INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: https://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Generating Indonesian-Wide Vs30 Map Using The Engineering Geomorphology Approach

Athanasius Cipta

Center for Vulcanological and Geological Hazard Mitigation
Jln. Diponegoro No. 57 Bandung, Jawa Barat, Indonesia

Corresponding author: ciptito@gmail.com
Manuscript received: September, 08, 2024; revised: April, 20, 2025;
approved: June, 19, 2025; available online: August, 11, 2025

Abstract - Earthquake hazards can be viewed from two perspectives. The first, source of earthquake, and the second, a place where the human live and carry out activities. From the second point of view, information regarding the physical properties of soil becomes crucial, especially for calculating its vulnerability. Physical properties of soil/rock, are often represented by a single value, namely Vs30, which stands for the average shear-wave velocity on the 30 m uppermost of soil. Measuring Vs30 for the whole country is a job with the next-to-zero-possibility to complete. Consequently, it is needed to have a technique to accurately estimate Vs30. Engineering gemorphology, a method that utilizes geology and morphology to approximate Vs30 in national-scale level, has been applied to create robust Vs30 data set for the whole Indonesian regions. Furthermore, the Mean Absolute Percentage Error (MAPE) is employed to judge the accuracy of the Vs30 produced from engineering geomorphology technique for Jakarta and Jayapura data sets. According to the MAPE score, which are 28.16 % and 37.83 %, engineering geomorphology is able to produce reasonable Vs30. If the MAPE calculation is split into soil class of E and D, in Jakarta the value is 39.63 % (reasonable) and 24.75 % (reasonable). While in Jayapura the MAPE score for E, D, and C classes are 74.22 % (inaccurate), 40.09 % (reasonable), and 24.00 % (reasonable), respectively. In short, this study is aimed to establish a technique to estimate Vs30 based on HVSR inversion and geomorphic parameters as well as to provide a Vs30 data set for the whole regions of Indonesia with a quantified accuracy.

Keywords: earthquake hazard, Mean Absolute Percentage Error (MAPE), HVSR

How to cite this article:
Cipta, A., 2025. Generating Indonesian-Wide Vs30 Map Using The Engineering Geomorphology Approach. *Indonesian Journal on Geoscience*, 12 (2), p.217-229. DOI:10.17014/ ijog.12.2.217-229

Introduction

Background

Earthquake shaking experienced in a particular area is not only controlled by source parameter (magnitude, type of fault, site-to-source distance), but also by local geology. Certain seismic waves might be amplified depending on the thickness and stiffness of soil overlying the bedrock where those waves propagate through. Furthermore, basin geometry may prolong and magnify seismic waves trapped inside (Cipta *et al*. 2017, 2018). Seismic waves amplification is closedly related to acoustic impedance which exists where a layer of soft soil having low seicmic-waves velocity, overlying the stiffen bedrock that has higher seismic-waves velocity. Amplification A is inversly proportional to the square root of multiplication of shear-wave velocity V_S and density ρ (Aki and Richards, 2002).

$$A \propto \frac{1}{\sqrt{Vs.\rho}} \quad \text{...} (1)$$

with density ρ and shear-wave velocity V_S are considered constant at the same depth.

Owing to its simpleness yet yield reliable result (Comina *et al*., 2011), the average shear-wave velocity at the upper 30 m of the soil (Vs30) is favoured by scientists and engineers to be used as a parameter for estimating response of site against seismic waves (Rošer and Gosar, 2010). Mazanec *et al.* (2024) stated there was a clear relation between Vs30 and amplification in certain frequency windows. Hence, referring to this basis, Vs30 is used in National Standard of Indonesia (SNI) no 1726:2019 as well as Eurocode8 (EC8) to clasifiy local site into five main categories and two specific classes based on vulnerability to liquefaction. Although Vs30 is the most pupular key parameter to classify soil, there is no consensus regarding its effectiveness as a proxy for seismic amplification (Castellaro *et al*., 2008). Other proxies often used for soil classification are N-SPT and dominant period.

Stiffness of the clastic sediment is strongly related to the age and the type of the rock, the older the unit, the more compacted, thus harder the rock. Therefore alluvium, the most recent and nonpetrified unit, is much softer than the Tertiary rock units. Likewise, the coarser the detritus the harder the sedimentary rock, for example sandstone is stiffen than claystone and softer than while breccia. For instance, the older and the coarser the detritus, the harder the rock, thus the more effective that rock in propagating seismic waves, hence, the Vs30 tends to be higher, and vice versa.

Geological Settings

The archipelago of Indonesia consists of about 17,000 islands extending over 5,000 km from the west to the east (95^{0}E-141^{0}E), and almost 2,000 km from the north to the south (6^{0}N-11^{0}S). The country is situated at the junction of major tectonic plates: Eurasia, Indo-Australia, Pacific, and Philippine Sea. The interaction among these plates are carving the morphology of the country, forming mountains, volcanoes, plains, valleys, and gorges.

The tropical climate of Indonesia greatly contributes to weathering, erosion, sediment transport, and sedimentation processes. Likewise, the very active volcanoes successively demolishing and rebuilding their bodies during the eruptions, creating new landforms.

The variety both in morphology and lithology characterizes physical properties of each site which in turn will respond differently against seismic waves propagating through this particular site. These physical properties of the sites are often represented by a single parameter popularly known as Vs30. The Vs30 is the average velocity of the shear-wave propagating through the 30 m uppermost soil. The higher the value of Vs30, the stiffer the soil, the deeper the bedrock could be expected, and vice versa (Matsuoka *et al*., 2000).

Broad area of flat to gentle slope morphology along the east coast of Sumatra and the north coast of Java are dominantly composed of loose material of alluvium. Meanwhile, peatland and other organic soil occupy vast areas in the south of Central Kalimantan and southern Papua. Areas covered by these soft soil are marked by red colour in Figure 1. Terrestrial soft sediments are also deposited in intermountain basins, valleys, and lowlands which developing over time by the movement of the active faults (PSG, 2023).

Rather soft clastic volcanic materials deposited around volcanic belts in Sumatra, Java, Nusa Tenggara, Maluku, and the northern arm of Sulawesi. In volcanic arcs, these volcanoclastic formations alternately deposited with lavas and lahars. Intrusive and extrusive rocks are also exposed in these volcaninc arc regions along the central range of Sumatra and Java as well as the northern arm of Sulawesi and Maluku Islands (PSG, 2023).

Pre-Tertiary formations are forming high mountain in the middle of the island, such as along The Great Sumatran Fault in the north and central Sumatra, as well as the central range of

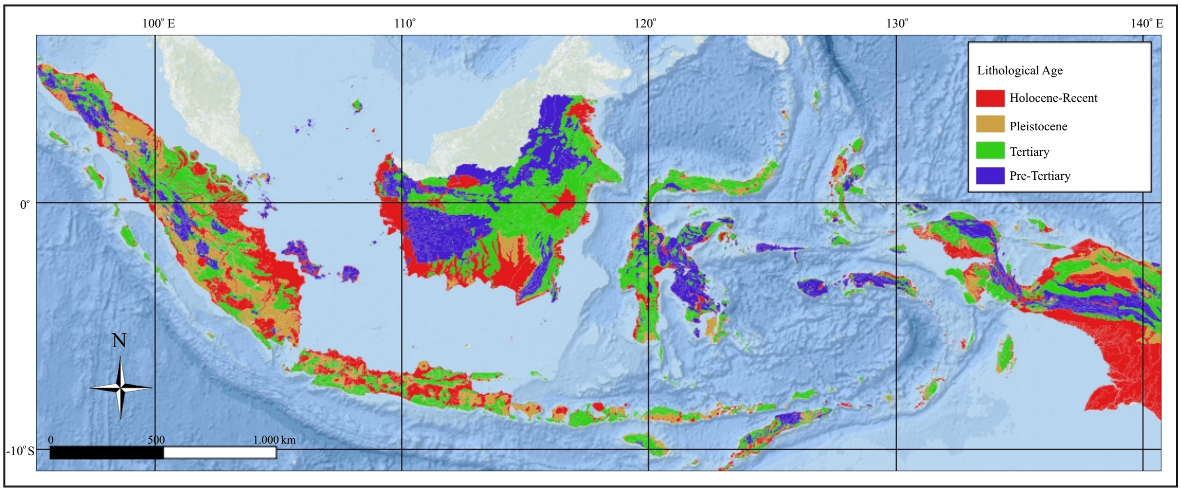

Figure 1. Simplified geological map of Indonesia, rock units are classified by age. Digital geological map of Indonesia provided by The Geological Survey of Indonesia (2023) in this link: https://vsi.esdm.go.id/portalmbg/.

Papua, Seram, Buru, and Sulawesi. These old rocks are also dominating the southeast and the east arm of Sulawesi and Kalimantan, along the Indonesia-Malaysia border. In between, soft rock of Quaternary and Pre-Tertiary formations, the Tertiary formations are deposited (PSG, 2023). In Figure 1, the Pre-Tertiaty and Tertiary rocks are marked in blue and green colours.

Materials and Methods

Two basic data needed are to create geomorphoplogy maps are digital geologic and morphologic datasets. These data sets allow us to extract engineering geomorphology classes and contribution each class, elevation, slope, and distance from source rocks to sediment sites to the value of Vs30. Furthermore, Vs30 resulting from N-SPT and HVSR microtremor datasets analyses will be utilized to validate Vs30 creating from geology and morphology proxies. Although single station HVSR inversion has a lot of advantages such as double in densely populated area by using only a single seismometer, however inversion yields non-unique solution. Consequently, validating the inversion result with geotechnical technique, such as N-SPT, which is more direct approach, is hence theoretically more accurate, enabling us to measure errors quantitatively.

Materials

The digital geological map of Indonesia produced by The Geological Survey of Indonesia (Figure 1) was used as the basic information providing rock formations and their ages and geological structures. The Geological Survey of Indonesia (Pusat Survei Geologi) provides a collection of 177 sheets of geological maps with the scale of 1:100,000 covering Java and 1:250,000 outside Java. Those maps are accessible through the following link https://vsi.esdm.go.id/portalmbg/.

As many as 445 samples of N-SPT in Jakarta and 142 HVSR microtremors in Jayapura are processed to produce Vs30 maps of Jakarta and Jayapura. These data sets, inferred and modelled Vs30, allow us to assess the reliability of the engineering geomorphology for creating Vs30 maps in Indonesia.

Data Availability

The Atlas of Local Site (Vs30) of Indonesia based on engineering geomorphology classification in pdf format is available in this link https://drive.google.com/file/d/1udMlNrNbfD1Uoo9d-k9JIZjDxkNAnAQx_/view?usp=drive_link, while raster grid files can be freely downloaded through the following link: https://github.com/cheathanasius/ ATLAS_VS30_INA/blob/main/VS30_PROVINCIAL_GRD_2022.zip.

Methods

There are two major the approaches to estimate Vs30 values. The first is the slope-topography technique which was popularized by Wald and Allen (2007) and Allen and Wald (2007). Shortly, this method assumes that the higher the slope, the easier ground failure to occur. Hence, only the firm, dense, and compact lithology can withstand weathering processes and form steep morphology. On the contrary, the flat morphology is a place where young and uncompacted sediments accumulated. The second approach adds one more parameter into account, namely rock unit and age. In Indonesia, volcanoes actively erupt and accumulate pyroclastic material around their bodies from the top to flank. Hence, relying only on topographic-slope may inaccurately classify these very recent pyroclastic material layers into hard soil. Here, the engineering geomorphology offers the better accuracy in physical-classification of recent volcanic rocks.

The initial step to materialize a national-wide Vs30 map is to build an engineering geomorphology map. The second stage, after having this map completed, the works of Matsuoka *et al.* (2006), Wakamatsu *et al.* (2006), and Wakamatsu and Matsuoka (2006) were followed in estimating the Vs30 value. The third step, as a product of an empirical approach, it needs a validation. Hence, Vs30 map coming from this method was compared to Vs30 resulting from N-SPT and HVSR microtremor inversion in Jakarta and Jayapura, respectively.

Creating An Engineering Geomorphology Map

The first step to be conducted is composing an engineering geomorphology map. Maps of lithology, elevation, and slope are essential in creating enginering geomorphology maps as introduced by Matsuoka *et al.* (2006), Wakamatsu *et al.* (2006), and Wakamatsu and Matsuoka (2006). The classification of Matsuoka *et al.* (2006), Wakamatsu *et al.* (2006), and Wakamatsu and Matsuoka (2006) were simplified as presented in Table 1, to adapt the availability of geological maps in Indonesia.

Sedimentation is controlled by depositional environment, so that finer detritus is transported further than the coarser. Clay is deposited in a plain area where water current is very weak. On the contrary, very coarse sand is accumulated closer to the source in a steeper area where water flows faster. Furthermore, sloping areas such as mountain flank and hillsides are not ideal places for sediment to abundantly accumulate, while a basin is favourable. Hence, in mountainous and hilly regions only a thin layer of soft deposited is over bedrocks, whereas in a basin sediment it piled up tens or even hundreds of meters above bedrocks.

In short, stiffness sediment is controlled by the age and the type of the rock unit, while the thickness of sediment is predominantly controlled by morphology, *i.e.* elevation and slope. In turn, the value of Vs30 depends on geological and morphological proxies previously mentioned. Based on this basis, Matsuoka *et al*. (2006), Wakamatsu *et al.* (2006), and Wakamatsu and Matsuoka (2006) introduced a classification of engineering geomorphology for estimating Vs30 for the whole of Japan. Built upon geology and morphology parameters, Wakamatsu and Matsuoka (2006) established twenty classes of engineering geomorphology, each of which has a regression coeficient *a*, *b*, *c*, and *d*, as presented in Table 2. Values of *a*, *b*, *c*, and *d* represent the contribution of geomorphology class, slope, and distance from Pre-Tertiary or Tertiary mountain/hill to Vs30 at each point of interest. In this case, Pre-Tertiary or Tertiary rocks on the mountains or hills are considered as a source of Quaternary sediments.

Following Matsuoka *et al*. (2006), Wakamatsu *et al*. (2006), and Wakamatsu and Matsuoka (2006) this technique was implemented to classify engineering geomorphology of Indonesia. Eighteen classes of engineering geology have been indentified which will be the basis of nation-wide Vs30 estimation. These eighteen classes are: abandoned river channel, alluvial fan, back marsh, valley bottom lowland, sand dune, sand and gravel bars, and delta and coastal lowland which are composed of

Tabel 1. Engineering Geomorphic Units (adapted from Wakamatsu and Matsuoka, 2006)

Slope (deg.)	Elev (m)	Rock units	Geomorphic units (Matsuoka *et al.*, 2006; *etc.*)	Topography
> 15	> 700	Pre-Tertiary rocks	Pre-Tertiary Mountain	Steep topography
		Tertiary rocks	Tertiary mountain	Steep topography
> 15	< 700	Any rock	Hill	Steep topografy
> 15	< 700	Loose pyroclastic rocks	Volcanic hill	Rather steep topograficut by number of rivers
5 - 15	Can be deposited in any elevation	Thalus, colluvium, debris, landslide materials	Mountain footslope	Lower part of slope break
< 5	Can be deposited in any elevation	Moderately dense to dense gravel or boulders in the mountains or loose sandy soil to very soft cohesive soil in the plains	Valley bottom lowland	long and narrow lowlands formed by rivers or streams between steep to rugged slopes of mountains, hills, volcanoes or terraces
< 5	Can be deposited in any elevation	dense gravel with large stones to fairly dense sandy gravel	Alluvial fan	The semi-conical shape composed of coarse materials that form at the boundary between mountains and lowlands
< 5	Can be deposited in any elevation	Very soft cohesive soil contains peat or humus	Back marsh	swampy lowlands formed behind natural embankments and lowlands surrounded by mountains, hills and terraces
< 5	Can be deposited in any elevation	Very loose sandy soil, might be covered by soft cohesive soil tanah lunak-kohesif	Abandoined river channel	shallow depression along a former river channel with an elongated shape
< 5	Can be deposited in any elevation	Loose sandy fluvial soil over very soft cohesive soil	Delta and coastal lowland	delta: low land formed at the mouth of a river by the accumulation of river sediments coastal lowlands: flat lowlands formed along coastlines by the occurrence of shallow marine deposits, including discontinuous lowlands along sea or lake shores
< 5	Can be deposited in any elevation	Fairly dense-dense marine sand or gravel, may contains boulder	Marine sand and gravel bars	rather high elevation, formed along the coastline, consisting of fine to medium aeolian sand, generally lying on sandy lowlands
> 10	Can be deposited in any elevation	Volcanic rocks	Volcano	moderate to steep topography, cut by rivers
< 5	Can be deposited in any elevation	Soft-hard rock, limestone and coral	Rocky strath terrace	fluvial and marine terraces with flat surfaces and ladder-like shapes including limestone or coral reef terraces, covered by less than 5 m of soil
< 5	Can be deposited in any elevation	Dense gravelly soil	Gravelly terrace	fluvial and marine terraces with a flat surface and a ladder-like shape, covered with a layer of gravel or sandy soil of more than 5 m
< 5	Can be deposited in any elevation	Abu vulkanik padat (Dense volcanic ash?)	Terrace covered by volcanic ash soil	fluvial and marine terraces with flat surfaces and step shapes, covered with more than 5 m of cohesive volcanic ash
5 - 10	Can be deposited in any elevation	Fine-medium size aeolian sand	Sand dune	Wavy topography usually forms along coastlines or rivers
< 5	Can be deposited in any elevation	Loose sand covering very soft cohesive soil	Reclaimed land	sea, lake, lagoon or river that has been reclaimed by drying
< 5	Can be deposited in any elevation	Loose sand covering very soft cohesive soil	Filled land	Former riverbeds, seas, and lakes that have been reclaimed through filling
< 5	Can be deposited in any elevation	Loose sandy soil	Natural levee	slightly higher areas are formed along river banks by fluvial deposition during floods

Quaternary clastic sediments. Volcano, volcanic footslope, and volcanic hill occupied volcanic belt, regardless of their age (Table 2 and Figure 2).

Pre-Tertiary and Tertiary mountains, where sedimentation at minimum and erosion at the maximum level, act as sources for Quaternary clastic sediments. Hence, in these mountain zones, slope, elevation, and distance from the source have no contribution to Vs30, having regression coefficient of *b, c,* and *d* equal to zero (Table 2 and Figure 2).

Terrace covered by volcanic ash is a fluvial or a marine terrace covered with ash, indicating tectonic processes formed a terrace followed by volcano eruption. Other classes, gravelly terrace, rocky terrace, hill, natural levee, and mountain footslope may be composed of various rocks unit of any age (Table 2 and Figure 2).

Estimating Vs30

Shen-Tu *et al*. (2010) claimed that compared to slope-topography, the geological method estimates more accurate Vs30, especially for B (760 m/s > Vs30 >= 1500 m/s) and C (360 m/s > Vs30 >= 760 m/s) classes. In comparison with measured Vs30, the value of Vs30 estimated from slope-topography proxy gives higher deviation than the Vs30 approximated from the geological approach, with standard deviation of 0.14 and 0.11, respectively. However, for classes D and E, slope-topography performed better than geology. The main reason for these larger uncertainties is because of lithological

Tabel 2. Coefisient of Regression as Provided by Wakamatsu And Matsuoka (2006)

No	Geomorphic Class	Regression Coefisien				Standard deviation
		a	*b*	*c*	*d*	
1	Mountain Pre-Tertiary	2.900	0	0	0	0.139
2	Mountain Tertiary	2.807	0	0	0	0.117
3	Mountain Footslope	2.602	0	0	0	0.092
4	Hill	2.349	0	0.152	0	0.175
5	Volcano	2.708	0	0	0	0.162
6	Volcanic footslope	2.315	0	0.094	0	0.100
7	Volcanic hill	2.608	0	0	0	0.059
8	Rocky strath terrace	2.546	0	0	0	0.094
9	Gravelly terrace	2.493	0.072	0.027	-0.164	0.122
10	Terrace covered with volcanic ash soil	2.206	0.093	0.065	0	0.115
11	Valley bottom lowland	2.266	0.144	0.016	-0.113	0.158
12	Alluvial fan	2.350	0.085	0.015	0	0.116
13	Natural levee	2.204	0.100	0	0	0.124
14	Back marsh	2.190	0.038	0	-0.041	0.116
15	Abandoned river channel	2.264	0	0	0	0.091
16	Delta and coastal lowland	2.317	0	0	-0.103	0.107
17	Marine sand and gravel bars	2.415	0	0	0	0.114
18	Sand dune	2.289	0	0	0	0.123
19	Reclaimed land	2.373	0	0	-0.124	0.123
20	Filled land	2.404	0	0	-0.139	0.120

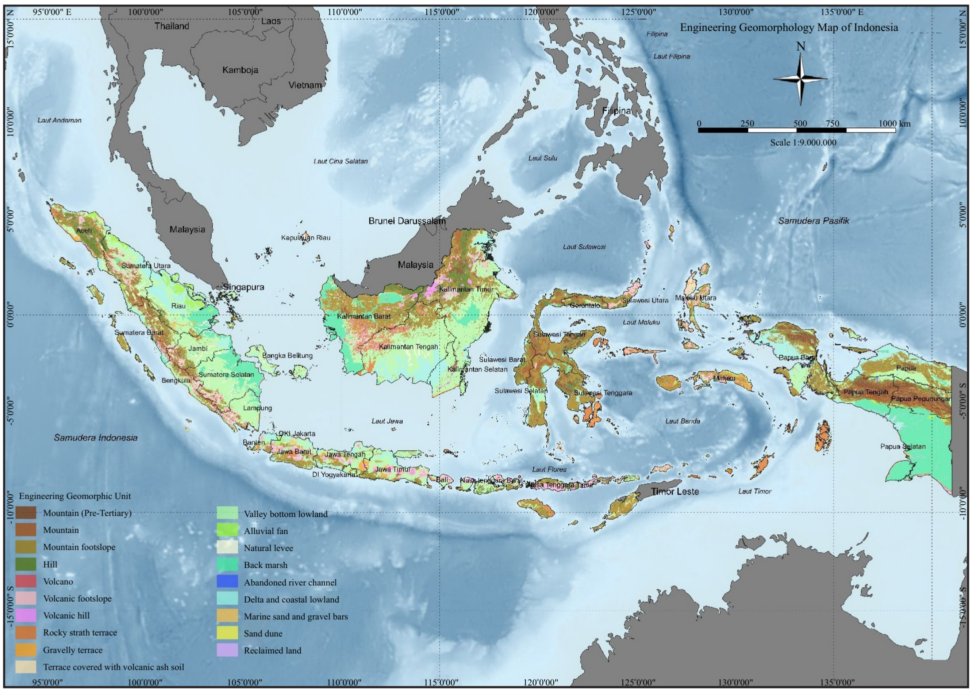

Figure 2. Engineering geomorphology map of Indonesia. By applying Matsuoka *et al.* (2006), Wakamatsu and Matsuoka (2006), and Wakamatsu *et al.*. (2006) nineteen geomorphic units can be recognized: Pre-Tertiary mountain, [1]Tertiary mountain, [2]mountain footslope, [3]hill, [4]volcano, [5]volcanic footslope, [6]volcanic hill, [7]rocky strath terrace, [8]gravelly terrace, [9]terrace covered with volcanic ash soil, [10]valley bottom lowland, [11]alluvium fan, [12]natural levee, [13]back marsh, [14]abandoned river channel, [15]delta and coastal lowland, [16]marine sand and [17]gravel bars, [18]sand dune, and [19]reclaimed land.

units. In particular, Quaternary rock units that may cause considerable amplification, are generally grouped based on the basis of age and depositional environment, rather than on the density, grain size, and thickness that determine Vs30. Important to note, measured Vs30 means Vs30 derived from strong motion recording.

Matsuoka *et al*. (2006), Wakamatsu *et al*. (2006), and Wakamatsu and Matsuoka (2006), among others, integrate slope topography and geological approaches to better estimate Vs30. Hence, the engineering geomorphology was introduced to take advantages from geological and slope-topographical methods. This engineering geomorphology approach will be utilized to estimate the Indonesian-wide V30 map.

Wakamatsu and Matsuoka (2006) provides detailed guidance to calculate Vs30 based on engineering geomorphology classes and contribution of slope, elevation, and source-rock to site distance to the Vs30 as displayed in Table 2.

Wakamatsu and Matsuoka (2006) proposed a general formula to calculate Vs30 as follow:

$$\log Vs\,30 = a + b \log Ev + c \log Sp + d \log Dm \pm \alpha \quad \text{... (2)}$$

with *Ev*, *Sp* and *Dm* are elevation, 1000*tangent of slope and distance from Pre-Tertiary/Tertiary mountain/hill, respectively. Units for *Ev* and *Dm* are meter dan kilometer, respectively.

Assessing the Error

Each dataset, inferred and predicted Vs30 would be grouped into soil type classification of National Earthquake Hazard Reduction Program (NEHRP). Reliability of the Vs30 resulted from engineering geomorphology approach would be assessed by counting the the number of inferred Vs30 and predicted Vs30 falling in the same NEHRP class of soil. The Mean Absolute Percentage Error (MAPE) would also be counted both for each NEHRP soil class and for the whole data in the cities of Jakarta and Jayapura.

Following is the formula to calculate MAPE:

$$MAPE = \frac{1}{n} x \sum_{i=1}^{n} \frac{\left(A_i - F_i\right)}{A_i} x100 \quad \text{................ (3)}$$

where n, A_i and F_i are number of observations, actual data and forecast value, respectively.

In this manuscript, actual data and forcast value are referring to inferred Vs30 and Vs30 estimated from engineering geomorphology approach. The lower the MAPE percentage errors means the more accurate the forecast. Lewis (1982) interpret MAPE results as a tool to judge the accuracy of the forecast, less than 10 %, is a highly accurate forecast, 11 %-20 % is a good forecast, 21 %- 50 % is a reasonable forecast, and larger than 50 % is an inaccurate forecast.

Result and Analysis

The lowland of Jayapura City is predominantly composed of the alluvium (Qa) which discordantly covers The Jayapura Formation (Qpj). While the alluvium takes place at low elevation (< 25 m) and formed flat to gentle sloping morphology, the limestone of Qpj configurated a steep mountainous region (slope up to 25^0) within the lowland and in southeastern-most of the city. Meanwhile, The Pre-Tertiary and Tertiary Formations dominate the west and southwest of the city, forming the high and steep mountains (Figure 3).

All those information divides Jayapura City into eight classes of engineering geomorphology which are Pre-Tertiary Mountain (PTM), Tertiary Mountain (TMO), Mountain Foot Slope (MFS), Hill (HLL), Rocky Strath Terrace (RST), Valley Bottom Lowland (VBL), Abandoned River Channel (ARC), and Marine Sand and Gravel Bar or (MSG). The VBL occupies the lowland in the middle of the city, while ARC takes place in a small patch within the VBL and ARC which dominates the coastal strip in the west. These classes are composed of The Quaternary Formations, forming plain areas. The RST can be found in the northeast corner of the city, near the border with Papua New Guinea. The PTM, TMO, MFS, and HLL sit on the mountainous areas surrounding four classes mentioned earlier (Figure 3).

The VBL in the middle of the city, the ARC, a small spot inside the VBL, and MSG in and around Hamadi are zones having the lowest Vs30, less than 200 m/s, marked by orange-red colour in the map. The RST which composed of Quaternary formation with a slightly elevated elevation (50-100 m asl.) and gentle slope (5-7^o) in the northeast corner having rather high Vs30, in the range of 300-450 m/s (Figures 3 and 4).

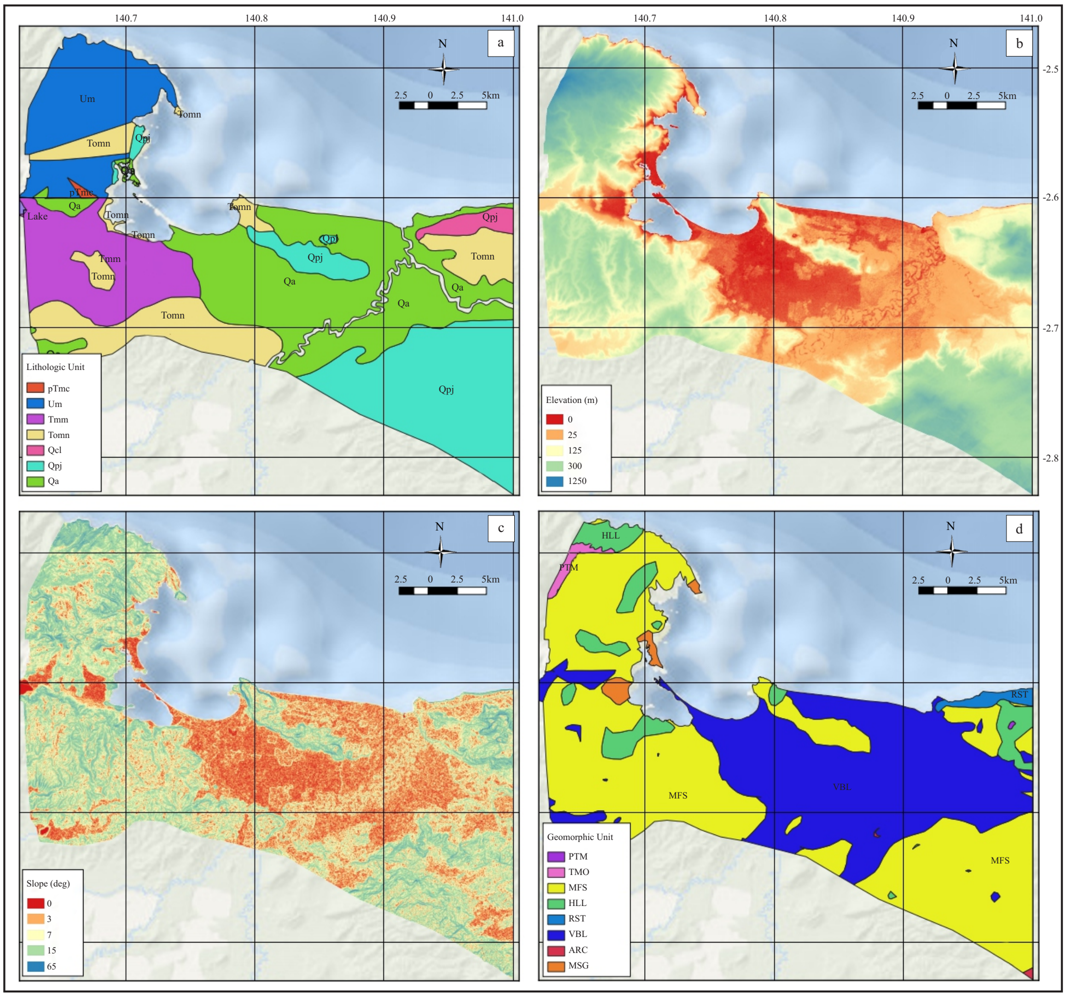

Figure 3. Example of (a) lithology, (b) elevation, (c) slope, and (d) engineering geomorphology maps of Jayapura Lithology of the Jayapura is taken from Suwarna and Noya (1995), while DEM is from DEMNAS, and slope was calculated from DEMNAS elevation model. Engineering geomorphology was produced by utilized a, b, and c following the method introduced by Matsuoka et al. (2006), Wakamatsu et al. (2006), and Wakamatsu and Matsuoka (2006). In lithologic map (a), pTmc, Umm, Tmm, Tomm, Qpj, and Qa are referring to Cycloops Metamorphic Group, Ultramafic Group, Makat Formation, Nubai Formation, Jayapura Formation, and alluvium, respectively. In engineering geomorphology map (d), PTM, TMO, MFS, HLL, RST, VBL, ARC, and MSG are Pre-Tertiary Mountain, Tertiary Mountain, Mountain Footslope, Hill, Rocky Strath Terrace, Valley Bottom Lowland, Abandoned River Channel, Marine Sand, and Gravel Bar, respectively.

The region dominated by older formations which form steeper morphology in the hinterland of the city shows highest Vs30, ranging from 400 to 700 m/s. It means this region is composed of quite hard rock or a thin layer of weathered rock or soft soil overlying the bedrock (Figures 3 and 4). Not only Jayapura, map of Vs30 for the whole regions of Indonesia also have been created as shown in Figure 5.

The first question coming to one's mind would be: how reasonable is engineering geomorphology method in estimating Vs30. By counting the number of sites of inferred Vs30 falling in the same NEHRP class as modeled Vs30 (Vs30 resulted from engineering geomorphology technique), the reliability of the model could be quantitatively assessed. Furthermore, by calculating the error, using Mean Absolute Percentage Error (MAPE), the accuracy of the model could be judged.

Out of 445 points in Jakarta having Vs30 inferred (observed Vs30) from N-SPT, 102 sites are classified as E class (Vs30 < 180 m/s) soil type, and 343 sites are in D class (180 m/s <= Vs30 < 360 m/s). More than half (fifty-two sites) of observed Vs30 being in E class are also grouped in the same class with forecasted Vs30 calculated by

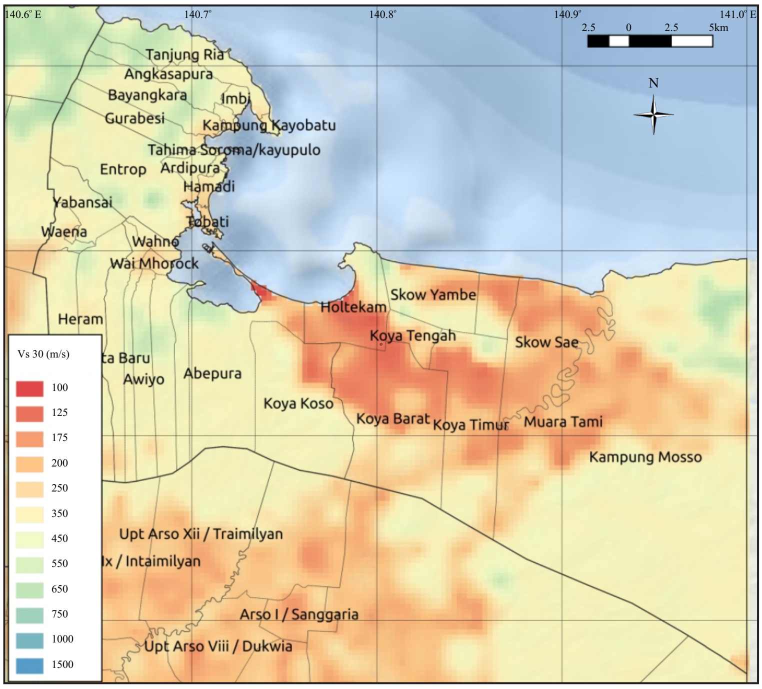

Figure 4: Map of Vs30 in Jayapura City resulted from engineering geomorphology technique.

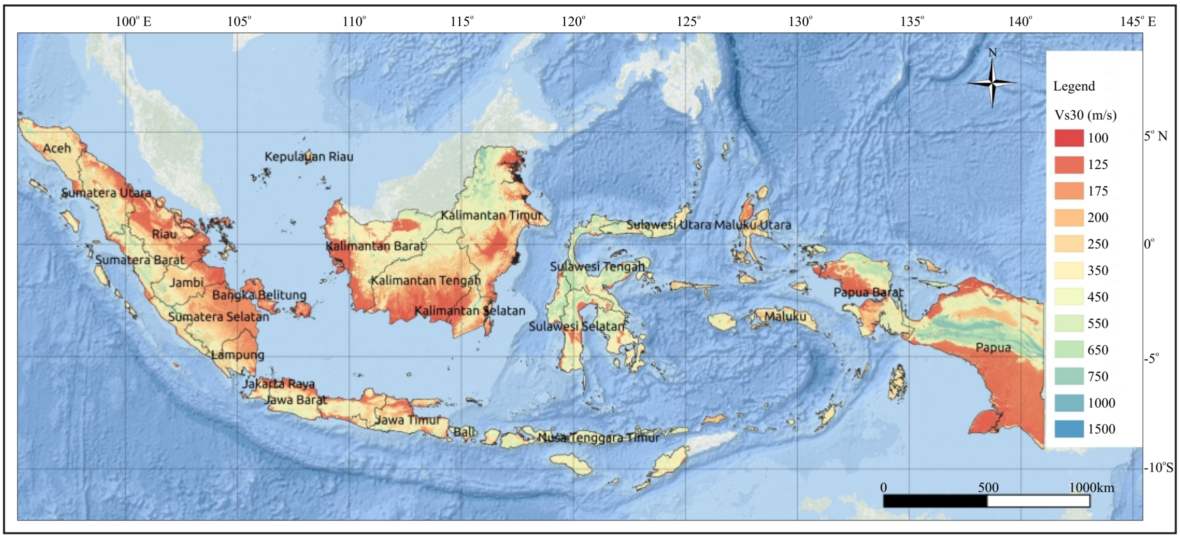

Figure 5. Map of Vs30 of Indonesian Archipelago deduced from *engineering geomorphology map. The* whole raster files of this map, divided into *thirty-eight* provinces, can be downloaded through following link: https://ln.run/dHIKY

the engineering geomorphology. However, almost half (fifty sites) got over estimate forecast, meaning the forecasted Vs30 are in D class, a group of stiffer soil (having higher Vs30) than E class. Hence, it can be said that for the E class, modeled Vs30 predicts accurately slightly more than 50% of the data. Engineering geomorphology accurately predicts 258 out of 343 (75 %) sites on D class, while the other eighty-five points (25 %) are slightly underestimated, or the modelled Vs30 are falling in E class, softer than the actual data (Table 3).

In Jayapura, engineering geomorphology over predict the whole seventeen data in E class, meaning inferred Vs30 classified to E class pairs with D class of modeled Vs30. On the other hand, D and C

Table 3. Distribution of Vs30 Classes or Soil Type for Inferred Vs30 in Comparison with Engineering Geomorphology Technique

Inferred Vs30 class (no. of data)	Engineering Geomorphology no. of data			Mean Absolute Percentage Error (MAPE) %			
	E	D	C	All	E	D	C
Jakarta (NSPT)							
E (102)	52	50	-				
D (343)	85	258	-	28.16	39.63	24.75	-
C (0)	-	-	-				
Jayapura (HVSR)							
E (17)	-	17	-				
D (69)	2	39	28	37.83	74.22	40.09	24.00
C (56)	-	20	36				

classes are well estimated, having more than 56 % and 64 % accurate prediction, respectively (Table 3).

Mean Absolute Percentage Error (MAPE) was also applied to measure the relative accuracy of the engineering geomorphology in estimating Vs30. Jakarta hosts only two types of soil, which are D and E classes, where each class is having MAPE of 24,76 % and 39.63 %, respectively. It means that engineering geomorphology produced a reasonable estimation of Vs30. Overall MAPE, combined D and E classes is 28.18 % or reasonable prediction.

In Jayapura, MAPE indicates reasonable prediction of modeled Vs30 for C and D classes. However, engineering geomorphology produced less accurate estimation for soil in E class. Since there are small number observed points in E class and much larger observed points in D and C classes, overall, engineering geomorphology is capable to bring out a worthy Vs30 model (Table 3).

Discussion

It has been shown that engineering geomorphology is a proper technique to appropriately estimate Vs30, especially for D and C classes.

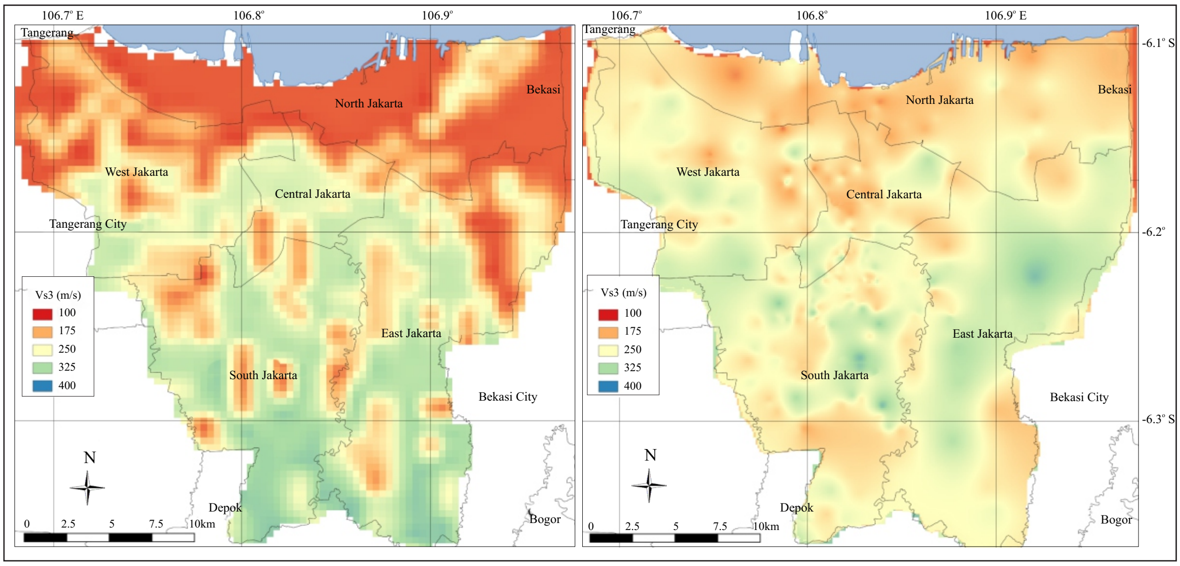

Figure 6. a) Map of Vs30 derived from engineering geomorphology approach in comparation to (b) map generated from N-SPT (redrawn from Irsyam *et al*., 2017). By exploiting a geologic map of 1:100,000 scale and a topographic map of Rupa Bumi Indonesia (Badan Informasi Geospasial, 2023) scale 1:25,000, the Vs30 map is able to be produced, and is having very similar pattern with the map produced by using standard penetration test. However, the geomorphology method results lower Vs30 than N-SPT, especially in an area composed of thick alluvium fan.

On the other hand, it shows lower accuracy for E class. In Jayapura, this technique over estimated all seventeen observed sites and in Jakarta, where there is 51 % of accuracy. Likewise, MAPE also shows that error for E class is higher than D and C classes.

The E class of soil with Vs30 </= 180 m/s, composed mainly of the youngest formation such as alluvium, alluvium fan, fluvial, colluvium, debris flow, dune, and lacustrine deposits. In most geological maps, information regarding physical properties such as density, thickness of layer, and grain-size are not provided. Hence, a more detailed geomorphic classification is hard to create. In turn, this simplification can not estimate Vs30 more precisely.

Engineering geomorphology Vs30 and N-SPT Vs30 in Jakarta enable to have a detailed geological map in a larger scale, and to create a more robust Vs30 map as also claimed by Shen-Tu *et al*. (2010). Likewise, an accurate estimation of Vs30 could be produced when the detailed terrain DEM is available. For example, a pair of maps in Figure 6 show the similar pattern between Vs30 derived from engineering geomorphology, HVSR, and N-SPT Vs30 in Jakarta. However, since the available geological map is at 1:100,000 of scale, the actual values of Vs30 of these maps are different, the engineering geomorphology Vs30 has lower values than the N-SPT, especially in the city's north coast.

Another example is provided in Figure 7. A map of engineering geomorphology Vs30 is paired with map of Vs30 derived from HVSR inversion. This map is showing the similar pattern, although in some parts HVSR inversion produced higher value of Vs30.

With all the limitations, nonetheless, the engineering geomorphology Vs30 map was able to explain the pattern of destruction during the 2018 Central Sulawesi Earthquake. While many thought that Palu was not suitable for living, a study by Cipta *et al*. (2021) showed that inside The Palu Basin, spectral acceleration at 0.2 s (SA 0.2) was significantly lower (0.73-0.8 g) than the outside the basin (1.1 g in the west and east - 1.58 g in the south). On the other hand, for SA 0.5, it was 1.18-1.33 inside the basin, and lower than 0.9 outside the basin. As for SA 1.0, it was 1.16-1.33 g inside the basin and lower than 0.85 g outside the basin (Figure 8). It may explain the number and the percentage of damage of the 1-2 story residential house inside The Palu City was significantly lower than in Donggala, excluding the damage caused by tsunami and liquefaction (Cipta *et al*., 2021).

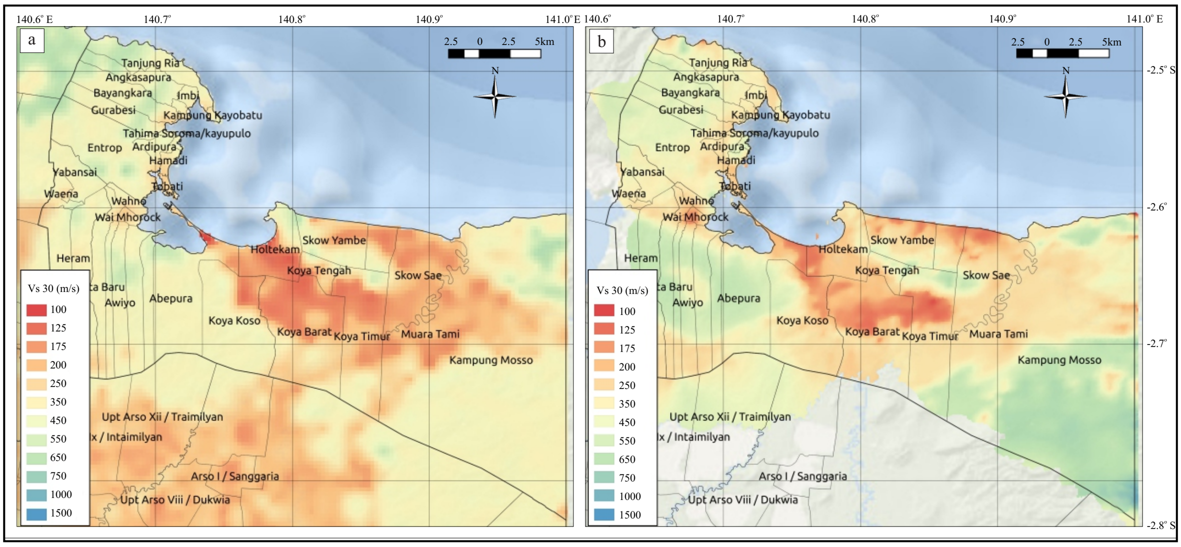

Figure 7: Maps of Vs30 derived from (a) engineering geomorphology and (b) HVSR microtremor inversion. Both maps show the similar pattern. However, the engineering geomorphology Vs30 tends to have lower values except in the area in the middle of the map and the north coast between the longitude of 140.8^0–140.9^0.

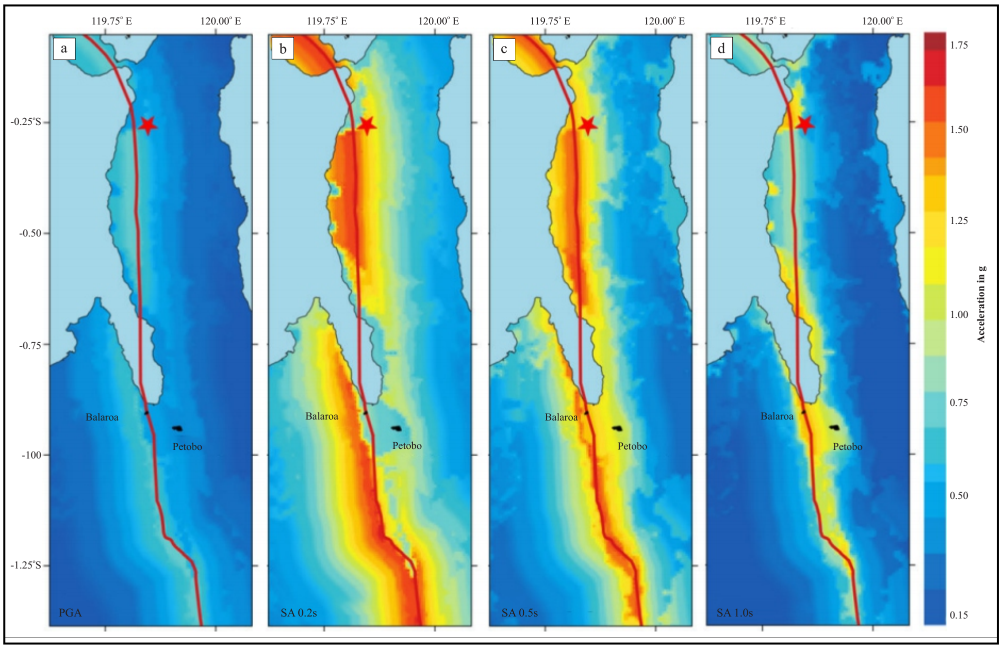

Figure 8. Map of (a) peak ground acceleration, (b) spectral acceleration 0.2 s (c) spectral acceleration 0.5 s and (d) spectral acceleration 1.0 s. The red star and lines are the epicentre and surface rupture of the 2018 Central Sulawesi Earthquake.

Conclusions

It has been shown that engineering geomorphology can be utilized to produce reasonable Vs30 in regional scale, with the average accuracy larger than 50 % (site E class: 26%, site D class: 70% and site C class: 64%) and MAPE of less than 40 % (reasonable estimation). The map produced from this technique is also appropriate as an input to model behaviour of seismic waves propagates through various subsurface layers.

The larger error in very soft soil is primarily caused by the lack of detail in the geological map. A more detailed geologic map, in addition to unit and depositional environment, should also contain the soil thickness, graind size, and water table level.

Acknowledgments

A number of surveys were dedicated to acquired HVSR microtremor data in a couple of hundred points. The surveys were fully supported by the PVMBG. Great thanks to the institution and all staff members. Finally, my gratitude delivers to the anonymous reviewers who work very hard to examine the manuscript.

References

Aki, K. and Richards, P.G., 2002. *Quantitative Seismology. 2nd edition*. University Science Books, 700pp.

Allen, T.I. and Wald, D.J., 2007. *Topographic slope as a proxy for global seismic site conditions (VS30) and amplification around the globe*, U.S. Geological Survey Open-File Report 2007-1357, 69pp.

Badan Informasi Geospasial (BIG), 2023. *Peta Rupa Bumi Indonesia*. https://tanah air.indonesia.go.id/portal-web/downloadpetacetak?skala=25K [28 June 2023].

Castellaro, S., Mulargia, F., and Rossi, P.L., 2008. Vs30: Proxy for Seismic Amplification? *Seismological Research Letters*, 79 (4), p.540-543 .

Cipta, A., Robiana, R., Griffin, J.D., Horspool, N., Hidayati, S., Cummins, P.R., 2017. A probabilistic seismic hazard assessment for Sulawesi, Indonesia. Geological Society, London, *Special Publications,* 441 (1), p.133152. DOI: 10.1144/SP441.6.

Cipta, A.P., Cummins, J., Dettmer, E., Saygin, M., Irsyam, A., Rudyanto, and Murjaya. J., 2018. Seismic velocity structure of the Jakarta Basin, Indonesia, using trans-dimensional Bayesian inversion of horizontal-to-vertical spectral ratios. *Geophysical Journal International*. 215 (1), p.431-449. DOI: 10.1093/gji/ggy289.

Cipta, A., Rudyanto, A., Aff, H., Robiana, R., Solikhin, A., Omang, A., Supartoyo, and Hidayati. S., 2021. Unearthing the buried Palu–Koro Fault and the pattern of damage caused by the 2018 Sulawesi Earthquake using HVSR inversion. Geological Society, London, *Special Publications,* 501 (1), p.185203. DOI: 10.1144/SP501-2019-70 .

Comina, C., Foti, S., Boiero, D., and Socco. L.V., 2011. Reliability of Vs30 evaluation from surface. *J. Geotech. Geoenviron. Eng*. 137, p.579-586. DOI: 10.1061/(ASCE)GT. 1943-5606.0000452.

Irsyam, M., Asrurifak, M., Mikhail, R., Wahdiny, I.I., Rustiani, S., and Munirwansyah. 2017. Development of Nationwide Vs30 Map and Calibrated Conversion Table for Indonesia Automated Topographical Classification. *Journal of Engineering and Technological Science*, 49 (4), p.457-471.

Lewis, C.D., 1982. *Industrial and business forecasting methods: A practical guide to exponential smoothing and curve fitting.* London; Boston: Butterworth Scientific.

Matsuoka, M., Sito, T., and Sato, H., 2000, Mapping the Vs30 Distribution for Japan Based on Geomorphology and Site Classification, *Procee- dings of the 12th World Conference on Earthquake Engineering*, 1 (1), p.345-350.

Matsuoka, M., Wakamatsu, K., Fujimoto K., and Midorikawa, S., 2006, Average Shear-wave Velocity Mapping Using Japan Engineering Geomorphologic Classification Map, *Structural Engineering/Earthquake Engineering, JSCE*, 23 (1), p.57-68.

PSG (Pusat Survey Geologi), 2023. *Peta Geologi-Litologi*, https://vsi.esdm.go.id/portalmbg/

Rošer, J. and Gosar, A., 2010. Determination of Vs30 for seismic ground motion in the Ljubljana area, Slovenia. *Acta Geotechnica Slovenica*. p.61-76.

Shen-Tu, B., Mahdyiar, M., Rong, Y., Shabestari, K., and Guin, J., 2010. On The Correlation of Site Classifications Estimated from Surface Geology, Topographic Slope, and Shear-Wave Velocity Measurements. *Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering*. July 25-29, 2010, Toronto, Ontario, Canada. Paper No. 406.

Suwarna, N. dan Noya, Y. 1995. Peta geologi lembar Jayapura (Pegunungan Cycloops), Irian Jaya, Pusat Penelitian dan Pengembangan Geologi (P3G), Bandung.

Wakamatsu, K. and Matsuoka. M., 2006. Development of the 7.5-arc-second engineering geomorphologic classification database and its application to seismic microzoning. *Bulletin of the Earthquake Research Institute*, Univ. Tokyo, 81, p.317-324.

Wakamatsu, K., Matsuoka, M., and Hasegawa, K., 2006. GIS-based Nationwide Hazard Zoning Using the Japan Engineering Geomorphologic Classification Map, *Proceedings of the 8th U.S. National Conference on Earthquake Engineering*, Paper No. 849, California, USA.

Wald, D.J. and Allen, T.I., 2007, Topographic slope as a proxy for seismic site conditions and amplification: *Bulletin of the Seismological Society of America*, 97 (5), p.1379-1395.