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SPATIAL DISTRIBUTION OF VS30 BASED ON MASW AND MICROTREMOR INVERSION IN GUNUNGKIDUL, YOGYAKARTA, INDONESIA

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ABSTRACT: Gunungkidul Regency, Yogyakarta, is one of the earthquake-prone areas in Java. Hazard assessments are necessary to create an earthquake risk map for the area. An earthquake hazard assessment can be performed by identifying the site conditions from the average value of the shear wave velocity to a depth of 30 meters (Vs30). This research aims to analyze the spatial distribution of Vs30 in the Gunungkidul region. We collected 98 microtremors and MASW from site surveys and previous studies. The data inversion was done to obtain a one-dimensional (1D) Vs30 model and estimate the Vs30 value. The results are presented in the Vs30 spatial distribution map and site classification. They show that the value of Vs30 is mostly high, with a range of 355 – 1092 m/s. The site classification is in the very dense soil or soft rock (SC) to rock (SB). The Vs30 value tends to be higher than the United States Geological Survey (USGS), especially in the karst plateau area, which has a gentle slope, where the site class was SC while the USGS was stiff soil (SD). Based on the landform analysis, fluvial landforms have low Vs30 with an average of 437 m/s. However, karst and structural landforms have high Vs30 with an average of 713 m/s and 691 m/s, respectively. The difference in these values indicates that local conditions significantly affect the Vs30. This study benefits disaster mitigation and serves as the basis for regional development based on earthquake risk reduction.

Keywords: Vs30, Spatial distribution, MASW, Microtremor, Inversion, Gunungkidul

1. INTRODUCTION

Gunungkidul region, located 39 km southeast of Yogyakarta City, is tectonically one of the most active areas in Indonesia. The location of Gunungkidul, which is closer to the subduction zone of the Indo-Australian Plate against the Eurasian Plate in the Indian Ocean south of Java Island, causes this condition. In addition, the Gunungkidul region and its surroundings are also highly prone to earthquakes due to activities of local faults on land [1]. The seismicity map of Gunungkidul and its environs for 2009-2020 shows that seismic activity in the area is very high [2] (Figure 1). Based on the history of Java earthquakes, several destructive earthquakes caused damage and casualties. One of which is the Yogyakarta earthquake on May 27, 2006, with a magnitude of 6.3, causing 5716 fatalities and more than US$ 3134 million in economic losses [3]. The ground shaking was very intense and caused widespread destruction due to a relatively shallow earthquake [4].

When earthquake prediction efforts have not been successful, earthquake mitigation is the best effort to anticipate earthquake disasters. The first step in earthquake mitigation efforts is to develop an earthquake risk map. One of the variables for developing an earthquake risk map is earthquake hazard assessment. An earthquake hazard assessment can be done by analyzing the intensity of ground surface shaking. Ground surface shaking is obtained by the intensity of base rock shaking and the amplification factor of ground motion. The potential amplification of ground motion can be estimated by identifying local site characteristics. The local site characteristics or site conditions can be determined from the mean value of the shear wave velocity to a depth of 30 meters (Vs30) [5 – 7]. Vs30 is an excellent indicator to illustrate the characteristics of soil stiffness and strength [8-9]. The use of Vs30 as a site effect variable has been widely debated [10 – 11]. However, it is agreed and recognized that the value of Vs30 will continue to be used in the future [12 – 13].

Measuring Vs30 using the drilling method provides a good subsurface profile, but it is time-consuming and expensive. Subsequently, geophysical techniques have been developed to obtain a shear wave velocity profile to a depth of 30 meters (Vs30) [14]. This study used the inversion method of Multichannel Analysis of Surface Waves (MASW) and microtremor. This technique is quite popular because of its convenience. Vs30 site survey results represent the subsurface layer under the measurement site. These values are then transformed into the spatial distribution of Vs30.

The main objective of this research is to analyze the spatial distribution of Vs30 for the Gunungkidul area using the inversion of MASW and microtremor measurements. The research results are expected to benefit the development of science due to the limited literature related to Vs30. Furthermore, the spatial distribution of Vs30 can be used as a basis for regional development in Gunungkidul Regency based on earthquake risk reduction and as a consideration for the initial design of earthquake-resistant infrastructure.

2. RESEARCH SIGNIFICANCE

This study will contribute to earthquake disaster mitigation and reduce risks to people and infrastructure in the Gunungkidul area. The Vs30 for earthquake hazard assessment is one of the exciting research topics in earthquake mitigation. Some research on Vs30 has been done by previous researchers [5, 7, 15 – 16]. However, research on Vs30 in Gunungkidul based on on-site measurements is limited. This study is based on exploratory applied research using site measurements and spatial analysis. As an innovation, this study used MASW and microtremor inversions to analyze the spatial distribution of Vs30 in Gunungkidul. This approach also opens up new perspectives for analyzing the spatial distribution of Vs30 in any area when the budget for the survey is limited.

3. METHODS

We used 98 site measurements with the method of MASW (27 sites) and microtremor (71 sites) to estimate the value of Vs30 in Gunungkidul. The data came from a direct site survey of 86 sites and previous studies at 12 sites [17]. The distribution map of measurement sites is presented in Figure 2.

3.1 MASW Method

MASW is a seismic technique performed on the ground surface to characterize shear wave velocity distribution in the shallow subsurface. The MASW method utilizes Rayleigh surface waves identified as the most substantial seismic waves. The technique determines the wave dispersion curve (different frequencies move at different speeds), which is then inserted into the shear wave velocity of the soil layer [18 – 19].

A 7 kg hammer and 24 geophones with a vertical frequency of 4.5 Hz and a spacing of 2 m between geophones were used to record MASW data. The SeisImager software was used to analyze the data. The recorded time-domain data captured by the geophone were converted into the frequency domain using the Fourier Transform. The results were converted into a dispersion curve (different frequencies move at different speeds). The dispersion curve picking process was used for fundamental model selection [20]. Subsequently, an inversion of the shear wave velocity profile was obtained using the procedure described in the SeisImager/SW software manual [21]. Inversion was performed to obtain a one-dimensional (1D) model of shear wave velocity (Vs) concerning depth by considering the resulting Root Mean Square Error (RMSE). The smaller the RMSE, the better the 1D model produced.

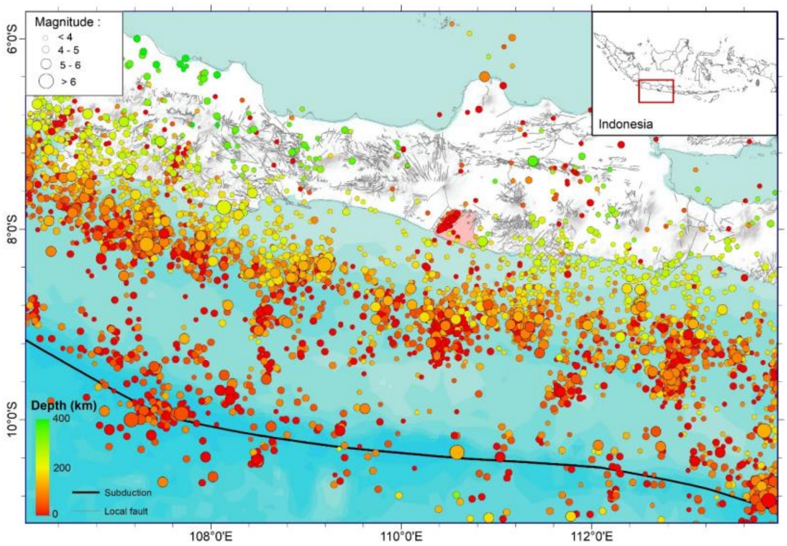


Fig.1 Seismicity map of Gunungkidul and surrounding areas, period 2009 – 2020 [2]

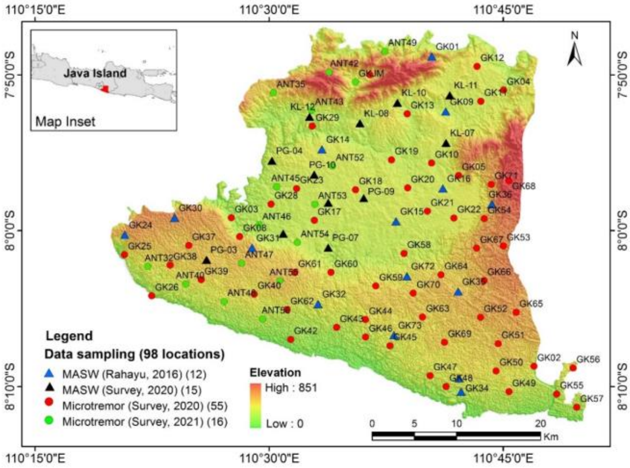


Fig.2 Distribution map of Vs30 site measurement

3.2 Microtremor Processing and Inversion

Horizontal-to-Vertical Spectral Ratio (HVSR) method was used for microtremor data processing. A short period seismograph with three components, horizontal (N and E), and vertical (V), was used to record microtremor data. According to the expected results, the minimum recording time is 30 minutes to get the lowest fundamental frequency of 0.2 Hz [22]. The HVSR amplitude spectrum was obtained by Geopsy software. The spectrum was calculated every 25 seconds of the entire signal divided into windows. The recorded data from the time sequence was converted into a frequency sequence by the Fast Fourier Transform (FFT) process. This process converts the recorded signal into an amplitude spectrum. The average HVSR in each window can be determined by equation (1).

$$\mathrm{HVSR} = \sqrt{\mathrm{F}_{\mathrm{N}}^{2} + \mathrm{F}_{\mathrm{E}}^{2}/(2\mathrm{F}_{\mathrm{V}}^{2})} \qquad (1)$$

where FN, FE, and FV are the Fourier amplitude spectrum in the north-south, east-west, and vertical components.

The HVSR inversion process was used to determine the value of the shear wave velocity by minimizing the objective function, namely the difference between the observed and calculated HVSR. OpenHVSR Software [23] was used for HVSR inversion to obtain a subsurface Vs model. HVSR inversion was carried out using the principle of forwarding modeling (FWD). The subsurface layer was assumed to be a homogeneous viscoelastic layer stack over half the space. It is described in terms of thickness (H), density (Rho), compression and shear wave velocities (Vp, Vs), and appropriate damping factors (Qp, Qs).

A 1D subsurface model was defined for each location. FWD was used to calculate the amplification spectrum of body waves and surface waves based on the HVSR curve. A constraint was needed during the inversion process of the HVSR curve to get an accurate value of Vs. In this case, we used the drill data provided for initialization or the input entered when inverting.

3.3 Vs30 Estimation and Site Class

The value of the shear wave velocity represents the shear properties of the soil structure and is an important parameter to determine the dynamic characteristics of the soil. Shear waves analyze and evaluate local site effects, especially in sedimentary layers above bedrock. The National Earthquake Hazard Reduction Provisions or NEHRP [24] has included criteria for determining local site conditions based on Vs30, while the National Standard of Indonesia (SNI) 1726:2019 [25] issued rules for estimating the value of Vs30 by calculating based on equation (2).

$$\mathrm{V_s30} = \frac{\sum_{\mathrm{i}}^{\mathrm{n}} \mathrm{h_i}}{\sum_{\mathrm{i}}^{\mathrm{N}} \frac{\mathrm{h_i}}{\mathrm{v_{si}}}} \qquad (2)$$

where Vs30 is the average shear wave velocity to a depth of 30 m, $\mathrm{h_i}$ and $\mathrm{V_{si}}$ are the thickness of the soil layer, and the shear wave velocity in each layer, respectively.

The earthquake resistance building planning is strongly influenced by the location and soil conditions. SNI 1726:2019 regarding earthquake resistance building planning procedures for building and non-building structures has classified site classes into six types: Hard Rock, Rock, Very Dense Soil or Soft Rock, Stiff Soil, Soft Soil, and Site-Specific. Table 1 shows the site class classification referring to SNI 1796:2019 [25].

Table 1 Site classification by Vs30 value [25]

Site Class	Vs30 (m/s)
SA (Hard Rock)	> 1500
SB (Rock)	>750 – 1500
SC (Very Dense Soil or Soft Rock)	>350 – 750
SD (Stiff Soil)	175 - 350
SE (Soft Soil)	< 175
SF (Others)	The site-specific, geotechnical investigation required

3.4 Spatial Distribution of Vs30

The spatial distribution of the Vs30 value in Gunungkidul was obtained by interpolating all Vs30 values between sites one to another using the Kriging method. Furthermore, the spatial distribution of Vs30 as a result of our interpolation was reclassified into eight classes following the United States Geological Survey (USGS), with classification <180, 180 – 240, >240 – 300, >300 – 360, >360 – 490, >490 – 620, >620 – 760, and >760 m/s. In addition, we also reclassified based on the size classification of SNI 1796:2019 [25] in Table 1 into five classes. Furthermore, this spatial distribution was proposed for the spatial distribution map of Vs30 for the Gunungkidul region.

4. RESULTS AND DISCUSSION

The spatial distribution of Vs30 in the Gunungkidul area was carried out after the inversion of the MASW and microtremor data. The result of the inversion process is a 1D Vs curve, which contains information on the shear wave velocity at each depth. Figure 3 shows the dispersion curve and 1D model of Vs30 at the GK31 MASW measurement site, while Figure 4 shows results from the inversion of the HVSR curve and the 1D model of Vs at the GK03 microtremor measurement site.

The value of Vs30 from each research location was calculated using equation (2). Based on the results of data processing at 98 site measurements, it shows that the value of Vs30 is in the range of 355 – 1092 m/s, as shown in Table 2. In general, the value of Vs30 in the Gunungkidul area is relatively high, with an average value of 693 m/s. Low Vs30 values were found in five sites only (GK10, GK16), Nglipar (GK13, KL10), and Ngawen (GK09) with values ≤490 m/s. Referring to the site classification of SNI 1796:2019 in Table 1, the site class value for the Gunungkidul area is in the range of site class SC (Very Dense Soil, Soft Rock) to SB (Rock). The detail of 98 site measurements shows that 61 sites are SC and 37 sites are SB. Site class SC has Vs30 values between 350 – 750 m/s and SB between 750 – 1500 m/s.

The spatial distribution map of the Vs30 is shown in Figures 5a and 5b. Almost the entire area of Gunungkidul has a high Vs30 value above 490 m/s. Site classification into SC and SB classes was proposed for the spatial distribution map of Vs30 in Gunungkidul. Medium Vs30 values are in some areas of Nglipar, Karangmojo, and Ngawen district, with values from 355 – 490 m/s, but they are still in the SC site class range. Site class SC is a type of soft rock or very dense soil. Microtremor observations in Padang City revealed that the soft soil condition values of Vs30 were below 400 m/s [26]. The high value of Vs30 that dominates the Gunungkidul area is related to shallow sediment layers or rock outcrops located in the highlands. Due to these conditions, a large earthquake in the Gunungkidul area rarely causes damage or casualties compared to other regions [3]. This is evidenced by the lack of references that discuss the damage and losses caused by the earthquake in the Gunungkidul region.

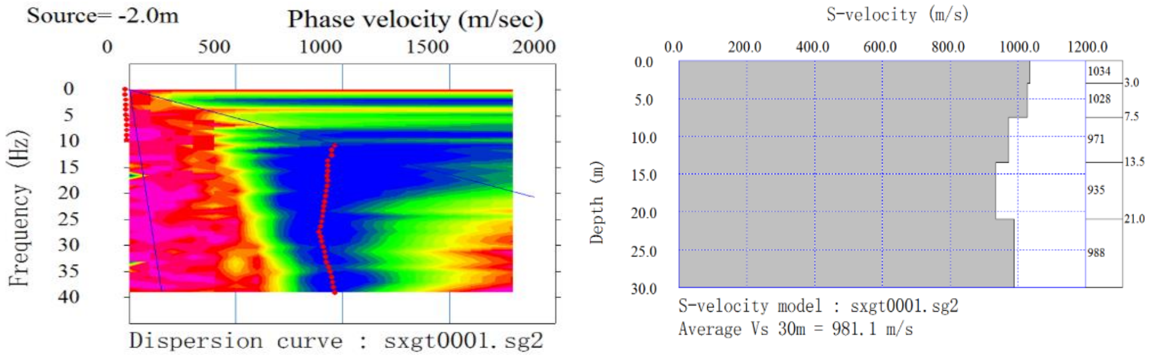
Each type of site class provides a different response when an earthquake occurs, including increasing the amplitude of the earthquake waves or just continuing the waves [27-28]. In the site class SC or lower, earthquake waves propagate at a lower speed but higher amplitude. On the other hand, earthquake waves are only transmitted at site class SA or SB [28]. Subsurface deposits that have a lower Vs than bedrock tend to amplify earthquake shaking while prolonging the duration. This kind of amplification potential is commonly referred to as the local site effect.

In general, the spatial distribution of Vs30 that we propose has higher values than the USGS model, as shown in Figures 6a and 6b. The Vs30 value of the USGS model is a proxy of the topographic slope model developed by Wald and Allen [7, 29 – 30]. There is a significant dissimilarity between the Vs30 results of this study and the Vs30 predicted from the topographic slope proxy, especially in the highland area, which has a gentle slope. These areas include the Wonosari basin area and the Gunung Sewu karst plateau. The value of Vs30 as a result of this study is in the range of 350 – 750 m/s or site class SC, while the USGS model provides values from 175 – 350 m/s or site class SD. A comparison of the results of this study with the USGS model shows that the estimated value of Vs30 based on the USGS model is not appropriate for the Gunungkidul region.

The Gunungkidul plain area has three landform units from the ten landform classes proposed by Verstappen [31]. These are landforms from solutional processes or karts (rock dissolving processes), structural (tectonic activity), and fluvial (river flow activity). The fluvial landform (river flow activity) in the Gunungkidul area is a fluviocolluvial plain with marl-tuff material. Karst landforms (rock dissolving activity) are dominated by organic sedimentary rocks. It results from the metamorphosis of coral reefs in limestones that form a karst topography [32]. Most of the Gunungkidul region consists of karst landforms, known as the Gunung Sewu Karst Hills. The karst landforms are located in the southern, central, and eastern parts of Gunungkidul with coral limestone material. Structural landforms (tectonic activity) result from lifting processes due to the subduction zone of the Indian Ocean plate under the Eurasian plate in the south of Java. The phenomenon of structural landforms in the border area between Gunungkidul Regency and Bantul, Sleman, and Klaten forms a natural wall of the Baturagung hills escarpment which are stretches from the Parangtritis coast to the north to the Boko hills in Prambanan, then turns straight to the east past Klaten district to Wonogiri [32].

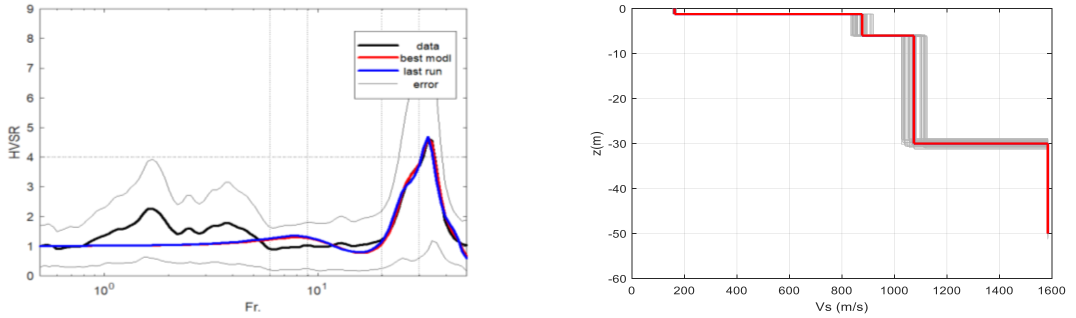
The landforms are correlated with the Vs30 (site conditions) value and seismic vulnerability [33, 34]. The results of this study indicate that the fluvial landforms in some areas of Karangmojo, Nglipar, and Ngawen have a low Vs30 value with an average value of 437 m/s, whereas karst and structural landforms that dominate most of the Gunungkidul area have a high Vs30 value with an average of 713 m/s and 691 m/s, respectively. Further detail of the sub-landform unit was obtained based on genesis, morphology, and material type, as shown in Figure 7 (a) [32, 35 – 38]. Genesis was interpreted from the Land System map from the Geospatial Information Agency (BIG) [35]. Morphology was interpreted based on digital elevation models of the Shuttle Radar Topographic Mapping Mission from USGS [36]. The material type was interpreted based on the geological map of the Yogyakarta region from the Geological Agency, as shown in Figure 7 (b) [37 – 38]. The average value of Vs30 for each landform and sub landform unit in Figure 7 (a) is shown in Table 3. Based on the average value of Vs30, it shows changes that follow the landform.

Landforms composed of alluvium material tend to have lower Vs30 values and higher seismic vulnerability when compared to landforms composed of hard rock [39 – 41].



(a) (b)

Fig.3 (a) Dispersion curve obtained from the MASW at GK31, (b) 1D model of Vs obtained from MASW data processing at GK31



(a) (b)

Fig.4 (a) The HVSR curve obtained from Microtremor at GK03, the black line represents the calculated HVSR curve, the blue line represents the HVSR simulation curve for the last iteration, and the red line represents the HVSR simulation curve for the best model, (b) 1D model of Vs obtained from Microtremor data processing at GK03

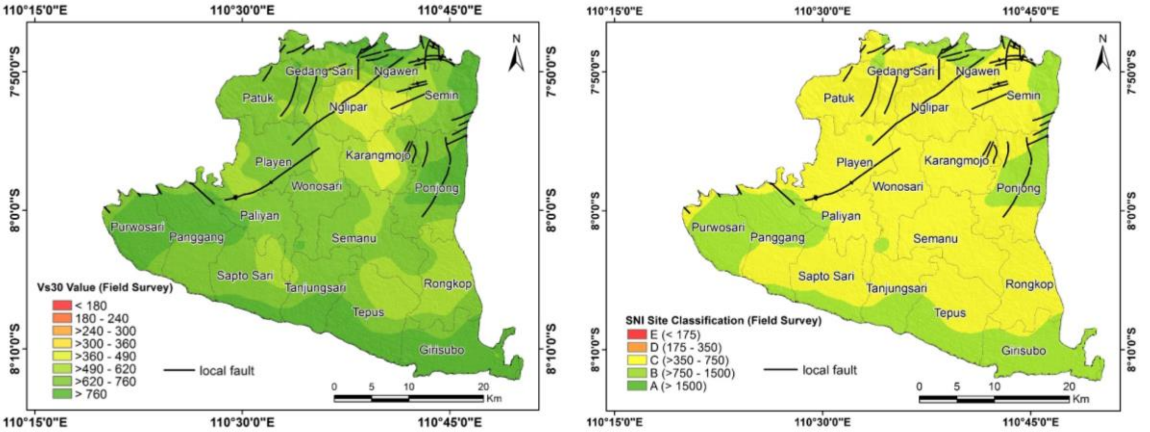
Table 2 The value of Vs30 analysis results at 98 site measurements

No	Code	Vs30	Class
1	ANT32	788	B
2	ANT35	746	C
3	ANT40	740	C
4	ANT42	775	B
5	ANT43	603	C
6	ANT45	687	C
7	ANT46	676	C
8	ANT47	774	B
9	ANT48	742	C
10	ANT49	777	B
11	ANT52	643	C
12	ANT53	649	C
13	ANT54	663	C
14	ANT55	654	C
15	ANT56	749	C
16	GK01	935	B
17	GK02	878	B
18	GK03	850	B
19	GK04	795	B
20	GK05	690	C
21	GK06	515	C
22	GK08	915	B
23	GK09	399	C
24	GK10	370	C
25	GK11	525	C
26	GK12	610	C
27	GK13	365	C
28	GK14	782	B
29	GK15	746	C
30	GK16	422	C
31	GK17	698	C
32	GK18	584	C
33	GK19	626	C
34	GK20	550	C
35	GK21	490	C
36	GK22	787	B
37	GK23	631	C
38	GK24	740	C
39	GK25	962	B
40	GK26	765	B
41	GK28	510	C
42	GK29	597	C
43	GK30	1092	B
44	GK31	981	B
45	GK32	502	C
46	GK33	915	B
47	GK34	780	B
48	GK35	680	C
49	GK36	1045	B
50	GK37	838	B
51	GK38	802	B
52	GK39	740	C
53	GK40	678	C
54	GK42	795	B
55	GK43	744	C
56	GK44	754	B
57	GK45	791	B
58	GK46	825	B
59	GK47	796	B
60	GK48	794	B
61	GK49	794	B
62	GK50	745	C
63	GK51	585	C
64	GK52	586	C
65	GK53	569	C
66	GK54	792	B
67	GK55	752	B
68	GK56	773	B
69	GK57	845	B
70	GK58	565	C
71	GK59	667	C
72	GK60	785	B
73	GK61	515	C
74	GK62	657	C
75	GK63	517	C
76	GK64	638	C
77	GK65	571	C
78	GK66	634	C
79	GK67	598	C
80	GK68	795	B
81	GK69	495	C
82	GK70	574	C
83	GK71	785	B
84	GK72	720	C
85	GK73	755	B
86	GKJM	690	C
87	KL-07	678	C
88	KL-08	546	C
89	KL-10	355	C
90	KL-11	524	C
91	KL-12	640	C
92	PG-03	743	C
93	PG-04	596	C
94	PG-06	752	B
95	PG-07	711	C
96	PG-08	774	B
97	PG-09	601	C
98	PG-10	618	C

According to Nurwihastuti [42], the landforms composed of thick unconsolidated material such as the fluvial, marine, and aeolian landforms are earthquake-prone. Severe damage occurred in these areas. In contrast, the landforms composed of consolidated material such as the structural, denudational, and solutional landforms are earthquake-safe. Only slight damage occurred in these areas.

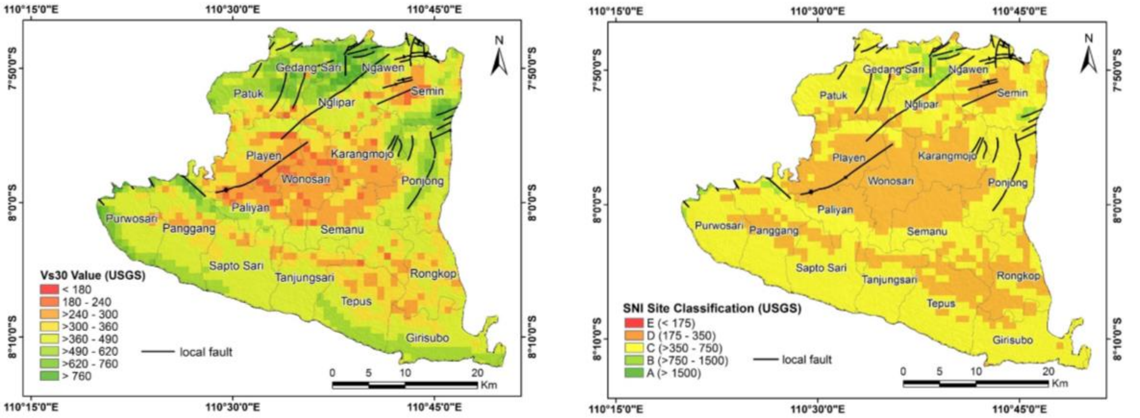
In general, the results of this research show that local conditions significantly affect Vs30 in the Gunungkidul area. Considering the landform effect when estimating the value of Vs30 is required. Regarding the validity of the inversion results, there is a possibility that the inversion results do not match with the actual Vs30. However, the MASW and microtremor inversion program that was used has proven to be a valuable and powerful tool for interpreting the Vs30 model [9, 19, 43 – 45]. Increased data density and better spatial distribution will improve the Vs30 model

The Vs30 obtained in this study provides a valuable assessment, especially for the Gunungkidul area affected by local site effects. The spatial distribution of Vs30 that we propose is a significant step in the disaster mitigation program and is the basis for regional development based on earthquake risk reduction**.** For future planning of the Gunungkidul region, the spatial distribution of Vs30 should be considered in the initial planning of earthquake-resistant infrastructure.



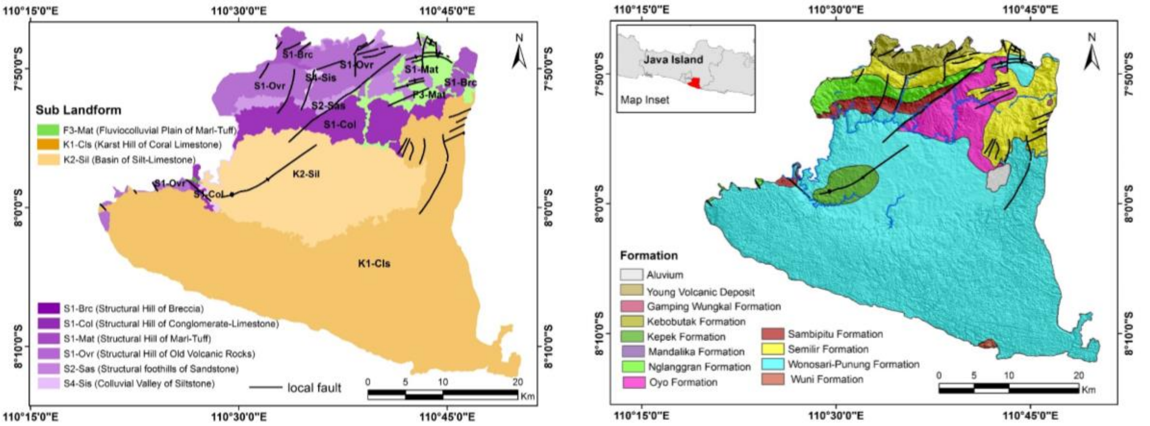
(a) (b)

Fig.5 (a) Spatial distribution map of the Vs30 from MASW and Mikrotremor inversion, (b) spatial distribution map of site classification from MASW and Microtremor inversion



(a) (b)

Fig.6 (a) Spatial distribution map of the Vs30 from USGS, (b) spatial distribution map of site classification from USGS



(a) (b)

Fig.7 (a) Sub-Landform unit in Gunungkidul [32, 35-38], (b) Geology map in Gunungkidul [37-38]

Table 3 The average value of Vs30 on Landform unit and Sub-Landform unit

No	Code	Description of Landform Unit	Average Vs30 on Landform
1	K	Karst	715
2	S	Structural	679
3	F	Fluvial	403
No	Code	Description of Sub-Landform Unit	Average Vs30 on Sub-Landform
1	F3-Mat	Fluviocolluvial Plain of Marl-Tuff	403
2	K1-Cls	Karst Hill of Coral Limestone	739
3	K2-Sil	Basin of Silt-Limestone	654
4	S1-Brc	Structural Hill of Breccia	785
5	S1-Ovr	Structural Hill of Old Volcanic Rocks	743
6	S4-Sis	Colluvial Valley of Siltstone	690
7	S1-Col	Structural Hill of Conglomerate-Limestone	638
8	S1-Mat	Structural Hill of Marl-Tuff	608
9	S2-Sas	Structural foothills of Sandstone	596

5. CONCLUSION

Assessment of the spatial distribution of Vs30 is fundamental in understanding local site characteristics and estimating the potential amplification of ground motion. In this study, the spatial distribution of Vs30 in the Gunungkidul region was investigated using the MASW inversion method and microtremor. The results indicate that the value of Vs30 is generally high, with a range of 355 – 1092 m/s and an average of 693 m/s. The Vs30 value is in the SC to SB site class. The Vs30 value tends to be higher than the USGS Vs30, especially in the karst plateau area, which has a slight slope. The results in this area showed that the site class was SC while the USGS was SD.

The landforms are correlated with the Vs30 value and seismic vulnerability. Fluvial landforms have low Vs30 values with an average of 437 m/s. However, karst and structural landforms have high Vs30 values with average values of 713 m/s and 691 m/s, respectively. The difference in these values indicates that local conditions significantly affect the value of Vs30. Therefore, an assessment of the spatial distribution of Vs30 based on landform units is necessary, such as the development of Vs30 models.

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