Shallow One-Dimensional Shear Wave Velocity Structure in Lhokseumawe, Aceh-Indonesia

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Abstract. A series of microtremor array measurements, consisted by thirty-one sites, has been designed and conducted in Lhokseumawe. There were three lines of microtremor measurement consisting triangular seismic array for each point to study shear wave velocity model. A Spatial Auto Correlation method was applied in order to reveal the 1D velocity structure beneath the three lines at each measurement point. The analysis successfully revealed one dimensional shear wave velocity model down to 30 meters depth. The results show that the highest shear wave velocity of 639 m/s at depth of 30 m while the lowest value of 45 m/s at depth of 5 m. The results indicate that 12 out of 13 sites have low shear wave velocity with a range between 100 to 200 m/s. Low velocity structures are mainly located in Banda Sakti subdistrict. The areas with low shear wave velocity are associated with less compact sediment material which are mostly located in paddy field and ponds areas.

1. Introduction
Lhokseumawe is a city located in northern part of Aceh which is crossed by a river named Krueng Cunda [1]. The deposits of Krueng Cunda are carried away and sedimented around Lhokseumawe. Lhokseumawe with population of 170.000 [2], had experienced several earthquakes located nearby. The Mw 6.4 2016 Pidie Jaya earthquake shook Lhokseumawe with intensity level of IV in Modified Mercalli Intensity (MMI) (Figure 1a). In 2018, Lhokseumawe was shaken by an Mw 4.7 earthquake with an intensity level of III MMI (Figure 1b) [3-4] felt in the city. The earthquakes occurred around Lhokseumawe were sourced from several faults located nearby. The closest fault is Lhokseumawe fault which passes through the city and responsible for the M 4.7 earthquake in 2018. Lhokseumawe is also close to Nisam and Trienggadeng Fault in the west as well as Lampahan and Aceh faults in the south [5-7].
Topographically, Lhokseumawe is mostly flat area with average altitude between 0 to 20 meters. The flat area is mostly located along Krueng Cunda river or Banda Sakti subdistrict which has many swamps. The geology map issued by Indonesian government (Figure 2) suggests that Lhokseumawe is generally dominated by clay and sand which consist of sediment materials [8]. The detailed properties of soil or rocks are important to be studied to help civil engineers to design buildings for future constructions in Lhokseumawe. One of the methods to understand the rock properties is based on the values of shear wave velocity. Good understanding of subsurface material characteristic also can be implemented in disaster risk reduction [9].
2. Shear wave velocity measurements

Seismologists use several common methods to measure seismic wave velocity especially for shallow depths. Horizontal to Vertical Ratio (HVSR), Multichannel Analysis of Surface Waves (MASW) and Microtremor Array Measurements (MAM) are several methods commonly used and each one of them has limitations. MASW needs a wide area to stretch lines but gives good result [10], while HVSR needs small area but very sensitive to noises [11]. MAM is commonly used in urban area since it is not easily affected by noises which are normally found [12]. MAM consists of several sensors that is configured into an array such as line, L-shape, or circular [13-14]. The circular array consisted of 3 sensors is picked out in every point of these measurements. The radius to sensors is determined to be 1 and 3 meters. The experiment is conducted by plotting 31 microtremor array measurements sites. Every site is separated by roughly 1 kilometer and the measurements are carried out for 30 minutes minimum. There are 3 lines stretching southwest to northeast consisted by several points of measurement that will be analyzed. The lines are designed to cross the Lhokseumawe fault that lies northwest-southeast (Figure 3). In order to obtain shear wave velocity, waveform needs to be converted into frequency domain, then calculate the SPAC coefficients and the velocity model can be constructed as illustrated in Figure 4 [15].

![Microtremor Array Measurements Sites](image)

Figure 3. Sites of Microtremor Array Measurements in Lhokseumawe.
3. Shear wave modelling results
The measurements recorded microtremors which was used to determine shear wave velocity model. There were three lines that have been analyzed, namely line 1, 2 and 3. Line 1 consisted 4 points of measurements which are S4 to S7 which were located in the northernmost of Lhokseumawe. The 1-D shear wave velocity model of line 1 is shown in Figure 5. The horizontal axis gives shear wave velocity in m/s, while the vertical axis gives the layer depth in meter. The most western point, S4, has fastest velocity at depth down to 20 meters of 582 m/s. The upper 20 m is relatively low velocity layer. This gives an initial information of the thickness of sediment that covers area around the site. Further east, the area beneath S5 has higher shear wave velocity at depth down to 20 meters, but slower velocity at shallow depth. The further east areas have slower shear wave velocity. The slowest shear wave velocity in this line can be found beneath S6 at the depth of 25 to 30 meters that measured at 93 m/s which was located very close to the Cunda River. The top 15 meters of each site has low shear wave velocity that indicates less compact sediment at the top layer. Site beneath S7 has the lowest shear wave velocity at line 1 because it was located at ponds or sea.

Figure 5. 1-D Shear Wave Velocity Model of Line 1. The locations of lines are shown in Figure 3.
The second line is consisted of five points of measurements as shown in Figure 3. The S8 is located in the westernmost of the line while S12 is the opposite. The shear wave velocity model of line 2 is shown in Figure 6. This line has relatively low velocity in all points. The top five meters of line 2 has low shear wave velocity. The fastest shear wave at the top 5 meter is recorded at S9 that reaches of 208 m/s.

![Figure 6](image)

**Figure 6.** 1-D Shear Wave Velocity Model of Line 2. The location of the line is shown in Figure 3.

In general, the shear wave velocity along Line 1 is nearly identical. However, among all the points along the Line 1, the average velocity beneath Point S10 located along the Lhokseumawe Fault is the highest (445 m/s). The highest values beneath S10 need to be investigated in detail.

When we take a closer look, we can notice a similar pattern in some particular depths. Three most western points, S8, S9 and S10, have an increase in velocity at the depth of 10 meters, then slow velocity was observed at the depth of 15 meters (Figure 6). While S11 and 12, we notice the slowing pattern happens in 10 meters depth. The velocity values beneath S11 and S12 are similar at the depth down to 5 meters that indicates similar properties of soil beneath the areas. In average, S11 is the slowest along line 2, followed by S12. The graph indicates that along the line 2 has mixed material but has similar characteristic which is not very compact.

![Figure 7](image)

**Figure 7.** 1-D Shear Wave Velocity Model of Line 3. The location of the line is shown in Figure 3.

The last line is probably the best representation of gradual sedimentation of Lhokseumawe. Site S13 which is located in the west, has higher velocity than S14 located on the east of it. Site S13 has maximum velocity at depth between 10 m to 20 m that reaches 639 m/s. The maximum velocity at S14 only reaches
408 m/s which is slower than S13. While S15, which is located on the east of S14, is relatively slower than S14, and has maximum shear wave velocity at 249 m/s. The maximum velocity of S14 is higher than S15. The last point, S16 is the slowest of all which has maximum shear wave velocity only at 45 m/s.

The results give us an idea that most of Lhokseumawe has higher probability of consisted by less compact sediments. This is suggested by the low shear wave velocity that recorded by microtremor array measurements. Banda Sakti subdistrict where S7, S11, S12, and S16 are located, has the lowest recorded shear wave velocity in average of each line. Banda Sakti itself is located near Krueng Cunda and has many swamps and ponds which is normally found near a river. It supports the idea that the sedimentation is result of material that is carried by the Cunda River. Even though it needs more study, a comprehensive study, to reveal the dynamics of Lhokseumawe. The results support the geological map which mentions that Lhokseumawe is mostly composed by sediments. Low shear wave velocity in almost all sites needs to be given more attention when engineers want to design buildings for future city developments. The building code as issued by Indonesian government needs to be well implemented in Lhokseumawe.

4. Conclusions
Microtremor array measurement is capable to model shear wave velocity to certain depth. The three lines measurements gave us better understanding of the shallow subsurface velocity model of Lhokseumawe, including the idea of gradual sedimentation. The western part of Lhokseumawe has relatively higher S-wave velocity, especially in line 1 and 3 that reach almost 600 m/s, while the eastern part is composed by thick sediments as suggested by low velocity of shear wave. The lowest shear wave velocity was observed at line 3, in Banda Sakti subdistrict of around 45 m/s. The second line, which the differences are not clearly visible indicates that the area along the line has mixed materials but similar characteristics. The results suggest that Lhokseumawe is composed by sediments in almost all area as which is also consistent with geological map, except in some particular place. The low shear wave velocity model indicates that more detail investigation is necessary before developing new buildings and infrastructure

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