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Topic Paper #4-5

DENT INSPECTION AND ASSESSMENT

Prepared for the
Technology Advancement and Deployment Task Group

On December 12, 2019 the National Petroleum Council (NPC) in approving its report, *Dynamic Delivery – America's Evolving Oil and Natural Gas Transportation Infrastructure*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Permitting, Siting, and Community Engagement for Infrastructure Development Task Group. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 26 such working documents used in the study analyses. Appendix C of the final NPC report provides a complete list of the 26 Topic Papers. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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Topic Paper

(Prepared for the National Petroleum Council Study on Oil and Natural Gas Transportation Infrastructure)

4-5	Dent Inspection and Assessment
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SUMMARY

The inspection and assessment of pipeline dents is made challenging by the complex feature shapes and interactions that can occur over the life of the pipeline. Inspection of dents is not always effective, as tools may not be able to identify cracking located in dents; this leads to a greater need for effective assessments. Assessment techniques are typically developed for plain dents and advanced analysis is often required when there are complex dent shapes or interacting features. Field inspection is a useful tool for assessing dents but there remains some debate in the industry about how to define a safe operating pressure. This topic paper proposes several enhancements to improve dent management.

I. INTRODUCTION

The inspection and assessment of pipeline dents remains a challenging portion of pipeline integrity programs. Dents are typically static features but can be susceptible to fatigue-induced cracking (especially within liquid lines) or corrosion growth over long periods of time. Given challenges with inspection and assessment due to the geometry of dent features, there can be a high degree of uncertainty within integrity decision making leading to high levels of conservatism and potential inefficiencies in dent programs. Dent assessment is an area of active research and has been well documented in industry publications; a recent book chapter[1] provides a more detailed background regarding dent measurement and assessment. This paper discusses relevant background information regarding pipe deformation, inspection technologies, dent assessment methods, the potential need for safe excavation pressures, and relevant regulatory challenges, and provides conclusions and recommendations for industry advancement.

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[1] Gao, M., & Krishnamurthy, R., 2015, "Mechanical Damage in Pipelines: A Review of the Methods and Improvements in Characterization, Evaluation, and Mitigation," Chap. 22, Oil and Gas Pipelines: Integrity and Safety Handbook, First Edition, R. Winston Revie eds., John Wiley & Sons, Inc., Hoboken, pp. 289-325.

II. BACKGROUND INFORMATION

Pipeline deformation can occur due to a number of factors, such as intentional deformation during construction (cold bends), settlement onto rocks, equipment impact, and geological movement. Asset integrity programs typically address damage caused by settlement or equipment impact, which are commonly referred to as dents and gouges. Management of ovality (or out-of-roundness) is also included in asset integrity programs, but this is primarily well established and is not discussed here in detail. Other forms of deformation such as geological movements are managed by other programs (such as operational integrity).

Damage caused by deformations can lead to instantaneous (leading to immediate rupture as may be the case with a puncture) or delayed failures, where a deformation may stay in place for a long period of time. Instantaneous failures cannot be managed by asset integrity programs and are avoided through signage, landowner relations, etc. and monitored by leak detection programs. Delayed dent failures typically have two fundamental causes, strain and fatigue. Excessive straining in a material can lead to changes in the material properties or tearing which can make a dent more susceptible to failure. Fatigue is caused by load cycling (such as caused by pressure changes) which can cause cracks to develop. In some cases, dents will interact with other features (like welds or corroded areas), which could lead to other failure mechanisms.

Pipeline dents refer to permanent localized deformations along a pipeline, which can take a variety of shapes and sizes. These features can have significant variations that make them challenging to analyze, as different combinations of parameters can have a significant impact on their pressure containing capacity and remaining life. Historically, dent depth was the most important factor used in evaluating the severity of dents, as deeper dents are seen as having more deformation to the pipeline steel. However, industry research and investigations into historical failures has found that there are many more factors of importance that must be considered to fully understand a dent feature. The dent shape can have a significant role in determining the level of strain within the dent, and includes factors like the dent's sharpness, number of peaks (e.g., a U-shaped feature versus one that is W-shaped), and orientation (relative to the pipe centerline). As dent features may cover a large area (sometimes including several meters of pipe), there is a possibility that dents will interact with welds or other dents. Also, the creation of the dent may cause gouging or lead to the formation of localized cracking or corrosion that interacts with the dent. In some cases, the combination of the dent and interacting features (or "stress risers") can be much more severe than any of the features considered alone and require additional consideration. Another important area to consider is the fatigue loading of the dent, as pressure cycling in the line can lead to material degradation and eventually crack formation. A dent's susceptibility to fatigue is typically dependent on how much pressure cycling occurs over the life of the dent (both in terms of severity and frequency) and the restraint condition of the dent (e.g., if the dent is constrained by sitting on a rock or free to deform with pressure changes). The pipe design characteristics such as material properties, pipe diameter, and pipe wall thickness can also play a factor in a dent's behavior. Thus, a key challenge with dent management lies in the wide breadth of parameters and their many permutations.

Dent integrity programs typically consist of in-line inspections, field inspections, and engineering assessments used to identify features that pose integrity concerns. As dent features can often remain dormant for long periods of time, multiple inspections are often required, and their results are tracked by operators to identify any changes in condition such as changes in the shape or the generation of cracks or corrosion within the dent. Due to challenges associated with inspection and assessment (as discussed later in this paper), the integrity programs also heavily rely on historical experience and operator-specific procedures and criteria for managing this integrity threat.

Recent pipeline incidents related to pipeline dents have prompted additional conservatism in dent management programs. Overly conservative assumptions have resulted in operators mitigating a large number of features that do not pose a direct or immediate threat. General industry consensus shows a need for finding ways to improve efficiency (i.e., minimize the number of unnecessary mitigation actions) and effectiveness (i.e., ensure that injurious features are mitigated appropriately) by optimizing integrity actions.

III. IN-LINE INSPECTION TECHNOLOGIES

Effective inspection of dent features involves measurement of both the dent and any interacting welds or features such as cracks, corrosion, or other dents. Most dent programs center their analysis on the findings of caliper tools, which are very effective at identifying and profiling any deformations to the pipeline. High resolution caliper tools can provide sufficient information about a dent's shape to allow for the dent's strain condition to be analyzed and can help to identify the locations of some weld types. However, other tools are required to identify any interacting threats. Interacting threat identification is important when calculating burst pressure or remaining life, as interacting stress risers can significantly impact these results.

Identification of interacting threats within dents can be challenging, as most sensor technologies rely on relatively undeformed pipe. For many tools, the vendor-published performance specifications are not valid in deformed pipe, and thus cannot be relied upon to accurately identify, measure, or characterize these interacting features. The presence of a dent can have a significant impact on the effectiveness of crack inspection tools, especially ultrasonic tools, as the change in shape can affect the travel and reflection of the ultrasonic signal. These limitations significantly reduce the probability of crack detection and in many cases, the crack cannot be identified using traditional review of the tool provided inspection data. Operator experience indicates that magnetic flux leakage tools can often find areas of metal loss within dents, and when used as part of a combo-tool (which combines the magnetic flux leakage and caliper tools), threat integration uncertainties can be minimized.

For cases with effective metal loss measurements, there still remain challenges in differentiating between different metal loss morphologies, as a gouged dent is typically more severe than one with generalized corrosion. Identification of gouging is typically made based on assumptions relating to the shape of the dent, the orientation of the dent, and the location of the metal loss within the dent (e.g., topside dents with metal loss at the apex are most likely to have gouging present). Some vendors are working to enhance their algorithms to identify gouging within dent features; however, these methods have not been fully validated or implemented into standard integrity programs.

Identification of metal loss within dents is beneficial, as it helps to determine the presence of feature interaction to align with current regulatory requirements for repair. However, these requirements do not account for the degree of interaction between the features, as metal loss at the dent's apex is typically much more severe than the same metal loss in the far field of the dent. Industry research is currently ongoing to help determine the degree of interaction from an engineering perspective (such as through examining the stress strain field within the dent) through empirical and numerical means.

In-line inspection still has significant limitations when it comes to determining the fulsome condition of pipeline dents. The capabilities of high-resolution calipers can provide highly accurate dent shape information that can be tied with metal loss measurements to support more advanced assessment technologies in determining feature severity. However, future development and implementation of tools that can accurately identify and measure cracking within dents will allow for greatly improved dent management.

IV. FIELD INSPECTION TECHNOLOGIES

Field inspection of dents is an important part of an integrity program, as it allows an operator to determine actual conditions of a dent feature to support integrity decision making, augments in-line inspection results, and helps to validate assessments. Initial observations of the dent location and soil conditions surrounding the dent can be useful for identifying the cause of the dent and determining history. Once excavated, field inspections typically focus on two main areas: evaluating the dent shape and identifying any feature interactions.

When evaluating the dent shape, the excavated dent can be measured using simple hand tools (such as datum lines and depth gauges) or laser devices depending on the required measurement precision. Multiple measurements can be taken to fully identify the shape of the feature, which can be used to assess strain levels and estimate the susceptibility to fatigue failure. However, the act of excavation alters the boundary conditions on the pipeline, as soil excavation, pressure changes, and changing of the pipe support mechanism (i.e., the soil that supports the pipe) can cause the dent's shape to change in a process sometimes referred to as "rebounding." In this case, the depth of the dent feature will typically decrease as the external pressure on the pipe (i.e. that caused by the cover) is reduced. This can lead to challenges with comparing ILI and field-measured depth; however, some correlations have been found to help account for this factor.

Determination of feature interactions is essential for selecting the required repair or mitigation methods required for the features. Thus field inspections often use multiple inspection technologies. Techniques such as penetrant testing (which uses dyes to identify surface breaking flaws within the feature area) and magnetic particle inspection (which uses magnets and magnetic particles to identify sub-surface flaws) can be very effective at detecting the presence of cracking within a dent. Ultrasonic and eddy-current methods can be used to measure metal loss (or other wall thickness changes) and measure any crack-like anomalies within the dent. When cracking or metal loss is identified, special effort is usually made to determine the location and orientation of the features with respect to the dent, as this can provide valuable insight into the cause and severity of these features. In lines with multiple dents, identification of fatigue cracking during any given field inspection may be indicative of a larger problem within the pipe segment and will encourage the operator to perform additional inspections or assessments. Lines that consistently show smooth rock dents with no interactions may give an operator confidence that the dent features are stable and warrant only continued monitoring.

Effective field inspections using existing technologies can help operators to better assess the severity of dents, supporting improved assessment and repair decision making. Analysis of crack patterns and locations within a feature may provide information regarding the line's susceptibility to cracking or corrosion and may guide the operator to update their integrity program for dent features along the line. This data also provides valuable information regarding tool performance and can be used to validate and update their engineering assessment methods.

V. DENT ASSESSMENT

Accurate assessment of dent features remains a challenge for the industry, as different dent shapes, sizes, and feature interactions make accurate standardized assessment methods challenging to develop. As in-line inspection may not find all of the interacting features associated with dents (especially cracking), analysis is required to identify those features that may appear to be simple deformation based on the inspection but in reality, are actually more complex and potentially injurious.

Following a recent industry failure, the American Petroleum Institute is developing a recommended practice[2] to help support the industry with dent assessment and management. This group will leverage a wide body of research in this area to support regulatory adoption of performance-based approaches for dent management, which will support use of detailed engineering assessment to identify repair requirements. The recommended practice is expected to be completed in late 2019 and will be an important factor in supporting dent assessment in the industry.

There has been significant industry research and development on the subject of dent assessment, and this work has included a variety of academic, corporate, industry, and government initiatives to help solve the challenges associated with dent assessment. These research efforts have resulted in analytical and empirical assessment methods, numerical assessment methods, and dent assessment frameworks, which are discussed herein.

a. Analytical and Empirical Assessment Methods

The objective of many research studies is to create dent assessment techniques that are simple to implement and can be used to analyze large datasets within regulatory timeframes. Threats like cracking and corrosion have simple closed-form equations that offer reasonable accuracy and can be used for the majority of features on a pipeline. Given the multiple variables and ranges of shapes possible within dented pipes, these simple, characteristic equations have not yet been found. Thus, industry has been relying on a series of analytical and empirical models to support assessments. However, these models have limited accuracy, especially when interpolating and extrapolating from their applicable variable ranges. As most of these models were designed for simple dent shapes, complex, multi-peaked dents or dents interacting with welds or other features can be difficult to assess accurately.

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[2] American Petroleum Institute Recommended Practice RP1183: Assessment and Management of Dents in Pipelines. Currently under development.

Some of the most prolific assessment methods include means of addressing strain,[3] predicting pipe re-bounding following excavation, estimating burst pressure (for dents associated with gouges), and estimating fatigue life (using empirical means or through stress concentration factors). These methods are primarily focused on simple plain dents and can only be used for a portion of features found in the industry.

Recent work by the Pipeline Research Council International[4] has led to development of semi-empirical techniques for estimating the restraint condition, assessing the severity, and evaluating remaining fatigue life for plain (smooth, single-apex) dents based primarily on high-resolution caliper data. Determination of the restraint condition is important for assessing a dent's susceptibility to fatigue loading and historically had to be assumed based on a dent's location. The severity and fatigue models are also relatively simple to implement and allow an operator to perform multiple assessments with minimal computational efforts and resource requirements, supporting more quantitative dent integrity decision making. Research for these models was performed using a combination of full-scale testing and finite element analysis and the models have been shown to offer promising results when implemented by some operators. These models appear to be among the most accurate available in the industry and leverage significantly more information (especially regarding dent shape) than their predecessors. However, further research is required to validate these models and further enhancement is underway to account for more complex dent shapes and dent interactions with welds and metal loss.

b. Numerical Methods

Numerical analysis provides the most detailed engineering assessment available for structures and is heavily used in other safety critical industries such as construction, aviation, and nuclear. This type of analysis allows the detailed stress-strain state of a structure to be analyzed under a variety of loading conditions and also considers material properties, pipe geometry, feature geometry, and potential failure mechanisms. The challenge with this method relates to its complexity, as analysis can require hours (or days) of time for each individual feature, making it impractical for use with a large dataset in practical integrity timeframes. Thus, many operators are using analytical or semi-empirical methods to identify those features where numerical methods are appropriate to use in integrity decision making.

Research has proven the effectiveness of using numerical methods (such as finite-element analysis) to model the behavior of pipelines under indentation. These methods have been extensively studied through the Pipeline Research Council International,[5] which has amassed a significant number of full-scale pipeline tests and used them to support development of pipeline-

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[3] American Society of Mechanical Engineers Standard B31.8 Gas Transportation and Distribution Systems, non-mandatory Appendix R – Estimating Strain in Dents

[4] Pipeline Research Council International Project MD-4-9: Fatigue Screening and Life Assessment of Plain Dents and Dents Interacting with Welds and Metal Loss

[5] Pipeline Research Council International Project MD-4-2: Full-Scale Demonstration of the Interaction of Dents with Localized Corrosion Defects.

specific numerical models. Numerical models have been used to support generation of semi-empirical models, evaluate dent strain and fatigue, investigate the effects of interacting features (such as corrosion or cracking), and find the effects of uncertainty to estimate the probability of failure. The extensive body of published work in this field shows an industry push for the acceptance of these advanced techniques to support engineering assessment as a means of integrity decision making.

c. Assessment Frameworks

Operators often assess and select dents for excavation using a combination of factors, including meeting regulatory requirements; using simple risk ranking methods or subject matter expertise to identify potentially injurious features; and performing detailed analysis on a small group of features. Regulatory requirements are primarily based on feature depth and the presence of interacting features but do not include many provisions for the actual damage mechanisms within the feature (such as strain and fatigue). Risk ranking based on simple analytical or semi-empirical models may not include all relevant feature characteristics or accurately assess complex features which fall outside of their developed capabilities. Use of subject matter expertise to rank feature severity requires a long history of dent assessment and may be inconsistent among different integrity engineers or companies. Detailed analysis using advanced engineering techniques may provide the most accurate results but has a very high computational cost and cannot be used for every feature identified by in-line inspection using current technology.

Most operators use some form of staged assessment approach to account for the limitations of each individual technique. These staged assessments typically include a combination of these techniques to screen for any features requiring more in-depth analysis or mitigation. Given the uncertainties in the methods, excavation programs can be inefficient with a large percentage of the excavated features having no integrity concerns. Several frameworks for dent management have been presented by different industry sources, some rely heavily on subject matter expert experience while others use simple engineering assessments based on the dent shape. However, there is limited industry consensus on which frameworks should be used for assessment, leading to variability and inconsistency among operators. An industry recommended practice that is under development will help to ensure that all dents are being assessed consistently and may help to guide continuous future improvement.

VI. SAFE EXCAVATION OF DENTS

Given the uncertainties in measurement and assessment of dents, one area of current industry discussion relates to determining what pressure the pipeline should be operated under during excavation (for direct inspection or repair). During excavation, the rebounding process can affect the dent's shape and could lead to changes in its integrity, potentially leading to some form of failure during the excavation. Different operators have a variety of procedures for excavation to help account for this potential uncertainty, which can range from complete line shutdown to no pressure decrease during the excavation depending on the dent characteristics. In some cases, the pressure reductions can have customer impacts, especially if the feature poses no integrity concerns. This has been an area of debate in the industry literature and is an area of active investigation and research. A recent study by the Pipeline Research Council International[6] provides procedures for two-levels of assessment to help support accurate determination of excavation pressure. Other researchers have presented means assessing excavation pressure using numerical methods.[7] Some regulations have requirements and recommendations regarding pipeline pressures for safe excavation for specific feature types (such as dents interacting with metal loss).

VII. REGULATORY CHALLENGES

Management of dents is challenging, as there currently is not a consistent industry-accepted method to estimate burst pressure or remaining life. Current regulations focus on dent depth, dent location on the pipe, and the presence of interacting features. While these methods are helpful for finding a large portion of critical features, additional research and analysis methods are required to ensure that injurious dents are being identified and addressed and minimize unnecessary investigations and repairs. For example, a deep, smooth dent with minor corrosion far from its apex would require excavation while a shallow sharp dent on a heavily cycled line may not need attention. This could be concerning, as the sharp shallow dent may be more susceptible to fatigue failure than the smooth dent. Regulators have been active in looking to address these problems, recommending working "with pipeline trade and standards organizations to modify the pipeline dent acceptance criteria to account for all the factors that lead to pipe failures caused by dents, and promulgate regulations to require the new criteria be incorporated into integrity management programs."[8]

Enhancements to the existing regulations would support better dent management, especially as assessment technology improves and more advanced engineering analysis continues to develop and gain industry acceptance. Introduction of provisions for detailed engineering assessments, such as are available for complex cracking, would allow operators to make integrity decisions based on quantitative measures rather than broad generalizations that may miss certain types of threats under specific operating conditions. Performance-based regulations for dent management supported by strong technical guidelines and standards associated with assessments would be beneficial.

VIII. CONCLUSION

The analysis of dents and other forms of deformation can be much more complicated than plain cracking or corrosion due to the feature complexity and the likelihood for feature interac-

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[6] Pipeline Research Council International, Safe Inspection Pressures for Dent and Gouge Damage (MD 4-5), PR-218-063505, November 2018.

[7] For example, see International Pipeline Conference 2018 papers: "Study of Safe Dig Pressure Levels for Gas Pipelines" (IPC2018-78616) and "Do We Need a Safe Excavation Pressure for Dents? How Should it Be Defined?" (IPC2018-78376).

[8] National Transportation Safety Board Safety Recommendation P-17-001.

tions. Limitations in in-line inspection technologies leave uncertainty in the features left on the pipeline and available assessment methods tend to be insufficient or overly resource intensive. While the industry works to address these challenges through industry consortiums and collaborative research, there remain three areas for continued advancement to best solve the integrity challenges related to dents. The first area for advancement includes the continued development of inspection tools that can better identify cracking within dents to give operators more confidence in determining what threats remain on the pipeline. The second area should focus on continuing to develop better assessment techniques, including analytical, empirical, and numerical results, focusing on complex dent shapes and interacting features. Lastly, the industry should develop a recommended framework for analyzing dent features and allow for detailed engineering assessments to be included in decision making under similar provisions to those allowed for other threats. Adoption of these development areas will help to ensure improved efficiency and effectiveness of excavation programs and better maintenance of dented pipelines.