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Research Article

The Planning of Revetment For Coastal Protection of Candikusuma Jembrana Bali

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Abstract: Candikusuma Beach in Bali has experienced significant erosion since 2009, threatening public facilities, including a mosque in Candikusuma village. This issue is critical as it affects a coastal fishing community. To mitigate the erosion, a revetment structure using concrete block armor is proposed. This revetment aims to protect the coastal cliff from wave forces and prevent further erosion. The planning process begins with analyzing bathymetric and topographic data to assess land and sea conditions. Tidal analysis determines key water elevations, while wind data is used to calculate maximum and average wind speeds and directions. Wave hindcasting, based on wind data and effective fetch length, provides estimates of wave height and period. Shoreline changes are evaluated by comparing satellite imagery from 2003 and bathymetric surveys from 2012, revealing an average shoreline retreat of 21.70 meters over nine years. The design of the revetment includes a crest elevation of +3.70 meters MSL, constructed on a base at -0.5 meters MSL. The concrete foundation extends to a depth of -1.5 meters MSL. Hindcasting results show maximum wave heights of 1.21 to 1.50 meters from the southwest, with an average wave height of 0.01 to 0.30 meters from the south. The design wave height for a 25-year return period is 1.37 meters with a period of 4.58 seconds, resulting in a wave height of 1.31 meters at a depth of 2 meters. The estimated budget for the 200-meter-long revetment is Rp. 7,778,174,000.

Keywords: Candikusuma; Planning; Revetment.

1. Introduction

Bali is one of Indonesia's most well-known islands, particularly renowned for its beautiful beaches. The island has a coastline stretching approximately 436.5 kilometers, of which about 91.07 kilometers, or 20.8%, has suffered from coastal erosion (according to a 2007 survey by the Directorate General of Water Resources, Ministry of Public Works). One of the affected areas is Candikusuma Beach, located in Candikusuma Village, Melaya Subdistrict, Jembrana Regency, in western Bali. This beach, which is home to a fishing community, has been experiencing severe erosion since 2009. The erosion poses a serious threat to local infrastructure, including public facilities such as a mosque located in Tirtakusuma Hamlet. To address this critical issue, a coastal protection structure in the form of a revetment using concrete block armor is proposed. This revetment is expected to protect the shoreline from wave attack, thus helping to prevent further erosion. Revetments are typically constructed from protective layers—commonly natural stones—but the decreasing availability of large stones (over 100 kg) in certain areas has led to the adoption of concrete blocks as an alternative. Commonly used concrete blocks include tetrapods, quadripods, tripods, and concrete cubes. These units are generally arranged randomly, resulting in no interlocking between them. Consequently, the effectiveness of the revetment depends heavily on the individual weight of each unit, requiring large dimensions. Additionally, the random layout can hinder beach access, which is particularly problematic in tourism areas. To overcome these limitations, the development of interlocking concrete block revetments offers a more efficient and accessible solution. Coastal protection structures play a crucial

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role in mitigating the impacts of coastal erosion and wave action. Among these, revetments are widely used to protect shorelines, particularly in areas where communities and infrastructure are at risk. A well-designed revetment must possess stability, flexibility, and durability. Stability ensures that no structural unit's collapse, flexibility allows for slight movements without losing interlocking integrity, and durability ensures resistance to weathering and environmental forces.

Research conducted by the Coastal Research and Development Center (Balai Pantai Puslitbang SDA) has led to the development of the "pusair lock" concrete block type revetment. Laboratory tests, both in two-dimensional and three-dimensional models, have demonstrated the effectiveness of this design in withstanding wave forces. The pusair lock system not only enhances structural stability but also meets aesthetic and cultural needs—particularly in Bali, where coastal areas are often used for religious and traditional ceremonies, requiring safe and accessible pathways to the sea. The revetment design takes into account various environmental factors including wind, waves, tides, and sediment movement. Wind data are transformed into wave characteristics through hindcasting methods using effective fetch lengths. Wave dynamics, such as refraction, diffraction, and breaking, are also considered in the design process, as well as sea-level fluctuations due to tides, storms, and climate change. These calculations guide the structural design of revetment elements such as crest elevation, armor type, and foundation depth, ensuring effective and long-lasting shoreline protection.

2. Preliminaries or Related Work or Literature Review

This section outlines the theoretical foundations and prior research that support the design and implementation of revetment structures, especially in the context of coastal erosion mitigation.

Literature Review

[1], [2], [3], [4] describe an ideal revetment structure as one that is stable, flexible, and durable. Stability ensures that no unit fails under pressure; flexibility allows movement without loss of integrity; durability ensures weather resistance. Research by [5], [6] tested physical models of concrete block armors, including the pusair lock and non-lock types. Laboratory tests showed that pusair lock types have a stability coefficient (Kd) of 24 and a wave run-up coefficient of 1.26, indicating high performance under wave impact. Further studies on the 3B interlocking concrete block system—applied in Banyupoh Beach, Bali—concluded that such blocks provide strong protection and are aesthetically suitable for coastal communities like those in Bali, where shoreline access for religious rituals is vital. However, the structure is less suitable on gravel beaches, as the blocks are prone to break under intense wave action. [7], [8], [9] employed the Analytical Hierarchy Process (AHP) to select the most appropriate coastal protection system at Wori Beach, North Minahasa. Revetments scored the highest (42.25%) based on wave conditions, erosion severity, environmental considerations, and sedimentation dynamics

Theoretical Framework

The coastline is defined through distinctions between coast and shore. [10], [11]The theory explains dynamic coastal interactions influenced by tidal movements, sediment transport, wave dynamics, and sea-level fluctuations. [12], [13], [14], [15]Coastal erosion, a key concern, can result from natural factors such as global warming, wave storms, tsunamis, and sediment supply changes, as well as anthropogenic activities like coastal construction and material extraction. [16], [17], [18], [19]Wind-generated waves are analyzed using data conversion models to transform terrestrial wind data into offshore conditions. The fetch—distance over water that wind blows without obstruction—is a critical factor in wave generation, as is the depth of water, which influences wave refraction, diffraction, and breaking. [20], [21], [22], [23]Design models for revetments also consider wave run-up, tidal elevation, and sea-level rise, ensuring that structures can withstand long-term climatic and hydrodynamic conditions. The pusair lock revetment, a focus of this study, is modeled for these parameters to ensure optimal placement and functionality.

3. Proposed Method

This chapter outlines the methodology used in planning the revetment structure to address coastal erosion at Candikusuma Beach. The methodology includes several key stages: data preparation, data collection, data analysis, revetment design, and cost estimation.

Data Collection and Preparation

Before conducting analysis and design, necessary data and literature were collected:

- **Literature Review**: References and previous studies related to coastal protection, particularly revetments.
- **Primary Data**: Collected from field visits, including photographs and general observations of the study site.
- **Secondary Data**: Obtained from relevant government agencies and online resources, such as:
    - Wind data (1999–2008) from Banyuwangi Station
    - 15-day tidal data (September 16–30, 2012)
    - Bathymetric maps from Balai Pantai Puslitbang SDA
    - Topographic maps from Google Earth

This data forms the basis for further analysis in wave modeling and structural planning.

Data Analysis and Revetment Design

The analysis process consists of several key components:

- **Shoreline Change Analysis**: Comparing satellite imagery from 2003 with bathymetric maps from 2012 to determine the extent of shoreline retreat.
- **Hydro-oceanographic Analysis**:
    - **Bathymetry**: Used to determine the underwater profile for accurate structural placement.
    - **Topography**: Helps define fetch length and land elevation around the revetment site.
    - **Wind Data Analysis**: Wind data is transformed to offshore conditions and used to hindcast wave characteristics.
    - **Wave Analysis**: Wave height and period are calculated using the SPM 1984 method to determine the design wave conditions.
    - **Tidal Analysis**: Establishes key tidal elevations (HHWL, MHWL, MSL, MLWL, LLWL) as reference points for revetment design.
- **Revetment Design**:
    - Determine structure crest elevation based on wave run-up and water level.
    - Design includes foundation depth, armor layer type (pusair lock), and protective layers.
    - Ensure the structure meets stability, flexibility, and durability requirements.
- **Cost Estimation**:
    - Calculate materials and construction requirements.
    - Prepare a detailed budget for a 200-meter revetment section.

4. Results and Discussion

Topographic and bathymetric surveys were tied to benchmarks BM1 and BM2, providing precise elevation references. These surveys yielded elevation data that support the design of the revetment structure and were presented in detailed maps.

Tidal Data Analysis

Tide data collected over a 15-day period in September 2012 were analyzed using the Admiralty method, revealing important tidal constants. The predicted design water level

(DWL) combining tidal elevation, wave setup (19.5 cm), and sea level rise due to global warming (20.39 cm) resulted in a DWL of approximately +1.00 m MSL. The results of tidal observations can be seen which were carried out by the Coastal Center of PUSLITBANG SDA from 16 to 30 September 2024 and are presented in Table 1 below.

Tabel 1.Tide observation data at Candikusuma Beach

O'clock	Date														
	September														
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1:00		314	313	308	310	289	304	290	275	226	265	264	294	318	326
2:00		278	283	280	283	275	291	269	255	211	253	218	285	293	287
3:00		218	248	226	239	228	239	249	249	170	231	166	245	285	207
4:00		178	194	192	205	200	208	203	235	159	211	120	237	261	163
5:00		145	163	157	172	170	173	167	225	142	183	191	225	229	141
6:00		98	120	112	121	150	119	125	213	237	213	208	199	184	116
7:00		92	123	101	116	117	179	207	248	269	288	221	175	129	83
8:00		121	130	111	137	147	161	191	260	277	276	240	225	171	119
9:00		168	141	148	160	122	150	170	247	284	283	267	295	221	189
10:00		218	187	181	188	132	156	149	220	281	270	292	305	300	252
11:00		258	229	246	197	148	161	162	198	206	248	274	305	311	284
12:00		277	261	263	217	168	173	180	182	171	201	249	275	320	310
13:00		284	268	247	251	180	175	186	147	149	180	222	255	272	269
14:00		256	270	235	237	204	180	150	152	143	120	210	195	251	238
15:00		215	227	214	229	227	190	168	142	160	108	159	165	207	201
16:00		188	187	197	198	205	199	193	144	180	162	133	105	173	177
17:00		153	162	170	163	189	213	212	167	189	181	150	85	114	149
18:00	120	134	141	158	145	173	199	220	210	202	208	159	115	90	101
19:00	123	128	134	182	167	170	205	222	245	236	243	238	186	182	
20:00	160	151	159	187	179	163	208	223	258	257	255	288	275	213	
21:00	208	191	163	208	187	194	196	226	250	267	304	299	300	267	
22:00	265	239	231	233	212	200	206	236	249	266	313	316	329	298	
23:00	305	286	272	260	228	239	234	254	252	254	303	338	347	345	
24:00	320	311	291	297	246	274	267	279	235	247	292	318	323	335	

(Source: Coastal Center PUSLITBANG SDA)

Wind and Wave Analysis

Wind data (1999–2008) were processed to determine dominant wind directions and speeds. Maximum wind originated from the north, while average wind was from the south. Using these wind parameters, wave heights were predicted through hindcasting. The highest forecasted deep-sea wave (25-year return period) came from the southwest with a height of 1.37 m and period of 4.58 seconds. At a depth of 2 meters, the wave height was 1.31 m after applying shoaling and refraction coefficients. Meanwhile , wind analysis was also conducted based on the average daily wind direction and speed . The purpose of this analysis is to determine the characteristics of the wind type and predict the daily wave height it generates . The percentage results of the average wind event count can be seen in Table 2.

Tabel 2. Percentage of maximum wind events based on direction and speed

Wind direction	Wind Speed (m/s)					WIND (%)
	0.0 - 3.0	3.1 - 6.0	6.1 - 9.0	9.1 - 12.0	12.1 - 15.0	
East	0.00	0.83	2.5	0.00	0.00	3.33

Southeast	0.00	7.5	11.67	0.00	0.00	19,167
South	0.00	9.17	15.00	2.50	0.00	26.67
Southwest	0.00	0.00	3.33	1.67	1.67	6.67
West	0.00	0.00	3.33	1.67	0.83	5.83
Northwest	0.00	0.00	0.83	0.83	0.00	1.67
North	0.00	1.67	13.33	14.17	0.83	30.00
Northeast	0.00	0.00	2.50	4.17	0.00	6.67
					TOTAL	100.00

From the percentage of wind data that has been calculated visually it will be presented in the form of a wind rose as shown in Figures 1.

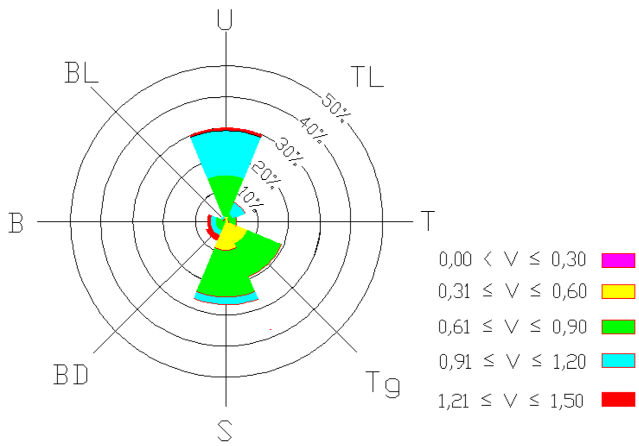

Figure 1. Wind rose of maximum wind events in 2016-2024

Shoreline Change Analysis

A comparison between Google Earth imagery from 2003 and bathymetric/topographic surveys from 2012 indicated an average shoreline retreat of **21.70 meters** over 9 years. This highlights the urgency for structural coastal protection, especially in the 200-meter-long critical zone identified as a fisherman settlement. . The input data for predicting the tides are the location coordinates and tidal data from direct observations in hours. After the forecast is made, the output data is obtained in the form of an estimate of the water level for one month, namely in November 2003. The results of the water level elevation forecast can be seen in Figure 2.

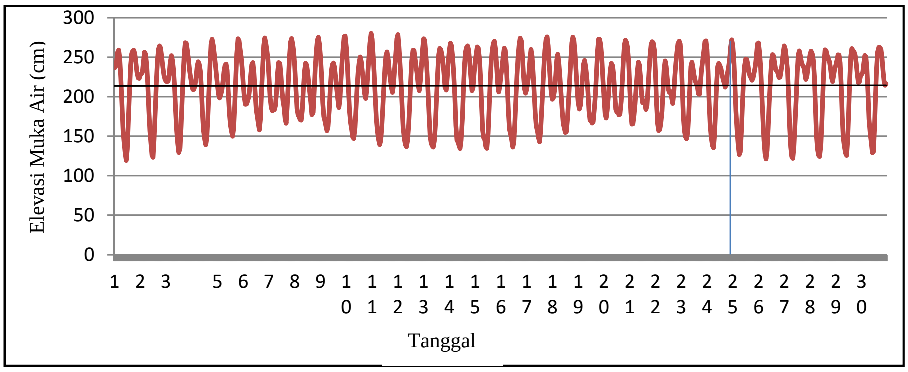

Figure 2. Tidal elevation of Candikusuma Beach in November 2020

based on forecast results

To determine the average retreat that occurs, the coastline is divided into several markers. So that the retreat of the coastline can be known at each marker. The division of marker points in critical areas due to erosion can be seen in Figure 3 below.

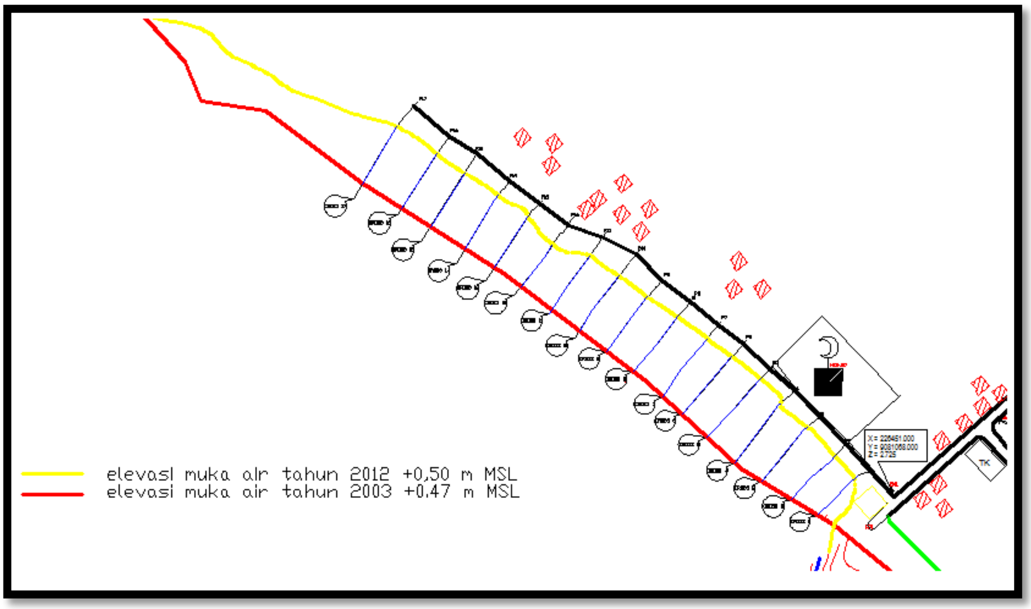

Figure 3. Location of the cross-section points of the image overlay results

From figure 3 then digitization is done to obtain the coordinates and distance between the two coastline situation lines at each point. The coordinates of the points in the 2020 coastline situation and their distances to the points in the 2024 coastline situation can be seen in Table 3 below.

Table 3. Coordinates and elevation of points at each marker from satellite imagery dated 25 November 2020

Benchmark Point	Coordinate		Retreat of the 2003 shoreline to the 2012 shoreline (m)
	(X)	(Y)	
P1	224620.68	9084145.25	-19.05
P2	224609.26	9084150.18	-21.28
P3	224600.49	9084156.39	-24.43
P4	224591.7	9084163.67	-25.95
P5	224582.3	9084172.38	-27.55
P6	224573.84	9084180.78	-26.18
P7	224565.32	9084185.39	-25.11
P8	224554.41	9084192.5	-24.34
P9	224545.15	9084199.7	-23.53
P10	224535.41	9084206.64	-23.02
P11	224526.28	9084214.57	-23.02
P12	224516.09	9084223.25	-18.03
P13	224505.26	9084227.52	-20.79
P14	224495.16	9084234.01	21.85
P15	224482.93	9084241.26	22.24
P16	224474.79	9084250.54	22.60
P17	224460.99	9084259.23	22.92

Based on Table 4.15 above, it can be seen that the average decline in the coastline that occurred at Candikusuma Beach in a period of nine years was 21.70 m. This will be a more serious problem if not addressed immediately, considering that the area behind the beach is a fishing settlement area. In further planning, the construction of a revetment structure will be planned in a critical area along 200 meters.

Revetment Design

The revetment crest elevation was determined to be **+3.70 m MSL**, with the structure's base at **–0.5 m MSL**, giving a total height of **4.20 meters**. The design uses **pusair lock concrete blocks**, known for their interlocking stability. The calculated required block weight was 51.2 kg, while the design used 180 kg blocks, ensuring sufficient resistance to wave forces.

The structure includes:

- Concrete pipe foundations at –1.5 m MSL
- Multi-layer stone and geotextile underlay
- A wave run-up (Ru) of **1.64 m**
- Armor blocks placed with cranes, forming an 11-tier system

To adjust the beach profile that has a slope of 1:5, there will be excavation work and filling of the original soil to obtain a beach profile with a slope that matches the slope of the structure, which is 1:1.5. The design details can be seen in Figure 4 and the revetment floor plan in Figure 5.

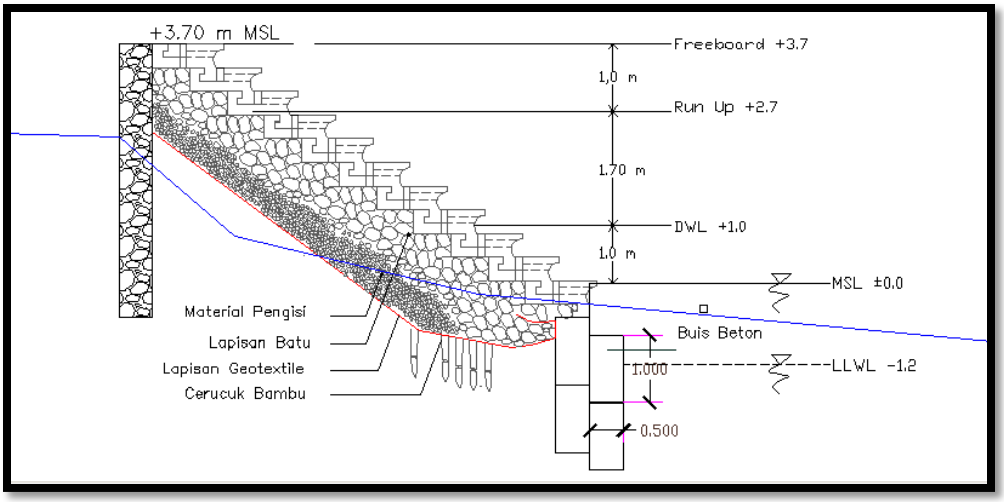

Figure 4. Details of the design of the concrete block armor revetment, type puair lock

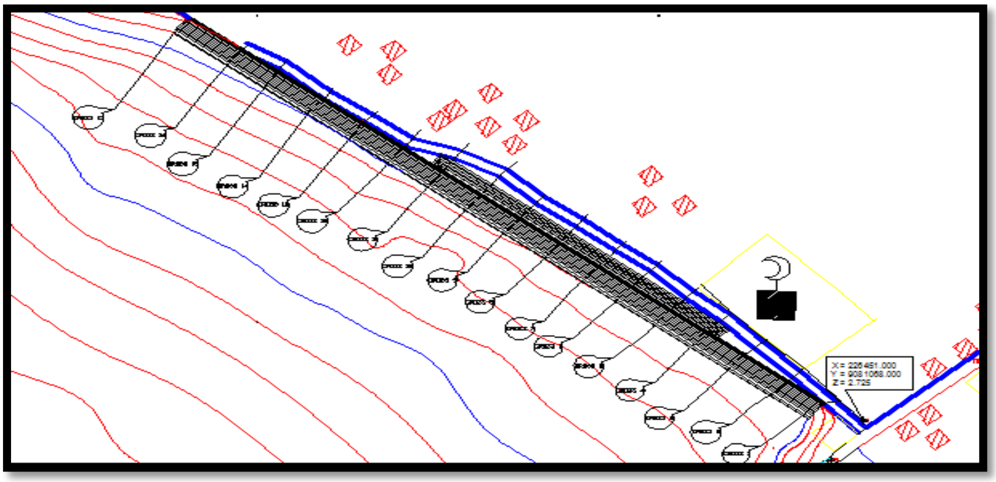

Figure 5. Revetment construction plan

Budget Estimation

The total estimated cost for constructing the 200-meter revetment, including materials, labor, and equipment, is Rp. 7,778,174,000 (approximately USD 500,000). This budget includes a 10% profit margin and 10% VAT. The unit price of materials, wages and equipment rental as well as the unit price analysis of construction work can be seen in the appendix. The recapitulation of the planned budget for the construction of the revetment structure can be seen in Table 4 below.

Table 4. Summary of cost budget plan

No.	Job description	Unit	Volume	Price (Rp)	Amount (Rp)
1.	Installation of Bouplank	m	408	476,650	194,473,200
2.	Regular Earth Excavation Work	m3	483.6	31,870	15,412,332
3	Foundation Excavation Work	m4	400	31,870	12,748,000
3.	River Stone Pair 1 PC : 3 PP	m3	504	926,910	467,162,640
4.	m3 Earth Filling Work	m3	1728	140,630	243,008,640
5.	Concrete Pipe Work as Foundation (0.5 x 0.6 m)	fruit	1600	394,256	630,809,353
6.	Bamboo Ceiling Installation	m2	530	109,415	57,989,950
7.	Installation of Geotextile Layer	m2	1568	41,950	65,777,600
8.	Empty Stone Work Diameter 10-30 cm	m3	1004	306,230	307,454,920
9.	Sand Filling Work	m3	250	104,150	26,037,500
10.	Armor Pusai Lock Molding Work	fruit	15	2,798,938	41,984,063
11.	Armor Making and Fabrication Work Navel Lock	fruit	5500	650,357	3,576,962,540
12.	Job 1 Concrete Block 20 x 10 x 200	fruit	2000	394,211	788,421,857
	Amount				6,428,242,595
	Profit 10%				642,824,259
	VAT 10%				707,106,685
	Total price				7,778,173,540
	Rounding				7,778,174,000
	(Seven Billion Seven Hundred Seventy Eight Million One Hundred Seventy Four Thousand Rupiah)				

5. Comparison

To better illustrate the contribution and relevance of this study, a brief comparison is presented between the proposed revetment design using Pusair Lock concrete armor blocks and other widely recognized state-of-the-art coastal protection methods.

Most conventional revetment structures, such as those using Tetrapod, Dolos, or natural rubble mound armors, rely on irregular interlocking for energy dissipation and wave resistance. While effective, these often lack ease in production standardization and precise placement. In contrast, the Pusair Lock system features:

- Modular, interlocking design, allowing systematic installation and stronger inter-unit locking, minimizing displacement during high wave events.
- High stability coefficient (Ks = 24), which is competitive with modern precast units such as Accropode and Xbloc.
- Simplified fabrication process using steel molds and conventional reinforcement, enabling cost-effective mass production in developing contexts.
- Effective performance in dissipating wave energy, with wave run-up and overtopping within acceptable design limits for a 50-year return period.

Moreover, the structure height (4.20 m from -0.5 m to +3.70 m MSL) and armor weight (180 kg) were optimized through empirical design using Hudson's formula. Compared to designs that require larger units (>1 ton) for similar conditions, the use of a 180 kg block presents logistical and economic advantages, particularly in remote coastal areas. In addition, the coastal retreat analysis based on shoreline digitization over a 9-year span reinforces the urgency and justification of implementing a hard protection strategy in this location. The integration of wave transformation, fetch analysis, and Fisher-Tippett frequency analysis adds robustness to the predictive capacity of the design.

6. Conclusions

Based on the analysis and discussion presented in Chapter IV, several conclusions can be drawn regarding the design and feasibility of the proposed coastal protection structure using Pusair Lock-type concrete armor blocks at Candikusuma Beach. The analysis of topographic, bathymetric, tidal, wind, and wave data shows that Candikusuma Beach is subjected to moderate hydrodynamic forces. The dominant wave direction originates from the southwest, with a maximum forecasted wave height of 1.37 m and a period of 4.58 seconds, corresponding to a 50-year return period. Shoreline change analysis indicates an average coastal retreat of 21.70 meters over a 9-year period, especially impacting a 200-meter critical zone in front of a local fishing settlement. This highlights the urgency of constructing a permanent coastal protection structure. The design water level (DWL) was established at +1.00 m MSL by accounting for tidal levels, wave set-up (19.5 cm), and sea level rise projections due to climate change (20.39 cm). The crest elevation of the revetment was set at +3.70 m MSL, which includes the calculated wave run-up (1.64 m) and a 1.00 m freeboard. The revetment design features a three-layer system consisting of a Pusair Lock armor layer (180 kg units), an underlayer of graded rock, and a bedding layer atop geotextile fabric over compacted subsoil. Hudson's formula confirms the armor weight is sufficient to withstand the predicted design wave height. The revetment was designed with practical construction considerations, including reusable steel molds and standardized armor unit geometry. The total estimated construction cost is approximately IDR 7.78 billion for a 200-meter stretch, which is economically viable for government-funded coastal infrastructure. Compared to other state-of-the-art coastal protection methods, the Pusair Lock system presents a cost-effective, modular, and replicable solution for medium-energy coastal environments, particularly suited for implementation in developing regions with logistical constraints.

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