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Strength Analysis and Repair Strategy of Aged Steel Jetty Pile

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Abstract

Indonesia has 95.161 km coastal lines with a total of 17,504 islands. With this nature, Indonesia has 1,226 ports, with a total accumulated length of up to 92 km. However, not all these ports are in proper condition. For ports that have steel jetty piles, corrosion is one of the problems. This paper provides technical experience and methodology for analyzing the pier's corrosion conditions and evaluating existing corrosion's effect on its strength. The survey methodology and required data, including a survey of cathodic protection, visual conditions, and pile thickness, are discussed in this paper. The static strength analysis of the existing state structure was carried out. This article provides repair strategies, including repair methods and a study of the number of piles repaired. This methodology results in the recommendations for pile repair strategies and guidance on effective analytical methods in determining the number of repaired piles for aged steel jetty pile repair.

1. Introduction

Indonesia's coastline spreads 95,161 km with 17,504 islands, covered by territorial waters up to 5.9 million km^2 [1]. With these specific characteristics, its connectivity is very dependent on sea transportation modes that consist of many support systems. Besides ships as the main subject, the port is vital in supporting sea transportation. Generally, a port has jetties as infrastructure for berth and mooring.

The number of ports in Indonesia registered at the Ministry of Transportation is 1,226 ports, with a total jetty length of up to 92 km [2]. Unfortunately, with such a considerable number, not all jetties in the port are in decent condition because many of them are aged more than 20 years. The aged operational jetties are prone to failure due to corrosion notably, jetty piles, which are the main load bearer of vertical loads in the form of operating loads. These piles also withstand lateral loads due to environmental loads and ship berthing loads. Piles unable to withstand these loads can suffer permanent damage, even at risk of fatal failure.

This paper provides a technical recommendation and methodology for analyzing corrosion conditions of aged steel jetty piles. It also provides the method to evaluate the effects of existing corrosion on its static strength. The strategy for pile repair and its protection against corrosion will be developed from static strength evaluation as a reference point. The example of a single-purpose jetty was taken in North Sumatra Province, built-in 1990, and only had minor repairs in 2004.

Figure 1 shows the existing jetty condition that is in severe corrosion. The jetty is intended to be repaired and renewed to extend its service life up to 20 years. With the limited repairing budget, the strength analysis and repair strategy must be carried out to provide the best possible result.

Several studies have been carried out to provide the methodology to repair aged jetty structures. Studies on surveys and repairs on jetty structures have been carried out on structures that are 15 years old [3]. This study showed that the improper thickness of concrete covers could cause unwanted early corrosion. The study also indicated that the patching method was more suitable for repairing the jetty piles. The next research carried out the reinforced concrete jetty structure survey, including the corrosion rebar steel taking an example in the Persian Gulf area [4].

One of the strategies to repair corroded piles is by concrete encasement [5]. Corroded piles could also be repaired by patching methods, namely by replacing corroded parts with thicknesses similar to the initial conditions [6]. This method was consistent with the study conducted in the literature [3].

Figure 1. Aged Steel Pile Jetty in Severe Corrosion

A study was carried out on examples of repairs to piles on several countries' docks in the world. Jetty piles located in the river could be repaired by patching methods and methodologically did not experience any problems due to relatively calmer environmental conditions [7]. The loading and bridging piers in the estuary area can be improved by considering the factors that are the pile structure's main strengths by taking an example of an estuary in the United States [8]. Evaluation of jetty piles repair by patching method has been done [9]. and provided an assessment of the strength of the original structure and the structure that has been done patching.

2. Methods

Figure 2 explains the methodology, including the data gathering, the survey process, structural strength analysis, and the repair strategy that are carried out.

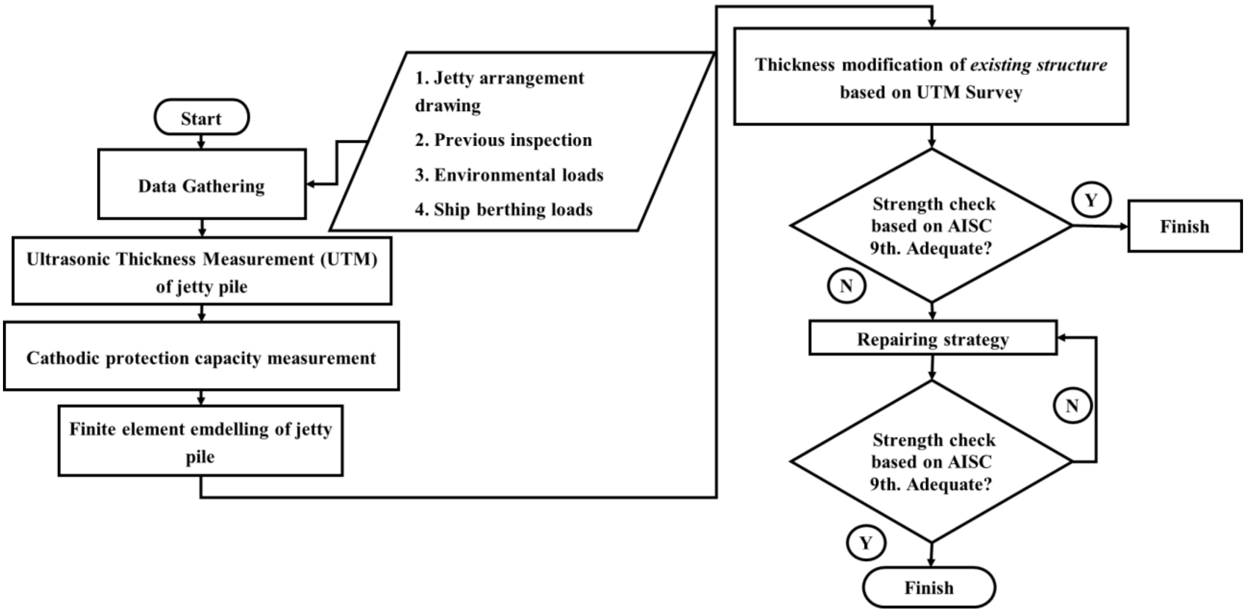

Figure 2. Methodology Flowchart

2.1. Data Gatehering

The data are gathered from the port owner. The data needed in this study consist of jetty structural drawings, environmental data, and the general arrangement of operational conditions on the jetty deck. Ship data are also needed in this study. A statistical study should be performed to generate maximum and mean vessel size that docked in the port following the vessel berthing load. A consensus between the port owner and the analyst is necessary to determine the maximum and mean vessel size that ever docked in the port if there are no ship berthing data in the last 20 years. If that is the case, the port owner will only provide the largest ship DWT (Dead Weight Tonnage) so that the analyst can generate the particular vessel size.

2.2. Survey and Inspection

Two types of surveys must be carried out to assess the existing jetty condition. The first survey is to measure the cathodic protection potential to determine the existing corrosion protection systems. The second survey conducted is Ultrasonic Thickness Measurement (UTM) to determine the existing pile conditions' thickness.

2.3. Modelling and analysis

Modeling is done by Structural Analysis Computer System (SACS) Finite Element Analysis (FEA) software, in the form of the beam element. Thickness reduction modeling on corrosion is done by segmenting method. The Unity Check ratio (UC ratio) of stresses to allowable stresses in static analysis is used to measure structural strength. In this study, allowable stresses are based on AISC 335-89 Specification for Structural Steel Buildings [10].

2.4. Repairing scenario

The patching method is carried out to repair the reduced jetty thickness, especially on structures with a UC ratio of more than 1.0. Analysis of the number of piles patched and the structural strength predicted will be used to determine repairing scenarios.

2.5. Jetty Data

Based on the existing specifications gathered from the owner, the port structure type is a deck on pile type jetty, with concrete decks and steel piles. The jetty has a length of 1,020 m and a width of 200 m, capable of holding ship loads up to 90,000 DWT (Deadweight Tonnage). Figure 3 below explains the jetty layout.

In total, there are 133 jetty piles. One hundred twenty-five (125) piles are located on the jetty, and eight (8) piles are located on the trestle connecting the quayside with the land. Each pile has a diameter of 30 inches (762 mm) and a thickness of 0.5 inches (12 mm). The pile elevation is 4 m from the Mean Sea Level (MSL). MSL elevation for the quay's farthest side (Row A in Figure 3) is 10 m. The material specifications used for decks (concrete) and piles (steel) are listed in Table 1.

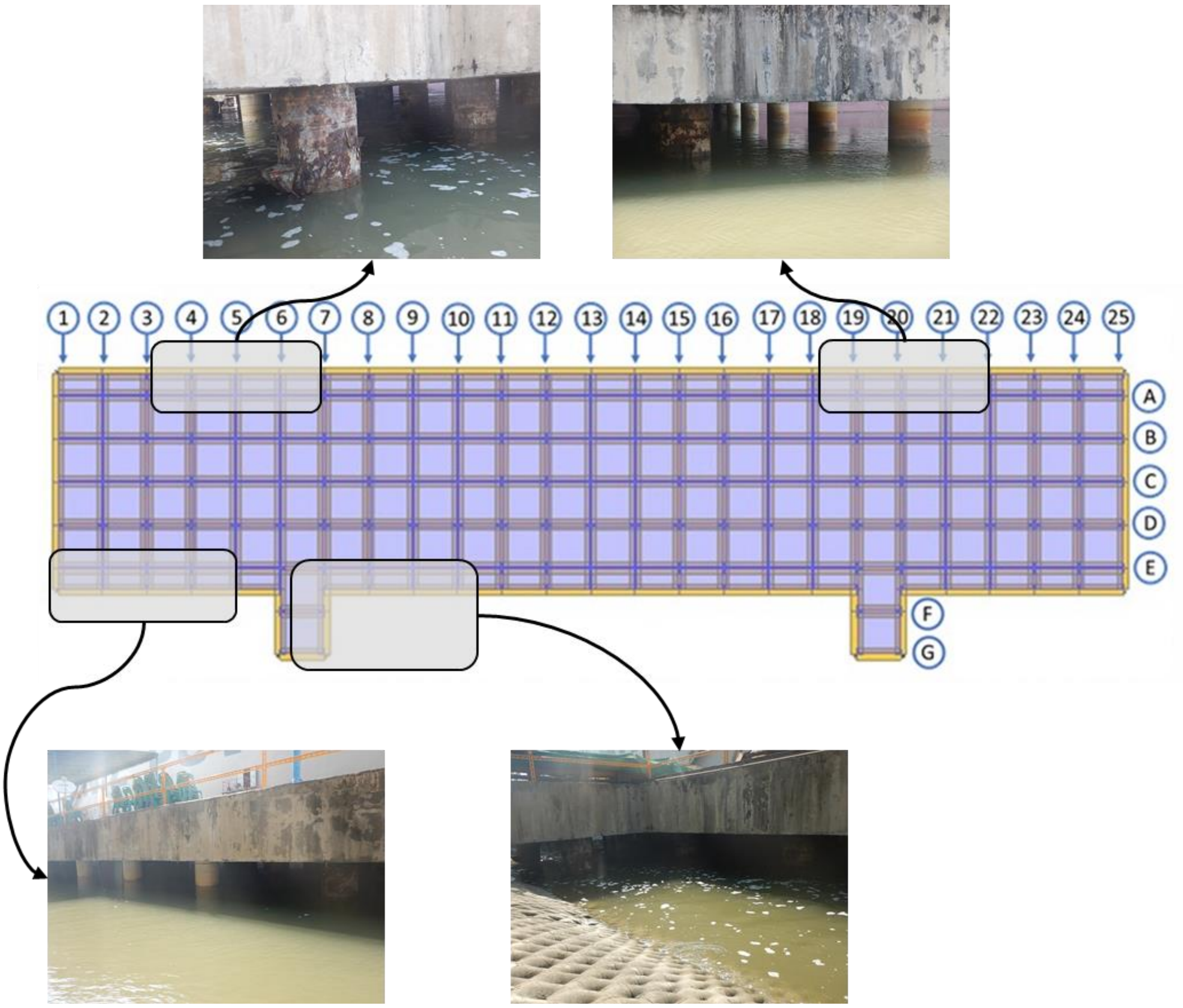

Figure 3. Jetty structural arrangement

Table 1. Material Specification [11]

Specification	K300 Concrete	AISC A36 Steel
Density	2,400 kg/m^3	7,850 kg/m^3
Possion Ratio	0.22	0.29
Elastic modulus	23,500 MPa	210,000 MPa
Compressive strength (fc′)	30 MPa	-
Yield Strength	-	250 MPa
Ultimate Tensile Strength	-	400 MPa

3. Results and Discussion

3.1. Cathodic Protection (CP) Potential Survey Results

The CP survey was carried out by measuring the pipe to water potential. This method is used to determine the level of CP electronegativity at the pile. The equipment used is as follows [12]:

- Multimeter Fluke 87 V
- Digital Clamp Meter 325
- Portable Reference Electrode Ag/AgCl
- Portable Reference Electrode Cu/Cu SO4

Based on applicable codes and standards, namely DNV-RP-B401, CP readings must be in the range of -1050 mV to -800 mV [13]. The more negative Readings than -1050 mV are included as over-protection, which causes damage to structural members. Meanwhile, a more positive reading than -800 mV is included as an under-protection that can cause corrosion to structural members. Figure 4 below explains the results of the CP reading mapping. Mapping is done by giving a red color to the pile that does not meet the protection criteria. While the green color is given to piles that meet the protection criteria.

CP Reading Potential

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
A	N	N	N	N	Y	Y	Y	Y	Y	N	N	N	N	N	Y	N	Y	Y	N	Y	N	N	N	N	N	A
B	N	N	N	Y	Y	Y	Y	Y	N	N	N	N	N	Y	N	Y	Y	Y	Y	N	N	Y	Y	N	Y	B
C	N	N	N	Y	Y	Y	N	N	Y	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	C
D	Y	Y	Y	Y	N	N	Y	Y	Y	N	N	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	D
E	N	Y	N	Y	N	Y	N	N	Y	N	N	N	N	Y	N	Y	Y	N	Y	Y	Y	Y	Y	N	Y	E
					F	N	N												N	Y	F					
					G	N	N												N/A	N/A	G					

N	=	Does not statisfy the minimum CP reading criteria	62
Y	=	Statisfies the minimum CP reading criteria	69
N/A	=	No reading data	2

Figure 4. CP Potential Survey Results

3.2. Pile UTM Inspection Results

A visual survey was conducted on all 133 existing piles. It was found that 17 piles were repainted from previous repair activities in 2004. These 17 piles have a relatively fair condition, i.e., no holes due to corrosion occur. The survey then proceeded to the UTM process. The number of jetty piles undertaken by UTM inspection is highly dependent on the budget availability and the inspector's justification. In this case study, the UTM inspection was carried out on 40 piles that experienced the severest corrosion visually. Figure 5 explains piles' location carried out by the UTM survey based on visual surveys.

Maps of Surveyed Piles

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
A	R	S	S	S	S		R		S		S		S		S	R								R	S	A
B											S		S		S		S		S		S		S	S	R	B
C	R							R	R	S		S		S		S		S				S		S	S	C
D			S		S		S		S			S											S		R	D
E	R	S		S	R			S	R	R	S			R		R		S		S	S	R		S	R	E
					F	S	S														F					
					G																G					

Keterangan

R	=	Visual survey: repainted from previous repair activities	17
S	=	Thickness survey measured	41

Figure 5. Maps of Surveyed Pile

The selection of jetty piles that undergo the UTM survey is based on the inspector's justification. The corrosion inspector assessed the level of corrosion visually and then chose the pile. Figure 6 gives the visual example of a jetty group that did not experience damage due to corrosion. Hence UTM was not chosen for this group. Pile number 6A is an example of the pile facing the sea. Pile number 20F represents the pile in the trestle area, while pile number 13D gives an overview of the pile's condition facing the land.

The pile group that had undergone repairs was not chosen for UTM. Figure 7 gives a visual example of the group. Pile number 16A gives the example of a condition for the pile facing the sea, while pile number 25D for the pile facing the land. There are no piles repaired in the trestle area.

The two groups above can be compared visually with Figure 8, which provides visual inspection examples of piles that fall within the inspection criteria. Pile number 2A gives the example of heavily corroded piles facing the sea, pile number 7F presents a picture of jetty piles condition in the trestle area, while pile number 15D represents jetty side facing the land.

Thickness measurements are made at five segment elevation points with each of 4 quadrants at each segment. The selected elevation is 0 m from MSL (Mean Sea Level); 1 m above and below the MSL, 2 m above and below the MSL so that the corrosion conditions in the splash zone can be well-mapped. Figure 9 gives the illustration of the measurement point.

Table 2 provides an example of UTM results on pile number 2A. The remainder of the inspection result gives a relatively similar result that there are excessive corrosion and holes in the piles.

Figure 6. Visual Inspection of Relatively Healthy Jetty Pile (from left to right: 6C, 13D, 20F)

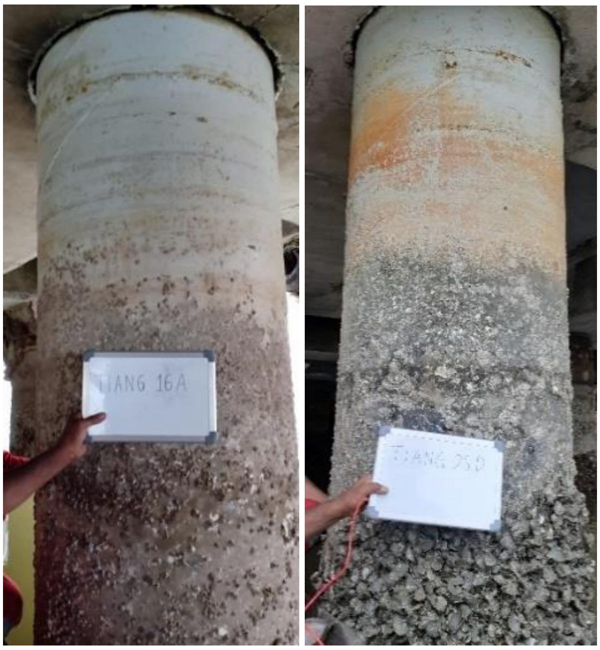
Figure 7. Visual Inspection of Previously Repaired Jetty Piles (from left to right: 16A dan 25D)

Figure 8. Visual inspection of heavily corroded jetty piles (from left to right: 2A, 7F, dan 15D)

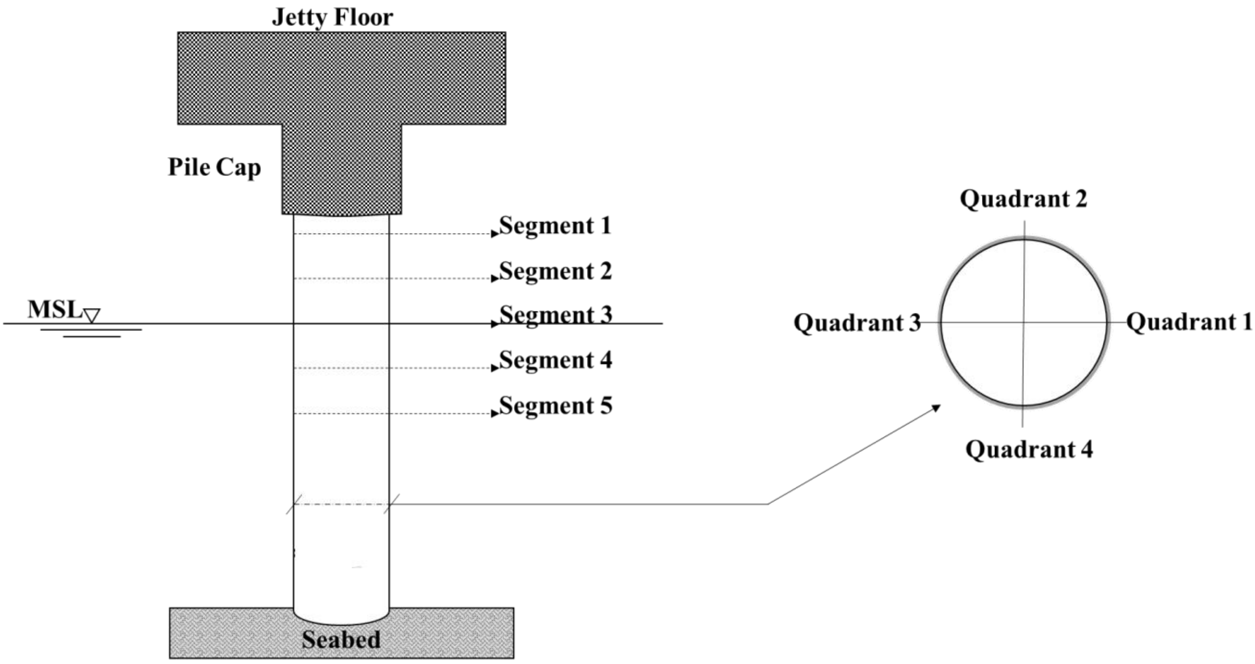

Figure 9. Inspection Measurement Point

Table 2. Example of UTM Result for Pile Number 2A

Quadrant	Thickness per segment (mm)				
	1	2	3	4	5
1	3.00	3.05	3.00	0.00	2.85
2	4.55	4.85	5.10	4.75	4.65
3	8.80	8.80	8.80	8.85	5.55
4	5.10	4.90	5.20	5.50	5.95

3.3. Structural Modelling

The jetty structure is modeled using SACS (Structural Analysis Computer System) software. This software is a Finite Element Analysis (FEA) software, using the beam element type for each member. The beam element is a finite element whose stiffness matrix includes axial force, shear force, and bending moment effects written in Eq. 1 [14]:

$$k = \left[\begin{array}{cccccc:cccccc}
\hat{d}_{1x} & \hat{d}_{1y} & \hat{d}_{1z} & \hat{\theta}_{1x} & \hat{\theta}_{1y} & \hat{\theta}_{1z} & \hat{d}_{2x} & \hat{d}_{2y} & \hat{d}_{2z} & \hat{\theta}_{2x} & \hat{\theta}_{2y} & \hat{\theta}_{2z} \\
\frac{AE}{L} & 0 & 0 & 0 & 0 & 0 & -\frac{AE}{L} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{12EI_z}{L^3} & 0 & 0 & 0 & \frac{6EI_z}{L^2} & 0 & -\frac{12EI_z}{L^3} & 0 & 0 & 0 & \frac{6EI_z}{L^2} \\
0 & 0 & \frac{12EI_y}{L^3} & 0 & -\frac{6EI_y}{L^2} & 0 & 0 & 0 & -\frac{12EI_y}{L^3} & 0 & -\frac{6EI_y}{L^2} & 0 \\
0 & 0 & 0 & \frac{GJ}{L} & 0 & 0 & 0 & 0 & 0 & -\frac{GJ}{L} & 0 & 0 \\
0 & 0 & -\frac{6EI_y}{L^2} & 0 & \frac{4EI_y}{L} & 0 & 0 & 0 & \frac{6EI_y}{L^2} & 0 & \frac{2EI_y}{L} & 0 \\
0 & \frac{6EI_z}{L^2} & 0 & 0 & 0 & \frac{4EI_z}{L} & 0 & -\frac{6EI_z}{L^2} & 0 & 0 & 0 & -\frac{2EI_z}{L} \\
\hdashline
-\frac{AE}{L} & 0 & 0 & 0 & 0 & 0 & \frac{AE}{L} & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{12EI_z}{L^3} & 0 & 0 & 0 & -\frac{6EI_z}{L^2} & 0 & \frac{12EI_z}{L^3} & 0 & 0 & 0 & -\frac{6EI_z}{L^2} \\
0 & 0 & -\frac{12EI_y}{L^3} & 0 & \frac{6EI_y}{L^2} & 0 & 0 & 0 & \frac{12EI_y}{L^3} & 0 & \frac{6EI_y}{L^2} & 0 \\
0 & 0 & 0 & -\frac{GJ}{L} & 0 & 0 & 0 & 0 & 0 & \frac{GJ}{L} & 0 & 0 \\
0 & 0 & -\frac{6EI_y}{L^2} & 0 & \frac{2EI_y}{L} & 0 & 0 & 0 & \frac{6EI_y}{L^2} & 0 & \frac{4EI_y}{L} & 0 \\
0 & \frac{6EI_z}{L^2} & 0 & 0 & 0 & \frac{2EI_z}{L} & 0 & -\frac{6EI_z}{L^2} & 0 & 0 & 0 & \frac{4EI_z}{L}
\end{array}\right] \quad (1)$$

Only the main structural component, i.e., steel piles and concrete decks, are modeled. Soil data is not available from the initial data, so the hard soil is assumed as the two times the deck elevation from seabed [11]. The pinned boundary conditions are used for the bottom end of the pile. The material properties are based on Table 1.

Figure 10 shows the jetty global FEM model. The inset shows the single pile model. The pile thickness is modified as per the inspection report by segmenting method. The pile members' stiffness is reduced by reducing the pile thickness per segment. The segments are divided based on the inspection report described in Figure 9.

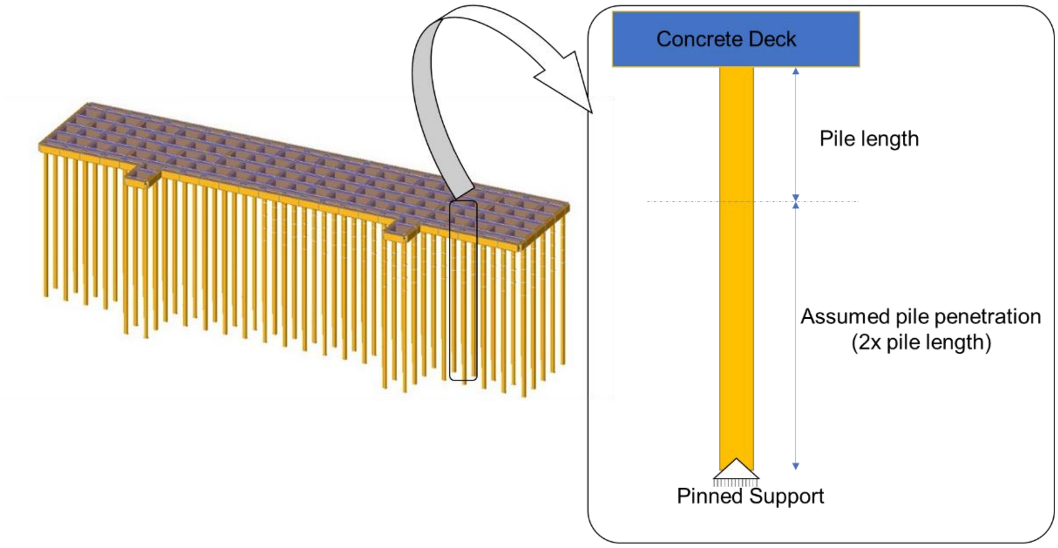

Figure 10. Jetty FEM Model

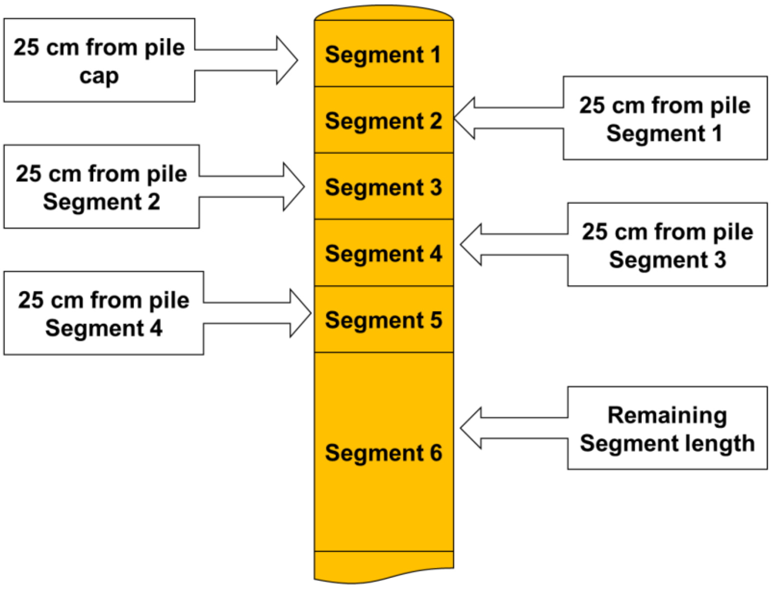

Figure 11. Segmentation Modeling of Pile

Figure 11 explains the detailed measurement of segmenting performed in this paper. The total pile depth being modeled is 30 m (10 m pile + assuming 20 m foundation depth). Sectioning is done every 25 cm according to the inspection. Section 1 to section 5, with thickness according to inspection results, is modeled in FEA software. Whereas section 6, under the splash zone, is modeled with thickness according to the design criteria.

With the segment modeling described in Figure 11, the stiffness matrices of each segment are different in their inertial properties (cross-sectional area A for axial, G for torsional, and I for bending) and are prorated according to each segment length, and can be expressed as:

$$[k] = \sum_{1}^{n} [k_{segment\ n}] \cdot \frac{L_{segment\ n}}{L_{total}} \qquad (2)$$

The marine growth is mainly present based on the survey result; hence the hydrodynamics coefficient is set to rough condition with Cd = 1.1 and Cm = 1.2. The wave kinematics factor is set to 0.95, and the current blockage factor is set to 0.80 [14].

3.4. Load Estimation and Modelling

3.4.1. Dead Load (DL)

Dead loads are the weights of the jetty structure and any permanent equipment and appurtenant structures that do not change with operation mode [14]. Dead loads (Table 3) are modeled as member weight directing towards the Z-axis with waterdepth 10 m.

Table 3. Dead Load

Load (kN)		Center of Gravity (m)
Total Dead Load =	66,869.8	X = -0.009
		Y = -0.393
		Z = 2.308
Element Bouyancy =	15,759.9	X = 0.000
		Y = -0.842
		Z = -12.925
Net Load =	51,109.9	-

3.4.2. Live Load (LL)

Live loads are loads imposed on the jetty during its use that may change either during a mode of operation or from one mode of operation to another. In this study, we use a distributed load with light to heavy activities. Based on reference [15], the live load unit is described as 0.05 ton/m^2.

3.4.3. Ship Berthing Load (SL)

Based on the jetty owner requirement, the maximum assumed vessel type berth to the jetty is a generic Aframax Vessel with tonnage up to 90000 DWT. Vessel size is determined by the following equations [16]:

$$B = 167.39 + 0.0006421\ DWT \qquad (3)$$
$$D = 8.875 + 0.000325\ DWT \qquad (4)$$
$$T = 10.7 + 0.0001\ DWT \qquad (5)$$
$$L_{PP} = 7.35 + 0.00007\ DWT \qquad (6)$$

where Lpp = Length between perpendicular (m), B = Vessel breadth (m), H = Vessel height (m), T = Vessel draft (m). Based on Eq. 3 to Eq 6., the generic vessel data has been generated as shown in Table 4.

Table 4. Generic 90000 DWT Aframax Vessel Particular

Dimension	Notation	Value (m)
Length Between Perpendicular	L_{PP}	226
Breadth	B	39
Height	H	20
Draft	T	14

Ship berthing load is calculated using the static load approach. Figure 12 shows the maximum berthing load scenario. The main aspect to consider when calculating ship berthing load is the wave velocity and the ship trajectory area encountered by the current. Ship static maximum berthing load is calculated as Eq. 7 [17]:

$$S_L = \frac{V_c^2}{2g} C_c \gamma A_s \qquad (7)$$

where S_L = ship berthing load (kN), V_c = maximum current velocity (m/s), C_c = shape coefficient, γ = water specific weight density (kN/m^3), A_s = ship beam area that encountered by current (m^2).

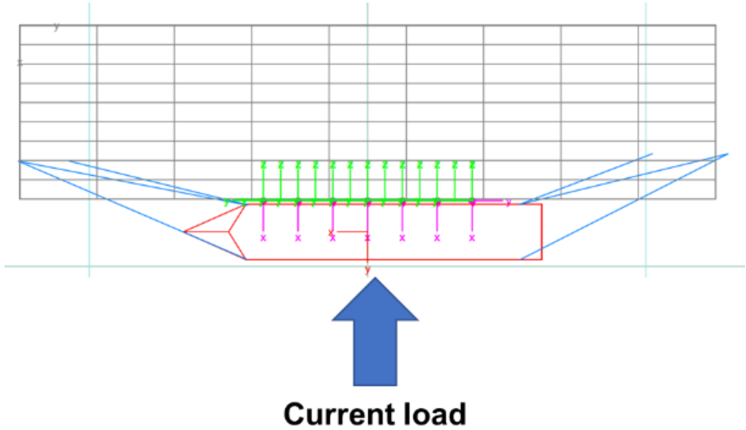

Figure 12. Ship Berthing Load Scenario

3.4.4. Environmental Load (EL)

This study only accounts for the maximum design load of the jetty structure. Therefore, the 100-year return period is used in this analysis, as shown in Table 5 [15].

Table 5. Environmental Load

Items	Value
Encountering angle	90° (beam seas)
Maximum wind speed (Va)	25 m/s
Seawater specific weight (γ)	1.025 ton/m^3
Maximum current velocity (Vc)	1.7 m/s
Significant wave height (Hs)	1 m
Peak-to-peak wave period (Tp)	4 s

3.4.5. Combination Load (CL)

The combination load is based on AISC 9th codes. The matrix is described in Table 6.

Table 6. Combination Load

Combinations	DL	LL	SL	EL
1	1.4	-	-	-
2	1.2	1.6	0.5	-
3	1.2	-	1.6	0.8
4	1.2	-	0.5	1.3
5	1.2	-	-	1.0
6	0.9	-	1.2	1.0

3.5. Strength Analysis of Existing Jetty Piles

Before the repairing strategy decision is made, we must analyze the existing jetty strength to assess its redundancy and strength level based on the existing condition with corrosion and damages as a per-field survey report. Performing this analysis with an appropriate modeling technique is critical because it is at this stage that the existing jetty strength level and its repair strategies will be determined based on the numerical analysis carried out. Static strength analysis is performed in this study to assess the existing jetty piles with corresponding codes and strength criteria, which is also known as Unity Check (UC) ratio [10]. The criteria are determined using the following equation.

$$\frac{f_a}{F_a} + \frac{C_m\sqrt{f_{bx}^2 + f_{by}^2}}{\left(1 - \frac{f_a}{F'_e}\right)F_b} \leq 1.0 \quad (8)$$

$$F'_e = \frac{12\pi E}{23\left(\frac{K l_b}{r_b}\right)^2} \quad (9)$$

where f_a = Actual axial stress (MPa), F_a = Allowable axial strength (MPa), C_m = Reduction coefficient, f_{bx} = Actual bending stress in x-axis (MPa), f_{by} = Actual bending stress in y-axis (MPa), F_b = Allowable bending strength (MPa).

The required UC value for each of the piles is below 1.0. Whenever piles with UC exceed 1.0, they are categorized as 'damaged' so that the repairing strategy is needed. Based on the analysis performed, there are 25 out of 133 piles are categorized as 'damaged' piles. These 25 piles are the numerically modified stiffness piles based on the inspection result. Figure 13 below shows the mapping of the damaged structures. From the figure, we can see that the majority of the damaged structures are the seaside-facing piles. The most considerable portion of the stress is caused by the vessel berthing force and the environmental loads.

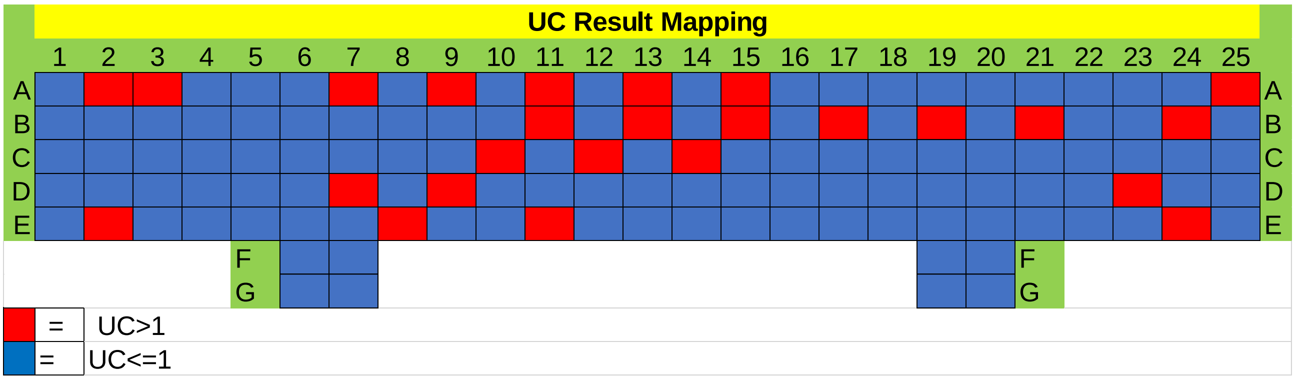

Figure 13. Damaged jetty piles mapping

3.6. Repairing Strategy

The repairs are carried out by the method of patching. This method is done by firstly depriving the part of corroded piles. Then two parts of replacement plates are sleeved onto the piles with a length of 2 meters from the pile cap. Finally, the parts are welded to generate a 'patch' for the damaged pile. The cross-sectional dimension of the part is equal to the initial design criteria, 762 mm and 12 mm for diameter and thickness, respectively. Yield strength was reduced to 85% from initial yield strength to accommodate the uncertainties and the possibility of strength reduction from the patched piles. The yield strength of the piles that are found have been repaired before this analysis are also reduced. The illustration of the patching method is shown in Figure 14.

Improvement of the corrosion protection system (CP) is also carried out by installing a new system that protects the pile section underwater. Meanwhile, the piles above the waterline, especially in the splash zone, are equipped with composite wrapping and coating to avoid corrosion, as shown in Figure 15.

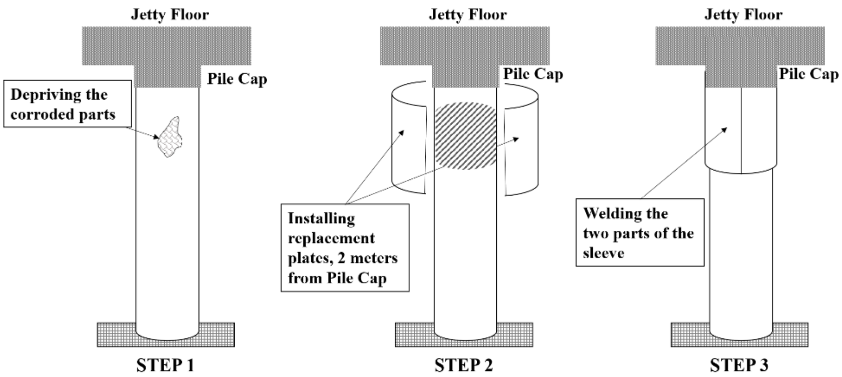

Figure 14. Patching method illustration

Figure 15. Composite Wrapping Installation

vary the number of piles repaired. The first scenario is to repair only 25 damaged piles from the existing jetty piles strength analysis. This is the bare minimum scenario that should be performed to restore the jetty performance. The second scenario is to repair all 40 corroded piles based on the field survey report. The third is the most conservative scenario, which is to repair all 133. We assess the possibility of extending the service life of this jetty up to 35 years after the repair by examining whether the structure can withstand the maximum load from the operation. The factors are not only the structural strength, but also related with the service life of the CP system installed to this jetty.

Based on the applicable codes [16], Table 7 expresses jetty piles' corrosion rate. It can be inferred that the corrosion rate of the steel pile jetty above HWL is 0.3 mm/year. The corrosion is assumed to occur when the CP system is entirely depleted and unable to protect the corrosion pile. Based on the specification, this CP system's failure period is 20 years before the corrosion starts to occur.

Table 7. Corrosion Rate Per Year Code [16]

Position	**Elevation**	**Corrosion rate (mm/year)**
Sea side	Above HWL	0.3
	HWL to LWL -1 m	0.1 - 0.3
	LWL -1 m to Seabed	0.1 - 0.2
	Below seabed	0.03
Ground side	Above ground	0.1
	Below ground	0.03
	Above HWL	0.3

Table 8 shows the pile thickness prediction for repaired and unrepaired piles, assuming no repairs are performed onwards. The thickness reduction due to corrosion is started at year-21 after the depletion of the CP system.

Table 8. Prediction of Pile Thickness

Years after repair	Corrosion occured?	Wall thickness of repaired piles (mm)	Wall thickness of unrepaired piles (mm)
20	No	12.00	9.00
25	Yes	11.15	8.15
30	Yes	10.30	7.30
35	Yes	9.45	6.45

3.6.1. Scenario 1: Repairing the damaged piles (25 Piles)

The first scenario is to apply repair to 25 damaged piles as per existing structure strength analysis. Figure 16 shows the UC prediction for up to 30 years of service life. The piles' performance declines as the UC increase along with decreasing pile thickness due to corrosion. The chart is divided into two zones, blue and red. The blue zone represents the condition where the UC <1 and the structure is considered safe. The red zone represents the condition where the UC> 1 and the structures are considered unsafe. The line diagram in black is the UC's condition immediately after repair until the 20th year, assuming the CP is working correctly. It can be observed that all the piles are in the blue zone. The line chart in red shows the UC in the 25th year of operation. It can be seen that some of the piles have UC> 1, namely piles in row numbers 1, 4, 19, and 25. The blue graphs are for the 30-year corrosion scenarios and are mostly in the red zone, so they are declared unsafe. Thus, with a repair scenario of 25 piles, the structure can last up to 25 years.

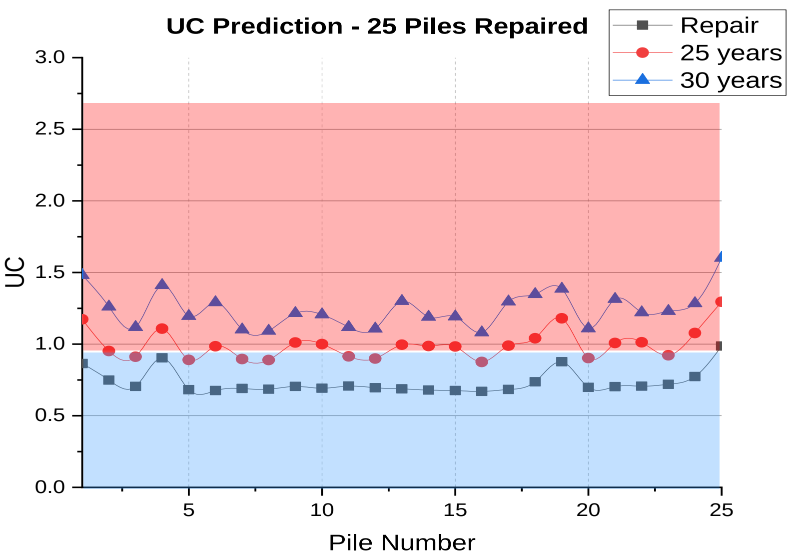

Figure 16. Average jetty piles UC ratio for each row – Scenario 1

3.6.2. Scenario 2: Repairing the Corroded Piles (40 Piles)

The second scenario is to apply repair to 40 corroded piles as per existing structural strength analysis. Figure 17 shows the UC prediction for up to 35 years of service life. It can be observed that with a repair scenario at 40 piles, the structure can last up to 30 years. The chart is again divided into blue and red, with the same criteria as Scenario 1. The line black in yellow is the UC's condition immediately after repair until the 20th year, assuming the CP system works correctly.

The red and orange lines are the UC in years 25 and 30, respectively. There are six piles in the red zone. However, they are still within safe limits because the value is below 1.05. In comparison, the green lines are a 35-year corrosion scenario. Most of the UC is in the red zone. Hence, with a repair scenario of 40 piles, the structure could last up to 30 years.

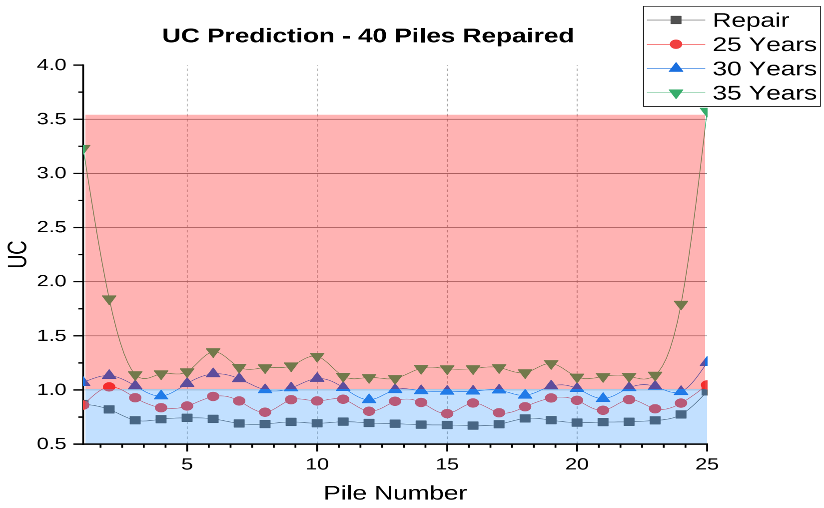

Figure 17. Average Jetty Piles UC Ratio for Each Row – Scenario 2

3.6.3. Scenario 3: Repairing All Piles

The last scenario to be carried out is to repair all 133 piles. It can be observed from Figure 18 the structure can last up to more than 35 years. This scenario is an obvious result looking at the numbers of jetty repairs performed. However, this scenario's best UC result does not represent the best strategy for aged jetty repair. The main factor to select scenario 1, scenario 2, or scenario 3 is the designated duration of jetty life extension.

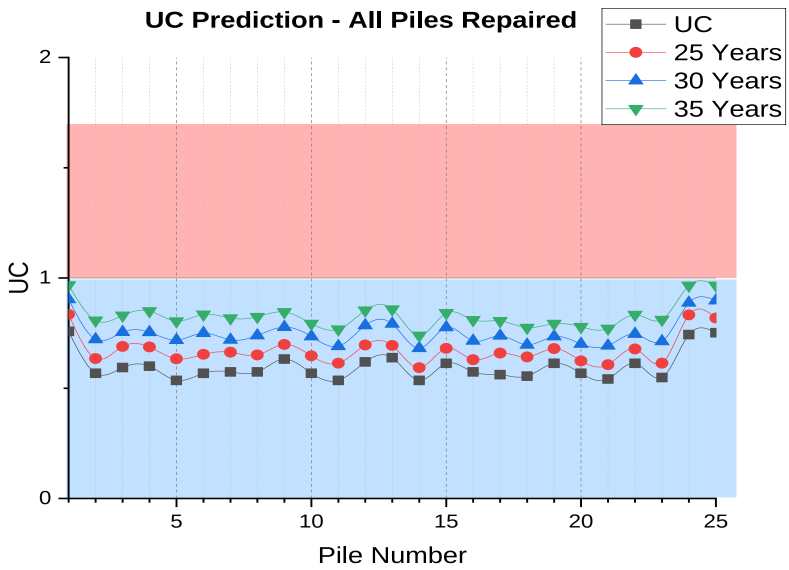

Figure 18. Average jetty piles UC ratio for each row – Scenario 3

4. Conclusion

The strategy to select the number of piles to be repaired is provided. The strategy is supported by the thickness and corrosion protection measurement from the field inspection. From the visual survey results, 40 piles were monitored visually in need of repair, and 69 piles do not meet the minimum Cathodic Protection standards, while 62 piles still meet the Cathodic Protection minimum standards. These surveys are the requirement that should be carried out to determine the current condition of the pile structure.

The structure's static analysis is then carried out by modifying the thickness according to the survey results. Based on the structural analysis, 25 piles exceed the allowable stress criteria. Piles that exceed the allowable stress criteria are the ones with mild to severe corrosion. Planning and analysis of repair scenarios have been carried out on damaged piles, corroded piles, and entire piles. The number of piles to be repaired is made based on the current static analysis results, survey results, and cost justification based on the jetty owner's financial capacity. The selection of the number of piles to be repaired is also measured from structure service life determined by the port owner.

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