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Smart Disaster Prevention and Mitigation Systems for Resilient Urban Reconstruction: Opportunities and Barriers

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Abstract

Against the backdrop of global urbanization, this article addresses the issue of infrastructure disaster prevention and mitigation. By examining the current status and challenges of global infrastructure disasters, it highlights the dual responsibilities of civil engineers in both the prevention and response phases of infrastructure disasters. It systematically elaborates on the core role of civil engineers in disaster prevention and response, and proposes the necessity of advocating resilience design to enhance infrastructure's resistance, recovery, adaptability, and sustainability capacities. The conclusion emphasizes that engineers must drive technological innovation, policy improvement, and collaborative cooperation to achieve a transformation of infrastructure from "post-disaster response" to "resilience resistance," ultimately building a safe and sustainable future.

Keywords

Infrastructure Disasters; Resilience; Prevention and Response; Smart Systems.

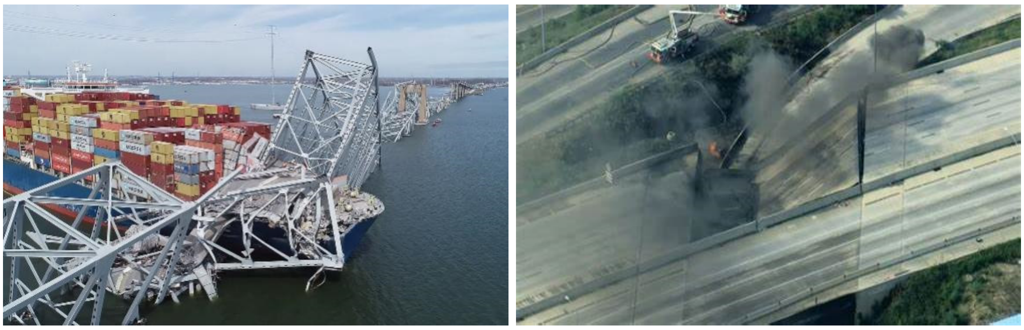
1. Introduction

Table 1. Selected Major Infrastructure Disasters

Event	Cause	Loss	Date
Zhengzhou, Henan Province Floods	Extreme rainfall; lack of proper awareness of disaster risks among relevant management personnel	Over 13 million people affected; direct losses of ¥88.534 billion	July 2021
Derna Dam Collapse, Libya	Extreme rainfall; war; aging and poor maintenance of infrastructure	Officially reported 5,923 deaths	September 2023
Baltimore Bridge Collapse	Cargo ship power failure; lack of reinforcement measures on the bridge	Estimated losses exceeding $1.6 billion	March 2024
Interstate 95 Collapse	Fuel tanker fire	Over $1 billion in damages	June 2023

With the advancement of global urbanization, infrastructure systems have become the "lifeline projects" underpinning the operation of modern society. These include roads, bridges, subways, hospitals, and other engineering facilities that provide services for social production and residents' daily lives. Once damaged, these infrastructures can lead to immeasurable losses. According to the 2022 Global Risk Assessment Report by the United Nations Office for Disaster Risk Reduction (UNDRR), the annual direct economic losses caused by major infrastructure disasters over the past decade have averaged $412 billion, with a compound annual growth rate of 7.8%. Among these, climate change and human negligence are significant contributing factors. Table 1 lists some major infrastructure disasters caused by climate change and human negligence in recent years, while Figure 1 illustrates some of the affected scenes. These disasters serve as a stark reminder to contemporary civil engineers that protecting critical infrastructure from climate change and human impacts is an urgent imperative.

(a) Zhengzhou, Henan Province Floods (b)Derna Dam Collapse, Libya



(c)Baltimore Bridge Collapse (d)Interstate 95 Collapse

Fig 1. Selected Affected Scenes

2. Role of Civil Engineers Play in the Prevention and Response

2.1. Prevention

In addressing infrastructure disasters, the primary responsibility of civil engineers is prevention. To achieve this goal, it is imperative to incorporate considerations for various potential loads and adhere to stringent safety codes and design standards during the design and construction phases of infrastructure projects. This approach effectively prevents major safety incidents and ensures the smooth progression of infrastructure projects.

Furthermore, Civil engineers are also responsible for conducting regular assessments and maintenance of infrastructure. According to China's Technical Code for Maintenance of Urban Bridges (CJJ 99-2017), periodic inspections must be carried out, including: Routine inspections at least annually to check for surface cracks, bearing deformations, etc. Structural assessments every 3-6 years, using load tests or non-destructive testing to evaluate load-carrying capacity. Special inspections immediately following disasters such as earthquakes or floods.

Following the 2021 Zhengzhou heavy rainfall, Henan Provincial Transportation Department conducted emergency inspections of bridges province-wide. A river-crossing bridge was found to have exposed pile foundations due to scouring, prompting engineers to reinforce it with riprap protection and steel cofferdams, avoiding collapse risks. Preventive maintenance measures include updating anti-corrosion coatings and repairing fatigue damage. For example: The Qingdao Jiaozhou Bay Subsea Tunnel applies silane impregnation agents to concrete structures every five years to delay chloride ion corrosion. Shanghai Yangpu Bridge undergoes periodic magnetic particle inspections on steel truss joints, with carbon fiber reinforcement used to address detected cracks.

With technological advancements, modern bridges utilize sensor networks for real-time monitoring. Increasingly dense sensors generate vast datasets for structural performance evaluation. The online analysis of monitoring data to assess in-service bridge behavior has become a critical issue in Structural Health Monitoring (SHM).

The Ningbo Waitan Bridge, a single-pylon, four-cable-plane extradosed bridge with a 225-meter main span and composite steel box girders, employs a health monitoring system that transmits data via fiber-optic networks to the Ningbo Urban Bridge Monitoring and Management Center. Monitoring points are distributed at the main girder sections (STR1-16) at the tower-girder integration zone and the root sections of the front pylons (STR17-24)

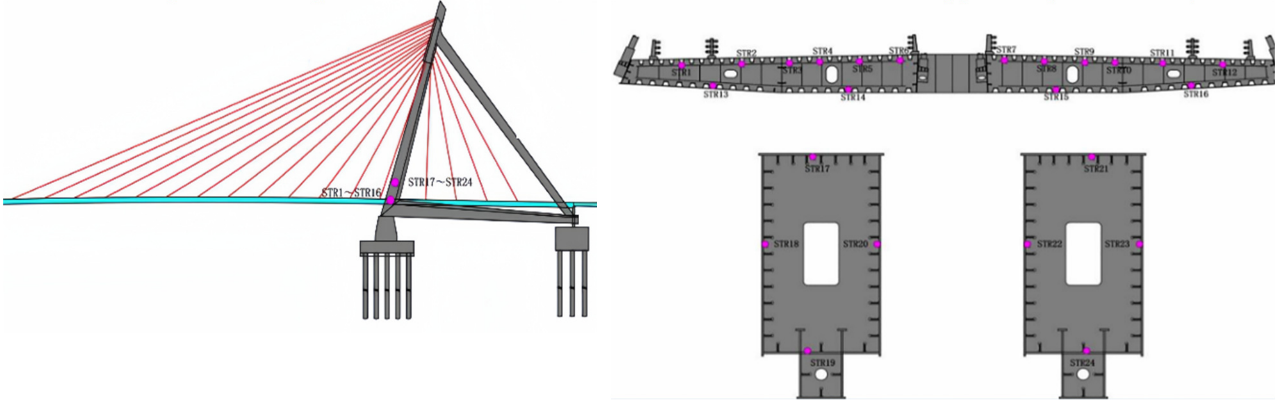


Fig 2. Sensor Layout of Bridge Inspection System for Ningbo Waitan Bridge

Finally, modern civil engineers are continuously advancing theoretical research and designing innovative devices to address potential major infrastructure disasters. For instance, Wanbin Technology's bridge health monitoring system deploys intelligent structural diagnostic devices (equipped with BeiDou satellite high-precision positioning) to monitor parameters such as bridge displacement, settlement, and cable force in real-time, achieving millimeter-level accuracy. Shanghai Shuoguan's SGQL-001 system uses wireless remote-controlled high-definition cameras to inspect bridge substructures, supporting deterioration size measurement and lifecycle tracking.These examples demonstrate that civil engineers play a pivotal role in preventing major infrastructure disasters.

Fig 3. Installation of Beidou High-Precision Monitoring Station Equipment

2.2. Response

In responding to infrastructure disasters, civil engineers are also responsible for post-disaster response efforts. As the technical core, civil engineers must immediately rush to the disaster site to assess the impact and coordinate repair work. They evaluate the damage extent through visual inspections, non-destructive testing (e.g. ultrasonic, infrared imaging), or structural calculations.

Furthermore, civil engineers are responsible for evaluating infrastructure functional losses such as transportation disruptions and utility outages (water/power supply). They carry out emergency repair work, implementing measures like temporary reinforcement and emergency power/water supply systems. After that, combining on-site investigations with data analysis, engineers quantify losses and design scientific, cost-effective repair plans to ensure long-term safety and functionality. During post-disaster reconstruction, advanced technologies like intelligent monitoring systems, new materials, and innovative construction methods are adopted to enhance assessment/repair efficiency and disaster resistance while reducing human errors. Through technological innovation and collaboration, civil engineers not only restore infrastructure functionality efficiently but also significantly improve its resilience, laying a foundation for future disaster prevention.

3. Advocating Resilient Design

3.1. Background

However, with prominent climate issues such as global warming and infrastructure disasters caused by various human-induced problems, traditional theories have become insufficient to support our responsibilities as civil engineers. To address this issue, advocating resilience design should become our future solution for combating climate and anthropogenic disasters. Nevertheless, according to the 2021 edition of the Infrastructure Resilience Assessment Guidelines by the American Society of Civil Engineers (ASCE), technical standards related to resilience design account for less than 15% of existing engineering specifications. Moreover, current research on resilience design predominantly focuses on optimizing quality control systems during the construction phase, revealing evident cognitive limitations in the understanding of infrastructure resilience design.

3.2. Necessity

Resilient design of infrastructure primarily encompasses four key aspects: resistance capacity, rapid recovery capacity, adaptability, and sustainability. Resistance capacity refers to the ability of infrastructure to maintain its functionality without significant impairment under stress or shocks. For example, adding supplementary support structures to infrastructure ensures that partial structural failure does not lead to immediate collapse. Rapid recovery capacity denotes the capability to restore normal operations swiftly after damage. Modular design can be employed to enable quick replacement or repair of damaged components.

Adaptability represents the infrastructure’s ability to accommodate long-term environmental and socioeconomic changes. The sponge city concept, for instance, effectively addresses extreme weather events induced by climate change. The adaptability of infrastructure goes beyond "disaster resistance"; it involves designing "evolutionary interfaces" that enable continuous optimization alongside environmental and societal changes, much like living organisms. Achieving true resilience requires interdisciplinary collaboration (engineering, ecology, sociology) and long-term investment.

For example, to address long-term environmental changes, the Netherlands’ Delta Works employs dynamic flood defense systems, such as the Maeslantkering storm surge barrier—a retractable floodgate that dynamically adjusts defense levels based on rising sea levels and extreme weather data, rather than relying on fixed-height levees. This initiative integrates real-time meteorological monitoring with automated control systems, closing gates only during storms while remaining open during normal times to preserve ecology and shipping.

To adapt to social changes, Tokyo’s subway system uses real-time passenger flow monitoring and AI scheduling to dynamically adjust train frequencies, accommodating short-term fluctuations like rush hours and major events while reserving redundant tracks for future population growth.

Sustainability refers to the infrastructure's capacity to operate efficiently over the long term without depleting environmental and social resources. Through sustainable design, climate issues such as global warming can be mitigated, reducing risks of natural disasters to infrastructure.

Fig 4. Test Closure of Maeslantkering Storm Surge Barrier

Fig 5. Shenzhen Bidao Loop Sponge City Wetland Park

In summary, resilient infrastructure design enhances disaster resistance capabilities, reduces loss of life and property, improves preparedness for extreme weather events and natural disasters, and mitigates human-induced risks. It also ensures economic stability and sustainable development by strengthening environmental adaptability, ecological benefits, and resource efficiency, while fostering ecological synergy. Through smart technological innovations and cross-sector collaboration, resilience design elevates societal resilience and equity, reduces long-term maintenance costs, and minimizes post-disaster recovery expenditures.

As a core competency for future infrastructure systems, resilience design shifts from passive defense to proactive adaptation in the context of intensifying climate change and interconnected global risks, positioning itself as a strategic imperative for urban and national sustainability. Its value extends beyond mere "survival"; it lies in enabling system evolution through flexibility and learning capacity, ultimately forging a safe, inclusive, and resilient socio-ecological system.

4. Conclusion

Civil engineers serve as both engineering experts and guardians of public safety. A series of catastrophic disasters have revealed gaps in existing systems but also provided opportunities for innovation. The professional responsibility of civil engineers extends beyond constructing buildings and bridges; it also entails building resilient networks to withstand future risks. Infrastructure disaster prevention has entered the era of "resilient design," requiring engineers to drive a shift from "disaster response" to "resilient resistance" through technological innovation, policy advocacy, and global collaboration—transforming their ethical obligations into actionable steps. Only through these efforts can the ultimate commitment of "creating safe, resilient, and sustainable infrastructure" be fulfilled, fostering a sustainable future for humanity.

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