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Research Paper

Probabilistic Analysis of HDPE-100 Pipe Pullback Failure Risk in Horizontal Directional Drilling Projects Using Monte Carlo Simulation

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ABSTRACT: *The Horizontal Directional Drilling (HDD) method is increasingly used for underground pipe installation in high-density areas because it can minimize open excavation work and disruption to existing traffic and utilities. However, the pullback stage of HDPE-100 pipes has a high risk of failure if the pull force used is not controlled to the actual tensile strength limit of the pipe. This study analyzes the risk of HDPE-100 pipe pullback failure probabilistically by integrating laboratory tensile strength test data and a tensile force calculation model based on ASTM F1962-22, then evaluating the uncertainty through Monte Carlo simulation. The random variables studied include tensile strength value, pipe class (SDR/PN), pipe–soil friction coefficient, slurry influence, and the use of rollers at the entry point. The simulation results show that for the analyzed design configuration, the maximum tensile force along the HDD path is below the permissible tensile load, with the probability of pullback failure in the very low range, and a significant increase in the chance of success when friction can be reduced through the use of rollers. This study recommends the use of actual tensile strength values as a basis for determining tensile force limits and the application of Monte Carlo simulation as a tool for HDD planning to manage the risk of pipe withdrawal failure.*

KEYWORDS: *Horizontal Directional Drilling; tensile strength; Monte Carlo Simulation*

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I. INTRODUCTION

Underground infrastructure development in urban areas demands construction methods that minimize The rapid expansion of underground utility networks in urban areas requires construction methods that minimize interference with surface activities. In this context, trenchless technologies, particularly Horizontal Directional Drilling (HDD), have become a preferred solution for the installation of drinking water pipelines, gas pipelines, power cables, and telecommunication lines[1]. Among the available pipe materials, HDPE-100 has gained widespread use in HDD applications due to its favorable mechanical performance, including high corrosion resistance, good flexibility, and long service life[2].

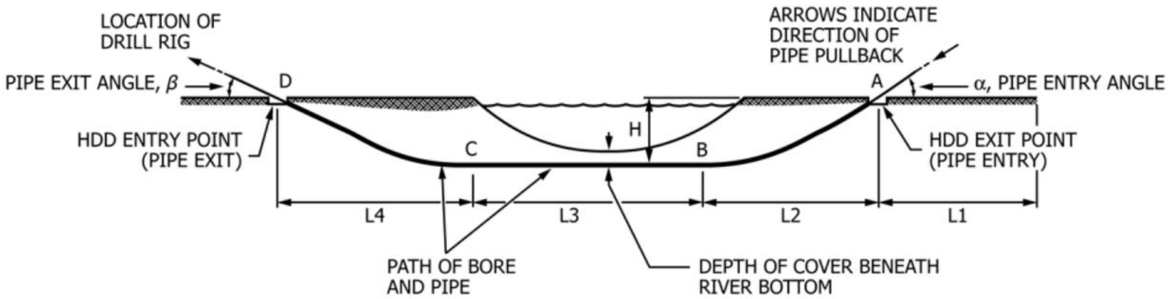
Source: Vinilon Group Documentation
Figure 1: HDD Method PE Installation for Water Supply System and Medium/High Voltage Cable Lines

However, in current engineering practice, the determination of allowable tensile forces during pipe pullback operations is commonly based on theoretical tensile strength values provided in product specifications. Existing standards such as ISO 4427[3] and SNI 4829[4] do not explicitly require experimental verification of tensile strength as a compulsory design parameter. As a result, there is a potential discrepancy between nominal material properties and the actual tensile performance of pipes in the field. This discrepancy may lead either to unsafe designs, where the risk of pipe breakage or permanent deformation increases, or overly conservative designs, which can reduce operational efficiency and increase project costs.

Guidance for calculating pipe tensile forces in HDD projects is available in ASTM F1962-22[5], which provides a framework for estimating drag forces and tensile loads along the drill path. Nevertheless, the conventional use of this standard is largely deterministic. It typically assumes fixed input values for material properties, soil characteristics, and operational parameters, and therefore does not properly represent their inherent variability in real construction conditions. In practice, uncertainties arise from variations in pipe tensile strength, joint performance, soil stratigraphy, frictional resistance, drilling fluid behavior, and execution procedures. A deterministic approach is limited in its ability to capture these uncertainties and to quantify the associated risk of failure.

To address this gap, a probabilistic framework is required that can represent the distribution of possible tensile forces and pipe capacities rather than relying on single-point estimates. By modeling the variability of key parameters, the probability of pullout failure can be quantified in a more rational and transparent manner. Such an approach enables risk-informed decision-making in HDD design and construction, supports the definition of more realistic safety margins, and provides a basis for optimizing operational strategies.

This study is therefore guided by two central research questions. The first concerns the influence of differences between theoretical tensile strength values and experimentally measured tensile properties of HDPE-100 pipes on the risk assessment of pullout failure in HDD projects. This issue is particularly important, as discrepancies between catalog data and laboratory test results may lead to misestimation of allowable tensile loads during pullback, with direct implications for structural safety and installation reliability. The second research question examines how variations in tensile force profiles along the HDD alignment, including the effects of soil conditions and frictional resistance along the drill path, affect the probability of pullout failure. By clarifying the relative contributions of these factors, the study aims to provide a more comprehensive understanding of the mechanisms governing pipe failure during HDD installation.



Source: ASTM F1962-22

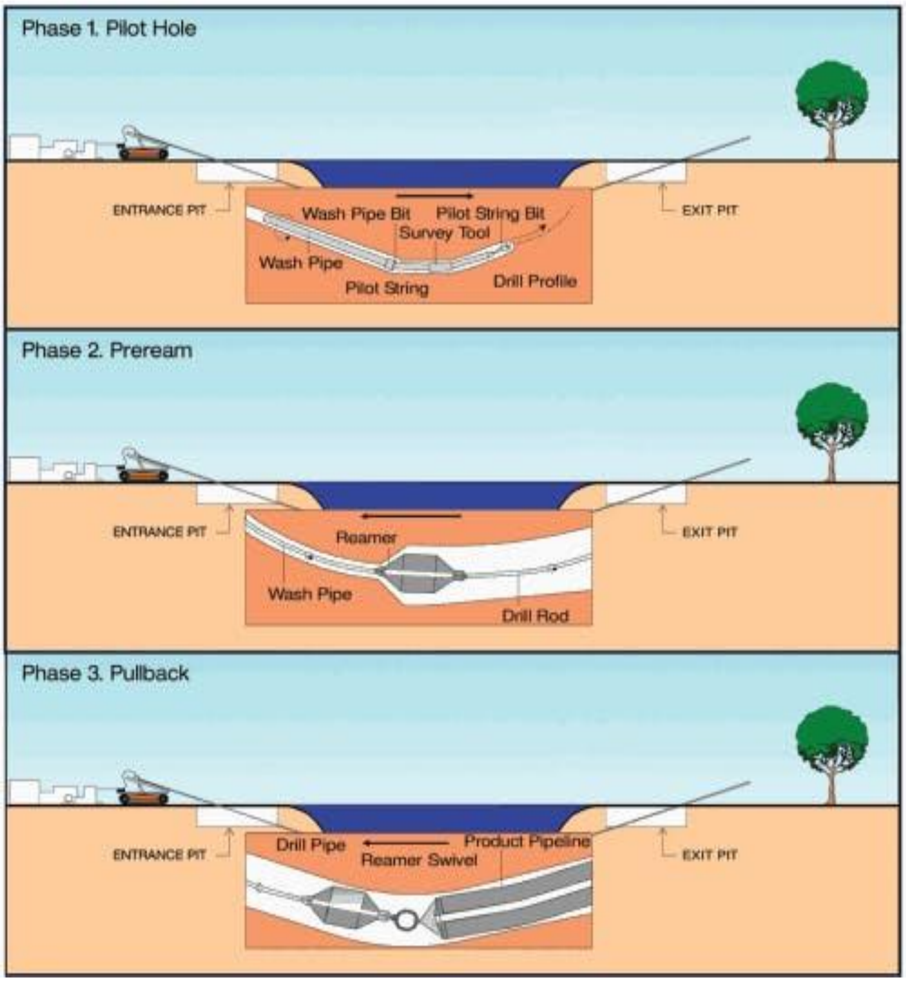
Figure 2: Horizontal Directional Drilling (HDD) Method of Piping Installation

In line with these research questions, the present work pursues four main objectives. First, it aims to quantify the actual tensile strength of HDPE-100 pipes joined by butt fusion, based on a systematic experimental program conducted in accordance with relevant international tensile testing standards. This objective is intended to provide reliable input data on the true tensile capacity of the pipe–joint system. Second, the study seeks to develop and implement a tensile force calculation model grounded in the methodology of ASTM F1962-22, calibrated specifically to the geometric and geotechnical characteristics of the HDD route examined in this research. Third, a probabilistic assessment is carried out by means of Monte Carlo simulation, in order to evaluate the impact of variability in material properties, soil parameters, and operational conditions on the probability of tensile failure. Finally, based on the insights gained from the experimental and numerical analyses, the study aims to formulate technical recommendations regarding permissible tensile force limits and HDD operating configurations that are both safe and efficient. Through these contributions, the research is expected to support more robust design practices and enhance the reliability of HDPE-100 pipe installations in HDD applications.

II. LITERATURE REVIEW

Horizontal Directional Drilling (HDD) is a trenchless construction method used to install underground pipes and cables without the need for open-cut excavation. The technique is widely applied for crossings beneath rivers, highways, and railways because it minimizes disturbance to existing surface infrastructure and significantly reduces surface restoration costs. An HDD installation is typically executed in three sequential stages: pilot drilling to establish the intended bore path, reaming to enlarge the pilot hole to the required diameter, and pipe pullback in which the product pipe is drawn into the prepared borehole as outlined in Figure 3.

During the pullback stage, the tensile force acting on the pipe is governed by several interacting factors. The primary contributors include the self-weight of the pipe, the buoyant force due to immersion in drilling slurry, and frictional resistance along the interface between the pipe and the borehole wall. In addition, geometric aspects such as the curvature of the bore path influence the normal forces and thereby the frictional response, while hydrokinetic pressure generated by slurry flow around the pipe can add further resistance to movement. ASTM F1962-22 provides a rational framework for quantifying these effects by specifying equations to calculate the pulling force along the bore at several critical locations (for example, points A, B, C, and D), based on the bore geometry, segment lengths, and relevant field conditions.



Source: Platosh[6]

Figure 3: HDD Installation Steps

High-density polyethylene (HDPE) pipe of the PE100 grade (HDPE-100) is commonly used in HDD applications due to its favorable mechanical and durability characteristics. The tensile behavior of HDPE-100 is represented by a stress–strain curve with three key parameters: yield stress, ultimate tensile strength, and tensile strength at break[7]. To characterize these properties in a consistent manner, tensile testing of plastic pipes is conducted in accordance with standardized procedures such as ISO 527-1[8], ISO 6259-1[9], and ISO 6259-3[10]. These standards regulate specimen preparation, test setup, and loading protocols, thereby ensuring that the resulting material properties are comparable and reproducible.

In practice, the tensile strength values obtained from laboratory tests often deviate from those reported in product data sheets. Such discrepancies arise from variations in manufacturing processes, differences in raw material quality, and the influence of butt fusion welding parameters on the integrity of pipe joints. As a consequence, reliance solely on nominal specification values may lead to non-conservative or overly conservative designs. For HDD design purposes, it is therefore more appropriate to adopt actual measured tensile properties from representative tests, as these values provide a more realistic basis for estimating the tensile capacity of HDPE pipes under installation loads.

ASTM F1962-22[5] outlines a stepwise procedure for computing tensile forces in polyethylene pipes during HDD installation. The method explicitly accounts for the average radius of curvature of each bore segment, the segment lengths (typically denoted as L_1 to L_4), the unit weight of the empty pipe, and the effect of buoyancy in slurry-filled conditions. It further incorporates the coefficient of friction between the pipe and the borehole, as well as the contribution of hydrokinetic pressure induced by fluid motion around the pipe. Through this approach, the distribution of tensile force along the bore can be determined and the segment in which the maximum pulling load occurs can be identified.

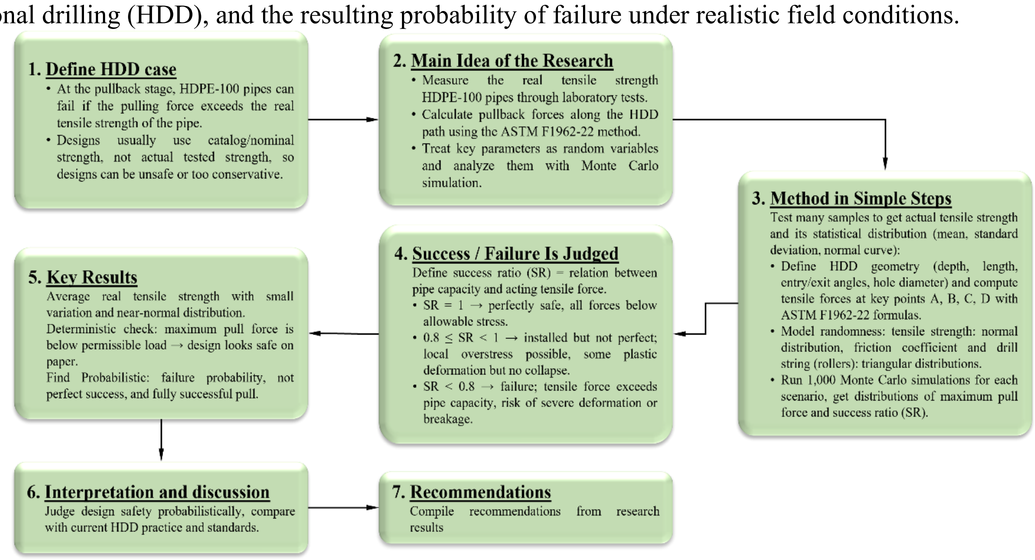
In general, the highest tensile force is observed in the bore segment that combines an unfavorable set of conditions, namely a relatively long segment length, a small radius of curvature (i.e., sharper bend), and a relatively high coefficient of friction. From a structural safety perspective, the maximum calculated tensile force during pullback must not exceed the allowable tensile load of the pipe. This allowable load is defined as a function of the pipe's tensile strength, outer diameter, standard dimension ratio (SDR), and an appropriate safety factor that reflects the level of uncertainty and the desired reliability of the design.

To address uncertainties inherent in both material properties and installation conditions, Monte Carlo simulation can be applied as a probabilistic analysis tool. This technique relies on random sampling from predefined probability distributions for model inputs to generate a corresponding distribution of outputs. In the HDD context, critical input variables such as pipe tensile strength, friction coefficient, and hydrokinetic pressure can be modeled as random variables rather than deterministic values. By repeatedly simulating the HDD installation process with different combinations of these inputs, the distribution of the maximum tensile force and its ratio to the available tensile capacity can be obtained.

The resulting probabilistic characterization of the tensile demand–capacity ratio enables the estimation of the probability of pullback failure for a given HDD design configuration. This information can be used to assess the reliability of alternative design options and to quantify the benefits of mitigation measures. For instance, the introduction of surface rollers at the entry and exit points, the optimization of bore geometry, or the selection of a pipe with a lower SDR (and hence higher wall thickness and tensile capacity) can be systematically evaluated in terms of their effect on reducing the likelihood of tensile overstress during installation.

III. RESEARCH METHODS

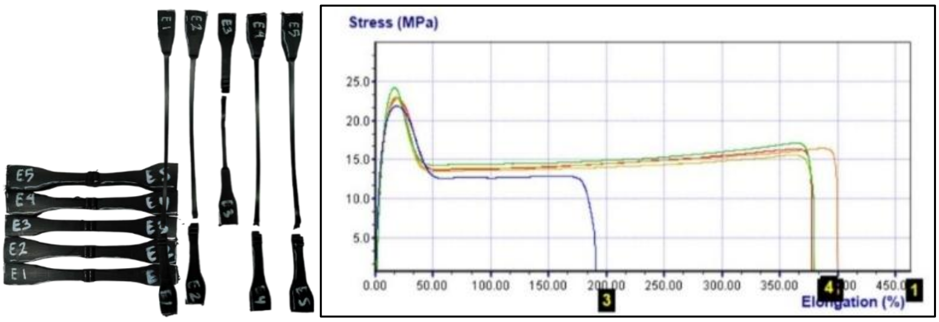
The methodological framework employed in this study follows a quantitative approach and is structured into a series of sequential stages. The primary objective of these stages is to establish a clear linkage between the mechanical performance of HDPE-100 pipes, the calculated installation loads during horizontal directional drilling (HDD), and the resulting probability of failure under realistic field conditions.



Source: own research, 2025

Figure 4: Research framework

The first stage consists of laboratory tensile tests performed on HDPE-100 pipe specimens incorporating butt-fusion joints. These tests are conducted under controlled conditions to obtain a reliable characterization of the pipes' mechanical behavior, with particular emphasis on their response at yield and the associated modes of failure. The tensile tests yield strength data at the yield stress for a number of representative samples.



Source: Research documentation

Figure 5: Tensile Strength Test Documents

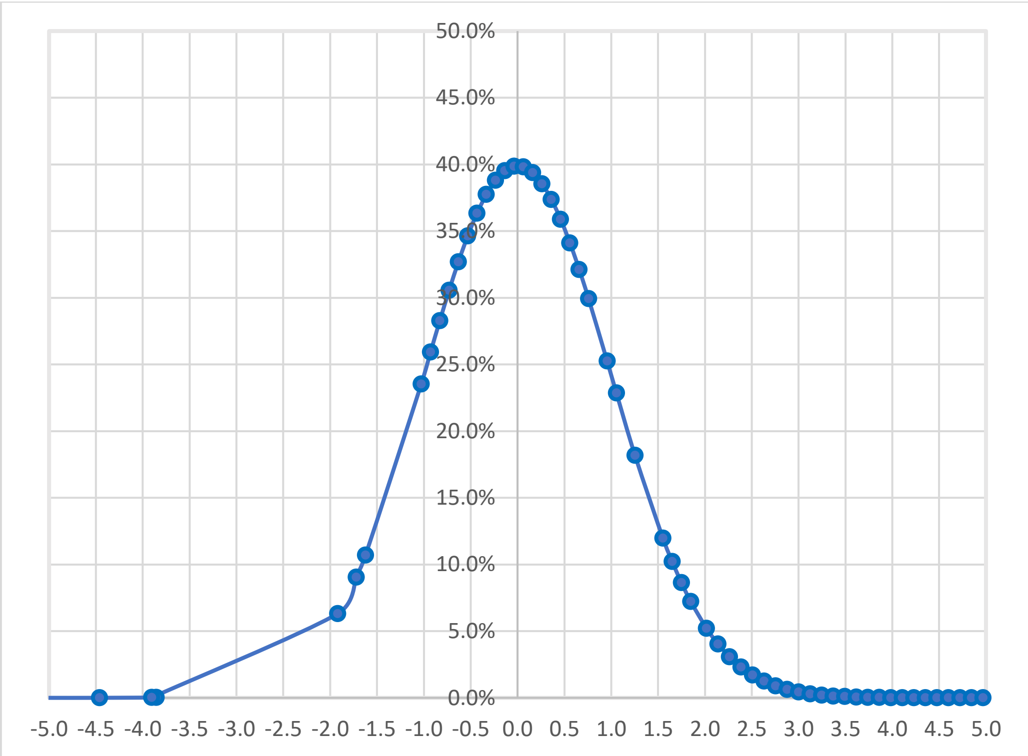
These experimental data are subsequently processed to determine key statistical parameters, including the mean value, standard deviation, and the underlying probability distribution, as summarized in Table 1 and illustrated in Figure 6.

Table 1. Tensile Test Result Data

Production date	Welding number	Sample code	Tensile Strength @ yield (MPa)
June 26th, 2025	509	A1	23,4
		A2	22,7
		A3	24,3
		A4	22,9
		A5	24,0
	510	B1	22,7
		B2	22,2
		B3	22,7
		B4	22,3
		B5	22,5
	511	C1	22,7
		C2	22,7
		C3	22,8
		C4	22,5
		C5	22,8
	512	D1	22,6
		D2	21,7
		D3	20,5
		D4	22,4
		D5	23,7
	514	E1	23,0
		E2	22,8
		E3	21,5
		E4	24,2
		E5	22,9
	515	F1	22,6
		F2	23,5
		F3	22,1
		F4	23,4
		F5	22,6
December 18th, 2024	517	G1	22,9
		G2	22,7
		G3	23,2
		G4	21,9
		G5	22,3
	518	H1	22,1
		H2	23,1
		H3	21,6
		H4	22,0
		H5	22,2
	519	I1	20,7

Production date	Welding number	Sample code	Tensile Strength @ yield (MPa)
		I2	22,2
		I3	21,4
		I4	21,8
		I5	22,0
	520	J1	21,6
		J2	24,1
		J3	22,0
		J4	20,8
		J5	18,5

Source: own research, 2025



Source: Processing of research results, 2025

Figure 6: Normal distribution graph

The third stage involves the construction of a probabilistic assessment framework to evaluate the likelihood of pipe pullout failure. In this stage, Monte Carlo simulation is employed to account for the inherent variability and uncertainty associated with material properties, installation loads, and subsurface conditions[11]. The simulation framework integrates the probabilistic characterization of tensile strength obtained from the laboratory tests with the calculated tensile demand from the ASTM F1962-22[5] model. As a result, the risk of failure can be quantified in terms of probability, enabling a more rigorous and transparent evaluation of system reliability across a range of plausible operational and geotechnical scenarios.

The statistical analysis of the experimental data yielded a mean compressive strength of 22.436 MPa, which represents the central tendency of the sample. The median value of 22.6 MPa and the mode of 22.7 MPa are both in close agreement with the mean, indicating that the data are approximately symmetrically distributed and suggesting no substantial skewness in the distribution of the observations. The standard deviation was 1,0080816, denoting a relatively low dispersion of the data around the mean and implying a high degree of consistency among the measured values. The close proximity of the mean, median, and mode further supports the assumption that the data approximate a normal distribution, which is favorable for subsequent parametric statistical analyses and indicates a relatively homogeneous response of the specimens under the applied loading conditions.

For each of these segments, the mechanical actions on the pipe are then evaluated. The empty pipe weight is calculated, followed by the buoyancy force acting on the pipe when it is submerged in the drilling slurry, and finally the friction forces that arise between the pipe and the surrounding soil or slurry. Initial friction coefficients are taken from published literature and relevant standards, and then adjusted (calibrated) based on actual field experience from similar HDD works on site, so that the model better reflects real installation conditions.

Using these segment-based forces, the tensile force along the pipe is calculated at several key control points, labeled A, B, C, and D. The model then identifies the maximum tensile force that occurs at any of these points. Next, the allowable tensile load for the pipe is calculated based on the tested tensile strength of the HDPE-100 material, the pipe diameter, the Standard Dimension Ratio (SDR), and an appropriate safety factor. By comparing the calculated tensile forces at each point to the allowable tensile load, the risk of damage or deformation can be evaluated.

Before performing the calculation, the values of the fixed variables and their conditions are first determined, namely the pipe diameter (*OD*), the planned *SDR* or *DR*, the depth of the passage (*H*), the angle of entry (α) and exit (β) of the pipe, the length of the passage (L_{cross}) and the diameter of the reaming hole (D_{hole}). The calculations use the following formulas[5]:

1. Determine the radius of curvature at the entrance and exit of the pipe. (R_{avg}).

$$R_{avg} = \frac{2H}{\theta^2} \longrightarrow (1)$$

note: θ is the inlet (α) and outlet (β) angle of the pipe.

2. Determining the length of each path (L_1, L_2, L_3 and L_4)

$$L = \frac{2H}{\theta} \longrightarrow (2)$$

3. Calculating axial bending strain (ϵ_a)

$$\epsilon_a = \frac{D}{2\,R} \longrightarrow (3)$$

4. Calculating axial bending stress (σ_a)

$$\sigma_a = E_a \epsilon_a \longrightarrow (4)$$

note: E_a is modulus of elasticity of the pipe.

5. Calculating the weight of an empty pipe (w_a)

$$w_a = \pi D^2 \frac{(DR-1)}{DR^2} \rho_w \gamma_a \longrightarrow (5)$$

where ρ_w is the weight of water, and γ_a is the specific gravity of the pipe material

6. Calculating the buoyancy force acting on the pipe (w_b)

$$w_b = \frac{\pi D^2}{4} \rho_w \gamma_b - w_a \longrightarrow (6)$$

note: γ_b is the specific gravity of mud slurry

7. Calculating the increase in tensile force (ΔT)

$$\Delta T = \Delta P \frac{\pi}{8} (D_{hole}^2 - D^2) \longrightarrow (7)$$

note: ΔP is the hydrokinetic pressure.
The results of this calculation must be added to the T_B, T_C and T_D calculations

8. Calculating the tensile force (T_A, T_B, T_C and T_D)

$$\left.\begin{aligned}
T_A &= \exp(v_a\alpha)\ (v_a w_a (L_1 + L_2 + L_3 + L_4)) \\
T_B &= \exp(v_b\alpha)\ (T_A + v_b |w_b| L_2 + w_b H - v_a w_a L_2 \exp(v_a\alpha)) \\
T_C &= T_B + v_b |w_b| L_3 - \exp(v_b\alpha)(v_a w_a L_3 \exp(v_a\alpha)) \\
T_D &= \exp(v_b\beta)\ (T_C + v_b |w_b| L_4 - w_b H - \exp(v_b\alpha)(v_a w_a L_4 \exp(v_a\alpha)))
\end{aligned}\right\} \longrightarrow (8)$$

note: v_a is the friction coefficient at the entry point and v_b is the friction coefficient inside hole.

9. Determination of allowable tensile load (*ATL*)

$$ATL = f_y f_T \sigma_{pb} \pi D^2 \left(\frac{1}{DR} - \frac{1}{DR^2} \right) \longrightarrow (9)$$

note: f_y is the design safety factor of tensile strength at yield and f_T is the design safety factor of time at stress

10. Determination of breaking strength ($F_{breakaway}$)

$$F_{breakaway} = \sigma_{pb} \text{ x } (\pi/4) \text{ x } (D^2 - ID^2) \longrightarrow (10)$$

note: *ID* is inside diameter of pipe.

To capture the natural variability in material properties and installation conditions, the analysis is extended using a probabilistic model combined with Monte Carlo simulation. Two main random variables are considered. The first is the tensile strength *T* of the HDPE-100 pipe, obtained from laboratory testing and modeled as a normal distribution using the Box-Muller method[12], with its mean and standard deviation derived directly from the test results. The second is the friction coefficient μ between the pipe and the surrounding soil or slurry. This coefficient was modeled using the inverse transform method[12] of the triangular distribution in the range 0.2–0.55, with the most likely value taken as 0.4, following general design recommendations. The third model, also modeled using the triangular distribution of the inverse transform method, is a combination of support conditions (with/without rollers) within the range of 0.1–0.5, with the most likely value being 0.25.

Several installation scenarios were then defined to reflect realistic field conditions. For each scenario, a Monte Carlo simulation was run with 1,000 iterations. In each iteration, random values for the tensile strength and friction coefficient were drawn from their respective probability distributions, and the full tensile force calculation along the HDD path was repeated. This process produces two main outputs: the probability distribution of the maximum tensile force and the distribution of the success ratio, denoted as the success ratio (RK).

The pipe pulling success ratio SR is used to classify the outcome of the installation into three categories. If SR = 1, the pullback operation is considered pullback successful perfectly. In this case, all tensile forces at points A, B, C, and D remain below the allowable stress σ_{allow}, so no significant deformation of the pipe is expected. If the result falls in the range $0.8 \leq SR < 1$, the pipe is still successfully installed, but not perfectly. Here, the tensile force may exceed the allowable stress at some locations, while still remaining below the ultimate tensile capacity of the pipe, meaning that plastic deformation is possible but catastrophic failure is unlikely. If SR< 0.8, the operation is categorized as a failure, because the tensile force at one or more points is estimated to exceed the pipe's capacity. Under these conditions, permanent plastic deformation, collapse, or even breakage may occur, so the installed pipe would no longer comply with the relevant standards.

The pipe's capacity to sustain tensile loads in this model is derived by multiplying the allowable stress by a safety factor of 1.25. This safety factor is based on the design coefficient for PE pipes specified in ISO 4427-1:2019[13], SNI 4829-1:2015[4], and SNI 9383:2025[14]. By combining deterministic structural calculations with probabilistic modeling and Monte Carlo simulation, the method provides both a conservative design check and a quantitative estimate of the likelihood of successful HDD installation under varying field conditions.

IV. RESULTS AND DISCUSSION

Test results showed that the average tensile strength of butt-fused HDPE-100 pipes was 22.436 MPa, with a standard deviation of 1.008081629 MPa, a minimum value of 18.4 MPa, and a maximum value of 24.3 MPa. The data distribution showed a near-normal pattern, thus being used as the basis for determining distribution parameters in the probabilistic model. This value differs little from the nominal value in the product specifications, so relying solely on theoretical data could potentially overestimate the pipe's tensile capacity. This underscores the importance of actual testing as input for HDPE planning.

Deterministic calculations using average parameters indicate a maximum tensile force at point D of 138,580 kN, still below the permissible tensile load limit of 145,448 kN with a safety factor of 0.4. This indicates that the design configuration is considered safe under nominal conditions. However, small differences in the coefficient of friction or tensile strength can cause the tensile force-to-capacity ratio to approach or exceed 1, requiring a probabilistic analysis to assess the distribution of possible outcomes.

The Monte Carlo simulation results for the HDD operation provide a clear picture of the risks associated with different design and mitigation options. In the baseline scenario, where no rollers are used and the coefficient of friction ranges from 18.4 MPa to 24.3 MPa, the model predicts a 0.3% probability of pipe pulling failure. In addition, there is a 10.1% probability that the pipe can be pulled but not fully installed, while the probability of a fully successful pull is 89,6%. This means that, under current conditions, the likelihood of not reaching full completion is higher than the likelihood of complete success.Sample calculations is shown in table 2.

Table2: Monte Carlo Simulation Calculation for SDR 13,6

Data for HDD calculation																				
Pipe specification					Tensile Load			Path profile			Calculation									
Outside Diameter	SDR or DR	Tensile Strength @ yield point	specific gravity of pipe	Safety factor of tensile strength	Allowable tensile force	Safety factor of tensile load	Tensile load	Path of bore	Coef. of friction		Pull force (T)				Conslution		fail	pull back successful but not perfectly	pull back successful perfactly	Success ratio
OD			γ_a	f_y	σ_{allow}			L_{cross}	drill string	slurry	T_A	T_B	T_C	T_D						
mm		Mpa	kg/mm³		kN		kN	m	v_a	v_b	kN	kN	kN	kN						
160	13,6	21,8	0,9530	1	66,675	1,25	83,3441	500	0,217	0,289	5,803	19,290	35,187	41,535	pull back successful	perfectly	0	0	1	1,0000
160	13,6	20,1	0,9530	1	61,556	1,25	76,9452	500	0,139	0,230	3,671	15,264	28,582	32,897	pull back successful	perfectly	0	0	1	1,0000
160	13,6	22,8	0,9530	1	69,830	1,25	87,2872	500	0,297	0,360	8,068	23,983	43,101	52,285	pull back successful	perfectly	0	0	1	1,0000
160	13,6	20,7	0,9530	1	63,341	1,25	79,1761	500	0,112	0,209	2,944	13,900	26,311	29,979	pull back successful	perfectly	0	0	1	1,0000
160	13,6	23,5	0,9530	1	72,026	1,25	90,0328	500	0,434	0,489	12,047	32,611	57,503	72,793	pull back successful	not perfect	0	1	0	0,9895
160	13,6	19,6	0,9530	1	59,913	1,25	74,8919	500	0,488	0,539	13,657	36,134	63,243	81,286	fail		1	0	0	0,7371
160	13,6	22,9	0,9530	1	70,222	1,25	87,7772	500	0,307	0,369	8,332	24,552	44,067	53,625	pull back successful	perfectly	0	0	1	1,0000
160	13,6	23,1	0,9530	1	70,587	1,25	88,2338	500	0,389	0,446	10,720	29,721	52,735	65,876	pull back successful	perfectly	0	0	1	1,0000
160	13,6	20,2	0,9530	1	61,677	1,25	77,0957	500	0,289	0,352	7,824	23,459	42,210	51,054	pull back successful	perfectly	0	0	1	1,0000
160	13,6	20,9	0,9530	1	63,819	1,25	79,7732	500	0,301	0,363	8,163	24,188	43,449	52,767	pull back successful	perfectly	0	0	1	1,0000
160	13,6	22,9	0,9530	1	70,220	1.25	87,7755	500	0,151	0,239	3,998	15,879	29,600	34,215	pull back successful	perfectly	0	0	1	1,0000
160	13,6	20,6	0,9530	1	63,092	1,25	78,8654	500	0,459	0,512	12,778	34,208	60,114	76,634	pull back successful	not perfect	0	1	0	0,8233

Source: own research, 2025

A further improvement is seen when the pipe class is upgraded (i.e., using a lower SDR pipe with higher strength). In this case, the simulations indicate that the probability of failure is removed and the probability of successful and complete pulling reaches 100.00%. However, this option comes with an increase in material cost, which must be weighed against the benefits of reduced risk and higher certainty of successful completion. Sample calculations is shown in table 3.

Table 3: Monte Carlo Simulation Calculation for SDR 11

Data for HDD calculation																				
Pipe specification					Tensile Load			Path profile			Calculation									
Outside Diameter	SDR or DR	Tensile Strength @ yield point	specific gravity of pipe	Safety factor of tensile strength	Allowable tensile force	Safety factor of tensile load	Tensile load	Path of bore	Coef. of Friction		Pull force (T)				Conslution		fail	pull back successful but not perfectly	pull back successful perfactly	Success ratio
OD			γ_a	f_y	σ_{allow}			L_{cross}	drill string	slurry	T_A	T_B	T_C	T_D						
mm		Mpa	kg/mm³		kN		kN	m	v_a	v_b	kN	kN	kN	kN						
160	11	21,8	0,9530	1	90,653	1,25	113,3164	500	0,217	0,289	7,040	19,549	33,994	39,828	pull back successful	perfectly	0	0	1	1,0000
160	11	20,1	0,9530	1	83,693	1,25	104,6163	500	0,139	0,230	4,454	15.297	27,571	31.565	pull back successful	perfectly	0	0	1	1.0000
160	11	22,8	0,9530	1	94,942	1,25	118,6775	500	0,297	0,360	9,787	24,475	41,677	50,110	pull back successful	perfectly	0	0	1	1.0000
160	11	20,7	0,9530	1	86,120	1,25	107,6494	500	0,112	0,209	3,572	13,858	25,364	28,774	pull back successful	perfectly	0	0	1	1,0000
160	11	21,4	0,9530	1	88,948	1,25	111,1848	500	0,338	0,399	11,211	27,126	45,830	55,823	pull back successful	perfectly	0	0	1	1,0000
160	11	22,2	0,9530	1	92.337	1,25	115,4208	500	0,172	0,255	5.557	17,106	30,320	35,077	pull back successful	perfectly	0	0	1	1,0000
160	11	22,5	0,9530	1	93,674	1,25	117,0925	500	0,296	0,359	9,733	24,374	41.519	49,893	pull back successful	perfectly	0	0	1	1,0000
160	11	23,5	0,9530	1	97,928	1,25	122,4105	500	0,434	0,489	14,616	33,518	55,658	69,724	pull back successful	perfectly	0	0	1	1,0000
160	11	22,5	0,9530	1	93,706	1,25	117,1321	500	0,248	0,315	8,115	21,378	36,768	43,477	pull back successful	perfectly	0	0	1	1,0000
160	11	21,6	0,9530	1	89,886	1,25	112,3574	500	0,204	0,279	6.604	18,829	32,915	38,426	pull back successful	perfectly	0	0	1	1,0000
160	11	24,4	0,9530	1	101,385	1,25	126,7308	500	0,478	0,530	16,201	36,520	60,189	76,312	pull back successful	perfectly	0	0	1	1,0000
160	11	20,6	0,9530	1	85,782	1,25	107,2270	500	0,459	0,512	15,502	35,194	58,195	73,398	pull back successful	perfectly	0	0	1	1,0000

Source: own research, 2025

The distribution of the ratio between pulling force and pipe capacity shows that most simulation outcomes lie in a safe region, with a ratio close to 1. This suggests that, in the majority of cases, the applied pulling forces remain within the allowable capacity of the pipe. Nonetheless, the presence of tails in the distribution highlights the possibility of rare but extreme events. These extreme scenarios underline the importance of strict operational control, careful monitoring, and contingency planning during field execution.

From a practical perspective, these results show that using actual tensile strength data combined with probabilistic analysis can provide valuable support to planners and contractors. First, it helps them define operating limits for tensile force that are both realistic and safe, rather than relying solely on conservative assumptions or deterministic calculations. Second, it allows them to quantitatively compare the effectiveness of different mitigation strategies, such as adding rollers, optimizing drilling slurry, or upgrading pipe grade, before implementing them in the field. Finally, this approach enables project teams to communicate the level of risk to project owners in clear, numerical terms, improving decision-making and facilitating more transparent discussions on cost, safety, and performance.

The findings of this study have several practical implications for planners and contractors. By using actual tensile strength values together with probabilistic analysis, project teams can make more informed and reliable decisions.First, these methods help in setting operating tensile force limits that are both realistic and safe. Instead of relying solely on conservative assumptions, planners can base their limits on data that reflect actual conditions in the field.Second, the approach allows engineers to evaluate the effectiveness of different mitigation strategies, such as the use of rollers, slurry, or different pipe grades, before they are applied on site. This makes it possible to compare various combinations and select the most efficient and cost-effective solution.Finally, using probabilistic analysis provides a way to express risk in quantitative terms. This helps planners and contractors communicate more clearly with project owners, enabling them to explain the level of risk involved and justify technical and financial decisions with transparent, data-driven evidence.

V. CONCLUSION

This study shows that by combining real tensile strength data from HDPE-100 pipes with the ASTM F1962-22 tensile force calculation model and Monte Carlo simulation, engineers can estimate how likely it is that a pipe will be pulled out and fail during horizontal directional drilling (HDD) work. For the design conditions examined in this research, the chance of failure is low, but it is still influenced by changes in the friction between the pipe and the ground, as well as by the type of equipment used, such as whether rollers are installed. Based on these findings, the study recommends that actual tensile strength testing of the pipe be included as a standard step in HDD project planning. It also suggests that probabilistic analysis should be used as a decision-making tool in both design and operations to help increase the reliability and safety of HDD projects.

REFERENCES

[1] M. Krechowicz and D. Ph, "Comprehensive Risk Management in Horizontal Directional Drilling Projects," vol. 146, no. 5, pp. 1–11, 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001809.

[2] PPI, *Handbook of Polyethylene Pipe - 2nd Edition*. 2008.

[3] ISO, *ISO 4427-2:2019 Plastics piping systems for water supply, and for drainage and sewerage under pressure -Polyethylene [PE] - Part 2: Pipes*. 2019.

[4] BSN, *SNI 4829-1:2015 Sistem perpipaan plastik - Pipa polietilena (PE) dan fiting untuk sistem penyediaan air minum – Bagian 1: Umum*. 2015.

[5] ASTM, *ASTM F1962-22 Standard Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings*. 2025. doi: 10.1520/F1962-22.1.

[6] James A. Platosh, "Trenchless Technology Helps Force Main Cross Harbor." [Online]. Available: https://www.waterworld.com/drinking-water-treatment/potable-water-quality/article/16194013/trenchless-technology-helps-force-main-cross-harbor

[7] SpecialChem, "Strength at break (Tensile)." [Online]. Available: https://www.specialchem.com/plastics/guide/strength-at-break-tensile

[8] ISO, *ISO 527-1:2019 Plastics — Determination of tensile properties — Part 1: General principles*. 2019. [Online]. Available: www.iso.org

[9] ISO, *ISO 6259-1 Thermoplastics pipes — Determination of tensile properties — Part 1: General test method*. 2015.

[10] ISO, *ISO 6259-3:2015 Thermoplastics pipes - Determination of tensile properties Part 3: Polyolefin pipes*, vol. 2015. 2015.

[11] Samik Raychaudhuri, "Intrduction to Monte Carlo Simulation," *Proc. 2008 Winter Simul. Conf.*, pp. 91–100, 2008.

[12] G. Ökten and A. Göncü, "Generating low-discrepancy sequences from the normal distribution: Box-Muller or inverse transform?," *Math. Comput. Model.*, vol. 53, no. 5–6, pp. 1268–1281, 2011, doi: 10.1016/j.mcm.2010.12.011.

[13] ISO, "ISO 4427-1:2019 Plastics piping systems for water supply, and for drainage and sewerage under pressure - Polyethylene [PE] - Part 1: General," vol. 2019.

[14] BSN, "SNI 9362:2025 Pipa polietilena (PE) untuk sistem perpipaan air minum , drainase dan saluran pembuangan bertekanan," 2025.