Pipeline Digital Twins and Geohazards: Combining Pipeline Material and Inline Inspection Data with Geohazard Modeling for Comprehensive Geohazard Threat Assessments.

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Executive Summary:

This paper underscores the transformative synergy between pipeline material data, progressive inline inspection data analysis technologies, earth movement data, and weather modeling for comprehensive geohazard threat assessments. By amalgamating detailed static and predictive data from these sources, operators can create dynamic digital twins of various scale that offer real-time insights into pipeline integrity. These digital twins facilitate proactive risk mitigation and maintenance strategies. The discussion emphasizes the significance of this integrated approach in providing a holistic understanding of geohazard-induced stresses, enabling operators to simulate various scenarios and make informed decisions. Through compelling case studies and best practices, we investigate the practical benefits of this innovative methodology for managing and implementing an effective geohazard management program.

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Abstract

The integration of pipeline digital twins with geohazard modeling presents a groundbreaking approach to enhance the safety and resilience of critical energy infrastructure. This presentation explores the synergy between pipeline material data, inline inspection technology, and advanced geohazard modeling techniques to create comprehensive geohazard threat assessments.

Traditional geohazard assessments often rely on limited data sources, leading to potential vulnerabilities in pipeline systems. However, by combining detailed pipeline material information and high-resolution inline inspection data, a more accurate and robust representation of the pipeline's condition and vulnerabilities can be achieved. These digital twins provide a dynamic and real-time view of the pipeline's integrity, enabling proactive maintenance and risk mitigation strategies.

The core of this paper delves into the following key areas:

- **Pipeline Material Data:** We discuss the importance of comprehensive knowledge of pipeline materials including vintage, seam type, and toughness – as well as the records backing those properties. By incorporating this information into the digital twin, operators gain a better understanding of how materials respond to geohazard-induced stresses.

- **Inline Inspection Data:** We explore the capabilities of inline inspection technologies, in capturing precise data on pipeline condition. These tools offer invaluable insights into defects and potential vulnerabilities which can be integrated into the digital twin for more comprehensive analysis.

- **Geohazard Modeling:** The presentation showcases how geohazard modeling, utilizing geological, environmental, and climatic data, can predict potential threats such as landslides, earthquakes, and erosion. By merging this modeling with the pipeline's digital twin, operators can simulate various scenarios and assess their impact on pipeline integrity.

- **Comprehensive Threat Assessments:** By combining pipeline material and inline inspection data with geohazard modeling, operators can perform comprehensive geohazard threat assessments. This approach enables informed decision-making regarding maintenance prioritization, emergency response planning, and resource allocation.

- **Case Studies and Best Practices:** Real-world case studies and best practices highlight successful implementations of pipeline digital twins and geohazard modeling. These examples illustrate the tangible benefits in terms of safety, operational efficiency, and cost savings.

In conclusion, the integration of pipeline digital twins and geohazard modeling represents a transformative paradigm shift in pipeline integrity management practices. This paper demonstrates how this innovative approach empowers pipeline operators to proactively identify and mitigate geohazard-related risks, ensuring the long-term reliability and sustainability of energy infrastructure.

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Background

When considering geohazards and overall pipeline integrity, operators face multifaceted challenges. Influenced by weather events that gradually transform the surrounding landscape over years, pipelines are also vulnerable to sudden, impactful weather events. Interactive threats, such as areas with corrosion experiencing bending strain, can reach a point of criticality, posing immediate risks. The intricate landscape of pipeline vulnerabilities is compounded by emerging material threats. These include concerns such as seam integrity issues in both newer and older pipes, as well as manufacturing defects arising from prolonged exposure to cyclic loading. These concerns have been underscored by recent PHMSA bulletins in 2019 and 2022, bringing heightened attention to the forefront of industry dialogue in recent years.

In addition, we see the volume, quality, and richness of much of the data being produced by various forms of inspection methodologies for pipeline and asset inspection increasing. A similar trend is seen for environmental and terrestrial data available for modeling and in-depth analysis.

The industry has surpassed the point where the human eye or spreadsheet-based analysis can make best use of the varying and extensive data available.

A question for the industry is not which is the correct data to use but how should all the data be used effectively and efficiently?

With new computational methodologies and collaborations to ensure that we make best use of the data available an area in which these newer techniques can be most beneficially applied is in the highly accurate transformations and alignments of datasets. If we take the scenario of what is possible using diverse data inputs to construct representative digital twins with the aim of risk mitigation, in this case with the aim of assisting risk mitigation due to pipeline movement not otherwise readily detectable.

Previous Incidents

The reader is likely familiar with the PHMSA bulletins focused on Earth Movement and Other Geological Hazards published in 2019 and 2022: Docket Nos. PHMSA–2019–0087 and Docket No. PHMSA–2022–0063, respectively. Common themes across the incidents mentioned therein include the impact of environmental factors such as land movement, heavy rainfall, and flooding. The causes involve issues with girth welds, axial stress, and/or Stress Corrosion Cracking (SCC), coupled with mostly lateral movement of the pipelines. This highlights the possibility of multiple factors – some decidedly outside of what is commonly thought of as 'geotechnical' – playing a part in any one of the given failures.

These incidents demonstrate that several diverse combinations of external loading, time, weather events, and operational conditions lead to failures in pipelines of both newer high strength steel and more ductile vintage steel. As an industry, we are at a point where a pipeline's mechanical integrity cannot be assumed simply because a line has operated without incident since it was installed – nor can we assume that current mitigative measures will withstand real-world weather events. This is especially true with geohazards due to interactive threats and root causes existing in previous blind spots. An effective approach for addressing this concern is by leveraging digital twins.

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Digital Twins

Here we consider the concept of a digital twin: a digital model of a real-world system used for simulation purposes. For this discussion, we are looking at an existing pipeline or pipeline system with known physical characteristics in an environment with dynamic surroundings.

These two main elements are combined to ascertain those areas of the pipeline that are most likely to be exposed to geotechnical stresses. We then can refine the resolution of the digital twin in these areas through additional data gathering and investigation to further determine areas with the highest likelihood of geotechnically-related pipeline incidents. The indexed severity of risk is a crucial outcome metric of the digital twin, and must be constructed in a way to reflect both a dynamic environment and incorporation of additional data acquisition, field investigation, and mitigation.

For the case of geohazard threat assessment, we choose several digital twin model inputs:

- Detailed pipeline location, material, and construction data including vintage, grade, wall thickness, manufacturer, seam type, external support, spans, etc.
- Inline inspection data with defects and anomalies noted - including Inertial Mapping Unit (IMU) data
- Dynamic and predictive geohazard modeling of the pipeline right of way and surroundings
- SCC, cracking, seam weld toughness, etc. susceptibility analysis
- Finite Element Analyses (FEA)

Combining these elements into the digital twin model, we gain the ability to perform a comprehensive geohazard threat assessment using data on a regional, local, and feature-specific level.

Digital Twins in the Context of Geohazards Analysis

The digital twin element is used to locate areas of interest, after which several things are assessed.

1. The current strain on the pipeline at point of most recent inspection.
2. Probability of further movement at the same location, and likelihood of variation in rate of movement.
3. Determination of associated variables including:
    - Rate of change in strain,
    - Rate of change in ground movements, this is improved by parallel processing of multiple datasets representative of a reasonable time period,
    - Time to exceedance of limit states, and
    - Requirements and timelines for further monitoring and mitigation activities.

This data is then combined with live or quasi-live data sources, such as:

- Inclinometer sensors,
- Ground-water monitoring,
- Pipeline strain gauges,
- Pressure monitoring,
- Process monitoring,
- CP monitoring,

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- Corrosion coupons/sensors,
- LIDAR point clouds,
- Field verifications,
- Rainfall radar & weather forecasting, and
- Seismic monitoring.

The complement of some or all these data sets provide the operator with a real time immutable source of reference to understand the health of their assets and the appropriate mitigations that need to be considered for risk.

The ability to overlay high risk and high probability areas is based on asset features from pipeline feature records, new and historic ILI data, and then coupled with high probability areas caused by the abovementioned weather and geohazard threats.

Pipeline Location, Material, and Construction Data

When building the digital twin model for geohazard threat assessment, we start with a basic understanding of a pipeline's location and material properties. As the industry is over 20 years and several assessment cycles into the requirements outlined in 49 CFR § 192 Subpart O and § 195.452, domestic U.S. pipeline operators are already required to have the location and material data required for the initial data gathering efforts to build the digital twin. Expected as-built data types include vintage, grade, diameter, and wall thickness for the line and may include more granular resolution for replacement sections and additional data such as manufacturer and toughness. These serve as a fundamental starting point for our model.

Known data – as well as the records validating those properties – are required to properly assess fitness for service under specific loading conditions determined in further analysis on a detailed level. Unknown material properties may be determined from methods such as opportunistic in-situ testing, inline inspection, and records research – among others.

By incorporating and refining this information into the digital twin, operators can accurately determine how the line responses to geohazard-induced stresses. One way of refining this information, as mentioned above, is through inline inspection (ILI) and ILI data refinement.

ILI data

Inline inspection technology has advanced extensively in recent years with detection capabilities of individual sensors as well as sensor density ever increasing. ILI vendors offer a variety of tools – from basic geometric and corrosion tools to those with more sophisticated capabilities in locating cracks of various types as well as material and manufacturing defects with extreme accuracy. The complete feature log for an inline inspection can become a powerful tool when building specific models of localized conditions within our digital twin environment.

In addition, Inertial Measurement Unit (IMU) use is common, with many operators choosing to refine pipeline centerline data with every smart tool inspection including IMU data collection capabilities.

Positional data from scanning alignment sheets, alignment to aerial imagery, or aboveground survey is simply not accurate enough for determining the location of ground movements, particularly where

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subtle ground movements with respect to the pipeline are a possibility. IMU use offers extensive advantage over traditional methods of pipeline centerline location for geohazard analysis.

IMU inspections are used to record the changes in direction as a tool travels the length of a pipeline. IMU data typically provides the azimuth and inclination at discrete points along the pipeline as a function of chainage. Locational co-ordinates either in WGS84 or other format are typically supplied where an IMU component has recorded data. We can use these readings to determine current strain experienced on the pipeline due to external forces. Additionally, using proprietary algorithms, we have the capability of calculating strain on two or more similar IMU runs on a given segment of pipe.

Geohazard Analysis

Landslide, and ground movements in general, can be instigated by natural causes such as erosion, excess pore water pressure in susceptible soils, tectonic activities, and subsidence, or via human activity such as poorly designed embankments, historical mining activities or though changes made to local hydraulic profiles or other civil engineering challenges.

It is standard practice to consider all environmental threats that may affect the pipeline during the design stage. These include landslides, noted in figure 1 below, geological faults, liquefaction, river crossings, and both natural and man-made ground subsidence issues. Geological, geomorphological, geotechnical, river and seismic specialists are normally involved in the identification and characterization of these threats and the route is adjusted to avoid significant hazards as required. Where it is not possible to avoid specific threats such as the crossing of active geological faults or some types of landslide due to other constraints, mitigation is applied to reduce the loading on the pipeline or to stabilise the hazard.

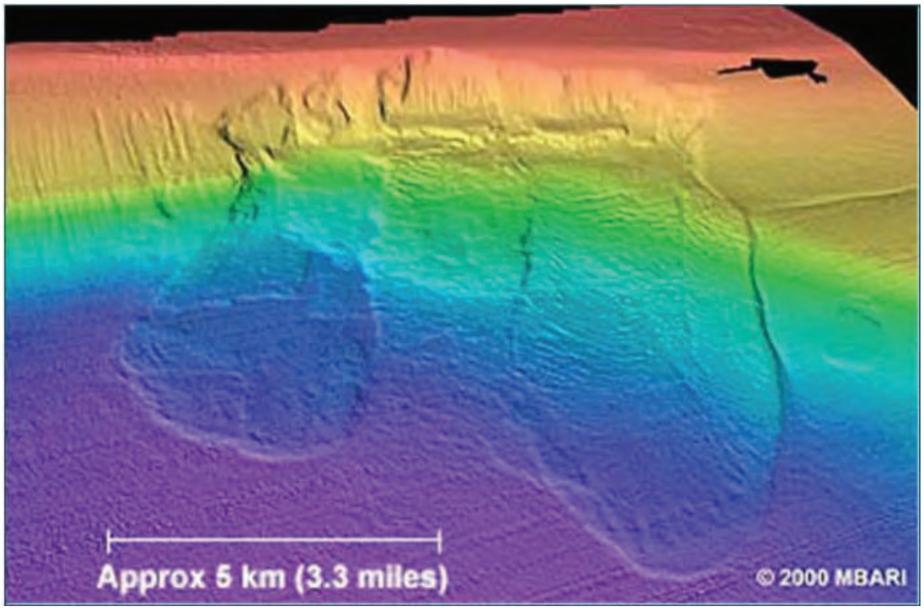

Figure 1 - Example of bathymetric imagery following movement.

Data gathering is typically very difficult for landslide monitoring purposes other than at discrete points. Pipelines typically cross vast distances, through areas which have limited connectivity to

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communication. However, with the combined data gathered for disparate sources and appropriately analyzed, new insights to risk mitigation allow operators more comprehensive outputs. Teren provides the foundational underpinning of geospatial data about the environment in a common platform as a base layer of analytics to the digital twin stored and spatially referenced in geodatabases and computation engines that facilitate data fusion of environmental threats (see figure 2).

These layers include:

- Landslide Threat,
- Subsidence,
- Seismic Threat,
- Coastal Flooding Threat,
- Inland Flooding Threat,
- River Scour Threat,
- Depth-of-Cover Threats, and
- Precipitation data (continuously updated).

Landslide analytics predict the likelihood that a geohazard will occur in a particular area based on terrain, hydrologic energy, and soil conditions. Landslide threats are summarized to the pipeline to generate quantified landslide risk zones for the asset footprint. Subsidence threats are summarized to the pipeline to generate quantified subsidence risk zones for the asset footprint due to karst and expansive soils. The hydrology analytics characterize the way that surface water moves, erodes, or accumulates on and around the pipeline right of way directly affects landform cohesiveness. Thus, managing right-of-way integrity is often a matter of managing hydrology. Seismic threats are summarized to the pipeline to generate quantified seismic threat zones for the asset footprint. The Depth-of-Cover Threat analytics identify areas where agriculture, wind erosion, and road activity threaten to reduce ground cover and expose the pipeline to surface hazards.

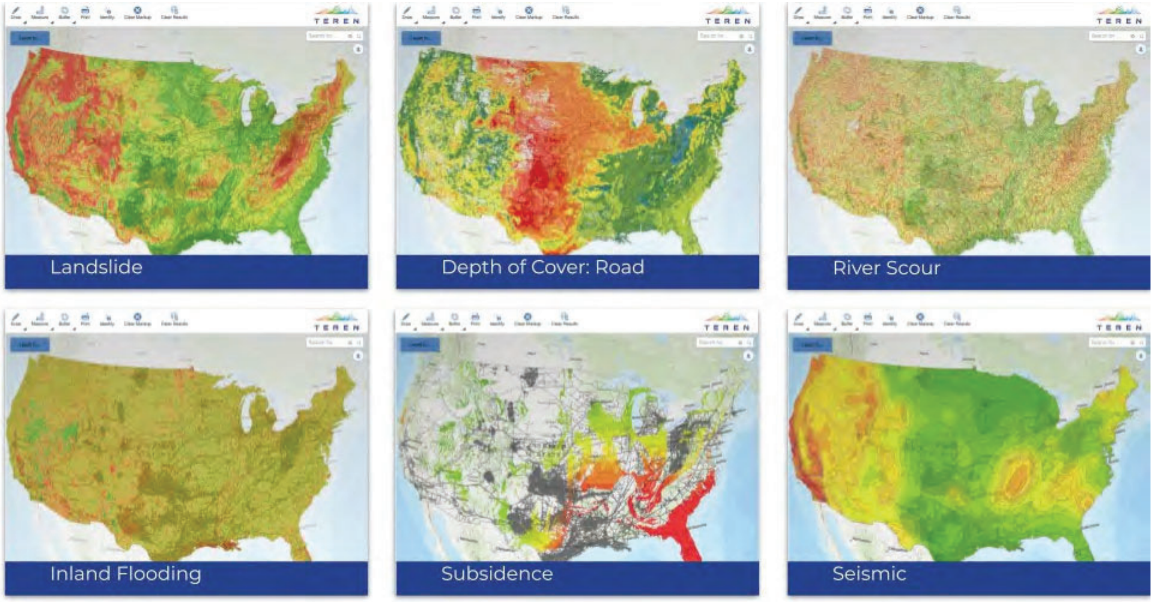

Figure 2 – Teren Essentials Threat Layers

While each threat analytic is valuable in its own context, the practice of collocating these layers allows for pipeline operators to cross reference threat and risk as independent and co-factored behaviours, such as precipitation related landslide risks. The combination of these layers represents a critical component of the digital twin; collocated information about an asset and its associated environment that allow insights through data fusion that would be cumbersome. When further leveraged against databases of materials, as-built construction, and ILI data, in a pipeline-centered linear referenced (see Figure 3) format, this digital twin creates an impact multiplication of any analysis or prioritization indexing and ultimately serves the purpose of assessing holistic and co-factored risk. With this information in hand, the operator can operationalize these insights to identify incipient failure modes, anticipate data collection needs, and demonstrate that field inspection and mitigation activities are aligned with the comprehensive risk profile of the asset.

This integration of sensor and geospatial data allows Teren to process and filter massive datasets, providing a solution that is accurate and standardized within key geographies. In addition, remotely sensed information combined with material databases and localized investigations information will better inform Teren's threat models.

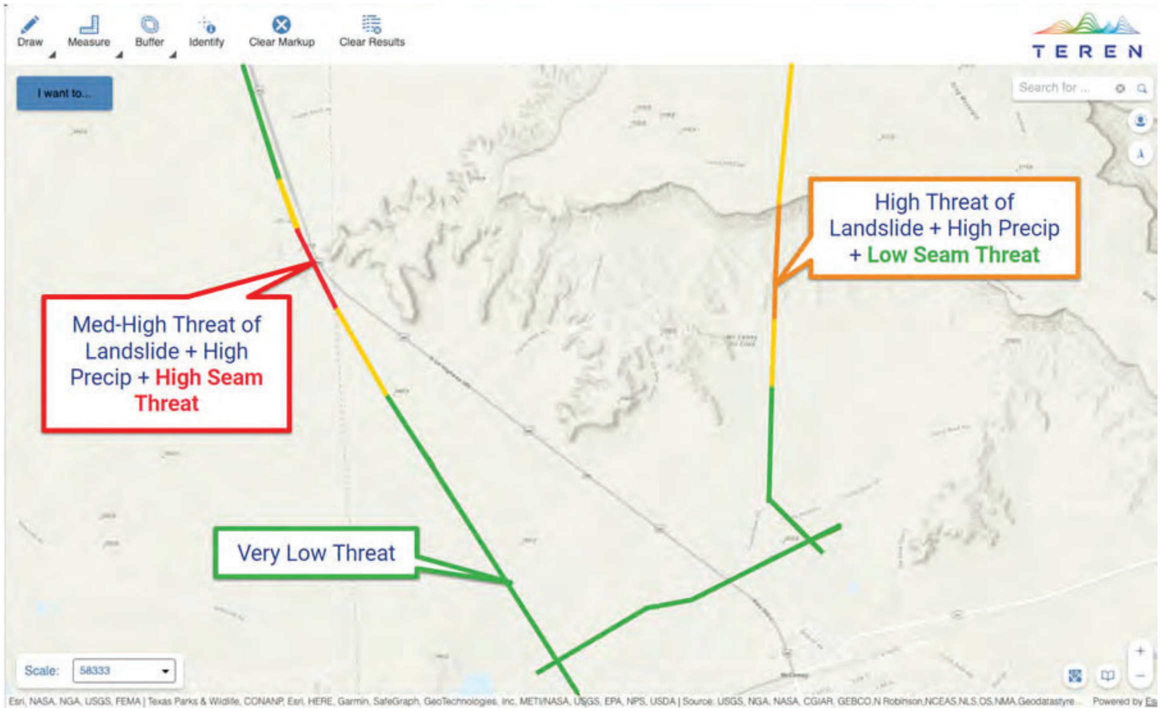

Figure 3 - Example Covariate linear referencing of pipelines to multiple threats

Combining high probability risk areas based on asset features from current/historical ILI data with high probability areas caused by terrain movement in conjunction with known accepted industry methodologies, provides operators with a powerful mechanism to extrapolate into future years and maximise efficiency in risk mitigation.

Localized, Specific Pipeline Loading Conditions

Movement of soils in an axial direction where the pipeline is orientated longitudinally downslope, as shown in figure 4, would be expected to develop an axial buckle at the downhill compression end, and deformation & tearing at the uphill tension end. Identification of pipeline location subject to axial slides via variation in positional data can be difficult, in many cases the pipeline has not moved sufficiently to positively identify signals from a dataset which has been normalised to marker locations.

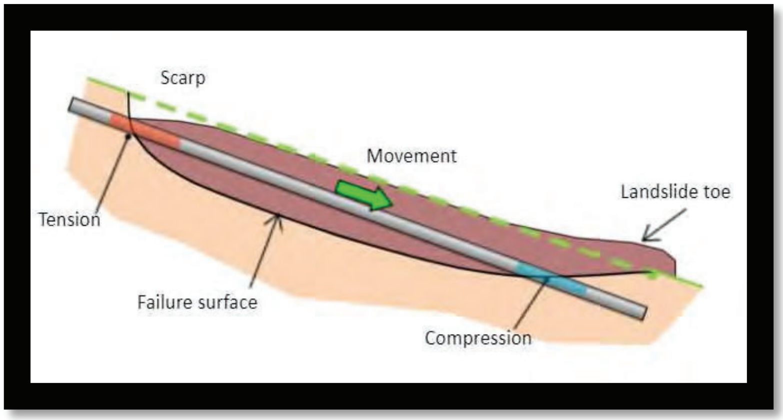

Figure 4 - Diagram of axial slide relative to pipeline.

Loss of support to the pipeline by subsidence – characteristic of areas of karst topography or mining – can be expected to result in broadly comparable strain profiles and failure modes to those caused by soil movements traverse to the buried pipeline. In this case the pipeline can sometimes exhibit measurable differences in positional mapping data; and will typically develop axial tension and bending about the pipeline axis. Failure mode can be expected to occur by tensile fracture, or if the force is sufficient; full bore rupture.

Figure 5 provides an indicative strain plot at the location of a traverse soil movement relative to a pipeline using Penspen internal FEA programming.

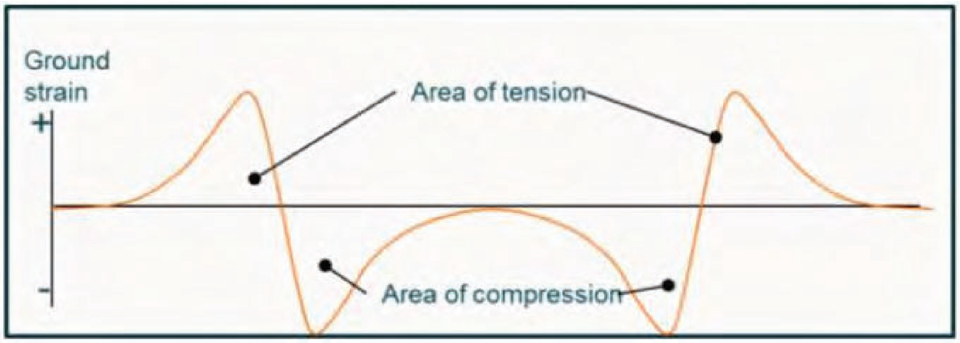

Figure 5 - Example strain plot using Penspen FEA program.

Example Digital Twin Threat Assessment – SCC Case Study

Existing SCC analysis frameworks such as NACE SP 0204, ASME B31.8S and CEPA recommended practices contain many of the risk factors which are commonly associated with formation of stress corrosion cracking, and methodologies to assess the risk in order to prioritise inspection and validation strategies.

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The methodology proposed allows quick and accurate alignment, correction & comparison of various IMU datasets so that a more complete strain model can be developed for each pipeline in a reasonable timeframe.

The revised strain model can incorporate additional strain features where known; in the example given this includes the estimated strain present near to smooth plain dents and strain caused by temperature differential subsequent to pipeline installation.

SCC Likelihood as a Function of External Geohazard-Induced Stress

Stress corrosion cracking is recognised as a potential threat to pipeline integrity for those pipelines which show susceptibility. Several mechanisms and risk factors have been identified by industry, however predicting specific locations at higher risk of circumferential stress corrosion cracking (CSCC) remains difficult.

Methodologies to categorise the risk of SCC have been published, this includes NACE SP 02041[1], ASME B31.8S2[2] and CEPA3[3] recommended practices. All are well established and contain risk factors for SCC which are accepted for use in developing risk assessment models for SCC. Factors such as coating type, appropriate cathodic protection and pipeline age are all relevant, but are either fixed factors or factors which are directly under the operator's control.

Accepted methods of assessing the risk of SCC normally designate a threshold value of 60% of SMYS under which SCC is not generally expected to initiate, or where present can generally be expected to remain dormant for a significant period of time.

Where principal stress is predominantly orientated in the circumferential direction it is reasonable to expect SCC would preferentially form axially (ASCC), and conversely where principal stress is orientated axially it is reasonable to expect SCC will preferentially form in the circumferential direction[4]. Where the ratio of axial to circumferential stresses is not heavily biased it would also be reasonable to expect that SCC would not exhibit a strong orientational preference.

This requires that any digital twin of pipeline stress-state must detail not only the magnitude of stress at any point on the pipeline, but also the direction of dominant principal stress, and the ratio of principal stresses in axial and circumferential directions.

Where excessive deformation is not expected, it is reasonable to apply the two- dimensional elastic constitutive equations. Figure 6 shows the location about the pipeline circumference at which peak tensile Von Mises stress can be expected, utilisation as a factor of SMYS and ratio of stress in axial direction to stress in circumferential direction.

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[1] https://www.mbari.org/news/news_release/2000/dec15_greene.html

[2] Anon

[3] Anon

[4] Charlton, A. Rowell, J. Kelly, B. Nieves, C. Prediction of the risk of circumferential stress corrosion cracking by analysis of digital twins. PTC2020 Berlin.

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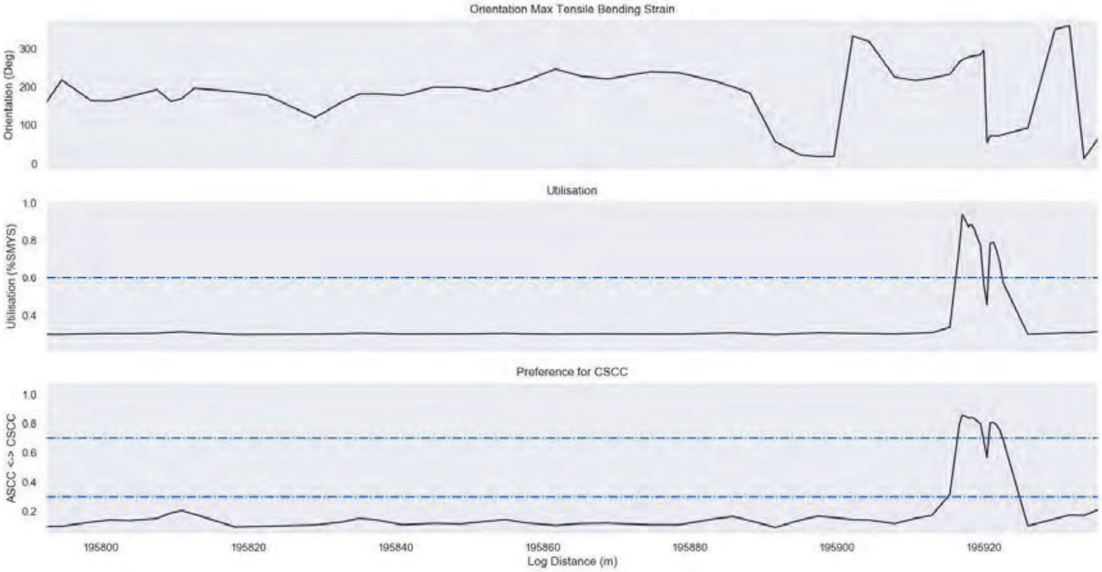

Figure 6 - Plot showing; Pipeline orientation at peak tensile stress, pipeline utilisation as factor of SMYS & expected propensity to form CSCC or ASCC at peak stress location.

Figure 6 shows that peak tensile stress changes from a location about the pipeline circumference from approximately 270° to 90°, at a similar chainage to a utilisation above 60% SMYS and a ratio of axial to tensile which indicates a preference of formation of CSCC rather than ASCC. The area indicated is not a hot-formed bend section, therefore where other risk factors of SCC are present this may indicate an area of the pipeline at higher risk of CSCC and which may be selected for examination as part of a direct assessment programme.

It is important to note that additional sources of stress in the pipeline can be expected, particularly near to welds. For this reason, the digital twin is not considered as a complete stress/strain model, but as a method of identifying areas at higher risk of CSCC in conjunction with consideration of other risk factors. The following additional factors should be included when prioritising pipeline segments susceptible to CSCC;

- Seam weld orientation relative to principal stresses
- Stress-model and dwell period above utilisation of 60% SMYS
- History of prior ground movement evidence by historical strain-rate
- Probability of future ground movement

By including consideration of the additional factors the existing methodologies such as NACE SP 0204[5], ASME B31.8S[6]and CEPA[7] recommended practices can be modified to assess relative risk of Circumferential Stress Corrosion Cracking which can help drive subsequent targeted inspection strategy as part of risk management.

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[5] NACE SP 0204:2015, Stress Corrosion Cracking (SCC) Direct Assessment Methodology, NACE International, Houston, 2015.

[6] ASME B31.8S:2018, Managing System Integrity of Gas Pipelines, ASME, New York, 2018.

[7] CEPA, Recommended Practices for Managing Near-neutral pH Stress Corrosion Cracking, CEPA, 3rd edition, Calgary, 2015

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Best Practice Approaches for Additional Threat Assessment

Above we have outlined an approach to site-specific threat analysis for SCC with respect to external loading as well as given an overview of a threat assessment approach for pipeline systems that has been used by several operators to date. Applying these methodologies, there are two approaches that are relevant to highlight as proposed best practices due to the inclusion of comprehensive data and analysis techniques for threat assessment.

1. Taking a top-down approach using the macro-level view of the abovementioned datasets and tools, refining that to "hot spots" where geohazards are the highest threat, and then diving into areas using a prioritized approach to build out the data for a digital twin on the very local level. Such an approach would work well for operators in the early stages of developing a targeted geohazards program.

2. Revisiting known hazard areas, considering specific as-built and inline inspection data, determining localized loading conditions as in the example above, and then incorporating Teren's models on top of that to generate a re-prioritized approach to geohazard mitigation for the pipeline operator. This likely would be more applicable for those operators with geohazard programs already somewhat developed - or those looking to bolster their approach to address previous blind spots in their overall threat assessment.

In all cases, additional integrity concerns such as low toughness seam welds, lack of fusion, manufacturing defects, and selective seam weld corrosion – along with the orientation and loading conditions of individual defects – should also be considered when determining overall pipeline integrity and fitness for service in the areas of high likelihood of external loading from geohazard-induced forces.

Data and Threat Granularity

Threat assessment of large geographically disperse assets requires consolidation and harmonization of environmental datasets at multiple scales and with multiple iterations of resolution. Temporal currency is also important in decreasing time to decision for ongoing assessment of the asset in a dynamic environment. A holistic digital twin requires assembly of relevant data collation and comparison of datasets with multiple scales of spatial and temporal resolution.

While the availability of data at any point in the asset lifecycle will be variable, the approach of creating a digital twin of the environment in addition to the asset material parameters accomplishes two important results:

1. Screening and focused investigation studies are indexed and prioritized according to potential threat and input data variability. Covariates of environmental datasets related to geotechnical threat are joined and overlayed with the asset footprint to better order and contextualize environmental threats characterizing correlated events (precipitation and land movement).

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2. Gaps in data are assessed for potential impact to the screening and assessment activities and are also prioritized for according to the impact of additional information will be to decreasing epistemic uncertainty of the overall risk model.

These two components are actively coordinated with each other as the database of the digital twin grows providing an ongoing order of “hotspots” along the pipeline that would most greatly benefit from addition data acquisition, refinement, or threat covariant characterization. Importantly, the digital twin approach requires formalizations of the workflows to be recursively incorporated to continuously updated as more data is ingested into the twin.

Summary

Pipeline operators face the complexities of managing geohazards and ensuring overall pipeline integrity amidst evolving environmental conditions, including material and earth movement threats manifesting over long periods of time as well as sudden threats caused by weather events and earth movement. Considering this, and the plethora of data from diverse inspection methods and remote sensing capabilities, digital twins emerge as a robust solution, providing a simulated model of pipelines based on real-world data for comprehensive threat assessment.

A focus on geotechnical stresses requires integrating various datasets, from both pipeline inspection as well as weather and outside forces remote sensing and modeling. Above we explored a case study on SCC, showcasing how digital twins enhance risk assessment frameworks. Two best practice approaches for digital twin implementation were outlined and recommend: a top-down method for early geohazard program development and a localized approach for operators with established programs. Emphasizing the importance of data granularity and continuous refinement, we underscore the iterative nature of the digital twin methodology for proactive pipeline integrity management in dynamic environments.

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