

Characteristics of Boleng Strait Sediments, East Nusa Tenggara, and its Relationship with Current Velocity

Karakteristik Sedimen Dasar Laut Selat Boleng, Nusa Tenggara Timur, dan Hubungannya dengan Kecepatan Arus

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ABSTRACT: Islands of Nusa Tenggara are separated by narrow and deep straits resulted from complex tectonic activities. One of the strait is Boleng Strait where tidal current as high as 310 cm/s occurred which might be suitable for an ocean current power plant. Utilization of such resources would need various information of the area, one of them is sediment textures that characterized the seafloor and coastal area and their relationship to current velocity. Grain size analyses were conducted on 12 seafloor sediment samples and 26 coastal sediment samples to identify sediment texture. An additional 14 seafloor sediment samples with limited volume were observed to determine their sediment types. The result of analysis yielded six types of seafloor sediments: Sand, Gravelly Sand, Sandy Gravel, Silty Sand and Sandy Silt. The sediment grain size is equally influenced by current velocity ($r = 0.57$) and water depth ($r = 0.52$) which is reflected by sediment distribution: coarse-grain sediments cover the area near Boleng Strait which has stronger current and fine-grain sediments cover the inner part of the Lewoleba Bay. Plot of six sets of mean grain size and current velocity on Hjulström diagram shows that most of seafloor sediments are on the move and one (SBL. 14) is being eroded. This condition might affect the turbine and thus needs to be taken into consideration when designing the turbine. Grain size analyses on coastal sediment samples show that the mean grain size of coastal sediments ranges between 0.19 mm and 0.62 mm with average value of 0.33 mm that is classified as medium sand. Sand fraction in coastal sediments composes 57% to 100% of the sediments. Observation on mineralogy of the sediments shows abundance of magnetite that concentrates in the fine and medium sand fractions. The presence of magnetite indicate that current-related selective entrainment occurs in the study area. This condition suggests that the coastal area is also strongly affected by ocean current.

Key words: current velocity, sediment grain size, Boleng Strait.

ABSTRAK: Aktivitas tektonik di Nusa Tenggara Timur menyebabkan terbentuknya batimetri yang kompleks di sekitar kepulauan tersebut yang dicirikan oleh adanya selat sempit dan dalam yang memisahkan pulau-pulau. Salah satu selat tersebut adalah Selat Boleng yang memiliki kecepatan arus terukur maksimum sebesar 310 cm/s yang dapat digunakan sebagai pembangkit energi listrik. Desain turbin arus akan membutuhkan banyak informasi, salah satunya adalah sedimen dasar laut dan pantai serta hubungannya dengan kecepatan arus. Analisis besar butir dilakukan pada 12 sampel sedimen dasar laut dan 26 sampel sedimen pantai untuk menentukan jenis sedimen. Sebanyak 14 sampel sedimen dasar laut dengan volume terbatas diamati untuk mengetahui jenis sedimen. Hasil analisis menunjukkan bahwa sedimen dasar laut terdiri atas enam jenis: Pasir, Pasir Kerikilan, Kerikil pasiran, Pasir Lanauan dan Lanau Pasiran. Ukuran butir sedimen dipengaruhi oleh kecepatan arus ($r = 0.57$) dan kedalaman laut ($r = 0.52$) yang tercermin pada distribusi sedimen: sedimen berukuran kasar menutupi dasar laut di dekat Selat Boleng yang berarus lebih kuat, dan sedimen berukuran halus menutupi dasar laut di bagian dalam Teluk Lewoleba. Plot enam set ukuran butir rata-rata dan kecepatan arus pada diagram Hjulström menunjukkan bahwa hampir seluruh sampel berada dalam kondisi bergerak dan bahkan satu (SBL. 14) sedang mengalami erosi. Kondisi ini akan mempengaruhi turbin sehingga perlu dijadikan pertimbangan saat mendesain turbin. Hasil analisis besar butir pada sedimen pantai menunjukkan bahwa ukuran butir rata-rata sedimen pantai berkisar 0.19 mm dan 0.62 mm dengan nilai rata-rata 0.33 mm yang termasuk dalam fraksi pasir sedang. Fraksi pasir dalam sedimen pantai menyusun 57%–100% sedimen. Pengamatan mineralogi menunjukkan melimpahnya magnetit yang terkonsentrasi pada fraksi pasir halus–sedang. Keberadaan magnetit menunjukkan adanya proses pemisahan yang berkaitan dengan arus laut. Kondisi ini menunjukkan bahwa daerah pantai Selat Boleng juga dipengaruhi oleh arus laut.

Key words: kecepatan arus, ukuran butir sedimen, Selat Boleng.

INTRODUCTION

Seafloor sediments are the product of various processes that involved erosion, transportation and deposition. The erosional processes are influenced by geological setting, geographical position and climate conditions. The resulted detritus are then transported by ice, air and water into the sea to be deposited on the seafloor. Those processes are recorded in sediment characteristics, such as grain size and sediment composition.

As the most fundamental sediment physical property, grain size has been studied extensively to understand depositional processes and environment (Venkatesan *et al.*, 2017). The size of grains reflect the erosional and transportation mechanisms. Previous studies tied grain size to seafloor morphology in Knight Inlet, British Columbia (Ren *et al.*, 1996) in Taiwan Strait (Liao *et al.*, 2008) and in Abu Dhabi coast (Al Rashedi and Siad, 2016). Heise *et al.* (2004) conducted a semi-quantitative study on near bottom current impact on seafloor sediment by correlating granulometric parameters to hydrographical data. Ziervogel and Bohling (2003) compared the results of measured velocity to the one calculated from grain size. Studies that correlate sediment grain size to hydrological data in Indonesia are mostly focused on coastal erosion (Lanuru *et al.*, 2018) or tsunami hazard modelling (Tang and Weiss, 2016).

This paper presents the correlation of sedimentological parameter and hydrological data from Boleng Strait, East Nusa Tenggara. Boleng Strait that separates Adonara from Lembata Islands (Figure 1) has been studied for its potential ocean current energy. Ocean current that flows through the narrow strait was reported to have velocities between 150 and 310 cm/s (Rachmat *et al.*, 2013) for water depth between 75 and 100 m. The current velocity in this strait is classified as strong (> 200 cm/s) following Fraenkel (2002), thus the

strait has potential for ocean current energy development.

Rachmat *et al.* (2013) suggested that the most favourable location for development of ocean current energy is at the central part of the strait with two options of electrical turbines: gravity based or floating. Either option needs additional information such as geological conditions and seafloor sediments that are presented in this paper. The aim of this paper is to understand the relationship between current velocity and seafloor sediment.

Geology of Boleng Strait

The 1400 km long island chain of Nusa Tenggara or Lesser Sunda Islands occupies a geanticline ridge that tapers from 100 km wide in the west to 40 km in the east (Bemmelen, 1949) and formed by collision of the Australian with island arc (Silver *et al.* 1983). Nusa Tenggara consist of eastern part that extends from Timor uplift to Komodo Island, and western part that covers islands from Sumbawa to Bali (Bemmelen, 1949). The NE-SW orientation of eastern Nusa Tenggara is interpreted as the result of transform faults (Figure 1). These faults are considered by Silver *et al.* (1983) as a cross-arc faulting and together with magmatic activity, surface slopes, uplift and forearc structure are in the process of thrust formation. Muraoka *et al.* (2005) considers the ENE-WSW orientation of Nusa Tenggara as *en echelon* topographic structures characterized by anticline culmination and young volcanic belt. Those tectonic activities form unique island shapes that are separated by deep narrow straits, such as Boleng Strait.

Those tectonic activities form unique island shapes that are separated by deep narrow straits, such as Boleng Strait. Figure 2 (right) shows geological structure of Boeng Strait based on structural pattern of Lembata Island. The lineation is considered to the continuation of Semau Fault that also separate West

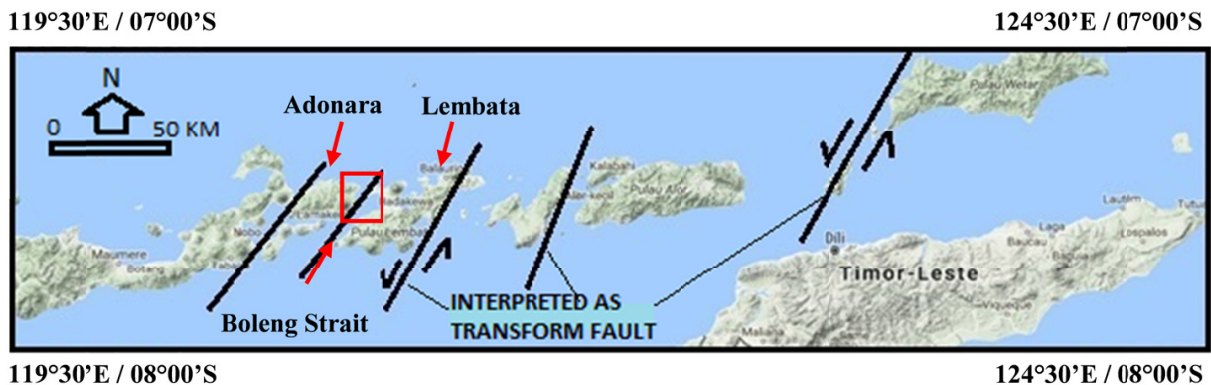


Figure 1. The study area in Boleng Strait (red box). Red arrows indicate the strait and islands of Adonara and Lembata. Black lines and arrows indicate interpreted transform faults that are considered by Silver *et al.* (1983) as cross-arc faulting. Base map is taken from Google Earth.

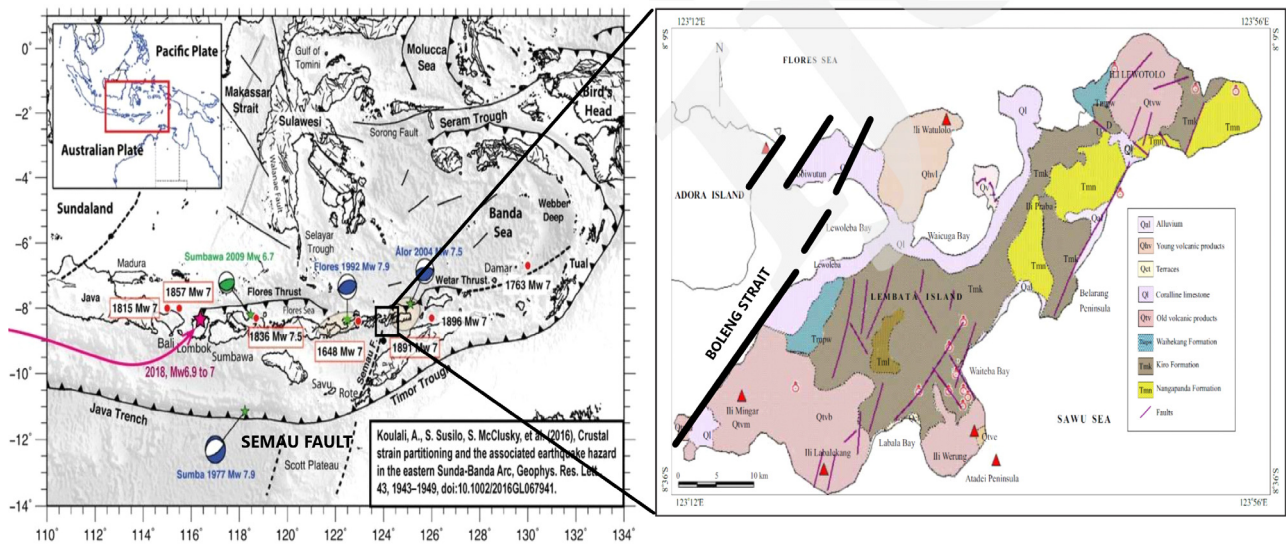


Figure 2. Faults interpretation in Boleng Strait (right) deduced from Lembata Island structural geology pattern (Koesoemadinata and Nova, 1990) and continuation of Semau Fault (left) (Koulali *et al.*, 2016).

Timor and Rote in the south (Figure 2 left). Those structures form the complex bathymetry of Boleng Strait.

The geology of the study area was studied by Koesoemadinata and Noya (1990). Volcanic activities in Nusa Tenggara formed the Miocene Kiro Formation that is composed of lava, breccia, and calcareous to sandy tuff (Figure 3). The activity that was followed by sea level change formed Waihekang Formation (Miocene – Pliocene) that comprises limestones, calcareous sandstones with intercalation of calcareous tuff. This formation is covered by Young Volcanic Rocks (Holocene) and Holocene Coralline Limestone. These rocks experience subaerial weathering under tropical monsoonal climate that would yield typical tropical coastal and marine sediments that according to Komar (1998) are mostly dominated by quartz, feldspars and heavy minerals that are mixed with shell, shell fragments and ooliths. These types of sediments were observed in various areas of Indonesian coasts and seas (Sampurno *et al.*, 2017; Zuraida *et al.*, 2017), thus it is also expected to form the coastal and marine sediments of the study area.

Hydrography of Boleng Strait

The Indonesian Seas are influenced by various currents, such as the Indonesian Throughflow (ITF) that carries heat and freshwater from Pacific Ocean in the north to the Indian Ocean in the south (Sprintall *et al.*, 2003), as well as tidal current. The ITF is mostly flowing through the straits of Makassar, Lombok, Ombai and Timor Passage (Gordon, 2005) and

predominantly observed in open and deep waters. Tidal current is mostly affected shallow and coastal seas.

The tides that affect the Lesser Sunda Islands or Nusa Tenggara are mostly flowing from the Pacific and Indian Oceans. Geographical distribution of tidal types put the study area in mixed tide prevailing semidiurnal that ranges between 0.25 – 1.5 m (Wyrтки, 1990).

Rachmat *et al.* (2013) observed that during high tide, the current flows northward and during low tide the current flows southward (Figure 4), indicating that the study area is mostly influenced by tides from the Indian Ocean as was suggested by Wyrтки (1990). Current velocity is strongest during high tide (40 – 60 cm/s) than low tide that is interpreted by Rachmat *et al.* (2013) as the result of larger volume of water mass that flows into the strait due to its wider southern opening than the northern part.

The bathymetry of Boleng Strait is characterized by steeply dipping slope from Adonara to reach the deepest part of the strait (approximately 200 m) before rising gently toward Lembata (Figure 4). The strait is wider in the southern part (approximately 4000 m wide) that becomes narrower to the north (2000 m wide). The shape of this strait plays an important role in regulating current velocities in this area.

A relatively wide and shallow shelf (maximum water depth is 50 m) covers Lewoleba Bay to the east of the strait (Figure 4). The closure pattern of Boleng Strait bathymetry (Rachmat *et al.*, 2013) provides small depositional basin that allows accumulation of sediment. This area is expected to be covered by finer-grained sediments than the strait proper.

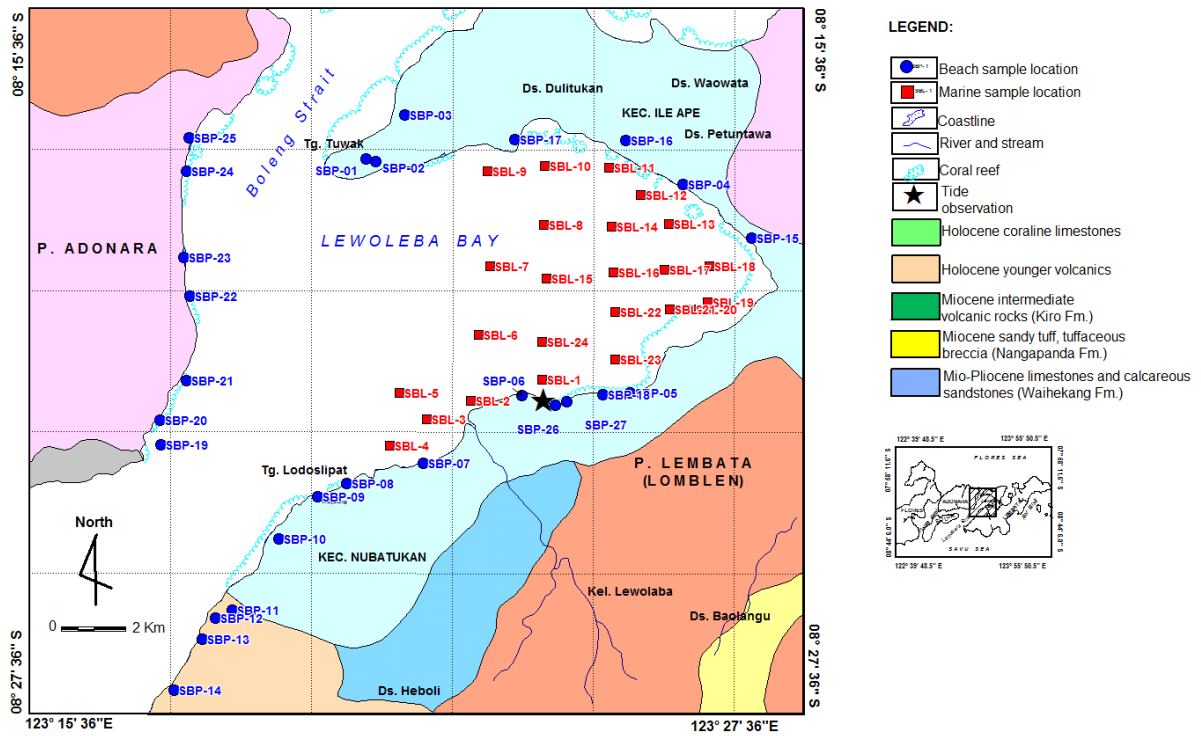


Figure 3. Seafloor and coastal sediment sampling locations and the surrounding geology. The geology of Adonara and Lembata is from Koesoemadinata and Noya (1990).

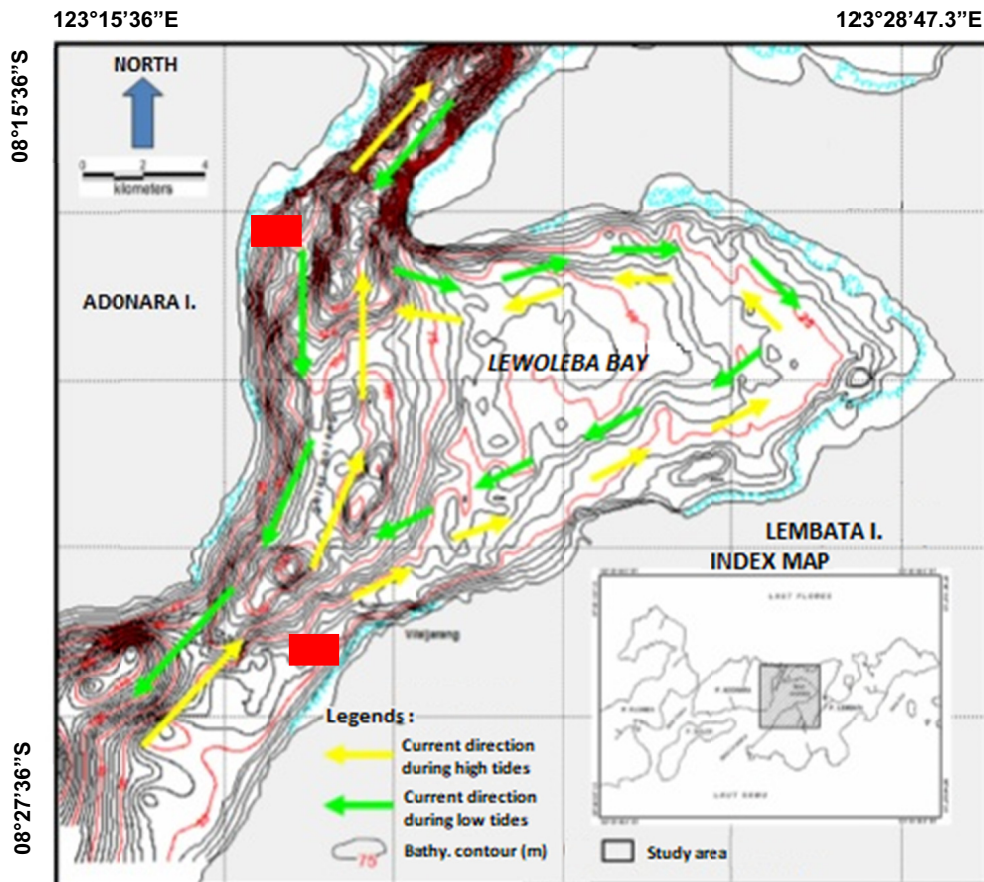


Figure 4. Bathymetry of Boleng Strait with current directions. Yellow arrows denote current direction during high tide and green arrows during low tide. Red boxes denote locations of ocean current and tide measurements. Map is taken from Rachmat *et al.* (2013).

METHODS

Seafloor sediment sampling was conducted by grab sampler and coastal sediment sampling was conducted by spatula. A total of 24 seafloor sediment samples were acquired from Lewoleba Bay and no sample was recovered from Boleng Strait due to strong current that flows in the strait that can reach 3 m/s (Figure 3). Coastal sediment sampling was conducted on 26 locations along the western coast of Lembata and the eastern coast of Adonara (Figure 3). Sieve analysis was conducted on 12 seafloor sediment samples with enough materials and 26 coastal sediment samples to determine sediment type. Sediment classification that is used in this study is the classification of Folk (1980). Sediment classification for small volume samples are based on sample description. Observation of magnetite content within each Φ class was conducted in coastal samples.

Mean grain size of seafloor sediment and measured current velocity from Rachmat *et al.* (2013, Table 2) are plotted on the Hjulström diagram to find the state of the particles, i.e. eroded, transported or settled on the seafloor. Initial movement of particles is started when certain value is reached, which is described as critical shear stress velocity (u_{cr}^*) by Ziervogel and Bohling (2003). The u_{cr}^* that is used in this paper is the theoretical shear stress velocity based on Hjulström diagram ($u_{cr-Hjulström}^*$) following Ziervogel and Bohling (2003):

$$u_{cr-Hjulström}^* = \sqrt{C_D u_{cr-Hjulström}}$$

where:

$u_{cr-Hjulström}^*$ = critical shear stress velocity (m/s)

C_D = drag coefficient (0.0025)

and $u_{cr-Hjulström}$ is calculated as follows (Ziervogel and Bohling, 2003):

$$u_{cr-Hjulström} = 2.8 * (\sqrt{\rho'gd}) + 14.7 * \frac{v}{d}$$

where:

$u_{cr-Hjulström}$ = critical Hjulstrom current velocity (m/s)

$\rho' = (\rho_s - \rho_f)/\rho_f$ (relatively density of sediment particles to the density of fluid)

$\rho_s = 2650 \text{ kg/m}^3$ (density of sediment particles)

$\rho_f = 1250 \text{ g/m}^3$ (density of water)

$g = 9.81 \text{ m/s}^2$ (gravitation)

d = mean grain size (m)

v = kinematic viscosity of water ($10^{-6} \text{ m}^2/\text{s}$)

While the relationship between grain size and current velocity is very straightforward, the effect of

water depth to grain size is less so. The role of water depth in marine sedimentation is determining the impact of wave and current on the sediments, such as preserving seafloor sediment (Weiss and Bahlburg, 2006). To understand the relationship between mean grain size, current velocity and water depth, we calculate their correlation coefficients using PAST (Hammer *et al.*, 2001). The calculation only applied on six stations that have current velocity data. To plot the $u_{cr-Hjulström}^*$ in the classical Hjulström diagram, the velocity unit is converted from m/s to cm/s. There is a possibility that the mean grain size that is used to calculate $u_{cr-Hjulström}^*$ does not represent actual mean grain size due to the presence of biogenic shells in the samples. However, in this study, we assumed that the mean grain size is not affected by biogenic shells.

RESULTS

Seafloor sediments

Six sediment types are recognized from grain size analyses (Table 1a and 1b) and presented in seafloor sediment distribution map (Figure 5). The sediments types are mostly coarse sediments (Sand, Gravelly Sand, and Sandy Gravel), Coral fragments, and fine sediments (Silty Sand and Sandy Silt). Gravelly sand unit includes slightly gravelly sand and slightly gravelly muddy sand that were observed in only 3 samples (Table 1a).

In general, approximately 90% of seafloor sediments of study area consist of coarse fraction which indicates strong current influence (Folk, 1980; Visher, 1969; Kurnio and Aryanto, 2013). Coarse-grain sediments tend to be deposited closer to Boleng Strait in the west while fine-grain sediments are mostly found in calmer water within Lewoleba Bay (Figure 5).

Sand

Sand is the most widespread unit in the study area. The distribution pattern of this unit might be controlled by current that branches from Boleng Strait to Lewoleba Bay (Figures 4 and 5). The mean grain size of this unit ranges between 1.6 and 2.4 Φ (Table 1a) that falls into coarse – fine sand in the Wentworth grain size scale (Williams *et al.*, 2006). The sediments of this unit is well – moderately well sorted (0.4 – 0.8 Φ , Table 1a).

The sand fraction composes 99.9% of this unit. Figure 5 shows that coarse sand is deposited at shallower water (11 m, SBL.21) where the influence of agitation of marine processes such as currents and waves are more prominent, while fine sand is deposited in relatively quiet water (25 m, SBL.24) with current velocity of equal or less than 20 cm/s.

Table 1a. The result of grain size analyses on seafloor sediments completed with sediment classification following Folk (1980).

No	Sample ID	Mean (Φ)	Sort.	Skew.	Kurt.	Gravel	Sand	Silt	Clay	Sediment classification (Folk, 1980)
1	SBL.06	0.2	1.0	-0.5	3.6	7.0	93.0	0.0	0.0	Gravelly sand
2	SBL.14	1.4	1.2	-0.4	2.3	2.0	98.0	0.0	0.0	Slightly gravelly sand
3	SBL.15	2.3	0.8	-1.3	5.7	0.2	99.8	0.0	0.0	Sand
4	SBL.16	4.9	1.5	-1.0	4.1	0.0	16.1	83.8	0.0	Sandy silt
5	SBL.18	3.3	1.9	0.0	1.8	0.0	52.7	47.3	0.0	Silty sand
6	SBL.20	1.8	1.0	-0.6	2.9	0.3	99.7	0.0	0.0	Slightly gravelly sand
7	SBL.21	1.6	0.7	-0.0	2.1	0.0	99.9	0.0	0.0	Sand
8	SBL.22	2.8	2.4	-0.0	2.5	4.5	59.4	36.1	0.0	Slightly gravelly muddy sand
9	SBL.23	1.6	1.1	-0.3	2.2	0.2	99.8	0.0	0.0	Slightly gravelly sand
10	SBL.24	2.4	0.4	-1.6	8.0	0.0	99.9	0.0	0.0	Sand

Table 1b. Sediment classification based on macroscopic observation of seafloor sediments with limited sample volume, The classification follows Folk (1980).

No.	Sample ID	Sediment classification (Folk, 1980)
1	SBL.01	Sandy gravel
2	SBL.02	Gravelly sand
3	SBL.03	Sand
4	SBL.04	Sand
5	SBL.05	Gravelly sand
6	SBL.07	Sand
7	SBL.08	Gravelly sand
8	SBL.09	Gravelly sand
9	SBL.10	Gravelly sand
10	SBL.11	Sandy gravel
11	SBL.12	Coral fragments
12	SBL.13	Coral fragments
13	SBL.17	Sand
14	SBL.19	Sand

Gravelly sand

As the second widespread distribution unit in the study area, the existence of gravel indicates that its dispersal is controlled by strong current derived from Boleng Strait. This unit covers two parts of study area (Figures 5) and is characterized by mean grain size that ranges 0.2 – 1.8 Φ and the sediments are poorly – very poorly sorted (1 – 2.4 Φ , Table 1a).

The distribution pattern of this unit (Figure 5) and observation of the current pattern (Figure 4) suggest that this unit is deposited close to the strait where the current is strongest. Grain size analyses show high percentage of gravel (7%, Table 1a) that indicates strong current influence (Folk, 1980). Measured current velocity that was conducted in sample locations of this unit yielded 40 – 60 cm/s (Table 2) which indicate

relatively strong current. The absence of fine fractions, such as silt and clay, in this unit further supports the interpretation that strong current is the agent that controls gravelly sand distribution that washes finer-grained sediments.

Sandy gravel

No clear distribution pattern for sandy gravel unit is observed (Figure 5). This unit was found at two sample locations at 7 m water depth in the southern (SBL.01) and 17 m (SBL.11) in the northern parts of Lewoleba Bay. The sediment of SBL.01 is finer than of SBL.11 (Table 1b). The difference might be related to stronger current velocity in the north (20 cm/s) than the south (10 cm/s) (Table 2).

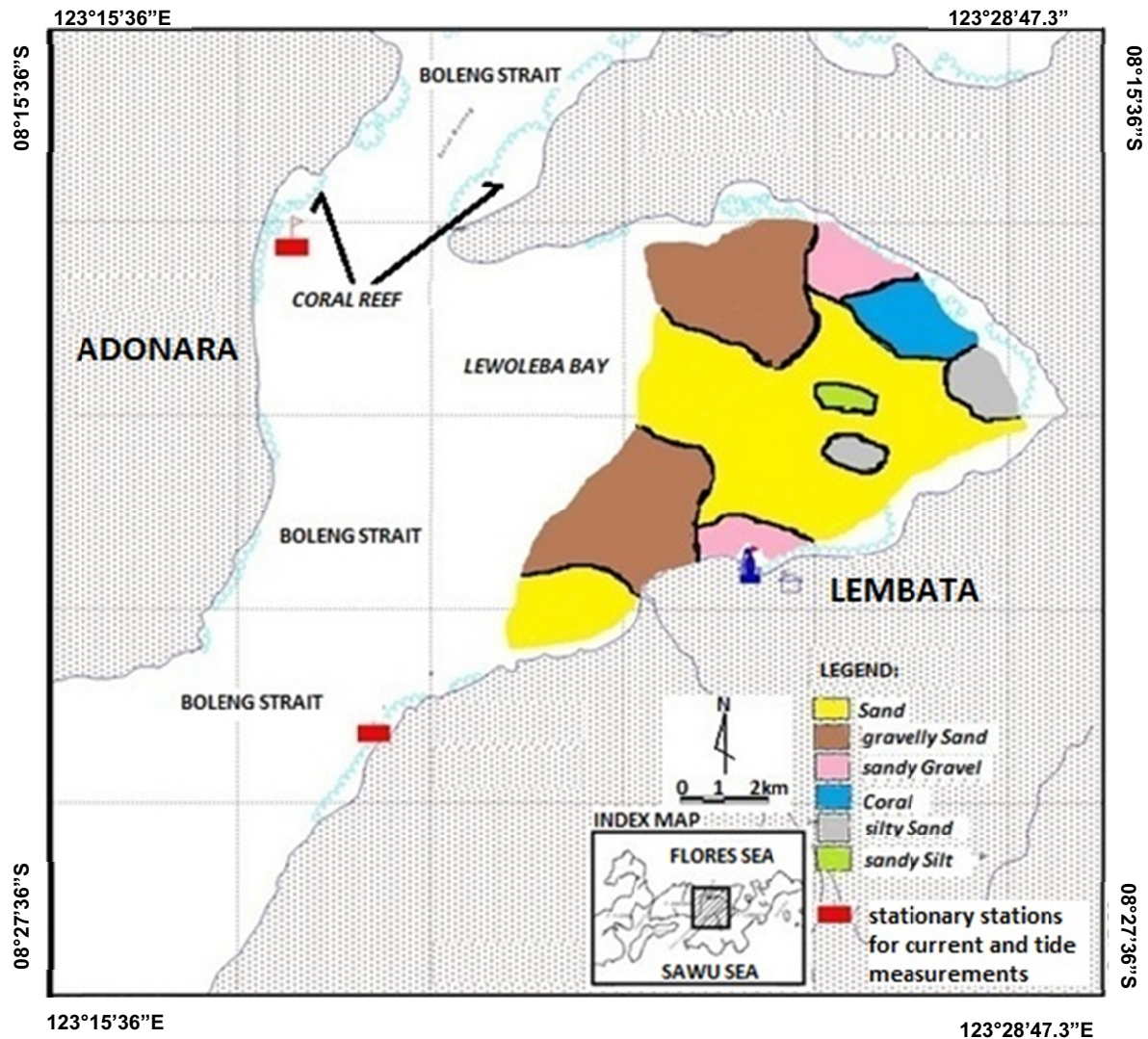


Figure 5. Boleng Strait seafloor sediment distribution that is dominated by coarse-grained sediments consist of sand, gravelly sand, sandy gravel and coral fragments. Fine-grained sediments consist of silty sand and sandy silt were found within the Lewoleba Bay. Solid red boxes indicate locations for stationary current and tide measurements that were reported in Rachmat *et al.* (2013) and which data was used in this study.

Coral fragments

Coral reef covers almost all of the shallow water (<5 m water depths) of the study area (Figure 5). Coral fragment unit is represented by two samples from the eastern part of Lewoleba Bay (SBL.12 and SBL.13) that were found close to coral reef (Figure 6). The current velocity in this part of the bay ranges from 20-40 cm/s (Rachmat *et al.*, 2013) which might be too weak to transport coral fragments further offshore (Table 2).

Silty sand

Sedimentation of silt fraction indicates weak current velocity (Folk, 1980) that allows flocculation of finer-grained particles which then settled (Boggs, 2006) to be mixed with sand fraction at one location within the bay (SBL.16 and SBL.18). The mean grain size of this

unit is 3.3Φ and poorly sorted (1.9Φ , Table 1a) and it is consisted of 52.7% sand and 47.3% silt. The unit was deposited at 23 m water depth. The measured current velocity at sample location is 20 cm/s (Rachmat *et al.*, 2013).

Sandy silt

The Sandy Silt unit is dominated by silt fraction (83.8%, Table 1a) which represents very calm environmental deposition (Folk, 1980) that allows flocculation (Boggs, 2006). This condition suggests that this unit could only be deposited further from the strait. This unit is characterized by mean grain size of 4.9Φ and poorly sorted sandy silt (1.5Φ , Table 1a). This unit covers the middle part of Lewoleba Bay at 31 m water depth where the current velocity is only 20 cm/s (Rachmat *et al.*, 2013).



Figure 6. Coral specimens obtained from seafloor using grab sampler (left). Coral reef distribution in shallow water (< 5 m) near Lewoleba Airport.

Table 2. Mean grain size (X), measured current velocities, water depths and sediment types data from Boleng Strait. Data in italics denote the ones used to calculate correlation coefficient for each element as is presented in Table 3.

No.	Sample ID.	X (cm)	Measured current velocity (cm/s)*	Water depth (m)	Sediment Types
1	SBL.01		10	7	Sandy Gravel
2	SBL.02		20	20	Gravelly Sand
3	SBL.03		60	26	Sand
4	SBL.04		40	36.3	Sand
5	SBL.05		60	38	Gravelly Sand
6	<i>SBL.06</i>	<i>0.09</i>	<i>40</i>	<i>45</i>	<i>Gravelly Sand</i>
7	SBL.07		50	55	Sand
8	SBL.08		20	44	Gravelly Sand
9	SBL.09			27	Gravelly Sand
10	SBL.10			28	Gravelly Sand
11	SBL.11		20	17	Sandy Gravel
12	SBL.12		40	14	Coral fragments
13	SBL.13		20	13	Coral fragments
14	<i>SBL.14</i>	<i>0.04</i>	<i>60</i>	<i>28</i>	<i>Slightly gravelly sand</i>
15	<i>SBL.15</i>	<i>0.02</i>	<i>20</i>	<i>48</i>	<i>Sand</i>
16	<i>SBL.16</i>	<i>0.00</i>	<i>20</i>	<i>31</i>	<i>Sandy Silt</i>
17	SBL.17	0.01		28	Sand
18	<i>SBL.18</i>	<i>0.01</i>	<i>20</i>	<i>23</i>	<i>Silty Sand</i>
19	SBL.19			12	Sand
20	SBL.20	0.003		12	Slightly gravelly Sand
21	SBL.21	0.003		11	Sand
22	SBL.22	0.001		27	Slightly gravelly muddy Sand
23	SBL.23	0.003		17	Slightly gravelly Sand
24	<i>SBL.24</i>	<i>0.02</i>	<i>13</i>	<i>25</i>	<i>Sand</i>

* measured current velocities from Rachmat *et al.* (2013)

Critical Velocities of Sediments

The current velocities, mean grain size and water depth data are presented in Table 2. Measured current velocity follows Rachmat *et al.* (2013). Plot of six mean grain size and current velocity data on the Hjulström diagram is shown in Figure 7 and the correlation coefficient is presented in Table 3.

Figure 7 shows that only the fine-grain sample (SBL. 16) is below the critical erosion velocity curve, while coarser-grain sediments are either at the threshold or above threshold velocity. However, all samples are above critical shear stress velocity that indicate that particles in sample locations have exceeded the incipient motion threshold.

Table 3 shows that water depth and current velocity equally influence seafloor sediment texture. The relationship is demonstrated by sample SBL. 14 that was taken from shallow water with the strongest current velocity (Table 2) that is being eroded (Figure 7).

Coastal sediments

Coastal sediments are almost entirely consisted of coarse fractions (Table 4): Sand, Slightly Gravelly Sand and Gravelly Sand (Figure 8 and Table 4). Samples that were obtained close to coral reefs, such as in the northern coasts (SBP.01 and SBP.02) and southern coasts (SBP.08, SBP.09 and SBP.10) of Lembata Island, are characterized by reworked corals and shell fragments.

Table 3. Correlation coefficient of each elements for 6 samples that have mean grain size (X) and measured current velocities data. The correlation coefficient was calculated by PAST (Hammer *et al.*, 2001).

	Mean (cm)	Measured current vel. (cm/s)	Water depth (m)
Mean (cm)	1		
Measured current vel. (cm/s)	0.57415	1	
Water depth (m)	0.52112	0.083156	1

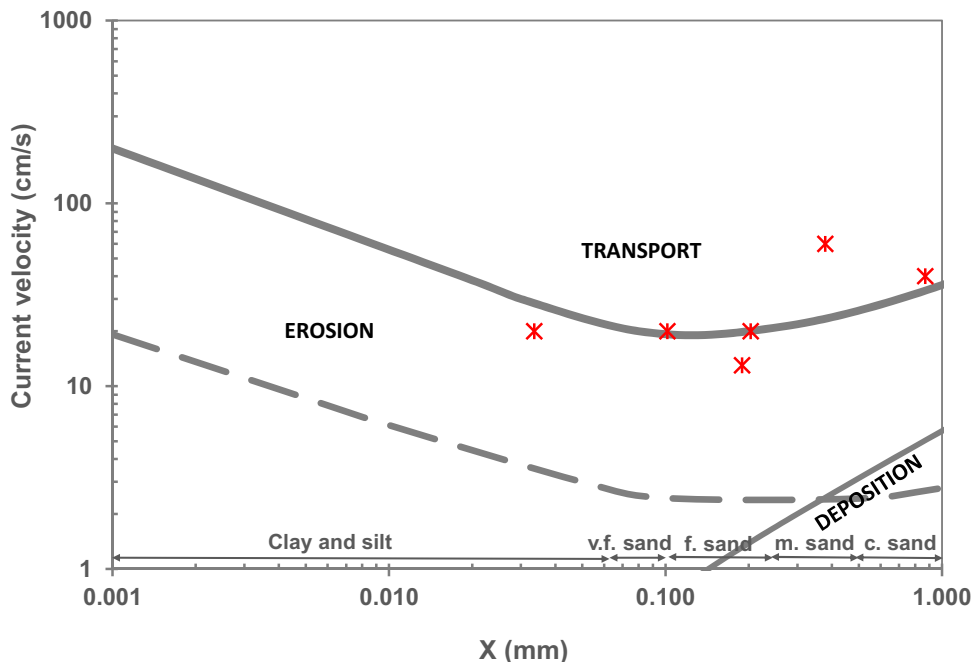


Figure 7. Plot of mean grain size of seafloor sediment to measured velocities on Hjulström curve. Solid line between Transport and Erosion delineates Hjulström threshold value where sediments are started to be eroded and between Deposition and Transport denotes the state where sediments are still being transported. Dashed line indicate critical shear stress velocity (u^*_{cr} -Hjulström). Red stars are samples. Abbreviations: v.f. is for very fine, f is for fine, m is for medium, and c is for coarse.

Table 4. Coastal sediments grain size and their statistical parameters. Abbreviations: Sort.=sorting, Skew.=skewness, Kurt. = kurtosis, G = gravel, S = sand, Z = silt, and C = clay.

No.	Sample ID	Mean (phi)	Sort.	Skew.	Kurt.	G	S	Z	C	Sediment types
1	SBP.01	1.2	0.8	-0.0	3.0	0.4	99.6	0.0	0.0	Slightly gravelly Sand
2	SBP.02	1.2	0.7	-0.4	4.5	0.4	99.6	0.0	0.0	Slightly gravelly Sand
3	SBP.03	2.2	2.5	0.1	2.2	12.2	56.7	31.0	0.2	Gravelly muddy Sand
4	SBP.04	0.9	1.3	-1.0	3.3	11.0	89.0	0.0	0.0	Gravelly Sand
5	SBP.05	1.3	1.2	-0.3	2.5	1.9	98.1	0.0	0.0	Slightly gravelly Sand
6	SBP.06	2.3	0.5	-1.2	6.2	0.0	99.9	0.0	0.0	Slightly gravelly Sand
7	SBP.07	1.7	0.7	-0.7	4.2	0.3	99.7	0.0	0.0	Slightly gravelly Sand
8	SBP.08	2.1	0.6	-1.1	3.6	0.0	100.0	0.0	0.0	Sand
9	SBP.09	2.4	0.4	-2.2	7.6	0.0	100.0	0.0	0.0	Sand
10	SBP.10	1.4	0.8	-0.1	2.2	0.0	100.0	0.0	0.0	Sand
12	SBP.12	1.8	0.7	-0.7	3.5	0.0	100.0	0.0	0.0	Sand
13	SBP.13	0.7	0.7	-0.3	2.6	0.7	99.3	0.0	0.0	Sand
14	SBP.14	1.8	0.8	-1.2	4.9	0.8	99.2	0.0	0.0	Slightly gravelly Sand
15	SBP.15	0.8	1.5	-0.6	2.6	15.1	84.9	0.0	0.0	Gravelly Sand
16	SBP.16	1.9	0.6	-0.4	3.9	0.1	99.9	0.0	0.0	Slightly gravelly Sand
17	SBP.17	2.1	0.6	-1.5	7.1	0.2	99.8	0.0	0.0	Slightly gravelly Sand
19	SBP.19	1.9	0.6	-0.4	2.7	0.0	100.0	0.0	0.0	Sand
20	SBP.20	1.6	0.8	-0.7	3.4	0.4	99.6	0.0	0.0	Slightly gravelly Sand
21	SBP.21	1.3	1.2	-0.6	2.4	2.7	97.3	0.0	0.0	Slightly gravelly Sand
22	SBP.22	2.0	0.6	-1.2	7.0	0.5	99.5	0.0	0.0	Slightly gravelly Sand
23	SBP.23	1.3	1.5	-1.4	4.1	12.4	87.6	0.0	0.0	Gravelly Sand
24	SBP.24	0.7	1.2	-0.8	3.4	10.9	89.1	0.0	0.0	Gravelly Sand
25	SBP.25	2.3	0.7	-3.4	21.8	0.8	99.2	0.0	0.0	Slightly gravelly Sand
26	SBP.26	1.6	1.0	-0.9	4.0	1.1	98.9	0.0	0.0	Slightly gravelly Sand

Away from the coral reefs, some samples show abundance of magnetite in coastal sediments (SBP.04 and SBP.06). The abundance of magnetite are more prominent in sample from SBP.06 where high concentration of magnetite is found in the 2.0 – 3.0 Φ fractions (Figure 8 left).

At Adonara Island, to the west of Boleng Strait, iron-rich sand was observed in coastal sediments from SBP.22 and SBP.23 (Figure 9). The two samples show that magnetite is concentrated within 2.0 and 3.0 Φ fractions (Figure 9, bottom left and bottom right) where it comprises more than 20% of the sediments. Magnetite abundance in those locations might be facilitated by strong current velocity (300 cm/s) in western part of Boleng Strait.

DISCUSSIONS

Seafloor Sediments of Lewoleba Bay

The general pattern of seafloor sediments of Boleng Strait is that coarse-grain sediment is deposited close to deeper water of Boleng Strait, while fine-grain sediment is found in shallower water (Figure 5). This pattern is reflected in the correlation of mean grain size to water depth (Table 3). In open seas, fine-grain sediment tend to be deposited in relatively calm condition of deeper water (McCave *et al.*, 1995), which is not observed in Lewoleba Bay that shows no correlation between water depth and mean grain size (Table 3). The difference could be explain by the fact that: 1) Lewoleba Bay is a relatively closed shallow

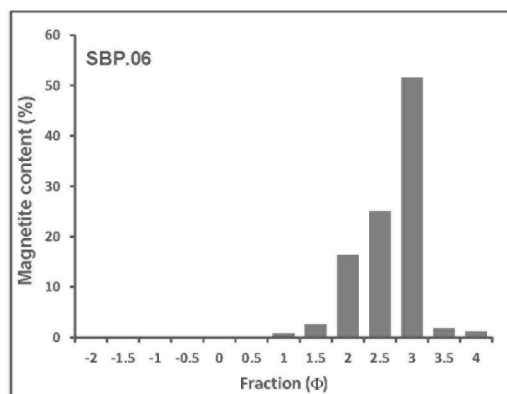


Figure 8. Magnetite content in each fractions of sample SBP.06 showing highest concentration in 3 Φ (left) and iron sand deposit (right).

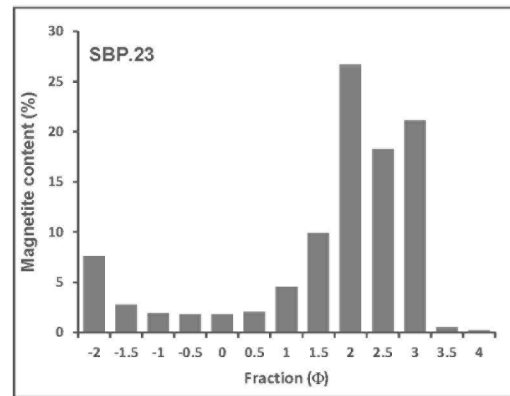
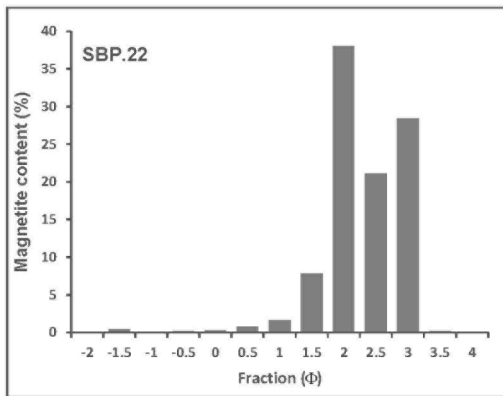


Figure 9. Iron deposit that covers Adonara beach (upper figure). Iron sand content in each size fraction for SBP.22 (lower left) and SBP.23 (lower right).

marine environment that enables deposition of fine sediment close to the beach, 2) Lewoleba Bay is characterized by relatively flat sea-bottom morphology.

Figure 7 shows that the sediments of the study area are still being moved, either transported as suspension or bedload or even being eroded (SBL. 14). This result represent the top 20 cm of seafloor sediment, which is based on the depth of grab sampler. Although the foundation of ocean current turbine would be deeper than 20 cm, this fact that seafloor sediments of the area are still on the move might affect the turbine itself.

Current Influence on Coastal Sediments

The sediments that are deposited in the bay might also be influenced by current deviation from Boleng Strait to Lewoleba Bay (Figure 3). Considering the strongest current is observed in Boleng Strait, the currents that flow on the northern and southern parts of the bay are stronger than the current that flows in the

eastern part of the bay. The current is considered to cause the winnowing of lighter minerals from the sediments that resulted in iron-rich beach sand in the northern and southern part of the bay (Figures 8 and 9). The iron-rich beach sand is also located closed to Ile (local term for volcano) Boleng in the Adonara Island, that is considered as the source of the iron minerals. The process of selective entrainment of lighter minerals to form lag deposit with high heavy minerals content is also observed in southeast Baltic Sea coast (Pupienis *et al.*, 2011) and northwestern Lake Erie (Hatfield *et al.*, 2010).

CONCLUSIONS

The bathymetry of Boleng Strait reflect the tectonic activity in the area and characterized by deep channel on the west and small shallow platform on the east. This condition gives rise to strong tidal current that can be utilized to generate electricity. The design of

ocean current turbine would need various information of the area, one of them is the sediments that composed the seafloor and coastal area.

A total of 25 seafloor sediment samples and 26 coastal sediment samples were acquired to understand sediment texture and inferred the process that is influencing sedimentation of Boleng Strait and surrounding area. Grain size analysis on 12 seafloor sediment samples yield six sediment types: Sand, Gravelly Sand, Sandy Gravel, Silty Sand, Sandy Silt, and Coral fragments. The sediment grain size is equally influenced by current velocity ($r = 0.57$) and water depth ($r = 0.52$) which is shown by coarse-grain sediments cover the area near Boleng Strait which has stronger current and fine-grain sediments cover the inner part of the Lewoleba Bay.

Plot of mean grain size and current velocity on Hjulström diagram shows that most of the sediments are still being transported either as suspension or bedload or even being eroded (SBL. 14). All of the sediments are above the threshold for incipient motion that indicate that the particles are on the move. This condition might affect the turbine and thus needs to be taken into consideration when designing the turbine.

Development of the area also needs information on coastal sediments. The mean grain size of coastal sediments ranges between 0.19 mm and 0.62 mm with average value of 0.33 mm that shows that coastal sediments of the study area are skewed toward medium sand. This tendency is reflected by the percentage of sand that ranges between 57% and 100%. Iron-rich sands that were found in both Adonara and Lembata Islands are the result of selective entrainment that might be generated by the current.

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