Analysis of submarine landslide potential that can trigger tsunami based on seismic reflection interpretation

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Abstract. The megathrust at the west part of Sumatera can produce a lot of earthquakes. Several earthquakes in Sumatera that occurred from 2004 to 2007 raised tsunami with various heights. The high tectonic activity in this area can trigger landslides in the ocean which may lead to tsunami. Therefore, research about seabed landslides needs to be done in this zone. The study identified the seabed geological structure from 2D seismic section in the east part of Siberut Island. The seismic section was generated from seismic processing of Seismic Line-05 (AA’). The seismic data were acquired using LIPI Baruna Jaya VIII research vessel on the Pre-Tsunami Investigation of Seismic Gap (PreTI-Gap) marine expedition in 2008. Seismic section interpretation shows the presence of backthrust on this seismic line. The bathymetry data from the Geospatial Information Agency and marine survey are used to make bathymetry map, bathymetry charts, and slope map. Analysis using 2D seismic section, bathymetry data, and slope map shows the steep zones at 3–5 km and at 15–16 km from the south west edge of Seismic Line-05 (AA’) with 180 m and 300 m bathymetry drop, respectively. These steep zones must be watched because they can trigger submarine landslides and tsunami.

Keywords: Seismic, submarine landslide, tsunami

1. Introduction

Indonesia is prone to tectonics and vulcanics activity due to its location [1, 2]. There are plate boundaries between four tectonic plates that surround this country [3]. Tectonic and vulcanic activity can trigger sea landslides. The landslides may raise tsunami waves which endanger the surrounding coastal areas.

From 2004 to 2007, a series of significant and destructive earthquakes occurred in megathrust area of Sumatera. The earthquakes happened in Aceh–Andaman at December 26th, 2004 (Mw ~ 9.3), in North Sumatera and West Sumatera at March 28th, 2005 (Mw ~ 8.7), and in Bengkulu at September 12th, 2007 (Mw ~ 8.5) [4-6]. The four earthquake events caused tsunamis with different heights [7]. There were also other earthquakes during the four years which were also recorded as significant and destructive earthquakes without tsunami event. The megathrust is located at the west part of Sumatera Island where Indo-Australia Plate subducts beneath Eurasia Plate. This tectonic movement produces tectonic activities which may trigger sea landslides in this zone. Therefore, research about sea landslides in this area should be done.
The research about sea landslides potential can be done by analysing the subsurface geological condition using seismic method. This method can be used to illustrate subsurface geological structure by measuring travel time of seismic waves [8]. This method identifies the structure and stratigraphy of seabed sediments based on seismic waves propagation recording [9]. Shallow seismic reflection recording can be used to identify rock debris on the seabed [10]. This research aims to process and interpret a marine seismic line in the east of Siberut Island and analyse the potential of submarine landslides in this zone involving bathymetry data.

2. Materials and method

This study uses marine seismic data in the east of Siberut Island, Sumatra. Subduction zone lies in the west part of Siberut Island as the boundaries between Indo-Australia Plate and Eurasia Plate. Sumatera Fault and Mentawai Fault are other main faults in this area. The map of Siberut Island can be seen in figure 1. The data of this research were acquired by Indonesian Institute of Sciences (LIPI) in collaboration with research institution from Paris during the Pre-Tsunami Investigation of Seismic Gap (PreTI-Gap) marine expedition on February 15th–March 6th, 2008. Line-05, a seismic line in this research is located at the latitude of 1°45'41.4"S – 1°33'09.7"S and the longitude of 99°22'36.8"E – 99°35'01.9"E, shown as pink line (AA’) in figure 1. This seismic line has acquisition parameters as shown in table 1. National bathymetry data from the Geospatial Information Agency via the http://tidespage.big.go.id/DEMNAS/ at longitude of 095°E – 105°E and latitude of 05°S – 00° with 6 arc-second (about 180 m) spatial resolution data and bathymetry data of Line-05 from marine survey with a spatial resolution of about 25 m were also used for analyzing the sea floor steepness.

Figure 1. The map of Siberut Island. SFZ = Sumatera Fault Zone, MFZ = Mentawai Fault Zone, pink line AA’ = the seismic line-05. *Modified from Pusat Studi Gempa Nasional, 2017.
Table 1. The acquisition parameters of Line-05 seismic data.

| Information                  | Acquisition parameters |
|------------------------------|------------------------|
| The number of sources        | 4                      |
| The number of channels       | 28                     |
| Source interval              | 25 m                   |
| Group interval               | 25 m                   |
| Near offset                  | 30 m                   |
| Source depth                 | 3 m                    |
| Receiver depth               | 6 m                    |
| Sampling interval            | 2 ms                   |
| Line azimuth                 | 44.75°                 |

Figure 2 shows the diagram of the research workflow. SEGY file of seismic data from acquisition is processed to produce high resolution 2D seismic section using ProMax 5000.0.2.9 version software. A 2D section from seismic processing is interpreted using Petrel 2009 software to find seabed geological structure. Submarine landslides are analysed based on seismic interpretation result with bathymetry map and slope map. These maps were made using ArcMap 10.5 version software. The seismic processing flow chart can be seen in figure 3.

3. Results and discussion

A seismic section in figure 4 is produced from seismic processing through mentioned several steps in figure 3. The noises have been attenuated through the processing steps, such as mute, bandpass filter, true amplitude recovery, deconvolution, time-frequency domain seismic rejection, surface consistent amplitudes, and migration. The section shows the clearer horizon continuity, therefore it has high enough resolution to be interpreted. Figure 5 shows a structure-interpreted seismic section. The subduction between ocean crust and continental crust in this zone produces horizontal pressure in rock. The pressure triggers rock deformation which can form fault, fold, or joint.

Faults are indicated from horizon discontinuity in seismic section. The thrust/reverse faults are found in seismic interpretation step at CDP 150–CDP 401 (a), CDP 1100–CDP 1300 (b), CDP 1300–CDP 1500 (c), and CDP 1900–CDP 2100 (d). The seismic section shows an indication of syncline at CDP 400–CDP 1200. Anticline-syncline is also found at CDP 1400–2612.

Based on seismic model, the south west part of the seismic line has shallower bathymetry depth than the north east part of the seismic line. This result fits with the geological condition. The south west part of the seismic line is located near the shore of Siberut Island while the north east part of the seismic line is in the middle of the sea. The identified anticline-syncline type of fold from the seismic section indicates horizontal pressure in ductile formation which is commonly mentioned as buckling process. Rock folding process in this zone exceeds rock’s plastic limit and produce a fault at (d) zone.

The thrust/reverse fault is one of contractional regime product. This regime is usually formed at accretionary wedge in subduction zone. Prawirodirdjo et al. [11] found that Indo-Australia Plate subducts beneath Eurasia Plate at the west part of Siberut Island with the rate of about 50–60 mm/year [12]. The subduction zone in this research area can be mentioned as Middle 2 Sumatera Megathrust. This megathrust zone has maximum earthquake magnitude of Mw 8.7 [12]. Since the research location is in megathrust zone, it can be presumed that the seismic line was lain above accretionary wedge. The thrust/reverse fault in this zone can be mentioned as backthrust.
Figure 2. Research flow chart.

Figure 3. Seismic data processing flow.
Figure 4. A seismic section of Line-05 in time domain depth. It is produced from seismic processing.

Figure 5. Fault interpretation on seismic section of Line-05 from CDP 1–2612. There are (a), (b), (c), and (d) zone which mark the fault zones in this seismic section. The colours of interpretation lines show the different layers.

If the interpretation result in this research is compared to the study result of Wang et al. [13], the faults at (a) zone are part of coastal backthrust (CBT). Faults at (b) and (c) zone are part of main backthrust. Fault at (d) zone is part of frontal backthrust (FBT).

3.1. Bathymetry map
Bathymetry data in this research are used to analyse submarine landslides potential. The map in figure 6 shows the depth of the seafloor in research zone is about 0–2000 m. There are tight contour lines in the green circle zone which indicate the steep seabed. The steep zone continues to North West direction.

3.2. Slope map
Slope map is made using classification in table 2. The map in figure 7 shows Line-05 has slope range from flat to steep or 0–70 %. There are two steep zones with percentage of 30–70 % in this line, marked red on the map. These zones have steep dip between 16°–35°.
Table 2. Van Zuidam slope classification [14].

| Slope class         | Percentage | Slope angle | Information                                                                 |
|---------------------|------------|-------------|-----------------------------------------------------------------------------|
| Flat to almost flat | 0–2 %      | 0–2°        | No meaningful denudation process                                            |
| Gentle              | 2–7 %      | 2–4°        | Ground motion speed is low. Sheet and soil erosions are identified.          |
| More gentle         | 7–15 %     | 4–8°        | The same as above, but with a higher magnitude.                             |
| Slightly steep      | 15–30 %    | 8–16°       | Flat landslides with a lot of ground movement and erosion                    |
| Steep               | 30–70 %    | 16–35°      | Intensive denudation processes and ground movements are common              |
| Very steep          | 70–140 %   | 35–55°      | Rocks generally begin to unfold, a very intensive denudational process, have begun to produce rework material. |
| Very steep          | > 140 %    | > 55°       | Exposed rocks, a very strong denudational process and prone to falling rocks, rarely grown plants (limited) |

Bathymetry data from marine survey have high spatial resolution. Bathymetry graph is produced from those data and combined with interpreted seismic section to predict the depth of the seafloor in meter as shown in figure 8. Based on this image, the first steep zone is at 3–5 km from the south west of seismic line and the second steep zone is at 15–16 km from south west of seismic line. The first steep zone has bathymetry drop as far as 180 m from the depth of -280 m to -460 m. The bathymetry from the second steep zone drops about 300 m from -875 m to -1175 m. Based on the research by
Khomsin et al. [15] about submarine landslides in Tanjung Labuan, Wani, Central Sulawesi, mass drop as far as 50 m is considered as the cause of tsunami in Donggala, Central Sulawesi in 2018. The two steep zones in this research where the thrust/reverse faults are also identified must be watched, because those geological features can produce tectonic activity. The tectonic activity can trigger submarine landslides with mass drop potential over 50 meters far. This potential of mass drop may raise tsunami.

Based on the analysis using 2D seismic section, bathymetry map, and slope map, the submarine landslides potential distribution map can be made as shown in figure 9. The two steep zones in this map is marked with thrust fault symbol.

Figure 7. Slope map of the research location. This map is classified into 7 classes with different colours of each class.

Figure 8. Combined image of Line-05 seismic section at CDP 1–2612 and bathymetry graph.
4. Conclusion
Marine seismic processing through several steps produced high resolution 2D seismic section. The noises have been reduced, the horizon continuity and the geological features have been seen clearer. Thrust/reverse faults has been identified at CDP 150–CDP 401 (a), CDP 1100–CDP 1300 (b), CDP 1300–CDP 1500 (c), and CDP 1900–CDP 2100 (d). The seismic section shows an indication of syncline at CDP 400–CDP 1200. Anticline-syncline is also found at CDP 1400–CDP 2612. The fault is identified in this anticline-syncline fold zone. The bathymetry graph which is overlayed on the 2D interpreted seismic section shows two submarine landslides potential zone at 3–5 km and at 15–16 km from south west of seismic line with bathymetry drop of 180 m and 300 m, respectively.

Acknowledgments
Authors would like to thank Research Center for Geotechnology of the Indonesian Institute of Sciences (LIPI) for providing the seismic and bathymetry data. We also thank Geospatial Information Agency for providing the open access bathymetry data. This project was supported by the PUTI Saintekes 2020 research programme under the Universitas Indonesia grant agreement with contract number NKB-4879/UN2.RST/HKP.05.00/2020.

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