Ships and Offshore Structures

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tsos20

Enhancing safety and resilience of ageing land-based LNG Tank structures through digital healthcare engineering: a feasibility assessment in seismic environments

Weixing Duan, P.J. Tan & Jeom Kee Paik

To cite this article: Weixing Duan, P.J. Tan & Jeom Kee Paik (19 Nov 2024): Enhancing safety and resilience of ageing land-based LNG Tank structures through digital healthcare engineering: a feasibility assessment in seismic environments, Ships and Offshore Structures, DOI: 10.1080/17445302.2024.2428229

To link to this article: https://doi.org/10.1080/17445302.2024.2428229

Published online: 19 Nov 2024.

SHIPS AND OFFSHORE STRUCTURES
https://doi.org/10.1080/17445302.2024.2428229

Taylor & Francis
Taylor & Francis Group

REVIEW ARTICLE

OPEN ACCESS Check for updates

Enhancing safety and resilience of ageing land-based LNG Tank structures through digital healthcare engineering: a feasibility assessment in seismic environments

Weixing Duan [a], P.J. Tan [a] and Jeom Kee Paik [a,b,c,d]

[a]Department of Mechanical Engineering, University College London, London, UK; [b]School of Maritime and Transportation, Ningbo University, Ningbo, People's Republic of China; [c]Yantai Research Institute, Harbin Engineering University, Yantai, People's Republic of China; [d]Hangzhou City University Binjiang Innovation Center, Hangzhou, People's Republic of China

ABSTRACT
Liquefied natural gas (LNG) is a critical energy source in modern times, with storage tanks strategically located in coastal regions for efficient sea transport. However, these vital infrastructures face dual threats: rare but severe natural disasters and age-related degradation. Such vulnerabilities can result in catastrophic events, including fires and explosions. To proactively address these challenges, digital healthcare engineering (DHE) provides a framework for continuous monitoring and maintenance. This paper offers a comprehensive review of key DHE technologies relevant to ageing land-based LNG storage tanks, with a particular focus on enhancing seismic resilience. Additionally, it presents a feasibility study on implementing a DHE system for a 160,000 m^3 LNG storage tank during seismic events, underscoring the importance of proactive safety measures against evolving environmental and operational risks.

ARTICLE HISTORY
Received 5 June 2024
Accepted 2 November 2024

KEYWORDS
Land-based LNG storage tank; Earthquake; Digital healthcare engineering; Digital twin; Soil–structure-fluid interaction

1. Introduction

In contrast to coal and oil, liquefied natural gas (LNG) stands out as a clean energy alternative, boasting an exceptionally high energy density. Upon regasification, 1 m^3 of LNG expands to approximately 600 m^3 of natural gas. Forecasts indicate robust growth in the LNG market, with its size projected to escalate from USD 74.60 billion in 2023 to USD 103.41 billion by 2028, representing a compound annual growth rate (CAGR) of 6.75% during the 2023–2028 period (Mordor Intelligence 2024). Recent analyses of the global energy landscape underscore the ascending trajectory of natural gas, poised to encompass nearly 30% of total energy demand by 2050, following a consistent upward trend (ExxonMobil 2023). This trend transcends geographical boundaries, positioning natural gas as an indispensable primary energy source across industrialised, newly industrialised, and developing nations alike (Rötzer 2019) (Figure 1).

Land-based LNG storage tanks serve as pivotal nodes in the global LNG supply chain, facilitating the seamless transition between production and consumption. However, their strategic placement in coastal regions and seismically active areas exposes them to a spectrum of hostile environmental conditions, including hurricanes, tsunamis, earthquakes, cryogenic temperatures, and challenging soil compositions. Compounding these challenges, the structural complexity and vulnerability of LNG storage tanks, such as intricate combined beam-plate-shell inner tank designs and oversized radius-thickness ratios, exacerbate their susceptibility to damage. The frigid temperatures associated with LNG storage induce embrittlement in the steel inner tank, rendering it susceptible to failure under sloshing and impact loads. Moreover, the cryogenic conditions precipitate structural steel's vulnerability to brittle fracture, presenting failure modes distinct from those observed at ambient temperatures (Paik et al. 2020a, 2020b).

Over the past few decades, seismic events have triggered a range of damages to both steel and concrete storage tanks, manifesting in phenomena such as elephant foot buckling, diamond-shaped buckling, joint fractures, roof-wall joint failures, floating roof sinking, complete roof rupture, tank drift, collapse, and foundation settlement (Akira and Clough 1982; Malhotra 2006; Sezen et al. 2008; Cruz and Valdivia 2011; Zama and Nishi 2012; Zareian et al. 2012; Brunesi et al. 2015; Fischer et al. 2016; Ulloa-Rojas et al. 2024). Additionally, accidents, including fires and explosions, stemming from LNG and vapour leakage, external explosions, buckling, and seismic activity, have been documented (see Figure 2), posing significant challenges to LNG terminals worldwide. Throughout their operational lifespan, land-based LNG storage tanks are susceptible to various forms of deterioration, including age-related issues such as corrosion, fatigue cracking, localised denting, and settlement, necessitating efficient and accurate monitoring and assessment of their health conditions (Paik 2020).

Recent discoveries have highlighted significant discrepancies between traditional seismic hazard analyses and real earthquake observations, with some recorded amplitudes surpassing those documented in extensive databases of shallow crustal earthquakes (Altindal and Askan 2024). These findings suggest potential dangers inherent in existing seismic design codes, potentially leading to overestimated safety margins. Consequently, it becomes imperative to reevaluate the safety levels of current LNG storage tank structures in light of these revelations. Fortunately, contemporary structural monitoring and inspection techniques, coupled with advancements in communication technologies, have become readily accessible. Now is the opportune moment to leverage these technologies to enhance the long-term health and integrity of ageing land-based LNG storage tanks through a more comprehensive and integrated approach.

CONTACT Weixing Duan weixing.duan.22@ucl.ac.uk Department of Mechanical Engineering, Roberts Engineering Building, Torrington Place, London, WC1E7JE, UK

Figure 1. Zhuhai LNG terminal, located in Guangdong Province, China (Zhuhai LNG terminal 2022). (This figure is available in colour online.)

China among other countries stands out as one of the foremost importers of LNG globally, with a significant concentration of LNG receiving, storage, and regasification facilities situated along its coastal regions. Data compiled from various sources, including the oil and gas industry (CNOOC 2023; CNPC 2023; PipeChina 2023; SINOPEC 2023), National and Provincial Energy Administrations (National Energy Administration 2023), relevant LNG companies (ENN Natural Gas Co. 2023), and official media outlets, have been aggregated into Table 1 and Figure 3. These resources provide a comprehensive snapshot of land-based LNG storage tank infrastructure across 28 LNG terminals in China, spanning the period from 1996 to 2026, encompassing existing, planned facilities and those currently under construction.

Significantly, the 160,000 m^3 LNG storage tank has emerged as the predominant choice in China over the past two decades. Prior to 2023, a total of 66 such tanks had been constructed in the country, despite plans to erect much larger tanks between 2023 and 2026. As of the conclusion of 2022, the maximum capacity for land-based LNG storage tanks in China stood at 220,000 m^3, with 10 tanks already in operation. Notably, construction is underway for 270,000 m^3 land-based LNG storage tanks in Qingdao, Yancheng, Ningbo, and Zhuhai, heralding their imminent status as the preferred choice in the foreseeable future.

Similar to human bodies, engineering structures require consistent and comprehensive care to ensure their longevity and operational safety, shown in Figure 4. In this study, the focus lies on ageing land-based LNG storage tanks, with a specific emphasis on the 160,000 m^3 full containment LNG storage tank selected as a representative example for the Digital Healthcare

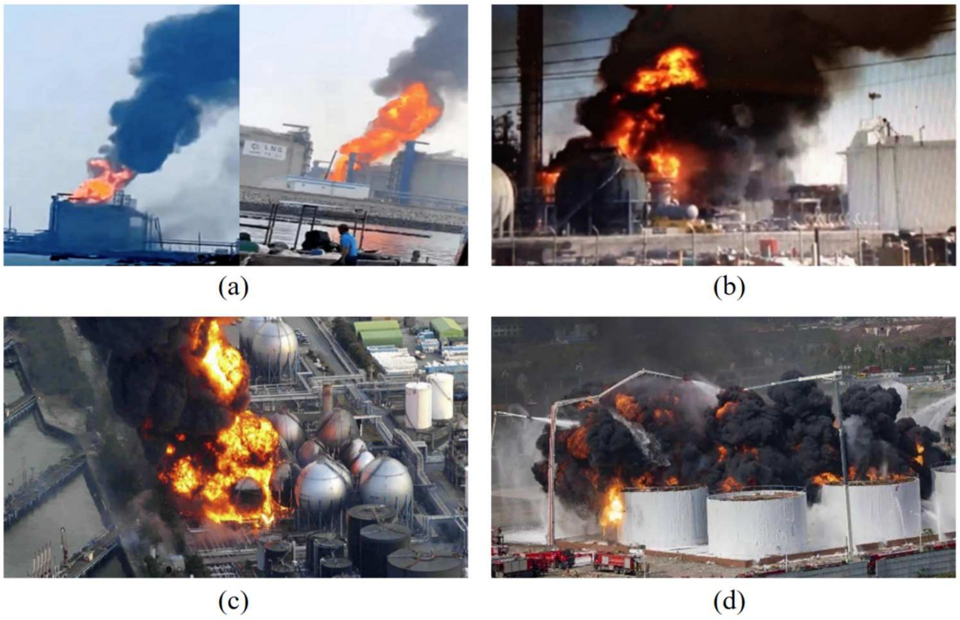

Figure 2. Accidents at LNG terminals worldwide. (a) LNG leakage induced explosion, 2020, Guangxi, China, (b) Tank fracture induced leakage and explosion, 1985, Alabama, USA, (c) Fire and explosion induced by earthquake, 2011, Fukushima, Japan, (d) LNG vapour leakage induced explosion, 1979, Maryland, USA. (This figure is available in colour online.)

Table 1. Overview of land-based LNG storage tanks in 28 LNG terminals across China.

Terminal	Location	Tank Capacity* Quantity	Operation Year
Dalian	Liaoning	160,000 × 3(2011)	2011
Tangshan	Hebei	160,000 × 4(2013) + 160,000 × 4(2021)	2013, 2021
CNOOC	Tianjin	30,000 × 2(2014) + 160,000 × 1(2018) + 220,000 × 6(2022)	2013, 2018, 2022
SINOPEC	Tianjin	160,000 × 4(2018) + 220,000 × 5(2023)	2018, 2023
Beijingranqi	Tianjin	200,000 × 4(2022) + 200,000 × 4(2023) + 200,000 × 2(2024)	2022, 2023, 2024
Qingdao	Shandong	160,000 × 4(2014) + 160,000 × 2(2021) + 270,000 × 1(2023)	2014, 2021, 2023
Rudong	Jiangsu	160,000 × 3(2011) + 200,000 × 1(2016) + 200,000 × 2(2020)	2011, 2016, 2020
Qidong	Jiangsu	50,000 × 2(2017) + 160,000 × 1(2018) + 160,000 × 1(2020) + 200,000 × 1(2022) + 200,000 × 1 (2023)	2017, 2018, 2020, 2022, 2023
Yancheng	Jiangsu	220,000 × 4(2022) + 270,000 × 6(2023) + 270,000 × 10(2025)	2022, 2023, 2025
Wuhaogou	Shanghai	20,000 × 1(1996) + 50,000 × 2(2008) + 100,000 × 2(2017)	1996, 2008, 2017
Yangshan	Shanghai	160,000 × 3(2009) + 200,000 × 2(2020)	2009, 2020
Zhoushan (Xinao)	Zhejiang	160,000 × 2(2018) + 160,000 × 2(2021) + 220,000 × 4(2026)	2018, 2021, 2026
Zhoushan (SINOPEC)	Zhejiang	220,000 × 4(2024)	2024
Zhoushan (ZHENENG)	Zhejiang	220,000 × 4(2024)	2024
Ningbo	Zhejiang	160,000 × 3(2012) + 160,000 × 3(2020) + 270,000 × 6(2026)	2012, 2020, 2026
Jiaxing	Zhejiang	100,000 × 2(2022)	2022
Putian	Fujian	160,000 × 4(2009) + 160,000 × 2(2019)	2008, 2019
Zhangzhou	Fujian	160,000 × 3(2023)	2023
Yuedong	Guangdong	160,000 × 3(2018) + 220,000 × 4(2026)	2018, 2026
Dapeng	Guangdong	160,000 × 2(2006) + 160,000 × 1(2007) + 160,000 × 1(2015)	2006, 2007, 2015
Diefu	Guangdong	160,000 × 4(2018)	2018
Jiufeng	Guangdong	80,000 × 2(2012)	2012
Zhuhai	Guangdong	160,000 × 3(2013) + 270,000 × 5(2024)	2013, 2024
Huizhou	Guangdong	200,000X3(2023)	2023
Beihai	Guangxi	160,000 × 4(2016) + 200,000 × 2(2024) + 220,000 × 4(2025)	2016, 2024, 2025
Fangchenggang	Guangxi	30,000 × 2(2018)	2018
Yangpu	Hainan	160,000 × 2(2014)	2014
Shennan	Hainan	20,000 × 2(2014)	2014

Engineering (DHE) introduced by Paik (2023, 2024). The DHE framework is recognised as a proactive approach to enhancing the safety and sustainability of ageing structures. The DHE system comprises five key modules: (1) on-site monitoring and measurement of health parameters, including environmental and operational conditions and in-service damages, (2) transmission of the measured data to a data analytics centre, (3) data analytics and simulations using digital twins, (4) AI-driven diagnosis and remedial recommendations, and (5) predictive health analysis for future maintenance planning. A feasibility study on the application of DHE to ships and offshore structures is detailed in (Sindi et al. 2024).

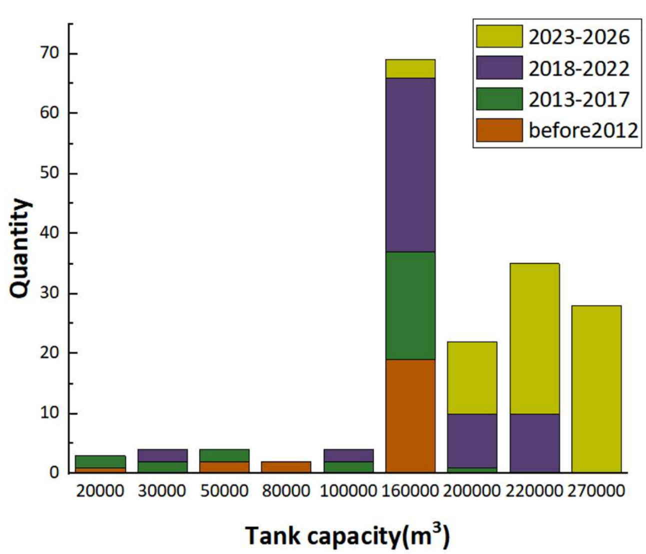

Figure 3. Capacity, quantity, and operational years of land-based LNG storage tanks in China. (This figure is available in colour online.)

Figure 5 illustrates the structural layout of a typical full containment land-based LNG storage tank. The tank features a cylindrical shape with a spherical dome and consists of a steel inner tank for storing LNG, encased by a pre-stressed reinforced concrete outer tank designed to prevent LNG leakage. The inner tank is constructed from 9% Ni steel plates of varying thickness along its vertical axis, with its bottom positioned approximately 800 mm above the top surface of the reinforced concrete base slab. An insulation layer, composed of perlite and resilient blanket materials, is placed between the inner and outer tanks. Additionally, a layer of ordinary concrete and perlite concrete is cast between the bottom of the inner tank and the base slab of the outer tank to support the inner tank and provide thermal insulation for the LNG. The insulated deck plate of the inner tank is suspended from the roof of the outer tank using numerous vertical steel hangers. The material properties of the main structural components of the LNG storage tank are detailed in Table 2.

As outlined in the pertinent standards BS-7777 (BSI 1993) and BS-EN-14620 (BSI 2006) governing land-based LNG storage tanks, the steel inner tank assumes the crucial role of the primary protective structural element. It is engineered to withstand significant air pressure, hydrostatic pressure, and cryogenic conditions during routine operation, while also being resilient to sloshing and hydrodynamic forces during seismic events or other abnormal circumstances. In contrast, the reinforced concrete outer tank serves as a secondary protective barrier, activated in the event of LNG vapour or liquid leakage from the inner tank. The arrangement of its walls and basement is detailed in Figure 6.

Given the criticality of ageing land-based LNG storage tanks situated in coastal and seismically active regions, there is a pressing need to meticulously monitor and assess their health conditions with precision. This entails comprehensive consideration of various factors including capacity, construction materials, site conditions, ageing conditions, and hazard levels.

Figure 4. Lifetime healthcare processes for human bodies and engineering structures (Paik 2022). (This figure is available in colour online.)

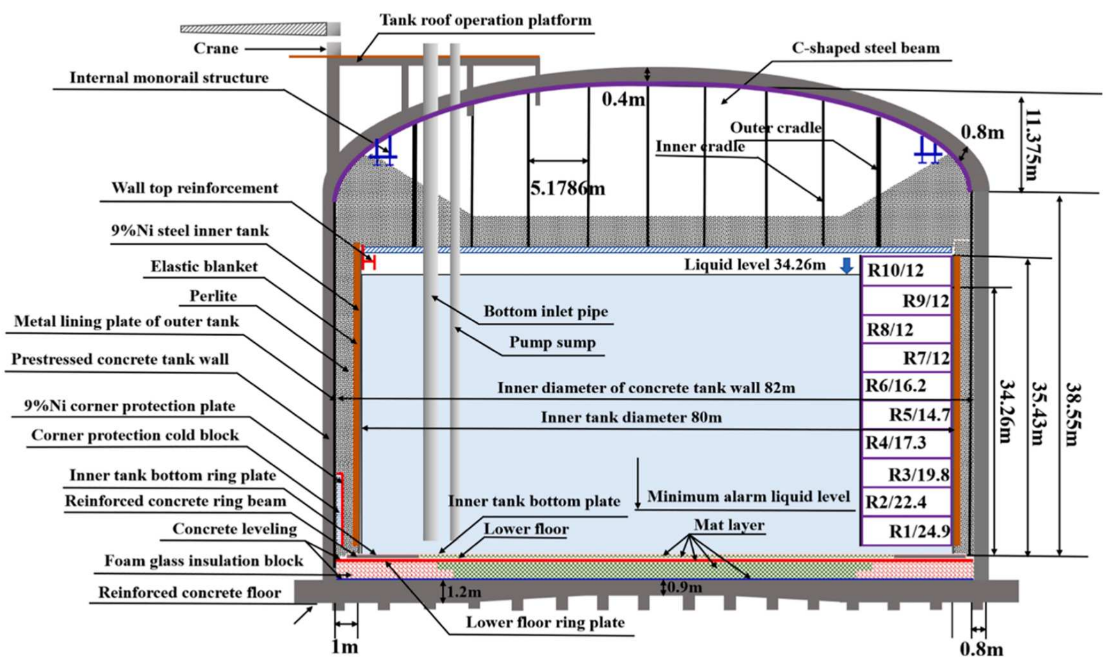

Figure 5. Structural diagram of a typical full containment land-based LNG storage tank (Luo et al. 2022). (This figure is available in colour online.)

The primary objective of this study is to conduct a thorough review of the essential tasks involved in developing a Digital Healthcare Engineering (DHE) system tailored for ageing land-based LNG storage tank structures, particularly in earthquake-prone areas. Furthermore, the study aims to delineate the existing technological gaps in comparison with the requirements of DHE implementation and propose a pragmatic methodology to bridge these gaps effectively. Through this comprehensive approach, the study seeks to enhance the resilience, safety, and longevity of land-based LNG storage tanks, ensuring their continued operational viability in challenging environmental contexts.

Table 2. Material properties of key structural components in land-based LNG storage tanks (Luo et al. 2022).

Structural member	Material	Parameter	Value
Inner tank	Steel containing 9% Ni	Density/kg·m^{-3}	7850
		Elastic modulus/N·m^{-2}	2.06×10^{11}
		Poisson's ratio	0.3
Outer tank	Prestressed concrete	Density/kg·m^{-3}	2500
		Elastic modulus/N·m^{-2}	3.45×10^{10}
		Poisson's ratio	0.17
Liquid	LNG	Density/kg.m^{-3}	480
		Bulk modulus/N·m^{-2}	2.56×10^{8}
Insulation	Perlite	Poisson's ratio/N·m^{-2}	1.2×10^{7}
		Poisson's ratio	0.33

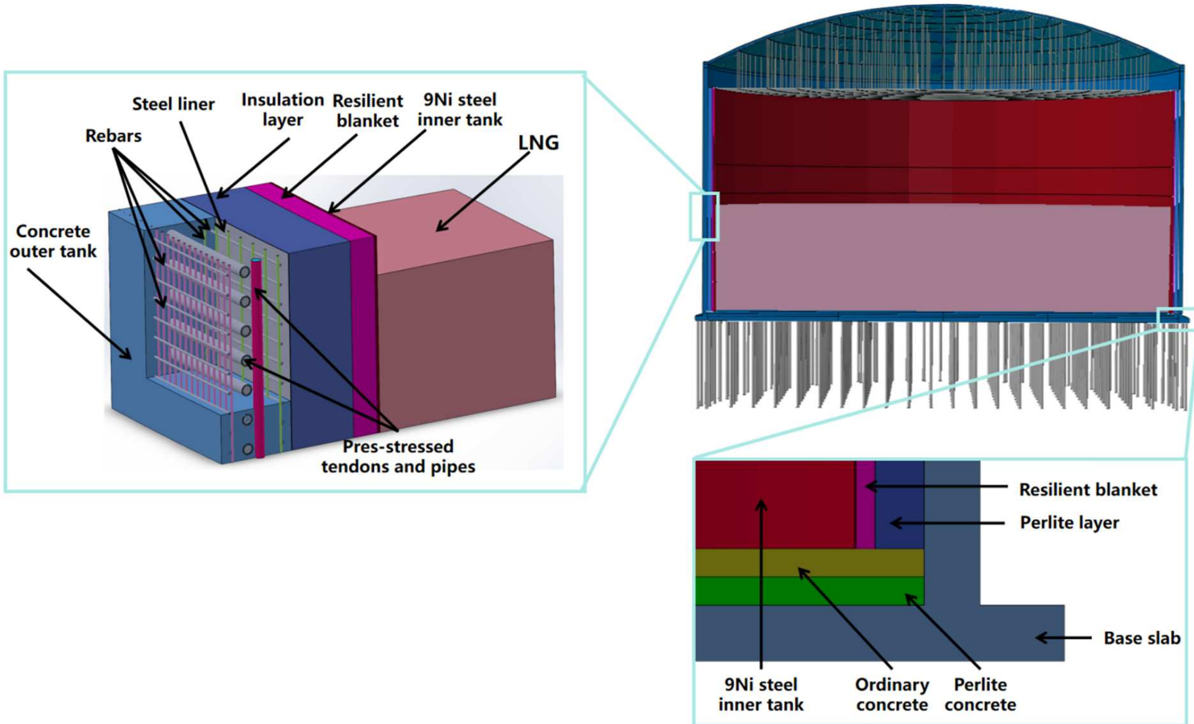

Figure 6. Wall and basement arrangement of a typical full containment land-based LNG storage tank. (This figure is available in colour online.)

2. State-of-the-art review

2.1. Digital healthcare engineering for structural lifecycles

In contemporary engineering practices, digital healthcare engineering has become pivotal in ensuring the prolonged wellbeing of both human bodies and various structural entities, including ageing structures and infrastructures. This is made possible through the utilisation of communication and digital technologies, often manifested in the form of digital twins. These digital twins serve as data-driven systems, meticulously mirroring the real-time characteristics and properties of physical systems within immersive digital environments, often referred to as the metaverse (Sindi et al. 2024). Figure 7 illustrates a digital twin-based process for the lifetime healthcare management of ships and offshore installations, as pioneered by Paik (2022, 2023, 2024), and it was further applied for ageing ships as shown in Figure 8 (Paik 2024). Notably, while significant strides have been made in digital healthcare engineering for maritime structures, similar advancements for land-based structures and infrastructures remain relatively underdeveloped.

Building Information Modelling (BIM), as defined by the U.S. National Building Information Model Standard Project Committee, serves as a digital portrayal of both the physical and functional attributes of a facility. It constitutes a shared knowledge resource, offering comprehensive information about a structure throughout its entire lifecycle, spanning from conception to demolition (Costin et al. 2018). Over the past few decades, BIM technology has become a cornerstone in the building industry, facilitating various stages including planning, design, construction, and management. While its application in the building sector is well-established, its utilisation in infrastructure projects (Chen and Shirolé 2006; Hammad et al. 2006; Shirole et al. 2009; BIEŃ 2011; Okasha and Frangopol 2011; Mawlana et al. 2015) has emerged as a powerful tool, providing an extensive visual database that can be leveraged across the infrastructure's lifecycle.

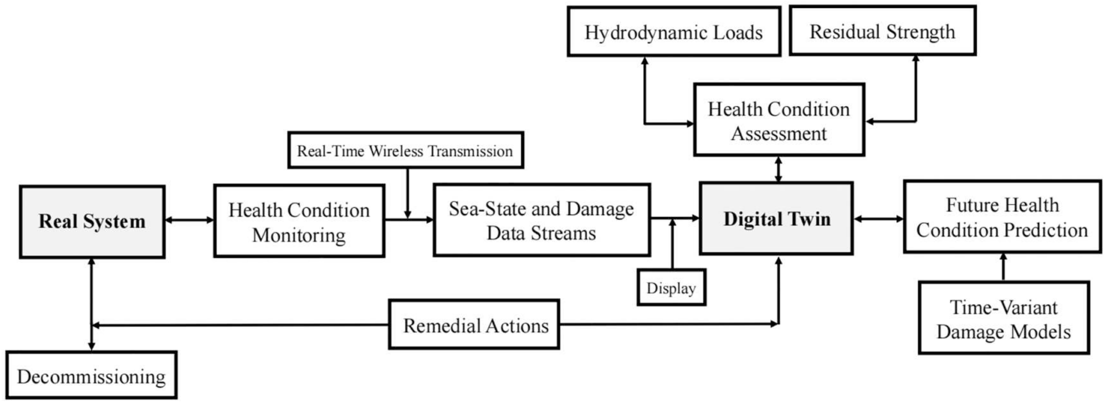

Figure 7. Digital twin system-based process for lifetime healthcare of ageing engineering structures (Paik 2022). (This figure is available in colour online.)

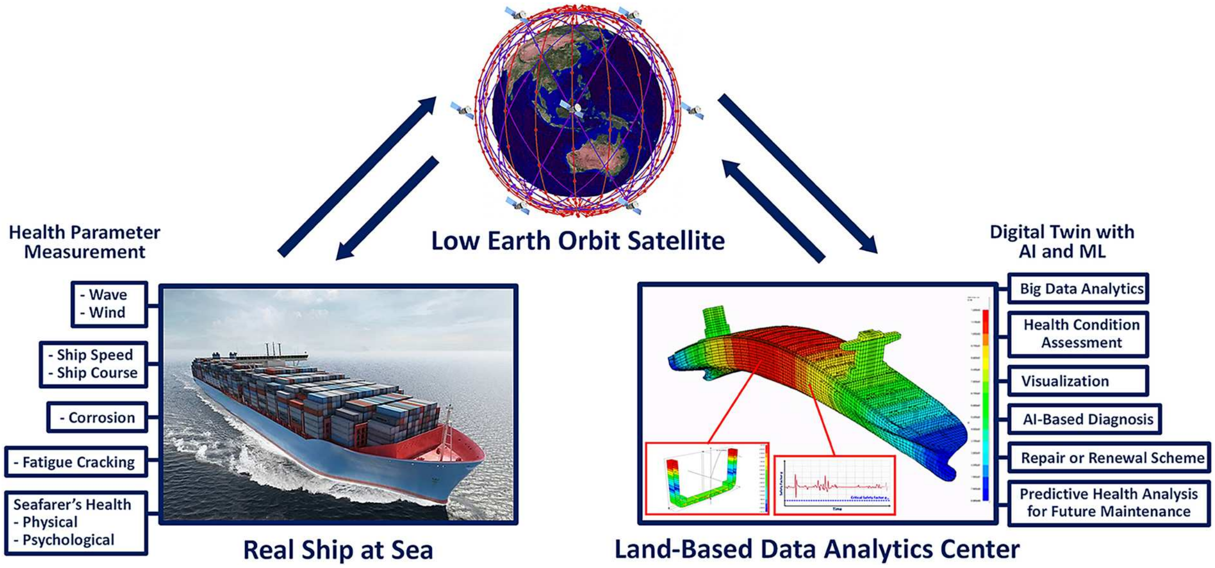

Figure 8. A prototype digital healthcare engineering system for ageing ships (Paik 2024). (This figure is available in colour online.)

In essence, BIM models serve as repositories for vast amounts of information during design and construction phases, offering easy visualisation and integration capabilities that prove invaluable for future operation and management. Moreover, the scope of BIM application extends beyond mere visual representation of schedules and resource requirements. Recent years have witnessed endeavours to integrate BIM with a myriad of other technologies, including unmanned systems and robotics, sensing technology and sensors, cloud computing and mobile services, augmented and virtual reality, as well as global positioning systems and geographic information systems (Costin et al. 2018). These integrations have propelled infrastructure managers and governmental bodies towards automated operations, enhancing precision, quality, safety, and overall efficiency throughout the infrastructure's lifecycle (Table 3).

Digital Twin (DT) is a virtual system widely employed to mirror the real-time characteristics and properties of physical systems (Semeraro et al. 2021; Tao et al. 2022; X. Liu et al. 2023). The concept was initially proposed by Grieves (Grieves and Vickers 2017) in 2003 for product lifecycle management (PLM) and has since found rapid application across diverse industries such as manufacturing, aviation, aerospace, agriculture, mining, smart cities, structures, infrastructures, and beyond. Owing to its versatility and broad applicability, the definition and key characteristics of digital twins may vary (Callcut et al. 2021; C. Liu et al. 2023).

In the realm of structures and infrastructures (Zhou et al. 2022; Honghong et al. 2023; Jeon et al. 2024), various techniques such as finite element modelling (FEM), IoT-based data-driven approaches, laser scanning, and UAV-based 3D reconstruction modelling are utilised to construct digital twin models. Additionally, camera and sensor-based structural health monitoring, IoT, and wireless sensor networks (WSN) are employed to gather data from the physical system. Subsequently, cloud computing, big data analytics, and AI-based technologies are leveraged to analyze the collected data, enabling real-time interaction with the physical system and providing continuous monitoring, assessment, and decision-making support.

To sum up, this section has examined the utilisation of advanced digital technologies for the healthcare and analysis of structures and infrastructures throughout their lifecycle. In summary, Building Information Modelling (BIM) technology predominantly concentrates on the early stages of the structure lifecycle, serving as a valuable tool for data management, visualisation, and utilisation. Its functionality can vary significantly depending on the integration of different techniques. On the other hand, DTs find widespread application in the operational, management, and maintenance

Table 3. Comparison of digital technologies for lifecycle healthcare and structural analysis

Digital Tech	Tagert structure	Application stage	Integrated key techniques	Limitation	Main functions
BIM	Mainly new structure and structure under construction	Life cycle but mainly on early stage such as Planning, Design, Construction, Management	CAD, 3D modelling and visualisation, AR and VR, GIS and GPS	Mainly focusing on geometric model instead of physical model	Data management, visualisation and utilisation
Digital Twin	Mainly structure in operation	Whole life cycle but mainly on middle stage such as Operation, Management, Maintenance,	Camera and sensor-based operation monitoring, SHM, IoT, Wireless sensor network, Visualisation, FEM	Although focus on operation, ageing condition were ignored	Visualisation and real-time interaction, Real-time monitoring, assessment, and management, Providing suggestion for maintenance
DHE	Mainly ageing structure and human bodies	Later stage of life cycle such as operation, Management, Maintenance, Life extension, Decommission	Structural monitoring and inspection techniques, Data transmission, CFD and FEM, Advanced structural safety study, AI-based diagnosis	Accurate on-site measurement is needed for analysis, Computational costly	Health monitoring, Health condition assessment, Real-time characteristics, Risk assessment, management, and prediction, Renewal and remedial actions, Visualisation and real-time interaction

phases of the structure lifecycle. They facilitate real-time monitoring of structural behaviour, assessment, and fault diagnosis, thereby offering actionable suggestions for maintenance interventions.

Significantly, there's a discernible trend towards the integration of advanced techniques such as sensor-based structural health monitoring (SHM), unmanned robotics, Internet of Things (IoT), wireless sensor networks (WSN), cloud computing, augmented reality (AR), virtual reality (VR), GPS, GIS, big data analytics, and AI-based technologies within digital frameworks. Both Building Information Modelling (BIM) and DTs have been introduced to structures and infrastructures, including bridges and highways. Through the incorporation of these advanced techniques, BIM models and Digital Twins now provide enhanced options for structural lifecycle healthcare and analysis.

Research on the application of BIM and DT for land-based LNG storage tanks remains notably limited (Y. Wu et al. 2023). Furthermore, the monitoring, inspection, and prompt assessment of extreme environmental conditions and in-service damages of structures have been lacking. Consequently, structural health condition assessment and prediction have not been thoroughly investigated within BIM and DT models. Additionally, there has been a notable oversight in focusing on the ageing conditions of structures in both BIM and DT frameworks, although some DT systems do address abnormal phenomena such as unusual noise, vibration, and deflection based on sensor data. Nonetheless, the implementation of digital healthcare engineering systems holds promise in bridging this gap.

2.2. Advanced structural monitoring and inspection

Land-based structures and infrastructures, including bridges, dams, roads, tunnels, as well as oil, gas, and nuclear facilities, require continuous or periodic monitoring of health parameters such as vibration, temperature, corrosion, cracking, and deformation to ensure safe operation throughout their lifecycle. Advanced structural monitoring and inspection techniques have emerged to provide accurate and efficient measurements for this purpose. This section presents a review of on-site measurement methods for health parameters, with the goal of identifying feasible advanced methods and devices for integration into DHE systems.

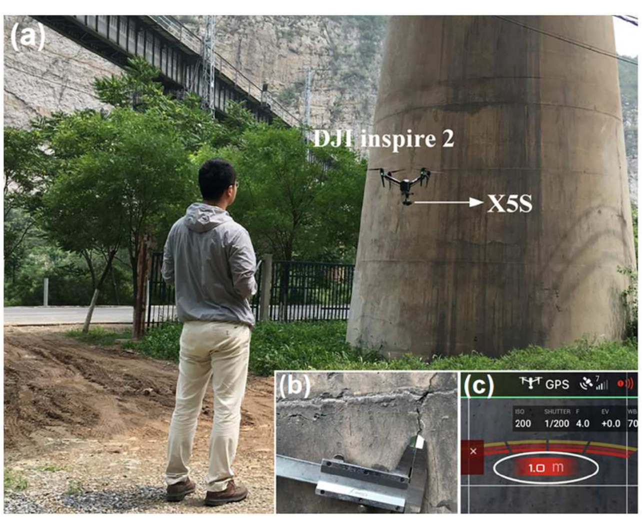

Figure 9. Image-based visual inspection for bridges assisted by UAV (a) UAV operation, (b) measurement, (c) radar map (Liu et al. 2020). (This figure is available in colour online.)

2.2.1. UAV-assisted visual inspection

Traditionally, visual inspection of large-scale engineering structures is fraught with challenges such as high costs, low efficiency, limited detection capabilities, and risks to surveyors. However, the emergence of unmanned aerial vehicles (UAVs) has revolutionised visual inspection methods. UAV-assisted image-based visual inspection offers a novel approach, leveraging 3D Lidar for navigation and mapping, along with high-precision cameras for data collection (see Figure 9).

With extensive research and rapid advancements in digital image processing, deep learning, three-dimensional reconstruction, and simultaneous localisation and mapping (SLAM) technology (Huang et al. 2018; Ma and Liu 2018; Thériault et al. 2022; Colvalkar et al. 2023), image-based visual inspection methods have gained popularity, especially with the assistance of UAVs and other unmanned vehicles (Fan and Liu 2022). This method is applicable to both steel and concrete structures for detecting surface damages such as cracking, spalling, and delamination, as well as identifying other unusual phenomena. Furthermore, the 3D models of target structures enable easy representation of the size, direction, area, and location of detected damage.

2.2.2. Non-destructive testing (NDT)

Non-Destructive Testing (NDT) methods are increasingly employed for the examination of structures and infrastructures, allowing for the determination of structural properties and evaluation of structure members without causing damage. In the case of steel structures, NDT is utilised to detect in-service damage, including corrosion wastage, cracking, and local denting (Paik 2020). Corrosion wastage is primarily assessed by examining parameters such as reduction in wall thickness due to general corrosion or maximum pit depth, pit intensity (expressed as a percentage of the plate surface), and average remaining thickness. Cracking damage is evaluated based on its direction, size, and location. Local denting is inspected with regard to its shape, depth, and size.

The following methods are available for this purpose:

- Visual or close-up detection
- Digital imaging
- Leak or pressure testing
- Ultrasonic testing
- Acoustic emission or natural frequency measuring
- Thermal imaging
- Electromagnetic field techniques
- Magnetic particle inspection
- Chemical sensing
- X-ray
- Eddy Current

In the case of concrete structures, NDT methods are employed to detect in-service damage such as cracking, voids, and concrete spalling. Cracking is assessed based on parameters including width, depth, direction, and location. Void damage is evaluated in terms of depth, location, and size. Concrete spalling damage is inspected to determine thickness reduction, shape, and location. The 'Report on Nondestructive Test Methods for Evaluation of Concrete in Structures' (ACI 2013), issued by the American Concrete Institute (ACI), summarises NDT methods, providing essential and detailed information for assessing the structural performance of concrete.

The following NDT methods are deemed feasible for on-site measurement of in-service damage in existing concrete structures:

- Ultrasonic through transmission (pulse velocity)

- Ultrasonic-echo
- Impact-echo
- Impulse-response
- Sonic-echo
- Impulse-response (mobility) method
- Direct transmission radiometry

It is important to acknowledge the rapid development in NDT methods, with new technologies continually emerging. Different levels of devices may offer varying functions for measuring and displaying in-service damages. Take ultrasonic testing, for example, which stands as the most popular and widely used NDT method due to its ability to generate and receive ultrasonic waves, thereby providing amplitude-time curves for defect analysis. While basic ultrasonic devices utilise A-scan (point measurement) to determine the thickness of steel plates or locate cracks, advanced ultrasonic flaw detectors can offer B-scan (cross-section view) or C-scan (plan view) capabilities to detect cracking size, location, and direction within the steel plate.

When choosing on-site measurement techniques for ageing land-based structures, three factors must be considered. Firstly, the NDT method should be readily commercially available, and with affordable price. Secondly, the selected device should be portable, as testing needs to be conducted on-site rather than in a laboratory setting. Thirdly, and most importantly, it's crucial to determine what kind of damage data the selected technique can measure. For instance, some techniques may only detect the presence of cracking, while others can assess cracking direction, size, and location. Also, the accuracy or quality of NDT measurement results should be considered when selecting inspection techniques. Related studies(Bato et al. 2020; Payão Filho et al. 2022) on probability of detection of NDT method could be used to improve reliability of measurement.

2.3 Seismic response analysis with digital twin

2.3.1. Methodologies

- Push-over analysis: This method, a nonlinear static approach, assesses the performance of structures by subjecting them to a monotonically increasing lateral load to compute the effects of seismic loads. Typically, it assumes that seismic loads are induced by the horizontal component of ground motion, disregarding the vertical component.
- Multi-mode response spectra analysis: This method proves highly effective in examining the response of complex linear elastic structures to earthquake excitations, particularly suitable for structures with irregular geometries, masses, or stiffnesses. The comprehensive response can be approximated through mode combination following calculations of natural frequencies and mode shapes via free vibration analysis. However, a critical assumption is that all supports (piles) experience identical ground motion, disregarding soil-structure interaction. Additionally, this method may lose validity when accounting for the inelastic response of structures under substantial ground motion.
- Time-history analysis: In situations where structures transition into the nonlinear range, modal analysis and response spectra analysis become impractical. The time-history method involves numerical step-by-step integration of equations of motion and had found widespread application in both linear and nonlinear analyses of engineering structures. It offers a more precise and realistic assessment of structural behaviour compared to elastic analysis.

All three seismic analysis methods are extensively employed in the assessment of structures and infrastructures(Gioncu and Mazzolani 2010; Chen and Duan 2014), including liquid storage tanks (Sobhan et al. 2017; Zhao et al. 2020a, 2020b; Luo et al. 2021, 2022). However, the nonlinear time history method stands out as the most prevalent approach for simulating the nonlinear behaviour of liquid storage tanks.

2.3.2. Dynamic responses to seismic loads

In recent years, numerous studies have explored the seismic analysis of liquid storage tanks through theoretical, experimental, and numerical investigations. These studies aim to understand the influence of factors such as height-to-diameter ratio (H/D), tank wall flexibility, liquid volume, seismic wave direction and period, on the dynamic response of tank structures.

Regarding the theoretical analysis of liquid-tank interaction for vertical liquid storage tanks subjected to horizontal seismic excitation, a simplified mechanical model was initially introduced by Jacobsen and Housner (Jacobsen 1949; Housner 1957). This model considered the liquid through convective and impulsive components for rigid wall-liquid interaction to calculate the base shear and overturning moment induced by earthquakes. Subsequently, the model was refined to accommodate flexible walls, foundations, soil effects, double wall tanks, and other applications (Peek and Jennings 1988; Veletsos and Tang 1990; Malhotra et al. 2000; Shekari et al. 2010; Vathi and Karamanos 2012; Luo et al. 2021).

While efforts have been made to simplify liquid-tank interactions, limitations persist when applying these techniques to large-scale land-based LNG storage tanks. These challenges arise from the material properties of structural components, the complexity of tank structures – including features such as vertically variable thickness inner walls, suspended roofs, large-span diameters, sandwich side walls, and intricate environmental and operational conditions such as LNG vapour and liquid pressure, liquid filling ratio, and cryogenic conditions.

Recent advances in the seismic analysis of large-scale LNG storage tanks have focused on various factors including the effect of insulation layers and their positions, filling ratios, site effects, types of ground motions, soil conditions, and isolation systems. Zhao et al. (2020a, 2020b) developed an SPH-FEM method to investigate the seismic response of a 160,000 m3 LNG storage tank considering four site conditions and different liquid volumes. The results indicated that the SPH-FEM method is accurate and more efficient than the CEL method. Appropriately applied site-based safety factors can minimise material costs and improve economic feasibility without compromising structural safety. Zhang and Weng (2014) evaluated the seismic effect of insulation layers on extra-large LNG storage tanks. It was observed that the coupling period decreases with the presence of insulation layers, leading to reductions in base shear and overturning moment in anchored LNG tanks. The insulation layer exhibits a seismic mitigation effect on the inner tank wall, suggesting that the conventional design of the inner steel tank may be conservative. Luo et al. (2021) proposed a simplified mechanical model of LNG storage tanks validated through scaled shaking table tests on the effects of insulation position and site conditions, further verified through numerical simulations. Additionally, Luo et al. (2022) developed a bidirectional coupling method, compared it with the direct coupling method, and validated it through three shaking table tests on sloshing effects. This method was subsequently applied to investigate the sloshing effect and hydrodynamic pressure of large-scale LNG tanks under pulse-like earthquakes.

Recently, base isolation techniques and seismic energy dissipating techniques received considerable attention. Li et al. (2023) conducted simulation for a large-scale isolated LNG storage tanks in deep soil under horizontal bidirectional seismic action considering dynamic soil-pile interaction, evaluated the effects of isolation system (e.g. lead core rubber bearing) on various aspects of tank performance such as outer tank acceleration, inner tank base shear, overturning moment, and pile force distribution. It was found the base isolation system, specifically LRBs, can reduce the horizontal restraint stiffness of the superstructure and the group pile foundation, and is effective in reducing seismic response of LNG tanks. This study addressed the gap of seismic response of isolated tanks in deep soft soil. Zhang et al. (2023) and Zhang and Wu (2024) conducted several shaking table tests and proposed FE modelling strategy for dynamic response of extra-large LNG storage tank in earthquake, where soil-pile interaction and fluid-tank interaction was considered by simplified mass-damper-spring model and mass-spring model, respectively. It indicates that maximum dynamic responses occur at the wall-roof junction, and the soil-pile interaction has non-negligible effects by altering the damage pattern and dissipating seismic energy. Table 4 gives an overview of recent advances and dynamic modelling techniques proposed for seismic analysis of large-scale land-based LNG storage tank.

2.3.3. Limitations of previous research and gap analysis

After reviewing the dynamic response analysis of large-scale LNG storage tanks during earthquakes, several limitations and gaps in existing research become evident. The limitations of previous studies and the challenges can be summarised as follows:

- Experiment studies or shaking table tests face limitations in meeting scale laws due to the thickness of inner walls and the complexity of large-scale tank structures. Consequently, they can only partially validate numerical models such as simplified mechanical models and fluid-structure interaction (FSI) modelling techniques. The validity of proposed simplified mechanical models and numerical modelling techniques for the dynamic response analysis of the entire tank structure, considering soil-structure-fluid interaction (SSFI), remains uncertain.
- Simplified mechanical models, such as mass-spring models for liquid-tank interaction, may prove invalid in the inelastic region and are typically suitable only for horizontal ground motion analysis. Additionally, multi-mode response spectra analysis used by some researchers is only suitable for elastic region analysis, failing to capture the highly nonlinear behaviour of storage tanks. These analyses often overlook soil-pile interactions, as they assume that all piles experience the same ground motion during earthquakes.

Gaps in the seismic analysis of land-based LNG storage tanks can be summarised as follows:

- Recent studies suggest that the vertical seismic component in near-fault earthquake may be higher than the horizontal component, potentially inducing significant effects on LNG tank structures. However, most previous studies have focused solely on horizontal unidirectional seismic excitation, neglecting seismic waves in three directions. Only limited research (Wu et al. 2023) has examined the effects of vertical and combined horizontal and vertical ground motions, with soil-structure interactions often ignored. Further investigation is needed to understand the dynamic response and behaviour of large-scale land-based LNG storage tanks under vertical and combined ground motions, considering soil-structure interactions.
- Previous research has overlooked the influence of LNG vapour pressure, with only liquid-tank interactions considered. The effects of inner tank vapour pressure, the suspended roof, and inner pipes on the dynamic buckling behaviour of tank structures during earthquakes have received little attention. However, inner tank vapour pressure can range from negative to positive pressures exceeding 30 kPa(G) during operation. Additionally, the suspended roof may affect compression forces and limit horizontal displacement of the inner tank wall. Furthermore, the response of inner pipes to liquid sloshing impact loads requires investigation.
- Previous studies have primarily focused on intact tank structures, neglecting ageing conditions and other in-service damages that may significantly affect structural dynamic behaviour and ultimate limit states. Future research should address these factors.
- While fluid-structure interactions (FSI) have been considered in most previous studies, soil-structure interactions (SSI) have been oversimplified or even ignored for large-scale land-based LNG storage tank structures. Detailed investigations are needed to understand how soil-large group pile interactions influence the overall dynamic response of tank structures.
- Previous research has primarily focused on key parameters of tank performance during earthquakes, with limited exploration of ultimate limit states and buckling behaviour, particularly in large-scale land-based LNG storage tanks. Comparisons between the ultimate strength of intact tanks and the residual strength of damaged or aged tanks are necessary to assess the structural health conditions.

2.4. Seismic diagnosis and remedial recommendations

The methodologies for risk assessment and management in seismic environments are used for the diagnosis and remedial recommendations. In safety studies of structures and infrastructures, two methodologies are commonly utilised: qualitative and quantitative approaches. Qualitative approaches may lack sufficient accuracy, making quantitative methods more suitable for conducting advanced safety studies (Paik 2020). While seismic risk analysis and management have been extensively studied for infrastructures, particularly bridges and highways (Tesfamariam and Goda 2013; Lin et al. 2021; Rachedi et al. 2021; Aroquipa et al. 2023; Ozsarac et al. 2023; Shao and Xie 2024), related investigations for LNG storage tanks (Korkmaz et al. 2011; Bursi et al. 2018; Renjith et al. 2018) remain limited.

Korkmaz et al. (2011) utilised a solid lumped mass and spring system to model the tank structure, conducting performance estimations under 40 different earthquakes through nonlinear time history analyses. This was followed by fragility analyses to produce probabilistic assessments for the tank model. The displacement limits determined in the nonlinear analysis were evaluated in terms of exceedance probability, and the resulting curve was utilised to define risks. Bursi et al. (2018) investigated the behaviour of LNG tanks, support structures, and pipework, including elbows and flanges, under 36 historical earthquakes using finite element modelling and a series of nonlinear time history analyses. Fragility curves were developed, and fragility functions were computed based on a linear regression approach. It was observed that the estimated probability of LNG tank loss exceeded the probability associated with ultimate limit states outlined in the structural Eurocode. Renjith et al. (2018) proposed a fuzzy Risk Priority Number (RPN) method to conduct a fuzzy failure mode effect and criticality analysis (fuzzy FMECA) for LNG storage facilities. The results of the proposed fuzzy FMECA method were compared to those of the

Table 4. Overview of recent advances and dynamic modelling techniques proposed for seismic analysis of land-based LNG storage tanks.

Reference	Tank size	FSI	SSI	Study approach	Seismic excitation	Contribution	Limitation	Remarks
Li et al. 2023	200,000m^3	Lumped mass model based on Housner's theory	Simplified equivalent linear model based on Seed and Idriss (Idriss and Seed 1968)	Numerical	Horizontal bidirectional	This study evaluated the effects of isolation system on tank performance considering soil-pile interaction, addressed the gap of isolated LNG tanks in deep soft soil site under seismic excitation.	Both FSI and SSI were over-simplified for the extra-large tank structures, Without considering interaction between inner and outer tank wall, Vertical ground motion component was ignored.	The results indicate that the base isolation system can reduce the horizontal restraint stiffness of the superstructure and the group pile foundation, and it is effective in reducing seismic response of LNG tanks.
Zhao et al. 2020a	160,000m^3	SPH-FEM method	Not considered	Numerical SPH-FEM method	Horizontal unidirectional	This study investigated the effect of 12 earthquakes under different site conditions on the seismic response of LNG tanks.	The effect of soil-large pile groups was not considered in the model, Modal analysis used in this study is not suitable to simulate nonlinear behaviour of the tank structures, Vertical ground motion component was ignored.	It was concluded that liquid volume and site conditions are important influencing factors in the dynamic analysis and structural design of LNG tanks. Appropriate site-based safety factors can minimise material cost and improve economic feasibility without jeopardising structural safety.
Zhao et al. 2020b	160,000m^3	SPH-FEM	Not considered	Numerical CEL and SPH-FEM method	Horizontal unidirectional	This study compared CEL method with SPH-FEM method to demonstrate the advantage of SPH-FEM method in terms of efficiency and accuracy. Then use SPH-FEM method to analyze the effect of liquid level on dynamic response of LNG tanks	The effect of SSI and vertical ground motion component were not investigated,	The SPH-FEM algorithm is accurate and more efficient than the CEL method. And it exhibits excellent capability for simulating large storage tanks under a reasonable time to provide a reference for the design and construction of large LNG tanks.
Zhang and Weng 2014	160,000m^3	Lumped mass model	Not considered	Numerical	Horizontal unidirectional	This study investigated the effect of insulation on the extra-large LNG tank in earthquake.	The proposed FE model was not sufficiently validated, The effect of SSI was not considered in the analysis.	The results show that when the insulation layer is considered, the base shear and overturning moment decrease in the anchored LNG tank. The insulation layer has a seismic mitigation effect for the inner tank wall, and the common design of the inner steel tank is conservative.
Luo et al. 2021	160,000m^3	Lumped mass model	Not considered	Numerical and experimental	Horizontal unidirectional	This study proposed a simplified mechanical model of an LNG storage tank, which validated by a scaled shaking table test on the effect of main position of insulation layer on tank and site effect. Then conducted numerical simulation to verify the proposed mechanical model.	The proposed simplified mechanical model assumes the tank is fully symmetric, and the seismic loads is horizontal unidirectional, Effect of SSI was not considered.	It was found that there is an obvious interaction between the insulation layer and the liquid-solid coupling position of the storage tank. And the results indicate in the seismic design of large-scale LNG storage tanks, considering the damping effect of insulation is helpful to save design capital.
Luo et al. 2022	160,000m^3	Direct coupling method and bidirectional coupling method	Not considered	Numerical and experimental	Horizontal unidirectional pulse-like and non-pulse seismic wave	This study developed a bidirectional coupling method compared by direct coupling method and validated by three shaking table tests on sloshing effect. Then apply this method to investigate sloshing effect and hydrodynamic pressure of large-scale LNG storage tanks under pulse-like earthquake.	The effect of SSI and vertical ground motion component were not investigated, The proposed numerical method was not sufficiently validated by experiment with only sloshing height compared.	It concluded that the developed bidirectional coupling method is more suitable for estimating the sloshing peak value of the liquid. The sloshing of storage tank is demonstrated to be sensitive to long-period earthquake. Pulse-like ground motion will cause great liquid sloshing, and the violent overturning of upper liquid will

(Continued)

Table 4. Continued.

Reference	Tank size	FSI	SSI	Study approach	Seismic excitation	Contribution	Limitation	Remarks
								result in the liquid leakage and the large hydrodynamic pressure.
Zhang et al. 2023	160,000m^3	Direct coupling method,	Not considered	Experimental and numerical	Horizontal unidirectional	A 1:14 scaled benchmark shaking table test and numerical simulation were conducted to investigate the seismic response of LNG storage tank. Then verified finite element simulations were presented as supplements to the experimental study.	The proposed experiments did not sufficiently consider the complexity of real tank structures, cryogenic temperature, and inner pressure. Less attention was put into the inner steel wall. The effect of SSI and vertical ground motion component were not investigated.	It was found maximum dynamic responses occur at the wall-roof junction due to the large differences in mass and stiffness of the dome roof and the wall of the outer tank. And liquid sloshing mitigates considerably vibrations of the outer concrete tank.
Zhang and Wu 2024	160,000m^3	Mass-spring model	Mass-damper-spring model	Experimental and numerical	Horizontal unidirectional, deterministic and stochastic seismic actions	This work proposed a FE modelling strategy considering soil-pile interaction for seismic responses of extra-large LNG storage structures and validate it by shaking table test. Then investigate the dynamic responses and structural reliability of tank structure in earthquake by this proposed FE modelling strategy.	Less attention was placed on inner steel tank and the interaction between inner and outer tank. The proposed experimental scaled model was not fully consistent with the similarity ratio and did not consider the complexity of real tank structures, cryogenic temperature, and inner pressure. The vertical ground motion component was not investigated.	The numerical and experimental results both reveal that the maximum dynamic response of the protective outer structure occurs at the wall – roof junction. And the soil-pile interaction has non-negligible effects because it may alter the damage pattern of the protective outer structure, as well as mitigate hydrodynamic pressure by dissipating some seismic energy.
Wu et al. 2023	160,000m^3	S-ALE and FEM method	Not considered	Experimental and numerical	Horizontal, Vertical, Combined horizontal and vertical, far-fault and near fault ground motion.	This study proposed a FE modelling methodology using structured Arbitrary-Lagrange-Eulerian (S-ALE) solver and FSI algorithm for seismic analysis of LNG storage tank, and then conducted shaking table test on a 1:25 scaled steel tank to validate the proposed methodology. Also, three different types of near and far-fault ground motions, especially vertical ground motions, were considered for seismic analysis by using proposed numerical modelling methodology.	The proposed experiment only considered the inner steel tank with insufficient scaled wall thickness, where the insulation layer, outer tank, and roof were ignored. Both experiment and numerical studies did not consider soil-large pile group interactions.	Both experimental and numerical results shown that the convective and impulsive motions was amplified by vertical excitations, as well as the peak sloshing wave heights. Also, the LNG inner tank was more vulnerable to inelastic buckling due to presence of vertical seismic component. Moreover, the results indicates that the effect of vertical excitations of near-fault earthquakes on hydrodynamic pressure and tank stresses was underestimated by the current seismic design codes. The vertical earthquake also promoted the development of plastic deformation.

traditional FMECA method, demonstrating its effectiveness in prioritising critical component failures in complex systems.

To ensure the safe operation and management of LNG terminals and safeguard surrounding communities, it is imperative to conduct safety studies for existing LNG storage tanks, particularly those situated in seismically active areas. Figure 10 shows a typical procedure for the risk-based safety study, which can be applied to seismic risk assessment and management for ageing land-based LNG storage tanks. The main tasks encompass (1) planning, (2) defining the structural system, (3) identifying hazards, (4) selecting scenarios, (5) conducting frequency analyses, (6) conducting consequence analyses, (7) calculating risk, (8) evaluating risk, (9) defining risk mitigation options, and (10) defining supplementary risk mitigation options.

Nevertheless, when adapting this methodology for land-based LNG storage tanks, adjustments are necessary for seismic risk analysis and management. Various parameters and factors must be taken into account, such as seismic hazard levels, failure scenarios, site and soil conditions, construction materials, ageing conditions, in-service damages, failure modes, consequences, and seismic mitigation options. The modified procedure should identify key tasks required to conduct seismic risk assessment and management for ageing large-scale land-based LNG storage tank structures.

3. Technical challenges and gap analysis

Based on the literature review, the development of a DHE system for land-based LNG storage tank structures during seismic events to ensure their safe operation and management throughout their lifecycle faces several challenges and gaps:

- Research on the application of lifetime healthcare digital technologies such as Building Information Modelling (BIM) and DT for land-based LNG storage tanks remains limited. BIM and DT models often overlook environmental conditions, ageing conditions, and in-service damages, although some DT systems focus on abnormal phenomena detected by sensors. Bridging this gap requires the identification of specific procedures for developing a DHE system.
- On-site measurement of health parameters and data transmission pose challenges. Core structural components' health parameters need identification based on potential failure modes. Feasible structural monitoring and inspection techniques, along with corresponding data transmission devices, must be selected, and strategies for on-site measurement should be proposed.
- Experimental studies on seismic analysis encounter challenges due to the inability to meet scale laws owing to the thickness of inner walls and the complexity of large-scale tank structures. Simplified mechanical models, such as mass-spring models, may be inadequate in the inelastic region and are only suitable for horizontal ground motion analysis.
- Numerical studies on seismic analysis often overlook ageing conditions and in-service damages, which can significantly affect structural dynamic behaviour and ultimate limit states. Addressing this gap is essential for the comprehensive health condition assessment of DHE systems.
- Seismic risk assessment and management require consideration of various parameters and factors, including seismic hazard levels, failure scenarios, site and soil conditions, construction materials, ageing conditions, failure modes, consequences, and seismic mitigation options. Specific procedures and tasks need identification to conduct seismic risk assessment and management for ageing large-scale land-based LNG storage tank structures.

Given the gaps and limitations highlighted above, advanced numerical modelling techniques should be developed to account for factors such as inner tank vapour pressure, vertical pipes inside the tank, suspended steel roofs, and soil-large pile group interactions under different types of ground motions. This advancement aims to enhance accuracy and efficiency in seismic analysis. Overall, addressing these challenges and gaps is crucial for the development and implementation of effective DHE systems and seismic risk management strategies for land-based LNG storage tanks.

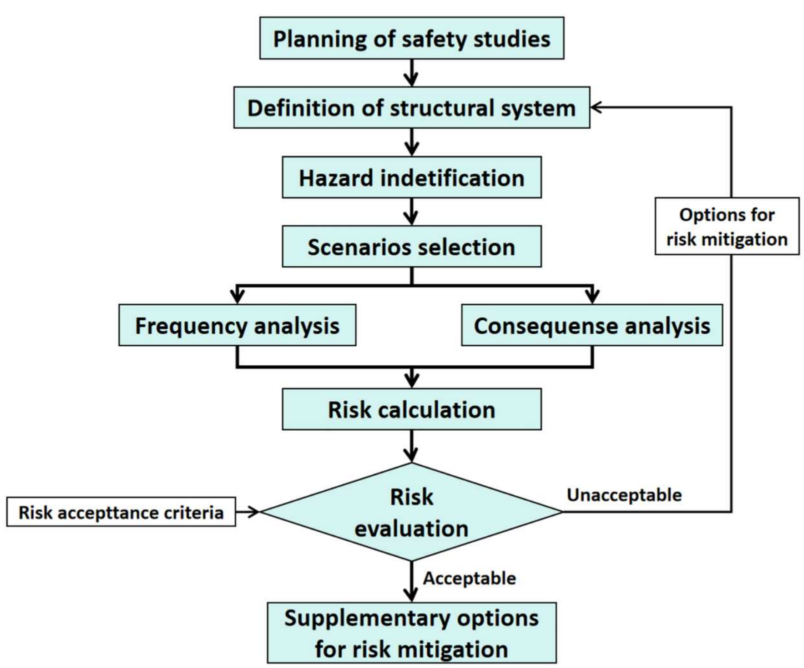

Figure 10. Procedure for risk-based safety studies for structural systems. (This figure is available in colour online.)

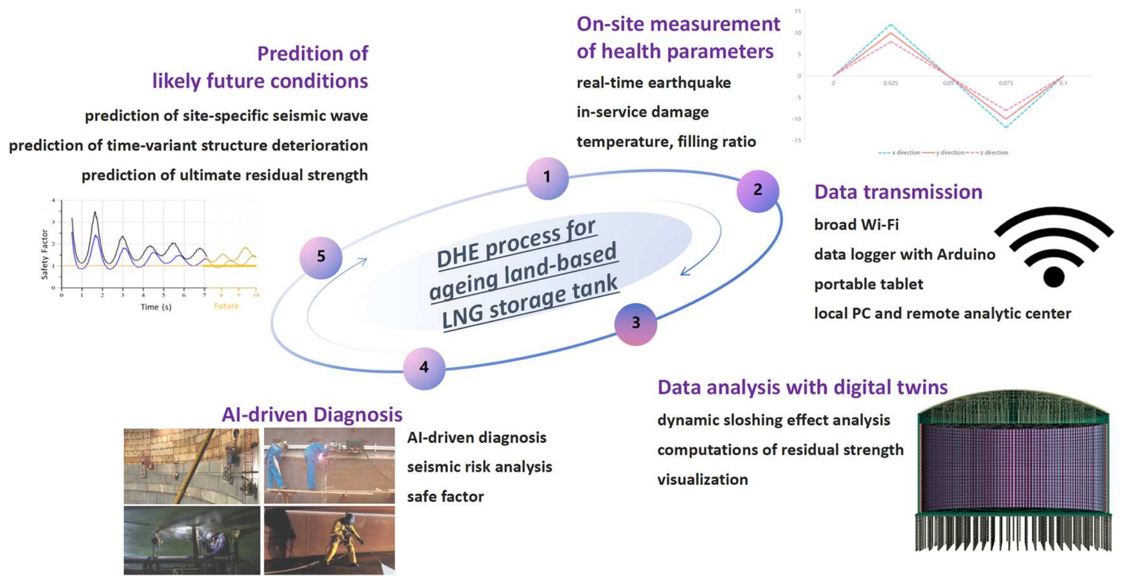

Figure 11. A prototype DHE system for ageing land-based LNG storage tanks in earthquake. (This figure is available in colour online.)

4. Discussion and practical solutions

4.1. Methodologies

Drawing from the literature review on DHE systems, specific procedures for ageing land-based LNG storage tanks in seismic environment have been proposed and depicted in Figure 11. This proposed procedure commences with on-site measurement of health parameters, proceeds with data transmission of measured data, and concludes with the prediction of likely future conditions. The key procedure lies in data analysis for health condition assessment, wherein computational models and digital twins will be developed.

4.2. On-site measurements of health parameters and data transmission

4.2.1. Identifying health parameters

Following the literature review, for ageing land-based LNG storage tanks, health parameters are categorised into three aspects: environmental parameters, in-service damages, and operational parameters. The details are outlined as follows:

- Environmental: Real-time earthquake waves in three directions.
- In-service damage: Corrosion, cracking, and local denting for steel structures, as well as carbonation, cracking, and delamination for concrete structures.
- Operational: temperature, tank settlement (at slab level), filling ratio.

4.2.2. Structural monitoring and inspection

Additionally, as the defined health parameters above require varied measurement methods, the transmission of measured data may depend on the corresponding devices utilised. Following the literature review, the monitoring and inspection methods for each health parameter, along with the corresponding devices, are outlined: A possible strategy as shown in Figure 12, combining initial inspection and detailed inspection, can be proposed as follows:

- For initial rapid inspection, the unmanned aerial vehicle (UAV) assisted image-based visual inspection technique can be employed. Equipped with 3D Lidar for navigation and mapping, as well as a high-precision camera, this method aims to swiftly identify surface defects in steel and concrete structures, along with other abnormal phenomena. Additionally, the guided wave detector (Alleyne 2001; Wang et al. 2020; Hu et al. 2022; Trushkevych et al. 2023; Cawley 2024) can be utilised to locate corrosion and cracking damages on steel plates, shells, and inner pipes, owing to its rapid, long-range, and large-area detection capabilities. The data measured by UAVs and guided wave detectors can be easily recorded on a local laptop for further analysis.
- For detailed in-service damage data, encompassing parameters such as the area, depth, and shape of steel corrosion, as well as the direction, size, and depth of steel and concrete cracking, along with the area, depth, and shape of concrete spalling, and the shape, size, and depth of concrete voids, various types of ultrasonic flaw detectors can be employed. Additionally, basic tools such as vernier calipers can aid in these measurements.
- For seismic waves and other operational parameters like temperature and inner tank pressure, suitable technologies have been sufficiently developed, with commercially available devices. Additionally, real-time seismic wave data from around the world can be accessed through global research institutions (European-Mediterranean Seismological Centre 2023; Incorporated Research Institutions for Seismology 2023; United States Geological Survey 2023), third-party institutions (Bousai 2023), and related companies (Raspberryshake 2023).
- Based on the survey results of recent technologies, we have chosen to use seismometers for real-time monitoring and digitisation of seismic load parameters. In-service damages, such as corrosion wastage, fatigue cracking, and mechanical denting, will be monitored and measured through close-up inspections and portable scanning devices, such as ultrasonic NDT tools. These devices will be assisted by a tablet PC to record and transmit the collected data to a data analytics centre, where digital twins will be used for numerical simulations. While our team is currently developing a DHE system for aging land-based LNG storage tank structures, we will select the most suitable options for this purpose, which will be reported in future publications.

The measured data can be conveniently recorded using tablet PCs and local laptops. Utilising remote control technology

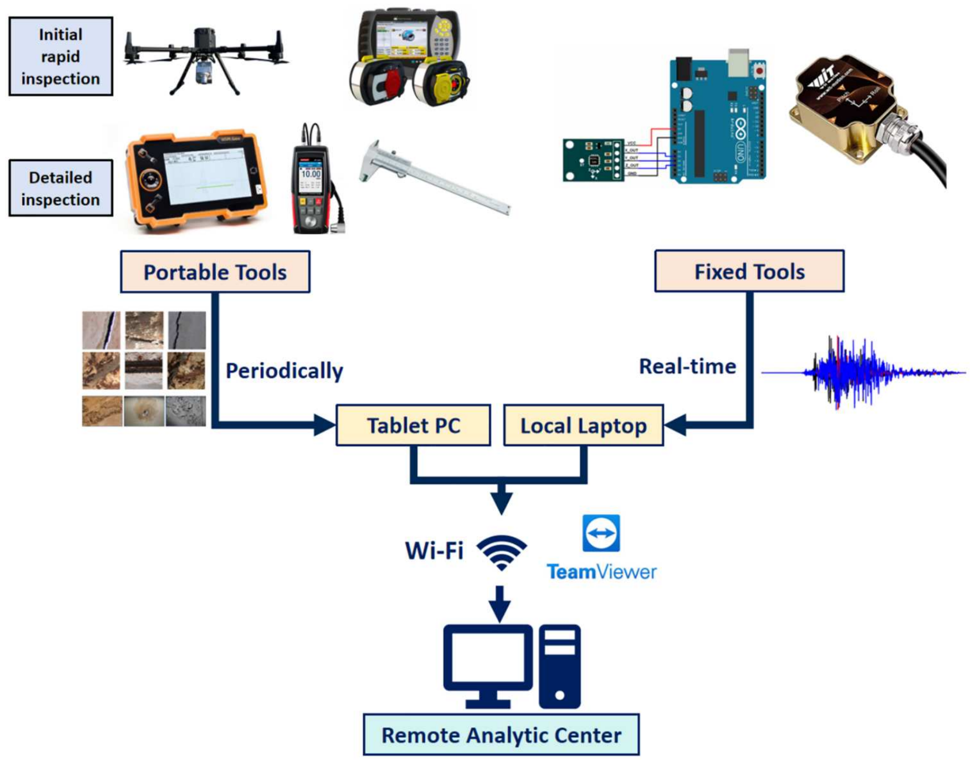

Figure 12. Proposed strategy for onsite measurement of health parameters and data transmission. (This figure is available in colour online.)

Table 5. Inspection techniques for health parameters and utilisation of measured data

Health parameter		Monitoring/ inspection technique	Measured data	The use of data
Environmental parameter	Seismic wave	Accelerometer	Acceleration data in three directions	FEA model input as boundary condition
In-service damage of steel	Corrosion	Guided wave detector/ Ultrasonic flaw detector	Reduction on thickness or diameter	Change of geometry in FEA model
	Cracking	Guided wave detector/ Ultrasonic flaw detector	Cracking location, size, depth, direction	Change of geometry in FEA model
	Denting	Camera/Calipres	Denting depth and diameter	Change of geometry in FEA model
In-service damage of concrete	Carbonation	Core sampling tool/ Rebound hammer	Reduction on strength and depth	Change of material properties in FEA model
	Cracking	Ultrasonic flaw detector/ Calipre	Cracking location, size, depth, direction	Change of geometry in FEA model
	Delamination	Camera/ Calipres	Delamination depth and shape	Change of geometry in FEA model
	Reinforcement corrosion	Ultrasonic flaw detector/ Calipres	Reduction on diameter	Change of geometry in FEA model

(TeamViewer 2024), the recorded data can be periodically or real-time transmitted to a remote data analytics centre. All transmitted data will serve as inputs for nonlinear Finite Element Analysis (FEA) models, which act as digital twins for further analysis.

Table 5 describes possible on-site monitoring and inspection techniques, and the data can be accessed directly or indirectly from inspection, which will be proceed as change of tank geometry, material properties, and boundary condition of the FEA model. In addition, those measured in-service damage data can be used for visualisations of 3D model within the DHE system.

4.3. Digital twin and visualisation

Drawing from the literature review, to efficiently and accurately calculate the dynamic response and ultimate residual strength of ageing land-based storage tank structures during earthquakes, the following considerations are imperative:

- The impact of inner tank pressure, suspended roof, and inner pipes on the dynamic behaviour of tanks.
- The influence of soil-large pile group interaction or soil-structure-fluid interaction (SSFI).
- The influence of seismic waves in three directions.
- The impact of ageing conditions and other in-service damages.
- Exploration of potential advanced computational modelling techniques.

Commercial software like ABAQUS, ANSYS, LS-DYNA, and ADINA (ABAQUS 2024; ADINA 2024; ANSYS 2024; LS-DYNA 2024) offer finite element analysis capabilities, with computational models serving as digital twins within the DHE system. The data measured on-site and transmitted in real-time will periodically input into these computational models. The results generated by these models will then be utilised to assess the health conditions and predict future conditions of the targeted LNG tank structures. Furthermore, it is essential to develop advanced FEA modelling

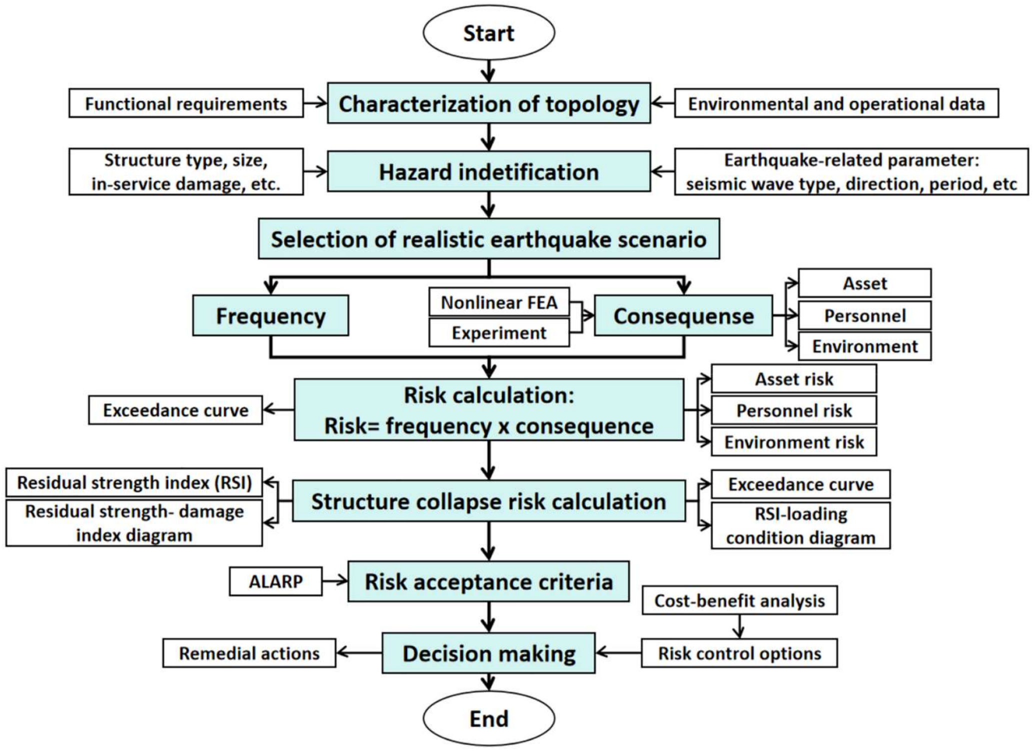

Figure 13. Proposed methodology for seismic risk analysis of ageing land-Based LNG storage tanks. (This figure is available in colour online.)

techniques aimed at reducing computational costs without sacrificing accuracy.

4.4. Seismic risk analysis

Drawing from the literature review, a methodology for seismic risk assessment and management of land-based LNG storage tanks has been proposed, as illustrated in Figure 13.

This methodology begins with the characterisation of topology and hazard identification and concludes with decision-making for renewal and remedial actions. Nonlinear Finite Element Analysis (FEA) and experiment-supported structure collapse risk analysis serve as pivotal components within this procedure. Based on the results of above analysis, renewal, repair actions, as well as reasonable risk mitigation suggestions will be made for seismic risk management and maintenance.

5. Concluding remarks and future work

By leveraging emerging technologies such as advanced structural monitoring, digital twins, artificial intelligence, and cloud computing, the DHE system introduces innovative solutions to enhance safety and resilience for ageing structures and infrastructures under challenging environmental and operational conditions.

The paper makes significant contributions by: (1) presenting a thorough review of key DHE technologies with an emphasis on seismic resilience and (2) providing a methodology for developing the DHE system and addressing technical gaps within its core modules. This paper offers a comprehensive review of key DHE technologies relevant to ageing land-based LNG storage tank structures in seismic environments. It compares advanced digital technologies for structural lifecycle healthcare and analysis, including BIM, DT, and DHE. The paper demonstrates how DHE can significantly improve safety and resilience for these structures. The paper summarises and analyzes challenges and technical gaps in core DHE technologies. Using a typical 160,000 m^3 full containment LNG storage tank as a case study, it proposes strategies for on-site structural monitoring and inspection, along with suitable data transmission solutions.

Based on the survey results of recent technologies, we have chosen to use seismometers for real-time monitoring and digitisation of seismic load parameters. In-service damages, such as corrosion wastage, fatigue cracking, and mechanical denting, will be monitored and measured through close-up inspections and portable scanning devices, such as ultrasonic NDT tools. These devices will be assisted by a tablet PC to record and transmit the collected data to a data analytics centre, where digital twins will be used for numerical simulations. While our team is currently developing a DHE system for aging land-based LNG storage tank structures, we will select the most suitable options for this purpose, which will be reported in future publications.

Additionally, the paper addresses limitations in previous studies on the seismic analysis of large-scale land-based LNG storage tanks and suggests methods to improve efficiency and accuracy in calculating dynamic responses and ultimate residual strength within digital twins. It also proposes a seismic risk analysis methodology supported by finite element analysis and experimental data.

Future research should focus on advancing computational modelling techniques to improve the efficiency and accuracy of digital twins for land-based LNG tank structures in seismic environments. Additionally, large-scale experiments are needed to validate these models, and on-site measurements should be conducted for real LNG storage tanks. Ultimately, the proposed DHE system will undergo rigorous verification in future studies.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available from the corresponding author, [W. D.], upon reasonable request.

ORCID

Weixing Duan http://orcid.org/0009-0004-5015-2747

References

ABAQUS. 2024. Analysis user's manual (version 2024). Paris: Dassault Systems Similia Corp.

ADINA. 2024. ADINA series software. Exton, PA: Bentley Systems Corp.

Akira N, Clough RW. 1982. Buckling of cylindrical liquid-storage tanks under earthquake loading. Earthq Eng Struct Dyn. 10:107–122. doi:10.1002/eqe.4290100108.

Alleyne DN., Pavlakovic B. 2001. Rapid, long range inspection of chemical plant pipework using guided waves, 30 April 2001. AIP Conference Proceedings, Ames, Iowa, USA. https://doi.org/10.1063/1.1373757.

Altindal A, Askan A. 2024. Traditional seismic hazard analyses underestimate hazard levels when compared to observations from the 2023 Kahramanmaras earthquakes. Commun Earth Environ. 5(1):14. doi:10.1038/s43247-023-01148-y.

American Concrete Institute. 2013. Report on nondestructive test methods for evaluation of concrete in structures, Farmington Hills, MI, USA. ACI 228.2R-13.

ANSYS. 2024. ANSYS user's manual (version 2024R2). Canonsburg, PA: ANSYS, Inc.

Aroquipa H, Hurtado A, Angel C, Aroquipa A, Gamarra A, Almeida Del Savio A. 2023. A cost-benefit analysis for the appraisal of social and market prices in the probabilistic seismic risk assessment of building portfolios: A methodology for the evaluation of disaster risk reduction programs. Int J Disaster Risk Reduct. 90:103637. doi:10.1016/j.ijdrr.2023.103637.

Bato MR, Hor A, Rautureau A, Bes C. 2020. Experimental and numerical methodology to obtain the probability of detection in eddy current NDT method. NDT & E Int. 114:102300. doi:10.1016/j.ndteint.2020.102300.

BIEŃ J. 2011. Modelling of structure geometry in bridge management systems. Arch Civil Mech Eng. 11(3):519–532. doi:10.1016/S1644-9665(12)60099-5.

Bousai. 2023. [accessed 2023 Dec 1]. https://bousai.cn/.

British Standards Institution. 1993. BS 7777 - Flat-bottomed, vertical, cylindrical storage tanks for low temperature service. doi:10.3403/BS7777.

British Standards Institution. 2006. BS-EN-14620, Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0°C and -165°C. doi:10.3403/30033875.

Brunesi E, Nascimbene R, Pagani M, Beilic D. 2015. Seismic performance of storage steel tanks during the May 2012 Emilia, Italy, earthquakes. J Perform Constr Facil. 29(5). doi:10.1061/(ASCE)CF.1943-5509.0000628.

Bursi OS, di Filippo R, Salandra L, Pedot V, Reza M. 2018. Probabilistic seismic analysis of an LNG subplant. J Loss Prev Process Ind. 53:45–60. doi:10.1016/j.jlp.2017.10.009.

Callcut M, Cerceau Agliozzo J-P, Varga L, McMillan L. 2021. Digital twins in civil infrastructure systems. Sustainability. 13(20):11549. doi:10.3390/su132011549.

Cawley P. 2024. Guided waves in long-range nondestructive testing and structural health monitoring: Principles, history of applications and prospects. NDT & E Int. 142:103026. doi:10.1016/j.ndteint.2023.103026.

Chen S, Shirolé A. 2006. Integration of information and automation technologies in bridge engineering and management: extending the state of the art. Transp Res Rec. 1976:2–12. doi:10.1177/0361198106197600101.

Chen W-F, Duan L. 2014. Bridge Engineering Handbook, 2nd ed. New York, NY: CRC Press.

China National Offshore Oil Corporation. 2023. Chaoyang, Beijing, People's Republic of China. [accessed 2023 Dec 1]. https://www.cnoocltd.com/.

China National Petroleum Corporation. 2023. Xicheng, Beijing, People's Republic of China. [accessed 2023 Dec 1]. https://www.cnpc.com.cn/en/.

Colvalkar A, Pawar SS, Patle BK. 2023. In-pipe inspection robotic system for defect detection and identification using image processing. Mater Today Proc. 72:1735–1742. doi:10.1016/j.matpr.2022.09.476.

Costin A, Adibfar A, Hu H, Chen SS. 2018. Building information modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations. Autom Constr. 94:257–281. doi:10.1016/j.autcon.2018.07.001.

Cruz EF, Valdivia D. 2011. Performance of industrial facilities in the Chilean earthquake of 27 February 2010. The Structural Design of Tall and Special Buildings. 20(1):83–101. doi:10.1002/tal.679.

ENN Natural Gas Co. L. 2023. Langfang, Heibei, People's Republic of China. [accessed 2023 Dec 1]. https://www.enn-ng.com/.

European-Mediterranean Seismological Centre. 2023. [accessed 2024 Apr 1]. https://www.emsc-csem.org/.

ExxonMobil Corporation. 2023. Energy demand: Three drivers. [accessed 2023 Dec 1]. https://corporate.exxonmobil.com/what-we-do/energy-supply/global-outlook/energy-demand.

Fan JS, Liu YF. 2022. A review of in-service bridge inspection and health monitoring technology and a new system of spatio-temporal fusion assessment. Journal of Municipal Technology. 40(8):1–11.

Fischer EC, Liu J, Varma AH. 2016. Investigation of cylindrical steel tank damage at wineries during earthquakes: lessons learned and mitigation opportunities. Practice Periodical on Structural Design and Construction. 21(3). doi:10.1061/(ASCE)SC.1943-5576.0000283.

Gioncu V, Mazzolani F. 2010. Earthquake engineering for structural design. Oxfordshire: Spon Press.

Grieves M, Vickers J. 2017. Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems. In: Transdisciplinary perspectives on complex systems. Cham: Springer International Publishing; p. 85–113.

Hammad A, Zhang C, Hu Y, Mozaffari E. 2006. Mobile model-based bridge lifecycle management system. Comput Aided Civ Infrastruct Eng. 21(7):530–547. doi:10.1111/j.1467-8667.2006.00456.x.

Honghong S, Gang Y, Haijiang L, Tian Z, Annan J. 2023. Digital twin enhanced BIM to shape full life cycle digital transformation for bridge engineering. Autom Constr. 147:104736. doi:10.1016/j.autcon.2022.104736.

Housner GW. 1957. Dynamic pressures on accelerated fluid containers. Bull Seismol Soc Am. 47(1):15–35. doi:10.1785/BSSA0470010015.

Hu X, Ng C-T, Kotousov A. 2022. Numerical and experimental investigations on mode conversion of guided waves in partially immersed plates. Measurement (Mahwah N J). 190:110750. doi:10.1016/j.measurement.2022.110750.

Huang H, Li Q, Zhang D. 2018. Deep learning-based image recognition for crack and leakage defects of metro shield tunnel. Tunn Undergr Space Technol. 77:166–176. doi:10.1016/j.tust.2018.04.002.

Idriss IM, Seed HB. 1968. Seismic Response of Horizontal Soil Layers. J Soil Mech Found Div. 94(4):1003–1031. doi:10.1061/JSFEAQ.0001163.

Incorporated Research Institutions for Seismology. 2023. [accessed 2023 Dec 1]. https://www.iris.edu/hq/.

Jacobsen LS. 1949. Impulsive hydrodynamics of fluid inside a cylindrical tank and of fluid surrounding a cylindrical pier*. Bull Seismol Soc Am. 39 (3):189–204. doi:10.1785/BSSA0390030189.

Jeon C-H, Shim C-S, Lee Y-H, Schooling J. 2024. Prescriptive maintenance of prestressed concrete bridges considering digital twin and key performance indicator. Eng Struct. 302:117383. doi:10.1016/j.engstruct.2023.117383.

Korkmaz KA, Sari A, Carhoglu AI. 2011. Seismic risk assessment of storage tanks in Turkish industrial facilities. J Loss Prev Process Ind. 24(4):314–320. doi:10.1016/j.jlp.2011.01.003.

Li Z, Zhang R, Liu X, Chen S, Li X. 2023. Analysis of seismic response of a large-scale isolated LNG tank considering dynamic soil-pile interaction. Structures. 58:105460. doi:10.1016/j.istruc.2023.105460.

Lin K, Xu Y-L, Lu X, Guan Z, Li J. 2021. Digital twin-based collapse fragility assessment of a long-span cable-stayed bridge under strong earthquakes. Autom Constr. 123:103547. doi:10.1016/j.autcon.2020.103547.

Liu C, Zhang P, Xu X. 2023. Literature review of digital twin technologies for civil infrastructure. J Infrastruct Intell Resil. 2(3):100050. doi:10.1016/j.iintel.2023.100050.

Liu X, Jiang D, Tao B, Xiang F, Jiang G, Sun Y, Kong J, Li G. 2023. A systematic review of digital twin about physical entities, virtual models, twin data, and applications. Adv Eng Inform. 55:101876. doi:10.1016/j.aei.2023.101876.

Liu Y, Nie X, Fan J, Liu X. 2020. Image-based crack assessment of bridge piers using unmanned aerial vehicles and three-dimensional scene reconstruction. Comput Aided Civ Infrastruct Eng. 35(5):511–529. doi:10.1111/mice.12501.

LS-DYNA. 2024. LS-DYNA User's Manual (version 2024). Livermore, CA: LSTC.

Luo D, Liu C, Sun J, Cui L, Wang Z. 2021. Liquefied natural gas storage tank simplified mechanical model and seismic response analysis. Soil Dyn Earthq Eng. 141:106491. doi:10.1016/j.soildyn.2020.106491.

Luo D, Liu C, Sun J, Cui L, Wang Z. 2022. Sloshing effect analysis of liquid storage tank under seismic excitation. Structures. 43:40–58. doi:10.1016/j.istruc.2022.06.030.

Ma Z, Liu S. 2018. A review of 3D reconstruction techniques in civil engineering and their applications. Adv Eng Inform. 37:163–174. doi:10.1016/j.aei.2018.05.005.

Malhotra PK. 2006. Earthquake induced sloshing in tanks with insufficient freeboard. Struct Eng Int. 16(3):222–225. doi:10.2749/101686606778026466.

Malhotra PK, Wenk T, Wieland M. 2000. Simple procedure for seismic analysis of liquid-storage tanks. Struct Eng Int. 10(3):197–201. doi:10.2749/101686600780481509.

Mawlana M, Vahdatikhaki F, Doriani A, Hammad A. 2015. Integrating 4D modeling and discrete event simulation for phasing evaluation of elevated urban highway reconstruction projects. Autom Constr. 60:25–38. doi:10.1016/j.autcon.2015.09.005.

Mordor Intelligence. 2024. LNG Market Size & Share Analysis - Growth Trends & Forecasts (2024 - 2029). [accessed 2023 Dec 1]. https://www.mordorintelligence.com/industry-reports/global-lng-market-industry.

National Energy Administration. 2023. China natural gas development report (2023). [accessed 2023 Dec 1]. https://www.nea.gov.cn/2023-07/21/c_1310733569.htm.

Okasha NM, Frangopol DM. 2011. Computational platform for the integrated life-cycle management of highway bridges. Eng Struct. 33(7):2145–2153. doi:10.1016/j.engstruct.2011.03.005.

Ozsarac V, Furinghetti M, Monteiro R. 2023. Seismic risk assessment of ageing existing reinforced concrete bridges accounting for uncertainty in bearing properties. Eng Struct. 293:116730. doi:10.1016/j.engstruct.2023.116730.

Paik JK. 2020. Advanced structural safety studies with extreme conditions and accidents. Singapore: Springer.

Paik JK. 2022. Ship-shaped offshore installations: design, construction, operation, healthcare and decommissioning. Cambridge: Cambridge University Press.

Paik JK. 2023. Digital healthcare engineering for marine applications. International Conference on Marine Equipment & Technology and Sustainable Development, 31 March–1 April, Beijing, People's Republic of China.

Paik JK. 2024.. Enhancing safety and sustainability through digital healthcare engineering. Marine Technology, The Society of Naval Architects and Marine Engineers, Alexandria, VA, USA, April, p. 34–40.

Paik JK, Lee DH, Noh SH, Park DK, Ringsberg JW. 2020a. Full-scale collapse testing of a steel stiffened plate structure under axial-compressive loading triggered by brittle fracture at cryogenic condition. Ships Offshore Struct. 15(sup1):S29–S45. doi:10.1080/17445302.2020.1787930.

Paik JK, Lee DH, Noh SH, Park DK, Ringsberg JW. 2020b. Full-scale collapse testing of a steel stiffened plate structure under cyclic axial-compressive loading. Structures. 26:996–1009. doi:10.1016/j.istruc.2020.05.026.

Payão Filho JC, Maia VP, Passos EKD, Gonzaga RS, Juliano DR. 2022. Probability of detection of discontinuities by ultrasonic phased array inspection of 9% Ni steel joints welded with alloy 625 as the filler metal. Ultrasonics. 119:106582. doi:10.1016/j.ultras.2021.106582.

Peek R, Jennings PC. 1988. Simplified analysis of unanchored tanks. Earthq Eng Struct Dyn. 16(7):1073–1085. doi:10.1002/eqe.4290160709.

PipeChina, China Oil & Gas Pipeline Network Corporation. 2023. [accessed 2023 Dec 1]. https://www.pipechina.com.cn/.

Rachedi M, Matallah M, Kotronis P. 2021. Seismic behavior & risk assessment of an existing bridge considering soil-structure interaction using artificial neural networks. Eng Struct. 232:111800. doi:10.1016/j.engstruct.2020.111800.

Raspberryshake. 2023. [accessed 2023 Dec 1]. https://stationview.raspberryshake.org/.

Renjith VR, Jose kalathil M, Kumar PH, Madhavan D. 2018. Fuzzy FMECA (failure mode effect and criticality analysis) of LNG storage facility. J Loss Prev Process Ind. 56:537–547. doi:10.1016/j.jlp.2018.01.002.

Rötzer J. 2019. Design and Construction of LNG Storage Tanks. Berlin: Wiley.

Semeraro C, Lezoche M, Panetto H, Dassisti M. 2021. Digital twin paradigm: A systematic literature review. Comput Ind. 130:103469. doi:10.1016/j.compind.2021.103469.

Sezen H, Livaoglu R, Dogangun A. 2008. Dynamic analysis and seismic performance evaluation of above-ground liquid-containing tanks. Eng Struct. 30 (3):794–803. doi:10.1016/j.engstruct.2007.05.002.

Shao Y, Xie Y. 2024. Seismic risk assessment of highway bridges in western Canada under crustal, subcrustal, and subduction earthquakes. Structural Safety. 108:102441. doi:10.1016/j.strusafe.2024.102441.

Shekari MR, Khaji N, Ahmadi MT. 2010. On the seismic behavior of cylindrical base-isolated liquid storage tanks excited by long-period ground motions. Soil Dyn Earthq Eng. 30(10):968–980. doi:10.1016/j.soildyn.2010.04.008.

Shirole AM, Riordan TJ, Chen SS, Gao Q, Hu H, Puckett JA. 2009. BrIM for project delivery and the life-cycle: state of the art. Bridge Struct. 5(4):173–187. doi:10.1080/15732480903143003.

Sindi A, Kim HJ, Yang YJ, Thomas G, Paik JK. 2024. Advancing digital healthcare engineering for aging ships and offshore structures: an in-depth review and feasibility analysis. Data-Centric Engineering. 5:e18-1–e18-31. doi:10.1017/dce.2024.14.

SINOPEC GROUP. 2023. Chaoyang, Beijing, People's Republic of China. [accessed 2023 Dec 1]. http://www.sinopec.com/listco/en/.

Sobhan MS, Rofooei FR, Attari NKA. 2017. Buckling behavior of the anchored steel tanks under horizontal and vertical ground motions using static pushover and incremental dynamic analyses. Thin-Walled Struct. 112:173–183. doi:10.1016/j.tws.2016.12.022.

Tao F, Xiao B, Qi Q, Cheng J, Ji P. 2022. Digital twin modeling. J Manuf Syst. 64:372–389. doi:10.1016/j.jmsy.2022.06.015.

TeamViewer. 2024. [accessed 2024 Apr 1]. https://www.teamviewer.com/en/.

Tesfamariam S, Goda K. 2013. Seismic risk analysis and management of civil infrastructure systems: an overview. In: Handbook of Seismic Risk Analysis and Management of Civil Infrastructure Systems. Cambridge: Elsevier; p. 141–174.

Thériault F, Noël M, Sanchez L. 2022. Simplified approach for quantitative inspections of concrete structures using digital image correlation. Eng Struct. 252:113725. doi:10.1016/j.engstruct.2021.113725.

Trushkevych O, Dixon S, Tabatabaeipour M, Potter MDG, MacLeod C, Dobie G, Edwards RS. 2023. Calibration-free SH guided wave analysis for screening of wall thickness in steel with varying properties. NDT E Int. 135:102789. doi:10.1016/j.ndteint.2023.102789.

Ulloa-Rojas J, Colombo J, Wilches J, León R, Almazán J. 2024. Influence of soil - foundation - tank interaction on buckling strength of liquid storage tanks. Eng Struct. 305:117744. doi:10.1016/j.engstruct.2024.117744.

United States Geological Survey. 2023. [accessed 2023 Dec 1]. https://earthquake.usgs.gov.

Vathi M, Karamanos SA. 2012. Effects of Base Uplifting on the Seismic Response of Unanchored Liquid Storage Tanks. In: Volume 8: Seismic Engineering. Boston, MA: American Society of Mechanical Engineers; p. 183–190.

Veletsos AS, Tang Y. 1990. Soil-structure interaction effects for laterally excited liquid storage tanks. Earthq Eng Struct Dyn. 19(4):473–496. doi:10.1002/eqe.4290190402.

Wang X, Gao S, Liu H, Li J. 2020. Low frequency ultrasonic guided waves excitated by Galfenol Rod Ultrasonic Transducer in plate inspection. Sens Actuators A Phys. 313:112196. doi:10.1016/j.sna.2020.112196.

Wu J-Y, Yu Q-Q, Peng Q, Gu X-L. 2023. Seismic responses of liquid storage tanks subjected to vertical excitation of near-fault earthquakes. Eng Struct. 289:116284. doi:10.1016/j.engstruct.2023.116284.

Wu Y, Sun J, Yang G, Cui L, Wang Z, Wang M. 2023. Research on digital twin based temperature field monitoring system for LNG storage tanks. Measurement (Mahwah N J). 215:112864. doi:10.1016/j.measurement.2023.112864.

Zama S, Nishi H. 2012. On damage of oil storage tanks due to the 2011 off the Pacific Coast of Tohoku Earthquake (Mw9.0). Lisboa, Japan.

Zareian F, Sampere C, Sandoval V, McCormick DL, Moehle J, Leon R. 2012. Reconnaissance of the Chilean Wine Industry Affected by the 2010 Chile Offshore Maule Earthquake. Earthq Spectra. 28(1_suppl1):503–512. doi:10.1193/1.4000048.

Zhang D, Wu J, Zhou H, Gong M. 2023. A benchmark shaking table test on the seismic responses of an extra-large LNG storage tank. Earthq Eng Struct Dyn. 52(2):439–459. doi:10.1002/eqe.3767.

Zhang D-Y, Wu J-Y. 2024. Experimentally validated numerical analyses on the seismic responses of extra-large LNG storage structures. Thin-Walled Struct. 195:111407. doi:10.1016/j.tws.2023.111407.

Zhang R, Weng D. 2014. Assessment of the seismic effect of insulation on extra-large cryogenic liquid natural gas storage tanks. J Loss Prev Process Ind. 30:9–16. doi:10.1016/j.jlp.2014.04.003.

Zhao Y, Li H-N, Fu X, Zhang S, Mercan O. 2020. Seismic Analysis of a Large LNG Tank considering the Effect of Liquid Volume. Shock Vib. 2020:1–18. doi:10.1155/2020/8889055.

Zhao Y, Li H-N, Zhang S, Mercan O, Zhang C. 2020. Seismic Analysis of a Large LNG Tank Considering Different Site Conditions. Appl Sci. 10(22):8121. doi:10.3390/app10228121.

Zhou S, Dumss S, Nowak R, Riegler R, Kugu O, Krammer M, Grafinger M. 2022. A Conceptual Model-based Digital Twin Platform for Holistic Large-scale Railway Infrastructure Systems. Procedia CIRP. 109:362–367. doi:10.1016/j.procir.2022.05.263.

Zhuhai LNG terminal receives and discharges 20 million tons of LNG. 2022. Zhuhai, Guangdong, People's Republic of China. [accessed 2024 Apr 1]. https://www.sohu.com/a/621895231_100116740.