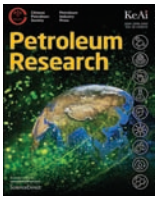
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Review Article

Dynamic loads on energy pipelines: Origins, mitigation strategies, and future research directions



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ABSTRACT

Pipelines are an indispensable part of the global infrastructure for energy transportation, and their integrity poses a significant risk as the dynamic loads generated throughout their life cycle might result in catastrophic failures if not properly managed. A systematic review is presented, including the sources, effects, and mitigation measures of dynamic loads classified into four categories: environmental, mechanical, accidental, and human-induced. A thorough literature review highlights computational methods, particularly finite element method and computational fluid dynamics, contribute to estimating failure modes and developing preventive measures. Primary mitigation measures comprise flexible joints for the seismic response of pipelines, vortex-induced vibration suppressors for offshore applications, and protective barriers against impact loads. There are gaps in modeling coupled multi-axial loads and aging infrastructure under seismic loading conditions, with limitations in real-time monitoring. Adaptive computational frameworks integrating FSI with probabilistic risk assessments should be developed, with innovative technologies such as self-healing coatings and IoT-enabled monitoring requiring rigorous attention. This study aims to serve as a guide to enhancing pipeline resilience in extreme environments, thus directing future endeavors toward safe and sustainable transportation of energy through resilient infrastructures.

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1. Introduction

Pipelines, the lifeline of oil and gas engineering, are essential for transporting hazardous chemicals, such as oil and natural gas (NG), and are integral to global energy infrastructure. They exist in three main configurations, marine/offshore pipelines laid on or beneath the seabed, buried/onshore pipelines installed underground, and above-ground pipelines in facilities or crossings, and all are subjected to dynamic loads throughout their lifecycle. These loads, including internal pressure fluctuations, bending moments, axial forces, sea currents, flow-induced vibration (FIV), impact forces, and accidental blasts (Limam et al., 2008; Savari et al., 2021), originate from construction, installation, and operational stages. Although they share fundamental structural principles, marine and buried pipelines differ in load-transmission pathways and governing failure modes; for example, subsea pipelines face hydrodynamic forces and seabed instabilities, whereas buried pipelines are influenced by soil-pipe interaction and seismic ground deformation. These loads can cause several failure mechanisms, such as buckling, fatigue, and fracture, particularly in harsh subsea and underground environments. The consequences of pipeline failures, such as leaks, may lead to severe economic losses and environmental damage, emphasizing the importance of ensuring the structural integrity of pipelines under dynamic loading conditions (Nie et al., 2020).

The structural integrity of pipelines undergoing dynamic loads is crucial due to the severe consequences of failure, including environmental disasters, financial losses, and safety risks. Corrosion, dents, cracks, and gouges are significant threats to pipeline integrity (Hosseinzadeh and Bahaari, 2025; Hosseinzadeh et al., 2025; Jacques et al., 2010). Failures caused by corrosion in oil and gas pipelines lead to serious environmental and ecological damage, considerable energy loss, and potentially fatal incidents.

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Nomenclature

AHMs	Arrowhead Markings
ALE	Arbitrary Lagrangian-Eulerian
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CFD	Computational Fluid Dynamics
CIPP	Cured-In-Place Pipe
CR	Cyclic Stress Ratio
CTF	Crack Tip Flipping
CVN	Charpy V-Notch
DAS	Distributed Acoustic Sensing
DBN	Dynamic Bayesian Network
DFOS	Distributed Fiber Optic Sensing
DT3	Dynamic Tensile Tear Test
DWTT	Drop Weight Tear Test
NDT	Non-Destructive Testing
FE	Finite Element
FEM	Finite Element Method
FIV	Flow-Induced Vibration
FL	Fusion Line
GFRP	Glass Fiber Reinforced Polymer
GPS	Global Positioning System
HFACS	Human Factor Analysis and Classification System
HDD	Horizontal Directional Drilling
HHI	High Heat Input
ILI	In-Line Inspection
LHI	Low Heat Input
MBW	Modified Bai-Wierzbicki
MFL	Magnetic Flux Leakage
MHI	Medium Heat Input
ML	Machine Learning
MLP	Multi-Layer Perceptron
MPD	Multi-Cavity Particle Dampers
MR	Magnetorheological
MVIMD	Multi-Dimensional Vibration Isolation and Mitigation Devices
NG	Natural Gas
PGA	Peak Ground Acceleration
PGD	Permanent Ground Deformation
PGV	Peak Ground Velocity
PIM	Pipeline Integrity Management
FSI	Fluid-Structure Interaction
PIP	Pipe-in-Pipe
PPV	Peak Particle Velocity
SCRs	Steel Catenary Risers
SCADA	Supervisory Control and Data Acquisition
SEM	Scanning Electron Microscopy
SHM	Structural Health Monitoring
SIF	Stress Intensity Factor
SINTAP	Structural Integrity Assessment Procedure
TAP	Trans Adriatic Pipeline
TGD	Transient Ground Deformation
TMD	Tuned Mass Dampers
TSC	Tensile Strain Capacity
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UT	Ultrasonic Testing
VIV	Vortex-Induced Vibration
Viscoelastic	VE

Each year, billions of dollars are required to address corrosion-related accidents, maintenance, and monitoring of underground metal pipelines. In 2018 alone, corrosion cost the US oil and gas exploration sector $1.4 billion, as highlighted by estimations (Wang et al., 2023b). In addition, dents, especially kinked and folded types, which cause an abrupt curvature variation of a pipe wall, act as stress concentrators, thereby reducing load-bearing capacity. Dents caused by third-party damage and construction incidents have been identified as one of the important contributors to pipeline failures in the UK. The overall impact can be substantial, particularly when fatigue cracking occurs or when defects interact with corrosion (Cosham and Hopkins, 2004).

While many studies focused on rehabilitating defective pipelines under static loads (Chan et al., 2012; Prakash et al., 2024; Rashed et al., 2019; Savari, 2022a, 2022b, 2025a; Savari et al., 2022, 2024; Shafaee Fallah et al., 2023), the evaluation of their structural integrity under time-dependent loads poses a challenge. Despite some research on this topic (Eskandari, 2018; Mazurkiewicz et al., 2018a, 2018b; Nie et al., 2020; Savari et al., 2021; Wang et al., 2016a), a holistic synthesis is lacking. Such a synthesis must account for the shared and type-specific responses of marine, buried, and above-ground pipelines, each of which faces distinct dynamic load environments, from hydrodynamic and seabed-instability effects offshore, seismic ground motion and soil-pipe interaction underground, to impact and blast forces above ground. Detecting and understanding the primary dynamic load categories, along with their mitigation strategies, is essential for ensuring operational safety and reliability. Previous reviews have tended to explore individual load types in isolation, rarely comparing their relative significance or systematically examining control measures. Therefore, this paper undertakes a comprehensive review of pipeline integrity under environmental, mechanical, accidental, and human-induced dynamic loads, highlighting both the commonalities that unify pipeline responses and the divergences that shape design priorities in different situations. The review begins with a bibliometric overview and keyword co-occurrence analysis, proceeds to a detailed exploration of loading origins, identifies research gaps for each category, and concludes with an assessment of integrity under dynamic loads and clear directions for future research.

2. Literature analysis

2.1. Data collection

The research methodology began with the systematic collection of literature, starting by defining the study scope and identifying relevant keywords. Key search terms were used: “pipeline,” “oil,” “gas,” “dynamic load,” “seismic response,” “blast and explosion,” “currents and waves,” “vibration,” “dropped objects,” and “thermal loads”, applied in Boolean combinations to ensure thematic specificity. Searches were conducted in two widely used databases, Scopus and Web of Science (WoS), covering publications from 2000 to 2025. Peer-reviewed studies were prioritized to ensure quality and balance, and results from Scopus and WoS were weighted equally. Only studies directly addressing energy pipeline load effects were retained. Duplicates were removed, and qualitative-only publications were excluded. As shown in Fig. 1, the initial retrieval yielded between 29 and 52 publications per theme. The largest set was for “Blast and explosion” (52 publications retrieved), followed by “Seismic loads” (39), “Mechanical vibrations” (33), “Impact and accidental loads” (42), “Currents and

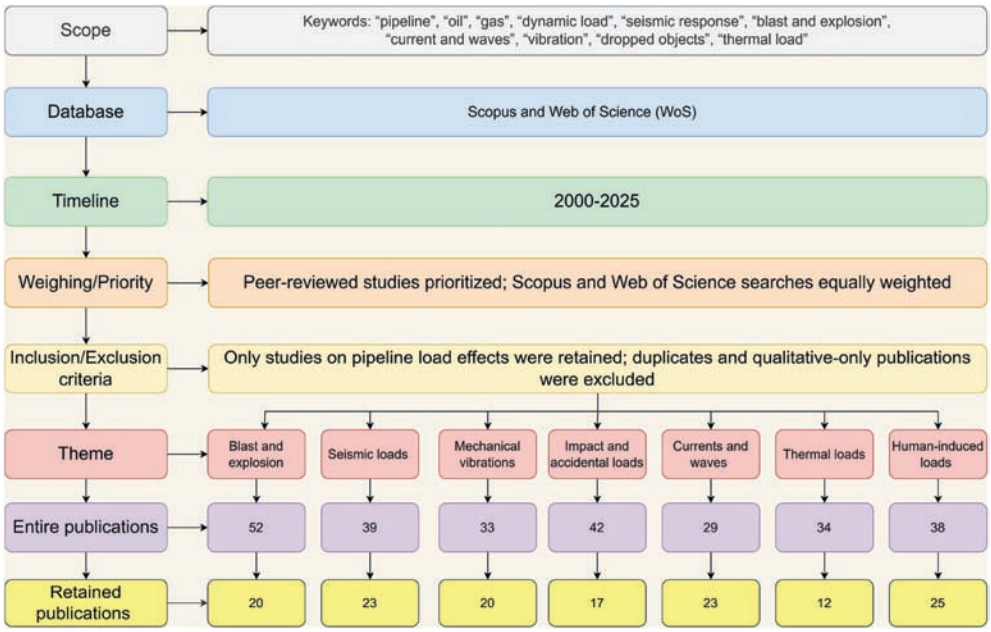


Fig. 1. Data collection map.

waves" (29), "Thermal loads" (34), and "Human-induced loads" (38). After screening, the retained publications numbered 20, 23, 20, 17, 23, 12, and 25, respectively.

The annual distribution of the retained publications spans from 2003 to 2025, with a noticeable increase in research output from 2015 onwards (Fig. 2). The early years (2003–2010) show relatively low activity (1–5 articles/year), reflecting limited scholarly attention to dynamic loads on energy pipelines during that period. A substantial rise is observed after 2015, with peak outputs in 2021 (26 articles) and consistent productivity above 15 publications/year thereafter. This trend suggests a growing recognition of the importance of dynamic load effects in oil and gas pipeline systems, likely driven by advances in condition monitoring technologies, increased awareness of extreme environmental events, and the emergence of stricter safety regulations. The time-series pattern also confirms that the topic remains highly active, justifying the choice of 2000–2025 as a comprehensive temporal scope for the present review.

2.2. Co-occurrence of keywords

The keyword co-occurrence analysis conducted using VOS viewer visualized the bibliometric network derived from the collected references (Fig. 3). The threshold-sensitivity analysis illustrates the variation of retained keywords and the mean total link strength with increasing occurrence thresholds. As the threshold rises from 2 to 16, the number of keywords decreases sharply, from over 300 to fewer than 10, while the mean link strength only increases approximately twice. This trend shows that higher thresholds excessively filter out relevant yet moderately recurrent terms, leading to an overly sparse, less representative network. Conversely, lower thresholds (e.g., 2) retain numerous weakly connected or redundant keywords, which reduce interpretability. Hence, a frequency threshold of 4 achieves an effective balance between network density, link strength, and usability, preserving meaningful co-occurrence relationships while maintaining computational clarity and thematic focus

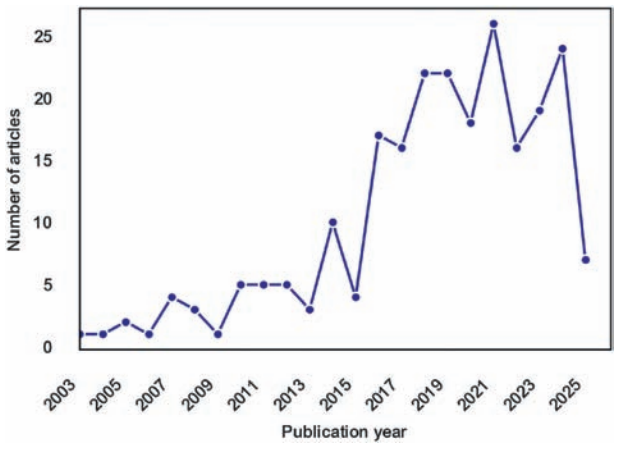


Fig. 2. Annual article counts.

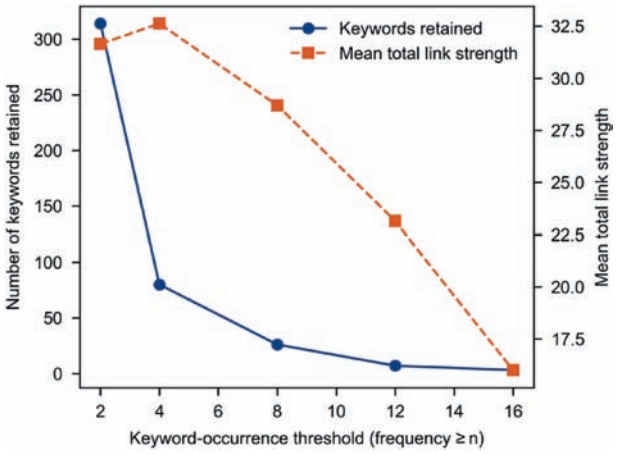


Fig. 3. Threshold-sensitivity analysis of keyword co-occurrence in the VOSviewer dataset.

within the bibliometric map. Therefore, a total of 146 relevant references were analyzed, generating a network of 80 keywords, each occurring at least 4 times. The co-occurrence patterns reveal a clear thematic structure in the literature. Research on explosion loads (Fig. 4a) is predominantly linked with buried pipelines, failure analysis, and computational fluid dynamics (CFD), indicating a strong emphasis on modeling catastrophic events and investigating their structural implications. Seismic response studies (Fig. 4b) are closely associated with soil-structure interaction and earthquake engineering, reflecting the depth of work on geohazard-infrastructure interactions. Investigations into mechanical vibrations presented in Fig. 4c frequently coincide with water hammer phenomena, gas pipeline operations, and deepwater conditions, while studies focused on ocean currents.

Fig. 4d are connected to pipe-soil interaction, stability analysis, and hydrodynamic-geotechnical coupling in subsea settings. Dropped object research (Fig. 4e) aligns with reliability analysis, trajectory prediction, and offshore risk assessment, underscoring continuing concerns over third-party accidental impacts. Across these themes, computational approaches such as CFD, finite element analysis (FEA), and machine learning (ML) remain central, yet integration across load types is limited. This fragmentation highlights a gap in addressing multi-load scenarios, such as seismic activity combined with material aging or impact coupled with thermal cycling, where greater interdisciplinary integration will be critical to advancing resilient pipeline integrity strategies.

The top keywords identified (Table 1) reveal that “pipelines” is the most prominent term, followed by “computational fluid dynamics,” “finite element method,” and “dynamic response”. Other significant keywords include “buried pipelines”, “seismic response”, “vibration”, and “offshore pipelines”, indicating that much of the research has focused on the structural response of pipelines to environmental loads, fluid interactions, and external dynamic forces like earthquakes and ocean currents. Keywords such as “stability” and “buckling” highlight concerns about pipeline safety and structural integrity under various dynamic conditions that cause pipeline failure. In addition, the prominence of terms like risk assessment, dropped objects, and deformation suggests a focus on evaluating accidental impacts and mitigating risks in harsh environments. The temporal keyword distribution (Fig. 5) complements the co-occurrence patterns by revealing when each theme emerged or intensified. Early research (2003–2010) focused sporadically on isolated topics such as seismic and blast loads, while post-2015 studies display broader coverage, with notable peaks in keywords like “seismic,” “dynamic response,” and “impact” between 2018 and 2022. These surges correspond to increased attention on multi-hazard assessments and accident prevention. The distribution also shows that some

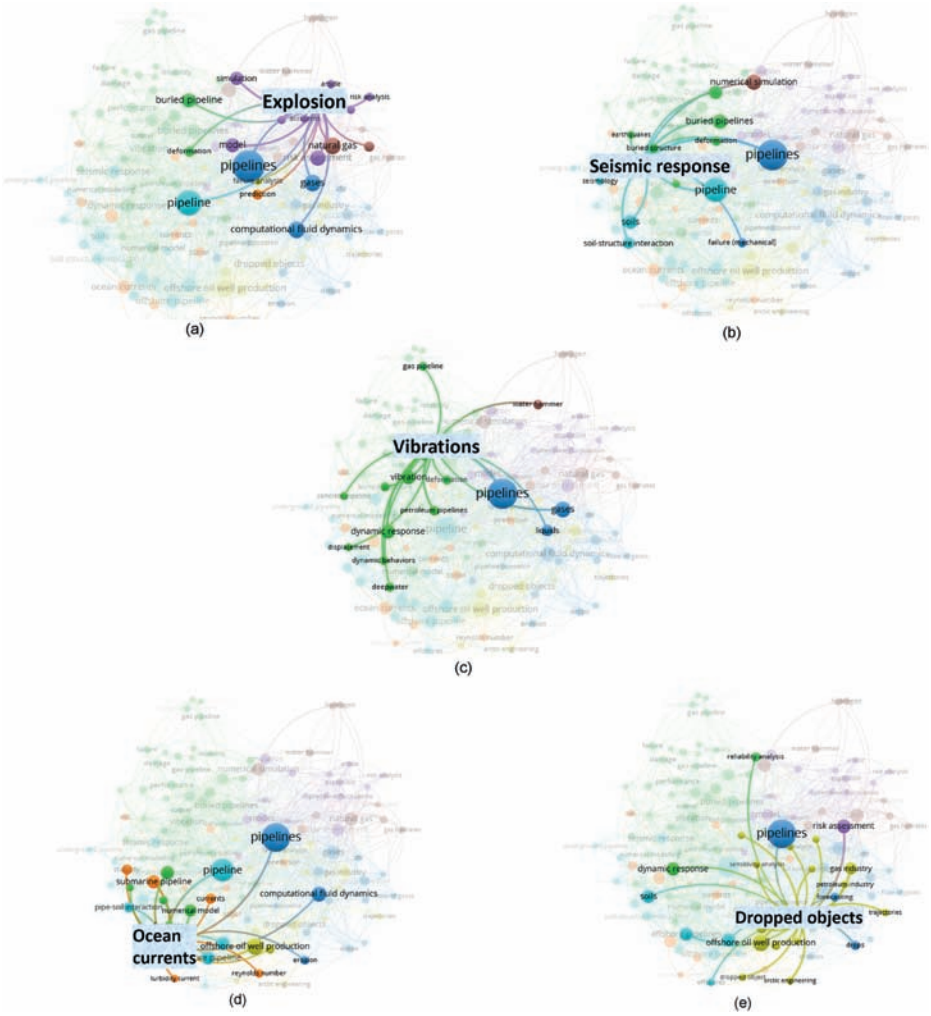


Fig. 4. Keywords occurrence visualization of dynamic loads imposed on pipelines in 148 relevant articles (a) explosion, (b) seismic response, (c) vibrations, (d) ocean currents, (e) dropped objects.

Table 1
Top keywords from 146 references.

Keyword	Occurrences	Total link strength	Keyword	Occurrences	Total link strength
Pipelines	50	163	Numerical model	8	40
Computational fluid dynamics	13	48	Soil-structure interaction	7	36
Numerical simulation	12	21	Two phase flow	7	28
Buried pipelines	11	30	Buckling	6	23
Risk assessment	11	29	Pressure	6	20
Dynamic response	10	29	Stability	6	17
Finite element method	10	50	Damage	5	8
Ocean currents	10	38	Deformation	5	24
Offshore pipelines	10	50	Drops	5	21
Soils	10	45	Earthquake	5	6
Submarine pipeline	10	25	Hydrodynamics	5	23
Vibration	10	27	Natural gas pipelines	5	23
Buried pipeline	9	23	Oil pipeline	5	24
Dropped objects	9	23	Reliability analysis	5	9
Seismic response	9	23	Water hammer	5	19

terms, such as “thermal expansion” and “currents”, maintain low but steady activity, indicating niche yet persistent research lines. Such temporal clustering underscores the shift of research priorities in response to technological advances, regulatory changes, and real-world incidents.

Overall, the keyword analysis indicates that current research heavily integrates computational methods to predict pipeline performance and failure mechanisms, with an increasing emphasis on managing dynamic and environmental challenges to maintain pipeline integrity. Computational methods are increasingly integrated into pipeline integrity management (PIM) due to their ability to address limitations inherent in online inspection techniques. While inspections (e.g., in-line tools) provide critical real-time data, they often require operational compromises (e.g., shutdowns, excavation) and lack predictive capacity for emerging failures (Olamide et al., 2020; Tuck and Lee, 2013). The combination of numerical techniques, such as ML and FEA, enables proactive risk assessment by modeling complex interactions between dynamic variables (pressure, temperature, corrosion rates) and predicting future failure states quickly (Ma et al., 2021; Vijaya Kumar et al., 2021). These techniques also optimize resource allocation by prioritizing high-risk segments and quantifying uncertainties (e.g., corrosion randomness, coating degradation) through probabilistic frameworks (Basha and Rao, 2018; Wong and McCann, 2021).

In relation to the objectives of this review, the literature analysis serves two complementary purposes: first, to confirm that the four dynamic-load categories adopted in this study, environmental, mechanical, accidental, and human-induced, align with the dominant themes in current research; and second, to highlight underexplored intersections, such as coupled multi-field effects (e.g., seismic + aging, pressure + thermal) and mitigation approaches beyond traditional mechanical reinforcement. The keyword trends reveal that computational methods (CFD, FEA, ML) are central to addressing these challenges but remain limited in their treatment of complex coupling and real-time adaptation. From this analysis, it is concluded that (i) accidental loads like explosions and dropped objects remain critical yet receive relatively insufficient treatment compared to environmental loads, (ii) seabed-pipe interaction and soil-structure effects are recurrent themes that cut across load categories, and (iii) future advancement will depend on integrating bibliometric-identified gaps with experimental and operational data to inform resilient pipeline design, monitoring, and repair strategies.

3. Dynamic loading origins

Pipelines encounter a broad range of dynamic loads during their service life, each with distinct origins and effects. In this review, these loads are grouped into four main groups. Environmental and natural loads arise from geophysical and oceanographic processes such as seismic shaking, permanent ground deformation (PGD), transient ground deformation (TGD), landslides, waves, currents, and permafrost thaw. Mechanical loads are generated by the pipeline's own operation or configuration, including internal pressure cycles, vibration, and thermal expansion or contraction. Impact and accidental loads are sudden, unintended events that impart high-intensity energy to the

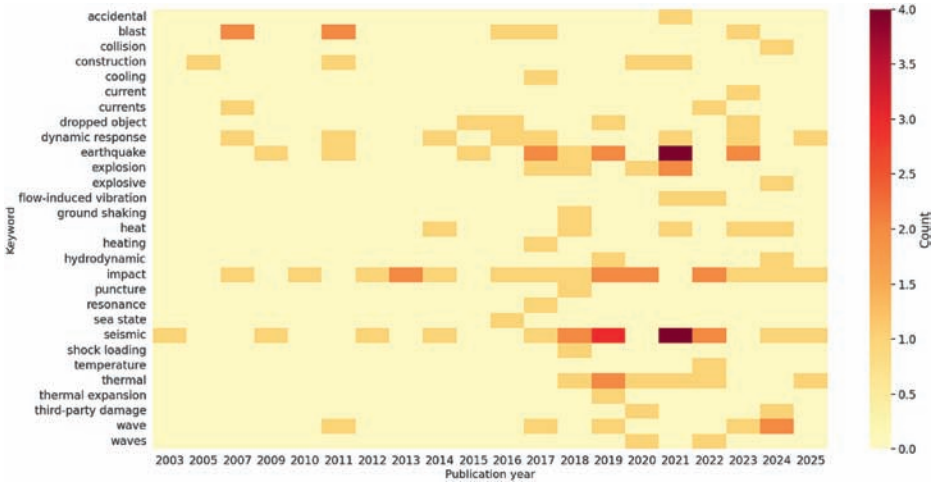


Fig. 5. Time evolution of keywords related to dynamic loads on energy pipelines.

structure; for example, anchor strikes, dropped objects, excavation hits, or blast overpressure. Human-induced loads, by contrast, originate from deliberate or recurring human activity without accidental collision, such as operational pressure excursions, flow-regime changes that cause vibration, or acts of sabotage. This classification differentiates between abrupt one-time incidents and ongoing or planned influences, providing a basis for assessing their impact on pipeline integrity. Table 2 outlines the four categories based on their origin, triggering mechanism, and typical structural consequences.

3.1. Environmental and natural loads

3.1.1. Seismic loads

Seismic loads differ from other types of loads, such as pressure or temperature, in that they can lead to lateral deformation, ground movement, and soil liquefaction, posing unique threats to pipeline integrity. Pipelines are particularly vulnerable to seismic hazards due to wave propagation, which can cause out-of-phase displacements and stress concentration, especially in bends. As shown in Fig. 6a, seismic effects can be further categorized into two main types of geohazards based on the temporal nature of the damage source: (a) TGD resulting from seismic wave propagation and (b) PGD, triggered by active fault movements, landslides, liquefaction-induced settlement, or lateral spreading (Psyrras and Sextos, 2018). In engineering assessments, the impact of geological disasters on pipelines is defined not only by hazard type but also by quantifiable parameters. For seismic hazards, the maximum PGD and its spatial extent, peak ground acceleration (PGA), and the frequency spectrum of seismic waves govern strain concentration and potential buckling. For landslides and slope failures, slope gradient, soil shear strength, and pore water pressure ratio are decisive for mobilizing large displacements (Choudhury and Chaudhuri, 2023; Kiani et al., 2019; Wu et al., 2015). In frozen or permafrost regions, thaw settlement rate and active-layer thickness inform long-term deformation risk (Chai et al., 2020). Groundwater-driven liquefaction is characterized by cyclic stress ratio (CSR) and relative density, which influence settlement and lateral spreading (Cubrinovski et al., 2011). These parameters are often obtained from geotechnical site investigations, seismic monitoring networks, or remote sensing; however, in many regions, the data lack temporal resolution for capturing transient dynamic events. Regarding pipeline failure modes due to ground deformation, there are four typical damage conditions in continuous steel-welded pipelines: (i) shell-mode buckling, (ii) beam-mode buckling, (iii) pure tensile rupture, and (iv) section ovalization (Fig. 6b) (O'Rourke and Liu, 1999), where D_o and ΔD denote pipe external diameter before and after ovalization, respectively. Seismic wave propagation may cause additional axial stretching and damage to underground pipelines. The mechanical properties of soil can significantly affect the response of the pipe, especially in elbow regions. Thus, nonlinear springs are employed to evaluate the interaction between soil and pipe, considering slipping between them.

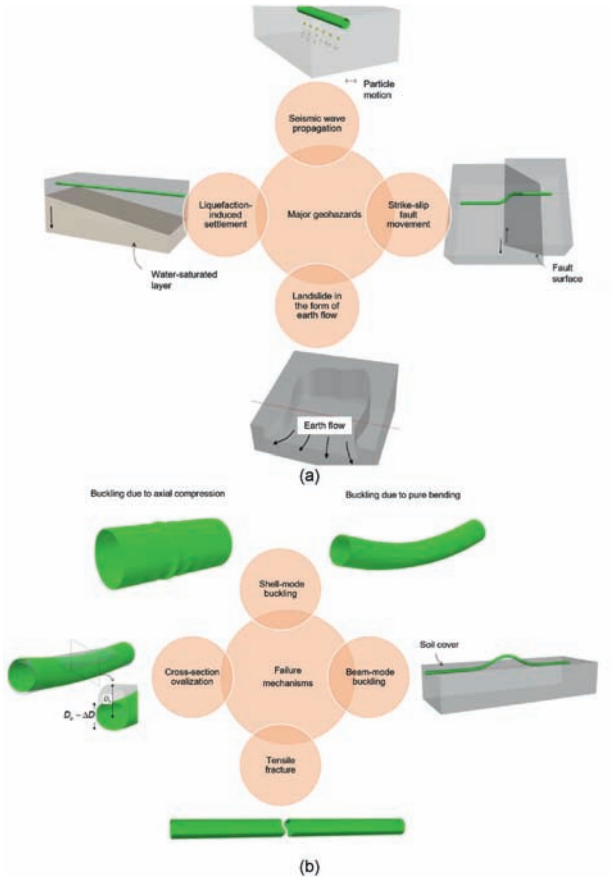


Fig. 6. Geohazard considerations extracted from (Psyrras and Sextos, 2018): (a) significant geohazards threatening the structural integrity of buried NG pipelines, (b) common failure mechanisms in buried, continuous steel pipelines.

Historical earthquakes, including the 1985 Michoacán (Mexico), 1989 Loma Prieta (USA), 1994 Northridge (USA), and 1995 Kobe (Japan) events, caused widespread pipeline failures. These were primarily linked to soil liquefaction in reclaimed or saturated deposits, large PGD, and shaking-induced joint separations (Berrones and Liu, 2003). The Trans Adriatic Pipeline (TAP) case in Albania demonstrates modern deterministic seismic hazard analysis (DSHA) for high-seismicity regions; broadband simulations revealed strong vertical ground motion components and static offsets at the compressor station, both critical for design verification (Moratto et al., 2021; Slejko et al., 2021). Empirical fragility relations for buried NG pipelines indicate a pronounced

Table 2
Classification framework of dynamic loads on energy pipelines.

Category	Trigger characteristics	Typical causes/examples	Representative structural effects
Environmental and natural loads	Geophysical or oceanographic processes; externally induced, non-anthropogenic	Seismic motion, landslide, liquefaction, ocean currents, waves, permafrost thaw	Ground deformation, buckling, ovalization
Mechanical loads	Operational or configurational; internally generated or periodic	Pressure cycling, thermal expansion/contraction, FIV, turbulence	Fatigue, thermal stress
Accidental loads	Sudden, unintended external impact events	Dropped objects, excavation hits, anchor strikes, explosions, collisions	Local denting, rupture, blast damage
Human-induced loads	Recurring or deliberate human activity, non-accidental	Overpressure operations, sabotage, flow-regime change causing vibration, maintenance-induced transients	Accelerated fatigue, corrosion, stress concentration

rise in loss-of-containment probability once peak ground velocity (PGV) exceeds roughly 30–50 cm/s, with observed repair rates for distribution networks in past earthquakes approaching 0.5–1.5 breaks per km under severe shaking (Lanzano et al., 2012; Tsinidis et al., 2019). At the facility scale, FE simulations of urban distribution stations indicate manifold connection stresses reaching 3.37 × the network average under seismic loading, a concentration that was reduced substantially through targeted retrofits (Wang et al., 2025).

Soil-pipe interaction investigated using FEA highlights the impact of seismic wave propagation on the non-linear interaction between soil and pipeline. Despite extensive research on the seismic performance of pile pipes, there are also papers focusing on energy pipelines subjected to seismic loads because they experience significant axial and transverse strains and displacements during seismic events, with the middle portions of the pipelines being particularly vulnerable. Nonuniform seismic excitations result in more enormous peak strains and uneven strain distribution along the gas pipeline than uniform excitations (Akshatha and Muranal, 2018; Dai et al., 2021; Lee et al., 2009). The type of soil and its characteristics play a crucial role in the seismic response of buried pipelines. Soft soils are particularly critical, leading to larger displacements and strains. The impedance contrast between different soil layers can amplify elastic strains, especially under low-frequency excitations, potentially generating local buckling (Dai et al., 2021).

Mitigation and preventive measures: The influential pipeline components for seismic resilience include flexible joints (Fig. 7a) to accommodate ground movement (EHASEFELX, 2019), reinforced ring-stiffeners (Fig. 7b) to prevent buckling (Shahandeh and Showkati, 2016), and corrosion-resistant coatings (Fig. 7c) to maintain integrity (Byrnes, 2017). Preventive measures involve site-specific seismic designs, including proper burial depth, flexible backfill materials, and seismic isolation system installation (Lanzano et al., 2014). Regular inspections, real-time monitoring, and early warning systems are critical for damage detection (Ma et al., 2023), while retrofitting older pipelines enhances their seismic performance (Fig. 7d) (Najafi and Gokhale, 2005). Route selection to avoid seismic hazards and using high-strength materials further reduce the risk of failure during earthquakes (Lanzano et al., 2014). In addition, trenchless repair technologies, such as cured-in-place pipe (CIPP) lining (Xia et al., 2022), sliplining (Rahmaninezhad et al., 2020), sectional replacement (Kaushal and Najafi, 2020), and robotic internal patching (Li et al., 2024; Lu et al., 2020), are increasingly applied for restoring buried pipeline integrity after geohazard damage without extensive excavation. Under ongoing dynamic loads, however, their performance can differ from static-load cases. For example, CIPP liners subjected to seismic aftershocks may experience cyclic ovalization and sliplined segments can develop annular gap migration under repeated PGD. Laboratory vibration-table tests and limited in-situ case studies indicate that joint interfaces, adhesive bonds, and liner modulus retention are critical to post-repair resilience. High-frequency dynamic excitation tends to accelerate coating delamination and lining fatigue (Zhao et al., 2024; Zhong et al., 2017). Seismic vulnerability assessments frequently apply analytical or empirical fragility curves to quantify the probability of failure at different intensity levels, informing risk-informed design and emergency planning (Lanzano et al., 2014). Both probabilistic and deterministic seismic hazard frameworks bridge seismological modeling with structural performance evaluation, allowing for site-specific mitigation strategies (Moratto et al., 2021). However, in many regions with critical infrastructure, high-resolution temporal datasets for transient events remain scarce, limiting precise modeling of TGD effects.

3.1.2. Ocean and marine loads

Risers and pipes are critical components in offshore oil and gas operations. As shown in Fig. 8, they are subjected to mechanical loads such as internal/external pressure, dead load, and various ocean and marine loads, including waves, currents, wind, and platform movements, which can induce vibrations and fatigue. Understanding the behavior of these structures under such conditions is essential for their design, reliability, and longevity. Marine risers experience Vortex-Induced Vibration (VIV) due to ocean currents and vessel movements, leading to fatigue and instability. Platform motion, riser suspension length, ocean load, and evacuation speed are critical factors for designing and operating complex suspension pipe strings, influencing the dynamic behavior of deep-water risers under emergency evacuation (Hosseinzadeh et al., 2024; Liu et al., 2018). Internally corroded risers under combined loads (axial tension and internal pressure) can be assessed for reliability using an analytical-numerical approach, which helps estimate failure probability and reliability index (Hu et al., 2014). Furthermore, the interaction between steel catenary risers (SCRs) and the seabed, particularly in the touchdown zone, is critical for fatigue assessment. Thus, experimental and numerical analyses contribute to understanding soil reaction and trench formation (Hodder and Byrne, 2010).

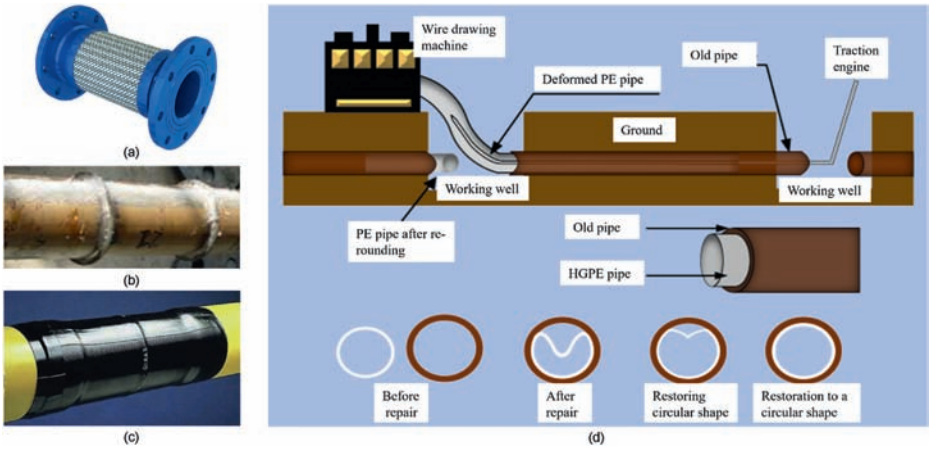


Fig. 7. Control and/or mitigation of pipeline's seismic response using: (a) flexible joints (EHASEFELX, 2019), (b) ring-stiffeners (Shahandeh and Showkati, 2016), (c) corrosion-resistant coatings (Byrnes, 2017), and (d) retrofitting techniques (Najafi and Gokhale, 2005).

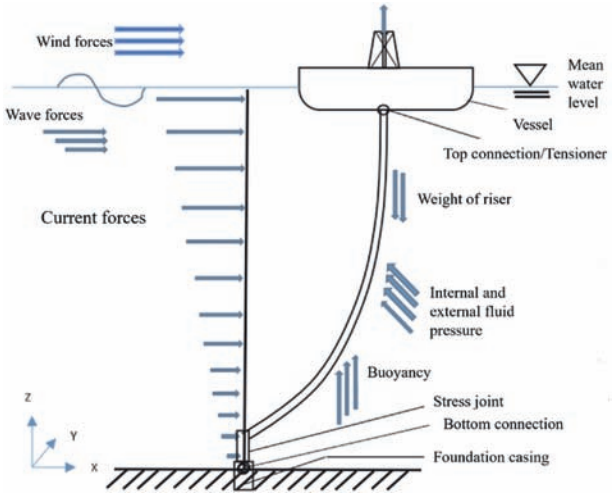


Fig. 8. Marine risers indicating various loading scenarios reproduced from literature (Amaechi et al., 2019).

Loads on marine risers are highly random and influenced by multiple factors. Probabilistic methods, including dynamic analysis and metamodels, help determine design loads based on influencing parameters. Two primary methods for quantifying the probabilistic distribution of loads on marine risers are dynamic riser analysis using site-specific metocean data and metamodel-based predictions using Monte Carlo (MC) simulations, with the latter contributing effectively to load description at low exceedance probabilities (Cabrera-Miranda and Paik, 2017). Time-domain random dynamic analysis using FEA can estimate the probabilistic distribution of bending stresses on marine risers, which uses the maximum likelihood method to assume a generalized gamma distribution for response statistics, providing insights into lifetime reliability and fatigue damage rates (Trim, 1990). Increased severity of sea conditions leads to higher stress responses and lower reliability, highlighting the importance of considering extreme scenarios (Sun et al., 2022). FE simulations and probabilistic models are also employed to assess the dynamic reliability of marine risers under extreme sea conditions.

Besides marine risers, offshore pipelines' dynamic response during deep-water operations is considerably influenced by sea states, including surface waves and ocean currents. These factors affect pipeline configuration, lateral displacement, axial tension, bending moments, and stress and strain distributions (Gong and Xu, 2016). Dynamic environmental loads during offshore pipeline installation, particularly in deep-water S-lay, can substantially exceed static analysis estimates. For example, coupled time-domain numerical modeling of a 22-inch gas export pipeline installation in the Pingbei-Huangyan oil and gas fields (East China Sea) showed that vessel motions, wave action, and other dynamic factors substantially influenced pipeline configuration, axial tension, and bending moments compared with static predictions (Gong and Xu, 2016). Similarly, for a 10-inch flexible pipeline being laid at a water depth of 3000 m, dynamic analysis showed that axial tension, bending moment, and stress-strain increased significantly under combined marine loads and vessel motions compared with static conditions, with surface waves exerting the most pronounced influence on pipeline response (Wang et al., 2020). Numerical simulations of freak waves, modeled using combined transient and random wave trains, showed that such extreme sea loads can induce pronounced short-duration increases in pipelay vessel motions and in pipeline axial tension, bending, displacement, and touchdown-zone embedment, highlighting significant risks for deepwater S-lay operations (Xu and Gong, 2020a). Time-domain simulations of a 1500 m-deep gas export pipeline installation in the South China Sea further showed that seabed soil characteristics and vessel motions induced by surface waves strongly affect pipeline bending capacity, embedment depth, and seabed resistance, thereby influencing fatigue performance (Gong and Xu, 2017). Parametric time-domain simulations based on real sea state data from the LW3-1 gas field showed that water depth, effective tension, stinger length, pipe diameter, and submerged self-weight all have a strong influence on deepwater S-lay pipeline dynamic behavior, with variations in these parameters significantly affecting maximum axial tension and bending moments, thereby reinforcing the need for site-specific dynamic analysis in installation design (Xu and Gong, 2020b).

The seawater layer influences the dynamic responses of offshore pipelines, suppressing vertical seafloor motions and affecting the propagation of waves. This results in different responses compared to onshore pipelines, with seawater depth and soil water saturation levels playing crucial roles (Bi et al., 2017). In addition, wave-induced pore pressures around subsea buried pipelines are critical for design considerations, affecting pipeline stability by altering the effective stress within the seabed soil. Excess pore pressure accumulation, driven by oscillatory and residual mechanisms, can weaken soil support, increasing the risk of pipeline settlement or displacement (Li et al., 2019). Advanced theoretical models based on Biot's consolidation theory help assess these effects under complex seabed conditions (Fu et al., 2024). Factors such as wave period, water depth, soil shear modulus, and pipeline configuration (e.g., burial depth and radius) significantly influence these pressure loads (Zhang et al., 2011). In addition, free spanning, a common issue in subsea pipelines, may occur due to seabed irregularities. Wavelet packet transform analysis can accurately identify free-span locations and lengths, enabling real-time monitoring and early detection of scouring damage (Li et al., 2018). The dynamic response of multi-span offshore pipelines is complex due to the interaction between adjacent spans. Simplified single-span methods are not valid for multi-spans, and semi-analytical techniques are developed to account for these interactions, which are crucial for accurate fatigue damage and load effect calculations (Sollund et al., 2014).

Mitigation and preventive measures: As shown in Fig. 9a, flexible couplings (Qingdao Judberd Machinery Co and L, 2024) tolerate platform movements, waves, and currents, while buoyancy modules (ceannews.com, 2017) presented in Fig. 9b help maintain the stability of steel lazy wave risers. Bend stiffeners depicted in Fig. 9c (Ltd, 2024) prevent stress concentration in curved sections, and passive devices like helical strakes mitigate VIV (Fig. 9d) (offshore, 2024), with spoilers mitigating VIV, and active control techniques using vessel movements addressing instability (Hong and Shah, 2018). Techniques such as fluid-bed powder coating further provide a thick, protective layer that adheres well to steel substrates, outperforming traditional techniques like galvanizing and painting in terms of longevity and effectiveness against corrosion (Teunou and Poncelet, 2005). Preventive measures involve route selection to avoid high-risk areas, dynamic analysis for wave-induced stresses, and real-time monitoring for early detection of fatigue or scouring damage.

3.1.3. Research gaps

Seismic fragility formulations indicate that pipelines are highly vulnerable to damage during earthquakes which trigger PGD and soil liquefaction, leading to abrupt stress concentrations at pipeline joints and potential fractures (Besstrashnov and Strom, 2011). Permafrost thaw induces uneven settlement, risking differential

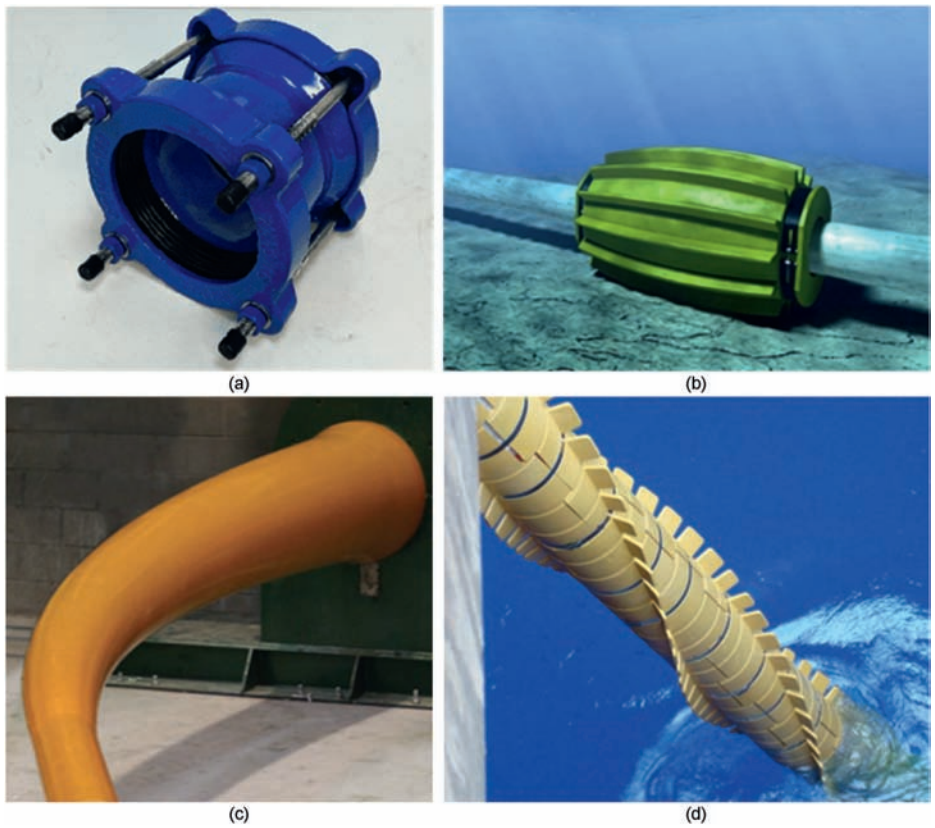


Fig. 9. Control and/or mitigation of offshore dynamic loads using: (a) flexible couplings (Qingdao Judberd Machinery Co and L, 2024), (b) buoyancy modules (oceannews.com, 2017), (c) bend stiffeners (Ltd, 2024), and (d) helical strakes (offshore, 2024).

deformation and leaks (Li et al., 2021c), and rockfalls generate dynamic impacts that exacerbate material fatigue. These challenges are amplified by aging infrastructure, where corrosion reduces seismic resilience (Huang et al., 2025). As such, addressing these loads is imperative to prevent irreversible socio-economic and ecological harm, necessitating advanced monitoring and adaptive designs to mitigate cumulative and immediate threats (Yu et al., 2022). A major gap exists in linking quantified geological-hazard parameters with post-damage repair effectiveness under repeat dynamic loading. While trenchless repair techniques offer rapid and non-disruptive restoration, there is insufficient experimental and field evidence on their long-term structural integrity in environments with recurrent seismic shaking, landslide movement, or thaw-settlement. Advances in this area will require coupled hazard-response datasets, full-scale cyclic-load testing of repaired segments, standardized protocols for testing trenchless repairs under multi-axis dynamic loads, and integrated geotechnical-structural reliability models to predict residual life after intervention.

Current seismic fragility frameworks are rich in empirical data but lack robust analytical and experimental foundations, necessitating further research for reliable damage assessment (Psyrras and Sextos, 2018). Furthermore, advanced numerical models and experimental setups, such as 3D parametric models and shaking table tests, are essential for understanding the complex interactions between soil and pipelines under seismic loads (Dai et al., 2021; Germoso et al., 2021; Shi et al., 2024). The impact of geological hazards like rockfalls on buried pipelines has been studied, but further research is essential to refine the theoretical models and improve the accuracy of predictions under various geological conditions (Dong et al., 2019). The influence of other natural phenomena, such as earthquakes and soil liquefaction, on pipeline integrity requires a more detailed investigation. Although there is significant work on the effects of hydrodynamic forces such as those induced by tsunamis and storm surges, there is a need for more comprehensive studies on the resistance and lift coefficients for pipelines in tsunami-prone areas (Ghodoosipour et al., 2019). Further research should be focused on the combined effects of tidal forces, currents, and wave action in offshore pipelines, especially in deep-water environments. Gaps also exist in understanding pipelines behave under permafrost melting or ice scouring in Arctic regions, with increasing exploration for oil and gas.

A key unresolved challenge lies in accurately characterizing multi-axis dynamic loads, which combine distinct physical fields and often magnify failure risks beyond the sum of individual effects. Combined earthquake and aging/corrosion scenarios have been shown to heighten local collapse probability, exacerbate stress concentration at welds or corroded segments, and in some cases precipitate rupture or explosions (Wang et al., 2025; Zheng et al., 2023). Similarly, combined effects of deep-sea pressure and thermal fluctuations can produce equivalent stress variations compared to decoupled analyses, accelerating instability and fatigue, particularly in gas-dominant multiphase flows (Iskanderov et al., 2024). While FEA, CFD, and multiphase coupling approaches have been used to model such effects, these methods face persistent bottlenecks: incomplete constitutive models for corroded materials and seabed soils, scarcity of full-scale multi-field experiments, excessive computational demands for high-fidelity simulations, and reliance on idealized boundary conditions (Liao et al., 2023; Lu et al., 2023; Shahrokhabadi et al., 2020). Addressing these limitations requires experimentally grounded

coupling models, scalable multi-physics solvers for real-time assessment, and integrated probabilistic frameworks that capture cascading risks in interconnected energy systems.

3.2. Mechanical and operational loads

Mechanical and operational loads significantly impact the integrity and reliability of oil and gas pipelines, arising from various sources, such as internal pressure variations, temperature changes, and external environmental factors, leading to fatigue and failure of pipeline materials. The following subsections review these loads.

3.2.1. Mechanical vibrations

Mechanical vibrations in pipelines are an important concern in various industrial applications, particularly those involving machinery and pulsating equipment. These vibrations can lead to structural damage, operational inefficiencies, and safety hazards. They primarily originate from high-pressure pulsations generated by fluid machinery (Zhang et al., 2021b), resonance phenomena (Zhang et al., 2019b), and the coupling of pressure pulsations with pipeline wall. External excitations and water hammer effects also play significant roles (Wan et al., 2024). High-pressure pulsations generated by turbomachines such as compressors and pumps are a primary source of pipeline vibrations, which can turn into shaking forces at elements like pipe bends and reducers, exciting vibrations in the connected piping network (Okasha et al., 2016). The periodic movement of pistons in reciprocating pumps causes fluid pressure pulsations, leading to pipeline vibrations that may cause instrument distortion, pipe failure, and equipment damage (Lu et al., 2018). Excessive vibrations often occur when the natural acoustic frequency of the piping system is excited by pulsations or mechanical sources, leading to resonance and, as such, significant damage if not controlled (Bettaieb and Haj Taieb, 2017). If the source pulsation frequency coincides with one of the natural frequencies of the piping network, resonance will magnify the vibrations, potentially inflicting severe damage to the system and foundation (Okasha et al., 2016). The interaction between pressure pulsations and the pipeline wall can lead to forced vibrations, with this coupling effect being a critical factor in the overall vibration behavior of the pipeline system. The vibration amplitude of pipelines increases with thermal stresses, particularly for the high fluid temperature, influencing the vertical vibration amplitude considerably (Lu et al., 2018; Tian et al., 2016). External excitations and fluid pulsations contribute to multi-dimensional vibrations in pipeline structures, affecting transportation efficiency and leading to accidents, along with water hammer, which occurs by sudden changes in fluid flow, inducing resonance in pipelines and subsequently exacerbating vibration issues (Wang et al., 2023a; Xu et al., 2019).

Mitigation and preventive measures: Fig. 10 shows four devices which are typically employed to control the vibration of pipelines. Devices like multi-dimensional vibration isolation and mitigation devices (MVIMD) shown in Fig. 10a, which use viscoelastic (VE) materials and U-shaped springs, can effectively isolate and mitigate vibrations in multiple dimensions, addressing horizontal and vertical vibrations (Ding et al., 2024). VE components denote VE elements composed of polymeric materials that simultaneously provide elastic restoring force and viscous energy dissipation under dynamic loading, improving vibration reduction and impact resistance (Kumar et al., 2025). Multi-cavity particle dampers (MPD) have shown significant damping effects, reducing vibration responses by up to 98% in resonant cases. These dampers effectively control horizontal vibrations in pipeline structures (Wang et al., 2023a). Pulsation suppression devices can be designed and inserted into pipeline networks to reduce pressure pulsations, a primary cause of mechanical vibrations, predicting and controlling pulsations for safer operation (Okasha et al., 2016).

A combination of passive and active control technologies, including optimal layout techniques, constrained layer damping, vibration absorbers, and hydraulic hoses, can control vibrations in hydraulic pipeline systems (Peixin et al., 2021). In the case of pump-induced vibrations, using variable frequency drives (VFD) in main pumps can reduce cyclic loading on pipelines, enhancing their operational lifespan (Anvar et al., 2019). Active damping methods, including vibration-isolating junctions and expansion joints, can significantly reduce vibration transfer from power plants to pipelines. Tuned mass dampers (TMD) are designed based on modal and harmonic analysis to optimize their performance in mitigating vibration and effectively reducing resonant vibrations in pipeline structures. When the pipe vibrates, the TMD oscillates out of phase, absorbing and dissipating the vibrational energy. Recent advances have integrated magnetorheological (MR) technology into TMDs (Fig. 10c), enabling semi-active control for more adaptable and effective vibration attenuation (Rohith et al., 2022; Wu et al., 2025). The MR composite refers to a magnetorheological elastomeric mixture containing ferromagnetic particles embedded within a flexible polymer matrix, whose dynamic modulus can be tuned by applying a magnetic field generated by the excitation coil (Kang et al., 2020). Pipe-in-pipe (PIP) systems shown in Fig. 10d consist of concentric inner and outer pipes, and can be used as a structure-tuned mass damper system, effectively mitigating seismic-induced vibrations in subsea pipelines (Bi and Hao, 2016). Proper design and placement of supports can alter the frequency of the pipeline, reducing vibrations, which is particularly useful in addressing vibrations caused by reciprocating compressors (Lu et al., 2018). Devices designed for passive quenching of pressure pulsations in pipelines with two-phase flow can reduce vibro-displacement by influencing the flow patterns of the coolant (Hossain et al., 2018).

3.2.2. Thermal loads

Thermal loads in pipelines result from environmental temperature variations, operational shutdown, and the shutdown/restart process. The temperature profile along the pipeline during shutdown and restart shows distinct characteristics, with two stages of temperature evolution due to the movement of cold and hot oil (Wei et al., 2018). The freezing and thawing cycles around buried pipelines can adversely affect their stability and integrity in cold regions, and heat flux from buried warm oil pipelines can accelerate permafrost thawing in permafrost regions, leading to structural instability. For seabed pipelines, thermal expansion and lateral buckling due to significant temperature changes require accurate modeling of pipe-soil interaction to ensure structural integrity (White and Cheuk, 2008). Apart from environmental factors, conveying fluid can cause thermal loads. Crude oil's dynamic viscosity is highly temperature-dependent, and minor temperature reductions can substantially increase viscosity, affecting flow rates and energy consumption; therefore, mechanical heating due to viscous dissipation also contributes to the thermal load within the pipeline (Wang et al., 2019).

Mitigation and preventive measures: Pipelines exposed to temperature fluctuations require robust thermal expansion joints to mitigate temperature variations. Fig. 11 shows different types of expansion joints with typical applications. Conventional thermal expansion joints typically consist of several key components: bellows, which are flexible, corrugated elements that absorb axial, lateral, or angular movements; end fittings such as flanges or weld ends that connect the joint to the pipeline; tie rods or control rods, which limit excessive axial movement; limit stops to define the

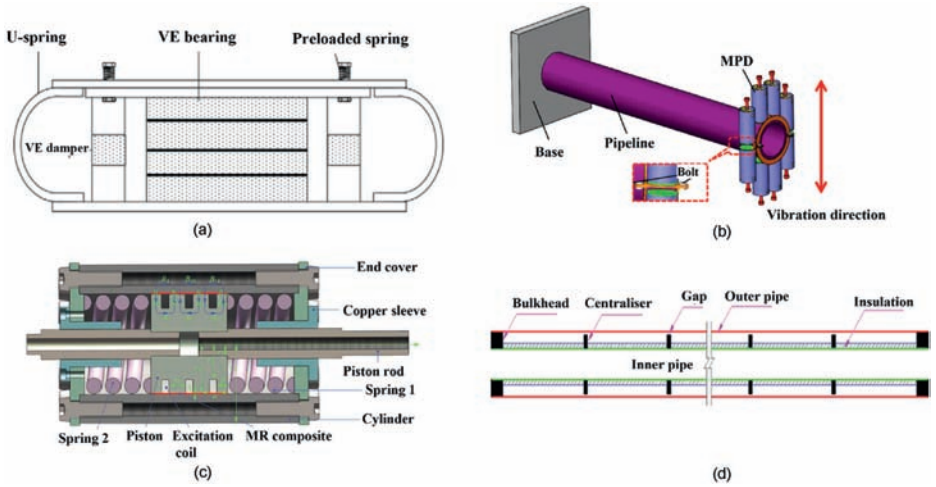


Fig. 10. Typical vibration control devices for pipelines: (a) MVIMD (Xu et al., 2019) (b) MPD (Wang et al., 2023a) (c) TMD (Wu et al., 2025) (d) PIP (Bi and Hao, 2016).

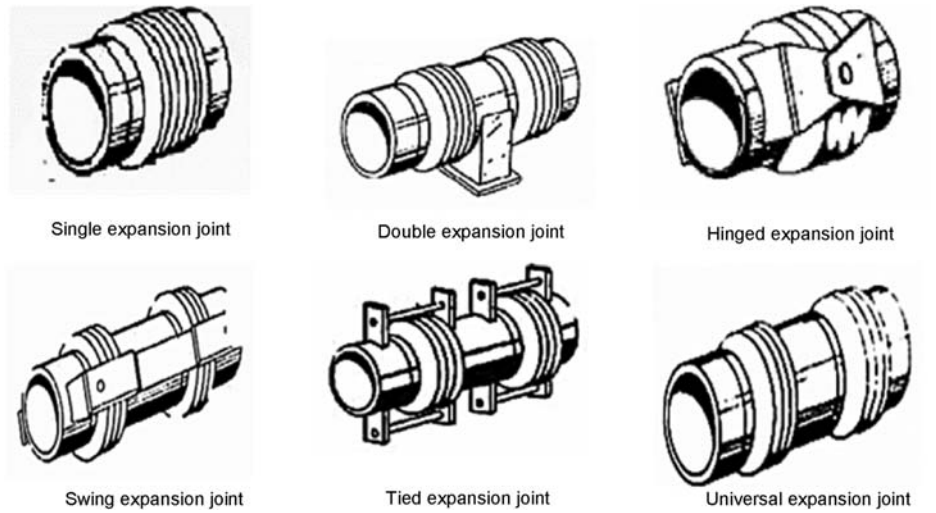


Fig. 11. Mechanical solutions for thermal expansion mitigation using expansion joints (Wankhede and Gawande, 2023).

maximum allowable movement; internal sleeves (liners) to protect the bellows from internal flow; and optional external covers or insulation for environmental protection. These components work together to accommodate thermal expansion in pipelines while maintaining structural integrity and preventing leaks (Stewart, 2016b). A tube is encircled by a ring connected to a sleeve in newly developed expansion joints. One end of the tube is linked to a pipeline, while one end of the sleeve is connected to another section of the pipeline. The tube, ring, and sleeve can move axially when the pipeline expands or contracts linearly. A seal between the ring and the tube guarantees the presence of a fluid-tight joint (Chase et al., 2017).

In addition, materials with low thermal expansion coefficients and high resistance to temperature extremes should be used (Hetnarski et al., 2019), and increasing burial depth protects pipelines from surface temperature fluctuations (Oh et al., 2014), maintaining more stable operational temperatures. Insulation and thermosyphons can help mitigate permafrost thawing effects by heat transfer management (Chen et al., 2021b). As for operational shutdown and restart processes, temperatures decrease during shutdowns, causing thermal contraction, while rapid heating during restarts can induce thermal expansion (Wei et al., 2018). Expansion loops (Fig. 12), bends, and stress-relief joints can accommodate this (Bertulessi et al., 2023). Temperature sensors and fiber-optic cables can be used along the pipeline to continuously monitor thermal loads, providing data to be fed into control systems to adjust operations as needed (Inaudi and Glisic, 2010).

3.2.3. Research gaps

Pipeline systems are increasingly challenged by the combined effects of mechanical vibrations, pressure pulsations, and thermal loads, serious in extreme environments, such as subsea, high-loads, which can lead to material fatigue, joint failures, and overall system degradation (Shemshadi et al., 2020). These challenges become critical with thermal, and permafrost conditions, where conventional design and predictive models often fail to capture the complex interplay of dynamic loads (Victorovna, 2018). Development of predictive models and adaptive monitoring technologies is essential for enhancing pipeline performance and mitigating potential hazards. Most studies focused on passive and active vibration control methods like TMDs, vibration isolation devices, and pulsation suppression systems for mechanical vibrations. However, more hybrid solutions should be explored to combine these approaches for improved efficiency under varying operational conditions. Research on predictive models that account for fluid-structure interaction (FSI) and external excitations in

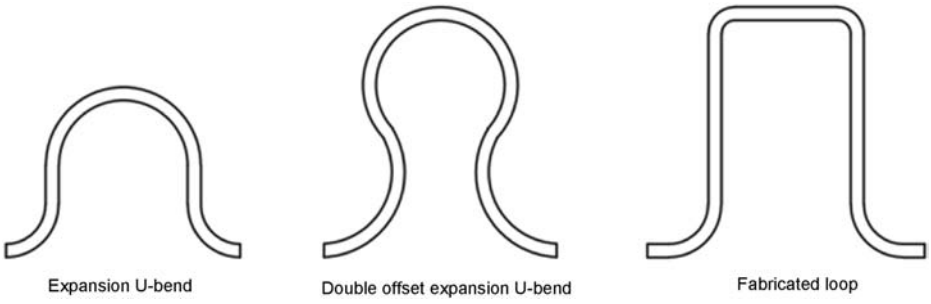


Fig. 12. Mechanical solutions for thermal expansion mitigation using expansion loops (Stewart, 2016a).

complex pipeline networks remains insufficient. For thermal loads, while extensive research has examined the effects of environmental temperature variations and operational changes, the long-term impact of thermal cycling on material fatigue and fracture resistance needs further investigation, particularly in permafrost and deep-sea conditions. Moreover, the development of adaptive insulation systems and smart monitoring technologies for more precise real-time control of thermal expansion and contraction is a promising area that requires further study to improve pipeline longevity.

3.3. Impact and accidental loads

3.3.1. Dropped objects and collisions

Dropped objects and collision loads pose significant risks to the integrity and safety of oil and gas pipelines. These incidents can occur during various phases, such as installation, construction, and operation, leading to potential damage, leaks, and even catastrophic failures. Internal pressure in pipelines can reduce the depth of impact dents, making deformation more localized (Wang et al., 2016b). However, dropped objects from platforms or supply vessels can cause serious damage to marine pipelines, resulting in local deformation and fractures (Odina et al., 2018). Factors such as drop angle, drag coefficients, and rolling frequency determining the trajectory and landing points of the objects influence the impact of dropped objects (Edmollaii et al., 2019). Probabilistic analyses facilitate the safety assessment of subsea pipelines under different accidental scenarios, including transverse loading and external forces (Jiang et al., 2019). Risk assessments following procedures like DNV-RP-F107 help predict impact-energy capacity of pipelines and establish acceptance criteria for damage, such as limiting dent-depth ratios (Odina et al., 2018).

Mitigation and preventive measures: Practical pipeline components for mitigating dropped objects and collision loads include protective barriers such as concrete mattresses (Fig. 13a) (Specialists, 2024), rock berms (Fig. 13b) (Intecsea, 2024), and steel cages (Fig. 13c) (Besta, 2018), which can absorb impact energy and prevent direct damage to pipelines. Impact-resistant polyurethane coatings (Fig. 13d) (2024), and thicker wall designs enhance durability against localized deformation. Preventive measures involve careful planning of pipeline routes and avoiding high-risk areas like active construction zones or vessel traffic corridors. Real-time monitoring systems and dynamic positioning of vessels can reduce the likelihood of collisions, ensuring adherence to safety guidelines, and proper impact assessments and damage criteria (Waskito et al., 2020).

3.3.2. Anchor and vessel impacts

The impact of anchors and vessels on energy pipelines is a critical concern in offshore engineering, which arises due to the increasing construction of submarine pipelines and the corresponding increase in shipping activities, with anchoring operations caused by vessel motion. Mathematical models for ordinary and emergency anchoring were developed to determine the required burial depth of submarine pipelines, considering anchoring height, water depth, and weight to calculate the necessary burial depth to protect pipelines from anchor impacts (Zhuang et al., 2016). Offshore pipelines subjected to anchor impacts experience complex loadings, which can lead to cracking and potential failure. The connection of floating production vessels to subsea pipelines introduces dynamic loads due to vessel motion, necessitating hold-back anchors or sufficient run-out lengths to maintain pipeline integrity (Reda et al., 2019). Studies involving three-point bending tests and numerical simulations have been conducted to characterize the material behavior and predict pipelines responses under impact loads (Manes et al., 2012). Laboratory experiments and FEA were used to study the interactions between pipelines, soil, and rock under anchor impact scenarios, indicating that increased height of rock berms can significantly reduce the stress on pipelines, similar to increasing the burial depth (Shin et al., 2020).

Mitigation and preventive measures: Rock berms (Wang et al., 2024b) and concrete mattresses (Tawekal and De Velas, 2019) are used for pipeline protection against impact loads caused by vessels and anchors, absorbing impact energy and shielding pipelines. Moreover, increased burial depths are essential to prevent direct anchor strikes. Flexible joints and couplings can accommodate dynamic loads from floating vessels, whereas pipeline protection systems like trenching or casing provide further defense (Chaloulos et al., 2015). Preventive measures include careful routing of pipelines away from heavy shipping lanes, real-time monitoring systems to track vessel movements, and the implementation of exclusion zones around pipelines. Regular inspections and maintenance also ensure ongoing protection against anchor and vessel-related damage.

3.3.3. Blast and explosion loads

Blast and explosion load on pipelines originate from various sources, including underground and surface explosions, construction activities, and internal pipeline failures. Buried pipelines can experience transversal vibrations and damage due to underground explosions, modeled as point loads that decrease exponentially over time (Nourzadeh et al., 2011). Surface explosions, such as those from terrorist attacks or disasters, can impose significant dynamic loads on buried pipelines, affecting their structural integrity (Tang et al., 2020). Blasting activities in construction, quarrying, and mining can induce ground vibrations that impact nearby pipelines. These vibrations are often conservatively limited due to a lack of standardized guidelines (Gad et al., 2007). Explosions within pipelines, caused by defects, third-party damage, or geological disasters, can lead to chain reactions affecting parallel pipelines (Xu et al., 2011). Field experiments and

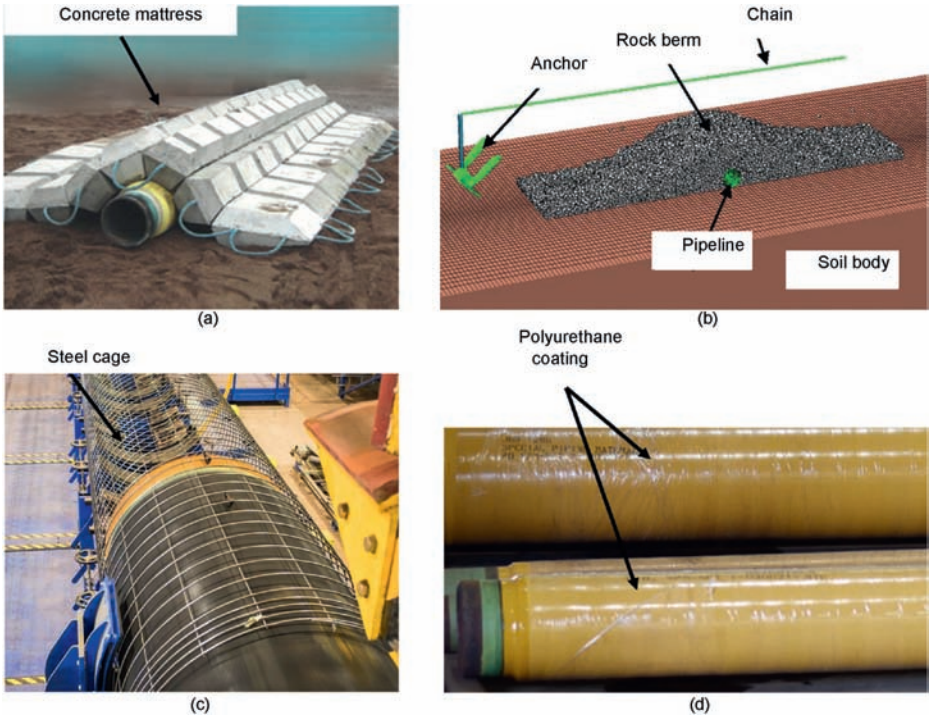


Fig. 13. Protection of pipelines against impact loads using (a) concrete mattresses (Specialists, 2024), (b) rock berms (Intecsea, 2024), (c) steel cages (Besta, 2018), and (d) polyurethane coatings (2024).

dynamic strain monitoring are employed to study the impact of surface explosions on buried pipelines, establishing safety parameters and damage prevention measures. Experimental investigations provide valuable data on the deformations of pipelines and failure modes under localized blast loading, enabling the validation of numerical models (Tang et al., 2020). In addition, researchers developed various analytical methods to calculate strains in buried pipelines due to surface point-source blasts, considering wave propagation and soil conditions (Kouretzis et al., 2007). Numerical simulation of buried pipelines under explosion using techniques like the Arbitrary Lagrangian-Eulerian (ALE) method reveals that soil density substantially affects the pressure and stress transfer to buried pipelines (Parviz et al., 2017). FEA was used to evaluate the blast response of pipelines, including the effects of internal pressure, stand-off distance, and explosive quantity, confirming that the wall thickness and diameter of pipelines play a crucial role in their deformation and failure mechanisms under blast loading (Song et al., 2016). The response of pipelines to blast loading varies with material properties, such as the elasto-plastic behavior of steel and polyethylene pipelines and the use of composite materials like glass fiber reinforced polymer (GFRP).

Mitigation and preventive measures: Using thicker walls and high-strength materials like steel or composite reinforcements like GFRP can enhance resistance to dynamic pressures (Hajiazizi and Kakaei, 2018). Moreover, applying protective barriers like GFRP blankets and improved soil conditions around buried pipelines helps absorb and disperse blast energy. Meta-material layouts for above-ground steel pipes demonstrate a significant reduction in maximum displacements during blast loading, indicating their potential for adequate blast protection (Kontogeorgos and Fuggini, 2023). Regarding preventive measures, the strategic selection of pipeline burial depth helps avoid high-risk areas prone to explosions, with real-time monitoring systems detecting abnormal internal pressures or external activities that could cause explosions (Olmati et al., 2017). Design standards should incorporate detailed blast load simulations to ensure pipeline resilience.

3.3.4. Research gaps

Pipeline safety is critically challenged by dynamic impact damage and accidental loads, particularly at vulnerable girth welds where mechanical stress, material properties, and environmental conditions converge to induce immediate or delayed failures. Under high-pressure operations and extreme environmental scenarios, the interaction of these complex loads can initiate crack propagation and compromise structural integrity. Moreover, limitations in current detection methods, such as Magnetic Flux Leakage (MFL) inspection, and the inability to quantify diverse risk indicators, including welding defects and external pressures, create significant gaps in existing safety measures (Dong et al., 2019; Feng et al., 2019). This emphasizes the urgent need for advanced, real-time systems to enhance detection, risk assessment, and preventive strategies in pipeline operations. The study of impact and accidental loads on pipelines has highlighted several research gaps. Although there are studies regarding the probabilistic and numerical modeling of accidental scenarios, such as dropped objects on subsea pipelines (Jiang and Dong, 2022; Kawsar et al., 2015; Li et al., 2023), more work is needed to develop comprehensive safety measures and risk mitigation strategies. Design standards and guidelines for protecting pipelines from dropped object impacts are often based on simplified assumptions, which necessitate more comprehensive analysis and design considerations (Yang et al., 2023). Dynamic impact damage, particularly on pipeline girth welds, is another critical area that lacks systematic research methods and comprehensive studies (Nie et al., 2020). Developing experimental and theoretical frameworks to better understand pipeline behavior under dynamic impact loads is essential for improving safety evaluations and protection systems. There is a gap in analyzing worst-case scenarios for pipeline ruptures due to accidental impacts and

their subsequent dynamic response under high pressure (Liu and Ortega, 2023). Although real-time acoustic monitoring of pipelines has been promising (Ni et al., 2024), there remains an incomplete understanding of signal propagation and fluid flow effects in energy pipelines, limiting the development of robust, automated detection and prevention systems capable of averting rupture or failure under accidental impact loads.

3.4. Human-induced loads

3.4.1. Transport and installation

Human-induced loads on energy pipelines during transport and installation stem from multiple sources. Surface loads from illegal buildings in urban areas can cause ground subsidence and pipeline deformation, leading to potential leakages and explosions. Ground overloads, such as those from heavy equipment or construction activities, can cause significant stress and deformation in buried pipelines. The stress distribution and deformation patterns depend on the load magnitude, pipeline parameters, and surrounding soil properties (Zhang et al., 2016). Traffic-induced vibrations can propagate through the soil and impact buried pipelines, generating dynamic stress and potential fatigue failure. However, compared to other factors, traffic-induced vibrations have a relatively minor impact on pipeline lifetime (Bajcar et al., 2012). Loads caused by heavy vehicles were studied, primarily focusing on static assumptions, necessitating more dynamic analyses to simulate real-world conditions better (Khademi-Zahedi and Alimouri, 2018). Reliability models can help assess the impact of loads from illegal buildings on pipeline safety (Peng et al., 2023).

Mitigation and preventive measures: Reinforced pipeline materials and protective coatings reduce the risk of damage during handling and positioning, with proper burial depth and trench boxes or padded sleeves preventing deformation from surface loads or heavy equipment. Techniques such as trenching, burial, and discrete dumping effectively prevent upheaval buckling and ensure the structural integrity of buried pipelines (Liu et al., 2012). Vibration-damping materials and supports can mitigate the impact of traffic-induced vibrations on buried pipelines, although their effects are generally minor. Devices incorporating viscoelastic bearings and dampers show high energy dissipation capacities, effectively controlling horizontal and vertical vibration (Xu et al., 2019). Metal rubber materials can also be optimized for stiffness and energy dissipation, making them suitable for practical applications in pipeline support design (Lazutkin et al., 2017).

3.4.2. Accidental impacts during operation

Accidental impacts on oil and gas pipelines during operation can lead to significant safety and environmental risks. These impacts can result from various human activities, including dropped objects, poor safety practices, and third-party intrusions. Dropped objects cause external impact loading, potentially compromising the integrity of subsea pipelines. Risk assessments and FEA evaluate the structural response and ensure safety measures are in place to mitigate damage (Kawsar et al., 2015; Odina et al., 2018). Human factors, such as inadequate safety training, poor risk management, and failure to report unsafe conditions, significantly contribute to pipeline accidents. Dynamic models incorporating the Human Factor Analysis and Classification System (HFACS) and Bayesian networks contribute to understanding and mitigating these risks (Zarei et al., 2019). Third-party intrusions, accidental and intentional, pose substantial risks to pipeline integrity.

Mitigation and preventive measures: Implementing a multidimensional pipeline protection system, which includes legal regulations and comprehensive safety measures during design, construction, and operation, can effectively prevent hazards associated with accidental impact loads and provide early warnings for accidents (Hu et al., 2022). Techniques like electromagnetic detection and satellite positioning can prevent third-party damage by detecting the magnetic field around pipelines and locating excavation equipment relative to the pipeline network (Lothon and Akel, 1996). Regular inspections using advanced Non-Destructive Testing (NDT) techniques, such as Ultrasonic Testing (UT), help detect early damage before it becomes critical. Acoustic technology, such as the PipeLIDS system, detects noise from impacts or leaks in onshore pipelines, employing acoustic sensors and Global Positioning System (GPS) synchronization to locate and raise alarms for accidental events (Mabily and Lehning, 2016). Enhanced safety training and implementation of risk management systems, such as HFACS, improve operational safety. Probabilistic risk assessments and game-theoretic models contribute to identifying high-risk areas and planning interventions to prevent accidental impacts during operation (Cui et al., 2020).

3.4.3. Research gaps

Human-induced loads resulting from construction activities and intentional attacks pose significant risks to pipeline integrity. The security and resilience of pipelines against intentional threats were studied; however, more guidelines and investigations are required to address these issues comprehensively (Chen et al., 2021a). Previous studies examined the effect of human activities, such as vehicle rollovers and other mechanical impacts on pipelines using FE models (Ma et al., 2024; Zhang et al., 2022; Zhou and Zhang, 2022); nevertheless, further research is needed to ensure an understanding of the long-term effects, and to develop more robust design and protection measures (Song et al., 2010). More accurate risk assessments and mitigation strategies should be developed for the interaction between the pipeline and the surrounding soil under traffic-induced dynamic loads. A promising solution for addressing human-induced threats is the deployment of Structural Health Monitoring (SHM) systems, which integrate sensing, data acquisition, and analysis to provide continuous condition awareness. Modern SHM solutions employ distributed fiber-optic sensing (DFOS) and distributed acoustic sensing (DAS) for real-time detection of strain variations, acoustic events, and vibrations along the entire pipeline length (Liu et al., 2016). These systems can differentiate between benign and hazardous events (e.g., localized construction vibration vs. excavation impact) when combined with Internet of Things (IoT)-based platforms that aggregate and process sensor data remotely (Zhou et al., 2022; Zuo et al., 2020). SHM techniques have also been applied for pattern recognition of third-party activities, ground movement detection, and early leak identification (Lee et al., 2025; Li et al., 2021a), enabling proactive intervention before structural compromise occurs. As summarized in Table 3, they offer much higher long-term cost-efficiency and diagnostic resolution than traditional inspection and Supervisory Control and Data Acquisition (SCADA)-based monitoring approaches. Conventional techniques, such as manual inspection and pressure testing, are inexpensive to install (1000–2000 USD/km).

However, conventional techniques provide only discontinuous data, require intensive labor, and have low sensitivity to early defects, leading to delayed damage detection (Chmelko et al., 2020; Liu et al., 2019; Sekhavati et al., 2022). In contrast, SHM systems using DFOS and DAS provide continuous coverage and deliver sub-meter spatial resolution and real-time response. These systems can reduce maintenance costs by more than 60 % and extend inspection intervals to once per decade (Bednarz et al., 2021; Chen et al., 2023b; Muggleton et al., 2020; Tan et al., 2024; Wong et al., 2018). The initial capital investment is

Table 3
Comparative cost and performance assessment of monitoring technologies for energy pipelines.

Monitoring method	Typical installation cost (USD/km)	Maintenance and calibration	Detection resolution ad coverage	Response time	Benefit-cost ratio (10-30-year lifecycle)	Articles
Manual inspection and pressure testing	1000–2000	High (frequent field labor)	Low-localized only; no continuous sensing	Days-Weeks	1.0–1.5	Chmelko et al. (2020)
Conventional SCADA and discrete sensors	3000–8000	Moderate	Medium-pressure/flow anomalies; limited spatial extent	Minutes-Hours	1.5–2.0	(Liu et al., 2019; Sekhavati et al., 2022)
Distributed Fiber-Optic Sensing	10000–25000	Low-automated calibration	High-strain/acoustic localization <5 m along full length	Seconds-Minutes	2.5–3.5	(Bednarz et al., 2021; Tan et al., 2024; Wong et al., 2018)
Distributed Acoustic Sensing (DAS)	12000–28000	Low-Moderate	High-acoustic and vibration signatures <5 m; full coverage	Seconds	2.8–4.0	(Chen et al., 2023b; Muggleton et al., 2020)
Hybrid IoT-integrated SHM (DFOS + edge sensors)	20000–30000	Low	Very High-multimodal sensing <1 m; predictive analytics	Real-time	3.5–5.0	(Wang et al., 2024a; Özdemir and Kömeç Mutlu, 2024)
Unmanned aerial or ground vehicles (UAV/UGV)	5000–12000	Moderate	Medium-visual/thermal limited to accessible sections	Hours	1.8–2.5	(Karkoub et al., 2021; Kovács et al., 2017)
Wireless sensor network (WSN-based SHM)	8000–15000	Moderate	Medium-High - distributed static nodes	Minutes	2.0–3.0	(Buckley et al., 2021; Sofi et al., 2022)

remarkable, typically 5–10 times that of traditional techniques (10000–28000 USD/km), but strong benefit-cost ratios (2.8–4.0) compensate for this, with benefits of lower failure rates, fewer service interruptions, and reduced environmental liabilities. Hybrid IoT-integrated SHM frameworks increase cost-benefit margins. By combining distributed sensing with edge analytics for adaptive monitoring and predictive diagnostics. Over a 30-year lifecycle, economic surveys show that data-driven SHM systems reach payback within less than a decade. They outperform conventional SCADA in reliability and operational sustainability Thus, while their upfront costs are higher, advanced SHM technologies offer a strong economic and performance advantage, making them a compelling choice for next-generation pipeline resilience strategies (Wang et al., 2024a; Özdemir and Kömeç Mutlu, 2024).

Despite these advances, persistent challenges limit large-scale adoption of SHM techniques. Signal attenuation and noise hinder detection of weak or transient events over long distances. Complex terrain and buried configurations make optimal sensor placement difficult, and environmental factors (temperature cycles, soil moisture, salinity) can degrade sensor performance (Liu et al., 2016; Surace, 2021). Real-time processing is further constrained by data transmission speeds, the need for robust algorithms to minimize false alarms, and the absence of standardized protocols for evaluating SHM performance under combined load conditions (e.g., human-induced vibration coinciding with seismic tremors). Financially, high installation costs, particularly for retrofitting existing lines, remain a key barrier (Singh et al., 2021). Addressing these limitations requires research into resilient, low-power sensing hardware, advanced data fusion methods for integrating multiple monitoring modalities, and field-validated benchmarks for SHM reliability in operational pipeline networks.

More studies should focus on the impact of nearby construction, drilling, and transportation infrastructure vibrations on pipeline integrity over time. It is also necessary to explore the cumulative impact of human-induced loads, such as operational overpressurization combined with construction activities, on long-term pipeline safety and the dynamic failure modes of pipelines. In addition, the current focus on isolated defect types rather than a comprehensive risk assessment, especially regarding the integration of human-induced loads with other degradation mechanisms, reveals a significant gap in existing monitoring strategies, underscoring the need for scalable, integrated solutions to enhance pipeline safety and reliability in complex operational settings (Ma et al., 2021; Zhang et al., 2023).

4. Pipeline integrity under dynamic loads

The integrity of energy pipelines is a critical concern due to the potential for catastrophic failures resulting from defects such as corrosion, cracks, and dents. Table 4 summarizes some research on dynamic loads affecting the integrity of pipelines, covering a range of load types such as impact loads, seismic waves, dynamic tensile loads, and cyclic pressure. The mentioned studies explore diverse topics, including thermal buckling (Zhang et al., 2025), anchor impact damage (Hou et al., 2025), life-extension performance (Savari, 2025b), rockfall-induced fatigue crack growth (Xie et al., 2024), fracture analysis (Singh et al., 2023), fatigue failure (Li et al., 2021b), and seismic response (Han et al., 2022). Significant findings indicate that factors like heat input, corrosion, pipeline spacing, and operational vibrations significantly affect pipeline integrity. However, several limitations are noted, such as focusing on specific conditions or materials, reliance on controlled experiments, and requiring further field validation.

Finite Element Method (FEM) was employed in a variety of applications for structural integrity evaluation of pipelines. A new procedure for the burst pressure assessment of corroded pipelines using FEM was introduced, generating FE models from field inspection data and performing nonlinear analyses to obtain failure pressures, with MC simulations used to calculate statistical properties of burst pressure (Marques Ferreira et al., 2021). The structural integrity assessment procedure (SINTAP) was employed to evaluate the structural integrity of X52 gas pipes with external corrosion defects using FEM, comparing the SINTAP predictions with other assessment methods and demonstrating its applicability for a wide range of defect geometries (Adib-Ramezani et al., 2006). The dynamic crack growth in full-scale gas pipelines analyzed using FEM with a cohesive zone model revealed the dependence of crack-tip-opening angle on crack growth speed and highlighted the significant three-dimensional effects due to pipeline wall thickness (Yu et al., 2018). Nonlinear FEM analyses simulating the dynamic stress conditions of tubular segments in SCRs provided a detailed depiction of dynamic stress distribution,

Table 4
Summary of fundamental research on pipeline integrity under dynamic loads.

Year	Theme	Load type	Key findings	Limitations	Articles
2025	Vertical thermal buckling of high-temperature, high-pressure submarine pipelines	Thermal expansion	- Analytical/FEM models for varied seabed conditions - Buckling height/length ↑ with area; seabed strength affects embedment	- Lateral buckling not assessed - Limited field validation	Zhang et al. (2025)
2025	Anchor impact damage on subsea pipe-in-pipe systems	Anchor drop impact	- Damage governed by impact energy, not mass/velocity separately - Stronger, thicker, larger pipes + centralizers/bulkheads mitigate damage	- Results specific to DNV-RP-F107; no corrosion/combined loads	Hou et al. (2025)
2025	Crack assessment of spiral-welded pipelines with composite sleeves	Cyclic pressure	- Composite sleeves extend fatigue life, especially deep cracks - Larger diameters more brittle; effect varies by geometry	- No residual stress modeling; deterministic approach only	Savari (2025b)
2024	Fatigue crack growth under rockfall impact via Multi-Layer Perceptron (MLP)	Rockfall impact	- Stress Intensity Factor (SIF) impact ratio predicts crack growth; velocity most critical - MLP + Paris' law gives high accuracy	- Ignores operating pressure; linear elastic assumption	Xie et al. (2024)
2023	Dynamic fracture toughness of X80 pipeline steel welded joints under varying heat inputs	Impact load (from Charpy impact tests)	- High Heat Input (HHI) reduces fracture toughness due to coarser grain structure - Medium Heat Input (MHI) provides balanced toughness - Low Heat Input (LHI) increases martensite and bainite, lowering toughness in some areas - Fusion Line (FL) + 2 mm and FL + 3 mm showed better toughness in all cases	- Tested only at −20 °C - Limited heat inputs tested - Relies on Charpy impact tests - Focuses on specific weld locations	Singh et al. (2023)
2022	Dynamic behavior of buried gas pipelines under blasting seismic waves, focusing on pipe connection forms	Blasting seismic waves	- Peak strain increases as distance from the blast source decreases - Flange joints show higher Peak Particle Velocity (PPV) and stress concentration than pipelines without interfaces - Flange bolts are vulnerable to blasting vibrations - Flange deflection angle is a key failure criterion	- Specific to bolted flange joints and may not cover other joint types - Limited to seismic wave effects; other dynamic loads not studied - Focuses on a 1-m diameter pipeline, limiting generalizability	Zhao et al. (2022)
2022	Dynamic fracture behavior of X70 high-grade pipeline steel using Dynamic Tensile Tear Test (DT3)	Dynamic tensile load	- DT3 tests showed high crack speeds (up to 23 m/s) with three phases: crack growth, dynamic propagation, and tear-off - Scanning Electron Microscopy (SEM) images revealed complex ductile-brittle fracture morphology - Crack Tip Flipping (CTF) and Arrowhead Markings (AHMs) phenomena were observed, but their correlation is not fully understood - FEM using the Modified Bai-Wierzbicki (MBW) damage model closely matched experimental results	- CTF not reproduced by FEM, indicating an out-of-plane load component - Limited to room temperature; low-temperature behavior unexplored - Further research is needed for DT3 validation as an alternative to Charpy V-Notch (CVN) and Drop Weight Tear Test (DWTT) tests	Paermentier et al. (2022)
2021	Seismic response of parallel double pipelines to longitudinal ground motions	Seismic (longitudinal ground motions)	- Parallel pipelines' dynamic response depends on the spacing and seismic excitation - Maximum strain increases with spacing under uniform excitations at lower intensity but behaves nonlinearly under nonuniform excitation - Nonuniform excitation causes more strain differences at different pipeline sections than uniform excitation	- Limited to shaking table experiments under controlled seismic scenarios - Results need further validation under real-field conditions - No focus on other pipeline materials or configurations beyond sand-bed installations	Han et al. (2022)
2021	Reliability evaluation of local corrosion of X80 pipeline subjected to accidental earthquake considering geotechnical discontinuities	Seismic (earthquake loads)	- Corrosion defects and geotechnical discontinuities increase the dynamic vulnerability of X80 pipelines during earthquakes - A 3D random corrosion growth model with In-Line Inspection (ILI) data is combined with nonlinear FE modeling to predict failure pressure	- Model is dependent on ILI data accuracy and availability - More validation is required with field data, especially for practical earthquake scenarios and complex soil conditions - Assumes ideal conditions for mechano-electrochemical interactions	Wang et al. (2021)

Table 4 (*continued*)

Year	Theme	Load type	Key findings	Limitations	Articles
			- The method allows reliability-based safety assessments and helps design risk-informed inspection and maintenance plans		
2021	Probabilistic fatigue failure assessment of free spanning subsea pipeline using Dynamic Bayesian Network (DBN)	Cyclic fatigue loads due to scouring and seabed unevenness	- Proposes a dynamic probabilistic model using DBN to assess fatigue failure risk of subsea pipelines over time - Captures uncertainties in fatigue failure due to seabed unevenness and cyclic loading from scouring - Identifies six key fatigue causations, including pipeline corrosion and insufficient burial depth - Updates fatigue failure probabilities as new data is available, enabling real-time risk assessment	- Simplified correlations among fatigue causations - Future work is needed to improve correlation modeling using Copula functions - Dependent on the availability and quality of data for real-time updates	Li et al. (2021b)
2021	Dynamic response and safety assessment of buried gas pipe subjected to ground surface explosion	Safety assessment under explosion	- Identifies effects of ground explosions on buried gas pipes - Internal pressure and explosive charge are critical for safety	- The study may not account for all ground condition types or explosive scenarios - Full-scale models may have limitations in representing all possible real-world situations - Further investigation is required on the interaction between various parameters	Wu et al. (2021)
2021	Cyclic loading and fatigue on steel and PE pipe during Horizontal Directional Drilling (HDD) installations	Cyclic loading during HDD installations	- Fatigue analysis presented for steel and High-Performance Polyethylene pipes (HPE) - Fatigue strength of steel pipes unlikely to be exceeded if pullback stress is less than 2/3 of yield strength, even for infinite cycles - PE materials lack endurance limits, complicating fatigue predictions - Low-cycle fatigue analysis is crucial for accurate assessments	- Neglecting the dynamic nature of HDD operations - Limited exploration of low-cycle fatigue in different scenarios - More refined tools are required for PE pipe analysis	Campos et al. (2021)
2020	Fitness-For-Service (FFS) assessment and failure analysis	Vibration-induced fatigue	- FFS assessment (level 3) conducted per American Petroleum Institute (API) 579/American Society of Mechanical Engineers (ASME) FFS-1 guidelines deemed the crack acceptable - Failure occurred 11 months later due to deviations in operating conditions and vibration - Poor welding quality and sensitization contributed to crack formation	- FFS assessment may not account for future operational changes - Limited focus on quality control measures during welding - The specific effects of steam hammering were not quantitatively assessed	Zangeneh et al. (2020)
2017	Ratcheting behavior of defective API X80 steel pipes	Cyclic bending	- Defective specimens exhibited increased ratcheting rates and reduced cycles to failure compared to perfect specimens - Ovalization ratcheting occurred in both but with different local deformation modes - Cyclic softening observed; defects significantly impacted ratcheting response - Higher curvature amplitudes exacerbated the effects of defects	- Corrosion effects simulated through uniform thinning may not reflect real corrosion scenarios - Limited focus on different defect types and their specific impacts - Further experimental studies are needed for deeper insights into structural integrity under various conditions	Zeinoddini et al. (2017)
2017	Dynamic strain measurement in pipelines	Dead-load- induced vibration	- A novel Brillouin optical time domain reflectometer enables real-time distributed strain measurement - Achieved a 7.6 Hz acquisition rate with strain resolution of $\pm$40 μm/m and displacement resolution of $\pm$12 mm - Effective for monitoring vibrations in pipelines	- Limited dynamic range (600 μm/m) at tens Hz acquisition rate - Ongoing upgrades are needed to enhance dynamic range and acquisition speed - The test is conducted on a 10-m pipe, and further validation is needed for larger systems	Maraval et al. (2017)
2017	Damping effect on wave propagation in pipelines	Fluid hammer	- An analytical solution derived for dynamic radial vibration of pipelines under pressure shock	- Focuses only on material damping; other effects (hydrodynamic damping, corrosion, etc.) are unexplored	Pavlou and Ong (2017)

(*continued on next page*)

Table 4 (*continued*)

Year	Theme	Load type	Key findings	Limitations	Articles
			- Material damping significantly affects radial displacements; low damping may lead to catastrophic failures in short pipelines - Long pipelines exhibit reduced radial displacements due to pressure shock wave propagation	- Axial forces and pipeline curvature effects were not analyzed - Further research is needed on multiple flow conditions and pipeline repairs	
2017	Long-term monitoring of pipeline safety	Bending due to subsoil drop	- Monitoring systems are essential for real-time assessment of safety in high-pressure pipelines - Systems installed on gas pipelines can track fatigue damage and vibrations at critical points - Identified bending stress due to subsoil decreases after heavy rainfall	- Focuses on specific pipeline systems; results may not generalize - Limited discussion on sensor types and deployment strategies - Long-term effects and reliability of monitoring systems are not extensively evaluated	Martin and Vladimír (2017)

considering the pipeline as a shell structure (Katifeoglou and Chatjigeorgiou, 2016). FEM was further utilized to analyze the effects of initial imperfections, such as dents, on the collapse and buckle propagation pressures of submarine pipelines, incorporating material plasticity, residual stresses, and external pressure (Ramasamy and Ya, 2014). The dynamic stress-deformed condition of pipeline sides under external loads was investigated using FEM, demonstrating that different boundary conditions and geometric parameters significantly affected the dynamic characteristics and static stability of pipelines (Teshaev et al., 2017). A 3D parametric FEM model was used to analyze the failure of NG-buried X65 steel pipelines under deflection load, examining the effects of soil types and model sizes on the maximum deflection displacement, thereby providing a basis for safety design and evaluation (Liu et al., 2010). A tensile strain capacity (TSC) predictive model for welded X42 vintage pipes, developed using FEM and validated through nonlinear parametric and regression analyses, provided a practical tool for predicting TSC and conducting pipeline integrity assessments (Agbo et al., 2020).

Research gaps: Despite the increasing advancements in FE modeling for pipeline structural integrity assessment, several research gaps still need consideration. Although the impact response of corroded concrete pipes (Li et al., 2022) and intact metallic pipes (Odina et al., 2018) was studied, the behavior of corroded energy pipelines under impact loading remains less explored. The anchor-impact and rockfall-fatigue studies (Hou et al., 2025; Xie et al., 2024) bridge this area, but corrosion-impact interactions are still poorly quantified. Existing models often focus on a single damage mechanism, neglecting the complex interactions between multiple failure modes, such as the combined effects of corrosion, dynamic impact, and fatigue, which highlights the need for advanced models that can accurately account for these coupled processes. In addition, while crack initiation is modeled, gaps exist in predicting the growth of fatigue cracks under realistic, variable dynamic loads, such as fluctuating pressure and external vibrations. Recent cyclic-pressure research (Savari, 2025b) addresses composite repair performance under cyclic loads, but broader multiaxial and thermomechanical analysis of residual stresses impact of spiral welding on pipeline fracture remains underdeveloped. Many models also fail to account for material degradation in aging pipelines, highlighting the need for fracture mechanics-based FE models that simulate crack propagation under multiaxial stress states and combined dynamic-thermal loads. Although the integration of FE models into real-time SHM data can be found in the literature (Mendez et al., 2018; Wu et al., 2024), more research should be conducted to develop adaptive models that update based on real-time feedback for continuous integrity assessment. Moreover, most existing models are deterministic, while probabilistic approaches can capture the uncertainties in dynamic loading and material properties. Finally, accidental localized damage from impacts or collisions must be better represented in models, as they often assume uniform loading conditions.

5. Challenges and directions for future research

Integrating insights from the literature, this section outlines the key challenges and proposes directions for future research. Table 5 provides an overview of dynamic loads and proposed preventive measures, discussed in previous sections. Fig. 14 summarizes gaps and potential research directions associated with these dynamic loads. Current seismic fragility frameworks, although rich in empirical data, lack robust analytical and experimental foundations. Whereas the pipe-soil interaction was studied in the literature (Bi et al., 2017; Choi et al., 2024; Dai et al., 2021; Germoso et al., 2021; Ghodoosipour et al., 2019; Hodder and Byrne, 2010; Reda et al., 2019; Shi et al., 2024; Wang et al., 2021; White and Cheuk, 2008), advanced 3D parametric models and comprehensive shaking table tests are required to better understand the interactions between seismic wave propagation, soil liquefaction, and pipeline response (Dai et al., 2021; Germoso et al., 2021; Han et al., 2022; Shi et al., 2024). Furthermore, there is a need to assess the combined effects of seismic loads and aging infrastructure, including the role of corrosion-induced degradation in exacerbating soil-pipeline interaction (Amaya-Gómez et al., 2019; Yu et al., 2022). While several studies examined individual aspects of hydrodynamic forces (e.g., wave-induced pressures, currents, and tidal forces), comprehensive analyses addressing the coupled effects of tidal forces, wave action, and deep-water pressure fluctuations on pipeline stability are scarce (Bi et al., 2017; Gong and Xu, 2016; Zhang et al., 2011). Future research should focus on developing integrated models that capture the complex interactions between hydrodynamic forces and soil-pipeline dynamics (Choi et al., 2024). Existing models often neglect the intricate interactions among pressure pulsations, thermal stresses, and mechanical vibrations. It is required to develop FSI models and the synergistic effects of multi-axial dynamic loads, particularly in extreme environments such as subsea and permafrost regions (Lu et al., 2018; Okasha et al., 2016; Tian et al., 2016; Victorovna, 2018). There is emerging potential in the development of self-healing coatings and smart materials that can autonomously repair minor damages and mitigate corrosion, thus extending the service life of pipelines (Thanawala et al., 2014; Ulaeto et al., 2023). Future research should focus on the application and long-term performance of these materials under dynamic loading conditions. Moreover, as pipelines are increasingly subjected to extreme

Table 5
Overview of load types affecting pipeline integrity: sources, effects, and mitigation measures.

Load type	Source of load	Frequency	Magnitude	Primary effects	Failure modes	Effected components	Preventive/mitigation measures	Articles
Seismic loads	Earthquakes and ground movements	Sudden, short-term	High (varies by event)	Large-scale ground movement, and stress waves	Buckling, fracture, and shear failure	Entire pipeline, particularly joints	Flexible couplings, ring-stiffeners, corrosion-resistant coatings, and retrofitting techniques	(Dai and Zhou, 2018; Zhang et al., 2019a)
Blast and explosion	Explosions, accidental blasts, and detonation	Sudden, short-term	Very high	High-energy shockwave propagation	Fracture, buckling, and plastic collapse	Entire pipeline, welds, and supports	Blast-resistant designs, GFRP blankets, and meta-material layouts	(Kouretzis et al., 2007; Zhang et al., 2018, 2021a, 2024)
Cyclic loads	Operational pressure cycles, and startup/ shutdown events	Repetitive, long-term	Moderate to high	Repeated stress cycles	Fatigue crack growth, and fracture	Joints, welds, and stress concentration zones	Fatigue-resistant materials, and proper operation control	(Adamchuk et al., 2023; Azadeh and Taheri, 2014; Haider et al., 2014)
FIV	Internal fluid flow, and turbulent flow	Continuous	Moderate	Oscillatory forces, and vortices in fluid flow	Fatigue crack initiation, and vibration damage	Pipe walls and bends	Vibration dampeners, and flow control devices	(He et al., 2021; Li et al., 2021d; Liu et al., 2022)
Pressure fluctuations	Sudden changes in internal pressure (e.g., water hammer)	Sporadic or cyclic	High	High-pressure spikes, and pressure transients	Burst, and fatigue	Entire pipeline, particularly near valves and fittings	Surge relief valves, and pressure monitoring systems	(Lu, 2019; Malesińska et al., 2021)
Mechanical vibrations	Rotating equipment, pumps, and compressors	Continuous, often at equipment frequency	Low to moderate	Vibration forces	Fatigue, and cracking	Pipe supports, and nearby machinery	MVIMD, MPD, TMD, and PIP	(Al Bkoor Alrawashdeh et al., 2021; Liang et al., 2015; Lu et al., 2016; Matta and Szasz, 2018)
Ocean and marine loads	Wave action, tides, and underwater currents	Continuous, variable with storms	Moderate to high	Cyclic loading due to waves and currents	Fatigue, and vibration-induced damage	Subsea sections, and pipeline risers	Flexible couplings, buoyancy modules, bend stiffeners, and helical strakes	(Chen et al., 2023a; Gao et al., 2007; Gibson and Christou, 2019; McDougal et al., 1988)
Thermal loads	Temperature fluctuations due to environmental or operational changes	Daily or seasonal variations	Low to moderate	Thermal expansion/ contraction	Thermal fatigue, and buckling	Pipeline segments exposed to temperature changes	Thermal insulation, expansion joints, and expansion loops	(Hobbs, 1984; Shahrokhabadi et al., 2020; van der Heijde et al., 2017)
Anchor and vessel impacts	Offshore vessels, and anchoring operations	Occasional, unpredictable	High	Localized impact forces	Localized buckling, and fracture	Subsea pipeline segments	Protective barriers, and concrete mattresses	(Olunloyo et al., 2007; Pavlou, 2023)
Dropped objects and collisions	Dropped equipment, and collisions during maintenance	Accidental, unpredictable	High	Impact forces on pipeline surface	Denting, and plastic deformation	Pipeline surfaces, and coating	Concrete mattresses, rock berms, steel cages, and coatings	(Jiang et al., 2019; Wang et al., 2016b; Zeinoddini et al., 2013)
Accidental impacts during operation	Machinery impacts, and tool strikes during maintenance	Occasional, human-induced	Low to moderate	Localized mechanical damage	Surface cracks, and localized fracture	Exposed pipeline sections	Worker training, and protective covers	(Kristoffersen et al., 2013, 2014, 2018)
Transport and installation	Manual or machine handling during pipeline placement	Short-term	Low to moderate	Handling-induced stresses during placement or movement	Dents, and localized buckling	Entire pipeline, especially near lifting points	Proper lifting techniques, and handling guidelines	(Hwang and Lee, 2019; Sen and Zhou, 2008; Zhang et al., 2014)

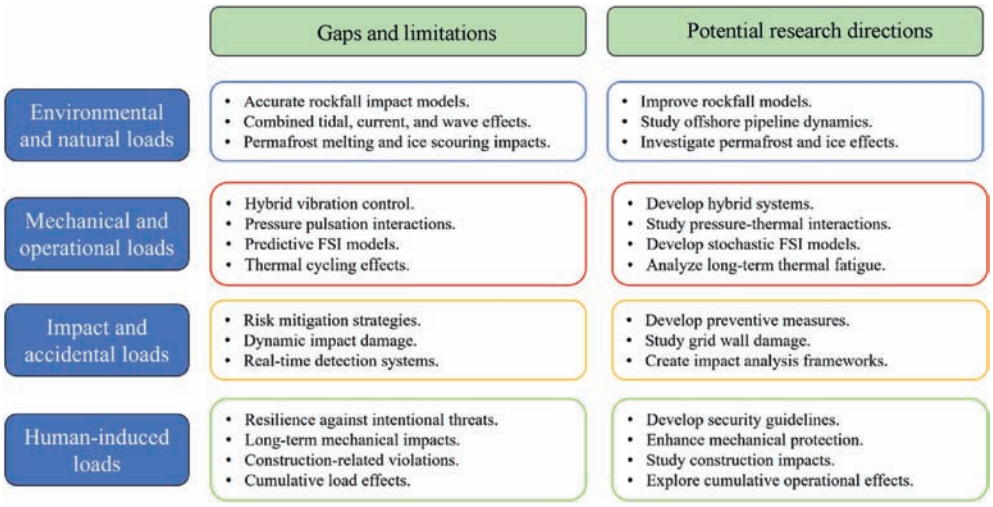


Fig. 14. Gaps and limitations, along with potential research directions based on the origins of dynamic loads.

conditions due to climate change and expanding exploration into harsh environments (Li et al., 2021c), it becomes essential to design pipeline systems that can adapt to such challenges. Future studies should investigate adaptive insulation systems, real-time monitoring of thermal expansion, and robust design strategies for permafrost or deep-water scenarios (Gong and Xu, 2016; Hong and Shah, 2018; Hu et al., 2014).

6. Conclusions

Pipelines are subjected to various load types, each presenting distinct challenges and requiring specific preventive measures. Seismic and blast loads involve sudden, high-magnitude forces. While the former results from ground movements causing widespread impact, the latter is due to high-energy shockwaves that affect the pipeline and its supports. Though both are related to repetitive stress, cyclic loads and FIV differ in their origins. Cyclic loads are caused by operational pressure cycles, leading to fatigue in joints and welds. FIV stems from turbulent internal flow, generating oscillatory forces that impact pipe walls and bends. Pressure fluctuations and mechanical vibrations affect pipelines through high-pressure spikes and low-to-moderate vibration forces, respectively, with the former necessitating surge relief valves and the latter requiring vibration isolation. Ocean and marine loads impose cyclic loading in marine environments due to wave action, while thermal loads cause expansion and contraction from temperature changes. Finally, anchor and vessel impact and dropped objects introduce high-impact forces but differ in frequency and sources; the former is related to offshore operations, while the latter occurs during maintenance activities.

Each load type requires specific preventive measures to ensure pipeline integrity and safety. Seismic design standards, flexible joints, blast-resistant structures, and vibration dampeners are crucial for reducing seismic explosion and FIV risks. Applying fatigue-resistant materials and proper pressure monitoring systems enhances resilience against cyclic and pressure fluctuation loads. Protective measures, including barriers, coatings, and worker training, mitigate accidental impacts and operational hazards; however, continued research is necessary to refine these strategies. Despite decades of research and development, key aspects of global energy pipeline dynamics still lack comprehensive experimental validation for coupled multi-axial loading models, interaction of corrosion, aging, and soil-pipeline interaction evolving under seismic and hydrodynamic coupling, limited integration of digital twins and AI-driven SHM systems into real-time risk assessment, and insufficient cost-benefit data for resilience-focused retrofitting. Bridging these gaps requires coordinated international testing, scalable numerical-experimental frameworks, and linking material, geotechnical, and operational domains with open-access databases. In summary, addressing these research gaps through interdisciplinary approaches, combining advanced numerical modeling, innovative experimental techniques, and cutting-edge sensor technology, will be crucial for developing safer and more resilient pipeline systems capable of withstanding complex dynamic loading scenarios.

CRediT authorship contribution statement

Ardeshir Savari: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Arameh Eyvazian:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Narinderjit Singh Sawaran Singh:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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