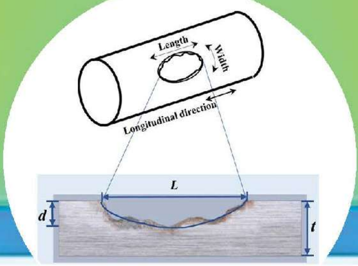

DEFECT ASSESSMENT FOR INTEGRITY MANAGEMENT OF PIPELINES

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WILEY

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To Jianshu and Winston

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Preface

Defect assessment is an essential component which is integral to the integrity management program of pipelines. By processing and analyzing the data collected by in-line inspection (ILI) tools and from other sources such as historical records, operating control and monitoring system, and offline/aboveground inspections with various models, formulas and numerical algorisms, the defect assessment provides information about performance condition of the pipelines, including prediction of failure pressure, determination of fitness-for-service (FFS), and further, estimation of the remaining service life. The defect assessment also contributes to failure risk and reliability evaluation, and recommendations of proper measures and actions for pipeline failure mitigation and control.

The pipeline defect assessment technique has evolved in the past several decades, experiencing development of three levels of technical progress, i.e., Levels I, II, and III methods. Targeting determination of the stress and strain distributions at the defects and evaluation of pipeline FFS and failure pressure, the three levels of methods distinguish themselves mainly by improved accuracy of the defect sizing, inclusion of the interaction of multiple defects, and solving highly nonlinear problems in defect assessment on pipelines, respectively. Nowadays, Levels I and II methods have been extensively used in industry for improved integrity management, while the Level III method, which relies on finite element (FE) modeling and analysis for solving nonlinearity at pipeline defects, has found its applications mainly in engineering research community due to background knowledge requirement and computational complexity.

In the last decade, my research group has been focusing on Level III defect assessment on pipelines, developing various FE-based models and methods to determine the stress and strain distributions at corrosion defects based on accurate definition of the defect dimension under pipeline operating conditions, evaluating their effect on FFS of the pipelines and predicting the failure pressure. Moreover, the assessment targets not only a single corrosion defect on pipelines, but also multiple defects between which a mutual interaction may exist to further degrade the pipeline integrity. For various orientations the corrosion defects are aligned with each other, critical spacings between them are defined to determine if an interaction exists so that they should be assessed either together or separately.

The major contribution of my group to development of the Level III defect assessment technique is, based on the mechano-electrochemical interaction theoretical concept I proposed in 2013, to integrate the mechanical force with electrochemical force, developing a multi-physics field coupling model for defect assessment while considering the dynamic nature of corrosion defects in actual service environments. Prior to that, the corrosion defects have been usually treated as metal-loss features, while ignoring the dynamic process of defect growth due to corrosion reactions. This is regarded as "revolutionary" to pipeline defect assessment techniques. The novel Level III defect assessment method, at the first time of its kind, enables prediction of the rate of corrosion defect growth on pipelines under the synergism of mechanical and electrochemical forces, reproducing the reality and thus providing more accurate and reliable results.

In addition to corrosion defects, the mechano-electrochemical interaction integrated Level III assessment method has also expanded its use to other types of surface anomalies such as dents, buckles and wrinkles, as well as combinations of different types of defects. Moreover, the defect assessment applies on both straight pipes and pipeline elbows where the defects experience different mechanical and corrosion conditions. Criteria and methods are developed to evaluate the pipeline performance and predict burst failure.

The book starts with an overview of pipeline integrity management program in Chapter 1, where the basic principle, main components and methods, and design pathway of integrity management of pipelines are introduced. Various threats to degrade the pipeline integrity in the field are reviewed, and common ILI tools for detecting surface defects are summarized. Chapter 2 introduces the historical development of defect assessment techniques, while focusing on the principles, criteria, and applications of Levels I and II methods. Commentary remarks are given to analyze the limitations of the two levels of assessment method. In Chapter 3, the FE-based Level III defect assessment method is detailed in terms of the principles, criteria, and applications for pipeline FFS determination and failure pressure prediction. The assessment applies for both single and multiple corrosion defects, straight pipes and pipeline elbows, internal and external defects, and the defects on pipelines under vibration induced by running of ILI tools. Chapters 4 and 5 contain the important innovation of

Level III defect assessment method by integrating mechanical and electrochemical forces at corrosion defects, considering the synergism of stress/strain and electrochemical corrosion and its effect on pipeline performance and failure during service. The fundamentals of mechano-electrochemical interaction for pipeline corrosion are imparted in Chapter 4, followed by development of a multi-physics field coupling model for defect assessment. The defects are either regularly shaped or with complex shapes encountered in the field, where a definitive method is proposed to accurately size the defects. Particularly, when a corrosion defect is present on a pipe in suspension under soil-erosive conditions, additional mechanical factors such as surface loading and a non-uniform stress distribution in the suspended pipe segment are considered and modeled. Moreover, the defect growth rate on pipelines is modeled and predicted under both mechanical stress and electrochemical corrosion effects, and the results help estimate the remaining life of corroded pipelines in the field. In addition to single corrosion defect, multiple corrosion defects where a mutual interaction exists are modeled with the novel Level III assessment method. The adjacent corrosion defects are oriented either longitudinally, circumferentially, or overlapped with each other. Critical spacings between them are defined to determine if an interaction exists to degrade the pipeline integrity. Furthermore, a new criterion based on anodic current density, i.e., corrosion rate, at the adjacent area between the corrosion defects is proposed and validated to evaluate the defect interaction. In Chapter 6, dent assessment on pipelines is included, where the dent assessment principle, uniqueness, challenge, and failure criteria are reviewed. A new method to define the critical strain at a dent is introduced. In addition to dent assessment, the combinations between a dent and a gouge, corrosion, and a crack are modeled and assessed on pipelines. Finally, assessment of buckles on pipelines and buckling failure analysis by FE-based models are included in Chapter 7. Buckling failure of pipelines usually occurs under pipe–soil interactions, where an axial compressive load or bending moment is generated on the pipelines. The critical compressive force or the critical bending moment is defined for pipelines containing a dent or corrosion defect where buckling failure potentially occurs, while considering the parametric effects such as pipe dimension, defect size, internal pressure, and steel properties. A new method for prediction of burst capacity of corroded pipelines under a combined bending moment and axial compressive load is proposed.

I acknowledge numerous fruitful discussions I have had with many industry partners and academic colleagues. I am indebted to the dedicated and unfailing assistance and contributions provided by the students and postdoctoral fellows that I have the pleasure to supervise to study defect assessment

on pipelines in my research group. They are Drs. Luyao Xu, Jialin Sun, Jian Zhao, Zhuwu Zhang, Yi Shuai, and Guojin Qin. Thank you very much for your hard work and research accomplishments!

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Finally, I thank my wife, Jianshu, and my son, Winston, who have provided encouragements and have supported the creation of this book.

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List of Abbreviations and Symbols

2D	2-dimensional
3D	3-dimensional
AC	Alternating current
ACVG	Alternating current voltage gradient
API	American Petroleum Institute
ASME	American Society of Mechanical Engineering
BS	British Standard
BS&W	Basic sediments and water
CEPA	Canadian Energy Pipeline Association
CFR	Code of federal regulations
CIS	Close interval survey
CO_2	Carbon dioxide
CP	Cathodic protection
CSA	Canadian Standardization Association
CSE	Copper sulfate electrode
CTOD	Crack tip opening displacement
DC	Direct current
DCVG	Direct current voltage gradient
DFDI	Ductile fracture damage index
DNV	Det Norske Veritas
DSAW	Double submerged arc-welded
EAC	Environmentally assisted cracking
ECA	Engineering critical assessment
ECDA	External corrosion direct assessment
EIS	Electrochemical impedance spectroscopy
EMAT	Electromagnetic acoustic transducer
EPRG	European Pipeline Research Group
ERW	Electric resistance-welded

FAD	Failure assessment diagram
FE	Finite element
FERC	Federal Energy Regulatory Commission
FFS	Fitness-for-service
H	Hydrogen atom
H_2	Hydrogen molecule
H_2S	Hydrogen sulfide
HAZ	Heat-affected zone
HE	Hydrogen embrittlement
HEDE	Hydrogen-enhanced decohesion
HELP	Hydrogen-enhanced local plasticity
HIB	Hydrogen-induced blistering
HIC	Hydrogen-induced cracking
HVAC	High voltage alternating current
HVDC	High voltage direct current
ICCP	Impressed current cathodic protection
ICDA	Internal corrosion direct assessment
ILI	In-line inspection
LOF	Lack of fusion
LOP	Lack of penetration
MAOP	Maximum allowable operating pressure
M-C	Mechanical–chemical
M-E	Mechano-electrochemical
MFL	Magnetic flux leakage
MIC	Microbiologically influenced corrosion
MnS	Manganese sulfide
NACE	National Association of Corrosion Engineers
NDT	Non-destructive testing
NEB	National Energy Board
NSC	Net Section Collapse
PDCA	Plan-Do-Check-Act
PE	Polyethylene
PHMSA	Pipeline and Hazardous Materials Safety Administration
ROW	Right-of-way
RP	Recommended practice
RPA	Rectangular parabola area
R-O	Ramberg-Osgood
ROW	Right-of-way
SBD	Strain-based design
SCADA	Supervisory control and data acquisition

SCC	Stress corrosion cracking
SCCDA	SCC direct assessment
SCE	Saturated calomel electrode
SCF	Stress concentration factor
SF	Safety factor
SHE	Standard hydrogen electrode
SL	Suspension length
SLD	Strain limit damage
SME	Subject matter expert
SMYS	Specified minimum yield strength
S-N	Stress–Number of cycles
SP	Shape parameter of a dent
SRB	Sulfate-reducing bacteria
SSC	Sulfide stress cracking
UKOPA	UK Onshore Pipeline Association
UT	Ultrasonic tool
XFEM	Extended finite element method
a	Activity
$\tilde{a}$	M-C activity
$\bar{a}$	Electrochemical activity
$\tilde{\bar{a}}$	M-E activity
$2a$	Length of the secondary axis of a semi-ellipsoidal corrosion defect
b_a	Anodic Tafel slope
b_c	Cathodic Tafel slope
c_1	Length of the primary semi-axis of the bigger semi-ellipsoidal corrosion defect
c_2	Length of the primary semi-axis of the smaller semi-ellipsoidal corrosion defect
$2c$	Length of the primary axis of a semi-ellipsoidal corrosion defect
C_1	A constant obtained through burst test on a non-indented pipe
C_2	Elongation rate of pipe steel measured in uniaxial tensile testing
A_0	Cross-sectional area of a pipe before corrosion occurs
A	Area
A_{eff}	Effective area
A_{P}	A coefficient depending on dent geometry
B_{P}	A coefficient depending on pipe dimension
c	Curvature coefficient of a pipe elbow
C_{P}	A coefficient depending on steel properties
d	Depth

d_1	Depth of the top defect for two overlapped corrosion defects
d_2	Depth of the bottom defect for two overlapped corrosion defects
d_{ave}	Average defect depth
d_{clus}	Depth of the defect cluster
d_{e}	Equivalent depth of multiple defects
d_{g}	Maximum depth of a gouge
d_{i}	Maximum depth of the composite defect
d_{max}	Maximum depth of an irregularly shaped corrosion defect
D	Pipe outer diameter
D_{e0}	Simplified DFDI value before spring-back
D_{eform}	Damage resulted from deforming
$D_{\mathrm{e,k}}$	Damage during the *k*th load increment
D_{em}	Maximum DFDI at a dent
D_{et}	An indicator of the limit state for a pipeline to carry no further load
D_{max}	Maximum pipe outer diameter
D_{min}	Minimum pipe outer diameter
E	Young's modulus
F	Faraday's constant
F_{c}	Critical buckling load
F_{comp}	Compressive force
F_{ref}	Reference buckling load
f	Frequency
f_1	A factor representing the difference of strains after and before spring-back of an unconstrained dent
h	Final depth of the dent after removal of the indenter
h_{o}	Initial displacement of the indenter applied on a pipe
i_{a}	Anodic reaction current density
$i_{0,\ \mathrm{a}}$	Anodic exchange current density
$i_{\mathrm{a}}{}^{\mathrm{e}}$	Anodic current density of an elastically stressed steel in a corrosive environment
$i_{\mathrm{a}}{}^{\mathrm{f}}$	Anodic current density of a plastically stressed steel in a corrosive environment
$i^{\mathrm{a}}_{\mathrm{far-defects}}$	Anodic current density of the steel pipe far away from the corrosion defects
$i^{\mathrm{a}}_{\mathrm{mid-defects}}$	Anodic current density at the middle of two adjacent corrosion defects
i_{c}	Cathodic reaction current density
$i_{0,c}$	Cathodic exchange current density

I	An integral value used as the damage indicator
k	An index for either liquid or solid
K	R-O material parameter, a constant
$K_1, K_2, \ldots$	Curvature of each node in a pipe during buckling modeling
K_{Buckling}	Pipe curvature at a local buckling position
K_{d}	Stress concentration factor at a dent
K_{F}	Fatigue stress concentration factor
K_{r}	Toughness ratio
L	Length
L_1	A half of the length of the top defect for two overlapped defects
L_{clus}	Length of the defect cluster
L_{e}	Equivalent length of multiple defects
L_{eff}	Effective length
L_{g}	Length of a gouge
L_i	Total length of the composite defect
L_{p}	Length of a pipe segment
$L_{\mathrm{r}}^{\mathrm{p}}$	Load ratio
M	Folias factor
M_{c}	Critical buckling moment
M_{o}	Critical elastic buckling moment
n	R-O material parameter, a constant
N	Fatigue life in cycles
N_0	Initial density of dislocations prior to plastic deformation
$N_1, N_2, \ldots$	Nodes in modeling of curvature of a pipe during buckling
P	Internal pressure
P_1	Pressure at initial stage
P_2	Pressure at end stage
P_0	Tresca strength solution
$P(0)$	Initial pressure capacity
P_{b}	Burst pressure
P_e	Minimum external hydrostatic pressure
P_{F}	Failure pressure
$P_{\mathrm{F,add}}$	Failure pressure of a pipe when additional internal defects are included
P_{FE}	Burst pressures of a defect-containing elbow predicted by FE model
P_{GM}	Burst pressure of a defect-free elbow
P_i	Maximum design internal pressure
$P_{\max}$	Upper limit burst pressure

$P_{\min}$	Lower limit burst pressure
P_{multiple}	Failure pressure of a pipeline containing multiple corrosion defects
$P_{\text{overlapped}}$	Failure pressure of a pipeline containing overlapped corrosion defects
P_{single}	Failure pressure of a pipeline containing a single corrosion defect
P_{y}	Critical internal pressure when pipe steel yields
Q	Length correction factor
Q_{k}	A general source term
r_{cc}	Ratio of the lengths of primary axis of the smaller semi-ellipsoidal defect to that of the bigger semi-ellipsoidal corrosion defect in a double ellipsoidal defect
R	Ideal gas constant
R_0	Initial pipe surface radius
R_1	External surface radius of curvature in the transverse plane through a dent
R_2	External surface radius of curvature in the longitudinal plane through a dent
R_{b}	Bending radius of elbow
R_{c}	Stress ratio during cyclic loading
R_{d}	Surface radius of the curvature at a dent
R_{p}	Pipe outer radius
R_{r}	Outer radius of sealing cup of the ILI tool
S_{C}	Circumferential spacing between two adjacent corrosion defects
$S_{\text{C}}^{\text{Lim}}$	Limiting circumferential spacing between two adjacent corrosion defects
S_{L}	Longitudinal spacing between two adjacent corrosion defects
$S_{\text{L}}^{\text{Lim}}$	Limiting longitudinal spacing between two adjacent corrosion defects
$S_{\text{L,ext}}^{\text{Lim}}$	Limiting longitudinal spacing between external defects
$S_{\text{L,int}}^{\text{Lim}}$	Limiting longitudinal spacing in the presence of both external and internal defects
S_{Li}	Longitudinal spacing between adjacent defect projections
t	Pipe wall thickness
T	Temperature
u	Profile functions in the longitudinal direction of a pipe
v	Profile functions in the circumferential direction of a pipe
V	Volume
V_{o}	Initial volume
V_m	Molar volume

w	Pipe wall deflection in the radial direction of a pipe
W	Width
W_{clus}	Width of the defect cluster
z	Chemical valence or charge number
α	A coefficient
β	Width angle of a defect
β_{e}	Equivalent width angle of multiple defects
σ	Stress
σ_1, σ_2, σ_3	Principal stresses of a pipeline
σ_{a}	Alternating stress
σ_{e}	Effective stress
σ_{eq}	Equivalent stress
σ_{exp}	Experimental stress function
σ_{F}	Failure stress
σ_{FS}	Fatigue strength
σ_{flow}	Flow stress
σ_{k}	Conductivity
σ_{m}	Mean stress
σ_{max}	Maximum stress
σ_{min}	Minimum stress
σ_{Mises}	von Mises stress
σ_{Tresca}	Tresca yield stress
σ_{u}	Ultimate tensile strength
σ_{y}	Yield strength
σ_{yhard}	Stress enhancement hardening factor during plastic deformation
σ_{θ}	Hoop stress
σ_{z}	Axial stress
ε	Strain
$\varepsilon_{\mathrm{as}}$	Strain at the dent apex after spring-back
$\varepsilon_{\mathrm{ini}}$	Strain at the dent apex before spring-back
ε_0	True strain to failure
ε_1	Bending strain in the circumferential direction
ε_2	Bending strain in the longitudinal direction
ε_3	Membrane strain in the longitudinal direction
$\varepsilon_{\mathrm{apex}}$	Equivalent strain at the dent apex
$\varepsilon_{\mathrm{crit}}$	Critical strain to initiate cracks
ε_{i}	Equivalent strain on the inside surface of a pipe
ε_{o}	Equivalent strain on the outside surface of a pipe
$\varepsilon_{\mathrm{eff}}$	Effective strain
$\varepsilon_{\mathrm{eq}}$	Equivalent strain

$\varepsilon_{\mathrm{lim}}$	Strain limit
$\varepsilon_{\mathrm{max}}$	Maximum equivalent strain
ε_{p}	Plastic strain
ε_x	Strain in the axial direction of a pipe
ε_y	Strain in the circumferential direction of a pipe
ε_z	Strain in the radial direction of a pipe
ε^{b}	Bending strain
ε^{m}	Membrane strain
γ_{xy}	Shear strain
Δ	Pipe ovality
$\Delta\varepsilon$	Cyclic strain range
θ	Angular position of a corrosion defect on pipe elbow
θ_{b}	Orientation of bending load
θ_{incl}	Inclination angle of corrosion defect relative to the axial direction of a pipeline
φ	Electrical potential
φ_{eq}	Equilibrium electrode potential
$\varphi_{a,eq}$	Equilibrium potential of anodic reaction
$\varphi^0_{a,eq}$	Standard equilibrium potential of anodic reaction
$\varphi_{c,eq}$	Equilibrium potential of cathodic reaction
$\varphi^0_{c,eq}$	Standard equilibrium potential of cathodic reaction
Φ	Axial routing angle of the pipe
μ	Chemical potential
μ_0	Chemical potential of solid in a standard state
$\mu_0{}'$	Standard chemical potential of solid considering the M-C interaction
$\Delta\mu$	Chemical potential difference
ΔP	Pressure difference
$\Delta\varphi^e_{a,eq}$	Change of electrochemical anodic equilibrium potential under an elastic stress
$\Delta\varphi^p_{a,eq}$	Change of electrochemical anodic equilibrium potential under a plastic stress
χ	Compressibility coefficient of solid
υ	An orientation-dependent factor
η_a	Anodic activation overpotential
η_c	Cathodic activation overpotential
ν	Poisson's ratio

1

Pipeline Integrity Management

1.1 Introduction

Pipelines provide an effective and efficient means to transport oil, natural gas, and petrochemical products across provinces, countries, and even continents, meeting continuously increasing energy demands. The oil and gas transmission pipelines around the world are up to 3,500,000 km, with about 32,000 km of new pipelines constructed each year [Hopkins, 2007]. The total length can be multiplied many times if gathering and distribution pipelines are included. The world's energy consumption is predicted to increase by 71% from 2003 to 2030, with fossil fuels continuing to supply much of the energy used worldwide [Department of Energy, 2006]. It is thus expected that pipeline construction and operation activities will continue growing. In recent years, with great efforts made to combat climate change and achieve the net-zero emission target globally, pipelines have been used for safe, economical, and highly efficient transportation of "green" energies and fuels such as hydrogen gas, hydrogen/natural gas blends, biofuels, and supercritical carbon dioxide (CO_2) [Ogden et al., 2018; Reuß et al., 2019; Cerniauskas et al., 2020]. The new energy pipelines are expected to experience rapid development in the next decade.

Energy transportation by pipelines is safe. Statistics showed that, in the United States, 1.7 fatalities to operators, personnel, and the public per year were caused by oil and gas pipeline accidents. As a comparison, transportation of oil and gas by rail and truck resulted in 2.4 and 10.2 fatalities per year, respectively [Hansen and Dursteler, 2017]. Pipeline transportation of hydrocarbon products was 4.5 times safer than rail on a like-for-like basis from analysis of the North American data [Green and Jackson, 2015].

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The integrity of pipelines can be adversely affected by many factors in the field, such as corrosion, stress corrosion cracking (SCC), fatigue, mechanical damage, stray current, materials and manufacturing faults, equipment and component failures, geotechnical factors, incorrect operation, and external interference such as excavation [Godin, 2014; Canadian Energy Pipeline Association, 2015]. Although occurring occasionally, pipeline failures can result in energy loss, environmental and ecological impact, and, sometimes, death [Cheng, 2016]. Thus, pipeline incidents usually attract wide attention from news media and the public. One of the most widely reported pipeline incidents is the rupture and release of Enbridge's oil pipeline in Marshall, Michigan, on July 25, 2010, which resulted in the largest inland oil spill and one of the costliest spills in US history [National Transportation Safety Board, 2012]. Following the spill, the volatile hydrocarbon diluents evaporated, leaving the heavier bitumen to sink in the water column. Thirty-five miles of the Kalamazoo River were closed for clean-up until June 2012.

Safety is the top priority for pipeline operators. The concept of Integrity First has been accepted by pipeline companies and become integral to corporation culture [Canadian Energy Pipeline Association, 2013]. In today's pipeline industry, an integrity management program has been developed and implemented to ensure the safety, reliability, and longevity of the pipeline system by mitigating and preventing pipeline failure, achieving the goal of zero pipeline incidents. Particularly, defect assessment is a critical component of a well-developed pipeline integrity management program. Development of models and methods for accurate and reliable assessment of various defects, such as corrosion, cracks, dents, and other anomalies, detected on pipelines is critical to determination of the pipeline fitness-for-service (FFS), prediction of failure pressure and estimation of the remaining service life of the pipelines [Qin and Cheng, 2021].

1.2 Overview of Threats to Pipeline Integrity

During long-term service of pipelines in the field, the integrity of the pipeline system can be compromised by multiple types of threats or their combinations. According to Canadian Energy Pipeline Association (CEPA), metal loss including corrosion, cracking, and external inference remains the leading cause of incidents occurring on CEPA member operators' oil/gas transmission pipelines [Canadian Energy Pipeline Association, 2021]. Collectively, these accounted for 82% of the total incidents over the period from 2016 to 2020, as seen in Figure 1.1. Other factors affecting the pipeline

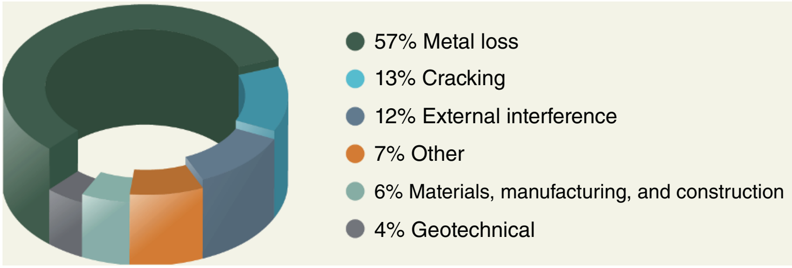

Figure 1.1 Causes of rights-of-way incidents 2016–2020 occurring on CEPA member operators' pipelines. *Source:* From Canadian Energy Pipeline Association [2021].

integrity included geohazards, external interference, and some unidentified reasons.

In the United States, the leading cause of accidents impacting people or the environment on liquid pipeline systems is corrosion according to the statistics of the Pipeline and Hazardous Materials Safety Administration (PHMSA). The second and third leading causes are equipment failure and material failure of pipe or weld, respectively. These three leading causes accounted for 65% of accidents since 2010 [Pipeline and Hazardous Materials Safety Administration, 2020]. Other factors included excavation damage, incorrect operation, natural force, and others. Similarly, the main causes resulting in onshore gas pipeline failures in the period of 2005–2020 included corrosion, equipment failure, material failure of pipe or weld, excavation damage, natural force, and others [Pipeline and Hazardous Materials Safety Administration, 2021]. Figures 1.2 and 1.3 show the statistical analysis of total number of accidents and their causes for PHMSA-regulated liquid and gas pipelines, respectively, in the United States [Pipeline and Hazardous Materials Safety Administration, 2020; 2021].

1.2.1 Corrosion

Corrosion has been recognized as one of the primary mechanisms causing pipeline failures in North America. As stated, corrosion, as the most important reason causing failures of transmission pipelines in Canada, was responsible for 46% of all reported failure incidents from 2015 to 2019 [Canadian Energy Pipeline Association, 2021]. In a comparative analysis of pipeline performance issued by the National Energy Board (NEB) in Canada, the primary cause of ruptures on NEB-regulated pipelines between 1991 and 2009 was corrosion-related cracking (38%) and metal loss (27%) [National

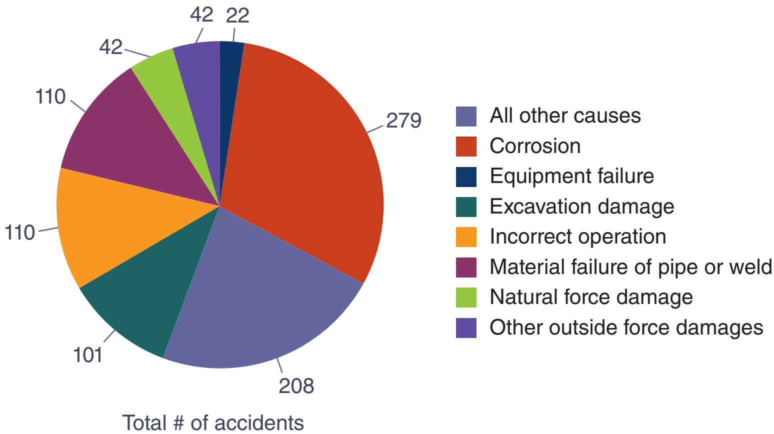

Figure 1.2 Statistical analysis of total number of accidents and their causes for PHMSA-regulated liquid pipelines in the United States from 2010 to 2019. *Source:* From Pipeline and Hazardous Materials Safety Administration [2020].

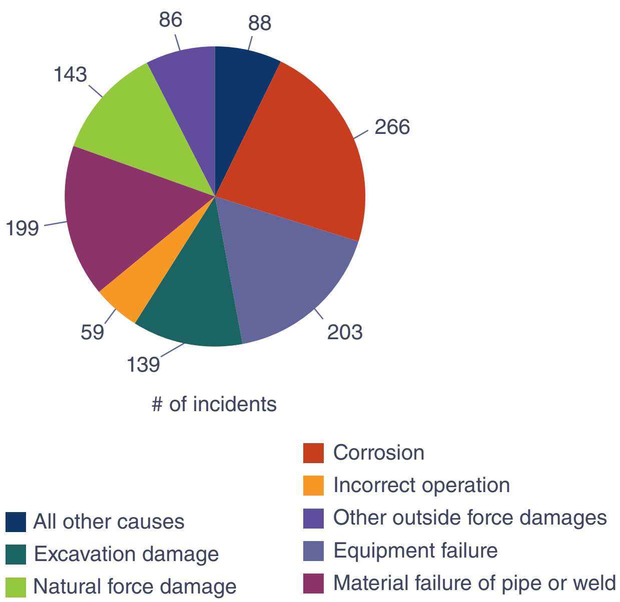

Figure 1.3 Statistical analysis of total number of accidents and their causes for PHMSA-regulated gas pipelines in the United States from 2005 to 2020. *Source:* From Pipeline and Hazardous Materials Safety Administration [2021].