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Development of die drawing design factor prediction models for trenchless rehabilitation of water pipes: a case study

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ABSTRACT

Maintenance and replacement of aging water pipes are critical for urban development. To this end, trenchless rehabilitation methods that do not require excavation offer an efficient replacement for aging water pipes. Thus, this study developed a trenchless method using die drawing, which continuously inserts polyethylene (PE) liners into the reach point while maintaining traction in the host aging pipe. If the traction is removed after a certain period, the initially contracted liner pipe undergoes expansion under natural restoration and tightly adheres to the inner wall of the host pipe to achieve structural regeneration of the aging pipe. This study aimed to determine the factors influencing the die drawing process using a rehabilitation design. Accordingly, we experimented with the die drawing method to achieve structural reinforcement using high elasticity PE liners. Thereafter, based on the experimental data, we developed prediction models to estimate traction, pipe restoration rate after traction release, and pipe restoration period. The developed models estimated the minimum required restoration period and provided deeper insights into the restoration behavior of the die drawing method employed in pre-equipment maintenance before on-site construction.

Key words: die drawing, regression model, trenchless rehabilitation technology, water pipe

HIGHLIGHTS

- This study developed a trenchless method based on die drawing for aging pipelines, specifically applicable to large diameters.
- The influential factors were determined with test-bed experiments.
- We developed prediction models to estimate traction, pipe restoration rate after traction release, and pipe restoration period.
- This can evaluate the appropriate construction time and work scale.

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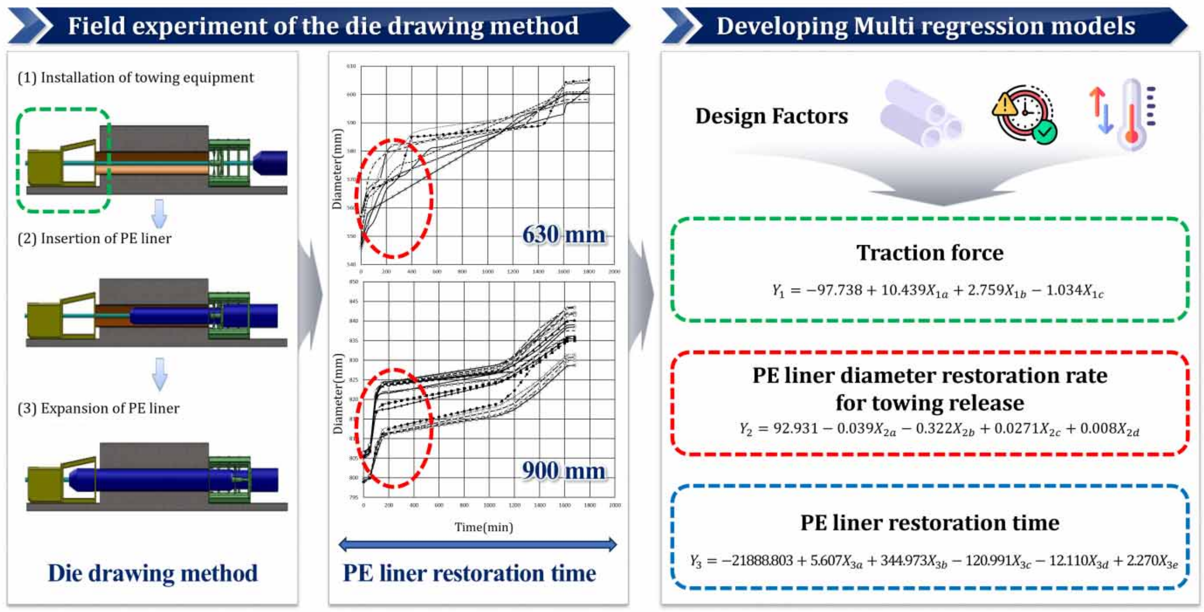
GRAPHICAL ABSTRACT



1. INTRODUCTION

An adequate supply of safe water with sufficient pressure through water pipelines is essential for sustenance. Accordingly, timely maintenance, repair, and replacement of aging water pipelines are necessary to address the quantitative and qualitative issues that have emerged in recent years (Bubtiena *et al.* 2012; Elshaboury *et al.* 2020; Kerwin & Adey 2020). However, excavation work for the maintenance of old pipes is gradually experiencing limitations in constructability owing to issues such as rising traffic volume and the complexity of buried pipes within urban networks (Fang *et al.* 2018; Loss *et al.* 2018; Wu *et al.* 2021). As a result, insertable lining construction technology, which is a trenchless method that can overcome the limitations of constructability, including minimizing traffic disruption and improving economic feasibility compared to excavation, has garnered increasing social interest (Haas *et al.* 1995; Fuselli *et al.* 2022; Jin *et al.* 2023).

In principle, the insertion lining method inserts a new lining into a buried host pipe to prevent internal corrosion and provide structural reinforcement. Specifically, the insertion lining method can be classified into slip-lining (SL), close-fit lining (CFL), and cured-in-place pipe (CIPP) (Wang *et al.* 2021; Zhu *et al.* 2021). In the SL method, a smaller new pipe is inserted into the host pipe, and the space between the host pipe and the inserted pipe is filled with grout to provide reinforcement (Li *et al.* 2020; Rahmaninezhad *et al.* 2020). However, a significant drawback of this method is that the hydraulic capacity decreases substantially because the new pipe is smaller than the host pipe (Hastak & Gokhale 2000; Najafi 2011). On the other hand, both CFL and CIPP methods use steam or hot water to adhere the inserted liner to the host pipe (Barber *et al.* 2005; Gras-Travesset *et al.* 2023). However, steam or hot water generation, along with temperature maintenance, can be applied in the case of limited capacity. Therefore, the rehabilitation of a pipe with a diameter greater than a certain size is impossible (Das *et al.* 2016; Zhu *et al.* 2021).

To resolve the limitations of the host insertion lining method, the die drawing method was developed as a modification of CFL. The die drawing method continuously inserts a highly elastic polyethylene (PE) pipe of a reduced diameter into the arrival port by passing it through a diameter reduction die while maintaining the traction force (Szymiczek & Wróbel 2007). Upon releasing the traction force after a certain period, the initially contracted PE pipe begins to expand under the natural restoration force. This process effectively restores the structure of the old pipe by fitting it to the inner wall of the host pipe. However, the constructability of the die drawing method may vary based on factors such as construction length, diameter of the host pipe, lining material, average temperature, and other related conditions. More importantly, implementing the die drawing method at a specific site requires careful consideration of various organizational and operational factors during construction (Zwierzchowska & Kuliczkowska 2019).

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Unfortunately, despite the potential advantages of the die drawing method, it remains unclear which factors should be controlled on-site when implementing this method. Until recently, there have been few studies conducted related to the construction process of the die drawing method. Wróbel & Szymiczek (2004) employed the die drawing method in experiments involving a 63-mm diameter pipe, during which they explored various parameters such as the standard dimension ratio (SDR), pipe diameter reduction rate, and diameter reduction angle (die angle). Their findings indicated that the required traction force decreased as the pipe thickness and SDR increased. Moreover, they observed that the time required for restoration was significantly affected by the pipe diameter reduction rate, extending to a minimum of 3,000 min. Their analysis specifically highlighted the impact of SDR, pipe diameter reduction rate, and pipe diameter reduction angle on traction force and restoration time. However, they did not account for the influence of pipe diameter and temperature and focused solely on the correlation between traction fitting and other related factors. Subsequently, Wróbel *et al.* (2012) performed a die drawing experiment by considering temperature as an additional variable that influences traction force and traction time (Wróbel & Szymiczek 2004). In addition, they developed a physical model by considering the stress of the reduction die as a factor for evaluating traction force. As reported, the traction force required for the construction method tends to decrease as the temperature increases. However, their results suggested that the liner deformed when the constant temperature was exceeded, and the workability decreased. Following their previous study, Wróbel & Szymiczek (2004) and Wróbel *et al.* (2012) experimented with a pipe having a smaller diameter (63 mm). However, the applicability of die drawing to larger diameters needs to be examined due to the large number of connected water pipes. In addition, their research had limitations as it failed to address the relationship between traction force and restoration time concerning pipe diameter, and their developed physical model involved complex calculations and estimations, limiting practical field application. In conclusion, there has been no research to date on what factors should be controlled to improve the field constructability of the die drawing method, so literature gaps exist in the die drawing construction process.

Traditional construction design has often been limited to considering the physical characteristics of host pipes, such as material strength, durability, and dimensional stability. However, this approach misses a crucial aspect: the environmental variables at the construction site. Temperature variations, for example, can significantly affect the feasibility and timing of construction projects. Overlooking these factors can result in extended construction durations, escalated costs, and a higher risk of structural failures. Thus, it is imperative to undertake a comprehensive experimental investigation that encompasses these environmental considerations. By doing so, this study aims to fill a notable gap in the existing literature, offering a more accurate and practical construction design methodology.

To this end, this study undertook a series of experiments aimed at optimizing the key construction factors that must be carefully controlled to enhance the on-site feasibility of the die drawing method. Furthermore, we aimed to develop an experimental model capable of predicting on-site constructability. Our initial phase involved evaluating the liner's thickness, utilized within the construction method, to ensure it adhered to the American Water Works Association (AWWA) Class standard. This assessment was crucial to ascertain its suitability for structural reinforcement. Subsequently, we conducted a series of experiments on a specially designed test bed to identify the most favorable operating conditions for construction. These experiments took into account the specific design parameters of the newly developed die drawing method. Notably, we conducted these experiments on pipe diameters of 630 and 900 mm, successfully verifying the method's suitability for large diameter pipelines. Using the valuable data obtained from these experiments, we developed prediction models for estimating the PE liner's traction force, the PE liner's restoration rate upon the release of traction, and the time required for PE liner restoration. These predictive models will enhance the practical applicability in the design and execution of site construction.

2. MATERIAL AND METHODS

2.1. Minimum liner thickness

This study applied the design criteria of the structural classification system recommended by the American Water Works Association (AWWA) to determine whether the liner specifications meet the standards. The PE liner used for structural reinforcement of water pipelines must meet AWWA Class II. Therefore, determining the appropriate liner thickness is crucial (Matthews *et al.* 2013; AWWA 2014). Depending on the pipe diameter and thickness, the PE pipe can be designed as AWWA Class IV or higher to replace the structural performance of the host pipe. If the structural performance of the host pipe is adequate, it can be designed as AWWA Class II or Class III to optimize the construction design (Selvakumar *et al.* 2015; Table 1).

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Table 1 | Structural classification of linings according to AWWA Class classifications (AWWA 2014)

AWWA structural classification	Definition
Class I	• Non-structural • Coating/corrosion protection
Class II	• Semi-structural – pressure transferred to the host pipe • Requires adhesion to the host pipe
Class III	• Semi-structural – pressure transferred to the host pipe • Does not require adhesion to the host pipe
Class IV	• Fully structural • Independent of the host pipe • Pipe within a pipe

The minimum pipe thickness of AWWA Classes II–IV, which is the structural reinforcement classification standard for liners that ensures the structural safety of the lining method, can be calculated as follows:

Minimum lining thickness calculation according to Class II:

$$t_{2a} = \frac{D}{\left[(D/d)^2(5.33\sigma_{\mathrm{FAL}}/(P_w \times N))\right]^{1/2} + 1} \tag{1}$$

where t_{2a} is minimum lining thickness to span holes in the host pipe wall (in.); D is the inner diameter of the host pipe (in.); d is diameter of the hole in the host pipe wall (in.); σ_{FAL} is long-term flexural strength of the lining system and axial direction (psi); P_w is internal working pressure (psi); and N is design factor of safety.

Minimum lining thickness calculation according to Class III:

$$t_{3a} = \frac{D}{\left[(2\mathrm{KE}_{\mathrm{FHS}}C/((1-v^2)N(P_N + W_s)/2))\right]^{1/3} + 1} \tag{2}$$

where t_{3a} is minimum lining thickness to resist short-term buckling pressure (in.); K is the enhancement factor of the soil and host pipe adjacent to the new pipe (enhancement factor); C is the ovality reduction factor (dimensionless); q is ovality of the host pipe (%); v is Poisson's ratio of lining system (dimensionless); and W_s is surface live load at the pipe burial depth (psi).

Minimum lining thickness calculation according to Class IV:

$$t_{4a} = \frac{D}{(2 \times \sigma_{\mathrm{THL}}/P_w \times N) + 1} \tag{3}$$

where t_{4a} is minimum recommended lining thickness at the maximum allowable operating pressure (in.); D is inner diameter of the host pipe (in.); σ_{THL} is long-term tensile strength of the lining system and hoop direction (psi); P_w is internal working pressure (psi); and N is design factor of safety.

The thicknesses satisfying the AWWA Class grade criteria were evaluated according to various design conditions and liner characteristics. In this study, to ensure the structural safety of the die drawing method using a PE liner, the minimum pipe thickness for each pipe diameter satisfying AWWA Class II–IV standards was calculated by adjusting the design conditions, such as the inner diameter of the host pipe. The internal pipe diameter of the host pipe was set at 100–1,200 mm. Moreover, the minimum thickness of the liner suitable for the AWWA Class standard for each pipe diameter was determined by assuming the same buried environmental and operating conditions.

In addition, since the minimum thickness of the liner required for each AWWA Class depends on the physical properties of the lining, we considered parameters such as the flexural modulus, long-term flexural strength, long-term tensile strength, Poisson's ratio of lining system, hole diameter, internal working pressure, design factor of safety, and enhancement factor were set as the physical properties of HDPE, as listed in Table 2.

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Table 2 | Design conditions and liner characteristics input by liner type

Input condition	Value
Initial flexural modulus (hoop)	10,197.2 kgf/cm^2
Long-term flexural strength (axial)	175.8 kgf/cm^2
Long-term tensile strength (hoop)	250 kgf/cm^2
Poisson's ratio of lining system	0.45
Hole diameter (future external corrosion)	10 mm
Internal working pressure	7 kgf/cm^2
Design factor of safety	2.0
Enhancement factor	7.0

2.2. Die drawing

The developed die drawing method involves passing a PE pipe through a reduction die while maintaining the traction force of the host pipe, resulting in the continuous reduction of the pipe's diameter.

The construction procedure for the die drawing process is outlined in Figure 1. First, before reducing the pipe diameter by passing through the pipe diameter reduction die (Figure 1(a)), the head and PE liner must be attached to the PE liner traction. The fusion of the PE liner head (Figure 1(b)) is an essential preliminary step to ensure stable traction. Following the cooling process of the fusion site of the head and the PE liner, the PE liner and pulling rod (Figure 1(c)) should be connected. After completing these preliminary works, the PE liner is towed by a pulling rod and passed through the reduction die starting from the head (Figure 1(d)), thereby reducing the diameter of the PE liner (Figure 1(e)). The structural rehabilitation concludes by restoring the liner's diameter using an elastic force (Figure 1(f)), ensuring secure adhesion to the host pipe's inner wall.

2.3. Field experiment of the die drawing method

The performance of the die drawing method can vary based on factors such as the diameter and thickness of the PE liner, diameter reduction rate, traction force, and temperature. Therefore, to secure on-site constructability, the PE liner traction

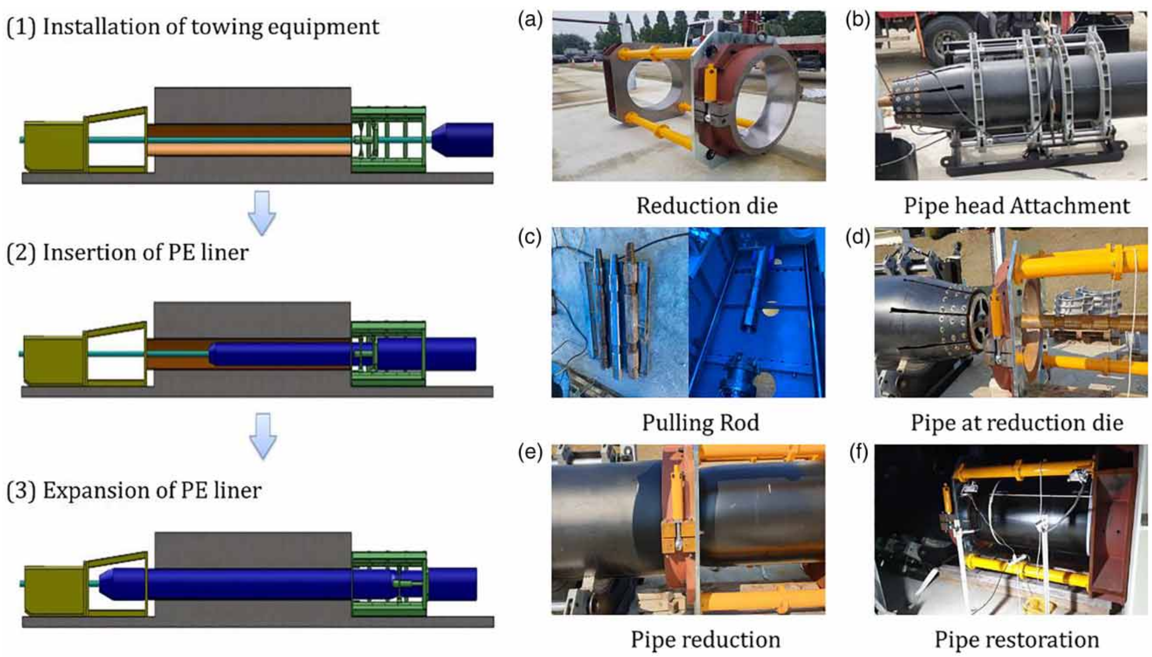

Figure 1 | Procedure for a trenchless method using die drawing.

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force and restoration time should be analyzed according to various influencing factors, e.g., temperature, diameter reduction rate, and pipe thickness.

To evaluate the impact of the construction conditions of the die drawing method on the construction results, 25 field experiments were conducted from 30 September 2020 to 28 July 2021. These experiments aimed to analyze the influence of different construction factors with specific SDR settings for the PE liner and diameter reduction equipment, as outlined in Table 3. The experiments involved assessing the variation in traction force and pipe diameter over time. Notably, the PE liners with diameters of 900 mm (SDR 26, SDR 33) and 630 mm (SDR 26) were used to confirm the applicability of medium to large diameter pipes.

The PE liner's diameter contracts due to the influence of elastic forces and subsequently gradually returns to its original diameter. However, because the elongation rate varied with the specifications and physical properties of the PE pipe used in the construction method and the temperature at the construction site, the degree of diameter restoration decreased over time. Therefore, measurement of the temperature and diameter restoration rate of the PE liner was required to perform field experiments. In this study, the temperatures inside and outside the pipe and the on-site ambient temperature were measured for analysis. Within 5 min of passage through the reduction die, the diameter of the PE liner was measured up to two decimal places. When the diameter remained unchanged, measurements were conducted for 1,620–1,800 min. In addition, the length of the PE liner used in the experiment ranged from 1 to 4 m. For liners linger than 2 m, the diameter restoration over time was measured at 1 m intervals.

2.4. Multiple regression analysis

Multiple regression analysis can be used to derive and analyze the relationship between one dependent variable and two or more independent variables, and it acts as an extension of simple regression analysis with one independent variable. The multiple regression model can be mathematically expressed as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon_i \quad (4)$$

where y is dependent variable; x_k is independent variable; β_k is regression coefficient; and ε_i is residual. $\beta_0, \beta_1, \ldots, \beta_k$ represent the $k+1$ regression coefficients to be estimated, and the residuals were assumed as normal distributions with a mean of

Table 3 | Experimental scenarios for analyzing influence factors of the die drawing method

No.	Pipe diameter (mm) Host	Pipe diameter (mm) PE Liner	SDR	Pipe length (m)	Reduction ratio (%)	Temp. (°C)
1	600	630	26	1	17.14	27.5
2						17
3						19.9
4						18
5						14
6						16
7					15.08	12.2
8						18
9–10	900	900	26	2	10.81	26
11–13			33	3	10.61	
14			26	1	10.81	16.5
15–16			33	2	10.61	
17–18			26	2	10.81	15.4
19–21			33	3	10.61	
22			26	1	10.81	26.7
23–25			33	3	10.61	

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zero and variance σ^2, which were independent of each other. Regression analysis estimates the regression parameter value and tests the hypothesis based on the relationship between the dependent and independent variables obtained from the sample.

In this study, to evaluate the construction status of high elasticity PE liners, we developed prediction models based on multiple regression analysis to estimate the PE liner traction force, PE liner restoration rate for traction release, and PE liner restoration time to select the necessary equipment based on the traction required for towing the PE liner and predicting the time required for construction.

3. RESULTS AND DISCUSSION

3.1. Minimum thickness of the liner

Assuming that the host pipe was a cast iron and steel pipe, the minimum thickness of the PE liner required for structural reinforcement according to the AWWA Class standard was calculated for each pipe diameter. The minimum thickness values of the PE liner for each pipe diameter in accordance with the AWWA Class standard are presented in Table 4, which are required for the field application of the die drawing method for cast iron and steel pipes.

Upon evaluating the minimum thickness required by the AWWA Class standard for the structural reinforcement of the die drawing method, we determined that the minimum required thickness increased proportionally with the pipe diameter. Moreover, the minimum required thickness under AWWA Class III and Class IV (external pressure and internal and external pressure reinforcement standards, respectively) was higher than that under the AWWA Class II standard (internal pressure reinforcement standard). To replace the structural performance of the host pipe, the liner thickness was designed according to AWWA Class IV or higher, and if the host pipe exhibited adequate structural performance, the construction cost and design were optimized according to AWWA Class II and Class III standards.

The PE liner thickness used in the experiment was 34.62 and 27.27 mm for the 900 mm diameter, based on the SDR, and 24.23 mm for the 630 mm diameter, as listed in Table 5. After comparing these measurements with the AWWA standard, it was determined that fully structural reinforcement was achievable.

Table 4 | Calculation results of minimum thickness according to AWWA Class standard

	Minimum thickness according to AWWA Class (mm)			
Diameter (mm)	**Class I**	**Class II**	**Class III**	**Class IV**
100		1.21	2.24	2.92
125		1.21	2.80	3.65
150		1.21	3.36	4.38
200		1.22	4.49	5.84
250		1.22	5.62	7.30
300		1.22	6.75	8.75
350		1.22	7.89	10.21
400		1.22	9.03	11.67
450		1.22	10.17	13.13
500		1.22	11.32	14.59
600		1.22	13.62	17.51
700		1.22	15.93	20.43
800		1.22	18.26	23.34
900		1.22	20.61	26.26
1,000		1.22	22.96	29.18
1,100		1.22	25.33	32.10
1,200		1.22	27.71	35.02

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Table 5 | Calculation result of minimum thickness according to experimental scenarios

Pipe diameter (mm)				
Host	PE Liner	SDR	Thickness (mm)	Minimum liner thickness according to AWWA Class IV
600	630	26	24.23	17.51
900	900	26	34.62	26.26
		33	27.27	

3.2. Field experiment results of the die drawing method

The variations in the traction force concerning the diameter reduction rate of the PE liner and the temperature are presented in Figure 2. The traction force exhibited a range between 62 and 140 bar, influenced by factors such as average temperature, reduction rate, reduction die, and SDR. Notably, the traction force displayed an upward trend with the diameter reduction rate, while showing a tendency to decrease with higher average temperatures. Thus, the traction force decreased as the elongation rate of the PE increased with the average temperature, and the traction force increased with the resistance acting on the diameter reduction equipment as the diameter reduction rate increased during the towing of the PE liner. Comparing the 630-mm diameter PE liner pipe with the 900-mm diameter counterpart, it was observed that the traction force for the former was greater. This difference can be attributed to the higher diameter reduction rate of 15–17% in the 630 mm pipe, surpassing that of the latter. Evaluating the impact of SDR on traction revealed that a lower amount of traction was required with an increasing SDR, owing to the reduced pipe thickness associated with higher SDR values. However, a wide range of traction was required for PE liners with the same SDR of 26. From this perspective, the effect of the SDR on traction was smaller than that of the average temperature and diameter reduction rate.

The temporal variations in PE liner diameter are shown in Figures 3 and 4. The diameter of the PE liner (630 mm) varied with the diameter reduction rate and temperature, requiring (approximately) 27 h to adhere to the host pipe diameter at an average restoration rate of 95.4%. Similarly, the PE liner with a diameter of 900 mm required (approximately) 30 h to adhere to the host pipe diameter, and the restoration rate was 94.4%. These findings offer valuable insights for designing the appropriate PE liner size, traction equipment, and construction time necessary for effective pipeline structural reinforcement. It is important to note that while these results contribute to the understanding of PE liner behavior, further experiments encompassing diverse pipe diameters, thicknesses, and SDRs are essential for a comprehensive analysis of the PE liner's diameter restoration rate over time. Furthermore, restoration time and traction force analyses are necessary for this consideration.

3.3. Results of design factor prediction model development using the die drawing method

In this study, we developed prediction models to estimate the PE liner traction force, PE liner restoration rate upon traction release, and PE liner restoration time, subsequently deriving the design factor of the die drawing method. The models were

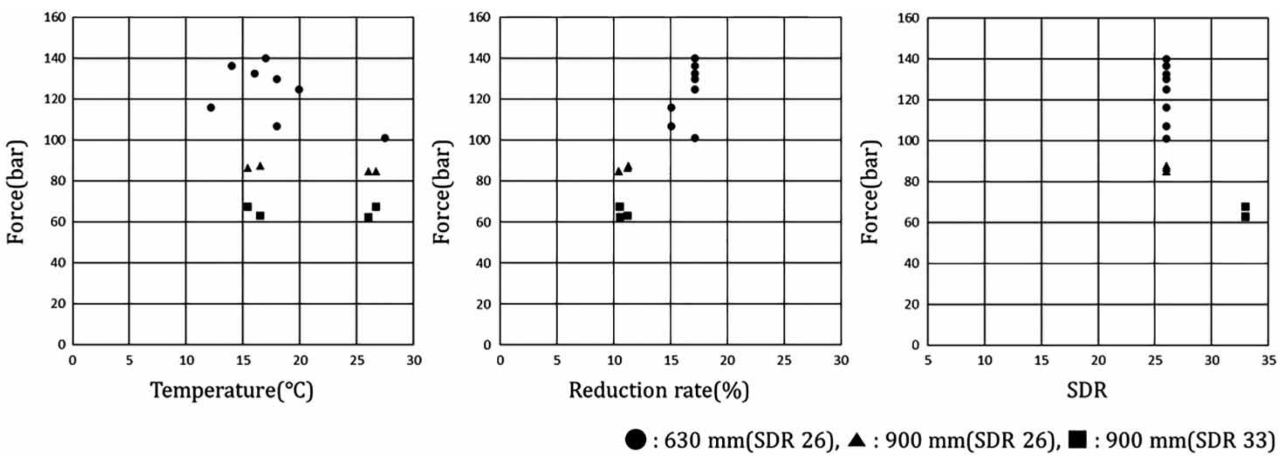

Figure 2 | Traction force according to temperature, reduction rate of PE liner, and SDR.

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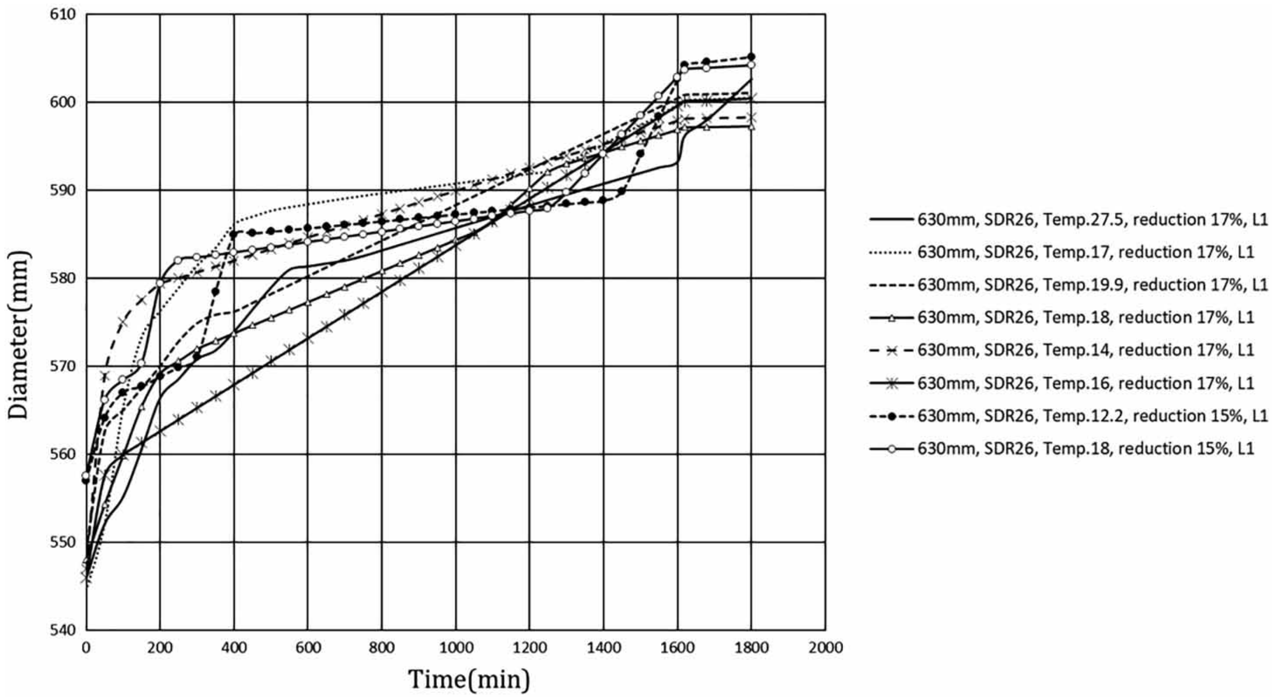

Figure 3 | Diameter variations as a function of time (630 mm).

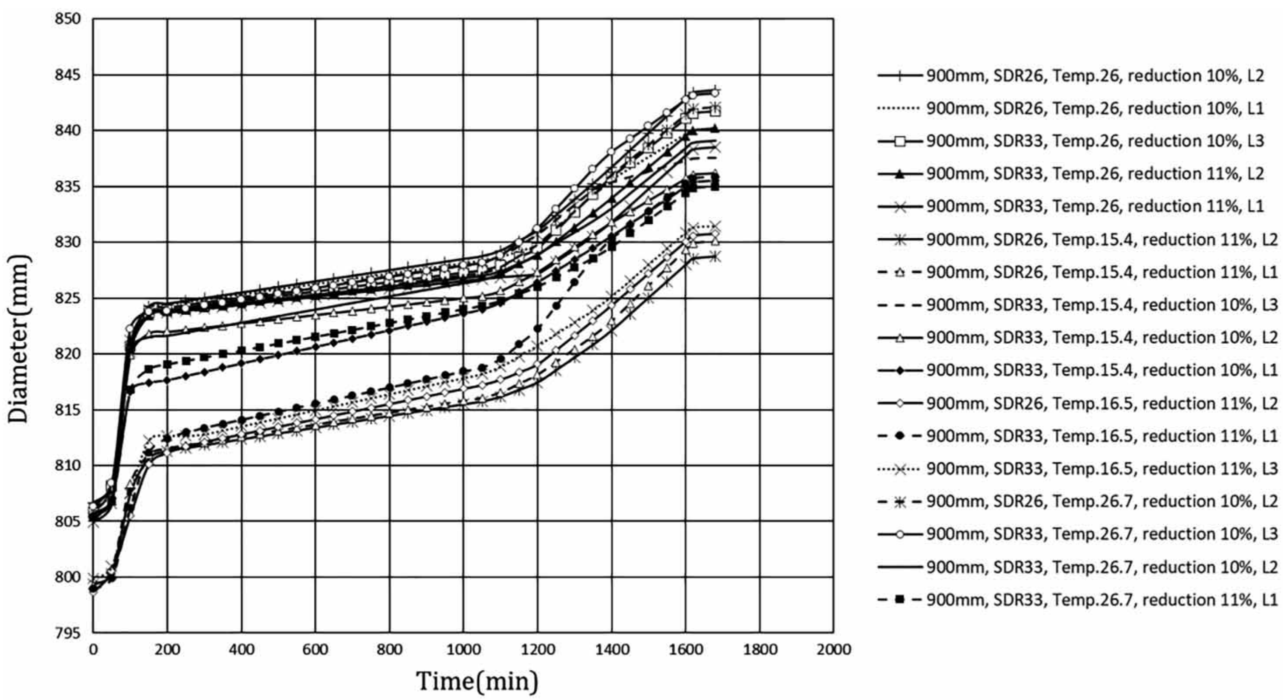

Figure 4 | Diameter variations as a function of time (900 mm).

developed using multiple regression analysis, according to the step-input method. Based on the collinearity statistics, a statistically significant model was derived by examining the significance probability of the coefficients and the presence of multicollinearity between each independent variable.

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3.3.1. PE liner traction force prediction model

A traction force prediction model was developed to assess the maintenance of traction equipment required before site construction. For the model development, 16 data points were used, except for the data measured by the same PE liner among the 25 experimental data points. The PE liner traction force required for construction was set as the dependent variable, and the PE liner diameter, thickness, diameter reduction rate, and average temperature were selected as independent variables. Equation (5) represents the derived PE liner traction force prediction model.

$$Y_1 = -97.738 + 10.439X_{1a} + 2.759X_{1b} - 1.034X_{1c} \quad (5)$$

where Y_1 is PE liner traction force (bar); X_{1a} is reduction rate (%); X_{1b} is PE liner thickness (mm); and X_{1c} is temperature (°C).

Table 6 displays the statistical indicators of the regression analysis applied to the PE liner traction prediction model. Three scale-type variables (PE liner reduction rate (X_{1a}), PE liner thickness (X_{1b}), and temperature (X_{1c})) were selected as statistically significant variables through step-input method, with no constraints on multicollinearity. Overall, the results were statistically significant because the significance probability was less than 0.05, the correlation coefficient (R) of the developed model was 0.959, and the modified coefficient of determination (R^2) was 0.899.

The developed model for predicting the traction force required for installing PE liners delves into how factors like the reduction rate, thickness of the PE liner, surrounding temperature, and the SDR value influence the necessary traction force. A pivotal aspect of this model is the use of standardized coefficients to assess and compare the relative impact of each variable on the traction force, with variables exhibiting more significant coefficients deemed to have a more substantial influence. Analysis reveals that the reduction rate of the PE liner is the most critical factor, exerting the greatest impact on traction force and thus standing out as the primary consideration in predictions. The PE liner's thickness follows in significance, contributing notably to the required force. Additionally, temperature emerges as a key determinant, with findings indicating that an increased temperature corresponds to a reduced need for traction force. The key findings can be summarized as follows:

(1) *PE liner size and thickness:* Under the same conditions, a pipe with a diameter of 900 mm requires more traction force than a pipe with a diameter of 630 mm. Specifically, under an SDR 26, the larger pipe demands a traction force of 134 bar, whereas the smaller pipe requires only 105 bar. This variation is due to the thicker walls of the larger pipe, which require more traction force.

(2) *Impact of SDR value:* The SDR value, which indicates the thickness of the pipe wall, affects the amount of traction force needed. Pipes of the same diameter but with different SDR values demand different levels of traction force. For example, a 900 mm pipe with an SDR 26 needs 134 bar, compared to only 113 bar for a pipe with an SDR 33. This demonstrates that lower SDR values, signifying thicker walls, necessitate more traction force.

(3) *Effects of temperature and reduction rate:* This model illustrates that as the pipe diameter reduction rate escalates to 10, 15, and 20%, the required traction force increases accordingly. This increase is due to the need for a larger angle of the reduction die used for reducing the pipe, thereby requiring greater traction force. Moreover, a rise in temperature results in a decreased need for traction force. The PE liner material becomes more pliable at higher temperatures, allowing it to deform with less force.

This analysis underscores that the selection of traction equipment for the installation of PE liner at construction sites must consider the pipe's physical properties (size, thickness, SDR value, reduction rate) and the environmental factors

Table 6 | Results of regression analysis of the PE liner traction prediction model

Variables	Unstandardized coefficients		Standardized coefficients			Collinearity statistics	
	B	Std. error	Beta	*t*	Sig.	Tolerance	VIF
Constant	−97.738	38.044		−2.569	0.025		
X_{1a}	10.439	1.179	1.193	8.856	0.000	0.372	2.689
X_{1b}	2.759	0.830	0.443	3.325	0.006	0.380	2.634
X_{1c}	−1.034	0.449	−0.198	−2.304	0.040	0.912	1.097

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(temperature) comprehensively. Adopting this holistic approach can maximize the efficiency of on-site activities and ensure the accurate preparation of necessary traction equipment, optimizing the overall installation process.

3.3.2. PE liner diameter restoration rate prediction model for towing release

The pipe diameter restoration rate while maintaining traction varies with an increase in the pipe restoration rate after releasing the traction. Therefore, the restoration of the pipe diameter should be monitored and analyzed while maintaining traction and after releasing traction. This is essential for predicting the pipe diameter restoration rate after releasing traction, and predicting the construction period required for natural restoration. Accordingly, 25 experimental data points were used to develop a prediction model for estimating the PE liner diameter restoration rate after the traction force was released. Thus, we performed a regression analysis considering the diameter of the PE liner after releasing the traction force as the dependent variable, whereas the PE liner diameter, thickness, diameter reduction rate, average temperature, average traction force, and traction time were regarded as the independent variables.

$$Y_2 = 92.931 - 0.039X_{2a} - 0.322X_{2b} + 0.0271X_{2c} + 0.008X_{2d} \quad (6)$$

where Y_2 is PE liner restoration rate at traction release (%); X_{2a} is PE liner thickness (mm); X_{2b} is reduction rate (%); X_{2c} is temperature (°C); and X_{2d} is PE liner traction time (min).

Table 7 displays the statistical indicators of the regression analysis applied to the PE liner diameter restoration rate prediction model for towing release. Four scale-type variables (PE liner thickness (X_{2a}), diameter reduction rate (X_{2b}), average temperature (X_{2c}), and traction time (X_{2d})) were selected as statistically significant variables through step-input method, with no constraints on multicollinearity. Overall, the results were statistically significant because the significance probability was less than 0.05, the correlation coefficient (R) of the developed model was 0.832, and the modified coefficient of determination (R^2) was 0.689.

Similar to the previous (3.3.1) traction force prediction model, the analysis based on the standardized coefficients of independent variables has determined their impact on diameter restoration. The results indicate that PE liner traction time has the most significant influence, followed by the PE liner diameter reduction rate, average temperature, and lastly, the liner's thickness, in order of impact. The key findings can be summarized as follows:

(1) *PE liner size and thickness:* When comparing PE liners of diameters 630 and 900 mm (both with an SDR of 26), the liner of diameter 630 mm demonstrated a higher restoration rate of 89.39% compared to 88.98% for the 900 mm diameter liner, under the same traction time and average traction force. This difference is partly because the 900 mm diameter liner required a greater traction force for restoration due to its larger size and resulting higher thickness. Additionally, the reduction rate in the diameter of the 900 mm liner was smaller, which contributed to its slightly lower restoration rate.

(2) *Impacts of PE liner traction time:* The study meticulously examined how the duration of traction affects the rate at which the PE liner's diameter is restored during the towing release phase. It was noted that the pipe diameter restoration rate slightly increases by about 0.2% for traction durations of 10, 30, and 60 min, with other factors like average temperature, diameter reduction rate, and PE liner specifics held constant. This trend indicates that diameter restoration proceeds under continuous traction, albeit with diminishing efficacy as traction time is extended. However, the effectiveness of this restoration process gradually decreases over time as the traction is prolonged.

Table 7 | Results of regression analysis of the PE liner restoration rate prediction model

Variables	Unstandardized coefficients		Standardized coefficients	t	Sig.	Collinearity statistics	
	B	Std. error	Beta			Tolerance	VIF
Constant	92.931	0.410		226.430	0.000		
X_{2a}	−0.039	0.009	−0.174	−4.366	0.000	0.513	1.951
X_{2b}	−0.322	0.014	−0.939	−22.538	0.000	0.470	2.128
X_{2c}	0.027	0.006	0.176	4.841	0.000	0.614	1.627
X_{2d}	0.008	0.000	0.983	23.153	0.000	0.452	2.211

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(3) *Effects of temperature:* As the ambient temperature increases, so does the restoration rate of the pipe's diameter. This phenomenon can be attributed to the thermal properties of the PE liner material, which becomes more pliable and easier to stretch or restore at higher temperatures. The increased malleability of the liner under warmer conditions facilitates a more efficient return to its original dimensions after being subjected to traction forces. This temperature dependency underscores the importance of considering environmental conditions when planning the restoration process, as higher temperatures can significantly enhance the effectiveness of diameter restoration. Consequently, this insight provides a valuable strategy for optimizing the restoration outcomes by leveraging temperature conditions to the project's advantage.

Integrating these observations, it becomes evident that both the physical dimensions of the PE liner and the extent of its diameter reduction significantly influence the efficiency of diameter restoration. Additionally, while increased traction time contributes to some degree of restoration, the degree of improvement lessens with prolonged traction. This underscores a critical balance between traction time and restoration efficiency, highlighting the importance of optimizing traction duration to enhance restoration outcomes without unnecessary extension. Therefore, the PE liner's diameter restoration rate can be accurately predicted during towing release by considering variables such as the liner's diameter reduction rate, average temperature, SDR, and the traction time employed during on-site construction.

3.3.3. PE liner restoration time prediction model

The PE liner traction prediction model was developed to assess the maintenance of traction equipment required before on-site construction. The PE liner diameter restoration time prediction model estimated the time required to restore the PE liner diameter during the actual construction. Furthermore, we developed a model to predict the PE liner diameter restoration time by inputting the PE liner restoration time required for the construction and the on-site conditions to evaluate the construction status of a highly elastic PE liner.

To develop the model, 7,775 data points were measured at 5 min intervals from the time of traction release to the completion of construction. The final diameter restoration rate, diameter restoration rate at towing release, diameter, thickness, and average temperature were the independent variables, and the PE liner diameter restoration time was set as the dependent variable.

$$Y_3 = -21,888.803 + 5.607X_{3a} + 344.973X_{3b} - 120.991X_{3c} - 12.110X_{3d} + 2.270X_{3e} \tag{7}$$

where Y_3 is PE liner restoration time (min); X_{3a} is PE liner thickness (mm); X_{3b} is final PE liner restoration rate (%); X_{3c} is PE liner restoration rate during traction release (%); X_{3d} is temperature (°C); and X_{3e} is diameter (mm).

In the final derived model, the scale variables of the PE liner thickness (X_{3a}), final diameter restoration rate (X_{3b}), diameter restoration rate at traction release (X_{3c}), average temperature (X_{3d}), and pipe diameter (X_{3e}) were selected with no constraints on multicollinearity. As shown in Table 8, the coefficient for each variable was statistically significant because the significance probability was $\leq$0.05. Moreover, the correlation coefficient (R) of the developed model was 0.782, and the modified coefficient of determination (R^2) was 0.611, which demonstrated significant predictive power with an adequately strong correlation.

Table 8 | Results of regression analysis of the PE liner restoration time prediction model

	Unstandardized coefficients		Standardized coefficients			Collinearity statistics	
Variables	***B***	**Std. error**	**Beta**	***t***	**Sig.**	**Tolerance**	**VIF**
Constant	–21,888.803	347.229		–63.039	0.000		
X_{3a}	5.607	1.116	0.049	5.023	0.000	0.535	1.869
X_{3b}	344.973	3.129	0.934	110.248	0.000	0.697	1.435
X_{3c}	–120.991	3.228	–0.338	–37.478	0.000	0.614	1.629
X_{3d}	–12.110	0.658	–0.140	–18.392	0.000	0.864	1.158
X_{3e}	2.270	0.045	0.632	50.328	0.000	0.317	3.150

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The analysis reveals a hierarchy of influences where the final PE liner restoration rate emerges as the foremost factor, succeeded by the diameter of the PE liner, the restoration rate during traction release, average temperature, and, finally, the PE liner's thickness. These determinants collectively shape the restoration dynamics, offering a nuanced understanding of the process. The critical insights derived from this investigation are detailed as follows:

1. *Pipe diameter and restoration time:* An analysis focusing on PE liners with a 900 mm diameter, which achieved a 90% restoration rate of their original diameter at the point of traction release and under an average temperature condition of 20 °C, reveals that approximately 1989 min (about 33 h) are required to elevate the restoration rate to 95% or higher, provided the specification is SDR 26. In contrast, for PE liners with a smaller diameter of 630 mm, targeting the same final restoration rate of 95% under identical conditions – a 90% restoration rate at tow release, an average temperature of 20 °C, and an SDR of 26 – the necessary restoration time drops significantly to 1,318 min (about 22 h). This stark comparison underscores the pivotal influence of pipe diameter on the restoration process's efficiency and overall duration.
2. *Impact of liner thickness:* When considering PE liners under the same conditions but with a reduced thickness, the analysis shows a notable decrease in the required restoration time. Specifically, to achieve a 95% recovery rate, the time needed is reduced to 1948 min (approximately 32 h), compared to the 33 h required for thicker liners under similar conditions. This delineation highlights the pivotal role of liner thickness in the restoration process, suggesting that adjustments in liner thickness could lead to substantial time savings. The efficiency of diameter restoration, therefore, is notably influenced by the physical properties of the liner, pointing toward strategic liner selection based on thickness to optimize construction schedules.
3. *Final restoration rate considerations:* Achieving higher restoration rates necessitate a nuanced understanding of the dynamics of the restoration process. As the target for the final PE liner restoration rate is set higher, the complexity and duration of the restoration process increase. This is particularly evident when aiming for a recovery rate of 95% or more, where the time required for restoration escalates. This observation underlines the importance of balancing project goals with realistic timelines, acknowledging that aspirations for near-complete restoration demand a proportional investment in time and resources.
4. *Temperature's role in restoration efficiency:* Ambient temperature has a profound influence on the efficiency of the restoration process. Elevated temperatures contribute to a more malleable PE liner material, which, in turn, facilitates a more efficient and expedited restoration to its original diameter. This effect underscores the importance of environmental considerations in planning the restoration process, where warmer conditions can significantly reduce the time required to achieve desired restoration outcomes.

The pipe's diameter predominantly dictates the restoration duration for PE liners, yet it is also influenced by the liner's thickness, even when operating under identical environmental and site conditions. The prediction model developed for estimating the necessary time for PE liner restoration is a strategic tool for planning and optimizing construction timelines. By factoring in the targeted restoration rate, diameter of the PE liner, thickness, rate of restoration during tow release, and ambient temperature, it becomes possible to devise a construction schedule that maximizes both the structural integrity and operational efficiency, ensuring that a minimum of 95% restoration of the PE liner is achievable within the projected timeframe.

4. CONCLUSIONS

In this study, we developed a die drawing method as a non-excavation rehabilitation method for water pipelines, specifically applicable to large diameter. Additionally, design factor prediction models to determine the appropriate construction time and scale prior to on-site construction of die drawing method were developed. To develop the models, experiments were conducted on the test bed to assess the factors influencing on-site construction.

Using the experimental data, prediction models were developed to estimate the traction force required for construction condition design, the diameter restoration rate for traction release, and optimal restoration time for PE liner pipes. Here, PE liner pipes with diameters of 900 mm (SDR = 26 and 33) and 630 mm (SDR = 26) were used in the experiment, which satisfied the standards for structural reinforcement (AWWA Class II–IV standards). The results indicate that structural safety can be secured in the rehabilitation of old water pipes using the die drawing method.

Developing prediction models using the test-bed experimental data yielded *R*-values ranging from 0.782 to 0.959, and the R^2 was between 0.611 and 0.899, demonstrating significant predictive power with strong correlation. The PE liner traction

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force prediction model allows for the anticipation of the required traction force, aiding in the selection of appropriate traction equipment before construction. The prediction model for pipe restoration rate during towing release indicates the extent of pipe diameter restoration while maintaining traction force. Additionally, the prediction model for PE liner restoration time estimates the minimum time required for at least a 95% restoration rate, providing valuable insights for evaluating the optimal construction time and scale for die drawing.

Building on these insights, it becomes clear that when establishing construction plans, careful consideration must be given not only to the physical characteristics of the existing host pipe, such as diameter and length, but also to the physical properties of the PE liner. Moreover, environmental factors, such as the surrounding temperature, significantly impact the construction process and its outcomes. Additionally, understanding the extent of diameter restoration achieved by the liner during the construction process is crucial, as it directly influences the project's timeline. This multifaceted approach emphasizes the need to integrate a wide range of factors, from the physical and mechanical properties of the materials to environmental conditions and construction progress metrics, to ensure the successful execution and completion of the project. The models developed in this study provide a foundational framework for adopting this comprehensive perspective, facilitating the establishment of a detailed planning phase that enables more efficient and effective construction activities and optimizes adherence to project timelines.

While the current predictive models have provided valuable insights for PE liner diameters ranging from 630 to 900 mm, there is a recognized need for additional experimentation to extend the models' applicability to medium and large diameter pipes. Future studies should aim to explore variations in pipe diameter restoration times across a broader range of diameters, SDR values, and environmental temperatures. Furthermore, after achieving an optimal level of restoration through natural recovery, strategically considering the use of hydraulic pressure to complete the restoration process can be beneficial. This approach takes advantage of the gains made from traction and temperature adjustments, using hydraulic pressure as a precise mechanism to ensure full diameter restoration. This method could be particularly effective in instances where the initial restoration process brings the liner close to its target restoration rate but falls short of complete recovery.

In conjunction with hydrostatic testing, a deeper analysis of the variations in pipe diameter and length will further enhance our understanding and ability to predict construction outcomes more accurately. Through continued research and the accumulation of data on various pipe diameters, it is anticipated that more effective construction conditions can be established, facilitating the non-excavation rehabilitation of large diameter water pipelines more efficiently and reliably.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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