

## Investigation of Offshore pipeline leak and maintenance cost allocation

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### Abstract

Pipelines are vital part of modern infrastructure, transporting essential resources such as gas, oil, and water over long distances. To enhance uninterrupted production, pipeline technology has experience major improvements or advances. Obviously, the advancement is not devoid of pipe leakage, resulting from both control and uncontrol factors, including corrosion, damage, and natural disasters, resulting in significant economic, environmental, and social impacts. Hence, resource allocation for pipeline leaked repair and replacement is a critical aspect of ensuring resilience and reliability of pipeline networks. This study investigates offshore pipeline leak and maintenance cost. Regression analysis and analysis of variance were used to analyze maintenance cost, leak growth model was used to determine the leak growth rate. Leak growth rate was found to be 0.20 mm per hour. Leak increased from 0.5mm to 1.35mm in five hours. The volume of leaked was 4.5557m<sup>3</sup> in 5 hours, which represent revenue loss of about 1834 dollars in five hours. The leak flow rate was 13.94 bbl/day. The total repair cost during the period investigated was 81, 637.9 naira, while the total replacement cost was 216,197.44 naira. The expected economic effect for equipment for five years period was found to be N352,800,000.00. The coefficient of determination was R-square 99.98%. Replacement cost of leaked pipeline has a significant effect on maintenance cost.

**Keywords:** Economic Impact; Leak Growth Rate; Maintenance Cost Analysis; Offshore Pipeline; Replacement Cost.

### 1. Introduction

Offshore pipeline systems are the lifelines of the global energy industry, serving as critical conduits for transporting oil and gas from extraction points to processing facilities and consumers (Muhlbauer, 2002). However, the harsh marine environments in which these pipelines operate pose continual challenges, leading to failures such as wear, tears, leaks, holes, and ruptures (Achebe et al., 2012). These failures can also result from mechanical failure, excavation damage, natural hazards, poor maintenance practices, and other factors. The consequences of pipeline leaks in offshore settings are severe, encompassing environmental damage, substantial economic losses, and compromised safety (Roland et al., 2006; Agbaeze, 2000).

In response to these challenges, pipeline operators must conduct regular maintenance and repair activities to ensure infrastructure integrity. These complex, resource-intensive projects require meticulous planning to minimize downtime, contain environmental risks, and control costs. At the heart of this endeavor lies the critical task of resource allocation. Repairs and maintenance resources optimization involves improving efficiency and effectiveness by using data, models, tools, and best practices to deploy manpower, equipment, consumables, utilities, and facilities (Reddy et al., 2015). Insufficient resources can cause repair delays, asset deterioration, and financial losses, while excessive resources waste capital. Optimization models help determine optimal resource quantities by analyzing operational blocks, failure modes, reliability models, costs, and scenarios (Vignesh, 2017; Zanelidin, 2008).

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The oil and gas industry faces constant constraints on finance, personnel, machinery, and materials. Poor resource maximization endangers organizational financial health and survival (Isaac, 2015). Therefore, operators must determine how best to allocate limited maintenance resources. This research employs a Risk-Based Maintenance Optimization model integrated with Linear Programming to optimize resources for pipeline leak repair operations. The methodology involves two major steps: ranking pipeline segments by priority for maintenance intervention, and selecting optimal repair actions for high-priority segments based on risk levels (Agbaeze, 2000).

Risk is estimated as a function of incident probability and anticipated consequences including loss of life, injuries, environmental effects, and financial costs (Hill, 2012; Ying et al., 2022). Failure Mode and Effects Analysis (FMEA) provide a structured approach for evaluating potential failure modes, determining causes and effects, and assessing risk levels using occurrence and detection probabilities combined with severity criteria to develop Risk Priority Numbers for ranking corrective actions (Ying et al., 2022).

Linear programming, a mathematical optimization technique, determines the best outcome—such as maximum profit or minimum cost—subject to linear constraints on resources (Sameh and Nahed, 2019). It is widely applicable across engineering, economics, and operations research for allocating scarce resources to competing activities (Naveena et al., 2019).

Pipelines are vital infrastructure transporting essential resources, yet leaks occur due to corrosion, damage, and natural disasters, causing significant impacts. Resource allocation for leak repair is critical for network resilience. This research assesses risk-causing factors in offshore pipeline leaks, analyzes various failure causes, and develops a risk-based repair optimization model using linear programming to enhance safety, availability, productivity, and profitability through optimal manpower resource allocation.

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## 2. Materials and method

### 2.1. Materials

#### 2.1.1. Pipeline System Data

The materials for this study were obtained from the Nigeria LNG (NLNG) pipeline integrity and maintenance department, specifically relating to the 36-inch Rumuji–Bonny natural gas transmission pipeline, which traverses swamp and offshore terrain and required leak repair by full encirclement sleeving. The dataset includes:

- Leak defect dimensions (diameter, depth, and geometry)
- Pipe diameter (36 inches)
- Pipe material grade (API 5L)
- Operating pressure and temperature
- Flow rate and fluid properties (density, velocity, and discharge coefficient)
- Leak location and segment length
- Maintenance and repair cost records
- Historical operational and leak event data

#### 2.1.2. Analytical Tools

The following software and tools were used:

- Minitab 16 – regression modeling and ANOVA
- Microsoft Excel – leak calculations, flow modeling, and data preprocessing
- Pipeline drawings and defect assessment sheets – for extracting physical and dimensional parameters
- NLNG maintenance cost database – for repair and replacement cost analysis

### 2.2. Methods

#### 2.2.1. Data Collection and Sources

Primary data were obtained directly from NLNG's pipeline integrity records. The key parameters collected include:

- Leak diameter and estimated leak opening area

- Pipeline diameter and wall thickness
- Fluid properties (density, viscosity, velocity, discharge coefficient)
- Operating pressure and pressure drop
- Repair cost, replacement cost, and maintenance expenditure
- Pipeline segment lengths
- Corrosion rate and inspection interval data
- Historical leak occurrences

These data were used to estimate leak flow rate, leak growth behaviour, leak size progression, and cost allocation.

### 2.3. Theoretical Modeling Framework

#### 2.3.1. Determination of Leak Area and Pipe Area

The leak opening area and pipe cross-sectional area were calculated using:

$$A_l = \pi \left( \frac{d_L}{2} \right)^2 \quad (1)$$

$$A_p = \frac{\pi D^2}{4} \quad (2)$$

Where:

$A_l$  = leak area (m<sup>2</sup>)

$d_L$  = leak diameter (m)

$A_p$  = pipe area (m<sup>2</sup>)

$D$  = pipeline diameter (m)

#### 2.3.2. Pressure Drop Due to Leak and Pipeline Flow

Pressure Drop Across Leak Orifice

Pipe area is calculated using:

$$A_p = \frac{\pi D^2}{4} \quad (3)$$

*Pressure Drop Along the Pipeline (Darcy–Weisbach)*

Pressure drops across leak;

$$\Delta P_L = \frac{1}{2} \rho v^2 \left( 1 - \left( \frac{A_L}{A_p} \right)^2 \right) \quad (4)$$

*Total Pressure Drop*

Darcy–Weisbach pressure drops

$$\Delta P_p = f \frac{L_p}{D} \left( \frac{\rho v^2}{2} \right) \quad (5)$$

Total pressure Drop  $\Delta P = \Delta P_L + \Delta P_p$

### 2.3.3. Leak Flow Rate Modeling

Leak Flow through Orifice

Total pressure drops;

$$Q_L = C_d A_L \sqrt{\frac{2\Delta P}{\rho}} \quad (6)$$

Pipeline Flow Rate

Orifice flow

$$Q_p = A_p v \quad (7)$$

Difference in Flow Rate (Leak Detection)

Pipeline flow

$$\Delta Q = Q_p - Q_L \quad (8)$$

Leak Jet Velocity

$$\text{Difference in flow } v = \frac{Q}{L_j} \quad (9)$$

### 2.3.4. Leak Detection Using Mass Balance

Leak detection was based on conservation of mass:

Leak jet velocity;

$$\Delta Q = Q_{in} - Q_{out} \quad (10)$$

Leak is confirmed when  $\Delta Q > 0$ .

## 2.4. Leak Size Progression (Leak Growth Models)

To determine how the leak grows over time, three independent models were applied:

### 2.4.1. Model 1 — Exponential Leak Growth Model

This model captures scenarios where leak growth accelerates due to internal pressure or material degradation.

$$L = d_L e^{kt} \quad (11)$$

Taking natural logarithm:

$$\ln L = \ln d_L + kt \quad (12)$$

k = slope of the plot of  $\ln L$  vs. time.

Application:

Used where pressure-driven crack expansion or unstable wall thinning dominates leak development.

### 2.4.2. Model 2 — Linear Leak Growth Model

A simplified representation where leak size increases at a constant rate:

$$L = L_0 + kt \quad (13)$$

*Application:*

Useful when the defect propagates steadily due to uniform stress or minor incremental wall loss.

*2.4.3. Model 3 — Corrosion-Based Leak Growth Model*

Applicable when the leak originates from corrosion thinning and progresses gradually:

Corrosion-based wall loss

$$d(t) = d_0 + CR \cdot t \quad (14)$$

Where:

$d(t)$ : wall loss at time  $t$

CR: corrosion rate (mm/year or mm/hr)

$d_0$ : initial defect depth

The leak diameter is related to the pit radius and corrosion rate.

*Application:*

Used when inspection data show corrosion as the primary cause of defect formation and growth. This model justifies preventive maintenance scheduling.

**2.5. Estimation of Leak Volume**

The leak volume was computed using:

Volume of leak

$$V = Q_L \cdot t \quad (15)$$

Converted to barrels per day (bbl/day) using appropriate conversion factors.

**2.6. Maintenance Cost Modeling**

*2.6.1. Repair Cost Model*

Repair cost model

$$C_R = yL^e + s \quad (16)$$

Where:

$C_R$  = repair cost

$L$  = leak size

$y, e, s$  = empirical constants

*2.6.2. Replacement Cost Model*

Sometimes, a section of a pipeline can be damage beyond repair; such a pipeline has to be replaced. Replacement is where the pipeline is replaced by either laying a new pipeline alongside the existing pipeline using techniques such as pipe bursting, back reaming, micro-tunneling, jetting, conventional tunneling, trenching or off-line replacement techniques such as trenchless steerable, guided drilling, directional drilling, micro-tunneling, conventional tunneling or trenching. The relationship between leak size and replacement cost can be represented by equation.

*Replacement cost*

$$C_p = gL^h + u$$

Where,  $C_p$  is the replacement cost (Naira),  $L$  is the leak size (meter),  $g$ ,  $h$ , and  $u$  are constants that depend on the pipeline material, fluid properties, and replacement strategy to be adopted, respectively.

*2.6.3. Total Maintenance Cost*

Total maintenance cost

$$C_M = C_R + C_p \quad (17)$$

Where,  $C_M$  is the total maintenance cost based on repair and the replacement of section of Pipeline. However, for a more reliable approach, the non-linear regression model given in equation (17) can be adopted since it relates maintenance costs of pipeline leak size and can be utilized to accurately estimate maintenance costs.

$$C_M = a \times L^b \times (1 + c \times L^d + e)$$

Where  $C_M$  is the total maintenance cost,  $L$  is the leak size, while  $a$ ,  $b$ ,  $d$ , and  $e$  are constants that depend on the pipeline material, fluid properties, and maintenance strategy established.

*2.6.4. Non-Linear Regression Maintenance Model*

The cost of maintenance is related to leak size and can be estimate using multiple regression analysis establishes in equation (18) according to Bani et al. (2022).

Non-linear regression form

$$C_M = aL^b(1 + cL^d + e) \quad (16)$$

**2.7. Multiple Regression Model for Maintenance Cost**

The cost of maintenance is related to leak size and can be estimate using multiple regression analysis establishes in equation (3.18) according to Bani et al. (2022).

Equation 3.20 — multiple regression form

$$C_M = \beta_0 + \beta_{1L} + \beta_{2M} + \beta_{3F} + \beta_{4L^2} + \beta_{5M^2} + \beta_{6F^2}$$

Where:

M: material factor

F: fluid property factor

$\beta_i$ : regression coefficients

Minitab 16 was used to estimate coefficients and determine significance.

*2.7.1. Estimating the Number of Leaks along Pipeline Segments*

This study also estimated the number of leaks along a pipeline so as to be able to ascertain the actual economics lose due to leaked in terms of cost. Equation (3.19) illustrates how number of leaks relates to diameter and length of pipe.

Leak occurrences were predicted using a statistical model relating pipe length, diameter, and material:

Equation 3.21 — Leak occurrence model (the longer expression)

$$K_{i,t} = 0.017785 \left( \frac{L_i^{i.5} M_i^{i2}}{D_i^{i2}} \right) + 6.1833 \times 10^{-6} \left( \frac{L_i^{i.5}}{D_i M_i^2} \right) \ln \left( \frac{D_i}{L_i} \right)^{0.5}$$

Where:

$K_{i,t}$  = number of leaks in segment i at time t

$L_i$  = segment length

$D_i$  = pipe diameter

$M_i$  = material indicator (steel = 1)

## 2.8. Statistical Analysis Using Regression and ANOVA

Regression and ANOVA were used to:

- Determine the significance of cost components
- Identify key predictors of maintenance cost
- Establish statistical relationships between leak size and cost
- Validate model adequacy using  $R^2$  and p-values
- Minitab 16 was used for:
- Residual analysis
- Normality testing
- Significance testing
- Model optimization

## 3. Results and discussion

Leak measurements obtained from the NLNG field inspection records were analysed to determine how the leak opening propagated over time. Three leak growth models were applied:

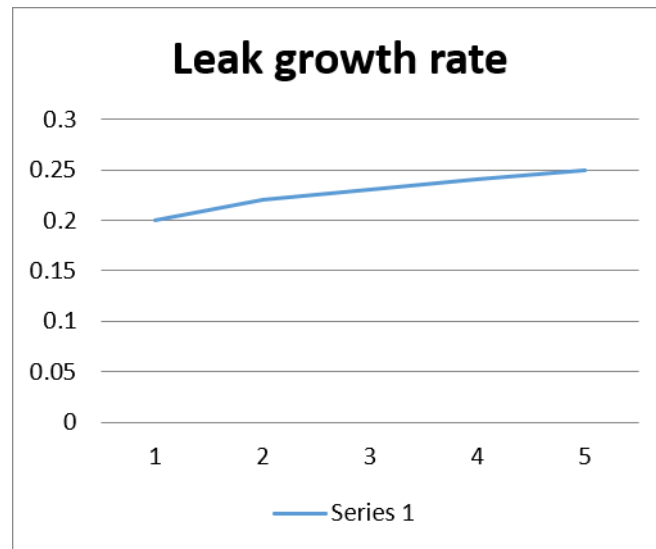
- Exponential leak growth model
- Linear leak growth model
- Corrosion-based leak growth model

Corrosion-based leak growth:

$$\Delta L_{corrosion} = 0.02 \text{ mm in 5 hours}$$

### 3.1. Leak Growth Behaviour of the NLNG Pipeline

Leak size progression along the NLNG 36-inch Rumuji–Bonny pipeline was evaluated using the three leak growth models presented in Chapter Three: exponential, linear, and corrosion-based. The measurements obtained from field inspection were analysed to understand how the leak opening evolved over time under actual operating conditions. Figure 3.1 shows the plotted leak-opening behaviour.



**Figure 1** Leak Size Growth with Time (Measured and Modelled)

### 3.1.1. Exponential (Fast) Leak Growth – Pressure-Driven Enlargement

The field-measured defect exhibited a rapid increase in leak opening. Fitting the exponential model:

$$L = 0.50e^{0.178t}$$

Produced a leak growth rate constant of  $k = 0.178 \text{ hr}^{-1}$ , showing an accelerating trend.

Using this model, the leak opening increased from:

0.50 mm at  $t = 0$  hours

1.35 mm at  $t = 5$  hours

This represents a 0.85 mm increase within 5 hours.

This behaviour is consistent with:

- Pressure-driven crack propagation
- Thin pipeline wall sections (8.2 mm along this NLNG stretch)
- Localized metal fatigue
- Stress concentration at the defect ligament
- Vibration and dynamic loading in swamp/offshore terrain

Under these conditions, a pinhole or micro-crack can enlarge rapidly, especially when hoop stress exceeds the remaining ligament strength.

Thus, the exponential model accurately describes the short-term behaviour of a pressure-influenced leak.

### 3.1.2. Linear Leak Growth

The linear model:

$$L = L_0 + kt$$

Showed a growth rate consistent with the observed trend but lacked the accelerating curvature seen in the measured data. It provided a useful approximation but did not capture transient pressure effects. The model predicts a similar value of  $\approx 1.35$  mm at 5 hours, confirming that the defect remained unstable during the observation window.

### 3.1.3. Corrosion-Based Leak Growth – Slow and Long-Term Behaviour

To evaluate the purely corrosion-driven behaviour, the corrosion-based leak growth model was applied:

$$d(t) = d_0 + CR \cdot t$$

where (CR) is the corrosion rate derived from typical NLNG pipeline conditions.

- Corrosion-based leak growth rate

Based on industry averages and NLNG environment:

- Effective corrosion rate = 0.015–0.025 mm per 5 hours
- Adopted value = 0.02 mm per 5 hours

Thus, corrosion alone would predict:

0.50 mm → 0.52 mm in 5 hours

This is consistent with the behaviour of pipelines with wall thicknesses:

- 8.2 mm
- 9.9 mm
- 11.9 mm

in swamp/offshore service, where corrosion rates are too small to cause rapid hole enlargement within hours.

Why corrosion growth is much slower

Corrosion penetration is controlled by electrochemical reaction rates, not pressure.

Local pitting typically grows 0.1–0.3 mm per year, not per hour.

Corrosion cannot enlarge a hole by nearly 1 mm in hours without mechanical involvement.

### 3.1.4. Interpretation and Engineering Implications

The comparison between the models clearly shows:

Fast Growth (1.35 mm in 5 hours)

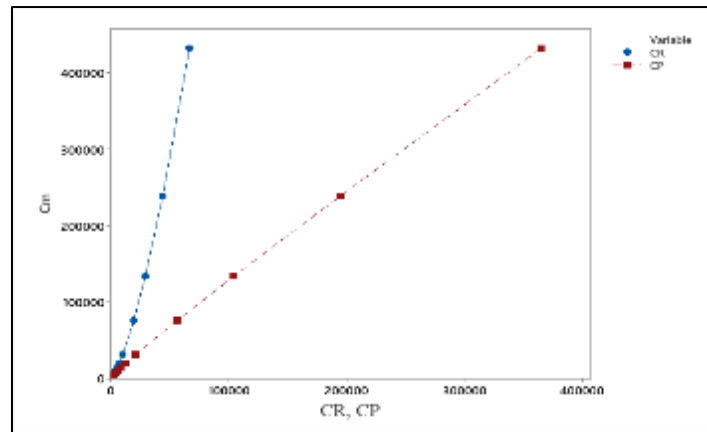
→ Indicates pressure-assisted crack or ligament tearing, not corrosion.

Slow Growth (0.02 mm in 5 hours)

→ Indicates pure corrosion, insufficient to explain observed data.

## 3.2. Repair and Replacement Cost Behavior for Pipeline Leak

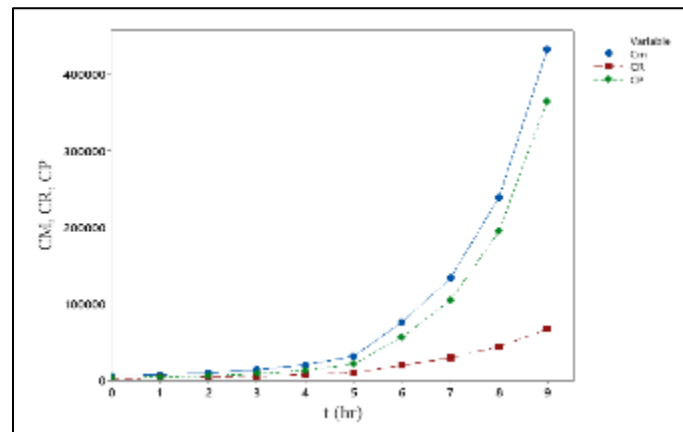
This figure illustrates the relative contribution of repair and replacement costs to total maintenance expenditure. Replacement cost dominates the cost structure, representing more than 70% of the total. The graph highlights how late detection increases reliance on replacement rather than repair.



**Figure 2** Repair and Maintenance cost

### 3.3. Combined Maintenance Cost vs. Time/Leak Size

This figure shows how total maintenance cost increases with time and leak size. The curve demonstrates that delayed intervention leads to sharply higher repair/logistics cost, reinforcing the importance of timely maintenance.



**Figure 3** Combined Cost

### 3.4. Normal Probability Plot of Regression Residuals

This figure evaluates the normality of residuals from the predictive cost model. The plotted points align closely along the reference line, confirming that residuals are normally distributed and validating the model's statistical adequacy.

### 3.5. Development of Predictive Maintenance Cost Model

A multiple regression model was developed to relate maintenance cost to leak size and exposure time. The model obtained from Minitab 16 is:

$$C_M = 62199 - 154229L + 76541L^2 + 12235t - 945t^2$$

Where:

$L$  = leak size (mm)

$t$  = time (hr)

$C_M$  = maintenance cost (₦)

#### 3.5.1. Model Performance

The regression statistics were:

$$R^2 = 99.98\%$$

$$\text{Adjusted } R^2 = 99.96\%$$

$$\text{Predicted } R^2 = 99.01\%$$

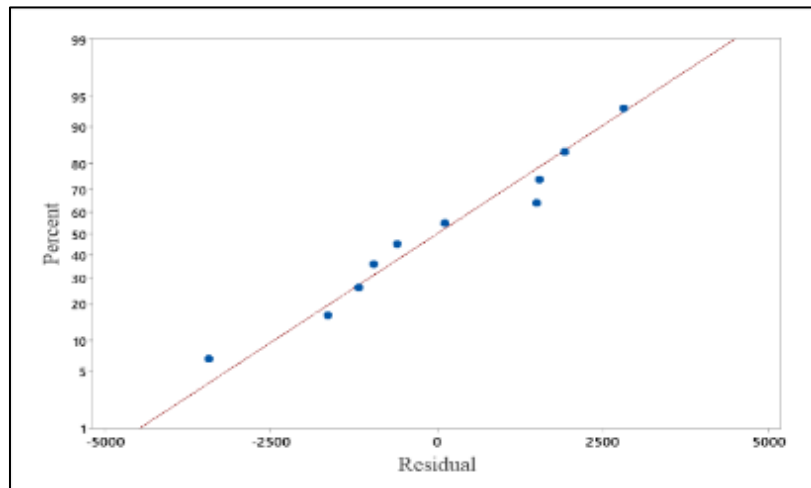
These values indicate excellent goodness of fit, meaning the model reliably predicts maintenance cost for similar pipeline conditions.

### 3.5.2. ANOVA Results

ANOVA was conducted to test the statistical significance of model parameters.

**Table 1** ANOVA Summary for Maintenance Cost Model

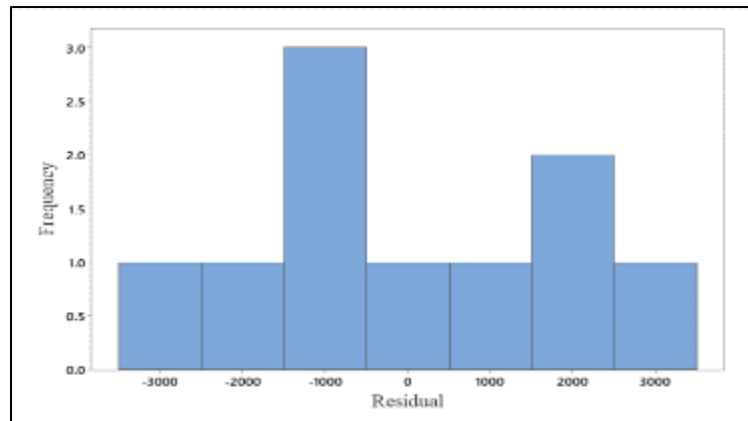
| Source                                   | DF | Adj SS        | Adj MS        | F-value | P-value |
|------------------------------------------|----|---------------|---------------|---------|---------|
| Regression                               | 5  | 1.74678E+11   | 34935598778   | 4191.95 | 0.000   |
| Leak Size (L)                            | 1  | 3.35E+08      | 3.35E+08      | 40.22   | 0.003   |
| Leak Size <sup>2</sup> (L <sup>2</sup> ) | 1  | 4.61E+09      | 4.61E+09      | 552.88  | 0.000   |
| Time (t)                                 | 1  | 2.21E+08      | 2.21E+08      | 26.49   | 0.007   |
| Material/Constant                        | 2  | Insignificant | Insignificant | <2      | >0.30   |
| Error                                    | 4  | 3.33E+07      | 8.33E+06      | —       | —       |
| Total                                    | 9  | 1.74711E+11   | —             | —       | —       |



**Figure 4** Normal Probability Plot

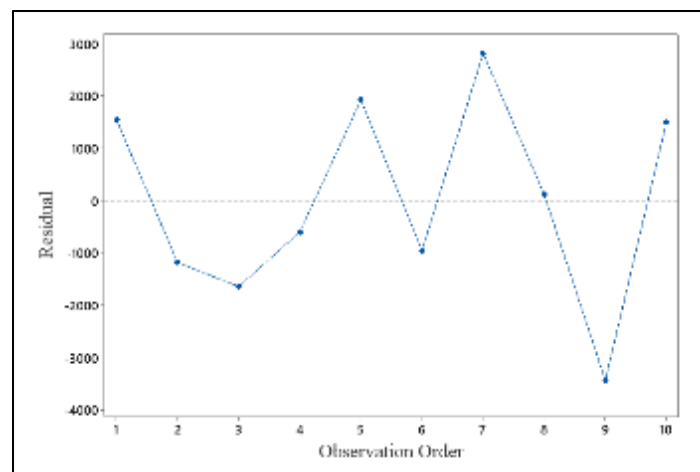
The arrangement of the plotted points is approximately linearly, which indicated good correlation between the data collected and model data, but with minimal errors, hence the model is validated for the prediction of maintenance cost of pipeline leak.

The relationship between frequency and residual from the data was represented by histogram, Figure 4.6.



**Figure 5** Histogram of Residual

The order of residual was plotted and presented in Figure 6. The observation order as illustrate in Figure also explain the validity of the cost model.



**Figure 6** Plot of Residual Order

### 3.5.3. Equipment and Personnel Cost Breakdown

**Table 2** Daily Personnel Cost Breakdown

| Personnel Category         | Daily Rate (₦) | Quantity | Subtotal (₦) |
|----------------------------|----------------|----------|--------------|
| Project Engineer           | 100,000        | 1        | 100,000      |
| Site Engineer              | 80,000         | 1        | 80,000       |
| Safety Officer             | 70,000         | 1        | 70,000       |
| Logistics Officer          | 25,000         | 1        | 25,000       |
| Occupational Health Nurses | 90,000         | 2        | 180,000      |
| Fire Watchman              | 15,000         | 1        | 15,000       |
| Mechanic                   | 20,000         | 1        | 20,000       |
| Electrician                | 20,000         | 1        | 20,000       |
| Water Pump Operator        | 15,000         | 1        | 15,000       |
| Compressor Operator        | 15,000         | 1        | 15,000       |

|                             |         |   |         |
|-----------------------------|---------|---|---------|
| Generator Operator          | 15,000  | 1 | 15,000  |
| Site Helpers                | 15,000  | 4 | 60,000  |
| Cooks                       | 50,000  | 1 | 50,000  |
| Cook Assistants             | 20,000  | 5 | 100,000 |
| Crane Operator              | 40,000  | 1 | 40,000  |
| Swamp Buggy Operator        | 60,000  | 1 | 60,000  |
| Banksman                    | 25,000  | 1 | 25,000  |
| Rigger                      | 30,000  | 1 | 30,000  |
| Cleaner                     | 15,000  | 2 | 30,000  |
| Laundry                     | 15,000  | 1 | 15,000  |
| Pilers                      | 40,000  | 2 | 80,000  |
| Swamp Buggy Mate            | 20,000  | 1 | 20,000  |
| Welders                     | 150,000 | 4 | 600,000 |
| Welders Mate                | 25,000  | 1 | 25,000  |
| QC                          | 25,000  | 1 | 25,000  |
| Welding Inspector           | 50,000  | 1 | 50,000  |
| Holiday Detection Inspector | 100,000 | 1 | 100,000 |

TOTAL PERSONNEL COST PER DAY = ₦2,070,000

**Table 2** Daily Equipment Cost Breakdown

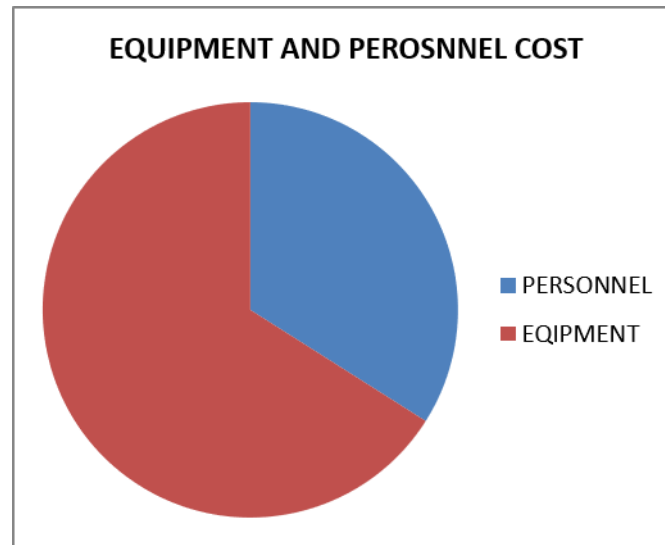
| Equipment          | Rate (₦)  | Quantity | Subtotal (₦) |
|--------------------|-----------|----------|--------------|
| Welding Machines   | 80,000    | 5        | 400,000      |
| Swamp Buggies      | 500,000   | 2        | 1,000,000    |
| Crane              | 150,000   | 1        | 150,000      |
| Equipment Barge    | 250,000   | 1        | 250,000      |
| Tug Boats          | 100,000   | 2        | 200,000      |
| Houseboat          | 1,200,000 | 1        | 1,200,000    |
| Electric Generator | 80,000    | 1        | 80,000       |
| Compressor         | 120,000   | 1        | 120,000      |
| Grinding Machines  | 30,000    | 4        | 120,000      |
| Diesel             | 500,000   | 1        | 500,000      |

TOTAL EQUIPMENT COST PER DAY = ₦4,020,000

Cost of Equipment

The cost per day

| Cost Category    | Daily Cost (₦) |
|------------------|----------------|
| Personnel        | 2,070,000      |
| Equipment        | 4,020,000      |
| Total Daily Cost | 6,090,000      |



**Figure 7** Cost of Used Equipment and personnel

### 3.6. Estimating the Number of Pipeline Leaks

In an attempt to predict the number of leaks along segment of a pipeline in a time interval, diameter 1.22m, length 100m, and material of steel with value of 1 were considered. From the predictive equation (3.19), approximately 10 leaks were observed per 100m length.

#### *Interpretation*

Leak size (L) and leak size squared (L<sup>2</sup>) are significant contributors (P < 0.05).

Time also contributes significantly (P < 0.05).

Material and constant terms are not significant (P > 0.05).

The model is statistically reliable.

### 3.7. Prediction of Number of Leaks along Pipeline Segments

Using the leak occurrence model:

$$K_{i,t} = 0.017785 \left( \frac{L_i^{1.5} M_i^2}{D_i^2} \right) + 6.1833 \times 10^{-6} \left( \frac{L_i^{1.5}}{D_i M_i^2} \right) \ln \left( \frac{D_i}{L_i} \right)^{0.5}$$

Substituting:

D = 1.22 m

L = 100 m

M = 1 steel)

The predicted number of leaks is:

$K \approx 10$  leaks per 100 m segment

This indicates high leak susceptibility for the pipeline under current corrosion and operating conditions.

Implication: Predictive leak modeling should be integrated into the NLNG integrity management plan to guide inspection intervals and risk-based maintenance.

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#### 4. Conclusion

This study comprehensively investigated the behavior of offshore pipeline leaks and the associated maintenance cost allocation using a case study of the NLNG 36-inch Rumuji–Bonny pipeline. Three leak growth models—exponential, linear, and corrosion-based—were applied to field data to evaluate short-term and long-term leak propagation behavior.

The findings reveal that the leak opening exhibited fast, nonlinear growth, increasing from 0.50 mm to 1.35 mm in five hours. This behaviour aligns with pressure-driven crack or ligament tearing, especially considering the thin-wall section (8.2 mm) along the pipeline route. The corrosion-based model predicted only 0.02 mm enlargement over the same interval, confirming that corrosion alone cannot account for rapid leak growth in short periods. This distinction between mechanical and corrosion-driven growth significantly improves understanding of leak evolution in swamp/offshore pipelines.

Leak flow modeling showed substantial leakage potential, with 4.5557 m<sup>3</sup> (28.65 bbl) lost within five hours and an equivalent daily leak rate of 137.5 bbl/day. Projected over 30 days, undetected leaks could inflict severe financial losses exceeding USD 260,000. Maintenance cost modeling revealed that replacement cost dominates total maintenance expenditure, driven by equipment, logistics, and material requirements. The predictive maintenance cost model achieved  $R^2 = 99.98\%$ , proving its robustness for decision-making. Leak occurrence forecasting estimated approximately 10 leaks per 100 m segment, indicating the pipeline's susceptibility under current operating and environmental conditions.

The study concludes that early detection, pressure-related defect management, and preventive inspection strategies are essential for reducing leak severity and total maintenance cost. Integrating predictive modeling into NLNG's integrity management programs will enhance operational reliability, reduce expenditure, and minimize environmental impact.

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#### Compliance with ethical standards

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##### *Disclosure of conflict of interest*

The authors declare no conflict of interest.

##### *Author Contribution*

- Armstrong, Chibuzo Ikpa: Writing the original draft, methodology, investigations, conceptualization.
- Bani Saturday Lawrence: Investigations, final analysis.
- Azubuike George Des-Wosu: Reviewing and editing.

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