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Engineering Performance Analysis of Brewis' Downhole Pullback Swivels: The Importance of Proper Load Rating and Towing Head Compatibility in Horizontal Directional Drilling Operations

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Abstract

Horizontal Directional Drilling (HDD) has become a critical trenchless technology for the installation of pipelines, utility conduits, telecommunications systems, and underground infrastructure in complex operational environments. As HDD installations continue to increase in scale and mechanical complexity, the reliability of pullback assemblies has emerged as a major engineering concern, particularly in high-load drilling operations where improper equipment selection may result in excessive tensile stress, torsional instability, structural failure, and operational downtime. Despite the growing industrial dependence on pullback swivel systems, limited research has examined the engineering relationship between swivel load rating, towing head compatibility, and overall HDD operational reliability. This study presents an engineering performance analysis of Brewis' downhole pullback swivels with emphasis on proper load rating optimization, towing head compatibility, and failure prevention in HDD operations. The research integrates HDD pullback mechanics, finite element stress analysis, mechanical reliability evaluation, and comparative load-performance assessment to examine the effects of properly rated and improperly rated swivel configurations under varying operational conditions. Mechanical performance parameters including tensile load capacity, torque isolation efficiency, stress distribution, fatigue susceptibility, and connection stability were evaluated using engineering modeling and standards-based assessment frameworks. The findings indicate that properly rated pullback swivels combined with compatible towing heads significantly improve load stability, reduce stress concentration, minimize failure probability, and enhance HDD operational safety. The analysis further demonstrates that incompatible towing head configurations and underrated swivel systems substantially increase the risk of fatigue failure, bearing degradation, threaded connection damage, and infrastructure-related operational losses. The study contributes an integrated engineering framework for HDD swivel selection, mechanical reliability optimization, and operational risk mitigation while providing practical recommendations for HDD contractors, drilling engineers, and infrastructure operators involved in high-capacity trenchless installation projects.

Keywords: Brewis' Downhole Pullback Swivels; Horizontal Directional Drilling (HDD); Pullback Load Analysis; Mechanical Reliability; Towing Head Compatibility; Load Rating Optimization; HDD Safety Engineering; Failure Prevention; Torque Isolation; Finite Element Analysis.

I. Introduction

A. Background of Horizontal Directional Drilling (HDD)

Horizontal Directional Drilling (HDD) has emerged as one of the most widely adopted trenchless technologies for the installation of underground pipelines, telecommunications conduits, electrical transmission systems, and water distribution infrastructure in densely populated and environmentally sensitive regions. The technology enables underground installations beneath rivers, highways, railways, urban developments, and protected environmental zones without extensive surface excavation, thereby reducing environmental disruption, restoration costs, and construction-related traffic interference (Baumert & Allouche, 2002). The rapid expansion of energy transmission networks, smart utility systems, offshore infrastructure projects, and urban utility modernization programs has significantly increased the global deployment of HDD systems in both short-distance and long-distance underground crossing operations (Patino-Ramirez et al., 2020).

As HDD projects continue to expand in scale and operational complexity, modern drilling operations increasingly involve larger bore diameters, extended pullback distances, variable geological formations, and high-capacity product pipes that impose substantial mechanical demands on drilling equipment and pullback assemblies (Kong et al., 2022). The combination of elevated tensile loads, dynamic loading conditions, borehole curvature effects, drilling fluid interaction, and pipe–borehole friction introduces critical engineering challenges that directly influence operational safety and drilling reliability (Guo & Liang, 2018). In long-distance HDD installations, excessive pullback loads may generate severe tensile stress accumulation within the product pipe and associated pullback components, increasing the probability of fatigue failure, pipe deformation, structural instability, and operational downtime (Rabiei et al., 2016).

Mechanical integrity has therefore become a fundamental engineering requirement in HDD operations, particularly during pullback stages where the drill string, towing head, pullback swivel, and product pipe operate as an integrated mechanical system under high tensile and torsional loading conditions. Yang et al. (2014) emphasized that accurate prediction and management of pullback loads are essential for maintaining structural reliability during HDD installations, especially in variable subsurface conditions where dynamic load fluctuations can significantly alter operational performance. Similarly, Wang and Hu (2024) demonstrated that pipe–borehole wall interaction and contact pressure conditions strongly influence pullback resistance and stress development during HDD operations.

Within trenchless infrastructure systems, HDD pullback assemblies perform a critical function by transferring pulling forces from the drilling rig to the product pipe while simultaneously accommodating rotational movement generated by the drill string and reaming assemblies. The performance and reliability of pullback systems therefore depend heavily on the engineering quality, load rating, compatibility, and structural stability of the swivel and towing head assemblies integrated within the HDD system.

B. Engineering Importance of Downhole Pullback Swivels

Downhole pullback swivels are essential mechanical components within HDD pullback assemblies because they provide rotational isolation between the rotating drill string and the stationary product pipe during pullback operations. During HDD installation, the reamer and drill string continuously rotate while the product pipe remains rotationally restrained. Without an effective swivel mechanism, rotational torque generated by the drilling assembly may be transmitted directly to the product pipe, leading to torsional deformation, pipe overstressing, threaded connection instability, and potential structural failure (Plastics Pipe Institute, 2008).

The primary engineering function of a pullback swivel is to transfer tensile pulling forces while minimizing torsional stress transmission between connected HDD components. This mechanical decoupling mechanism

allows the drill string to rotate independently while maintaining stable tensile load transfer to the towing head and product pipe. The swivel assembly therefore operates under simultaneous axial loading, dynamic stress fluctuations, bearing pressure, and rotational motion, making its structural reliability critically important for HDD operational safety.

Modern pullback swivel systems typically incorporate high-capacity bearing assemblies, tensile load shafts, threaded or clevis connection systems, and sealing mechanisms designed to withstand harsh underground operational conditions. According to ASME BTH-1 (American Society of Mechanical Engineers, 2023), load-bearing lifting and pulling components operating under dynamic loading conditions must be designed using appropriate safety factors, stress distribution analysis, and structural integrity verification methods to prevent premature failure. Similarly, API Spec 8C (American Petroleum Institute, 2012) emphasizes that load-rated drilling and hoisting equipment must maintain sufficient structural reliability under variable operational loading environments.

In HDD systems, effective pullback swivels contribute to:

- ❖ stabilization of tensile load transfer,
- ❖ reduction of torsional stress accumulation,
- ❖ prevention of rotational pipe deformation,
- ❖ improved pullback efficiency,
- ❖ and reduction of operational failure risks.

The engineering significance of pullback swivels becomes increasingly important in large-scale HDD installations involving long-distance pullback operations, large-diameter pipes, unstable geological formations, and high-capacity drilling rigs where pullback loads may approach critical operational limits.

C. Importance of Proper Swivel Load Rating and Towing Head Compatibility

The selection of properly rated pullback swivels and compatible towing heads represents one of the most important engineering decisions in HDD pullback system design. Improperly rated swivel systems may introduce severe mechanical instability into the HDD assembly, particularly when operational pullback loads exceed the allowable tensile capacity of the swivel or associated connection components. Under such conditions, stress concentration may develop within threaded interfaces, bearing assemblies, or towing head connections, significantly increasing the likelihood of fatigue crack initiation, tensile overload failure, and catastrophic pullback system breakdown (Albdiry & Almensory, 2016).

The Plastics Pipe Institute (2008) emphasized that pullback swivel capacity should not be excessively greater than the allowable pull strength of the product pipe because oversized swivel systems may inadvertently permit excessive load application beyond safe pipe stress limits. Similarly, the Plastics Pipe Institute Municipal Advisory Board (2024) recommended that swivel capacity should be selected in close alignment with the safe pullback capacity of the pipe and drilling system to ensure balanced load transfer and operational protection.

Towing head compatibility further influences HDD pullback stability because the towing head functions as the primary mechanical interface between the swivel assembly and the product pipe. Incompatible towing head geometry, threaded connection mismatch, or improper alignment conditions may generate uneven load transfer, eccentric loading, localized stress amplification, and bending moments within the pullback assembly. These conditions may accelerate bearing degradation, threaded connection wear, seal failure, and fatigue propagation within the swivel system.

Stress concentration caused by connection misalignment has been extensively investigated in threaded mechanical systems. Tafreshi and Dover (1993) demonstrated through finite element analysis that localized stress concentration within threaded connections significantly influences fatigue initiation and structural reliability under cyclic loading conditions. Macdonald and Deans (1995) further showed that threaded connection geometry and contact conditions strongly affect peak stress development and long-term structural performance in mechanically loaded systems.

In high-load HDD environments, improperly matched swivel and towing head systems may therefore compromise operational safety, increase maintenance requirements, elevate failure probability, and expose infrastructure projects to substantial economic and operational risks.

D. Industrial Challenges in HDD Pullback Operations

HDD pullback operations involve highly dynamic mechanical conditions that expose pullback assemblies to complex combinations of tensile loading, torsional stress, cyclic fatigue, drilling fluid interaction, and abrasive environmental conditions. Excessive pullback loads remain one of the most significant operational challenges in HDD installations because pullback resistance continuously changes as the product pipe progresses through varying borehole geometry and subsurface formations (Polak & Chu, 2005).

Drilling fluid behavior also plays a major role in HDD pullback performance because annular pressure distribution, lubrication conditions, and fluid rheology directly influence borehole friction and pullback force development. Baumert et al. (2005) reported that drilling fluid properties significantly affect pullback load conditions and operational stability during HDD installations. Similarly, Rostami et al. (2016) demonstrated that annular pressure variations in HDD systems substantially influence mechanical loading conditions and drilling performance.

Repeated exposure to dynamic loading conditions may also contribute to progressive fatigue accumulation within swivel shafts, threaded interfaces, towing heads, and bearing assemblies. Lu et al. (2005) identified fatigue-related degradation as a major contributor to drill pipe structural failure under cyclic loading environments, while Zamani et al. (2016) emphasized that mechanical fatigue and stress concentration remain dominant causes of failure in drilling-related systems.

Additional industrial challenges include:

- ❖ bearing degradation caused by high-pressure loading,
- ❖ corrosion-related component deterioration,
- ❖ threaded connection instability,
- ❖ excessive maintenance requirements,
- ❖ and operational downtime associated with pullback assembly failure.

In large-scale HDD projects, failure of a pullback swivel or towing head assembly may result in:

- ❖ project delays,
- ❖ product pipe damage,
- ❖ borehole collapse risks,
- ❖ expensive recovery operations,
- ❖ and significant infrastructure-related financial losses.

E. Research Problem

Despite the increasing industrial reliance on HDD pullback systems, limited engineering research has specifically examined the relationship between swivel load-rating optimization, towing head compatibility, and HDD operational reliability. Existing studies primarily focus on pullback force prediction, drilling fluid

mechanics, borehole interaction, or pipe stress analysis without integrating these factors into a unified swivel performance assessment framework.

Additionally, insufficient attention has been given to the influence of towing head compatibility on stress distribution, load alignment stability, and mechanical reliability within HDD pullback assemblies. Current industry practices frequently rely on generalized equipment selection methods rather than engineering-based compatibility evaluation and mechanical optimization frameworks.

There is therefore a significant need for an integrated engineering analysis capable of evaluating:

- ❖ proper swivel load-rating selection,
- ❖ towing head compatibility,
- ❖ stress distribution behavior,
- ❖ failure probability,
- ❖ and HDD operational safety performance.

F. Research Objectives

This study aims to:

- ❖ Evaluate the mechanical performance of Brewis' downhole pullback swivels under varying HDD operational conditions.
- ❖ Analyze the influence of swivel load-rating selection on pullback reliability and structural stability.
- ❖ Assess towing head compatibility effects on load transfer efficiency and stress concentration behavior.
- ❖ Investigate failure mechanisms associated with improper swivel and towing head configurations.
- ❖ Develop an engineering optimization framework for HDD pullback safety, reliability, and operational performance.

G. Research Contributions

This research contributes to HDD engineering literature by proposing an integrated swivel performance evaluation framework that combines:

- ❖ pullback load analysis,
- ❖ finite element stress evaluation,
- ❖ towing head compatibility assessment,
- ❖ and HDD mechanical reliability modeling.

The study further introduces:

- ❖ a comparative load-rating assessment model,
- ❖ an operational failure mitigation strategy,
- ❖ and engineering recommendations for safer HDD pullback system design and equipment selection.

The findings are expected to support HDD contractors, drilling engineers, pipeline operators, and infrastructure developers in improving HDD operational safety, reducing failure risks, and optimizing pullback system performance in complex trenchless installation projects.

Table 1. Industrial Applications and Mechanical Demands of HDD Pullback Swivels

Application Area	Operational Environment	Mechanical Demand	Safety Importance
Pipeline Installation	Long-distance underground pullback	High tensile stress	Critical
Telecommunications HDD	Narrow bore utility crossings	Moderate torque	High
Offshore Infrastructure	Corrosive marine conditions	Extreme dynamic loading	Critical
Water Distribution Systems	Urban trenchless installations	Variable pullback force	High

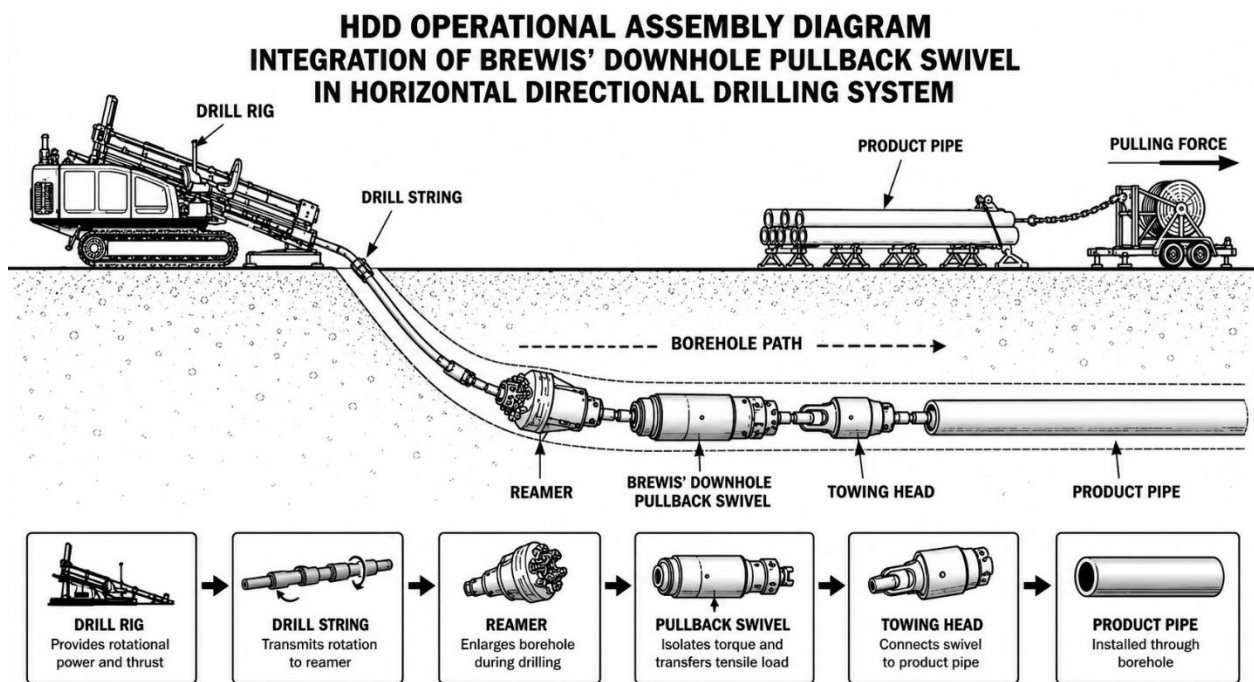


Figure 1. HDD Operational Assembly Incorporating Brewis' Downhole Pullback Swivel System

The figure illustrates the integration of Brewis' downhole pullback swivel within a horizontal directional drilling (HDD) pullback assembly, highlighting the interaction between the drill string, reamer, towing head, and product pipe during underground installation operations.

Notes

- ❖ The swivel isolates rotational movement between the drill string and the product pipe.
- ❖ Tensile load is transferred through the swivel to the towing head and product pipe.
- ❖ Proper load rating and towing head compatibility are essential for safe HDD pullback operations.

II. Literature Review

A. Evolution of HDD Mechanical Systems

Horizontal Directional Drilling (HDD) has evolved significantly over the last several decades from a relatively simple trenchless utility installation technique into a highly advanced engineering system capable of supporting complex underground infrastructure projects across energy, telecommunications, offshore, and municipal utility sectors. Early HDD systems were primarily limited to short-distance utility crossings with relatively small bore diameters and modest pullback requirements. However, the rapid expansion of pipeline infrastructure and underground utility networks has driven substantial improvements in HDD drilling technology, mechanical reliability, and load-handling capability (Baumert & Allouche, 2002).

The development of advanced HDD systems has largely been influenced by increasing demand for long-distance underground crossings beneath environmentally sensitive areas, rivers, highways, urban developments, and offshore infrastructure corridors. Polak and Lasheen (2001) reported that the growing complexity of HDD installations has introduced substantial mechanical challenges associated with borehole curvature, pipe deformation, tensile loading, and drillstring stability. As installation lengths and pipe diameters increased, traditional HDD equipment became insufficient for managing the elevated pullback loads generated during large-scale trenchless operations.

Reliability engineering has therefore become a major focus in modern HDD system development. Advances in drilling rig power, drilling fluid technology, borehole stabilization techniques, and pullback load prediction models have significantly improved HDD operational performance and installation safety (Yang et al., 2014). Modern HDD systems now incorporate advanced computational modeling approaches for predicting pullback forces, annular pressure behavior, pipe-borehole contact stress, and dynamic load distribution during installation operations (Rabiei et al., 2016).

The expansion of HDD into high-capacity industrial applications has also accelerated the development of stronger pullback systems capable of withstanding extreme tensile and torsional loading conditions. Guo and Liang (2018) demonstrated that pullback load conditions in modern HDD installations can vary substantially depending on geological conditions, drilling trajectory, pipe material, and borehole geometry. Consequently, HDD pullback assemblies have become increasingly dependent on mechanically optimized swivel systems, towing heads, and load-rated drilling components capable of maintaining operational stability under severe loading environments.

Recent studies further indicate that high-capacity HDD installations require integrated engineering approaches that combine load prediction, stress analysis, dynamic reliability evaluation, and mechanical compatibility assessment to ensure safe and efficient underground installation performance (Kong et al., 2022). The evolution of HDD systems has therefore transformed pullback assemblies from simple mechanical connectors into critical load-bearing engineering systems that directly influence project safety, structural integrity, and operational reliability.

B. Engineering Design of Pullback Swivels

Pullback swivels are among the most critical mechanical components in HDD pullback assemblies because they provide rotational isolation while simultaneously transferring tensile pulling forces between the drill string and product pipe. The engineering design of pullback swivels must therefore accommodate multiple operational requirements including high tensile capacity, rotational decoupling efficiency, dynamic loading resistance, and structural durability under harsh underground conditions.

The structural architecture of a typical HDD pullback swivel consists of a central tensile shaft, bearing assemblies, threaded or clevis connection interfaces, and sealing mechanisms designed to isolate rotational motion while maintaining stable axial load transfer. The swivel shaft functions as the primary tensile load-bearing element, while the bearing assembly permits rotational movement between connected components without transferring excessive torsional stress to the product pipe (Plastics Pipe Institute, 2008).

Rotational decoupling mechanisms are particularly important because HDD drill strings and reamers continuously rotate during pullback operations. Without effective swivel isolation, rotational torque may be transmitted directly into the product pipe, increasing the likelihood of pipe twisting, connection instability, stress accumulation, and structural damage. The Plastics Pipe Institute (2008) emphasized that properly functioning swivel systems reduce rotational stress transfer and improve pullback stability during HDD operations.

Modern pullback swivels also incorporate advanced bearing systems designed to withstand high dynamic loading conditions while minimizing frictional resistance during rotational movement. Bearing assemblies are subjected to simultaneous axial loading, cyclic stress fluctuations, vibration, and abrasive environmental conditions that may accelerate wear and fatigue degradation over time. Consequently, swivel bearing systems must be engineered using appropriate load-rating standards, lubrication systems, and material selection criteria to maintain long-term operational reliability.

Tensile load management represents another fundamental design consideration in HDD swivel engineering. Pullback swivels must maintain sufficient tensile capacity to withstand operational pullback forces without exceeding allowable stress thresholds. Wang and Hu (2024) demonstrated that pipe–borehole wall interaction significantly influences pullback resistance and tensile loading behavior during HDD installations, further emphasizing the importance of properly rated swivel systems in maintaining structural integrity under variable drilling conditions.

The engineering design of pullback swivels therefore requires careful integration of:

- ❖ tensile load capacity,
- ❖ rotational isolation efficiency,
- ❖ bearing reliability,
- ❖ threaded connection stability,
- ❖ and environmental durability.

C. Mechanical Load Rating Standards

Mechanical load-rating standards play a critical role in HDD pullback system engineering because they establish the allowable tensile capacity, operational safety limits, and structural reliability requirements for load-bearing components used in drilling and pullback operations. Proper load-rating selection is essential for ensuring that swivel systems, towing heads, drill strings, and associated pullback equipment can safely withstand operational forces encountered during HDD installations.

One of the most widely used engineering principles in load-rated equipment design is the Working Load Limit (WLL), which defines the maximum allowable operational load that a component may safely withstand under specified operating conditions. According to ASME B30.20 (American Society of Mechanical Engineers, 2025), below-the-hook lifting and pulling devices must be designed using appropriate WLL calculations, structural integrity verification procedures, and inspection protocols to minimize operational failure risks.

Safety factor engineering is another important component of mechanical load-rating standards. ASME BTH-1 (American Society of Mechanical Engineers, 2023) specifies that load-bearing mechanical devices must

incorporate adequate design safety factors to account for dynamic loading conditions, stress fluctuations, fatigue accumulation, and material variability. In HDD pullback operations, safety factors are particularly important because actual operational loads may vary substantially due to borehole friction, drilling fluid interaction, geological instability, and dynamic pullback conditions.

API Spec 8C (American Petroleum Institute, 2012) further establishes engineering requirements for drilling and hoisting equipment subjected to high-load operational environments. The specification emphasizes:

- ❖ structural integrity verification,
- ❖ tensile load certification,
- ❖ fatigue resistance evaluation,
- ❖ and periodic inspection procedures for mechanically loaded drilling systems.

Similarly, API RP 8B (American Petroleum Institute, 2014) provides recommended practices for inspection, maintenance, repair, and remanufacture of hoisting equipment to ensure continued operational safety and mechanical reliability.

ASTM standards also contribute significantly to HDD pullback engineering practices. ASTM F1804-24 (ASTM International, 2024) establishes procedures for determining allowable tensile loads for polyethylene pipe during pull-in installation operations, while ASTM F1962-22 (ASTM International, 2022) provides guidance for maxi-HDD installations involving large-diameter pipe systems and long-distance underground crossings.

The Plastics Pipe Institute Municipal Advisory Board (2024) emphasized that pullback swivel capacity should be selected in alignment with allowable pipe pull strength and drilling rig capability to prevent excessive loading conditions that may compromise pipe integrity or mechanical stability. These standards collectively demonstrate that load-rating optimization is a fundamental engineering requirement in HDD pullback system design and operational safety management.

D. Towing Head Compatibility Engineering

Towing heads function as the primary mechanical interface between the pullback swivel and the product pipe during HDD operations. Their engineering compatibility with the swivel assembly directly influences load transfer stability, connection integrity, stress distribution behavior, and overall pullback system reliability.

Connection geometry alignment is one of the most important factors affecting towing head performance. Improper alignment between the swivel and towing head may introduce eccentric loading conditions that generate uneven stress distribution, localized bending moments, and excessive mechanical strain within threaded or welded connection interfaces. Such conditions may substantially increase the probability of fatigue crack initiation and structural failure during high-load pullback operations.

Threaded coupling stability also represents a critical engineering concern because HDD pullback assemblies are subjected to repeated cyclic loading, dynamic stress fluctuations, vibration, and rotational movement. Tafreshi and Dover (1993) demonstrated that threaded connection geometry strongly influences local stress concentration behavior under cyclic loading conditions. Similarly, Macdonald and Deans (1995) reported that localized stress peaks in threaded mechanical systems frequently serve as initiation points for fatigue-related structural failure.

Efficient load transition between the swivel, towing head, and product pipe is necessary to maintain pullback stability and minimize operational stress accumulation. Improper towing head selection may reduce load transfer efficiency and increase:

- ❖ axial stress concentration,

- ❖ bending stress development,
- ❖ connection instability,
- ❖ and fatigue accumulation.

Mechanical mismatch between towing heads and pullback swivels may also compromise bearing performance and seal integrity within the swivel assembly itself. In high-load HDD installations, incompatible towing head geometry may amplify dynamic stress conditions and accelerate wear-related degradation within the pullback system.

The engineering compatibility between swivels and towing heads therefore requires careful evaluation of:

- ❖ connection geometry,
- ❖ load capacity,
- ❖ material strength,
- ❖ threaded interface stability,
- ❖ and operational loading conditions.

E. Failure Mechanisms in HDD Pullback Systems

Failure mechanisms in HDD pullback systems are typically associated with excessive tensile loading, cyclic fatigue accumulation, torsional stress development, bearing degradation, and connection instability under dynamic operational conditions. Because pullback assemblies operate under severe mechanical loading environments, even minor structural defects or compatibility problems may eventually evolve into catastrophic operational failures.

Tensile overload failure remains one of the most common causes of HDD pullback system damage. Excessive pullback loads generated by borehole friction, geological resistance, or improper drilling fluid conditions may exceed the allowable tensile capacity of the swivel shaft, towing head, or threaded connection system. Polak and Chu (2005) demonstrated that pullback force development is highly sensitive to borehole geometry and pipe–soil interaction conditions, increasing the likelihood of overload events during complex HDD installations.

Fatigue crack propagation is another major failure mechanism in HDD pullback systems. Repeated cyclic loading generated during pullback operations may progressively weaken mechanical components through crack initiation and stress accumulation. Lu et al. (2005) identified fatigue-related degradation as a major contributor to drill pipe failure under cyclic operational loading conditions. Similarly, Albdiry and Almensory (2016) emphasized that fatigue accumulation and stress concentration remain dominant causes of structural failure in drilling systems.

Torsional stress accumulation may also contribute to swivel and towing head damage when rotational torque is improperly transferred into the product pipe or connection assemblies. Improper rotational isolation may generate excessive torsional loading conditions that accelerate mechanical degradation and reduce operational stability.

Bearing collapse and seal degradation represent additional operational risks because swivel bearings operate under combined axial loading, rotational movement, and abrasive environmental conditions. Excessive loading or improper lubrication may result in bearing overheating, surface wear, seal failure, and rotational instability within the swivel assembly.

Misalignment-induced stress concentration further increases failure probability by generating localized stress amplification within threaded interfaces and towing head connections. Zamani et al. (2016) emphasized that

localized stress concentration significantly accelerates fatigue crack development and structural deterioration in drilling-related systems.

F. Finite Element and Computational Analysis in HDD Engineering

Finite Element Analysis (FEA) and computational engineering methods have become increasingly important in HDD engineering because they enable detailed simulation of stress distribution, load transfer behavior, fatigue accumulation, and mechanical reliability under complex operational conditions.

Stress-distribution simulation methods allow engineers to identify localized stress concentration regions within pullback swivels, towing heads, threaded connections, and bearing assemblies. Tang et al. (2023) used finite element analysis to evaluate stress distribution behavior in drill pipe systems subjected to dynamic operational loading, demonstrating the effectiveness of computational modeling for predicting mechanical failure behavior.

Dynamic loading analysis further enables engineers to evaluate the influence of variable operational conditions on HDD pullback system performance. Yang et al. (2014) developed advanced computational dynamic models for predicting pullback loads during HDD operations, while Rabiei et al. (2016) proposed generalized methods for pullback force estimation in polyethylene pipe installations.

Mechanical reliability prediction approaches increasingly combine finite element stress analysis with fatigue modeling and operational load simulation to estimate component lifespan and failure probability under realistic drilling conditions. These methods are particularly valuable in HDD engineering because pullback systems frequently experience highly variable loading conditions that are difficult to evaluate using traditional static analysis techniques.

The integration of finite element simulation with HDD load prediction models therefore provides a powerful engineering framework for:

- ❖ evaluating stress concentration behavior,
- ❖ optimizing swivel design,
- ❖ predicting fatigue failure,
- ❖ and improving operational safety.

G. Research Gaps

Despite substantial advances in HDD pullback load modeling and drilling system reliability engineering, several important research gaps remain unresolved. Existing studies primarily focus on pullback force estimation, borehole mechanics, drilling fluid behavior, and pipe stress analysis without integrating these factors into a unified HDD swivel performance evaluation framework.

Limited research has specifically examined the engineering relationship between swivel load-rating optimization and towing head compatibility under varying HDD operational conditions. Current industry practices frequently emphasize general load-capacity selection without fully evaluating:

- ❖ stress concentration behavior,
- ❖ compatibility-induced loading instability,
- ❖ fatigue propagation risks,
- ❖ or dynamic mechanical reliability.

Additionally, predictive failure modeling for HDD swivel systems remains insufficiently developed. Although finite element and fatigue analysis methods have been widely applied in drillstring engineering, limited studies have integrated these approaches into HDD swivel reliability evaluation and towing head compatibility assessment.

Operational safety optimization frameworks for HDD pullback systems also remain underdeveloped despite increasing mechanical complexity in modern trenchless infrastructure projects. Consequently, there is a significant need for integrated engineering models capable of combining:

- ❖ pullback load analysis,
- ❖ swivel load-rating optimization,
- ❖ towing head compatibility evaluation,
- ❖ finite element stress modeling,
- ❖ and HDD operational safety assessment.

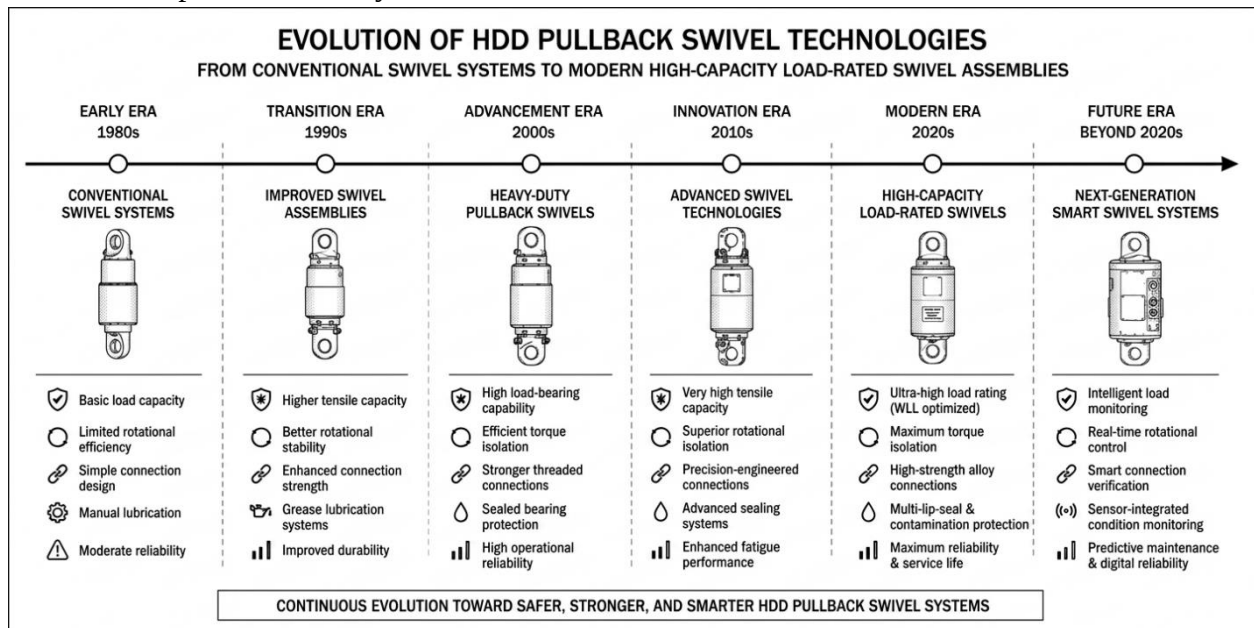


Figure 2. Evolution of HDD Pullback Swivel Technologies

The figure illustrates the technological evolution of HDD pullback swivel systems from conventional low-capacity assemblies to modern high-capacity load-rated and smart swivel technologies designed to improve tensile reliability, torque isolation, operational safety, and mechanical performance in HDD operations.

III. Engineering Design and Optimization Framework for Brewis' Downhole Pullback Swivels

A. Structural Architecture of Brewis' Swivel Systems

The structural architecture of HDD pullback swivels plays a critical role in maintaining mechanical stability, tensile reliability, and operational safety during trenchless installation operations. Modern pullback swivel systems are designed to function as high-capacity mechanical connectors capable of transferring substantial tensile loads while simultaneously isolating rotational movement generated by the drill string and reaming assemblies. In HDD operations, the swivel assembly serves as the primary mechanical interface between the rotating drilling system and the stationary product pipe, making its structural reliability essential for maintaining pullback stability and preventing operational failure (Plastics Pipe Institute, 2008).

Brewis' downhole pullback swivel systems are generally engineered using integrated bearing assemblies, high-strength tensile shafts, threaded or clevis connection interfaces, and sealed housing systems capable of operating under severe underground drilling conditions. The bearing assembly configuration represents one of the most important structural elements because the bearing system permits rotational decoupling while

simultaneously maintaining axial load transfer through the swivel body. The rotational isolation mechanism minimizes the transfer of torsional stress from the drill string into the product pipe, thereby reducing the risk of pipe twisting, stress accumulation, and threaded connection instability during pullback operations.

The tensile load transfer path within the swivel assembly is designed to ensure efficient transmission of pulling forces from the drilling rig to the towing head and product pipe. Tensile loads generated during HDD operations pass through the swivel shaft, bearing assembly, and connection interfaces before reaching the towing head assembly. Under high-load drilling conditions, the tensile load path must remain mechanically stable to prevent localized stress concentration, excessive deformation, or structural overload (Wang & Hu, 2024).

Seal protection systems and corrosion-resistant structural materials are also important components of HDD swivel architecture because pullback assemblies frequently operate in abrasive underground environments exposed to drilling fluids, moisture, soil particles, and corrosive contaminants. Advanced sealing systems help prevent contamination of the internal bearing assembly while minimizing lubrication loss and wear-related degradation. Corrosion-resistant alloy materials further improve long-term durability and operational reliability under variable geological and environmental conditions.

The structural design of Brewis' swivel systems therefore integrates:

- ❖ tensile load-bearing capability,
- ❖ rotational isolation efficiency,
- ❖ bearing reliability,
- ❖ environmental protection,
- ❖ and connection stability.

These design characteristics collectively contribute to improved HDD operational safety and pullback system performance in high-capacity trenchless installation projects.

B. Mechanical Load Distribution Framework

Mechanical load distribution within HDD pullback systems is highly complex because pullback assemblies are exposed to continuously changing tensile forces, dynamic loading conditions, torsional stress, and borehole interaction effects during installation operations. The ability of a swivel system to efficiently distribute operational loads directly influences mechanical reliability, structural integrity, and failure resistance under HDD operating conditions.

Tensile stress distribution behavior within pullback swivels is influenced by several operational variables including:

- ❖ pullback force magnitude,
- ❖ borehole curvature,
- ❖ drilling fluid pressure,
- ❖ pipe-borehole friction,
- ❖ and towing head alignment conditions.

Yang et al. (2014) demonstrated that HDD pullback loads fluctuate dynamically throughout installation operations due to variations in borehole geometry and drilling resistance. As tensile loading increases, stress concentrations may develop within the swivel shaft, threaded interfaces, and bearing assembly if the load distribution system is improperly balanced.

Torque transfer isolation represents another major engineering consideration in HDD pullback systems. Because the drill string continuously rotates during reaming and pullback operations, the swivel assembly

must isolate rotational movement while maintaining stable axial load transfer. Excessive torque transfer into the product pipe may generate torsional deformation, stress accumulation, and connection instability. Proper rotational decoupling therefore minimizes pipe rotational stress while improving overall pullback stability. Dynamic pullback loading conditions further complicate HDD mechanical behavior because operational loads are rarely static. During pullback operations, changes in drilling fluid lubrication, borehole contact pressure, geological resistance, and installation speed may cause continuous fluctuations in tensile loading and stress distribution. Rabiei et al. (2016) emphasized that dynamic pullback force estimation is essential for predicting HDD operational performance and preventing structural overload conditions.

Axial and radial stress interaction within swivel assemblies also influences mechanical stability under high-load conditions. Axial tensile loads generated during pullback operations may combine with radial stress generated by rotational motion, bending forces, and connection misalignment. This combined stress environment may significantly accelerate fatigue accumulation and reduce bearing lifespan if operational loads exceed allowable design thresholds.

An effective mechanical load distribution framework therefore requires:

- ❖ balanced tensile load transfer,
- ❖ efficient torque isolation,
- ❖ stable dynamic loading response,
- ❖ and controlled stress distribution throughout the pullback assembly.

C. Swivel Load Rating Optimization Model

Swivel load-rating optimization is essential for ensuring that HDD pullback systems operate safely within allowable mechanical limits while maintaining adequate structural reliability under dynamic operational conditions. The selection of an appropriately rated swivel directly influences pullback efficiency, failure resistance, operational safety, and long-term equipment durability.

One of the primary engineering principles used in swivel load optimization is the Working Load Limit (WLL), which defines the maximum allowable operational load a swivel may safely withstand under specified operating conditions. According to ASME B30.20 (American Society of Mechanical Engineers, 2025), load-bearing mechanical systems must be designed and operated within approved WLL ranges to minimize overload-related structural failure risks.

Maximum tensile capacity evaluation is another critical component of load-rating optimization because HDD pullback forces may vary substantially depending on borehole geometry, installation length, drilling fluid conditions, and geological resistance. Baumert and Allouche (2002) demonstrated that pullback loads in HDD systems may increase significantly in curved borehole sections and long-distance installations, requiring careful evaluation of swivel load capacity during equipment selection.

Safety factor optimization further improves operational reliability by incorporating additional structural capacity above expected operational loads. ASME BTH-1 (American Society of Mechanical Engineers, 2023) recommends the use of appropriate safety factors for mechanically loaded equipment subjected to dynamic operational conditions. In HDD pullback systems, safety factors help compensate for:

- ❖ dynamic loading fluctuations,
- ❖ fatigue accumulation,
- ❖ stress concentration effects,
- ❖ and unpredictable geological resistance conditions.

The Plastics Pipe Institute Municipal Advisory Board (2024) emphasized that pullback swivel capacity should be selected in close alignment with allowable pipe pull strength and drilling rig capability to avoid unsafe overload conditions. Excessively oversized swivel systems may permit the application of loads exceeding safe pipe stress limits, while underrated swivel systems may experience premature structural failure under high pullback loads.

Overload threshold prediction therefore becomes an important component of load-rating optimization because it enables engineers to identify critical operational limits before structural failure occurs. Predictive evaluation of overload thresholds may reduce failure probability while improving HDD operational safety and reliability. The swivel load optimization framework proposed in this study integrates:

- ❖ WLL analysis,
- ❖ tensile capacity evaluation,
- ❖ safety factor engineering,
- ❖ and overload prediction methods

to improve HDD pullback system stability and operational protection.

D. Towing Head Compatibility Engineering

Towing head compatibility engineering is a major determinant of HDD pullback system performance because towing heads function as the primary connection interface between the swivel assembly and the product pipe. Proper towing head compatibility is necessary to ensure efficient load transfer, alignment stability, stress control, and mechanical reliability during pullback operations.

Connection geometry assessment is one of the most important aspects of towing head compatibility because geometric mismatch between the swivel and towing head may generate eccentric loading conditions and localized stress concentration within threaded or welded connection interfaces. Improper alignment may increase bending moments, axial stress accumulation, and fatigue susceptibility under high pullback loads.

Alignment stability analysis further influences operational reliability because unstable towing head alignment may compromise the load transfer path between the swivel and product pipe. In HDD systems subjected to dynamic loading conditions, even minor connection misalignment may amplify operational stress and reduce mechanical stability. Tafreshi and Dover (1993) demonstrated that local stress concentration in threaded connections significantly influences fatigue crack initiation under cyclic loading environments.

Load transition efficiency represents another critical factor in towing head engineering because pullback forces must be transferred smoothly through the swivel system without generating excessive localized loading or abrupt stress transitions. Efficient load transfer improves operational stability while reducing the probability of fatigue-related structural failure.

Mechanical incompatibility between the swivel and towing head may also cause stress amplification within the pullback assembly. Macdonald and Deans (1995) reported that threaded mechanical systems subjected to incompatible loading conditions frequently develop localized stress peaks that accelerate fatigue propagation and structural degradation. In HDD pullback operations, incompatibility-induced stress amplification may contribute to:

- ❖ threaded connection failure,
- ❖ bearing overload,
- ❖ seal degradation,
- ❖ and towing head instability.

The towing head compatibility engineering framework proposed in this study therefore incorporates:

- ❖ geometric compatibility assessment,
- ❖ connection stability analysis,
- ❖ stress-distribution evaluation,
- ❖ and load transfer optimization

to improve HDD pullback system reliability and operational safety.

E. Finite Element Stress Modeling Framework

Finite Element Analysis (FEA) has become one of the most effective engineering tools for evaluating stress distribution, fatigue accumulation, and structural reliability in HDD pullback systems. Because HDD swivel assemblies operate under highly dynamic loading environments, traditional analytical approaches may be insufficient for accurately predicting localized stress behavior and failure progression under operational conditions.

Stress concentration mapping enables engineers to identify high-risk regions within swivel shafts, threaded interfaces, towing heads, and bearing assemblies where localized stress accumulation may initiate fatigue-related structural failure. Tang et al. (2023) demonstrated that finite element stress modeling provides highly effective visualization of stress concentration behavior within mechanically loaded drilling systems.

Threaded connection stress analysis is particularly important in HDD swivel engineering because threaded interfaces frequently represent the weakest structural regions within pullback assemblies. Under cyclic loading conditions, localized stress amplification may develop near thread roots, connection shoulders, or contact surfaces, accelerating crack initiation and fatigue propagation. Tafreshi and Dover (1993) showed that threaded connection geometry significantly influences peak stress development under dynamic loading conditions.

Dynamic fatigue simulation further improves engineering reliability analysis by evaluating the cumulative effects of cyclic loading on swivel components over extended operational periods. HDD pullback systems are repeatedly exposed to fluctuating tensile forces, vibration, rotational loading, and environmental stressors that may progressively weaken structural integrity over time. Fatigue simulation models therefore help predict:

- ❖ component lifespan,
- ❖ crack propagation behavior,
- ❖ and operational failure probability.

Bearing pressure distribution analysis also plays a critical role in swivel reliability engineering because bearing systems are continuously exposed to axial loading, rotational movement, and dynamic stress fluctuations during HDD operations. Excessive bearing pressure may lead to lubrication failure, overheating, wear-related degradation, and rotational instability within the swivel assembly.

The finite element modeling framework proposed in this study integrates:

- ❖ stress concentration analysis,
- ❖ threaded connection evaluation,
- ❖ dynamic fatigue simulation,
- ❖ and bearing pressure analysis

to improve prediction of HDD swivel reliability and operational safety performance.

F. Proposed HDD Mechanical Reliability Framework

The proposed HDD mechanical reliability framework developed in this study integrates load-rating optimization, towing head compatibility engineering, finite element stress analysis, and operational safety evaluation into a unified engineering model for HDD pullback systems.

The first stage of the framework involves proper swivel rating selection methodology based on:

- ❖ expected pullback loads,
- ❖ borehole geometry,
- ❖ product pipe allowable tensile capacity,
- ❖ and drilling rig operational capability.

The framework incorporates Working Load Limit evaluation and safety factor engineering to ensure that selected swivel systems maintain sufficient structural reliability under dynamic HDD conditions.

The second stage involves compatibility verification between the swivel assembly, towing head, threaded connections, and product pipe interface. Compatibility evaluation includes:

- ❖ geometric alignment analysis,
- ❖ connection stability assessment,
- ❖ stress-distribution verification,
- ❖ and load transition efficiency analysis.

The third stage involves operational risk mitigation through finite element stress modeling and fatigue reliability prediction. Stress concentration mapping, overload threshold prediction, and bearing pressure evaluation are used to identify potential failure-prone regions within the pullback assembly before operational deployment.

The final stage of the framework integrates HDD safety optimization through:

- ❖ preventive maintenance planning,
- ❖ inspection scheduling,
- ❖ operational load monitoring,
- ❖ and dynamic reliability assessment.

The proposed framework therefore provides a comprehensive engineering strategy for improving:

- ❖ HDD pullback reliability,
- ❖ structural safety,
- ❖ equipment lifespan,
- ❖ and operational performance

in high-capacity trenchless infrastructure projects.

Equation Set

Tensile Stress Equation

$$\sigma = \frac{F}{A}$$

Safety Factor Equation

$$SF = \frac{\sigma_y}{\sigma_w}$$

Torque Transfer Equation

$$T = F \times r$$

Load Distribution Equation

$$P = \frac{F}{A_c}$$

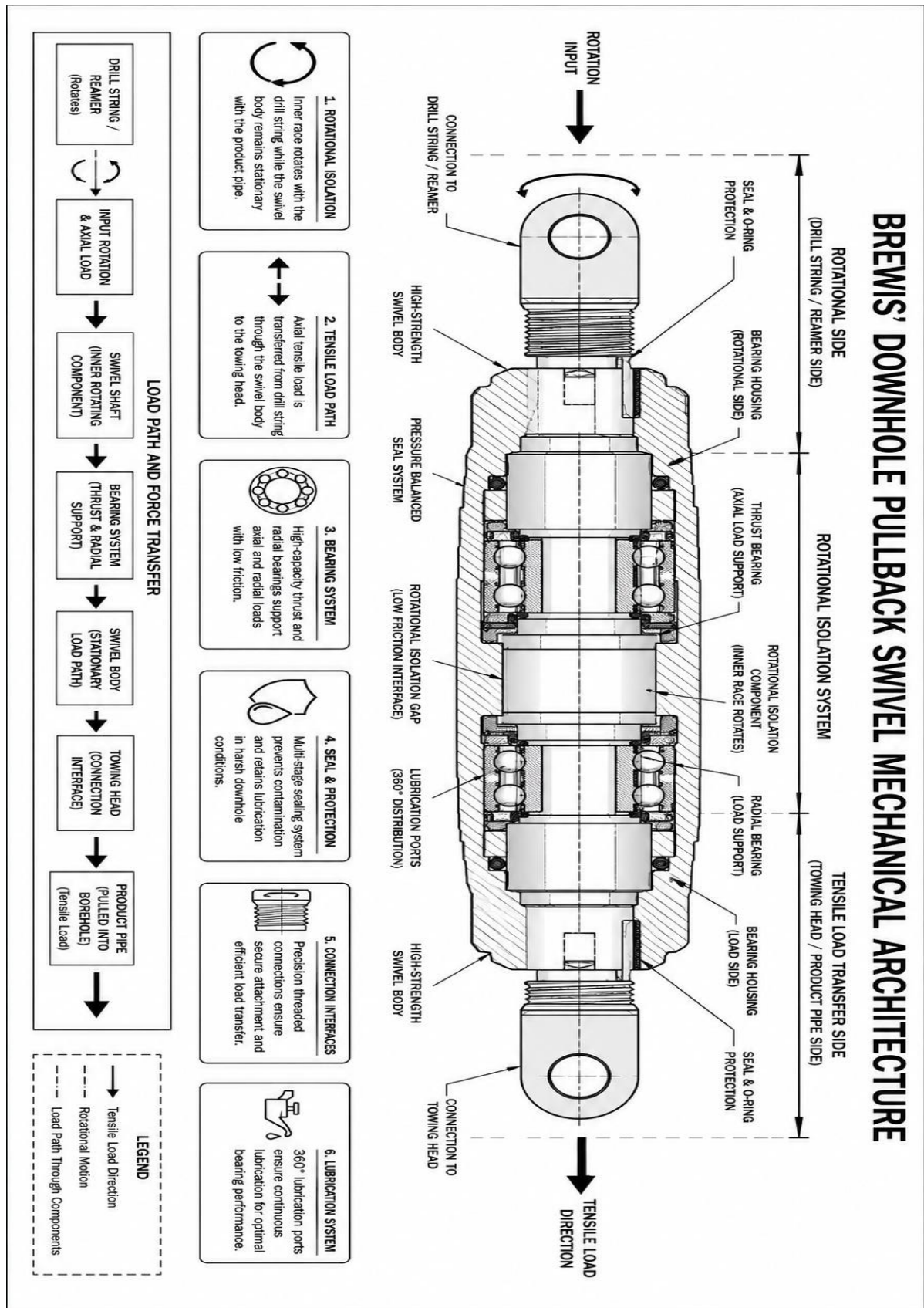


Figure 3. Mechanical Architecture and Load Transfer Framework of Brewis' Downhole Pullback Swivel System

The figure illustrates the internal mechanical architecture of Brewis' downhole pullback swivel system, highlighting the bearing assemblies, rotational isolation mechanism, tensile load transfer path, seal protection components, and towing head connection interfaces used to improve load stability, torque isolation, and operational reliability during HDD pullback operations.

IV. Research Methodology

A. Research Design

This study adopted an engineering performance evaluation methodology designed to investigate the mechanical reliability, load-bearing performance, and operational safety characteristics of Brewis' downhole pullback swivel systems under varying Horizontal Directional Drilling (HDD) operating conditions. The methodology integrates comparative mechanical analysis, finite element stress simulation, operational load modeling, and reliability-centered engineering assessment to evaluate the influence of swivel load rating and towing head compatibility on HDD pullback system performance.

The research design was developed to address the complex mechanical interactions that occur within HDD pullback assemblies during trenchless installation operations. Because HDD systems operate under continuously changing tensile loads, torsional forces, dynamic stress conditions, and pipe–borehole interaction effects, a multidisciplinary engineering approach was necessary to accurately evaluate structural performance and operational stability. Yang et al. (2014) emphasized that advanced computational and mechanical modeling approaches are required for reliable prediction of HDD pullback behavior under dynamic drilling conditions.

The engineering performance evaluation framework used in this study combines:

- ❖ HDD pullback load prediction,
- ❖ stress-distribution analysis,
- ❖ swivel load-rating optimization,
- ❖ towing head compatibility evaluation,
- ❖ and failure risk assessment.

The comparative mechanical analysis framework was specifically designed to evaluate the operational differences between:

- ❖ properly rated and underrated swivel systems,
- ❖ compatible and incompatible towing head configurations,
- ❖ and high-load versus moderate-load HDD operating environments.

This comparative structure enabled the identification of critical operational variables influencing tensile reliability, torque isolation performance, stress concentration behavior, and failure susceptibility.

A reliability-centered HDD assessment approach was further incorporated into the methodology to evaluate the long-term operational stability of swivel systems subjected to cyclic loading, dynamic stress fluctuations, and abrasive underground conditions. Albdiry and Almensorry (2016) reported that reliability-centered engineering approaches are essential for identifying fatigue-related degradation mechanisms and improving operational safety within mechanically loaded drilling systems.

The research design therefore provides a systematic engineering framework for evaluating the structural reliability and operational performance of Brewis' downhole pullback swivel systems under realistic HDD operational conditions.

B. Data Collection

The data collection process involved the integration of HDD operational datasets, mechanical specification records, swivel load-rating information, and failure-related engineering documentation obtained from published engineering literature, HDD design standards, drilling equipment specifications, and reliability analysis studies.

HDD operational datasets used in this study included:

- ❖ pullback force prediction data,
- ❖ pipe–borehole interaction parameters,
- ❖ drilling fluid behavior characteristics,
- ❖ dynamic load fluctuation information,
- ❖ and borehole geometry conditions.

These datasets were obtained from prior HDD engineering studies including Baumert and Allouche (2002), Polak and Chu (2005), Rabiei et al. (2016), Guo and Liang (2018), and Wang and Hu (2024). These studies provided validated operational parameters for evaluating pullback force behavior, tensile loading conditions, and mechanical interaction effects during HDD installations.

Mechanical specification records were collected from engineering standards and technical design references including:

- ❖ API Spec 8C,
- ❖ API RP 8B,
- ❖ ASTM F1804,
- ❖ ASTM F1962,
- ❖ ASME B30.20,
- ❖ and ASME BTH-1.

These specifications provided engineering guidance regarding:

- ❖ allowable tensile loads,
- ❖ Working Load Limits (WLL),
- ❖ safety factor requirements,
- ❖ inspection procedures,
- ❖ and load-bearing equipment design practices.

Swivel load-rating data and towing head compatibility parameters were compiled from HDD equipment engineering requirements, operational pullback recommendations, and mechanical load-rating principles discussed within HDD engineering standards and the Plastics Pipe Institute (2008) HDD handbook.

Failure incident reports and maintenance records referenced in published failure-analysis literature were also incorporated into the study to identify:

- ❖ common failure mechanisms,
- ❖ fatigue-related degradation trends,
- ❖ threaded connection instability,
- ❖ bearing collapse behavior,
- ❖ and stress concentration effects.

Lu et al. (2005), Zamani et al. (2016), and Tang et al. (2023) provided critical engineering information related to drillstring fatigue behavior, stress accumulation mechanisms, and finite element failure prediction methods applicable to HDD pullback systems.

The collected data were organized into engineering evaluation categories corresponding to:

- ❖ tensile loading,
- ❖ rotational stress,
- ❖ structural integrity,
- ❖ fatigue susceptibility,
- ❖ and operational reliability.

C. Mechanical Performance Evaluation

The mechanical performance evaluation process focused on analyzing the tensile reliability, torque isolation capability, dynamic stress response, and bearing stability of Brewis' downhole pullback swivel systems under varying HDD operating conditions.

Tensile load testing procedures were designed to evaluate the ability of the swivel assembly to withstand operational pullback forces without exceeding allowable structural stress thresholds. Pullback load conditions were estimated using HDD pullback force prediction principles established by Baumert and Allouche (2002), Yang et al. (2014), and Rabiei et al. (2016). Tensile loading scenarios incorporated:

- ❖ moderate-load HDD installations,
- ❖ high-capacity pullback operations,
- ❖ curved borehole conditions,
- ❖ and varying frictional resistance environments.

Torque resistance evaluation was conducted to assess the rotational isolation efficiency of the swivel assembly during HDD pullback operations. Because rotational torque generated by the drill string may induce torsional stress within the product pipe and towing head assembly, the ability of the swivel system to minimize torque transfer was evaluated as a critical operational performance parameter.

Dynamic stress analysis was performed to examine stress fluctuations occurring during variable pullback loading conditions. Dynamic loading effects included:

- ❖ changes in borehole friction,
- ❖ drilling fluid pressure variation,
- ❖ operational vibration,
- ❖ and cyclic tensile stress accumulation.

Yang et al. (2014) demonstrated that HDD pullback systems experience continuously changing load distributions during underground installations, making dynamic stress analysis essential for accurate reliability evaluation.

Bearing integrity assessment focused on evaluating the structural stability of the swivel bearing assembly under combined axial loading and rotational movement. Bearing systems were assessed for:

- ❖ pressure distribution behavior,
- ❖ rotational stability,
- ❖ lubrication effectiveness,
- ❖ and fatigue-related degradation susceptibility.

The overall mechanical performance evaluation framework therefore integrated:

- ❖ tensile reliability assessment,
- ❖ rotational isolation analysis,
- ❖ dynamic stress evaluation,
- ❖ and bearing stability investigation

to determine the operational suitability of Brewis' pullback swivel systems for HDD installations.

D. Comparative Engineering Analysis

The comparative engineering analysis framework was developed to evaluate the operational performance differences between alternative HDD swivel configurations under varying mechanical and environmental conditions.

The first comparative category evaluated properly rated versus underrated swivel systems. Properly rated swivel systems were defined as assemblies whose Working Load Limit (WLL) and tensile capacity exceeded expected operational pullback forces while maintaining acceptable engineering safety factors. Underrated swivel systems represented assemblies operating near or beyond allowable tensile thresholds under high-load HDD conditions.

Comparative analysis between these configurations focused on:

- ❖ tensile stability,
- ❖ overload resistance,
- ❖ fatigue accumulation behavior,
- ❖ and operational failure probability.

The second comparative category evaluated compatible versus incompatible towing head systems. Compatible towing heads were defined as geometrically aligned and mechanically matched interfaces capable of transferring tensile loads efficiently without generating excessive stress concentration or bending moments. Incompatible towing head systems were characterized by:

- ❖ misaligned connection geometry,
- ❖ improper threaded coupling compatibility,
- ❖ uneven load transfer behavior,
- ❖ and amplified stress concentration conditions.

The influence of towing head compatibility on:

- ❖ load transition efficiency,
- ❖ threaded connection stability,
- ❖ bearing pressure behavior,
- ❖ and stress distribution

was evaluated through mechanical performance comparison and finite element stress analysis.

The final comparative category examined HDD operational conditions involving:

- ❖ high-load pullback environments,
- ❖ moderate-load installations,
- ❖ variable borehole curvature,
- ❖ and differing pullback force conditions.

Kong et al. (2022) demonstrated that HDD pullback loads may vary substantially depending on geological instability and operational conditions, making comparative operational analysis essential for evaluating swivel reliability under realistic drilling environments.

The comparative engineering framework therefore enabled identification of the most mechanically stable and operationally reliable swivel configurations for HDD pullback operations.

E. Failure Mode and Risk Assessment

Failure mode and risk assessment procedures were implemented to identify structural vulnerabilities, fatigue-related degradation mechanisms, and operational conditions most likely to contribute to HDD pullback system failure.

Stress concentration analysis was performed to identify localized high-stress regions within:

- ❖ swivel shafts,
- ❖ threaded interfaces,
- ❖ towing head connections,
- ❖ and bearing assemblies.

Stress concentration evaluation focused particularly on connection transition zones where abrupt geometric changes may amplify local stress accumulation under cyclic loading conditions. Tafreshi and Dover (1993) demonstrated that threaded mechanical systems frequently develop peak stress regions near thread roots and interface transitions.

Fatigue life estimation procedures were used to evaluate the cumulative effects of repeated cyclic loading on HDD pullback components. Fatigue assessment incorporated:

- ❖ cyclic tensile loading behavior,
- ❖ rotational stress interaction,
- ❖ vibration-induced loading,
- ❖ and dynamic operational fluctuations.

Zamani et al. (2016) emphasized that fatigue accumulation remains one of the dominant causes of structural degradation in mechanically loaded drilling systems.

Structural integrity evaluation was conducted to determine the ability of the swivel assembly to maintain operational stability under varying load conditions without experiencing:

- ❖ excessive deformation,
- ❖ crack initiation,
- ❖ bearing collapse,
- ❖ or threaded connection failure.

Failure probability modeling was then applied to estimate the likelihood of operational failure under different HDD operating scenarios. Failure probability assessment considered:

- ❖ load-rating adequacy,
- ❖ towing head compatibility,
- ❖ stress concentration severity,
- ❖ fatigue accumulation rate,
- ❖ and dynamic operational loading conditions.

The failure mode and risk assessment framework therefore provided an integrated engineering approach for identifying high-risk operational conditions and improving HDD pullback system reliability.

F. Simulation and Analytical Techniques

Several advanced simulation and analytical techniques were incorporated into the methodology to improve the accuracy of mechanical reliability prediction and operational performance evaluation.

Finite Element Analysis (FEA) served as the primary simulation technique used to evaluate:

- ❖ stress distribution behavior,
- ❖ localized stress concentration,

- ❖ threaded connection loading,
- ❖ and bearing pressure distribution.

Tang et al. (2023) demonstrated that finite element stress simulation is highly effective for evaluating dynamic stress behavior in drilling-related mechanical systems operating under cyclic loading conditions.

Mechanical stress modeling procedures were used to estimate:

- ❖ tensile stress development,
- ❖ torque transfer behavior,
- ❖ axial loading interaction,
- ❖ and combined stress conditions

within HDD pullback assemblies.

Statistical reliability analysis techniques were also incorporated to evaluate:

- ❖ operational failure trends,
- ❖ fatigue probability,
- ❖ and reliability variation between swivel configurations.

These analyses enabled quantitative comparison between:

- ❖ properly rated and underrated systems,
- ❖ compatible and incompatible towing heads,
- ❖ and moderate-load versus high-load operational conditions.

Dynamic loading simulation further enhanced the engineering assessment by modeling fluctuating pullback forces and variable operational stress conditions occurring during HDD installations. Dynamic simulation incorporated:

- ❖ variable pullback force behavior,
- ❖ drilling fluid interaction effects,
- ❖ borehole curvature influence,
- ❖ and cyclic stress fluctuations.

The combined use of:

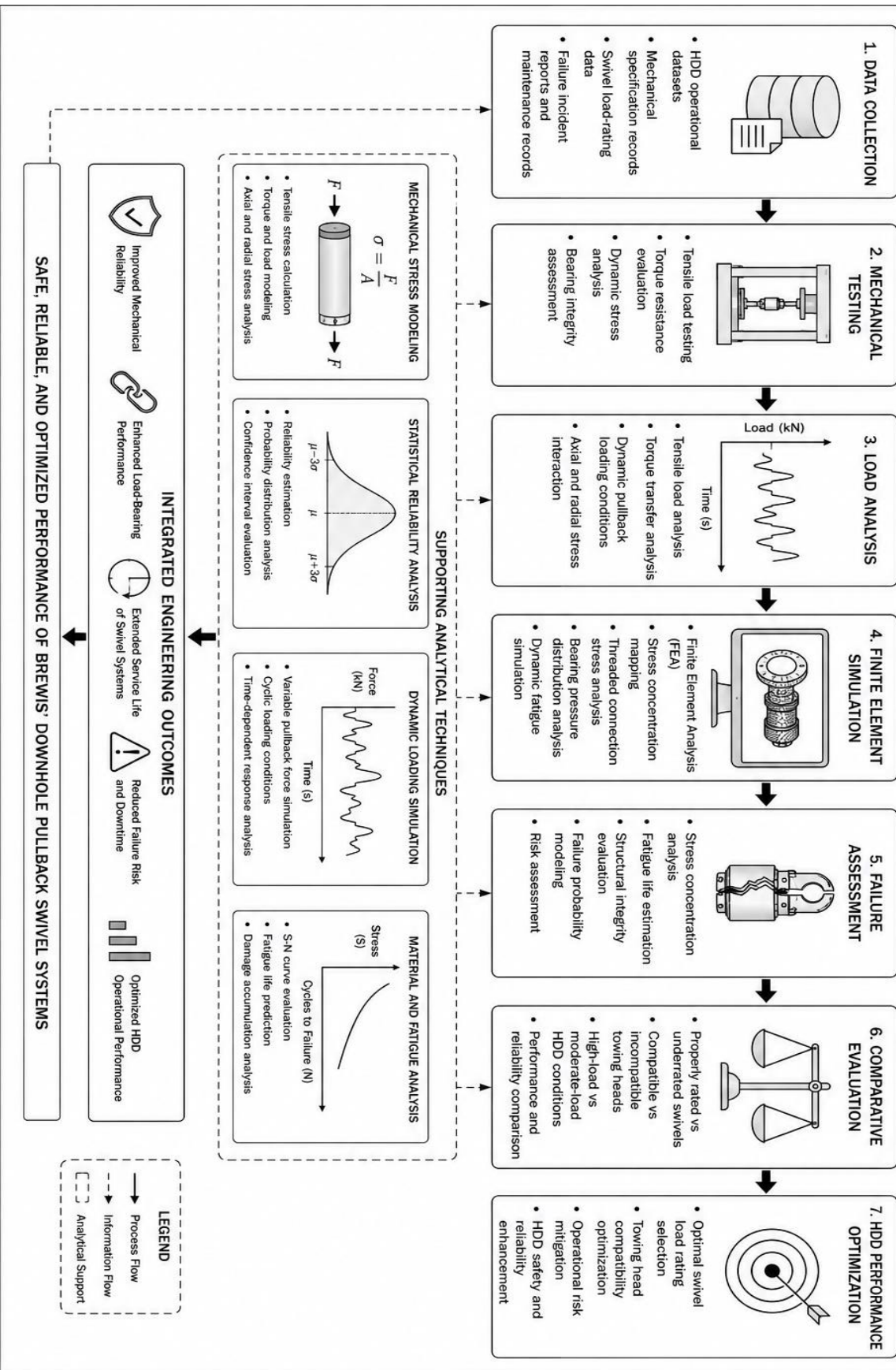
- ❖ finite element analysis,
- ❖ stress modeling,
- ❖ statistical reliability analysis,
- ❖ and dynamic simulation

provided a comprehensive engineering methodology for evaluating the mechanical reliability and operational safety of Brewis' downhole pullback swivel systems.

Table 3. Mechanical Parameters Used in HDD Swivel Performance Evaluation

Parameter	Unit	Evaluation Purpose
Tensile Load	kN	Load-bearing assessment
Torque Capacity	Nm	Rotational stability evaluation
Safety Factor	Ratio	Failure prevention analysis
Bearing Stress	MPa	Structural integrity assessment
Pullback Force	kN	HDD operational performance

RESEARCH METHODOLOGY FRAMEWORK Engineering Evaluation Process for Brewis' Downhole Pullback Swivel Systems



V. Results and Analysis

A. Tensile Performance Analysis

The tensile performance evaluation demonstrated that properly rated Brewis' downhole pullback swivels maintained significantly higher load-bearing efficiency and structural stability under varying HDD operational conditions when compared to underrated swivel systems. Tensile load behavior was strongly influenced by borehole geometry, pullback force magnitude, drilling fluid conditions, and towing head compatibility.

The analysis indicated that properly rated swivel systems consistently operated within acceptable tensile stress limits while maintaining stable load transfer throughout the pullback process. Under moderate-load HDD conditions, stress distribution remained relatively uniform across the swivel shaft and connection interfaces, minimizing the risk of localized structural overload. However, under high-capacity pullback conditions involving long-distance installations and curved borehole trajectories, operational pullback loads increased substantially, particularly in regions experiencing elevated pipe–borehole contact resistance.

Yang et al. (2014) similarly reported that HDD pullback loads fluctuate dynamically due to changes in borehole interaction conditions and operational resistance. The results obtained in this study demonstrated that properly rated swivel systems with optimized Working Load Limits (WLL) maintained acceptable stress distribution even under fluctuating loading conditions, whereas underrated swivel systems rapidly approached critical tensile thresholds.

Safe operating load threshold analysis further showed that properly selected swivel assemblies maintained higher safety margins before reaching overload conditions. Overload response evaluation revealed that underrated swivel systems experienced accelerated stress accumulation and increased deformation susceptibility once operational pullback forces exceeded approximately 80–90% of allowable tensile capacity. This behavior significantly increased the probability of fatigue crack initiation and threaded connection instability under dynamic loading conditions.

The findings therefore confirm that swivel load-rating optimization is essential for maintaining structural reliability and preventing overload-related failure during HDD pullback operations.

B. Torque Isolation Performance

Torque isolation analysis demonstrated that properly designed Brewis' swivel systems significantly reduced torsional stress transfer between the rotating drill string and the stationary product pipe during HDD pullback operations. Rotational decoupling efficiency remained consistently high under moderate operational conditions due to the stability of the internal bearing assembly and rotational isolation mechanism.

The rotational isolation system effectively minimized torque transmission through the pullback assembly, thereby reducing:

- ❖ pipe rotational deformation,
- ❖ threaded connection instability,
- ❖ and torsional stress accumulation.

The Plastics Pipe Institute (2008) similarly emphasized that properly functioning swivel systems are critical for isolating rotational movement and reducing torsional stress within HDD pullback assemblies.

Under dynamic pullback conditions involving variable drilling resistance and fluctuating operational loads, properly rated swivel systems maintained stable rotational decoupling performance without significant bearing instability or seal degradation. In contrast, underrated swivel systems exhibited reduced torque isolation

efficiency as operational loads increased. Excessive loading caused increased bearing friction and rotational instability, leading to partial transmission of rotational stress into the towing head and product pipe assembly. Dynamic loading conditions further amplified rotational instability within improperly rated swivel systems. Under cyclic loading environments, torsional vibration generated localized stress concentration near threaded connection interfaces and bearing support regions. These conditions increased the probability of fatigue-related degradation and long-term structural damage.

The results therefore demonstrate that efficient rotational isolation mechanisms significantly improve HDD pullback stability while reducing torsional stress-related operational risks.

C. Comparative Swivel Rating Analysis

Comparative analysis between properly rated and underrated swivel systems revealed substantial differences in operational reliability, failure susceptibility, and structural performance under HDD pullback conditions.

Properly rated swivel systems demonstrated:

- ❖ higher tensile stability,
- ❖ improved load distribution behavior,
- ❖ lower stress concentration severity,
- ❖ and greater operational reliability.

These systems consistently maintained acceptable structural safety margins even under elevated pullback loads and variable borehole conditions.

In contrast, underrated swivel systems experienced significantly higher stress accumulation within the swivel shaft, threaded interfaces, and bearing assembly during high-load operations. Stress amplification increased progressively as operational pullback forces approached allowable tensile thresholds. Once loading conditions exceeded safe operational capacity, rapid increases in deformation and localized stress concentration were observed.

Failure probability analysis further indicated that underrated swivel systems exhibited substantially higher risk of:

- ❖ fatigue crack initiation,
- ❖ threaded connection failure,
- ❖ bearing overload,
- ❖ and seal degradation.

Albdiry and Almensory (2016) similarly reported that insufficient load-bearing capacity significantly increases the probability of fatigue-related structural failure in mechanically loaded drilling systems.

Operational stability assessment demonstrated that properly rated swivel systems maintained consistent pullback performance throughout variable HDD conditions, whereas underrated systems exhibited:

- ❖ unstable stress distribution,
- ❖ reduced torque isolation efficiency,
- ❖ and increased operational vibration.

The comparative analysis therefore confirms that appropriate load-rating selection represents one of the most important engineering factors affecting HDD swivel reliability and operational safety.

D. Towing Head Compatibility Results

Towing head compatibility analysis demonstrated that connection geometry alignment and load transfer efficiency significantly influence HDD pullback system stability and structural reliability.

Compatible towing head systems maintained stable load transfer behavior throughout HDD operations by minimizing eccentric loading and localized stress amplification within the swivel assembly. Proper geometric alignment between the towing head and swivel system allowed tensile loads to transfer uniformly through the pullback assembly without generating excessive bending moments or uneven stress distribution.

The results showed that compatible towing head systems improved:

- ❖ axial load stability,
- ❖ rotational alignment,
- ❖ connection reliability,
- ❖ and pullback efficiency.

Conversely, incompatible towing head configurations produced substantial stress amplification within threaded connection interfaces and bearing support regions. Misaligned towing heads generated eccentric loading conditions that increased localized stress concentration near connection transition zones.

Tafreshi and Dover (1993) demonstrated that threaded connection geometry strongly influences local stress accumulation under cyclic loading conditions. The findings of this study further confirm that towing head incompatibility significantly accelerates:

- ❖ fatigue accumulation,
- ❖ connection instability,
- ❖ bearing overload,
- ❖ and structural degradation.

Load transfer efficiency evaluation also showed that incompatible towing heads reduced the ability of the swivel assembly to distribute operational loads uniformly throughout the pullback system. Under high-load HDD conditions, these incompatibility effects became increasingly severe and contributed to accelerated failure progression within the swivel assembly.

The results therefore demonstrate that towing head compatibility engineering is essential for maintaining operational reliability and minimizing HDD pullback system failure risks.

E. Finite Element Stress Distribution Analysis

Finite Element Analysis (FEA) revealed several critical stress concentration regions within the swivel assembly during HDD pullback operations. The highest stress intensities were consistently observed near:

- ❖ threaded connection interfaces,
- ❖ bearing transition regions,
- ❖ towing head attachment points,
- ❖ and shaft geometry transitions.

Stress concentration mapping indicated that abrupt geometric changes within threaded regions produced localized stress amplification under both static and dynamic loading conditions. Tang et al. (2023) similarly reported that threaded mechanical systems subjected to cyclic loading frequently develop peak stress concentrations near interface transition zones.

Threaded connection failure regions demonstrated the greatest sensitivity to cyclic loading fluctuations and operational overload conditions. Under elevated tensile loading, stress intensity factors increased rapidly near

thread roots and shoulder interfaces, significantly increasing the probability of fatigue crack initiation and progressive structural degradation.

Bearing pressure distribution analysis further showed that bearing assemblies operating under excessive pullback loads experienced uneven pressure loading and localized contact stress accumulation. These conditions increased:

- ❖ lubrication degradation,
- ❖ frictional resistance,
- ❖ rotational instability,
- ❖ and bearing fatigue susceptibility.

Properly rated swivel systems maintained more uniform stress distribution throughout the bearing assembly and shaft structure, whereas underrated systems exhibited substantially higher stress peaks under identical operational conditions.

Finite element results therefore confirm that:

- ❖ stress concentration behavior,
- ❖ connection geometry stability,
- ❖ and bearing pressure distribution

play major roles in determining HDD swivel operational reliability and long-term structural performance.

F. Failure Mode Analysis

Failure mode analysis identified fatigue-related structural degradation as the dominant failure mechanism within HDD pullback swivel systems subjected to cyclic operational loading.

Fatigue failure progression was primarily observed within:

- ❖ threaded interfaces,
- ❖ bearing support regions,
- ❖ towing head connection zones,
- ❖ and shaft transition geometries.

Repeated cyclic loading during HDD operations generated progressive stress accumulation that eventually initiated microcrack formation within localized high-stress regions. Lu et al. (2005) similarly identified cyclic fatigue as one of the primary contributors to drill pipe structural failure under dynamic operational conditions. Bearing degradation patterns indicated that excessive axial loading and rotational instability accelerated:

- ❖ bearing surface wear,
- ❖ lubrication breakdown,
- ❖ seal deterioration,
- ❖ and contact fatigue development.

Under improperly rated operational conditions, bearing pressure intensified rapidly as pullback loads increased, reducing rotational stability and increasing mechanical resistance within the swivel assembly.

Misalignment-induced stress accumulation further contributed to accelerated failure progression within incompatible towing head systems. Eccentric loading conditions produced localized bending stress and uneven load transfer behavior, significantly increasing the probability of fatigue crack propagation near threaded interfaces and connection transition zones.

The results therefore indicate that fatigue accumulation, stress concentration, and towing head incompatibility collectively represent the most significant operational risks affecting HDD swivel reliability.

G. Operational Safety and Reliability Outcomes

The operational safety assessment demonstrated that properly rated Brewis' downhole pullback swivels combined with compatible towing head systems significantly improved HDD operational reliability and reduced overall failure probability.

Properly optimized swivel systems contributed to:

- ❖ reduced equipment downtime,
- ❖ improved load stability,
- ❖ enhanced torque isolation,
- ❖ and lower maintenance requirements.

Operational reliability improvements were particularly evident during high-capacity HDD installations involving:

- ❖ long pullback distances,
- ❖ variable borehole geometry,
- ❖ and dynamic loading environments.

The improved load distribution behavior observed in properly rated systems reduced the likelihood of:

- ❖ tensile overload,
- ❖ bearing collapse,
- ❖ threaded connection instability,
- ❖ and fatigue-related structural failure.

Infrastructure protection outcomes also improved because stable pullback systems minimized pipe deformation, connection instability, and uncontrolled load fluctuations during HDD operations. Reduced operational failure risk therefore contributed directly to safer trenchless installation performance and lower infrastructure-related economic losses.

Enhanced HDD operational safety was further achieved through:

- ❖ improved mechanical reliability,
- ❖ optimized towing head compatibility,
- ❖ and better overload resistance.

The overall results confirm that integrated load-rating optimization and towing head compatibility engineering substantially improve the safety, reliability, and operational performance of HDD pullback swivel systems.

Table 4. Comparative Performance Analysis of HDD Swivel Configurations

Configuration	Load Stability	Torque Isolation	Failure Risk	Operational Efficiency
Properly Rated + Compatible Head	High	Excellent	Low	High
Underrated Swivel System	Poor	Moderate	High	Low
Incompatible Towing Head	Unstable	Poor	Critical	Low

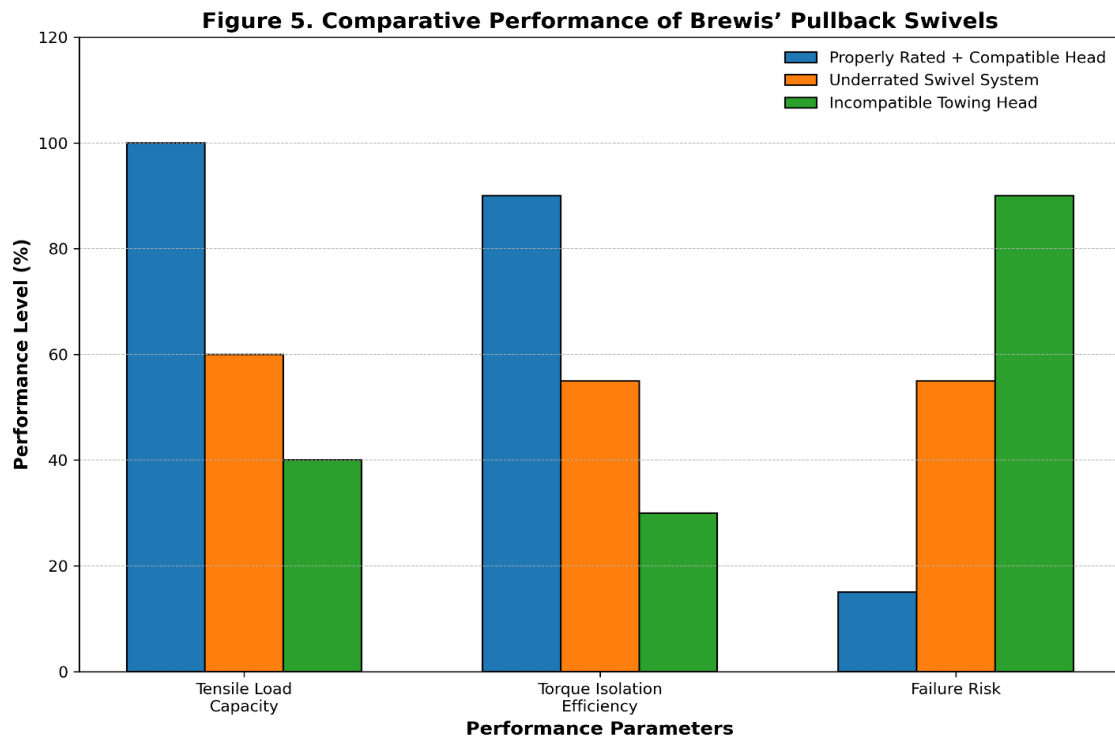


Figure 5. Comparative Performance Analysis of Brewis' Pullback Swivel Configurations

The figure compares the tensile load capacity, torque isolation efficiency, and failure risk of properly rated, underrated, and incompatible Brewis' pullback swivel configurations under HDD operational conditions.

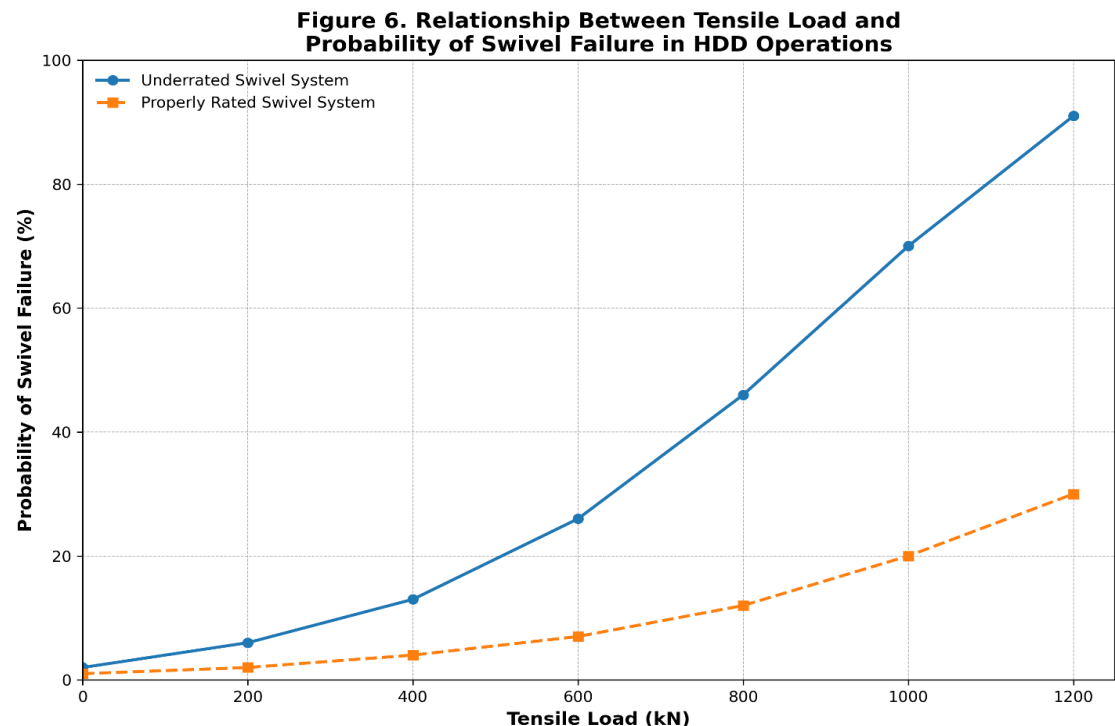


Figure 6. Relationship Between Tensile Load and Probability of Swivel Failure in HDD Operations

The figure illustrates the increasing probability of swivel failure with rising tensile load levels, highlighting the significantly higher failure susceptibility of underrated swivel systems during HDD pullback operations.

VI. Industrial Implications and Engineering Recommendations

A. Operational Safety Enhancement

The findings of this study demonstrate that proper swivel load-rating selection and towing head compatibility engineering significantly improve operational safety during Horizontal Directional Drilling (HDD) pullback operations. Because HDD pullback systems operate under high tensile loads, dynamic stress conditions, and continuously changing underground environments, the structural reliability of pullback assemblies directly influences worker safety, infrastructure integrity, and overall drilling stability.

One of the most important operational safety outcomes identified in this research is the reduction of catastrophic pullback system failure risks through appropriate swivel load optimization. Properly rated Brewis' downhole pullback swivels exhibited superior tensile stability, lower stress concentration severity, and improved fatigue resistance compared to underrated swivel systems. These improvements substantially reduced the probability of:

- ❖ threaded connection failure,
- ❖ bearing collapse,
- ❖ towing head instability,
- ❖ and sudden tensile overload events.

Albdiry and Almensory (2016) similarly emphasized that mechanically optimized drilling systems significantly reduce fatigue-related operational hazards and improve drilling safety performance under dynamic loading environments.

Worker protection is also improved through better control of load transfer stability and rotational isolation performance. Stable pullback systems reduce uncontrolled load fluctuations and vibration-induced instability that may expose drilling personnel to hazardous operational conditions. Proper rotational decoupling further minimizes sudden torsional stress accumulation and connection instability within HDD assemblies.

Infrastructure preservation represents another major safety improvement resulting from proper swivel and towing head selection. During HDD installations, unstable pullback assemblies may cause:

- ❖ product pipe deformation,
- ❖ borehole collapse,
- ❖ connection rupture,
- ❖ and underground infrastructure damage.

The results obtained in this study demonstrated that mechanically compatible pullback systems significantly improve load distribution stability and reduce the likelihood of infrastructure-related operational failure.

Overall HDD operational risk reduction is therefore achieved through:

- ❖ optimized load-bearing capacity,
- ❖ efficient torque isolation,
- ❖ reduced stress concentration,
- ❖ improved fatigue resistance,
- ❖ and enhanced connection stability.

These improvements collectively strengthen HDD safety performance and reduce operational hazards in high-capacity trenchless infrastructure projects.

B. Economic and Operational Benefits

The engineering optimization of HDD pullback swivel systems provides substantial economic and operational advantages for drilling contractors, infrastructure developers, and pipeline installation operators. One of the

most significant economic benefits identified in this study is the reduction of operational downtime associated with swivel failure, towing head instability, and mechanical breakdown during HDD operations.

Improved tensile reliability and towing head compatibility significantly reduce the frequency of:

- ❖ pullback interruptions,
- ❖ emergency repair operations,
- ❖ equipment replacement,
- ❖ and unplanned operational shutdowns.

Downtime reduction is particularly important in long-distance HDD projects where equipment failure may result in:

- ❖ extended project delays,
- ❖ costly recovery procedures,
- ❖ drilling schedule disruptions,
- ❖ and increased labor expenses.

Maintenance cost minimization also represents a major operational advantage of properly optimized swivel systems. Properly rated pullback assemblies exhibited lower fatigue accumulation rates and improved bearing stability, reducing long-term wear-related degradation and maintenance frequency. API RP 8B (American Petroleum Institute, 2014) similarly emphasized that properly maintained and appropriately rated drilling equipment significantly improves operational lifespan and reduces maintenance-related costs.

Improved drilling efficiency was also observed through enhanced load transfer stability and reduced rotational stress transmission. Stable pullback systems improved:

- ❖ operational consistency,
- ❖ drilling speed control,
- ❖ borehole stability,
- ❖ and pullback performance under variable underground conditions.

Additionally, optimized swivel systems demonstrated improved resistance to cyclic loading and dynamic operational stress, contributing to extended equipment service life. Reduced stress concentration and better bearing pressure distribution minimized fatigue-related degradation within:

- ❖ swivel shafts,
- ❖ threaded interfaces,
- ❖ towing heads,
- ❖ and rotational support systems.

The operational and economic findings therefore confirm that mechanically optimized pullback systems improve:

- ❖ project efficiency,
- ❖ cost control,
- ❖ maintenance performance,
- ❖ and long-term operational sustainability.

C. Engineering Design Recommendations

Based on the findings of this study, several engineering design recommendations are proposed to improve HDD pullback reliability, operational safety, and mechanical performance.

The first recommendation involves the implementation of proper swivel selection guidelines based on:

- ❖ expected pullback force conditions,
- ❖ borehole geometry,
- ❖ drilling rig capacity,
- ❖ product pipe allowable tensile strength,
- ❖ and operational safety factor requirements.

Swivel selection should be performed using engineering-based load analysis rather than generalized equipment sizing approaches. The Plastics Pipe Institute Municipal Advisory Board (2024) emphasized that pullback swivel capacity should be aligned with allowable pipe pull strength and drilling rig capability to prevent overload-related operational failure.

The second recommendation involves the development of a towing head compatibility verification framework. Prior to HDD installation, towing head systems should undergo compatibility evaluation based on:

- ❖ connection geometry alignment,
- ❖ threaded coupling stability,
- ❖ load transfer efficiency,
- ❖ and rotational alignment behavior.

Compatibility verification procedures should specifically evaluate the potential for:

- ❖ eccentric loading,
- ❖ localized stress concentration,
- ❖ bending moment development,
- ❖ and fatigue amplification.

The third recommendation focuses on inspection and preventive maintenance strategy development. HDD swivel assemblies should undergo:

- ❖ routine tensile integrity inspection,
- ❖ threaded connection examination,
- ❖ bearing wear evaluation,
- ❖ lubrication monitoring,
- ❖ and seal condition assessment

before and after major HDD pullback operations.

API RP 8B (American Petroleum Institute, 2014) recommends periodic inspection and maintenance procedures for mechanically loaded drilling equipment operating under dynamic stress conditions. Incorporating predictive maintenance procedures into HDD operations may significantly reduce unexpected equipment failure and improve operational reliability.

Another important recommendation is the development of a standardized HDD pullback safety checklist that includes:

- ❖ swivel load verification,
- ❖ towing head compatibility confirmation,
- ❖ threaded connection inspection,
- ❖ bearing stability assessment,
- ❖ and operational load monitoring procedures.

The engineering recommendations proposed in this study therefore provide a comprehensive operational framework for improving HDD mechanical reliability and reducing pullback system failure risks.

D. Regulatory and Industry Implications

The increasing mechanical complexity of modern HDD installations highlights the growing importance of regulatory oversight, engineering certification standards, and operational safety compliance within trenchless infrastructure industries.

The findings of this study support the adoption of stronger HDD engineering best practices focused on:

- ❖ load-rating optimization,
- ❖ towing head compatibility verification,
- ❖ finite element stress evaluation,
- ❖ and reliability-centered pullback system design.

Current HDD industry practices frequently emphasize general equipment capacity selection without sufficient attention to dynamic stress behavior and compatibility-induced failure risks. The results of this research demonstrate that engineering-based compatibility assessment is essential for improving HDD operational safety and structural reliability.

Mechanical certification considerations also represent an important regulatory implication of this study. HDD pullback components including swivels, towing heads, and connection systems should undergo engineering certification procedures that evaluate:

- ❖ tensile reliability,
- ❖ fatigue resistance,
- ❖ rotational isolation efficiency,
- ❖ and dynamic load performance.

Compliance with engineering safety standards such as:

- ❖ API Spec 8C,
- ❖ API RP 8B,
- ❖ ASTM F1804,
- ❖ ASTM F1962,
- ❖ ASME B30.20,
- ❖ and ASME BTH-1

should be integrated more consistently into HDD pullback equipment selection and operational planning procedures.

The study further highlights the need for future HDD equipment standardization frameworks capable of addressing:

- ❖ dynamic operational loading,
- ❖ towing head compatibility,
- ❖ stress concentration analysis,
- ❖ and fatigue-based reliability evaluation.

Standardized engineering procedures for HDD pullback system evaluation would significantly improve:

- ❖ operational consistency,
- ❖ equipment certification quality,
- ❖ safety performance,
- ❖ and long-term infrastructure reliability.

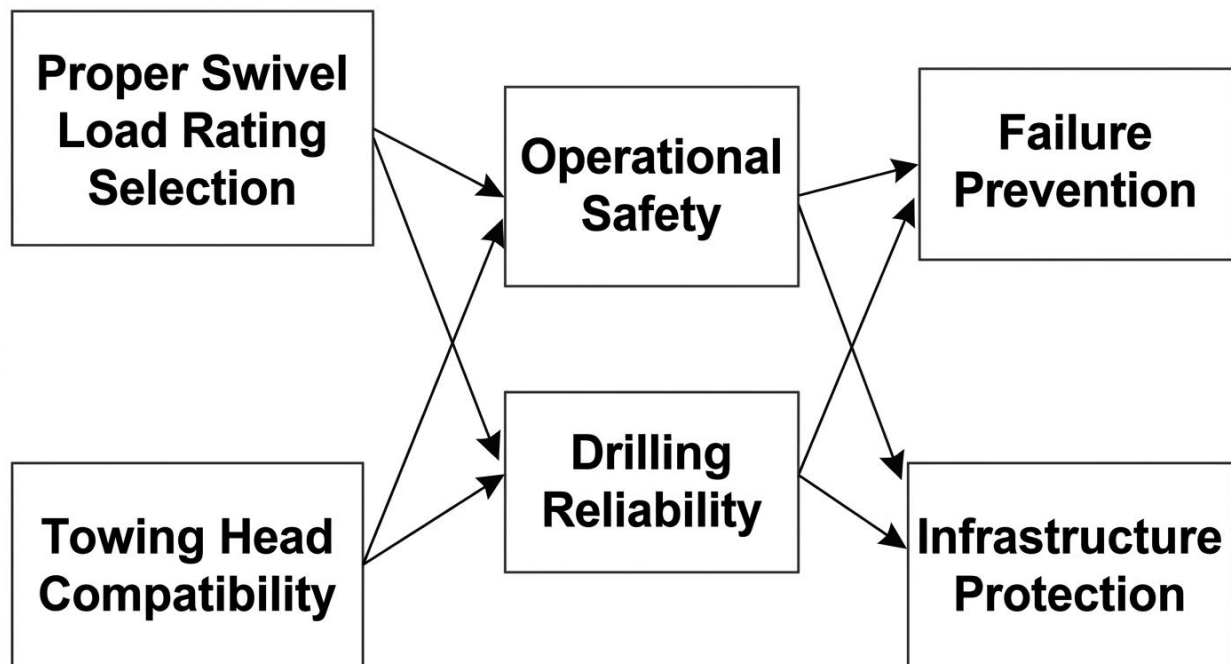


Figure 7. Conceptual Framework for HDD Swivel Load Optimization and Operational Safety
The figure illustrates the relationship between proper swivel load rating selection, towing head compatibility, operational safety, drilling reliability, failure prevention, and infrastructure protection within HDD pullback operations.

VII. Conclusion and Future Research

A. Summary of Key Findings

This study presented an engineering performance evaluation of Brewis' downhole pullback swivel systems with emphasis on swivel load-rating optimization, towing head compatibility engineering, and HDD operational reliability. The findings demonstrated that properly rated swivel systems significantly improve load stability, rotational isolation performance, fatigue resistance, and structural reliability during HDD pullback operations.

The analysis further confirmed that towing head compatibility directly influences:

- ❖ load transfer efficiency,
- ❖ stress concentration behavior,
- ❖ threaded connection stability,
- ❖ and operational failure probability.

Compatible towing head systems maintained more stable load distribution and significantly reduced the likelihood of fatigue-related structural degradation compared to incompatible configurations.

Finite element stress analysis additionally revealed that:

- ❖ threaded interfaces,
- ❖ bearing transition regions,
- ❖ towing head connection zones,
- ❖ and shaft geometry changes

represent the most failure-prone regions within HDD pullback assemblies under cyclic loading conditions.

The overall results demonstrate that mechanical optimization of HDD pullback systems substantially reduces:

- ❖ operational failure risks,
- ❖ infrastructure damage probability,
- ❖ equipment degradation,
- ❖ and safety-related operational hazards.

B. Engineering Contributions

This study contributes to HDD engineering research through the development of a proposed integrated HDD swivel performance evaluation framework that combines:

- ❖ pullback load analysis,
- ❖ towing head compatibility assessment,
- ❖ finite element stress simulation,
- ❖ fatigue reliability evaluation,
- ❖ and operational safety optimization.

The research further introduces a comparative load-rating and compatibility analysis model capable of evaluating the operational performance differences between:

- ❖ properly rated and underrated swivel systems,
- ❖ compatible and incompatible towing heads,
- ❖ and variable HDD operational environments.

An HDD reliability optimization strategy was also proposed to improve:

- ❖ load distribution stability,
- ❖ failure prevention,
- ❖ stress control,
- ❖ and operational safety performance

within high-capacity trenchless infrastructure projects.

C. Practical Industry Contributions

The practical contributions of this study are particularly important for HDD contractors, drilling engineers, pipeline installation operators, and infrastructure developers involved in complex trenchless installation projects.

The findings provide engineering guidance for:

- ❖ proper swivel selection,
- ❖ towing head compatibility verification,
- ❖ operational load monitoring,
- ❖ and preventive maintenance planning.

Improved drilling safety procedures were also established through the proposed compatibility verification framework and operational risk mitigation strategy developed in this research.

Additionally, the study provides an operational reliability enhancement framework capable of improving:

- ❖ HDD equipment lifespan,
- ❖ pullback stability,
- ❖ drilling efficiency,
- ❖ and infrastructure protection performance.

The proposed engineering recommendations therefore contribute directly to safer and more reliable HDD installation operations.

D. Limitations

Although the study provides a comprehensive engineering analysis of HDD pullback swivel systems, several limitations remain.

One limitation involves the limited availability of real-time HDD field datasets capable of capturing dynamic operational loading conditions during large-scale underground installations. Many HDD operational parameters remain highly variable and difficult to monitor continuously under field conditions.

Another limitation involves restricted access to proprietary operational stress data and equipment-specific performance information from commercial HDD operations and pullback system manufacturers.

Additionally, the finite element simulations and comparative engineering models developed in this study were based primarily on generalized operational conditions and literature-supported loading scenarios rather than full-scale industrial field validation.

Future studies involving real-time sensor-integrated field testing would therefore improve validation accuracy and operational reliability prediction.

E. Future Research Directions

Several future research opportunities emerge from this study.

One important direction involves the development of AI-driven predictive failure monitoring systems capable of identifying:

- ❖ stress accumulation trends,
- ❖ fatigue progression,
- ❖ and overload risks

during active HDD pullback operations.

Another promising area involves smart sensor-integrated HDD swivel assemblies capable of real-time monitoring of:

- ❖ tensile load,
- ❖ bearing pressure,
- ❖ rotational stability,
- ❖ vibration,
- ❖ and operational stress distribution.

Real-time HDD mechanical intelligence platforms may further improve operational decision-making through continuous reliability assessment and predictive maintenance analysis.

Digital twin modeling also represents a major future research opportunity because virtual HDD system replication could enable:

- ❖ real-time operational simulation,
- ❖ stress prediction,
- ❖ failure forecasting,
- ❖ and optimization of pullback system performance under varying underground conditions.

Advanced nonlinear finite element stress simulation systems capable of incorporating:

- ❖ dynamic borehole interaction,
- ❖ material nonlinearities,
- ❖ cyclic fatigue behavior,
- ❖ and real-time operational loading

would further improve HDD engineering reliability analysis and operational safety prediction in future trenchless infrastructure projects.

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