CAAP Quarterly Report

Dec. 30th

***Project Name**: A Framework and Integrated Solution of a Dynamic Pipeline Hazard and Risk Data Repository for All Pipelines*

Contract Number:693JK32450004CAAP

Prime University: University of Dayton

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Reporting Period:10/01/2024-12/31/2024

1. Project Activities for Reporting Period:

Items Completed During this Quarterly Period

Per the contract, Task 1 is associated with the first quarterly report. The following activities have been completed

Item #	*Task #*	*Activity/Deliverable/Title*
1	1	1st Quarterly Report (the main text)
2	1	Comprehensive literature review report (the Appendix)

Items in Progress During this Quarterly Period

We have briefly started the Task #2 based on the literature review outcomes from Task 1 and this item is still on-going at the very early stage hence is not presented in this report and will be covered in the following quarterly report.

Item #	*Task #*	*Activity/Deliverable/Title*
1	2	Identify critical data and confirm the availability from public data sources

Task #1 Objective:

During this report quarter, our team mainly focused on Task 1: Literature review. The primary goal of this task is to conduct an exhaustive review of existing knowledge, methodologies, tools, and regulatory frameworks related to the development of a dynamic pipeline hazard and risk data repository. This repository aims to provide robust and actionable insights into the challenges posed by climate change and geohazard threats to pipeline systems. Emphasis is placed on understanding state-of-the-art practices in hazard identification, data collection, geohazard risk assessment, and the integration of predictive analytics for effective pipeline safety management. The review will identify critical gaps, emerging technologies, and opportunities for improving pipeline resilience through enhanced data-driven approaches using a modernized dynamic database.

Scope of work:

This literature review synthesizes insights from a diverse array of sources, including academic research, government regulations, industry standards, and technical reports, to evaluate the state of pipeline hazard and risk management. Particular focus is given to understanding regulatory frameworks, identifying geohazard threats, and examining methodologies for data collection and analysis. By integrating findings from these sources, the review highlights the strengths, limitations, and opportunities for innovation in managing pipeline systems exposed to climate-related and geotechnical risks. Furthermore, it outlines actionable recommendations to enhance pipeline resilience through improved risk assessment and data repository frameworks. The detailed review outcomes are listed below at a high level and the comprehensive literature review is presented in the appendix.

Summary of literature review work performed:

1) Pipeline Hazard Identification and Data Collection

Federal regulations, including those by PHMSA, provide a foundational framework for identifying and managing risks associated with climate change and geohazards in pipeline systems. Key guidelines, such as 49 CFR Parts 192 and 195, mandate assessments and mitigation measures for threats like flooding, seismic activity, landslides, and soil subsidence. Complementary industry standards, such as API RP 1133 and ISO 31000, emphasize systematic risk identification and management for both geotechnical and hydrotechnical hazards.

Industry practices highlight structured approaches for geohazard risk management. API RP 1133 provides methods for evaluating risks at pipeline water crossings, while AMPP standards focus on corrosion threats, emphasizing environmental monitoring and soil resistivity measurements. Data collection integrates geospatial tools, high-resolution imagery, and field inspections to improve hazard assessment accuracy. Technologies like GIS and LiDAR map vulnerable areas, with standards such as API RP 1187 guiding the incorporation of site-specific environmental factors like groundwater conditions and soil composition.

Academic journal articles contribute to understanding the multifaceted impacts of geohazards on pipeline systems. Research highlights the interplay between climate factors, such as temperature fluctuations and heavy rainfall, and their cumulative effects on pipeline integrity. For instance, studies emphasize the need for data-driven frameworks to predict pipeline vulnerabilities using GIS technology, machine learning models, and remote sensing data. These methodologies advance the predictive capabilities for assessing risks like landslides, erosion, and seismic activity.

Technical reports further enrich the literature by providing practical insights into geohazard management strategies. The reviewed reports document case studies of hazard identification, terrain analysis, and field surveys, illustrating best practices for integrating remote sensing with on-the-ground inspections. Examples include the use of LiDAR and InSAR technologies to map subsidence and landslide-prone areas. These studies underscore the importance of continuously updating hazard databases and leveraging real-time data to improve pipeline risk management.

However, *challenges* remain in public data timely integrating, dynamic data updating, and predictive analytics in risk models. Gaps in data resolution and integration underline the need for innovative methodologies to establish a dynamic, adaptive hazard and risk data repository.

2) Risk Assessment Models and Approaches

Risk assessment models for pipeline integrity address the likelihood of geohazard occurrences and their impact on pipeline systems. These models, essential for predicting and mitigating risks, fall into qualitative, quantitative, and probabilistic categories. Qualitative models often use expert/engineering judgment and scoring systems to identify hazards and estimate risks, offering an empirical understanding of potential threats. Quantitative models, on the other hand, rely on numerical data and statistical analyses to provide detailed risk metrics, such as probabilities of failure and potential consequences.

Probabilistic risk assessment frameworks are particularly valuable for addressing the uncertainties inherent in geohazard threats. These models integrate multiple variables, including climate and geotechnical data, pipeline material properties, and environmental conditions, to predict failure scenarios under varying critical conditions. Techniques such as Bayesian inference and Monte Carlo simulations are frequently used to quantify risks and evaluate the effectiveness of mitigation measures.

Integration of geotechnical data, soil-pipeline interaction models, and environmental variables enhances these frameworks, enabling precise simulations of risks such as landslides, seismic activity, and soil erosion. Probabilistic models are particularly effective in real-time applications, offering actionable insights for dynamic risk mitigation.

Despite their advantages, challenges include limited adoption of real-time monitoring and gaps in integrating predictive analytics. Addressing these issues through advanced IoT sensors, machine learning, and comprehensive data repositories can transform risk assessment into a more adaptive and resilient process.

3) Existing Data Sources and Repository Design

Pipeline data repositories provide foundational information critical for hazard assessment and risk mitigation. Prominent systems, such as the National Pipeline Mapping System (NPMS), U.S. Energy Atlas, and FracTracker, offer comprehensive geospatial data on pipeline infrastructure and energy systems. These repositories support various stakeholders by consolidating static data on pipeline routes, storage facilities, and natural gas systems.

However, these platforms primarily rely on static datasets and lack real-time updates on environmental and geohazard factors. For example, while the NPMS provides detailed pipeline mapping, it does not dynamically integrate data on evolving climate threats or geohazards from other publicly available database such as NOAA and USGS. Similarly, the U.S. Energy Atlas emphasizes static infrastructure information without predictive risk analytics. These limitations hinder proactive risk management and decision-making.

Emerging technologies, such as IoT-enabled sensors and real-time data integration, together with public data sources hold promise for addressing these gaps. Advanced visualization tools like GIS dashboards and digital twins can enhance repository functionalities, enabling stakeholders to dynamically monitor threats and prioritize mitigation strategies. Overcoming challenges such as data integration complexities and high implementation costs will be key to creating a robust, adaptive pipeline data repository.

4) Existing Visualization and Decision Support Tools

Visualization and decision support tools are vital for translating complex data into actionable insights for pipeline hazard management. GIS-based dashboards are a key technology, offering layered maps that integrate pipeline routes with environmental, climate, and geohazard data. These dashboards enable operators to identify high-risk areas, monitor changes, and prioritize mitigation efforts.

Advanced visualization techniques, such as augmented reality (AR) and virtual reality (VR), enhance spatial understanding by providing immersive environments for analyzing pipeline systems. These tools allow stakeholders to simulate geohazard scenarios, evaluate risk mitigation strategies, and train personnel effectively.

Digital twin technologies represent the forefront of decision support tools. By creating a dynamic, real-time digital replica of pipeline infrastructure, digital twins enable continuous monitoring, predictive analytics, and scenario testing. These systems leverage IoT sensors and machine learning algorithms to identify anomalies, forecast potential failures, and optimize maintenance schedules.

Despite their potential, challenges such as high implementation costs, facility requirements, data integration complexities, and the need for skilled personnel limit widespread adoption. Addressing these barriers is essential to fully realize the benefits of visualization and decision support tools in pipeline risk management.

2. Project Financial Activities Incurred during the Reporting Period

A cost breakdown list of the expenses during this quarter in each of the categories according to the budget proposal is provided below:

Sponsor Number: 21-000370
Prime Contract Number: 693JK32450004CAAP
Contract Value: $774,997.00
Funded Value: $774,997.00
Cost-share amount: $116,270

	Current Period Actual	Year To Date Actual	Contract To Date Actual
Salaries & Wages FTFac-Non-Tenure	$3,944	$3,944	$3,944
Benefit-Faculty/Staff	$530.7	$530.7	$530.7
Total Labor Cost	$2,625.83	$2,625.83	$2,625.83
Total Indirect Cost	$1,318.17	$1,318.17	$1,318.17
Total Expense	$3,944	$3,944	$3,944
Cost-share	$0	$0	$0

The full-time labor hour cost is for the research staff Dr. Sreelakshmi Sreeharan. The University of Dayton (UD) team has recruited a PhD student Kiranmayee Madhusudhan, whose graduate assistant contract will start from Jan 13th. The PI's research time will be consolidated and charged during the summer partially using the cost-share and partially USDOT fund.

We have been working on subcontracting processes with Texas A&M University (TAMU), University of Cincinnati (UC), and Rutgers University (RU). Currently, we have sent the subcontracting documents to UC and TAMU for signing and on the paperwork preparation and review stage with RU. It is expected to have the paperwork finished in the early January and the subcontractors will start to charge the project accordingly.

3. Project Activities with Cost Share Partners:

Overview: This project has three cost share partners: Texas A&M University (TAMU), University of Cincinnati (UC), and Rutgers University (RU). In this project quarter, the prime institute University of Dayton (UD) hosted the kick off meeting with co-PIs Dr. Homero Castaneda (TMAU), Dr. Lei Wang (UC), and Dr. Hao Wang (RU) together with external industry partners and PHMSA program administration team. In addition to the kick-off meeting, UD has set up regular progress discussion and report meetings with TAMU and UC. The outcomes from these cross-institution activities can be summarized below:

Research outcomes: The UD team worked with all three cost-share partners on literature review. More detailed, the ***RU team*** focuses on the climate change and impact to pipeline resiliency, the ***UC team*** focuses on the geohazard threats, ground-pipe interaction and pipeline risk models, and the ***TAMU team*** focuses on climate and geohazard induced pipeline integrity corrosion and integrity management. The ***UD team*** focus on the literature review compilation and summarization on Federal agency regulations, industry practices for implementing the regulations, risk assessment models and approaches, existing data sources, management and repository design, existing visualization and decision support tools, emerging technologies and trends. The detailed literature review is provided in the appendix.

Team management: as mentoring is a key component of this CAAP program, in this quarter, we have recruited the following mentees into our team:

RU team has recruited one PostDoc Jay Shah in Civil and Environmental Engineering.

UC team has recruited one PostDoc Liang Zhang in Civil and Environmental Engineering.

TAMU team has recruited one PhD student Myunghwan Jeong in Material Science and Engineering.

UD team has one PostDoc Sreelakshmi Sreeharan in Civil Engineering listed in the original proposal and has recruited one more PhD student Kiranmayee Madhusudhan in Electrical and Computer Engineering starting from the Spring 2025. We are actively recruiting another PhD student Qianyi Wu expected to be starting in Summer 2025.

4. Project Activities with External Partners:

In this project, we have three industry partners as external partners: Integrated Solutions (IS) field services (Cay Strother, Kevin Cowan); API (Mark Piazza, David Murk); Rosen (David Bastidas).

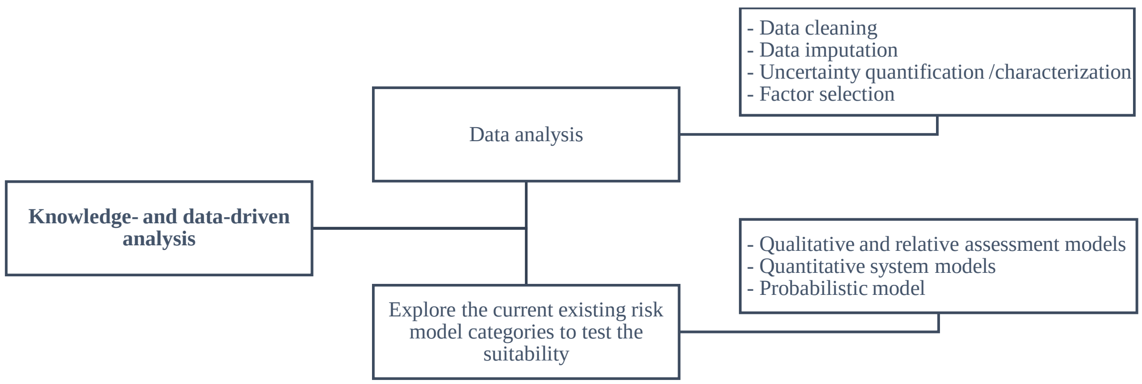
We conducted the kick-off meeting together with Integrated Solutions (IS) field services and API. Rosen joined our team in December. We requested two API Recommended Practices from API. We will conduct a review meeting in mid January to have feedbacks and comments regarding the literature review outcomes.

5. Potential Project Risks:

The project is moving forward as expected so far, no potential risks is noticed at this stage. During the performance of Task #2 in the next reporting period, we identify the potential risk for project delay as the possible paperwork process for getting assess to certain pipeline private data from industry partners and the government pipeline database such as NPMS.

6. Future Project Work:

The project is on-schedule as originally-proposed. During the following quarter, the team will perform the Task #2 Identify critical data and confirm the availability from public data sources. More specifically, we will first summarize the major factors for pipeline climate and geohazard risk assessment. RU team will focus on climate related factors; UC team will focus on geological and geotechnical factors; TAMU team will provide experimental validation using physics model in a controlled lab environment; UD team will perform data interpretation and conduct knowledge and data driven analysis. The scope workflow chart is shown below.



Data source:

1) Public data (open-source platforms): Google Earth Engine, NASA earth data, USGS EarthExplorer, NOAA Climate Data Online (CDO), SoilGrids

2) The (existing) private data base/sample from the pipeline owners/operators.

7. Potential Impacts to Pipeline Safety:

We are preparing a draft conference paper to be submitted to the ASCE UESI Pipelines 2025 Conference, and a review article to be submitted to Journal of Pipeline Science and Engineering based on the outcomes from the literature review.

Appendix A: Comprehensive literature review

A.1. Objective

The primary aim of this literature review is to analyze and synthesize existing knowledge, tools, and methodologies related to developing a dynamic pipeline hazard and risk data repository. This targeted repository is intended to provide comprehensive, accurate, and actionable insights for pipeline systems facing climate and geohazard threats. The review focuses on existing regulations, literature, prior work, and relevant standards, emphasizing database establishment and management tailored to pipeline systems under these specific challenges.

A.2. Review scope

Overview: We start the literature review by compiling a list of literature related to climate and geohazards threats to different pipelines. The reviewed literature includes federal regulations, academic journals, conference papers, technical reports, government publications, industry guidelines, and standards. We have reviewed a total of 63 documents, comprising 8 federal regulations, 19 federal and industry technical reports, and 36 research articles to analyze advancements, identify gaps, and explore opportunities in pipeline risk management and geohazard mitigation strategies. The main findings from the reviewed documents highlight critical advancements and gaps in pipeline data management and risk management. Federal regulations emphasize the need for comprehensive frameworks for identifying and mitigating geohazards, with a growing focus on integrating real-time monitoring technologies. Industry technical reports highlight the significance of tailored risk assessments, advanced geospatial visualization tools, and proactive strategies for addressing site-specific hazards, particularly at high-risk locations like water crossings. Research articles explore innovative methodologies, including machine learning, remote sensing, and GIS-based systems, for improving geohazard prediction, monitoring, and mitigation. Collectively, these findings point to the necessity of developing dynamic, data-driven repositories that seamlessly integrate diverse datasets to enhance pipeline safety and resilience. Both academic literature databases and industry documentation platforms have been explored. More detailed efforts are provided below.

A.2.1 Pipeline Hazard Identification and Data Collection

A.2.1.1 Literature reviewed

Geohazards, a specific category of natural hazards, originate from Earth's dynamic processes, including both meteorological and geological mechanisms. They are typically classified into two major groups: (1) geotechnical hazards, which are characterized by the displacement of soil or rock masses, thereby imposing mechanical loads, and (2) hydrotechnical hazards, which involve the imposition of loads through the kinetic action of flowing water, often coupled with the transport of debris[1][2]. Geohazards occur either as distinct events or as extensive areas with an elevated risk of specific hazards. Their formation and movement exhibit a wide range of characteristics, from slow, gradual developments to rapid, instantaneous events. Geotechnical hazards, for example, can impose loads through gradual ground displacement over long periods, as seen in slow-moving landslides or subsidence, or through sudden displacements, such as faulting during earthquakes or rapidly moving landslides. Similarly, hydrotechnical hazards are often associated with transient loads, such as those experienced during flood events when pipelines are exposed to hydrodynamic forces, but they can also arise from slower processes, such as channel migration[1].

Below we conduct a detailed review on hazard identification and data collection from different literature sources.

i) Federal agency regulations

The Pipeline and Hazardous Materials Safety Administration (PHMSA) addresses climate and geohazard-related threats through targeted provisions within its regulatory framework. Key sections, such as 49 CFR Part 195[3][4] (Transportation of Hazardous Liquids by Pipeline) and Part 192[5][6] (Transportation of Natural and Other Gas by Pipeline), mandate risk assessments and mitigation measures for environmental factors, including flooding, riverbank erosion, coastal storm surges, seismic activity, landslides, and soil subsidence. These regulations also emphasize the importance of identifying and managing risks posed by hydrotechnical hazards, such as vertical and lateral channel movements, and the associated hydrodynamic forces, debris impacts, and vortex-induced vibrations on pipeline infrastructure.

ii) Industry practices for implementing the regulations

<u>Hazard identification</u>: Advisory bulletins issued by PHMSA further address climate and geohazard related natural force damages, including extreme weather events intensified by climate change, such as hurricanes and heavy rainfall events. This underscores the need for a robust and

dynamic data repository that synthesizes diverse datasets for enhanced pipeline safety and resilience. Complementing these regulations are industry technical guidelines and PHMSA advisory bulletins that address critical topics such as stress corrosion cracking, hydrotechnical hazards, and emergency response protocols. Notable examples include PHMSA Advisory Bulletin ADB-2019-01[7] and ADB-2016-01[8], which provide guidelines on managing the the risk from the potential for damage to pipeline facilities caused by severe flooding, Advisory Bulletin ADB-2015-02[9] , focusing on potential for damage to pipeline facilities caused by the passage of hurricanes, and Advisory Bulletin ADB-2019-02[10], focusing on potential damage to pipeline facilities caused by external loads imposed by earth movement and other geologic hazards on and adjacent to pipeline right-of-way corridors. Similarly, API Recommended Practice 1133[11] focuses on managing hydrotechnical hazards for pipelines located onshore and in coastal zones, while API Recommended Practice 1187[12] offers comprehensive guidance for assessing, identifying, and mitigating risks associated with geohazards, including landslides, seismic activity, and subsidence. These documents provide a robust framework for identifying and managing natural force damages to pipelines. The API RP 1133[11] recognizes the importance of understanding how rivers and coastal zones change and alter landscapes, which is crucial for assessing the potential impact of hydrotechnical hazards on pipeline infrastructure. It incorporates hydrological data, including the timing, duration, and quality of water flow, which are essential components in defining a river's hydrology. ISO 31000[13] (Risk Management) emphasizes the systematic identification of environmental and operational hazards, offering standardized approaches applicable globally. Additionally, ASME B31.8S[14] (Supplement to ASME B31.8) emphasizes risk management practices for gas transmission pipelines, including methods for identifying and mitigating geotechnical and hydrotechnical risks. Emergency response is supported by PHMSA's Incident Reporting Protocols[15] , which outline immediate and long-term responses to pipeline failures. AMPP (formerly NACE International) focuses on external corrosion and mechanical damage as critical hazards. Its guidelines, such as SP0169, emphasize understanding soil corrosivity and environmental impacts like moisture and temperature variations, which are pivotal in identifying external corrosion threats to pipelines. The Federal Energy Regulatory Commission (FERC) requires comprehensive environmental assessments (EAs) and environmental impact statements (EISs) for pipeline projects as part of the certification process under the Natural Gas Act (NGA). These assessments follow the guidelines set forth by the National Environmental Policy Act (NEPA), which mandates the evaluation of potential environmental impacts from pipeline construction and operation. Relevant regulations include 18 CFR Part 380: regulations implementing the national environmental policy act, which outlines the procedures for preparing EAs and EISs.

Data Collection: Data collection efforts required by the above organizations focus on creating comprehensive, multi-source datasets to support hazard assessment and mitigation strategies. Current practices are summarized below. Geospatial tools like the National Pipeline Mapping System (NPMS)[16] and GIS platforms are critical for integrating pipeline data with environmental features such as floodplain boundaries and seismic hazard zones, enabling detailed hazard assessments. Current practices leverage high-resolution data from sources like FEMA's flood maps and USGS seismic hazard maps to identify areas prone to risks such as flooding, erosion, and seismic activity. Additionally, remote sensing technologies, including LiDAR and satellite imagery, are being incorporated to enhance the spatial accuracy of pipeline route analyses and geohazard assessments. Environmental and material-specific data, such as soil resistivity, pH levels, and cathodic protection performance metrics, are key to managing corrosion-related hazards in pipelines. Geospatial mapping tools enhance these efforts by identifying high-risk areas through the integration of environmental factors, including soil composition and seasonal variations.

API RP 1133[11] provides a structured approach for data collection aimed at assessing risks related to geohazards and climate threats at pipeline water crossings. The data collection process begins with assembling a comprehensive dataset to ensure accurate risk evaluation and management. Key elements of this dataset include a unique crossing identification number, precise geographic location, and a detailed description of the waterway. The latter encompasses attributes such as the waterway's name, type (e.g., stream, river, or lake), and its navigability classification, whether commercially navigable, navigable, or non-navigable. Additionally, information regarding the specific pipeline system or segment associated with the crossing is documented to establish clear context. API RP 1133[11] applies specifically to steel pipelines that transport gas, hazardous liquids, alcohols, or carbon dioxide, which provides context for the types of pipeline systems or segments that would be associated with these waterway crossings.

API RP 1187[12] provides guidelines for assessing and managing geohazards and climate-related risks along pipeline routes, with a particular focus on protecting pipeline infrastructure from natural forces such as landslides, seismic events, and soil movement. The recommended practice outlines a systematic approach to identify and evaluate geohazards by collecting essential data on the terrain, geological conditions, and environmental factors that might affect pipeline stability. Key elements of the data collection process include the geological composition of the area, the type of potential hazard (e.g., landslides, erosion), and the expected impact on pipeline integrity. Additionally, API RP 1187[12] emphasizes the importance of incorporating site-specific environmental factors, such as groundwater conditions, rainfall patterns, and seismic activity, into the risk assessment process. This information is expected to help operators design pipelines to minimize vulnerability to geohazards and implement appropriate mitigation measures. The guideline specifically applies to pipelines transporting hazardous materials, including gas, liquids, and chemicals, offering a framework for assessing and managing geohazard risks across diverse environmental conditions.

AMPP provides several key recommendations for data collection to effectively assess and manage corrosion-related hazards in pipeline systems, drawing on various industry standards. These recommendations include measuring soil resistivity, a critical factor in understanding the potential for pipeline external corrosion, as outlined in NACE SP0169 and API RP 1169[17]. The Wenner four-pin method is commonly used for resistivity measurements, particularly in regions with varying moisture content or salinity. Monitoring pH levels in the surrounding environment is another recommendation, as highly acidic or alkaline conditions can accelerate corrosion, as discussed in API RP 1189 and ASME B31.4. NACE SP0104-2020 addresses the use of coupons for cathodic protection monitoring applications. This standard covers the application of CP coupons attached to buried pipelines to determine the level of corrosion protection provided by a CP system. NACE SP0177 focuses on the mitigation of alternating current (AC) and lightning effects on metallic structures and corrosion control systems. Additionally, temperature, humidity, and rainfall patterns should be collected as they influence corrosion rates, with guidelines provided in NACE RP0100 for environmental considerations. Inspection data, such as from in-line inspections or visual assessments, should be incorporated to track pipeline conditions over time. Integrating these data points helps form a comprehensive risk profile and develop mitigation strategies that are in line with API RP 1133[11] for assessing pipeline vulnerability to environmental threats.

Other key references include NACE TM0497-2012, which outlines measurement techniques for cathodic protection criteria. Another important standard is NACE RP0502 for external corrosion direct assessment. Additionally, API 1160[18] provides further guidance on pipeline integrity management. Integrity management includes checking the condition of the pipeline through in-line inspection and internal inspection, checking for defects through pressure testing, and evaluating the defect status of the pipeline directly on site. When evaluating the integrity of a pipeline, an appropriate method is selected depending on the type of threat (nature damage, external pressures and force, pH of the soil, presence of friction with the surface, etc.). If the evaluation method is not appropriate, the threat is eliminated through preventive measures. Collectively, these standards emphasize the importance of comprehensive data collection on environmental conditions, geological factors, and pipeline characteristics to effectively assess and mitigate risks associated with climate change and geohazards.

iii) Journal and conference articles

Academic research highlights the significant impact of geohazards and climate change on pipeline failures. Climate encompasses long-term weather patterns, including temperature, precipitation, and wind, which can fluctuate over years or even decades. The interaction of various natural forces—such as temperature fluctuations, rainfall, and wind—along with their unpredictable simultaneous occurrences, can heighten the vulnerability of pipeline infrastructure, leading to an increased risk of leaks, ruptures, and mechanical damage. Ahmed et al.[19] provide a comprehensive review of how weather-related events contribute to pipeline failure propagation. They focus on the combined effects of climate change and external natural force factors, such as corrosion, erosion, and mechanical damage, on the integrity of pipelines. Similarly, Almheiri et al. [20] emphasize the role of climatic factors, such as air temperature, minimum antecedent precipitation index, and net evaporation, in contributing to the failure of water pipelines. A detailed meta-data analysis highlights the importance of these critical factors in predicting the failure rates of water distribution pipelines using data-driven and artificial intelligence methods. Furthermore, Cruz et al. [21] present assessment frameworks designed to ensure the safety of people, the environment, and investments in the oil and gas sector amidst the challenges posed by climate change.

Although corrosion is a relatively slower mechanism impacting pipeline integrity compared to challenges like fault displacement and soil erosion, it remains intricately linked to weather-related events. The correlation between soil moisture and corrosion rate is well-documented [22], as moist soils facilitate the flow of ions, accelerating electrochemical reactions responsible for corrosion. Prolonged wet conditions caused by increased rainfall or flooding, often associated with climate change, can exacerbate this effect. Furthermore, waterlogged soils can deplete oxygen levels, creating localized zones that favor anaerobic microbial activity, such as sulfate-reducing bacteria, which further accelerate corrosion [23]. Climate change-induced phenomena, such as rising temperatures and shifting precipitation patterns, also influence soil chemistry by altering pH levels, salinity, and redox potential—all of which play critical roles in the corrosion process. These factors highlight the need for climate-adaptive corrosion prevention strategies to safeguard buried pipelines in the face of evolving environmental conditions.

Ozkan et al. [24] employed dose-response functions (DRFs) to categorize atmospheric corrosion in Canadian steel infrastructure using historical field data. Their findings demonstrated variations across different cities, influenced by temperature and relative humidity. Notably, declining sulfur dioxide levels significantly altered corrosion patterns. Pritchard et al. [25], in their review, assessed the impact of climate change on soil behavior and its potential contribution to pipeline corrosion. Shifts in seasonal temperature and precipitation patterns can exacerbate soil geohazards. Increased summer temperatures may induce cracks in the soil bed, facilitating oxygen ingress at the pipeline interface. Conversely, heavy rainfall can drive moisture deeper into the soil, enhancing corrosive conditions within these crevices. Fan et al. [26] developed a climate-fragility failure rate model to predict pipeline failure using the database from Cleveland water division for the past 30 years. They reported that water pipes in colder regions are relatively safer than hotter regions from corrosion related damage. Moreover, climate change is also projected to intensify soil erosion, particularly in non-cohesive soils.

Oviedo et al. [27] developed a methodology for field data collection, using GIS technology, as well as the process of validation and publication of the data in the Geodatabase of the company and the benefits associated with having updated and available information to guarantee the best decision making. Budzich et al.[28] proposed an approach to prioritize vulnerable pipelines by assessing and prioritizing them through a combination of publicly available data, operator knowledge, and site-specific information (e.g., pipeline characteristics, recent survey data, etc.). To better support geohazard risk management, Johnson et al. [29] from TC Energy together with WSP developed GeoForce, a customized geohazard management platform built within the ESRI ArcGIS Enterprise environment, to identify, inventory, and track geohazards across its U.S. pipeline system. Hosted on ArcGIS Portal, the platform integrates multiple custom apps, dashboards, and geospatial scripts to enable efficient data viewing, updating, and summarization. It utilizes ArcGIS GeoEvent Server to provide near real-time geohazard threat notifications for seismic events, flooding, and precipitation, alongside recommended actions based on TC Energy procedures. Additionally, the system incorporates over 4 terabytes of LiDAR imagery through ArcGIS Image Server and links geohazard data with TC Energy's asset and regulatory datasets via automated scripts, ensuring data accuracy and proactive risk management. The platform supports predictive analytics for landslide risk, seismic threats, and system-wide risk scoring, with historical threat data visualized through PowerBI (a data visualization tool) and analyzed using algorithms developed in ArcGIS Notebook Server to enhance pipeline safety and resilience. Varela et al. [30] developed a new GIS-based method to estimate the annual probability of landslide-induced pipeline failures across transmission systems using historical data. This approach combines high-resolution LiDAR mapping to identify terrain anomalies linked to landslides with regional susceptibility maps that assess soil stability along pipeline corridors. By inventorying potential landslides based on their activity, proximity to pipelines, and interaction characteristics, this method provides a comprehensive framework for assessing and mitigating landslide risks in pipeline systems.

Satipaldy et al.[31] proposes the Convergence of Geotechnical Data Analytics and Machine Learning and explores how artificial intelligence (AI) and machine learning (ML) are transforming geotechnical engineering. The integration of AI with geotechnical data analytics, helps improve the analysis and prediction of complex data, particularly in site analysis, foundation design, and construction monitoring. By leveraging ML algorithms, geotechnical engineers can more accurately interpret large datasets, predict soil behavior, and enhance the efficiency and safety of projects. The paper also highlights the challenges of incorporating AI into traditional geotechnical workflows, such as the need for high-quality data and standardization. Despite these challenges, the authors emphasize the potential benefits of AI in improving decision-making, reducing human error, and optimizing design processes, making geotechnical engineering projects more cost-effective, sustainable, and safer.

iv) Technical reports

Report by Michael Baker Jr., Inc.[32] highlights the intersection of geohazards and mechanical damage in pipelines is the critical importance of proactive monitoring and mitigation strategies in a technical report in PHMSA. Geohazards such as landslides, flooding, and soil subsidence can exacerbate mechanical damage, leading to pipeline instability or failure. Effective prevention and management require advanced technologies like In-Line Inspection (ILI), continuous monitoring of terrain shifts, and immediate response plans to detect and address damage from both natural events and human activities. By integrating geohazard risk assessments into pipeline integrity programs, operators can enhance safety and reduce the likelihood of significant mechanical damage.

Michael Porter et al.[33] proposed geohazard risk management, highlighting various geohazards that can impact Canadian onshore pipeline projects, including geotechnical, hydrotechnical, seismic, and other environmental hazards.The technical report highlights that pipeline operators are increasingly adopting geohazard management practices that align with risk-based approaches, as outlined in the Canadian Standards Association's Z662-11 guidelines. The U.S. DOT (2013) summaries of all reported incident data for the period 1993 to 2012 indicate geohazards contributing to about 6.8% of incidents. The Data published by the National Energy Board (2011) for Canadian Regulated pipelines indicates the leading cause of failure during the period 1991 to 2009 with geohazards contributing to about 5% of incidents. The geohazard integrity management program begins with reviewing historical data and creating a detailed inventory of potential geohazards, supported by a robust database linked to GIS for easy storage and retrieval. The data collection process involves a combination of field inspections and remote sensing methods. Over 13,500 geohazard sites across approximately 63,000 km of pipelines in Canada and the U.S. were visited by inspectors, focused on identifying and documenting geotechnical and hydrotechnical hazards such as frost heave, soil movement, and erosion. Remote tools like satellite imagery, air photos, and LiDAR surveys are used to gather terrain data, which is further supplemented by field reconnaissance, including vehicle or helicopter-based surveys. This data helps in the identification, mapping, and assessment of geohazards along the pipeline corridors, allowing for the integration of these findings into risk management strategies during pipeline planning and operation stages.

A section of the report by Michael Baker Jr. Inc. [34] focuses on Corrosion due to geohazards refers to the accelerated deterioration of pipelines caused by natural geological events or conditions. These include soil movement (landslides or erosion), flooding, seismic activity, corrosive soil types, geothermal activity, and permafrost thawing. These factors can expose pipelines to moisture, harmful chemicals, and physical stress, which accelerate corrosion, including forms like pitting, stress-corrosion cracking, and microbiologically influenced corrosion (MIC).

M. Porter et al.[35] as a part of the hazard identification and data collection for the Gasoducto Nor Andino pipeline proposes a proactive approach that combines historical analysis, terrain analysis, and field inspections. Initially, historical failure incidents caused by geohazards were reviewed to identify specific problem areas along the pipeline route. Aerial photography, stereo images, and satellite imagery were then used to conduct detailed terrain analysis, enabling the identification and mapping of geohazard features such as slopes, riverbanks, and landforms susceptible to landslides, erosion, and flooding. Field surveys were conducted to validate the findings and assess the physical conditions of the terrain, with a focus on areas showing signs of instability or erosion. The identified geohazards were classified into categories such as geotechnical (e.g., landslides, rock falls), hydrotechnical (e.g., erosion, flooding), and tectonic (e.g., fault ruptures, seismic activity). In addition, the potential influence of surrounding terrain beyond the pipeline right-of-way (RoW) was considered, particularly in areas where upstream watershed or geological instability posed a risk. This comprehensive hazard identification process was essential in prioritizing high-risk areas for further risk evaluation and mitigation efforts.

The report *"Landslide and Land Subsidence Hazards to Pipelines"* (Baum, Galloway, and Harp, 2008)[36] outlines methods for identifying and collecting data related to landslide and land subsidence hazards. The authors emphasize regional landslide hazard evaluation using geological maps, aerial photos, and satellite imagery to identify landslide-prone areas. For land subsidence, they highlight techniques such as differential radar interferometry (InSAR) to detect ground movement over large areas. Additionally, for investigating individual landslides, the report details field methods including site surveys, geotechnical data collection (e.g., soil, rock types, groundwater conditions), and reviewing historical data on past landslides and their triggers. These methods are designed to assist in assessing potential pipeline risks and planning mitigation measures.

v) Pipeline incident data collection

The (PHMSA), defines pipeline incidents under Title 49 CFR 191.3, and regulates pipeline safety under 49 CFR 191.5 for incident reporting and tracking incidents. PHMSA tracks incidents for pipeline systems, including natural gas distribution, hazardous liquids, gas transmission and LNG.The pipeline operators report incidents involving significant harm, such as fatalities, injuries, property damage exceeding $50,000 for hazardous liquid and $145,400 for other gas pipeline systems, within 30 days of incident. The pipeline incident data[37] caused by geohazards (natural force damage), is collected based on the cause details, including location, operator details, and costs, which are made available through platforms like National Pipeline Mapping System (NPMS) and DAC PHMSA. The data [38] helps identify high-risk areas affected by natural force damage.

PHMSA represents the data publicly through equity in pipeline safety using tools like the Equitable Transportation Community (ETC) Explorer and NPMS, which tracks incidents in disadvantaged communities. Failure Investigation Reports (FIR)[39] provide insights into causes and solutions for pipeline failures. PHMSA’s current reporting and investigation framework helps improve safety, and supports effective risk management strategies in pipeline operations.

A.2.1.2 Main findings

i) Federal agency regulations (PHMSA) findings

These guidelines collectively establish a framework for identifying, assessing, and managing risks associated with environmental and geotechnical hazards. However, despite their comprehensiveness, integrating multimodality monitoring technologies, such as IoT-based sensors and satellite imagery, remains a challenge. PHMSA leverages its extensive incident data repository, incorporating historical data on pipeline failures and environmental impacts, to guide inspection planning and enhance risk-based assessment models. Efforts such as the PHMSA Risk Modeling Work Group aim to improve methodologies for incorporating these insights into dynamic risk frameworks. These initiatives emphasize the importance of continued development in predictive analytics and real-time hazard monitoring to address the increasing threats posed by climate change and geohazards.

ii) Industry practices findings.

The findings from API 1133[11] provide key insights for managing risks at pipeline water crossings. By collecting essential data such as unique crossing identifiers, precise locations, and waterway details, the framework ensures a systematic approach to identifying and prioritizing high-risk crossings. This targeted focus allows resources to be allocated to areas most vulnerable to geohazards and hydrotechnical challenges.

API 1133[11] highlights two primary hydrotechnical hazards: vertical channel movements (e.g., scour and sediment erosion) and lateral channel movements (e.g., bank migration and meandering). These hazards subject pipelines to various risks, including hydrodynamic loading, debris impact, vibration-induced fatigue, and sagging caused by sediment erosion. Additionally, exposed pipelines face heightened risks of third-party damage from vessels or equipment. Using collected data, API 1133 employs a range of risk assessment methods, from qualitative and semi-qualitative approaches that offer broad risk categorizations to quantitative methods that predict specific failure scenarios, such as excessive riverbed scouring or channel migration. Quantitative methods provide a more detailed analysis, enabling precise identification of when pipeline integrity might be compromised and facilitating targeted risk mitigation strategies. API 1133 emphasizes proactive monitoring and mitigation strategies to address these risks. Tools like LiDAR and photogrammetry enable effective monitoring of dynamic conditions such as channel migration and sediment transport. These insights guide pipeline design and maintenance strategies, including proper burial depths, scour protection, and resilience against hydrodynamic forces. Regular inspections are also essential to validate assessments and adapt to changing conditions.

Despite the advances in field methods like resistivity measurements and cathodic protection monitoring guided by standards such as AMPP SP0169, limitations persist in adopting real-time monitoring systems and predictive analytics. Emerging technologies like machine learning and remote sensing offer promising avenues for improving corrosion risk assessment and proactive mitigation strategies.

The framework distinguishes between hazard assessment, which identifies potential threats, and risk assessment, which evaluates the likelihood and consequences of failure. Risk assessment incorporates not only the probability of failure but also the potential impact, which can vary significantly depending on factors such as product type, volume, response time, and environmental receptors. This variability underscores the importance of tailored risk assessments by operators to address site-specific conditions and consequences. This approach aligns with the vision of a dynamic pipeline hazard and risk data repository by integrating comprehensive datasets with real-time monitoring and predictive analytics. By incorporating geohazard and climate data, such a repository would provide actionable insights for managing pipeline risks, allowing stakeholders to make informed decisions on maintenance, mitigation, and emergency response. The principles in API 1133 demonstrate how dynamic and adaptive solutions can enhance pipeline safety and resilience in the face of evolving environmental challenges.

A structured summary of findings is presented in Table 1.

Table 1: Hazard identification according to industry standards

Document	Source of threat	Threat identifies	Impacts
ADB-2019-01 [7]	1) Flooding 2) River Scour 3) River Channel Migration	1) Undermining support soils, causing pipeline exposure to lateral forces. 2) Debris impact 3) Potential soil movement.	1)Spillage of hazardous liquid and spread of contaminants over large areas due to currents. 2)Increased cost of maintenance. 3)Significant environmental and public health risks.
ADB-2015-02[9]	Hurricanes	1) The underwater pipelines exposure and inlet exposure. 2) Structural damage to piping and valves.	1) Disrupted oil and gas production and transportation. 2) Impacted navigation, posing risks to marine vessels and operations.
API 1133[11]	Hydrotechnical hazards: 1) Vertical channel movements. (e.g., scour and sediment erosion) 2) Lateral channel movements (e.g., bank migration and meandering)	1) Riverbed erosion affecting pipeline stability. 2) Pipeline positioning. 3) Vibration-induced fatigue	1)Adopting real-time monitoring systems and predictive analytics.
API 1187[12]	1) Landslides 2) Seismic events	1) Soil movement 2) Erosion	1) Impacted data of terrain and the geological conditions.

API 1160[18]	1)Soil/environment interaction between surface of the external pipeline 2)Landslides, earthquakes, floods, and other geohazards	Pipeline integrity such as external corrosion, internal corrosion, mechanical damages and environmental conditions of soil (pH)	1) Impacted to assess pipeline integrity including internal inspection (In-line Inspection) 2)To check for defects through pressure testing, and evaluate the defect status directly on site.

iii) Journal findings

The major findings from journal articles are presented in Table 2.

Table 2: Hazard identification according to academic research

Reference	Source of threat	Threat identifies	Findings
Ahmed et al. [19]	1)Weather-Related threats 2) Climate change	1)Corrosion 2)Erosion and soil Movement 3)Mechanical Damage	The study develops challenges in risk management and predictive models to improve pipeline sustainability and infrastructure.
Almheiri et al. [20]	1) Air temperature 2) Precipitation index 3) Net evaporation	1) Pipe damage due to excessive water pressure. 2)Soil moisture variations.	Emphasizes on meta analysis using pipe material andwater pipe size for water pipeline failure
Cruz et al. [21]	1)Hurricanes, 2) Floods	1)Chemical spills	Highlights the vulnerability of the oil and gas sector in coastal areas. The need for

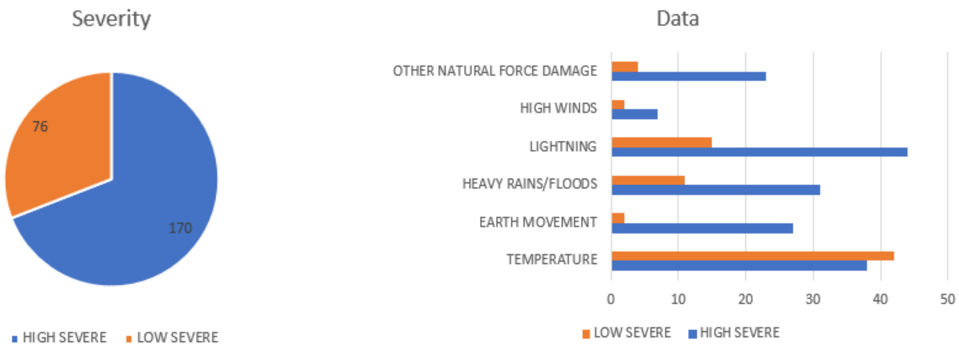
	3) Rising sea levels	2) Fires and explosions caused by natural hazards	comprehensive risk assessments and proactive mitigation and adaptation strategies.
Noor et al. [22]	Rainfall	Soil moisture	The study reveals that the corrosion rate of X60 steel increases with soil moisture content up to 10%, beyond which it decreases, with different corrosion patterns and pit characteristics influenced by moisture levels. Correlation between soil properties and corrosion behavior highlights the critical role of environmental factors in steel degradation.
Al-Judaibi et al.[23]	Rainfall	Soil moisture	The study highlights that microorganisms, particularly sulfate-reducing bacteria (SRB), play a critical role in accelerating metal corrosion through the production of sulfide ions and extracellular polymeric substances. Corrosion is further intensified in mixed microbial populations, where SRBs and iron-reducing bacteria (IRB) create synergistic conditions that degrade protective metal layers and promote the formation of corrosive iron sulfide compounds.

Ozkan et al.[24]	Climate change	Atmospheric corrosiveness	The study demonstrates the use of ISO dose-response functions to classify atmospheric corrosiveness in Canada, highlighting changes due to reduced sulfur dioxide levels and the impact of de-icing salts. It underscores the need for updated corrosiveness mapping to improve steel infrastructure protection amid climate change.
Pritchard et al.[25]	Landslide and erosion	Soil movement and corrosivity	The study highlights the increasing impact of climate change on UK soil-related geohazards, such as clay shrink-swell cycles, shallow landslides, and erosion, which threaten infrastructure. It emphasizes the need for a probabilistic approach and shared best practices to manage these risks, leveraging geohazard assessments, climate projections, and infrastructure data for sustainable planning.
Fan et al.[26]	Climate change	Temperature-induced changes in pipe dimensions and soil moisture.	Older pipes experience higher failure rates under high temperatures, while precipitation generally reduces failures, except for newly installed cast iron pipes. Climate change is projected to decrease failures, but further research is needed to address other hazards.

Oviedo et al.[27]	Geohazards	Applicable to all threats identified	Implementing GIS technology for field data collection in pipeline transportation systems significantly improved data accuracy and accessibility, leading to better decision-making in areas like maintenance and risk management.
Budzich et al. [28]	1)Landslides, 2)Earthquakes 3) Floods	1) Soil movement. 2)Terrain damage	Focus on Risk methodologies for pipeline assessment and pipeline infrastructure
Johnson et al. [29]	Geohazards	Applicable to all threats identified.	The study highlights the recognition and challenges of the transformative potential of geospatial data visualization, economic factors and integration into business decision-making processes in the US and UK.
Varela et al. [30]	Landslides	Soil instability	The GIS-based method is designed to estimate the annual probability of pipeline failure using LiDAR mapping.The challenges include the difficulty of collecting comprehensive,high resolution data over long distances and complexity of accurately integrating various data.

iv) Historical incident data report findings

The reported incident data from Figure 1, detailing natural force damage such as temperature fluctuations, earth movement, heavy rains/floods, lightning, high winds, and other environmental factors, underscores the critical need for the development of more precise risk assessments in addressing geohazards for pipeline operators. To further strengthen pipeline safety measures, risk model has to be equipped with robust, data-driven systems capable of detecting, assessing, and responding to potential threats posed by climate-related changes. It is imperative to develop advanced frameworks that prioritize the prevention of such risks, facilitate early detection, and enhance the resilience of pipeline infrastructure in accordance with PHMSA regulations.



(a) (b)

Figure 1: The severity levels of reported incidents for (a) all geohazards and (b) each category of geohazards.

PHMSA's regulatory framework for pipeline safety includes incident data and tracking but lacks geospatial data for gas distribution pipelines and excavation damage incidents, which are critical gaps. Excavation-related hazards are prevalent in gas distribution systems and pose challenges for emergency response, data tracking, and overall pipeline monitoring. To enhance safety and mitigate risks, including those from geohazards like flooding, earth movement, and lightning, there is a need to integrate advanced infrastructure and geospatial visualization tools. These improvements would support better emergency planning, risk management, and monitoring. It is also essential to confirm whether PHMSA's data includes comprehensive information on all pipeline systems to identify and address any existing gaps in safety measures.

v) Technical report findings

The technical reports highlights the geohazard integrity management which reviews historical data following Canadian and US guidelines, creating a geohazard inventory, and establishing a robust database linked to GIS, which makes data storage and retrieval more efficient. The field inspections and remote sensing methods, including satellite imagery, aerial photos, and LiDAR surveys, have been crucial for identifying over 13,500 geohazard pipeline sites in Canada and the U.S. The hazards categorization is done into three main types: geotechnical, hydrotechnical, and tectonic, each with tailored identification and mitigation strategies. The identification process also took into account the surrounding terrain beyond the pipeline right-of-way (RoW), especially where upstream watershed instability or geological features could impact the pipeline.The reviewing of historical data on past incidents using (InSAR) data for ground movement and geotechnical data (such as soil and rock types) is one of the field methods for landslide investigation. The use of tools like InSAR for land subsidence detection and GIS for continuous data updates are crucial for monitoring pipeline corridors, particularly in complex terrains or areas prone to landslides, erosion, or flooding.

From the technical reports, the need for detailed data on the geohazards identification and collection in areas with limited accessibility is required for better risk assessment. The reliability of data in extreme weather conditions is not considered for the geohazard management. The methods outlined in these studies have several limitations. Remote sensing technologies like satellite imagery, LiDAR, and GIS may struggle in regions with dense vegetation, low-resolution data, or complex terrains, leading to inaccurate or incomplete hazard detection. Field inspections, while essential for validating remote data, are resource-intensive and often hindered by inaccessibility, adverse weather, or difficult terrain. Moreover, remote sensing cannot detect internal pipeline conditions or immediate geohazards that may emerge suddenly, necessitating additional monitoring or sensor-based technologies. Furthermore, GIS requires cost efficient accurate, up-to-date spatial data and ongoing maintenance. These challenges highlight the need for complementary data collection and monitoring methods to ensure comprehensive geohazard risk management.

The data types relevant to the study include historical failure records, real-time monitoring data, inspection reports, and external environment data. Historical failure records are primarily obtained from PHMSA, specifically their incident report data available in CSV format through their website. These records are used by PHMSA during data analysis and when presenting 20-year trends. Additionally, public databases discussed in Section 3 draws data from multiple origins and encompass various data types. Inspection reports are also sourced from company-specific databases that hold private data on pipelines and inspections.

vi) Stakeholder Feedback and Industry Surveys

Will be filled after the review meeting

A.2.2 Risk Assessment Models and Approaches

Risk is broadly defined as the product of the likelihood of an event and the consequences of that event. In the context of pipeline integrity, particularly in relation to geohazards, the likelihood of an event is determined by the probability of geohazard occurrence and the vulnerability of the pipeline to such events. This approach allows risk to be expressed as a function of geohazard occurrence probability and a vulnerability term, which quantifies the interaction between the geohazard and the resulting damage to the pipeline. This dual-factor model provides a robust framework for assessing and managing risks associated with pipeline failures [40].

A.2.2.1 Literature reviewed

The Pipeline and Hazardous Materials Safety Administration (PHMSA) employs risk models that fall into four primary categories: qualitative, relative assessment/index, quantitative, and probabilistic. These categories differ in the nature of their inputs, outputs, and the algorithms used to transform inputs into actionable risk assessments. Probabilistic models are widely regarded as the best practice within PHMSA’s framework because they offer a rigorous and statistically sound basis for estimating risks and their associated uncertainties.

In addition to PHMSA’s classification, the American Society of Mechanical Engineers (ASME) B31.8S-2004 [14] presents four alternative approaches for risk assessment in gas transmission pipeline integrity management: (1) Subject Matter Experts (SMEs), (2) Relative Assessment Models, (3) Scenario-Based Models, and (4) Probabilistic Models. While there is some overlap between the ASME and PHMSA categories, the Risk Modeling Work Group (RMWG) notes that the ASME approaches are a blend of risk assessment tools and models rather than purely risk models.

Risk assessment related to geohazard and pipeline integrity involves integrating various data sources and analytical techniques. Commonly used inputs include Inertial Measurement Unit (IMU) results (strain and relative movement analysis), insights from subject matter experts, fitness-for-service (FFS) assessments, soil-pipeline interaction models, and comprehensive threat integration. These components help in characterizing the potential impacts of geohazards on pipeline infrastructure. Advanced soil-pipeline interaction models, for example, enable detailed simulations of how geohazards such as landslides or earthquakes might induce strain or deformation in pipelines, while threat integration helps in correlating multiple risk factors for a holistic assessment [41]. Table 3 presents the risk assessment models for pipelines related to geohazards and climate, based on academic research

A.2.2.2 Main findings

Overview: Regardless of the framework used, the primary output of any risk model is an estimation of actual risk, which must account for uncertainties inherent in the modeling process. By combining probabilistic modeling with geohazard-specific data, pipeline risk assessments can provide more precise insights into the likelihood and consequences of failure. This approach supports decision-making for integrity management, resource allocation, and emergency response planning, ensuring both safety and operational efficiency.

Table 3: Risk assessment models in research

Risk Assessment Model Category	**Assessment Method**	**Findings**
Probabilistic	1)Hybrid fuzzy Bayesian network [42]. 2)Strain calculation model for geohazard zones [43]. 3) Pipeline integrity under spatiotemporal seismic loading [44].	1)Model developed incorporates external factors like flood and thunder/ lightning, third party interference and other incidents in the model. 2)The study proposed a reliability-based method for assessing pipeline failure in geohazard areas using strain models and Monte Carlo simulations. It emphasizes the need for site-specific data to improve accuracy in probabilistic analyses. 3) Highlights the importance of considering spatial and temporal variations in seismic loads to avoid underestimating failure probabilities and emphasizes the model's potential for real-time damage monitoring and reliability-informed decision-making

Relative assessment/index	1) Risk scoring and ranking [45]. 2) Risk ranking based modified Muhlbauer model [46]. 3) Scoring index method [47].	1) The study highlights the use of reliability methods to address challenges in quantifying risk for modern pipelines, incorporating geotechnical threats and spill consequence modeling. By implementing design improvements the overall risk was reduced by 84%. 2) Demonstrates that the probability of pipeline failure due to geohazards varies significantly based on the specific location and can differ substantially across different sites. Data limitations and information gaps pose challenges in accurately quantifying these risks. 3)The assessment system effectively evaluated 21 landslides and 18 rockfalls, demonstrating ease of use with an average assessment time of less than 20 minutes per site. Expert consensus on the index state was high, and the system's results showed strong agreement with expert assessments, achieving similarity indices of 0.96 for landslides and 0.87 for rockfalls, indicating reliable performance.
Quantitative	1) Probabilistic and risk assessment and scoring [48]. 2)Consequence-Based Risk Assessment [49]. 3)Probabilistic model using frequency of loss of containment.	1) Temporary geohazard mitigation is crucial for construction safety, though it may be limited by footprint constraints and the need for special permits. Practical solutions are prioritized for ease of implementation, while maintaining long-term mitigation efforts. 2)Leverages the concepts of "fatal length" and "cumulative fatal length" as core components of its risk assessment model. These concepts are specifically designed to enhance the evaluation of potential consequences within high-consequence areas. 3)The framework refines spatial probability by separating it into the likelihood of the geohazard reaching the pipeline's right-of-way and its probability of exceeding the pipeline's depth and causing interaction. It

	also incorporates a mitigation factor (M) enabling a more realistic assessment of how mitigation measures reduce the overall FLoC.

Additionally, emerging AI systems like IBM Watson [50] are applied in critical response scenarios to optimize decision-making during pipeline incidents. In pipeline inspection, ROSEN [51] Group researches AI-powered smart pigging technologies to detect damage caused by external hazards . New trends involve advancements in real-time seismic hazard detection and the development of machine learning models to create detailed geohazard risk maps by integrating vast environmental datasets.

A.2.3 Existing Data Sources, Management and Repository Design

A.2.3.1 Literature reviewed

Current available database:

i) U.S. Energy Atlas: https://atlas.eia.gov/

The U.S. Energy Atlas is a cloud-based system built on ArcGIS Online, designed to enable efficient management of large datasets. Its database structure includes information on power plant locations, coal mine locations, oil and natural gas well locations, pipeline locations, storage facility locations, natural gas processing plant locations, refinery locations, and other types of energy facilities. Data is sourced from organizations such as the Federal Energy Regulatory Commission, the U.S. Geological Survey, the U.S. Bureau of Ocean Energy Management, and the National Oceanic and Atmospheric Administration. The data is accessible in various formats, including shapefiles, KML files, geodatabase files, and spreadsheets.

ii) National pipeline mapping system: https://www.npms.phmsa.dot.gov/

The U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) maintains a comprehensive geospatial database that provides critical information about hazardous liquid and gas transmission pipelines across the United States. The database includes data on interstate and intrastate hazardous liquid and natural gas pipeline systems, pipeline systems covered under Integrity Management Programs (IMP), LNG plants, and breakout tanks. Access is available at two levels: the public viewer and the Pipeline Information Management Mapping Application (PIMMA). The public viewer, open to everyone, provides limited information, allowing users to view details for one county per session and access a list of transmission pipeline operators in the area. In contrast, PIMMA offers restricted access for government officials and pipeline operators, containing sensitive pipeline infrastructure information. However, this data is for reference purposes only and cannot be downloaded.

iii) FracTracker: Few interesting pages: https://www.fractracker.org/

FracTracker Alliance is a nonprofit organization that provides interactive maps, data, and analyses focused on oil, gas, and energy infrastructure, including underground pipeline systems. It emphasizes the environmental and social impacts of energy development, offering publicly accessible tools to visualize pipeline routes, associated risks, and nearby community or environmental features. FracTracker's maps cover a range of topics, including the locations of pipelines, wells, spills, and other energy-related incidents, making it a valuable resource for understanding the broader implications of energy infrastructure. The platform is freely accessible to the public and serves as a complement to other tools like the U.S. Energy Atlas and the National Pipeline Mapping System by focusing on transparency and the intersection of energy development with public health and environmental concerns.

A.2.3.2 Main findings

Existing pipeline databases provide valuable but fragmented information on pipeline infrastructure. Current systems primarily focus on static infrastructure data, such as pipeline routes, LNG plants, and transmission systems, without dynamically updating risk factors like extreme weather events, shifting geohazards, or real-time environmental changes. There is limited integration of real-time climate and geohazard data, which is crucial for effectively assessing and mitigating risks associated with changing environmental conditions. Additionally, predictive analytics and risk modeling capabilities are underdeveloped, limiting the ability to anticipate and address potential threats proactively. Collaboration features that facilitate stakeholder engagement and real-time coordination are also lacking, making it challenging for operators, regulators, and communities to work together seamlessly. Addressing these gaps is essential for developing a more adaptive and resilient approach to pipeline risk management.

Table 4: Comparative study of existing pipeline infrastructure databases

Features	**U.S. Energy Atlas**	**National pipeline mapping system**	**FracTracker**
Objective	Provides comprehensive geospatial data on energy infrastructure, including pipelines, power plants, and storage facilities.	Offers detailed mapping and information about hazardous liquid and gas transmission pipelines.	Focuses on energy infrastructure with an emphasis on environmental and social impacts.
Scope	Broad coverage of energy infrastructure, not limited to pipelines.	Specific to hazardous liquid and gas pipelines, LNG plants, and breakout tanks.	Includes pipelines, wells, spills, and other energy-related infrastructure.
Data Sources	Federal Energy Regulatory Commission, U.S. Geological Survey, NOAA, and others.	Pipeline operators, PHMSA historical records, and government data.	Public reports, environmental organizations, and energy data aggregators.
Access	Public access with downloadable data in	Interactive maps showing pipeline	Interactive maps of pipelines, wells,

	formats like shapefiles, KML, and spreadsheets.	systems with detailed access for authorized users.	spills, and risks to nearby communities and environments.
Data formats	Shapefiles, GeoJSON, KML, and CSV formats for geospatial and tabular data.	Geospatial data in shapefiles, KMZ, and proprietary formats for secure sharing with authorized stakeholders.	GeoJSON, CSV, and other user-friendly formats tailored for public and research accessibility.
Database structure	Centralized relational databases linking geospatial, tabular, and metadata for various energy assets.	Relational database with a focus on linking pipeline attributes, geospatial data, and inspection history.	Hybrid database structure combining relational and NoSQL elements to handle diverse datasets and user types.
Infrastructure	Cloud-based infrastructure with GIS integrations and high-performance querying for large datasets.	Secure, hybrid infrastructure combining on-premise and cloud elements with restricted access and encryption mechanisms.	Open-access cloud platform with real-time updates and tools for data visualization and community collaboration.

Repository design in modern industry practice emphasizes scalability, reliability, and accessibility to manage and analyze complex datasets effectively. Key elements include adopting standardized data formats, such as JSON, CSV, and geospatial formats like shapefiles and GeoJSON, to ensure interoperability across tools and platforms. Robust database structures, often leveraging relational models for structured data and NoSQL models for unstructured or semi-structured data, are implemented to accommodate diverse data types and ensure efficient querying. Cloud-based infrastructure is increasingly preferred for its scalability, availability, and support for real-time data access, often complemented by on-premise systems for sensitive or mission-critical information. Advanced repositories integrate data visualization tools, machine learning capabilities, and APIs to enable seamless data analysis, predictive modeling, and decision-making. Industry standards for metadata, encryption, and access controls further enhance data integrity, security, and regulatory compliance, supporting diverse applications across sectors like energy, transportation, healthcare, and finance.

A.2.4 Existing Visualization and Decision Support Tools

A.2.4.1 Literature reviewed

Geospatial Information System (GIS)-based platforms are pivotal in geohazard modeling, visualization, and pipeline integrity management. ArcGIS, developed by Esri, is the most widely used GIS platform, offering comprehensive tools for mapping, spatial analysis, and geohazard modeling. It enables the creation of detailed geospatial models, analysis of hazards such as landslides, floods, and earthquakes, and advanced data visualization through various mapping techniques. Johnson et al.[52] utilized ArcGIS to develop *GeoForce*, a private online geohazard database platform, while Li et al. elaborated on the GIS design and implementation process for pipelines, detailing the technologies applied to enhance system functionality.

QGIS (Quantum GIS)[53], an open-source alternative to ArcGIS, offers similar capabilities without licensing fees. It supports multiple data layers and integrates various data sources, including LiDAR, satellite imagery, and field surveys, making it a cost-effective choice for geohazard mapping. GRASS GIS[54], another open-source software, excels in spatial modeling, raster processing, and environmental analyses, such as landslide susceptibility and hydrological modeling for flood risk assessments. Global Mapper[55], a paid GIS tool, focuses on terrain, topography, and geohazard risk analysis, offering additional functionality for handling and visualizing geospatial data.

Beyond traditional GIS platforms, immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are transforming geospatial visualization and decision-making in the oil and gas industry. These technologies integrate seamlessly with IoT sensors, GIS platforms, and real-time monitoring systems to provide dynamic updates on hazards, including weather changes, seismic activity, and pipeline conditions. VR enables realistic simulations of pipeline environments, enhancing operators' understanding of hazard-prone areas affected by corrosion, ground movement, or extreme weather. AR overlays real-time data, such as stress analysis or leak detection, onto physical pipeline models, improving field inspections and risk mitigation efforts. Immersive training simulations further prepare teams to respond effectively to emergencies, contributing valuable insights to hazard and risk models. Zhou et al.[56] highlighted the critical role of visualization techniques in enhancing decision-making processes across industries. Behzadan et al.[57] explored the applicability of advanced visualization for underground pipelines, while Zahlan et al.[58] categorized AR visualization methods, including X-Ray, transparent, shadow, topo, image rendering, and cross-section views. Zhang et al.[59] investigated computer vision and sensor fusion within ArcGIS, comparing these techniques based on performance and user experience. Additionally, Temizel et al.[60] reviewed intelligent technologies shaping the oil and gas industry, and Li et al.[61] discussed the development of digital twins, integrating AI to ensure sustainability and functionality in engineering systems.

Moreover some AI technologies have emerged as transformative tools in geohazard risk management. Platforms like Geoplat AI[62] leverage predictive analytics to anticipate pipeline risks, while Planet Labs[63] integrates satellite imagery analysis with GIS platforms to provide real-time geospatial insights.

<u>A.2.4.2 Main findings</u>

Table 5: Competitive study of available GIS platform

Feature	**ArcGIS**	**QGIS**	**GRASS GIS**	**Global Mapper**	**Planet Labs**	**Geoplat AI**

Type	Proprietary	Open-source	Open-source	Proprietary	Proprietary	Proprietary
Cost	Paid	Free	Free	Paid	Paid	Paid
Primary Use	Comprehensive GIS platform for mapping, spatial analysis, and modeling	Multi-layer mapping, data integration, and geohazard mapping	Spatial modeling and environmental analysis	Terrain analysis, topograph, and geohazard risk assessment	Satellite imagery analysis integrated with GIS	Predictive analytics for geohazard risk
Key Features	Advanced mapping, 3D visualization, robust analytics	Customizable with plugins, multi-source integration	Raster processing, hydrological modeling, environmental simulations	3D visualization, terrain modeling, and geospatial data management	Real-time geospatial data and satellite imagery	AI-powered risk prediction and decision support
Data Sources	Wide range of data formats including satellite imagery, field data, and LiDAR	LiDAR, satellite imagery, field surveys	Field data, environmental models	Satellite imagery, LiDAR, terrain data	Satellite data from proprietary satellites	Integrated GIS and AI datasets
Integration	Seamless integration with other Esri tools and systems	Supports external plugins and custom scripts	Highly compatible with environmental modeling tools	Moderate integration capabilities	Compatible with GIS and external analytics tools	GIS and AI platforms integration
Ease of Use	User-friendly but	Beginner friendly,	Steeper learning	Moderate learning	Simple interface,	Designed for expert

	requires training for advanced features	with extensive community support	curve for environmental modeling	curve, good documentation	specialized for satellite data	use with predictive modeling
Scalability	Scales well for enterprise use	Scales for small to medium projects	Ideal for research and specialized analysis	Suitable for small to medium-scale projects	Scales for global satellite data	Scales for large datasets and AI integration

By combining the strengths of GIS platforms, AI tools, and immersive technologies, we can develop dynamic and interactive repositories for geohazard and climate data. These repositories not only enhance data visualization but also enable proactive pipeline integrity management, effectively addressing the challenges posed by evolving geohazard and climate risks.

3. Conclusion from the literature review.

Effective pipeline risk management relies on real-time monitoring, predictive analytics, and geospatial visualization to identify and mitigate potential hazards. Tailored risk assessments are essential to address site-specific conditions and environmental factors, ensuring that strategies are proactive and responsive. Integrating various data sources—such as historical records, real-time monitoring, and advanced analytics—enhances the accuracy and reliability of risk management frameworks. Furthermore, developing advanced frameworks for seamless integration of real-time data from IoT sensors, satellite imagery, and field inspections is crucial. Improving remote sensing technologies will provide high-resolution, accurate geohazard monitoring, especially in challenging or inaccessible environments. Additionally, designing adaptable risk models that encompass a broader range of geohazards, including emerging climate risks, along with establishing standardized data formats and interoperable systems, will support effective and dynamic risk management in the face of evolving environmental challenges. To further enhance these efforts, it is recommended to adopt a holistic data integration approach, ensuring seamless integration of diverse data sources. Implementing standardized data formats and establishing interoperable systems will facilitate smooth data sharing across platforms and stakeholders. Encouraging cross-disciplinary collaboration between geospatial specialists, data scientists, and industry professionals will enable the development of comprehensive risk management frameworks. Continuous improvement should be prioritized by regularly updating predictive models with the latest research findings and technological advancements.

It highlights an intriguing opportunity to develop new or updated models that integrate evolving climate trends. These models should incorporate a broader range of parameters, such as rainfall patterns, temperature fluctuations, soil characteristics, and flood risks, to better address the complex interplay between climate change and pipeline integrity.

References:

1. Wang, Y. Y., Fleck, P., McKenzie-Johnson, P., Theriault, B., West, B. (2023). Framework for Geohazard Management, prepared for NGAA, The INGAA Foundation, and a Group

of Sponsors by the Center for Reliable Energy Systems, LLC (CRES) and Geosyntec Consultants, Inc.

2. Baumgard, A. J., Coultish, T. L., Ferris, G. W. (2014). Implementing a geohazard integrity management program - statistics and lessons learned over 15 years, 10th International Pipeline Conference IPC2014, Calgary, Alberta, Canada.

3. U.S. Government. (n.d.). *49 CFR § 195—Transportation of hazardous liquids by pipeline*. Electronic Code of Federal Regulations. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-D/part-195

4. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (n.d.). *49 CFR 195 - Pipeline safety regulations for hazardous liquids and carbon dioxide pipelines*. U.S. Department of Transportation. https://www.phmsa.dot.gov/pipeline/annotated-regulations/49-cfr-195

5. U.S. Government. (n.d.). *49 CFR § 192 - Transportation of natural and other gas by pipeline*. Electronic Code of Federal Regulations. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-D/part-192

6. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (n.d.). *49 CFR 192 - Pipeline safety regulations for transportation of natural and other gas by pipeline*. U.S. Department of Transportation. https://www.phmsa.dot.gov/pipeline/annotated-regulations/49-cfr-192

7. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (2019, April 8). *Pipeline safety: Safety of underground natural gas storage facilities; Final rule*. Federal Register. https://www.phmsa.dot.gov/regulations/federal-register-documents/2019-07132

8. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (2016, January 19). *Pipeline safety: Potential for damage to pipeline facilities caused by flooding, river scour, and river migration; Final rule*. Federal Register. https://www.federalregister.gov/documents/2016/01/19/2016-00765/pipeline-safety-potential-for-damage-to-pipeline-facilities-caused-by-flooding-river-scour-and-river

9. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (2015, June 23). Pipeline safety: Potential for damage to pipeline facilities caused by the passage of hurricanes; Final rule. Federal Register. https://www.federalregister.gov/documents/2015/06/23/2015-15401/pipeline-safety-potential-for-damage-to-pipeline-facilities-caused-by-the-passage-of-hurricanes

10. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (2019, May 2). Pipeline safety: Potential for damage to pipeline facilities caused by earth movement and other natural forces; Final rule. Federal Register. https://www.federalregister.gov/documents/2019/05/02/2019-08984/pipeline-safety-potential-for-damage-to-pipeline-facilities-caused-by-earth-movement-and-other

11. American Petroleum Institute. (n.d.). API 1133 - Pipeline Leak Detection Programs. American Petroleum Institute. https://www.apiwebstore.org/standards/1133

12. American Petroleum Institute. (n.d.). RP 1187 - Pipeline safety standard for managing geohazards. American Petroleum Institute. https://www.api.org/products-and-

services/standards/important-standards-announcements/rp1187-pr-pipeline-safety-standard-for-managing-geohazards

13. Purdy, G. (2010). ISO 31000: 2009—Setting a new standard for risk management. Risk Analysis: An International Journal, 30(6), 881–886. https://doi.org/10.1111/j.1539-6924.2010.01455.x
14. American Society of Mechanical Engineers. (2022). ASME B31.8S: Managing system integrity of gas pipelines. American Society of Mechanical Engineers. https://www.asme.org/codes-standards/find-codes-standards/b31-8s-managing-system-integrity-gas-pipelines/2022/pdf
15. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (n.d.). Incident reporting. U.S. Department of Transportation. https://www.phmsa.dot.gov/incident-reporting
16. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (n.d.). National Pipeline Mapping System (NPMS). U.S. Department of Transportation. https://www.npms.phmsa.dot.gov/
17. American Petroleum Institute. (n.d.). API RP 1169 - Recommended practice for basic inspection requirements for new pipelines. American Petroleum Institute. https://www.api.org/products-and-services/standards/important-standards-announcements/recommendedpractice1169
18. American Petroleum Institute. (n.d.), API 1160 - Managing system integrity for hazardous liquid pipelines. https://www.apiwebstore.org/standards/1160
19. Ahmed, T., Mahmood, Y., Yodo, N., & Huang, Y. (2024). Weather-related combined effect on failure propagation and maintenance procedures towards sustainable gas pipeline infrastructure. Sustainability, 16(13), 5789. https://doi.org/10.3390/su16135789
20. Z. Almheiri, M. Meguid, and T. Zayed, "Review of critical factors affecting the failure of water pipeline infrastructure," Journal of Water Resources Planning and Management, vol. 149, no. 10, p. 03123001, 2023, doi: 10.1061/(ASCE)WR.1943-5452.0001587
21. A. M. Cruz and E. Krausmann, "Vulnerability of the oil and gas sector to climate change and extreme weather events," Climatic Change, vol. 121, no. 1, pp. 41-53, 2013.
22. Noor, Ehteram A., and Aisha H. Al-Moubaraki. "Influence of soil moisture content on the corrosion behavior of X60 steel in different soils." Arabian Journal for Science and Engineering, 39 (2014): 5421-5435.
23. Al-Judaibi, Awatif, and Aisha Al-Moubaraki. "Microbial analysis and surface characterization of SABIC carbon steel corrosion in soils of different moisture levels." (2013).
24. Ozkan, Istemi F., Nafiseh Ebrahimi, Jieying Zhang, Dario Markovinovic, and Hamidreza Shirkhani. "Atmospheric Corrosion of Steel Infrastructure in Canada Under Climate Change." *Corrosion* 79, no. 9 (2023): 1064-1078.
25. Pritchard, Oliver G., Stephen H. Hallett, and Timothy S. Farewell. "Soil impacts on UK infrastructure: current and future climate." In *Proceedings of the Institution of Civil*

Engineers-Engineering Sustainability, vol. 167, no. 4, pp. 170-184. Thomas Telford Ltd, 2014.

26. Fan, Xudong, Xijin Zhang, Allen Yu, Matthew Speitel, and Xiong Yu. "Assessment of the impacts of climate change on water supply system pipe failures." *Scientific Reports* 13, no. 1 (2023): 7349.
27. Oviedo, Karin, and John Erick Malpartida Moya. "Field data collection using gis technology for the management of geohazards and third-party damage threats in the pipeline transportation system of natural gas (ng) and natural gas liquids (ngl)." In *ASME International Pipeline Geotechnical Conference*, vol. 59117, p. V001T03A002. American Society of Mechanical Engineers, 2019
28. J. J. Budzich and Q. Lan, "Programmatic approaches to assessing and mitigating risk to pipelines from geohazards," in Pipelines 2024, pp. 93-103.
29. C. Johnson, S. Schmidt, J. Taylor, and J. deLaChapelle, "Geospatial database development: Supporting geohazard risk assessments through real-time data and geospatial analytics," in International Pipeline Conference, vol. 86564, p. V001T06A001, Sep. 2022, American Society of Mechanical Engineers.
30. P. Varela, S. Cheng, R. Sancio, D. Cook, A. McKenzie-Johnson, and S. Koduru, "A new GIS-based method to estimate annual probability of pipeline failure resulting from landslides based on actual failure locations," in International Pipeline Conference, vol. 86564, p. V001T07A002, Sep. 2022, American Society of Mechanical Engineers.
31. B. Satipaldy, T. Marzhan, U. Zhenis, and G. Damira, "Geotechnology in the age of AI: The convergence of geotechnical data analytics and machine learning," Fusion of Multidisciplinary Research, An International Journal, vol. 2, no. 1, pp. 136-151, 2021.
32. Michael Baker Jr., Inc., U.S. Department of Transportation, Mechanical damage final report, Pipeline and Hazardous Materials Safety Administration, 2014. [Online]. Available: https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/technical-resources/pipeline/gas-distribution-integrity-management/65991/mechanicaldamagefinalreport.pdf.
33. M. Porter, M. Leir, A. Baumgard, and G. Ferris, "Integrating terrain and geohazard knowledge into the pipeline lifecycle," in Proceedings of the 6th Canadian GeoHazards Conference-GeoHazards 2014, June. 2014, vol. 6, pp. 15-18.
34. Michael Baker Jr. Inc.,U.S. Department of Transportation, Final report: Pipeline corrosion, Pipeline and Hazardous Materials Safety Administration, 2016. https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/technical-resources/pipeline/gas-distribution-integrity-management/65996/finalreportpipelinecorrosion.pdf.
35. M. Porter, "Geohazard risk management for the Nor Andino gas pipeline," ResearchGate, 2015. [Online]. Available: https://www.researchgate.net/profile/Michael-Porter-7/publication/267649796_Geohazard_Risk_Management_for_the_Nor_Andino_Gas_Pipeline/links/55b5037508aec0e5f436a525/Geohazard-Risk-Management-for-the-Nor-Andino-Gas-Pipeline.pdf.

36. G. Baum, D. Galloway, and J. Harp, "Landslide and land subsidence hazards to pipelines," U.S. Geological Survey, Tech. Rep. 2008-1006, 2008

37. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (n.d.). Operator reports submitted to PHMSA: Forms and instructions. Pipeline and Hazardous Materials Safety Administration. https://www.phmsa.dot.gov/forms/operator-reports-submitted-phmsa-forms-and-instructions.

38. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (n.d.). Incidents/accidents data for download. Pipeline and Hazardous Materials Safety Administration. https://dac-phmsa-usdot.hub.arcgis.com/pages/incidents-accidents-data-for-download.

39. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. (n.d.). Pipeline failure investigation reports. Pipeline and Hazardous Materials Safety Administration. https://www.phmsa.dot.gov/safety-reports/pipeline-failure-investigation-reports.

40. R. S. Read, "Pipeline geohazard assessment: Bridging the gap between integrity management and construction safety contexts," in International Pipeline Conference, vol. 51883, p. V003T04A033, Sep. 2018, American Society of Mechanical Engineers.

41. D. Zapata, I. Pederson, and S. Keane, "Geohazard management approach within safety case," in International Pipeline Conference, vol. 51876, p. V002T07A025, Sep. 2018, American Society of Mechanical Engineers.

42. Y. Mahmood, J. Chen, N. Yodo, and Y. Huang, "Optimizing natural gas pipeline risk assessment using hybrid fuzzy Bayesian networks and expert elicitation for effective decision-making strategies," Gas Science and Engineering, vol. 125, p. 205283, 2024.

43. Q. Zheng, I. Allouche, W. Qiu, Y. Li, N. Yoosef-Ghodsi, M. Fowler, and S. Adeeb, "Probabilistic analysis of pipelines in geohazard zones using a novel approach for strain calculation," Journal of Pipeline Systems Engineering and Practice, vol. 15, no. 1, p. 04023054, 2024.

44. Y. Wang, A. Xia, and G. Qin, "Probabilistic modeling for reliability analysis of buried pipelines subjected to spatiotemporal earthquakes," Probabilistic Engineering Mechanics, vol. 69, p. 103315, 2022.

45. Mitchell, J., Jasper, S., & Mihell, J. (2014, September). A semi-quantitative risk assessment to support oil pipeline risk-based design. In International Pipeline Conference (Vol. 46124, p. V003T12A027). American Society of Mechanical Engineers

46. Esford, F., Porter, M., Savigny, K. W., Muhlbauer, W. K., & Dunlop, C. (2004). A risk assessment model for pipelines exposed to geohazards. In International Pipeline Conference (Vol. 41766, pp. 2557-2565). American Society of Mechanical Engineers.

47. Jing, Hongyuan, Jianbin Hao, Bing Han, and Zhangzhong Wu. "Semi-quantitative assessment technology of geohazard risk for pipeline." In ICPTT 2009: Advances and Experiences with Pipelines and Trenchless Technology for Water, Sewer, Gas, and Oil Applications, pp. 1542-1551. 2009.

48. R. S. Read, "Pipeline geohazard assessment: Bridging the gap between integrity management and construction safety contexts," International Pipeline Conference, vol. 51883, pp. V003T04A033, Sept. 2018. American Society of Mechanical Engineers.

49. Y. Yin, H. Yang, P. Duan, L. Li, E. Zio, C. Liu, and Y. Li, "Improved quantitative risk assessment of a natural gas pipeline considering high-consequence areas," Reliability Engineering & System Safety, vol. 225, p. 108583, 2022.

50. IBM, "Watsonx AI," IBM, https://www.ibm.com/products/watsonx-ai.

51. Rosen Group, "Artificial Intelligence," Rosen Group, [Online]. Available: https://www.rosen-group.com/en/technology-and-innovation/technology-fields/artificial-intelligence.

52. C. Johnson, S. Schmidt, J. Taylor, and J. deLaChapelle, "Geospatial database development: Supporting geohazard risk assessments through real-time data and geospatial analytics," in International Pipeline Conference, vol. 86564, p. V001T06A001, 2022. American Society of Mechanical Engineers.

53. S. P. Maurya, A. Ohri, and S. Mishra, "Open source GIS: a review," in Proc. National Conf. Open-Source GIS: Opportunities and Challenges, Varanasi, India, 2015, pp. 9-10.

54. S. Gebbert and E. Pebesma, "The GRASS GIS temporal framework," Int. J. Geogr. Inf. Sci., vol. 31, no. 10, pp. 1273-1292, 2017.

55. C. Maxwell, C. Njoku, N. Nnaemeka, E. Patrick, and O. Okay, "Global Mapper 15.0: A comparative software tool in the design of open channel drainage systems," Poljoprivredna Tehnika, vol. 46, no. 3, pp. 61-73, 2021.

56. Zhou, Fangfang, Xiaoru Lin, Chang Liu, Ying Zhao, Panpan Xu, Liu Ren, Tingmin Xue, and Lei Ren. "A survey of visualization for smart manufacturing." Journal of Visualization 22 (2019): 419-435.

57. A. H. Behzadan and V. R. Kamat, "Interactive augmented reality visualization for improved damage prevention and maintenance of underground infrastructure," in Construction Research Congress 2009: Building a Sustainable Future, 2009, pp. 1214-1222.

58. M. Z. A. Muthalif, D. Shojaei, and K. Khoshelham, "A review of augmented reality visualization methods for subsurface utilities," Adv. Eng. Informatics, vol. 51, p. 101498, 2022.

59. X. Zhang, Y. Han, D. Hao, and Z. Lv, "ARGIS-based outdoor underground pipeline information system," J. Vis. Commun. Image Represent., vol. 40, pp. 779-790, 2016.

60. C. Temizel, C. H. Canbaz, Y. Palabiyik, D. Putra, A. Asena, R. Ranjith, and K. Jongkittinarukorn, "A comprehensive review of smart/intelligent oilfield technologies and applications in the oil and gas industry," in SPE Middle East Oil and Gas Show and Conference, Mar. 2019, p. D042S087R001.

61. L. Wei, D. Pu, M. Huang, and Q. Miao, "Applications of digital twins to offshore oil/gas exploitation: From visualization to evaluation," IFAC-PapersOnLine, vol. 53, no. 5, pp. 738-743, 2020.

62. GeoPlat AI, "GeoPlat AI, https://geoplat.ai/.
63. Planet Labs, "AI & satellite imagery," Planet, https://www.planet.com/pulse/ai-satellite-imagery/.