in urban planning, especially in subsiding zones with unfavorable subsurface conditions.

Keywords: Gombel Village; Microtremor; HVSr; GSS; PGA; Seismic Vulnerability; SDGs

INTRODUCTION

Landslides represent one of the most common geological hazards for steep-slope terrains and hilly areas specifically those

with weak lithology along with high water saturation. An imbalance of resisting and driving forces inside soil masses causes this phenomenon. Heavy rainfall and also earthquakes and human activities can each trigger it. Landslides can cause meaningful impacts such as human safety, infrastructure damage, with socioeconomic disruption, especially in tactically located or densely populated urban areas.

Semarang City is known as a large metropolitan area of Indonesia. Complex geological plus diverse geological with morphological conditions exist now. Southern upland hills rise plus northern lowlands lie; two main morphological zones split the city [1]. The southern sector has very steep slopes with weak lithological formations given that it is geologically near to the Semarang Fault so it is very vulnerable in regard to landslides [2].

One of the geotechnically unstable areas is Gombel Lama, located in the southern hills of Semarang. The area frequently experiences land subsidence, slope instability, and landslides, especially around Jalan Gombel Lama, a vital transportation route connecting the upper and lower parts of the city. The lithology of Gombel comprises four primary rock units: claystone of the Kerek Formation (Tmk), volcanic breccia of the Kaligetas Formation (Qpkg), conglomerate of the Damar Formation (Qtd), and alluvial deposits (Qa) [3]. These formations exhibit weak mechanical characteristics and are exacerbated by high rainfall intensity and dense urban development. A large-scale landslide in February 2021 near Gombel Village highlighted the area's high hazard potential. According to data from the Semarang Regional Disaster Management Agency (BPBD of Semarang City), between 2020 and 2024, at least 12 landslide and ground subsidence events were recorded across the Banyumanik–Gombel–Candisari region, underscoring the need for urgent mitigation and risk assessment.

Previous scientific investigations have extensively explored subsurface conditions

using microtremor analysis, both nationally and within Gombel. In general, microtremor analysis has proven effective for assessing seismic site vulnerability. Through the Horizontal to Vertical Spectral Ratio (HVSr) method, it yields two key parameters—dominant frequency (f_0) and amplification factor (A_0)—that can be used to calculate the Seismic Vulnerability Index (Kg), Peak Ground Acceleration (PGA), and Ground Shear Strain (GSS) [4].

In geophysical studies, several key parameters have been developed to assess soil vulnerability to ground shaking and deformation, including Peak Ground Acceleration (PGA), Ground Shear Strain (GSS), and the Seismic Vulnerability Index (Kg). High PGA and GSS values are known to correlate with an increased risk of soil deformation due to seismic shaking [5]. Soft soil layers in older urban areas, such as Kota Lama Semarang, also tend to experience high amplification and seismic vulnerability due to thick and water-saturated subsurface structures [6].

In the Gombel area specifically, microzonation studies using the microtremor method remain relatively limited. While the identification of dominant frequency to assess local amplification potential has been carried out, a comprehensive integration of PGA, GSS, and Kg parameters in a single analysis framework has not yet been fully implemented [7]. These parameters, however, are critical for mapping slope failure risks and local site effects, as also emphasized in earthquake microzonation studies conducted in the Bantul region [8].

Landslide-prone zones near Gombel have been identified through the combination of slope stability analysis and HVSr-derived shear wave velocity (V_s), focusing on areas where V_s is less than 400 m/s and slope safety factors are below 1.5 [2]. Slip surfaces in Jalan Gombel Lama have also been characterized using HVSr, with V_s values ranging from 100 to 300 m/s at low dominant frequencies of 0–2.5 Hz [3]. Further insight was provided through the integration of V_p , V_s , density, and layer thickness modeling

along the Kaligarang Fault zone, adjacent to the research area [9].

Based on this background, this study employs the single-station microtremor method to obtain dynamic subsurface data, which are then analyzed using the parameters of Seismic Vulnerability Index (Kg), Peak Ground Acceleration (PGA), and Ground Shear Strain (GSS). These parameters are used to comprehensively evaluate seismic vulnerability in the study area. While previous studies have primarily focused on shear wave velocity (V_s) or slope stability factors, this research presents a site-specific multiparameter approach that strengthens the assessment of seismic risk mitigation and urban development planning in high-risk areas such as Gombel Village. The outcomes of this study are expected to contribute to the

advancement of engineering geophysics and serve as a scientific foundation for the planning of earthquake-resilient infrastructure in seismically active urban regions.

MATERIALS & METHODS

The primary data in this study comes from microtremor measurements taken in Gombel Village, Semarang City. This area experienced a landslide event on February 22, 2021, which caused damage to residential areas, disrupted vital routes connecting the upper and lower areas of Semarang City, and affected the mobility and economic activities of the community (Figure 1). The specific research site, which exhibited ground subsidence, is illustrated in Figure 2.



Figure 1. Landslide on Jalan Gombel Lama, Semarang City, Central Java Monday (February 22, 2021) at Point D2, E2, F2.



Figure 2. Collapsed Road Condition Due to Ground Subsidence at Point D2, D3, E2, E3, F2, and F3

Based on the records of BPBD Semarang City, in the period of 2020-2024, there were at least 12 subsidence and landslide events in the Banyumanik - Gombel - Candisari area. Data acquisition was conducted at 65 measurement points (Figure 3) using GL-840 and GL-240 series data loggers, with a measurement duration of 10 minutes at each point. Microtremor data were collected on February 10

and March 9, 2024 in the study area. The acquisition was divided into two phases: the first phase was conducted at 25 points (marked in red on the post map) covering a wider observation area; the second phase was a detailed focus around the subsidence road section, with 40 additional measurement points (marked in yellow on the post map).

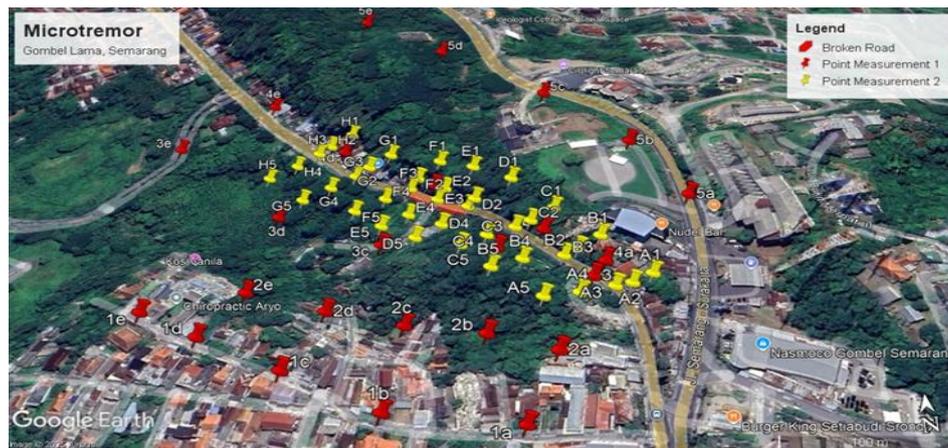


Figure 3. Single Station Microtremor Data Acquisition Survey Design

Data processing and analysis were conducted from January to April 2025 at the Geophysical Laboratory of Diponegoro University, Semarang. The microtremor recording data were first converted into .txt format using Notepad software, then processed using Geopsy software to obtain HVSR (Horizontal to Vertical Spectral Ratio) curves. Next, the data was continued to the inversion process using Dinver, and 2D modeling was done using Surfer 13.

There are four parameters obtained after performing the inversion process through dinver, namely, depth value, V_p value, V_s value, and density at each point. The results were frequency and amplification factor values, soil susceptibility index (Kg) values, peak ground acceleration (PGA) values, and ground shear (GSS) values analysis.

RESULT

Identification of ground layer characteristics can be done by analyzing the dominant frequency value produced by microtremor waves. A high dominant frequency reflects

the condition of sedimentary layers that tend to be thin and dominated by hard rock [10]. Conversely, the lower the frequency value, it indicates the presence of thicker sedimentary layers, which are generally softer and have greater potential to amplify ground vibrations during an earthquake.

The frequency value is a measure of the number of vibrations per unit time and is an important indicator in determining subsurface seismic characteristics.

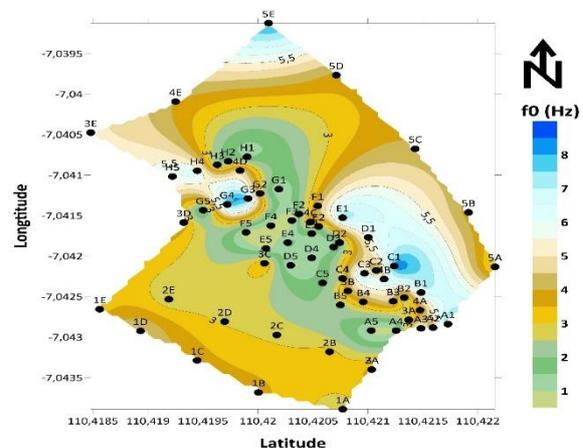


Figure 4. Contours of dominant frequency values in the study area

Based on the measurement results shown in Figure 4, the dominant frequency value at the study site varies between 0.59 Hz and 8.51 Hz. The lowest dominant frequency is found at point F3 with a value of 0.59 Hz, which indicates the presence of a very thick and soft soil layer. On the other hand, the highest dominant frequency was at point C1 at 8.51 Hz, indicating that the area is dominated by harder rocks with thin sedimentary layers. Meanwhile, the road that collapsed due to land subsidence at points D2, D3, E2, E3, F2, and F3 showed dominant frequencies of 1.59, 1.44, 1.56, 1.50, 1.43, and 0.59 Hz. These values are relatively low and geotechnically categorized as soil with type IV classification. This reflects that at this point there is a fairly thick accumulation of sedimentary layers, ranging from ≥ 30 m, which can affect the soil response to seismic activity.

The amplification value is an important indicator in seismic studies that describes the magnitude of increase in the amplitude of earthquake waves when crossing a geological medium. This factor is strongly influenced by wave velocity: the faster the waves propagate, the greater the amplification value that may occur [11]. Thus, this parameter becomes relevant in assessing the potential for vibration amplification in a region.

In this study, the results of the analysis of subsurface amplification values were obtained from microtremor data processing and visualized in Figure 5. The range of amplification values identified is in the range of 0.13 to 7.79. The lowest recorded value of 0.13 is found at point 5B, indicating that this area only experiences low wave amplification. In contrast, point F1 shows the highest amplification value of 7.79, which in the context of the general classification of soil susceptibility levels falls into the high category.

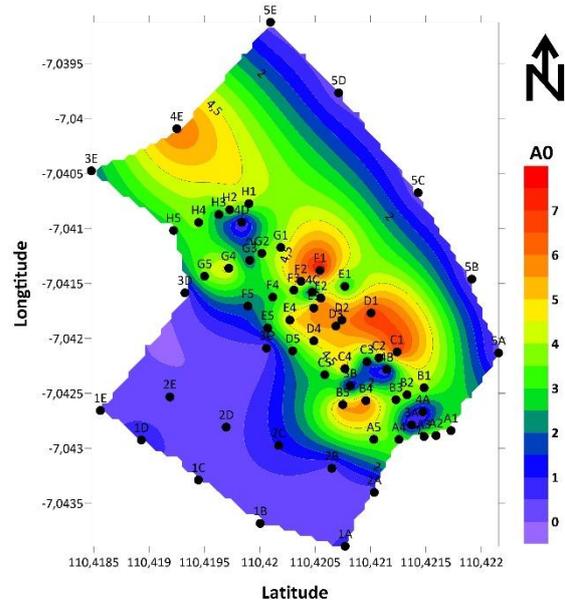


Figure 5. Contours of Amplification Factor Values in the Study Area

Meanwhile, points D2, D3, E2, E3, F2, and F3, which are known to have collapsed roads, have amplification values of 5.99, 5.54, 5.42, 5.77, 5.58, and 3.67, where the classification of soil vulnerability levels according to Daryono (2009) is classified as high. This data shows the relationship between the thickness of the sediment layer and the size of the amplification value, where the thicker the sediment layer traversed by waves, the greater the possibility of amplification of earthquake waves.

The soil susceptibility index (K_g) is a quantitative parameter obtained from the integration of several geotechnical variables, including amplification value, dominant frequency, sediment layer thickness, and seismic wave propagation speed. This parameter provides an overview of the potential level of soil susceptibility to earthquake shaking in an area. Based on the results of the primary data analysis in this study, the identified K_g values vary from 3.25×10^{-3} to 22.74.

Referring to the classification developed by Daryono (2009), the soil susceptibility index values are divided into three zone categories: non-hazardous zones with K_g values < 10 , moderately hazardous zones for the value range $10 \leq K_g \leq 20$, and hazardous zones with K_g values > 20 .

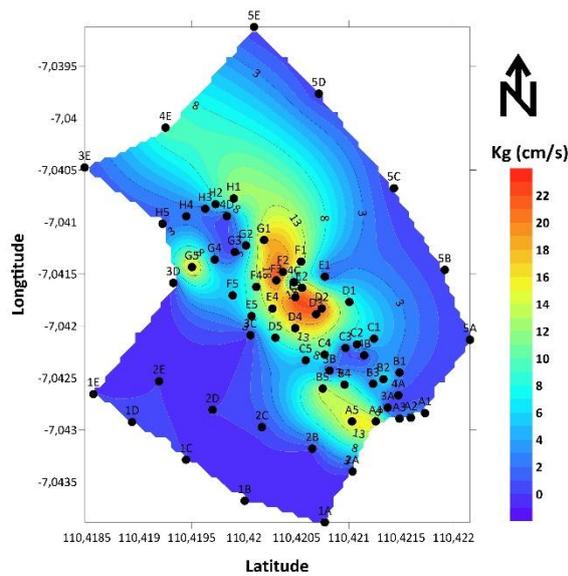


Figure 6. Contours of Seismic Vulnerability Index Values in the Research Area

The lowest index value of 3.25×10^{-3} is found at point 4B, indicating that the area falls into the safe or non-hazardous category. Meanwhile, the highest value of 22.74 is found at point F3, indicating that the area is classified as dangerous and has a high potential for soil vulnerability to seismic activity. Looking at Figure 6, point D2, D3, E2, E3, F2, and F3 recorded a Kg value of 22.54, 21.26, 18.82, 22.17, 21.85, and 22.74 which is classified as a high hazard zone (high category).

The moderate Kg value at point D2, D3, E2, E3, F2, and F3 are most likely influenced by the presence of the Kaligarang Fault located to the west of the study site. This river plays a role in influencing the subsurface characteristics, especially in terms of increasing the amplification value which then has an impact on increasing the soil susceptibility index. In a seismic context, amplification value and Kg index have a linear relationship; the greater the amplification value, the greater the potential susceptibility of the soil to seismic waves [12].

The calculation of the maximum ground acceleration (PGA) value at the bedrock layer was carried out using the approach formulated by Nakamura (1997) [13]. This model was applied based on the parameters

of the large earthquake that shook Yogyakarta on May 27, 2006, with a magnitude of 6.4 SR and an initial depth of 10 km. Based on these calculations, the PGA values at the study site ranged from 5.22 Gal to 5.24 Gal.

The resulting PGA values are strongly influenced by several seismic variables, including earthquake strength (magnitude), earthquake focal depth, and proximity of the study area to the epicenter.

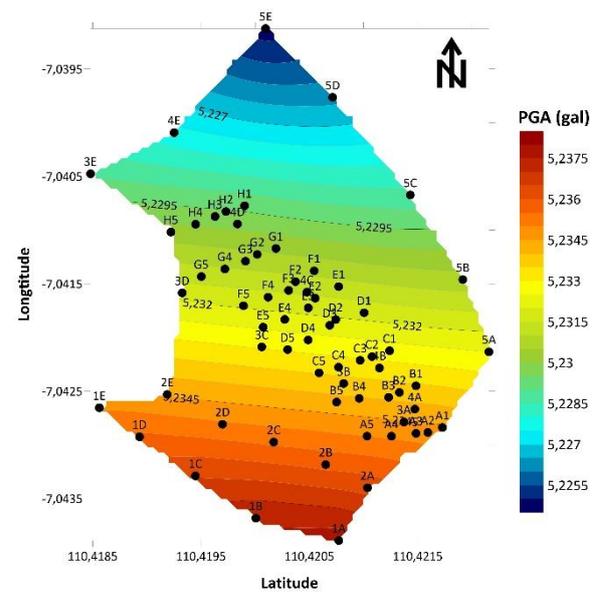


Figure 7. Contours of PGA Value in the Study Area

The landslide site is located at coordinates $7^{\circ}2'8.034''$ South latitude and $110^{\circ}24'52.330''$ - $110^{\circ}24'51.447''$ East longitude, with an elevation between 80 and 300 meters above sea level. The results of these calculations are visualized in Figure 7, which shows the variation of PGA at various observation points.

Point 5E recorded the lowest PGA value of 5.22 Gal, which based on the USGS (2017) classification is at the V intensity level. In contrast, point 1A showed the highest value of 5.24-Gal, equivalent to intensity V. Meanwhile, point D2, D3, E2, E3, F2, and F3 have a value of 5.23 Gal, which is classified as intensity V with moderate shaking and slight damage impact.

All these data indicate that the maximum ground acceleration value will increase

significantly when there is a vibration source such as an earthquake in the nearby area. In addition, there is a comparable relationship between PGA values and wave frequency; high-frequency waves tend to propagate more easily in low-density soil layers or looser structures than in dense, more homogeneous soils [14].

In seismic microzonation studies, the value of Ground Shear Strain (GSS) plays an important role as an indicator of the level of deformation that may occur in the soil due to earthquake wave propagation. This parameter is directly correlated with the values of the soil susceptibility index (Kg) and PGA; thus, an increase in one or both of these parameters will result in an increase in the GSS value. In other words, the greater the recorded values of Kg and PGA, the higher the magnitude of shear strain that occurs in the soil.

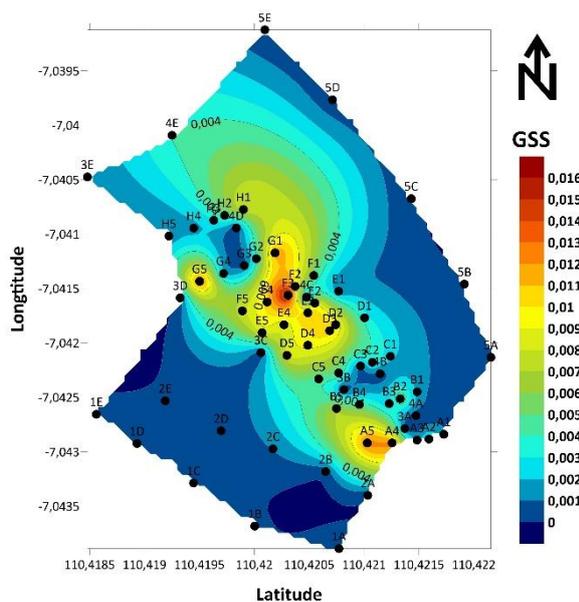


Figure 8. Contours of GSS Values in the Study Area

In geotechnical assessments of disaster-prone areas, the Ground Shear Strain (GSS) value serves as a critical parameter to represent the level of deformation that may occur in soils due to dynamic loads or subsurface stress changes. While commonly associated with seismic activity, GSS is also highly relevant for analyzing the potential for land subsidence and slope failure,

particularly in areas underlain by unconsolidated geological materials.

Based on the results illustrated in Figure 8, GSS values in this study range from 6.16×10^{-5} to 16.66×10^{-3} . Point F3 recorded the highest GSS value (16.66×10^{-3}), indicating a high degree of shear deformation and a significant potential for mass movement or slope instability. In contrast, point 4B exhibited the lowest value (6.16×10^{-5}), suggesting relatively stable ground conditions. Several points identified as experiencing land subsidence namely D2, D3, E2, E3, F2, and F3—also presented elevated GSS values, measured at 10.29×10^{-3} , 10.48×10^{-3} , 9.4×10^{-3} , 10.44×10^{-3} , 10.54×10^{-3} , and 16.66×10^{-3} , respectively. These values are consistent with the observed surface deformation, including gradual sinking and localized landslides. Such conditions are closely linked to the local geological setting, which is influenced by the presence of the Kaligarang Fault located to the west of the study area, as well as the geomorphological impact of the Kaligarang River, which intersects and erodes the surrounding slopes. Tectonic activity along the fault zone may generate subsurface weaknesses, while continuous erosion and weathering processes driven by the river contribute to soil softening and slope degradation. The combined effects of subsurface strain and slope instability result in a high susceptibility to ground deformation, particularly in zones exhibiting elevated GSS values.

CONCLUSION

The results of the microtremor investigation in Gombel Village, Semarang City, indicate that the area exhibits a high level of ground vulnerability, not only due to potential seismic activity but also significantly influenced by local geological conditions, steep slope morphology, and anthropogenic dynamic loads such as heavy traffic and construction activities. The seismic vulnerability index (Kg) values range from 3.25×10^{-3} to 22.74, categorizing the study area within high hazard zones on the ground

surface. Although the Peak Ground Acceleration (PGA) values range modestly between 5.22 and 5.24 Gal, based on the USGS classification, this level of ground motion could still intensify instability in areas with weak subsurface conditions.

Furthermore, the Ground Shear Strain (GSS) values, ranging from 6.16×10^{-5} to 16.66×10^{-3} , confirm significant strain behavior in the soil, especially at points D2, D3, E2, E3, F2, and F3, which also show clear signs of land subsidence and localized landslide occurrences. The elevated GSS values at these points reflect active elastic dynamics within the subsurface layers, highlighting zones of potential soil deformation and failure.

This condition is strongly associated with the presence of the Kaligarang Fault, located west of the study area, and the geomorphic influence of the Kaligarang River, which contributes to slope weakening through continuous erosion. The combination of fault-induced structural weakness, unconsolidated sediments, and slope steepness results in a high susceptibility to land movement and slope failure, even without the presence of a triggering earthquake.

Therefore, the parameters GSS, PGA, and Kg, derived from single-station microtremor data, prove to be effective in identifying areas with elevated geotechnical hazard potential, and serve as a valuable reference for future land subsidence and landslide risk mitigation in vulnerable regions such as Gombel Village.

Declaration by Authors

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