

Strength Analysis of a 6-Inch Gas Pipeline Under Deflection Using ASME B31.8 Strain-Based Design: A Case Study at KP.03+500

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Abstract: Natural gas transmission pipelines are susceptible to deflection due to ground settlement, heavy traffic loads, and surrounding construction activities. This study evaluates the structural response of a 6-inch API 5L X52 gas pipeline experiencing a vertical deflection of 9 cm over a chord length of 370 cm at KP.03+500. The assessment uses the sagitta-based radius of curvature together with a strain-based framework. The revised calculation separates longitudinal bending strain from extensional strain. The measured geometry gives a radius of curvature of 1905.9 cm and a deflection angle of 11.12°. The longitudinal bending strain is 0.0186%, the extensional strain is 0.0296%, and the combined longitudinal strain is 0.0482%, below the material yield strain of 0.1760% and the adopted 0.25% normal-operation criterion. The elastic bending stress is 37.9 MPa, while the hoop stress due to MAOP is 36.77 MPa. Sensitivity analysis indicates that the yield-strain threshold is reached at approximately 19.3 cm and the 0.25% strain criterion at approximately 23.5 cm. The measured 9 cm deflection therefore retains a calculated yield-strain margin of approximately 10.3 cm. The assessment provides an analytical screening framework for field integrity evaluation while recognizing limitations associated with single-point measurement and simplified pipe-soil interaction.

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INTRODUCTION

Natural gas transmission pipeline systems constitute the backbone of national energy infrastructure, playing a vital role in transporting natural gas from production facilities to industrial consumers and distribution networks (Wang et al., 2022; Tang et al., 2025; Gillessen et al., 2019; Zhang et al., 2022; Kleperis et al., 2022). In Indonesia, the total length of gas transmission and distribution pipelines has exceeded 12,000 km and continues to expand in line with the increasing national demand for energy (BPH Migas, 2022; Rahmanta et al., 2025). One of the strategic gas transmission corridors is the Simpang Lubuk Panjang Permai Pipeline Installation in Jambi Province, operated by PT XYZ. The pipeline has been in operation since 2011, with a total length of 51.514 km (PT XYZ, 2026).

As their operational age increases, buried natural gas transmission pipelines become susceptible to various forms of mechanical degradation resulting from interactions with the surrounding environment (Ahmed et al., 2024; Li et al., 2022; Hrabovskyy et al., 2024). One commonly encountered phenomenon is deflection, defined as a change in the vertical position of the pipeline from its original alignment (Luo et al., 2025). Deflection in buried pipelines can be caused by several factors, including (1) ongoing consolidation of soft soil or peat, particularly in Jambi, where peat and soft clay soils are widespread; (2) dynamic loading from heavy vehicles traveling on roads above the pipeline route; (3)

soil erosion caused by surface water flow; and (4) construction activities such as soil backfilling and concrete installation around the pipeline corridor (Revie, 2015; Y. Bai & Bai, 2014).

Unmonitored and unevaluated pipeline deflection can generate accumulated bending stresses in the pipe wall (Sobanke et al., 2021). When these stresses exceed the yield strength of the material, the pipeline may undergo permanent plastic deformation, potentially resulting in cracking, leakage, or, in extreme cases, pipeline rupture, which may lead to fire and explosion hazards (Lam & Zhou, 2018). Given that the transported medium is high-pressure natural gas, the potential consequences of pipeline failure are particularly serious in terms of safety, environmental impact, and economic losses (ASME, 2020a).

The international standard ASME B31.8, Gas Transmission and Distribution Piping Systems, provides comprehensive guidelines for stress analysis and integrity assessment of natural gas transmission pipelines (Kappes & Perez, 2023). The standard introduces the strain-based design (SBD) approach, which evaluates pipeline integrity based on actual strain and can provide a more representative assessment than stress-based approaches alone, particularly when pipeline geometric deformation can be directly measured in the field (J. Bai & Bai, 2014). Nonmandatory Appendix R of ASME B31.8 specifically addresses strain estimation for pipelines subjected to dents or deflections, making it a relevant reference for the case investigated in this study (ASME, 2020b).

Several previous studies have investigated the behavior of buried pipelines under deformation-induced loading. Vazouras et al. (2015) examined pipe-soil interaction in fault movement zones and found that ground deformation can induce significant longitudinal strains in pipelines. Sarvanis and Karamanos (2017) and Tiku et al. (2016) developed analytical models for estimating pipeline strain responses in areas subjected to continuous ground deformation. Zhou et al. (2019) investigated the influence of internal pressure on the deformation capacity of X52 steel pipelines and concluded that internal pressure can either increase or decrease bending capacity depending on the geometric conditions of the pipeline. Gresnigt (1986) and the European Pipeline Research Group (EPRG) (Dāmas & Gresnigt, 2002) developed plastic design methodologies for buried pipelines in areas affected by ground subsidence, which remain important references in the pipeline industry. Nevertheless, studies specifically addressing measured vertical deflection in existing natural gas pipelines in Indonesia using a sagitta-based approach integrated with the strain-based design methodology of ASME B31.8 remain limited in the available literature (Fekete & Varga, 2015).

In addition to the technical aspects, national regulations through Minister of Energy and Mineral Resources Regulation No. 32 of 2021 on the Safety of Oil and Gas Transmission Pipelines require pipeline operators to conduct periodic inspection, evaluation, and maintenance to ensure safe operation (Ministry of Energy and Mineral Resources, 2021). This regulatory requirement further emphasizes the importance of conducting systematic and standardized pipeline strength assessments at locations identified as experiencing deflection, such as the KP.03+500 section.

This study aims to: (1) calculate the actual radius of curvature of the pipeline using the sagitta formula based on field measurement data; (2) determine the bending strain, yield strain, bending stress, and hoop stress using the strain-based design method in accordance with ASME B31.8; (3) evaluate pipeline safety based on the ASME B31.8 criteria for normal operation of natural gas transmission pipelines; and (4) conduct a sensitivity analysis to determine the maximum allowable deflection. The novelty of this study lies in the comprehensive integration of the sagitta formula with the ASME B31.8

strain-based design approach within a systematic and reproducible calculation framework for field-based integrity assessment of natural gas transmission pipelines in Indonesia.

RESEARCH METHOD

This study employed an analytical-quantitative approach based on field measurements of pipeline deflection obtained through direct inspection of a 6-inch gas pipeline at the KP.03+500 section. All calculations were performed with reference to the requirements of ASME B31.8 and other relevant standards.

Research Object and Field Data

The research object was a 6-inch API 5L X52 seamless natural gas transmission pipeline that has been in operation since 2011. The complete technical specifications of the pipeline and the field deflection conditions are shown in Tables 1 and 2.

Table 1. Technical Specifications of the API 5L X52 Natural Gas Pipeline

PARAMETER	VALUE	UNIT
Total pipeline route length	51.514	km
Construction year	2011	-
Pipe type	Seamless	-
Material specification	API 5L X52	-
Outside diameter (OD)	168.3	mm
Nominal wall thickness	7.10	mm
Inside diameter (ID)	154.1	mm
SMYS (Specified Minimum Yield Strength)	358	MPa
SMTS (Specified Minimum Tensile Strength)	455.1	MPa
Young's Modulus (E)	203,395.34	MPa
External coating	3LPE	-
Internal coating	Not available	-
MAOP (Maximum Allowable Operating Pressure)	3.103	MPa
Design pressure	6.205	MPa
Product fluid	Natural gas	-
Location design factor (F)	0.72	-

Table 2. Pipeline Deflection Condition Data at KP.03+500

Parameter	Value
Deflection location	KP.03+500
Chord length	370 cm
Maximum deflection (sagitta)	9 cm

Direction	Vertical downward
Measurement method	Direct measurement using a measuring tape and ruler
Measurement points	4 reference points inlet, outlet, start of curvature, and maximum-deflection point
Measurement frequency	Single measurement during the March 2026 field inspection
Measurement date	March 2026

The field deflection measurement was conducted at KP.03+500 in March 2026 through direct measurement of the inspected pipeline segment. A measuring tape and a ruler were used as the field measurement instruments. Four reference points were identified, consisting of the inlet point, outlet point, the point where the pipeline began to curve, and the point of maximum deflection at the middle of the curved section. The chord length was measured as 370 cm, while the maximum vertical deflection (sagitta) was measured as 9 cm. The measurement was performed once because the pipeline was considered relatively stationary during the inspection, and ground movement during the measurement period was considered negligible based on the observed field condition.

The measurement results were recorded directly from the field inspection and used as the geometric input for the subsequent calculations. Because conventional measuring tools were used and no formal instrument accuracy or repeated measurements were available, no numerical measurement uncertainty was assigned. Therefore, the reported chord length of 370 cm and sagitta of 9 cm represent field-measured geometric values and should be interpreted within the limitations of the measurement method.

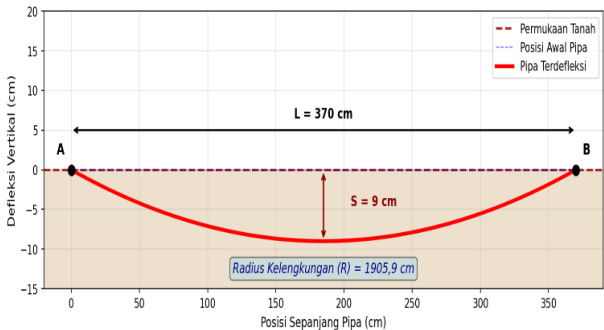


Figure 1. Schematic of Pipeline Deflection at KP.03+500 Showing the Chord Length (L) and Sagitta (S)

Figure 1 shows the geometry of the pipeline deflection observed in the field. Points A and B represent the reference points at the ground surface used as the basis for measuring the chord length (L), while the sagitta (S) represents the maximum vertical distance between the deflected pipeline position and chord line AB.

Applicable Standards and Reference Codes

The analysis was conducted based on the standards and regulations listed in Table 3.

Table 3. Applicable Standards and Reference Codes

Code / Standard	Title	Relevant Clause
ASME B31.8 (ASME, 2020)	Gas Transmission and Distribution Piping Systems	Appendix R, Sections 833 and 841
API 5L (API, 2018)	Specification for Line Pipe	X52 material specification
ASME B36.10M (ASME, 2018)	Welded and Seamless Wrought Steel Pipe	Pipeline dimensions
Minister of Energy and Mineral Resources Regulation No. 32/2021	Occupational Safety of Oil and Gas Transmission Pipelines	Inspection requirements

Calculation Method

The calculations were performed sequentially in six stages, as described in the following subsections. The research methodology flowchart is shown in Figures 2 and 3 to facilitate understanding of the analytical sequence.

Radius of Curvature

The radius of curvature (R) was calculated using the sagitta formula, which represents the geometric relationship between the chord length, arc height, and radius of a circular arc. The formula is derived from circular geometry and is expressed as follows (Schofield, 2018):

$$R = \frac{L^2}{(8S)} + \frac{S}{2} \quad (1)$$

where R is the radius of curvature (cm), L is the chord length (cm), and S is the sagitta or maximum deflection at the midpoint of the chord (cm). This calculation assumes that the measured deflected profile can be approximated by a circular arc and that the chord length and sagitta adequately represent the deflected pipeline segment. This geometric simplification does not explicitly account for soil heterogeneity, pipe-soil interaction, local settlement, cross-sectional ovalization, or local restraint conditions. Therefore, the calculated radius represents an analytical approximation of the field-measured deflection (API, 2018).

Deflection Angle

The deflection angle or central angle (θ) was calculated using the trigonometric relationship between half of the chord length and the radius of curvature:

$$\theta = 2 \arcsin\left(\frac{L}{2R}\right) \quad (2)$$

The conversion from radians to degrees was performed using:

$$\theta \text{ (derajat)} = \theta \text{ (radian)} \times \left(\frac{180}{\pi}\right) \quad (3)$$

Bending Strain

The bending strain was recalculated from the longitudinal curvature of the deflected pipeline. The previous formulation of Equation (4) represented the extensional strain term rather than the bending strain term. The revised calculation therefore separates the longitudinal bending and extensional strain components. For the measured pipeline profile, the longitudinal bending strain is calculated from the pipe-wall thickness and radius of curvature as:

$$\varepsilon^2 = \frac{t}{2R} \quad (4)$$

where ε_2 is the longitudinal bending strain, t is the nominal wall thickness of the pipe (m), and R is the radius of curvature of the pipe centerline (m). The extensional strain associated with the measured sagitta is calculated separately as:

$$\varepsilon^3 = \frac{1}{2} \left(\frac{d}{L} \right)^2 \quad (5)$$

where d is the measured sagitta (deflection depth) and L is the chord length. Equations (4) and (5) therefore represent different longitudinal strain components rather than two alternative expressions for the same strain. For the present simplified geometry, the combined longitudinal strain is obtained from the sum of the bending and extensional components. Because no transverse dent curvature was measured, the circumferential strain component is not included in the present calculation.

Yield Strain Comparison

The yield strain (ε_y) represents the elastic strain limit of the material and was determined from the ratio of the specified minimum yield strength (SMYS) to Young's modulus (E):

$$\varepsilon_y = \frac{SMYS}{E} \quad (6)$$

The yield strain serves as the primary comparison limit. When $\varepsilon < \varepsilon_y$, the pipeline remains within the elastic deformation range and does not experience permanent deformation. In addition, ASME B31.8 establishes strain limits based on operating conditions, as shown in Table 4.

Table 4. Operating Strain Limits According to ASME B31.8 for Gas Transmission Pipelines

Operating Condition	Strain Limit	Description
Normal operation	$\leq 0.25\%$	Routine conditions without extreme loading
Special condition (strain-based design)	$\leq 0.50\%$	Subject to engineering justification
Exceeding 0.50%	Requires further engineering analysis	Full engineering assessment

Bending Stress

The bending stress (σ_b) was calculated using Hooke's law within the linear elastic region, namely as the product of Young's modulus and the actual bending strain:

$$\sigma b = E \times \varepsilon \quad (7)$$

The resulting stress was then compared with the SMYS to determine the safety factor against yielding. The bending stress must remain below the SMYS to prevent the pipeline from undergoing plastic deformation.

Hoop Stress

Hoop stress (σh) is generated by the internal fluid pressure within the pipeline and was calculated using the Barlow formula referenced by ASME B31.8 Section 805.233:

$$\sigma h = P \times \frac{D}{(2t)} \quad (8)$$

Where P is the operating pressure (MAOP) in MPa, D is the outside diameter of the pipeline (mm), and t is the pipeline wall thickness (mm). The allowable hoop stress according to ASME B31.8 Section 841.1 is given by:

$$\sigma h, izin = F \times E \times T \times SMYS \quad (9)$$

Where F is the location design factor (0.72 for Class Location 1), E is the longitudinal joint factor (1.0 for seamless pipe), and T is the temperature derating factor (1.0 for).

Combined Stress

For a more comprehensive integrity assessment, the combined stresses acting on the pipeline were evaluated. The total axial stress (σa) represents the superposition of bending stress and the axial stress caused by internal pressure due to the closed-end effect:

$$\sigma a = \sigma b \pm \frac{(P \times D)}{(4t)} \quad (10)$$

The equivalent stress was subsequently calculated using the Von Mises criterion for isotropic materials:

$$\sigma eq = \sqrt{\sigma h^2 - \sigma h \times \sigma a + \sigma a^2} \quad (11)$$

The resulting equivalent stress must not exceed 90% of the SMYS in accordance with the ASME B31.8 Section 833 criterion for normal operating conditions.

RESULTS AND DISCUSSION

Field documentation of the 6-inch natural gas pipeline at the KP.03+500 section is shown in Figures 2-5. The photographs were taken during the field inspection conducted by the PT XYZ technical team in March 2026.



Figure 2. Exposed 6-inch Natural Gas Pipeline in the Excavation at KP.03+500



Figure 3. Top View of the Field Team Conducting Excavation and Pipeline Inspection at KP.03+500



Figure 4. PT XYZ Technical Personnel Conducting Direct Inspection of the Pipeline and Coating Condition at the Inspection Site



Figure 5. Soil Stabilization and Structural Support Activities in the Pipeline Excavation Area at KP.03+500

Radius of Curvature

Based on the field measurement data, the chord length was $L=370$ cm and the sagitta was $S=9$ cm. Based on Equation (1), the calculated radius of curvature was 1,905.9 cm or 19.06 m.

The resulting radius of curvature is equivalent to approximately 113.3D, where the outside diameter of the pipeline is $D=168.3$ mm or 16.83 cm. This shows that the pipeline deformation represents a relatively shallow curvature rather than a sharp bend. For comparison, the commonly referenced minimum cold-bending radius for steel pipelines is approximately 40D, equivalent to 673.2

cm for this pipeline. Thus, the measured radius is approximately 2.83 times greater than this reference value, indicating that the observed curvature is relatively mild.

The sagitta-based calculation assumes that the deflected pipeline profile can be approximated by a circular arc. Although the actual deformation profile may vary depending on soil conditions and load distribution, this assumption provides a practical geometric basis for the preliminary assessment of pipeline integrity.

Deflection Angle

Based on Equations (2) and (3), the calculated central deflection angle was 0.194 rad, equivalent to 11.12°. A deflection angle of 11.12° represents a moderate geometric deformation for the investigated buried gas transmission pipeline. However, because the pipeline is seamless and the observed deformation is associated with ground conditions rather than an angular displacement at a pipe joint, the actual strain is a more relevant parameter for evaluating structural integrity. Therefore, the subsequent assessment focuses primarily on bending strain, yield strain, and the resulting stress state.

Bending Strain

Using the nominal wall thickness $t = 0.00710$ m and the calculated radius of curvature $R = 19.0589$ m, Equation (4) gives the longitudinal bending strain:

$$\varepsilon_2 = 0.000186$$

equivalent to 0.0186%. The extensional strain calculated from Equation (5), using $d = 0.09$ m and $L = 3.70$ m, is 0.0296%. Therefore, the combined longitudinal strain used for the present strain-based assessment is 0.0482%.

The combined longitudinal strain of 0.0482% is below the material yield strain of 0.1760% and below the adopted 0.25% normal-operation assessment criterion. The same formulation is used in the sensitivity analysis.

The ratio between the combined longitudinal strain and the yield strain is approximately 27.39%, indicating that the calculated strain demand remains within the elastic range under the adopted analytical assumptions.

The strain components are retained separately because the bending component is used for the elastic bending-stress calculation, whereas the combined longitudinal strain is used for the strain-based acceptance comparison.

It should be noted that the bending-strain expression adopted from ASME B31.8 Appendix R and the radius-based geometric expression represent different approximations of pipeline deformation. Therefore, the Appendix R formulation was retained as the primary assessment basis, while the alternative geometric relationship was considered as a supplementary verification.

Yield Strain

For the API 5L X52 material, with an SMYS of 358 MPa and Young's modulus of 203,395.34 MPa, the calculated yield strain based on Equation (6) is:

$$\varepsilon_y = 0.001760, \text{ equivalent to } 0.1760\%.$$

The ratio of the combined longitudinal strain to the yield strain is therefore:

$$\varepsilon/\varepsilon_y = 58.75\%$$

The combined longitudinal strain is approximately 27.39% of the calculated yield strain. Thus, the measured 9 cm deflection remains below the theoretical yield threshold under the revised analytical formulation.

Bending Stress

Based on Equation (7), the elastic bending stress corresponding to the longitudinal bending strain component ε_2 is 37.89 MPa. The extensional strain component is included in the strain-based assessment but is not converted into bending stress.

Compared with the API 5L X52 SMYS of 358 MPa, the bending stress ratio is:

$$\sigma_b/SMYS = 58.7\%$$

Compared with the API 5L X52 SMYS of 358 MPa, the bending stress utilization is 10.6%, leaving a margin of approximately 89.4%.

These results indicate that the observed pipeline deflection produces a relatively small elastic bending-stress component. The strain-based assessment remains below the material yield strain under the revised calculation.

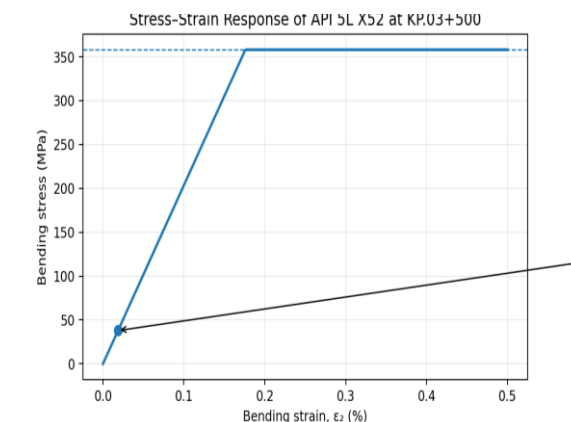


Figure 6. Stress-Strain Curve of API 5L X52 Material Showing the Actual Operating Point at KP.03+500

Figure 6 shows the actual bending component at approximately 0.0186% strain and 37.9 MPa bending stress. The point remains below the SMYS of 358 MPa. The total longitudinal strain used for the strain-based assessment is 0.0482% because it also includes the extensional component.

Hoop Stress

The hoop stress generated by the internal operating pressure was calculated using an MAOP of 3.103 MPa, an outside diameter of 168.3 mm, and a wall thickness of 7.10 mm. Based on Equation (8), the resulting hoop stress was 36.77 MPa.

The allowable hoop stress based on the adopted ASME B31.8 design parameters was calculated as 257.76 MPa. Thus, the ratio of actual hoop stress to allowable hoop stress is:

$$\sigma_h/\sigma_{h,allow} = 14.3\%$$

The actual hoop stress therefore represents only 14.3% of the allowable value, leaving an approximately 85.7% margin. This relatively low utilization shows that internal pressure is not the governing factor in the assessed pipeline condition. Instead, the bending response associated with geometric deflection represents the more significant stress component.

Combined Stress and Von Mises Assessment

The axial stress generated by the internal pressure through the closed-end effect was calculated as 18.38 MPa. For the conservative case in which bending stress and pressure-induced axial stress act in the same direction, the total axial stress was obtained as:

$$\sigma_a = 228.38$$

The resulting Von Mises equivalent stress, using the revised elastic bending-stress component and the pressure-induced stresses, is approximately 49.5 MPa. For comparison, 90% of the API 5L X52 SMYS is 322.2 MPa.

$$0.90 \times 358 = 322.2 \text{ MPa}$$

The equivalent-stress utilization is approximately 15.4%, leaving a margin of approximately 84.6% relative to the adopted 90% SMYS criterion.

The combined-stress assessment therefore confirms that the pipeline remains below the adopted ASME B31.8 acceptance criterion under the evaluated loading condition. Even when the bending stress and pressure-induced axial stress are conservatively considered to act in the same direction, the calculated equivalent stress remains within the allowable range.

Calculation Results

The complete calculation results and corresponding safety assessment are presented in Table 5.

Table 5. Pipeline Strength Assessment Results

Parameter	Actual Value	Reference/Limit	Status
Radius of curvature (R)	1,905.9 cm	> 673.2 cm (40D)	SAFE
Deflection angle (θ)	11.12°	-	INFORMATION
Bending strain (ϵ)	0.0482%	0.25%	SAFE
Yield strain (ϵ_y)	0.1760%	Material yield limit	REFERENCE
Strain-to-yield ratio	27.39%	< 100%	SAFE
Bending stress (σ_b)	37.9 MPa	358 MPa (SMYS)	SAFE
Margin to SMYS	89.4%	Positive margin	SAFE
Hoop stress (σ_h)	36.77 MPa	257.76 MPa	SAFE
Hoop stress utilization	14.3%	< 100%	SAFE
Von Mises equivalent stress	49.5 MPa	322.2 MPa (90% SMYS)	SAFE
Equivalent stress utilization	15.4%	< 100%	SAFE

The results show that all principal assessment parameters remain within their respective acceptance limits. The most significant utilization is associated with the combined Von Mises stress at

65.9% of the adopted limit, followed by the bending stress at 58.7% of SMYS. In contrast, hoop stress has a substantially lower utilization of only 14.3%.

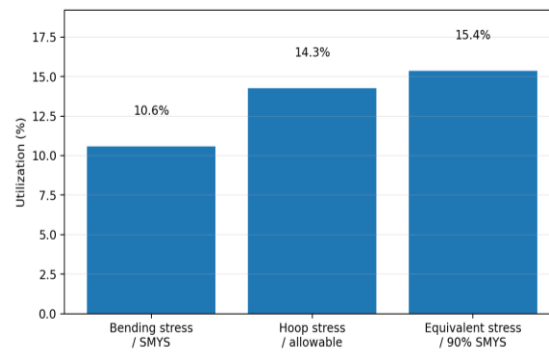


Figure 7. Comparison of Actual Parameter Values with Their Corresponding Allowable Limits According to the Adopted ASME B31.8 Assessment Criteria

Figure 7 shows the utilization of the principal stress parameters. The revised bending-stress utilization is 10.6% of SMYS, the hoop-stress utilization is 14.3% of the adopted allowable value, and the combined equivalent-stress utilization is 15.4% of the adopted 90% SMYS criterion.

Sensitivity Analysis

A sensitivity analysis was conducted to determine the sagitta levels associated with the material yield strain and the adopted 0.25% normal-operation strain criterion. The sagitta was varied from 3 to 25 cm while maintaining a chord length of 370 cm. For each sagitta, the radius of curvature, longitudinal bending strain, extensional strain, and combined longitudinal strain were recalculated using the same equations applied to the actual field condition.

Table 6. Sensitivity Analysis of Combined Longitudinal Strain with Varying Sagitta at $L = 370$ cm

Sagitta, S (cm)	Radius, R (cm)	Combined Strain, ϵ (%)	Assessment
3	5,705.7	0.0095	SAFE
5	3,425.0	0.0195	SAFE
7	2,448.1	0.0324	SAFE
9	1,905.9	0.0482	SAFE
11	1,561.2	0.0669	SAFE
13	1,322.8	0.0886	SAFE
15	1,148.3	0.1131	SAFE
17	1,015.1	0.1405	SAFE
19.3	896.3	0.1757	Yield threshold
20	865.6	0.1871	ATTENTION
23.5	739.9	0.2497	0.25% threshold
25	697.0	0.2792	CRITICAL

The sensitivity results indicate a nonlinear reduction in the radius of curvature as sagitta increases. At the actual sagitta of 9 cm, the radius is 1905.9 cm and the combined longitudinal strain is 0.0482%. The yield-strain threshold is reached at approximately 19.3 cm, while the adopted 0.25% normal-operation strain criterion is reached at approximately 23.5 cm. Therefore, the current

deflection of 9 cm provides a calculated margin of approximately 10.3 cm before the yield-strain threshold and approximately 14.5 cm before the 0.25% assessment limit.

The corrected sensitivity results show that the combined longitudinal strain reaches the material yield strain at approximately 19.3 cm and the adopted normal-operation strain limit of 0.25% at approximately 23.5 cm. Therefore, the current deflection of 9 cm provides a calculated deflection margin of approximately 10.3 cm before the yield-strain threshold and approximately 14.5 cm before the 0.25% assessment limit.

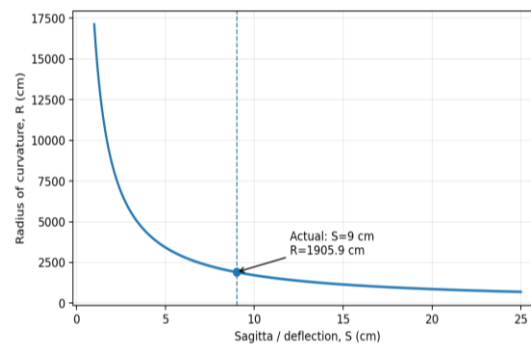


Figure 8. Sensitivity Curve of Radius of Curvature as a Function of Sagitta at a Constant Chord Length of 370 cm

Figure 8 shows that the radius of curvature decreases rapidly as the sagitta increases. The relationship is nonlinear and approximately hyperbolic, reflecting the geometric dependence of the radius on sagitta. The current condition of 9 cm remains substantially below the deflection associated with the minimum reference bending radius.

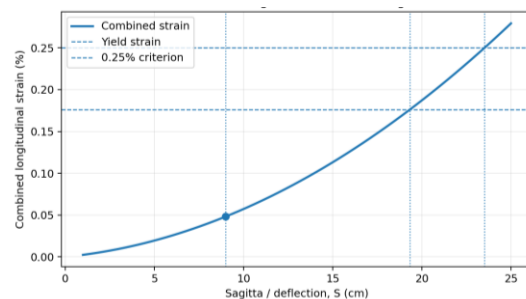


Figure 9. Combined Longitudinal Strain as a Function of Sagitta at a Constant Chord Length of 370 cm

Figure 9 shows that the combined longitudinal strain increases with increasing sagitta. The actual condition of $S = 9$ cm gives a combined strain of 0.0482%, which remains below the calculated yield strain of 0.1760% and the adopted normal-operation strain criterion of 0.25%. The sensitivity analysis indicates that the corresponding thresholds occur at approximately 19.3 cm and 23.5 cm, respectively.

These findings are important for pipeline integrity management. If ground settlement continues, an increase in sagitta should be monitored because the relationship between deflection and strain is nonlinear. Consequently, periodic field measurements are recommended to identify changes in the deflection profile before the pipeline approaches the calculated yield or operating strain thresholds.

The previously assumed settlement rate of 1-2 cm/year should, however, be treated as a site-specific monitoring parameter rather than a general value for all peat soils in Jambi. If such a rate is confirmed through repeated field measurements, the remaining deflection margin can subsequently be converted into an estimated time to reach the relevant assessment threshold.

Comparison with Previous Studies

Table 7 compares the findings of this study with previous investigations concerning the behavior of gas transmission pipelines subjected to ground deformation or similar loading conditions.

Table 7. Comparison of the Present Study with Previous Research

Study	Material	Method	Actual Strain	Main Finding
Present study (2026)	API 5L X52, 6-inch	ASME B31.8 Appendix R	0.0482% ($< \epsilon_y$)	Within yield strain; elastic analytical response
Vazouras <i>et al.</i> (2015)	API 5L X65, 24-inch	FEA (ABAQUS)	0.30-1.50%	Dependent on fault displacement magnitude
Sarvanis & Karamanos (2017)	API 5L X65, 16-inch	Analytical + FEA	0.20-0.80%	Requires SBD assessment
Zhang <i>et al.</i> (2019)	API 5L X52, 20-inch	Experimental + FEA	0.15-0.35%	X52 shows adequate strain capacity
Gresnigt (1986)	Various steel pipes	Analytical	0.25-2.00%	Plastic design applicable

As shown in Table 7, the combined longitudinal strain obtained in the present study is 0.0482%, which is lower than the strain ranges reported in the selected previous studies. However, the difference should not be interpreted solely as evidence of greater pipeline resistance, because the studies differ in pipe diameter, material grade, deformation magnitude, loading configuration, and analytical approach.

The strain-based assessment applied in this study is conceptually consistent with deformation-based approaches used in previous pipeline studies. The present approach uses field-measured sagitta and chord length to estimate curvature, separates the longitudinal bending and extensional strain components, and combines them for the strain-based comparison. Unlike three-dimensional numerical studies, local soil restraint and full pipe-soil interaction are not explicitly represented.

The comparison also shows the specific contribution of the present study which are rather than examining pipeline response under a prescribed ground-displacement scenario, the study evaluates an existing 6-inch gas pipeline using an actual field-measured deflection at KP.03+500 and translates that geometric measurement into strain and stress parameters under the ASME B31.8 assessment framework. The novelty therefore lies in the application of a field-measurement-based geometric assessment to an existing pipeline segment, together with sensitivity analysis to identify deflection levels associated with the adopted strain criteria. The integration of field-measured sagitta with a strain-based assessment provides a practical framework for evaluating existing buried pipelines (Laichoubi *et al.*, 2025). The results show that the current KP.03+500 deflection remains within the adopted strain and stress criteria, while the sensitivity analysis shows that continued ground deformation could progressively reduce the available assessment margin.

For more complex deformation profiles, significant ground movement, interaction between the pipeline and surrounding soil, or conditions exceeding the normal operating strain criterion, a more comprehensive engineering assessment is recommended. Such an assessment may include three-dimensional finite element analysis incorporating the actual soil properties, pipeline-soil interaction, internal pressure, and load distribution along the pipeline (Det Norske Veritas, 2021; Alexander & Kiefner, 2019).

Technical Recommendations

Based on the results of the pipeline strength analysis and safety assessment, several technical recommendations are proposed for the pipeline operator to maintain the integrity and safe operation of the pipeline at KP.03+500. The recommendations are presented in Table 8.

Table 8. Technical Recommendations Based on the Pipeline Strength Assessment

No.	Aspect	Recommendation
1	Deflection monitoring	Conduct periodic deflection measurements every two years at KP.03+500 and surrounding locations using precision surveying equipment, such as a total station or GNSS survey.
2	Intervention threshold	Immediate corrective action should be considered when the sagitta reaches 14 cm. This value is retained as a conservative engineering intervention threshold, providing approximately 5.3 cm of margin below the calculated yield-strain threshold of approximately 19.3 cm, equivalent to about 72.5% of the yield-threshold sagitta. The threshold is an engineering recommendation for preventive intervention and is not presented as a specific limit prescribed by ASME B31.8.
3	Soil mitigation	Install concrete saddle supports or reinforce the surrounding soil using compacted granular material to improve pipeline support at KP.03+500.
4	Visual inspection	Conduct annual visual inspections along the pipeline corridor around KP.03+500 to identify signs of changes in soil conditions, settlement, erosion, or other surface anomalies.
5	Inline inspection	Perform inline inspection (ILI) using a caliper pig or magnetic flux leakage (MFL) tool to comprehensively characterize the pipeline's geometric and integrity condition.
6	Further assessment	If the measured deflection increases by more than 5 cm during the monitoring period, conduct a three-dimensional finite element analysis (FEA) to provide a more comprehensive assessment of pipeline-soil interaction and structural integrity.

CONCLUSION

The strength assessment of the 6-inch API 5L X52 natural gas pipeline at KP.03+500 subjected to a 9 cm vertical deflection over a 370 cm chord was revised using a consistent strain decomposition. The radius of curvature is 1,905.9 cm (approximately 113.3D). The longitudinal bending strain is 0.0186%, while the extensional strain is 0.0296%, giving a combined longitudinal strain of 0.0482%. This value remains below the material yield strain of 0.1760% and the adopted 0.25% normal-operation criterion. The corresponding elastic bending stress is 37.9 MPa, while the hoop stress remains 36.77 MPa. The combined equivalent elastic stress is approximately 49.5 MPa, below the adopted 90% SMYS limit of 322.2 MPa. Sensitivity analysis indicates a yield-strain threshold at approximately 19.3 cm and a 0.25% strain threshold at approximately 23.5 cm. Thus, the measured 9 cm deflection retains a calculated margin of approximately 10.3 cm to the yield-strain threshold. The result should nevertheless be interpreted as an analytical screening assessment because the field data consist of a single measurement and the model does not explicitly represent three-dimensional pipe-soil interaction, corrosion, local defects, residual stress, ovality, or temperature effects.

This study has several limitations that should be considered when interpreting the results. The assessment was performed using an analytical approach based on the measured chord length and sagitta and the assumptions adopted in the geometric and strain-based calculations. The analysis does not explicitly model three-dimensional pipe-soil interaction, non-uniform soil conditions, local settlement, corrosion, existing pipe defects, residual stress, cross-sectional ovality, or temperature effects. Therefore, the calculated strain and stress values represent an analytical assessment of the evaluated deflection condition rather than a complete representation of the pipeline's in-service structural response. Further assessment using three-dimensional finite element analysis and detailed integrity inspection is recommended when more complex deformation or additional integrity concerns are identified.

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