ENHANCING PIPELINE SAFETY: A GEOHAZARD MANAGEMENT PROGRAM ALIGNED WITH API RP 1187

Un Programa de Gestión de Geoamenazas Alineado con API RP 1187

Jaime H. Aristizabal C., Oscar J. Gualdron O., Carlos E. Motta T., Carlos J. Pedraza A.

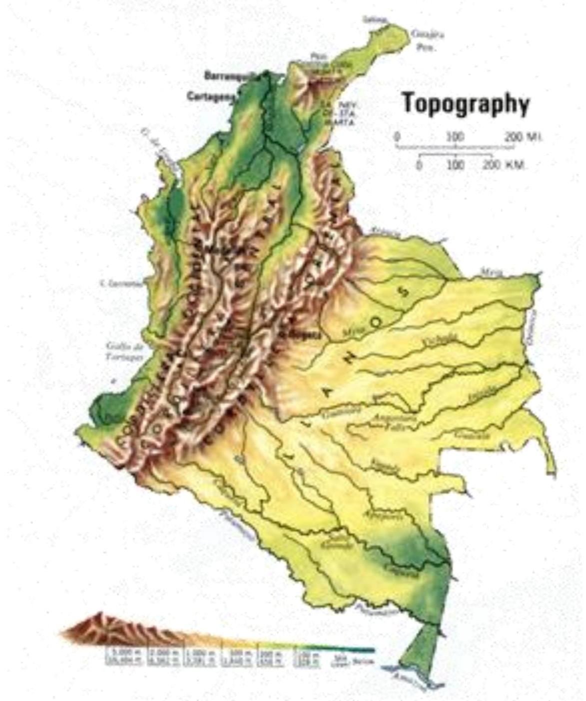
cenit TRANSPORTE Y LOGÍSTICA DE HIDROCARBUROS

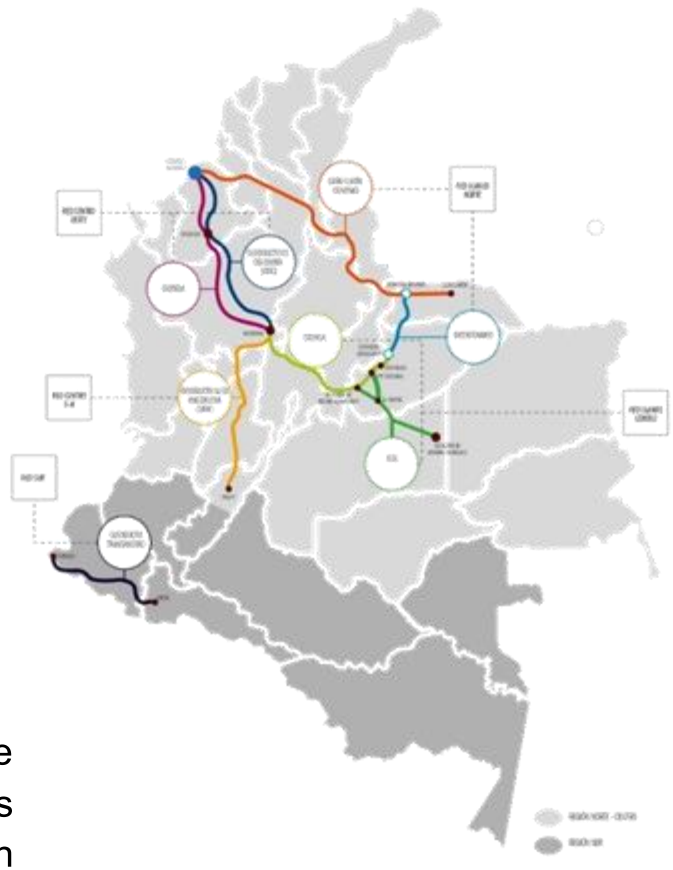
Cenit Transporte y Logistica de Hidrocarburos
Bogotá, Colombia

06 de Noviembre de 2025

Contenido

El Desafío: ¿Cómo aumentar la confiabilidad?





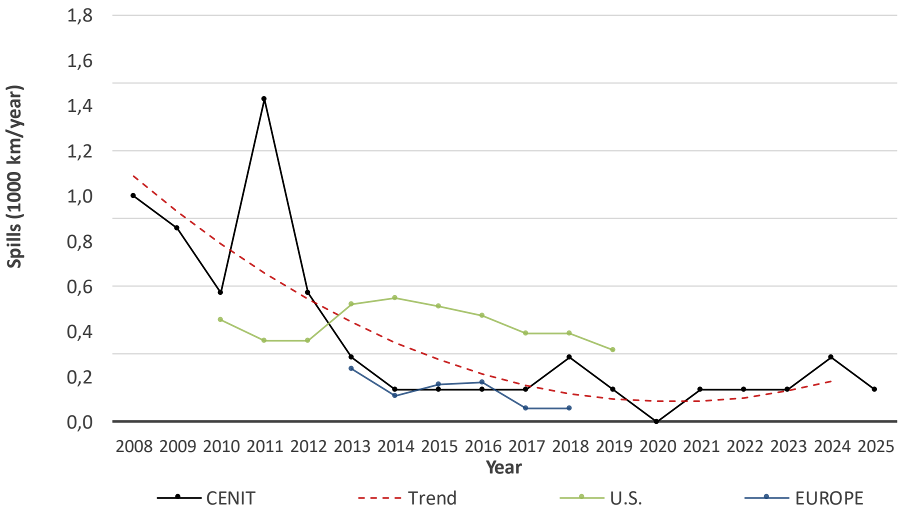
Complejidad del terreno

Cenit opera aproximadamente 9000 km de ductos en Colombia atravesando terrenos montañosos complejos. Donde la exposición a geoamenazas requiere una gestión constante y especializada.

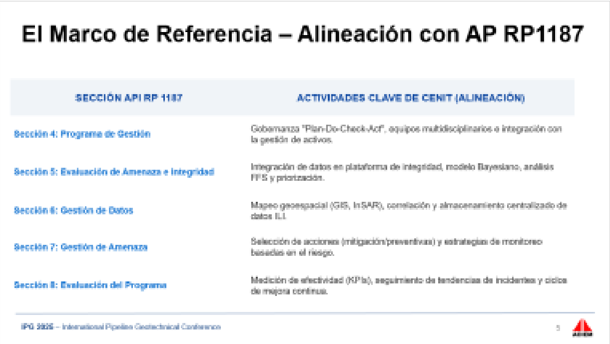
Estrategia: Filosofía proactiva

Desde 2014, se cambia hacia un enfoque proactivo (centrado en la amenaza), una gestión de integridad (Integrity – Focused)

La Meta: **No Fallas por Geoamenazas**
Camino: Integración multidisciplinaria (geotecnia, integridad, operaciones) con enfoque en análisis multiamenaza en pro de anticipar riesgo



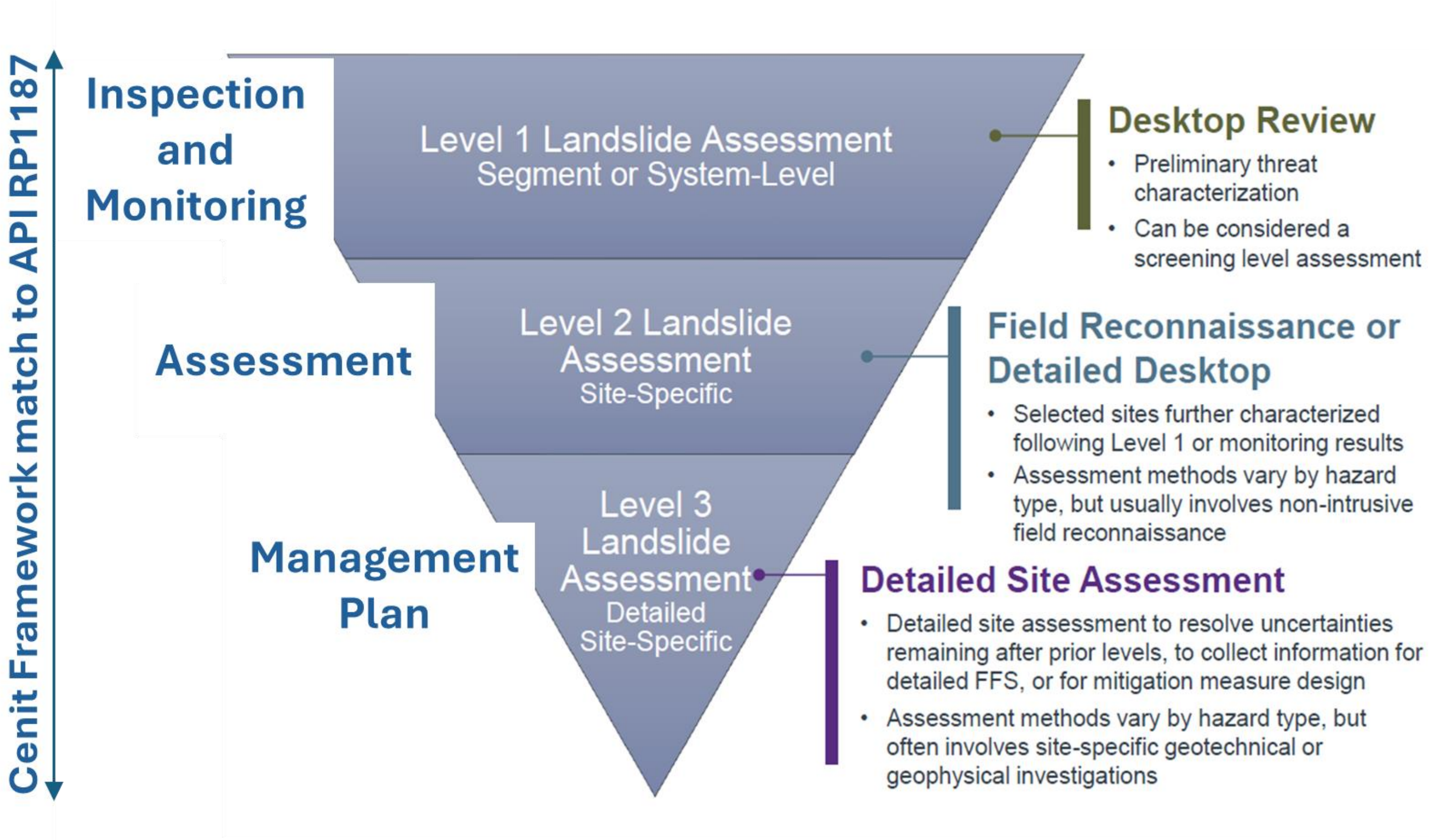
El Marco de Referencia – Alineación con AP RP1187



El Marco de Referencia – Alineación con AP RP1187

SECCIÓN API RP 1187	ACTIVIDADES CLAVE DE CENIT (ALINEACIÓN)
Sección 4: Programa de Gestión	Gobernanza "Plan-Do-Check-Act", equipos multidisciplinarios e integración con la gestión de activos.
Sección 5: Evaluación de Amenaza e Integridad	Integración de datos en plataforma de integridad, modelo Bayesiano, análisis FFS y priorización.
Sección 6: Gestión de Datos	Mapeo geoespacial (GIS, InSAR), correlación y almacenamiento centralizado de datos ILI.
Sección 7: Gestión de Amenaza	Selección de acciones (mitigación/preventivas) y estrategias de monitoreo basadas en el riesgo.
Sección 8: Evaluación del Programa	Medición de efectividad (KPIs), seguimiento de tendencias de incidentes y ciclos de mejora continua.

IPG 2025 – International Pipeline Geotechnical Conference 5



El Marco de Referencia – Alineación con AP RP1187

SECCIÓN API RP 1187	ACTIVIDADES CLAVE DE CENIT (ALINEACIÓN)
Sección 4: Programa de Gestión	Gobernanza "Plan-Do-Check-Act", equipos multidisciplinarios e integración con la gestión de activos.
Sección 5: Evaluación de Amenaza e Integridad	Integración de datos en plataforma de integridad, modelo Bayesiano, análisis FFS y priorización.
Sección 6: Gestión de Datos	Mapeo geoespacial (GIS, InSAR), correlación y almacenamiento centralizado de datos ILI.
Sección 7: Gestión de Amenaza	Selección de acciones (mitigación/preventivas) y estrategias de monitoreo basadas en el riesgo.
Sección 8: Evaluación del Programa	Medición de efectividad (KPIs), seguimiento de tendencias de incidentes y ciclos de mejora continua.

Proceso de evaluación

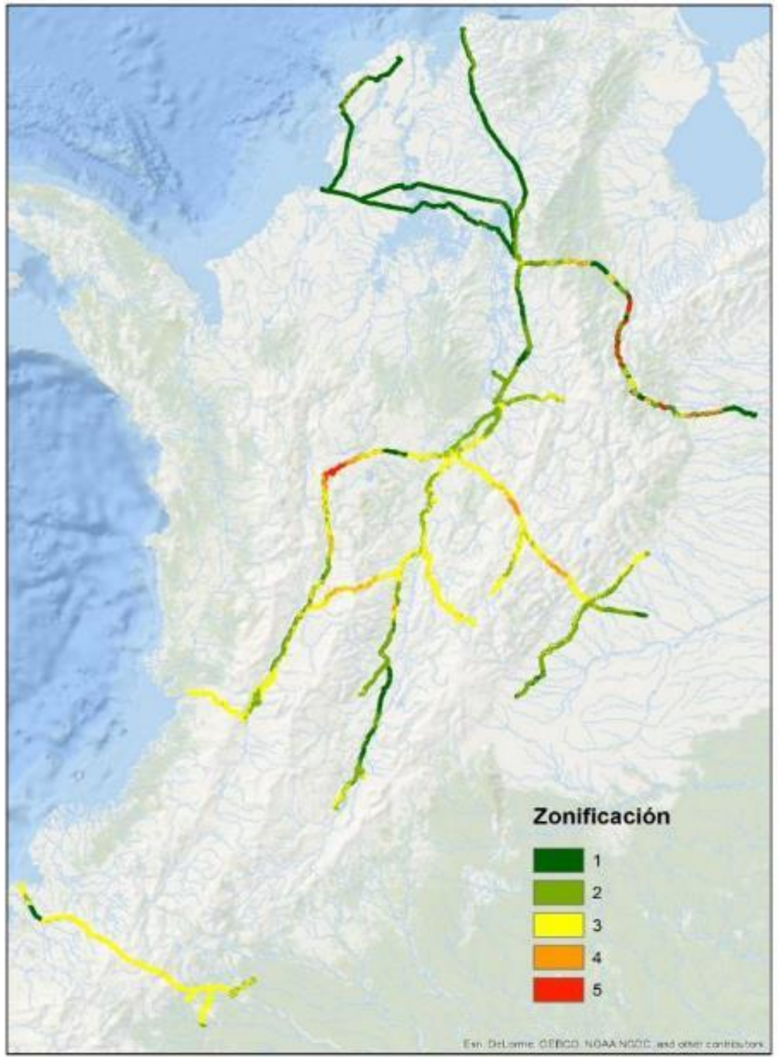
Proceso de evaluación: Línea Base

Dominio A (Tier 1 API). Identificar Zonas potenciales

Primer filtro con el objetivo de identificar zonas con potencial de inestabilidad mediante un análisis de oficina y un screening de gran área.

- Mapeo Geoespacial (GIS)
- Imágenes satelitales y modelos de elevación (DEM)
- Análisis InSar
- Zonificación Geotécnica y Climática integrada

Enfocar el recurso en las áreas que requieren inspección mas detallada.



Aristizábal, J. et al (2023). Predictive Schemes in Geohazards Management of Hydroclimatological Origin. IPG2023-65003. Proceedings of the 2023 International Pipeline Geotechnical Conference. Bogotá D.C., Colombia. November 23-24, 2023

Proceso de evaluación: Confirmación Amenaza Strain Demand

Dominio B (Tier 2 API) – Verificación dominio A

Validación de zonas críticas

- Confirma áreas susceptibles a interacción suelo-ducto para asegurar integridad del ducto.

Integración de datos

- Combina inspección interna y observación geotécnica para evaluación detallada.

Decisiones precisas

- Facilita decisiones sobre mitigación, reparación o monitoreo basado en evidencia.

Priorización de recursos

- Enfoca esfuerzos en áreas de mayor riesgo para garantizar operación segura.

Definición de Strain Demand

- Strain Demand es la deformación real que sufre un ducto por movimientos del terreno.

Causas Geológicas

- Movimientos como deslizamientos y asentamientos generan la deformación del ducto.

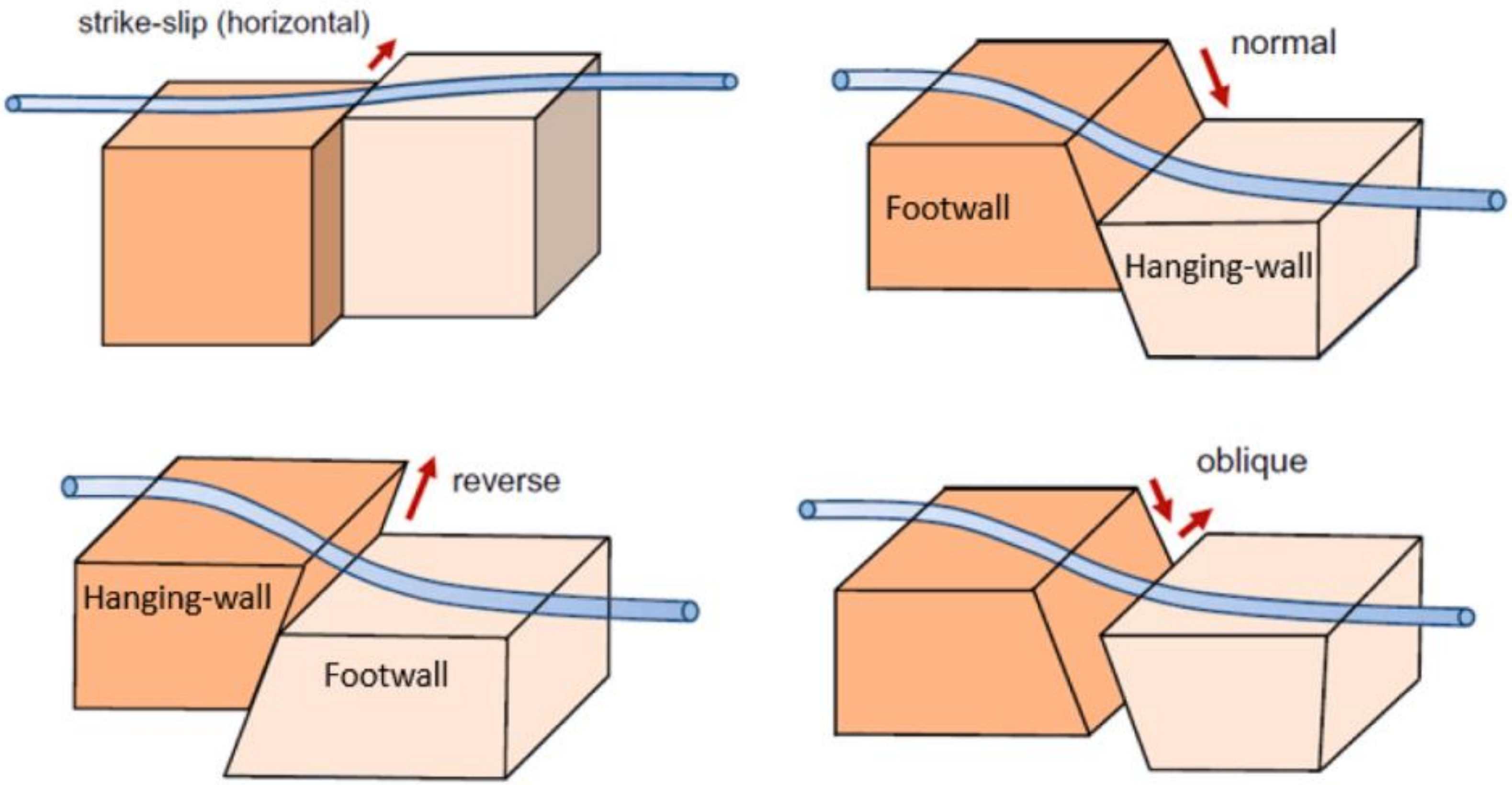
Importancia para la Seguridad

- Strain Demand indica el esfuerzo interno y riesgo de falla estructural en ductos.

Medidas de Mitigación y Monitoreo

- Medir el Strain Demand permite diseñar mitigaciones y asegurar integridad a largo plazo.

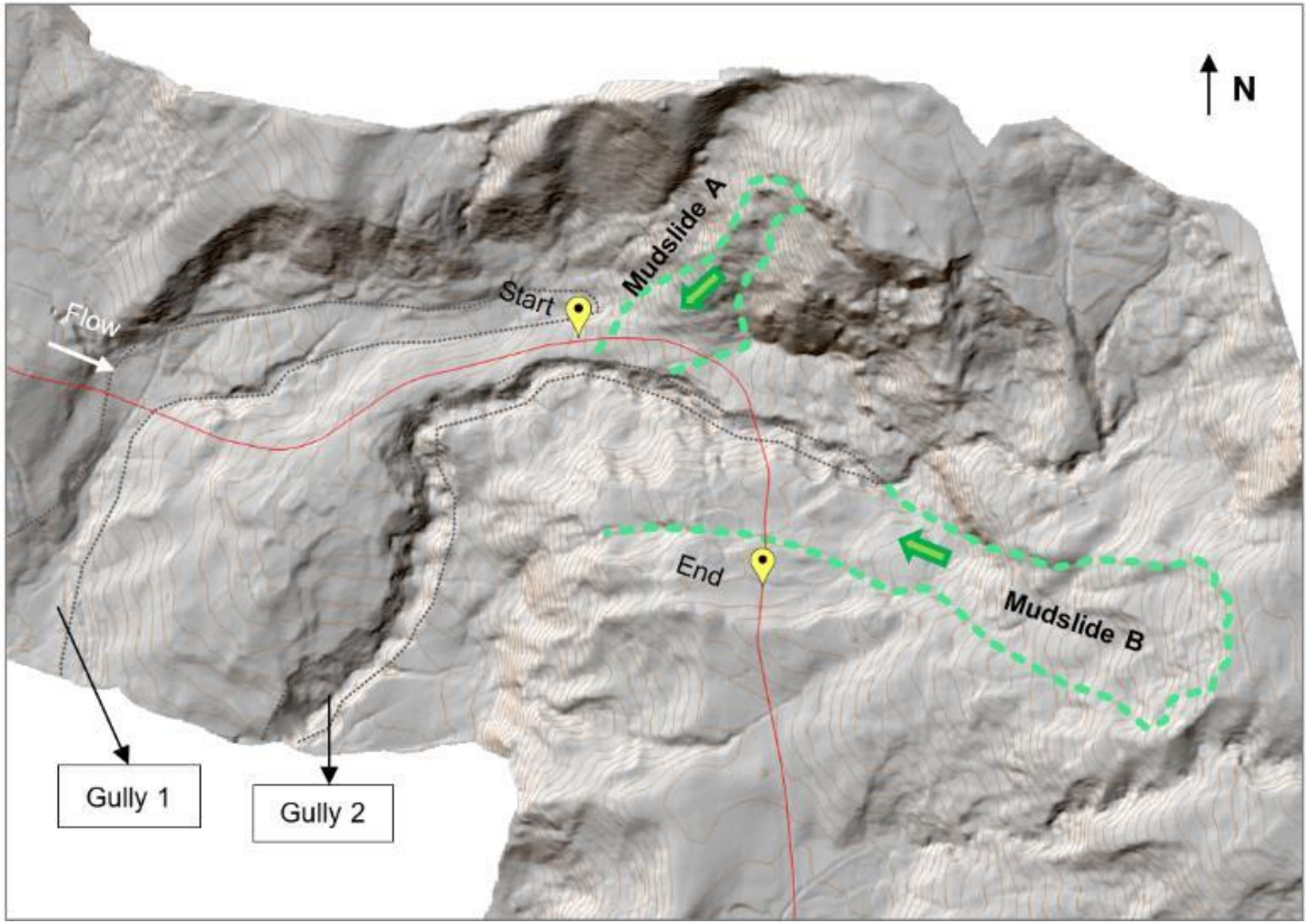
Proceso de evaluación: Confirmación Amenaza Strain Demand



Dijkstra, G.J., Karamanos, S.A., Gresnigt, A.M., Sarvanis, G.C., Dakoulas, P., 2021. Actions due to severe ground-induced deformations. In: Geohazards and Pipelines. Springer, Cham. https://doi.org/10.1007/978-3-030-49892-4_3.

Proceso de evaluación: Confirmación Amenaza

Strain Demand



Proceso de evaluación: Priorización por Strain

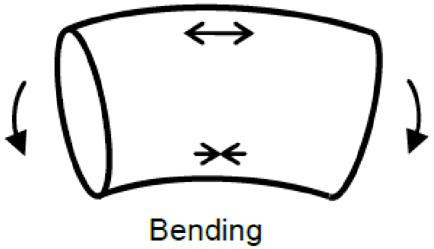
Strain Capacity

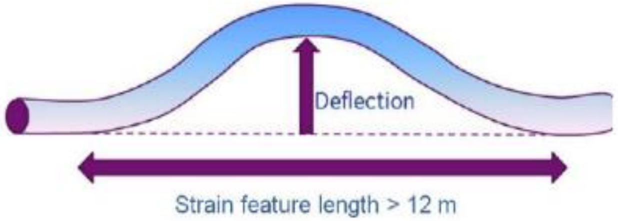
Dominio C (Tier 2 API) – Evaluación y priorización

¿Qué es? Es la deformación *máxima* que el ducto puede soportar de forma segura antes de fallar (arrugamiento o fractura).

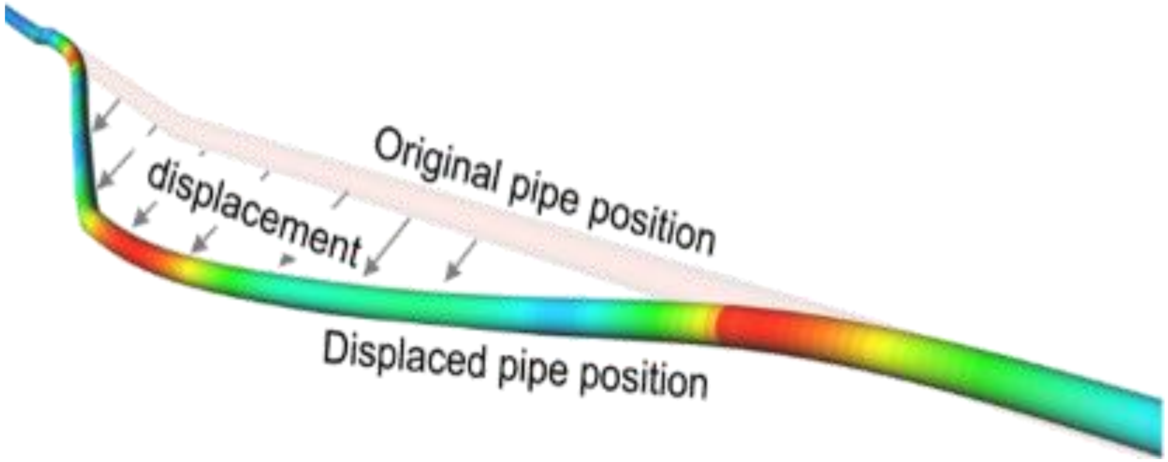
¿Cómo se calcula? Usando análisis de aptitud para el Servicio (FFS) y estándares de la industria.

¿Cuánto se puede flectar la tubería?





Demanda de deformación	**Deformación reportada ILI**
Vs	**Vs**
Capacidad de deformación	**Criterios Limite Strain Limit Criteria SCL**



Proceso de evaluación: Priorización por Strain Strain Capacity

¿Cuánto se puede flectar la tubería?

Nivel 1: Monitoreo

Zonas de bajo riesgo o deformación estable.

$\varepsilon T < 70\%$ SCL
$\Delta\ \varepsilon T < 0.04\%$
PM = 0

Se mantiene vigilancia continua y seguimiento de tendencias.

Nivel 2: Intervención Preventiva

Riesgo moderado o alta tasa de crecimiento.

$70\% < \varepsilon T < 99\%$ SCL
$\Delta\ \varepsilon T > 0.04\%$
PM > 0.1 m

Se programan intervenciones preventivas (CAPEX) para mitigar el riesgo.

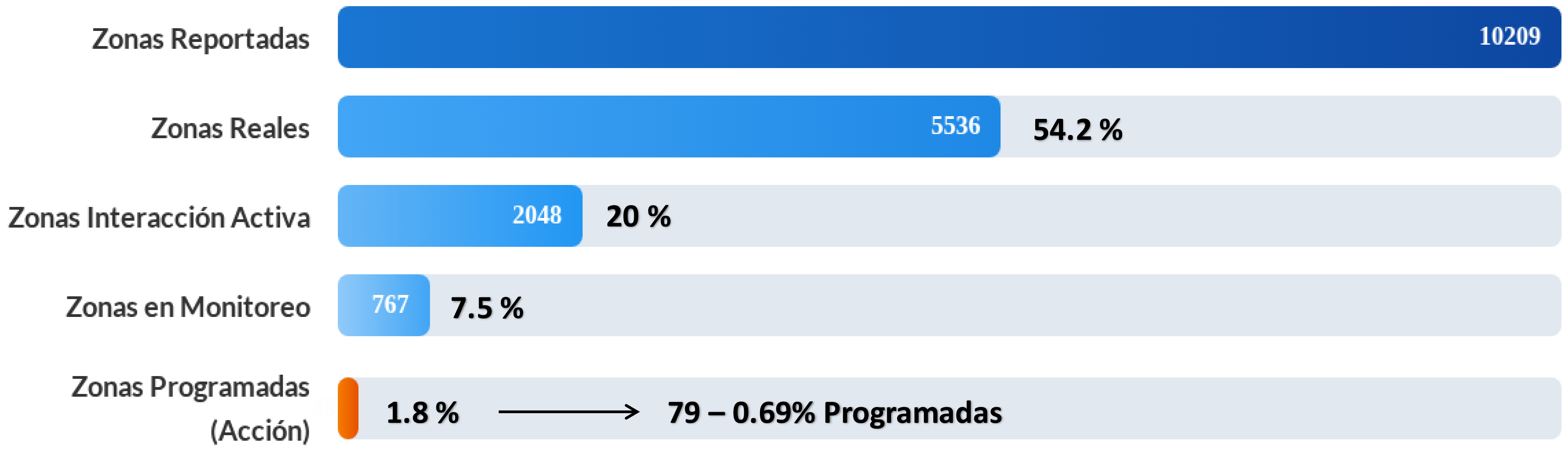
Nivel 3: Intervención Correctiva

Riesgo crítico; la deformación supera los límites.

$\varepsilon T >$ SCL
εT GWD > TCL
εT no BND

Requiere acción inmediata para garantizar la integridad del ducto.

Proceso de evaluación: Priorización por Strain



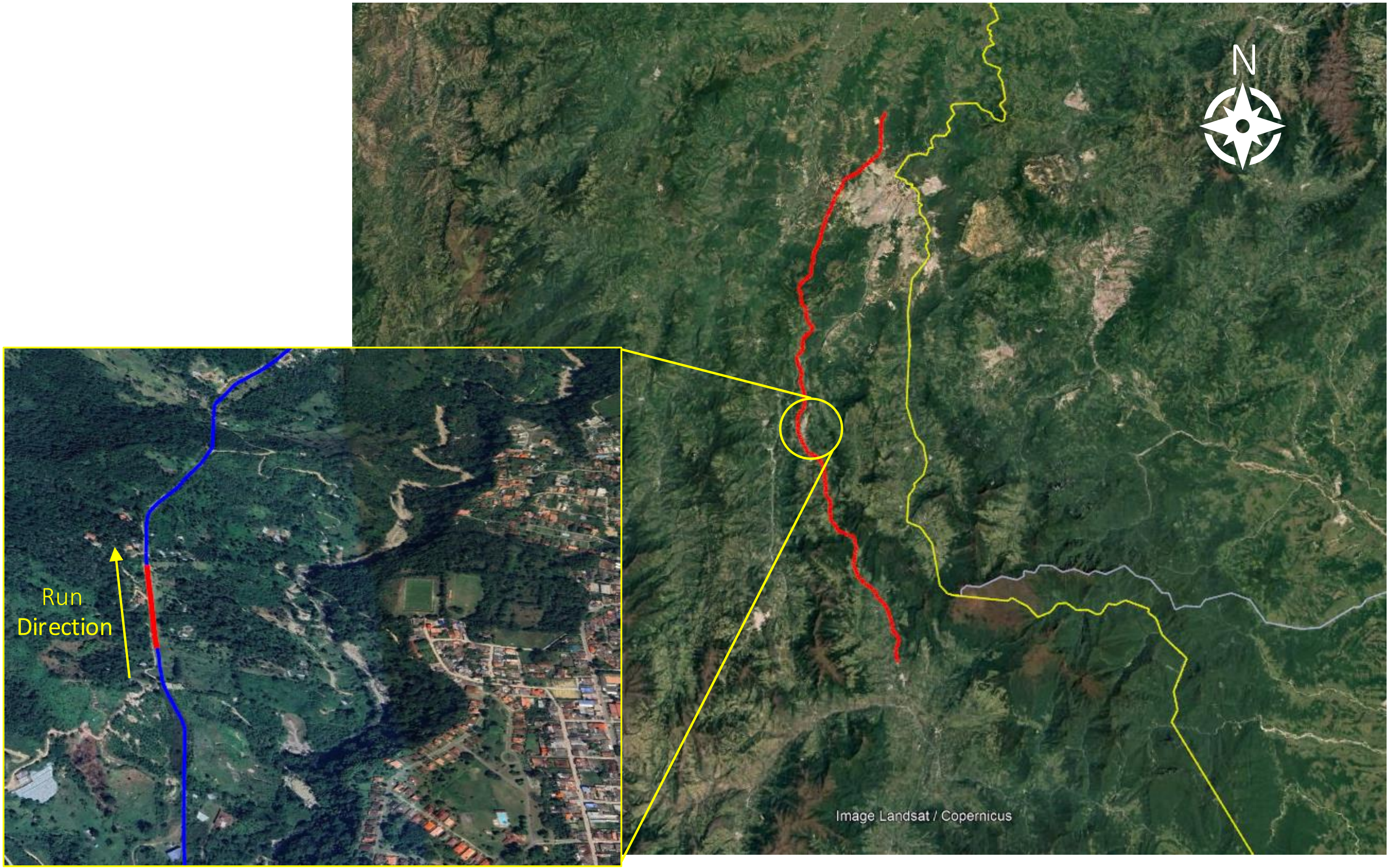
Nuestra metodología de filtrado jerárquico nos permite enfocar recursos (CAPEX/OPEX) solo en las zonas que presentan un riesgo real y activo.

Caso Estudio:

Caso Estudio: Ubicación y caracteristicas

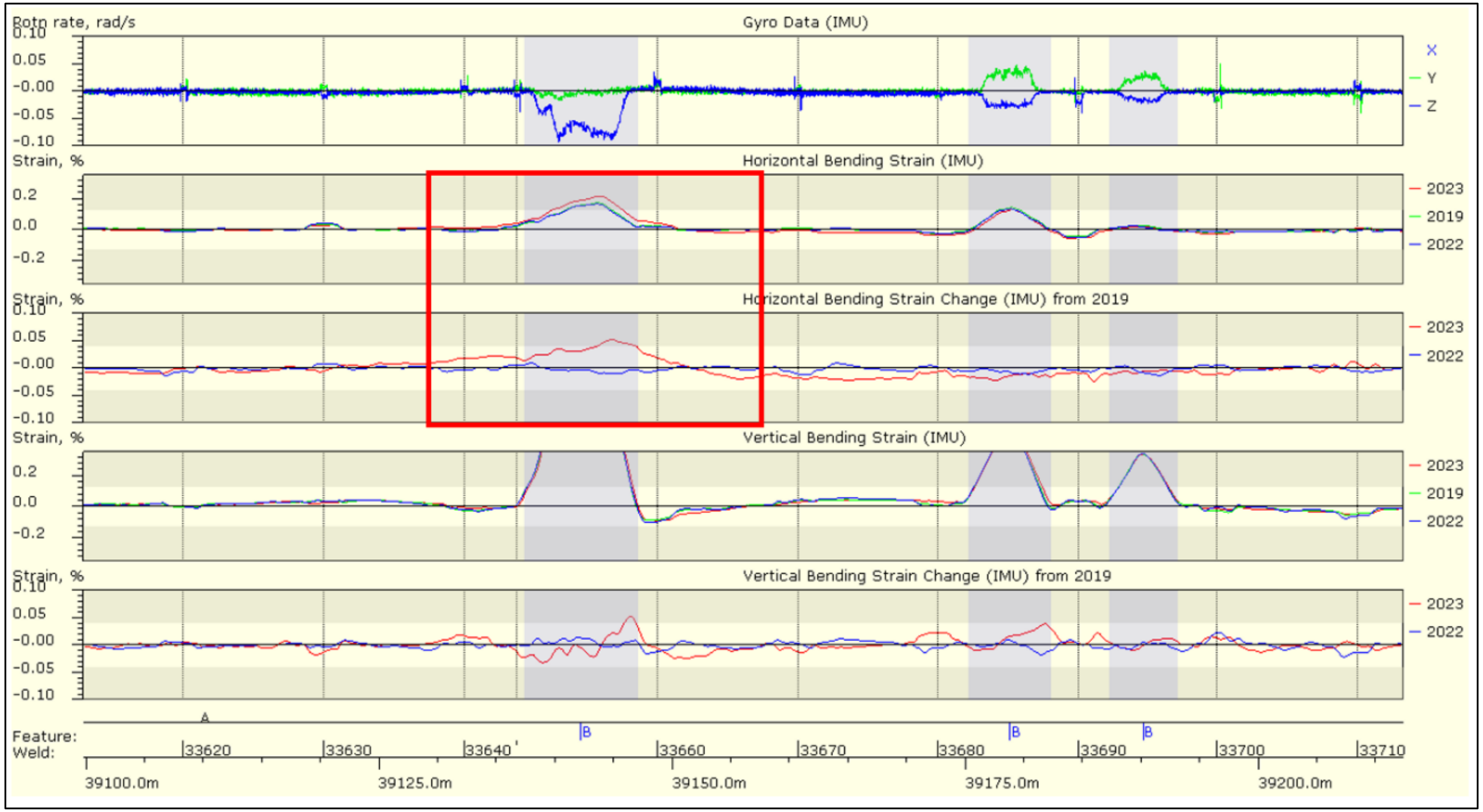
- Tubería 18 pulgadas
- Aproximadamente 60 millas longitud
  Corridas Inerciales 2019, 2022 y 2023
- Conocimiento de inestabilidad – En monitoreo
- Área de interés

El ducto se encuentra dentro de un casing (Lamina ARMCO) de 42 pulgadas construido en 2016.



Caso Estudio: Análisis inicial

El problema:
El reporte vendor no identificaba zona BS o PM.
Curva de construcción y casign enmascaran el desplazamiento que al revisarse se presenta de 0.8 m.
Que concordaba con reportes de instrucción geotécnica en sitio (IDDV, inclinómetros, topografía)



ACIEM

Caso Estudio: Verificación en campo

🔗 Integración es un 'Todo': Correlación de datos ILI-IMU con hallazgos geotécnicos para decisiones efectivas.

👁 Mitigación necesita monitoreo: El casing reduce curvatura pero enmascara movimiento real. Monitoreo independiente es clave.

Conclusiones

- **Soporte al Sector:** Este trabajo ofrece a operadores y geotecnistas un protocolo práctico, alineado con API RP 1187, para la gestión sistemática del riesgo.
- **Proactivo y Predictivo:** El análisis Demanda/Capacidad y la Proyección de Deformación garantizan la planificación anticipada de las reparaciones (corto y medio plazo).
- **Integración de Amenazas:** La correlación de la data de deformación (IMU) con otras amenazas (ej. defectos de ILI, hallazgos geotécnicos) permite un diagnóstico integral.
- **Resultados Comprobados:** La estrategia ha mejorado la seguridad operacional y demostrado una reducción sostenida de incidentes en entornos complejos.

Siguiente Paso

Estrategia de mejora continua:

- *Refinamiento de metodologías*
- *Mejorar sensibilidad de detección*
- *Afinar el modelo de riesgo con redes Bayesianas con mas variables dinámicas para mejorar la perspectiva predictive.*
- *Consolidación de toda la información de integridad.*

¡Gracias!

IPG 2025 7th International Pipeline Geotechnical Conference
IPG2025
6-7 November 2025, Bogota, Colombia

IPG2025-0027

ENHANCING PIPELINE SAFETY: A GEOHAZARD MANAGEMENT PROGRAM ALIGNED WITH API RP 1187

Jaime H. Aristizábal C.
Cenit Transporte y Logística de Hidrocarburos
Medellín, Colombia

Oscar Gualdrón
Cenit Transporte y Logística de Hidrocarburos
Bogotá, Colombia

Carlos E. Motta T.
Cenit Transporte y Logística de Hidrocarburos
Bogotá, Colombia

Carlos J. Pedraza A.
Cenit Transporte y Logística de Hidrocarburos
Bogotá, Colombia

ABSTRACT

In South America, pipeline integrity challenges due to geohazards are widely recognized as a significant concern. Over the last decade, this perception has been spreading to other latitudes, highlighting that, despite the difficulties associated with the sometimes-stochastic nature of the natural phenomena involved in geohazards (i.e. rainfall, earthquakes), it is possible to proactively manage this threat.

A hazard-focused approach has contributed to a sustained reduction in spills caused by geohazards within CENIT's infrastructure (a midstream company in Colombia – South America); however, in recent years this approach has evolved and been integrated into an integrity-focused management strategy. Through multidisciplinary analysis, the approach has shifted to incorporate multi-hazard analysis, enhancing the overall effectiveness of risk mitigation.

At CENIT, an integrity-focused Geohazard Management Program has proven to be more effective from a process safety perspective by simultaneously considering the characteristics associated with geohazards and pipelines. This approach aligns well with API RP 1187, as it provides a systematic and structured process for managing landslides in accordance with industry standards. It encompasses key components such as the identification, assessment, and management of landslide threats while promoting the integration of hazard and integrity assessments.

This article will explore how CENIT has aligned its Geohazard and Integrity Management Strategy with the steps outlined in the Recommended Practice mentioned above. Specifically, it will discuss the strain analysis approach (examining both strain demand and strain capacity). This includes illustrative cases such as analyses from ILI IMU (strain demand) and Fitness for Service (FFS) assessments (strain capacity). Additionally, the article will highlight opportunities for improvement in assurance activities within the framework of this recommended practice.

Keywords: Geohazard Management, Pipeline Integrity, Multi-hazard Analysis, Strain Analysis, API RP 1187, Fitness for Service (FFS), Risk Mitigation.

1. INTRODUCTION

CENIT operates an extensive network spanning close to 9000 kilometers dedicated to the transportation of hydrocarbons across Colombia. This infrastructure traverse diverse and challenging terrains, including significant sections through mountainous regions and geohazard-prone areas. The system includes pipelines with diameters ranging from 6 to 42 inches, supporting both crude oil and refined product transport.

Historically, geohazard management focused on reactive measures and isolated hazard assessments. Recognizing the limitations of this approach, CENIT initiated in 2014 a strategic transition toward an integrity-focused methodology that integrates geotechnical, hydrotechnical, and operational data into a unified management framework. This shift has enabled more proactive decision-making, enhanced risk identification, and improved long-term asset resilience

Pipeline systems in geotechnically complex regions face increasing exposure to natural threats such as landslides, seismic activity, and extreme rainfall. In Colombia, these challenges are amplified by topography and climate variability [1]. CENIT has recognized the need for a proactive and structured approach to geohazard management [2] (see FIGURE 1).

FIGURE 1: GEOHAZARDS MANAGEMENT STRATEGY PROCESS MAP OF CENIT (2021)

Considering API RP 1187 [3], this recommended practice provides a systematic framework (see FIGURE 2) for managing landslide hazards affecting pipeline infrastructure. It outlines processes for threat identification, risk assessment, monitoring, and mitigation. The standard emphasizes multidisciplinary collaboration, data integration, and continuous improvement. Its alignment with broader integrity management systems makes it a valuable tool for operators seeking to enhance safety and reliability in geohazard-prone areas.

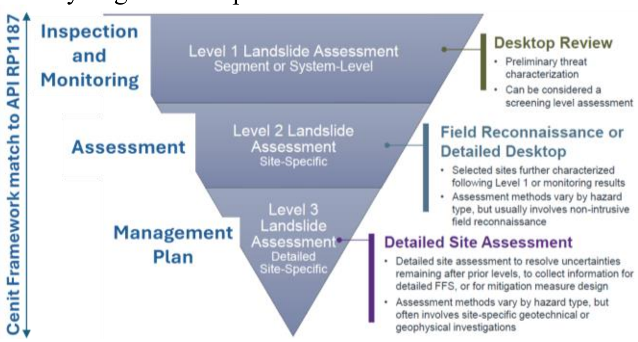


FIGURE 2: THREE-LEVEL FRAMEWORK FOR THREAT IDENTIFICACION AND ASSESSMENT IN API RP 1187 [3]

This paper explores the alignment between API RP 1187 and CENIT´s existing Geohazard Management strategy, highlighting how the recommended practices complement current efforts to minimize spill incidents (refer to CENIT's operational experience in FIGURE 3), and enhance compliance with international standards.

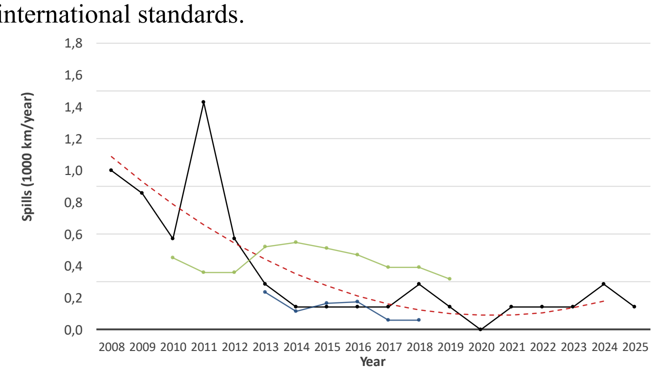


FIGURE 3: CONSISTENT DOWNWARD TREND IN SPILL INCIDENTS IN CENIT [4]

2. IMPLEMENTATION STRATEGY

CENIT's pipeline integrity framework has required a structured, multidisciplinary approach tailored to the organization's operational and geotechnical realities. Recognizing the need to transition from reactive hazard management to proactive integrity-focused decision-making, CENIT developed a strategy that integrates geohazard risk into its broader asset management system. This strategic direction aligns closely with the principles outlined in API RP 1187, which emphasize the integration of geohazard considerations in pipeline integrity programs.

The first phase involved the systematic identification of historically vulnerable zones, using a combination of finding databases, incident records, terrain analysis, and remote sensing data [5] (see FIGURE 4).

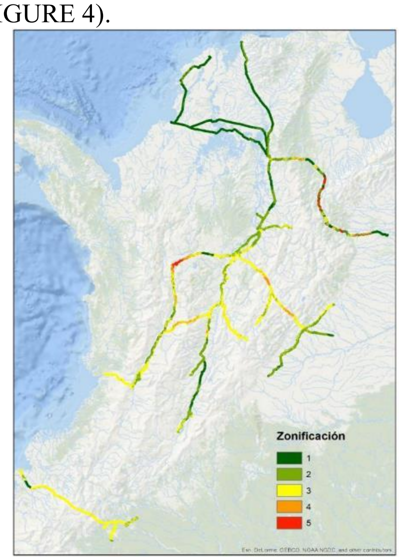


FIGURE 4: CENIT'S INTEGRATED GEOTECHNICAL AND CLIMATE ZONE MAPPING (2023) [5]

The implementation strategy involved forming multidisciplinary teams and integrating geohazard risk into the broader asset management framework. This approach aligns with API RP 1187 Section 4: Landslide Management Program, which outlines the program's structure and key components—including threat identification, continuous improvement, and governance through the "Plan-Do-Check-Act" cycle—to reduce the likelihood and impact of landslide-related hazards.

The use of geospatial mapping, GIS platforms, ILI data correlation, and Bayesian models for risk assessment supports API RP 1187 Section 6: Data Management, providing mechanisms for capturing, storing, sorting, and integrating data like pipeline characteristics, as-built details, and operating conditions to facilitate efficient threat evaluation.

This collaborative approach enabled the development of a comprehensive Geohazard Assessment Model (see FIGURE 5) that incorporates domain-specific insights from each discipline. Instead of limiting its scope to geotechnical landslide susceptibility, the model assesses a broader range of geohazard-related factors (including pipeline vulnerability) to provide a more accurate estimation of pipeline failure probability

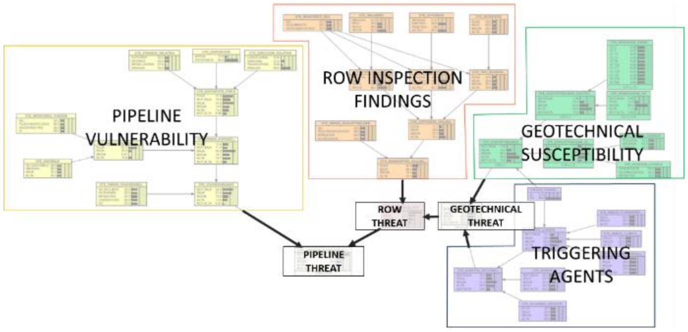


FIGURE 5: BAYESIAN NETWORK MODEL FOR GEOHAZARD RISK ASSESSMENT IN CENIT [2]

The integration of geohazard data into CENIT's integrity management platform enhanced collaborative decision-making by enabling experts from diverse disciplines to jointly assess risk zones, align mitigation strategies, and prioritize actions based on shared insights. Overall, the implementation strategy reflects a shift toward predictive, data-driven geohazard management, positioning CENIT to anticipate threats, reduce spill risk, and safeguard infrastructure integrity in accordance with API RP 1187. This approach forms a core component the Landslide Threat and Integrity Assessment outlined in Section 5.

The threat characterization, prioritization of short- and medium-term actions, and mitigation and monitoring strategies described in Sections 4 and 5 of this paper (including hierarchical zone classification and associated measures) align with API RP 1187 Section 7: Threat Management. This section emphasizes the selection of fit-for-purpose preventive and mitigative actions aimed at minimizing the impacts of landslide hazards

The results and discussion in Section 5 of this paper (highlighting spill incident trends and identifying opportunities for assurance activities) align with API RP 1187 Section 8: Program Evaluation. This section emphasizes the importance of conducting periodic evaluations of program effectiveness through key performance indicators such as assessment coverage, implementation of mitigation strategies, and reductions in incident frequency, all of which support a framework for continuous improvement.

In this way, the structure of API RP 1187 and its three-tiered philosophy: (1) Geohazard Mapping & Initial Screening, (2) Site-Specific and Strain Demand Evaluation, and (3) Detailed Strain Capacity and Prioritization, should be explicitly linked within the document.

Tier 1: Description of satellite imagery, InSAR, digital elevation models (DEMs), and GIS-based zoning as part of the inventory phase, consistent with API RP 1187's emphasis on leveraging existing data to identify zones of slope instability.

Tier 2: Right-of-way (RoW) patrols, field surveys, instrumentation (e.g., inclinometers), and strain demand assessment using ILI IMU data. These non-intrusive methods help confirm landslide interaction and quantify physical exposure, such as pipeline orientation relative to the landslide vector.

Tier 3: Applies fitness-for-service (FFS) methodologies, finite element modeling, and critical strain limit (CSL) calculations in accordance with CSA Z662, along with short- and medium-term projections. This tier resolves uncertainties from earlier stages, including forecasting CSL exceedance to enable proactive intervention. Prioritization of short- and medium-term actions is a key output of Tier 3.

3. ANALITYCAL DOMAINS FOR EVALUATION PROCESS

To enhance clarity and operational alignment with API RP 1187 Section 5: Landslide Threat and Integrity Assessment, the following analytical domains are proposed to structure the evaluation process and to allow precise threat characterization and targeted mitigation.

3.1 Domain A – Baseline Characterization

Focuses on identifying zones of potential instability using preliminary datasets such as satellite imagery, InSAR, digital elevation models (DEMs), and GIS zoning. This domain establishes strain demand baselines and tracks changes over time.

The process began with geospatial hazard mapping using high-resolution satellite imagery, InSAR data, and digital elevation models to identify slope instability prone zones. These datasets were layered within a GIS platform to generate geotechnical zoning maps aligned with pipeline corridors.

3.2 Domain B – Threat Confirmation and Exposure Assessment

Involves reviewing ILI IMU strain demand data alongside field-based inputs (e.g., RoW patrols, geotechnical surveys, and instrumentation). This domain supports the detection of deformations and correlates pipeline orientation with landslide vectors to confirm physical exposure and initial threat engagement.

RoW Patrol and field investigations complemented remote sensing efforts through geotechnical surveys. Instrumentation such as inclinometers, piezometers, extensometers, and rain gauges were installed in areas of interest to monitor slope movement, groundwater fluctuations, soil pressure, and precipitation patterns. Rain monitoring was particularly critical for correlating rainfall intensity with slope instability, enabling more accurate forecasting of potential failures. UAVs were also employed to enhance reconnaissance, providing high-resolution imagery and supporting real-time assessment of evolving geohazard conditions.

Risk assessment was conducted using a structured framework, that began with hazard characterization based on type, magnitude, and recurrence interval. Pipeline Vulnerability analysis considered pipeline disposition (buried or above ground), its orientation relative to the primary landslide vector (parallel, oblique, or transverse), and its location within the terrain profile (crest, mid-slope, or toe) to quantify physical exposition. Operational conditions, including internal pressure and historical integrity, were evaluated alongside bending strain analyses to assess structural response under geomechanical stress (see FIGURE 6), to include strain demand, derived from ILI IMU data to detect deformation.

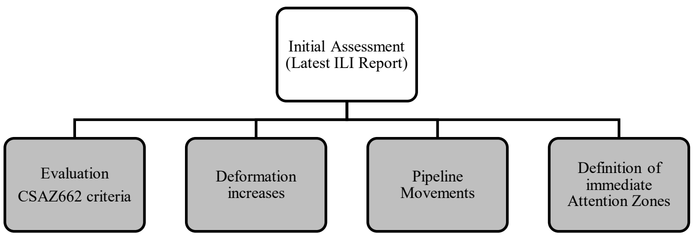


FIGURE 6: ANALYSIS SEQUENCE FOR INITIAL STRUCTURAL EVALUATION IN GEOHAZARD CONDITIONS**.**

3.3 Domain C – Capacity Evaluation and Prioritization

Applies fitness-for-service (FFS) methodologies, finite element modeling, and critical strain limit (CSL) calculations (e.g., per CSA Z662). This domain enables uncertainty reduction through forward-looking projections and informs short- and medium-term prioritization for mitigation planning (see FIGURE 7).

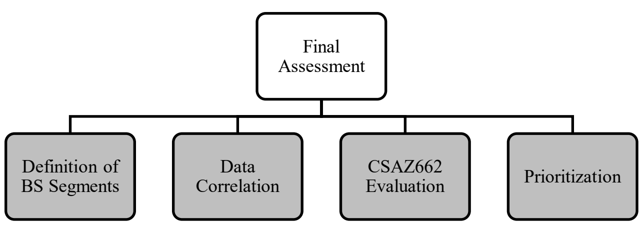


FIGURE 7: INTEGRATED ANALYSIS SEQUENCE FOR STRUCTURAL EVALUATION IN GEOHAZARD CONDITIONS**.**

These analyses provided critical insight into pipeline's deformation potential due to ground movement, ensuring that strain levels remain within CSL. The results are integrated into the geohazard assessment model as Diagnostic Anomalies, which, combined with physical exposition metrics, form the basis for determining pipeline vulnerability.

Once the bending strain monitoring segments and the magnitude of the maximum deformation recorded in the latest ILI run are defined, an evaluation is carried out based on the regulatory criteria for compressive and tensile strain capacity established in CSA Z662 ([4] - Annex 1), to establish a Critical Strain Limits - CSL for structural integrity assessment.

The tensile capacity of an in-service pipeline is governed by the strain capacity of its circumferential welds. This is because experience has shown these welds to be the weakest points—whether because of welding discontinuities, stress concentration, or lower strength compared to the base metal. This underscores the importance of having qualified welding procedures for both construction and maintenance and ensuring that essential and non-essential variables are controlled before, during, and after the welding process.

Although no longer included in the 2019 edition of CSA Z662, this criterion continues to be widely adopted across the industry due to its strong acceptance and proven effectiveness. In Colombia, it has demonstrated significant value in preventive analysis and proactive fieldwork. This model remains a practical tool due to its conservative nature and usefulness in providing a quantitative reference for comparing deformations reported by ILI runs with inertial modules. The calculation will be performed according to section C.6.3.1.3 of CSA Z662-11.

Considering criteria for compressive strain capacity, numerous tests have been developed in the industry to determine compressive capacity in pipelines. Their purpose is to identify the maximum compressive load or bending moment under which the pipeline collapses. Under compressive loads, the pipe initially develops a slight ripple effect; as the load increases, wrinkles form and evolve into a buckle, leading to collapse of the cross-section. The model presented here aims to determine the maximum load or bending moment at which only a small ripple forms. Wrinkles with structural implications typically exhibit much greater deformations than those calculated as compressive strain capacity limits. These wrinkles occur when deformation is completely unrestrained.

The strain capacity model from CSA Z662 (2015 edition), section C.6.3.3, is recommended as it offers a practical and conservative approach that meets the requirements for calculating compressive strain capacity (CSC) in pipelines. These equations can be applied under combined compressive loading conditions involving bending and axial forces, taking internal pressure into account.

To translate these assessment outcomes into actionable strategies, prioritization criteria must be defined and applied consistently. Prioritization also enables operators to allocate resources where the risk is highest, ensuring safety, regulatory compliance, and operational continuity. In this context, prioritization was developed based on deformation data, integrating multi-year monitoring insights with geospatial and anomaly correlations.

Short-Term – Prioritization Based on Deformation

The development of deformation-based prioritization was carried out through the cross-referencing of events using geographic matching within a geographic information system (GIS), with refined weld matching from ILI runs conducted by various vendors. This process identified multi-year recurrence in Bending Strain (BS) and Pipeline Movement (PM) zones, as well as correlations with various deformation anomalies such as diameter changes, metal loss, cracks, event interactions, geotechnical findings, and field interventions.

Once the multi-year deformations for each bending strain monitoring segment were obtained and cross-referenced with the different findings or events, a prioritization of these segments was performed. This was based on short-term prioritization levels determined by the severity of deformations, ground movements, and/or field findings.

Medium-Term Prioritization – Deformation Projection

Based on the definition of bending strain monitoring segments and the annual deformation data obtained, a projection of future deformations is performed using the multi-year deformation differentials identified through inertial runs.

The purpose of projecting deformation is to evaluate whether, at any point in time, the deformation exceeds the regulatory criteria established in CSA Z662 for compressive and tensile strain capacity. This analysis generates short-term prioritization for intervention, ensuring pipeline integrity.

Deformation Monitoring

Using both historical and current inertial mapping data, total deformation profiles must be developed for the zones affected by bending strain. These profiles allow for the determination of deformation variation over time (i.e., deformation growth rate):

$$\dot{\varepsilon}_T = \frac{\Delta\varepsilon_T}{\Delta t} \quad (1)$$

Where:

$\Delta\varepsilon_T$ = Difference in total deformation between runs (in %)

ΔT = Time between runs (in years)

If more than two runs are available, the deformation differential $\Delta\varepsilon_T$ should be calculated using the best-fit function based on available data. Using historical weld matching aligned with the latest run, each zone is located within the deformation profile, and the maximum deformation at the monitoring point is identified and translated to the distance coordinates of the latest run.

From this weld-matched deformation data, the multi-year deformation profile is reviewed to extract annual deformation values for both pipe body and welds. This review is conducted as follows:

- If visualization software for deformation profiles is available from the vendor, multi-year deformation data can be reviewed directly in the software.
- If vendor software is unavailable or deformation profiles are incomplete, deformation must be calculated using the inertial module from the missing runs.

Once multi-year deformation data for pipe and welds are obtained, the temporal variation of deformation in the sector can be assessed—specifically for the weld with the highest deformation recorded in the latest run.

The multi-year deformation profile is developed for each reported inertial run. However, for other runs—regardless of technology—if they include inertial modules, deformation profiles can be analyzed for defined sites of interest to verify deformation trends.

- **Deformation Projection**

To estimate future total deformation in a zone ($\varepsilon_T{}^*$), the projection is calculated over time (Δt) using current total deformation values and accumulated deformation rate:

$$\varepsilon_T{}^* = \varepsilon_T + \Delta t * \dot{\varepsilon}_T \quad (2)$$

If the zone to be projected includes attachments or anomalies, this method should not be used. Instead, a numerical method is recommended to evaluate local deformation increases at those specific points of interest.

4. THREAT CHARACTERIZATION AND TARGETED MITIGATION

Zones of interest are defined based on deformation prioritization and projection results. These zones are then designated for intervention and/or monitoring, along with their respective monitoring timelines (see FIGURE 8).

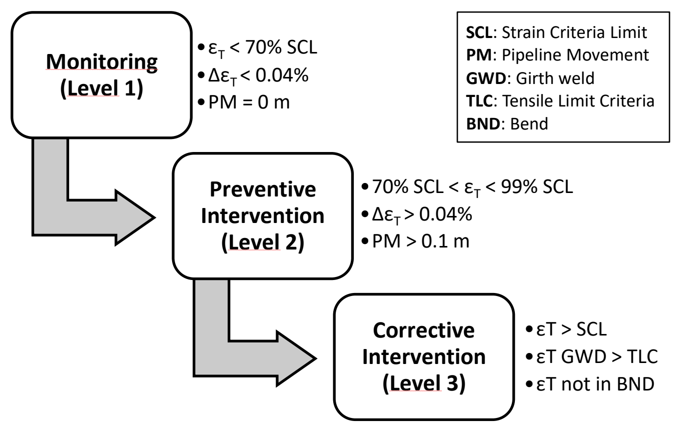


FIGURE 8: INTERVENTION LEVEL PRIORIZATION

Through the application of this analytical framework, a progressive refinement of geohazard-related pipeline zones, beginning with a broad set of Reported Zones identified via initial inspections and data acquisition. These are subsequently narrowed down to Real Zones, validated through detailed field assessments. Within the Real Zones, two distinct categories emerge: Stable Zones, which show no significant geomechanical activity, and Active Interaction Zones, where soil–pipeline interaction is evident and poses potential integrity risk. From the Active Interaction Zones, two operational categories are further delineated: Monitoring Zones, which require ongoing observation to assess hazard evolution, and Zones Addressed and Scheduled, representing areas where mitigation measures have either been completed or are planned. This hierarchical structure supports targeted decision-making and efficient resource allocation for pipeline integrity management (see FIGURE 9).

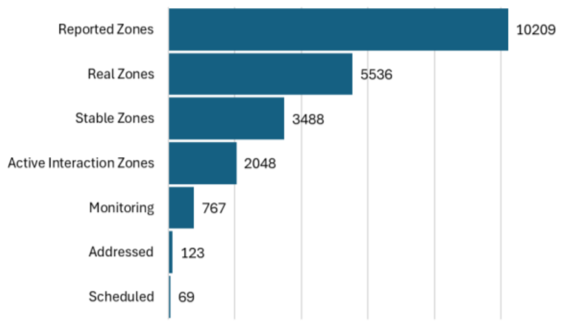


FIGURE 9: HIERARCHICAL CLASSIFICATION OF GEOHAZARD-RELATED PIPELINE ZONES IN CENIT (2024)

5. MITIGATION AND MONITORING IN SOIL-PIPELINE INTERACTION ZONES

Mitigation and monitoring of both the pipeline and the surrounding terrain in areas of soil–pipeline interaction are essential activities for preventing failures and coordinating system interventions in a predictive and safe manner and align with API RP 1187 Section 7: Threat Management.

Mitigation can be understood as the management of a geological hazard and its potential effects on the pipeline. Once mitigation is implemented, its effectiveness can be measured through monitoring to ensure the mitigation action continues to fulfill its intended purpose.

Both mitigation and monitoring depend on the development of site-specific modeling. This modeling should be designed to provide a physical understanding of the hazard and its progression, which is fundamental for determining the most appropriate monitoring and mitigation actions. Mitigation can take various forms, including:

- Avoiding the hazard
- Stabilizing and controlling the area
- Reducing the hazard's impact on the pipeline
- Increasing the pipeline's deformation capacity

Monitoring can be performed on the pipeline, the terrain, or a combination of both. Terrain monitoring typically uses geotechnical tools. These tools provide information about the geotechnical hazard but not about the soil–pipeline interaction or the pipeline's response to it. Commonly used instrumentation includes:

- Topographic control: Detects lateral and vertical movements
- Surface extensometers: Measures relative movements
- Inclinometers: Measures horizontal deformation at various depths
- Extensometers: Controls depth-related deformation
- Piezometers: Measures water level or pore pressure

Due to the wide range of devices available for monitoring both terrain and pipeline, selecting appropriate technologies and sampling frequencies is not a straightforward process and should be guided by a specific procedure. In all cases, the application and definition of these technologies require a thorough understanding of the unstable zone, its interaction with the pipeline, and the pipeline's vulnerability.

This understanding is only possible with proper instrumentation, accurate modeling, and knowledge of the mechanical properties of the pipeline and its welds.

It is recommended that, regardless of the terrain monitoring program, some form of pipeline monitoring should also be implemented—independent of any soil–pipeline modeling that may have been developed.

One illustrative case involved a pipeline segment in a high-risk landslide zone as shown below. This 18-inch diameter pipeline traverses the Colombian mountain range, transporting crude oil over approximately 60 miles. It was inspected using an in-line inspection geometry and inertial measurement unit (IMU) tool in 2019, 2022 and 2023. The study area corresponds to a monitored zone of active ground movement. To mitigate external loading effects, the pipeline runs within a corrugated steel casing over a ~500m (1640ft) section. This casing, installed in 2016, features bolted joints every 1.2 meters and has an outer diameter of 42 inches. Verifying the effectiveness of this mitigation measure was essential, making the ILI results critical.

A Bending Strain comparison between December 2019 and May 2022 inspection runs revealed no significant variation in this area. Additionally, strain values reamained below the reporting threshold considered for this study (0.125%), except at field bends.

Upon processing and aligning the 2023 IMU strain data with previous datasets, the area underwent further review. Initially, no apparent bending strain changes were observed. However, a more detailed analysis (particularly of the difference plots) revealed subtle displacement activity.

In this case, a minimal strain change was detected, coinciding with a field bend. The bend follows a sag (under) direction, while the strain change appears predominantly in the horizontal plane. This variation, only evident in the 2023 data, exceeded the reporting threshold at approximately 0.05%. Such scenarios demand advanced analytical expertise, as the presence of the bend can obscure strain changes (FIGURE 10). It is also common for strain signals to exhibit responses opposite to the direction of field bends, potentially leading to misinterpretation during signal analysis.

Building on the initial indication of possible displacement in the area, additional plots were generated to support a more detailed investigation. Given the extent of the region of concern, all visualizations were adjusted to cover a 300-meter (~1,000-foot) segment of the pipeline (FIGURE 11). Focus was placed on the plan view difference and heading variation between inspection runs, as the observed strain change was primarily occurring in the horizontal plane. This targeted analysis enabled the identification of subtle displacement patterns within the data, confirming ground movement in the monitored section.

Given the horizontal nature of the movement, the plan view—representing pipeline out-of-straightness—reveals a clear trajectory variation across the three inspection runs. This deviation is quantified in the plan difference plot, which indicates a maximum lateral displacement of 0.8 meters (2.6 feet), as shown in FIGURE 12. Subsequent field verification shows ILI report of 0.8 of lateral displacement was correct.

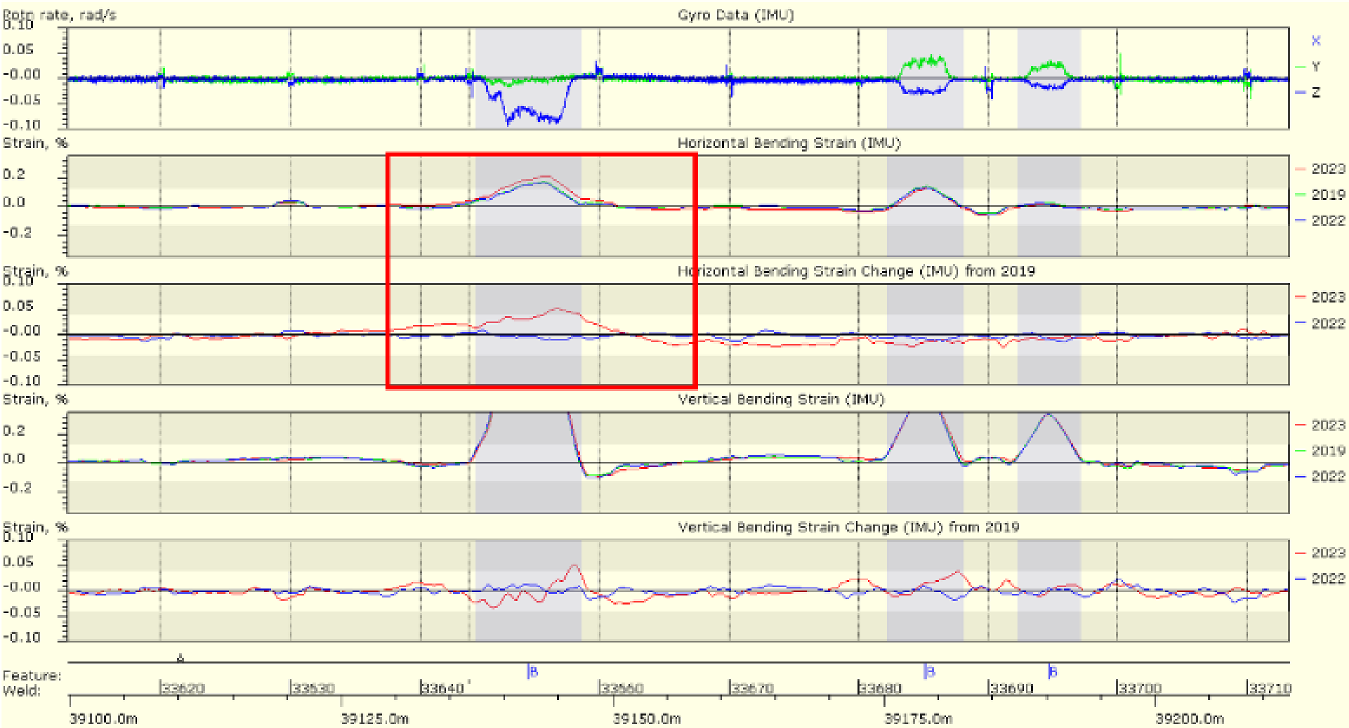


FIGURE 10: BENDING STRAIN PLOTS INDICATE MINIMAL VARIATION IN HORIZONTAL STRAIN

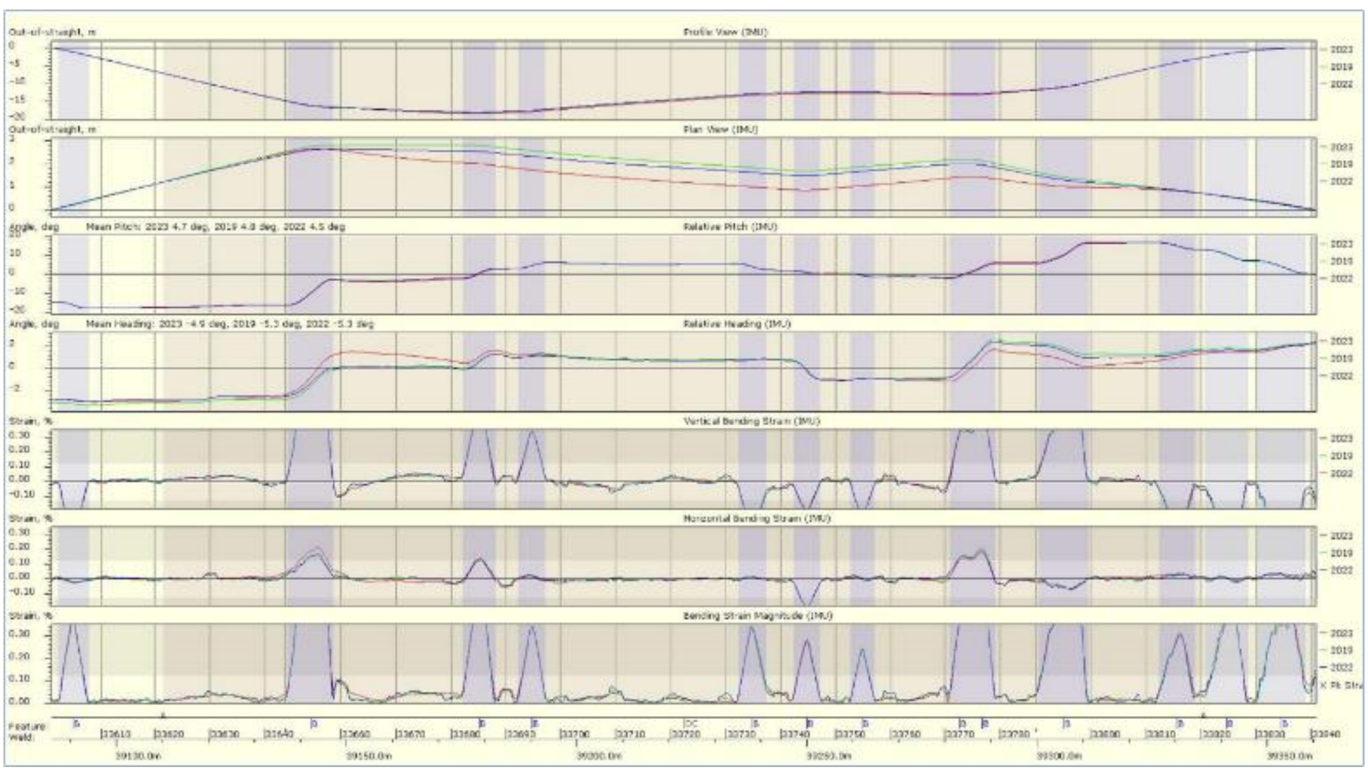


FIGURE 11: STRAIN PLOTS COVERING AN APPROXIMATE 300-METER SEGMENT

FIGURE 12: DISPLACEMENT IS EVIDENT IN THE PLAN DIFFERENCE PANEL.

Additionally, changes in the heading angle were instrumental in delineating the boundaries of the affected segment. Strain Change plots show limited evidence of this event: a distinct signal at the onset, corresponding to the previously observed horizontal strain variation, and a subtle indication near the end of the displacement, with strain levels falling below the reporting threshold.

This specialized construction arrangement effectively reduced the actual load transferred to the pipeline, resulting in a noticeable reduction in curvature change. However, this also made displacement identification more challenging. Fortunately, the mitigation system functioned as intended, stabilizing the landslide and enabling timely planning of remediation measures.

Stress relief was initiated during the excavation phase, and during this process, damage was observed at the upstream flank of the displacement—specifically at the location corresponding to the horizontal strain change—where the external casing was found to be fractured. Field verification confirmed the accuracy of the ILI-reported lateral displacement of 0.8 meters. The outcomes of the remediation activities undertaken in response to this finding are documented in FIGURES 13 and 14.

FIGURE 13: DISPLACEMENT AND EXTERNAL CASING FRACTURE OBSERVED AT THE UPSTREAM FLANK OF THE MOVEMENT (SOURCE: CENIT)

FIGURE 14: PIPELINE DISPLACEMENT AND ECCENTRIC CASING CROSS-SECTION OBSERVED AT THE DOWNSTREAM FLANK OF THE MOVEMENT (SOURCE: CENIT)

6. RESULTS AND DISCUSSION

Geohazards pose a significant threat to the integrity and safe operation of pipeline infrastructure, particularly in regions characterized by complex terrain and dynamic geological processes. As the energy industry advances toward more resilient and sustainable operations, the need for robust geohazard management frameworks has become increasingly critical. This paper presents a comprehensive methodology for assessing, prioritizing, and mitigating geohazard-related risks in pipeline systems, with a particular focus on bending strain analysis, vulnerability classification, and integrated decision-making.

The approach outlined herein reflects a multidisciplinary effort that combines geotechnical engineering, structural integrity assessment, and operational data analytics. By leveraging In-Line Inspection (ILI) technologies, terrain modeling, and predictive strain growth analysis, the framework enables proactive intervention planning and enhances long-term asset reliability. The integration of mitigation and monitoring strategies ensures that both immediate and evolving threats are addressed through targeted, data-driven actions.

This work is intended to support pipeline operators, integrity engineers, and geohazard specialists in developing effective risk management protocols that align with industry standards such as CSA Z662 and API RP 1187. It also contributes to the broader discourse on infrastructure resilience in the face of natural hazards, offering practical insights and scalable solutions for geohazard-prone environments.

A risk-based prioritization framework was developed to guide mitigation and monitoring efforts. Short-term prioritization was based on deformation anomalies identified through geographic matching of ILI data and weld alignment across multiple vendors. Multi-year recurrence in Bending Strain (BS) and Pipe Movement (PM) zones was correlated with diameter changes, metal loss, cracking, and geotechnical findings. Segments were ranked according to deformation severity and movement trends, resulting in a CAPEX repair plan for immediate intervention.

Medium-term prioritization involved deformation projection using historical ILI data. The deformation growth rate was calculated to estimate future strain levels. If projected deformation exceeded CSL thresholds, the segment was flagged for proactive intervention. This approach enabled predictive planning and informed both CAPEX repair and OPEX monitoring strategies.

Mitigation and monitoring were implemented in zones of soil–pipeline interaction to prevent failures and ensure safe operation. Mitigation was defined as the management of geological hazards and their potential effects on the pipeline. Techniques included hazard avoidance, slope stabilization, impact reduction, and enhancement of pipeline strain capacity. Table 3 summarizes the mitigation options considered.

Monitoring was conducted on both the terrain and the pipeline. Terrain monitoring employed geotechnical instrumentation to detect ground movement. Pipeline monitoring focused on strain evolution and structural response, independent of soil–pipeline modeling. The integration of monitoring data enabled validation of mitigation effectiveness and refinement of intervention priorities.

The selection of monitoring technologies and sampling frequencies was guided by site-specific modeling, which provided a physical understanding of hazard progression and pipeline vulnerability. This modeling was essential for defining zones of interest and establishing appropriate intervention timelines.

The study case demonstrates the value of proactive mitigation systems and detailed post-event diagnostics in preserving pipeline integrity and guiding effective remediation. Future work should consider enhancing detection sensitivity in low-strain scenarios and refining casing design to better accommodate eccentric loading conditions

The shift to an integrity-focused model has strengthened safety process and organizational resilience. However, opportunities remain in assurance activities, particularly in automating data flows and refining risk thresholds.

- Reduction in geohazard-related spill incidents over five years
- Enhanced coordination between technical teams and field personnel
- Improved accuracy in threat detection and prioritization

6. CONCLUSION

This paper presented a structured and multidisciplinary framework for geohazard management in pipeline systems, emphasizing the critical role of bending strain assessment, vulnerability analysis, and integrated decision-making. Using In-Line Inspection (ILI) data, terrain modeling, and Fitness-for-Service (FFS) evaluations, pipeline segments were systematically classified based on their exposure and structural response to geomechanical stress.

The integration of CENIT's geohazard management process with the phased framework of API RP 1187 demonstrates a comprehensive and systematic approach to pipeline integrity. By aligning satellite-based screening, field validation, and advanced strain capacity modeling with the standard's levels (from initial mapping to detailed threat prioritization) CENIT ensures that geotechnical risks are proactively identified, assessed, and mitigated. This alignment not only reinforces regulatory compliance but also enhances operational resilience and supports continuous improvement in landslide threat management.

The prioritization methodology—anchored in both short-term anomaly detection and medium-term deformation projection—enabled targeted CAPEX and OPEX planning, ensuring that resources were allocated to the most critical segments. Mitigation strategies, ranging from hazard avoidance to strain capacity enhancement, were complemented by robust terrain and pipeline monitoring systems, providing real-time insights into hazard evolution and pipeline performance.

By embedding geohazard data into the integrity management platform and fostering collaboration across disciplines, the framework supports predictive, risk-informed decision-making. It aligns with industry standards and regulatory expectations, offering a scalable model for enhancing pipeline resilience in geohazard-prone regions.

CENIT's application of API RP 1187 demonstrates that structured geohazard management is both feasible and impactful in complex terrains. By aligning hazard and integrity assessments, the organization has enhanced its ability to anticipate and mitigate risks.

Ultimately, this work serves as a model for other operators in similar geotechnical contexts, reinforcing the value of integrating international standards into local strategies and contributes to the advancement of geohazard integrity management by bridging the gap between geotechnical hazard characterization and pipeline operational safety. It empowers operators to move beyond reactive maintenance toward proactive, data-driven stewardship of critical infrastructure.

ACKNOWLEDGEMENTS

To Cenit for promoting and driving the development of human talent competencies.

REFERENCES

[1] Chaves, J. et al (2019). *A New Approach for the Geotechnical Zoning of the Rights of Way. IPG2019-5343*. Proceedings of the ASME 2019 International Pipeline Geotechnical Conference. Buenos Aires, Argentina. June 25-27, 2019.

[2] Chaves, J. et al (2017). *Probabilistic Approach for Assessing the Weather and External Forces Hazard Using Bayesian Belief Networks*. Proceedings of the ASME 2017 International Pipeline Geotechnical Conference. Lima, Perú. July 24-26, 2017

[3] CRES America. (2025). API RP 1187 Webinar: Introduction to Recommended Practice 1187 [Webinar recording]. Internal SharePoint site: https://cresamericaoh.sharepoint.com

[4] Aristizabal, J. et al (2024). Geohazards Risk Management Strategy on Rights of Way of Pipelines in the Colombian Andes. PTC-2024_229. Proceedings of the EITEP 19th Pipeline Technology Conference. Euro Institute for Information and Technology Transfer. Berlín, Alemania. April 8-11, 2024

[5] Aristizábal, J. et al (2023). Predictive Schemes in Geohazards Management of Hydroclimatological Origin. IPG2023-65003. Proceedings of the 2023 International Pipeline Geotechnical Conference. Bogotá D.C., Colombia. November 23-24, 2023

[6] Canadian Standards Association. (2011 & 2015). CSA Z662: Oil and Gas Pipeline Systems. Mississauga, ON: CSA Group.