ARTIKEL RISET

Integrated Analysis Of Microtremor Horizontal To Vertical Spectral Ratio, Surface Waves Dispersion Curve, And Seismic Refraction Tomography To Estimate Weathered Layer Thickness And Seismic Vulnerability: Case Study Kalirejo Village, Kokap Sub-District, Kulon Progo Regency

Anna Wahyu, Ade Filla Intan, Ardhilles Adhitama, Febrian Nur Fadhli, Ferda Elita Putri, Gunarta Sutantio, Henest Paskah, Intan Permata Sari, Kirana Ndaru Pertiwi, Luthfan Kin Gumandar, Milya Dwi Lestari, Naufal Abdila, Neneng Alif Karlina, Nita Utami, Patria Ufaira Aprina, Reymon Agra Medika and Budi Arjo[*]

Abstract

Subduction of Indo-Australia plate to Eurasia plate and locally active fault nearby Kulon Progo play as major source for earthquake events. After effect due to earthquake has different level of damage which depend on the magnitude and site characteristics. The horizontal-to-vertical spectral ratio (HVSR) passive seismic method is being used drastically to help in mapping the level of site vulnerability to earthquake event. HVSR analysis results help us acquire some physical values including weathered layer thickness where Vs 30 reference came from surface waves dispersion curve analysis of the MASW method as it is used as a parameter in calculating thickness value. Seismic refraction tomography is used to create subsurface model thus we may see the extent of underlying layer and its implication to earthquake event.

Data measurements distribution are scattered in Kalirejo Village with the total of 63 passive seismic data, 33 MASW data, and 7 lines of seismic refraction acquisition. Some data show inadequate quality to be taken into further processing step, so data sorting activity should be carefully done. As a result, 21 of 63 passive seismic data are considered adequate to represent site physical values. Dominant frequency values ranging from 2 to 20 Hz, amplification factor varies between 1.5-12.5, and seismic vulnerability indices varies between 0.3-20. Surface waves dispersion curve inversion results are Vs 30 values ranging from 350 m/s to 980 m/s and seismic refraction tomography model shows Vp model with velocity values ranging from 0.2 to 3.2 km/s.

Keywords: HVSR; dominant frequency; amplification; seismic vulnerability indices; dispersion curve; tomography

I. Introduction

Kulon Progo ($7^0 38' 42$"S - $7^0 59' 3$" S and $110^0 1' 37$" E – $110^0 16' 26$" E) is one of five regencies in Special Region of Yogyakarta with area equal to 586.3 km^2.

[*]Correspondence: *budiarjo@ugm.ac.id*
Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada, Yogyakarta, Indonesia
Full list of author information is available at the end of the article
[†]Equal contributor

Administratively, Kulon Progo consist of 12 districts, 87 villages, and 917 hamlets while geographically adjacent to Magelang, Indian Ocean, Purworejo, and Bantul-Sleman respectively to north, south, west and east side. Badan Pusat Statistik (BPS) data shows that more than 400.000 peoples live in Kulon Progo.

Kulon Progo is located in southern part of Java Island which is known has complex geology settings

caused by presence of convergent zone that indicated by Australian subduction to Eurasian plate. The Australian plate is subducting Eurasian plate with slightly different velocity at the Sumatran border and Java border with the approximate velocity of 70 mm/year to NE direction. Australian plate known has the fastest rate of movement compared to Eurasian, African, and Somaliyan plate. Eurasian plate is also known moving slow to SE direction with velocity ranging from 25 to 33 mm/year [1]. Reverse movement between two plates resulting compressional regimes leading to high seismicity zone and some aseismic zone which indicates probable seismic activity in the future.

Earthquake that shocked Kulon Progo not only affected by compressional regimes but also affected by Opak fault. In 2006, an earthquake with magnitude of 6.4 Mw had shocked Yogyakarta for 52 seconds. This quake took massive loss as 6.000 peoples died, 50.000 injured, and material loss equal to 3,1 billion USD [2]. Previous earthquake events associated with Opak fault activity had characteristics of shallow hypocenter around 10 to 30 km with magnitude varies between 2 to 3 Mw [3]. There are also some active faults in Special Region of Yogyakarta that may cause rather low magnitude earthquake such as Dengkeng fault and fault associated to Menoreh hills.

Geophysical method to evaluate site characteristics and investigate weathered layer thickness are seismic related survey such as passive seismic (micro seismic), seismic refraction, and multichannel analysis of surface waves (MASW). Final results from those methods are seismic vulnerability indices, Vs^{30} values, and subsurface tomographic model.

II. Basic Theory

A. Microseismic

Microseismic is continuous motion on earth with wide frequency range due to natural sources and/or artificial and not corresponding to earthquake related motion [4].

HVSR

Microseismic analysis using horizontal to vertical spectral ratio (HVSR) method is used to estimate dominant frequency (f_0) and amplification factor (A_0) in research area. HVSR analysis have been carried out to identify resonance response to basin exitance filled with sediments by single observation [5].

$$\frac{H_{(f)}}{V_{(f)}} = \frac{\sqrt{A_{east(f)}^2 + A_{north(f)}^2}}{A_{vertical(f)}} \tag{1}$$

Dominant frequency (f_0) represent subsurface condition affected by natural vibration and artificial vibration coming from human activities. An area with low dominant frequency will have high amplification factor which implicate to vibration motion through the area.

Seismic Vulnerability Indices

Seismic vulnerability indices (Kg) represent vulnerability level in an area and its response to deformation. Dominant frequency and amplification factor are parameters required to obtain Kg value as shown in equation below,

$$Kg = \frac{A_0^2}{f_0} \tag{2}$$

Instrumentation and Software

There are 2 different sensors used in this research, Lennartz Electronic LE-3D/20s and Seismometer Tai De TDL-303S. LE-3D/20s sensor has frequency cut-off 0.05 to 50 Hz, while TDL-303S has frequency cut-off 1 to 50 Hz. Both sensors are attached to logger and computer with Windaq installed before acquisition conducted. Raw data is processed using Geopsy to obtain good H/V curve, clear peak is highly desirable [6].

B. Seismic Refraction

Geological structure and subsurface layer possibly modelled using seismic refraction as an active seismic method [7]. Its acquisition need same equipment as seismic reflection commonly used geophone as receiver and active source (e.g. sledgehammer). Seismic waves from active source that interact with interface between 2 layers will be reflected, refracted, and forwarded. Seismic waves which are move along the interface will be refracted if there is another wave in critical angle. Thus, that wave will play as a source to the waves that move along the interface. This method involves P-wave acoustic velocity estimation near the surface at depth less than 30 m [8].

P-wave or compressional wave is one of body waves with particle motion parallel to wave direction. Waves propagation affected by elastic modulus of medium [9], so P- wave velocity can be calculated using equation below,

$$V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \tag{3}$$

$$V_p = P - wave\ velocity$$
$$\lambda = Lambda\ cpefficient$$
$$\mu = Shear\ modulus$$
$$\rho = Density$$

Seismic refraction raw data are group of time-domain seismic traces in each geophone. Picking routine on first arrival wave for each geophone will allow us to plot travel time graph that contain seismic velocity information in different layers. Number of layers are not shown directly on the data but implicitly on travel time data distribution that correlate with gradient (Fig.1).
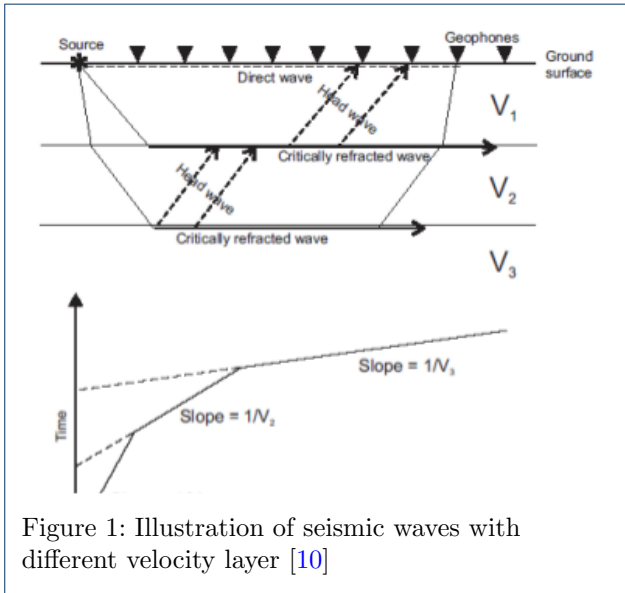

Figure 1: Illustration of seismic waves with different velocity layer [10]

C. MASW

Multichannel Analysis of Surface Waves (MASW) is used to determine shear wave velocity profile (Vs). Generally, shear wave velocity is used for construction and geohazard purposes. Vs^{30} mapping and soil classification have been done in Turkey where correlation between alluvium basin and low Vs^{30} distribution result high damage level due to earthquake [11].

MASW method is a development from previous method calls SASW (Spectral Analysis of Surface Waves). The difference between those 2 is number of receiver used in measurement, SASW use 2 geophones which will take much more time to obtain same data values with MASW that use more than 8 geophones. MASW can be deploy either as active or passive method. MASW commonly used to determine 1D Vs profile and 2D Vs profile [12]. Active method has depth penetration capability up to 30 m while passive method has deeper penetration as passive method record 1 to 30 Hz low frequency wave [12].

Rayleigh wave generated by intervention of P-wave and SV-wave. Dispersion of Rayleigh wave can define different phase velocities correspond to different

frequencies by assuming velocity changes to vertical axis [13]. Elastic modulus would affect Rayleigh wave propagation as well as other waves. Thus, shear wave velocity can be defined by mathematical calculation as shown below,

$$Vs = \sqrt{\frac{\mu}{\rho}} \qquad (4)$$

$$\mu = \frac{F/A}{r\tan\theta} \qquad (5)$$

$$
\begin{aligned}
\mu &= Rigidity\ modulus \\
F &= External\ force \\
A &= Extent\ of\ medium \\
r &= Change\ of\ length \\
\theta &= Change\ of\ position\ radially \\
\rho &= Density
\end{aligned}
$$

Raw data of MASW method are group of seismic traces in time-domain and transformation to frequency-phase velocity is needed to obtain dispersion curve (Fig 2). Picking routine in dispersion curve is the most important process to get reliable 1D Vs profile through inversion. Average shear wave velocity in the first 30 m from surface can be determined from equation below,

$$Vs^{30} = \frac{30}{\Sigma_{t=1}^{N}(h_t/\nu_t)} \qquad (6)$$

$$
\begin{aligned}
h_t &= Depth\ (m) \\
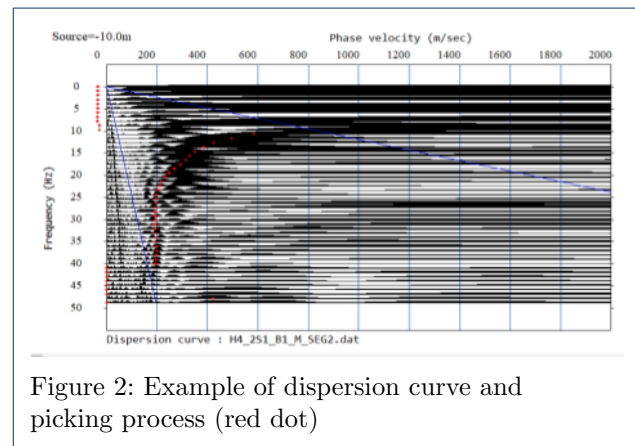\nu_t &= Vs\ at\ t-layer\ on\ N\ number
\end{aligned}
$$

Figure 2: Example of dispersion curve and picking process (red dot)

Instrumentation and Software

SARA instrument is used in this research with sledgehammer as seismic source. Receivers used are 22 vertical geophones (4.5 Hz) along with 22 data loggers. A set of equipment including laptop, receiver, inverter, geophone trigger synced together to SARA. DoReMi ver 1.2.32 is used as acquisition software while processing software used is SeisImager. Picking routine, inversion, and tomography modelling carried out within SeisImager.

III. Results And Discussion

Microseismic analysis use horizontal to vertical spectral ratio (HVSR) with 2 different types of sensor as mention in previous explanation. Specification and sensitivity between those sensors are different, thus calibration was carried out before processing routine executed. Calibration has been done by doing some measurements and results both sensor have rather similar dominant frequency (f_0) but Lennartz Electronic LE 3D/20s amplification factor value is doubled by another sensor (Fig. 3). Calibration results was referred in processing routine where time series data from Lennartz should be times by 2 to have rather same amplification factor to Tai De sensor.

Measurements data were checked to see its quality and reliability before advance to processing routine, data which considered not fulfil the quality control criterion will be sided and not used in further process. Good quality data proceed to HVSR analysis and H/V curve with single peak (clear peak) showing dominant frequency and amplification factor values is the ideal result (Fig.4). Dominant frequency and amplification value are mapped overlaying topographic map to see its distribution and correlation to elevation. Dominant frequency range between 2 to 20 Hz while amplification factor varies between 1.5 to 12.5 (Fig.5). Seismic vulnerability indices known from mathematical calculation as shown in Kg equation where dominant frequency and amplification factor take part in calculation process. Amplification values are strongly controlled by vulnerability indices as the amplification is powered by 2 in the equation. Previous statement is proven from amplification values correlation with vulnerability indices where values of both physical values is highly distributed in NW part of the measurement area. Vulnerability indices dominant values vary between 0 to 20 with NS oriented spread values 20 to 56 (Fig.6 left).

Badan Nasional Penanggulangan Bencana (BNPB) Indonesia has published disaster vulnerability indices all over Indonesia includes site response to vibration events such as earthquake. This index considering historical events and its damage to environment, infrastructure, life lost, etc. Index ranging from 6 to 35 is categorized as an area that has medium disaster vulnerability while index ranging from 36 to 139 categorized as an area that has high disaster vulnerability. Higher index value may result to higher damage level. Yogyakarta with high number of earthquake history categorized as highly vulnerable area averaging index 74 to 97. Refer to BNPB categorization, research area categorized as relatively low to medium area as vulnerability indices ranging between 0 to 56. which means the area will have big level of damage if such earthquake happens.

Level of damage in an area may affected by weak points with prescribed of less resistant power [14]. In this research, weak points refer to thickness of weather layer due to either weathering process or alteration product. Ground durability with thick weather layer will produce big shook to propagating seismic waves. Thickness of weathered layer can be obtained by using mathematical solution where dominant frequency and Vs^{30} are used. Vs^{30} which represents shear wave velocity for top 30 m beneath the surface can be obtained by dispersion curve picking of the shear wave and inversion routine. Vs^{30} has wide range velocity from 380 m/s to 860 m/s. Badan Meteorologi Klimatologi dan Geofisika (BMKG) has categorized probable rock types from its shear wave velocity where Vs^{30} value from 350 m/s to 750 m/s is categorized as soft rock and higher velocity ($>$ 750 m/s) is categorized as hard rock. Velocity distribution shows a NS trend where its value decreases gradually from north to south. North area has higher elevation than south area, so we assumed shear wave velocity is strongly influenced by topography elevation. Area with higher altitude mostly composed from fresh in-situ rock (e.g. igneous rocks, andesite) and low portion of soil or/and weather layer while lower altitude seems have bigger portion of soil or/and weather layer due to transportation mechanism, natural weathering process, or alteration product.

Weathered layer map shows relatively low thickness value in research area (5-25 m) where in the western side and northern side of area have relatively high thickness value ($>$ 30 m). Those 2 spotty closure with high values are correlated with high altitude hills which have high probability to contribute moving the mass from the hills to lower ground. These just an example what could possibly happen if an earthquake happened in research area.

Weathered layer than can be modelled by using P-wave velocity profile provided by seismic refraction method. Two dimensional Vp profile acquired through picking first-arrival routine in seismic traces. Picking process results time travel graph which implied
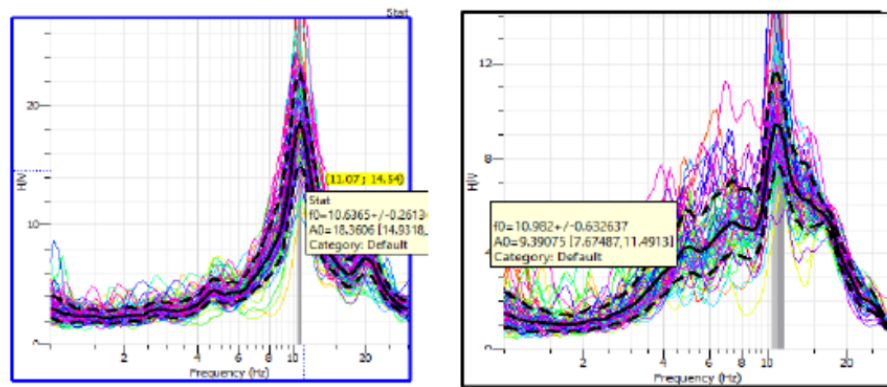
Figure 3: H/V curve with MS 11 calibration frequency Tai De TDL-303S Seismometer (left) H/V curve with MS11 calibration frequency Seismometer Lennartz Electronic LE-3D/20s (right)
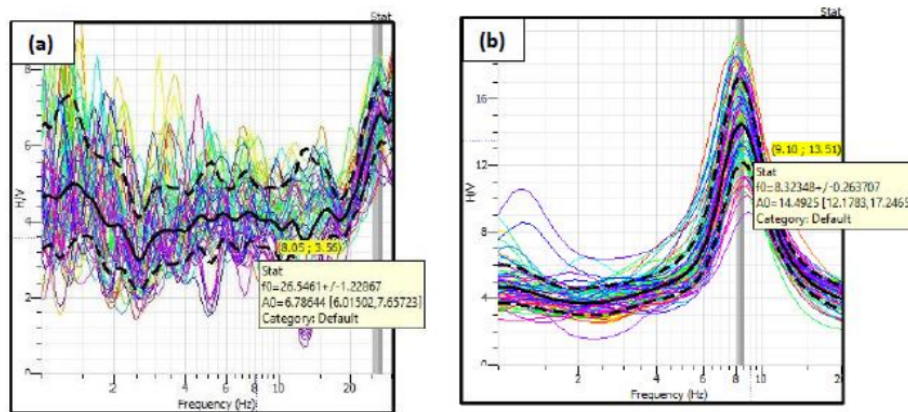

Figure 4: H/V curve with frequency in Geopsy software, MS74 shows a clear peak result (left) MS37 shows a clear peak result (right)

number of layers underneath the surface from its gradient. Time-term inversion process allow us to modelled subsurface layer into 2 and 3 layers model which number of layers assigned is depends on probable gradient s that appear in time travel curve. Model results from this process shows strong boundaries between low velocity layer (LVL) and high velocity layer (HVL) that couldn't possibly exist if we refer to lithology in research area. Seismic refraction tomography modelling is then carried out to smoothen the gradation of Vp values (Fig. 7).

Seismic refraction tomography model shows Vp value varies from 0.2 to 3.2 km/s. Weather layer from tomography is indicated by blue color to green color which have value ranging between 0.2 to 1.6 km/s. The

thickness of the weather layer is approximately 10-15 m thick from the surface and it is well correlated with thickness map acquired from previous calculation in Fig.6 right.

IV. Conclusion

Passive seismic and active seismic methods are suitable to investigate physical properties of near surface such as wave velocity, dominant frequency, amplification factor, etc. Investigating those physical values are really important to evaluate site characteristics and its response to natural phenomena such earthquake. Seismic vulnerability map shows relatively low value ranging between 0 to 20 with some spotty value
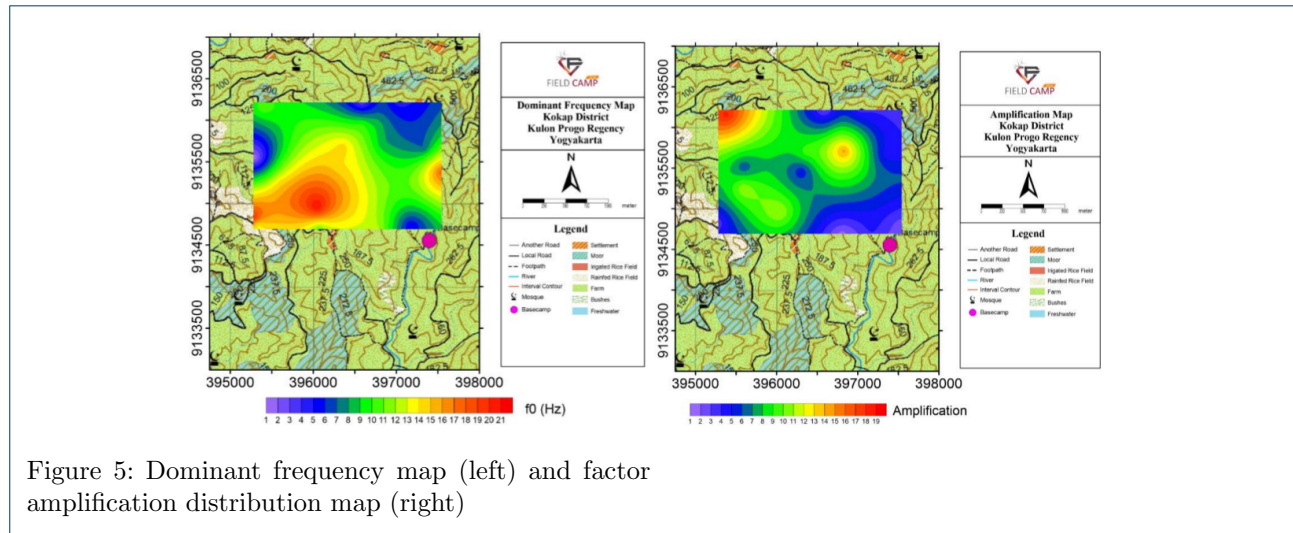
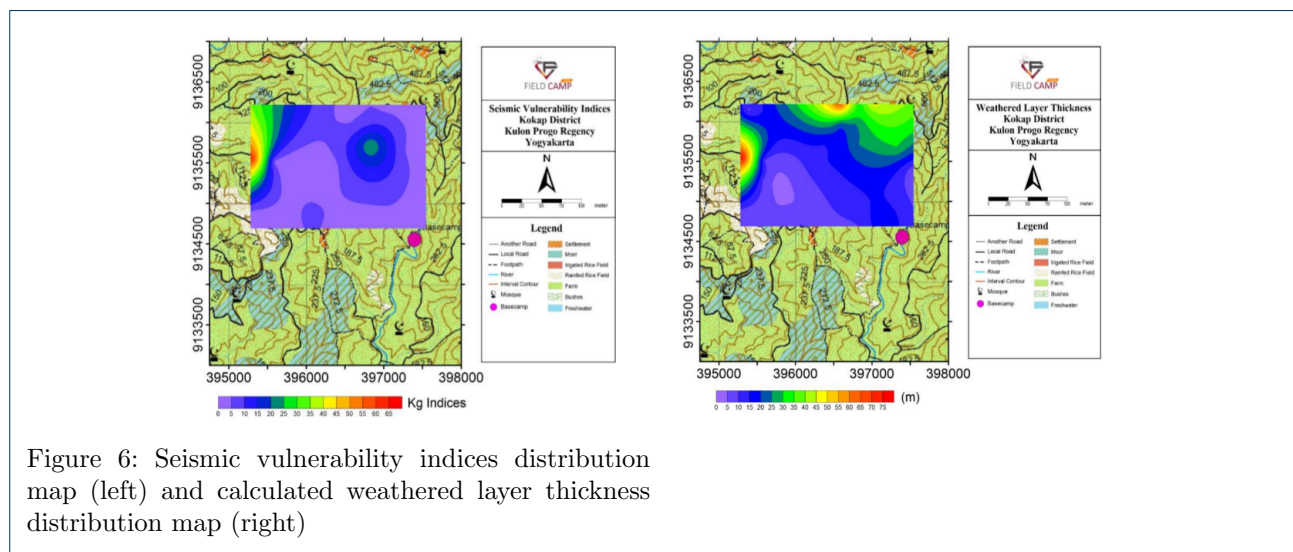Figure 5: Dominant frequency map (left) and factor amplification distribution map (right)

Figure 6: Seismic vulnerability indices distribution map (left) and calculated weathered layer thickness distribution map (right)

ranging from 25 to 56 in the NW area. Vs^{30} has wide range value predominantly 380 to 540 m/s and relatively higher value ranging from 580 to 860 m/s in the northern area. P-wave velocity value ranging from 0.2 to 3.2 km/s and its model shows weather layer is 10 to 15 m thick which correlate well with calculated weather layer. Integrating these 3 methods, we can conclude that research area has characteristic of low seismic vulnerability indices with relatively thin weather layer.

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Author

1   Anna Wahyu
    From :
    (1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

2   Ade Filla Intan
    From :
    (1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada
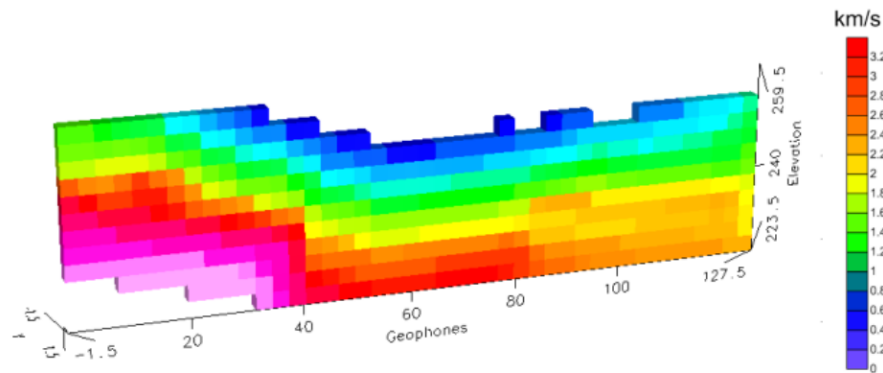
Figure 7: Seismic refraction tomography model showing weathered layer boundaries

3   Ardhilles Adhitama
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

4   Febrian Nur Fadhli
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

5   Ferda Elita Putri
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

6   Gunarta Sutantio
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

7   Henest Paskah
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

8   Intan Permata Sari
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

9   Kirana Ndaru Pertiwi
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

10   Luthfan Kin Gumandar
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

11   Milya Dwi Lestari
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

12   Naufal Abdila
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

13   Neneng Alif Karlina
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

14   Nita Utami
From :

(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

15 Patria Ufaira Aprina
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

16 Reymon Agra Medika
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

17 Budi Arjo
From :
(1) Geophysics Sub-Department, Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada

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