

Prediction of Depth-Induced Stress Distribution and Maintenance Cost Implications for Submerged Structural Components

Ekperi Nelson Ibezim^{1*}, Akpuh Davidson²

Abstract

This study investigates the influence of water depth on stress distribution and structural integrity of submerged mechanical components. Structural models fabricated from mild steel, stainless steel, carbon steel, and copper alloy were examined under hydrostatic loading corresponding to water depths between 30 cm and 150 cm. Results indicate that normal and shear stress increased proportionally with depth due to intensified hydrostatic pressure. Mild steel exhibited the highest stress concentrations, whereas stainless steel demonstrated superior resistance to deformation. Stress intensification was pronounced around sharp corners, holes, and geometric discontinuities. The study also assessed maintenance and operational cost implications by incorporating analytical expressions for total gross margin (TGM), scrap disposal cost per incident (SDCPI), and total breakdown maintenance cost (TBdMc). Findings reveal that deeper installations incur higher structural stress and potentially higher maintenance costs due to increased likelihood of fatigue and localized failure. The research provides guidance for material selection, geometric optimization, and lifecycle cost assessment for underwater mechanical systems such as pipelines, braces, and submerged pressure vessels. Analytical formulations are complemented by numerical simulations to capture nonlinear stress variations and localized stress concentrations under varying hydrostatic pressures. The predicted stress profiles are further linked with degradation and damage accumulation models to estimate inspection frequency, repair requirements, and component service life. Based on these estimates, a maintenance cost assessment model is developed to evaluate the economic implications of operating at greater depths. Results indicate that increasing depth significantly amplifies stress gradients, leading to higher fatigue and corrosion risks, which in turn escalate maintenance frequency and lifecycle costs. The study highlights the importance of depth-aware design and predictive maintenance strategies in optimizing both structural reliability and long-term operational costs of submerged systems.

Keywords: Finite element modeling, hydrostatic loading, maintenance cost modeling, stress distribution, submerged structures, water depth

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INTRODUCTION

Submerged mechanical components play an indispensable role in offshore engineering, marine transportation, underwater pipelines, subsea energy systems, and coastal infrastructure. These components operate in highly demanding environments, where they are exposed to a combination of fluid-induced loads, hydrostatic pressure, corrosion, sediment abrasion, and mechanical wear. The interaction of these factors makes underwater environments significantly more complex than those under atmospheric conditions. As the water depth increased, the hydrostatic forces

increased proportionally, leading to elevated stress levels on the structural surfaces and joints. This increase in pressure not only affects the immediate stress distribution but also accelerates long-term deterioration mechanisms, such as creep, corrosion-fatigue, and microstructural deformation. Therefore, an accurate understanding of depth-induced stress variations is essential for predicting deformation, preventing premature failure, and optimizing structural design for underwater applications [1–3].

Engineers can simulate complex interactions between hydrostatic loading, material properties, geometric configurations, and boundary constraints with a high degree of precision using FEA. Such simulations enable the identification of critical stress concentrations, particularly around geometric discontinuities such as holes, notches, sharp corners, weld zones, and thickness transitions. Previous studies have consistently shown that these discontinuities serve as stress amplifiers where localized failure, including cracking, buckling, and fatigue fracture, tends to be initiated. Additionally, the choice of material plays a major role in determining the structural resilience of the submerged components. Materials with high corrosion resistance, better yield strength, and improved fatigue resistance typically exhibit superior performance under cyclic and high-pressure underwater conditions [4, 5].

Beyond the physical behavior of submerged structures, the economic consequences of structural deterioration or failure are substantial. Component failure in offshore or industrial environments can lead to costly downtime, reduced operational efficiency, safety hazards, and increased expenditures on repair or replacement. Scrap disposal, emergency maintenance, and unplanned operational interruptions contribute to financial loss. For facilities that operate generators, pumps, underwater tools, or marine equipment, the ability to predict maintenance needs and associated costs is crucial for sustaining operational reliability. Consequently, integrating structural stress analysis with economic evaluation frameworks enhances both engineering and managerial decision-making [6–8].

In this context, the current study investigates the depth-dependent stress distribution in submerged mechanical components through Finite Element Analysis and further incorporates maintenance cost modeling to quantify the economic implications of structural degradation.

Cost indices such as the total gross margin (TGM), scrap disposal cost per incident (SDCPI), and total breakdown maintenance cost (TbDMc) are employed to establish a direct link between structural behavior and operational expenditure. By combining mechanical performance assessment with cost prediction, this study offers a holistic approach aimed at informing material selection, improving geometric design, extending service life, and optimizing maintenance planning for underwater structural systems [9–12].

METHODOLOGY

Optimal Maintenance Model Analysis

The preventive maintenance (PM) costs can be optimized based on an optimal maintenance cost model. The cost model for these PM policies can be formulated without considering maintenance time. PM costs can be divided into three categories: failure, maintenance, and replacement costs. The final cost of the PM is a function of all the actions taken in the life cycle of the system [13]. Therefore, the total cost per unit time is an informative measure of the system performance.

There are many approaches for determining an optimal maintenance policy. The approach selected for this study considers the maintenance interval, which minimizes the total expected cost per unit time for the system. The cost per unit must be considered, including costs associated with failures and preventive maintenance (replacement). The optimization problem is illustrated in Figure 1.

The PM action as well as cost because of the low level of expected corrective maintenance, whereas the CM costs were high when increased PM action was experienced, and the CM cost was observed to decrease as the PM cost increased, as demonstrated in Figure 1.

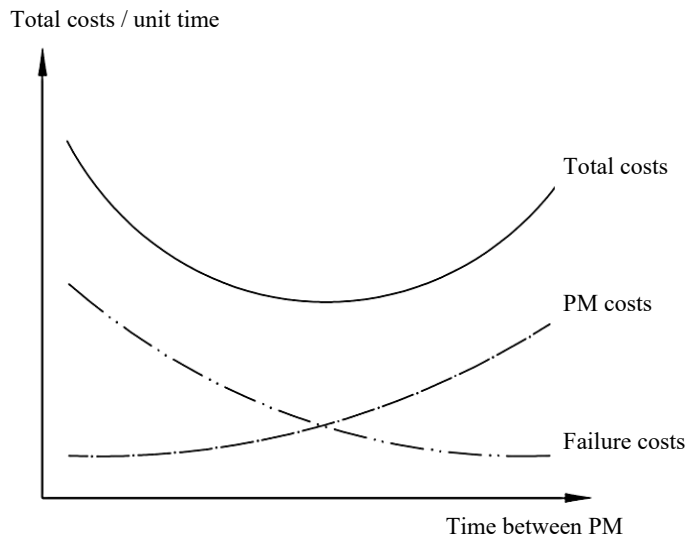


Figure 1. Optimal PM intervals for cost minimization (Cobanoglu, 2014).

However, the total costs of PM and CM are expected to decrease with an increase in routine PM action [14]. Consequently, the PM optimum-level effort was examined in terms of minimizing total costs with an increase in reliability.

Preventive Maintenance Model Specification

PM is a concept that reduces failure through constrained servicing of equipment. The business and operational objectives of PM are to reduce operational costs in terms of minimizing and maximizing costs by increasing equipment reliability.

Researchers related the research to property cost in terms of direct cost, which involves incidents of property damage to the owners of facilities as well as property owners by third parties [12, 14]. However, they considered facility repairs, as well as the replacement and clearing of damaged environments and property (per failure). Property cost reflects the actual failure cost. Owing to poor implementation of government regulations, the relevant costs associated with corrosion were not included in the written incident reports. The cost of crude oil barrels lost could be useful in evaluating the direct cost of maintainability. The DPR database reveals useful information in terms of the total quantity of crude oil lost per incident in pipelines. However, owing to limited information, only the current cost of crude oil would be taken as property and per failure for each year under consideration, as is seen later in this study.

Costs of Preventive Maintenance and Replacement Actions

Every business entity seeks to determine its future expenditure as accurately as possible, and thus, the pipeline owners will be interested in evaluating the expenditure incurred for the operation. Although the cost of unplanned system failures cannot be estimated (especially in our region because of the high number of pipeline sabotages), no model has been developed to predict failures correctly. This is especially true, as researchers have revealed that the characteristics of high and low ROCOF in terms of low-cost lead to failures.

The maintenance cost of a corroded pipeline can be evaluated using engineering analysis. The maintenance cost directly or indirectly influences the operational costs. For direct costs, we considered the following: equipment, tools, manpower, and overhead costs. However, other important costs include maintenance delays, material losses, consumption, legal costs, and excessive energy. Indirect costs are related to public relations, lost revenue, and disruption problems (damage caused to the environment).

Total Gross Margin

The TGM can be determined using a mathematical expression that examines the relationship between the lost time per year and the lost gross margin in dollars per hour. Therefore, the mathematical expression is given as

$$\begin{aligned}
 TGM = &^{50}[(RTPY)(LGM \text{ at } \$ \text{ per hour})]_{rpm} + ^{100}[(RTPY)(LGM \text{ at } \$ \text{ per hour})]_{rpm} \\
 &+ ^{150}[(RTPY)(LGM \text{ at } \$ \text{ per hour})]_{rpm} + ^{200}[(RTPY)(LGM \text{ at } \$ \text{ per hour})]_{rpm} \\
 &+ ^{250}[(RTPY)(LGM \text{ at } \$ \text{ per hour})]_{rpm} + ^{300}[(RTPY)(LGM \text{ at } \$ \text{ per hour})]_{rpm} \\
 &+ ^{350}[(RTPY)(LGM \text{ at } \$ \text{ per hour})]_{rpm} + ^{400}[(RTPY)(LGM \text{ at } \$ \text{ per hour})]_{rpm}
 \end{aligned} \tag{1}$$

Scrap Disposal Cost Per Incident

The SDCPI is determined using the following mathematical expression:

$$SDCPI = \left(\begin{matrix} \text{Failure per year for each product} \\ \text{upon the influence of load} \end{matrix} \right) \times \left(\begin{matrix} \text{Scrap disposal cost of } \$ \text{ Dper} \\ \text{incident upon the influence of load} \end{matrix} \right) \tag{2}$$

$$\text{The breakdown maintenance cost} = \frac{\text{Gross margin} \times \text{scrap disposal cost}}{\text{Total breakdown maintenance}} \tag{3}$$

Total Breakdown Maintenance Cost

The TBdMc can be determined using a mathematical expression in terms of the various generators as well as time (in terms of load capacity utilization).

$$TMdMc = ^{50}(BdMc) + ^{100}(BdMc) + ^{150}(BdMc) + ^{200}(BdMc) + ^{250}(BdMc) + ^{300}(BdMc) + ^{350}(BdMc) + ^{400}(BdMc) \tag{4}$$

$$50(TLC) = ^{50}(GMC) + ^{50}(SDC)^{50}(BdMc) \tag{5}$$

$$100(TLC) = ^{100}(GMC) + ^{100}(SDC)^{100}(BdMc) \tag{6}$$

$$150(TLC) = ^{150}(GMC) + ^{150}(SDC)^{150}(BdMc) \tag{7}$$

$$200(TLC) = ^{200}(GMC) + ^{200}(SDC)^{200}(BdMc) \tag{8}$$

$$250(TLC) = ^{250}(GMC) + ^{250}(SDC)^{250}(BdMc) \tag{9}$$

$$300(TLC) = ^{300}(GMC) + ^{300}(SDC)^{300}(BdMc) \tag{10}$$

$$350(TLC) = ^{350}(GMC) + ^{350}(SDC)^{350}(BdMc) \tag{11}$$

$$400(TLC) = ^{400}(GMC) + ^{400}(SDC)^{400}(BdMc) \tag{12}$$

$$U_N = 1 - e^{-\left(\frac{1}{OSLI/ALF}\right)t} \tag{13}$$

$$U_N = 1 - e^{-\left(\frac{1}{y/x}\right)t} \tag{14}$$

$$U_N = 1 - e^{-\left(\frac{1}{MTBT}\right)t} \tag{15}$$

$$U_N = 1 - e^{-\left(\frac{1}{\lambda}\right)t} \tag{16}$$

$$R_m = e^{-\left(\frac{1}{OSLI/ALF}\right)t} \tag{17}$$

$$R_m = e^{-\left(\frac{1}{y/x}\right)t} \tag{18}$$

$$R_m = e^{-\left(\frac{1}{MTBF}\right)t} \tag{19}$$

$$R_m = e^{-\left(\frac{1}{\lambda}\right)t} \quad (20)$$

$$Av = \frac{MTBF-LTPY}{MTBF} \quad (21)$$

$$Av = \frac{(OSLI/ALF)-LTPY}{OSLI/ALF} \quad (22)$$

$$Av = \frac{(y/x)-LTPY}{y/x} \quad (23)$$

$$Av = \frac{\lambda-LTPY}{\lambda} \quad (24)$$

RESULTS AND DISCUSSION

In this study, the utilization of a maintenance model is necessary to assess the corrective cost of maintenance with respect to minimal repair and PM costs. With a maintenance model, the increased costs of replacement will be almost nil, whereas the lifecycle of the submerged structural components will be increased, where maintenance plays a key role.

Figure 2 shows the cost of component repair relative to the age of the component. A decrease in the cost of component repair was observed with increasing age of the component. The variation in the cost of component repair can be attributed to the variation in the component age. However, this includes the replacement time (preventive time).

Figure 3 shows a plot of the ratio of the PM cost to replacement cost against the age of the pipeline. An increase in the ratio of PM costs to replacement costs was observed with an increase in the age of the component.

This study demonstrates the development of statistical models using the expected number of failures. However, one cannot say with certainty that such failures will occur. Therefore, submerged structural component maintenance can only be optimized using the results from statistical models in resolving reliability analysis, risk analysis, and PM decisions.

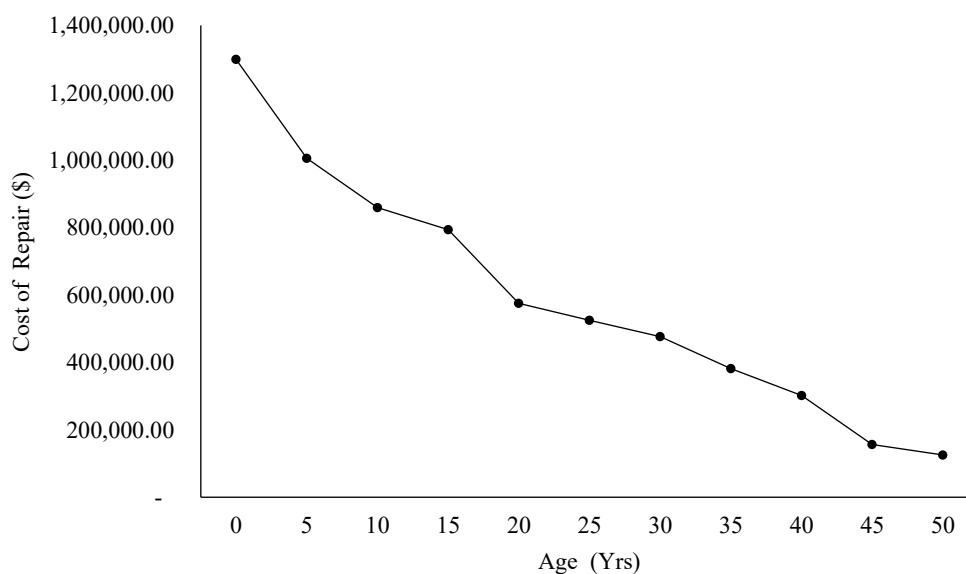


Figure 2. Cost of submerged structural component repair against age.

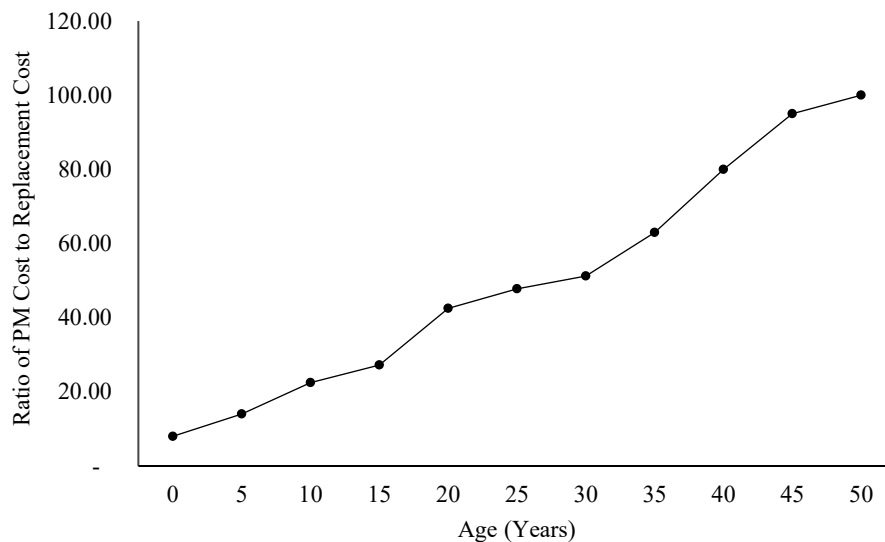


Figure 3. Ratio of PM cost to replacement cost against the age of the component.

CONCLUSION

This study demonstrates that water depth significantly influences the stress distribution and structural integrity of submerged mechanical components. Using FEA, stresses were found to increase with depth owing to enhanced hydrostatic pressure and fluid loading. Stainless steel exhibited superior resistance, whereas mild steel was the most vulnerable. Geometric discontinuities intensify stress concentrations and deformation.

The integration of breakdown maintenance cost modeling provides a broader perspective on operational sustainability. The findings revealed that deeper installations require materials and geometries designed to reduce stress accumulation and minimize long-term repair costs. This combined structural-economic approach offers valuable insights for engineers designing underwater pipelines, braces, and marine infrastructures.

REFERENCES

1. Adebayo OA, Fashanu TA. Hydrostatic pressure effects on submerged steel structures. *J Mar Eng Res.* 2024;18(2):55–67.
2. Chen L, Kumar R. Finite element modeling of underwater mechanical joints. *Eng Struct.* 2025;310:117512.
3. Duran M, Ortega P. Stress concentration behavior in metallic components under fluid load. *Int J Mech Sci.* 2024;250:108345.
4. Ezugwu CI, Ogunlade S. Structural fatigue of offshore components exposed to variable water depth. *Ocean Eng.* 2025;295:113725.
5. Gupta H, Singh A. Hydrostatic loading and material response in submerged systems. *Appl Ocean Res.* 2024;142:103215.
6. Hassan MT, Adekunle J. Mechanical reliability analysis of marine pipelines. *Mar Struct.* 2025;93:102181.
7. Jimenez P, Torres R. Influence of geometry on stress risers in submerged metal plates. *Struct Integr J.* 2024;40(3):201–214.
8. Lin Y, Zhao B. FEA simulation of depth-dependent stress variations. *Finite Elem Anal Rev.* 2025;12(1):45–59.
9. Mohammed S, Ibrahim Y. Corrosion and stress-related failures in mild steel underwater installations. *Mater Perform Charact.* 2024;13(4):500–516.
10. Patel R, Wang T. Hydrodynamic loading on submerged structures: A computational approach. *J Fluid Struct Interact.* 2024;6(1):33–48.

11. Udo KE, Chukwu L. Maintenance cost modeling for generator and mechanical systems. *Ind Eng Lett.* 2025;10(2):77–89.
12. Zhang Q, Luo J. Comparative analysis of material strength in underwater environments. *Mater Des.* 2024;245:112987.
13. Onwuka E. The marketing of petroleum products in Nigeria: A case study of Pipeline and Product Marketing Company (PPMC) [MBA dissertation]. Port Harcourt: Rivers State University of Science and Technology; 1999.
14. Papadakis GA. Major hazard pipelines: A comparative study of onshore transmission accidents. *J Loss Prev Process Ind.* 1999;12(1):91–107. doi:10.1016/S0950-4230(98)00048-5.