Meulaboh Tombolo Response to Large Tsunami, West Coast of Sumatra Island, Indonesia

W B Setyawan¹,*

¹ Research Centre for Oceanography, Indonesia Institute of Sciences. Jl. Pasir Putih Raya, Ancol Timur, Jakarta Utara, Indonesia

Email: wahyubudisetyawan@yahoo.com

Abstract. Meulaboh city which is devastated by the tsunami of 26 December 2004, is situated on the west coast of northern part of Sumatra Island. The city is located on a tombolo that currently also acts as a peninsula in the existing coastline system. West coast of the tombolo which consists of natural sandy beach coastline in high energy condition of coastal waters was studied for its response to the tsunami. Images from Google Earth were the main data in this study and used for coastal landform analysis before and after the tsunami. Photograph data from various sources and fieldwork data from 2002 also used. Results of this study show that the tsunami was eroded the sandy beach and resulted in an irregular coastline patterns, but the general shape of the coastline pattern remains curved. The erosion had been produced many incised channels and low cliffed coast. Recovery processes was start in a week after the tsunami. The plan shape of the sandy beach was recovered in accordance with eliminating the cliffed coast and closing of incised channel and producing enclosed water bodies. Almost all traces of the tsunami were lost following sandy beach recovery with an exception of enclosed water bodies that far enough from reaching by normal wave activities.

1. Introduction

The 26 December 2004 tsunami that occurred in the waters west of Sumatra Island caused erosion to the west coast of the northern part of Sumatra Island and the countries surrounding the Bay of Bengal [1, 2] (Figure 1). On the west coast of Sumatra Island, the tsunami hit and damaged the coastal landforms of about 175 km from Meulaboh to Banda Aceh. Almost all of coastal depositional landform such as sandy beach, low sand dunes and wetland were lost due to erosion, and the coastline shifting landwards reaching 500 m [1, 3]. The severe erosion of coastal lands by the tsunami also occurred in Thailand [1, 3, 4, 5, 6], India [2, 7], Sri Lanka [3], and Andaman Islands [8].

The effect of the tsunami on the coastal zone and its recovery has been widely studied. The studies were done on various types of coastal morphology units. Headland, bayhead beach, j-shape beach, barrier beach with lagoon, tambak wetland [1], and straight coast with beach ridge [1, 9] at Sumatra; beach and estuary or tidal channel in Thailand [5]; estuary with huge sand dunes and barrier island in India [7]; beach with beach ridge in India [4]; spit in Thailand [10]; and estuary with sand spit in Thailand [11].

Results of the research on various environmental settings of various coastal landforms have provided a lot of information or knowledge about the response of coastal areas to tsunamis and their recovery processes. However, study on response of a tombolo to the tsunami has not been studied yet. Tombolo is a spit connecting an island to the mainland that formed by wave diffraction and refraction.
of ordinary wave that move toward the coastline of the mainland from an open sea. So, coastlines of the tombolo tend to change due to seasonal changing of the wave condition. Neck of tombolo can be an isthmus and can also be quite large for residential activities, such as Meulaboh tombolo. Until before the large tsunami of 26 December 2004, there were no information on how the large tsunami effects on of the large tombolo to an extraordinary wave, and how it recovers from the effects. This study is conducted to fill these shortcomings.

Meulaboh is one of the coastal cities on the edge of the Indian Ocean (Figure 1) which was mostly damaged by the tsunami of 26 December 2004, and experienced significant erosion [1]. Geomorphologically, the city grows on a tombolo. The condition provides an opportunity to study how the tombolo gives response to the tsunami. This paper provides an overview of the effects of the tsunami on a tombolo and the subsequent recovery processes, as well as the results.

![Image](118x387 to 478x590)

**Figure 1.** Study area location. Image from Google Earth, dated: 2 July 2019, image axis: 04°07’51.28”N, 96°08’32.90”E. Identification objects is in an appendices.

2. Materials and Methods
This research studied the west coast of Meulaboh tombolo at coastal segment from Ujung Karang to Suak Ujung Kalak that was in natural conditions (Figure 1). In order to figure out how the tsunami affected the tombolo and the subsequent recovery processes had been took place on the coastal zone, multi year’s images from Google Earth dates from years before and after the 26 December 2004 tsunami were analysed visually in this study to find out coastal landform and coastal processes data. This study also use field works data from year of 2002.

3. Results and Discussion
3.1. Result
3.1.1 Meulaboh Tombolo
Meulaboh tombolo is a peninsula. Geologically, the peninsula is composed of carbonate rocks and alluvial (Figure 2). The carbonate rocks found at the tip of the headland and forming low cliff coast; meanwhile, alluvial deposits connecting the cape with the island of Sumatra and forming sandy beach. The beach on the west side of the tombolo is still in natural condition, while the east coast is developed coast that strengthened with seawall because it is a seaport area (Figure 3).

According to Karig in 1978, the carbonate rock was an uplifted reef limestone, age of Pliocene [13]. The alluvium is deposits composed of beach sand resulted from wave activities existing along the coast [13]. Considering to definition of tombolo [14, 15, 16], geological condition of around Meulaboh indicates that the peninsula is a tombolo, with core of the reef limestone.
Before the tsunami hit the tombolo, images from Google Earth recorded on 28 May 2004 show the western coastal area of the tombolo having three distinct segments of the sandy beach (Figure 4). First, a sandy beach with a background of coconut trees overgrowth plains. On this segment, the width of the sandy beach from the first berm to the edge of the coconut plant zone ranges from about 15-20 m and a length of about 950 m (Figure 5). Second, a sandy beach with coastal plain of residential area as background. On this segment, the sandy beach is directly adjoining to the residential area and the width of the sandy beach ranges from 40-50 m and a length of about 2300 m (Figure 6). Third, the sandy beach with background of coastal plain overgrown with shrubs dominantly. The width of the sandy beach ranges from zero to about 17 m to a length of about 160 (Figure 4).

The west coast of Meulaboh tombolo has a straight coastline with a slight curved at the end near to Ujung Karang headland with a northwest - southeast orientation and faces the Indian Ocean (Figure 1). The coast is a wave dominant coast exposed to high-energy waves and Indian Ocean swell with high reaching up more than 2 m that dominantly come from southwest direction or normal to west coast of the tombolo [1]. Significant wave high of about 0.75-1.5 m dominantly come from southwest direction [17]. Base on beach profile and wave energy condition, according to beach classification from [18], in general, the beach at study area can be categorized as intermediate beach in characteristic. From Kampung Pasir to Ujung Karang, the sandy beach tends to become dissipative beach gradually (Figure 6). Meanwhile, from Kampung Pasir to Suak Ujung Kalak the sandy beach has intermediate characteristic (Figure 5). At intermediate beach, the beach behave as dissipative beach when low water level, and it behave as reflective beach when high water level.
3.1.2 Effect of the Tsunami
The picture of the condition of the west coast of the tombolo after being hit by the tsunami can be seen in the photograph dated December 28, 2004 (Figure 7) [19, 20]. The figure shows tsunami eroded-coastline conditions that have not been significantly affected by normal coastal processes, and some things to note are:

1) All of the sandy beach in segment of B-1 and B-3 were lost. The remaining of sandy beach was found in segment of B-2 (coastline segmentation in Figure 4). Loss of the sandy beach had caused the coastline shifted landward 15-20 m at segment of B-1, 40-50 m at B-2, and 0-17 m at B-3.

2) Erosion that occurred along the coast of the tombolo resulted in incision linear and branching channels that incised the coastal plain landward nearly 250 m. The length of the incision channels is estimated by measuring the distance of a recognizable object around the landward end of the channels in the pre-tsunami image recorded on 18 May 2004. The channels appear to be fan-shaped and open out to sea. According to [3], the incision channels with this characteristic shows that the channels was formed by the mass of tsunami water that returned to the sea after inundating the land.

3) Coastal erosion caused by the tsunami occurred unevenly along the coastline resulting in irregular coastline; however, general curved pattern of the coastline did not change significantly.

4) Low cliffed coast was formed along the coastline resulting from the erosion of the tsunami.

5) The vegetation along the coast that can survive the tsunami is coconut trees.

A visual representation of the magnitude of the change in the position of the coastline on part of the west coast of Meulaboh tombolo due to the tsunami can be seen by comparing the initial conditions of the coastal area before the tsunami (Figure 8) with after the tsunami (Figure 7).

3.1.3 Coastline Recovery
The recovery process of the Meulaboh tombolo coastline has started since the first week after the tsunami of 26 December 2004. Photo dated 01 January 2005 [22], 6 days after the tsunami, shows the presence of a new sandy beach on the west coast of tombolo, which is the result of a normal coastal process (Figure 9). The presence of the new sandy beach shows that the normal beach process has been working again and the recovery process has been running. Image recorded on 07 January 2005 (Figure 10) shows that the recovery process has taken place along the west coast of tombolo. The recovery process has caused many of the channel mouths along the coast to be closed and the coastline,
which was originally irregular to become smoother, even though there are two large channels that have not been closed. Further changes resulting in a new, smoother coastline (Figure 11).

**Figure 7.** West coast of Meulaboh tombolo, 28 December 2004, two days after the tsunami showing an irregular coastline. IC: incision channel, CB: clifled beach, RSB: remaining sandy beach. Photo from [19].

**Figure 8.** Initial conditions of part of the west coast of Meulaboh tombolo near the Ujung Karang area before the tsunami (18 May 2004). Image from [21].

**Figure 9.** Part of west coast of Meulaboh tombolo that showing an early grow of new sandy beach six days after the 26 December 2004 tsunami. Photo from [22]. References buildings position can be seen in Appendices Figure A1, and position of the photograph in Figure 1.

**Figure 10.** Meulaboh coastline 11 day after the tsunami, 07 January 2005. Recovery processes was occurred along the west coastline. New sandy beach intensely formed along the coastline. Image from [21].

In the image recorded on 15 May 2008 (Figure 12), the physical form of the coastline seems to have recovered even though the position of the coastline has not returned to its original position before the tsunami (position dated 18 May 2004). The coastline has become smoother again after coastal sediment deposits resulting from the activities of the normal wave process cover all of the tsunami incision channels. After 2008, no more significant coastline changes have occurred on the west coast.
of tombolo. The next coastline change that occurred until 2019 seems to be only a seasonal change in the width of the sandy beach to the position in 2008.

**Figure 11.** The new sandy beach was intensely grown along west coast of Meulaboh tombolo, 10 January 2005, in 15 days after the tsunami. Photo from [23]. References objects position can be seen in Appendices Figure A1, and position of the photograph in Figure 1.

**Figure 12.** Coastline of west coast Meulaboh tombolo before and after the tsunami of 26 December 2004. Before the tsunami (18 May 2004) the coast has wide sandy beach. The tsunami removed sandy beaches and incised channels on the coastal plain that result in irregular coastline (07 Jan 2005). Recovery processes has been resulted in coastline resembles coastline before the tsunami (15 May 2008). Coastline of 2009 is very similar to coastline 2008 (21 Oct 2019). Images from Google Earth. Image axis: 04°08’16.32”N, 96°07’20.45”E.
The tsunami has also caused changes in the coastal plains of the tombolo in the form of the presence of several enclosed water bodies on the coastal land, the formation of which is related to the recovery process of the shoreline that closes the mouths of the incised channels on the beach by coastal sand deposits. At the beginning of the recovery process, many water bodies are formed due to the closure of the mouths of the erosion channels, but over time, their size decrease (Figure 13) and their numbers diminish. Many water bodies that close to the shoreline are covered by sand deposits that are deposited ashore by the waves, especially when the tide is high through an overswash mechanism.

![Image](http://example.com/image1.png) ![Image](http://example.com/image2.png)

**Figure 13.** Development of incision channels into enclosed water bodies at Ujung Kalak, Meulaboh. Images from Google Earth. Image axis: 04°08′40.70″N, 96°07′10.32″E.

### 3.2 Discussion

#### 3.2.1 Coastline Recovery Completion

The tsunami of 26 December 2004 caused the loss of the sandy beach almost from the entire west coast of the tombolo, and the formation of incision channels that cut the coastal plain up to about 250 m inland. Broadly speaking, erosion by the tsunami produces irregular shoreline, although in general the curved coastline pattern of the tombolo is still visible (Figure 6). Loss of sandy beach by tsunamis is common phenomena occurring when a sandy beach is hit by a large tsunami because it is a “soft” part of the coast [1, 6, 24].

The coastline recovery process on the west coast of the tombolo appears to be taking place very fast in the early stages of the recovery period. New coastal sand deposits formed by normal coastal processes were encountered on the 6th day after the tsunami along the coast (Figure 8) causing the loss of low coastal cliffs from the tsunami coast. The image dated 07 January 2005 (Figure 9) shows that coastal sand deposits have covered almost all of the incision channels formed by the tsunami. The fast recovery process is likely due to the environmental conditions in coastal waters with high wave-energy [9] [25].

The image dated May 15, 2008 shows that physically the coastline has been smooth like the coastline before the tsunami and all the mouths of the incision channel have been closed even though the position has not returned to its original position (position dated 18 May 2004). It is not known in what year the smooth coastline was completed because no image or photo recording was obtained between 2005 and 2008. Furthermore, between 2008 and 2019 the coastline experienced only slight
shifting. This situation shows that the coastline recovery process has been completed, namely when the shoreline position has stabilized even though it does not return to its original position [4, 5, 8, 9]. The changes occurring along the coast as above indicate that the erosional coastline created by the tsunami were temporary [25].

3.2.2 Tsunami Incision Channels Development
It was mentioned in the early that along the west coast of Meulaboh tombolo, many incision channels were formed (Figure 6) whose length was up to about 250 m from the shore into the mainland. The consequence of the formation of these channels is that the coastline became irregular. When the coastline recovery process begins, the initial stage, the mouths of these channels are closed by coastal sediment deposits that deposited by normal wave activity. The initial closure of these channels causes two things, namely: (1) restoring the condition of the coastline from irregular to smoother, and (2) forming enclosed water bodies along the west coast of tombolo. In the next stage, when the recovery process of the shoreline continues, the following conditions occur: (1) the condition of the shoreline is getting smoother and (2) the disappearance of enclosed water bodies near the beach due to the sedimentation process by normal wave activity that rebuilds the sandy beach. After the coastline recovery process reaches the final stage, when the position of the shoreline is in a balanced/stable condition even though it was not in the initial position before the tsunami, then the remaining enclosed water bodies are those that are far enough from the coastline (about 70-150 m) and are not reachable by normal wave activity. With such developments, it is very possible that the closure of enclosed water bodies near the coastline occurs when high wave energy in the west wind season and the coastline shifts landward [26, 27].

3.2.3 Trace of the Tsunami
The tsunami that hit the coastal plains of Meulaboh tombolo produced various erosional forms on the coastal plain. However, as the eroded coastal areas recovered by normal wave activity, the traces of the tsunami gradually disappeared along with the arrival of new sandy beaches. This pattern of coastal land development after the tsunami also occurs in various places on the west coast of Sumatra Island [1, 9, 24, 28]. In Meulaboh tombolo, the traces of the tsunami in the form of an enclosed water body can still be seen until 2019, 15 years after the tsunami, in a location that cannot reached by normal wave activity. The enclosed water bodies are part of the tsunami incision channels that was formed inland so that they are not reached by normal wave activity when the recovery process takes place and stable sand beach conditions are achieved. However, in the next few years this water body is very likely to disappear due to human activities.

4 Conclusion
The tsunami of 26 December 2004 that struck Meulaboh tombolo eroded the coastal plain. This erosion process removes the sandy beach and forms incision channels which results in an irregular erosional coastline. Recovery process that following the tsunami restored sandy beach, and eliminated almost all traces of tsunamis which is near to the coastline that can be reached by normal wave activity during the recovery process. In the early stages of the recovery process, ordinary wave activity turns the incision channels into enclosed water bodies. And then, it fill up enclosed water bodies or part of enclosed water bodies that near to the coastline through over-swashing beach sand into it, and leaving the distant part of the water bodies as smaller enclosed water bodies. High-energy environment of the west waters of Meulaboh tombolo is very conducive for coastline recovery.

Acknowledgments
The author would like to thank Mr. Hari Dwi Nugroho (Harry Scout Picture) for his permission for the author to use the recorded images of the city of Meulaboh (Figure 2 and 3), and to an anonymous reviewer that improved the quality of this manuscript.
Appendices

Key identification objects. Several objects in the city of Meulaboh that existed before the tsunami can withstand the damage caused by the tsunami, so they can be used as a key to identify a location recorded in a photo after the tsunami (Figure A1).

![Figure A1. Key identification objects. Image of Meulaboh city before the tsunami of 26 December 2004. Some objects that can be used as identification point after the city was devastated. B-1 to B-5: building; 3-WJ: three way junction; CT: coconut tree. Refer to Figure 1 for location of this figure. Image from Google Earth, dated 18 May 2004.](image)

References

[1] Liew S C, Gupta A, Wong P P and Kwoh L K 2010 Recovery from a large tsunami mapped over time: The Aceh coast, Sumatra Geomorphology 114 520-9
[2] Jaya Kumar S, Naik K A, Ramanamurthy M V, Illangovalan D, Gowthaman R and Jena B K 2008 Post-tsunami changes in the littoral environment along the southeast coast of India J. Environ. Manage. 89 35-44
[3] Fagherazzi S and Du X 2008 Tsunamigenic incisions produced by the December 2004 earthquake along the coast of Thailand, Indonesia and Sri Lanka Geomorphology 99 120-9
[4] Masaya R, Suppari A, Yamashita K, Imamura F, Gourmanis C and Leelawat N 2019 Investigating beach erosion related with its recovery at Phra Thong Island, Thailand caused by the 2004 Indian Ocean tsunami Nat. Hazards and Earth Sys. Sci. Preprint https://doi.org/10.5194/nhess-2019-263
[5] Choowong M, Phantu Wongraj S, Charoentitirat T, Chutakositkanon V, Yumuang S and Charusiri P 2009 Beach recovery after 2004 Indian Ocean tsunami from Phang-nga, Thailand Geomorphology 104 134-42
[6] Szczucinski W, Chaimanee N, Niedzielski P, Kochlewicz G, Saisuttichai D, Tepsuwan T, Lorenc S and Siepak J 2006 Environmental and geological impacts of the 26 December 2004 tsunami in coastal zone of Thailand – Overview of short and long-term effects Polish J. of Environ Stud. 15 793-810
[7] Pari Y, Ramana Murthy M V, Jaya Kumar S, Subramanian B R and Ramachandra S 2008 Morphological changes at Vellar estuary, India – Impat of the December 2004 tsunami J. Environ. Manage. 89 45-57
[8] Ali P Y and Narayana A C 2015 Short-term morphological and shoreline changes at Trinkat Island, Andaman and Nicobar, India, after the 2004 tsunami Mar. Geodesy 38 26-39
[9] Monecke K, Templeton C K, Finger W, Houston B, Luthi S, McAdoo B G, Meilianda E, Storm J E A, Walstra J – J, Amna R, Hood N, Karmanocky F J III, Nurjanah, Rusdy I and Sudrajat S U 2014 Beach ridge patterns in West Aceh, Indonesia, and their response to large earthquake along the northern Sunda trench Quat. Sci. Rev. Article in Press http://dx.doi.org/10.1016/j.quascirev.2014.10.014
[10] Koiwa N, Takahashi M, Sugisawa S, Ito A, Matsumoto H, Tanavud C and Goto K 2017 Barrier spit recovery following the 2004 Indian Ocean tsunami at Pakarang Cape, southwest Thailand Geomorphology http://dx.doi.org/10.1016/j.geomorph.2017.05.003
[11] Pantanahiran W 2014 Monitoring coastal change after the tsunami in Thailand IOP Conf. Series: Earth and Environmental Science 17 012108 DOI: 10.1088/1755-1315/17/1/012108
[12] Harry Scout Picture 2019 6 menit di atas Meulaboh (Video file) Retrieved from https://www.youtube.com/watch?v=F4Ik5uKaPcE&t=14s Accessed 18 Oct 2020

[13] Cameron N R, Bennett J D, Bridge D McC, Clarke M C G, Djunudin A, Ghazali S A, Harahap H, Jeffery D H, Keats W, Ngabito H, Rocks N M S and Thompson S J 1983 Geology of Takengon Quadrangle, Sumatera (Bandung, Indonesia: Geological Research and Development Center) p 26 + 1 sheet Geological Map scale 1:250,000

[14] Earle S 2019 Physical Geology 2nd ed. (Victoria, BC: BC Campus) Retrieved from https://opentextbc.ca/physicalgeology2ed/

[15] Bates R L and Jackson J A 1987 Glossary of Geology 3rd ed. (Alexandria, Virginia: American Geological Institute) p 788

[16] Ongkosongo O S R 1981 Tombolo and the formerly Quaternary islands in Java and Bali Proceedings of the 10th Indonesian Geologist Association Annual Meeting (Jakarta, Indonesia) pp 121-136

[17] Rizal A M and Ningsih N S 2020 Ocean wave energy potential along west coast of the Sumatra Island, Indonesia J. Ocean Engineering and Mar. Energy https://doi.org/10.1007/s40722-020-00164-w

[18] Wright L D and Short A D 1984 Morphodynamic variability of surf zones and beaches: a synthesis Marine Geology 56 93-118

[19] Paparas-Carayannis G 2005 The Great Earthquake and Tsunami of 26 December 2004 in Southeast Asia and Indian Ocean Retrieved from http://www.drgeorgepc.com/Tsunami2004/Indonesia.html Accessed 13 Oct 2020

[20] HO/AFP 2004 An overview shows Meulaboh city under water 28 December 2004 (GettyImage) 51897745

[21] NASA Earth Observatory (n.d.) Earthquake Spawns Tsunami’s Retrieved from https://earthobservatory.nasa.gov/images/14420/earthquake-spawns-tsunamis Accessed 12 Oct 2020

[22] Ardian D 2005 Aerial images shows the extent of devastation in Sumatra (GettyImage) 51906888

[23] Bauer B A 2005 File: Meulaboh Hovercraft 050110-N-7586B-120.jpg (Wikimedia Commons) Retrieved from https://commons.wikimedia.org/wiki/File:Meulaboh_Hovercraft_050110-N-7586B-120.jpg Accessed 18 Oct 2020

[24] Wong P P 2009 Impact and recovery from a large tsunami: Coast of Aceh Polish J. Environ. Stud. 18 5-16

[25] Yu F, Switzer A D, Lau A Y A, Yeung H Y E, Chik S W, Chiu H C, Huang Z and Pile J 2013 A comparison of the post-storm recovery of two sand beaches on Hong Kong Island, southern China Quaternary International 304 163-72 http://dx.doi.org/10.1016/j.quaint.2013.04.002

[26] Anthony E J 2019 Beach Erosion ed C W Finkl and C Makowski Encyclopaedia of Coastal Science Encyclopaedia of Earth Science Series (Sringer, Champ) http://doi.org/10.1007/978-3-319-93806-6 33

[27] Rodrigues B A, Matias A and Ferveira O 2012 Overwash hazards assessment Geologica Acta 10 427-37

[28] Liew S C, Gupta A, Wong P P and Kwoh L K 2008 Coastal recovery following the destructive tsunami of 2004: Aceh, Sumatra, Indonesia The Sedimentary Record September 4