

Assessment and Management of Pipeline Dents

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Introduction

This Recommended Practice (RP) provides guidance to the pipeline industry for assessing and managing dents present in pipeline systems as a result of mechanical contact by rocks, machinery, or other forces. Emphasis is placed on conditions where dents are either closely aligned or coincident with other threats, and the applicable data screening and assessment methods available to guide decision making on mitigation, remediation, or repair. Additional emphasis is placed on the pipeline operational parameters and the influence of those parameters on dent fatigue.

The RP presents comprehensive guidance for developing a dent assessment and management program including:

- 1) Selecting suitable methods for inspecting and characterizing the condition of the pipeline with respect to dents;
- 2) Establishing data screening processes to evaluate dents relative to extent and degree of deformation and operational severity;
- 3) Provide response criteria for dents based upon the dent shape and profile as determined by in-line inspection;
- 4) Applying engineering assessment methods to evaluate fitness-for-service of dents including reassessment interval;
- 5) Presenting remediation and repair options to address dents;
- 6) Developing preventive and mitigative measures for dents in lieu of, or in addition to, periodic dent integrity assessment, including pressure reductions and pressure cycle management.

This document provides guidance on elements of an engineering critical assessment for dents to determine fitness- for-service.

This RP may be used to supplement requirements included in 49 *CFR* 195, 49 *CFR* 192, CSA Z662, SOR/99-294, and other integrity management codes and standards. The RP provides the process and tools to conduct screening and engineering assessment (e.g., fitness for purpose, engineering critical assessment) for dents. These processes and tools represent criteria for the assessment of dents accounting for the factors that lead to pipeline failures caused by dents.

While this RP is generally applicable to all pipeline systems, it does not:

- include detailed requirements for new construction to prevent dents. For information on this, reference API 1169 and API 1177,
- provide guidance on prevention of dents in-service,
- outline design precautions for preventing and limiting susceptibility to denting,
- provide guidance on the assessment of wrinkles, ripples, long seam misalignment, ovalized bends, or buckles, and
- explicitly identify the differences between onshore and offshore pipeline systems.

This RP is intended for use by pipeline operators to support planning, developing, implementing, and improving a pipeline dent management program. This RP is closely aligned with and augments the API 1160 RP for liquid hazardous pipeline integrity management. It is also equally applicable to natural gas pipeline systems, and is written as a framework for both hazard liquid and gas pipelines.

This RP provides guidance based upon an understanding of the current state of industry knowledge and expertise. Research to improve upon the current state of knowledge continues and it is expected that this RP will be updated to incorporate future enhancements in industry knowledge and expertise.

A prior API publication, API Publication 1156, described the effects of dents on liquid petroleum pipelines but was issued prior to the hazardous liquids pipeline integrity management rule. The RP provides the current industry understanding of dent formation and post-formation behavior and response to environmental and operational factors. This understanding is based on the practical experience of pipeline operators that have been managing dents under the pipeline integrity management regulations included in 49 CFR §192 and §195 and integration of over 20 years of research on dents through work completed by the pipeline industry.

Assessment and Management of Pipeline Dents

1 Scope

This recommended practice (RP) is applicable to any pipeline system used to transport hazardous liquid or natural gas. This RP includes detailed technical discussion on dent formation, strain and fatigue, and failure modes and mechanisms. These details are provided to give pipeline operators the information and knowledge necessary to make informed integrity management decisions regarding the management of dents on their systems. This RP describes preventive and mitigative measures that pipeline operators can apply to manage dents after detection. The in-service response of dents to a range of loading conditions is discussed in detail.

Mechanisms that promote denting are discussed, methods to inspect dents are described, and approaches and tools to estimate dent fitness-for-service (i.e., dent formation induced cracking, failure pressure, and pressure cycling fatigue life) are presented. Selection of the appropriate dent integrity assessment methods and integration of pipeline operating data is also discussed.

This RP is specifically designed to provide the operator with guidelines on industry-proven practices in the integrity management of dents. The guidance is largely targeted to the line pipe along the right-of-way, but some of the processes and approaches can be applied to pipeline facilities, including pipeline stations, terminals, and delivery facilities associated with pipeline systems.

This RP includes a review of currently available in-line inspection (ILI) technologies for detecting and characterizing dents, and provides guidelines for collecting data in the ditch when excavation is performed based on ILI data review and the pipeline and dent is exposed. Data integration practices are also addressed. Mitigation and repair techniques and approaches are discussed.

This RP provides general information on the dent formation process and describes approaches to evaluate fitness-for-service of dents regarding their potential to reach a structural limit state. A limit state represents an operator-defined condition where the pipe is no longer fit for purpose. This document provides tools to address three primary limit states: formation strain, failure pressure, and fatigue damage. The document provides screening tools and detailed assessment methods to address each of these limit states. This methodology is consistent with other design and fitness-for-service codes that address both static and fatigue limit states¹.

In the context of plain dents, the assessment of formation strain is considered to be an indication of the potential for cracking due to dent formation, and has been included as part of ASME B31.8 since 2006.

The assessment of failure pressure is typically not performed for most dents. Plain dents regardless of shape with depths up to 10 % of the pipe diameter, without coincident features such as metal loss, welds, or cracks have been shown in testing to have the same failure pressure as plain line pipe². Consequently, failure pressure is typically addressed for dents with coincident features or in detailed fitness-for-service assessments.

¹ ASME *Boiler and Pressure Vessel Code*

² Bood, R., Gali, M., Marewski, U., Steiner, M., Zarea, M., "EPRG Methods for Assessing the Tolerance of and Resistance of Pipelines to External Damage (Parts 1 + 2)," European Pipeline Research Group (EPRG)

Pressure cycling fatigue determines the remaining life and susceptibility of a dent to failure as a result of operational cyclic pressure.

Dent assessment is also addressed when coincident or closely-aligned features are present and could be affecting the fitness-for-service.

2 Normative References

The following referenced documents are indispensable for the application of this recommended practice. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Standard 579-1/ASME FFS-1, *Fitness-For-Service*

API 1160, *Managing System Integrity for Hazardous Liquid Pipelines*

API 1166, *Excavation Monitoring and Observation for Damage Prevention*

API 1173, *Recommended Practice for Pipeline Safety Management Systems*

API 1176, *Recommended Practice for Assessment and Management of Cracking in Pipelines*

API 1177, *Recommended Practice for Steel Pipeline Construction Quality Management Systems*

API 1178, *Integrity Data Management and Integration Guideline*

ASTM E1049-85³, *Standard Practices for Cycle Counting in Fatigue Analysis*

ASME B31.4-2019⁴, *Liquid and Slurry Piping Transportation Systems*

ASME B31.8-2018, *Gas Transmission and Distribution Piping Systems*

ASME B31.8S-2018, *Managing System Integrity of Gas Pipelines*

ASME PCC-2 -2018, *Repair of Pressure Equipment and Piping*

BS 7608:2014+A1:2015⁵, *Guide to Fatigue Design and Assessment of Steel Product*

BS 7910- 2015, *Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures*

NACE⁶ SP0102-2017-SG, Item No. 21094, *In-Line Inspection of Pipelines*

NACE Publication 35100, Item No. 24211, *In-Line inspection of Pipelines*

³ ASTM, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.

⁴ American Society of Mechanical Engineers, Two Park Avenue, New York, New York, 10016, www.asme.org.

⁵ British Standards Institute, 12950 Worldgate Drive, Suite 800 Herndon, Virginia 20170, www.bsigroup.com.

⁶ NACE International, 15835 Park Ten Place, Houston, Texas 77084, www.nace.org

3 Terms, Definitions, Acronyms, and Abbreviations

For the purposes of this document, the following definitions, acronyms, and abbreviations apply.

3.1 Terms and Definitions

3.1.1

anomaly

An unexamined deviation from the normal sound pipe material, coatings, or welds.

NOTE 1 See also “defect,” “feature,” “flaw,” and “imperfection.”

NOTE 2 An indication generated by nondestructive inspection; see NACE 35100.

3.1.2

assessment

Evaluation or estimation of the nature, quality, or ability of a person or object.

NOTE The term “integrity assessment” is used to determine the pipe’s current condition.

NOTE See “integrity assessment,” “risk assessment,” “engineering critical assessment,” or “fitness-for-service” assessment.

3.1.3

buckle

A deformation of the pipe wall caused by lateral instability under longitudinal compressive stresses imposed by axial or bending loading acting on the pipe cross section.

3.1.4

characteristic lengths

Dimension of dent along the pipe axis [e.g., axial (length)] or transverse to the pipe axis [e.g., circumferential (width)].

3.1.5

coincident feature

A feature that is geometrically overlapping a dent. Coincidence does not always imply that there is an impact on fitness-for-service.

3.1.6

constrained dent

restrained dent

Dent that remains in contact with its indenter such that the indenter restricts the movement of the pipe wall due to internal pressure fluctuations.

3.1.7

corrosion

Electro-chemical reaction reducing the pipe wall thickness.

3.1.8

defect

An imperfection of a type or magnitude exceeding acceptable limits.

NOTE See also “anomaly” and “imperfection.”

3.1.9**dent**

A local inward depression in the pipe surface caused by external force that produces pipe wall plastic deformation and a disturbance in the curvature of the pipe. Not all dents affect the fitness-for-service of a pipeline.

3.1.10**dent apex**

Deepest point of dent or point of maximum reduction in pipe diameter.

3.1.11**dent profile**

Two-dimensional geometric description of the deformed pipe wall position along or perpendicular to the pipe wall axis, typically through the deepest point of the dent.

3.1.12**ductile failure damage indicator****DFDI**

An assessment technique used to infer if there is a risk of crack formation during the indentation process.

3.1.13**electric resistance welded pipe****ERW**

Pipe that has a straight longitudinal seam produced without the addition of filler metal by the application of mechanical force and heat obtained from electric resistance.

3.1.14**failure pressure**

Internal pressure at which pipe has become functionally inoperable due to a leak or rupture.

3.1.15**fatigue**

Process of progressively reducing the remaining life of a dent or dent with coincident features as a result of repeated cycles of stress.

3.1.16**fatigue life reduction**

Reduction in fatigue life expressed as the ratio of plain dent fatigue life to that of a dent including an interacting defect.

3.1.17**feature**

Any physical object or change in pipe characteristics detected by an ILI system.

3.1.18**fitness-for-service assessment****FFS****engineering critical assessment**

Procedure by which the effects of certain types of anomalies on the pressure-carrying capacity of a pipe is assessed.

3.1.19**flaw**

An imperfection that is smaller than the maximum allowable size.

NOTE See also “anomaly,” “defect,” and “imperfection.”

3.1.20**geometric magnetic anomaly**

A geometric feature identified using a magnetic inspection technology.

3.1.21**girth weld**

A weld joining, in the circumferential direction, two base materials in the shape of a cylinder or cone.

3.1.22**gouge**

An elongated mechanical deformation of material at the surface of a component, causing a reduction in wall thickness.

3.1.23**in-line inspection****ILI**

An inspection of a pipeline from the interior of the pipe using a tool that captures characteristics of the intended anomaly.

3.1.24**in-line inspection system**

An inspection tool and the associated hardware, software, procedures, and personnel required for performing and interpreting the results of an inline inspection.

3.1.25**imperfection**

A flaw or other discontinuity noted during inspection that passes acceptance criteria during an engineering and inspection analysis.

3.1.26**indenter**

The object transferring load to the pipe wall that results in a dent.

3.1.27**integrity assessment**

A method for determining the current operability of a system including but not limited to ILI, pressure testing, and direct assessment.

3.1.28**interacting defect**

A coincident defect (e.g., corrosion, weld, gouge, crack) that reduces the fitness-for-service of the dent.

3.1.29**limit state**

A condition of a structure beyond which it no longer fulfills the relevant design and or service criteria.

3.1.30**long seam misalignment**

Mismatch of the pipe edges at the long seam causing the internal and/or external pipe surfaces to be stepped or at an angle relative to each other.

3.1.31**long seam weld**

A full penetration butt weld joining plate edges of a cylinder or cone.

3.1.32**metal loss**

Any pipe anomaly in which metal has been removed.

3.1.33**mill test report****MTR**

A report listing the specification(s) governing the product and all tests conducted by the manufacturer and the results of the tests.

3.1.34**mitigation****mitigative measures**

Activities designed to reduce or eliminate the likelihood or consequence of a pipeline failure.

3.1.35**multi-peak dent**

Dent that has more than one apex.

3.1.36**pipeline operator**

Organization that operates a pipeline.

3.1.37**ovality**

The deviation from perfect circularity of the pipe cross section (i.e., egg-shaped or broadly elliptical).

3.1.38**plain dent**

A dent without coincident features.

3.1.39**out-of-roundness**

Non-circularity of a pipe cross-section.

3.1.40**pipe grade**

Designation of pipe specified minimum yield strength in accordance with industry standards.

3.1.41**pressure spectrum**

Histogram developed by rainflow counting describing the magnitude and frequency (or number per unit time) of pressure cycles.

3.1.42**preventive measures**

Activities designed to reduce the likelihood of a pipeline failure (preventive) and/or minimize or eliminate the consequences of a pipeline failure (mitigative).

3.1.43**rainflow counting**

Cycle counting is used to summarize irregular load-versus-time histories by providing the number of times cycles of various sizes occur.

3.1.44**rebound**

Change in the shape of a dent due to the removal of the indenter.

3.1.45**remediation****remedial action**

Taking appropriate action to remove or mitigate one or more causes of pipeline risk or of an injurious anomaly consisting of, but not limited to, further testing and evaluation, changes to the physical environment, operational changes, continued monitoring, and administrative/procedural changes.

3.1.46**rerounding**

Cyclic change in the shape of a dent due to internal pressure fluctuation.

3.1.47**restrained dent**

Dent that remains in contact with its indenter such that the indenter restricts the movement of the pipe wall due to internal pressure fluctuations. Used interchangeably with “constrained dent.”

3.1.48**restraint parameter**

Numeric parameter calculated from dent shape to evaluate restraint condition.

3.1.49**ripple**

A slight ridge or undulating surface in the smoothness of the surface of the pipe.

3.1.50**risk**

A measure of loss in terms of incident likelihood and consequence.

3.1.51**risk assessment**

A systematic, analytical process in which potential hazards from pipeline and pipeline facility operation are identified, and the likelihood and consequences of potential adverse events are determined.

3.1.52**screening**

Process used to separate dents and dents with coincident features into those that need or need not be studied further based on their potential to affect the integrity of the pipeline.

3.1.53**shape parameter**

Non-dimensional parameter developed for use in single-peak fatigue life screening procedures describing the severity of the dent shape.

3.1.54**spectrum severity**

Indicator of the fatigue damage potential of an operational pressure time history.

3.1.55**strain**

The change in length of a material in response to an applied force, expressed on a unit length basis [e.g., inches per inch (millimeters per millimeter)].

3.1.56**strain assessment
dent strain**

Represents the severity of a deformation with regards to indentation providing an indicator as to whether the potential for cracking exists in the deformation.

3.1.57**stress magnification factor**

The stress magnification factor increases the cyclic pressure-induced stress range experienced by the pipe wall due to the presence of a dent.

3.1.58**unrestrained dent
unconstrained dent**

A dent that is no longer in contact with its indenter such that there is no indenter restriction of the movement of the pipe wall due to internal pressure fluctuations.

3.1.59**wrinkle**

A smooth and localized undulation visible on the outside wall of the pipe.

3.2 Acronyms and Abbreviations

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BPVC	Boiler Pressure and Vessel Code
CEPA	Canadian Energy Pipeline Association
CFR	Code of Federal Regulations
CSA	Canadian Standards Association
cSt	centistoke
d_{dent}	local dent depth (see Figure 7)
d_{ov}	ovality depth at the deepest point of a dent (see Figure 7)
d_{tot}	total dent deformation depth or total pipe restriction depth at a dent (see Figure 7)
DFDI	ductile failure damage indicator
DSAW	double submerged arc weld
EPRG	European Pipeline Research Group
ERW	electric resistance weld
FAD	failure assessment diagram
FE	finite element

FEA	finite element analysis
GMA	geometric magnetic anomaly
ID	inner diameter
ILI	in-line inspection
IM	integrity management
MAOP	maximum allowable operating pressure
MFL	magnetic flux leakage
MOP	maximum operating pressure
MTR	mill test report
NDT	nondestructive testing
OD	outer diameter
PDCA	plan, do, check, adjust
PHMSA	Pipeline and Hazardous Materials Safety Administration
PRCI	Pipeline Research Council International
RP	recommended practice
P	restraint parameter
SCADA	supervisory control and data acquisition
SCF	stress concentration factor
SLD	strain limit damage
SMAW	shielded metal arc weld
SMS	safety management system
SMYS	specified minimum yield stress
S-N	stress-cycle life curve
SP	shape parameter
SSI	spectrum severity indicator
SSU	Saybolt seconds universal
TMCP	thermo-mechanical control processing
USDOT	United States Department of Transportation

4 Guiding Principles

4.1 General

The development of this RP was based on certain guiding principles. These principles are provided here to illustrate integrity management of dents in pipelines from a broad perspective.

A dent integrity management program should be flexible and customized to support an operator's unique conditions. The program should be continually evaluated and modified to accommodate changes in the pipeline design and operation, changes to the environment in which the system operates, and new operating data and other integrity-related information. Periodic evaluation is required to be sure the program takes appropriate advantage of new processes and improved technology and that the program remains integrated with the operator's business practices and effectively supports the operator's integrity goals. New technology should be evaluated and utilized as appropriate. Such new technology can enhance an operator's ability to assess risks and the capability of analytical tools to assess the integrity of system components. These are all fundamental elements of a pipeline safety management system and are consistent with USDOT pipeline safety regulations.

The integration of relevant information is a key component for managing threats to integrity posed by dents and supports effective decision-making. Data and information integration is particularly important regarding operating and inspection data. Integration of multiple integrity data sets, including ILI and other surveys, are also needed to evaluate conditions where other features are either closely aligned or coincident with a dent. Information that can impact an operator's understanding of the important risks to a pipeline system comes from a variety of sources. The operator is in the best position to gather and analyze this information. By integrating the relevant information, the operator can determine the risks of a failure and make prudent decisions to reduce those risks.

Operators should evaluate all important data related to dents present in pipeline systems and identify those that are potentially injurious to pipeline integrity. As operating conditions and dent characteristics are unique for each pipeline system, operators should supplement existing data and information with additional data as needed to properly assess the fitness-for-service of each dent. Operators should act to remediate or eliminate injurious dents.

Pipeline system integrity and integrity management programs should be evaluated on a periodic basis. Operators are encouraged to perform internal reviews to ensure the effectiveness of the integrity management program in achieving the program's goals. Some operators may choose to use the services of third parties to assist with such evaluations.

While this RP applies to dent management for both natural gas and hazardous liquids pipelines and facilities, there are specific factors to dent assessment for each type of operation. Due to the differences in operational parameters, many gas pipelines and some hazardous liquids pipelines have low susceptibility for fatigue failure; consequently, screening criteria may be used to demonstrate that explicit fatigue life assessment is not required to ensure pipeline safety. Liquid petroleum pipelines are generally subject to a greater degree of pressure cycling (number and magnitude of cycles) and tend to be affected by cyclic fatigue. Many gas pipelines cycle at lower magnitudes and see far less cycles on the systems, often running at closer to steady state. Gas pipelines can be susceptible to fatigue under certain circumstances. A primary element of dent assessment and management is the extent and degree of pressure cycling on a pipeline.

This RP is written to be consistent with API RP 1160 and API RP 1173. Figure 1 illustrates one example of the periodic cycle of a dent management program. Figure 1 also reflects the way this periodic cycle aligns with the plan-do-check-adjust (PDCA) cycle of a pipeline safety management system. Described in detail in API RP 1173, a pipeline safety management system (SMS) provides a mechanism for enhanced risk assessment and periodic pipeline safety performance improvement. API RP 1173 is a flexible and scalable framework, and its core principles of learning from experience, continuous improvement, and awareness and management of linked activities can improve the effectivity of a pipeline integrity management program.

Figure 1 shows an example of how the PDCA process can be applied to dent management. Guidance for the requirements of a dent management process are provided in the following sections.

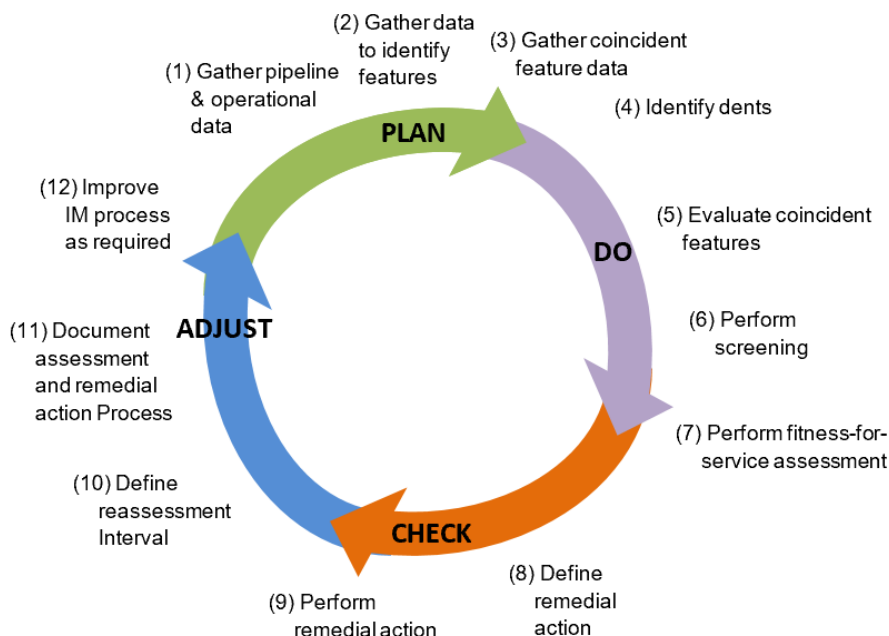


Figure 1—PDCA Cycle Applied to Dent Management Program

4.1.1 Exclusions

Prevention of dents during construction and during the operational life of a pipeline is important in pipeline integrity management. For further information, reference API 1166, API 1169, and API 1177. The practices included in this RP only apply to pipelines that have been constructed and are in-service and operational.

This RP does not provide guidance on:

- detailed requirements for new construction to prevent dents;
- damage prevention of in-service pipelines;
- design to prevent or limit susceptibility to denting;
- assessment of wrinkles, ripples, long seam misalignment, ovalized bends, or buckles;
- the differences between onshore and offshore pipeline systems;
- assessment of dents with the application of external loads (i.e., seismic loading);
- dent assessment in pipe fabricated from material other than carbon steel;
- low- and high-temperature applications;
- the effect of sour, hydrogen gas or CO₂ pipeline service;

- assessment of coincident environmentally assisted crack growth; or
- the assessment of dents near or coincident with appurtenances.

4.2 Dent Background

A dent is a local inward depression in the pipe surface caused by external force that produces pipe wall plastic deformation and a disturbance in the curvature of the pipe from its original shape.

A dent should be differentiated from related geometric features, such as:

- buckles;
- wrinkles;
- ripples;
- ovality; and
- pipe manufacturing out of roundness.

The characteristics of these features are described in industry reference materials.⁷

Section 6 describes the process for studying features identified by inspection, how they should be geometrically characterized, and deciding if they should be treated as a dent. There are several definitions for dent depth in use in the pipeline industry, and these are discussed and defined in Section 6.3.

4.2.1 Common Dent Types

Dents are commonly characterized as follows:

- A plain dent is a dent without geometrically coincident features (e.g., corrosion, gouge, weld).
- A dent with coincident feature is a dent geometrically overlapping other features (e.g., corrosion, gouge, weld), as described in Section 4.2.3.
- A single-peak dent is a dent in which the pipe wall deformation has only one apex.
- A multi-peak dent will have more than one apex. This type of pipe wall deformation may be referred to as having a saddle shape.
- A restrained dent has the indenter remaining in contact with the pipe at the indentation site. The indenter provides support to the pipe wall to reduce or restrict movement at the contact point in response to internal pressure fluctuations.
- An unrestrained dent has the indenter removed from pipe wall contact. The pipe wall at the dent is not restrained from movement in response to internal pressure fluctuations.

⁷ Rosen Group, "Encyclopedia of Pipeline Defects," Clarion Technical Publishers, ISBN-10: 0990670058, 2017.

4.2.2 Dent Formation Process

Dents are formed by the application of external concentrated force(s) to the exterior surface of the pipe. The formation process is illustrated in Figure 2.

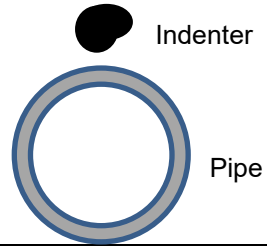
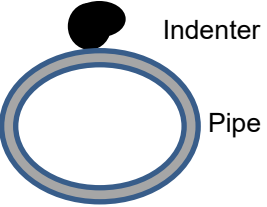
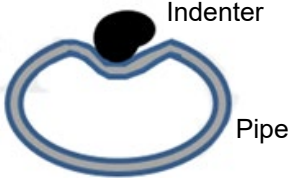
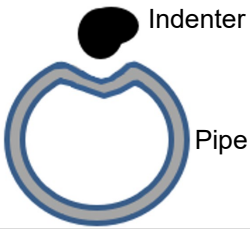
Process Stage and Description	Illustration (not to scale)
1) Round pipe—Prior to contact with the indenter.	
2) Elastic ovalization—The indenter contacts the pipe and deforms the pipe cross-section without inducing plastic deformation. If the indenter were removed, the pipe would revert to its round stage 1 shape. No dent has been formed. The extent of elastic ovalization will be dependent on whether the pipe is above or below ground; if below ground, soil properties may have an effect.	
3) Indentation—The indenter force causes the pipe cross section to deform such that the pipe wall experiences plastic deformation. The indenter deforms the pipe wall such that pipe out of roundness increases and the dent maximum depth is achieved (minimum internal pipe diameter achieved). Less pipe cross-section ovality will occur and the pipe wall will conform more closely to the indenter shape if the pipe is pressurized at this stage: — A restrained dent will remain in this condition. — The shape of the dent at this condition is defined primarily by the indenter shape, indentation depth, pipe diameter and wall thickness, pipe material, and internal pressure at indentation.	
4) Indenter removal—The indenter removal results in a change in pipe cross section for an unrestrained dent. The pipe wall displacement (rebound) includes both elastic spring back and pressure-driven rerounding. For most applications, these two contributing sources of pipe wall displacement are not isolated. — The elastic spring back will occur in the absence of pipe internal pressure and is driven by the material elastic relaxation. — The pressure-driven pipe wall deformation results in plastic deformation that permanently changes the shape of the dent. — The shape of the dent at this condition is defined primarily by the indenter shape, indentation depth, pipe diameter, wall thickness, pipe material, internal pressure at indentation, and indenter removal.	

Figure 2—Illustrative Dent Formation Process Stages

4.2.3 Coincident Features

The operator shall evaluate the impact of features that are geometrically coincident with dents in integrity assessment and management. The dent formation process may promote or result in the geometric coincidence of additional features with a dent. Examples of coincident features and their evolution include:

- External forces applied to the pipeline (e.g., dent formation) may remove material from the pipe wall (i.e., pipe wall thickness reduction), resulting in a gouge.
- The dent formation process or other service conditions may cause a holiday in the pipeline coating and, because of local environmental conditions, external pipe wall corrosion may result.
- The dent formation process may promote pipe wall cracking.
- Pipeline operations and product may promote internal corrosion of the pipe wall.
- The dent may be formed on or adjacent to a pipeline longitudinal seam or girth weld.
- Mill or manufacturing features may be present at the location where the dent is formed.

The fitness-for-service assessment should evaluate if the geometrically coincident feature affects the failure pressure or fatigue life and thus is interacting with the dent. Fitness-for-service procedures should incorporate the stress concentration effects of the coincident features, material inhomogeneity, changes in dent shape, and potential for coincident feature growth with time or loading.

Resulting maintenance decisions and repair strategies should include the coincident feature in the dent maintenance or repair processes.

5 Dent Integrity Management Process

Following the characterization of dents through inspection and data integration (Section 6), pipeline operators take steps in assessing the data and determining whether corrective actions need to be taken to mitigate or remediate the dent identified (Sections 7 and 8). The assessment process described in this recommended practice is summarized in Figure 3, which presents the elements of a dent management program. The elements include the following primary steps:

- collection and integration of data to characterize dents;
- screening and assessment of dents;
- mitigation and remediation of dents that require action;
- continuous improvement.

Practices addressing these elements are discussed in this section. Dents have the potential to threaten the integrity of a pipeline system. Pipeline operating companies should include procedures either explicitly or by reference to a process for managing this threat as an element of their integrity management program. The program shall include policies, processes, and procedures to identify, characterize, assess, remediate, and document their management of dents.

5.1 Overview

The failure of a dent can occur at two stages in its life cycle, with or without interacting defects:

- formation-induced failure: involves the pipe wall deformation and damage associated with indentation (and removal of the indenter for unrestrained dents). It is possible that the contact with the indenter promotes immediate or short-term failure that can be identified as a formation-associated event.
- service-induced failure: involves the response of the dented pipe to internal pressure. The modes of failure can be associated with fatigue damage accumulation related to cyclic loading and/or reaching the dent failure pressure.

If the dent survives the formation stage of its life cycle, the dent integrity assessment should evaluate the potential for dent formation cracking, fatigue damage accumulation, and its failure pressure. The evaluation of these limit states will depend on the characteristics of the dent and the operations of the line segment.

The tools provided in this RP were assembled to assess the potential for dent formation cracking, dent fatigue damage accumulation, and dent failure pressure. The approach presented includes two stages including screening and detailed fitness-for-service assessments. The screening assessment provides relatively simple and conservative rules of thumb or quantitative methods that indicate if a dent should be treated as non-injurious. If a screening assessment indicates that a dent is non-injurious, a detailed fitness-for-service assessment need not be applied.

When evaluating fatigue damage accumulation or failure pressure of a dent, having a crack present in a dent can significantly reduce the life or pressure-carrying capacity of a pipe. Criteria evaluating the potential for cracking during dent formation (e.g., dent indentation strain) are included in this RP. These criteria may be used in screening and/or detailed fitness-for-service assessment.

5.2 Dent Integrity Management Process Overview

The assessment and management of dents in a pipeline system involves collection of information, data integration, interpretation, fitness-for-service analysis, decision-making, and remedial action. Figure 3 shows the elements that should be included in developing a dent management program. The data requirement and general description of each element are in the sections that follow.

The dent integrity management process provided in this RP and illustrated in Figure 3 involves:

- 7) Collection and characterization of pipe wall deformation data. The characterization completed at this stage involves development of an understanding of the shape of the features for inclusion in the integrity management process.
- 8) Identification of pipe wall deformation features to be treated as dents. It is noted that not all dents are injurious to the integrity of the pipeline.
- 9) Characterization of features coincident with the dent. Not all features that are coincident with a dent affect the integrity of the dented pipeline segment and may not require remediation as determined in the integrity management process.
- 10) Perform screening of dents to identify those that are identified as non-injurious to the pipeline. Non-injurious dents do not require remediation; however, they may be monitored as part of an integrity management program.
- 11) Dents that could not be deemed non-injurious are assessed using fitness-for-service assessment tools provided in the RP. The fitness-for-service assessment techniques provide information on the requirement and urgency of remedial actions.
- 12) Remedial action decisions based on fitness-for-service assessment results and operator judgment.
- 13) Remedial action type and documentation completion to mitigate the hazard associated with the dent.

Operators shall document their data integrity management processes.

Guidance on each of the elements of the RP integrity management process are provided in the sections below. The details on the assessment tools and remedial actions are provided in Sections 6, 7, 8, 9, and 10.

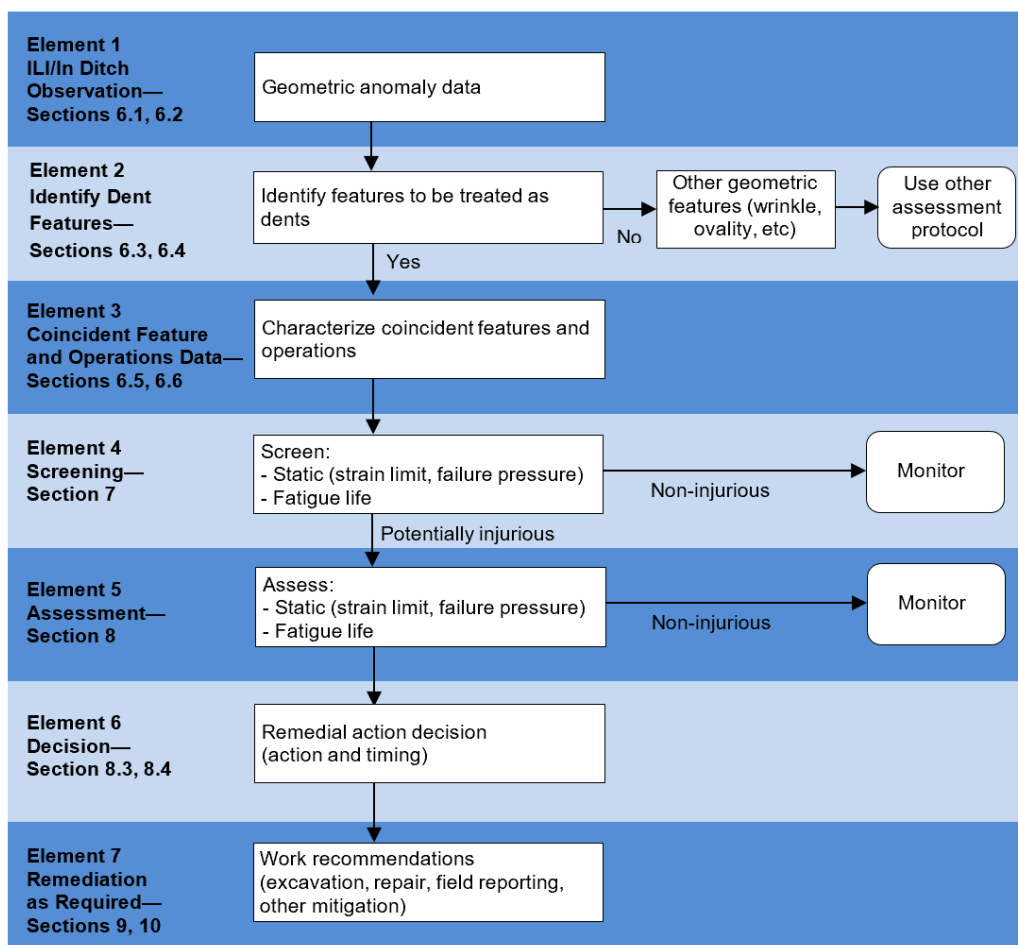


Figure 3—Elements of a Dent Management Program

The dent management program elements presented in Figure 3 accomplish the threat management goals through both direct pipeline integrity-related activities, as well as supporting activities to improve the quality of the program itself. In pipeline SMS terms, a successful dent management program includes integrity management "plan" and "do" assessment, inspection, and maintenance activities and "check" and "adjust" performance measuring, evaluation, and improvement activities, as outlined in the example approach in Figure 1 and Section 4.1.

5.2.1 Element 1—Data Collection

To understand the number and nature of pipe wall deformation features in a pipeline segment, the operator shall gather information describing these features. Not all pipe wall deformation features are dents (e.g., buckles, wrinkles), and the feature geometry is used to identify dents amongst other pipe wall deformation features.

Pipe wall deformation features are three-dimensional in nature and should be characterized in terms of their shape and location. The extent of the data required to describe a pipe wall deformation feature will depend on measurements around the circumference, as well as axially along the pipe (until the pipe has returned to a non-deformed shape). The shape of the feature may be collected using ILI systems, in-ditch surface scanning tools, or manual measurement techniques. ILI measurement of pipe wall deformation should be qualified by the conditions of the inspection (e.g., internal pressure). In ditch pipe wall deformation, measurement should also define the conditions at the time of the measurement and the

presence of the pipe wall indenter, and should include the reporting and inspection guidance provided in Section 9 and Annex C.

Further details on collecting and integrating data to characterize features can be found in Sections 6.1 and 6.2.

5.2.2 Element 2—Identify Dents

The first stage in the dent management process is concluded by identifying all pipe wall deformation features that should be treated as dents. This characterization process includes the shape of the feature, the direction of the pipe wall deformation (e.g., movement towards the pipe ID or OD), and its position relative to the overall pipeline geometry (e.g., position relative to bends, slopes). For example, a pipe wall deformation that increases the local pipe diameter, is relatively short along the pipe axis but long around the pipe circumference, and is located at the base of a pipe slope where pipe bending is observed, may be characterized as a wrinkle or buckle, depending on the extent of deformation. Feature characterization may be performed by the ILI service provider.

Another important factor in assessing dents is understanding whether the dent is restrained or unrestrained, i.e., whether the indenter contacting the pipe is still in contact or not. The behavior of dents will differ if the indenter remains in contact with the pipeline while in service. The indenter stabilizes the contacted area of the pipe wall against displacement due to internal pressure fluctuation, whereas unrestrained dents are less restricted from pipe wall movement due to internal pressure cycles. In completing a dent integrity assessment, the restraint condition of the dent should be included. In some integrity assessment procedures, an assumption is made with regards to the restraint condition of a dent. Restraint condition may be evaluated using ILI data. See Section 6.4 for further information.

Further information on dent identification can be found in Sections 6.3 and 6.4.

5.2.3 Element 3—Coincident Feature, Pipe Operations Data

The threat posed by a dent can be significantly affected by the interaction of other features, such as metal loss, welds, and other construction or material anomalies. The type of feature, its geometry, pipe surface, and position within the dent should be reported. Not all features coincident with dents will reduce the fitness-for-service of the dent. The required coincident feature information will be used to assess if the coincident feature interacts and has a negative impact on the dent.

To support integrity management of dents, the pipeline diameter, wall thickness, and material properties at the coincident feature location are required. The required material properties depend on the failure mode (e.g., static or fatigue) and level of the analysis being completed, but may include grade, yield strength, ultimate strength, tensile true stress, true strain curve, fracture toughness, and fatigue crack growth rate. Engineering judgment, data for similar pipe, or industry reference databases may be used to estimate material properties, if required.

To assess the significance of a dent with respect to its failure pressure, the loads applied to the pipe should be understood. In this respect, the highest historic or future operating pressure and operational pressure history are required, and these loads may be corrected based upon their distance and elevation relative to the SCADA reporting position. Assessing the safety of the dent should include its failure pressure with reference to the maximum operating pressure.

Assessing the long-term integrity of the dent for future operational loads should include evaluating its estimated fatigue life and comparing this to its operational life. The cyclic operating pressure history used to characterize the pipe's internal pressure should evaluate seasonal operational differences, as well as historic changes in operations. Operational data is typically collected from the pipeline SCADA system at a frequency high enough to capture significant pressure fluctuations. Prior to dent fitness-for-service assessment, the operational severity of the system should be evaluated. The operational severity of a pipeline segment includes the highest historical operating pressure and the frequency and magnitude of

operating pressure cycles. The pipeline design and SCADA system historic operating pressure data are used to characterize the severity of operation. For fatigue life assessment, the time history data is reduced to a cyclic pressure range data through a rainflow counting process that captures the range mean spectrum data. The pressure cycle at the dent location may be corrected based upon their distance and elevation relative to the SCADA reporting position. In scenarios where fatigue damage can be ruled out, this may be sufficient to screen out dents that require no response to be taken by the pipeline operator.

Further information on coincident features and operational data evaluation can be found in Sections 6.5 and 6.6.

5.2.4 Element 4—Screening

Prior to detailed fitness-for-service assessment (Element 5), a series of conservative and simplified screening tools may be used to identify those dents that are non-injurious and thus do not require the application of the fitness-for-service assessment or any response actions by the operator. Multiple screening tools demonstrating the significance of failure pressure or fatigue damage are available. Dents identified as non-injurious by all the relevant screening tools do not need further assessment for the limit state (e.g., failure pressure or fatigue damage) evaluated by the screening tool. The dents screened from fitness-for-service evaluation will continue to be inspected as part of the operator's continual assessment process under the integrity management program.

One screening tool that is included in this RP involves the potential for crack initiation during dent formation. The strain associated with a dent has been shown to be related to the likelihood that cracks were created during formation⁸. Several methods for calculating the strain associated with a dent shape are available using ILI data^{9,10}. Appropriate strain levels are calculated based on the available material information. Strain can be assessed from ILI data using the shape and curvature of the dent as the basis for the strain estimation. Strain assessment may be used as a precursor to fatigue life analyses. If the strain assessment indicates the possibility of cracking during dent formation, the dent requires further or direct assessment. If fatigue damage can be ruled out, a strain assessment may be sufficient to demonstrate that the feature is non-injurious.

Based on having access to data that provides an appropriate level of dent characterization, pipeline operators can screen out benign dents^{11,12}. Engineering experience and analysis has demonstrated that some dent shapes, dent restraint condition, operating pressure condition, interacting defects, and pipe D/t combinations do not pose a threat to fitness-for-service. These dents may be eliminated from further

⁸ Gao, M., McNealy, R., Krishnamurthy, R., Colquhoun, I, "Strain-Based Models For Dent Assessment—A Review", International Pipeline Conference, IPC2008-64565.

⁹ *ibid*

¹⁰ ASME B31.8-2018, *Gas Transmission and Distribution Piping System*, American Society of Mechanical Engineering.

¹¹ BMT Fleet Technology, "Fatigue Considerations for Natural Gas Transmission Pipelines," report prepared for Interstate Natural Gas Association of America (INGAA).

¹² Canadian Energy Pipeline Association, "Management of Shallow Retrained Dents", CEPA report prepared by BMT, 2018.

detailed assessment in a screening process^{13,14,15}. The details of this screening process should be documented to support the rationale for excluding dents from remediation or repair and for future integrity management reviews or reassessments.

Further information on screening of dents can be found in Section 7.

5.2.5 Element 5—Fitness-for-Service Assessment

Fitness-for-service assessment of a dent includes the potential for cracking initiated during dent formation, reaching the dent failure pressure, and fatigue damage accumulation. The effects of interacting features shall be evaluated in these assessments. It is useful to evaluate the potential for crack initiation resulting from dent formation such that the fitness-for-service assessment can evaluate the potential for the existence of a crack in the dent. Due to the reduction in pressure containment capacity of a dent due to the presence of cracking, in some instances the presence of cracking is used as the failure pressure limit condition. Alternatively, a FAD approach is applicable in conjunction with finite element analysis.

The pipeline operator should assess the integrity of its pipeline segments based on an evaluation of the results of its integrated data to assess the dent fatigue life. The fatigue life implications of dents may be evaluated at three levels of detail depending on the shape of the dent^{16,17,18,19,20,21}. Level 1—Fatigue Severity Ranking and Level 2—Closed form Fatigue Life Assessment may be used to evaluate the fatigue significance of restrained and unrestrained single-peak dents. Level 3—Finite Element Analysis-based detailed fatigue life assessment may be used to assess any dent shape, restrained or unrestrained. The implications of interacting features on the fatigue severity or life of these dents may be evaluated in any level of fatigue assessment.

Based on a comprehensive assessment of the data set available to a pipeline operator, an assessment of the integrity of its pipeline segments can be performed. The assessment should be based on an evaluation that includes the results of this integrated data. Testing has shown that plain dents (regardless of shape) with depths up to 10 % of the pipe diameter (without coincident metal loss, weld, or crack features) have

¹³ Pipeline Research Council International, "Fatigue Life Assessment of Dents with and without Interacting Features," MD 4-9 PRCI final report prepared by BMT, catalog no. PR-214-114500-R01, November 2018.

¹⁴ U.S. DOT PHMSA Research Project, DTPH56-10-T-000013, "Dent Fatigue Life Assessment—Development of Tools for Assessing the Severity and Life of Dent Features."

¹⁵ U.S. DOT PHMSA Research Project, DTPH56-14-H-00004, "Improving Models to Consider Complex Loadings, Operational Considerations, and Interactive Threats."

¹⁶ Pipeline Research Council International, "Fatigue Life Assessment of Dents with and without Interacting Features," MD 4-9 PRCI final report prepared by BMT, catalog no. PR-214-114500-R01, November 2018.

¹⁷ Bood, R., Gali, M., Marewski, U., Steiner, M., Zarea, M., "EPRG Methods for Assessing the Tolerance of and Resistance of Pipelines to External Damage (Parts 1 + 2)," European Pipeline Research Group (EPRG), October-November 1999, pg 739-744; December 1999, Pg 806-811.

¹⁸ U.S. DOT PHMSA Research Project, DTPH56-08-T-000011, "Structural Significance of Mechanical Damage."

¹⁹ U.S. DOT PHMSA Research Project, DTPH56-14-H-00002L, "Consolidated Project Full Scale Testing of Interactive Features for Improved Models."

²⁰ U.S. DOT PHMSA Research Project, DTPH56-10-T-000013, "Dent Fatigue Life Assessment—Development of Tools for Assessing the Severity and Life of Dent Features."

²¹ U.S. DOT PHMSA Research Project, DTPH56-14-H-00004, "Improving Models to Consider Complex Loadings, Operational Considerations, and Interactive Threats."

the same failure pressure as plain line pipe²². When these coincident features are present within or near a dent, the dent failure pressure may be evaluated using the dent shape, as well as material properties. When these coincident features are present within or near a dent, the dent failure pressure may be evaluated using a variety of techniques, including the shape of the dent and material properties. The assessment shall evaluate future operating pressure conditions.

Further information on detailed dent fitness-for-service assessments can be found in Section 8.

5.2.6 Element 6—Remedial Action Decision

Decisions on whether and when dent remediation is needed will be based on the assessment processes described above. A pipeline operator should establish and implement a process to evaluate the need for dent remedial action to reduce pipeline risk. The fitness-for-service of the pipeline is evaluated based on the dent's estimated remaining life using the maximum operating pressure. The remaining-life assessment should also consider potential changes to the maximum operating pressure. Factors such as the certainty of the pipeline operating pressure spectrum and maximum pressure, growth of coincident features, and operator maintenance program should all be evaluated in determining the appropriate response.

The timing of remedial actions is based on the assessment margin established in the fitness-for-service assessment evaluating the future highest operating pressure and the remaining pipeline segment's desired fatigue life. The operator should evaluate other factors, such as presence and potential growth of coincident features and their potential effect on pipeline integrity, other features adjacent or near the dent that may also require remedial action, seasonal site access and possible restrictions to implement repair if needed, dent shape and coincident feature sizing accuracy, consequence of failure, and other maintenance management factors.

The pipeline operator should conduct integrity reassessments on a periodic basis and establish a re-inspection interval for continual assessment of pipeline integrity. The reassessment interval is defined based upon the margin established in the fitness-for-service assessment evaluating the future highest operating pressure and the remaining pipeline segment's desired fatigue life. The consequence of failure, growth rate of coincident features, stability of operating pressure spectrum, and dent shape and coincident feature sizing accuracy should also be included in defining the reinspection and reassessment interval.

Remedial action decisions should be based on several factors. The shape of the dent, pipeline segment future operating pressure conditions, presence of coincident features, inspection observations, available materials, related integrity assessment data, and operator experience should contribute to the selection of the most appropriate remedial action(s). The durability or longevity of the remedial action and the desired fatigue life of the remedial action should also be included in the selection of the type and details of the remedial action.

Further information on dent remedial action decision-making can be found in Sections 8.4 and 8.5.

5.2.7 Element 7—Remediation as Required

The pipeline operator should implement appropriate remediation activities based on the pipeline dent integrity assessment(s). Specific remediation activities should address the threats to the pipeline segment and the risk represented by those threats. Field observations of the dent can differ from previously available information. In this instance, the details of the remedial action should be modified and documented. Repairs should follow the guidelines included in Sections 9 and 10.

²² Bood, R., Gali, M., Marewski, U., Steiner, M., Zarea, M., "EPRG Methods for Assessing the Tolerance of and Resistance of Pipelines to External Damage (Parts 1 + 2)," European Pipeline Research Group (EPRG), 10-11/1999 pg 739-744, 12/1999 Pg 806-811.

The processes, procedures, available data, and assumptions made in the assessment and remediation process should be documented. The application of assumptions to augment unavailable data will result in limitations in the assessment or remediation results. Modifications in operating conditions can affect the dent assessment and remedial action decisions, and change the threat posed by a dent. To preserve the justification for integrity management decisions made, the details of the assessment should be maintained to support future integrity management of these dents.

The operator should use the results of the program performance evaluation to modify the dent integrity management program as part of a continuous improvement process. Recommendations for changes and/or improvements should be based on analysis of the performance measures. All recommendations for changes and/or improvements should be documented, and the recommendations should be implemented in the next cycle of dent integrity assessment.

Enhancements to the integrity management program may include advancements of inspection technology or dent integrity assessment tools, new assessment procedures, or improvements in the field inspection of dents. For these reasons, records related to previous inspections, field observations, fitness-for-service assessments, and failure events should be documented and, as applicable, shared with third parties to support enhancement of elements of the integrity management program. Leveraging industry databases and statistics provides an opportunity to learn from other events.

Further information on dent mitigation and remediation can be found in Sections 9 and 10.

5.3 Significant Parameters

The parameters of importance in each step of the dent assessment and management program are related to details of the assessment. Table 1 relates the parameters of interest to the dent assessment and management program elements (see Section 4). In this table, parameters used in each element of the program are identified by an "X". It should be noted that all parameters may not be needed to address each of the elements. Furthermore, all elements identified here may not be needed to implement a prudent dent management program.

Program Elements 1 and 2 in Table 1 involve the collection of geometric data, most likely from ILI tools, to characterize pipe wall deformation and other data collected using the technology most appropriate for other coincident features of interest. This geometric information may be used in subsequent Elements to identify features as dents (4), screen features (6) as injurious or not, assess the fitness-for-service, and make decisions on feature remediation and program improvement (9 and 12).

Program Element 2 includes the feature geometric data collected in Element 1 to identify features that are dents. Assessment of the significance of features that are not dents is not included in this program. Program Element 2 also evaluates the restraint condition of the dent by evaluating the shape and clock position of the dent.

Program Element 3 is used to characterize the operational loading that the dent will be required to support. This information may be collected for each dent and updated each time the assessment is complete or typical operational pressure data may be assembled. This information is used to screen dents (4) as injurious or non-injurious and to assess the fatigue life (5) or failure pressure limit (5). The operational severity used for fatigue life assessment may be characterized by a spectrum severity index (SSI).

Element 4 is used to screen all dents and identify those that may be treated as non-injurious with respect to indentation crack formation, failure pressure, and fatigue life. A dent that is identified as non-injurious need not be evaluated further in the dent assessment and management process. The screening procedures should include the existence of coincident features. In these screening procedures, the dent formation strain may be inferred from the dent shape and thus indicates the potential for crack formation during the indentation process.

Element 5 is used to evaluate the fitness-for-service of a dent. This assessment should include the existence of coincident features. In these procedures, the dent formation strain may be inferred from the dent shape and thus indicate the potential for crack formation during the indentation process.

Element 6 employs the previously developed data to determine if remedial action is required and the relative timing of this action, including the results of Element 5.

Element 7 involves selecting and implementing appropriate remedial or mitigative actions. This element may include field excavation, including documentation. The documentation may be used to enhance the integrity management program components.

5.4 Pipeline Service

The recommended practices provided in this document are applicable to both gas and liquid pipelines. The following generalizations are made:

- Liquid pipelines generally have wider variation in pressures across pipeline segments and have lower maximum normal operating pressures than gas pipelines.
- Gas pipelines generally have fewer and less severe pressure cycling than liquid pipelines.

Based upon these generalizations, liquid pipelines are generally more susceptible to fatigue damage than gas pipelines. The screening tools incorporated in this recommended practice are intended to evaluate the dent, coincident features, pipe properties, and operational conditions to identify dents that are non-injurious.

This RP does not explicitly include the effect of sour, hydrogen gas or CO₂ pipeline service. The impact of these services on material properties should be evaluated before applying the procedures outlined in this recommended practice.

Table 1—Relationship Between Program Elements and Parameters

Dent Integrity Management Program Element Number and Actions ⁴	Line pipe/Design							Dent			Op. Pressure				Coincident Feature ³						Comments
	Size	Strength	Toughness	Ductility	Fatigue CGR	Curvature	Desired life	Shape	Clock position	Number of peaks	Design max	Highest service	At inspection	History	Location	ID/OD surface	Max ML depth	ML shape	Weld type	Weld quality	
(1) Identify features	X	—	—	—	—	X	—	X	X	X	—	—	X	—	—	—	—	—	—	—	Data collection elements
(2) Identify dents	X	—	—	—	—	X	—	X	X	X	—	—	—	—	—	—	—	—	—	—	
(2) Dent restraint	—	—	—	—	—	—	—	X	X	X	—	—	—	—	—	—	—	—	—	—	
(3) Coincident features	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X	X	X	X	X	X	
(3) Operations and pipe data	—	X	X	X	X	—	X	—	—	—	X	X	X	X	—	—	—	—	—	—	
(3) Operational severity	X	—	—	—	—	—	—	—	—	—	X	X	—	X	—	—	—	—	—	—	
(4) Screen dents (dent formation cracking and failure pressure)	X	—	—	X	—	—	—	X ¹	—	X	X	—	—	—	X	X	X	X	X	X	Procedure to identify non-injurious dents
(4) Screen dents (fatigue)	X	—	X	X	—	—	—	X	—	X	X	—	X	X ²	X	X	X	X	X	X	Procedure to identify non-injurious dents
(5) Dent fatigue life	X	X	—	X	X	—	—	X	—	X	—	X	X	X	X	X	X	—	X	X	
(5) Dent formation cracking and failure pressure	X	X	X	X	—	—	—	X ¹	—	—	—	—	—	—	X	X	X	X	X	X	
(6) Remedial action decision	—	—	—	—	—	—	X	—	—	—	X	—	—	X	X	X	X	X	X	X	Relies on fitness-for-service (Element 5)
(7) Select, implement, and document remedial action	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Depends on dent shape and coincident feature

¹ Dent shape may be used to infer dent formation strain to evaluate potential for crack formation during the indentation process.

² Operational pressure history may be characterized using spectrum severity index (SSI).

³ Plain dents will not have coincident feature data.

⁴ Number in each row references the program element number.

5.5 Coincident Features

The parameters used to define a coincident feature or interacting defect for the dent assessment and management processes may not be the same or may be less detailed than those employed in assessing the coincident feature on its own. ILI data quality for the coincident feature should be included in the assessment. Regardless of the outcome of the fitness-for-service assessment completed in this procedure, the coincident feature should be assessed independently to evaluate the threat it poses to pipeline integrity. For example, if the integrity of the dent with the coincident corrosion feature is acceptable, the threat posed by the corrosion feature on its own to the pipeline safe operating pressure should be assessed using procedures such as those outlined in ASME B31G²³ or API 1160.

6 Pipeline Dent and Operational Condition Characterization

Geometric, material, and load information is required to perform a dent integrity assessment. This information may be used to characterize the feature as a dent or not, evaluate the dent restraint condition, support fitness-for-service assessment, and remedial action planning.

The tools and procedures provided in the sections that follow may not be required for identification, screening, and assessment of all dents. ILI data is evaluated to identify deformation indications, and once a feature has been identified not to be a dent, it is not necessary to evaluate it using the screening and assessment tools in Sections 7 and 8. Once a dent has been identified as non-injurious in a screening tool, it need not be evaluated in assessment processes outlined in Section 8.

6.1 Pipe and Dent Geometry

The geometry of the pipe and the dent should be defined. Pipe geometric information includes the pipe diameter and wall thickness.

Traditional dent integrity assessment approaches characterized dents exclusively in terms of depth, often normalized by the nominal pipe outside diameter. While dent depth is a parameter that influences the behavior of a dent, the three-dimensional shape of the dent should be defined to understand its integrity threat and what response should be taken.

As described in Section 6.4, after the indenter has been removed, any operationally induced pipeline pressure increase may result in dent re-rounding and a change in the shape of the dent. As such, dent shape information should be gathered along with information describing the dent restraint (Section 6.4) and internal pressure condition at the time of measurement. The restraint condition will affect the response of the dent and subsequent fitness-for-service. A dent will change shape with changes in internal pressure; when measuring the dent geometry, it is important to define the internal pressure at the time of measurement. The maximum pressure historically experienced by the dent should also be reported if this is available. The maximum historic pressure experienced by a dent may be associated with operational pressures or events, such as pressure testing. The maximum historic pressure will indicate the pressure below which the dent shape is stable (i.e., will not permanently deform due to changes in internal pressure). If an internal pressure higher than the maximum historic pressure is applied to a dent, the shape of the dent may be permanently modified. If the dent shape is permanently modified, the dent should be reassessed.

If dent shape measurements are collected for the same dent during different inspections, it is common for them to have variations in depth and shape. This variation in dent depth and shape can result from:

- difference in measurement technology;

²³ American Society of Mechanical Engineering, "Manual for Determining the Remaining Strength of Corroded Pipelines", ASME B31G – 2017

- maturity of measurement technology;
- operating or inspection conditions;
- data analysis or interpretation; or
- other factors.

The geometry of a dent may be measured using ILI systems or field measurement techniques. In both cases, a three-dimensional description of the dent shape and the pipe surrounding it is developed. The assessment process provided in this recommended practice makes use of this information, and two-dimensional longitudinal and transverse profiles of the dent shape have been found to be useful in integrity management. The dent characterization process used to define these two-dimensional profiles is described in Section 6.2.

The geometry and analysis of the dent include the presence of any pipe cross-section ovalization. The information used to characterize the dent shape shall not be modified to remove pipe ovality, as the ovality should be included as part of the dent shape to be analyzed (see Figure 7).

The reported dent shape data should be extended to include measurements over a sufficient axial length to capture the location where the pipe cross section returns to its baseline shape. The definition of the baseline shape may require engineering judgement and may not be circular. This requires that the dent shape be described over an extended range that may include several feet upstream and downstream of the deepest point in the dent. In some instances, the pipe cross section may have been significantly ovalized or non-circular prior to indentation (more common in higher D/t pipes). In these cases, an even greater length of pipe geometry upstream and downstream of the deepest point of the dent may need to be collected to support dent assessment. Dent geometry should be collected until the pipe geometry returns to the baseline shape. As guidance, a practical limit of upstream and downstream data collection of 80 feet may be applied, or when a fitting/fixture is reached.

6.2 Dent Geometry Profile Characterization

The recommended approach for characterizing a dent involves the development of two-dimensional longitudinal and transverse profiles of the dent shape through the deepest point of the dent²⁴. The deepest point of the dent or the dent depth is defined in Figure 7. These dent profiles have proven useful in evaluating the dent restraint condition, strain, and shape parameter for fatigue life assessment of single-peak dents. The axial and transverse dent profiles are also useful in demonstrating the performance of FE model-based dent simulations in matching measured dent shapes.

For single-peak dent assessment, the axial and transverse profiles are characterized in terms of dent characteristic lengths and areas calculated from the axial and transverse profiles. Axial and transverse profile measurements are obtained using ILI data or data from measurements made in the ditch after excavating a dent. Prior to extracting the characteristic lengths and areas in the axial or transverse direction from the measured data, smoothing or approximation of the dent profile may be required depending on the level of noise that exists in the signal data.

The approximation algorithm shall, as closely as practical:

- preserve the shape of the profile;
- preserve the dent depth;

²⁴ Pipeline Research Council International, "Fatigue Life Assessment of Dents with and without Interacting Features", MD 4-9 PRCI Final Report prepared by BMT, Catalog No. PR-214-114500-R01, November 2018.

- remove noise from the measured (signal) data; and
- result in a plane smooth dent profile for evaluating characteristic lengths and areas in single-peak dents.

Approximation of the measured dent profile data shall remove/minimize any data that is due to the noise and/or any under-performing sensors of the tool. A smoothing algorithm shall not remove dent ovality. Peak axial total dent deformation depth, mentioned in this document, based on which dent geometric parameters are to be calculated, includes ovality because of dent formation.

Figure 4 shows an example of the smoothed dent profile plotted over the corresponding radial ILI data for both the axial and transverse single-peak dent profiles.

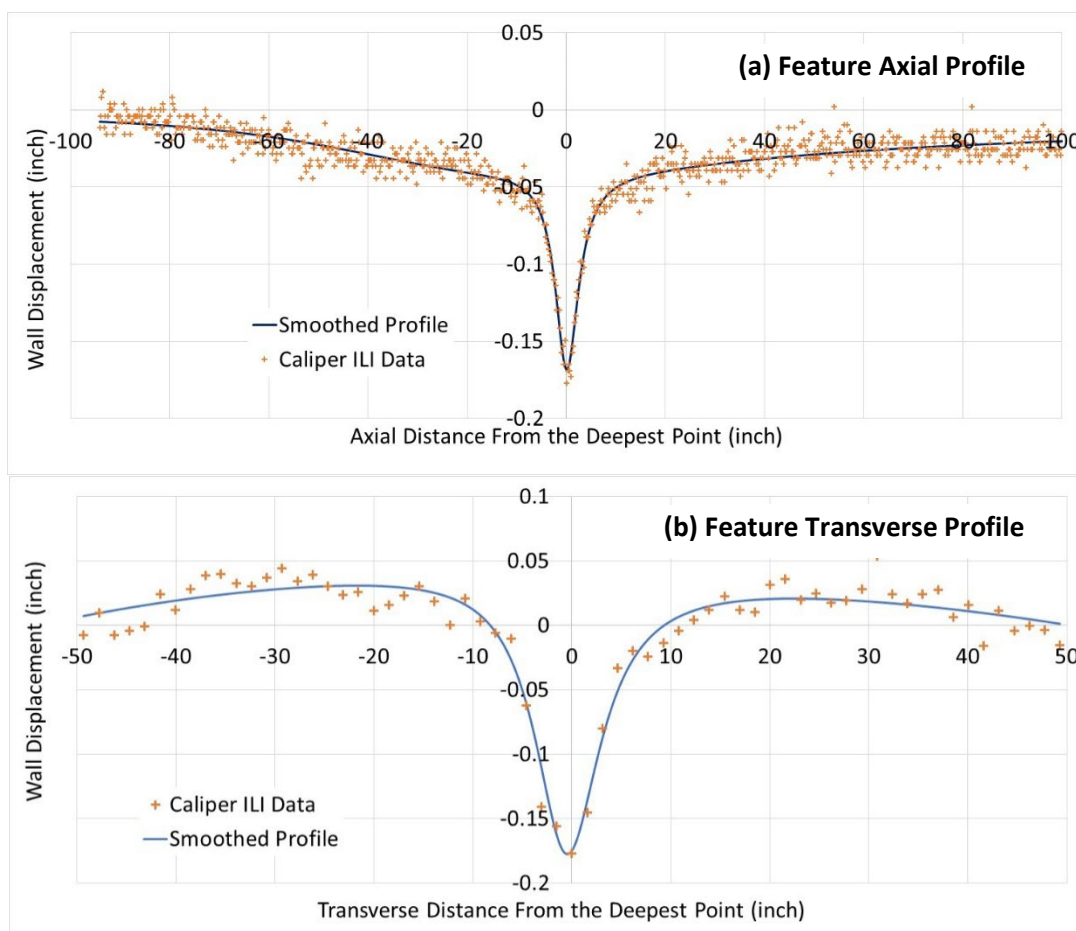


Figure 4—Example of an Acceptable Smoothed Dent Profile, (a) Axial Profile, (b) Transverse Profile

The number of data points available to define a dent profile depends on both the resolution of the ILI tool (spacing in the axial direction and the number of tool sensors around the pipe circumference) or the number of measurements taken in the ditch and the smoothing algorithm that is used afterwards to smooth the signal data. The number of data points should be determined by each operator based upon their need, pipe diameter, and usage of the information. Enough data points should be used to develop a smooth profile on each shoulder (side) of the dent transverse profile (clockwise and counterclockwise).

Table 2 includes geometric parameters used in calculating the dent restraint parameter (see Section 6.4.2) and the dent shape parameter (see Section 8.3.4). These parameters can be extracted from dent profiles derived from ILI or field measurement data for single-peak dents.

There are additional parameters listed in Table 2 that are not required for calculating the restraint and shape parameters. The additional parameters are highlighted in blue shaded text in Table 2 and are listed so that a dent profile can be generated directly from the characteristic lengths, if required, based on axial and transverse profile

and to support future developments of dent assessment techniques. The definition of the parameters listed in Table 2 are presented in Figure 5 and Figure 6. To check the characteristic lengths and areas, it is useful to review the full longitudinal or transverse profile through the deepest point of the dent.

The characteristic axial and transverse lengths and areas should be determined in the upstream and downstream direction and clockwise and counterclockwise direction from the deepest point of the dent. These characteristic lengths may support evaluation of asymmetric single-peak dents. Individual upstream and downstream (or clockwise and counterclockwise) characteristic lengths are calculated for asymmetric dents to calculate individual shape parameters.

When a uniformly ovalized pipe segment with greater than one pipe joint contains a dent, the characteristic lengths should be assessed in terms of the return of the pipe wall to the ovalized shape.

Table 2—Single-peak Dent Geometric Parameters Required to Capture Dent Shape at Dent Peak and the Restraint Parameter and the Shape Parameter Calculation

Axial Length	Transverse Extent or Width	Axial Area	Transverse Area
$L_{95\%}^{AX}$	$L_{90\%}^{TR}$	$A_{85\%}^{AX}$	$A_{85\%}^{TR}$
$L_{90\%}^{AX}$	$L_{85\%}^{TR}$	$A_{75\%}^{AX}$	$A_{75\%}^{TR}$
$L_{85\%}^{AX}$	$L_{80\%}^{TR}$	$A_{60\%}^{AX}$	$A_{60\%}^{TR}$
$L_{75\%}^{AX}$	$L_{75\%}^{TR}$	$A_{50\%}^{AX}$	$A_{50\%}^{TR}$
$L_{60\%}^{AX}$	$L_{70\%}^{TR}$	$A_{40\%}^{AX}$	$A_{40\%}^{TR}$
$L_{50\%}^{AX}$	$L_{60\%}^{TR}$	$A_{30\%}^{AX}$	$A_{30\%}^{TR}$
$L_{40\%}^{AX}$	$L_{50\%}^{TR}$	$A_{20\%}^{AX}$	$A_{20\%}^{TR}$
$L_{30\%}^{AX}$	$L_{40\%}^{TR}$	$A_{15\%}^{AX}$	$A_{15\%}^{TR}$
$L_{20\%}^{AX}$	$L_{30\%}^{TR}$	$A_{10\%}^{AX}$	$A_{10\%}^{TR}$
$L_{15\%}^{AX}$	$L_{20\%}^{TR}$	—	—
$L_{10\%}^{AX}$	$L_{15\%}^{TR}$	—	—
$L_{5\%}^{AX}$	$L_{10\%}^{TR}$	—	—

NOTE 1 All the parameters listed above (axial and transverse) should be calculated based on the Maximum Total Dent Deformation Depth determined from the axial profile as illustrated in Figure 5 which shows that the total dent deformation depth measured from the axial dent profile may be different from that inferred from the circumferential profile. Report maximum total dent deformation depth (that includes ovality, see Section 6.3 and Figure 7) based on which of the above parameters have been calculated.

NOTE 2 The internal pressure when the dent shape is measured should be collected, reported, and applied, as part of the characterization.

In Table 2, superscripts “*TR*” and “*AX*” refer to the transverse and axial profiles of the dent passing through the dent peak, respectively. The percentage values that appear as subscripts in the length and area parameters refer to the location where the deformed pipe wall in the dent has reached the specified percentage total dent deformation depth value. For example, $L_{10\%}^{AX}$ refers to the axial dent length, which is defined as the length measured from the dent peak depth to the location on the axial profile where the deformed position of the pipe wall in the dent has reached 10 % of the total depth deformation depth. Figure 5 shows some of the axial length definitions.

In the case of the dent lengths (axial orientation) corresponding to the different dent profile depths, the total dent deformation depth (i.e., dent apex) is always the same for a given dent and is determined from the axial profile. The axial profile is along the longitudinal axis of the pipe going through the deepest point of the dent, and the transverse profile is along the circumferential orientation intersecting the axial profile and going through the deepest point of the dent as defined in the axial profile.

Once the geometric axial and transverse lengths are determined, Equation (1), based on the trapezoidal rule, may be used as an approximation of the area (*A*) under the smoothed dent profile.

$$A = \frac{1}{2} \sum_{k=2}^m (x_k - x_{k-1}) |(y_k - y_1) + (y_{k-1} - y_1)| \quad (1)$$

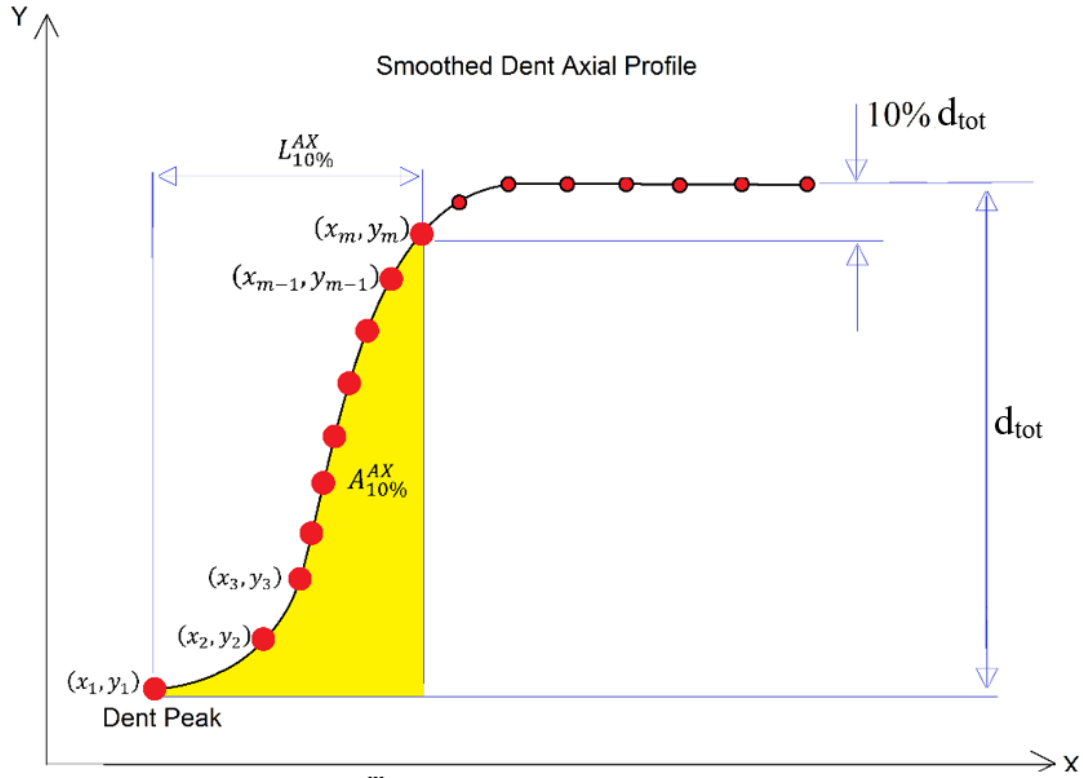
where

m is the number of data points on the smoothed dent profile;

(x_k, y_k) are the coordinates of the k^{th} point on the profile; and

(x_1, y_1) are the coordinates of the deepest point (dent peak) and is shown in Figure 5.

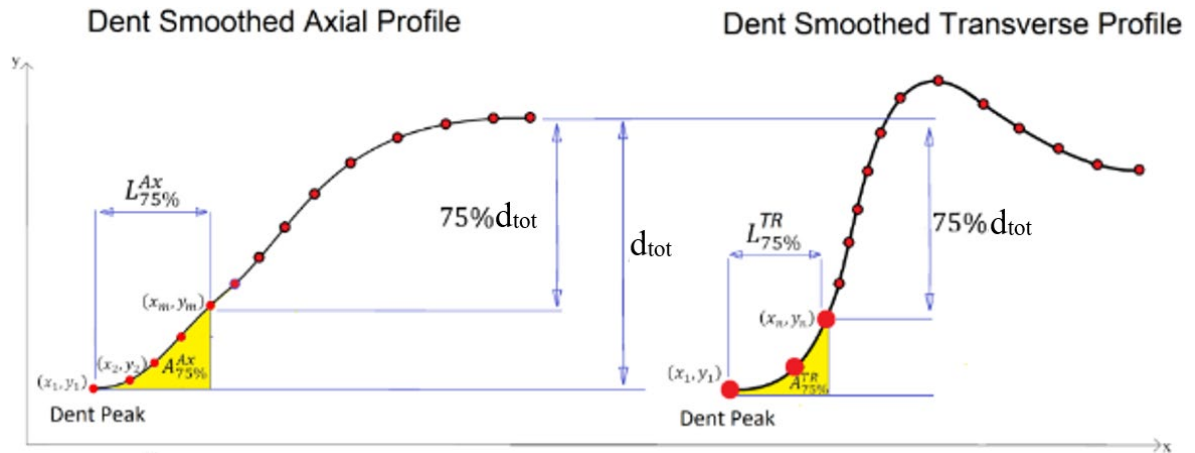
The same definition applies to the area and length calculation of the transverse profile. The total dent deformation depth, d_{tot} location, as defined in the longitudinal profile, is used as the reference location for the characteristic lengths measured in both the axial and transverse profiles.



$$A_{10\%}^{AX} = \frac{1}{2} \sum_{k=2}^m (x_k - x_{k-1}) [(y_k - y_1) + (y_{k-1} - y_1)]$$

where

m is the number of data points from the deepest point to $L_{10\%}^{AX}$ location.



$$A_{75\%}^{AX} = \frac{1}{2} \sum_{k=2}^m (x_k - x_{k-1}) [(y_k - y_1) + (y_{k-1} - y_1)] \quad A_{75\%}^{TR} = \frac{1}{2} \sum_{k=2}^n (x_k - x_{k-1}) [(y_k - y_1) + (y_{k-1} - y_1)]$$

m : number of data points from the deepest point to $L_{75\%}^{AX}$ location

n : number of data points from the deepest point to $L_{75\%}^{TR}$ location

Figure 5—Schematic Showing 10 % Axial Length and Area (top) and 75 % Axial and Transverse Length and Area (bottom)

If there is no data point available from the ILI or field data for the designated depth value, interpolation techniques, such as linear interpolation or spline interpolation, can be used to find the location of the designated length. Figure 6 shows this schematically. When in zones of high curvature, a higher order interpolation when few data points are available is desirable.

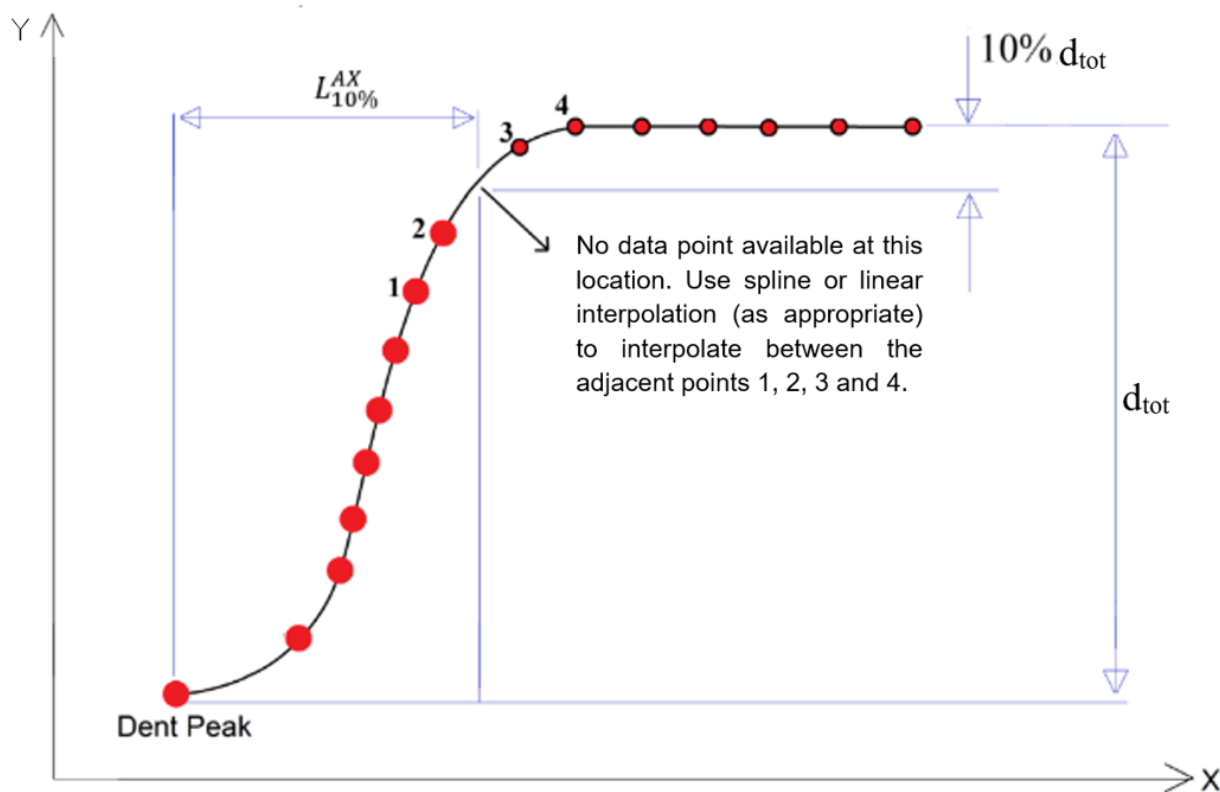


Figure 6—Spline Interpolation for Cases where No Data Point is Available at the Specified Deformed Pipe Wall Position in the Dent

6.3 Identification of Dents with In-Line Inspection Data

These criteria should only be applied to features that are potentially dents (see Section 4.2). A feature identified as something other than a dent shall not be assessed as a dent.

The objective of this element of the process is to differentiate features that should be treated as dents from other types of features.

Operators should clearly define reporting criteria for their dent assessment analyses.

A pipe wall out-of-roundness feature with a depression (e.g., wall displacement toward the inside of the pipe) should be treated as a dent based on defined indicator assessment criteria. Further guidance on the identification of a dent may be found in various references and standards (e.g. API 5L, Section 9.11.3.1). Dent identification criteria may include agreement with any one of the following, using the parameter definitions illustrated in Figure 7:

— The geometric feature meets either of the following (where $L_{10\%}^{AX}$ is distinguishable):

— formation strain $d_{tot} / L_{10\%}^{AX} > 0.05$; or

— sharpness $L_{10\%}^{AX} / OD \leq 0.25$;

- The geometric feature meets either of the following:
 - out of roundness $(D_{Nom} - D_{Min}) / D_{Nom} \geq 1\%$;
 - not just ovality at its deepest point $d_{tot} > d_{ov}$;
- Magnetic signatures associated with localized pipe wall plasticity exist; or
- The geometric feature has multiple peaks.

Multiple geometric indications, coincident features (e.g., metal loss), or magnetic indications (e.g., geometric magnetic anomaly) may indicate the presence of a dent. This is a subjective means of identifying dent features.

There are several definitions for dent depth in use in the pipeline industry. In developing this RP and its related screening and assessment tools, it was essential to establish a definition for dent depth, as shown and described in Figure 7. It may be useful to use the geometric parameters outlined in Figure 7 or report dent depth in several ways for different applications, as follows:

- Dent depth (d_{dent}) as defined in Figure 7 may be thought of as the “local dent depth,” and may be used for comparison with regulatory dent depth-based requirements or for comparison of ILI reported data in the ditch field measurement of dent depths;
- Total dent deformation depth (d_{tot}) as defined in Figure 7 may be thought of as the cross-section dent depth or total pipe restriction depth; it is used in the screening and assessment tools presented in this recommended practice; and
- Ovality depth (d_{ov}) as defined in Figure 7 describes the ovalization of the pipe at the deepest point of the dent.

The pipe cross-sectional shape remote from the dent feature may be used to define the baseline pipe shape (as discussed in Section 6.1), which can demonstrate pipe manufacturing, construction-related, and in-service measured ovality in the absence of a dent.

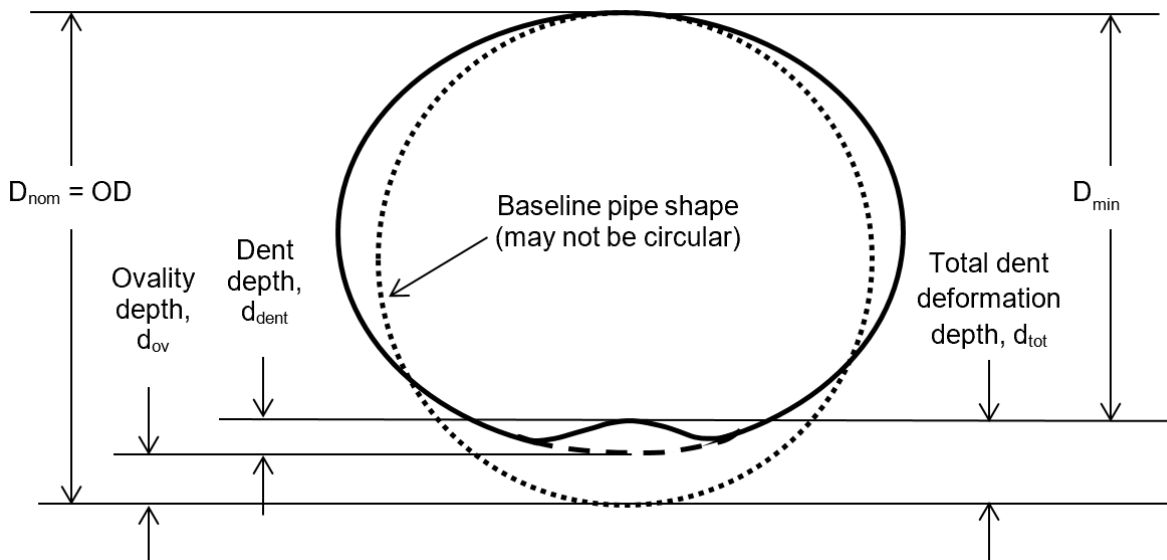


Figure 7—Dent Definition Parameters

6.4 Restraint Condition

Dents are formed by an external indenter contacting the pipe wall and applying a force. If the indenter remains in contact with the pipe at the indentation point while the pipeline is in service, the dent is restrained. If the indenter is removed from contact with the pipe after the dent is formed and the pipeline is in service, the dent is unrestrained.

Methods exist to estimate restraint conditions using ILI data; however, the only means to verify the restraint condition is through excavation and inspection.

Dent integrity assessment should evaluate the restraint condition of dents in evaluating fitness-for-service. The restraint condition will affect the dent response and thus the fitness-for-service (Sections 7 and 8) and cracking location (see Annex B)^{25,26,27}.

When dent shape is measured in the ditch, the restraint condition can generally be established visually, and the calculation of the restraint parameter need not be completed. The excavation process and removal of the indenter changes the restraint condition and the shape of the dent. The change in dent shape affects the calculated potential for crack formation and the dent's response to pressure fluctuation.

An indenter may not remain in contact with the pipe wall at all pressure conditions. Dents with intermittent indenter contact are called partially restrained dents. Currently, the empirical equation-based screening and fitness-for-purpose assessment tools only consider restrained and unrestrained dents. When the operator deems that the dent may be partially restrained, the dent should be assessed as restrained and unrestrained. Alternatively, partially restrained dents may be evaluated using finite element modeling (e.g., Level 3) assessment techniques.

Through implementation of pipeline integrity management programs and maintenance activities performed by pipeline operators, some restrained rock dents have been excavated and inspected, resulting in the indenter being removed from the pipe. Pipeline operators should review available records to understand these conditions and include the periods of time and pressure history analysis under both restrained and unrestrained conditions when performing dent assessment.

6.4.1 Restraint Condition by Clock Position

Traditionally, the clock position of the dent has been used to infer the restraint condition of a dent. ILI systems can report dent clock position to support this assessment. This is a judgment-based approach for dent restraint conditions that may not always be correct. Clock position may be used to infer restraint condition.

Dents located on the top side of the pipe (above the 4 o'clock and 8 o'clock positions) are more likely to be third-party damage and thus unrestrained dents. Similarly, dents having signs of gouging are generally third-party damage and thus unrestrained dents.

Dents located on the bottom-side of the pipe (below 4 and 8 o'clock positions) are more likely to be rock dents and thus restrained dents. The exception, as noted above, is for bottom-side dents that have been previously excavated, the indenter removed, and the pipeline put back in service.

²⁵ Pipeline Research Council International, "Fatigue Life Assessment of Dents with and without Interacting Features," MD 4-9 PRCI final report prepared by BMT, Catalog No. PR-214-114500-R01, November 2018.

²⁶ "Full-Scale Demonstration of the Interaction of Dents with Welds and Localized Corrosion Defects," PRCI Project MD-4-2 (PR-214-073510).

²⁷ "Full-scale testing of Interactive Features for Improved Models," DOT final report DTPH56-14-H-0002, 2017.