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SEDIMENTATION AND WAVE ATTENUATION BY *AVICENNIA MARINA* MANGROVES: IMPLICATIONS FOR SUSTAINABLE COASTAL PROTECTION

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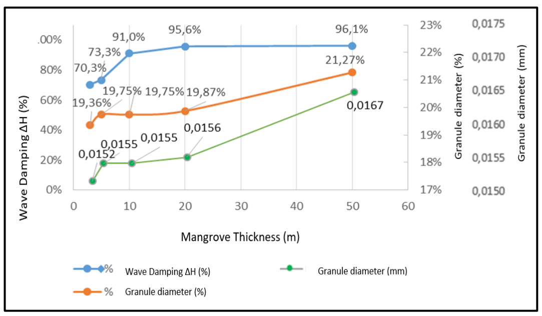
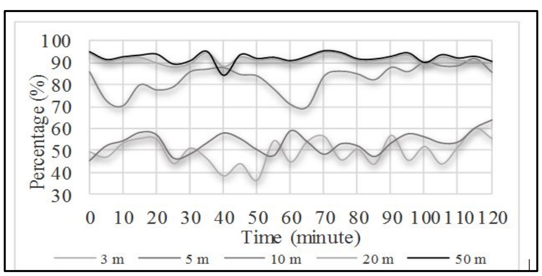
Graphical abstract





Abstract

Mangrove ecosystems protect coastlines from abrasion and erosion, attenuate strong sea breezes, and bind sediments periodically. A mangrove ecosystem can be set up to be a coastal building capable of breaking and reducing natural waves, but only through certain calculation methods, so that it serves as a solution by being an environmentally friendly breakwater alternative for sustainable coastal development. The objective of this study was to determine the effects of sedimentation by *Avicennia marina* mangroves on wave attenuation. Spot-check, transect-squared, and laboratory test methods were employed in this research. The wave data measurement performed using with SBE 26 and RBRDuo T.D. The measurement was performed at five stations at distances of 3 m, 5 m, 10 m, 20 m, and 50 m. The wave attenuation at the 5 stations was 49.5%, 53.8%, 82.9%, 91.4%, and 92.3% with grain diameters of 19.36%, 19.75%, 19.87%, 21%, and 27%. The higher the wave attenuation percentage, the lower the grain diameter percentage, and vice versa. When the waves came, the energy was so large that all the large particles of the sediment in the sea were carried back to the mangrove ecosystem, and when the waves left, the energy released was so small that only the small particles were carried back to the sea. The conclusion is that the diameter percentage of mangrove sediment is related to the percentage of wave attenuation. The higher the wave attenuation percentage is, the smaller the grain diameter percentage will be.

Keywords: Sedimentation, mangroves, Avicennia marina, energy, waves.

1.0 INTRODUCTION

The coast of Pasir Sakti, East Lampung, has a long dynamic of mangrove cover change. An insignificant increase in mangrove cover occurred from 1973 to 1983 and in 2004 the mangrove cover almost disappeared and then reappeared in 2013. *Avicennia marina* is the most common mangrove species on the coast of Pasir Sakti, East Lampung. With an area of approximately 296 ha, this location is managed by the Gunung Balak Protected Forest Management Unit (KPHL) [1].

A mangrove ecosystem involves a sedimentation process as the deposition of sediments reduces soil abrasion and the presence of high salinity and circulation of tidal inundation. This ecosystem is vital for living things since it has considerable ecological roles in food resources and industry, can prevent flooding and erosion through wave attenuation, and also serves recreational functions [2]. Mangrove forest is also resistant to strong sea breezes and able to hold and bind sediments periodically to form a new land [3,4].

Currently, in the protected forest area of 15 estuaries in Pasir Sakti sub-district, East Lampung, there are many *Avicennia marina* mangroves. Prior to 2004, the coastal area of East Lampung was eroded by sea water causing abrasion at an alarming rate. Mangrove forest is the best solution to cope with high-intensity sea breezes due to the encroachment of the deforested coastal area. By 2013, more than 1,000 hectares of mangrove forest had been formed [5]. The waves generated by ships and tidal currents cause severe erosion [6]. The presence of a mangrove ecosystem will protect the area behind it from the breaking of the waves [7]. In addition, a mangrove ecosystem also has various other benefits such as being a producer of oxygen and an absorber of carbon dioxide [8,9]. With this potential, we can also preserve coastal resources and, at the same, improve the welfare of the society.

The *Avicennia marina* mangrove has a root system called breathing roots or *pneumatophores*, which enables the plant to grow in various tidal conditions. The roots are able to help increase sediment and accelerate the emergence process and formation of new land as a place where mangrove seedlings are bred [10,11]. The root systems of mangrove and tree stands themselves are the factor of the protective function of mangroves on the coast [12].

Many parts of mangrove trees serve to withstand the process of wave reduction, one of which is the substrate. *Avicennia marina* mangroves are suitable for areas with muddy sand substrates, especially at the forefront of the coast, with an inundation frequency of 30-40 times/month [13]. The mangrove ecosystem is capable of capturing the sediment grains carried by incoming waves, which then are then deposited and remain when the waves leave, resulting in the generation of mangrove sedimentation [14]. During the sedimentation process, there are several forces, i.e. gravity, thrust, and buoyancy, affecting the movement process of the sediment particles from the sea to the land [15]. Mangrove ecosystem can possibly be designed to function as coastal barriers that can break and attenuate incoming waves. However, using certain calculating techniques, mangrove ecosystem can offer a solution by functioning as an alternative, eco-friendly barrier for long-term coastal development. [16]. This research was aimed at finding out the effects of the *Avicennia marina* mangrove sedimentation on wave attenuation through a case study at Pasir Sakti Coast, East Lampung.

2.0 METHODOLOGY

2.1 Research Location

This study was located in a protected forest area with 15 estuaries in Purworejo, Pasir Sakti, East Lampung (see Figure 1). In this research, 5 stations at thicknesses of 3 m, 5 m, 10 m, 20 m, and 50 m respectively in a range of 50 m were observed using SBE 26 (Sea-Bird Electronics) and RBRDuo TD [16,23].

2.2 Data Collection

The primary data in this research is the data obtained from direct field observation, which includes (see Figure 2)[23]:

1. Wave data (50 m from the outer mangrove line).
2. Sludge samples (4 test samples at each station).
3. Sludge depth measurement at each station.
4. Water depth measurement at each station.

The secondary data obtained from the related agencies or, in other words, not taken directly in the field is the layout of the area in the form of a map reference for finding the stations under review.

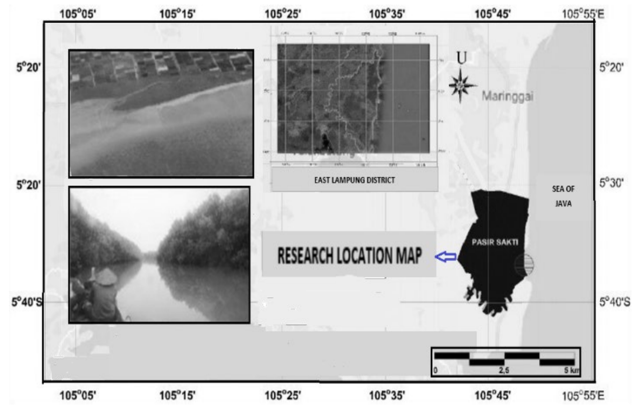


Figure 1 Research Location Map

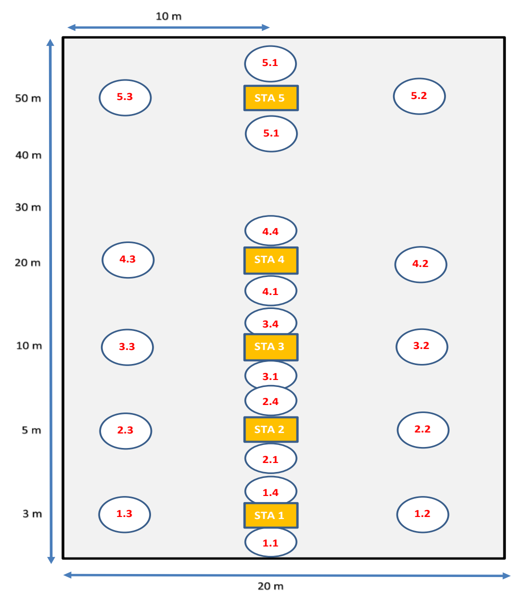


Figure 2 Schema of Research Points
Source: [24]

2.3 Hydrometer Analysis

Hydrometer analysis is intended to determine the division of the sizes of soil fine grains. The results of this test are then compared with the soil properties figured out via the Atterberg limits test for the determination of soil activity [17,23]. The basis of the calculation is Stokes' law, which is:

1. Soil grains are regarded as round like balls, while they do not have that kind of shape in actual fact. To overcome this, an equivalent diameter, i.e. the diameter of a fictitious ball consisting of the same material and with the same deposition velocity as those of the actual soil grains, is assigned.
2. The place where soil grains are deposited is semi-infinite and only one grain is taken into account, while in reality, the place is infinite and the grains influence each other; this is overcome by only taking a relatively small amount of soil, 50 grams in 1 liter, so the above objection can be disregarded.
3. The specific weight referred to is the average specific weight, whereas in fact, the specific weight of each soil

grain is not identical to the average specific weight. In this research, the specific weights were considered identical.

The following is the calculation:

$$\% \, finer = \frac{(Rc \, x \, a)}{Ws} x100\% \quad (1)$$

Where:

a = Correction Factor = (1.65 x Gs)/(2.65 x (Gs-1))
Rc = Hydrometer Reading Correction (Ra- C0 - Ct)
Ra = Actual Hydrometer Reading
C0 = Zero Correction
Ct = Temperature Correction

$$D = K\sqrt{\frac{L}{t}} \quad (2)$$

$$k = \sqrt{\frac{30\eta}{(g\,(Gs-Gw))}} \quad (3)$$

Where:

D = Grain Diameter
L = Effective Depth
T = Elapsed Time
η = Viscosity of Distilled Water (Poise)
Gs = Specific Weight of Oil
Gw = Specific Weight of Water

2.4 Sediment Data Collection Equipment

The equipment in this research included [16,23]:

1. UPVC tubes, which were used to obtain the sludge samples. These tubes are 4 inches and 40 cm long, and the number of tubes depends on the needs of the research. In this research, the number of tubes was 20.
2. Rubber caps, which were used to seal the bottoms and tops of the tubes to reduce their leakage.
3. GPS, which mapped and found the sampling points in the remote areas of the mangrove forest.
4. A yardstick for measuring the soil and sludge depths on the research site.
5. A roll meter for measuring the perimeter and area on the research site.
6. Paint for marking the test tubes so as to avoid confusion.
7. Snorkeling equipment for enhancing vision in water when taking the sludge samples.
8. Stationery for recording the research data obtained in the field.
9. A first aid kit for providing the first aid in the event of a work accident in the field.
10. Plastic containers for protecting the research items vulnerable to water.
11. Duct tape for attaching the sample storage device to the lid in order to reduce air leakage.
12. Life jackets as the safety equipment on the research site since it is at sea.
13. Lighting equipment for data collection at night.

2.5 Sediment Test Equipment

The following is the equipment involved in the sediment test:

1. A hydrometer for determining the specific weight of the suspension.
2. Single-structure sieves with lids at the top and at the bottom. The sieve numbers and sizes are as follows [18,23]:
   a) No.10 (2.00 mm)
   b) No.20 (0.85 mm)
   c) No.40 (0.425 mm)
   d) No.60 (0.250 mm)
   e) No.140 (0.106 mm)
   f) No.200 (0.075 mm)
3. Scales with a precision of 0.01 gram.
4. A glass cylinder with a capacity of 1,000 cc, a diameter of 2.5 inches = 6.35 cm, and a height of 18 inches = 45.7 cm, with the volume mark “1,000 cc” on the inside, 36 cm from the base of the glass.
5. A porcelain cup and a grinder with a rubber head or wrapped in rubber.
6. A suspension stirrer.
7. A 0-50°C thermometer.
8. A stopwatch for the experiment time calculation.
9. A water tub with adjustable constant temperature. This instrument is highly needed when the air temperature is not constant enough.
10. Distilled water
11. Dispersion material (reagents) in the form of water glass (sodium silicate) or Calgon (sodium hexametaphosphate).
12. A shaker sieve (vibrator sieve).

2.6 Mangrove Sedimentation Data Collection

The sludge samples obtained in the field were processed into data at the Civil Engineering Soil Laboratory of Lampung University. The hydrometer analysis experiment aimed to determine the distribution of the soil grain sizes. Hydrometer analysis is a method for the calculation of soil size distribution based on soil sedimentation in water, commonly called a sedimentation test [18,23]. The examination was carried out through the analysis with the hydrometer. The following are the implementation steps of the hydrometer test:

1. The sludge obtained from the field is dried and will be used as the test specimens.
2. Place the soil sample in glass tubes with capacities of 250 cc. Pour 125 cc of previously prepared water and reagent solution. Mix and stir until all the soil blends with the water. Let the soil soak for 16-24 hours.
3. Pour the mixture into a mixer, ensuring that no grain is left or lost by rinsing it with distilled water and pouring the rinse water over the instrument.
4. Then, transfer the suspension to the deposition glass cylinder immediately, ensuring that no soil is left by rinsing it and pouring the rinse water into the cylinder. Add distilled water until the volume reaches 1,000 cm^3.
5. Use another glass cylinder and fill it only with distilled water and reagents so that the same solution as that in the first cylinder is produced. Float the hydrometer in the second cylinder during the experiment.
6. Cover the cylinder filled with the suspension with a rubber lid (or with the palm of your hand). Shake the suspension by quickly turning the cylinder upside down repeatedly for 1 minute so that the soil grains evenly float in the water. This flipping motion should be done for about 60 times. Then, place the cylinder on a table in an upright position

and run the stopwatch and this is the initiation time to complete T=0.

7. Take hydrometer readings at T = 2; 5; 15; 30; 60; 250 and 1,440 minutes (after T = 0). About 20 or 25 seconds before each reading, take the hydrometer from the second cylinder, immerse it carefully and slowly in the suspension until it reaches the expected depth of the scale. Remove it (do not shake it) after it reads it. Then, at the right time, read the scale indicated by the peak of the meniscus water level = R1 (reading in correction). After reading it, immediately pick up the hydrometer slowly, and move it into the second cylinder. In the second cylinder of water, read the hydrometer scale = R2 (reading correction).
8. After each hydrometer reading, observe and record the temperature of the suspension by dipping the thermometer.
9. After taking the last hydrometer reading (T = 1,440 minutes), pour the whole suspension onto the No.200 sieve, not allowing any grains to be left. Wash the grains with clean water until the water flowing through the filter is clear and no finer grains are left.
10. Discard the remaining soil sample somewhere, then dry it in an oven (at a temperature of ± 110^o C).
11. After that, cool, weigh, and record the mass of the obtained dry soil = B1 gram.
12. Sift this soil with a sieve.
13. Weigh and record the mass of the remaining soil on each filter. Before filtration, check the masses of the remaining soil against each other to make sure that they are identical or close to each other.
14. Perform the above steps on each test sample obtained from the field.

The results of this test are then compared with the soil properties figured out via the Atterberg limits test for the determination of soil activity [18,23].

2.7 Analysis of Base Shear Stress

Water flowing in a channel can cause a force going in the same direction as the flow. This force, which is a tensile force on the wet cross section, is called shear stress [19,23,24]. The following are the formulae and the calculation steps [20,23]:

1. Sliding speed (U*)

   $U_1^* = (g.D.S)0,5$ (4)
2. Determining the Reynolds number

   $Re = \frac{U^*.D}{v}$ (5)

After the Re value is obtained, it is used to determine the shear stress dimension value using the Shield diagram (see Figure 3).

3. The shear stress dimension value is then used to determine the critical shear stress and its value.

   Critical shear stress : $\tau c = F^*(\gamma_s - \gamma_w).Ds$ (6)

   Shear stress : $\tau 0 = \gamma_w.g.Ds$ (7)
4. Depending on the results, the movement is then categorized as the following:

   $\tau 0 < \tau c$ bottom grains do not move (stable riverbed)

   $\tau 0 = \tau c$ bottom grains when starting moving (critical condition)

   $\tau 0 > \tau c$ bottom grains move (unstable riverbed)

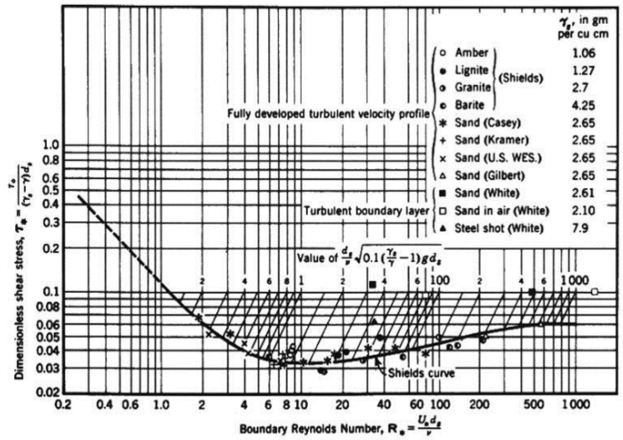


Figure 3 Shields diagram: dimensionless critical shearstress [19,23]

3.0 RESULTS AND DISCUSSION

Mangrove sedimentation measurement is carried out with a yardstick to determine the sludge and water depths and with closed UPVC tubes to take sludge samples at the predetermined points.

3.1 Wave Data Processing Results

Wave energy attenuation is the energy difference between incoming and outgoing waves in a mangrove forest. The following is the wave energy formula used to calculate wave attenuation [13].

$$E = \frac{1}{8}\rho.g.H^2 \quad (8)$$

From the results of the calculation of the wave energy attenuation at each thickness, it is known that the thicker the mangrove, the greater the attenuation (see Table 1).

Table 1 Wave Data Calculation Results

No	Distance	E Incoming Wave Average (SBE)	E Outgoing Wave Average (RBR)	E Wave Attenuation Average (J/m^2)
1.	3 m	1.1277	0.0989	0.5653
2.	5 m	1.3792	0.0974	0.7485
3.	10 m	1.5964	0.0129	1.3389
4.	20 m	1.7596	0.0034	1.6115
5.	50 m	1.7428	0.0027	1.6125

[Source: 16]

3.2 Hydrometer Analysis Processing Results

The hydrometer analysis was conducted at the Lampung University Soil Mechanics Laboratory. This analysis was carried out to find out the sizes of the sludge grains. Taken from each test sample, the weight of the tested soil sample was ± 50 g. The following are the hydrometer analysis results (see Table 2):

Table 2. Hydrometer Analysis Results

STA	3 m	5 m	10 m	20 m	50 m
Moisture Content Average	89.34	86.75	88.59	81.96	79.9
Specific Weight Average	2.2691	2.2691	2.2691	2.2691	2.2691
Temperature Average	28°	29°	28°	28°	26°
K Value	0.01264	0.01249	0.01264	0.01264	0.01291
Grain Diameter	0.0152	0.0155	0.0155	0.0156	0.0167

3.3 Percentage of Wave Attenuation by ΔE

Referring to Figure 4, the percentage of the wave attenuation at the mangrove thickness of 3 m was from 60% - 78%, 5 m from 65% - 82%, 10 m from 82% - 96%, 20 m from 93% - 98%, and 50 m from 94% - 98% [16].

Sedimentation is an important element in wave resistance as the accumulation of the sediment brought to and deposited on the coast inhibits wave velocity further.

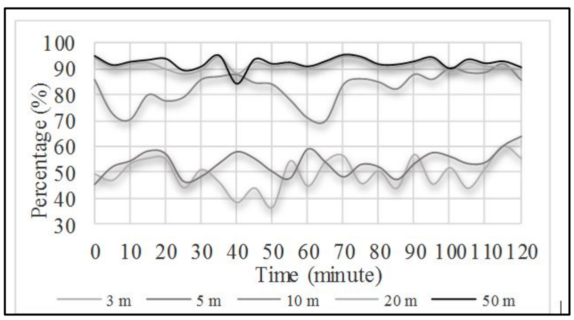


Figure 4 Percentage of Wave Attenuation by ΔE.[16]

3.4 Relationship between Grain Diameters and Percentage of Attenuation by ΔE

Mangrove thickness affects the absorption of wave energy. In this research, a thickness of 5 m, with an increase of 0.39% in the sediment grain diameters, was able to reduce 73.25% of the wave height. With a relatively small increase in the mangrove thickness, from 5 m to 20 m, although the average grain diameters ranged from 0.0155-0.0156 mm, the wave height was reduced to 95.6%. At a thickness of 50 m, the total wave height attenuation rate was 96.1%, with a grain percentage of 21.27% (see Figure 5). Table 3 presents the overall final data of the research. [16].

3.5 Relationship between Depths of Sludge and Water and Mangrove Thickness

The roots of *Avicennia marina* mangroves can accelerate and smoothen the processes of binding sediments and new soil emergence. This root system allows *Avicennia marina* mangroves to have the capability of growing in various tidal conditions [21,22], so they can be found on almost the whole coasts of Indonesia, especially those in the protected areas.

Containing a large number of nutrients and having different grain sizes at every location, sludge functions as a planting medium for *Avicennia marina* mangroves along with water, which also plays a vital part in the mangrove ecosystem. Therefore, sludge and water have an important relationship.

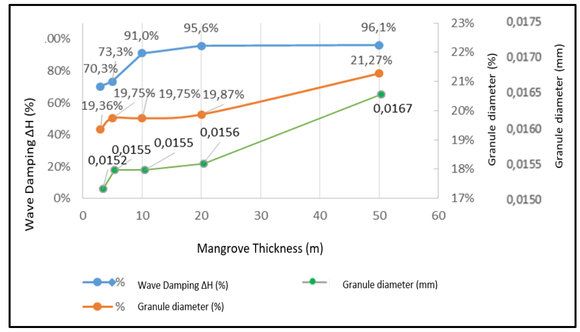


Figure 5 Relationship between grain diameters and reduction percentage in ΔE.

Table 3 Overall Final Data

Station	STA 1 (3 m)	STA 2 (5 m)	STA 3 (10 m)	STA 4 (20 m)	STA 5 (50 m)
Retained Wave (ΔE)	60% - 78%,	65% - 82%	82% - 96%	93% - 98%	94% - 98%
Water Depth (m)	0.6	0.4	0.2	0.09	0.05
Sludge Depth (m)	1.40	1.35	1.25	1.10	0.95
Sludge Grain Diameter (mm)	0.0152	0.0156	0.0155	0.0155	0.0167
Sludge Grain Diameter Percentage (%)	19.36	19.75	19.75	19.87	21.27

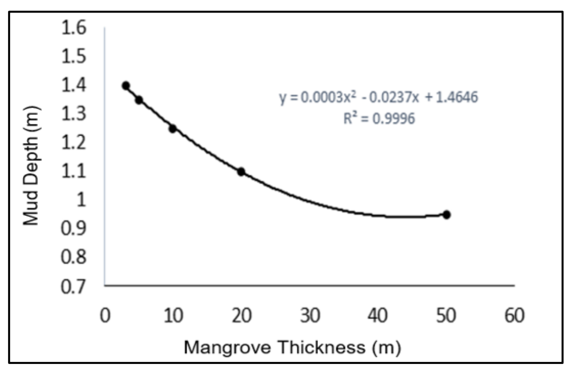


Figure 6 Relationship between water depth and mangrove thickness

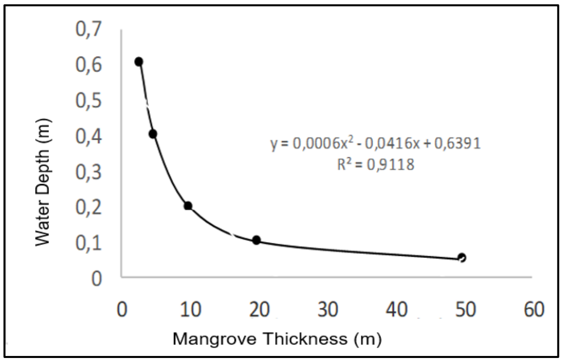


Figure 7 Relationship between sludge depth and mangrove thickness

In Figures 6 and 7, it can be seen that the sludge depth and the water depth at each station are related in the sense that the sludge level was in agreement with the water level and vice versa. The depths of the water and sludge affected their volumes at each station. So, the deeper the sludge, the higher the volume and the water.

The thicker the mangrove ecosystem, the lower the water level due to the distance and the occurring attenuation process, and the soft sludge became shallower and smaller as the substrate had dried up and rarely been submerged in water. So, it is safe to infer that the thicker the mangrove, the greater the wave attenuation.

3.6 Relationship between Sludge Grains and Mangrove Thickness

The grain sizes at each station varied and were related to the sludge depth. The grain sizes depended on the sludge depths at the stations. Deeper sludge resulted in larger grain sizes (see Figure 8).

The grain sizes increased at the thicknesses of 0 to 50 meters, so it is inferable that the thicker the mangrove, the larger the grain sizes. As a result of the incoming and outgoing waves, sediment was brought to the land and some was taken back to the sea, but various large sedimentary particles remained on the land as they were trapped in the mangrove ecosystem, resulting in a wide variation of grain sizes between the edge of the ecosystem and the land.

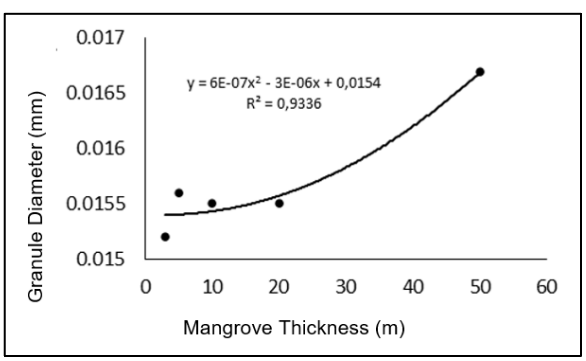


Figure 8 Relationship between soil grain diameters and mangrove thickness

3.7 Base Shear Stress

The average slope of the waters (S) was calculated with the equation S = H/0.9L [21], where H was the height difference between the observation point and the farthest point from the river and L was the length of the river, which was the distance of the thickest mangrove, 50 m, in this case (see Table 4).

Table 4 Data of Water Elevation at Research Location

No	Station	Distance	Elevation	
			(ft)	(m)
1	STA 1	3	38	11.5824
2	STA 2	5	40	12.192
3	STA 3	10	40	12.192
4	STA 4	20	41	12.4968
5	STA 5	50	41	12.4968

Based on the data in Table 4, the average slope of the waters was calculated as follows:

S = H/0.9L = (12.4968-11.5824)/(0.9 x 50) = 0.0203

1. Sliding Speed (U*)
   Known Data:
   g = 9.8 m/s²
   Da Average = 0.05 m
   S = 0.0203
   Then,
   U1* = (g.Da.S)0.5
   = (9.8 x 0.05 x 0.0203)0.5
   = 0.005 m/s
   (The calculation results were then tabulated (see Table 5))

Table 5 Shear Velocity Calculation Results

STA	g (m/s²)	D_a average (m)	S	U_i^* (m/s)
STA 1	9.8	0.05	0.0203	0.005
STA 2	9.8	0.03175	0.0203	0.0032
STA 3	9.8	0.0155	0.0203	0.0015
STA 4	9.8	0.008	0.0203	0.0008
STA 5	9.8	0.00525	0.0203	0.0005

2. Determining the Reynolds number
   The shear velocity was then used to determine the Reynolds number. The following is the calculation:
   Known Data:
   U1* = 0.005 m/s
   D Average = 0.05 m
   v = 1.567x10-6
   Then,
   Re = (U^*.D)/v
   = (0.005 x 0.05)/(1.567x10-6)
   = 158.69 ≈ 160

(The calculation results were then tabulated (see Table 6))

Figuring out the Re value made it possible to determine the she

ar stress dimension value with the Shield diagram in Figure 9.

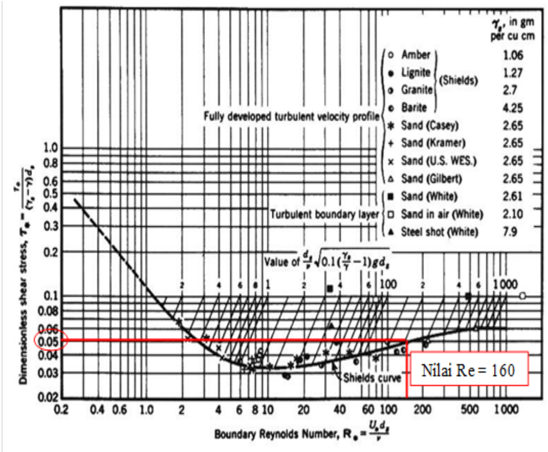


Figure 9. Example of Shield Diagram Reading of STA 1[19,24]

Based on the results of the Shield diagram reading of STA 1 with a value of Re = 160, the shear stress dimension (F*) = 0.05 was obtained. The results of the next diagram reading are presented in Table 6.

Table 6 Reynolds Number Calculation Results and F_*

STA	Re	F_*
STA 1	160	0,05
STA 2	64	0,04
STA 3	15	0,032
STA 4	4	0,039
STA 5	2	0,06

3. Based on the dimensional value of the shear stress, the values of the critical shear stress and the shear stress were determined.

4. Known Data:
   F* = 0.05
   γs = 2269.1 kg/m3 [8]
   γw = 1000 kg/m3 [8]
   Ds = 0.0000152 m (Table 2)
   Then,
   τc $= F^*(\gamma_s - \gamma_w).Ds$
   = 0.05 (2269.1 – 1000) 0.0000152

   Next, the occurred shear stress was calculated:
   τo $= \gamma_w.g.Ds$
   = 1000 x 9.8 x 0.05 x 0.0203
   = 9.947 kg/m.s

The value τo > τc (9.947 kg/m.s > 0.00096 kg/m2) indicates that the bottom grains moved so that the riverbed was unstable (for the further calculation results, see Table 7).

Table 7 Results of STA 1-5 Shear Stress Calculation

STA	τ_o (kg/m.s)	τ_c (kg/m^2)	Riverbed Condition	
STA 1	9.947	9.6×10^{-4}	Moving Grains	Unstable
STA 2	6.3163	7.9×10^{-4}	Moving Grains	Unstable
STA 3	3.0836	6.3×10^{-4}	Moving Grains	Unstable
STA 4	1.5915	7.7×10^{-4}	Moving Grains	Unstable
STA 5	1.0444	1.27×10^{-3}	Moving Grains	Unstable

4.0 CONCLUSION

The conclusion of this research is that the diameter percentage of mangrove sediment is related to the percentage of wave attenuation in the sense that the higher the percentage of wave attenuation, the lower the grain percentage. The greater the level of attenuation, the narrower the distribution of grains in the range of 3 - 10 m, and the farther it is from the sea, the higher the grain percentage, and the increase in attenuation is relatively modest within the 10 - 50 m range.

Unstable water conditions are a consequence of moving sedimentary particles. Hence, such a location requires mangroves to hold the movement of sedimentary particles in their roots, thus preventing abrasion.

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