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# Impact of flooding events on buried infrastructures: a review

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This review delves into the profound implications of flooding events on buried infrastructures, specifically pipelines, tunnels, and culverts. While these buried infrastructures are vital for community resilience, their susceptibility to damage from flooding, storm surges, and hurricanes poses significant challenges. Unlike the obvious impact on above-ground structures, the effects of flooding on buried infrastructures, being out of sight, are not quickly and easily observable. This review aims to 1) review the state-of-the-art research on the flooding effects on buried structures and summarize causes of failures of buried infrastructures induced by flooding; 2) identify the research gaps on this topic to motivate in-depth investigations; and 3) discuss the future research directions. This review sheds light on how factors contributing to the vulnerability of buried infrastructures are multifaceted and can vary based on the specific characteristics of the infrastructure, the local environment, and the nature of the flood event. Despite the availability of many articles on the topic, this review also highlights a lack of methodologies to assess flooding damage and its impact on the serviceability of buried infrastructures. We suggested three future research directions to bridge this research gap including investigating and distinguishing key factors to quantify flooding damage to buried infrastructures, developing advanced modeling techniques, and exploring the integration of smart technologies in health monitoring of buried infrastructures.

KEYWORDS

**flooding events, pipelines, tunnels, culverts, flood damages**

## 1 Introduction and background

Flooding continues to be one of the most destructive natural disasters globally and a primary contributor to economic losses from natural calamities in numerous nations, including the United States. As reported by the National Centers for Environmental Information (NCEI), in 2023, the United States encountered an unprecedented number of weather disasters, with costs surpassing $1 billion (NOAA, 2024). This record-setting year saw 28 confirmed weather and climate disasters, comprising four instances of flooding, one drought, 19 severe storms, two tropical cyclones, one wildfire, and one winter storm. These severe events led to the loss of 492 lives and had substantial economic repercussions in the affected regions. According to multiple studies, the frequency and magnitude of flooding events are expected to increase all over the world in the coming decades as the rainfall intensity increases (Prein et al., 2017; Ali et al., 2019; Neri et al., 2020; Swain et al., 2020; Tabari, 2020; Ebi et al., 2021; Li Z. et al., 2022). Prein et al. (Prein et al., 2017) examined the potential patterns, particularly in the context of the Mesoscale Convective System (MSC), discussing an anticipated 15%–40% rise in maximum rainfall rates, coupled with expanded regions affected by heavy precipitation, which could lead to an up to 80%

**TABLE 1 Summary of case histories of flooding effects on buried structures.**

| Event, year | Location | Type of infrastructure | Impact |
|---|---|---|---|
| Hurricane Andrew, 1992 | Gulf of Mexico | Pipeline | 485 pipelines were damaged (Veritas, 2006) |
| Hurricane Lili, 2002 | Gulf of Mexico | Pipeline | 120 pipelines damages were reported (Veritas, 2006) |
| Hurricane Ivan, 2004 | Gulf of Mexico | Pipeline | Produced high level of pipe damage with approximately 168 pipelines were damaged (Veritas, 2006) |
| Hurricane Katrina, 2005 | Gulf of Mexico | Pipeline | A total of 299 pipelines were damaged and about 2710 barrels of crude oil and condensate spilled into the Gulf of Mexico (Veritas, 2006) |
| Hurricane Rita, 2005 | Gulf of Mexico | Pipeline | 243 pipelines damages were reported, and 4577 barrels of crude oil and condensate spilled into the Gulf of Mexico (Veritas, 2006) |
| Flooding, 2011 | Laurel, Montana | Pipeline | A 12-inch crude oil pipeline was ruptured due to excessive stress caused by the blockage of the pipelines with debris |
| | | | The estimated discharge was approximately 63,000 gallons of oil |
| Hurricane Sandy, 2012 | New York | Pipeline | Corrosion, leaks, service disruptions |
| 2016 | Pennsylvania | Pipeline | Release of over 1,238 barrels of gasoline spilled |
| Hurricane Harvey, 2017 | Beaumont, Texas | Pipeline | 16-inch natural gas pipeline was ruptured (Davis et al., 2021) |
| Flooding, 2018 | Montecito, California | Pipeline | A fire and explosion, the release of an estimated 12,000 Mcf of natural gas |
| Flooding, 2020 | Michigan | Pipeline | 447 Mcf was released from a gas distribution, road washout/scouring |
| Flooding, 2003 | Virginia | Tunnel | Flooded the tunnel system in just 40 min with almost 167 million liters (Sosa et al., 2014) |
| Hurricane Katrina, 2005 | Alabama | Tunnel | The Wallace Tunnel suffered minor flood damage and was closed due to high water from the surge |
| Hurricane Sandy, 2012 | New York | Tunnel | Seven metro tunnels and three vehicular tunnels flooded |
| Flooding, 2001 | New York | Culvert | Washout of an interstate culvert, which resulted in two deaths. (Truhlar et al., 2020) |
| Flooding, 2016 | Wisconsin | Culvert | More than 100 culverts failed |

increase in MCS precipitation volume. Li Z. et al., 2022 indicated that flash floods in the United States are expected to become 7.9% more intense by the end of the century. Bian et al., 2023 concluded that a warmer climate is expected to contribute to a more severe flood magnitude in the region. Rodell and Li, 2023 used observations from the two satellites to identify and characterize 1,056 extreme events from 2002 to 2021. They found a strong correlation between the global intensity of extreme wet and dry events and global warming. This relationship has been confirmed in other studies as well (Hirabayashi et al., 2013; Arnell and Gosling, 2016; Wright et al., 2019; Diffenbaugh, 2020; Kirezci et al., 2020; Meresa et al., 2022; Bian et al., 2023; Rodell and Li, 2023).

The combined effects of urbanization and climate change pose a significant and growing threat of urban flooding, often referred to as flash floods (Miller and Hutchins, 2017; Hemmati et al., 2020; Sun et al., 2021; Yang et al., 2021; Hassan et al., 2022). Severe floods can damage civil infrastructures, including buildings, bridges, roadways, and buried structures, leading to economic and socio-environmental crises (Azevedo de Almeida and Mostafavi, 2016; Poirier et al., 2022). Hurricane Katrina in 2015 caused an estimated USD 5.5 billion in infrastructure damage, including roads and bridges. In 2017, Texas was hit by Hurricane Harvey, resulting in approximately USD 125 billion in damages. This damage includes 300,000 structures and up to half a million cars. According to a technical report of an investigation on the resilience of infrastructures during Hurricane Harvey (Mostafavi et al., 2022), 231 bridges were damaged by the storm from Hurricane Harvey. Buried infrastructures, often concealed beneath layers of soils and pavement structure, play a crucial yet frequently overlooked role in sustaining the functionality and development of urban environments. This intricate network of pipelines, cables, and tunnels constitutes the lifeline of our cities, providing essential services such as water supply, sewage disposal, energy distribution, and telecommunication (Azevedo de Almeida and Mostafavi, 2016; Wang and Yin, 2022). The United States is connected by twenty million mile-long of underground infrastructure, providing essential services such as power, water, and communication to every residence and business (CGA, 2018). Unlike the obviosity of the above-ground structures, the effects of flooding on buried infrastructures are usually not observable (Bennich et al., 2023). However, the consequences of flooding on buried infrastructures are significant and can lead to various challenges, such as structural

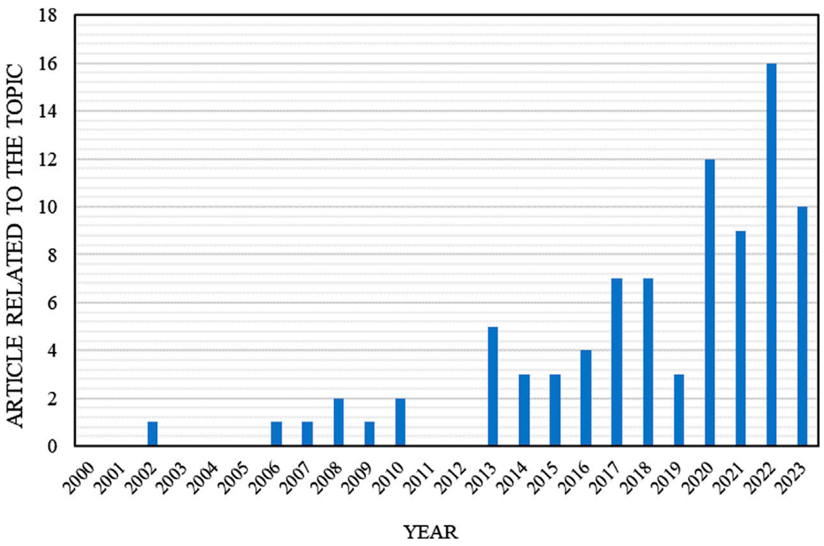

**FIGURE 1**
Publication number distribution in years of 2000–2023.

damage, erosion, displacement, and operational issues. Due to the concealed nature of buried structures, monitoring and assessing their conditions during and after floods can be challenging, and issues may not be immediately visible (Hughes et al., 2021; Bosserelle et al., 2022). Flood events may affect the stability of foundations of buried structures, especially if there is soil erosion of the surrounding soils (Guihui, 2013; Han et al., 2023). The case histories delve into the significant impact and aftermath of flood effects on buried structures across the United States are summarized in Table 1.

Considering the importance of buried structures to the communities and the severe damages of the buried structures caused by flooding, this paper aims to 1) review the state-of-the-art research on the flooding effects on buried structures and summarize causes of failures of buried infrastructures induced by flooding; 2) identify the research gaps on this topic to motivate in-depth investigations; and 3) discuss the future research directions.

## 2 Methodology

This review paper uses a systematic review of the literature to examine the various impacts of floods on buried infrastructure to obtain a deeper insight into their condition during flooding events and the various factors that contribute to their vulnerability. Initially, over two hundred research articles, government reports, and non-governmental documents were collected by exploring academic databases such as Google Scholar, Web of Science, and Science Direct. A detailed review of the selected articles focused on floods' impacts on buried infrastructure, specifically pipelines, tunnels, and culverts. Keywords were used for the literature search including flood, flooding events, hurricanes, civil infrastructure, buried infrastructure, underground infrastructure, pipelines, tunnel, sewer pipe, water pipe, subway, and culverts. After data retrieval, a meticulous cleaning process filtered out unrelated literature, resulting in 93 papers for systematic in-depth review. Figure 1 shows the yearly number of publications selected for this study in years from 2000 to 2023. Notably, there has been a growing trend of attention and substantial research increase in this field over the past 4 years.

## 3 State-of-the-art literature review

The determinants of flood damage on buried infrastructures are multifaceted and can vary based on the specific characteristics of the infrastructure, the local environment, and the nature of the flood event. Understanding and addressing these determinants is crucial for developing strategies to enhance the resilience of buried infrastructures to flood damage. In this section, we summarized the state-of-art research on three major types of buried infrastructures: pipelines, tunnels, and culverts.

### 3.1 Pipelines

Pipelines serve as crucial structural components in both industrial and civil facilities. There are different types of pipelines, such as natural gas, oil, water, sewer, liquid petroleum, and chemical. Pipelines have been identified as highly susceptible to flood effects, often resulting in the loss of containment and potential reactions between released chemicals and water. For example, hurricanes Rita and Katrina caused more than 600 hazardous material releases from gas installations, offshore oil facilities, and pipelines due to tanks being deformed and connected pipelines ruptured (Cruz and Krausmann, 2013). Several causes are attributed to the damage of pipelines induced by flooding including additional pressure on pipelines, corrosions by contaminants in floodwaters, floating debris, and soil erosion. The following paragraphs will discuss different causes in detail.

Floods can change the weight and density of the soil which can lead to bending and shifting, gradually thinning the pipeline's metal and causing it to rupture over time (Hyde-Smith et al., 2022). Flooding also exposes pipes to issues such as subsidence, soil swelling, and loss of support due to water infiltration. The rise of the water table during flood can result in a net upward force on the buried pipe when the buoyancy force exceeds the self-weight of the pipe and soil cover above the pipe which may lift the pipe out of the ground, resulting in a rupture or separation of the connecting pipes (Huang et al., 2021). Huang et al., 2021 also explored using Light Detection and Ranging (LiDAR) data for the vulnerability analysis of underground gas pipeline systems after hurricanes. They found out that forces on the pipe caused by flooding might have been the main cause for the pipeline damages in the Hurricane Sandy. In storm surge flooding situations, pressures higher than hydrostatic pressue can be transmitted through soils to buried pipelines, posing potential failure modes such as cracking, fracturing, or buckling (Gokhale and Rahman, 2008). Wang et al., 2013 conducted both numerical and analytical analyses on floating pipes subjected to distributed line loads caused by floods, modeling pipelines as cables without bending stiffness. They found that the change in the diameter of the pipe is the most sensitive factor to the stress of the pipe, which was influenced by the floods.

Corrosion, particularly on the outer surfaces, is a leading factor contributing to the failure of pipelines (Dai et al., 2017; Zhao et al., 2018; Łaciak et al., 2020; Qin et al., 2022; Hussein Farh et al., 2023). Floodwaters contain a significant amount of pollutants and aggressive contaminants, often harmful or toxic. The increased exposure to water can accelerate corrosion on the external surfaces of pipelines, weakening the material and compromising structural integrity (Łaciak et al., 2020; Hussein Farh et al., 2023). Laciak et al. (Łaciak et al., 2020) used a finite element method (FEM) to construct ball valve models to assess how floodwaters influence the occurrence of corrosion within natural gas transmission systems. They found that initiating or accelerating the corrosion of valve elements is the primary threat. Li et al., 2017 created a detailed nonlinear FEM model to simulate pipelines with corrosion defects to understand how this can impact the structural integrity of the pipelines when subjected to flooding. The findings of the study indicate that corrosion defects have a notable influence on the structural integrity of pipes during a flood. In addition to directly harming the pipe itself, corrosion can affect water quality as well (Gholizadeh et al., 2017; Yang et al., 2017). Awuku et al., 2023 used artificial intelligence algorithms to analyze pipeline failures. By integrating climate change data with the Pipeline and Hazardous Material Safety Administration (PHMSA) dataset spanning from 2010 to 2022, their model identifies corrosion is one of the major causes of pipeline failure caused by flooding.

Debris carried by floodwaters can also cause abrasion, impact, or structural damage to pipelines (Ballesteros-Cánovas et al., 2015). These damages may result in leaks, breaks, or complete failures in the water and wastewater systems. A watercourse pipeline can fail in a few ways because of the water's impact, which includes damage from objects carried by the water, like rocks or tree debris (Hans Olav Heggen, 2014; Ferris et al., 2015; Bainbridge, 2023).

Flow velocity is one of the parameters that greatly influenced severity of flood damage (Merz et al., 2007; Kreibich et al., 2009; Pistrika et al., 2014; Nofal & Van De Lindt, 2022). High-velocity floodwaters can erode soil and damage pipelines, in which the high flow causing scour of the bed, erosion of the banks and, in some cases, the formation of a new channel (avulsion) (Matthews and Matthews, 2013; Rossi et al., 2022; Othman et al., 2023). After a pipeline has been exposed by scouring, it's vulnerable to the impact from passing debris, particularly during times when there is a high-velocity flow. Underground erosion creates linear cavities in a process known as piping, where the soil is carried away by seeping groundwater (Aguilar-López et al., 2018). Heggen et al. ((Hans Olav Heggen, 2014) developed a model to predict the fatigue lives of onshore pipelines due to riverbed erosion. Their models showed that if riverbed scour causes an unsupported pipeline span, free span, to surpass a specific critical length where the natural frequency aligns with the driving frequency, fatigue failure can rapidly occur at the pipeline girth welds.

## 3.2 Tunnels

Tunnels play a critical role in the public transportation system of mega-cities. These structures are vulnerable to floods due to various factors associated with their design, location, and the nature of flood events. During heavy rainfall and flooding, water can overwhelm drainage systems, leading to excessive accumulation within the tunnel and posing risks to infrastructure integrity and transportation safety (Qian and Lin, 2016; Yum et al., 2020). Spyridis and Proske (Spyridis and Proske, 2021) concluded that 10%–20% of tunnel failures according to the study by, extreme weather, such as hurricanes, can cause flooding in tunnels, which can lead to damage or complete collapse of the tunnel. Ma et al. (Ma et al., 2022) investigated the water hazards in tunnels operating in China and identified two main causes: internal factors related to the geological conditions in the tunnel area and external factors associated with extreme weather conditions. Following paragraphs include major research findings in previous studies on these two main causes.

Lai et al., 2017 conducted an in-depth *in-situ* investigation on a highway tunnel in Gansu province, China, revealing that tunnel construction induced ground cracks, permitting surface water infiltration and compromising surrounding loess, which led to heightened loads on the tunnel structure, resulting in extensive cracking of the tunnel lining, particularly in the vault. This study further pointed out that flood caused excessive deformation in the secondary lining which induced severe cracking in the vault and adjacent sidewalls. Chen et al., 2022 discussed the collapse failure of a tunnel entrance under rainfall conditions, examining the failure mechanism, potential factors, and treatment measures through field investigation, theoretical analysis, and *in-situ* monitoring. The analysis results indicated that the reduction in soil shear strength was primarily due to a decline in the matric suction value caused by an increase in soil water content, leading to decreased sliding resistance in the entrance slope and ultimately triggering the collapse. Floodwaters can infiltrate the surrounding rock at the tunnel entrance can lead to erosion and softening of the material, which are the main causes of tunnel collapse (Yang et al., 2018; Wang and Cheng, 2021; Chen et al., 2022).

The high hydraulic pressure exerted by floodwaters can impose significant stress on tunnel walls and structures (Radovanović et al., 2022).

This pressure can contribute to erosion, scouring, and potential destabilization of the surrounding soil or support structures (Kondolf and Yi, 2022). Floodwaters often carry debris which can accumulate within road tunnels. Blockages can occur, hindering the proper functioning of drainage systems. Highway or road tunnels, especially near the coast, are critical infrastructure elements and are vulnerable to flooding in coastal areas, since large portions of these tunnels are beneath present sea level. This vulnerability is expected to grow due to rising sea levels and the effects of climate change (Jacobs et al., 2018; Li Q. et al., 2022). To provide references for the subway flood control design and optimize the location of flood sensor deployment, Dong et al., 2024 studied the overall pattern of floodwater intrusion into a subway tunnel through scaled-model experiments. The study involves investigating and analyzing flood flow patterns, water elevation, and flow velocity under varying conditions of tunnel slope and inlet water discharge. Lyu et al., 2018 used analytic hierarchy process (AHP) and the interval AHP (I-AHP) methods to evaluate regional flood risk, emphasizing the vulnerability of metro systems. Among the various factors contributing to the collapse of the tunnel entrance section, rainfall emerges as a significant factor, with a majority of tunnel collapse incidents attributed to rainfall (Chen et al., 2022).

Despite facing negative impacts and damage from flooding, tunnels can serve as an option to mitigate the effects of floods. These flood mitigation tunnels, known as underground flood tunnels, redirect excess flood or stormwater from the surface into underground tunnel facilities (Huang et al., 2019). This type of flood tunnel is constructed in stages and in areas where river channelization cannot occur due to established urban infrastructure. Some examples of underground flood tunnels in the United States include Waller Creek Tunnel, San Antonio River Tunnel, and Chicago Thornton Composite Reservoir.

## 3.3 Culverts

Culverts are important drainage systems made of concrete, steel, brick, or stone, providing pathways for water to travel under bridges, roads, or train tracks. These structures should convey flow without causing damaging backwater, excessive flow constriction, or excessive outlet velocities (Truhlar et al., 2020). During flooding events, culverts may face difficulties in performing their drainage function, due to factors such as high water volume, debris blockage, soil erosion, and/or other issues (Balkham et al., 2010; Gauthier et al., 2010). As a result, roads are damaged or impassable due to flooding-related issues, it can lead to interruptions and delays in traffic movement. There are multiple factors that can contribute to failures of culverts, including insufficient sizing, urbanization, the influence of climate change, and inadequate maintenance (Osei et al., 2023). Gauthier et al. (Gauthier et al., 2010) identified flood-vulnerable culverts based on their drainage capacity, utilizing a high-precision digital elevation model and considering topographic and hydrologic modifications induced by the road system. According to studies, it has been found that culvert failure is mostly due to blockage during a flood event (Rigby et al., 2002; Balkham et al., 2010; Kramer et al., 2015; Sorourian et al., 2016; Okamoto et al., 2020; Iqbal et al., 2021). Details of the blockage effects on culvert failures can be found in following paragraphs.

Floodwater often carries debris, including branches, leaves, sediment, and other materials, which can accumulate within and around culverts. As debris builds up inside the culvert, narrowing the passage through which water can flow, it can result in flow overtopping (Miranzadeh et al., 2023). Eventually, the reduction in capacity and flow overtopping can lead to inefficient water conveyance, potential damage, or a complete collapse of the culvert. The smaller the culvert, the more likely it is to become blocked. Small culverts are more prone to flooding compared to culverts with an opening wider than 6 m (Rigby et al., 2002; Miranzadeh et al., 2023). Flooding often involves a rapid and excessive flow of water. The culverts may fail if they are unable to handle the volume of water, leading to overtopping and potential structural failure (Miranzadeh et al., 2023). Miranzadeh et al., 2023 performed an experimental study to investigate the temporal variations of blockage upstream of culverts caused by woody debris under unsteady flow conditions, using a synthetic flow hydrograph to simulate floods. Wooden dowels of different diameters simulate the debris during flood events, with two culvert shapes (box and circular pipe) examined. Findings indicate that the maximum blockage percentage occurs during the falling limb of the hydrograph. While the feeding rate of smaller-diameter woody debris influences blockage, the feeding rate of larger debris does not impact the blockage percentage significantly. Additionally, pipe culverts were found to be more susceptible to blockage than box-shaped culverts. When there is a partial blockage in the culvert that cannot completely prevent the flow of water but causes some level of interference, it leads to a larger or more significant scour hole downstream (Sorourian et al., 2016; Taha et al., 2020a; Taha et al., 2020b). A large scour hole has the potential to undermine the foundations of the culvert. The erosive forces can remove supporting material, compromising the stability of the culvert structure and its surroundings (Jenssen, 1998). Taha et al. (Taha et al., 2020a; Taha et al., 2020b) performed experimental and numerical analyses to investigate the effects of blockage through a box culvert on flow and scour characteristics by different blockage ratios and compared with a nonblocked case. Their study emphasized that blockages is a major factor affecting flow and scour hole characteristics at culvert outlets. However, blockage through the culvert had a limited effect on the maximum scour depth.

The failure of aging, undersized, and poorly maintained culverts is a problem throughout the United States. Mainly because culverts are particularly prone to falling out of maintenance (Truhlar et al., 2020). After all, they are out of sight and, therefore, out of mind until a catastrophic failure occurs or deterioration is beyond repair (Kannangara and Kumara, 2008; Truhlar et al., 2020). Therefore, to reduce the failure probability of culverts during flood events, it is important to implement appropriate sizing and configuration (Furniss et al., 1997; Flanagan et al., 1998; Kannangara and Kumara, 2008), particularly when replacing undersized structures with appropriately designed culverts and bridges (Furniss et al., 1998).

# 4 Discussions and future research suggestions

The literature review reveals a comprehensive understanding of the associated vulnerabilities and consequences of flooding events. Influencing factors include the force of floodwaters (Gokhale and Rahman, 2008; Hans Olav Heggen, 2014; Ferris et al., 2015; Huang et al., 2021; Bainbridge, 2023), soil erosion (Merz et al., 2007;

Kreibich et al., 2009; Matthews and Matthews, 2013; Pistrika et al., 2014; Nofal & Van De Lindt, 2022; Rossi et al., 2022; Othman et al., 2023), and the intensity of floods/hurricanes (Bian et al., 2023; Rodell and Li, 2023). Techniques for assessing damage involve a combination of field inspections (Lai et al., 2017), remote sensing technologies (Forsyth et al., 2018), and data analysis (Taha et al., 2020a; Iqbal et al., 2021; Radovanović et al., 2022).

The limited focus on dedicated studies solely addressing the impact of floods on buried infrastructures, especially tunnels and culverts, can be attributed to several factors: misunderstanding, accessibility, lack of resources, and historical data. There is a common perception that flooding primarily affects above-ground structures, so the emphasis in research and studies may lean toward these visible impacts, leading to overlooking the specific vulnerabilities and consequences faced by buried infrastructures. Furthermore, challenges in their accessibility can be another factor since buried infrastructures are located underground, making it difficult to assess and monitor their conditions during and after flooding events. Despite the availability of many articles on the topic, this review highlights a lack of methodologies to assess flooding damage and its impact on buried infrastructures.

Understanding the impacts of flooding on buried infrastructures is vital for developing innovative solutions to enhance resilience and minimize consequences. This knowledge will contribute to more resilient infrastructure systems, fostering adaptability in the face of flooding events. Therefore, future research in this domain may consider the following directions:

(1) Investigate and distinguish key factors that dictate the severity of damage during flooding events, such as hurricanes and storms. It means broadening the scope of studies and including various factors to evaluate their potential to cause severe damage such as storm intensity and duration, climate change, and flooding patterns. The results of such studies can serve as a foundation for a more effective mitigation plan.
(2) Develop advanced modeling techniques, including numerical simulations and predictive analytics, to better assess the dynamic interactions between buried infrastructures and floodwaters.
(3) Explore the integration of smart technologies, such as sensors and real-time monitoring systems, to enable proactive infrastructure management during flooding events. For example, research on the application of artificial intelligence (AI), like machine learning to detect damages and failures during and after flooding events, can facilitate early detection of vulnerabilities and improve emergency response capabilities.

## 5 Conclusions

Buried infrastructures, vital to communities, are susceptible to damage from flooding events like hurricanes and storm surges. Challenges and risks arise during floods and hurricanes due to factors such as inundation, water pressure, and environmental stresses. This review paper uses a systematic review of the literature to evaluate the impacts of flooding events on buried infrastructures, particularly pipelines, tunnels, and culverts and summarize the causes of buried structure failures induced by flooding events. From our review, we withdrew the following conclusions:

(1) Additional pressure on pipelines, corrosions by contaminants in floodwaters, floating debris, and soil erosion are major causes of pipelines failures due to flooding.
(2) The failure of tunnels due to flooding can result from a combination of factors, encompassing structural, environmental, and geotechnical conditions, as well as the tunnel's location. Flood tunnels could mitigate the effects of floods.
(3) Blockage is the primary cause of culvert failures induced by flooding which could reduce the flow capacity of culverts and exaggerate soil erosion around culverts to cause collapse of culverts.
(4) Despite the availability of many articles on the topic, this review highlights a lack of methodologies to assess flooding damage and its impact on buried infrastructures. We suggested three future research directions based on this understanding including investigating and distinguishing key factors to quantify flooding damage to buried infrastructures, developing advanced modeling techniques, and exploring the integration of smart technologies in health monitoring of buried infrastructures.

## Author contributions

RA: Writing–original draft, Writing–review and editing. JX: Writing–review and editing. FW: Writing–review and editing. JH: Writing–review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# References

Aguilar-López, J. P., Warmink, J. J., Schielen, R. M. J., and Hulscher, S. J. M. H. (2018). Piping erosion safety assessment of flood defences founded over sewer pipes. *Eur. J. Environ. Civ. Eng.* 22 (6), 707–735. doi:10.1080/19648189.2016.1217793

Ali, H., Modi, P., and Mishra, V. (2019). Increased flood risk in Indian sub-continent under the warming climate. *Weather Clim. Extrem.* 25, 100212. doi:10.1016/j.wace.2019.100212

Arnell, N. W., and Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Clim. Change* 134 (3), 387–401. doi:10.1007/s10584-014-1084-5

Awuku, B., Huang, Y., and Yodo, N. (2023). Predicting natural gas pipeline failures caused by natural forces: an artificial intelligence classification approach. *Appl. Sci.* 13 (7), 4322. doi:10.3390/app13074322

Azevedo de Almeida, B., and Mostafavi, A. (2016). Resilience of infrastructure systems to sea-level rise in coastal areas: impacts, adaptation measures, and implementation challenges. *Sustainability* 8 (11), 1115. doi:10.3390/su8111115

Bainbridge, J. (2023). Proactive integrity management for pipeline river crossings. *Pipeline and Gas J.* 250 (6).

Balkham, M., Fosbeary, C., Kitchen, A., and Rickard, C. (2010). *Culvert design and operation guide*. London, UK: Construction and industry research and information association.

Ballesteros-Cánovas, J. A., Stoffel, M., St George, S., and Hirschboeck, K. (2015). A review of flood records from tree rings. *Prog. Phys. Geogr. Earth Environ.* 39 (6), 794–816. doi:10.1177/0309133315608758

Bennich, A., Engwall, M., and Nilsson, D. (2023). Operating in the shadowland: why water utilities fail to manage decaying infrastructure. *Util. Policy* 82, 101557. doi:10.1016/j.jup.2023.101557

Bian, G., Zhang, J., Song, M., Qian, X., Guan, T., and Wang, G. (2023). Projections of flood regime changes over the upper-middle Huaihe River Basin in China based on CMIP6 models. *Front. Environ. Sci.* 11. doi:10.3389/fenvs.2023.1247753

Bosserelle, A. L., Morgan, L. K., and Hughes, M. W. (2022). Groundwater rise and associated flooding in coastal settlements due to sea-level rise: a review of processes and methods. *Earth's Future* 10 (7). doi:10.1029/2021ef002580

Cga, C. G. A. (2018). Survey reveals nearly 40 percent of homeowners who plan to dig this year will put themselves and others at risk by not calling 811 before starting. Available at: https://commongroundalliance.com/Resource-Redirects/survey-reveals-nearly-40-percent-of-homeowners-who-plan-to-dig-this-year-will-put-themselves-and-others-at-risk-by-not-calling-811-before-starting.

Chen, L.-L., Wang, Z.-F., and Wang, Y.-Q. (2022). Failure analysis and treatments of tunnel entrance collapse due to sustained rainfall: a case study. *Water* 14 (16), 2486. doi:10.3390/w14162486

Cruz, A. M., and Krausmann, E. (2013). Vulnerability of the oil and gas sector to climate change and extreme weather events. *Clim. Change* 121 (1), 41–53. doi:10.1007/s10584-013-0891-4

Dai, L., Wang, D., Wang, T., Feng, Q., and Yang, X. (2017). Analysis and comparison of long-distance pipeline failures. *J. Petroleum Eng.* 2017, 1–7. doi:10.1155/2017/3174636

Davis, A., Thrift-Viveros, D., and Baker, C. M. S. (2021). NOAA scientific support for a natural gas pipeline release during hurricane Harvey flooding in the neches river beaumont, Texas. *Int. Oil Spill Conf. Proc.* 2021 (1). doi:10.7901/2169-3358-2021.1.687018

Diffenbaugh, N. S. (2020). Verification of extreme event attribution: using out-of-sample observations to assess changes in probabilities of unprecedented events. *Sci. Adv.* 6 (12), eaay2368. doi:10.1126/sciadv.aay2368

Dong, W., Huang, H., Zhong, M., and Long, Z. (2024). Experimental study on the inundation characteristics of flooding in a long straight subway tunnel. *Tunn. Undergr. Space Technol.* 144, 105566. doi:10.1016/j.tust.2023.105566

Ebi, K. L., Vanos, J., Baldwin, J. W., Bell, J. E., Hondula, D. M., Errett, N. A., et al. (2021). Extreme weather and climate change: population health and health system implications. *Annu. Rev. Public Health* 42, 293–315. doi:10.1146/annurev-publhealth-012420-105026

Ferris, G., Newton, S., Ho, M., Eichhorn, G., and Bear, D. (2015). *Flood monitoring for buried pipeline watercourse crossings*.

Flanagan, S. A., Furniss, M. J., Ledwith, T. S., Thiesen, S., Love, M., Moore, K., et al. (1998). *Methods for inventory and environmental risk assessment of road drainage crossings*. California: S. D. San Dimas Technology and Development Center.

Forsyth, R. A., Hartzell, C. S., Chader, S. A., and Browne, T. M. (2018). "Underwater inspection and imaging technologies for pipelines," in *Pipelines 2018*, 608–617. doi:10.1061/9780784481653.067

Furniss, M. J., Ledwith, T. S., Love, M. A., McFadin, B. C., and Flanagan, S. A. (1998). *Response of RoadStream crossings to large flood events in Washington, Oregon, and northern California*. California: S. D. San Dimas Technology and Development Center.

Furniss, M. J., Love, M., and Flanagan, S. A. (1997). Diversion potential at road-stream crossings. Available at: https://www.fs.usda.gov/t-d/pubs/html/wr_p/97771814/97771814.htm#:~:text=regardless%20of%20capacity.-,What%20is%20Stream%20Diversion%20Potential%3F,(Weaver%20and%20Hagans%201994).

Gauthier, M.-E., Leroux, D., and Assani, A. (2010). *Vulnerability of culvert to flooding*.

Gholizadeh, A., Mokhtari, M., Naimi, N., Shiravand, B., Ehrampoush, M. H., Miri, M., et al. (2017). Assessment of corrosion and scaling potential in groundwater resources; a case study of Yazd-Ardakan Plain, Iran. *Groundw. Sustain. Dev.* 5, 59–65. doi:10.1016/j.gsd.2017.04.002

Gokhale, S., and Rahman, S. (2008). *Pipelines 2008 - pipeline asset management: maximizing performance of our pipeline infrastructure*. doi:10.1061/9780784409947

Guihui, Z. (2013). Analysis of residential building failure under flood action based on building and human life safety. *J. Nat. Disasters*.

Han, Z., Ding, H., Yan, H., Zeng, C., Li, C., Xie, W., et al. (2023). Investigating the bearing performance of the foundation under the combined effects of flood scouring and soaking. *Sci. Rep.* 13 (1), 22823. doi:10.1038/s41598-023-50235-9

Hans Olav Heggen, R. F., Fyrileiv, O., Ferris, G., and Ho, M. (2014). Fatigue of pipelines Subjected to vortex-induced Vibrations at river *rio oil and gas expo and conference 2014*. Brazil: Rio de Janeiro.

Hassan, B. T., Yassine, M., and Amin, D. (2022). Comparison of urbanization, climate change, and drainage design impacts on urban flashfloods in an arid region: case study, new Cairo, Egypt. *Water* 14 (15), 2430. doi:10.3390/w14152430

Hemmati, M., Ellingwood, B. R., and Mahmoud, H. N. (2020). The role of urban growth in resilience of communities under flood risk. *Earths Future* 8 (3), e2019EF001382. doi:10.1029/2019ef001382

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., et al. (2013). Global flood risk under climate change. *Nat. Clim. Change* 3 (9), 816–821. doi:10.1038/nclimate1911

Huang, H., Zhang, L., Liu, L., Wang, X., Wang, X., Pan, C., et al. (2019). Assessing the mitigation effect of deep tunnels on urban flooding: a case study in Guangzhou, China. *Urban Water J.* 16 (4), 312–321. doi:10.1080/1573062x.2019.1669186

Huang, X., Gong, J., Chen, P., Tian, Y., and Hu, X. (2021). Towards the adaptability of coastal resilience: vulnerability analysis of underground gas pipeline system after hurricanes using LiDAR data. *Ocean Coast. Manag.* 209, 105694. doi:10.1016/j.ocecoaman.2021.105694

Hughes, J., Cowper-Heays, K., Olesson, E., Bell, R., and Stroombergen, A. (2021). Impacts and implications of climate change on wastewater systems: a New Zealand perspective. *Clim. Risk Manag.* 31, 100262. doi:10.1016/j.crm.2020.100262

Hussein Farh, H. M., Ben Seghier, M. E. A., Taiwo, R., and Zayed, T. (2023). Analysis and ranking of corrosion causes for water pipelines: a critical review. *npj Clean. Water* 6 (1), 65. doi:10.1038/s41545-023-00275-5

Hyde-Smith, L., Zhan, Z., Roelich, K., Mdee, A., and Evans, B. (2022). Climate change impacts on urban sanitation: a systematic review and failure mode analysis. *Environ. Sci. Technol.* 56 (9), 5306–5321. doi:10.1021/acs.est.1c07424

Iqbal, U., Barthelemy, J., Li, W., and Perez, P. (2021). Automating visual blockage classification of culverts with deep learning. *Appl. Sci.* 11 (16), 7561. doi:10.3390/app11167561

Jacobs, J. M., Cattaneo, L. R., Sweet, W., and Mansfield, T. (2018). Recent and future outlooks for nuisance flooding impacts on roadways on the U.S. East coast. *Transp. Res. Rec.* 2672 (2), 1–10. doi:10.1177/0361198118756366

Jenssen, L. (1998). *Assessing infrastructure vulnerability to major floods*. Trondheim, Norway: Norwegian University of Science and Technology.

Kannangara, K., and Kumara, M. (2008). *Culvert management system*.

Kirezci, E., Young, I. R., Ranasinghe, R., Muis, S., Nicholls, R. J., Lincke, D., et al. (2020). Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Sci. Rep.* 10 (1), 11629. doi:10.1038/s41598-020-67736-6

Kondolf, M., and Yi, J. (2022). Dam renovation to prolong Reservoir life and mitigate dam impacts. *Water* 14 (9), 1464. doi:10.3390/w14091464

Kramer, M., Peirson, W., French, R., and Smith, G. (2015). A physical model study of culvert blockage by large urban debris. *Australas. J. Water Resour.* 19 (2), 127–133. doi:10.1080/13241583.2015.1116184

Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., et al. (2009). Is flow velocity a significant parameter in flood damage modelling? *Nat. Hazards Earth Syst. Sci.* 9 (5), 1679–1692. doi:10.5194/nhess-9-1679-2009

Łaciak, M., Włodek, T., Kozakiewicz, T., and Liszka, K. (2020). Impact of flood water on the technical condition of natural gas transmission pipeline valves. *J. Loss Prev. Process Industries* 63, 103998. doi:10.1016/j.jlp.2019.103998

Lai, H., Song, W., Liu, Y., and Chen, R. (2017). Influence of flooded loessial overburden on the tunnel lining: case study. *J. Perform. Constr. Facil.* 31 (6), 04017108. doi:10.1061/(asce)cf.1943-5509.0001100

Li, Q., Qian, R., Gao, J., and Huang, J. (2022a). Environmental impacts and risks of bridges and tunnels across lakes: an overview. *J. Environ. Manag.* 319, 115684. doi:10.1016/j.jenvman.2022.115684

Li, S., Duan, Q., Zhang, H., and Wang, J. (2017). Failure analysis of the floating pipeline with defect under flooding load. *Eng. Fail. Anal.* 77, 65–75. doi:10.1016/j.engfailanal.2017.02.011

Li, Z., Gao, S., Chen, M., Gourley, J. J., Liu, C., Prein, A. F., et al. (2022b). The conterminous United States are projected to become more prone to flash floods in a high-end emissions scenario. *Commun. Earth Environ.* 3 (1), 86. doi:10.1038/s43247-022-00409-6

Lyu, H.-M., Sun, W.-J., Shen, S.-L., and Arulrajah, A. (2018). Flood risk assessment in metro systems of mega-cities using a GIS-based modeling approach. *Sci. Total Environ.* 626, 1012–1025. doi:10.1016/j.scitotenv.2018.01.138

Ma, Y., Yang, J., Li, L., and Li, Y. (2022). Analysis on ultimate water pressure and treatment measures of tunnels operating in water rich areas based on water hazard investigation. *Alexandria Eng. J.* 61 (8), 6581–6589. doi:10.1016/j.aej.2021.11.040

Matthews, E. C., and Matthews, J. C. (2013). Impacts of emergencies on water and wastewater systems in congested urban areas. *Waterlines* 32 (1), 74–86. doi:10.3362/1756-3488.2013.007

Meresa, H., Tischbein, B., and Mekonnen, T. (2022). Climate change impact on extreme precipitation and peak flood magnitude and frequency: observations from CMIP6 and hydrological models. *Nat. Hazards* 111 (3), 2649–2679. doi:10.1007/s11069-021-05152-3

Merz, B., Thieken, A. H., and Gocht, M. (2007). *Flood risk mapping at the local scale: concepts and challenges*. Netherlands: Springer, 231–251. doi:10.1007/978-1-4020-4200-3_13

Miller, J. D., and Hutchins, M. (2017). The impacts of urbanisation and climate change on urban flooding and urban water quality: a review of the evidence concerning the United Kingdom. *J. Hydrology Regional Stud.* 12, 345–362. doi:10.1016/j.ejrh.2017.06.006

Miranzadeh, A., Keshavarzi, A., and Hamidifar, H. (2023). Blockage of box-shaped and circular culverts under flood event conditions: a laboratory investigation. *Int. J. River Basin Manag.* 21 (4), 607–616. doi:10.1080/15715124.2022.2064483

Mostafavi, A., Padgett, J., Dueñas-Osorio, L., Sutley, E., Norton, T., Lester, H., et al. (2022). *Hurricane Harvey infrastructure resilience investigation report*. doi:10.17603/ds2-gcrf-h607

Neri, A., Villarini, G., and Napolitano, F. (2020). Statistically-based projected changes in the frequency of flood events across the U.S. Midwest. *J. Hydrology* 584, 124314. doi:10.1016/j.jhydrol.2019.124314

Noaa, N. C. f. E. I., and NCEI (2024). *U.S. Billion-dollar weather and climate disasters*. doi:10.25921/stkw-7w73

Nofal, O. M., and Van De Lindt, J. W. (2022). Understanding flood risk in the context of community resilience modeling for the built environment: research needs and trends. *Sustain. Resilient Infrastructure* 7 (3), 171–187. doi:10.1080/23789689.2020.1722546

Okamoto, T., Takebayashi, H., Sanjou, M., Suzuki, R., and Toda, K. (2020). Log jam formation at bridges and the effect on floodplain flow: a flume experiment. *J. Flood Risk Manag.* 13, e12562. doi:10.1111/jfr3.12562

Osei, J. D., Damoah-Afari, P., Anyemedu, F. O. K., Lartey, E. O., and Yevugah, L. L. (2023). Using integrated GIS and hydrological analysis for sizing culverts of multiple channel crossings at the flooded section of the Daboya-Mankarigu Road (IR10) in Ghana. *Heliyon* 9 (12), e22863. doi:10.1016/j.heliyon.2023.e22863

Othman, A., El-Saoud, W. A., Habeebullah, T., Shaaban, F., and Abotalib, A. Z. (2023). Risk assessment of flash flood and soil erosion impacts on electrical infrastructures in overcrowded mountainous urban areas under climate change. *Reliab. Eng. Syst. Saf.* 236, 109302. doi:10.1016/j.ress.2023.109302

Pistrika, A., Tsakiris, G., and Nalbantis, I. (2014). Flood depth-damage functions for built environment. *Environ. Process.* 1 (4), 553–572. doi:10.1007/s40710-014-0038-2

Poirier, L., Knox, P., Murphy, E., and Provan, M. (2022). *Flood damage to critical infrastructure*. doi:10.4224/40002986

Prein, A. F., Liu, C., Ikeda, K., Trier, S. B., Rasmussen, R. M., Holland, G. J., et al. (2017). Increased rainfall volume from future convective storms in the US. *Nat. Clim. Change* 7 (12), 880–884. doi:10.1038/s41558-017-0007-7

Qian, Q., and Lin, P. (2016). Safety risk management of underground engineering in China: progress, challenges and strategies. *J. Rock Mech. Geotechnical Eng.* 8 (4), 423–442. doi:10.1016/j.jrmge.2016.04.001

Qin, G., Tang, S., Li, R., Xia, A., Zhang, Z., and Wang, Y. (2022). An information entropy-based risk assessment method for multiple-media gathering pipelines. *J. Infrastructure Preserv. Resil.* 3 (1), 19. doi:10.1186/s43065-022-00066-1

Radovanović, S., Milivojević, M., Stojanović, B., Obradović, S., Divac, D., and Milivojević, N. (2022). Modeling of water losses in hydraulic tunnels under pressure based on stepwise regression method. *Appl. Sci.* 12 (18), 9019. doi:10.3390/app12189019

Rigby, E., Boyd, M., Roso, S., Silveri, P., and Davis, A. (2002). "Causes and effects of culvert blockage during large storms," in *Global solutions for urban drainage*, 1–16.

Rodell, M., and Li, B. (2023). Changing intensity of hydroclimatic extreme events revealed by GRACE and GRACE-FO. *Nat. Water* 1 (3), 241–248. doi:10.1038/s44221-023-00040-5

Rossi, L., Casson Moreno, V., and Landucci, G. (2022). Vulnerability assessment of process pipelines affected by flood events. *Reliab. Eng. Syst. Saf.* 219, 108261. doi:10.1016/j.ress.2021.108261

Sorourian, S., Keshavarzi, A., and Ball, J. E. (2016). Scour at partially blocked box-culverts under steady flow. *Proc. Institution Civ. Engineers-Water Manag.* 169, 247–259. doi:10.1680/jwama.15.00019

Sosa, E. M., Thompson, G. J., and Barbero, E. J. (2014). Testing of full-scale inflatable plug for flood mitigation in tunnels. *Transp. Res. Rec.* 2407 (1), 59–67. doi:10.3141/2407-06

Spyridis, P., and Proske, D. (2021). Revised comparison of tunnel collapse frequencies and tunnel failure probabilities. *ASCE-ASME J. Risk Uncertain. Eng. Syst. Part A Civ. Eng.* 7 (2), 04021004. doi:10.1061/AJRUA6.0001107

Sun, X., Li, R., Shan, X., Xu, H., and Wang, J. (2021). Assessment of climate change impacts and urban flood management schemes in central Shanghai. *Int. J. Disaster Risk Reduct.* 65, 102563. doi:10.1016/j.ijdrr.2021.102563

Swain, D. L., Wing, O. E. J., Bates, P. D., Done, J. M., Johnson, K. A., and Cameron, D. R. (2020). Increased flood exposure due to climate change and population growth in the United States. *Earth's Future* 8 (11). doi:10.1029/2020ef001778

Tabari, H. (2020). Climate change impact on flood and extreme precipitation increases with water availability. *Sci. Rep.* 10 (1), 13768. doi:10.1038/s41598-020-70816-2

Taha, N., El-Feky, M. M., El-Saiad, A. A., and Fathy, I. (2020a). Numerical investigation of scour characteristics downstream of blocked culverts. *Alexandria Eng. J.* 59 (5), 3503–3513. doi:10.1016/j.aej.2020.05.032

Taha, N., El-Feky, M. M., El-Saiad, A. A., Zelenakova, M., Vranay, F., and Fathy, I. (2020b). Study of scour characteristics downstream of partially-blocked circular culverts. *Water* 12 (10), 2845. doi:10.3390/w12102845

Truhlar, A. M., Marjerison, R. D., Gold, D. F., Watkins, L., Archibald, J. A., Lung, M. E., et al. (2020). Rapid remote assessment of culvert flooding risk. *J. Sustain. Water Built Environ.* 6 (2), 06020001. doi:10.1061/JSWBAY.0000900

Veritas, D. N. (2006). "Pipeline damage assessment from hurricane Ivan in the Gulf of Mexico," in *Houston*.

Wang, M., and Yin, X. (2022). Construction and maintenance of urban underground infrastructure with digital technologies. *Automation Constr.* 141, 104464. doi:10.1016/j.autcon.2022.104464

Wang, X., Wang, Z., and Han, B. (2013). "Mechanical response analysis of pipeline under the action of floods," in *Icptt 2013: trenchless technology*, 1185–1195.

Wang, Z.-F., and Cheng, W.-C. (2021). Predicting jet-grout column diameter to mitigate the environmental impact using an artificial intelligence algorithm. *Undergr. Space* 6 (3), 267–280. doi:10.1016/j.undsp.2020.02.004

Wright, D. B., Bosma, C. D., and Lopez-Cantu, T. (2019). U.S. Hydrologic design standards insufficient due to large increases in frequency of rainfall extremes. *Geophys. Res. Lett.* 46 (14), 8144–8153. doi:10.1029/2019gl083235

Yang, F., Shi, B., Zhang, W., Cui, J., Guo, J., Wang, D., et al. (2017). Pyrosequencing analysis of source water switch and sulfate-induced bacterial community transformation in simulated drinking water distribution pipes. *Environ. Sci. Pollut. Res.* 24 (36), 28220–28238. doi:10.1007/s11356-017-0370-y

Yang, Q., Zheng, X., Jin, L., Lei, X., Shao, B., and Chen, Y. (2021). Research progress of urban floods under climate change and urbanization: a scientometric analysis. *Buildings* 11 (12), 628. doi:10.3390/buildings11120628

Yang, Z.-M., Wu, S.-C., Gao, Y.-T., Jin, A.-B., and Cong, Z.-J. (2018). Time and technique of rehabilitation for large deformation of tunnels in jointed rock masses based on FDM and DEM numerical modeling. *Tunn. Undergr. Space Technol.* 81, 669–681. doi:10.1016/j.tust.2018.08.036

Yum, S.-G., Ahn, S., Bae, J., and Kim, J.-M. (2020). Assessing the risk of natural disaster-induced losses to tunnel-construction projects using empirical financial-loss data from South Korea. *Sustainability* 12 (19), 8026. doi:10.3390/su12198026

Zhao, W., Zhang, T., Wang, Y., Qiao, J., and Wang, Z. (2018). Corrosion failure mechanism of associated gas transmission pipeline. *Mater. (Basel)* 11 (10), 1935. doi:10.3390/ma11101935