Evaluation of Coastal Protection Structures (Revetment) and Management of Affected Communities on the Palu Bay Coastline

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Abstract: Disaster mitigation and coastal protection, a coastal protection structure in the form of a revetment was built. This study aims to evaluate the technical effectiveness of the revetment that has been built, as well as to review the social handling of the affected community in the coastal area of Palu Bay. The research method used is descriptive with a qualitative and quantitative approach, through the collection of primary and secondary data. This method is used to provide a clear picture/description of a situation without treatment of the research object and the suitability of the design to the characteristics of the beach, and the level of damage due to abrasion or waves. Social handling is evaluated through field studies, interviews with affected communities, and analysis of relocation and rehabilitation policies. The results of the study indicate that some revetment structures have functioned in reducing the rate of abrasion, but there are several segments that have been damaged due to lack of maintenance and designs that are not fully adaptive to local conditions. Periodic evaluation of coastal infrastructure is needed as well as more participatory and sustainable policies for handling affected communities to support the resilience of the Palu Bay coastal area.

Keywords: *Evaluation; Coastal Area; Mitigation; Revetment; Community.*

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I. INTRODUCTION

Development is essentially a series of changes towards progress [1]. The development of coastal buildings is more aimed at creating a reliable, highly capable coastal building system that is organized in an integrated, orderly, smooth, safe and efficient manner [2]. The coastal building development system plays a role in supporting coastal activities themselves, both those carried out by humans such as fishermen's activities and by nature (offshore / longshore) [3], [4].

The beach is an area on the edge of the waters that is influenced by the highest high tide and the lowest low tide [5]. The area around the coast is called the coast, which is a land area on the edge of the sea that is still influenced by the sea, such as tides, sea breezes and seawater seepage [6][7].

Adjustment of the shape of the coast is a natural dynamic response of the coast to the sea [8]. The dynamic process of the coast is greatly influenced by littoral transport, which is defined as the movement of sediment in the area near the coast (nearshore zone) by waves and currents [5], [9]. Littoral transport can be divided into two types, namely parallel transport (longshore transport) and perpendicular transport to the coast (onshore-offshore transport). The sand material that is transported is called littoral drift [10]. The perpendicular transport of the coast is mainly determined by the slope of the waves to the coastline, the size of the sediment and the slope of the coastline. The parallel transport is determined by the ebb and flow of the sea water [11], [12].

The coast always adjusts its profile shape so that it is able to destroy the energy of the incoming waves [10]. This adjustment of shape is a natural dynamic response of the coast to the sea [11]. One of the major problems in coastal areas is coastal erosion. Coastal erosion can cause significant losses by damaging residential areas and facilities in the area. The erosion and sedimentation processes discussed are in coastal areas located between the offshore boundaries of the coast where waves begin to move sediment and the shoreline boundaries [13]. This process occurs due to the interaction of wind, waves, currents, tides, sediment, and other factors in the coastal area [5], [14]

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The distribution of wind speed above sea level is divided into three areas according to the elevation above the surface. In the geostrophic area which is above 1000 m the wind speed is constant [15]. Below that elevation there are two areas, namely the Ekman area at an elevation of 100 to 1000 m and an area where the constant stress is at an elevation of 10 to 100 m. In both areas, the wind speed and direction change according to elevation, due to friction with the sea surface and the difference in temperature between water and air. To predict waves based on the wind speed measured at an elevation of y = 10 m. If the wind is not measured at an elevation of 10 m, then the wind speed must be converted to that elevation [16], [17].

II. LITERATUR REVIEW

Beaches can be formed from basic materials such as mud, sand, or gravel. The slope of the beach base depends on the shape and size of the basic material. On gravel beaches, the slope of the beach can reach 1:4, sandy beaches have a slope of 1:20 - 1:50 and for muddy beaches, the slope is very small, reaching 1:5000. Muddy beaches occur in coastal areas where there are many river estuaries that carry large amounts of suspended sediment to the sea [18]. In addition, the wave conditions on the beach are relatively calm so that they are unable to carry the sediment to the deep waters of the open sea. On sandy beaches, the shape is as shown in Figure 1. In the picture, the beach is divided into backshore and foreshore:

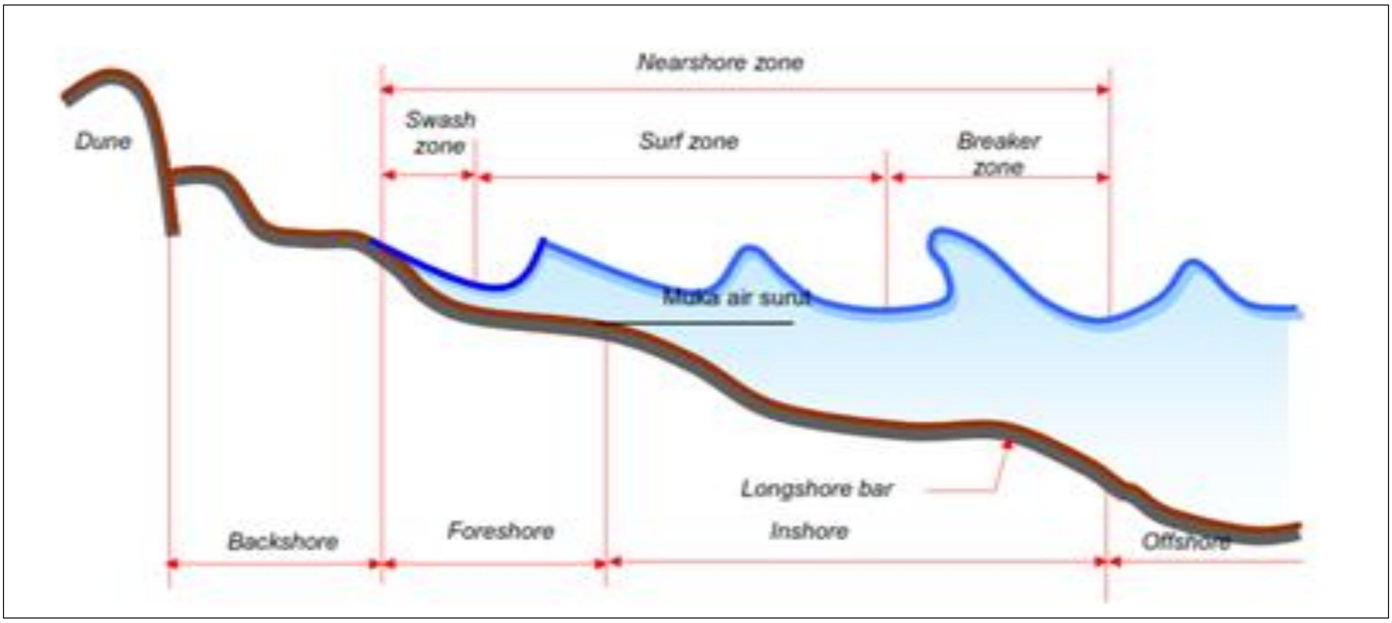

Fig 1 Beach Profile

The boundary between the two zones is the berm peak, which is the point of maximum run up under normal (normal) wave conditions. Run up is the rise of waves due to impacts on the berm peak or on the surface of buildings [19]. Wave run up reaches the boundary between the coast and the beach only during storm waves. The surf zone stretches from the point where the wave first breaks to the run up point around the location of the wave breaking. At the location where the waves break there is a longshore bar, which is a mound of sand at the bottom that extends along the coast.

Under normal wave conditions, the beach forms a profile that is capable of destroying wave energy [15]. If at any time there is a larger wave, the beach is unable to dampen the wave energy so that erosion occurs. The eroded sand will move towards the sea. After reaching an area where the water speed at the bottom is small, the sand settles [16]. The accumulation of these deposits will form an offshore bar, which is a mound of sand at the bottom of the beach that usually extends parallel to the coastline (longshore bar). This offshore bar, which has a small water depth, causes the location of the breaking wave to be further from the coastline, widening the surf zone where the remaining wave energy is destroyed. Thus, the offshore bar also functions as a coastal defense against wave attacks [18], [20].

The formation of this offshore bar is greater during storm waves. During high storms and large wave slopes. The wind and waves can cause an increase in sea level elevation (wind setup and wave setup), so that wave attacks can hit higher parts of the beach. These parts are usually not affected by wave attacks [1], [19]. The increase in water level allows large waves to pass through the offshore bar without breaking. The waves will break at a location that is already close to the shoreline, so that the width of the surf zone is not enough to destroy the energy of the storm waves. As a result, the beach is exposed to wave attacks and eroded. The eroded material is carried offshore in large quantities which are then deposited on the nearshore floor and form an offshore bar. The bar eventually grows large enough to break waves coming further offshore, so that the destruction of wave energy in the surf zone is more effective.

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III. RESEARCH METHODS

The research survey was conducted at eight project sites. The description of the work location. In this study, the author uses a descriptive research type, which provides a clear description/description of a situation without treatment of the research object. This process begins with the identification and formulation of the problem, which aims to obtain information about wave conditions in the waters of Palu Bay. Furthermore, it is continued with a literature study that covers various aspects, such as the influence of wind, wave forecasting, wave deformation, and wave height requirements in the Coastal Protection area. [11]

In this study, the data used are primary and secondary data, primary data is data obtained by researchers directly, while secondary data is data obtained from pre-existing sources [6]. Primary data taken directly by researchers include: bathymetry and tidal data. Secondary data is wind data. The stages of the research are as follows [20].

In this study, two types of data were used, namely primary data and secondary data. Primary data is information obtained directly by researchers, while secondary data includes information taken from pre-existing sources. Primary data taken by researchers includes bathymetry and tidal data, while secondary data used is data on wind. The following are the stages of the research carried out [1].

This research was conducted in Palu Bay or more precisely in the 7.4 km long Palu Bay Coastal Protection development area. This Coastal Protection was built after the 2018 Earthquake which had a huge impact on the road and coastal areas of Palu Bay. In this study, primary and secondary data were used. Primary data includes information on sea tides and bathymetric survey results. Tide data collection was carried out independently in the Palu Bay Coastal Protection area for 15 days with a measurement interval of one hour.

The purpose of processing tidal data is to record vertical movements of the sea surface periodically in order to determine depth references such as mean sea level (MSL) or ebb and flow (chart datum) which will be used as bathymetric depth corrections.

In this study, tidal constant analysis was carried out using the Least Square Method [8]. The Least Square Method is a method used to analyze tidal components so that tidal elevation can be predicted. The principle of tidal analysis with the Least Square Method is to minimize the difference in composite signals and size signals [21]. The advantage of this method is that it can predict long-term tides. In addition, this method can use more than 9 components. The least squares method equation can be seen in the following equation:

$$h(t) + v(t_n) = hm + \sum_{i=1}^{k} A_1 \cos(\omega_1 t - g_i)$$

Where:

h(t) = water level function of time

Ai = amplitude of the i-th component

i = angular velocity of the i-th component

gi = phase of the i-th component

Hm = average water level

T = time/time interval

K = number of components

V (: residue

Based on the amplitude of the tidal harmonic components, the ebb surface is determined at a distance of Zo from MSL. The difference in distance between MSL and the ebb surface based on international standards is obtained by the following equation:

$$Zo = \sum_{i=1}^{n} Ai$$

Where:

Ai = amplitude of tidal component i

n = number of components

Data correction is performed/calculated in MS. Excel software. The tidal correction formula is formulated as follows:

$$rt = TWLt - (MSL - Zo)$$

Where:

Rt = Amount of reduction (correction given to the depth measurement results at time t)

TWLt = Actual sea level position (true water level) at time t

MSL = Average sea level (Mean Sea Level)

Zo = Depth of ebb tide below MSL

If the reduction value has been obtained, then the next step is to calculate the actual depth value or depth of LLWL with the following equation:

$$D = dT - rt$$

Where:

D = Actual depth

dT = Transducer corrected depth

rt = Reduction (correction) of sea tides

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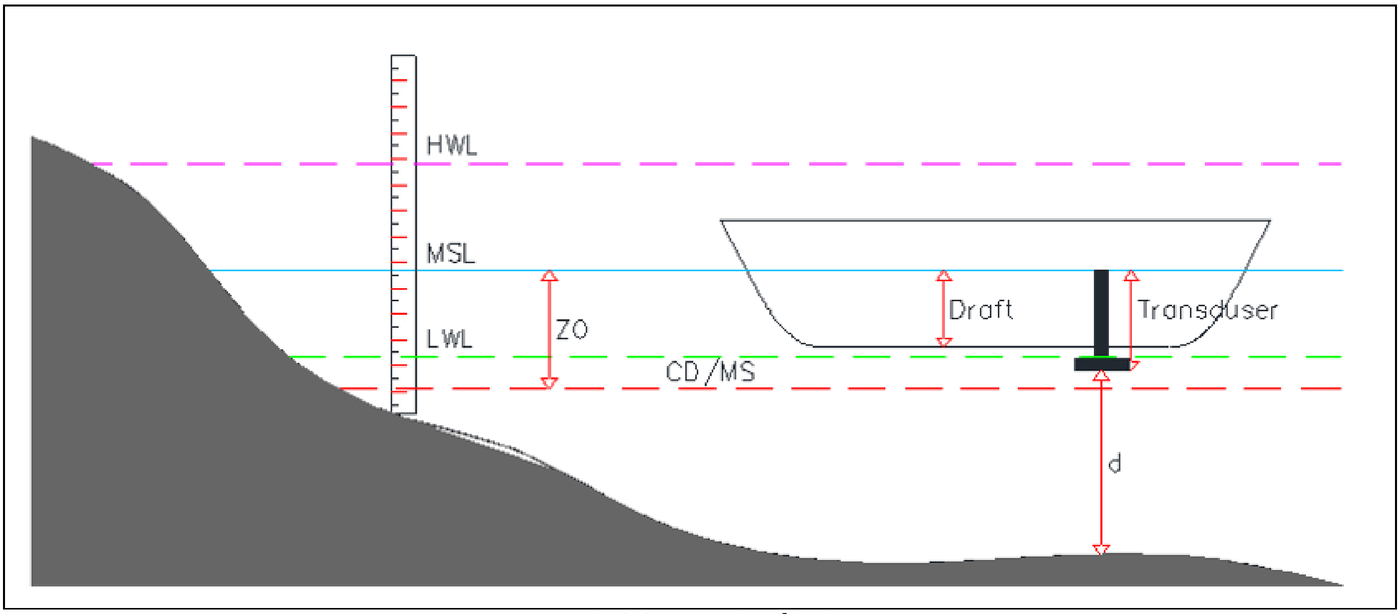

Fig 2 Survey Visualization

After the data analysis results from secondary data are obtained, the next step is to perform wave propagation modeling. This modeling is done using Surface Water Modeling System (SMS) software version 11. 2 by utilizing the CG-Wave module.

IV. RESULT AND DISCUSSION

The preferred spelling of the word "acknowledgment" in America is without an "e" after the "g." Avoid the stilted expression "one of us (R. B. G.) thanks ...". Instead, try "R. B. G. thanks...". Put sponsor acknowledgments in the unnumbered footnote on the first page.

Coastline changes are generally caused by abrasion, in addition to other natural processes such as wind, currents and waves, and tsunami disasters. One method to overcome coastal erosion is the use of coastal protection structures, where the structure functions as a wave energy damper at certain locations. The coastline must be protected from abrasion due to longshore currents by coastal protection structures. For coastal hydrodynamic analysis, wind, wave, and sediment information is required. The software used in wave modeling in the waters of Palu Bay is the Surface-Water Modeling System (SMS) version 10.1 (Environmental Modeling Research Laboratory (ERML) developed by the US Army Corps of Engineers. SMS is a pre and post processor for finite element and finite difference element modeling. The core program of SMS is a hydrodynamic modeling program that can calculate water surface elevation and flow velocity for a flow problem. In the SMS program there are several important program modules for modeling. Related to this work, the modules that will be used are:

- GFGEN (Geometry File Generation) is a file for creating geometry mesh files and finite elements that will be input for the SMS modeling system.
- RMA2 (Resources Management Associates-2) is the core program of SMS. RMA2 is a two-dimensional finite element program for solving hydrodynamic problems.
- CGWAVE is a wave forecasting model that is widely used and is currently the most reliable.
- This program can be applied to simulate wave conditions in port areas, open beaches, shallow water areas, areas around islands, and areas around permanent buildings or floating.
- The assumptions used in this modeling include:
- Moderate slope: changes in depth and current in one wavelength are very small.
- Average depth: the regulator equation is solved by depth integration.

Secondary data collection or field surveys are needed to collect the necessary data such as topographic and bathymetric maps, aerial photographs, tidal, wave, and wind data.The bathymetric survey activities carried out were to determine changes in the coastline and will be used for the layout and design of coastal protection and the location of boat moorings to help affected communities, especially those who work as fishermen, to easily moor their boats to avoid being hit by waves when anchored.

The condition of the Palu Bay Coast after the Tsunami and changes in the coastline can be seen in the following image:

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Fig 3 Conditions of the Palu Bay Coast after the Tsunami and changes in the Coastline

The percentage of wind blowing around the Palu Bay area and displayed in the form of a wind rose diagram or known as windrose. However, with a very large amount of data, an application is needed that can perform calculations quickly. Lakes Environmental is a company located in Ontario, Canada, conducting research and development of software that focuses on modeling the distribution of air masses that can be used by companies, government agencies, and academics. One of the software produced is WRPLOT View which can calculate the frequency, percentage, and display a classification diagram of wind direction and speed data in large quantities.

Wind direction is the direction from which the wind blows or where the wind current comes from and is expressed in degrees determined by the direction of the clockwise rotation and starting from the north point of the earth. Generally, wind currents are named by the direction from which the wind is blowing. Wind speed generally changes, so in determining wind speed, the average speed is taken over a period of ten minutes rounded to the nearest knot unit price.

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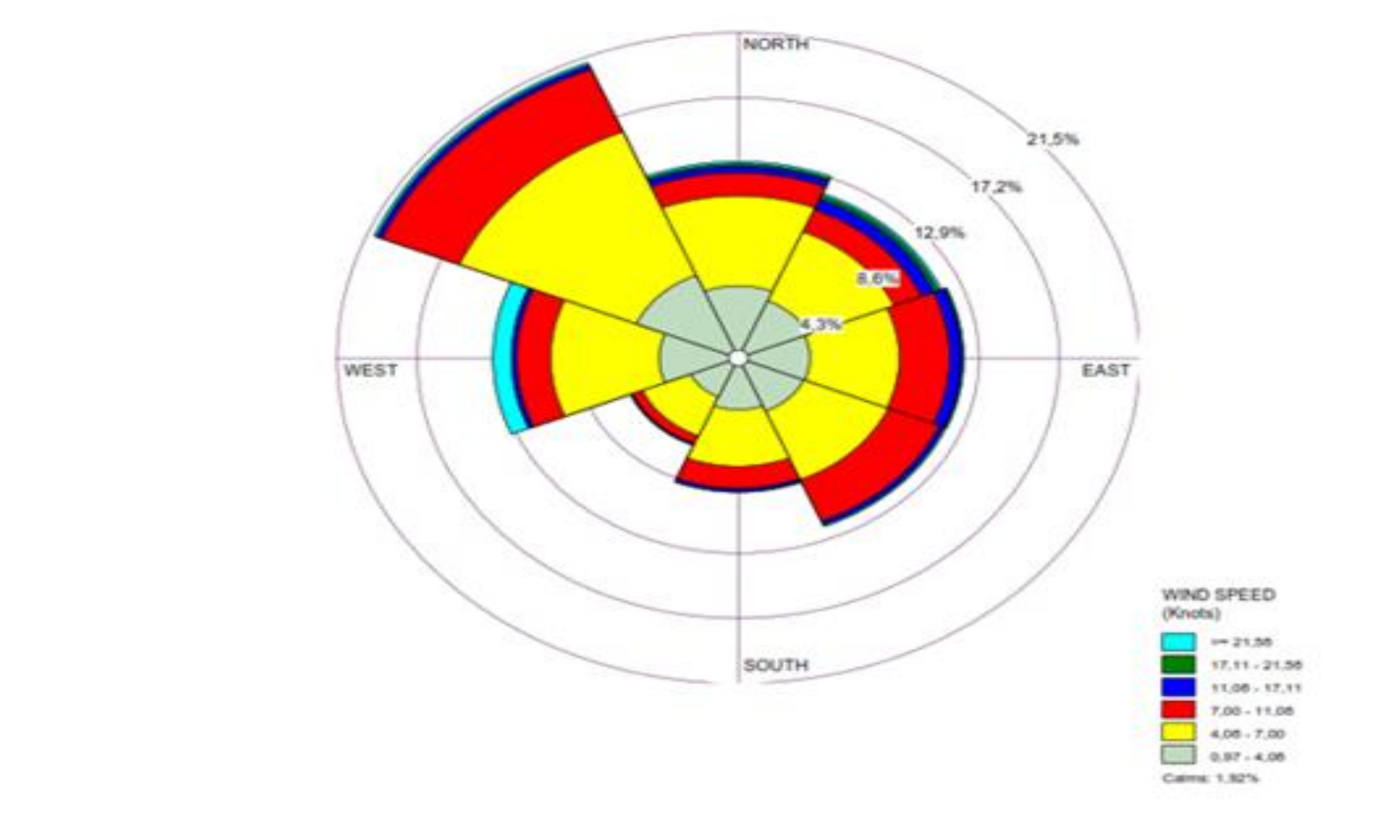

Fig 4 Characteristics of Wind in Palu City

Bathymetric conditions in waters are very important in relation to the use of space in coastal areas. Bathymetry is the process of depicting the bottom of the waters from measurement, processing to visualization. One of the important measurements needed to determine bathymetry accurately is the mean sea level or MSL (mean sea level) which is used as a reference of 0 meters and is also used for topography.

Tides are one of the hydro-oceanographic factors that affect the condition of a dock environment. The highest (high tide) and lowest (low tide) water level elevations are very important for port buildings, where the pier top elevation is determined by the high tide elevation and the depth of the dock pool is determined by the low tide level.

The bathymetric survey was carried out in two stages, namely the field observation stage and data processing. Field observations were carried out on April 6 - April 20, 2025 in the waters of Palu Bay. Where data processing was carried out at the end of April 2025.

At the sounding stage, it is carried out in accordance with SNI (Indonesian National Standard) hydrographic survey using singlebeam echosounder by:

- Preparing facilities and installation of equipment to be used in sounding.
- Conducting sounding trials or calibrating equipment so that the equipment used is in accordance with specifications
- Conducting bar checks before and after sounding.
- At high tide, sounding is carried out to obtain a zero depth line.
- Data collection of sea depths (sounding) is carried out using a singlebeam echosounder Garmin GPS map 585 and,
- Using a means of transportation in the form of a boat
- In the data collection process, an observed data is called a fixed point which has information about the position (x, y) and depth (z) observed simultaneously.
- Several fixed points that have been observed are then made into a bathymetric map that describes the topographic conditions of the seabed surface.

The corrected bathymetry data is then calculated using the following formula:

$$D = Hukur + dT \pm rt$$

where:

D: (actual depth),

Hukur : (measured depth),

dT : (transducer depth),

rt: (tidal correction - observed value of sea level when measuring depth relative to MSL).

The corrected depth data is then interpolated and extrapolated using the kringing method on Surfer 13 to produce depth contours. Furthermore, ArcGIS 10.3 is used to create bathymetry maps. Analysis of seabed morphology in

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the form of slope gradient is obtained from calculations using the resulting bathymetry contour map. The slope value is obtained using the Wentworth method. The equation is presented as follows:

$$S = [(n - 1)\ x\ Ic\ ] / \Delta h\ x\ 100$$

where:

S: (slope gradient value in percent),

n: (number of contours),

Ic: (contour interval),

Δh: (horizontal distance in meters)

The waves that occur in the waters of Palu Bay are related to the depth of the seabed or bathymetry. This is shown in Figure 4.5. The depth of the seawater is in accordance with the wave study, as presented in Figure .6. A comparison of these two images shows that the west coast has a higher seabed, so the water depth is shallower.

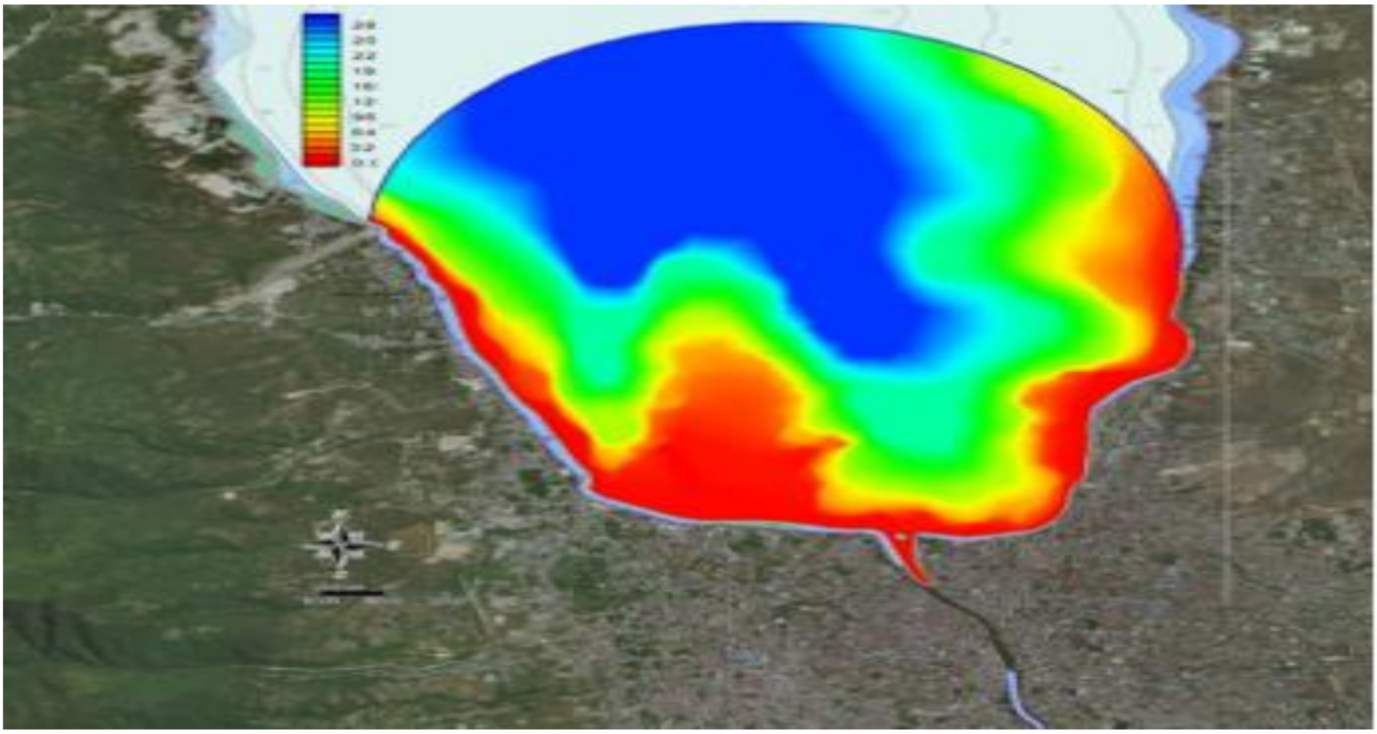

Fig 5 Depth of the Seabed of Palu Bay

The Input Parameters used for wave modeling (CGWAVE) are:

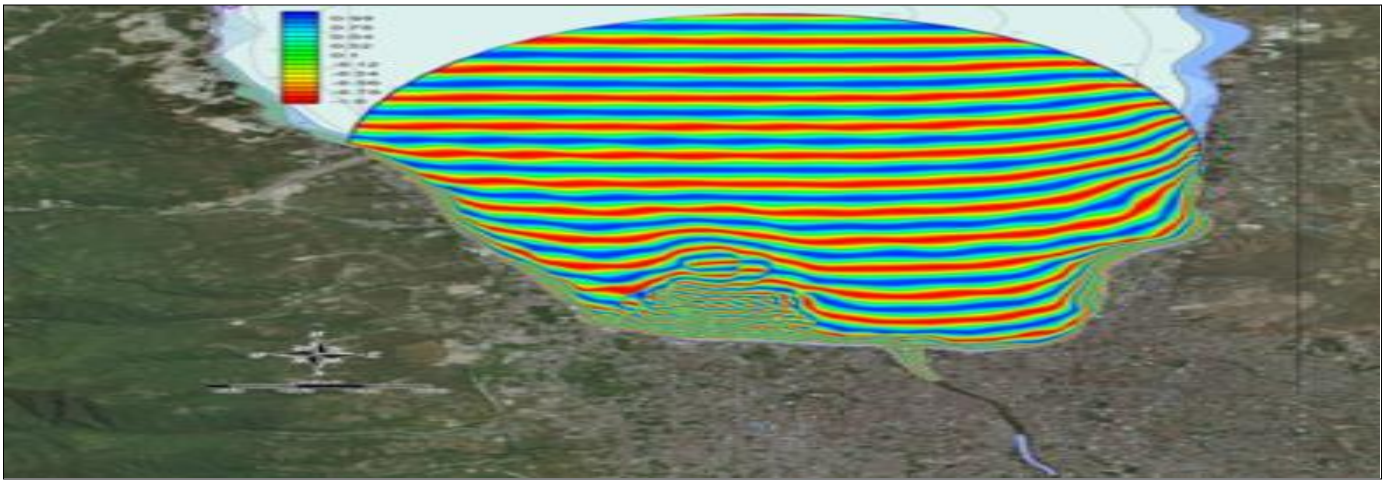

Fig 6 Wave Patterns Based on Wind and Wave Studies

From Figure 6 it can be seen that the wave height that occurs along the coast of Palu ranges from 0.55 - 1.10 meters. However, for the west coast of Palu Bay, due to the influence of refraction, the wave height varies at a distance of 300 meters from the coast, the wave height reaches 2.00 meters. While at a distance of 500 meters from the coast, the wave height reaches 3 meters.

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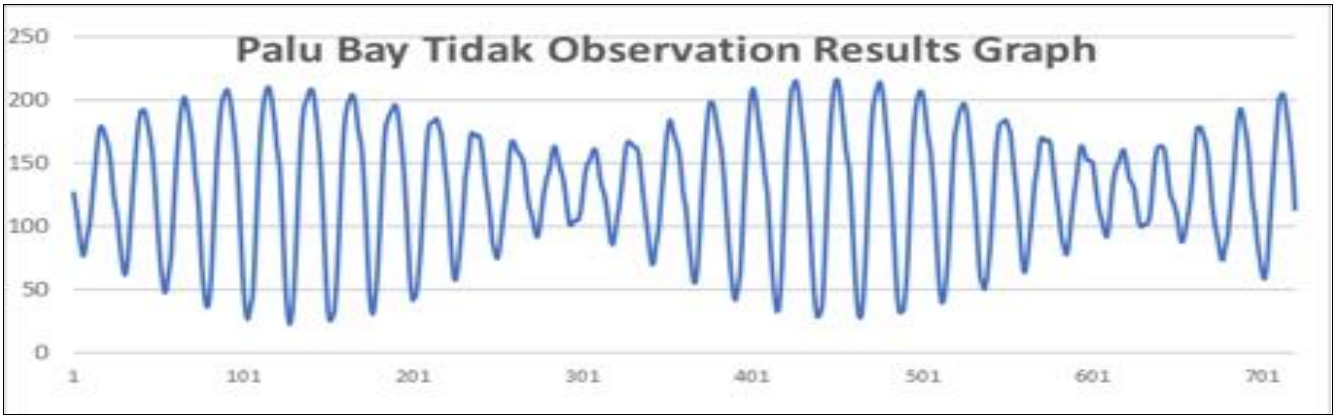

Fig 7 Tidal Observation graph at Talise Beach (1 April – 1 May 2025)

The calculation process of the Admiralty Method is calculated with the help of a formula system calculation table with the help of Microsoft Excel software, so that the calculation in this method will be efficient and have a fairly high accuracy and flexible for any time. Calculations using the Admiralty Method must perform interpolation with the help of a predetermined multiplier constant table, after the interpolation process is carried out, a harmonic constant will be obtained which will be continued with the analysis of the harmonic constant data using the Formzahl number to determine the type of tide at the case study location.

Evaluation of the height of coastal protection structures is very necessary to determine the impact of waves on the coast to avoid abrasion due to waves. Basically, the planned coastal protection line follows the existing embankment line. However, due to natural disasters, the coastline in several locations has shrunk towards the land and lowered the elevation. As happened on Jalan Komodo and Jalan Cut Mutia, Talise Village, whose location which was originally an arterial road was cut off. The embankments that originally followed the road were also lost due to the earthquake and tsunami.

Several areas that were previously land have turned into deep sea. So in the project plan, the new coastal protection line was forced to pass through a plot of land owned by the community. Previously, on the land passed by the project, there were residential buildings. Then after the natural disaster, the remaining buildings were only 4 permanent houses with minor damage and 1 non-permanent building. However, on this section there was coastal abrasion which resulted in the loss of land and only 1 building remained.

Evaluation is based on the area impacted by changes in the coastline. The construction of coastal protection structures has also been included in the Decree of the Governor of Central Sulawesi. The impact corridor includes affected land in the Talise and Tondo sections, as well as affected land owners and fishermen who have lost their boat moorings. The questionnaire used for the survey is attached in Appendix 1.

In addition to the survey, in-depth interviews were also conducted with the village office and community leaders around the study area. Data search and consultation with Bappeda and other institutions within the Palu Regional Government for affected areas along the coastline.

After the Tsunami, many areas and lands were affected and experienced erosion and changes in the coastline. The construction of coastal protection structures requires an area of 116,171.10 m² consisting of 111,714.18 m2 (96%) of government-owned land owned by Agencies in Central Sulawesi Province and 4,456.92 m2 (4%) of private land consisting of 35 plots of land owned by 32 land owners.

After post-construction handling and evaluation of coastal protection structures and data updating, it requires an area of 146,622.93 m² (14.6 hectares) consisting of 135,764.93 m2 of government land and 10,858.00 m2 of private land consisting of 31 plots of land owned by 25 AH. (see table 4.9 below).

Fig 8 Job Location Map

Based on input from the fishing community in the tsunami-affected area, they generally apply for the construction of a boat mooring area. Evaluation of the location of the boat mooring and the elevation of the peak of the boat mooring, researchers conducted to determine the high effectiveness of the boat mooring for protected friends. There are four boat mooring units built attached to the coastal protection embankment. Based on the evaluation of the location of the boat mooring (TP)

Evaluation of the 4 boat moorings generally refers to the size and direction of the waves and currents that occur at each boat mooring location. So that of the 4 boat mooring models, all have different models and characteristics. The mooring is designed using a trapezoidal model using a layer of large piles of rocks (Armour layer) on the outermost layer.

The boat mooring model follows the existing coastal protection model and still refers to the size and direction of the waves. With a model that adopts the wishes of fishermen and safety factors for fishing boats. Testing the bearing capacity of the soil at the boat mooring location is very important to determine the potential for the structure to overturn. So that the Cone Penetration Test (TKP) and Standard Penetration Test (TKP) are carried out to determine the bearing capacity of the soil around the location.

The construction of the mooring facilities consists of two parts, namely the lower part of the structure (core) which functions as a foundation and the upper part of the structure functions as a wave breaker. The lower part uses a pile of stones with a stone diameter of 30-50 cm, while the outer part uses a protective layer with a minimum stone diameter of 1 m.

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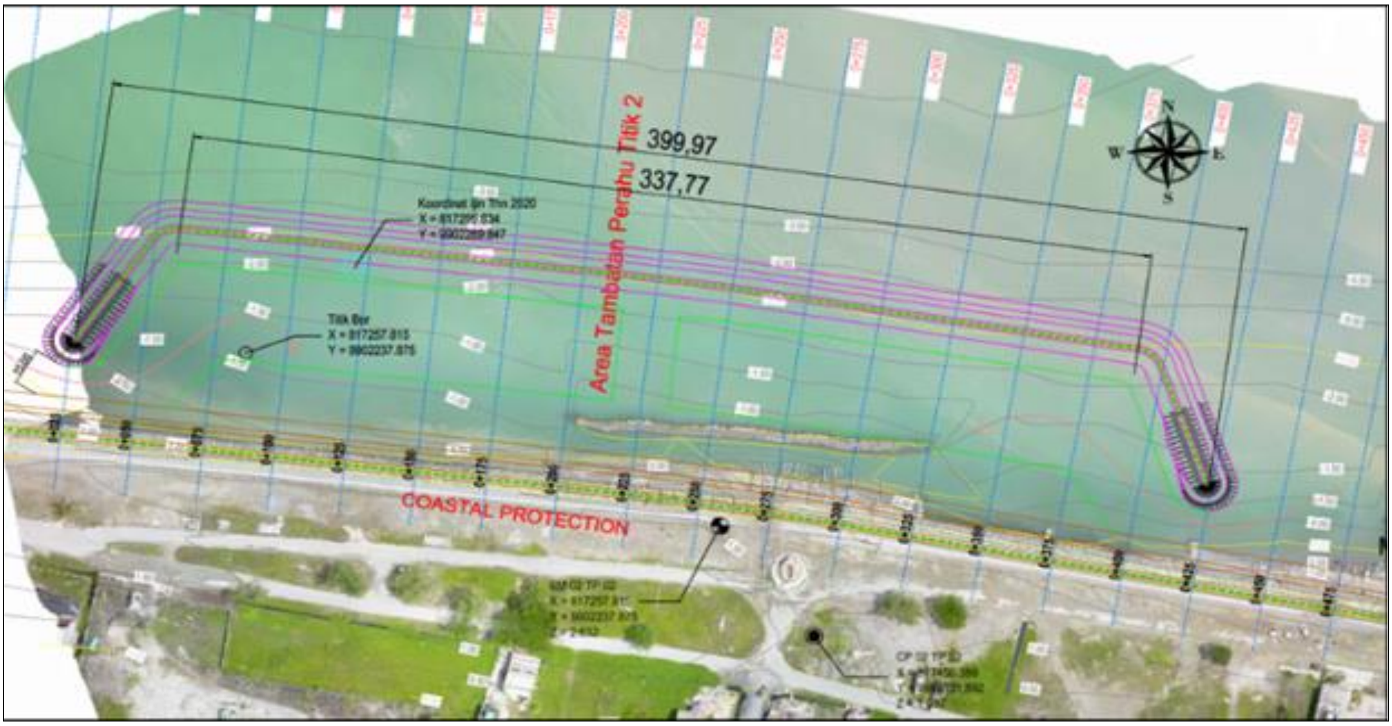

Fig 9 Bathymetry and Design of Boat Moorings

The construction of the boat moorings built at 4 locations such as the survey results obtained the height of the lighthouse is + 2.5 meters or 0.5 meters lower than the Coastal Protection of Palu Bay. And as the previous evaluation results where the following results were obtained:

- Highest tide or HHWL = 1.764 masl
- Wave set up (Sw) = 0.198
- Sea level rise (SWL) = 0.19 m

So that the planned water level elevation is obtained as follows:

DWL = HHWL + Sw + SLR

DWL = 1.764 m + 0.198 m + 0.19 m

DWL = + 1.962 meters

Based on the evaluation results that for the boat mooring building there is a possibility of Run up due to waves so there is no problem if there is overtopping above the mircu where behind the peak of the building is still part of the sea. Therefore, the design height of the boat mooring mircu of 2.5 masl is acceptable.

V. CONCLUSION

The Simultaneous Research Results Show That the Work Environment Variables (X1), Training Model (X2), Self-Concept (X3) And Leadership (X4) Significantly Affect the Performance of Construction Workers in Palu City With the Results of the Regression Equation Y = 1.083 + 0.285 X1 + 0.183 X2 + 0.256 X3 + 0.209 X4. While the Results of the Determination Coefficient Test (R Test) Obtained an Adjusted R Square Value of 0.674 Where All Independent Variables Are Able to Explain the Relationship and Its Effect on the Dependent Variable by 67.4%, the Remaining 32.6% Is Influenced by Other Factors. Coastline changes are generally caused by abrasion, in addition to other natural processes such as wind, currents and waves, and tsunami disasters. One method to overcome coastal erosion is the use of coastal protection structures, where the structure functions as a wave energy damper at certain locations. The coastline must be protected from abrasion due to longshore currents by coastal protection structures. For coastal hydrodynamic analysis, wind, wave and sediment information is needed.

To protect abrasion, coastal protection of Palu Bay has been built, where the results of the Hydrodynamic wave evaluation which includes the current bathymetry conditions, tides, waves due to wind and rising sea levels due to global warming, obtained the minimum height of the embankment is 3.00 m above sea level. Based on the results of the evaluation and survey that the researcher has conducted, it was obtained that the height of the coastal protection embankment construction is 3.00 m or can be said to be the same as the results obtained by the researcher. The impact felt by the community in addition to the loss of property also has an impact on their livelihoods as fishermen. Data was obtained that as many as 181 fishermen who acted as heads of families lost their livelihoods and places to anchor their boats.

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