Improving safety design for gas pipeline installation via horizontal directional drilling: a pipe stress analysis approach

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Abstract

Horizontal Directional Drilling (HDD) has today emerged as a significant and efficient technique for installing pipelines for a variety of purposes, including the production of oil, natural gas, water, sewer, electrical, and telecommunications. Due to the complexity of the technology and the intricate interplay of numerous processes, the safety risks associated with process uncertainty are substantial. However, risk analysis for HDD projects is generally done using qualitative methods. One of the most common factors used for HDD risk assessment is Pipe Stress Analysis (PSA). In this article, a combination of material evaluation and PSA for HDD safety design is suggested to improve the risk analysis. The evaluation will commence with an assessment of the material, followed by an examination of the wall thickness. Subsequently, an analysis of HDD design and pipe stress will be conducted. Using 10-inch API 5L Gr. B pipe, the safety design was successfully tested for a gas pipe project. When using HDD, a natural bend value of no less than 415.3 meters must have a horizontal length of 168 meters. According to the curvature, the length of the entire pipe is 169.03 meters. The combined installation stress was less than 1, while the combined operation stress was 114.87 MPa. These two values met the criteria specified in the standard. Overall, those steps were able to ensure that the HDD installation design is safe for constr

Keywords:

Gas pipeline, horizontal directional drilling, material evaluation, pipe stress analysis, installation safety.

1 Introduction

In the past, new underground utility pipelines were usually installed using conventional open-cut techniques. However, environmental damage or impacts to already-built infrastructure such as railways, roadways, and other surface structures have sometimes resulted from this traditional method. Moreover, installing pipelines beneath bodies of water like rivers and lakes is difficult with open-cut construction [1]. Horizontal Directional Drilling (HDD), originally in the oil and gas industry, is a trenchless installation technique used to install underground pipelines with little environmental impact or harm to existing infrastructure, such as roads and other surface structures. The procedure begins with a drill rig surface-launching a pilot hole along the planned design path at an entry angle of 8°–16°. Before installing the product pipe, the initial pilot bore is subsequently enlarged using a series of reamers with various diameters [2]. High-performance drilling fluids are used by the contractor during

drilling to cool the drill bit (or reamers), maintain borehole stability, and transport drill cuttings to the surface. The first HDD installation took place in 1971 in Watsonville, California, for the installation of an 187.5-meter steel natural gas pipe during a crossing of the Pajaro River. With the advancement of HDD innovations, it has today emerged as a significant and efficient technique for installing pipelines for a variety of purposes, including the production of oil, natural gas, water, sewer, electrical, and telecommunications [3].

Even though this technology is frequently used to successfully install pipelines, there are also known instances of failed projects. Due to the technology's complexity and the interplay of numerous processes, the risks associated with process uncertainty are significant. These risks are related to subsurface formation variability, changes in natural environmental conditions, changes in the economic environment, as well as facility limitations, technical disruptions, and human factors [4]. Prior to beginning the investment's realization, the contractors emphasize the importance of conducting a risk assessment because this serves as the foundation for analyzing the project's viability and cost projections [5]. However, most assessments are carried out qualitatively. Assessment is carried out through brainstorming, checklists, document reviews, and interviews [6], or by relying on assessments from experts who are familiar with HDD projects [7].

In addition to providing decision-makers with better information to help them set project objectives, identifying and quantifying HDD risks will help them avoid many serious and high-impact risks related to HDD failures. Furthermore, the sector would be in a better position to create risk response plans that would enhance performance [6]. One of the most common factors considered for HDD risk assessment is pressure or pipe loads [1]. HDD pipelines are put under tension, bending, and external pressure at the same time. These installation loads, which may be more severe than operational loads, may govern drilled path design and pipe specification [8]. Accordingly, to reduce the risk of failure during HDD installation, pipe stress analysis must be done [9], [10], and [11].

Furthermore, when choosing the appropriate pipe materials for an HDD installation, the borehole profile and pipe properties must be considered. To ensure that the pipeline can be installed and used without risk of damage, these two factors should be considered together [12]. Therefore, this paper proposes an HDD safety design by adding material evaluation to complete the pipe stress analysis. Moreover, the proposed method was demonstrated for a new HDD project for gas pipeline installation, which must cross a river.

2 Research Methods

In this article, four steps for HDD safety design were suggested. The evaluation began with an assessment of the material, followed by an examination of the wall thickness. The drilled path design and the analysis of pipe stress were then conducted.

2.1 Material Evaluation

The American Petroleum Institute (API) 5L specification is the most commonly utilized material for pipelines in the oil and gas industry [13]. More specifically, API 5L Grade B-compliant materials are among the best for HDD operations [9]. According to [14], seamless and welded line pipe intended for use in petroleum transportation systems in the natural gas and petroleum sectors is referred to as API 5L. The minimum yield strength of the pipe is 245 MPa, or around 35500 psi. To make sure that the steel pipe material used for HDD complies with the API 5L Grade B specification, the material evaluation stage is used.

2.2 Wall Thickness Evaluation

Pipes are produced in various standardized thicknesses. Each specific thickness of the pipe is given a name in the form of a

schedule number, not in terms of the actual pipe thickness. The thickness of the pipe greatly determines the stresses that occur in the piping system. So the calculation of pipe thickness really needs to be studied properly and adjusted to the formula in the pipe standard code. In addition, the determination of the standard code used in calculating the thickness of the pipe must be in accordance with what fluid is flowing in the piping system. As the streamed fluid is a gas, the American Society of Mechanical Engineers (ASME) B31.8 (gas transmission and distribution piping system) code is suggested in this study to calculate the thickness [15]. This code is recognized and used globally, and they have pioneered the creation of international rules for the safe design and construction of pipelines. Indonesian standard SNI 3474 (gas transmission and distribution piping system) is applied as a nationwide pipeline design standard. In essence, SNI 3474 refers to ASME B31.8 [16]. Eq. 1 and Eq. 2 give the formula for wall thickness evaluation.

$$t_m = \frac{PD}{2SFET} \tag{1}$$

$$t_{req} = \frac{t_m + A}{(1 - MT)} \tag{2}$$

where t is nominal wall thickness (in), D is nominal outside diameter pipe (in), E is longitudinal joint factor, F is design factor, P is design pressure (psig), S is specified minimum yield strength (psi), T is temperature derating factor, and A is allowance.

2.3 Drilled Path Design

A specified drilled path design is part of a well-designed HDD installation. The obstacle that needs to be crossed must be identified before a drilling path can be designed. Defining the obstacle and determining the approximate length of the intended HDD makes creating and describing a drilling path a relatively simple geometry exercise. According to [17], penetration angles, design radius of curvature, points of curvature and tangency, and desired vertical depth determine the location and configuration of a drilled path.

Measurements of penetration angles start at the horizontal. Equipment capabilities determine the maximum entry angles, which are typically between 8° and 20°. Regarding exit angles, they should typically fall between 5° and 12° [17]. The value 10°, both for entry angles (Φ_{in}) and exit angles entry angles (Φ_{OUT}), is used in this study, as suggested in [9].

The bending radius, also known as the radius of curvature, is a crucial factor to consider when designing a crossover using horizontal directional drilling. The allowed bending radius for steel pipe is often determined using Eq. 3 [19]. Furthermore, the obstacle's specification largely determines the penetration depth. Maintaining a minimum of 15 feet of space below the obstruction is recommended [17].

$$R = \left(\frac{3Er}{2 \cdot S_a}\right) \tag{3}$$

where: R is thee recommended smallest radius of curvature that can be used without overstressing a straight pipe, E is the modules of elasticity, r is radius of the pipe, and S_a is the allowable stress (0.9·SMYS).

The HDD drilled path design schematic is displayed in Fig. 1. Three straight sections (L_1, L_2, and L_3), one curved section (L_{arc1} with radius of curvature R_{arc1}) separating L_1 from L_2, and another curved section (L_{arc2} with radius of curvature R_{arc2}) separating L_2 from L_3 make up a typical HDD drill path profile. Each section can be determined using the Eq. 4.

$$L_1 = L_{depth} - \frac{R_{arc1} \times \left(1 - \cos\left(\pi \times \frac{\Phi_{in}}{180}\right)\right)}{\sin\left(\pi \times \frac{\Phi_{in}}{180}\right)}$$

$$L_{arc1} = \Phi_{in} \times \left(\pi \times \frac{R_{arc1}}{180}\right)$$

$$L_3 = L_{depth} - \frac{R_{arc2} \times \left(1 - \cos\left(\pi \times \frac{\Phi_{out}}{180}\right)\right)}{\sin\left(\pi \times \frac{\Phi_{out}}{180}\right)}$$

$$L_{arc2} = \Phi_{out} \times \left(\pi \times \frac{R_{arc2}}{180}\right)$$

$$\begin{aligned} L_2 = L_{crossing} &- \left(L_1 \times \cos\left(\pi \times \frac{\Phi_{in}}{180}\right)\right) \\ &- \left(L_3 \times \cos\left(\pi \times \frac{\Phi_{out}}{180}\right)\right) \\ &- \left(R_{arc1} \times \sin\left(\pi \times \frac{\Phi_{in}}{180}\right)\right) \\ &- \left(L_{crossing} \times \sin\left(\pi \times \frac{\Phi_{out}}{180}\right)\right) \end{aligned}$$

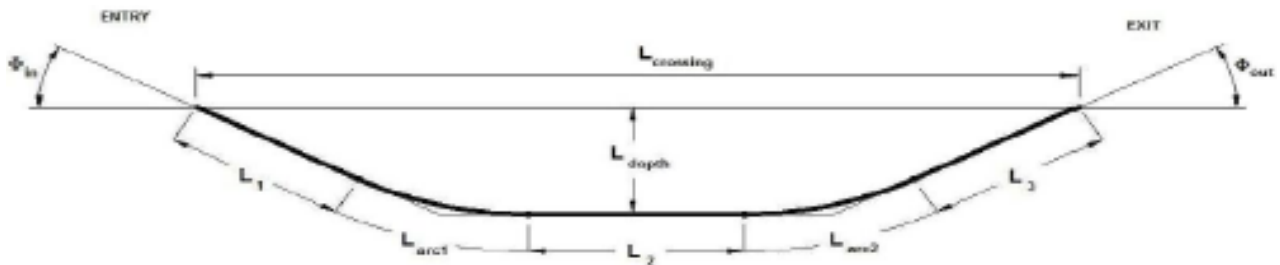$$L_{total} = L_1 + L_{arc1} + L_2 + L_{arc2} + L_3 \tag{4}$$

Fig. 1. Sketch of HDD pipe section length [18]

2.4 Pipe Stress Analysis (PSA)

To design or modify a piping system, the engineer must understand the behavior of the system under load and the code requirements that must be met. Load and stress analysis for an HDD pipeline installation is different from similar analyses of conventionally buried pipelines because of the relatively high-tension loads, bending, and external fluid pressures acting on the pipeline during the installation process. Analysis of the loads and stresses that govern pipe specification can most easily be accomplished by breaking the problem into two distinct events: installation and operation [17].

2.4.1 Initial Calculation

Before estimating stresses, initial calculations were performed for pipe profiles and the soil conditions that pipes will pass through. The calculations involve pipe cross-sectional area (A_P), steel cross-sectional area (A_S), earth pressure coefficient (K), weight of pipe (W_S), effective or submerged weight of pipe (W_{sub}), and arching factor (κ). The ASME standards provided in Eq. 5, Eq. 6 and Eq. 7 will be used to calculate the A_P, A_S, and W_S values. Whereas the W_{sub} and κ values will be determined using Eq. 8 and Eq. 11, which are based on ASTM standards [9].

$$A_p = 0.25 \times \pi \times D^2 \qquad (5)$$

$$A_s = (0.25 \times \pi \times D^2) - (0.25 \times \pi \times (D - (2 \times t)^2) \qquad (6)$$

$$W_s = \rho_s \times A_s \qquad (7)$$

$$W_{sub} = W_s - W_{mud} \qquad (8)$$

$$W_{mud} = \rho_{mud} \times A_p \qquad (9)$$

$$K = \tan\left(\left(\frac{\pi}{180}\right) \times \left(45 - \frac{\phi}{2}\right)\right) \qquad (10)$$

$$\mathcal{K} = \frac{1 - e^{-2 \times K \times L_{depth} \times 3,28084 \times \tan\left(\frac{\pi}{180} \times \frac{\phi}{2}\right)}}{2 \times K \times L_{depth} \times 3.28084 \times \tan\left(\frac{\pi}{180} \times \frac{\phi}{2}\right)} \qquad (11)$$

where D is the pipe external diameter, t is selected wall thickness, ρ_s is steel density, ρ_{mud} is displaced mud density, ϕ is soil friction angle, and L_{depth} is depth of cover.

2.4.2 Installation Stresses

As per [18], there are four types of stresses associated with HDD installation: bending stress, hoop (external pressure) stress, tensile stress, and combined installation stress. Next, using the appropriate formulas, the four stresses are computed and contrasted with the pipe's maximum allowable stress. HDD installation loads must be anticipated to compute the stresses that will arise from these loads, which is necessary to assess if a particular pipe specification is sufficient. This section aims to outline the loads that are applied to a pipeline during HDD installation and provide methods for estimating these loads.

In HDD work, pulling loads are the necessary weight during the pipe pullout process. Five segments make up the calculations for pulling loads. Each pipe section's length and division follow the guidelines in Fig. 2. Friction force ($|F_F|$), fluid drag (F_D), and pipe weight (W_P) are used to compute the pulling load (T) for each segment. The pulling load calculation makes use of Eq. 12 – Eq. 31. Table 2 provides a description for every variable.

$$|F_{f1}| = |W_s \times L_1 \times cos(\Phi_{in}) \times v_s| \qquad (12)$$

$$F_{D1} = \pi \times D \times L_1 \times v_{mud} \qquad (13)$$

$$W_{p1} = |W_{sub} \times L_1 \times sin(\Phi_{in})| \qquad (14)$$

$$T_1 = F_{f1} + F_{D1} + W_{p1} \qquad (15)$$

$$|F_{farc1}| = |W_s \times L_{arc1} \times cos(\Phi_{in}) \times v_s| \qquad (16)$$

$$F_{Darc1} = \pi \times D \times L_{arc1} \times v_{mud} \qquad (17)$$

$$W_{parc1} = |W_{sub} \times L_{arc1} \times sin(\Phi_{in})| \qquad (18)$$

$$T_{arc1} = T_1 + F_{farc1} + F_{Darc1} + W_{parc1} \qquad (19)$$

$$|F_{f2}| = |W_s \times L_2 \times sin(\Phi) \times v_s| \qquad (20)$$

$$F_{D2} = \pi \times D \times L_2 \times v_{mud} \qquad (21)$$

$$W_{p2} = |W_{sub} \times L_2 \times sin(\Phi)| \qquad (22)$$

$$T_2 = T_{arc1} + F_{f2} + F_{D2} + W_{p2} \qquad (23)$$

$$|F_{farc2}| = |W_s \times L_{arc2} \times cos(\Phi_{out}) \times v_s| \qquad (24)$$

$$F_{Darc2} = \pi \times D \times L_{arc2} \times v_{mud} \qquad (25)$$

$$W_{parc2} = |W_{sub} \times L_{arc2} \times sin(\Phi_{out})| \qquad (26)$$

$$T_{arc2} = T_2 + F_{farc2} + F_{Darc2} + W_{parc2} \qquad (27)$$

$$|F_{f3}| = |W_s \times L_3 \times cos(\Phi_{out}) \times v_s| \qquad (28)$$

$$F_{D3} = \pi \times D \times L_3 \times v_{mud} \qquad (29)$$

$$W_{p3} = |W_{sub} \times L_3 \times sin(\Phi_{out})| \qquad (30)$$

$$T_3 = T_{arc2} + F_{f3} + F_{D3} + W_{p3} \qquad (31)$$

Eq. 32 uses the pulling load (T) and steel cross-sectional area (A_S) to calculate the tensile stress. The allowable tensile stress is 90% of SMYS. While Eq. 33 provides the bending stress resulting from the pipe conforming to the drilled radius of curvature R.

$$\sigma_t = \frac{Pulling\ Loads}{Steel\ Area} \qquad (32)$$

$$\sigma_b = \frac{E \times D}{2R} \qquad (33)$$

where E is young modulus of elasticity and D is nominal diameter. The following design standards for bending stress on HDD pipeline during installation are specified by PRCI [17].

$$S_b = 0.75 \cdot S \text{ for } D/t \leq (1,500,000/S) \qquad (34)$$

$$S_b = [0.84 - (1.74 \cdot S \cdot D)/(E \cdot t)] \\ \cdot S \text{ for } 1,500,000/S < D/t \\ \leq (3,000,000/S) \qquad (35)$$

$$S_b = [0.72 - (0.58 \cdot S \cdot D)/(E \cdot t)] \\ \cdot S \text{ for } (3,000,000/S) < D/t \leq 300,000 \qquad (36)$$

The criteria for tubular members in offshore structures can be used to check for hoop stress caused by external pressure. The formulas for calculating the hoop stress and the elastic hoop buckling stress are provided by Eq. 37 and Eq. 38 respectively. The allowable hoop stress, which is made up of the critical hoop buckling stress F_{hc} and the hoop stress from external pressure σ_{hext}, will be calculated using Eq. 39 - Eq. 42. The permissible hoop stress is 67% of F_{hc}, per [18].

$$\sigma_{hext} = P_{ext} \cdot D/2 \cdot t \qquad (37)$$

$$F_{he} = 0.88 \cdot E(t/D)^2 \qquad (38)$$

$$F_{hc} = F_{he} \text{ for } F_{he} \leq 0.55 \cdot S \qquad (39)$$

$$F_{hc} = 0.45 \cdot S + 0.18 \cdot F_{he} \text{ for } 0.55 \cdot S < F_{he} \leq 1.6 \cdot S \qquad (40)$$

$$F_{hc} = 1.31 \cdot S / [1.15 + (S / F_{he})] \text{ for } 1.6 \cdot S < F_{he} \\ \leq 6.2 \cdot S \qquad (41)$$

$$F_{hc} = S \text{ for } F_{he} > 6.2 \cdot S \qquad (42)$$

Eq. 43 serves as the limiting condition for the combined stress analysis, which verifies the axial tension and bending.

$$\frac{\sigma_t}{0.9S} + \frac{\sigma_b}{S_b} \leq 1 \qquad (43)$$

Eq. 44 criteria should be used to restrict the total interaction of axial tension, bending, and external pressure stresses:

$$A^2 + B^2 + 2 \cdot v|A|B \leq 1 \qquad (44)$$

where;

$$A = [(\sigma_t + \sigma_b - 0.5\sigma_{hext})/1.25]/S \qquad (45)$$

$$B = 1.5\sigma_{hext}/F_{hc} \qquad (46)$$

2.4.3 Operating Stresses

The operating stresses placed on HDD pipes are the same as those placed on trenched pipelines with added bending loads. Thermal expansion and contraction as well as internal pressure will cause longitudinal and hoop stresses. To compare with allowable limits, bending stresses resulting from HDD installation are examined along with additional longitudinal and hoop stresses encountered during operation [18].

Eq. 47 and Eq. 48 provide the hoop stress resulting from internal pressure and thermal stresses resulting from the temperature differential between the soil and pipe, respectively. Eq. 33, which describes the bending stress that pipes experience during operational activities.

$$\sigma_h = P \cdot D/2 \cdot t \qquad (47)$$

$$\sigma_{th} = E \cdot \alpha \cdot |(T_1 - T_2)| \qquad (48)$$

α = coefficient of thermal expansion for steel in mm./°K.

The sum of the bending, thermal, and longitudinal components of the circumferential (hoop) stresses yields the total longitudinal stress, which can be calculated as Eq. 49

$$\sigma_L = \sigma_b + \sigma_{th} + \sigma_c v \qquad (49)$$

It is recommended that this value not surpass 90% of the specified minimum yield strength [18]. Eq. 50 gives the total circumferential stress σ_c, which is the difference between the internal and external hoop stresses.

$$\sigma_c = \sigma_h - \sigma_{hext} \qquad (50)$$

To assess the risk of failure, the bending, heat, and hoop stresses placed on the pipe during operation are integrated. This is achieved by looking at the maximum shear stress at specific pipe elements, as indicated by Eq. 50 and Eq. 51. The maximum values that are selected from those calculations should not be greater than 90% of the specified minimum yield strength [18].

$$S_{E1} = |\sigma_c + \sigma_L| \qquad (51)$$

$$S_{E2} = (\sigma_c{}^2 + \sigma_L{}^2 - \sigma_c\sigma_L)^{1/2} \qquad (52)$$

3 Results and Discussion

The proposed HDD installation safety design is demonstrated using project data for a gas pipeline installation that must cross a river, as depicted in Fig. 1. The results of each stage of safety design are then compared with the standard. The goal is to ensure that the design is in accordance with the requirements so that the installation process can run safely. Data from the field and technical documents are divided into two parts, namely for the needs of natural bending and pipe stress analysis calculations. These two data are presented in Tables 1 and 2 which describe the characteristics of the pipe and the environment.

3.1 Evaluation of Pipe Material and Wall Thickness

The pipe material to be used for this HDD is Non-Cash Items (NCI) with API 5L Grade B specification. This material is already available in the warehouse, so the material type and pipe thickness have been determined. The evaluation is:

$$t_m = \frac{720 * 10}{2 * 35000 * 0.4 * 1} = 0.257 \text{ inch } = 6.546 \text{ mm}$$

$$t_{req} = \frac{0.258 + 0.0625}{(1 - 0.1)} = 0.355 \text{ inch} = 9.037 \text{ mm}$$

Table 1. Pipe parameter data for natural bend calculations

Parameter	Symbol	Value	Units
Pipe external diameter	D	10.75	inch
Pipe radius	r	5.375	inch
Wall thickness selected	t_w	0.365	inch
Poisson's ratio	v	0.3	
Modulus of elasticity	E	28800000	psi
Steel density	ρ_{st}	7850	kg/m³
Specified minimum Yield strength of pipe	SMYS	35500	psi
Allowable stress (for pipeline = 40%×SMYS)	Sa	14200	psi
Pipe length	L	12	m

Table 2. Pipe and environmental parameter data for pipe stress analysis calculations

Parameter	Symbol	Value	Units
Pipeline diameter	D	10.75	
Wall thickness	t	9.271	
Pipeline material grade		API 5L Gr B	
SMYS of pipeline	S	241.49	Mpa
Steel density	ρ_s	7850	kg/m³
Water density	ρ_w	1000	kg/m³
Soil density		1615	kg/m³
Mud density		1200	kg/m³
Drilling fluid density	ρ_d	11	lb/gal
Soil friction angle	f	4	degree
Poisson ratio for steel	v	0.3	
Modulus of elasticity	E	200000	MPa
Installation temperature	T_1	35	°C
Operating temperature	T_2	54.4	°C
Steel coefficient thermal	a	0.0000117	mm/mm/°C
Friction factor of soil	v_s	0.3 (assumed)	
Fluid (mud) drag coefficient	v_{mud}	0.05	lb/in²
Test pressure	PT	2294.2	Bar
Design pressure	P	48.980	Bar
External hydrostatic pressure	P_{ext}	60	kPa

Based on the evaluation results, the pipe needed for this HDD work has a minimum wall thickness of 9.037 mm, while the available pipe in the warehouse has a minimum wall thickness of 9.271 mm. Therefore, because the specification meets the standard and the thickness of the calculated pipe is greater than the thickness of the NCI pipe, the available NCI pipe can be used.

3.2 Drilled Path Design Analysis

The load that the HDD will carry on the pipe must be less than its yield strength, given its natural bend. Based on calculation results using Eq. 3, the minimum radius of natural bending is 415.3 m. This value will be used to create an HDD installation drawing plan.

With the assumption that the ground elevation is constant around the river area, the image is made to scale. Since there was no topographic survey done in the area, no contour data from the land around the river area was collected, leading to the assumption of the same ground elevation. The local authority provided field survey information, which was combined with measurements made on-site using wooden tools inserted into the river's bottom. According to technical advice from the authority, the requirement for the depth of the pipe crossing the river is a minimum of 3 meters from the riverbed.

Based on those considerations, the plan for installing a gas pipe using an HDD is sketched in Fig. 2, and it indicates that the minimum length of the HDD horizontally from the entry pit to the exit pit is 168 meters. But since the pipe's length is unquestionably greater than the HDD's horizontal length, this number does not accurately reflect the pipe's length. Therefore, to ensure that the pipe provided matches the pipe installed, the length of pipe required for planning needs must be calculated. Eq. 4 is applied to the data in Table 3 to determine the total pipe length. The result is 169.03, which is the total length of pipe needed for HDD installation.

$$L_1 = 8 - \frac{415.3 \times \left(1 - \cos\left(\pi \times \frac{10}{180}\right)\right)}{\sin\left(\pi \times \frac{10}{180}\right)} = 9.73 \text{ meter}$$

$$L_{arc1} = 10 \times \left(\pi \times \frac{415.3}{180}\right) = 72.49 \text{ meter}$$

$$L_3 = 8 - \frac{415.3 \times \left(1 - \cos\left(\pi \times \frac{10}{180}\right)\right)}{\sin\left(\pi \times \frac{10}{180}\right)} = 9.73 \text{ meter}$$

$$L_{arc2} = 10 \times \left(\pi \times \frac{415.3}{180}\right) = 72.49$$

$$L_2 = 168.00 - \left(9.73 \times \cos\left(\pi \times \frac{10}{180}\right)\right)$$
$$- \left(9.73 \times \cos\left(\pi \times \frac{10}{180}\right)\right)$$
$$- \left(415.3 \times \sin\left(\pi \times \frac{10}{180}\right)\right)$$
$$- \left(168.00 \times \sin\left(\pi \times \frac{10}{180}\right)\right) = 4.58 \text{ meter}$$

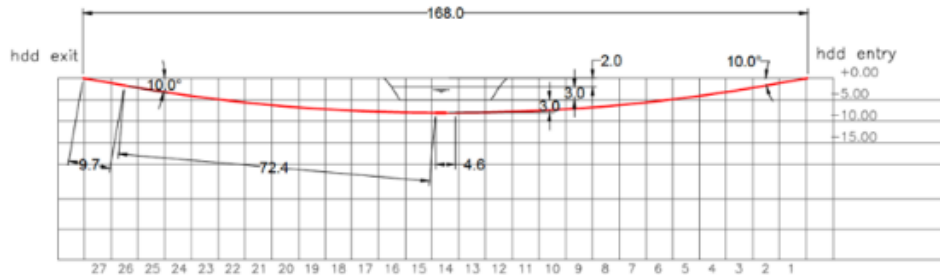$$L_{total} = 9.73 + 72.49 + 4.58 + 72.49 + 9.73 = 169.03 \text{ meter}$$

Fig. 2. HDD installation project plan for gas pipelines.

Table 3. HDD pipe length calculation parameters

Parameter	Symbol	Value	Units
Pipe depth from ground level	L_{depth}	8	meter
HDD horizontal length (from entry pit to exit pit)	$L_{crossing}$	168	meter
Radius natural bend (entry pit)	R_{arc1}	415.3	meter
Radius natural bend (exit pit)	R_{arc2}	415.3	meter
Angle between pipe and ground (entry pit)	Φ_{in}	10	degree
Angle between pipe and ground (exit pit)	Φ_{out}	10	degree

3.3 Initial Calculations for PSA

Initial calculations are performed for pipe profiles and the soil conditions that pipes will pass through. The calculations involve pipe cross-sectional area, steel cross-sectional area, earth pressure coefficient, weight of pipe, effective or submerged weight of pipe, and arching factor. It will be possible to estimate installation and operational loads with the help of that information. Table 4 presents the initial calculation outcomes utilizing Eq. 5 – Eq. 11.

Table 4. Initial calculation results

Parameter	Symbol	Value	Units
Pipe cross sectional area	A_P	0.059	m²
Steel cross-sectional area	A_S	0.008	m²
Earth pressure	K	0.933	
Weight of pipe	W_S	60.31	kg/m
Effective or submerged weight of pipe	W_{sub}	-9.96	kg/m
Arching factor	κ	0.466	

3.4 Installation Stresses Calculation

Based on Fig. 1, there are five sections of pipe installed using the HDD technique. The pipe will experience a tensile load, which is calculated using a series of Eq. 12 to Eq. 31. The calculation of the load on each section, which produces a total load of 8.123 tons.

1. Straight section L_1

$$|F_{f1}| = \left|60.31 \times 9.73 \times \cos\left(10 \times \frac{\pi}{180}\right) \times 0.3\right| = 173.41 \text{ kg}$$

$$F_{D1} = \pi \times \frac{273.05}{1000} \times 9.73 \times \frac{344.73785}{9.87} = 291.59 \text{ kg}$$

$$W_{p1} = \left|-9.96 \times 9.73 \times \sin\left(10 \times \frac{\pi}{180}\right)\right| = 16.83 \text{ kg}$$

$$T_1 = 173.41 + 291.59 + 16.83 = 448.18 \text{ kg}$$

2. Curve section L_{arc1}

$$|F_{farc1}| = \left|60.31 \times 72.49 \times \cos\left(10 \times \frac{\pi}{180}\right) \times 0.3\right|$$
$$= 1291.65 \text{ kg}$$

$$F_{Darc1} = \pi \times \frac{273.05}{1000} \times 72.49 \times \frac{344.73785}{9.87} = 2171.95 \text{ kg}$$

$$W_{parc1} = \left|-9.96 \times 72.49 \times \sin\left(10 \times \frac{\pi}{180}\right)\right| = 125.32 \text{ kg}$$

$T_{arc1} = 1291.65 + 2171.95 + 125.32 = 3786.45 \text{ kg}$

3. Straight section L_2

$$|F_{f2}| = \left|60.31 \times 4.58 \times sin\left(90 \times \frac{\pi}{180}\right) \times 0.3\right| = 82.93 \text{ kg}$$

$$F_{D2} = \pi \times \frac{273.05}{1000} \times 4.58 \times \frac{344.73785}{9.87} = 137.34 \text{ kg}$$

$$T_2 = 3786.45 + 82.93 + 137.34 + 45.63 = 4052.36 \; kg$$

4. Curve section L_{arc2}

$$|F_{farc2}| = \left|60.31 \times 72.49 \times cos\left(10 \times \frac{\pi}{180}\right) \times 0.3\right|$$
$$= 1291.65 \text{ kg}$$

$$F_{Darc2} = \pi \times \frac{273.05}{1000} \times 72.49 \times \frac{344.73785}{9.87} = 2171.95 \text{ kg}$$

$$W_{parc2} = \left|-9.96 \times 72.49 \times sin\left(10 \times \frac{\pi}{180}\right)\right| = 125.32 \text{ kg}$$

$$T_{arc2} = 4052.36 + 1291.65 + 2171.95 + 125.32$$
$$= 7641.27 \text{ kg}$$

5. Straight section L_3

$$|F_{f3}| = \left|60.31 \times 9.73 \times cos\left(10 \times \frac{\pi}{180}\right) \times 0.3\right| = 173.41 \text{ kg}$$

$$F_{D3} = \pi \times \frac{273.05}{1000} \times 9.73 \times \frac{344.73785}{9.87} = 291.59 \text{ kg}$$

$$W_{p3} = \left|-9.96 \times 9.73 \times sin\left(10 \times \frac{\pi}{180}\right)\right| = 16.83 \text{ kg}$$

$$T_3 = 7641.27 + 173.41 + 291.59 + 16.83 = 8123.10 \text{ kg}$$

Therefore, using Eq. 32 to determine the tensile stress that occurs in the pipe during installation, the result is 1.06 MPa. Meanwhile, the allowed tensile stress is 90% of the SMYS, or 217.35 MPa. Because the tensile stress is below the allowable tensile stress, the HDD design is accepted.

The bending stress that occurs on the pipe at the time of installation is calculated using the Eq. 33. Whereas the allowable bending stress is counted with the Eq. 34. The result of the two calculations is 65.74 MPa and 183.573 MPa, respectively. Since the value of the bending stress is less than the allowable binding stress value, the design of the HDD is acceptable.

Hoop stress due to external pressure and elastic hoop buckling stress that occur on the pipe at the time of installation are calculated using Eq. 37 and Eq. 38, yielding values of 0.88 MPa and 22142449856 psi, respectively. Based on these results, the critical hoop bucking stress value chosen is 35500 psi. According to [18], the allowed hoop Stress is 67% of the critical hoop buckling stress, which is 163.99 MPa. Since hoop stress due to external pressure is less than allowable hoop stress, the design of the HDD is acceptable.

The combined installation stress that occurs on the pipe is calculated as:

$$A = \left[\frac{(\sigma_t + \sigma_b - 0.5\sigma_{hext})}{1.25}\right]/S$$
$$= \left[\frac{(1.06 + 65.74 - 0.5 \times 0.88)}{1.25}\right]$$
$$/241.4965986 = 0.3435$$

$B = 1.5\sigma_{hext}/F_{hc} = 1.5 \times 0.88/244.76 = 0.0054$

$$\frac{\sigma_t}{0{,}9S} + \frac{\sigma_b}{S_b} = \frac{1.06}{0.9 \times 241.4965986} + \frac{65.74}{183.57} = 0.362982 < 1$$

$$A^2 + B^2 + 2vAB = 0.3435^2 + 0.0054^2 + 2 \times 0.3 \times 0.3435$$
$$\times 0.0054 = 0.119113 < 1$$

The result of the calculation meets the criteria given on the Eq. 43 and Eq. 44, which is less than 1, so the HDD design is acceptable.

3.5 Operating Stresses Calculation

Hoop (internal pressure) stress, bending stress, thermal expansion and external pressure are calculated first before determining whether the HDD design is acceptable.

1. Hoop stress due to internal pressure

$$\sigma_h = \frac{48.980 \times 0.1 \times 273.05}{2 \times 9.271} = 72.13 \text{ MPa}$$

2. Bending stress

$$\sigma_b = \frac{200000 \times 273.05}{2 \times 415.3 \times 1000} = 65.74 \text{ MPa}$$

3. Thermal expansion

$$\sigma_{th} = \left|\frac{200000 \times 0.0000117}{35 - 54.4}\right| = 45.40 \text{ MPa}$$

4. External pressure
$$P_e = \mathcal{K} \times \rho_s \times L_{depth} \times 3.28084/144$$
$$= 0.446 \times 100.82 \times 8.00 \times 3.28084/144$$
$$= 8.20 \text{ psi} = 0.0565 \text{ MPa}$$

The allowable operating stress is determined based on net longitudinal stress and combined stress. Using the Eq. 49 to Eq. 52, the calculation is:

$$\sigma_L = 65.74 + 45.40 + (72.13 - 0.88) \times 0.3 = 132.51 \text{ MPa}$$

$$S_{E1} = |\sigma_c + \sigma_L| = |71.24 + 132.51| = 61.27 \text{ MPa}$$

$$S_{E2} = (\sigma_c{}^2 + \sigma_L{}^2 - \sigma_c\sigma_L)^{1/2}$$
$$= (71.24^2 + 132.51^2 - 71.24 \times 132.51)^{1/2}$$
$$= 114.87 \text{ MPa}$$

Based on these calculations, net longitudinal stress and maximum combined stress values meet the allowable operating stress criteria [18]. So, the HDD design is acceptable.

3.6 Safety Design Analysis

The comparison of calculation results with design acceptance criteria is used to carry out HDD installation safety design analysis for gas pipelines. The Non-Cash Item (NCI) pipe material, API 5L Gr. B 10-inch diameter, with a minimum wall thickness of 9.270 mm, was discovered to be suitable for the gas pipeline project based on the findings of the material evaluation. According to the calculations done to determine the necessary pipe length, the pipe's minimum natural bend value is 415.3 meters with a 168-meter horizontal separation. The installation pressure and operating pressure calculations' results are compared with the allowable stress values. All calculation results for the two processes are found to be below the allowable stress value, according to Table 5. As a result, the HDD technique can be used to install gas pipes safely.

Table 5. Pipe stress analysis evaluation

Type of stresses	Calculation stress	Allowable stress	Status (OK/ FAIL)
Intallation stresses			
Tensile stress	1.06 MPa	217.35 MPa	OK
Bending stress	65.74 MPa	183.57 MPa	OK
Hoop (external pressure) stress	0.88 MPa	163.99 MPa	OK
Combined installation stress			
$s_t / 0.9S + s_b / S_b$	0.363	<1	OK
$A^2 + B^2 + 2n\|A\|B$	0.119	<1	OK
Operating stresses			
Net longitudinal stress	132.51 MPa	217.35 MPa	OK
Combined stress	114.87 MPa	217.35 MPa	OK

4 Conclusion

Four main steps make up the proposed safety design for HDD installation: material evaluation, wall thickness evaluation, drilled path design, and PSA. Using 10-inch API 5L Gr. B pipe, the safety design was successfully tested for a gas pipe project. The HDD drilled path design figures out that a natural bend value of no less than 415.3 meters must have a horizontal length of 168 meters. According to the curvature, the length of the entire pipe is 169.03 meters. Based on installation stresses and operating stresses, the HDD design meets the standards and regulations. Since PSA requires a considerable amount of calculation, software assistance is highly recommended to facilitate the calculation. A combination of the proposed method with qualitative risk analysis methods should be considered to produce a more comprehensive risk analysis. As a result, HDD engineers can install and operate the HDD with greater confidence.

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