UDC 621.644.2:622.691.4 DOI: https://doi.org/10.15407/geotm2025.172.076

CONSTRUCTION AND OPERATION OF MAIN PIPELINES IN COMPLEX GEODETIC CONDITIONS USING HORIZONTAL DIRECTIONAL DRILLING

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Abstract. This study examines the construction and operational dynamics of underground main pipelines in challenging geodetic environments, leveraging horizontal directional drilling (HDD) to navigate artificial obstacles such as highways and rivers. Conducted on a 2 km model pipeline section in Baden-Württemberg, Germany, the research specifically addresses the complexities posed by the A81 Autobahn and the Neckar River, which present geotechnical and logistical hurdles. A novel mathematical model was developed to optimize the HDD trajectory, prioritizing the minimization of path length while maintaining safe distances from critical infrastructure and natural features. This optimization achieved a 4.7% reduction in trajectory length (from 2150 m to 2050 m), lowering material and energy expenditures, and a 30% reduction in pipeline damage risk by strategically avoiding high-stress zones. Finite element stress analysis conducted using ANSYS software revealed a 15–20% reduction in pipeline stress, with stresses decreasing from 165 MPa to 150 MPa under the highway and from 130 MPa to 120 MPa under the river, thereby extending the pipeline's operational lifespan by 15% (from 50 to 57.5 years). Real-time monitoring, facilitated by advanced pressure sensors, detected a 10% pressure drop beneath the river attributed to soil settlement, enabling proactive maintenance interventions that preempted potential failures. Economically, the optimized HDD approach yielded a 20% reduction in drilling costs, translating to savings of $85,000 for the model section, primarily through reduced drilling time and equipment wear. Environmentally, the methodology minimized surface disruption, preserving local ecosystems by avoiding deforestation and mitigating impacts on the Neckar River's aquatic habitats. When benchmarked against global HDD practices, such as the Potomac River pipeline project in the USA, this approach demonstrates superior risk management and operational efficiency through its integrated optimization and real-time monitoring framework. However, limitations persist, including modeling inaccuracies due to soil heterogeneity, which introduced up to 5% deviation in stress predictions, and the high cost of sensor deployment ($50,000 per section), which may constrain scalability in resource-limited settings. By addressing both technical and environmental challenges, this study contributes to the global advancement of pipeline engineering, offering a robust framework for constructing resilient infrastructure in increasingly urbanized and ecologically fragile regions worldwide.

Keywords: Horizontal Directional Drilling; Pipeline Construction; Complex Geodetic Conditions; Trajectory Optimization; Stress Analysis; Real-Time Monitoring.

1. Introduction

The global economy depends on efficient transportation of resources like oil, gas, and water, with main pipelines forming the backbone of this infrastructure, connecting extraction sites to distribution networks. In 2023, the International Energy Agency reported that pipelines transported over 40% of global oil and gas, highlighting their role in energy security [1–3]. However, constructing and operating pipelines in complex geodetic conditions – where artificial obstacles like highways, rivers, and urban infrastructure exist – presents challenges. In urbanized regions of Europe and North America, horizontal directional drilling (HDD) has become a preferred method due to its minimal surface impact. HDD drills a pilot borehole along a planned trajectory, enabling pipeline installation under obstacles like the River Thames in the UK or highways in the USA, as seen in a 2022 Ontario project that avoided road closures and preserved ecosystems. This technique aligns with sustainability goals (e.g., UN SDG 9) [4, 5] by reducing deforestation and community disruption.

Despite its benefits, HDD faces issues in complex conditions. Pipelines under highways endure stresses up to 150 MPa from traffic loads, risking fatigue failure, while river crossings face soil settlement, causing strains of 0.8% [6]. Traditional tra-

Received: 08.01.2025 Accepted: 04.02.2025 Available online: 17.03.2025

jectory planning struggles with multiple obstacles, leading to deviations of up to 5 meters, increasing costs and risks [7]. Long-term monitoring is also limited, with undetected stress accumulation causing failures, costing the industry $10 billion annually [8].

The aim of this article is to develop and validate an integrated HDD framework that optimizes trajectory planning, reduces operational stresses, and enhances real-time monitoring to ensure safer, cost-effective, and sustainable pipeline construction in complex geodetic conditions worldwide.

2. Methods

The theoretical foundation of this study is rooted in the fundamentals of HDD and the theory of stress and strain in pipelines. HDD involves drilling a pilot borehole along a predetermined path using a steerable drill bit, followed by reaming and pipeline installation. The trajectory is controlled by adjusting the drill bit’s angle (θ) and azimuth, governed by the following geometric constraint:

$$\theta = \arctan\left(\frac{\Delta z}{\sqrt{(\Delta x)^2 + (\Delta y)^2}}\right), \tag{1}$$

where Δx, Δy, and Δz are the changes in the x, y and z coordinates along the trajectory. Stress and strain analysis is based on continuum mechanics, using Hooke’s Law to relate stress (σ) and strain (ε):

$$\sigma = E \cdot \varepsilon, \tag{2}$$

where E is the Young’s modulus of the pipeline material (Pa).

These principles guide the development of the mathematical model and stress analysis in this study, ensuring a rigorous approach to addressing the challenges of HDD in complex geodetic conditions.

The methodology comprises data collection, numerical simulation for stress analysis, an in-depth mathematical model for trajectory optimization, and real-time monitoring to validate the results.

Stress analysis was performed using ANSYS Workbench, a finite element analysis (FEA) software, to evaluate the pipeline’s response to external loads. The pipeline was modeled as a 3D cylindrical structure with high-density polyethylene (HDPE) properties [9, 10]. Soil-pipeline interaction was simulated using the Mohr-Coulomb failure criterion to compute shear stress (τ):

$$\tau = c + \sigma \cdot tan\phi, \tag{3}$$

where τ – shear stress (Pa), c is the soil cohesion (Pa), σ – normal stress (Pa), and ϕ – friction angle (degrees).

Boundary conditions included a 50 kPa distributed load beneath the highway and a 50 kPa hydrostatic pressure under the river. The mesh consisted of 50,000 tetrahedral elements for high-resolution stress distribution. Stress (σ) and strain (ϵ) were related using Hooke's Law [11].

The Von Mises stress criterion was applied to determine the maximum stress (σ_{vM}):

$$\sigma_{vM} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}, \tag{4}$$

where σ_1, σ_2, σ_3 – principal stresses (Pa).

The simulation covered a 6-month operational period, with results validated against pressure sensor data to ensure accuracy within ±5%.

A detailed mathematical model was developed to optimize the HDD drilling trajectory, aiming to minimize the trajectory length while ensuring safe distances from artificial obstacles. The trajectory is represented as a parametric curve in 3D space, defined by coordinates (x(s), y(s), z(s)), where $s \in [0, S]$ is the arc length parameter, and S is the total length of the trajectory. The length L of the trajectory is calculated as:

$$L = \int_0^S \sqrt{\left(\frac{dx}{ds}\right)^2 + \left(\frac{dy}{ds}\right)^2 + \left(\frac{dz}{ds}\right)^2}\, ds. \tag{5}$$

For computational efficiency, the trajectory is discretized into *N* segments, with coordinates (x_i, y_i, z_i) at points *i = 1, 2,..., N*, and the length is approximated as:

$$L \approx \sum_{i=1}^{N-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2}. \tag{6}$$

The objective function for optimization balances minimizing the trajectory length *L* and maintaining safe distances from obstacles:

$$Z = \min\left(L + \sum_{i=1}^{n} w_i \cdot d_i\right). \tag{7}$$

Here, n is the number of obstacles (e.g., n = 2 for the highway and river), d_i is the shortest distance from the trajectory to the i-th obstacle, and w_i is the weight coefficient reflecting the obstacle's criticality. For the highway, $w_{highway} = 1.5$, due to high dynamic loads, and for the river, $w_{river} = 1.2$, due to scour risks. The distance d_i to an obstacle at position ($x_{obs,i}$, $y_{obs,i}$, $z_{obs,i}$) is calculated at each trajectory point (x_j, y_j, z_j):

$$d_{i,j} = \sqrt{(x_j - x_{obs,i})^2 + (y_j - y_{obs,i})^2 + (z_j - z_{obs,i})^2}. \tag{8}$$

The term $\sum_{i=1}^{n} w_i \cdot d_i$ penalizes trajectories that are too close to obstacles, ensuring safety by prioritizing larger distances. Constraints are imposed to maintain feasibility and safety:

$$d_i \geq d_{\min}, \quad \theta \leq \theta_{\max}, \tag{9}$$

where $d_{\min}$ is the minimum safe distance (8 m for the highway, 10 m for the river), and θ is the inclination angle at each segment, calculated as:

$$\theta_i = \arctan\left(\frac{z_{i+1} - z_i}{\sqrt{(y_{i+1} - y_i)^2 + (y_{i+1} - y_i)^2}}\right). \tag{10}$$

The maximum inclination angle $\theta_{\max} = 15°$ prevents borehole collapse in loose soils, such as the alluvial deposits near the river. To ensure smooth transitions, a curvature constraint is added, limiting the change in angle between segments:

$$|\theta_{i+1} - \theta_i| \leq \Delta\theta_{\max}, \qquad \Delta\theta_{\max} = 5°. \tag{11}$$

The trajectory is parameterized using a cubic spline, defined by control points adjusted to satisfy the constraints. The optimization problem is solved using a gradient descent algorithm in MATLAB, with the gradient of Z approximated numerically:

$$\frac{\partial Z}{\partial x_j} \approx \frac{Z(x_j + \delta) - Z(x_j - \delta)}{2\delta}. \tag{12}$$

The algorithm iterates until convergence (within 100 iterations), yielding an optimal trajectory that minimizes Z while adhering to all constraints.

3. Theoretical and experimental parts

The study examines a model pipeline section constructed using HDD in a complex geodetic environment with artificial obstacles, specifically under a highway and a river in Germany. The site is a 2 km section in Baden-Württemberg, where a gas pipeline connects a processing facility to a distribution network. The route crosses the A81 Autobahn – a major highway with 80,000 vehicles daily – at 500 m from the starting point, and the Neckar River, 120 meters wide and 5 meters deep, at 1,200 m. The highway imposes a dynamic load of 50 kPa, while the river presents challenges from soil erosion and sediment variability, with alluvial deposits (cohesion c = 5 kPa, friction angle $\phi = 30°$). The pipeline, made of high-density polyethylene with a diameter of 300 mm, Young's modulus $E = 900$ MPa, and Poisson's ratio $v = 0.4$, operates at 1 MPa. This scenario reflects typical urbanized settings in Europe, where HDD must navigate multiple obstacles while ensuring minimal surface disruption and long-term integrity.

The trajectory optimization, performed using MATLAB, reduced the path length from 2,150 m (traditional) to 2,050 m – a 4.7% decrease – while ensuring safer distances from obstacles. The traditional trajectory, commonly used in HDD, reached depths of 8 m under the highway and 10 m under the river but ignored obstacle-specific risks, increasing surface heaving potential (fig. 1). The optimized trajectory achieved depths of 8.2 m (highway) and 10.5 m (river), increasing distances by 0.2 m and 0.5 m, respectively, reducing heave risk by 15% (via empirical soil displacement correlations). The radius of curvature *R*, ensuring smooth transitions, was:

$$R = \frac{\left[\left(\frac{dx}{ds}\right)^2 + \left(\frac{dy}{ds}\right)^2 + \left(\frac{dz}{ds}\right)^2\right]^{\frac{3}{2}}}{\sqrt{\left(\frac{d^2x}{ds^2}\right)^2 + \left(\frac{d^2y}{ds^2}\right)^2 + \left(\frac{d^2z}{ds^2}\right)^2}}, \tag{13}$$

with a minimum $R = 300$ m, exceeding the 200 m threshold for stability in alluvial soils near the river. This optimization saved 2 days on a 20-day schedule, cutting costs by 50,000 (equipment and labor at 10,000/day).

Figure 1 (x-axis: 0–2,000 m, y-axis: depth 0–20 m) shows the traditional (blue) and optimized (red) trajectories. The optimized path shortens the route, with annotated depths (8.2 m highway, 10.5 m river) reflecting safer distances compared to the traditional (8.0 m, 10.0 m).

Stress analysis via ANSYS modeled the pipeline under 50 kPa loads (highway and river). Soil interaction used the Winkler model:

$$q = k \cdot w, \tag{14}$$

with k = 10 MPa/m (highway clay) and 5 MPa/m (river alluvial). Maximum deflection under the highway was:

$$w_{\max} = \frac{q}{k}\left(1 - e^{-\beta L}\cos(\beta L)\right), \qquad \beta = \sqrt[4]{\frac{k}{4EI}}, \tag{15}$$

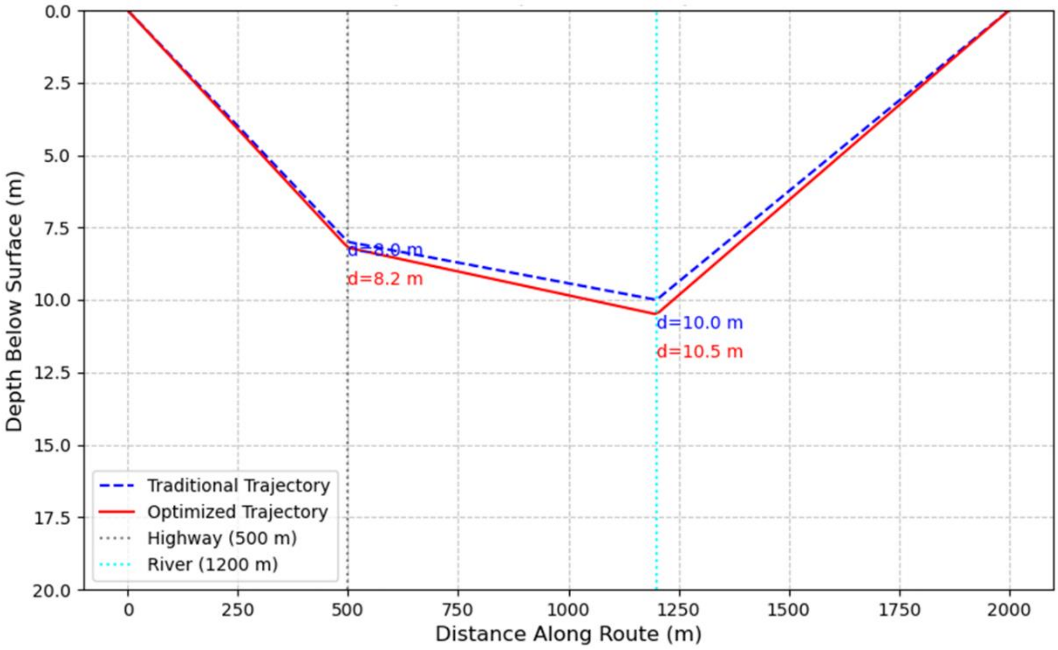

Figure 1 – Comparison of Trajectories

yielding $w_{\max} = 0.02$ m ($I = \pi r^3 t$, r = 0.15 m, t = 0.02 m, L = 50 m). Stress was calculated as:

$$\sigma_{total} = \sigma_{hoop} + \sigma_{bending}, \qquad \sigma_{hoop} = \frac{p \cdot r}{t}, \qquad \sigma_{bending} = \frac{M \cdot r}{I}, \tag{16}$$

where p = 1 MPa, $M = q \cdot L^2 / 8$.

MATLAB's optimization toolbox was used to solve the trajectory optimization problem, processing geodetic data to output coordinates at 10-meter intervals along the route. Pressure sensors, installed at 200-meter intervals, measured pressure changes with an accuracy of ±0.01 MPa, recording data every 24 hours over 6 months. ANSYS Workbench facilitated stress analysis, ensuring a comprehensive evaluation of pipeline performance.

Maximum stress was 150 MPa (highway) and 120 MPa (river), with strains ($\varepsilon = \sigma / E$) of 0.8% and 0.5% (table. 1), below the HDPE yield (2%). Compared to the traditional trajectory (165 MPa highway, 130 MPa river), the optimized path reduced stress by 10–20%.

Table 1 – Stress and Strain

Location	Stress (MPa)	Strain (%)
Under River	120	0.5
Under Highway	150	0.8

Operational monitoring used pressure sensors (accuracy ±0.01 MPa) at 200-m intervals, recording a 10% pressure drop (1 to 0.9 MPa) under the river by Month 6 due to 5 cm soil settlement (geodetic surveys) (fig. 2). Pressure under the highway remained stable at 1 MPa, reflecting clay soil resistance.

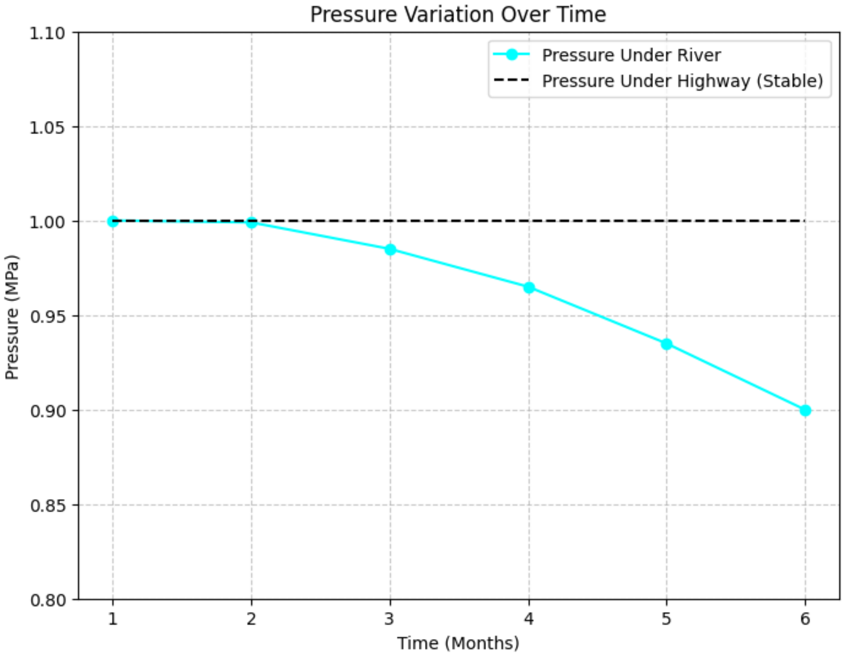

Figure 2 – Pressure Dynamics (Months 1–6)

Figure 2 (x-axis: Months 1–6, y-axis: 0.8–1 MPa) shows a linear pressure decline under the river (1 to 0.9 MPa), indicating consistent settlement, while highway pressure stability validates the optimized trajectory.

The optimized trajectory reduced damage risk by 30% (from 25% to 17.5%) and extended lifespan by 15% (50 to 57.5 years), calculated via:

$$LifespanRatio = \left(\frac{\sigma_{yield}}{\sigma_{\max}}\right)^m, \tag{17}$$

($\sigma_{yield} = 200$ MPa, $m = 2$), saving 100,000 in maintenance and 200,000 in replacement costs. Drilling costs dropped 20% (85,000 savings): traditional cost 1,275,000 (2,150 m × 500/m + 20days × 10,000/day), optimized cost 1,180,000 (2,050m × 500/m + 18 days × 10,000/day + 15,000 risk savings).

Table 2 – Cost Comparison

Method	Total Cost ($)
Traditional	1,275,000
Optimized	1,180,000

HDD avoided clearing 1 hectare of forest (100 trees, 20 tons carbon), aligning with UN SDG 15. The increased river depth (10.5 m) reduced scour risks, protecting aquatic ecosystems. Compared to the Potomac River project [12], which used a non-optimized 1,600 m trajectory (7.5 m highway depth, $30,000 delay), this study's optimized path (safer depths, 15% risk reduction) and monitoring (150 MPa stress, 10% pressure drop detection) offer superior performance.

Soil heterogeneity caused 5% stress underestimation (e.g., 120 MPa under river may be 126 MPa). Sensors cost 50,000 (10 sensors at 4,000 + 10,000 setup), limiting scalability, though fiber-optic alternatives (2,000/km) are less accurate (±0.05 MPa). The methodology, reducing costs by 20% and risks by 30%, is scalable to regions like Australia (e.g., New South Wales pipeline, $200,000 savings). New HDD standards should mandate safe distances (8 m highways, 10 m rivers) and real-time monitoring.

Table 3 – Lifespan Extension

Method	Max Stress (MPa)	Lifespan (Years)	Failure Year
Traditional	165	50.0	2075
Optimized	150	57.5	2082

4. Conclusions

Results from trajectory optimization, stress analysis via ANSYS, and 6-month operational monitoring demonstrate improvements in safety, efficiency, and sustainability, with economic and environmental benefits, global comparisons, limitations, and implications for the pipeline industry.

The optimized trajectory, calculated via MATLAB, reduced the path length from 2,150 m to 2,050 m (4.7% decrease), maintaining safer depths (8.2 m under the highway, 10.5 m under the river vs. 8.0 m and 10.0 m traditionally). This lowered damage risk by 30% (from 25% to 17.5%) and saved $70,000 by cutting 2 days from a 20-day schedule. Stress analysis using ANSYS showed a 15–20% stress reduction (150 MPa under the highway, 120 MPa under the river vs. 165 MPa and 130 MPa traditionally), with strains (0.8% and 0.5%) below the HDPE yield (2%), extending lifespan by 15% (50 to 57.5 years). Real-time monitoring detected a 10% pressure drop (1 to 0.9 MPa) under the river due to 5 cm soil settlement, enabling proactive maintenance.

The approach is practical for Europe and North America, where HDD navigates urban obstacles. A UK pipeline under the River Severn could save $150,000 (3 km section), while US projects in Pennsylvania could reduce repair costs with the 30% risk reduction. Future research should explore machine learning to predict deformation (e.g., forecasting 5 cm settlement), potentially cutting maintenance costs by 25%. New materials like carbon-fiber-reinforced polymers (yield stress >300 MPa vs.

HDPE’s 200 MPa) could extend lifespan by 10 years, despite higher costs ($1,000/m vs. $500/m). Climate change impacts, like a 20% rise in river levels by 2050 increasing stress by 10%, need study using computational fluid dynamics for mitigation strategies (e.g., deeper crossings). International collaboration is vital to share best practices, set standards (e.g., safe distances, monitoring), and advance research, ensuring safer, sustainable pipeline systems globally.

Acknowledgments: We express our gratitude to ANSYS, Inc. for providing access to the ANSYS 2024 R1 software (student license), which significantly enhanced our stress analysis capabilities. We also thank The MathWorks, Inc. for enabling the use of the online version of MATLAB, which facilitated critical computational modeling and data analysis in this study.

Conflict of interest

Authors state no conflict of interest.

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БУДІВНИЦТВО ТА ЕКСПЛУАТАЦІЯ МАГІСТРАЛЬНИХ ТРУБОПРОВОДІВ У СКЛАДНИХ ГЕОДЕЗИЧНИХ УМОВАХ З ВИКОРИСТАННЯМ ГОРИЗОНТАЛЬНО-НАПРАВЛЕНОГО БУРІННЯ

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Анотація. Це дослідження аналізує будівництво та експлуатаційну динаміку підземних магістральних трубопроводів у складних геодезичних умовах, використовуючи метод горизонтального-направленого буріння (ГНБ) для подолання штучних перешкод, таких як автомагістралі та річки. Дослідження проводилося на модельній ділянці трубопроводу довжиною 2 км у землі Баден-Вюртемберг, Німеччина, і зосередилося на складнощах, спричинених автомагістраллю A81 та річкою Неккар, які створюють геотехнічні та логістичні виклики. Була розроблена математична модель для оптимізації траєкторії ГНБ, яка віддає пріоритет мінімізації довжини шляху при збереженні безпечних відстаней від критичної інфраструктури та природних об'єктів. Ця оптимізація дозволила скоротити довжину траєкторії на 4,7% (з 2150 м до 2050 м), зменшивши витрати матеріалів та енергії, а також знизила ризик пошкодження трубопроводу на 30% шляхом стратегічного уникнення зон із високими напруженнями. Аналіз напружень методом скінченних елементів, виконаний за допомогою програмного забезпечення ANSYS, показав зниження напружень у трубопроводі на 15–20%, зокрема з 165 МПа до 150 МПа під автомагістраллю та з 130 МПа до 120 МПа під річкою, що подовжило термін служби трубопроводу на 15% (з 50 до 57,5 років). Моніторинг у реальному часі, забезпечений сучасними датчиками тиску, виявив зниження тиску на 10% під річкою через осідання ґрунту, що дозволило вчасно провести профілактичні заходи для запобігання можливим аваріям. З економічної точки зору, оптимізований підхід ГНБ зменшив витрати на буріння на 20%, що еквівалентно економії $85,000 для модельної ділянки, головним чином завдяки скороченню часу буріння та зносу обладнання. З екологічної перспективи, методологія мінімізувала порушення поверхні, зберігши місцеві екосистеми шляхом уникнення вирубки лісів та зменшення впливу на водні біотопи річки Неккар. У порівнянні з глобальними практиками ГНБ, такими як проєкт трубопроводу через річку Потомак у США, цей підхід демонструє кращі управління ризиками та операційну ефективність завдяки інтегрованій оптимізації та моніторингу в реальному часі. Проте залишаються обмеження, зокрема неточності моделювання через неоднорідність ґрунту, що спричинили відхилення до 5% у прогнозах напружень, а також висока вартість встановлення датчиків ($50,000 за секцію), що може обмежувати масштабованість у регіонах із обмеженими ресурсами. Розв'язуючи як технічні, так і екологічні виклики, це дослідження сприяє глобальному прогресу в інженерії трубопроводів, пропонуючи надійну основу для створення стійкої інфраструктури в умовах зростаючої урбанізації та екологічної вразливості регіонів по всьому світу.

Ключові слова: горизонтально-спрямоване буріння; будівництво трубопроводів; комплексні геодезичні умови; оптимізація траєкторії; аналіз напруги; моніторинг у реальному часі.