第 49 卷 第 6 期 湖南大学学报（自然科学版） Vol. 49 No. 6
2022 年 6 月 Journal of Hunan University (Natural Sciences) June 2022

Open Access Article https://doi.org/10.55463/issn.1674-2974.49.6.15

Characteristics and Spatial Distribution of Vs30 Based on Microtremor Inversion and MASW Data through Landform Unit in Yogyakarta, Indonesia

Wijayanto[1,3*], Djati Mardiatno[2*], Daryono[3], Udo Nehren[4], Muh Aris Marfai[2,5], Bambang Sunardi[3]

[1] Doctoral Program in Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia

[2] Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia

[3] Agency for Meteorology, Climatology, and Geophysics (BMKG), Jakarta, Indonesia

[4] Institute for Technology and Resources Management in the Tropics and Subtropics, TH Köln –
University of Applied Sciences, Cologne, Germany

[5] Geospatial Information Agency of Indonesia (BIG), Cibinong, Indonesia

Abstract: The Yogyakarta region is located in the earthquake-prone areas of Indonesia. An earthquake hazard can be assessed by identifying the site conditions from Vs30 to estimate the potential amplification of ground shaking. Site conditions are affected by the earth surface relief and material composition. The landform is characterized by differences in geomorphological structures and processes, relief/topography, and material. This research aims to analyze the characteristics and spatial distribution of Vs30 based on MASW and microtremor inversion for each landform unit in the Yogyakarta region. We collected 545 microtremor and MASW responses from field measurements. Data inversion was performed to obtain a 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 varied in a range of 140 – 1092 m/s. The site classification ranges from SE to SB. The Vs30 value tends to be similar to the USGS model, except in the karst landform in the Gunungkidul area. Here, the site class ranges from SC to SB, while the USGS model ranges from SD to SC. Based on the landform analysis, the higher average values of Vs30 are for karst, followed by structural, denudational, volcanic, fluvial, marine, and aeolian landforms. This difference indicates that local conditions significantly affect the Vs30. The higher the elevation and the steeper the slope, the larger the Vs30 value. Moreover, the higher values of Vs30 are determined by harder and solid/consolidated material.

Keywords: Vs30, spatial distribution, multichannel analysis of surface waves, microtremor, landform.

印度尼西亚日惹基于微震和 MASW 反演的 Vs30 特征及空间分布

摘要：日惹地区位于印度尼西亚地震多发地区。可以通过从 Vs30 中识别现场条件来进行地震危险评估，以估计地面震动的潜在放大。场地条件受地球表面地形和材料成分的影响。地貌的特点是地貌结构和过程、地形/地形和材料的差异。本研究旨在基于 MASW 和微震反演分析日惹地区各地貌单元的 Vs30 特征和空间分布。我们从现场测量中收集了 545 次微震和 MASW。进行数据反演以获得一维 Vs30 模型并估计 Vs30 值。结果显示在 Vs30 空间分布图和站点分类中。它们表明 Vs30 的值在 140–1092 小姐的范围内变化。站点分类范围从东南到某人。Vs30 值趋于与美国地质调查局 模型相似，除了古农吉杜尔地区的喀斯特地

Received: March 23, 2022 / Revised: April 27, 2022 / Accepted: May 21, 2022 / Published: June 30, 2022

About the authors: Wijayanto, Doctoral Program in Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia; Agency for Meteorology, Climatology, and Geophysics (BMKG), Jakarta, Indonesia; Djati Mardiatno, Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia; Daryono, Agency for Meteorology, Climatology, and Geophysics (BMKG), Jakarta, Indonesia; Udo Nehren, Institute for Technology and Resources Management in the Tropics and Subtropics, TH Köln – University of Applied Sciences, Cologne, Germany; Muh Aris Marfai, Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia; Geospatial Information Agency of Indonesia (BIG), Cibinong, Indonesia; Bambang Sunardi, Agency for Meteorology, Climatology, and Geophysics (BMKG), Jakarta, Indonesia

Corresponding authors Wijayanto, wijayanto2000@gmail.com, Djati Mardiatno, djati.mardiatno@ugm.ac.id

貌。这里，站点等级范围从 SC 到某人，而美国地质调查局模型在标清到 SC 范围内。根据地貌分析，Vs30 平均值较高的是岩溶地貌，其次是构造地貌、剥蚀地貌、火山地貌、河流地貌、海洋地貌和风成地貌。这种差异表明当地条件显着影响 Vs30。海拔越高，坡度越陡，Vs30 值越大。此外，较高的 Vs30 值是由于材料更硬、更坚固/更坚固。

关键词：Vs30, 空间分布, 表面波的多通道分析, 微震, 地形.

1. Introduction

Yogyakarta region and its surrounding areas are tectonically one of the most active areas in Indonesia due to the location of Yogyakarta, which is close to the subduction zone of the Indo-Australian Plate and the Eurasian Plate in the Indian Ocean in the south of Java Island. Therefore, the Yogyakarta Region and surrounding areas are highly prone to earthquakes because of the subduction activity and the activity of local faults. The seismicity map of Yogyakarta and the surrounding areas for the period 2009 to 2020 shows that the seismic activity in Yogyakarta is indeed very high (Figure 1).

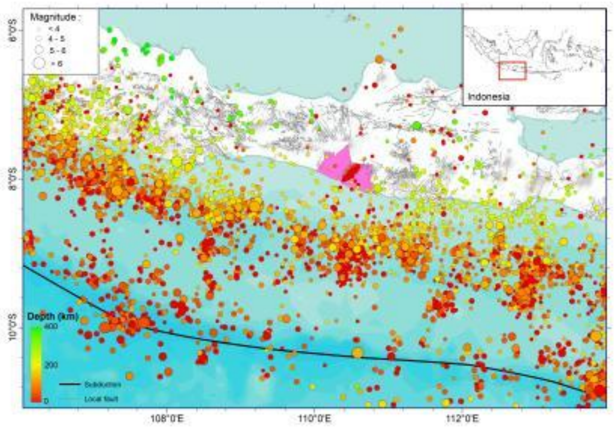


Fig. 1 Seismicity map of Yogyakarta and surrounding areas, period 2009–2020

When efforts to predict an earthquake have not been successful, earthquake mitigation is the best measure to prevent earthquake disasters. The first step in mitigating before an earthquake occurs is mapping earthquake risk. One of the variables for developing earthquake risk maps is earthquake hazard data. Earthquake hazard assessment in an area can be done by identifying local site characteristics to estimate the potential amplification of ground motion. Amplification of ground motion is caused by three factors: the earthquake source, the propagation path effect, and the local site effect. Local site conditions can be determined using the value of the shear wave velocity at a depth of 30 meters (Vs30) [1-3]. Vs30 is a good indicator to illustrate the characteristics of soil stiffness and strength.

Soil characteristics and seismic vulnerability are affected by the earth surface relief and the nature of the landform material, so landforms provide information regarding site conditions and earthquake vulnerability. The landform is a part of the earth's surface with a unique topographic shape due to the strong influence of natural processes and geological structures on the rock material in a particular spatial and chronological setting. Each landform is characterized by differences in geomorphological structures and processes, relief/topography, and material. Landforms correlate well with building damage when an earthquake occurs [4-6]. Therefore, geomorphologic classification is a more appropriate index for estimating site conditions and Vs30 than the topography slope [7].

Currently, several methods are used to calculate Vs30, including geophysical survey methods using MASW (Multichannel Analysis of Surface Waves) and the microtremor inversion of the Horizontal to Vertical Ratio (HVSR) curve [8-9]. In this research, the landform units are used as the study object of the Vs30, obtained by a geophysical method from a Vs30 measurement at each landform unit. By knowing the value of Vs30 in each landform unit, it is expected that we can estimate the response of each landform unit to seismic waves so that we can explain the relationship between the value of Vs30 and the landform unit.

This research aims to analyze the characteristics and spatial distribution of Vs30 for each landform unit in the Yogyakarta region using the inversion of MASW and microtremor measurements. The Vs30 value obtained in this study is useful for disaster mitigation programs and as a basis for regional development planning based on earthquake risk reduction.

2. Methods

2.1. Research Area and Data Collecting

The research area is located in Yogyakarta Special Province on Java Island, Indonesia. We used 545 site measurement data obtained by the MASW method (98 sites) and the microtremor (447 sites) to estimate the Vs30 values in the Yogyakarta region. The MASW data were obtained by direct field surveys (19 sites), from BMKG (Meteorological Climatological and Geophysical Agency of Indonesia) data (66 sites), and previous studies (13 sites). The microtremor data were obtained by direct field surveys (92 sites) and BMKG data (355 sites). The research area and distribution map of measurement sites used is presented in Figure 2.

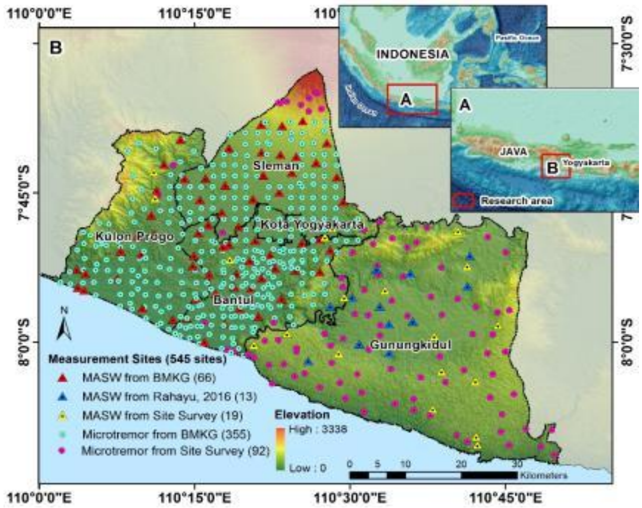


Fig. 2 The research area and distribution map of Vs30 sites measurement

2.2. MASW Method

MASW is a seismic technique performed at the ground surface to characterize shear wave velocity distribution in the shallow subsurface. This method utilizes the dispersion properties of surface waves that pass through the medium by extracting Rayleigh wave data into the frequency-phase velocity domain [10]. The SeisImager software was used to analyze the data. The results were converted into a dispersion curve. The dispersion curve picking process was used for fundamental model selection [10-11]. Subsequently, the inversion of the shear wave velocity profile was obtained following the SeisImager/SW software manual. 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 [10].

2.3. Microtremor Processing and Inversion

Microtremor data is a time series of ground vibrations with small amplitudes in three orthogonal directions NS, EW, and vertical [12]. The Horizontal-to-Vertical Spectral Ratio (HVSR) method was used for microtremor data processing. The HVSR amplitude spectrum was obtained using the Geopsy software. The average HVSR in each window can be determined by equation (1).

$$\mathrm{HVSR} = \sqrt{F_N^2 + F_E^2/(2F_V^2)} \qquad (1)$$

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

The value of the shear wave velocity is determined using the HVSR inversion process by minimizing the objective function, namely the difference between the observed and calculated HVSR [10]. OpenHVSR Software [13] was used for HVSR inversion to obtain a subsurface Vs model. HVSR inversion was carried out using forward modeling (FWD). The subsurface layer was assumed to be a homogeneous viscoelastic layer stacked over half the space. A 1D subsurface model was defined for each location. A constraint was needed during the inversion process of the HVSR curve to get an accurate value of Vs [10]. In this case, we used the drill data provided for initialization or the input entered when inverting.

2.4. Vs30 Estimation and Site Class

The National Standard of Indonesia (SNI) 1726:2019 [14] issued rules for estimating the value of Vs30 by calculating based on equation (2).

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

where Vs30 is the average shear wave velocity to a depth of 30 m, hi and Vsi 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 [14] classified site classes into six types: hard rock, rock, hard soil, dense and soft rock, medium soil, soft soil, and specific soil (Table 1).

Table 1 Site classification SNI 1726-2019 [14]

Site Classes	**Vs30 (m/s)**
SA (hard rock)	> 1500
SB (rock)	> 750–1500
SC (hard soil, dense and soft rock)	> 350–750
SD (medium soil)	175-350
SE (soft soil)	< 175
SF (specific soil)	Requires specific geotechnical investigations and site-specific response analysis

2.5. Characteristics and Spatial Distribution of Vs30 through Landform Unit Approach

The landform units were obtained based on morphology, morphogenesis, and material type interpretation. First, the morphology was interpreted based on digital elevation models of SRTM (Shuttle Radar Topographic Mapping Mission) from USGS (the United States Geological Survey) [15]. Next, the morphogenesis was interpreted from the Land System map from the Geospatial Information Agency (BIG) [16]. Finally, the material type was interpreted based on the geological map from the Geological Agency [17-18].

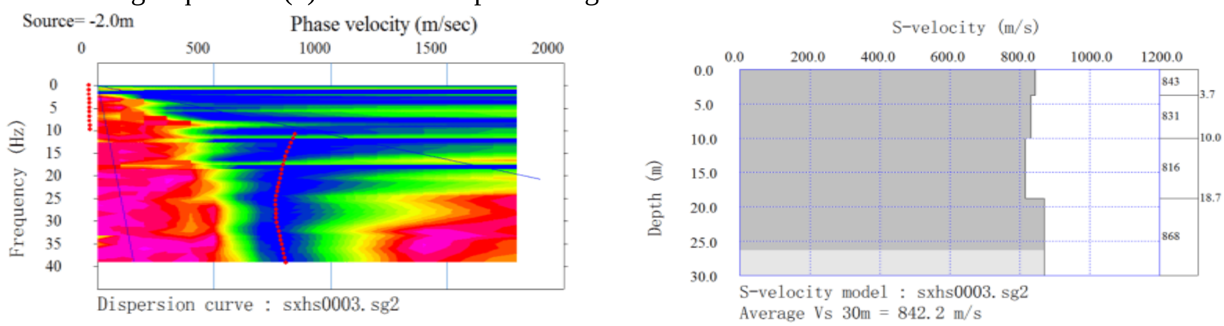
The spatial distribution of the Vs30 values in Yogyakarta was obtained by interpolating all Vs30 values between sites one to another using the Kriging method. Furthermore, the spatial distribution of Vs30, as a result of our interpolation, was reclassified into eight classes following the USGS. In addition, we also reclassified into five classes based on the site classification of SNI 1796:2019 [14]. Furthermore, this spatial distribution was used to identify the relationship between the Vs30 values, landform characteristics, and lithological characteristics. In addition, the research results were compared with the USGS model.

3. Results and Discussion

3.1. Characteristics of Vs30 by Each Landform Unit

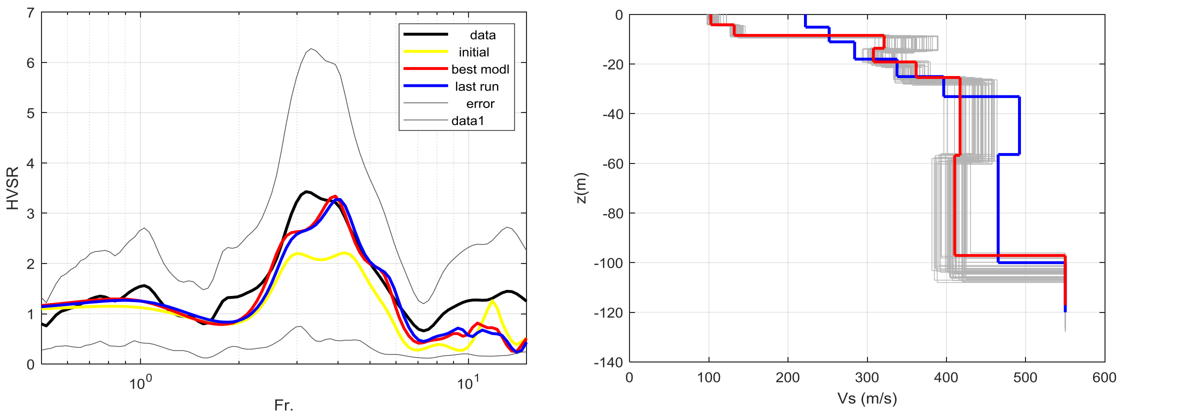
The Vs30 values in the Yogyakarta region were obtained after the inversion of the MASW and microtremor data. Figure 3 shows the dispersion curve and 1D model of Vs30 at the T16 MASW measurement site, while Figure 4 shows results from the inversion of the HVSR curve and the 1D model of Vs at the LB_030 microtremor measurement site. The value of Vs30 from 545 site measurements was calculated using equation (2). The data processing results show that the value of Vs30 is in the range of 140 – 1092 m/s. The Vs30 analysis results at 545 sites are shown in Table 2 and Table 3.

We classified the Yogyakarta region into seven main landform units according to the morphogenesis proposed by Verstappen [19], which was interpreted based on the land system map from BIG [16]. The seven types of main landform units are presented in Table 2 and shown in Figure 5a. Furthermore, we reclassified the main landform units into twenty-one sub landform units according to the morphology, morphogenesis, and material type. The twenty-one types of sub landform units are presented in Table 3 and shown in Figure 5b.



(a) (b)

Fig. 3 (a) Dispersion curve obtained from the MASW at T16, (b) 1D model of Vs obtained from MASW data processing at T16



(a) (b)

Fig. 4 (a) The results from the inversion of the HVSR curve, (b) 1D model of Vs obtained from microtremor data processing at LB_030

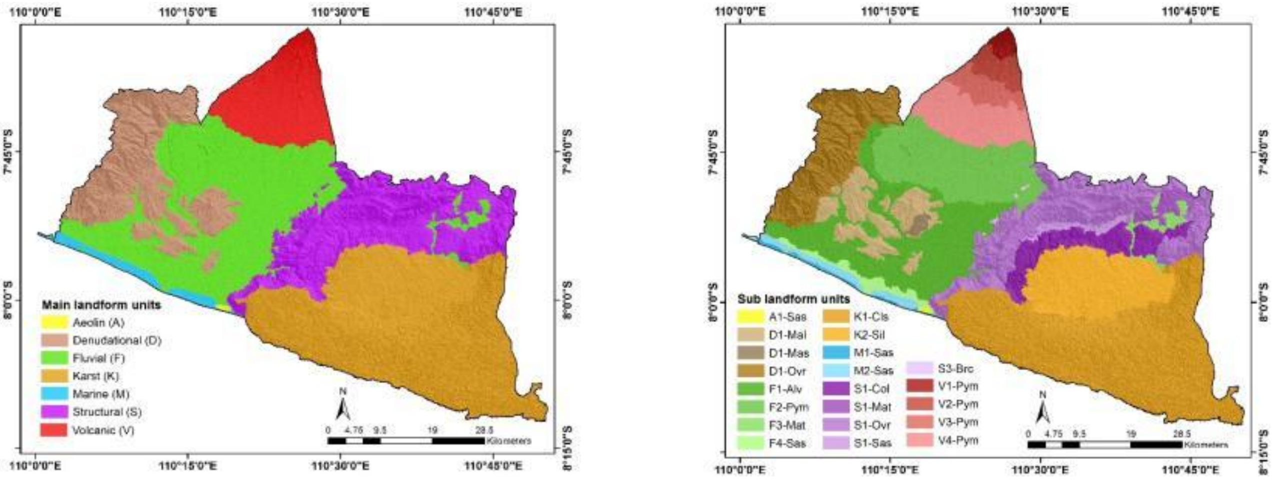
Table 2 The value of Vs30 analysis results at 545 sites by main landform units

No	Main landform unit	Code	Vs30 (m/s)				Data counts
			Mean	Minimum	Maximum	Standard deviation	
1	Karst	K	737	550	1092	110	74
2	Structural	S	620	477	859	114	57
3	Denudational	D	480	320	900	127	71
4	Volcanic	V	424	318	693	82	65
5	Fluvial	F	258	140	415	41	254
6	Marine	M	243	216	278	17	21
7	Aeolian	A	243	224	260	18	3

Table 3 The value of Vs30 analysis results at 545 sites by sub landform units

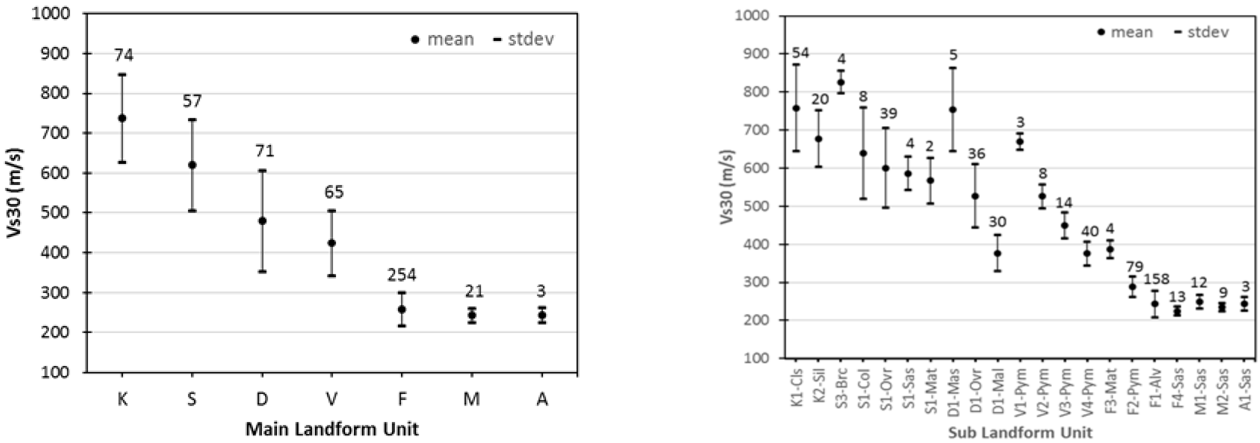
No	Sub landform unit	Code	Vs30 (m/s)				Data counts
			Mean	Minimum	Maximum	Standard deviation	
1	Karst hill of coral limestone	K1-Cls	758	565	1092	114	54
2	Basin of silt limestone	K2-Sil	678	550	787	74	20
3	Monocline hill of breccia	S3-Brc	827	790	859	30	4
4	Structural hill of conglomerate limestone	S1-Col	639	497	850	120	8

Continuation of Table 3							
5	Structural hill of old volcanic rocks	S1-Ovr	601	477	850	105	39
6	Structural hill of sandstone	S1-Sas	587	546	640	43	4
7	Structural hill of marl tuff	S1-Mat	567	524	610	61	2
8	Denudational hill of marl sandstone	D1-Mas	754	622	900	109	5
9	Denudational hill of old volcanic rocks	D1-Ovr	527	422	715	83	36
10	Denudational hill of marl limestone	D1-Mal	377	320	477	48	30
11	Volcanic cone and upper slope of pyroclastic	V1-Pym	670	651	693	21	3
12	Volcanic middle slope of pyroclastic	V2-Pym	526	472	566	32	8
13	Volcanic lower slope of pyroclastic	V3-Pym	450	389	519	34	14
14	Volcanic footslope of pyroclastic	V4-Pym	376	318	475	32	40
15	Fluvio-colluvial plain of marl tuff	F3-Mat	387	365	415	24	4
16	Fluvio-volcanic plain of pyroclastic	F2-Pym	288	242	362	26	79
17	Alluvial plain	F1-Alv	243	140	336	34	158
18	Fluvio-marine plain of sandstone	F4-Sas	225	202	238	11	13
19	Beach of sandstone	M1-Sas	249	216	278	18	12
20	Beach ridge of sandstone	M2-Sas	235	224	258	11	9
21	Dunes of sandstone	A1-Sas	243	224	260	18	3



(a) (b)

Fig. 5 (a) Main landform unit map in Yogyakarta region, (b) sub landform unit map in Yogyakarta region



(a) (b)

Fig. 6 (a) Mean value and standard deviation of Vs30 by main landform unit, (b) mean value and standard deviation of Vs30 by sub landform unit

Figure 6 shows the analysis results on the mean value and standard deviation of Vs30 by main and sub landform unit. The horizontal axis corresponds to the landform unit code, and the vertical axis corresponds to the Vs30 value. The numbers in a small font on the tops of standard deviation bars represent the data counts. As for the main landform unit, the analysis results are shown in Figure 6a. The mean values of Vs30 are in order of high to low values, namely Karst (737 m/s) > Structural (620 m/s) > Denudational > Volcanic (424 m/s) > Fluvial (258 m/s) > Marine (243 m/s) ≥ Aeolian (243 m/s). This tendency is regarded as reasonable considering the land formation process and composer material of each landform unit.

Organic sedimentary rocks dominate the karst landforms (rock dissolving activity). It results from the metamorphosis of coral reefs in limestones that form a karst topography [20]. The 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 denudational landform (degradational activity) is also known as stripping the earth surface due to weathering processes of very old rocks that trigger erosional processes and rock mass movements. This landform is characterized by frequent occurrences of mass movement in the form of landslides and rockfalls on the slopes of the foothills and steep mountains. The volcanic landform process (volcanic activity) results from endogenous processes due to magma activity and exogenous processes due to other geomorphological forces such as weather activities, mass wasting, erosion, and transportation. Pyroclastic materials dominate volcanic landforms. The fluvial landform process (river flow activity) results from water flow processes that cause erosion, transport, and sedimentation. The fluvial landform in the Yogyakarta region is dominated by volcanic material due to the activity of the Merapi mountain in the north, which flows to the south. The marine landform process (wave activity) is due to the deposition of Holocene-aged marine material, which is dominated by fine to coarse-grained sand. The aeolian landform process (wind activity) is due to moving clastic and loose materials such as sand by wind power from one place. The aeolian landforms are usually formed in dry climates or coastal areas.

As for the sub landform unit, the analysis results are shown in Figure 6b. As for the karst, the mean value of Vs30 of karst hill of coral limestone (758 m/s) is higher than that of the silt-limestone basin (678 m/s). As for the structural, the highest is the monocline hill of breccia (827 m/s), followed by the structural hill of conglomerate limestone (639 m/s), structural hill of old volcanic rocks (601 m/s), structural hill of sandstone (587 m/s), and structural hill of marl tuff (567 m/s). As for the denudational, the highest is the denudational hill of marl sandstone (754 m/s), followed by the denudational hill of old volcanic rocks (527 m/s), and the denudational hill of marl limestone (377 m/s). As for the volcanic, the highest is the volcanic cone and upper slope of pyroclastic flow (670 m/s), followed by the volcanic middle slope (526 m/s), volcanic lower slope (450 m/s), and Volcanic footslope of pyroclastic flow (376m/s). As for the fluvial, the highest is Fluvio-colluvial plain of marl tuff (387 m/s), followed by the fluvio-volcanic plain of pyroclastic (288 m/s), alluvial plain (243 m/s), and fluvio-marine plain of sandstone (225 m /s). As for the marine, the beach of sandstone (249 m/s) is higher than the beach ridge of sandstone (235 m/s). As for the aeolian, there are only sandstone dunes (243 m/s).

The correlation between Vs30 and elevation, as well as slope, is shown in Figure 7. In general, the higher the elevation and the steeper the slope, the larger the Vs30 value [3, 7, 21]. Areas with high values include karst, structural, denudational, and volcanic landforms with an average value of Vs30 above 400 m/s. They are located in hilly and mountainous areas with an average elevation above 100 m and a slope above 10%. In contrast, the lower the elevation and the slope flatter, the smaller the Vs30 value. Areas with low values include fluvial, marine, and aeolian landforms with an average Vs30 below 300 m/s located in lowland and coastal areas with an average elevation below 100 m and a slope of below 10%.

However, the type of material also has a very significant contribution to the value of Vs30. The higher the value of Vs30, the harder and more solid/consolidated the material is. On the other hand, the lower the Vs30 value, the softer the material and the less solid/unconsolidated. As for karst landforms, which are generally composed of coral limestone material, the values of Vs30 are high. Furthermore, the structural, volcanic, and denudational landforms typically consist of old volcanic rock, breccia, andesite, tuff marl, sandstone, and claystone. On the other hand, as for the fluvial, marine, and aeolian, the values of Vs30 are low. Generally, they consist of alluvial material, clay, silt clay, sand, gravel, and fine sand.

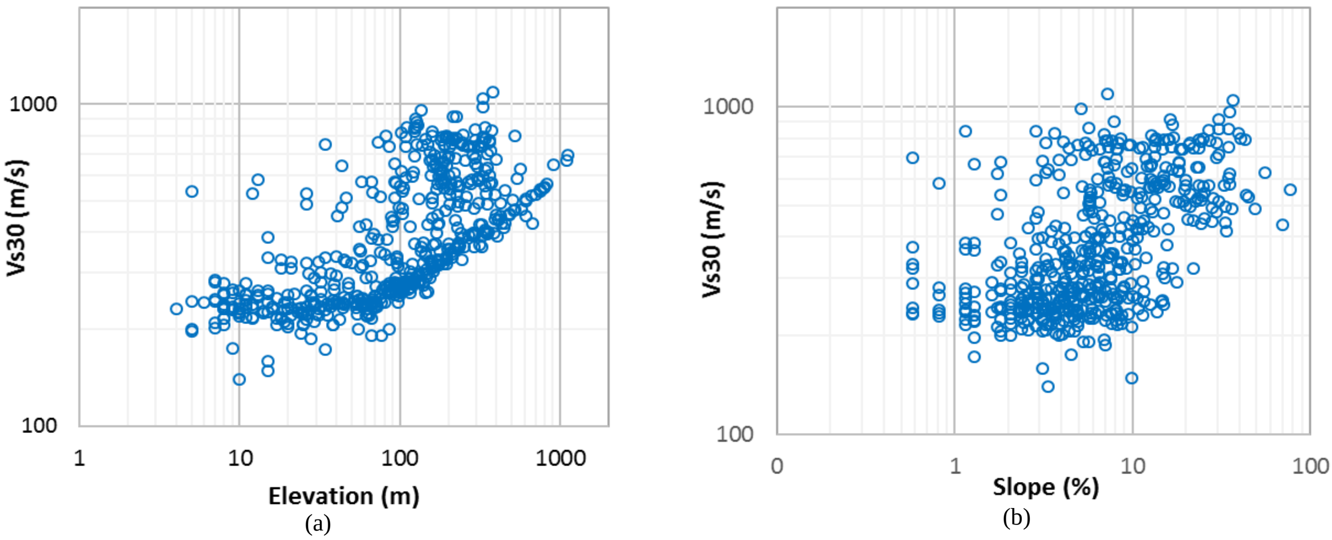


Fig. 7 (a) The correlation between elevation and Vs30, (b) the correlation between slope and Vs30

3.2. Spatial Distribution of Vs30 in the Yogyakarta Region

The data processing results at 545 measurement sites show that the value of Vs30 in the Yogyakarta region varies from low to high in the range of 140-1092 m/s, as shown in Tables 2 and 3. Low Vs30 values were found in the following areas:

1) The fluvial landforms in Kota Yogyakarta, central and western parts of Bantul, the southern parts of Sleman, and southeast and south of Kulon Progo are 140-415 m/s;

2) The marine landform in the southern part of Bantul and Kulon Progo is 216-278 m/s;

3) The aeolian landform in the south of Bantul is in the range of 224-260 m/s.

High Vs30 values were found in the following areas:

1) The karst landform in the central and southern part of Gunungkidul (550-1092 m/s);

2) The structural landform in the eastern part of Bantul and north of Gunungkidul (477-859 m/s);

3) The denudational landform in the western and southeastern parts of Kulon Progo and the western part of Bantul (320-900 m/s);

4) The volcanic landform in the northern part of Sleman (358-693 m/s).

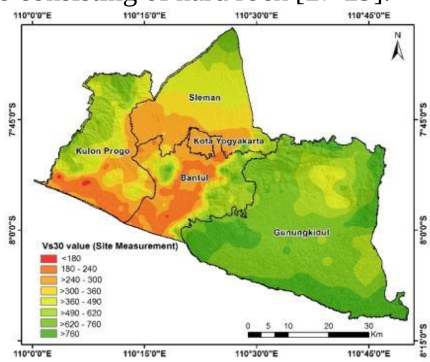
Referring to the site classification of SNI 1796:2019 in Table 1 [14], the site class value for the Yogyakarta region is in the range of site class SE (soft soil) to SB (rock). The 545 site measurements show that 48 sites are in the SB class, 204 sites are in the SC class, 288 sites are in the SD class, and five sites are in the SE class. The spatial distribution and site classification map of the Vs30 from site measurements is shown in Figures 8a and 8b.

The low value of Vs30 is related to the thick sediment layer rather than the solid and unconsolidated material. These materials are alluvial, clay, sand, and gravel deposits. Because of these conditions, major earthquakes in these areas cause severe damage and loss of life. One of them is the Yogyakarta earthquake on May 27, 2006, with a magnitude of 6.3, which caused 5,716 fatalities and economic losses of more than US$ 3,134 million [22]. The high value of Vs30 is related to shallow sediment layers or rock outcrops, solid and consolidated material, generally located in the highlands. Due to these conditions, minor damage occurs in these areas during large earthquakes. Each site class responds differently to an earthquake, including increasing the amplitude of the earthquake waves or just continuing the waves [23-24]. In the site class, SC or lower, earthquake waves propagate with lower velocity but higher amplitude.

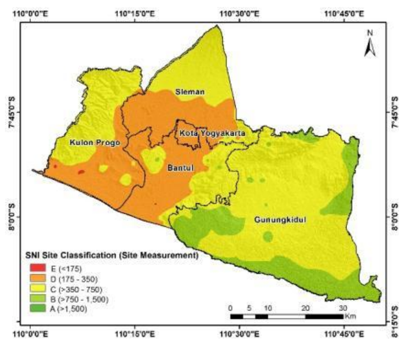
On the other hand, earthquake waves are transmitted only in site class SA or SB [24]. As a result, subsurface deposits with lower Vs than the bedrock tend to amplify earthquake shaking while prolonging the duration. This kind of amplification potential is commonly referred to as the local site effect.

In general, our proposed spatial distribution of Vs30 has similar values to the USGS model, as shown in Figures 9a and 9b. The Vs30 value of the USGS model is a proxy of the topographic slope developed by Wald and Allen [3, 25-26]. This similarity is shown in Sleman, Kulon Progo, Bantul, Kota Yogyakarta, and part of Gunungkidul in volcanic, denudational, fluvial, marine, aeolian, and structural landforms. However, there is a significant discrepancy between the Vs30 results of this study and the Vs30 predictions from the topographic slope proxy, especially in the karst landform, which has a gentle slope. 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 karst landform in the Gunungkidul region. These areas include the Wonosari basin area and the Gunung Sewu karst plateau [10]. The resulting value of Vs30 is 350-750 m/s or site class SC, while the USGS model assumes 175-350 m/s or site class SD. As for the karst landform in the south of Gunungkidul, this study is 750-1500 m/s or site class SB, while the USGS assumes 350-750 m/s or site class SC.

The landforms are correlated with the Vs30 (site conditions) value and seismic vulnerability [4, 7]. Based on the average value of Vs30, it shows changes that follow the landform. Landforms composed of alluvial material tend to have lower Vs30 values and higher seismic vulnerability when compared to landforms consisting of hard rock [27-29].

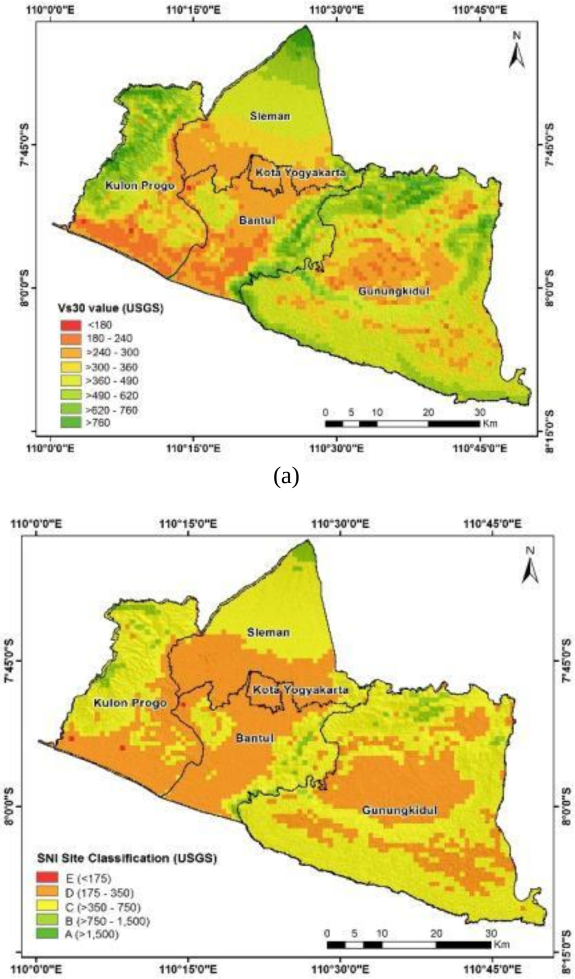


(a)



(b)

Fig. 8 (a) Spatial distribution map of the Vs30 from site measurement, (b) spatial distribution map of site measurement



(b)

Fig. 9 (a) Spatial distribution map of the Vs30 from USGS, (b) spatial distribution map of site classification from USGS

According to [6], 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 the past. 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.

This research shows that local conditions significantly affect Vs30 in the Yogyakarta region. Therefore, considering the landform effect when estimating the value of Vs30 is required. Regarding the validity of the inversion results, they may not match with the actual Vs30. However, the MASW and microtremor inversion program has proven valuable and powerful for interpreting the Vs30 model [30]. Furthermore, increased evenly distributed data density will improve the quality of spatial distribution of the Vs30.

Further assessment for developing the model of Vs30 based on the landform unit is necessary. Nevertheless, the Vs30 obtained in this study provides a valuable assessment, especially for the Yogyakarta region affected by local site effects. The spatial distribution of Vs30 that we propose is a significant step in the disaster mitigation program and can be used as the basis for regional development based on earthquake risk reduction.

4. Conclusion

Assessment of the characteristics and spatial distribution of Vs30 is fundamental to understanding local site characteristics and estimating the potential amplification of ground motions. In this study, the characteristics and spatial distribution of Vs30 in the Yogyakarta region were investigated using the MASW method and microtremor inversion through the landform unit. The results indicate that the value of Vs30 in the Yogyakarta region varies in a range of 140-1092 m/s. The site class for the Yogyakarta region varies in the range from SE to SB. The spatial distribution of Vs30 shows similarities to the USGS model for volcanic, denudational, fluvial, marine, aeolian, and structural landforms. A significant discrepancy is noted for the karst landform. The site class of this study is in the range of SC to SB, while the USGS model is in the range of SD to SC.

Based on the landform analysis, the mean values of Vs30 in each main landform unit are in the order of karst (737 m/s), structural (620 m/s), denudational, volcanic (424 m/s), fluvial (258 m/s), marine (243 m/s), and aeolian (243 m/s). The analysis results of the sub landform unit indicate that the values of Vs30 have a trend following the characteristics of morphology, morphogenesis, and material. Based on the morphology, the higher the elevation and the steeper the slope, the larger the Vs30 value. Areas with high Vs30 values are located in hilly and mountainous regions, while areas with low values are located in lowland and coastal regions. Moreover, the material type significantly influences the value of Vs30. The higher Vs30 values result from harder and consolidated materials, while the lower Vs30 values are due to softer and unconsolidated materials.

The average values of Vs30 show that they follow the landform. Furthermore, local conditions significantly affect the Vs30 value. Measuring Vs30 using the MASW and microtremor method provides a reliable subsurface profile, but it is time-consuming and not cheap. Further assessment for developing the Vs30 model based on the landform unit is necessary due to the limitation of the data and its uneven distribution. For future planning of the Yogyakarta region, the spatial distribution of Vs30 should be considered in the planning of earthquake-resistant infrastructure.

Acknowledgment

The authors gratefully acknowledge the Bureau of Planning of BMKG for the permission and support to continue the doctoral program. Additionally, the Education and Training Center of BMKG is acknowledged for providing scholarship support.

Thanks to the field survey teams from the Division for Engineering Seismology of BMKG and the Sleman Geophysics Station of BMKG for assisting in the field data collection.

References

[1] THAMARUX P, MATSUOKA M, POOVARODOM N, and IWAHASHI J. VS30 Seismic Microzoning Based on a Geomorphology Map: Experimental Case Study of Chiang Mai, Chiang Rai, and Lamphun, Thailand. *International Journal of Geo Information*, 2019, 8: 1–18.

[2] VERDUGO R. Seismic site classification. *Soil Dynamics and Earthquake Engineering*, 2019, 124: 317–329. https://doi.org/10.1016/j.soildyn.2018.04.045

[3] WALD D J, and ALLEN T I. Topographic slope as a proxy for seismic site conditions and amplification. *Bulletin of the Seismological Society of America*, 2007, 97(5): 1379–1395. https://doi.org/10.1785/0120060267

[4] DARYONO. *Seismic Vulnerability Index Based on Microtremor in each Land Form Unit in the Graben Zone of Bantul, Special Region of Yogyakarta*. Ph.D. thesis, Universitas Gadjah Mada, 2011.

[5] NURWIHASTUTI D. W. *Geomorphological Analysis on The Earthquake Damage Pattern: A Case Study of 2006 Earthquake in Bantul, Yogyakarta, Indonesia*. Ph.D. thesis, Universitas Gadjah Mada, 2013.

[6] NURWIHASTUTI D. W, SARTOHADI J, MARDIATNO D, NEHREN U, and RESTU. Understanding of Earthquake Damage Pattern through Geomorphological Approach: A Case Study of 2006 Earthquake in Bantul, Yogyakarta, Indonesia. *World Journal of Engineering and Technology*, 2014, 02(03): 61–70. https://doi.org/10.4236/wjet.2014.23b010.

[7] MATSUOKA M, WAKAMATSU K, FUJIMOTO K, and MIDORIKAWA S. Average Shear-Wave Velocity Mapping Using Japan Engineering Geomorphologic Classification Map. *Structural Engineering/Earthquake Engineering*, 2006, 23(1): 57s-68s. https://doi.org/10.2208/jsceseee.23.57s.

[8] MUZLI M, MAHESWORO R. P, MADIJONO R, SISWOYO, DEWI K. R, BUDIARTA, PRAMONO S. Measurement of Vs30 Using the MASW Method for the Yogyakarta Region. *Jurnal Meteorologi dan Geofisika*, 2016, 17(1): 25–32.

[9] RAHAYU A, PRAKOSO W. A, and SADISUN I. A. Modeling Estimated V S30 Based on Topography and Geomorphology for Padang, Indonesia. *International Journal of Civil Engineering and Technology*, 2019, 10(06): 103–111.

[10] WIJAYANTO, MARDIATNO D, DARYONO, NEHREN U, MARFAI M. A, and PRAMONO S. Spatial Distribution of Vs30 MASW-based and Microtremor Inversion in Gunungkidul, Indonesia. *International Journal of GEOMATE*, 2022, Vol. 22(94).

[11] LU Z, and WILSON G.V. Imaging a Soil Fragipan Using a High-Frequency Multi-Channel Analysis of Surface Wave Method. *Journal of Applied Geophysics*, 2017, 143: 1-8.

[12] GUO Z, AYDIN A, and KUSZMAUL J. Microtremor recordings in northern Mississippi. *Engineering Geology*, 2014, 179:146-157.

[13] BIGNARDI S, ANTOVANI A, and ZEID N.A. OpenHVSR: imaging the subsurface 2D/3D elastic properties through multiple HVSR modelling and inversion. Computers & Geosciences, 2016, 93: 103-113.

[14] SNI 1726:2019. *Procedures on Earthquake Resistance Planning for Building and Non-Building Structures*. Badan Standarisasi Nasional, Jakarta, 2019.

[15] Shuttle Radar Topography Mission 1 Arc-Second Global (Digital Object Identifier (DOI) number: /10.5066/F7PR7TFT.

[16] Land System Map Scale 250K and 50K. Badan Informasi Geospasial (BIG), 2020.

[17] RAHARDJO W, SUKANDARRUMIDI, and ROSIDI H.M.D. *Geological Map of the Yogyakarta Sheet, Jawa, Scale 1:100.000*. Geological Research and Development Centre, Bandung, 1995.

[18] SURONO, TOHA B, and SUDARNO I. *Geological Map of the Surakarta – Giritontro Sheet, Jawa, Scale 1:100.000*. Geological Research and Development Centre, Bandung, 1992.

[19] VERSTAPPEN H. *Applied Geomorphology: Geomorphological Survey for Environmental Development*. The Netherlands: Elsevier, Amsterdam, 1983.

[20] SANTOSA L.W, *The Specialty of Yogyakarta from a Geomorphological Point of View*. Gadjah Mada University Press, 2015.

[21] THOMPSON E. M, WALD D. J, and WORDEN C. B. A VS30 Map for California with geologic and topographic constraints. *Bulletin of the Seismological Society of America*, 2014, 104(5): 2313–2321. https://doi.org/10.1785/0120130312.

[22] BAPPENAS. *Preliminary Assessment of Damage and Loss of Natural Disasters in Yogyakarta and Central Java*, 15th Meeting of the Consultative Group for Indonesia, 2006.

[23] COE J, MAHVELATI S, SENIOR M, and ASABERE P. Mapping NEHRP Vs30 Site Class in Philadelphia Using Geophysical and Existing Subsurface Data. *Proceedings of the U.S. National Conference on Earthquake Engineering Integrating Science*, Los Angeles, California, 2018.

[24] CIPTA A, and SOLIKHIN A. *Estimation of Surface Wave Velocity (VS30) on Sulawesi Island Based on Geomorphological Classification and Its Application*. Pusat Vulkanologi dan Mitigasi Bencana Geologi, Bandung, 2015.

[25] ALLEN T I, and WALD D J. On The Use of High-Resolution Topographic Data as A Proxy for Seismic Site Conditions (Vs30). *Bulletin of the Seismological Society of America*, 2009, 99(2A): 935-943.

[26] HEATH D, WALD D. J, WORDEN C. B, THOMPSON E. M, and SCMOCYK G. A Global Hybrid VS30 Map with a Topographic-Slope-Based Default and Regional Map Insets. *Earthquake Spectra*, 2020, 36(3): 1570-1584.

[27] KAMAL A S, and MIDORIKAWAI S. Geomorphological Approach for Seismic Microzoning Within Dhaka City Area, Bangladesh, *Proceedings of the International Congress of IAEG 2006*, The Geology Society of London, 2006.

[28] MATSUOKA M, and WAKAMATSU K. Nationwide Site Amplification Zonation Study using Japan Engineering Geomorphologic Classification, *Proceedings of the 13th World Conference on Earthquake Engineering*, ID 1648. Vancouver, B.C, Canada, 2004.

[29] WAKAMATSU K, YAMAMOTO A, and TANAKA I. Geomorphological Criteria for Evaluating Liquefaction Potential Considering the Level-2 Ground Motion in Japan. International Conference on Recent Advance to

Geotechnical Earthquake Engineering and Soil Dynamics, 2001, 1–6.

[30] ALAN Y, ANTONY M, and JOHN B. Precision of VS30 Values Derived from Noninvasive Surface Wave Methods at 31 Sites in California. *Soil Dynamics and Earthquake Engineering*, 2019, 127: 105802.

参考文:

[1] THAMARUX P、MATSUOKA M、POOVARODOM N 和 IWAHASHI J. VS30 基于地貌图的地震微分区：泰国清迈、清莱和南奔的实验案例研究。国际地理信息杂志，2019，8：1-18。

[2] VERDUGO R. 地震场地分类。土壤动力学与地震工程，2019，124：317-329。https://doi.org/10.1016/j.soildyn.2018.04.045

[3] WALD D J 和 ALLEN T I. 地形坡度作为地震现场条件和放大的代表。美国地震学会公报，2007，97（5）：1379-1395。https://doi.org/10.1785/0120060267

[4] DARYONO.日惹特区班图尔地堑区基于每个地形单元微震的地震脆弱性指数。博士论文，加查马达大学，2011 年。

[5] NURWIHASTUTI D. W. 地震破坏模式的地貌分析：以 2006 年印度尼西亚日惹班图尔地震为例。博士论文，加查马达大学，2013。

[6] NURWIHASTUTI D. W、SARTOHADI J、MARDIATNO D、NEHREN U 和 RESTU。通过地貌学方法了解地震破坏模式：以 2006 年印度尼西亚日惹班图尔地震为例。世界工程技术杂志, 2014, 02(03): 61–70. https://doi.org/10.4236/wjet.2014.23b010。

[7] MATSUOKA M、WAKAMATSU K、FUJIMOTO K 和 MIDORIKAWA S. 使用日本工程地貌分类图的平均横波速度绘图。结构工程/地震工程, 2006, 23(1): 57s-68s. https://doi.org/10.2208/jsceseee.23.57s。

[8] MUZLI M、MAHESWORO R. P、MADIJONO R、SISWOYO、DEWI K. R、BUDIARTA、PRAMONO S. 日惹地区使用 MASW 方法测量 Vs30。气象气象杂志，2016 年，17(1)：25-32。

[9] RAHAYU A、PRAKOSO W. A 和 SADISUN I. A. 基于印度尼西亚巴东的地形和地貌学估计的 VS30 建模。国际土木工程与技术杂志, 2019, 10(06): 103–111.

[10] WIJAYANTO、MARDIATNO D、DARYONO、NEHREN U、MARFAI M. A 和 PRMONO S. 印度尼西亚古农吉杜尔的基于 Vs30 MASW 和微震反演的空间分布。国际 GEOMATE 杂志，2022，卷。22（94）。

[11] LU Z 和 WILSON G.V. 使用表面波方法的高频多通道分析对土壤脆皮潘进行成像。应用地球物理学报，2017，143：1-8。

[12] GUO Z、AYDIN A 和 KUSZMAUL J. 密西西比州北部的微震录音。工程地质学，2014，179：146-157。

[13] BIGNARDI S、ANTOVANI A 和 ZEID N.A. 开放式 HVSR：通过多个 HVSR 建模和反演对地下 2D/3D 弹性特性进行成像。计算机与地球科学，2016，93：103-113。

[14] SNI 1726:2019。建筑和非建筑结构抗震规划程序。巴丹国家标准，雅加达，2019。

[15] 航天飞机雷达地形任务 1 弧秒全球（数字对象标识符(DOI)编号：/10.5066/F7PR7TFT。

[16] 土地系统地图比例尺 250K 和 50K。巴丹信息地理空间（大的），2020。

[17] RAHARDJO W、SUKANDARRUMIDI 和 ROSIDI H.M.D. 日惹板块地质图，爪哇岛，比例 1:100.000。万隆地质研究与发展中心，1995。

[18] SURONO、TOHA B 和 SUDARNO I. 苏拉加达地质图 –吉里通特罗板材，爪哇, 比例 1:100.000。万隆地质研究与发展中心，1992。

[19] VERSTAPPEN H. 应用地貌学：环境发展地貌调查。荷兰：爱思唯尔，阿姆斯特丹，1983 年。

[20] SANTOSA L W. 从地貌学角度看日惹的特产。加札马达大学出版社，2015。

[21] THOMPSON E. M、WALD D. J 和 WORDEN C. B. 加利福尼亚州的 VS30 地图，具有地质和地形限制。美国地震学会公报，2014，104（5）：2313-2321。https://doi.org/10.1785/0120130312。

[22] BAPPENAS。日惹和中爪哇省自然灾害损害和损失的初步评估，印度尼西亚协商小组第 15 次会议，2006。

[23] COE J、MAHVELATI S、SENIOR M 和 ASABERE P. 使用地球物理和现有地下数据绘制费城国家人权保护计划 Vs30 站点类别。美国全国地震工程综合科学会议论文集，加利福尼亚州洛杉矶，2018。

[24] CIPTA A, 和 SOLIKHIN A. 基于地貌分类的苏拉威西岛表面波速度(VS30)估计及其应用。火山学和地质减灾中心，万隆，2015。

[25] ALLEN T I 和 WALD D J. 关于使用高分辨率地形数据作为地震场地条件(Vs30)的代理。美国地震学会公报，2009，99(2A)：935-943。

[26] HEATH D、WALD D. J、WORDEN C. B、

THOMPSON E. M 和 SCMOCYK G. 具有基于地形坡度的默认和区域地图插图的全球混合 VS30 地图。地震光谱，2020，36（3）：1570-1584。

[27] KAMAL A S 和 MIDORIKAWAI S. 孟加拉国达卡市区地震微分区的地貌学方法，2006 年国际原子能机构国际大会论文集，伦敦地质学会，2006。

[28] MATSUOKA M 和 WAKAMATSU K. 使用日本工程地貌分类进行全国场地放大分区研究，第 13 届世界地震工程会议论文集，ID 1648。温哥华，不列颠哥伦比亚省，加拿大，2004。

[29] WAKAMATSU K、YAMAMOTO A 和 TANAKA I. 考虑日本 2 级地面运动的液化潜力评估地貌标准。岩土地震工程和土壤动力学最新进展国际会议，2001，1-6。

[30] ALAN Y、ANTONY M 和 JOHN B。加州 31 个地点的无创表面波方法得出的 VS30 值精度。土壤动力学与地震工程，2019，127：105802。