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Seismic Hazard Zonation in Gedebage Future Development in Bandung City Using HVSR Inversion

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***Abstract*— Greater Bandung, the largest economic growth corridor in Indonesia after Jabodetabek, is sitting on the Bandung basin. This deep sedimentary basin is situated just 12 km south of the active Lembang fault. Gedebage is an area intended to be the new economic and business center located in the easternmost of Bandung. The research aims to identify the vulnerability of Gedebage area against seismic ground motions. The area's morphology is dominated by a flat area with 0 – 8% of slope and predominantly composed of an old lake deposit. Topography, including basement morphology, sediment thickness, and physical properties, plays a great role in escalating/de-escalating seismic ground motions. A specific morphology may trap and prolong seismic shaking. Furthermore, stiffness and bedrock depth are instrumental in passing the spectral ground motions to the surface. The HVSR inversion method is applied to map subsurface conditions that successfully applied in Palu and its surrounding area. The research shows that Gedebage areas are vulnerable to the seismic hazard, referring to the shear wave velocity (Vs30) distribution and seismic hazard micro zonation maps. The discussion of the research findings is useful for future infrastructure development in the research area. The area is categorized as soft soil and medium soil classes, and it has a high vulnerability for destruction if there is an earthquake. The area should be cleared from vital infrastructures such as government buildings, schools, or hospitals.**

***Keywords*— Seismic hazard; Gedebage; Bandung basin; HVSR inversion.**

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I. INTRODUCTION

Bandung basin is an intermontane basin surrounded by mountain ranges and volcanoes. The total area of the Bandung basin is 2300 sq. km, spans 60 km and 40 km in west-east and north-south directions, respectively, covering an area from 650 m above sea level to peak about 2400 m high the late tertiary volcanic ranges [1], [2]. Eastern part of Bandung basin extents from Nagreg to Cicalengka, central or middle part extents from Cicalengka to Cimahi – hill complex of Lagadar mountain, and western part extents from Cimahi-Batujajar to Cililin and Saguling reservoir [1]. Geologically, central Bandung plain is an important part of the Bandung basin since it is the location of 4 main cities or Greater Bandung, including Bandung city, Cimahi city, West Bandung regency, and Bandung regency. The four cities also famous as Bandung Metropolitan Area (BMA), as living space for more than eight million people [3]. However, the spatial planning for urban areas of Bandung basin covers five urban areas and 85 district areas, including all districts of Bandung regency, West Bandung regency, Cimahi city, Bandung city, and five districts of Sumedang regency based on the Presidential decree of Indonesia No.45/2018. Bandung city is a very important city in the Bandung basin because the city is the capital city of West Java and the center of economy and education in Indonesia.

According to the latest Bandung regional planning of 2011-2031, Bandung city is divided into eight sub-development areas, including West Sub Development area (i.e., Sokanagara, Cibeuying, Tegalega, and Karees) and East Sub Development area (i.e., Arcamanik, Ujungberung, Kordon, and Gedebage). Gedebage is a very important sub-development area due to allocated as a city center in the eastern part of Bandung to reduce condensed activities in the city center in the western part of Bandung [3]. Presently, the city's development was concentrated in Gedebage area by constructing infrastructures and facilities such as some new high-rise buildings for sports centers, apartments, offices, public services, and expensive settlement areas. The total population of Gebedage based on Central Bureau Statistic (BPS) in 2017 is 35,579, and the area is 9.78 sq. km.

Like other areas in Indonesia, Bandung city encompasses active tectonic regions and earthquake high prone zone [4]-[7]. Owing to its proximity to Sunda Megathrust (150 km to the south) and active crustal faults, enacting Bandung prone to seismic shaking [8]. At least three active faults are located in the surrounding area of Bandung basins, such as Cimandiri, Lembang, and Baribis faults [8], [9]. For example, there are at least four times of destructive earthquake occurred in Bandung city: Mw4.2 (July 7, 2003), Mw5 (April 15, 2005), Mw3.3 (August 28, 2011), and Mw4.5 (September 4, 2011) [10]. The distance of Gedebage future development area is about 12 km from the Lembang fault.

Sources and potentially affected areas should be considered for risk assessment to evaluate seismic hazards [11]. The near-surface effect (the site effect) relies on local geology conditions, which affected ground motion. The morphology of Gedebage area is relatively flat. However, an old lake deposit and a thick layer of sediment are dominated by an old lake deposit, amplifying seismic ground motion [12]. There is a need to prepare a comprehensive seismic micro zonation to support seismic hazard and risk assessment. Some geophysical methods to image interior area in the urban area are either active or passive seismic methods. However, passive seismic methods such as the horizontal to vertical spectral ratio (HVSR) method are very suitable, especially for a densely populated area. There are advantages such as good adaptability to site conditions and ease of measuring non-invasive, inexpensive, and safe [13]. The method already successfully researches seismic microzonation in earthquake research, analyzing site characteristics and site amplification and detecting underground shear wave velocity and sediment thickness [13]. This research applied the HVSR method to depict the subsurface condition as an input model to calculate seismic ground motions. Then, the seismic ground motion model was used to measure the degree of vulnerability of Gedebage area against a seismic hazard potential generated by active faults and megathrust.

The geological of the western part of Java is mostly dominated by subduction of active Sunda arc. During the last decade, the Sunda Arc has known a sequence of great earthquakes (>Mw 8), which not only caused large co-seismic offsets in GPS time series but also induced spatially and temporally significant post-seismic transients [8]. The Java subduction zone is one of the most tectonically active plate boundaries globally, extending ~1700 km from the Sunda Strait to eastern Indonesia [8]. In the southern part of Java island, the oceanic plate of Indo-Australia subducts beneath the Eurasian continental plate at a convergence rate of about 6 – 7 cm/year during the quarter-time [9].

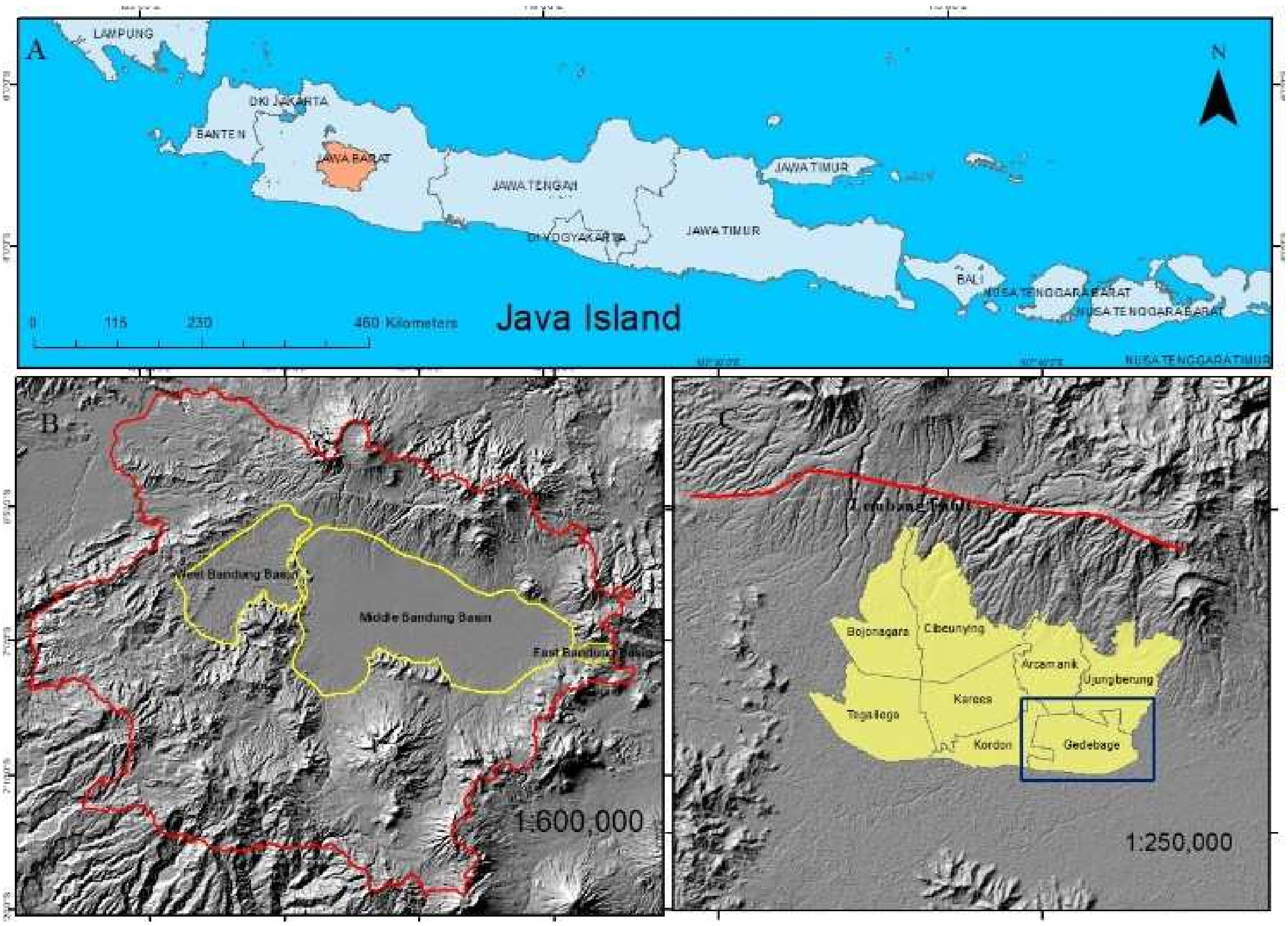

Fig. 1 A. Bandung basin in West Java province, B. Three areas of Bandung basin; west, middle, and east (yellow line) and the area development of Bandung basin based on the spatial plan (red line). C. Study area of Gedebage future development area in Bandung city (blue box).

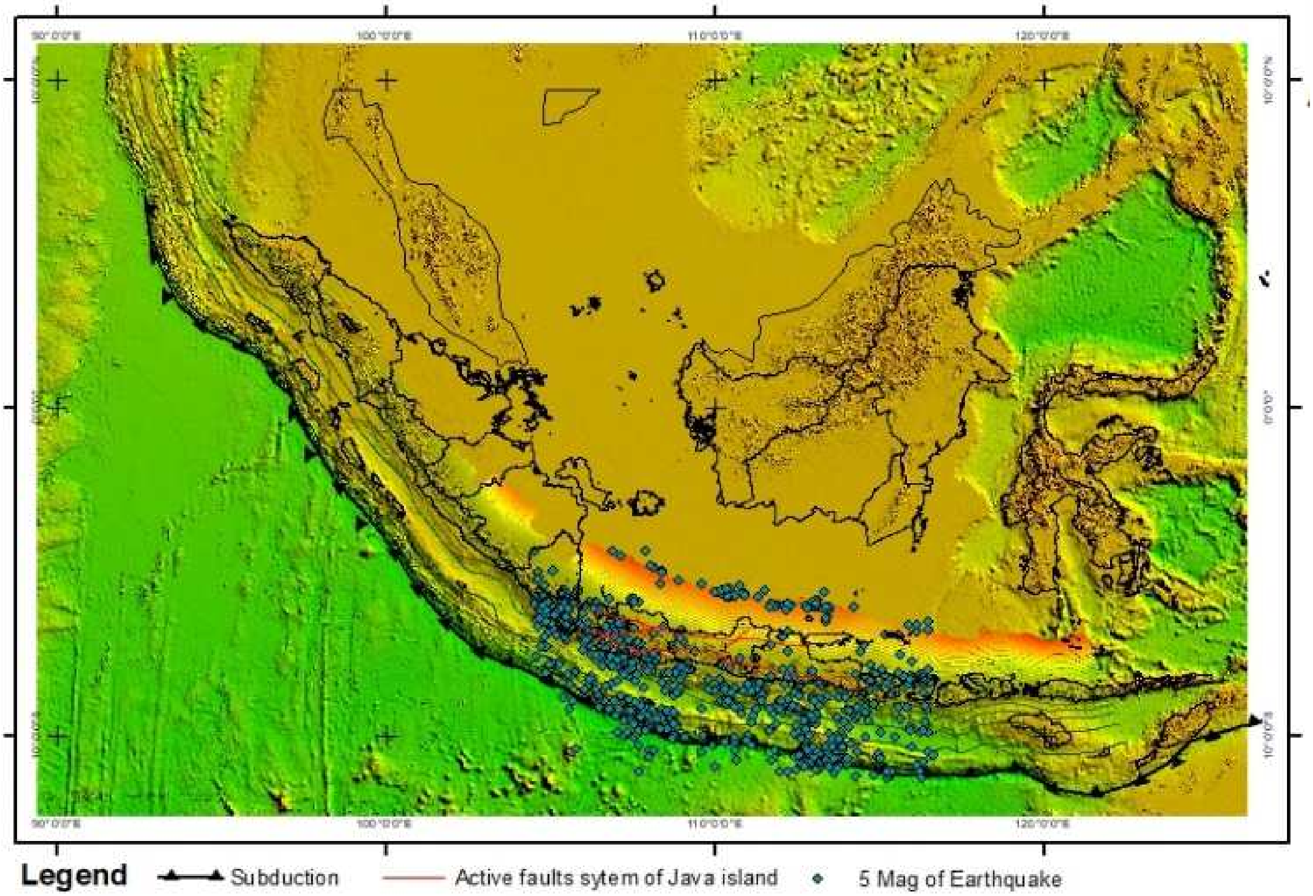

Fig. 2 Regional geology of Java island shows the main source of earthquake: megathrust in the south of Java and active faults in the land. [9].

Young volcanoes surround Bandung Basin; in the northern part, there is a complex of volcanoes Burangrang - Sunda-Tangkubanparahu, Bukittunggul, Cupunagara, Manglayang, and Tampomas. The volcanoes in the eastern part are Bukitjarian, Karengseng - Kareumbi, a volcanic rock complex Nagreg up to Mount Mandalawangi, and volcanoes in the southern part are Kamojang volcano complex, Malabar, Patuha, and Kendeng. Tertiary volcanic rocks and limestone bound the Bandung Basin only to the west, which is included in the formation Rajamandala [1].

The geology of the Bandung sedimentary basin is dominated by volcanic product deposit from early tertiary to quarterly, except for the upper western part of Bandung basin, there is the oldest tertiary sediment formation; Rajamandala formation that consists of limestone, clay stones, marl, dan quartzite sandstones in Upper Oligocene [14]-[17]. An old lake deposit dominates Gedebage area. The deposit is formed in the Holocene era or about 135ka, consisting of volcanic product and lake sediment [2]. The area is also considered the lowest part of the Bandung basin [1].

A back-arc thrust influences the geological structure of Bandung area in the Southern part of Java, forming fold and fault. The direction of fault is northwest-southeast, northeast-southwest, and north-south. In the north of the Bandung basin, the direction of the Lembang fault is east to west. The tip of the west segment of the Lembang fault is connected with Cimandiri fault, and the tip of the east part is connected with the Baribis fault. Lembang Fault is an interesting geological landmark in the highland of Bandung and a clear clue of neotectonics activity in the Bandung basin. The morphology of the Lembang fault is fault scarp, where its wall face to the north. The chronology of the Lembang fault is divided into the east Lembang fault, about 125 ka, and the west Lembang fault, about 50 – 35 ka ago [4]. East Lembang fault is covered by a product of big eruption of Tangkuban perahu volcano about 50-35 ka, since then west Lembang fault is starting to active about 35-20 ka. Lembang fault is a segmented left lateral fault, with a length of about 29 km and slip rate of about 3 – 5.5 mm/year, and the fault is capable of generating earthquake as large as 6.5-7 magnitude [18] and about 2000 and 500 year BP [19]. An earthquake of West Java province is mostly affected by the Indo-Australian subduction, Cimandiri Fault, and Lembang Fault. From 1883 to 2013, there are 37 destructive earthquakes in the West Java province [10].

Tohari *et al.* [20] showed the thickness of the soft soil layer in the center of the basin range between 25-150 m based on microtremor data. The southern, eastern, and southern mountain surrounding basin has a high-velocity structure, except the west of the Tangkuban Parahu volcano has a low-velocity structure [12]. The velocity amplification levels in the Bandung basin vary with a range of 1.3 – 6.5 [21].

Seismic hazard map of west Java province has also been published by the Geological Agency of Indonesia (BG), indicating that Bandung city is the high vulnerability of seismic hazard for 500 years return period, response spectra 0.3 Hz, 0.45 g of peak ground acceleration [16]. The earthquake hazard map is based on probabilistic seismic hazard assessment where the inputs are earthquake sources, earthquake catalog, and soil class. The West Java province area is divided into two seismic hazard classes: earthquake high prone zone or intensity scale more than VIII MMI (Modified Mercalli Intensity) and earthquake moderate prone zone or intensity scale about VII-VIII MMI.

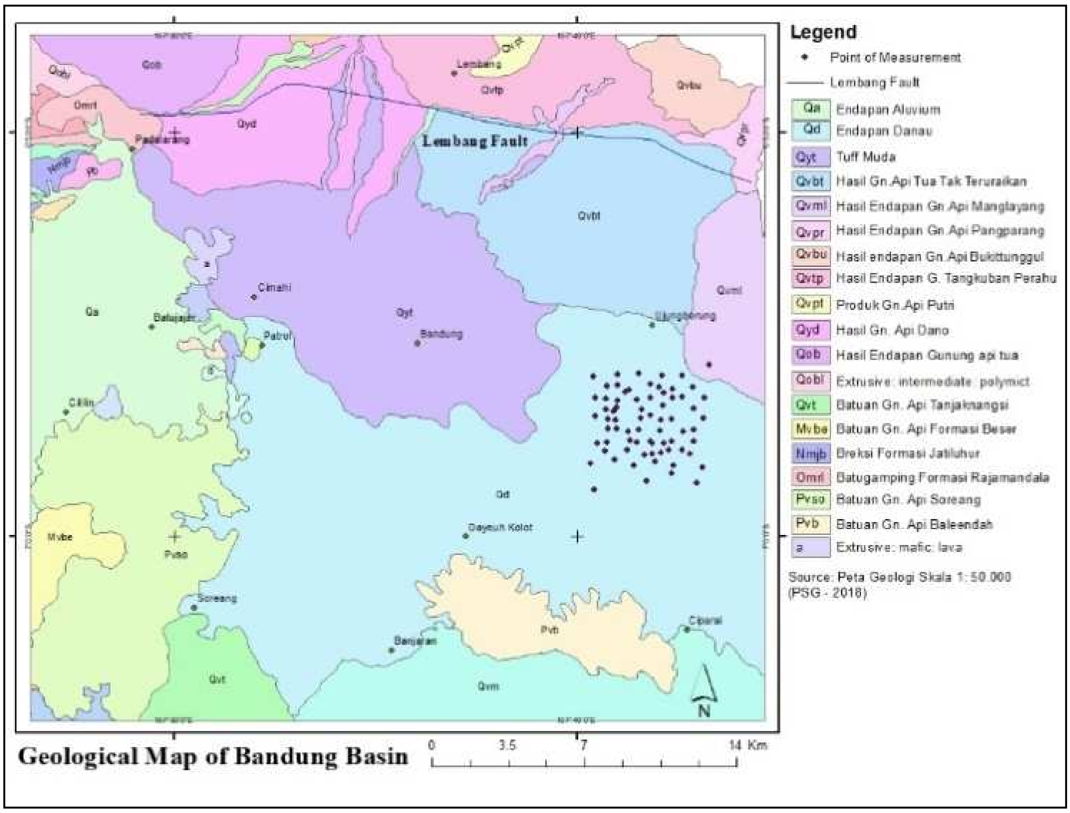

Fig. 3 Geology map of the Bandung basin is compiled and simplified from previously published maps [14]-[17]. The picture also shows the measurement location of microtremor (black dots).

II. Materials and Method

The research focuses on seismic hazard zonation in Gedebage future development area in Bandung City. The seismic hazard analysis heavily relies on the near-surface effect (the site effect) using geophysical data because based on geological and geomorphological data analysis, the study area is homogenous. However, the lesson learned from earthquake cases, for example, in Palu, has different impacts on the homogenous area. The method was used to locate possible impacts in the study area as a reference for field investigation.

A. Horizontal to Vertical Spectral Ratio (HVSR) Inversion

The application of the geophysical method for seismic hazard analysis in the Bandung basin is grown massively since the rise of seismic hazard awareness among all stakeholders, for example, the application of ambient noise tomography (ANT) to image subsurface structure in Bandung Basin and microtremor measurement to investigate velocity amplification in Bandung basin [12], [21]. The other regions next to the Bandung basin, the seismic velocity structure and seismic hazard analysis of the Jakarta basin, are already investigated using the HVSR method [22], [23]. The same method is also already applied in Palu to image subsurface structure, including to reveal unearthing the buried fault by the same author [11]. HVSR and SPAC also are already applied to reveal the subsurface characteristic of Palu city [12].

The main advantages of the HVSR method are relatively simple, low-cost measurement and precise estimate of the resonance frequency of sediment without previous knowledge of geological and S-wave velocity structure of the subsurface [24]. HVSR method exhibits a sharp peak at the fundamental frequency of the sediments, where there is a high impedance contrast between the sediments and underlying bedrock. Today it is widely accepted that the HVSR peak frequency reflects the main resonance frequency of the sediments.

The Microtremor method has been widely used for site effect studies in the last decade [21], [24], [25]. Microtremor is a very small motion compared to the amplitude of an earthquake. Ambient vibration (noise) from atmospheric phenomena and man activities can spread on the earth's surface, either microseismic or microtremor. In this research, microtremor measurement has been done with the intervals 500 m and one hour per location to collect reliable time series. The ellipticity curve is created from these time-series measurements. We can determine the dominant frequency from the ellipticity curve, either low frequency or high frequency, and peak amplitude low and high frequency. Dominant frequency and peak amplitude are related to the vulnerability of seismic motion.

Ellipticity curve inversion (HVSR Inversion) should be done to know the S-wave velocity profile. In short, the first step of HVSR inversion is microtremor measurement, then using *geopsy* software to produce HVSR curve. To begin the inversion process, we need input HVSR curve, a priory of the thickness of the layer model, S-wave velocity, P-wave velocity, rock density, and Poisson ratio. These five parameters can be elaborated from the geomorphological unit on microtremor measurement locations. The output of the inversion process is velocity S-wave for every location of measurement.

In this research, the spacing grid of microtremor measurement is 500 m from 80 locations. The time-series data format converts to the frequency domain using Fast Fourier Transform (FFT), as the results are frequency and amplitude spectra of H/V maximum. The graph of H/V for every measurement location is plotted to have a distribution map of the dominant period for surface rock in the study area.

TABLE I
SITE CLASSIFICATION AS PER NEHRP SCHEME [26]

No	Site Class	Description	Vs30 (m/s)
1	A	Hard rock	>1500
2	B	Firm and Hard rock	760 - 1500
3	C	Dense soil, soft rock	360 - 760
4	D	Stiff soil	180 - 360
5	E	Soft clays, special study soils, e.g., Liquefiable soil	<180

B. Deterministic Seismic Hazard Analysis

Deterministic Seismic Hazard Analysis (DSHA) methodology forms the basis for seismic hazard analysis [27]. The steps for analysis are: (1) to use geologic data and the historical earthquake record to define the locations of earthquake sources across and beneath the country, as well as the likely magnitudes, tectonic type or mechanism, and frequencies of earthquakes that each source may produce; (2) to control earthquake need to be identified this involved engineering judgment; (3) to estimate the ground motions that the sources produce at a gridwork of sites that cover the entire study area; (4) the earthquake hazard for the site is a peak ground acceleration resulting from earthquake magnitude from fault sources a specific distance.

III. RESULTS AND DISCUSSION

A. Near Surface Properties and Sediment Thickness

Figure 4a shows that the peak period from microtremor measurement is from 0.4 – 1.4 second and mainly in the range of 1.2 – 1.4 second. The dominant period has a close correlation with the depth of soft sediment layers [28]. Assuming that the sediment layer is homogeneous, the higher period means thicker soft sediment and vice versa.

Based on the assumption that the earth layer is homogeneous from the top to the depth of 30 m, the dominant period is represented by shear wave velocity [29], [30]. Zhao *et al.* [30] showed that the classification of the rock is divided into four classes that show the rock hardness, including class I (basement rock) with the value of T is 0.2 seconds, class II (hard rock) of T value is 0.2- 0.4 second, class III (medium rock) of T value is 0.4 – 0.6 second, and class IV (soft rock) of T value is > 0.6 second. It is concluded that the study area is dominated by class IV or soft rock. The HVSR peak amplitude map is shown in figure 4b shows the peak amplitude of the study area that mostly in the range 7 – 8; they reach lower values in some areas; south, middle, northeast, and northwest. The amplitude of 7 - 8 indicates a high impedance contrast with old lake deposit in the bedrock. The peak amplitude is related to the impedance contrast between sediment and the bedrock [24].

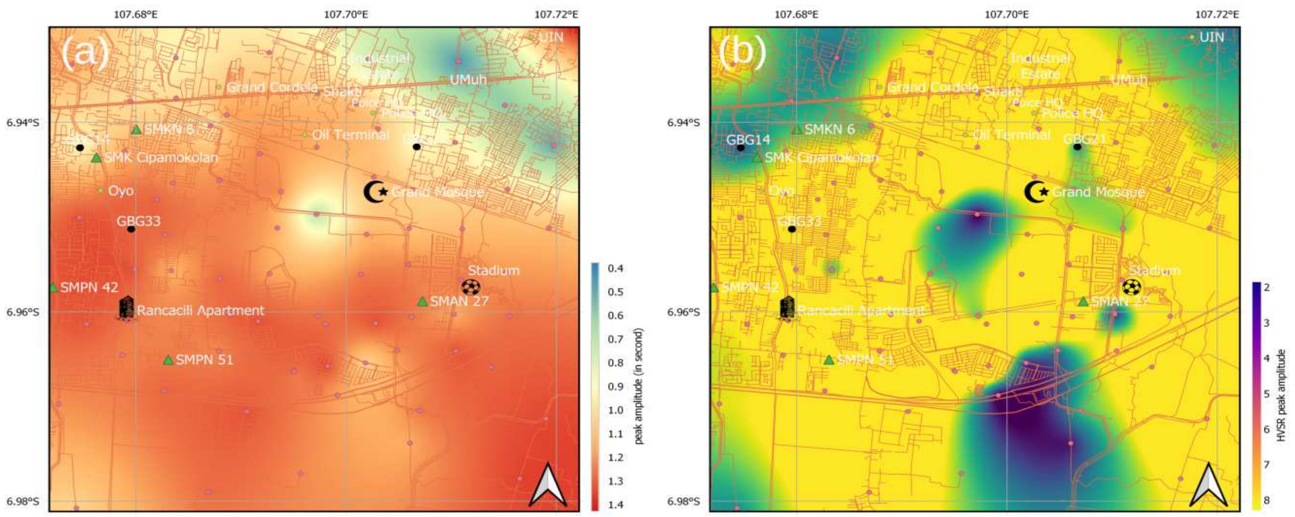

Fig. 4 Maps of HVSR (4a) peak period and (4b) peak amplitude. The figure 4a shows that peak period from 0.4 to 1.4 second mean medium and soft rock, mainly in the range of 1.2 – 1.4 second. Figure 4b shows the peak amplitude of the study area that mostly in the range 7 – 8; they reach lower in some areas.

HVSR inversion also shows the wave velocity profile of Vp and Vs. Every velocity contrast shows every soil layer in the subsurface. From figure 5, the velocity profile model shows the differences in sediment depth for every measurement point. For example, the differences in velocity contrast are clearly seen in point GBG014, the area around GBLA stadium (point GBG021), and Cipamokolan area (point GBG 033). The comparison value of Vp and Vs (Vp/Vs) also shows a saturation degree of rock, whereas if the value of Vp/Vs is 3, that means the occurrence of water. The value of Vp/Vs depends on porosity, clay contents, and water saturation. The higher the porosity and clay content, the higher the value of Vp/Vs [29]. If Vp/Vs' value is very high (>6), the layer content is clay and water-saturated, while the value of Vp/Vs between 3 and 6 indicated that the layer is sand with water-saturated. As we can see from Vp/Vs very high anomalies, the layer with water-saturated is predicted to have liquefaction when a strong earthquake occurred in the area. In short, the area with the high value of Vp/Vs should have special attention because the high potential of liquefaction usually occurs in an area that consists of fine sand or clayey sand.

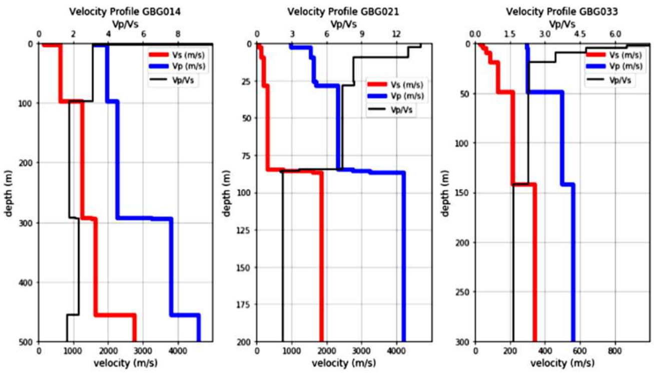

Fig. 5 The velocity profile for three sampling location with different depth.

The HVSR inversion of microtremor signal is used to make a model of shear wave velocity model. From the inversion proses, the result is the representative value of shear wave velocity until the depth of 30 meters (Vs30) because the velocity has been considered the complexity of the structure of the rock from the surface to the surface subsurface. Shear wave velocity is an important parameter to evaluate earth dynamic in shallow subsurface [31]. In terms of earthquake engineering technique, Vs30 is needed to classify sites based on earth type. Figure 6 shows the variation value of Vs30 in the study area between 80 m/s and 560 m/s dominated by the value of Vs30 from 320 to 480. Only a small area has a value of 160 m/s and a value of 560 m/s. Based on National Earthquake Hazard Reduction Program (NEHRP) can categorize as follows; Class of E (soft soil) is Vs30 <180 m/s, Class of D (medium soil) is 180 m/s < Vs30 < 360 m/s, and class of C (dense soil or soft rock) is 360 m/s < Vs30 <720 m/s.

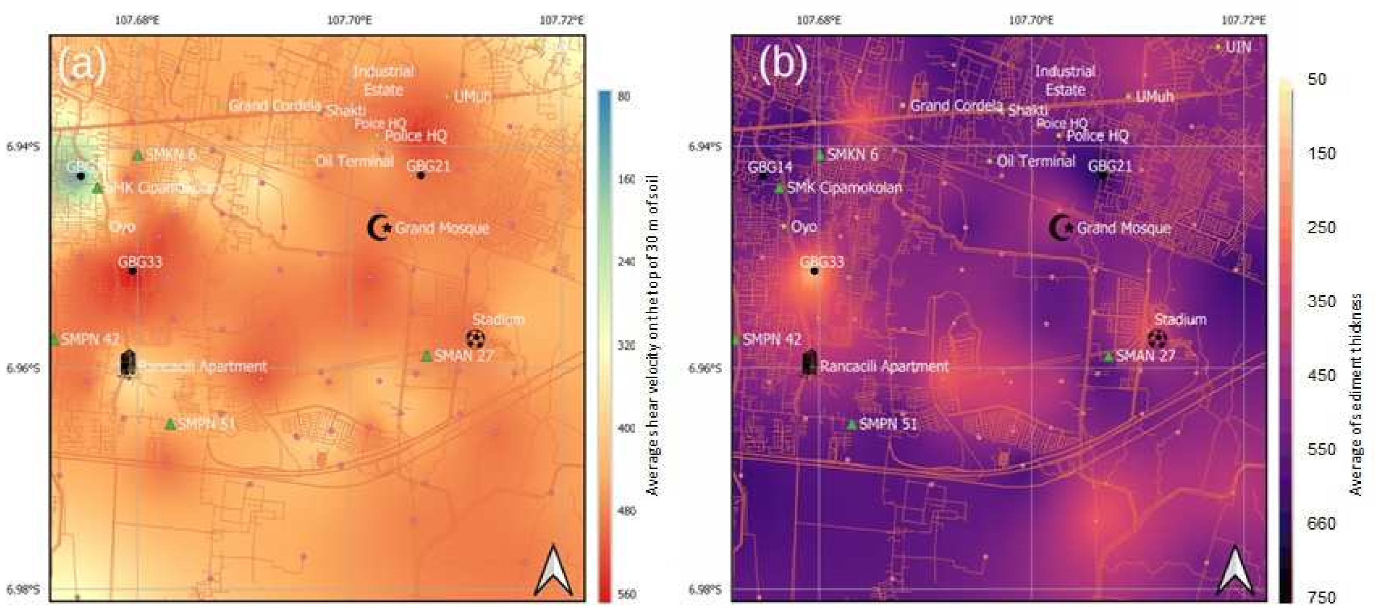

Fig. 6 Maps of (a) Vs30 and (b) sediment thickness (Z1.0) inferred from the inverted shear-wave velocity of Gedebage area. Figure 6a show the variation value of Vs30 in the study area between 80 m/s and 560 m/s and dominated by the value of Vs30 from 320 to 480. Only a small area has a value of 160 m/s and value of 560 m/s. Figure 6b show sediment thickness of study area ranging from 50 to 750 m.

The study area is dominated by class C or dense soil (soft rock). Vs30 analysis and the basin depth are used as input parameters for seismic hazard analysis that considers the local geology factors. Deterministic seismic hazard analysis is applied using two earthquake sources; Lembang fault and megathrust. The previous research shows that the value of Vs is 157 – 187 m/s [20]. In short, the study area is vulnerable to seismic hazards because the soil can amplify ground motion when the earthquake happened. Infrastructure development in this area should take into consideration earthquake-building resistant rules.

B. Seismic Hazard Zonation Analysis

Spectral Acceleration (SA) calculation for a period of 0.2 seconds from Lembang Fault is extended from 0.5 to 0.95 g (figure 7a). While the calculation result of Spectral Acceleration based on megathrust event is from 0.08 to 0.14 g (figure 7b). In general, the ground motion on the rock is declined toward the south since the source of an earthquake is located in the north. The distance has a significant effect on the value of ground motion.

The surface shock shows the variation of value shock because of the effect local condition differences, so that there is the specific area that has lower shock than the surrounding area, in association with the high value of Vs30, it is mean the amplification of earthquake shock is lower than the area with a low value of Vs30. It is very important to have a deep knowledge of the impact of seismic hazards in this area. The urban planner can create a spatial plan based on an earthquake mitigation plan to minimize the victim and economic loss [32].

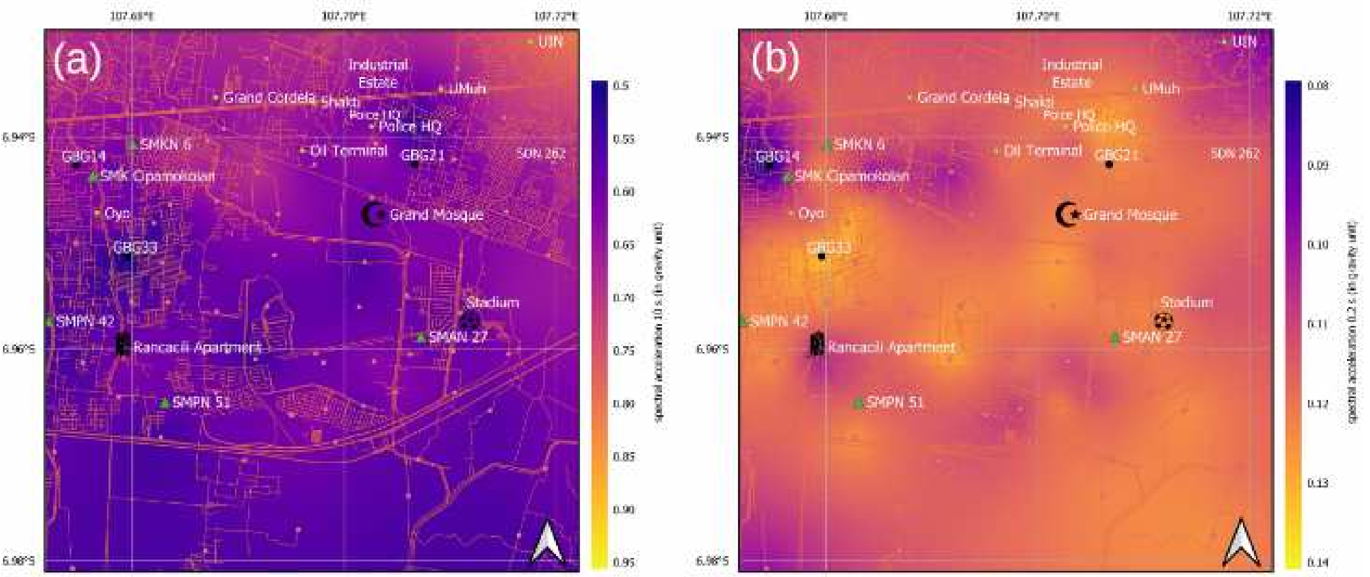

Fig. 7 Maps showing spectral acceleration for period 0.2 second (SA:0.2) resulted from scenarios (**a**) Mw6.8 event generated by Lembang Fault and (**b**) a megathrust event with a magnitude of Mw8.7. Notes: for a clearer view, these figures using different scale bars.

IV. Conclusion

The main result of the research is the distribution map of shear wave velocity to the 30-meter depth of Vs30 and the seismic hazard map. We can conclude from these two maps that the dominant microtremor measurement period has a high variation value of 0.4 – 1.4 seconds, which means thin, soft sediment. The variation value of Vs30 from 80 to 560 m/s show the classification of rock is class of E (soft soil) or < 180 m/s, class of D (medium soil) 180 < Vs30 <360 m/s, and class of C (densely soil or soft rock) or 360 m/s < Vs30 < 720 m/s. The velocity profile model shows the differences in sediment depth for every measurement point. The anomaly of velocity is located at Cimencrang (point GBG014), the surrounding area of GBLA (point GBG021), and Cipamokolan (point GBG033), with the value of Vp/Vs is quite high that means has potentially high liquefaction when the earthquake occurred.

The Value of PGA from the Lembang fault is 0.17 – 025 g on the basement rock, while after the consideration of local geology from HVSR inversion, the value of spectral acceleration about 0.5 – 0.95 g for the event generated by Lembang Fault and 0.08 and 0.14 g from megathrust. The area categorized as soil class of soft soil and medium soil will have high vulnerability for destruction if there is an earthquake in that area, so should be clear from vital infrastructure such as government building, schools, etc. Earthquake building resistance rules should be applied rigidly in these areas. The area with hard rock ground had strong resistance for earthquake but still should have considered PGA maximum as anticipated if there is a strong earthquake. The study results should be used as the main reference to make a spatial plan in Gedebage future development to minimize the risk of an earthquake.

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