Transactions on Engineering and Technology Research
ISSN: 2960-1797, eISSN: 2960-2246 | Volume 4
ACEGE 2024

Analysis on Bridge Collapse Accidents Caused By Rainfall and Flood: A Case Study of Xiaoqing River Bridge

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Abstract. This paper studies the structural integrity and ecological impact of Xiaoqing River Bridge in Beijing. Xiaoqing River Bridge is an important urban infrastructure spanning the Xiaoqing River, an important tributary in Beijing. Featuring a unique French design and reinforced concrete T-shape, the bridge has served a variety of urban functions for more than 40 years, including flood control and urban landscape improvement. However, the challenges posed by rapid urbanization and climate change, especially the increasing frequency and intensity of flood events, make it necessary to reassess the structural resilience and ecological impact of bridges. This paper analyzes the engineering background of the bridge, focuses on the combination of traditional and modern engineering of the bridge, and the adaptive measures taken to improve the bearing capacity and flood resistance of the bridge. The application of advanced materials and technologies in river management and ecological restoration was discussed, and the importance of environmental sustainable development and ecological balance was emphasized. The impact of climate on the bridge was studied, focusing on rainfall data for 2023 and its implications for urban planning and water management. In this paper, the collapse of river bridges caused by heavy flood is studied from the aspects of structural mechanics, historical background of material loss and bridge vulnerability. Ethical solutions to rain-induced bridge erosion are proposed, advocating responsible engineering practices, sustainable design, and robust maintenance strategies. The paper concludes with recommendations for the use of advanced technologies, such as high-resolution radar satellites, to monitor the bridge infrastructure and implement protective measures to protect the piers from erosion.

Keywords: Bridge collapse; Rainfall-induced flooding; Xiaoqing River Bridge; Structural integrity; InSAR monitoring technology.

1. Introduction

The Xiaoqing River Bridge serves as a crucial tributary in Beijing, contributing significantly to the city's hydrological management and ecological balance. As urban areas continue to expand and climate change intensifies, the challenges posed by increased flooding and extreme weather events have necessitated a thorough examination of urban infrastructure, particularly bridges that are vital for transportation and community safety [1]. The Xiaoqing River Bridges, an architectural feat designed over 40 years ago, exemplifies the intricate interplay between engineering, aesthetics, and functionality. However, recent flooding incidents have exposed vulnerabilities in its structural integrity, prompting concerns about the long-term resilience of such infrastructures in the face of climate change.

Research into the structural performance and adaptability of urban bridges is critical, especially considering the rising frequency and severity of extreme weather patterns. While prior studies have focused on traditional engineering methods and material usage, there is a growing recognition of the need for innovative solutions that enhance the durability of structures like the Xiaoqing River Bridge. The bridge's unique design, integrating both traditional and modern engineering practices, has facilitated its functionality but also raises questions about its capacity to withstand unprecedented hydrological stress.

This paper investigates the recent collapse of the Xiaoqing River Bridge, exploring the underlying climatic factors that contributed to this failure. It delves into the engineering background of the bridge, the evolution of its structure, and the material losses incurred during the flood event. By analyzing the mechanisms of scouring and the impact of heavy rainfall on bridge stability, the study aims to provide insights into effective strategies for mitigating future risks. Furthermore, it emphasizes the importance of sustainable engineering practices and robust maintenance strategies to safeguard urban infrastructures against the evolving challenges posed by climate change [2]. Through this analysis, the paper seeks to contribute to the broader discourse on enhancing the resilience of urban infrastructure in the face of environmental uncertainties, ultimately promoting safer and more sustainable urban living conditions.

2. The Xiaoqing River Bridge

As a key tributary within Beijing, Xiaoqing River Bridge traverses multiple urban areas. Originating from the northwest of Beijing, it eventually flows into the Yongding River. Playing a significant role as an urban river, Xiaoqing River Bridge is instrumental in regulating the city's hydrology and enhancing the ecological environment, and it also serves multiple functions such as flood control, irrigation, and urban landscape improvement. Faced with the challenges to water quality and ecology brought about by rapid urbanization, the Beijing Municipal Government has intensified the management and protection of Xiaoqing River Bridge. The aim is to restore the river's natural ecosystem, improve water quality, and make Xiaoqing River Bridge an ideal place for residents' leisure, entertainment, and tourism.

2.1. Engineering Background

This reinforced concrete T-shaped bridge, with its unique French design and construction, has been an architectural miracle for more than 40 years. It is characterized by bolted steel truss parts, and the bridge structure reflects the fusion of aesthetic elegance and functional toughness. Over the years, it has not only facilitated the flow of people and goods, but also played a key role in flood control measures, ensuring the safety of the surrounding communities during heavy rains.

The design of the bridge is the integration of traditional and modern engineering, which is crucial to withstand the test of time and natural strength. However, with the increasing frequency and intensity of flooding events due to increased global warming, this requires a reassessment of their structural integrity and implementation of adaptive measures.

(a) Bridge structure in 2013 (b) Flood discharge on July 30,2023

Figure 1. South Side Structural changes of Xiaoqing River Bridge caused by changes in time [3, 4]

As illustrated in Fig. 1, side-by-side images of 2013 with the recent Xiaoqing River Bridge show the evolution of bridge architecture. The original arch support system was strategically modified to add additional beams across the pier or abutment, enhancing the bearing capacity of the bridge and transferring the mechanical stress directly to the support structure. This adaptive change is crucial to strengthen the bridge against the continued impact of floods.

With people's grasp of mechanics and the increase of rainfall caused by global warming, the number of flood impacts continues to rise. The original arch support is gradually converted into one or more beams across the pier or abutment, so as to transfer the load directly to the supporting structure from the mechanical characteristics. Making Bridges stronger in the face of flooding.

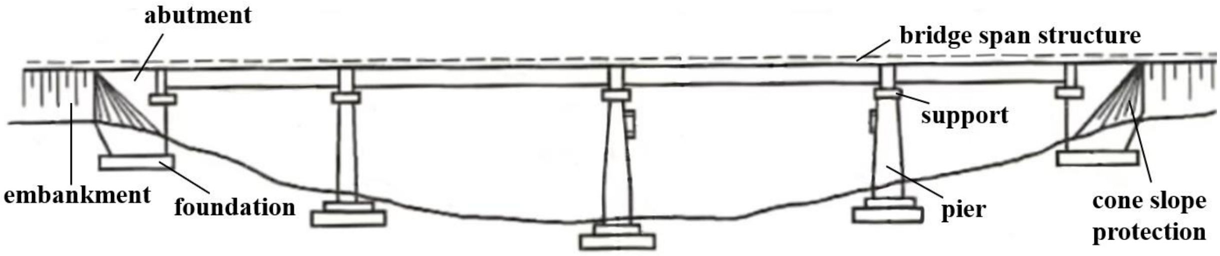


Figure 2. The mechanical structure change analysis diagram

According to the description of the Xiaoqing River Bridge in Fig. 2, that can understand that the bridge is a reinforced concrete T-shaped bridge with a unique French design and construction. It has been standing for more than 40 years, and is known for its bolted steel truss part and the fusion of aesthetic elegance and strong function. Over time, Xiaoqing River Bridge not only facilitated the flow of people and goods, but also played a key role in flood control measures, ensuring the safety of surrounding communities during heavy rains.

However, the increased frequency and intensity of flood events due to global warming poses new challenges to the structural integrity of the bridge. To meet this challenge, the design and structure of the bridge require adaptive changes. For example, the original arch support system was strategically modified to add additional beams across the pier or abutment to enhance the carrying capacity of the bridge and transfer mechanical stress directly to the support structure. This adaptive change is crucial to strengthening the bridge to withstand the sustained effects of flooding.

Combined with the content of Fig. 1, that can further understand the impact of these structural changes on the overall performance of the bridge. Bridge span structure may refer to the main structure of the bridge, including the bridge deck and its supporting structure, which echoes the T-shaped bridge structure mentioned in Fig. 2. Abutment support and piers are key parts of the bridge structure that support the bridge and transfer the load to the foundation. The carrying capacity of these structures is enhanced by adding additional beams. Foundation is to support the bottom structure of the entire bridge structure, to ensure the stability of the bridge. Cone slope protectionand embankment may be the structures that protect the slopes around the bridge from erosion and the embankments on the banks of the river to control the water flow and protect the bridge.

2.2. Utilization of Materials

In the process of river management, ecological restoration and landscape construction of Beijing Xiaoqing River Bridge, a variety of advanced materials and technologies are adopted to promote the sustainable environmental development and ecological balance. These include ecological concrete, which is widely used for ecological slope protection and riverbed restoration work by providing rich pore structures that support water penetration and plant root system development. The application of permeable pavement materials such as permeable concrete and permeable bricks increases the permeability of the surface, helping to reduce runoff and replenish groundwater. The establishment of the constructed wetland uses the natural purification function of plants and microorganisms to improve the self-purification ability of water bodies. The cultivation of aquatic plants, such as lotus flowers and cattail plants, not only beautifies the environment, but also helps to absorb nutrients in the water and reduce water eutrophication. The setting of ecologically floating islands provides habitat for aquatic life and helps to absorb and degrade pollutants in the water. The riverbank greening project increases vegetation coverage, reduces soil erosion, and provides leisure space for citizens. The installation of water quality monitoring equipment enables water quality changes to be monitored in real time, so as to timely warn and respond to water pollution incidents. Regular dredging of the river bottom has removed the sediment and pollutants, and further improved the water environment.

The implementation of these measures not only improves the ecological environment and landscape quality of Xiaoqing River Bridge, but also promotes the sustainable utilization of water resources and the protection of biodiversity.

3. The Collapse of Xiaoqing Rive Bridge

3.1. Climatic Impact

Fig. 3 is a graphical representation of rainfall data in Beijing for the year 2023, and offers a comprehensive overview of the city's precipitation patterns throughout the year. The vertical axis of the graph, marked with values ranging from 0 to 350, indicates the depth of rainfall in millimeters, while the horizontal axis likely represents the months of the year. This visual analysis is crucial for understanding the seasonal variations and overall rainfall trends in Beijing, which can have significant implications for urban planning, agriculture, and water resource management.

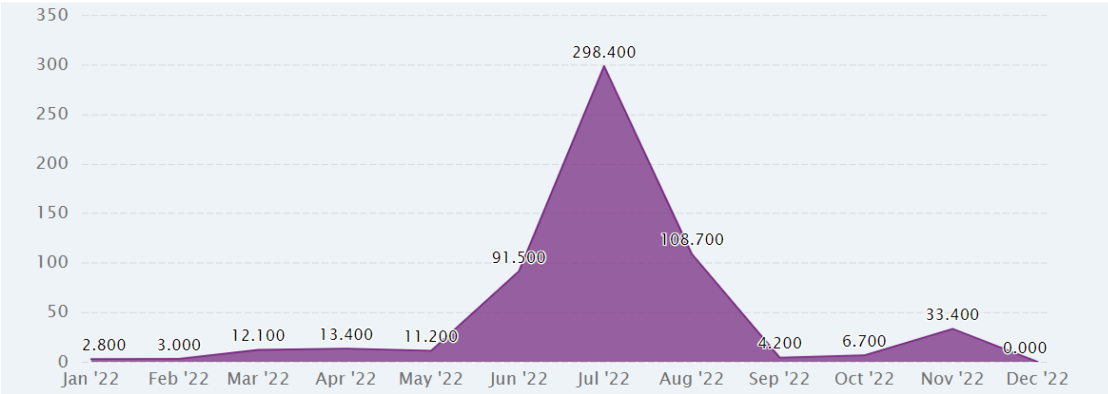


Figure 3. Statistics from the Meteorological Bureau on Beijing's rainfall in 2023 [5]

A detailed examination of the graph reveals distinct seasonal rainfall patterns. The higher bars on the graph suggest periods of greater precipitation, which typically align with Beijing's monsoon season, spanning from July to August. The lower bars indicate drier months, likely corresponding to the winter and early spring seasons when rainfall is less frequent and lower in volume.

In the context of urban planning, this rainfall data is invaluable for designing and maintaining Beijing's infrastructure. It informs the construction of drainage systems to cope with heavy downpours and aids in the planning of green spaces and permeable surfaces to mitigate flood risks.

After the Xiaoqing River Bridge flood discharge gate was opened, at more than 2 o'clock in the afternoon on July 31, the Xiaoqing River Bridge collapsed. The appearance leading to the collapse was caused by two main factors. The first is the impact of the water level characteristics.The flow of the Yongding River is significantly affected by factors such as precipitation, regulation of upstream reservoirs, and seasonal changes. The sharp rise in water level is closely related to soil saturation and insufficient drainage capacity of the river channel. On that day it took only 4.5 hours to rise from 500 cubic meters per second to a peak of 4649 cubic meters per second, of which it took only 1.5 hours to increase from 2000 cubic meters per second to 4649 cubic meters per second. The second is the impact of climate change, as mentioned in 1.1.The increase in extreme rainfall events has led to significant fluctuations in water levels in the Yongding River basin. The water level has risen rapidly above the warning level after multiple heavy rainfalls.

3.2. Collapse Structure Point

Xiaoqing River Bridge The design meets specific load standards to withstand multiple loads such as dead weight, traffic and environmental impacts. However, extreme situations such as the occurrence of flooding combined with daily bridge material degradation, hydraulic action, erosion and foundation instability threaten the integrity of the bridge structure.

The massive collapse caused by flood, hydraulic pressure and heavy rain highlights the serious collapse behavior in the center of the third section of the bridge under the extreme hydraulic action. It fully reflects that the bridge has a serious uneven force on the opposite side of the flood, making the central position a vulnerable point, as shown in Fig. 4. When the flood with huge flow cannot withstand the action of vehicle force and pressure force, the interaction of force will squeeze the bridge collapse phenomenon, as shown in Fig. 5.

Observed by the Fig. 6. North side of the bridge with the superstructure being variable cross-section reinforced concrete continuous T-beams (three pieces horizontally), with a beam height of 1.05 to 2.2m, four spans per union, and a total of 2 unions with 8 spans for the entire bridge. South side of the bridge using reinforced concrete to enlarge the foundation and piers. The superstructure adopted a truss rib arch structure (four pieces horizontally) to widen the bridge deck, with the arch feet being rigidly connected,and a total of 8 spans. There are defects in the strength distribution of the bridge on the south side, and each beam is too thin, causing it to break when subjected to excessive pressure. The arch structure is subjected to greater pressure at the arch top and arch foot, while the middle part is relatively small.

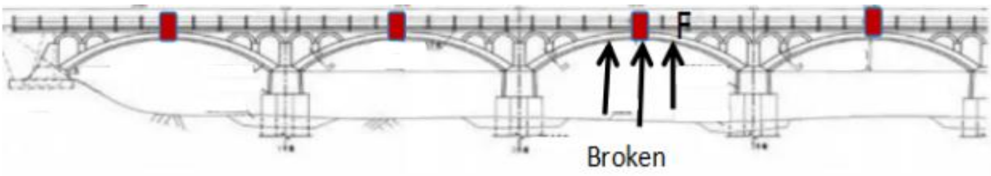


Figure 4. Point mechanics diagram of collapsed structures

Figure 5. Xiaoqing River Bridge Field pictures of the fracture point [6]

Figure 6. South side and north side of the bridge [7]

3.3. Material Loss Problem

The collapse of the Xiaoqing River Bridge in Beijing, triggered by a severe flood, led to substantial material loss and structural disintegration. This incident highlighted the vulnerability of the bridge's pier masonry, which was originally constructed in 1894 and later reinforced with concrete in 1971. The forceful impact of the flood not only damaged the piers but also caused significant loss to the upper fill material and the protective stonework. The erosive action of the flood compromised the connection between the concrete extension of the piers (reinforced concrete pier extension) and the lower protective stone band (lower Tampo strip stone), leading to the failure of the bridge's supporting structure, as shown in Fig. 7. Moreover, the flood also impacted the large stone blocks at the top of the piers (the upper part of Pier No.5), intensifying material loss and further weakening the overall stability of the bridge. After the flood, the neat interface of the piers was no longer present, replaced by loose debris and sediment, which not only affected the aesthetics of the bridge but also had a long-term impact on its safety and functionality, as shown in Fig. 8. This event underscores the importance of protecting bridge structural materials and designing against erosion under extreme climate conditions.

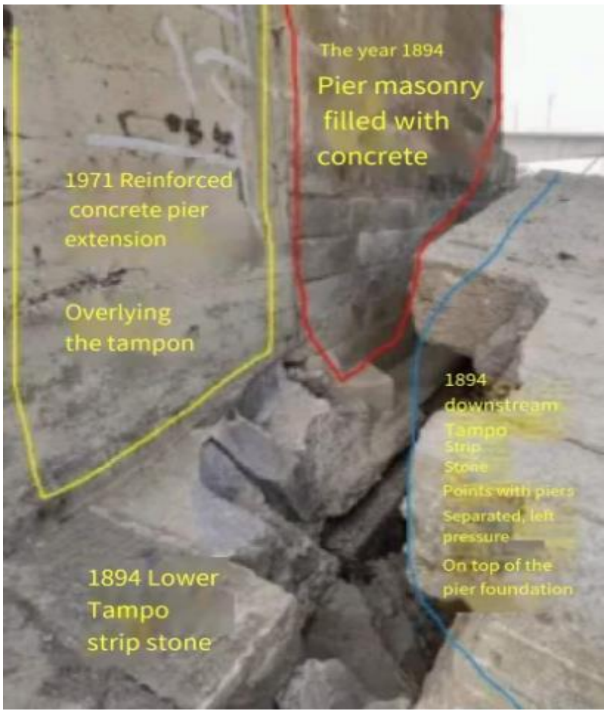


Figure 7. Historical Structural Evolution of Xiaoqing River Bridge Piers: A Visual Analysis [8]

Figure 8. Structural Components and Modifications of Pier No.5 [8]

4. Moral Solutions to the Bridge Caused by Rainfall Flushing

The moral solutions to bridge scouring caused by rainfall involve implementing responsible engineering practices, prioritizing sustainable design, and investing in robust maintenance strategies to ensure the longevity and safety of bridges amidst flood events.

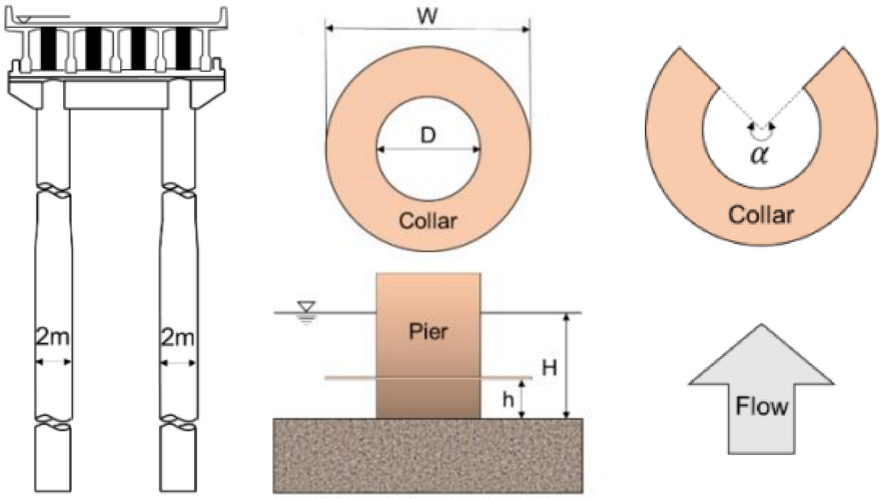
4.1. Causes of Collapse Caused by Flood and Rainfall

Continuous rainfall can lead to an increase in soil moisture until it reaches a saturated state, at which point the soil's bearing capacity significantly decreases, and the friction between particles is reduced, causing structural instability that may trigger collapses or landslides. On steep slopes, rainfall can cause the surface soil to lose cohesion, forming a sliding plane; the increase in moisture and the force of gravity, especially in areas with thin or loose soil layers, make landslides more likely. Heavy rainfall can also cause the water table to rise, increasing pore water pressure and weakening the effective stress of the soil, reducing stability and leading to collapses [9]. Vegetation roots can normally stabilize the soil and reduce erosion, but floods and heavy rainfall can damage vegetation, causing the soil to lose support and increasing the risk of erosion. During river floods, the erosion of riverbanks by water flow can weaken the stability of the slope and cause collapses. In addition, unreasonable human activities, such as excessive deforestation, urban construction, and mining, can destroy vegetation and soil structure, intensifying soil erosion and the risk of collapses. The intensity and duration of rainfall play a decisive role in the occurrence of collapses. Both short-term heavy rainfall and long-term light rain can lead to soil saturation and erosion, potentially causing collapses.

4.2. Historical Context and Vulnerability under Fire

Floods and heavy rainfall often lead to bridge collapses as they intensify the process of scouring, which involves the removal of sediment from around bridge piers. This scouring, combined with the pressure of the flowing water, can cause backwater effects that damage the bridge structure. While scouring is a significant factor in bridge failures, hydrodynamic forces generated by floods can also lead to bridge collapses, regardless of the composition of the riverbed. The presence of bridge piers can exacerbate flood impacts by acting as obstacles that reduce the flow area available for the floodwaters, thereby increasing the risk of structural damage [10]. In the case of increasing flow speed, the removal of bed material is more obvious, leading to the erosion phenomenon. When the flood flow rate is fast, the pressure generated by the water flow also increases. Therefore, a uniform pressure distribution along the height of the current is moving on the surface of the pier. In view of the increased flood strength, these factors must be considered in the bridge design to prevent the bridge from accidents such as collisions. With the increase of the flow rate, the flow pressure will increase accordingly, so in the design process of the bridge, the flow rate, pressure, viscosity and resistance around the bridge pier should be fully considered. When the center of the flow forms a certain angle with the pier, the downstream flow from the upstream to the downstream, the scouring phenomenon will decrease and lead to the expansion of the scouring area. Scouring effects can disrupt the sediment deposition process within a water channel, leading to instability in the foundation and altering flow dynamics. During catastrophic flood events, the water channel experiences increased velocity and depth, which can lead to the erosion of bed materials. This erosion weakens bridge abutments and jeopardizes the bridge's overall stability, as the forceful floodwaters can cause significant structural damage [10].

To avert such occurrences, the utilization of advanced high-resolution radar satellites, such as TerraSAR-X or COSMO Sky-Med, is anticipated to greatly enhance the capacity of InSAR data in surveilling bridges, dams, and other urban infrastructure. This technology offers a significant advancement by supplementing traditional structural monitoring methods, particularly in its ability to detect minor and gradual deformations, as well as providing a dense array of stable reference points for analysis [11]. To prevent bridge collapses, it is essential to protect bridge piers from scouring. Studies have shown that without protection, scouring can occur all around the piers. To safeguard the piers, protective collars can be installed around them. These collars are circular in shape to provide protection from all directions. Collars can come in various shapes, such as rectangular or circular. However, in terms of performance, rectangular collars have demonstrated better effectiveness in controlling scouring and its causes. For optimal performance, the width of the rectangular collars should be between 3 to 3.5 times the diameter of the piers, as shown in Fig. 9.



(a) Installation (b) Collar around pier of size (c) Wash the position

Figure 9. Installation of collar around pier [10]

5. Conclusion

The Xiaoqing River Bridge collapse serves as a stark reminder of the intricate interplay between urban infrastructure, environmental challenges, and the imperative for robust engineering solutions. The bridge's failure, precipitated by the confluence of extreme rainfall, soil saturation, and the inherent vulnerabilities of its structural design, underscores the critical need for a multifaceted approach to bridge engineering and maintenance. This includes the adoption of advanced materials and technologies, such as ecological concrete and permeable pavements, to enhance the resilience of bridges against the erosive forces of flooding. Moreover, the integration of high-resolution radar satellite technology, like InSAR, can significantly augment the surveillance and monitoring of bridge integrity, providing early warnings of potential structural failures.

The incident also highlights the significance of sustainable design principles that account for the dynamic nature of climate patterns and the increasing frequency of extreme weather events. It is imperative for engineers and urban planners to anticipate these challenges and incorporate adaptive measures into the design and construction of infrastructure. This may involve the strategic use of protective measures around bridge piers, such as collars, to mitigate the effects of scouring and ensure the long-term stability of bridges.

Furthermore, the moral and ethical dimensions of engineering practice must be acknowledged, with a commitment to prioritizing public safety and environmental stewardship. This encompasses responsible engineering practices that not only meet current standards but also anticipate future challenges, thereby safeguarding the infrastructure against the impacts of climate change and ensuring the longevity and safety of bridges for the communities they serve.

Ultimately, the Xiaoqing River Bridge collapse is a call to action for the engineering community to re-evaluate existing infrastructure, enhance monitoring systems, and invest in innovative solutions that can withstand the test of time and the pressures of a changing climate. Through a combination of technological innovation, sustainable design, and a steadfast commitment to ethical engineering, that can build a more resilient future for urban landscapes and the people who rely on them.

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