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The Impact of Earthquake Disasters on Urban Infrastructure and Seismic Design Strategies

Xuechao Ji, Liwei Wu

Faculty of Architectural Engineering, North China University of Technology, Tangshan 063210, China

Abstract

Earthquakes have always been natural disasters that seriously endanger the development of human society, and the occurrence of every strong earthquake will bring unavoidable huge losses to human society. This paper reviews the existing literature and case studies to analyze the impact of earthquake disasters on urban buildings, roads and bridges, water and electricity supply systems, communication and transportation systems, and other infrastructure. At the same time, the current mainstream seismic design strategies are discussed, including the seismic design of buildings, the seismic technology of roads and bridges, the seismic measures of water and electricity systems, and the seismic coping methods of communication and transportation systems. Through case analysis and empirical research, the application effect and limitations of these strategies in actual seismic events are evaluated, and the key factors and future development directions for improving urban earthquake resistance are finally summarized.

Keywords

Earthquake disaster; urban infrastructure; Seismic design strategies.

1. Introduction

As the global urbanization process continues to deepen, the proportion of the world's urban population has risen from 13.6% in 1920 to 49% in 2018, and is projected to reach two-thirds of the total population by 2025. During this period, China's urbanization also entered a phase of rapid development, rising from 12.5% in 1952 to 45.7% in 2008 [1,6], and by 2015, China's urbanization rate had surpassed the global average. With the high concentration of urban populations and the rapid expansion of urban spaces, the loss of life and economic damage caused by earthquakes of the same magnitude will significantly increase. This paper aims to systematically analyze the specific impacts of earthquakes on urban infrastructure and explore current mainstream seismic design strategies to effectively enhance urban seismic disaster prevention capabilities, minimize losses caused by earthquakes, and thereby achieve sustainable and healthy economic development.

2. Study of axial mechanical properties

Earthquakes, especially those that strike without warning, not only cause significant loss of life but also inflict severe damage on urban buildings and infrastructure. They can render critical public utilities—such as power lines, transportation networks, mobile communication systems, water supply and drainage systems, and gas pipelines—inoperable, thereby increasing the risk of secondary disasters such as fires, floods, disease outbreaks, and even nuclear leaks. For example, during the 1906 San Francisco earthquake in the United States, three main water supply pipelines were damaged, over 50 fires broke out, and firefighting water supplies were disrupted or completely cut off. The direct and indirect losses caused by the fires were three

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times higher than those caused by the earthquake itself. In the 1971 San Fernando earthquake, 450 gas pipelines were damaged, five bridges collapsed, and 42 bridges were damaged. In the 1976 Tangshan earthquake, the disaster caused the water supply system to fail, with pipeline damage rates as high as four per kilometer. The Luan River Bridge collapsed completely, and road damage accounted for 62% of the total length.

For normal production and daily life, as well as social stability, facilities such as power, transportation, communications, water supply and drainage, and gas supply are indispensable and even critical. They are like the blood vessels of a city, providing the necessary materials and capabilities to all parts of the city. They are also metaphorically referred to as lifeline projects. In earthquake engineering, the lifeline system refers to the collective term for the power system, communication system, transportation system, water system, gas supply system, and waste disposal system [2,5,10].

Typically, lifeline systems consist of the following five components:

1. Power system: Includes various power plants, nuclear power plants, substations, and transmission lines, etc.;

2. Transportation system: Includes ports, highways, railways, and airports, etc., each of which includes other facilities such as bridges and tunnels;

3. Communication System: Includes communication stations, base stations, communication lines, and associated electronic equipment;

4. Water Supply System: Includes water collection systems, water treatment plants, water supply pipelines, wastewater treatment facilities, reservoirs, etc.;

5. Gas Supply System: Includes natural gas and coal gas production plants, gas transmission pipelines, gas storage facilities, and related equipment, but does not include drilling and refining facilities belonging to the industrial system.

The destruction of lifeline infrastructure typically manifests as system collapse and the loss of overall system functionality. If lifeline infrastructure is damaged, it may trigger more severe subsequent disasters. For example, in the 1906 San Francisco earthquake and the 1923 Great Kanto Earthquake, the destruction of underground pipelines caused by the earthquakes completely cut off the water supply for firefighting, directly leading to the inability to extinguish the post-earthquake fires and resulting in losses far greater than those caused by the earthquakes themselves [3].

2.1. Seismic Hazard Analysis of Bridge Systems

Bridges often suffer damage to their superstructures, bearings and connections, pier structures, foundations, and bases when subjected to seismic forces.

(1) There are few examples of buckling failure of the bottom plates and side walls of steel box girders in bridge superstructures, but structural displacement of the superstructure is relatively common, and in severe cases can lead to girder drop. Relevant statistical data shows that over 90% of girder drops occur in the longitudinal direction.

(2) Earthquake damage to bridge bearings and connecting support structures includes bearing displacement, detachment of movable bearings, structural damage to bearings, and the pulling out or shearing of anchor bolts.

(3) Earthquake damage to pier and abutment structures primarily includes bending failure of tall piers, shear brittle failure of short piers, foundation failure of piers, displacement of abutments, and collisions between abutments and main beams.

(4) Earthquake damage to foundations primarily includes sand liquefaction and foundation failure, with sand liquefaction posing the greatest hazard.

On January 17, 1995, the Great Hanshin Earthquake struck Japan, causing a bridge abutment to collapse, as shown in Figure 1. This disrupted traffic and severely hampered rescue efforts.

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Figure 1: Beam damage caused by the Hanshin earthquake

2.2. Seismic hazard analysis of road systems

Roadbeds and pavements often experience uneven settlement or deformation due to seismic forces, accompanied by longitudinal and transverse cracks in the pavement. Such seismic damage commonly occurs in embankment roadbeds, particularly in weak roadbeds, where longitudinal cracking is more prevalent, while transverse cracking often occurs at bridge abutment roadbeds. Due to the layered compaction of the subgrade and variations in the compaction quality of each soil layer, the subgrade is subjected to tensile shear forces during an earthquake, leading to failure. As a result, the pavement is prone to displacement and sliding. When an earthquake causes damage to embankment structures, resulting in internal cracking and deformation of the subgrade, the pavement is susceptible to landslides.

As shown in Figure 2, the 8.0-magnitude earthquake that struck Wenchuan, China, on May 12, 2008, caused severe damage to the road system, with cracks in the roadbed, resulting in traffic disruptions and hindering rescue efforts.

Figure 2: Damage to roadbeds caused by the Wenchuan earthquake

2.3. Analysis of Earthquake Damage to Water Supply Systems

Buildings are often damaged by the inertial forces generated by ground motion acceleration and the failure of foundations caused by seismic hazards [4]. Therefore, during building design and construction, measures are often taken to avoid hazardous sites and implement necessary foundation treatments. However, the laying of water supply pipelines involves long-distance, cross-regional linear installations spanning various urban areas, where site conditions vary significantly. In many cases, unfavorable or hazardous sites cannot be avoided, and these hazardous sites may lead to damage to underground water supply pipelines, as shown in Figure 3. Earthquake-induced damage to water supply pipelines primarily manifests in the following three categories:

(1) Damage to pipeline connections, such as cracked welds or loose flange bolts.

(2) Cracking of the pipe material itself, such as longitudinal or diagonal cracks, or even breakage.

(3) Damage to pipe-to-pipe connection components, such as damage to tees, elbows, valves, and other connection parts.

The failure of pipes is generally caused by defects or corrosion in the pipes themselves, while connection failure is often caused by ground fractures, landslides, and other factors that result in stress concentration or inconsistent relative movement in the pipes. This is also a common form of failure.

Figure 3 Damage to water supply pipes during an earthquake

3. Seismic Design Strategies

To mitigate the damage caused by earthquakes to urban infrastructure, seismic design strategies have become critical technical tools and management measures. The main seismic design strategies include [7-9].

3.1. Structural Design Optimization

Seismic Wall Placement and Arrangement: Seismic walls are one of the key components for enhancing a building's seismic performance. In structural design, the proper placement and arrangement of seismic walls can effectively enhance the building's overall stiffness and stability, thereby reducing deformation and damage caused by seismic forces. For different types of building structures, the location, thickness, and arrangement of seismic walls should be determined based on the direction and intensity of seismic forces to maximize their seismic resistance; Structural Connection Design: Structural connections play a crucial role in connecting various components of a building and are responsible for transmitting and distributing seismic forces during earthquakes. Optimizing the design of structural connections can enhance the overall stability and seismic resistance of a building. Using high-strength, high-toughness connection component materials, along with reasonable connection methods and arrangements, can effectively enhance the structure's seismic performance and reduce structural damage under seismic forces; Selection of structural materials: The selection of structural materials directly impacts a building's seismic performance. Using high-strength, high-toughness structural materials, such as steel and high-strength concrete, can enhance a building's seismic resistance and reduce structural deformation and damage under seismic forces. Additionally, material performance indicators and grades should be selected appropriately based on the building's usage requirements and seismic design standards to ensure compliance with design specifications; Design parameter optimization: Optimizing design parameters is crucial for enhancing a building's seismic performance. During structural design, parameters such as structural section dimensions, member reinforcement ratios, and floor stiffness should be determined reasonably based on seismic design requirements and the building's actual conditions.

By optimizing design parameters, the overall stiffness and stability of the structure can be improved, enhancing its seismic resistance.

3.2. Foundation Treatment and Reinforcement

Foundation Treatment Technology: Foundation treatment is one of the key methods for enhancing a building's seismic resistance. By employing appropriate foundation treatment techniques, such as reinforcement, densification, and improvement, the bearing capacity and stability of the foundation soil can be enhanced, thereby reducing the impact of seismic forces on the building. Common foundation treatment techniques include soil reinforcement, grouting reinforcement, and vibration densification. These techniques can be selected based on the geological conditions and seismic hazard level of the region where the building is located; Foundation reinforcement techniques: In addition to foundation treatment techniques, foundation reinforcement techniques are also an important means of enhancing a building's seismic performance.

By adopting reinforcement measures such as reinforced concrete piles, steel pipe cast-in-place piles, and underground walls, the bearing capacity and seismic resistance of the foundation can be improved, thereby enhancing the stability and safety of the building under seismic loads. The selection of foundation reinforcement technology should be based on a comprehensive consideration of factors such as the structural form of the building, geological conditions, and construction conditions to ensure that the desired reinforcement effect is achieved.

4. Conclusions and Outlook

In summary, this paper explores the impact of earthquakes on urban infrastructure such as bridges, roads, and water supply systems, and analyzes how seismic design can be used to reduce losses caused by earthquake disasters. Based on the circumstances of past earthquake disasters, the characteristics of urban earthquake disasters primarily include their severity, complexity, and interconnectedness. Earthquake disasters in transportation systems primarily involve road damage and bridge/tunnel damage, while damage to water supply and gas supply systems primarily manifests as damage to water supply and gas supply networks. Therefore, ensuring a certain degree of redundancy in gas supply and water supply networks is crucial, and scientific seismic design can help reduce losses caused by earthquake disasters.

Future research can be conducted in the following areas:

1. Further optimize seismic design technology to improve the seismic resistance of infrastructure.

2. Strengthen the construction of earthquake disaster warning systems and emergency response mechanisms.

3. Promote seismic design concepts and technologies to enhance the seismic awareness of the public and policymakers.

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