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Pipeline Inspection and Health Monitoring Technology

The Key to Integrity Management

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Preface

The pipeline is a crucial lifeline project that can transport oil, gas, water, and other resources. It is often called the blood vessel of the energy system. Thus, pipeline engineering is essential in ensuring national energy security, promoting economic development, and ensuring social stability.

After many years of service, the pipeline gradually enters the aging stage. This will inevitably lead to accidents and serious economic losses. In addition, accidents in the city may lead to casualties, traffic paralysis, and other consequences. Using advanced technology to understand the health status of pipelines is a very challenging task in pipeline engineering.

In recent decades, many inspection and monitoring technologies have emerged worldwide to assess pipelines' conditions accurately. These technologies involve acoustics, optics, and electromagnetism. Not only that, in the context of big data and artificial intelligence, people use advanced computer and information techniques to cooperate with inspection and monitoring to solve the problems encountered.

This book deals with interdisciplinary knowledge. It can let readers know about the existing pipeline inspection and monitoring methods. This book is written for managers, technicians, and researchers engaged in pipeline safety and can also provide a reference for some graduate students engaged in relevant research. In this book, a reader who wants to understand the background and health status of global pipelines should read Chap. 1. In Chap. 2, pipeline inspection techniques are described in detail, including visual, electromagnetic, acoustic, optical, and chemical inspections, and the applicability of each method is indicated. Chapter 3 presents distributed fiber-optic and signal-based monitoring techniques for pipelines. In Chaps. 4 and 5, some artificial intelligence-based methods and data processing methods are presented. These contents mainly provide a reference for the post-processing part of inspection or monitoring. In addition, we set up Chapter 6. By providing several practical engineering cases, readers can have a more in-depth understanding of the application of related technologies.

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Contents

Chapter 1
Background and Health Problems of Pipelines

1.1 Introduction

Pipelines are essential lifeline projects and blood vessels for energy delivery. In the past, people paid attention to the construction of pipelines [1]. However, with the increase in pipeline accidents in recent years, an increasing number of managers have focused on the safety of pipelines [2]. Therefore, pipeline inspection and monitoring technology has received extensive attention [3]. This chapter introduces the construction and health status of the pipeline, leading to the current inspection and monitoring technology system.

1.2 Pipeline Classification and Construction Status

The pipeline is equipped with power devices (pumps, compressors), valves, and other accessories for conveying liquids and gases [4]. Its materials can be metallic and non-metallic, such as steel, concrete, and polyethylene [5]. Pipeline diameters can be as small as 5 cm and as large as 9 m, depending on the transport scale [6]. According to the transmission requirements, the pipeline can be pressure-free or as high as more than 10 MPa (such as oil and gas pipelines) [7].

Oil, gas, and water pipelines are the most common types of pipelines. Most pipelines are buried underground (some are laid overhead, see Fig. 1.1), so their essential contribution to the economy is often ignored. In fact, almost all the water transported from the treatment plant to the individual, the natural gas transported from the city gate station to the household, or the oil transported from the sea to the land refinery are transported through pipelines [8].

The pipeline is not the only way to transport oil, gas, and water. Especially for oil and gas resources, it is common to transport them by road, railway, and waterway [9]. Their advantages and disadvantages are shown in Fig. 1.2. Compared with trucks and railways, pipelines have always been the preferred transportation mode for liquid

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(a)

(b)

Fig. 1.1 Conventional pipe laying methods **a** buried method (the picture shows the excavation of buried pipelines); **b** overhead laying method

and gas due to its economic, safe, and reliable characteristics. Therefore, the use of pipelines is pervasive worldwide. As shown in Fig. 1.3, as of 2017, a total of 120 countries worldwide have built pipelines with a mileage of about 3.5 million km. Among them, the United States has 2,225,032 km, accounting for 64% of the total mileage in the world. Russia ranks second, with nearly 260,000 km of pipelines. China ranks fourth in pipeline mileage, about 87,000 km, and ranks first in Asia.

As of 2017, there are approximately 3800 transmission (long-distance) oil and gas pipelines worldwide, with a total length of approximately 1.95 million km [9, 11]. Global oil and gas pipelines are mainly distributed in Asia Pacific, Russia, Central

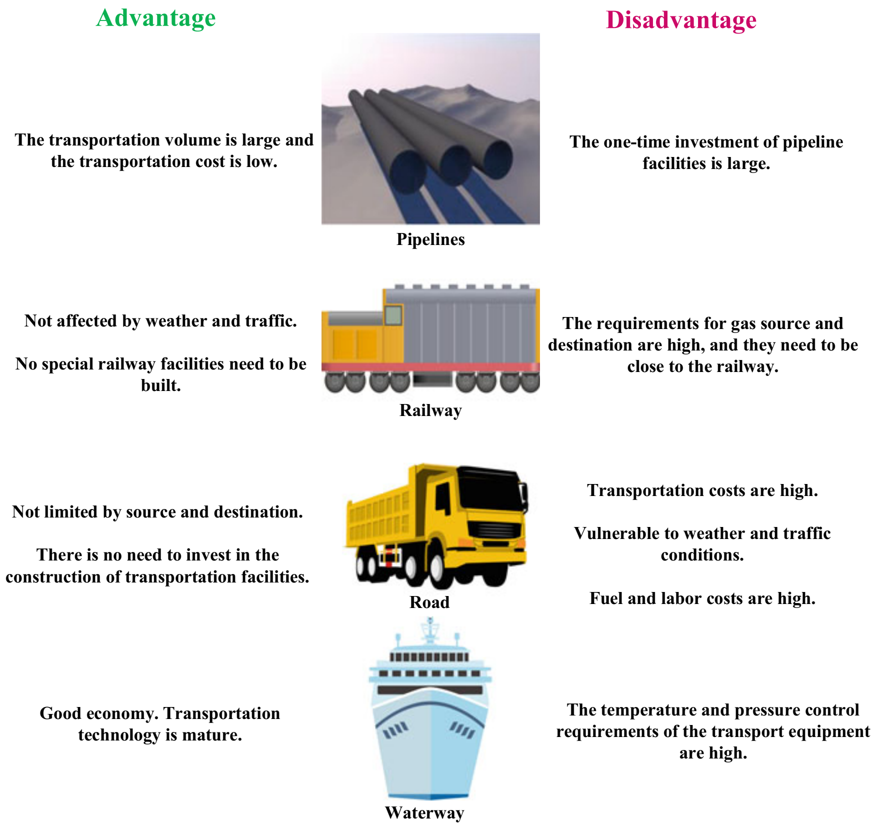

Fig. 1.2 Advantages and disadvantages of the four modes of transportation [10]

Asia, Europe, North America, Latin America, the Middle East, and Africa. As shown in Fig. 1.4, the total length of oil and gas pipelines in North America accounts for about 43% of the world [1].

Due to global oil and gas prices and economic recession, investment in oil and gas pipeline construction has declined since 2016, from 166 billion dollars in 2016 to 106 billion dollars in 2018 [11]. The new pipeline is mainly concentrated in gas and submarine pipelines, with the largest investment in North America and the Asia Pacific, followed by the Middle East and Latin America. For example, in the United States (as shown in Fig. 1.5), most of the gas pipeline construction was concentrated in the 1950s and 1960s, while oil pipeline construction was concentrated in the 1940s–1960s [12]. Table 1.1 lists large-scale oil and gas long-distance pipeline projects in recent years.

As shown in Fig. 1.6, from oil (gas) fields to users, oil and gas pipelines can be divided into gathering pipelines, transmission pipelines, and distribution pipelines

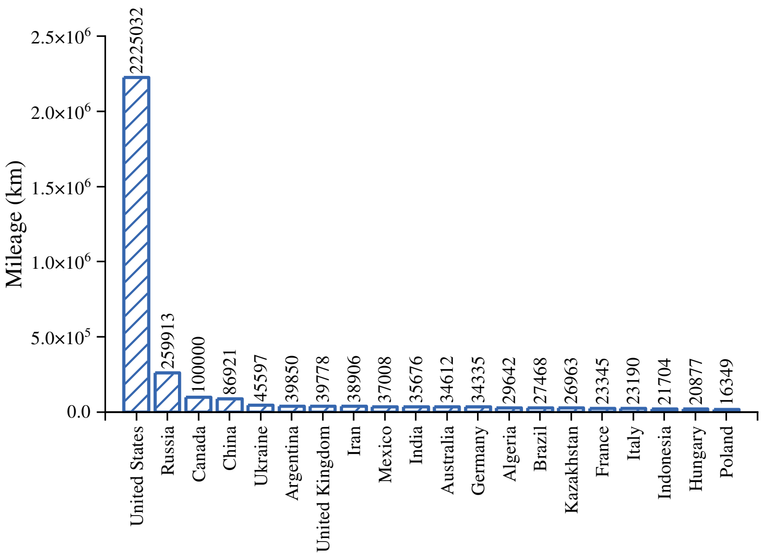

Fig. 1.3 20 countries with the longest pipeline mileage in the world. *Data source* https://www.worldatlas.com/articles/top-20-countries-by-length-of-pipeline.html

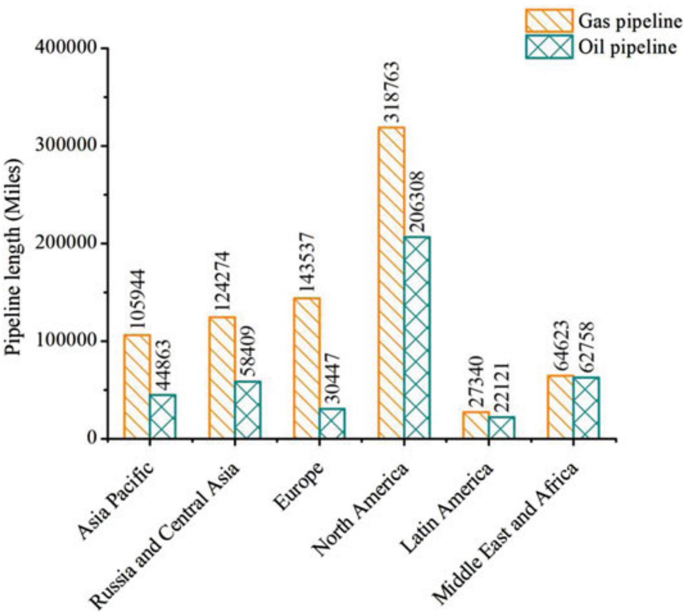

Fig. 1.4 Global transmission oil and gas pipeline length

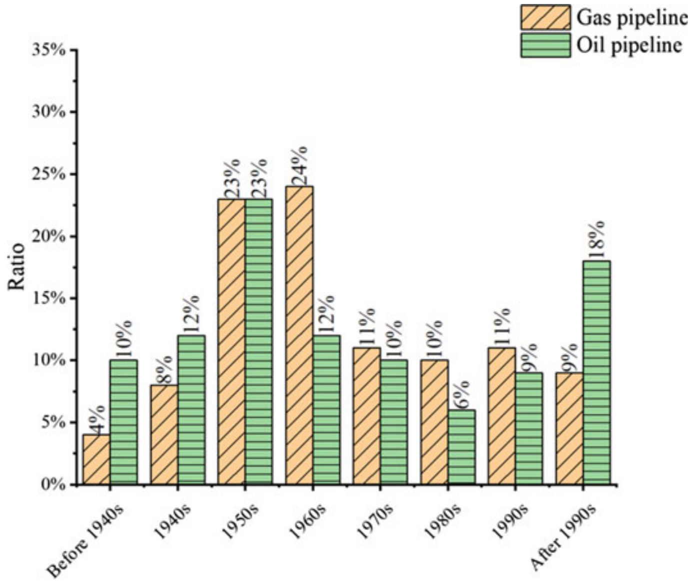

Fig. 1.5 Oil and gas pipelines built in different years in the United States

Table 1.1 Large oil and gas long-distance pipeline projects in recent years

Project	Medium	Length (km)	Diameter (mm)	Transport capacity
Central Asia–China gas pipeline	Gas	1833	1067	55 billion m^3/a
Nord Stream	Gas	1222	1220	55 billion m^3/a
Polarled gas pipeline	Gas	482	914	70 million m^3/d
TurkStream	Gas	930	813	31.5 billion m^3/a
Sino-Myanmar gas pipeline	Gas	793	1016	12 billion m^3/a
Sino-Myanmar crude oil pipeline	Crude oil	771	813	12 million t/a

(distribution pipelines are only applicable to the gas system) [13]. Their functions and features are shown in Table 1.2.

1.3 Pipeline Health Status Globally

During the long-run process, oil and gas pipelines will fail due to corrosion, weld defects, third-party damage, and other reasons [14]. Figures 1.7 and 1.8 show two conventional corrosion defects. Table 1.3 lists the major oil and gas pipeline accidents

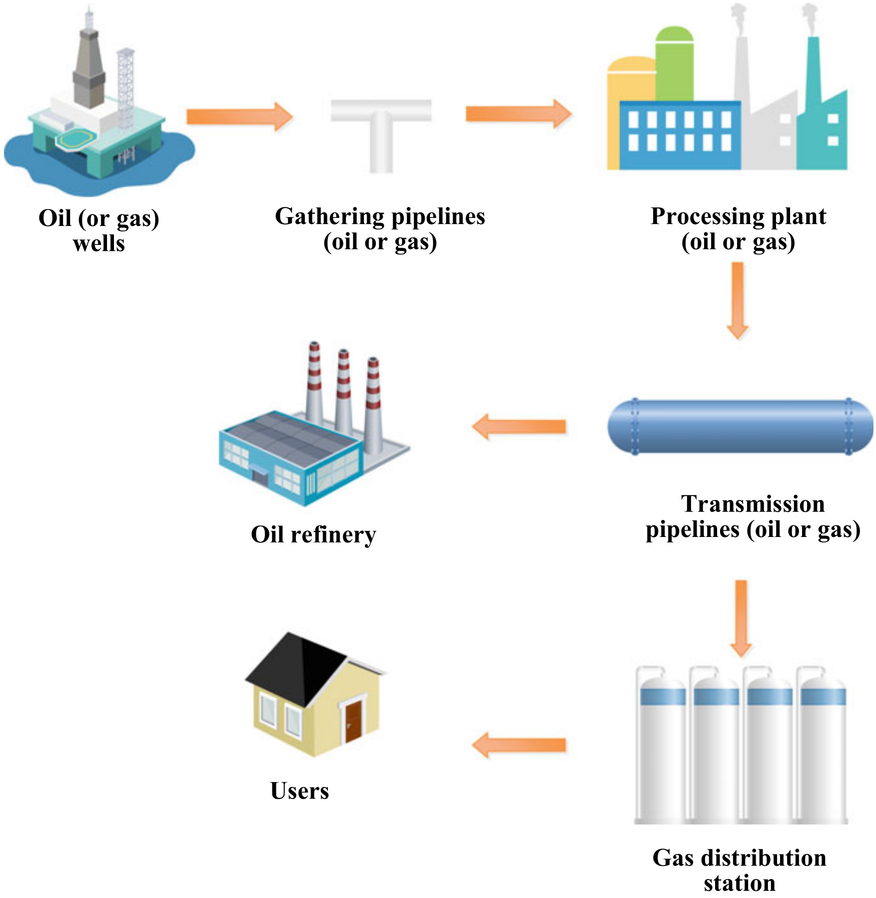

Fig. 1.6 Oil and gas systems

in the world in recent years. Many scholars have concluded that the failure modes of the gas pipeline are cracking and perforation, and the primary failure form of the oil pipeline is perforation. Tables 1.4 and 1.5 show the trend of failure rates of oil and gas pipelines based on the statistics of different countries or institutions [15–23].

In the United States, some pipeline accident statistics can be found in Pipeline and Hazardous Materials Safety Administration (PHMSA), as shown in Figs. 1.9 and 1.10. In general, the incident rate of gas pipelines showed a downward trend, and the peak period of accidents was from 2004 to 2009.

In the field of reliability, from the time of commissioning to scrapping, the failure probability usually follows the bathtub curve (Fig. 1.11). For oil and gas pipelines, the failure probability curve is divided into three stages: (1) Initial stage of pipeline production: due to design, construction, welding, and pipe material problems. The probability of accidents is high, the process usually lasts 0.5–2 years, and the number

Table 1.2 Characteristics of different types of pipes

Pipe type	Gathering	Transmission	Distribution
Function	Transport fluid from the wells to the processing plant or storage tank	Transport fluid over long distances across states, countries, and continents	Deliver gas to the user
Diameter (mm)	Under 450 for gas, 50–200 for crude oil	Usually 500–1200	Under 900 for main pipelines, less than 50 for service pipelines
Length (m)	Approximately 200	Up to thousands	–
Medium	Natural gas, crude oil, natural gas liquids	Natural gas, crude oil, natural gas liquids, and refined products	Natural gas
Pressure (MPa)	Under 5 for gas	1.5–8.5	Up to 1.5 for main pipelines, around 0.05 for service pipelines
Material	Steel	Steel	Steel, cast iron, plastic, and copper

Fig. 1.7 The old pipeline with external corrosion defects

Fig. 1.8 The old pipeline with corrosion perforation

of pipeline failures per 1000 km is about 5 times; (2) Stable operation stage of pipelines: mainly due to corrosion and third-party damage. The process usually lasts 15–20 years, and the number of pipeline failures per 1000 km is about 2 times; (3) Aging stage of pipelines: due to increased corrosion and wear. The probability of failure increases significantly, and the annual number of pipeline failures per 1000 km is usually greater than 2 times, so repairs at this stage are complicated [33].

From the perspective of accident cause, the European Gas pipeline Incident data Group's statistics [35] show that 25% of natural gas pipelines' failure is caused by corrosion, second only to external interference, as shown in Fig. 1.12. According to PHMSA (see Fig. 1.13), excavation damage is the leading cause of gas pipeline failure, followed by equipment failure. For oil pipelines, equipment failure is the primary cause of failure, followed by corrosion.

Oil and gas pipeline leakage is one of the common types of accidents and is also one of the leading causes of heavy losses. The leakage accident affects the regular pipeline operation and threatens the environment and personal safety. In many countries, the aging of pipelines is serious, and the condition of pipeline facilities is not optimistic. For example, according to the 2021 U.S. wastewater infrastructure condition assessed by the American Society of Civil Engineers (ASCE) (Fig. 1.14), although the data for some states are not available, it is not difficult to see that the

Table 1.3 Major accidents in oil and gas pipelines in recent years

Time	Location	Pipeline name	Loss	Cause
November 2013	Qingdao, Shandong, China	Donghuang oil pipeline [24]	62 people were killed and 136 were injured. The direct economic loss is 750 million Chinese Yuan (124.9 million U.S. dollars)	The oil pipeline leaked (because of corrosion) and exploded during the rush repairs
November 2017	Near Amherst, South Dakota, USA	Keystone crude oil pipeline [25]	9700 barrels of oil leaked	Construction damage
September 2011	Kenya	Nairobi pipeline [26]	About 100 people were killed in the fire, and at least 116 people were hospitalized for different degrees of burns	Pipe leakage
May 2014	Fort McMurray, Alberta, Canada	Northwestern Minnesota gas pipeline [27]	Estimated 16.5 million m^3 of gas were released	A bend is fractured
July 2014	Kaohsiung, Taiwan, China	Urban gas pipeline [28]	Several big explosions, 32 people were killed and 321 were injured	The pressure of the propylene pipe is abnormal

condition of wastewater infrastructure in most states (94.28% of the 35 states with a score) is C (mediocre, requires attention) or D (poor, at risk). The overall rating of wastewater facilities in the United States is D+. Looking back at the rating of C in 1988, it shows that the condition of the infrastructure has declined dramatically in about 30 years.

Inspection and monitoring of oil and gas pipelines are conducive to reducing carbon emissions and environmental pollution [36], and is also the key to pipeline integrity management [37, 38]. Currently, the inspection techniques for pipeline leaks are mainly for water pipelines, and most of them are based on the principle of acoustic inspection, such as SmartBall and Sahara [39]. Relative to the water pipelines, the particularity of oil and gas pipelines is mainly reflected in the following aspects [40]: (1) the pressure of oil and gas pipelines is much higher than that of water pipelines; (2) the medium in oil and gas pipelines has high risk.

Table 1.4 The trend of failure rates of oil pipelines based on statistical data

Country/Region	Institution	Statistical time range	Cause of failure (top three)	Failure rate trend	Reference
China	PetroChina Natural Gas & Pipeline Company	2006–2015	Third-party damage, manufacturing defects, construction quality	Descend	[29]
Canada	AER	1990–2012	Internal corrosion, third-party damage, external corrosion	Descend	[30]
United Kingdom	UKOPA	1962–2016	External corrosion, external interference, weld defects	Descend	[32]
United States	PHMSA	2004–2020	Corrosion, weld failure, third-party damage	Descend	[20]

AER Alberta Energy Regulator; *UKOPA* United Kingdom Onshore Pipeline Operators' Association; *PHMSA* Pipeline and Hazardous Materials Safety Administration

1.4 Pipeline Inspection Technology System

Different scholars have different classifications of inspection technologies. According to the degree of automation, inspection techniques can be divided into automatic, semi-automatic, and manual inspection [41]. According to the intuitive degree of inspection data, inspection technology can be divided into direct and indirect inspection [42, 43]. Moreover, some scholars have divided the inspection methods into optical and non-optical methods [44, 45]. The most common classification method is based on inspection technology characteristics and can be divided into hardware-based and software-based methods [46, 47]. Table 1.6 lists the system of pipeline inspection technology.

1.5 Technical System of Pipeline Health Monitoring

Unlike pipeline inspection, monitoring is a long-term process. It is an automatic system for condition monitoring, feature recognition, and condition evaluation to meet the needs of long-term service safety of pipelines, and to provide decision

Table 1.5 The trend of failure rates of gas pipelines based on statistical data

Country/Region	Institution	Statistical time range	Cause of failure (top three)	Failure rate trend	Reference
China	PetroChina Natural Gas & Pipeline Company	2006–2015	Third party damage, manufacturing defects, construction quality	Descend	[29]
Canada	AER	1990–2012	Internal corrosion, third party damage, external corrosion	Descend	[30]
Europe	EGIG	1970–2013	External interference, corrosion, construction defects/material failure	Descend	[31]
United Kingdom	UKOPA	1962–2016	External corrosion, external interference, weld defects	Descend	[32]
United States	PHMSA	2004–2020	Corrosion, weld failure, third party damage	Descend	[20]

EGIG European Gas Pipeline Incident Data Group

support for the management and maintenance of pipelines. Therefore, pipeline monitoring often requires sensing devices to collect data and employ models to build a system that provides decision-making. Pipeline health monitoring technologies can be distinguished by principle, as shown in Table 1.7.

1.6 Global Pipeline Inspection and Monitoring Standards and Specifications

In addition to developing techniques for detecting leakages in oil and gas pipelines, it is vital to establish relevant standards or specifications. According to the literature survey, the current common standards are shown in Table 1.8, totaling 20 standards. These standards come from the National Development and Reform Commission (China), American Petroleum Institute (API), American Society of Mechanical Engineers (ASME), International Organization for Standardization (ISO), Det

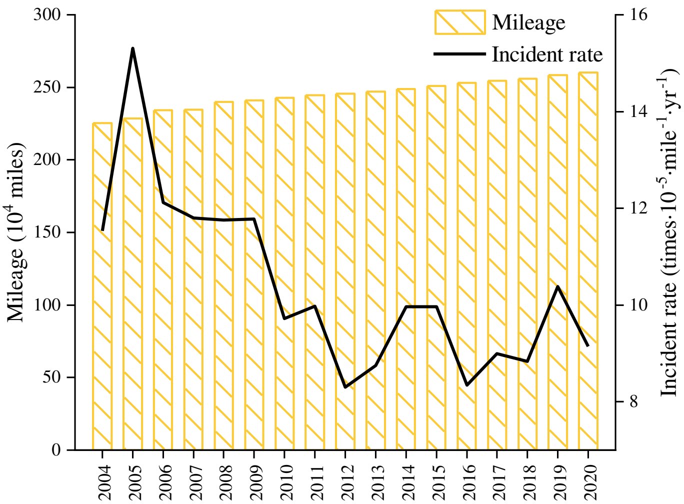

Fig. 1.9 Incident statistics of gas pipeline in the United States (gas pipeline safety events are called incidents according to 49 CFR 191.3)

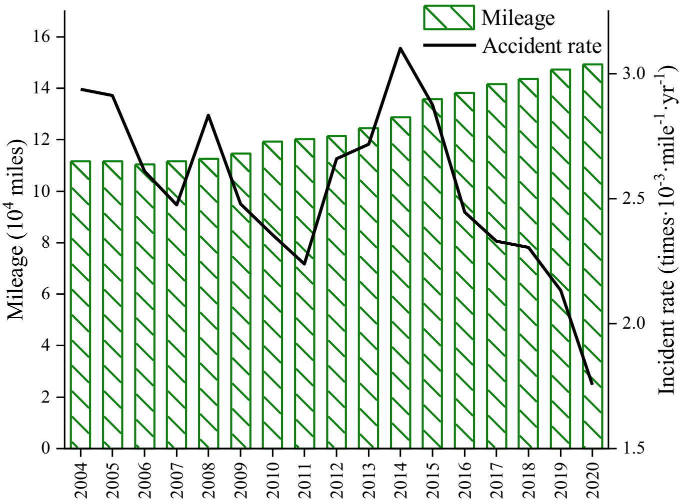

Fig. 1.10 Accident statistics of oil pipelines in the United States (oil pipeline safety events are called accidents according to 49 CFR 195.50)

Norske Veritas (DNV), and so on. These standards can be classified according to their primary functions: operating procedure (used to guide the operation and preparation requirements of inspection in the field), technical issues related (introduce the principle of related technology), and management related (requirements for inspection management). Based on these 20 standards, the statistic is made by the country (or

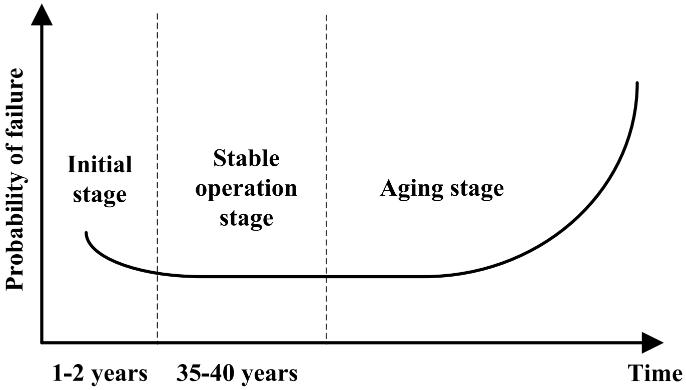

Fig. 1.11 Pipeline failure probability curve (bathtub curve) [34]

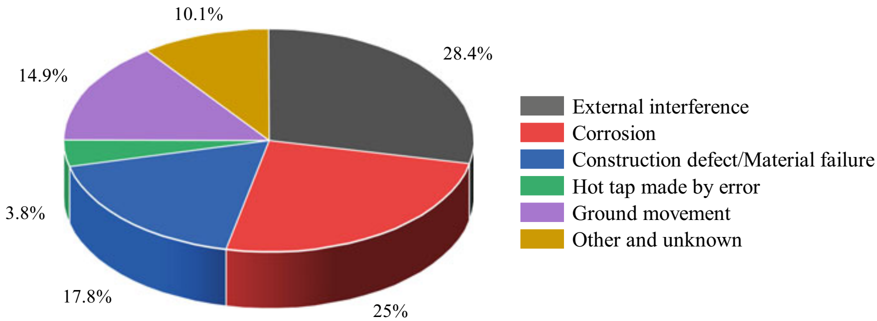

Fig. 1.12 Statistics of failure causes for natural gas pipelines (EGIG)

organization) that established the standard. It can be seen from Fig. 1.15 that most of the standards are issued by China and USA.

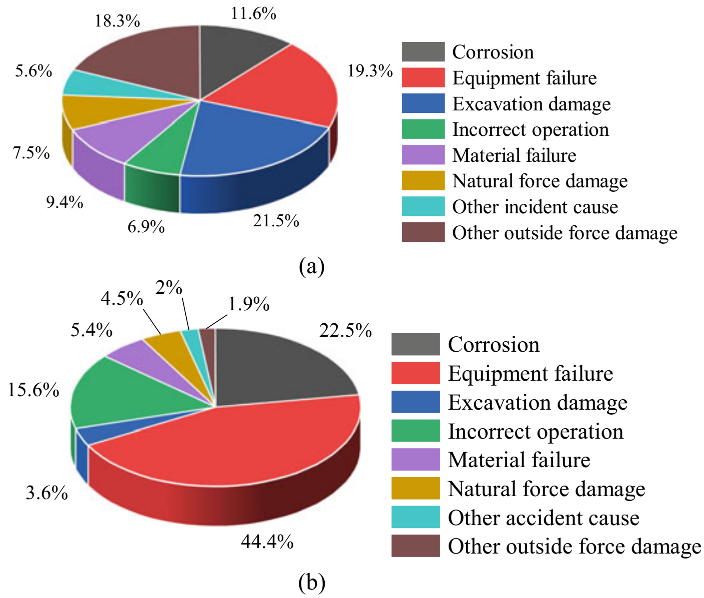

Fig. 1.13 Statistics of failure causes for oil and gas pipelines (PHMSA). **a** Natural gas pipelines; **b** oil pipelines

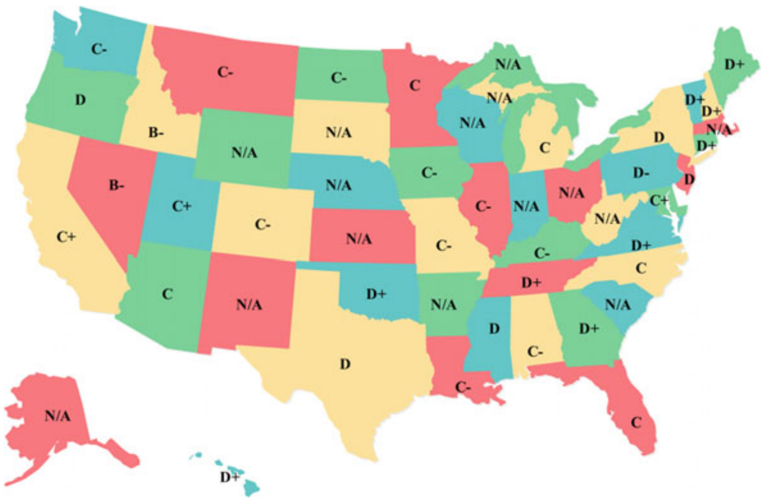

Fig. 1.14 The condition of wastewater infrastructure in the United States

Table 1.6 Classification of pipeline inspection technology

Classification of inspection techniques (by principle)	Inspection technique
Visual inspection technology	/
Electromagnetic inspection technology	Magnetic flux leakage
	Remote field eddy current
	Broadband electromagnetic
	Pulsed eddy current system
	Ground penetrating radar
Acoustic inspection technology	Acoustic emission method
	Ultrasonic method
	Ultrasonic guided wave method
	Echo impact
	Sonar system method
	Leakfinder
	Sahara
Optical inspection technology	Lidar system
	Diode laser absorption
	Thermal imaging
	Spectral imaging
Chemical component inspection technology	Sniffer method
	Vapor sampling method

Table 1.7 Classification of pipeline monitoring technology

Classification of inspection techniques (by principle)	Monitoring technique
Optical fiber sensing	Optical time domain reflection
	Fiber Bragg grating
	Interferometric optical fiber sensor
Signal-based method	Volume/mass balance method
	Negative pressure wave method
	GPS time tag method
	Pressure point analysis method
	Cross correlation analysis
	Transient test-based techniques
	State estimation method

Table 1.8 Related standards for pipeline inspection

Standard code	Name	Issuance department	Latest version
SY/T 4109 [48]	Nondestructive testing standard of oil and gas steel pipeline	National Development and Reform Commission (China)	2020
CJJ 181 [49]	Technical specification for inspection and evaluation of urban sewer	Housing and urban–rural development of the People's Republic of China	2012
DVGW G 465-4 [50]	Gas leak detection and gas measuring devices for supervision of gas pipeline systems	Deutscher Verein des Gas- und Wasserfaches	2001
CJJ 61 [51]	Technical specification for urban underground pipeline detection and survey	Housing and urban–rural development of the People's Republic of China	2017
API RP 1130 [52]	Computational pipeline monitoring for liquids	API	2007
GB/T 27699 [53]	Steel pipeline in-line inspection technical specification	Standardization Administration of the People's Republic of China	2011
API 1175 [54]	Pipeline leak detection program management	API	2015
T/CIRA 14 [55]	X-ray digital imaging inspection method for pipeline welds	China Isotope and Radiation Association (CIRA)	2020
API TR 1149 [56]	Pipeline variable uncertainties and their effects on leak detectability	API	2015
API PUBL 346 [57]	Results of range-finding testing of leak detection and leak location technologies for underground pipelines	API	1998
API PUBL 4716 [58]	Buried pressurized piping systems leak detection guide	API	2002
API RP 1175 [59]	Recommended practice for pipeline leak detection—program management, and companion guide bundle	API	2017

(continued)

Table 1.8 (continued)

Standard code	Name	Issuance department	Latest version
ISO 20486 [60]	Non-destructive testing—leak testing—calibration of reference leaks for gases	ISO	2017
ISO 20485 [61]	Non-destructive testing—leak testing—tracer gas method	ISO	2017
ISO 20484 [67]	Non-destructive testing—leak testing—vocabulary	ISO	2017
ISO 18081 [62]	Non-destructive testing—acoustic emission testing (AT)—leak detection by means of acoustic emission	ISO	2016
ASTM E432 [63]	Standard guide for selection of a leak testing method	ASTM	2017
ASTM E479 [64]	Standard guide for preparation of a leak testing specification	ASTM	2006
SY/T 6889 [65]	In-line inspection of pipelines	National Energy Administration (China)	2012
DNVGL-RP-F302 [66]	Offshore leak detection	DNV	2019

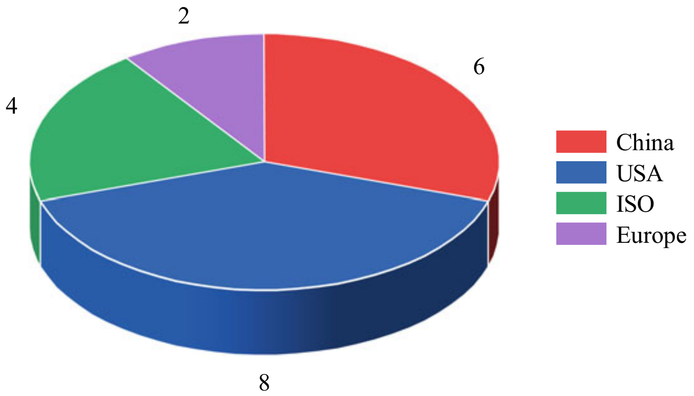

Fig. 1.15 Statistics of relevant standards for pipeline inspection released in different countries (or organizations)