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Nilai *Ground Shear Strain* Pada Kecamatan Berbah, Kabupaten Sleman

(Ground Shear Strain Values in Berbah Subdistrict, Sleman Regency)

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ABSTRAK

Kecamatan Berbah, Kabupaten Sleman, Daerah Istimewa Yogyakarta berada pada zona transisi antara endapan vulkanik Gunung Merapi di bagian utara dan zona aktif Sesar Opak di bagian selatan, sehingga tergolong wilayah rawan guncangan gempa bumi. Kondisi geologi yang bervariasi antarwilayah menyebabkan respons tanah terhadap gelombang seismik juga bervariasi, sehingga diperlukan kajian mengenai potensi deformasi tanah melalui parameter *Ground Shear Strain* (GSS). Penelitian ini bertujuan untuk mengestimasi nilai GSS di empat desa, yaitu Jogotirto, Kalitirto, Sendangtirto, dan Tegaltirto, sebagai indikator potensi deformasi tanah akibat aktivitas seismik. Nilai GSS dihitung dengan memanfaatkan data sekunder hasil akuisisi mikroseismik yang telah diolah menggunakan metode HVSR dari penelitian sebelumnya, meliputi nilai indeks kerentanan seismik (Kg) dan percepatan tanah maksimum (PGA), mengacu pada persamaan Nakamura ($\gamma = Kg \times 10^{-6} \times \alpha max$). Hasil penelitian menunjukkan nilai GSS di Kecamatan Berbah berkisar antara $8{,}063 \times 10^{-3}$ hingga $1{,}460 \times 10^{-2}$. Nilai tertinggi terkonsentrasi di bagian tengah hingga selatan Desa Tegaltirto, serta sebagian selatan Kalitirto dan tenggara Jogotirto, sedangkan nilai terendah tersebar di sebagian besar Sendangtirto, barat laut Kalitirto, dan bagian tengah Jogotirto. Berdasarkan klasifikasi Ishihara (1982), nilai GSS di wilayah penelitian tergolong dalam kategori elastoplastis hingga mendekati kategori keruntuhan, dengan Tegaltirto sebagai wilayah yang paling berpotensi mengalami penurunan tanah, pemadatan, dan likuefaksi akibat kedekatannya dengan Sesar Opak dan sedimen permukaan yang relatif longgar. Hasil ini menegaskan bahwa Tegaltirto perlu menjadi prioritas utama dalam upaya mitigasi bencana dan perencanaan pembangunan infrastruktur tahan gempa di Kecamatan Berbah.

Kata kunci: *Ground Shear Strain*, HVSR, Indeks Kerentanan Seismik, Kecamatan Berbah, PGA

ABSTRACT

Berbah Subdistrict, Sleman Regency, Special Region of Yogyakarta, lies in a transitional zone between the volcanic deposits of Mount Merapi to the north and the active Opak Fault zone to the south, making it a seismically hazard-prone area. Variations in local geological conditions across the subdistrict cause differing ground responses to seismic waves, requiring an assessment of potential ground deformation through the Ground Shear Strain (GSS) parameter. This study aims to estimate GSS values across four villages—Jogotirto, Kalitirto, Sendangtirto, and Tegaltirto—as indicators of potential ground deformation resulting from seismic activity. GSS values were calculated using secondary microseismic data previously processed with the HVSR method, incorporating the seismic vulnerability index (Kg) and peak ground acceleration (PGA) based on Nakamura's equation ($\gamma = Kg \times 10^{-6} \times \alpha max$). Results show that GSS values in Berbah Subdistrict range from 8.063×10^{-3} to 1.460×10^{-2}. The highest values are concentrated in central to southern Tegaltirto, as well as southern Kalitirto and southeastern Jogotirto. In contrast, the lowest values are distributed across most of Sendangtirto, northwestern Kalitirto, and central Jogotirto. Based on Ishihara's (1982) classification, GSS values in the study area fall within the elastoplastic category, approaching the collapse category, with Tegaltirto identified as most susceptible to land subsidence, compaction, and liquefaction due to its proximity to the Opak Fault and loose surface sediments. These findings underscore that Tegaltirto should be prioritized in disaster mitigation efforts and earthquake-resistant infrastructure planning in Berbah Subdistrict.

Keywords: *Berbah Subdistrict, Ground Shear Strain, HVSR, PGA, Seismic Vulnerability Index*

1. Introduction

Interactions between tectonic plates can trigger subduction and plate movement (Figure 1). Subduction zones exhibit high levels of geological activity, making them highly prone to earthquakes. Indonesia's location at the junction of several active tectonic plates causes this region to experience frequent earthquakes (PusGeN, 2017).

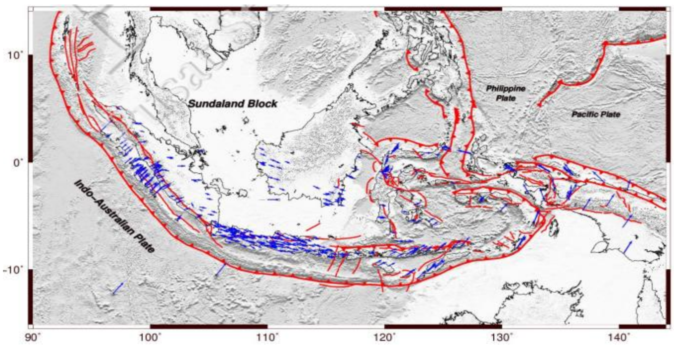

Figure 1 Tectonic Map of Indonesia Based on Geodetic Data Through 2016, Velocity Vectors in the ITRF 2008 Reference System (PusGeN, 2017)

The Special Region of Yogyakarta consists largely of Quaternary Merapi deposits, which include ash, tuff, breccia, agglomerate, and lava, while young alluvial deposits such as sand, gravel, silt, and clay dominate along rivers and in coastal areas. Furthermore, in the Southern Mountains, several formations occur, namely the Kepek Formation, along with the Wonosari Formation and the Sentolo Formation, which are dominated by limestone and sandstone. There is also the Sambipitu Formation, which contains tuff, shale, siltstone, sandstone, and conglomerate. Next is the Nglanggran Formation, composed of volcanic breccia, agglomerate, lava, and tuff. Then there is the Semilir Formation, consisting of breccia and various types of tuff, which is the oldest rock unit (Rahardjo et al., 1995).

Geologists have long been aware of the Opak Fault in Yogyakarta, a strike-slip fault oriented southwest–northeast that extends from the mouth of the Opak River to the Prambanan area. Following the 2006 Yogyakarta earthquake, several experts concluded that activity along the Opak Fault with the epicenter located near the river mouth was the primary factor causing the disaster. Information regarding the Opak Fault as a strike-slip fault can also be found on the Yogyakarta Geological Map compiled by Rahardjo et al. (1995), as cited by (Santoso, 2009).

Understanding the shear strain of the soil in a given area is important because it reflects the soil layers' ability to vibrate, shift, or even stretch during an earthquake. The potential for shaking and deformation during an earthquake is influenced not only by the magnitude and hypocenter but also by the region's geological conditions. To determine the geological characteristics, measurements using the HVSR (Horizontal-Vertical Spectral Ratio) method via microseismic waves can reveal the dominant frequency and amplification values in the area. The HVSR (Horizontal-Vertical Spectral Ratio) method is a technique that can estimate the amplification and dominant frequency of an area based on field acquisition recordings using microseismic equipment (Mala et al., 2021). Amplification values in Berbah Subdistrict range from low to very high. Low to moderate amplification is found in Kalitirto Village, Jogotirto Village, and Sendangtirto Village. Meanwhile, Tegaltirto has very high ground amplification values due to the presence of hard sediment and rock types, making this area prone to earthquakes. Furthermore, the dominant frequency values in the Jogotirto Village area correspond to regions with low surface sediment thickness, ranging from approximately 10 to 30 meters. In areas with sediments of relatively similar hardness and soil types, the dominant soil frequency shows an inverse relationship with sediment thickness. High dominant frequency values are generally found in locations with thinner sediment layers, while low dominant frequency values tend to indicate thicker sediment layers (Haniifah, 2023).

A previous study (Nugraheni et al., 2024), acquired microseismic data and subsequently combined HVSR processing with an inversion scheme to reconstruct shear wave velocity profiles down to a depth of 30 m (Vs30), which recorded shear wave velocity values (Vs30 values) around the Opak River in the Merapi Muda (Qmi) deposits ranging from 183 to 301 m/s, as most of the Qmi area consists of sand and silt-clay layers. Such characteristics of Merapi Muda volcanic deposits generally exhibit low frequencies and long wavelengths, causing seismic energy to dissipate slowly, resulting in relatively small amplification but a slower attenuation process. Consequently, seismic waves propagate more slowly as they travel through relatively soft material (Nugraheni et al., 2023).

The HVSR method is not only used to obtain Vs values, amplification, and dominant frequencies but can also be used to determine the seismic vulnerability index (Kg). This value is influenced by several factors, such as the dynamic response of the soil and subsurface structural conditions, including layer thickness (H) and geometry (2D/3D) (Zeroual et al., 2025). Based on the results of microseismic data acquisition, the seismic vulnerability index in the Berbah subdistrict shows a low (Kg) value. However, in the Tegaltirto village area, the (Kg) value is high because this area has a high amplification level and a low dominant frequency. This is due to impedance contrast that is, the ability of seismic waves to pass through rock and because the sedimentary layer is thinner than the underlying rock layer. Topographically, the Tegaltirto Village area is also a hilly region located near Mount Wangi (Haniifah, 2023).

The physical impact of an earthquake is greatly influenced by the magnitude of the maximum ground acceleration, or Peak Ground Acceleration (PGA), in the affected area. PGA represents the highest ground acceleration recorded at a given location, derived from the analysis of earthquake event data over a specific time period along with various related seismicity parameters (Ashadi & Kaka, 2019; Chasanah et al., 2022). The magnitude of the PGA value is determined by several factors, namely the characteristics of the earthquake source, the path of seismic wave propagation, and local geological conditions. These differences in regional geological characteristics cause PGA values to vary from one area to another (Ulfiana et al., 2018). Furthermore, it is important to distinguish between two key parameters: peak ground acceleration (PGA), which describes the magnitude of acceleration at bedrock, and peak ground acceleration at the surface (PGAm), which represents the acceleration value measured at the ground surface. Both parameters play a crucial role in estimating the level of damage that may result from a seismic event (Raharjo & Ahadi, 2024).

Young Merapi sediments (Qmi) produce higher PGA values compared to areas with hard rock lithology, because these young sedimentary layers amplify seismic vibrations more effectively. This is evident in a comparison of PGA values around the epicenter of the Yogyakarta earthquake, where vibration amplification in hard rock was significantly lower than in Young Merapi sediments (Pawirodikromo, 2020). Distribution of Peak Ground Acceleration (PGA) values in the Kalitirto, Sendangtirto, Tegaltirto, and Jogotirto areas. PGA values range from 290.64 to 827.98 gal, with the highest values concentrated in the eastern part of Tegaltirto. In contrast, the lowest values are found in the western part of Sendangtirto and the southern part of Tegaltirto. The red line on the map indicates the location of the Opak Fault, which lies on the eastern side of the study area (Haniifah, 2023).

This study aims to estimate the GSS values for the earthquake event in Berbah Subdistrict, Sleman Regency, Special Region of Yogyakarta.

2. Data and Methodology

2.1. Data and Location

In this study, Ground Shear Strain (GSS) values were determined using various microseismic data sets acquired in a previous study by Haniifah (2023) (Table 1). The dataset used in this study consisted of 36 observation points evenly distributed across the Berbah subdistrict in Sleman Regency, with a distance of approximately 1 km^2 between each point. The Berbah subdistrict in Sleman Regency was selected as the study site, encompassing four villages: Jogotirto, Kalitirto, Sendangtirto, and Tegaltirto.

Table 2 The value of, Seismic Vulnerability Index and PGA (Haniifah, 2023)

Number	**Kg** (s^2/cm)	**PGA (gal)**
1	27,0892	353,218
2	26,6925	361,399
3	28,4512	392,347
4	14,9692	400,627
5	10,4794	356,891
6	13,3052	385,136
7	15,2549	465,057
8	14,9392	465,586
9	14,2548	379,067
10	20,1175	390,339
11	91,0996	355,185
12	33,948	551,014
13	33,948	548,55
14	53,5277	386,555
15	42,6725	430,134
16	13,6326	490,345
17	24,9317	330,868
18	13,9068	487,483
19	23,7625	427,422
20	42,5136	424,137
21	4,2	830,451
22	1,8602	529,011
23	25,338	530,928
24	18,2909	526,709
25	14,9976	524,474
26	49,5397	484,488
27	49,5397	441,928
28	9,7601	685,922
29	564,6338	290,049
30	16,8005	502,784
31	16,2701	453,407
32	16,4071	478,965
33	17,3751	544,365
34	45,6696	407,083
35	27,6537	467,716
36	10,8464	634,309

In collecting microseismic data, Haniifah (2023) used a Lunitek TRITON-5s Digital Seismic microseismic sensor. This sensor was used to record microtremors captured from passive seismic vibrations originating beneath the ground surface. The microseismic data recorded vertical seismic waves and two horizontal seismic waves. The data were processed using the HVSR method with Geopsy software to generate an H/V curve (HVSR). This curve subsequently yielded the data used in this study, including amplification values, dominant frequency values, peak ground acceleration (PGA) values, and earthquake vulnerability index (Kg) values.

The choice of the Berbah Subdistrict as the research location was based on several factors. The geological and geomorphological conditions in this area are quite varied, necessitating an in-depth study of the soil's response to seismic shaking. Additionally, the Opak River flows through this area from the northeast to the south, bisecting the central part of Berbah Subdistrict. As one of the main geomorphological features, the presence of this river is expected to influence the surrounding lithological conditions, particularly in the alluvial plains, which in turn may affect the soil shear strength (GSS) values in the area. Based on these parameters, this study aims to produce more representative GSS estimates for Berbah Subdistrict and its surrounding areas.

2.2. Methodology

The ground shear strain (GSS) parameter measures the magnitude of strain occurring in the ground as a result of seismic activity. High ground shear strain values indicate that surface sediment layers are more likely to undergo stretching. Such stress and shear conditions can cause various forms of soil deformation, including landslides and liquefaction (Nakamura, 1989; Awaliyah et al., 2023). Meanwhile, a low ground shear strain value indicates that the potential for soil layer deformation is relatively small. When acceleration occurs in a soil layer, the magnitude of shear strain at the surface can be estimated hypothetically using the seismic vulnerability index (Kg) and maximum ground acceleration (αmax) (Nakamura, 2000; Nakamura, 2008; Farid and Hadi, 2018; Awaliyah et al., 2023)). The calculation of the GSS value is based on the following Equation (1):

$$\gamma = Kg \times 10^{-6} \times \alpha max \quad (1)$$

Notes:
γ = Shear Strain
Kg = Seismic Vulnerability Index (s^2/cm)
αmax = Maximum Ground Acceleration (gal) (Nakamura, 2000; Nakamura, 2008; Farid and Hadi, 2018; Awaliyah et al., 2023).

The relationship between ground shear strain (GSS) values and soil dynamic response is shown in Table 2. At low GSS values, approximately 10^{-6}–10^{-5}, the soil remains elastic and experiences only wave propagation and vibrations. In the range of 10^{-4}–10^{-3}, the soil begins to exhibit elastoplastic behavior, which can trigger cracks and ground subsidence (Ishihara, 1982; Awaliyah et al., 2023).

Table 2 The value of soil characters and the value of seismic ground shear strain
(Ishihara, 1982; Awaliyah et al., 2023)

GSS	**Value**		
	$\mathbf{10^{-6}–10^{-5}}$	$\mathbf{10^{-4}–10^{-3}}$	$\mathbf{10^{-2}–10^{-1}}$
Soil Conditions Phenomenom	Wave propagation, vibration	Crack. settlement	Landslide, compacting soil, liquefaction
Nature of soil dynamics	Elasticity	Elasto-plasticity	Collapse

3. Results and Discussion

The map of soil shear strength (GSS) distribution for Berbah Subdistrict shows GSS values ranging from 8.063 × 10^{-3} to 1.460 × 10^{-2}. The highest values are indicated by a red zone concentrated in the central to southern parts of Tegaltirto Village. Areas with relatively high values are also found in the southern part of Kalitirto and the southeastern part of Jogotirto, which are marked in shades of yellow to orange. Meanwhile, lower GSS values are distributed across most of Sendangtirto, the northwestern part of Kalitirto, and the central part of Jogotirto, which are shown in blue. This pattern indicates that the ground deformation response is not evenly distributed and tends to increase in the central part of the study area. Overall, this spatial pattern makes it clear that the potential for ground deformation in Berbah Subdistrict is not evenly distributed. Rather, it is tightly concentrated around a central hotspot, rather than spreading uniformly outward. Tegaltirto stands out as the centre of risk, with values gradually decreasing as one moves toward the western, eastern, and northern edges of the subdistrict. This concentric-like decrease, clearly visible on the map, reinforces the idea that local geological conditions around Tegaltirto not just the distance from the Opak Fault play a significant role in amplifying the shear stress in the village.

According to Ishihara's (1982) classification as cited in Awaliyah et al. (2023), GSS values in the range of 10^{-4}–10^{-3} are associated with elastoplastic soil behaviour that can cause cracks and ground subsidence, while values in the range of 10^{-2}–10^{-1} indicate soil conditions with the potential for collapse, consolidation, landslides, and liquefaction. With a maximum value of 1,460 × 10^{-2}, the red zone in Tegaltirto falls into the high-deformation category and has the greatest potential for soil collapse. Meanwhile, the area with a minimum value of 8.063 × 10^{-3} is close to the boundary of the 10^{-2} category and can therefore be considered a transition zone toward collapse behaviour. This is caused by various factors, primarily related to geological conditions; according to Rahardjo et al. (1995), the Opak Fault extends along the Opak River. Furthermore, previous research by Haniifah, (2023) indicates that the amplification values for the area in Tegaltirto Village suggest seismic wave amplification influenced by subsurface materials with soft sediment conditions; the low dominant frequency values indicate a thick sediment layer, which can cause seismic wave velocity to decrease and the amplitude to increase upon reaching the surface.

The results of this study are consistent with previous research, which indicated that the Berbah subdistrict exhibits varying GSS values, with Tegaltirto Village being the area with the highest potential for landslides due to its high amplification value and low frequency value in other words, its thick sedimentary layer. Ground shear strain provides insight into the likelihood of shear deformation occurring in the event of a future earthquake.

Therefore, the Berbah subdistrict particularly the Tegaltirto village area is a region that requires greater attention in earthquake hazard studies, especially regarding the potential for ground subsidence, compaction, and liquefaction. Conversely, the blue-shaded areas have a relatively lower level of vulnerability.

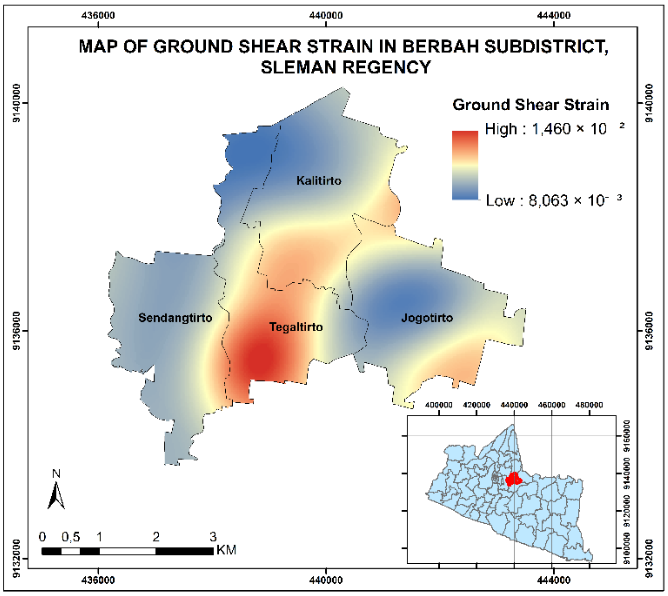

Figure 2 Ground Shear Strain Map of Berbah Subdistrict, Sleman Regency

4. Conclusion

The ground shear strain (GSS) distribution map for Berbah Subdistrict shows values ranging from 8.063×10^{-3} to 1.460×10^{-2}. The highest values (red zone) are concentrated in the central to southern parts of Tegaltirto Village, with other relatively high zones (yellow–orange) also found in southern Kalitirto and southeastern Jogotirto. In contrast, lower GSS values (blue zone) are distributed across most of Sendangtirto, northwestern Kalitirto, and central Jogotirto. This pattern indicates that ground deformation response is not evenly distributed and tends to increase toward the central–southern part of the study area.

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Accordingly, Tegaltirto is an area that requires greater attention in seismic hazard studies, particularly regarding the potential for ground subsidence, compaction, and liquefaction, given its proximity to the Opak Fault and its relatively loose surface sediments. In contrast, the blue-colored areas exhibit a relatively lower level of vulnerability. These findings underscore the importance of prioritizing Tegaltirto in disaster mitigation efforts and earthquake-resistant infrastructure planning in Berbah Subdistrict.

5. Acknowledgments

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