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Estimation of Vs Structure of Krueng Aceh and its Suburb Basin of Aceh Province, Indonesia, Derived from Microtremor Measurements

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Abstract: The Aceh and Seulimeum Faults flank the Krueng Aceh Basin in Indonesia, and the shear-wave velocity (Vs) structure of the basin is not extensively available. Understanding the Vs structure is very important in order to figure out how the basin structures seemingly appear, and this can eventually be used to generate a microzonation map for other forthcoming studies. To provide this, Vs was measured over an area approximately covering Banda Aceh City and its surroundings, by setting two lines consisting of eight points projected in the NW–SE and SW–NE orientations. This research aims to facilitate the approximation of the Vs structure characteristics of the Krueng Aceh Basin using the microtremor array method (MAM). Triangular configurations were set by deploying four seismometers following an M-station geometry for three different array sizes (i.e., 3, 10, and 30 m in distance). The data were then processed by utilizing the spatial autocorrelation (SPAC) technique. The result shows that the Vs structure generally dips down from SE to NW, and it gradually declines from SW to NE. The combination of these Vs structures tends to be oblique toward the SW–NE direction. This form may be affected by the Aceh Segment Fault which is more active than the Seulimeum Segment Fault. The average maximum penetration depth and Vs are 603 m and 947.5 m/s in the SE–NW orientation, and 650 m and 958 m/s in the SW–NE direction. Generally, the thickness of the strata is greater in the upstream area compared to the downstream area. Their composition consists of alluvium (A) at the uppermost layer and diluvium (D) at the underlying layers. Then, all of the identified strata are aged from the Pleistocene to Tertiary Pleistocene (Tp). These characteristics of the strata could potentially cause surface damages as a result of site effect responses when an earthquake is occurring.

Keywords: MAM; SPAC; Triangle array; Vs structure; Krueng Aceh Basin; Aceh Fault; Seulimeum Fault

1. Introduction

The prediction of shear-wave velocity (Vs) is critical for site response analysis in areas prone to destructive earthquakes. For example, in 2004, Aceh Province in Indonesia was hit by one of the biggest earthquakes of the last several decades worldwide, and it caused massive loss of life and property. To mitigate the loss of life and damages from devastating earthquakes in the future, many researchers [1,2] around the world have studied the site effect of ground motion. The authors of [3] also performed an investigation of the Vs structure at a depth of greater than 30 m to derive site effects after the Tohuko earthquake.

Furthermore, some researchers [4–6] have also studied the properties of shallow subsurface material by inverting the phase shear-wave velocity from microtremor surveys. The phase shear-wave velocity derived from microtremors versus frequency demonstrates the characteristics of near-subsurface ground [7]. Thus, having the Vs structure can be useful and is widely applied for generating the amplification factor, from which the microzonation map can be established [8].

The identical research has also been performed [9] by identifying near-surface soil using Poisson's ratio analysis in an area hit by a destructive earthquake (i.e., Pidie Jaya Regency, Aceh Province, Indonesia). The study involved Vs measurements using the multi-channel analysis of surface wave (MASW) survey. However, the shear-wave velocity (Vs) structure in Banda Aceh and Aceh Besar Regency has not been intensively studied. Previous studies [10] have only analyzed the average shear-wave velocity (Vs_{30}), and a geotechnical study [11] applied the cone penetration test (CPT) to investigate the level of vulnerability to liquefaction and the bearing capacity in Banda Aceh. Their results show that there is a high susceptibility to liquefaction in Kuta Alam and Syiah Kuala Subdistrict, with a moderate liquefaction degree in Banda Raya. The earlier studies neither investigated the shear-wave velocity (Vs) below a depth of 30 m, nor conducted a Vs structure analysis that approximately covers the Krueng Aceh Basin.

The comprehension of near-surface strata profiling is crucial for understanding the complex underground features of the 2004 tsunami flood in the Krueng Aceh vicinity [10]. This understanding is very important for viewing the Vs structure of the Krueng Aceh Basin. The output of the Vs structure could be critical for generating a microzonation map in other forthcoming studies. The relationships between shear-wave velocity (Vs) and the geological unit may prove to be valuable when producing and developing microzonation maps [12]. A similar application, microtremor measurements, for generating Vs was utilized to produce a microzonation perspective in Haiti [13], where creating a seismic microzonation map was a vital part of precise site grouping related to code-based seismic design and production of the best possible seismic plan.

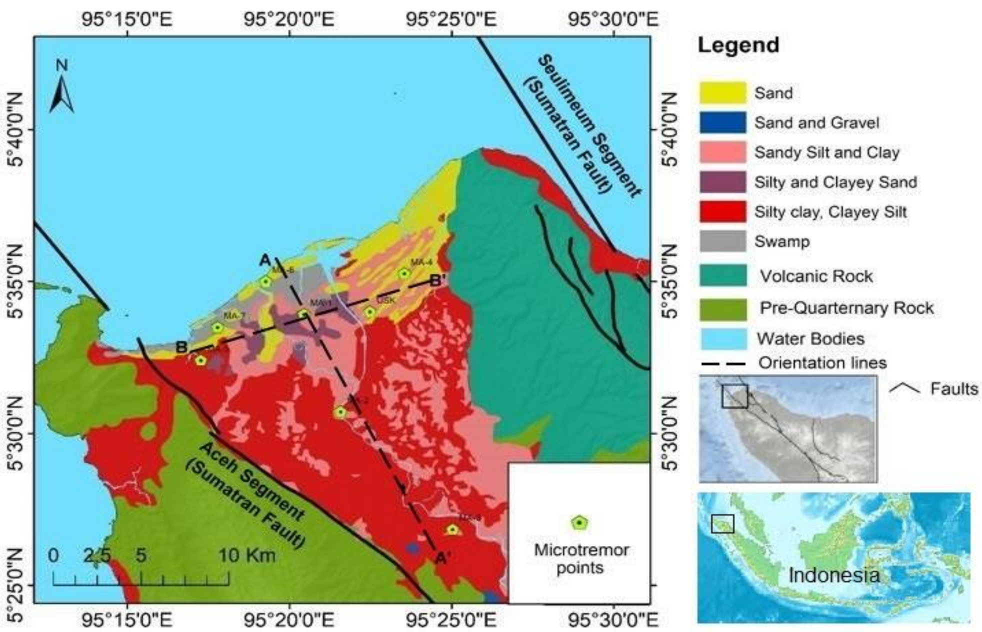

Figure 1. Engineering geology map of the Krueng Aceh Basin and its surrounding mountain and microtremor points; modified from [14].

Recently, Banda Aceh City has become a densely populated urban area. It is geologically located on a basin flanked by two active fault segments: The Seulimeum and Aceh Segments [15]. This tectonic setting should be of considerable attention for researchers. These active faults could potentially generate a devastating earthquake and possibly amplify the shaking of the young sediments of the Krueng Aceh Basin. A previous study [14] showed that these active faults flank the graben-type structure where the Krueng Aceh Basin was formed. The graben was filled to more than 179 m in depth [14,16] by different lithological deposits, such as silty clays, clayey silt, sandy silt and clay, silty and clayey sand, and gravel. These deposits are from the Quaternary period, as shown in Figure 1.

Among the potential geophysical methods, the microtremor survey method (MSM), rather than conventional seismic methods such as seismic refraction and reflection, was applied in urban areas and effectively contributed to geotechnical matters that allowed the Vs structure to be generated [17]. The method was previously implemented [18,19] in the Kanto Plains of Japan to serve the deeper structure of Vs. Applying the microtremor measurement is very helpful because it is rapid, easily applicable to a town or city, and cost-effective [20].

On the basis of the previous global and local studies mentioned above, combined with the importance of the Vs structure to the geological and tectonic perspective of the Krueng Aceh Basin and the limited local studies of the Vs structure in Banda Aceh, it is imperative to estimate the Vs structure in the Krueng Aceh Basin vicinity (Banda Aceh and its suburbs). To provide the Vs structure, a microtremor investigation was performed at eight points that were distributed to approximately cover the Krueng Aceh Basin area, as seen in Figure 1. This research aims to (1) estimate the shear-wave velocity (Vs) structure of several points in Banda Aceh and its suburbs (Aceh Besar) at a depth reaching more than 30 m, (2) illustrate the appearance of the sediment structure of the Krueng Aceh Basin, and (3) provide information about the sediment structure by revealing the strata characteristics and the approximate timing of the strata's formation.

2. Materials and Methods

The equipment deployed in the field for the microtremor survey is listed in Table 1. The equipment consisted of four seismometers, six connecting cables connected to the seismometers and data logger, a PC for data processing and monitoring, and a battery.

Table 1. Equipment for the microtremor survey.

Item	Manufacturer	Type	Qty
Data logger	Hand Made	7ch	1
Seismometer	Sato Shokai	MTK-1V	4
Seismometer cable	Hand Made	50 m	6
Measuring tape	Yamayo	100 m	2
PC	Panasonic	Lets Note	1
GPS	Garmin	Oregon 650	1

The seismometers used in this study were made by the Sato commercial company, model MTK-1V, and have the following specifications: output sensitivity of 13 V/cm/s (natural period 1 s), 0.25 V/cm/s (natural period 7 s); frequency range of 1–50 Hz (natural period 1 s), 0.13–50 Hz (natural period 7 s); measuring direction of up and down; conversion system of velocity-type (conduction-type); range of ±2 mm; and operating temperature range of −20 to +50 °C. The seismometers were deployed to record the ambient noise generated from an environment whose frequency band is 1–15 Hz. The ambient vibrations originate from various sources, such as human work (traffic and machinery) and natural phenomena (winds and ocean waves) [21]. The seismometers were laid out in a triangular array, which is also called the M-station circle array [22], as seen in Figure 2.

Four seismometer stations were set up so that each point for determining Vs was measured for the three different array sizes. Three seismometers were placed at each corner of the triangle and one seismometer was put at its center. The first, second, and third sizes of the triangles started from the smallest, followed by mid-sized, and then the largest of the array radii, with sizes of 3, 10, and 30 m, respectively. As seen in Figure 2, the first triangle is the smallest array size and is marked by the numbers 2-3-4. Then, the medium-sized and largest triangles are numbered 5-6-7 and 8-9-10, respectively. The duration of the recording time was from 15 to 30 min; a consequence of using a large-sized array is that longer time is needed. Different array radii were designed to investigate different depths of strata. The geometry and the radius sizes of the microtremor array are pictured in Figure 2.

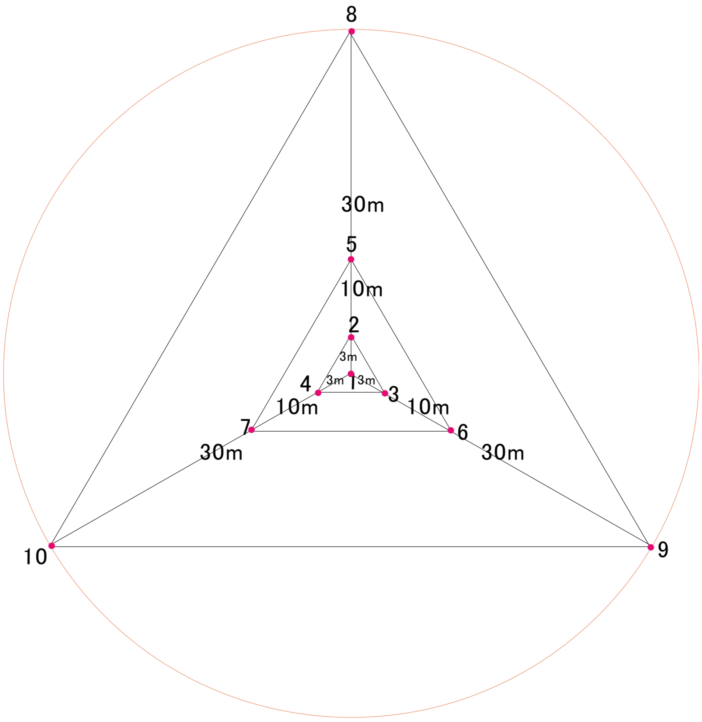

Figure 2. Geometry and size of radii for microtremor measurement. The 2-4-3 number represents a 3 m radius, and the numbers 5-6-7 and 8-9-10 represent radii of 10 m and 30 m, respectively.

A previous study [22] also proved that placing three stations or seismometers at the circumference yields the most efficient results compared with using more than three seismometers in a circular configuration, provided that the spatial autocorrelation (SPAC) coefficient is kept at its first minimum number. The data were processed by utilizing the SPAC technique as proposed in many previous studies [23], and widely used by many researchers [24]. The SPAC method is very convenient, as it can produce wave scalar velocity for a multidirectional or omnidirectional wave field, and it expresses the relationship of the waveform between each point and each circle's center point of the array as the coherence complex function (the real part). The average of the entire circumference (average orientation) is referred to as the spatial autocorrelation coefficient. This value is transformed into a Bessel function (first kind: zero-order), including the theoretical phase velocity equation to calculate the phase velocity from its inverse function [25].

The shear-wave velocity (Vs) model was generated in several steps. The process was started by taking the microtremor measurement from the multipoint simultaneous probing. From that, the surface wave phase velocity was then computed to produce the dispersion curve. The final step was to invert the phase velocity, and the shear-wave velocity (Vs) models were thus obtained. The summarized data-processing methodology is the quantification of the S-wave velocity structure model, which is highly related to a geological structure because the S-wave and layer thickness have the strongest correspondence to the phase velocity (high sensitivity) in the variable number of the velocity structure model. The typical data processing steps are displayed in Figure 3.

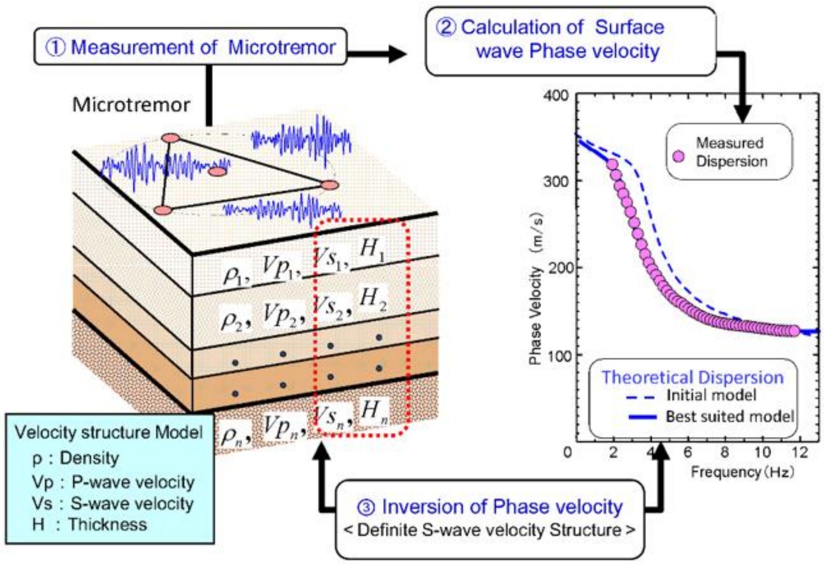

Figure 3. The general principle of the generated shear-wave velocity (Vs) data [17].

Finally, the above data-processing stages resulted in each of the dispersion curves, as can be seen in Figure 4.

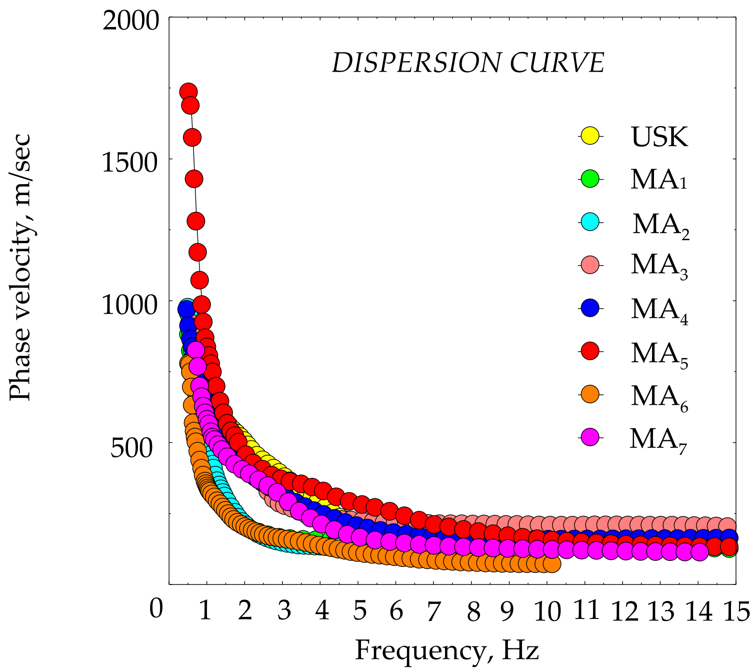

Figure 4. Aggregated dispersion curves from all site measurements.

The dispersion curves in Figure 4 could indicate that the phase shear-wave velocities (Vs) are higher than approximately 300 m/s, which is included in the higher mode [25], in a frequency interval of 1–3 Hz. It is inferred that these shear wave velocities originate from the deeper strata. On the other hand, phase velocities lower than 300 m/s, as the fundamental mode [7], in a frequency range of 3–15 Hz come from shallower layers. Then, these dispersion curves were converted through inversion processing to estimate the shear-wave velocity (Vs) profiles versus depth, as shown in Figures 5 and 6 [26]. The inversion was performed by applying the genetic algorithm (GA) [24] to calculate the given initial model of phase velocity until reaching the best fit or minimum error between calculated and observed data representing the approximate Vs structure of the strata. The detail of the inverted dispersion curves can be seen in Figure A1. Finally, the Vs strata were drawn on the basis of the Vs values and grouped into two orientation settings of the measurement (NW–SE and SW–NE).

3. Results

3.1. The NW and SE Orientation

The NW and SE orientation is a combination of four Vs measurement points: MA_6, MA_1, MA_2, and MA_3 (a 17.6 km surface distance). The combination of the four Vs measurements was intended to provide an internal Vs structure correlation in the NW–SE orientation, as shown in Figure 5.

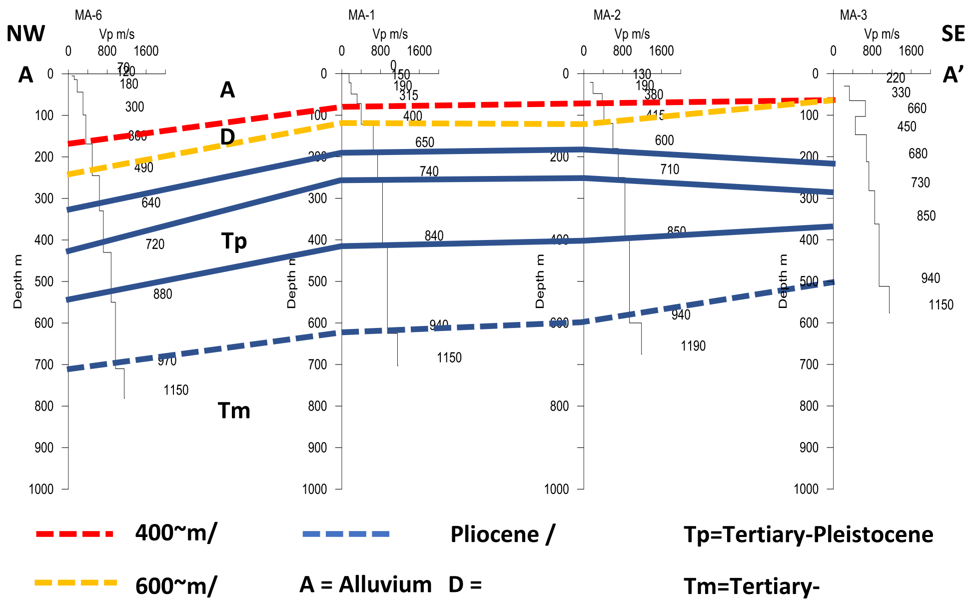

Figure 5. Shear-wave velocity (Vs) structure in NW and SE orientations.

From Figure 5, the maximum average shear-wave velocity obtained is 947.5 m/s, and the average depth reaches 603 m. The result displays three strata according to the correlated Vs values of MA_6–MA_1–MA_2–MA_3 (ordered from low to high ground) oriented toward NW–SE (AA′) as seen in Figure 1. The first layer is dominated by alluvium (A) and diluvium terrace (Dt) at the right end; it has a shear-wave velocity of approximately 400 m/s and is 100 m in depth. This layer was largely formed during the Pleistocene age and, generally, gently slopes up toward the upstream area from further down. As visualized in Figure 5, the MA_1 point, a close point to that from a previous study [10], is a good match to the average shear-wave velocity (Vs_{30}) in the 150–190 m/s interval. This top layer is classified as a less dense (soft soil or S_F as grouped by IBC which is the International Building Code) and slightly flat layered sediment. The moderate conformity of Vs_{30} is also found between MA_2 (380 m/s) and Babah Jurong (319 m/s), which is predicted to be stiff soil (IBC class S_D) and a fairly lateral bed [10]. The second layer inclines from MA_6 to MA_1 and is steadily lateral from MA_1 to MA_2, and it then gradually declines from MA_2 to MA_3. This layer has a Vs of approximately 600 m/s and is 120 m thick. This layer is dominated by diluvium (D) from the Tertiary–Pleistocene age (Tp) as a result of flooded sediment. The third layer consists of three identical subparallel beds with Vs values that range from 642 to 855 m/s. The third layer's trends and ages are similar to those of the second layer, but it is thicker than the two above (i.e., around 200 m in thickness). Below the third layer, the strata are undefined because of the poor Vs data, but it could be predicted as the speculative layer that has a Vs of 950 m/s and thickness that is incomplete; this layer was formed during the Tertiary–Miocene period.

These results enabled the authors to derive information about the strata characteristics in this orientation. The second and the third strata are similar in age, but they differ in velocity, meaning that they have different lithologies. This implies that these strata were likely sedimented for a relatively long period and had different types of sediment supplied when deposition occurred in the past.

According to the strata characteristic analysis, the Vs structures in this projection are prone to experiencing a ground amplification when vibration from an earthquake occurs. However, this prediction must be validated by another study focusing on the horizontal-to-vertical spectral ratio (HVSR) to provide more precise results in terms of ground amplification, as it is very important to delineate the resonant frequency, which indicates the presence of stiff or soft soil in investigations of site effects [27].

3.2. The SW and NE Orientation

The BB′ orientation of the Vs structures from SW to NE is a composite of five point measurements consisting of MA_5, MA_7, MA_1, USK, and MA_4 (12.6 km long), as seen in Figure 6.

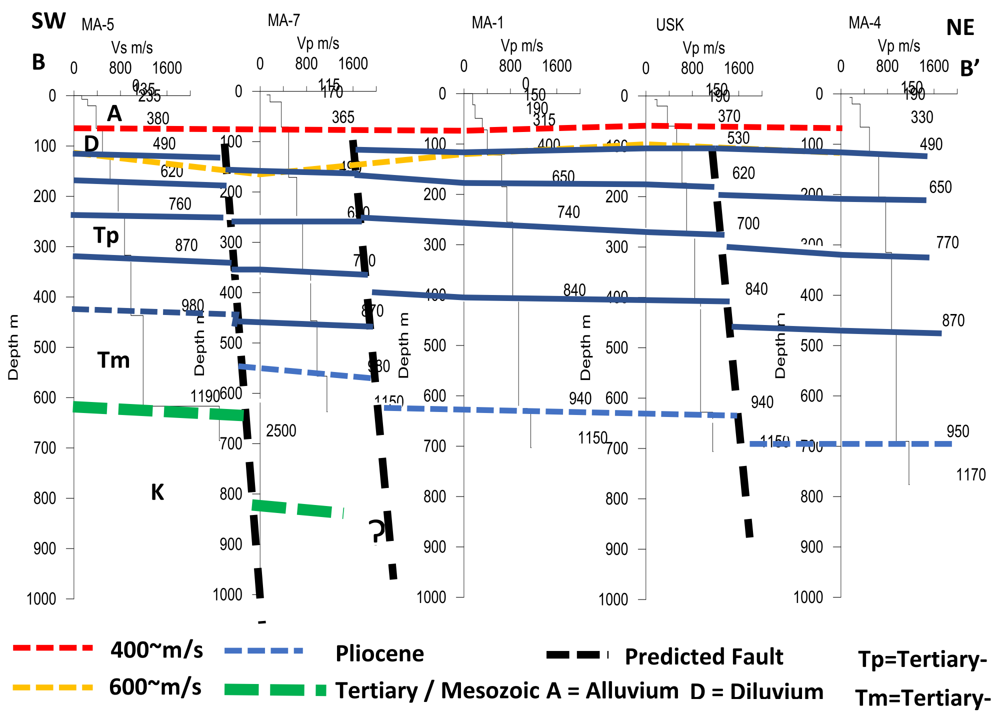

Figure 6. Shear-wave velocity (Vs) structure in the SW–NE orientation.

This projection intersects with the first orientation at the MA_1 point and nearly crosses the width of the Krueng Aceh Basin in a perpendicular configuration. Overall, the average maximum values of depth penetration and Vs are about 650 m and 958 m/s, respectively. These maximum values are almost similar to those in the first orientation.

The detailed information of the Vs structure profile in Figure 6 explains how the number of identified strata is approximately the same as that of the first Vs profile (Figure 5), where both orientations of the Vs structure have three layers of earth. The first layer is predicted to contain alluvium (A) only along the bed, where its Vs and thickness are 400 m/s and 70 m, respectively. This layer is included in the relative Pleistocene age, and the Vs structure is nearly wholly flat when viewed from end to end. The Vs value of the following layer is 600 m/s, and this layer is predicted to contain diluvium from the Pleistocene period. In contrast, its layering pattern is moderately wavy, such as the settlement appearance below the MA_7 point. This layer is approximately 40 m in thickness. The third layer is a group of three relatively similar beds that have Vs values ranging from 620 m/s to 840 m/s. This group is included in the Tertiary–Pliocene age, but the sub-layer models appear as terraces dipping down from SW to NE, and this identical layer model has a thickness of approximately 300 m. The bed has a Vs of 960 m/s, is predicted as a moderately unconfined layer, and its age relatively puts it in the Tertiary–Miocene period.

4. Discussion

The Vs structure information in Figure 5 implies that the strata generally dips down from SE to NW. This dipping may have followed the sedimentation process in the past, originating mainly from upstream and sloping downstream, and it is parallel to the long side of the Krueng Aceh Basin or graben. Although each layer is seemingly flat from MA_1 to MA_2, they descend moderately to their left side (downstream) and ascend to their right side (upstream). There are formations of a sub-strata trend on the right side of MA_1 and MA_2, with a Vs interval from 642 m/s to 855 m/s that tends to be convergent or appear to pinch out in the SE direction. This phenomenon might be affected by tectonic processes or concealed faults (black dashed line in Figure 6). The MA_3 point of the Vs measurement is relatively close to the Aceh Segment Fault (ASF) that extends about 6 km away. Thus, the subparallel layer may be related to ASF activities. This prediction should be validated by other geophysical methods to obtain a more accurate understanding. This estimation is in line with the results of the Aceh and Seulimeum Fault investigation [28], which explained that the Seulimeum Fault had not released energy greater than M 7.0 since 1936. Overall, the types of lithology consist of alluvium (A) in the top layer, which then changes to diluvium (D) as the depth increases.

For the SW–NE (BB′) orientation, it could be inferred that the lithology, velocity, and age of the uppermost layer are similar to those of the top layer of the first orientation (AA′), but the thickness of the first layer of the BB′ orientation, that is close to the coastal area, is thinner by about 30 m. From this form of layer, it can be roughly estimated that during the time of deposition, there were more sediments supplied from the upstream to the downstream compared with the sediment supplied in the reverse direction. In other words, it can be roughly stated that this top layer was deposited when the mean sea level was at the minimum or at low stand system tract (LST).

The sublayers below a 120-m depth in the BB′ orientation are likely to be disturbed by tectonic activities. Figure 6 shows how the architecture of the second layer on the left side of MA_1 heading toward SW (below MA_7 and MA_5 points) is lower than the right side of MA_1. The direction to the SW is an orientation crossing or relatively near to the ASF. This highly seated sub-layer could be lifted by the ASF tectonic mechanism. However, the strata generally dip down from the SW to the NE direction. The concealed drawn faults (black dashed line) clearly show that the strata are laterally discontinuous as a result of the nearly vertical elevation of some strata. This view was also revealed in a previous study [10], where the study site was Lampasi Engking at the Great Sumatran Faults (GSF) border, which is comparatively close to MA_5, implying moderately good conformity. The previous study [10] expressed that the seated sediment, approximately 30 m deep, was uplifted by GSF transform contact.

In addition to the thickness of each layer in the NW–SE (AA′) orientation, it varies starting from 100, 120, and 200 m for the top, middle, and lowest layers, respectively. On the contrary, the thickness of the two consecutive strata from the surface in the SW–NE (BB′) direction which are about 70 and 40 m is thinner than the uppermost and middle layers of the first Vs profile. However, the third layer of the second Vs profile is thicker by 100 m compared to the last layer of the first Vs cross section. So, the Vs structures both in the AA′ and BB′ orientation are in irregular form. The thickness and lithological types of every layer potentially contribute to site effect of the structure motion as the result of quake vibration. This prediction of ground motion would probably produce high amplification for the areas close to the Aceh segment and Seulimeum segment, which should eventually become the basis for further research, such as HVRS method.

To imagine the relative model of the Kreung Aceh Basin strata, the analyzed Vs structure from both profiles above indicates that the Vs structure declines from SE to NW (about 17.6 km in distance) and dips down from the SW to the NE orientation (approximately 12.6 km in spacing). These architectural structures would gradually and periodically change when driven by fault activities. Eventually, this will cause settlement and lead to a collapsing ground surface when experiencing an earthquake and other disasters.

5. Conclusions

It can be concluded that the analyzed Vs structure from both profiles (NW–SE and SW–NE orientations) indicates that the strata declines from SE to NW (17.6 km in distance) and dips down from the SW to NE orientation (12.6 km). The combination of these Vs structures tend to be oblique from the SW to NE direction. This form may be affected by the Aceh Segment Fault, which is more active than the Seulimeum Segment Fault. Their activity would gradually change the architectural Vs structure of the Krueng Aceh Basin; the fault activity may cause settlement and lead to a collapsing ground surface as a result of site effect response when experiencing earthquakes and other disasters.

Additional information about the Vs structure of the Krueng Aceh Basin can be deduced; its lithologies are composed of alluvium (A) in the uppermost layer, and the thickness is greater in the upstream area than downstream area. Furthermore, the underlying layer consists of diluvium (D). All of the delineated strata have ages that are dominantly from the Pleistocene to Tertiary Pleistocene (Tp). The shear-wave velocities of the strata gradually change from lower to higher as the depth increases. The average maximum penetration depth and Vs are 603 m and 947.5 m/s in the SE–NW orientation, and 650 m and 958 m/s in the SW–NE direction.

Author Contributions: Administrate the research permit: M.M. and A.A.; data acquisition: A.A., S.T., M.Y., and H.C.; data processing: S.T., A.A., and M.Y.; data analysis: U.M., R.I., and S.T.; writing draft and finalization of the manuscript: A.A. and S.T.; layout of manuscript: R.I.; review manuscript: F.Y.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

This is an inversion of data processing for all of the dispersion curves. They are ordered in a clockwise direction, based on the arrangement of the orientations starting from the upper left corner.

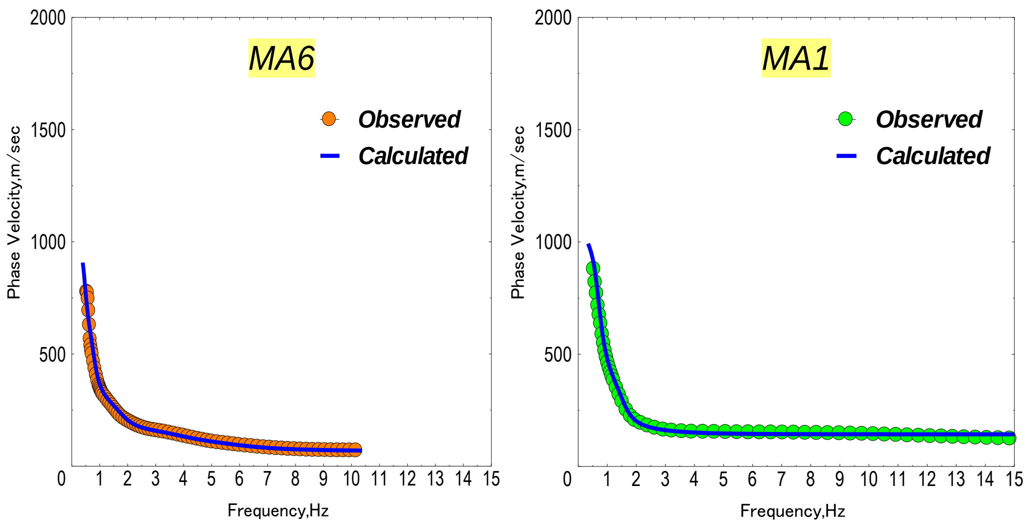
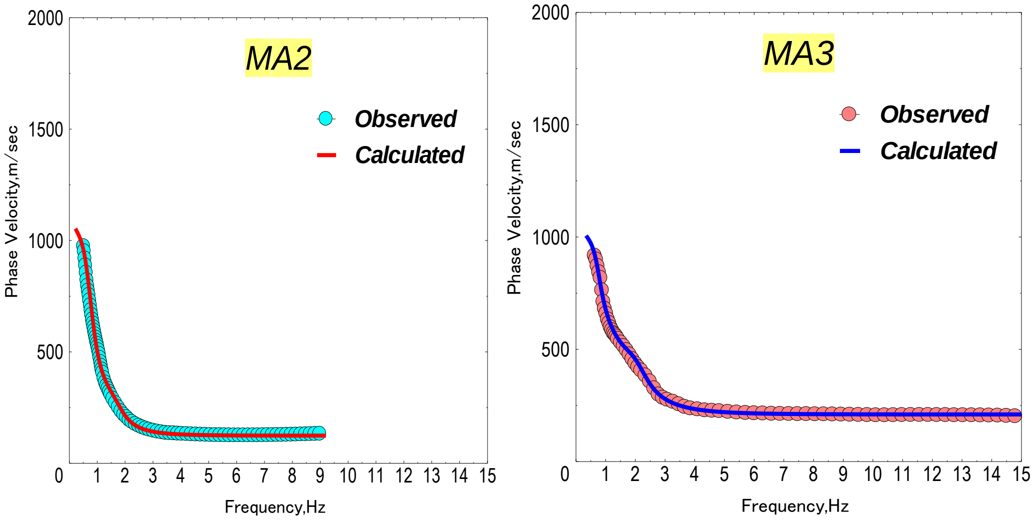
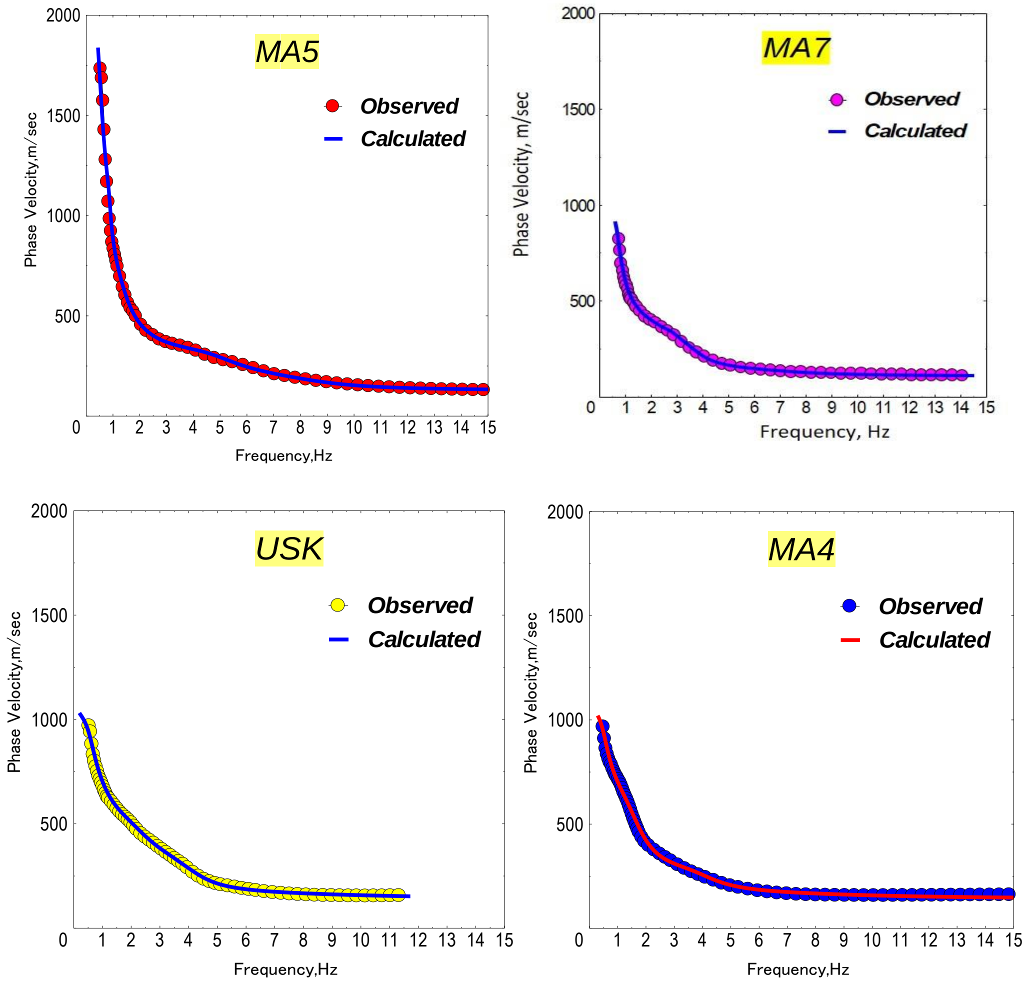


Figure A1. *Cont.*



(**a**)



(**b**)

Figure A1. The inversion process of dispersion curves fitting both of the Vs structure profiles (**a**) NW–SE (AA′) direction and (**b**) SW–NE (BB′) orientation.

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