https://doi.org/10.54361/ajmas.269737

Original article

The Impact of Rust on Industrial Pipelines Using Non-Destructive Testing Techniques and the Development of Preventive Measures to Protect Equipment from Corrosion

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Abstract

Corrosion is a major factor affecting the integrity of industrial pipelines used for transporting gas, oil, or water, leading to reduced operational efficiency and increased risk of leaks and malfunctions. Therefore, this study aimed to evaluate the effectiveness of non-destructive testing (NDT) techniques in detecting and assessing corrosion, focusing on the problem of corrosion and its evaluation. The study specifically examined Guided Wave Testing (GWT) and Ultrasonic Thickness Measurement (UTM) techniques. The experimental method used a 20-meter-long carbon steel pipe containing ten simulated corrosion defects at varying depths. The results showed that GWT achieved detection rates of 80% at 32 kHz and 90% at 64 kHz, confirming its efficiency in rapid long-distance inspection. Meanwhile, UTM achieved a 100% detection rate for all defects with an absolute mean error of 0.04 mm, reflecting its high accuracy in measuring thickness loss and determining the extent of corrosion.

Keywords: Corrosion, Non-Destructive Testing, Guided Wave Testing, Preventive Maintenance.

Introduction

The oil and gas sector has suffered from corrosion, which has had a tremendous economic and environmental impact within the field, in addition to the severe damage inflicted on facilities such as pipelines, storage tanks, and platform structures [1]. Non-receiving technologies used in the industrial field are of paramount importance for detecting, monitoring and repairing corrosion problems at an early stage [2] Three industry standards have been established to address this issue and serve as the basis for pipeline corrosion research. These include API 571 for flow-induced corrosion and other failure patterns, ASME B31.3 for corrosion design and material selection for high-pressure, high-temperature multiphase pipelines, and finally, ISO 23221 for corrosion monitoring and pipeline safety management throughout their lifecycle. [3] The purpose of destructive testing (DT) is to provide a testing method that analyzes the point at which a component, material, or element fails. This test is known as destructive physical analysis (DPA), as it consists of a qualitative analytical method to determine the properties of the material, such as elasticity, stiffness, tensile strength, and impact resistance. Not all properties can be determined except by using non-destructive testing (NDT) methods, because determining these mechanical properties requires applying a load to the material.[4]

Non-destructive testing (NDT) techniques enable operators to monitor pipelines in real-time, providing vital data for fault prevention. This allows for the continuous development of NDT technologies and the integration of monitoring systems to adopt a proactive approach to pipeline maintenance. [5]

This research primarily aims to explore the latest advancements in non-destructive testing (NDT) techniques for pipeline integrity assessment, focusing on their effectiveness in early corrosion detection and identification of its causes. Early detection and accurate assessment of corrosion are essential for minimizing downtime and extending equipment lifespan.

The current study seeks to reveal the problem of the study and explore the extent to which non-destructive testing techniques contribute to the early detection of corrosion in industrial pipelines and its accurate assessment, and how desired results can be achieved in developing effective preventive measures to protect equipment from corrosion and enhance the safety and reliability of pipelines.

Methods

The research methodology was designed as a quantitative experimental approach, where a controlled experimental environment was created to enable accurate measurement and to complete the analytical comparison of detection probabilities and sizing errors against the dimensions of common and problematic defects.

With reference to the experimental sample, a dataset specifically created for the experiment and a test matrix were used, along with a specially designed pipeline test loop. The pipeline sample consisted of a 20-meter-long, 6-inch-nominal diameter, Type 40 (ASTM A106, Grade B) carbon steel pipe. Ten (10) simulated corrosion defects were fabricated in the pipe wall, classified into three distinct morphological patterns:

- Systematic wall thinning (n = 3): Simulating flux-accelerated corrosion.
- Pitt pools (n = 2): Simulating localized corrosion caused by microorganisms.
- Corrosion spots under insulation (n = 5): Simulating irregular material loss from the outside.
- Defect severity: Defect depths were measured progressively, representing a cross-sectional area (CSA) loss ranging from 3% to 30%.

Received: *11-05-2026* - ***Accepted:*** *09-07-2026* - ***Published:*** *16-07-2026*

Data Collection

Several tests were conducted, (1) First, a directed wave test (GWT) was performed using the Teletest Focus system in conjunction with a piezoelectric magnetic transducer ring. For wave propagation, torsional wave patterns (T,0,1)$ were generated at excitation frequencies of (32 and 64 kHz) so that the frequency-dependent sensitivity could be evaluated. Data were obtained through a single fixed collar subject located at one end of a 20-meter-long tube sample, which led to the determination of the basic attenuation and reflection features.

Second (2) Ultrasonic Thickness Measurement (UTM): The local verification was carried out using an Olympus 38DL Plus Ultrasonic Smaco with a dual-element transducer (5 MHz). A high-dip rudder grid of 50 mm × 50 mm dimensions was focused on the target areas identified through the initial examination using GWT, along with random baseline positions. A set of 200 separate measurement points was also recorded to map the local residual wall thickness.

Third (3) The data were validated before the application of thermal insulation so that basic physical measurements were obtained directly from the uninsulated pipe, and the thickness of the remaining wall and the depths of the defects were documented using calibrated digital drilling gauges and vernier calipers so that they would serve as a set of absolute reference data.

Data Analysis Procedures

The Detection Standard (DR) is defined as the percentage of engineering defects that are successfully identified above the system's baseline signal-to-noise ratio (SNR). This rate is based on the following equation:

$$DR\ (\%) = \frac{Defects\ Detected}{Total\ engineered\ defects}\ x\ 100 \qquad (1)$$

Measurement accuracy (measurement error) is measured by the absolute difference between the depth measured through non-destructive testing and the actual depth on the ground. The measurement error is detected using the following equation.

$$Error = |d_{measured} - d_{actual}| \qquad (2)$$

($d_{measured}$) represents the depth recorded using the Universal Term Medium (UTM) or estimated using Global Ground Wave Reflectance (GWT) coefficients. However, $d_{measured}$ represents the actual depth measured using a borehole gauge.

The actual time efficiency (d_{actual}) is measured as the total cumulative operating hours required to complete system setup, sensor calibration, data collection, and post-processing/signal analysis for both methods.

To arrive at the necessary fundamental values and physical constants, the following was adhered to:

First: Physical constraints and reference figures. Before applying the equations, the basic physical measurements of the test circuit were followed. For the ($\boldsymbol{t - nominal}$) value of a 6-inch diameter, type 40 carbon steel pipe, the standard wall thickness is 7.11 mm, corresponding to the actual defect depth.

The ($\boldsymbol{d - actual}$) value indicates that for each of the ten defects, the actual depth measured using a digital drilling caliper before isolation was recorded. The percentage of actual cross-sectional area loss ($\boldsymbol{CSA}$) was recorded, representing the target geometric cross-sectional area loss for each defect, which was set to range between 3% and 30%.

Non-destructive testing readings, represented as "system outputs," are the variable measurements collected during the testing phases, Directed waves (GWT) are tested by the threshold signal-to-noise ratio (SNR) with the decibel (dB) level of the background noise floor, as well as the reflection amplitude. The peak amplitude of the reflected torsional wave is measured at 32 kHz and 64 kHz. If the peak is above the threshold curve (DAC), then yes, it is detected. If the peak is buried in the noise, it is no, i.e., "not detected."

The estimated depth (d_{GWT}) in millimeters is the depth of the defect estimated by the system and is usually calculated using reflection coefficients $d = t_{nominal} x\ reflection\ coefficient$.

Ultrasonic wall thickness measurement (UTM) and these readings reflect the network coordinates in millimeters, where the remaining wall thickness is measured at each network node (50mm x 50mm) gird, and the measured d_{UTM} depth in millimeters is the calculated depth of defects at the network node and is calculated using the following equation.

$$d_{UTM} = 7.11\ MM - t_{remaining} \qquad (3)$$

Table 1 Experimental defect matrix and physical parameters of the pipeline test specimen.

Defect ID	Defect Type	Target CSA Loss (%)	Actual Wall Depth (dactual) [mm]
D-01	Systematic Thinning	3%	0.4
D-02	Systematic Thinning	12%	1.8
D-03	Systematic Thinning	25%	3.5
D-04	Pitt Pool (MIC)	5%	0.8
D-05	Pitt Pool (MIC)	15%	2.1
D-06	CUI Patch	8%	1.1
D-07	CUI Patch	10%	1.4
D-08	CUI Patch	18%	2.5
D-09	CUI Patch	22%	3.1
D-10	CUI Patch	30%	4.2

***Received:** 11-05-2026 - **Accepted:** 09-07-2026 - **Published:** 16-07-2026*

https://doi.org/10.54361/ajmas.269737

The preceding table outlines three key criteria for evaluating non-destructive testing (NDT) performance through morphological variation. Ten simulated defects were classified into three distinct morphological categories: uniform thinning (n=3), pitting clusters (n=2), and corrosive patches under insulation (CUI) (n=5). Target cross-sectional area (CSA) loss was measured progressively from a minimum of 3% (representing early-stage deterioration) to a severe limit of 30% (representing advanced and high-risk structural loss). This distribution identified torsional wave patterns using the GWT test, in conjunction with UTM dimensions. Relative depth corresponds to actual wall depths ranging from 0.4 mm to 4.2 mm, with a significant portion of the nominal wall thickness of 7.11 mm for the Table 40 pipeline. This wide experimental range (5.6% to 59.1% wall thickness penetration) provides an accurate testing environment for calculating absolute dimensional errors. And defining the accuracy limits of each examination methodology.

Table 2 Experimental detection performance and signal-to-noise ratio (SNR) limits across NDT methods

Defect ID	CSA Loss (%)	GWT 32 kHz Detected?	GWT 64 kHz Detected?	UTM Detected?
D-01	3%	No (Below SNR)	No (Below SNR)	Yes
D-02	12%	Yes	Yes	Yes
D-03	25%	Yes	Yes	Yes
D-04	5%	No (Below SNR)	Yes	Yes
D-05	15%	Yes	Yes	Yes
D-06	8%	Yes	Yes	Yes
D-07	10%	Yes	Yes	Yes
D-08	18%	Yes	Yes	Yes
D-09	22%	Yes	Yes	Yes
D-10	30%	Yes	Yes	Yes
Total Detected ($\eta_{detected}$)	**—**	**8/10**	**9/10**	**10/10**
Detection Rate (DR)	**—**	**80%**	**90%**	**100%**

The table shows the combined experimental results between the comparative detection capabilities of the Guided Wave Test (GWT) at two dual excitation frequencies (32 kHz and 64 kHz) and Ultrasonic Thickness Measurement (UTM). It was observed that the physical limit of detection of the long-range ultrasonic inspection technique at the lowest intensity level is a loss of 3% of the cross-sectional area (D-01 defect), i.e., the reflected wave energy of the Guided Wave Test at frequencies of 32 kHz and 64 kHz did not exceed the threshold for the fundamental signal-to-noise ratio. In this case, the tubular formation was above 3% of the cross-sectional area. The frequency-dependent sensitivity data (32 kHz vs. 64 kHz) show a clear improvement in performance when moving to a higher excitation frequency of the torsion wave. Neither D-01 (3% CSA) nor D-04 (5% CSA) defect was detected (detection rate = 80%). However, at 64 kHz, the system successfully detected the D-04 defect (detection rate = 90%), which is attributed to the short wavelength associated with the convolutional wave at 64 kHz. This provides high spatial resolution and local sensitivity, allowing reflections from small structural discontinuities to overcome background noise.

Although the UTM system achieves a 100% detection rate (detection rate = 100%), this performance should be viewed within the context of a comprehensive inspection workflow, as the UTM system is a highly localized, point-by-point inspection tool. The perfect detection record in this study is attributed to the placement of the target grid (50 mm × 50 mm) over predefined areas. The results mathematically reflect the hierarchical inspection lifetime frame, where the GWT system acts as a fast and highly efficient universal inspection tool capable of identifying between 80% and 90% of anomalies along the 20-meter pipeline in a single operation, while the positional UTM system is used selectively to overcome the physical signal-to-noise ratio limitations of the GWT system and verify the target areas.

Detection Rate (DR) Calculations:

$DR_{GWT,32kHz}$:

$$DR = \frac{8}{10} X\ 100 = 80.0\%$$

$DR_{GWT,64kHz}$

$$DR = \frac{9}{10} X\ 100 = 90.0\%$$

DR_{UTM}

$$DR = \frac{10}{10} X\ 100 = 100.0\ \%$$

Sizing Accuracy (Depth Measurement) Calculations

UTM Depth Calculation:

$$d_{UTM} = T_{nominal} - t_{remaining} = 7.11\ mm - t_{remaining} \qquad (4)$$

GWT Depth Estimation (from Reflection Coefficient (R_c))

$$d_{GWT} = t_{nominal}\ x\ R_c \qquad (5)$$

Received: *11-05-2026 -* ***Accepted:*** *09-07-2026 -* ***Published:*** *16-07-2026*

https://doi.org/10.54361/ajmas.269737

Absolute Sizing Error

$$Error\ (E) = d_{measured} - d_{actual} \quad (6)$$

Table 3 Comparative depth sizing accuracy and absolute error analysis of GWT and UTM

Defect ID	Actual Depth (dactual)	GWT Estimated (dGWT)	GWT Absolute Error (EGWT)	UTM Measured (dUTM)	UTM Absolute Error (EUTM)
D-01	0.4	*Undetected*	—	0.38	0.02
D-02	1.8	1.5	0.3	1.76	0.04
D-03	3.5	3.1	0.4	3.48	0.02
D-04	0.8	0.6	0.2	0.75	0.05
D-05	2.1	1.7	0.4	2.05	0.05
D-06	1.1	0.9	0.2	1.14	0.04
D-07	1.4	1.1	0.3	1.38	0.02
D-08	2.5	2.1	0.4	2.47	0.03
D-09	3.1	2.8	0.3	3.06	0.04
D-10	4.2	3.8	0.4	4.15	0.05

The table above shows a comparison between depth measurement accuracy and absolute error analysis. The experimental data provided a quantitative assessment of depth accuracy using directed wave testing (GWT) and ultrasonic thickness measurement (UTM) compared to the actual value (d-actual) by analyzing absolute error distributions. The table illustrated several distinctive physical and operational characteristics of the two non-destructive testing (NDT) methods, such as measurement accuracy and mean absolute error (MAE). It showed a significant difference between the measurement accuracy of the two methods, as the UTM method across the range (from 0.4 mm to 4.2 mm) showed a remarkably low mean absolute error (MAE_UTM) of 0.04 mm. In contrast, GWT exhibited a much wider error margin, with an average absolute error of 0.32 mm for detected defects. This difference stems from the underlying physical boundary between the two techniques. UTM uses high-frequency localized acoustic pulses (5 MHz) directed perpendicular to the defect surface, while GWT relies on long-range torsional waves (32/64 kHz) propagating along the tube axis.
The understatement bias of GWT is evident in its depth measurement, which decreases consistently with the actual defect depths in all anomalies. This results in a systematic understatement bias (e.g., a measured 3.8 mm versus an actual 4.2 mm for the D-10 defect). Under UTM size determination, the error remained highly stable and independent of defect severity, maintaining a narrow error range between 0.02 mm and 0.05 mm regardless of whether the defect depth was shallow (0.4 mm) or deep (4.2 mm).

Mean Absolute Error (MAE) Calculations:
GWT Mean Sizing Error (for the 9 detected defects):

$$MAE_{GWT} = \frac{0.30 + 0.40 + 0.20 + 0.40 + 0.20 + 0.30 + 0.40 + 0.30 + 0.40}{9} = \frac{2.90}{9} = 0.322\ MM$$

UTM Mean Sizing Error (across all 10 points)

$$MAE_{UTM} = \frac{0.02 + 0.04 + 0.02 + 0.05 + 0.05 + 0.04 + 0.02 + 0.03 + 0.04 + 0.05}{10} = \frac{0.36}{10} = 0.036\ MM$$

We note from the previous calculation that guided wave testing (GWT) is highly time efficient, covering a full 20-meter distance in 0.85 hours with a peak detection rate of up to 90%, but it presents a larger error in depth measurement (average absolute error = 0.32 mm). Ultrasonic thickness measurement (UTM) is slow and limited in range (2.60 hours for mapping grid locations), but provides superior measurement accuracy (average absolute error = 0.04 mm).

Detection Capabilities Based on Defect Size (Loss of Cross-Sectional Area)
Based on the geometric classification, the ten geometric defects in the current study were classified into three groups according to their severity:

- Low Severity (less than 10% of the cross-sectional area) D-06 (8%) = 3 Defects
- Medium Severity (10% to 20% of the cross-sectional area) D-02 (12%), D-05 (15%), D-07 (10%), D-08 (18%) = 4 Defects
- High Severity (more than 20% of the cross-sectional area) D-03 (25%), D-09 (22%), D-10 (30%) = 3 Defects

Probability of Detection (PoD) Calculation by CohortUsing the formula:

$$PoD\ (\%) = \frac{Defects\ Detected\ in\ Cohort}{Total\ Defects\ in\ Cohort}\ X\ 100 \quad (7)$$

Received: *11-05-2026* - ***Accepted:*** *09-07-2026* - ***Published:*** *16-07-2026*

Table 4 Probability of Detection (PoD) by defect severity cohort across GWT and UTM systems.

Severity Cohort (CSA Loss)	GWT @ 32 kHz	GWT @ 64 kHz	UTM (Localized Grid)
Low Severity $(< 10\%)$	$\frac{1}{3} = 33.3\ \%$	$\frac{2}{3} = 66.7\ \%$	$\frac{3}{3} = 100\%$
Medium Severity $(10\% - 20\%)$	$\frac{4}{4} = 100\%$	$\frac{4}{4} = 100\ \%$	$\frac{4}{4} = 100\%$
High Severity $(> 20\%)$	$\frac{3}{3} = 100\%$	$\frac{3}{3} = 100\%$	$\frac{3}{3} = 100\%$

Standard Deviation of Sizing Error (σ_E) This measures the consistency (precision) of the measurement error:

$$\sigma_E = \sqrt{\frac{(E_i - MAE)^2}{n-1}} \qquad (8)$$

GWT Error Deviation (σ_E, GWT):

$$(E_i - 0.322)^2 = 0.0556 = \sigma_{E,GWT} = \sqrt{\frac{0.0556}{8}} = 0.083\ MM$$

UTM Error Deviation ($\sigma_{E,UTM}$):

$$(E_i - 0.036)^2 = 0.00123 = (\sigma_{E,UTM}) = \sqrt{\frac{0.00124}{9}} = 0.012\ mm$$

Table 5 Consolidated NDT system performance summary.

Metric	Guided Wave Testing (GWT)	Ultrasonic Thickness (UTM)
Overall Detection Rate (DR)	80% (at 32 kHz) / 90% (at 64 kHz)	100%
Lower Detection Limit (CSA)	≥5% CSA loss	<3% CSA loss
Sizing Accuracy (MAE)	0.322 mm	0.036 mm
Error Consistency (σE)	±0.083 mm	±0.012 mm
Sizing Trend Bias	Systematic Underestimation	Highly Linear / Neutral

These values mathematically demonstrate that GWT functions as an excellent and highly sensitive filter for inspecting long pipe sections with superior defect capture at 64 kHz, whereas UTM must be deployed locally to provide the high-resolution physical sizing data required for structural calculations.

Results and discussion

The experimental results demonstrated the complementary strengths of Guided Wave Testing (GWT) and Ultrasonic Thickness Measurement (UTM) for detecting and sizing corrosion defects in a 20 m Schedule 40 carbon steel pipeline containing ten simulated defects with depths ranging from 0.4 to 4.2 mm (5.6–59.1% wall-thickness loss).

GWT exhibited strong long-range screening capability, achieving detection rates of 80% at 32 kHz and 90% at 64 kHz. Increasing the excitation frequency significantly improved sensitivity to small defects because of the shorter wavelength and higher spatial resolution. However, GWT failed to detect the smallest defect (3% cross-sectional area loss) due to signal-to-noise ratio limitations and showed reduced sensitivity for defects below 10% CSA loss.

In contrast, UTM achieved a 100% detection rate for all defects owing to its localized point-by-point inspection approach. While highly accurate, its performance depends on direct access to the inspection area and predefined measurement locations, making it less suitable for rapid screening of long pipeline sections.

Depth measurement analysis further highlighted the superiority of UTM in defect sizing. UTM produced an exceptionally low Mean Absolute Error (MAE) of approximately 0.04 mm, with stable measurement accuracy regardless of defect depth. GWT, by comparison, recorded a MAE of approximately 0.32 mm and consistently underestimated defect depth because of the physical characteristics of long-range guided wave propagation.

Overall, the results validate a two-stage inspection strategy in which GWT is used for rapid long-range detection and localization of potential corrosion, followed by UTM for high-precision verification and accurate wall-loss measurement. This integrated approach combines the speed and coverage of GWT with the superior sizing accuracy of UTM, providing an efficient and reliable framework for industrial pipeline corrosion inspection.

Our study results are consistent with study [6], as both studies agree that effective corrosion management is not achieved by relying solely on protective measures or testing techniques, but rather by integrating non-destructive testing techniques for early corrosion detection with appropriate preventive protection systems, thereby ensuring improved pipeline safety and reduced maintenance costs and operational downtime.

***Received**: 11-05-2026 - **Accepted**: 09-07-2026 - **Published**: 16-07-2026*

Our study is also consistent with study [7] in terms of the overall objective of enhancing pipeline safety through the use of non-destructive testing techniques for early corrosion detection. The results of the current study showed that GWT achieved detection rates of 80% at 32 kHz and 90% at 64 kHz, while UTM achieved a 100% detection rate for all defects with an absolute mean error of 0.04 mm, confirming its high efficiency in determining the depth of corrosion. They confirmed that continuous monitoring using acoustic emission technology is necessary. The current study presents an integrated inspection strategy combining GWT for rapid scanning and UTM for accurate measurement, which provides a practical and effective framework for assessing the condition of pipelines and making preventive maintenance decisions.
The results of this study [8] align with our findings, confirming that corrosion is a major factor affecting the integrity of steel pipes, leading to deterioration of their mechanical properties and reduced operational reliability. This necessitates the use of non-destructive testing techniques capable of early corrosion detection and accurate assessment of its severity. Both studies agree that obtaining precise data on the extent and distribution of corrosion contributes to supporting preventive maintenance programs and extending the operational life of pipelines. They demonstrated that fiber optic sensors provide continuous corrosion monitoring and produce measurements consistent with 3D laser scanning results, thus confirming their reliability in harsh marine environments.

Conclusion

The study adopted non-destructive testing (NDT) techniques in industrial pipelines due to the clear challenges they face, and because early detection of corrosion and assessment of its condition without the continued operation of pipelines makes it one of the essential elements in preventive maintenance programs. The results showed that guided wave technology is characterized by its ability to conduct rapid inspection over long distances while identifying the locations of potential defects. The study proved that combining ultrasonic thickness measurement techniques with guided wave technology provides an integrated inspection strategy that combines speed of detection and measurement accuracy, which contributes to improving the efficiency of inspection operations and reducing the likelihood of overlooking critical defects.

Conflict of interest. Nil

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Received*: 11-05-2026 -* ***Accepted****: 09-07-2026 -* ***Published****: 16-07-2026*