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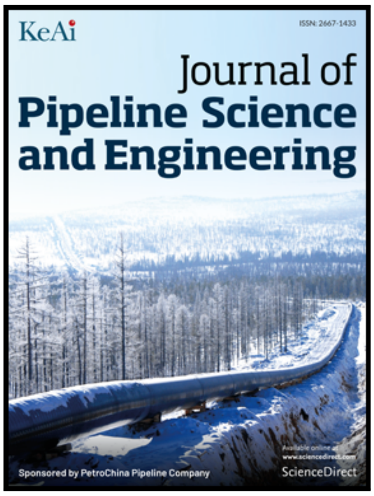

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Reliability Analysis of Slow Crack Growth in HDPE Pipes: Impact of Buried Pipeline Design and Soil Characteristics

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Abstract

This study delves into one of the most common fracture mechanisms in polyethylene pipes and the primary cause of their long-term failure, the slow crack growth (SCG) phenomenon. This failure mode in high-density polyethylene (HDPE) pipelines can potentially lead to brittle-like fractures without any localized yielding or plastic deformation. Leveraging the ISO 9080 standard for estimating pipe service life under SCG, we employ a reliability-based assessment incorporating Monte Carlo simulations to explore the impact of geometric burial design and soil characteristics on pipeline integrity.

Variables including pipe diameter, depth of cover, bedding angle, trench width, soil type, and compaction level were analyzed to determine their impact on the progression toward medium and high SCG-mediated probability of failure levels. In addition to a thorough examination of these variables, a machine learning analysis was employed as a supplementary tool to contrast and quantify their significance in influencing the time of entry into medium and high probability of failure states. This layered approach, combining detailed variable analysis with machine learning insights, underscores the complex interplay of design and environmental factors in mitigating SCG probability of failure.

Our research underscores that bedding angles under 90° substantially increase the likelihood of SCG-induced failures in HDPE pipelines. Although additional factors studied also affect failure probabilities, their impact is less critical in comparison to that of the bedding angle. By optimizing these lesser factors, minimal failure probabilities can be

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sustained across the standard 50-year service life of HDPE pipelines, thus bolstering their durability and reliability across diverse operating environments.

Keywords: HDPE pipelines, Slow crack growth (SCG), Pipeline reliability, Buried Pipeline Design, Soil characteristics, Monte Carlo simulation.

1. Introduction

High-density polyethylene (HDPE) pipelines constitute the backbone of contemporary distribution systems for fluids, crucial for industrial, municipal, and residential infrastructures [1]. Their inherent flexibility, durability, and resistance to corrosion have made HDPE pipelines a dominant choice, accounting for over 95% of gas distribution infrastructure in North America and extensively utilized in distribution networks around the globe [2].

This study delves into the behavior of HDPE, identifying two primary mechanisms of failure. Under conditions of excessive nominal stress, HDPE continues to deform slowly until it reaches a deformation large enough for the material to yield, swiftly followed by structural failure. This failure mechanism, preceded by creep or plastic deformation, manifests in what is known as the ductile state. Conversely, locally intensified stress can initiate and gradually propagate a localized, slowly growing crack. This SCG is characterized by the absence of plastic yield or localized deformation. This absence is indicative of the fracture process occurring in what is known as the brittle state. The working strength of each commercial grade of HDPE pipe material is determined by considering these two potential failure mechanisms [2].

Focusing on the slow crack growth mechanism, this article emphasizes a reliability analysis over time, guided by the life model of a polyethylene pipe as specified by [3]. Through a performance function informed by the evaluated time using the model, random variables, and Monte Carlo method, we aim to delineate the reliability behavior of the pipeline. The objective of this study is to assess how the times at which the pipeline enters high and medium probability of failure levels due to SCG are affected by variables related to the geometric design of burial and soil class. These variables include pipeline diameter, depth of cover, bedding angle, trench width, soil class, and compaction level.

While numerous investigations have explored the reliability of polyethylene pipelines over time [4][5], few have concentrated on the geometric burial variables and soil class, underscoring the importance of studying these aspects.

The typical lifespan expected for HDPE pipes is about 50 years. Nonetheless, the Plastics Pipe Institute notes that HDPE pipes used in municipal potable water or gas distribution systems can exceed a lifespan of 100 years. This impressive longevity stands out especially when compared to traditional materials like copper, cast iron, and galvanized steel, which generally last between 30 and 50 years. HDPE's superior durability underlines the need to investigate if and how certain installation and environmental factors might affect its expected lifespan [2].

In addition, the Second Edition of the [6] manual posits that the importance of specific burial conditions—such as precise bedding and embedment—might be overstated for pipes that are inherently stiff enough for basic installation. According to the manual, such pipes can be simply laid on the trench bottom and backfilled with the excavated soil, provided the depth of cover is shallow, there are no live loads, and the trench walls are stable. This suggests that under typical conditions, complex installation

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processes might not be necessary, raising questions about the conditions under which the integrity and functionality of HDPE pipes could be compromised.

In response, our study is designed to examine how varying geometric burial conditions and soil properties might influence the projected 50-year lifespan of HDPE pipelines. By doing so, we aim to determine whether standard guidelines underestimate the impact of certain environmental and installation factors on the pipeline's longevity and reliability. Through detailed simulations and machine learning analysis, we will identify which variables are most crucial and how they specifically affect the risk of pipe failure associated with the slow crack growth (SCG) mechanism.

2. Slow Crack Growth Model

ISO 9080 outlines a mathematical model to predict the failure time of thermoplastic pipes, such as those made from HDPE, due to slow crack growth (SCG). This failure mechanism is critical for the long-term performance of HDPE piping systems, where cracks propagate at a slow rate under sustained stress, potentially leading to failure.

Central to the standard is the formula (1), which estimates the time to failure (t_f) as a function of environmental and material parameters:

$$\log(t_f) = A + \frac{B}{T} + \frac{C\log(\sigma_c)}{T} \quad (1)$$

In this equation, A, B, and C are material constants derived from empirical data, T represents the absolute temperature in Kelvin, and σ_c is the hoop stress applied to the pipe. The model provides a quantitative framework to assess the durability of PE pipes under specific operating conditions, incorporating the effects of temperature and applied stress on the SCG process.

The constants A, B, and C within the formula have been extensively studied and determined through various methods. For this study, the values adopted are those obtained by [7] in their research on the structure and crack growth in gas pipes of medium-density and high-density polyethylene. The selected values A=-12.931, B=5904.042, and $C = -996.957$, are based on their findings for HDPE pipes. These constants reflect a comprehensive understanding of the material properties and crack growth behavior, providing a solid foundation for predicting the failure time of HDPE pipes due to SCG in our analysis.

3. Hoop Stress

Within the context of the SCG model for HDPE pipes, as outlined by ISO 9080:2012, hoop stress (σ_c) within the pipe walls is analyzed. This stress is a composite measure that integrates the effects of internal and external loads on the pipe, as illustrated in Figure 1. It is a parameter in the SCG model. Hoop stress is determined through the superposition of three principal stresses:

$$\sigma_c = \sigma_p + \sigma_s + \sigma_t \quad (2)$$

where σ_p denotes the hoop stress due to internal pressure P, σ_s the additional stress from soil load (dead load) W_s, and σ_t the additional stress from traffic (live load). For SCG failure mode analysis, only long-term permanent loads are pertinent, negating the influence of stress contributions from live loads.

For thin-walled pipes, the hoop stress attributable to internal pressure is explicitly described by:

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$$\sigma_p = \frac{Pr}{t} \quad (3)$$

Here, p symbolizes the maximum operating pressure, r the internal radius of the pipe, and t the pipe wall thickness.

To calculate the additional hoop stress due to soil load or traffic load, a modified version of Spangler's formula is utilized [8][9]. This method provides an estimate for the additional hoop stress at the bottom of the pipe due to a vertical load:

$$\sigma = \frac{6 \cdot K_b \cdot W_{\text{vertical}} \cdot E \cdot t \cdot r}{E \cdot t^3 + 24 \cdot K_z \cdot P \cdot r^3 + 0.732 \cdot E\prime \cdot r^3} \quad (4)$$

Equation (4) synthesizes the interaction between the pipe material, the load it bears, and the properties of the supporting ground to accurately estimate the hoop stress. W_{vertical} represents the vertical load due to soil or surface loads such as traffic, encompassing the weight directly applied over the pipe, including the impact of vehicles or other pressures exerted from the surface above the installed pipeline. E denotes the Young's modulus of the pipe material, E', the subgrade reaction modulus, quantifies the stiffness of the soil beneath the pipe, affecting how the ground supports the pipe and influences its deformation under load. K_z, the support factor, and K_b, the bending moment parameter, are influenced by the angle of bedding that supports the pipe. These parameters are necessary for determining the load distribution and the bending moments that the pipe will experience, directly impacting the hoop stress calculation.

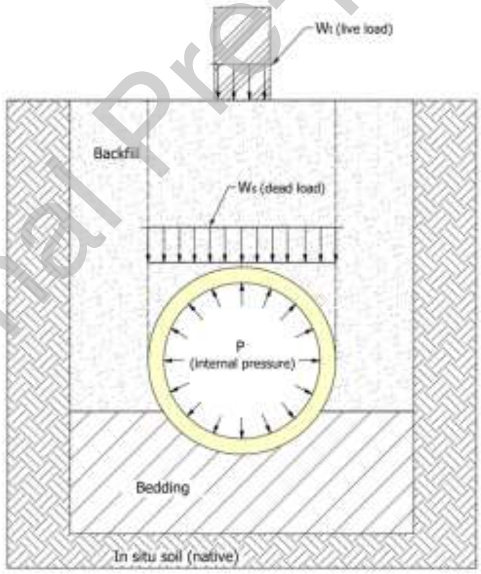

Figure 1 Cross-section of a buried pipeline illustrating the application of internal, dead, and live loads.

Soil loads on pipelines, resulting from the weight of the soil, are computed by considering the soil prism's weight directly above the pipe, in addition to shear forces transferred to this prism by adjacent soils. Spangler calculated the pressure transmitted to the pipe due to soil load, drawing on Marston's load theory [10], as follows:

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$$W_s = C_d \gamma B_d^2 \left(\frac{B_c}{B_d}\right) \quad (5)$$

where W_s is the dead load on the pipe due to soil, B_c the external diameter of the pipe, γ the unit weight of the backfill material, B_d the width of the trench at the pipe's crown, and C_d is the dimensionless load coefficient, a function of soil properties. The calculation of the dimensionless load coefficient C_d is conducted via the formula:

$$C_d = \frac{1 - e^{-2k\mu\frac{H_c}{B_d}}}{2k\mu} \quad (6)$$

Here, k is the ratio between lateral unit pressure and vertical unit pressure, μ is the sliding friction coefficient between the trench sides and the backfill material, and H_c is the height of the backfill material above the pipe crown. The values of k and μ can be determined as:

$$k = tan^2(45° - \frac{\phi}{2}) \quad (7)$$

$$\mu = tan(\phi) \quad (8)$$

where ϕ represents the soil's friction angle.

4. Reliability Model for Failure Probability Calculation

The reliability of HDPE piping systems against SCG can be quantitatively assessed using a performance function, denoted as $G(x_i) = t(x_i) - t_{service}$, where $G(x_i) \leq 0$ indicates failure, and a positive value signifies operational safety. Here, $t(x_i)$ represents the time to failure predicted by the ISO 9080:2012 model for a given set of conditions, and $t_{service}$ is the operational time of the pipe at the point of reliability analysis.

4.1. Monte Carlo Simulation for Probability of Failure

Monte Carlo simulation offers a robust method for estimating the probability of failure, that is, the likelihood that $G(x_i) \leq 0$. By randomly generating a large number of scenarios based on the variability of input parameters (such as material properties, environmental conditions, and applied stresses), this approach facilitates the computation of the distribution of $G(x_i)$. Consequently, the failure probability can be determined as the proportion of simulations where $G(x_i) \leq 0$.

4.2. Probability of Failure Thresholds

This study delineates specific ranges for probabilities of failure (PoF) due to SCG in HDPE pipelines, categorizing them into low, medium, and high levels, as detailed in Table 1. These thresholds have been defined in accordance with the guidelines provided by the Joint Committee on Structural Safety (JCSS) Probabilistic Model Code .

A transition to a medium probability of failure is identified when failure probabilities exceed 10^{-3} but remain below 10^{-2}. This range highlights an area of increased concern, suggesting heightened vigilance though not yet at a critical level. Conversely, a high probability of failure is recognized for probabilities greater than 10^{-2}, indicating a more urgent level of concern and the need for intervention to mitigate potential damages.

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Probability of Failure Range	Probability Category
$0 < Pof < 10^{-3}$	Low
$10^{-3} < Pof < 10^{-2}$	Medium
$Pof > 10^{-2}$	High

Table 1 Probability of Failure Categories.

5. Variables for Reliability Analysis

In this section we outline the study variables alongside the random variables that will be incorporated into the previously discussed reliability model.

5.1. Study Variables

The study variables considered for analyzing the reliability of HDPE pipelines are illustrated below. Figure 2 depicts the geometric variables that will be assessed throughout the study, including the excavated trench width B_d, pipe diameter D, bedding angle, and the depth of cover.

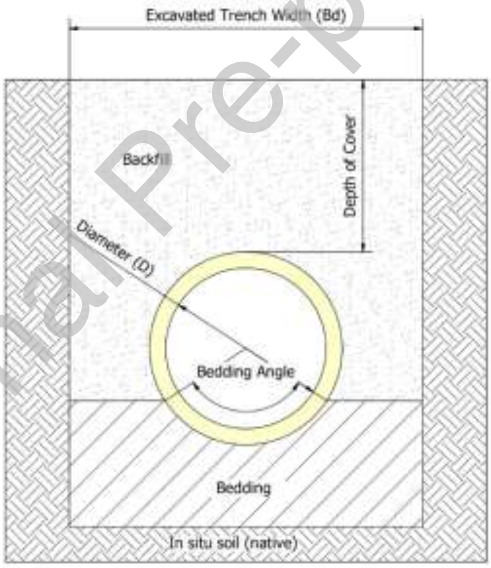

Figure 2 Geometric burial study variables.

- **Pipe Diameter:** The diameters under consideration are 3, 6, 10, and 12 inches. These dimensions represent commercial sizes of HDPE pipes widely utilized in gas distribution networks.
- **Depth of cover:** Depths of 60, 90, and 120 cm are analyzed, as these are commonly used in the burial of gas distribution pipelines.
- **Bedding Angle:** All bedding angles reported by Spangler, including 0°, 30°, 60°, 90°, 120°, 150° and 180°, are analyzed and their impact on the K_z and K_b factors is detailed in Table 2. These angles significantly influence the hoop stress resulting from soil load, a critical factor for assessing the structural integrity of pipelines as studied in [9].

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Bedding Angle (deg)	Moment Parameter K_b	Deflection Parameter K_z
0	0.294	0.110
30	0.235	0.108
60	0.189	0.103
90	0.157	0.096
120	0.138	0.089
150	0.128	0.085
80	0.125	0.083

Table 2 Spangler Stress Formula Parameters Kb and Kz.

- **Soil Classification and Compaction:** This study considers three backfill soil classes and their degree of compaction, represented as a percentage of Standard Proctor unit weight, as shown in Table 3. Both the soil class and the level of compaction significantly influence $E_b{}'$ (modulus of elasticity of the backfill surrounding the pipe), ϕ (friction angle), and γ (bulk unit weight of the backfill material). These factors are necessary for understanding the interaction between the surrounding soil environment and the pipe, impacting its stress conditions and the probability of failure. The values of ϕ used in this study, derived from the soil properties defined in Table 3, are 30° for Class I soils, 33° for Class II soils, and 30° to 36° for Class III soils, depending on the compaction level. These values were based on published standards and were applied consistently throughout the reliability analysis. The values for $E_b{}'$ and and γ were taken from [13].

ASTM D2321 Type of soil		**Slight < 85% Proctor**	**Moderate 85%-95% Proctor**	**High >95% Proctor**
CL, ML, ML-CL	**Class I**	3.4 MPa 30° 17.91 kN/m^3	4.8 MPa 30° 18.55 kN/m^3	6.8 MPa 30° 19.15 kN/m^3
SM , SC	**Class II**	4.1 MPa 33° 19.81 kN/m^3	6.2 MPa 33° 19.53 kN/m^3	9.3MPa 33° 20.00 kN/m^3
GW, GP, SW, SP	**Class III**	4.8 MPa 30° 19.99 kN/m^3	6.8 MPa 33° 20.76 kN/m^3	10.2 MPa 36° 21.54 kN/m^3

Note: CL = clay of low plasticity; ML = silt of low plasticity; ML-CL = combined clay and silt of low plasticity; SM-SC = silty and clayey sands; GW = well-graded gravel; GP = poorly graded gravel; SW = well-graded sand; and SP = poorly graded sand.

Table 3 Properties of Compacted Soils by Classification. This table presents the properties of backfill materials segmented by ASTM D2321 soil classification and compaction levels. It details the Elastic Modulus ($E_b{}'$), Friction Angle (φ), and Unit Weight (γ) for each soil type, across three compaction categories: less than 85% Proctor, 85% to 95% Proctor, and greater than 95% Proctor.

- **Trench Width to Pipe Diameter Ratio (B_d/D):** Ratios of 1.5, 3, and 5 are investigated to explore the significance of the trench width relative to the pipe diameter. This ratio is required for

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determining how external loads are distributed around the pipe and can affect the hoop stress experienced by the pipe.

- **Natural Ground to Backfill Elasticity Modulus Ratio (E_n'/E_b'):** The study considers ratios of $E_n'/E_b' = 0.5$ and 2, pivotal for calculating the combined modulus of elasticity of the soil reaction (E') in a buried pipeline environment. In conjunction with the trench width to pipe diameter ratio (Bd/D), these ratios aid in deriving the soil support combining factor, S_c, as outlined in Table 4. This factor is integral to formula 9, where E' synthesizes the moduli of the native soil (E_n') and the backfill (E_b') [13].

$$E' = S_c \cdot E_b' \tag{8}$$

This ratio and the corresponding calculation for E' are necessary for evaluating how variations in stiffness between the immediate surroundings of the pipeline and the native soil properties affect the pipe's behavior under load.

	S_c for $\frac{B_d}{D}$					
$\frac{E'_n}{E'_b}$	1.5	2.0	2.5	3.0	4.0	5.0
0.1	0.15	0.30	0.60	0.80	0.90	1.00
0.2	0.30	0.45	0.70	0.85	0.92	1.00
0.4	0.50	0.60	0.80	0.90	0.95	1.00
0.8	0.85	0.90	0.95	0.98	1.00	1.00
1.5	1.30	1.15	1.10	1.05	1.00	1.00
2.0	1.50	1.30	1.15	1.10	1.05	1.00
3.0	1.75	1.45	1.30	1.20	1.08	1.00
≥5.0	2.00	1.60	1.40	1.25	1.10	1.00

Table 4 Combined soil support factor values

5.2. Temporal Reliability Assessment and Identification of Critical Failure Probability Thresholds

In the reliability analysis previously outlined, the stochastic nature of critical parameters is captured through six selected random variables, as delineated in Table 5. The selection of these variables and their statistical properties is crucial, as they fundamentally influence the outcomes of the Monte Carlo simulations. The mean values and coefficients of variation (C.V.) for each variable were determined based on a combination of industry standards, manufacturer specifications, and relevant literature [4].

For instance, the modulus of elasticity (E) is set at a mean value of 750 MPa with a C.V. of 0.05, reflecting typical material properties for HDPE pipes, as reported in industry guidelines [14]. The internal pressure (P) has a mean value of 60 psi and a C.V. of 0.05, based on standard operating pressures for gas distribution pipeline systems. The pipe wall thickness is represented by the Standard Dimensional Ratio (SDR), a dimensionless parameter defined as the ratio of the external diameter of the pipe to its wall thickness. The SDR for the pipes in this study is specified as SDR 11, with a C.V. of 0.06, reflecting dimensional tolerances provided by the pipe manufacturer and accounting for variability due to manufacturing processes [6].

The external pipe diameters (D) of 3, 6, 10, and 12 inches were selected to represent a range of pipeline sizes commonly used in the industry, with a minimal C.V. of 0.001 to reflect precise manufacturing controls and minimal dimensional variability. The depth of cover (H_c) mean values of 60, 90, and 120 cm with a C.V. of 0.1 account for typical installation depths and variability due to construction practices and soil settlement over time.

By integrating these well-defined stochastic parameters into the Monte Carlo simulations applied to the limit state function, we compute the probability of failure for each unique set of study variables over an operational timeline spanning 0 to 200 years. This dynamic analysis not only yields year-by-year failure probabilities but also enables tracking of their progression over the pipeline's service duration. As a result, it generates a time-based profile of failure probabilities, providing the ability to identify trends and predict instances when a pipeline might reach designated thresholds of low, medium, or high failure probabilities. From this perspective, the study identifies the years within the service life of the pipeline when the failure probability exceeds the thresholds defined in Table 1.

Symbol	Description	Mean value	C.V
E	Modulus of elasticity	750 MPa	0.05
P	Internal pressure	60 psi	0.05
t	Pipe wall thickness	SDR 11	0.06
D	External pipe diameter	3, 6, 10, 12 in	0.001
H_c	Depth of cover	60, 90, 120 cm	0.1
γ	Unit weight of the backfill material	γ (soil class, Proctor)	0.1

Table 5 Random Variables in the Reliability Model

5.3. Deriving Relative Importances of Study Variables through Machine Learning

Following the identification of critical ages when pipelines exceed defined failure probability thresholds, specifically transitioning at 10^{-3} for medium and 10^{-2} for high levels of failure probability, an in-depth analysis was conducted using a Random Forest machine learning algorithm. This analysis aimed to quantify the impact of various study variables on the age at which pipelines are projected to reach these specified PoF thresholds.

Random Forest builds a multitude of decision trees during training and outputs the mean prediction of the individual trees. It quantifies the importance of variables based on the decrease in model accuracy when the values of a variable are permuted randomly across the dataset. This shuffling breaks the direct link between the variable and the outcome, allowing us to measure how much each variable contributes to model accuracy. The importance of each variable is computed by averaging the decrease in performance across all trees in the forest, which reflects the variable's predictive strength [15].

In our study, the Random Forest model was trained using the previously detailed study variables, with the response variable being the age at which pipelines are projected to enter defined probability of failure thresholds due to SCG. This approach is supported by literature that highlights the effectiveness of Random Forest in identifying critical risk factors and predicting infrastructure deterioration. For instance, studies like that emphasize the significance of factors such as pipe material and service life in the risk assessment of municipal pipeline networks, showcasing the ability of the algorithm to highlight

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critical risk factors. Additionally, [17] demonstrates how Random Forest can effectively predict sewer pipe deterioration, further underlining the utility of this method in maintaining infrastructure integrity by optimizing inspection and maintenance planning.

6. Results Analysis and Discussion

We present the outcomes from analyzing 4536 unique combinations of study variables. To illustrate these interactions, we employ a dual-diagram approach for each study variable: trends in failure probabilities as a function of time are depicted alongside box-and-whisker and half-violin plots. These visuals are designed to show when combinations exceed the defined thresholds of 10^{-3} for medium and 10^{-2} for high probability of failure. This presentation format aims to streamline visualization and analysis, facilitating a clear understanding of how each study variable influences the probability of failure and, by extension, pipeline reliability.

6.1. Diameter

In the analysis of the study variable 'diameter', the line graph in Figure 3 provides a clear average trend across the dataset. On average, HDPE pipes with larger diameters exceed critical SCG failure probability thresholds, marked as medium probability of failure ($Pof > 10^{-3}$) and high probability of failure ($Pof > 10^{-2}$), more quickly than pipes with smaller diameters. For instance, on average, pipes with a 12-inch diameter exceed the medium failure probability threshold about 18 years earlier and reach the high failure probability level approximately 25 years sooner than those with a 3-inch diameter. This pattern indicates an increased probability of SCG for larger pipes over a shorter time frame.

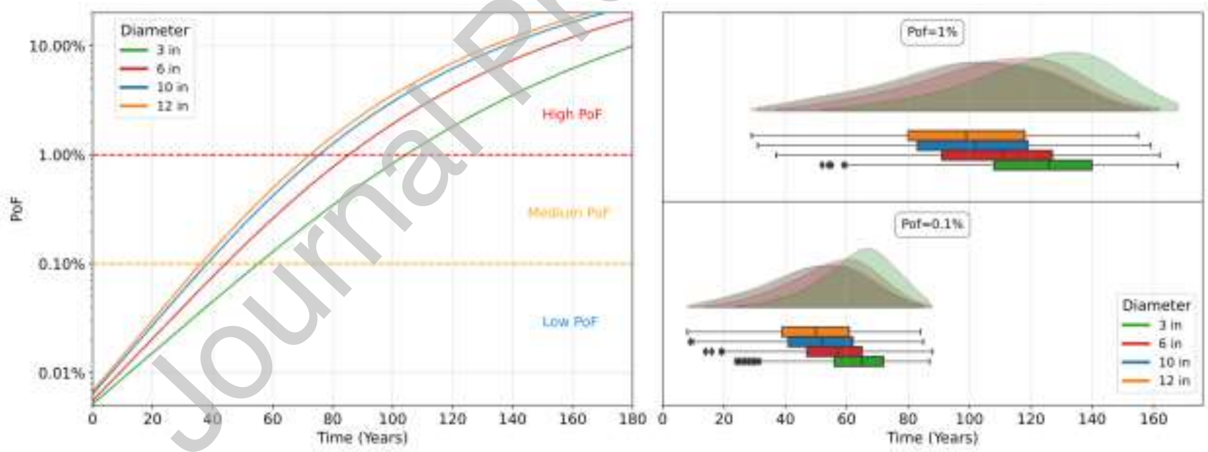

Figure 3 Line graph showing the variation of the average PoF with time for pipe diameters of 3, 6, 10, and 12 inches, alongside combined box-and-whisker and half-violin plots illustrating the distribution around the threshold values for medium and high PoF levels.

However, the box-and-whisker plots, coupled with the half-violin diagrams, reveal a wide variation in the times when these thresholds are exceeded, which could lead to significant implications for pipeline management. The considerable spread in the data points out that, while the average trend suggests a higher probability of SCG failure for larger diameters, there are instances where this may not be the case. Proper selection of other study variables could potentially mitigate the time it takes to exceed these probability of failure thresholds, particularly in situations where changing the diameter is not feasible due to flow rate or capacity requirements of the pipeline system.

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6.2. Bedding angle

The analysis of the impact of the bedding angle on pipeline reliability, examining a comprehensive range of angles, reveals critical insights. Both the line graph and the half-violin and box-and-whisker diagrams in Figure 4 indicate that changes in bedding angle beyond 90° are less significant compared to shifts from 0° to 90°. For instance, transitioning to a medium probability of failure ($Pof > 10^{-3}$) occurs 24 years earlier for pipelines with a 0° bedding angle compared to those at 90°. However, the difference in reaching a medium probability of failure between 90° and 180° angles is merely 5 years, suggesting that changes within lower angles have a more pronounced effect on the probability of failure.

This observation highlights the importance of selecting appropriate bedding angles in pipeline installations. It is particularly advisable to avoid configurations that result in bedding angles less than 90°, as they significantly accelerate the onset of medium and high probabilities of failure. This guidance is supported by both the trend analysis over time and the distribution patterns observed in the diagrams, underscoring the need for careful consideration of bedding angles to enhance pipeline durability and reliability. Additionally, the graphs illustrate that following this recommendation, pipelines on average would exceed the medium probability of failure threshold ($Pof > 10^{-3}$) after 50 years, aligning with the expected lifespan of HDPE pipes, thus further substantiating the advisability of avoiding lower bedding angles.

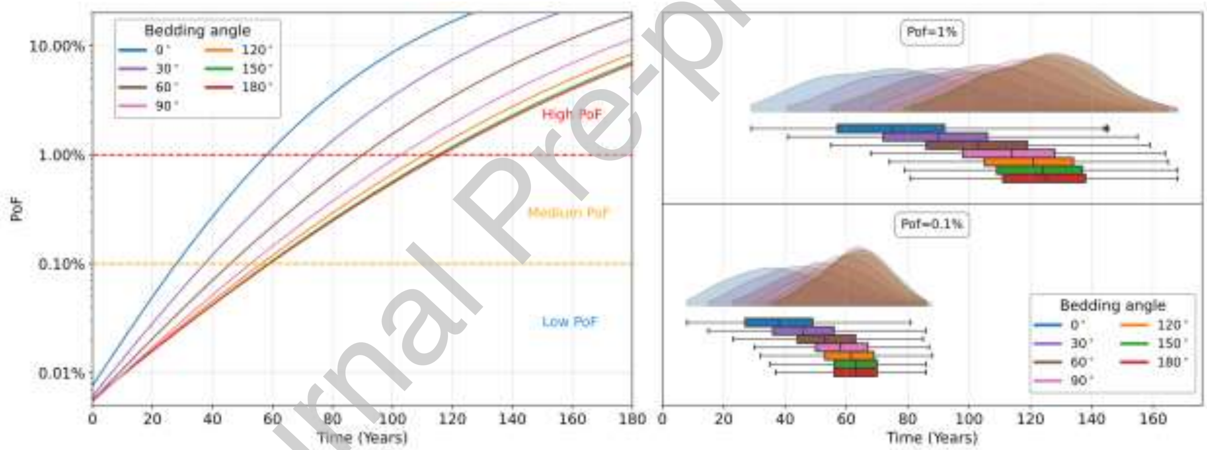

Figure 4 Line graph depicting the trends of average failure probabilities over time for bedding angles of 0, 90, and 180 degrees, alongside combined box-and-whisker and half-violin plots demonstrating the variability at medium and high failure probability thresh.

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6.3. Depth of cover

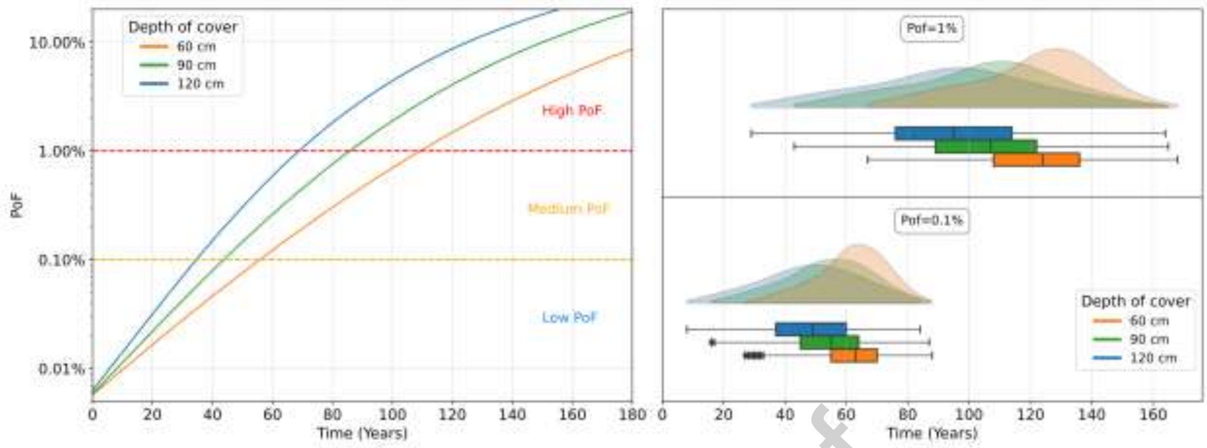

Figure 5 Line graph depicting the trends of average failure probabilities over time for depths of cover of 60, 90, and 120 cm, alongside combined box-and-whisker and half-violin plots demonstrating the variability at medium and high failure probability threshold

Analyzing the effect of the depth of cover on pipeline reliability, the line graph in Figure 5 clearly indicates an average trend where pipes buried at 120 cm reach medium ($Pof > 10^{-3}$) and high ($Pof > 10^{-2}$) probability of failure sooner than those at shallower depths. On average, pipelines at this depth transition to a medium probability of failure 20 years earlier and to a high probability of failure 40 years earlier compared to those buried at 60 cm. This could suggest that while deeper burial effectively shields pipelines from live loads or damages from external activities, it might also create conditions conducive to SCG. Factors such as increased soil pressure or variations in soil properties with depth could potentially contribute to this increased probability of failure.

However, despite this trend, the data also shows a broad variation in results across different depths, indicating that although deeper burial generally correlates with a faster onset of failure probabilities, this is not a uniform rule. This variability underscores the potential for strategic management of other variables to improve resilience against SCG. Even if depth adjustments are not feasible due to design constraints, optimizing other factors could mitigate the adverse effects of deeper burial or maximize the benefits of shallower installations.

In essence, while depth of cover is a significant factor, its impact on the probability of failure due to SCG can be effectively managed by carefully considering the interaction with other pipeline design variables.

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6.4. Compaction Level

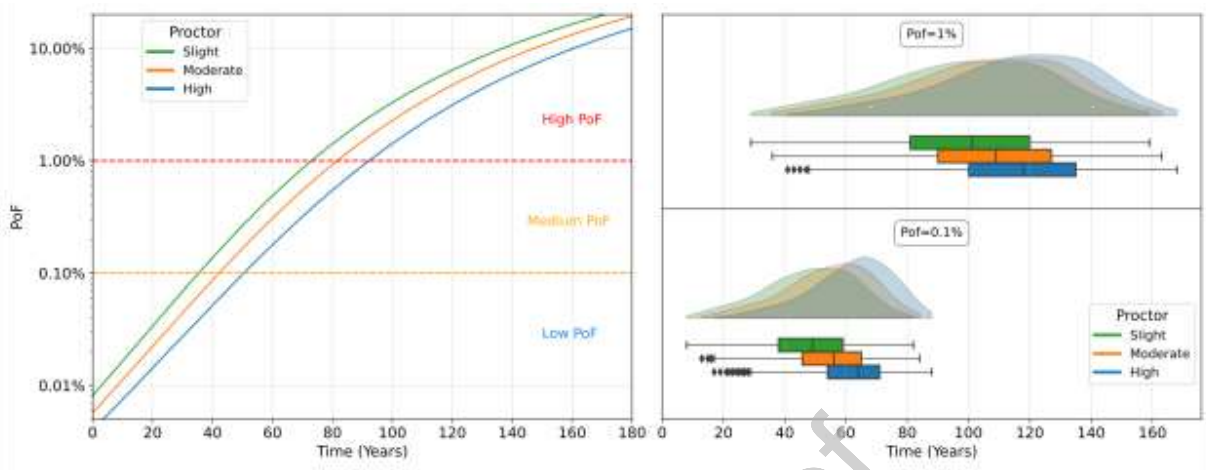

Figure 6 Line graph depicting the trends of average failure probabilities over time for different compaction levels, alongside combined box-and-whisker and half-violin plots demonstrating the variability at medium and high failure probability thresholds.

The examination of compaction levels, represented by Proctor values, uncovers their marked impact on the timing at which pipelines reach medium ($Pof > 10^{-3}$) and high ($Pof > 10^{-2}$) thresholds in pipelines. As illustrated in the line graph in Figure 6, pipes buried with a high Proctor compaction level tend to enter these higher failure probability thresholds later than those with slight compaction. On average, a high Proctor compaction delays the entry into the medium and high failure probability phases by 15 years compared to a slight compaction level.

Moreover, the data also reveals a wide variation in results across different compaction levels, suggesting that while compaction significantly influences the timing at which pipelines reach higher failure probabilities, its impact can be modulated by other design choices. This indicates that even if it is not feasible to alter the compaction level due to specific design constraints, selecting the appropriate combination of other variables can still enhance the resistance of the pipeline to SCG. As shown in Table 3, higher compaction levels increase the Elastic Modulus (E_b') of the backfill or foundation material, as well as the density of the backfill. Observing this behavior, the growth in E_b' is beneficial for reducing the probability of failure in SCG. Although the density also increases, which could impose a greater dead load on the pipeline, the effect of the increased E_b' is more substantial, suggesting that to enhance SCG reliability, a generalized increase in E_b' is advantageous.

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6.5. Soil Class

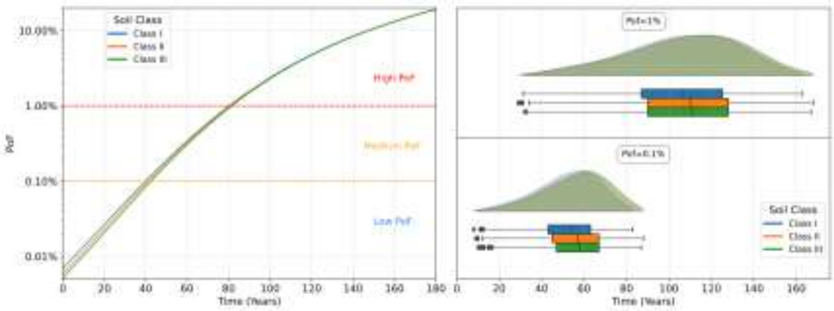

Figure 7 Line graph depicting the trends of average failure probabilities over time for different soil classes, alongside combined box-and-whisker and half-violin plots demonstrating the variability at medium and high failure probability thresholds.

In the assessment of soil classes defined by the particle size distribution, our analysis indicates that the average probabilities of failure for different soil classes do not show marked differences in the timeframes for reaching medium and high failure probabilities. The line graph in Figure 7 shows that the failure probability trends for Classes I, II, and III soils closely align, suggesting that particle size distribution (PSD), within the scope of these classifications, has a limited impact on the progression towards SCG.

The accompanying box-and-whisker plots further substantiate this observation, displaying a narrow and overlapping distribution of failure probabilities across the three soil classes. This convergence implies a relatively uniform failure probability profile regarding SCG across various soil classes.

While the interaction of soil properties with pipeline integrity is indeed important (highlighted by the marked influence of compaction level, depth of cover, and bedding angle) our data suggests that PSD, specifically within the range of Classes I to III, might not critically impact SCG susceptibility.

6.6. Trench Width to Pipe Diameter Ratio (Bd/D)

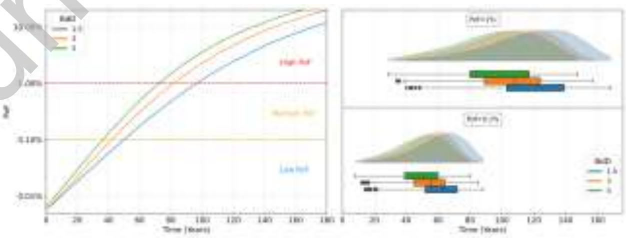

Figure 8 Line graph depicting the trends of average failure probabilities over time for trench width to pipe diameter ratios of 1.5, 3, and 5, alongside combined box-and-whisker and half-violin plots demonstrating the variability at medium and high failure probability thresholds.

Upon examining the Trench Width to Pipe Diameter Ratio (B_d/D), the analysis reveals a significant correlation between the trench width relative to the pipe diameter and the time at which pipelines exceed critical slow crack growth (SCG) failure probability thresholds. The graphical representation in Figure 8 illustrates that pipelines laid in trenches where the width is only 1.5 times the diameter show a slower progression towards the medium and high SCG failure probabilities, as opposed to those in trenches with a width five times that of the pipe diameter.

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The line graph delineates a pronounced delay for pipes with a B_d/D ratio of 1.5, reaching the medium failure probability threshold approximately 15 years later than pipes in trenches with a B_d/D ratio of 5. This pattern extends to the high probability of failure level transition, where a B_d/D ratio of 1.5 correlates with exceeding the high probability of failure threshold 25 years later compared to a B_d/D ratio of 5.

The accompanying box-and-whisker and half-violin plots not only corroborate the average trends observed in the line graph but also reveal a significant spread in the data. This variability underscores that while larger Bd/D ratios generally correlate with an earlier onset of SCG failure probabilities, the trend is not uniform across all instances. It suggests that there can be considerable divergence from the average, indicating that other variables may influence the timeline to exceed critical failure probability thresholds.

6.7. Natural Ground to Backfill Elasticity Modulus Ratio (E_n'/Eb')

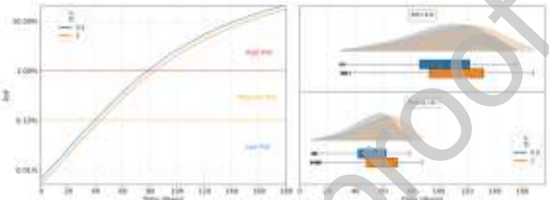

Figure 9 Line graph depicting the trends of average failure probabilities over time for natural ground to backfill elasticity modulus ratios of 0.5 and 2, alongside combined box-and-whisker and half-violin plots demonstrating the variability at medium and high failure probability thresholds.

The investigation into the E_n'/Eb' ratio, which compares the modulus of elasticity of the natural ground to that of the backfill material, reveals significant insights into its influence on the timing at which HDPE pipelines reach medium ($Pof > 10^{-3}$) and high ($Pof > 10^{-2}$) thresholds due to SCG. It is observed in Figure 9 that pipelines in environments where the natural ground's modulus of elasticity surpasses that of the backfill material (indicating a higher E_n'/E_b'ratio) tend to enter these higher failure probability thresholds later.

For instance, pipelines with an E_n'/E_b' ratio of 2 enter the medium failure probability threshold approximately 5 years later than those with a ratio of 0.5. This trend continues into the high failure probability threshold, maintaining the same temporal difference. This phenomenon is visually represented by the parallelism observed in the failure probability lines for the two En/Eb ratios of 0.5 and 2.

The examination of the E_n'/Eb' ratio in relation to SCG failure probabilities reveals a substantial variation in the timing to reach critical failure thresholds, as evidenced by the significant dispersion observed in the violin and box-and-whisker diagrams. This spread suggests that, while the E_n'/Eb' ratio is influential, its impact on SCG failure probabilities can be significantly modulated by the control and optimization of other study variables. Such variability in the data indicates that even in cases where the E_n'/Eb' ratio cannot be readily altered—due to the impracticality of changing inherent soil properties or economic constraints—strategic management of variables such as compaction level, bedding angle, and pipe diameter may offer avenues to mitigate SCG failure probabilities effectively. Additionally, these results show that a greater E_n'/Eb' ratio is beneficial in terms of SCG reliability, as a higher modulus of elasticity of the natural ground ensures that the combined modulus of elasticity (E'), which takes into

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account both the backfill and the natural ground's moduli, is increased. Ultimately, to enhance SCG reliability, the goal is to increase this E' value.

6.8. Analysis of Variable Importance in Pipeline Probability of Failure Level Assessment

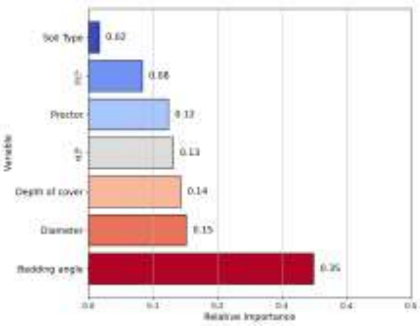

Figure 10 Relative importance of variables influencing pipeline PoF levels determined by Random Forest analysis.

In Figure 10, the values of relative importance for different variables in the Random Forest analysis are presented, highlighting their contributions to pipeline susceptibility to slow crack growth (SCG). The 'bedding angle' emerges as the most influential factor, scoring an importance of 0.35, which highlights the critical role of installation practices in determining pipeline durability. This factor is particularly significant, as it shows a pronounced increase in the probability of SCG failure for pipelines with bedding angles less than 90°, and its importance is more than double that of the next variable.

Following closely is 'diameter', with an importance score of 0.15. This variable plays a significant but not exclusive role in SCG failure probabilities, with larger diameters tending to accelerate the entry into medium and high failure probabilities. Although there is a clear trend, the wide variability in the data suggests that other factors may also modulate these probabilities.

The 'depth of cover' is similarly impactful with an importance score of 0.14. Deeper burials often hasten the entry into higher SCG failure probabilities, pointing to complex interactions with other variables such as bedding angle that may influence failure thresholds more quickly.

The 'B_d/D ratio' has a slightly lower importance at 0.13, illustrating that narrower trench widths relative to pipe diameter can delay entry into higher SCG failure probabilities, potentially serving as a protective measure. The variability observed in the data underscores the potential for adjusting other variables to mitigate the challenges imposed by the B_d/D ratio.

'Compaction level', indicated by Proctor values with an importance score of 0.12, significantly affects the timing of entering higher SCG failure probabilities. Higher compaction levels typically extend the time to reach these critical thresholds, a trend that is consistent across the data. Importantly, higher compaction increases the Elastic Modulus (E_b') of the backfill material, which contributes to an overall increase in the combined modulus of elasticity (E'), enhancing the pipeline's resistance to SCG.

The E_n'/E_b' ratio has a lower score of 0.08, yet it still impacts the timing of SCG failure probabilities. Pipes in environments where the natural ground's modulus of elasticity significantly exceeds that of the backfill tend to delay the entry into higher failure probabilities. This is because a higher E_n'/E_b'ratio contributes to an increased E', the subgrade reaction modulus, which considers both the modulus of elasticity of the natural ground and the backfill. The interplay between the E_n and E_b moduli thus significantly modifies E', reinforcing the pipeline's structural integrity against SCG.

Lastly, 'soil class' has the lowest relative importance at 0.02. While it has a minor direct impact on SCG failure probabilities according to the Random Forest analysis, the similar timings across soil classes

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suggest that soil PSD within Classes I to III may not be as pivotal to SCG failure probabilities as other factors.

The alignment of the Random Forest importance scores with the data underscores the need for a comprehensive approach in pipeline management, integrating all variables to effectively mitigate SCG failure probabilities.

Given the significant importance of the bedding angle derived from Random Forest analysis and the observed data trends, we conducted a thorough analysis of how variations in bedding angles affect the timing of entering medium and high SCG failure probabilities. Figures 11(a) and 11(b) visually encapsulate the impact of different bedding angles on the timing pipelines enter failure phases. Figure 11(a) includes all combinations and highlights that configurations with bedding angles less than 90frequently enter medium and high failure states much earlier—within 18 and 30 years respectively. In contrast, Figure 11(b) focuses solely on combinations that adhere to bedding angles greater than 90, demonstrating that these configurations largely avoid entering high probability of failure phases until after the standard 50-year lifespan of HDPE pipes. This stark contrast in outcomes between the two figures underscores the critical influence of bedding angle selection on pipeline durability and validates the recommendation to use bedding angles greater than 90° to optimize pipeline longevity and reliability.

a) Half-violin and box plot illustrating the distribution of the PoF over time for all combinations.

b) Half-violin and box plot focusing on combinations adhering to the recommended bedding angles greater than 90°.

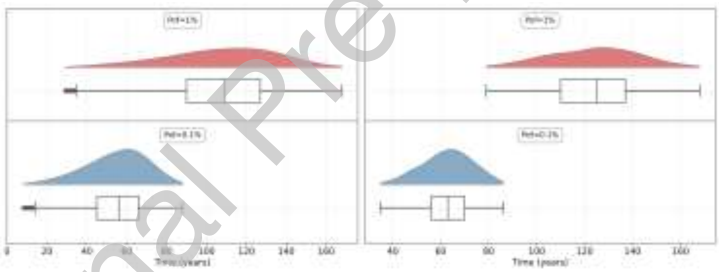

Figure 11 Comparative analysis of PoF distributions for different bedding angle conditions: (a) all combinations; (b) recommended combinations only.

While suggests that specific burial conditions such as precise bedding and embedment may not be crucial for HDPE pipes capable of basic installation, the importance of bedding angle in influencing the lifespan of pipelines should not be underestimated. Although the manual permits simpler installations where the pipe can be laid directly on the trench bottom under stable conditions, our findings indicate that angles less than 90could significantly reduce the operational life of HDPE pipes, potentially leading to medium or high PoF levels before reaching the expected 50-year lifespan. While other variables beyond bedding angle directly impact the reliability of HDPE pipelines in resisting SCG, their variation does not directly influence the standard 50-year lifespan of the pipelines. To extend the operational life of these pipelines beyond this baseline, it is crucial to consider the broader set of variables identified in our study. This approach ensures that even beyond the typical expectancy, the pipelines maintain high levels of integrity and functionality.

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7. Conclusions

This study has elucidated the significant influence of geometric burial design and soil characteristics on the SCG phenomenon in HDPE pipelines. By employing a reliability-based assessment approach that integrates Monte Carlo simulations and machine learning techniques, we have identified key factors that contribute to the probability of failure PoF due to SCG and provided insights into optimizing geometrical burial design for enhanced longevity.

Bedding Angle: Among the variables analyzed, the bedding angle is paramount. Pipelines with bedding angles less than 90° enter zones of medium and high PoF much more quickly. Our findings emphasize that maintaining bedding angles at or above 90° is crucial for minimizing the PoF. This recommendation is substantiated by the fact that bedding angles greater than 90° effectively mitigate SCG, aligning with the expected 50-year service life of HDPE pipelines. This highlights the importance of precise installation practices, particularly in trench bedding, to ensure pipeline reliability.

Diameter and Depth of Cover: While the diameter and depth of cover of HDPE pipelines do influence their progression towards higher failure probabilities, their impact is notably less critical than that of the bedding angle. Larger diameters and greater depths of cover do accelerate the move towards higher failure probabilities of SCG, but this effect can be significantly mitigated by optimizing other design parameters. For instance, adjusting trench width and compaction levels can effectively manage the adverse effects associated with larger diameters and deeper burial. Therefore, while important, the influence of diameter and depth of cover is considerably lower than that of the bedding angle in determining pipeline reliability.

Compaction Level and Soil Class: The level of soil compaction, indicated by Proctor values, slightly affects the (PoF). Higher compaction levels increase the modulus of elasticity of the backfill, which in turn enhances pipeline resistance to SCG. Although the soil class, based on particle size distribution, shows a relatively low impact across different classifications, the compaction level within each class is crucial for optimizing pipeline performance. Ensuring high compaction levels is thus recommended to improve the structural integrity of the pipeline.

Trench Width to Pipe Diameter Ratio (Bd/D) and En/Eb Ratio: The Bd/D ratio influences the load distribution around the pipeline, with narrower trench widths relative to pipe diameter proving beneficial for SCG resistance. Additionally, the En/Eb ratio, which compares the elasticity moduli of natural ground and backfill, impacts the combined modulus of elasticity (E'), with higher ratios contributing to better performance against SCG. Strategic management of these ratios is essential for enhancing pipeline reliability.

Machine Learning Insights: The use of Random Forest analysis has provided a nuanced understanding of the relative importance of different variables. The bedding angle emerged as the most significant factor, with an importance score markedly higher than all other variables. This underscores its critical role in determining pipeline failure probabilities. The other variables, such as diameter, depth of cover, trench width to pipe diameter ratio, and compaction level, have similar but significantly lower importance scores compared to the bedding angle. This analysis highlights the necessity of a holistic approach in pipeline design, considering all influential factors to mitigate SCG risks effectively, while emphasizing the paramount importance of optimizing the bedding angle.

References

[1] Thomas Walsh. The plastic piping industry in North America. In Applied Plastics Engineering Handbook, pages 585–602. Elsevier, 2011.

[2] Plastics Pipe Institute. Handbook of Polyethylene Pipe. 2nd ed., Plastics Pipe Institute, Irving, TX, 2008.

[3] ISO9080. ISO 9080:2012, Plastics piping and ducting systems – Determination of the long-term hydrostatic strength of thermoplastics materials in pipe form by extrapolation. International Organization for Standardization, 2012. Available at: https://www.iso.org/standard/43860.html.

[4] Rabia Khelif, Alaa Chateauneuf, and Kamel Chaoui. Reliability-based assessment of polyethylene pipe creep lifetime. International Journal of Pressure Vessels and Piping. 84 (2007): 697–707. https://doi.org/10.1016/j.ijpvp.2007.08.006.

[5] Sixi Zha, Hui-qing Lan, and Hui Huang. Review on lifetime predictions of polyethylene pipes: Limitations and trends. International Journal of Pressure Vessels and Piping. 198 (2022): 104663. https://doi.org/10.1016/j.ijpvp.2022.104663.

[6] American Water Works Association. PE Pipe—Design and Installation. Manual of Water Supply Practices—M55, 2nd ed., American Water Works Association, 2020.

[7] T. Tränkner, M. Hedenqvist, and U.W. Gedde. Structure and crack growth in gas pipes of medium-density and high-density polyethylene. Polymer Engineering & Science. 36, no. 16 (1996): 2069–2076.

[8] David J. Warman, James D. Hart, and Robert B. Francini. Development of a pipeline surface loading screening process & assessment of surface load dispersing methods. Canadian Energy Pipeline Association Report. 2009.

[9] Merlin G. Spangler. Pipeline crossings under railroads and highways. Journal-American Water Works Association. 56, no. 8 (1964): 1029–1046.

[10] Anson Marston. The theory of loads on pipe in ditches and tests of cement and clay drain tile and sewer pipe. Bulletin. 31 (1913).

[11] JCSS. JCSS Probabilistic Model Code. Joint Committee on Structural Safety, 2001. Available at: https://www.jcss-lc.org/jcss-probabilistic-model-code.

[12] James D. Hartley and James M. Duncan. E and its variation with depth. Journal of Transportation Engineering. 113, no. 5 (1987): 538–553.

[13] Jey K. Jeyapalan and Reynold Watkins. Modulus of soil reaction (E') values for pipeline design. Journal of Transportation Engineering. 130, no. 1 (2004): 43–48.

[14] Chevron Phillips Chemical Company LLC. Performance Pipe. 2024. Available at: https://www.cpchem.com (Accessed: 2024-11-30).

[15] Trevor Hastie, Robert Tibshirani, Jerome H. Friedman, and Jerome H. Friedman. The Elements of Statistical Learning: Data Mining, Inference, and Prediction. 2nd ed., Springer, 2009.

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[16]Hang Cen, Delong Huang, Qiang Liu, Zhongling Zong, and Aiping Tang. Application research on risk assessment of municipal pipeline network based on random forest machine learning algorithm. Water. 15, no. 10 (2023): 1964. https://doi.org/10.3390/w15101964.

[17]Razieh Tavakoli, Ali Sharifara, and Mohammad Najafi. Prediction of sewer pipe deterioration using random forest classification. arXiv preprint. arXiv:1912.04194, 2019.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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