Journal of Civil Engineering and Urban Planning (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/jceup.2024.060322
ISSN 2616-3969 Vol. 6 Num. 3

Resilience Recovery Strategies for Urban Infrastructure Systems under Earthquake Effects

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Keywords: Seismic effects, urban infrastructure, resilience recovery, disaster prevention and mitigation, system optimization

Abstract: With the acceleration of urbanization, the complexity and interdependence of urban infrastructure systems are increasing, and natural disasters such as earthquakes are causing more and more serious damage to them. The purpose of this paper is to explore the resilience recovery strategy of urban infrastructure systems under the effect of earthquakes, and identify the vulnerability of the systems and the key issues faced in the recovery process through an in-depth analysis of the impacts of seismic hazards on various types of urban infrastructures. The infrastructure of the city gradually increases with the rapid development of the city, and the management difficulty is getting bigger and bigger, and different industries often also have the problems of unclear access, non-uniform source, and untimely data updating when they need the support of urban infrastructure, etc. Combining with the systematic analysis method to optimize the different restoration schemes, specific measures are put forward to enhance the restoration efficiency and reduce the economic loss. Through reasonable resilience recovery strategies, the seismic capacity and recovery speed of urban infrastructure systems can be significantly improved, thus enhancing the city's ability to cope with earthquake disasters and long-term sustainable development potential.

1. Introduction

With the acceleration of global urbanization, the scale and complexity of urban infrastructure systems have increased significantly. Urban infrastructure is a public facility that provides general conditions for urban production and people's lives, and is the basis for the survival and development of cities, supporting their daily operation and socio-economic development[1]. However, the frequent occurrence of natural disasters such as earthquakes is very likely to cause damage to these infrastructures, which in turn affects the normal operation of the whole city[2]. In recent years, infrastructure damage caused by seismic disasters has occurred frequently, seriously affecting the quality of life of urban residents and economic vitality[3]. Therefore, how to improve the resilience of urban infrastructure systems, especially the ability to recover quickly after disasters, has become an important research topic in the field of urban planning and disaster management[4].

In response to the destructive effects of earthquakes on urban infrastructure, academia and the engineering community have carried out a great deal of research and proposed a variety of technical means, including structural reinforcement, emergency management and disaster warning. The value of various types of infrastructure cannot be maximized[5]. It is necessary to establish a cross-industry and cross-sectoral data closure and management mechanism for relevant data, to break down barriers, to further improve the efficiency of data use, and to release the application value of the digitized field to a greater extent, and it is difficult to meet the demand for rapid restoration of complex urban systems under earthquake disasters[6]. The highly interconnected nature of infrastructure systems makes it possible for damage to a single facility to trigger a chain reaction, leading to the failure of the entire city's functions. A set of systematic urban infrastructure resilience recovery strategies is established to cope with the complex impacts of earthquake disasters on urban infrastructure.

The aim of this paper is to systematically investigate resilience recovery strategies for urban infrastructure systems under the effects of earthquakes. The direct and indirect impacts of earthquakes on different types of infrastructure are analyzed to identify key vulnerabilities and their chain effects on urban functions. The framework of recovery strategies based on resilience theory covers system vulnerability assessment, recovery technology selection, multi-body collaboration and emergency management optimization. Optimization methods of recovery strategies are explored through specific cases and theoretical analyses in order to improve the recovery efficiency and sustainable development capacity of urban infrastructure after earthquake disasters. Resilience Index Calculation:

$$R = \frac{C_{\text{restored}}}{C_{\text{total}}} \tag{1}$$

2. Impact of seismicity on urban infrastructure systems

Earthquakes, as a violent crustal movement, are capable of generating strong ground shaking that can cause severe damage to critical infrastructure in cities, such as buildings, roads, bridges, power and water supplies[7]. Different types of infrastructures suffer different degrees and forms of damage depending on their structural characteristics, location and material strength. Earthquake-induced foundation settlement and fracture zones may lead to the collapse of bridges or cracking of roads, and underground piping systems such as water and gas lines are prone to breakage from shaking and even secondary disasters[8]. Vertical structures, such as high-rise buildings and power transmission towers, are at risk of collapse or severe damage, thus affecting the normal functioning of cities. Damage Assessment Model:

$$D = \frac{L_{\text{damaged}}}{L_{\text{total}}} \times 100 \tag{2}$$

Urban infrastructure systems are often highly interconnected, and the failure of one type of facility can trigger a chain of failures in other facilities[9]. An earthquake that disrupts the electrical system can affect traffic signals, hospital emergency equipment and communication facilities, further exacerbating the chaos in the aftermath of a disaster[10]. Disruption of the water supply system not only affects the daily lives of residents, but may also cause the fire protection system to fail, increasing the risk of fire. Gas leaks may interact with power system failures to trigger disasters such as explosions. Thus, earthquakes not only directly damage the infrastructure itself, but also amplify the scope and extent of the disaster through the interdependence of systems, showed in Figure 1.

There are significant differences in the extent of damage to urban infrastructure between different earthquake intensities and distances from the epicentre. Strong shaking at the epicentre directly affects a smaller area, but in large-scale cities, secondary hazards such as fires, floods and traffic jams can extend the reach. Large cities, in particular, are prone to wider system failures triggered by a single point of infrastructure failure due to their higher density of infrastructure. In addition, smaller cities may have slower post-disaster recovery due to limited resources, while larger cities may face challenges with infrastructure systems that are too complex for coordinated recovery. This regional and scale variability increases the challenge of developing recovery strategies that are adapted to different city sizes and geographic characteristics.

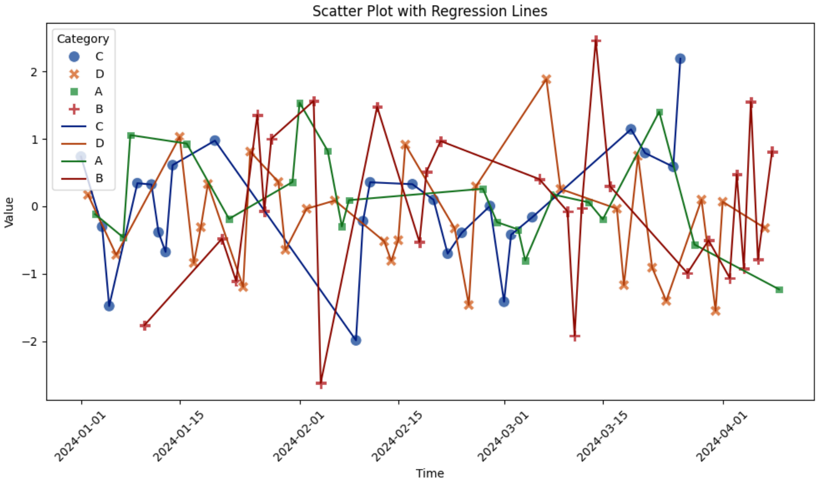

Figure 1: Scatter Plot with Regression Lines

The destruction of infrastructure by seismic hazards not only generates direct economic losses, but may also have long-term socio-economic impacts. The destruction of infrastructure often leads to a sharp decline in urban productivity, forced disruption of industrial and commercial activities, and even to the permanent failure of some urban functions, and core data should include at least basic geographic base maps, administrative divisions, buildings, urban roads, watersheds and rivers, and "one standard, three facts" data. During the recovery period, poor transportation, unstable power supply and disrupted communications can expose businesses to higher operating costs, and the quality of life of residents is greatly reduced, with a possible consequent increase in migration and unemployment. Infrastructure recovery cycles are often lengthy, and some resource-constrained cities still struggle to return to normalcy years after a disaster, increasing the pressure on and difficulty in scheduling resources for the Government and relevant authorities during the recovery period.

3. Key elements of resilient urban infrastructure recovery

The resilient restoration of urban infrastructure not only relies on scientific technical means and rapid repair capacity, but also requires comprehensive consideration of systematic vulnerability assessment, optimization of restoration strategies, as well as collaboration and emergency management among multiple actors. In this context, how to clarify the renewal strategy for the multiple status quo problems and needs hidden in the infrastructure has become a key issue to be solved urgently. By accurately assessing the vulnerability of infrastructure, selecting appropriate techniques and strategies, and coordinating the participation of all relevant parties, the recovery efficiency and long-term sustainability of cities in earthquake disasters can be maximized. In the following, we will discuss the three aspects of resilience evaluation and indicator system, vulnerability assessment and technology selection, and multi-stakeholder collaboration and emergency management.

3.1. Concept of toughness and evaluation indicators

Resilience is commonly defined in the context of urban infrastructure systems as the ability of a system to maintain its critical functions, absorb shocks, and quickly recover to a normal state in the face of sudden-onset disasters. This concept emphasizes the system's ability to adapt and cope, not only with shocks, but also the overall performance of the system in terms of how quickly it recovers and continues to function after a disaster. The resilience of urban infrastructure is reflected in prevention before a disaster, adaptive response during a disaster and rapid repair after a disaster, encompassing the resilience, redundancy and flexibility of the system, showed in Figure 2:

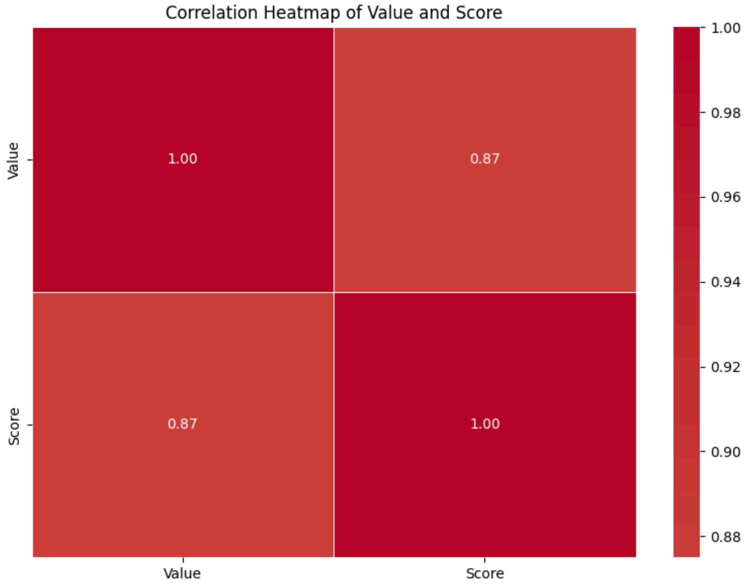

Figure 2: Correlation Heatmap of Value and Score

In order to comprehensively assess the resilience of urban infrastructure systems, it is usually measured in terms of four main dimensions: speed of recovery, i.e., the time required for the system to return to its normal operating condition after a disaster; system redundancy, which refers to the availability of alternative functional modules that can continue to safeguard urban functions in the event of partial facility failure; adaptive capacity, which reflects the ability of the system to cope with earthquake shocks of varying intensities and types and, through adaptation or optimization to achieve a new equilibrium; and seismic capacity, which refers to the physical seismic performance of the infrastructure itself in an earthquake, such as structural strength and the reasonableness of the design code.

Based on the multidimensional characteristics of resilience, the establishment of a scientific resilience evaluation index system is the key to assessing and improving the resilience of urban infrastructure. The evaluation indicators may include quantitative indicators such as the rate of recovery of system functions, the rate of economic loss during the time period of the disaster, and the cost-benefit ratio of infrastructure recovery inputs, combined with qualitative indicators such as the degree of post-disaster social impact and the efficiency of the emergency response; by comprehensively analyzing these indicators, the performance of the urban infrastructure system in the aftermath of the disaster can be comprehensively evaluated, and targeted recovery strategies can then be formulated.

Resilience assessment is not only a tool for post-disaster analysis, but should also be integrated in the early stages of urban planning and infrastructure development. Through the forward-looking assessment of resilience indicators, cities can identify and reduce potential vulnerabilities in advance of the construction process, enhancing the resilience and recovery capacity of the system. At the same time, incorporating resilience indicators into policy formulation and planning programs can help city governments make more strategic and long-term decisions in the process of post-disaster resource mobilization and recovery, and improve overall resilience and response levels.

3.2. System vulnerability assessment and risk identification

System vulnerability refers to the degree to which urban infrastructure systems are susceptible to damage or failure when exposed to disasters such as earthquakes. Assessing vulnerability is a critical starting point for resilience recovery strategies, as targeted recovery and protection measures can only be developed with an in-depth understanding of the weak links in the system. Vulnerability is reflected not only in the structural performance of individual facilities, but also in the dependencies between facilities, the level of maintenance, emergency response capabilities and other factors that directly affect the system's ability to withstand earthquakes and the speed of recovery.

Vulnerability assessment usually relies on a variety of technical means for systematic analysis, mainly including structural vulnerability assessment and functional vulnerability assessment. Structural assessments mainly analyze the seismic design, material strength, and historical maintenance records of buildings, bridges, pipelines, and other infrastructures to determine their resistance to damage in an earthquake. Most of the many software platforms are developed for applications in a particular region, using region-specific vulnerability models or exposure data . Functionality assessment, on the other hand, focuses on the operational stability of the system and its ability to cope with emergencies, such as the ability of power and water systems to quickly restore critical functions after being hit by an earthquake. In recent years, with the development of big data and intelligent algorithms, data-driven vulnerability assessment methods have been widely used to more accurately identify potential risk points in a system based on historical disaster data and real-time monitoring information.

During the risk identification process, several key factors need to be considered in a comprehensive manner. Geographic location and environmental conditions, such as infrastructure located in seismically active zones or soft soil areas, are more vulnerable to damage. The age and level of maintenance of facilities is also a central factor in vulnerability, with older facilities that are not regularly maintained being susceptible to severe damage during earthquakes. Systemic dependencies between facilities are also aspects that require special attention; failure of one key facility can trigger a chain reaction that leads to total paralysis of other facilities and urban functions. The seismic vulnerability assessment, damage and loss prediction for individual and groups of common frame, brick-concrete, reinforced concrete, and brick-column plants, as well as the group seismic hazard loss prediction function for more common structural types, are targeted for use by local seismic departments at all levels, taking into account specialized seismic hazard loss prediction research departments. By identifying these key factors, city administrators can make targeted protection and preparations in advance to reduce losses in the event of a disaster.

After completing the system vulnerability assessment and risk identification, it is important to conduct a comprehensive assessment of the different risks and prioritize them according to their severity, scope of impact and difficulty of recovery. Critical infrastructures with high vulnerability and risk, power, water supply, and transportation systems, are often prioritized for attention. The risk assessment model, combined with historical data and expert judgment, can provide a quantitative risk assessment report for urban disaster response, helping the government and relevant departments to rationally allocate resources and develop effective recovery programs. Comparative analysis of the current status of the development of earthquake disaster loss assessment software at home and abroad shows that the core calculation methods of earthquake disaster loss in practical applications are currently divided into the macro method based on the information of earthquake examples and the method based on vulnerability, which optimizes the post-disaster recovery strategy and improves the efficiency and effectiveness of the overall resilience recovery.

3.3. Technical and Strategic Options for Resilience Recovery

In order to effectively enhance the resilience of urban infrastructure, various technical means must be diversified and comprehensively applied. Structural repair technology is the foundation of the recovery strategy, and for damaged buildings, bridges and underground pipelines, the use of seismic reinforcement, dynamic monitoring and intelligent materials can effectively improve their post-disaster load-bearing capacity and recovery speed. At the same time, the introduction of intelligent monitoring and control systems, real-time monitoring of the operational status of infrastructure through sensors and IoT technology, can quickly find faults and accurately locate the damaged areas, thus improving the accuracy and efficiency of recovery. The synergistic application of these technical means can greatly shorten the recovery time of infrastructure and reduce the long-term impact of earthquakes on urban functions. Based on the macro data of historical earthquake cases, the economic loss rate, direct economic loss or total loss caused by the earthquake disaster is modeled, so as to assess the overall economic loss caused by the earthquake, and resilience restoration not only needs to rely on advanced technology, but also needs to formulate a systematic restoration strategy, and ensure the effect of each stage through the implementation of phases. Typically, recovery strategies are categorized into three phases: emergency repair, short-term recovery, and long-term reconstruction. The emergency restoration phase mainly focuses on restoring the basic functions of key infrastructure, such as restoring power supply, water supply and the smooth flow of major transportation channels; the short-term restoration phase focuses on the functional stability of the infrastructure, and ensures that the system can be restored to a more normal operating state in a shorter period of time through reinforcement and optimization adjustments; and the long-term reconstruction phase focuses on improving the overall system's resilience, and making fundamental improvements to systemic problems exposed by the disaster, and ensuring that each phase is effective. The long-term reconstruction phase focuses on improving the overall resilience of the system, making fundamental improvements to the systemic problems exposed by the disaster, and improving the ability to cope with similar disasters in the future.

Submarine node seismographs are deployed on the seafloor for seismic observation, which can realize high-precision, high-resolution and high-efficiency seismic exploration in deep-water environments. Generally, submarine node seismographs support four-component (pressure geophone and three-component velocity geophone) observation, which is useful in permanent reservoir monitoring and high-density, omni-directional, multi-component, wide-frequency, and large-amplitude seismic data acquisition.

Among the many recovery technologies and strategies, choosing the most suitable option is the key to enhancing recovery efficiency, and technology selection should follow the principle of cost-benefit analysis, by assessing the implementation cost, recovery effect and time consumption of different technologies, and choosing the one that can bring the greatest recovery benefit in the short term. Scalability and flexibility are also important criteria for technology selection, as the complexity of urban infrastructure requires that the selected technologies be able to cope with multiple disaster scenarios and be flexibly adapted and upgraded in different recovery phases. In addition, environmental and social sustainability are important considerations in the selection of recovery technologies, as the use of low-carbon, environmentally friendly and resource-efficient technologies not only reduces the environmental burden of post-disaster recovery, but also strengthens the resilience of cities in the face of future disasters.

In the resilience recovery process, the synergy of various technologies and strategies is crucial. As it is often difficult for a single technology to cope with complex post-disaster situations, there is a need for an organic combination of technical means, policy guidance and social participation. Through multi-sectoral coordination and policy support, we can ensure smooth and efficient resource dispatch in the recovery process and avoid bottlenecks in the recovery progress. At the same time, extensive social participation, such as community self-help, volunteer organizations and public education, can also effectively enhance the overall efficiency of recovery. A comprehensive strategy can not only better cope with the immediate damage to infrastructure caused by an earthquake disaster, but also lay a solid foundation for long-term reconstruction and resilience after the disaster.

4. Optimization and Implementation of Resilience Recovery Strategies

In the process of resilient recovery of urban infrastructure, it is crucial to formulate a reasonable recovery strategy, but the mere formulation of the strategy is not sufficient, and it must be adapted to the actual disaster situation and recovery needs through continuous optimization and adjustment. The degree of damage and the scope of impact on urban infrastructure may vary with each earthquake, so the optimization of the recovery strategy needs to be dynamically adjusted according to the real-time information of the disaster, the results of the system damage assessment, and the resource allocation to ensure the flexibility and effectiveness of the response plan. The goal of strategy optimization is to maximize the recovery effect with limited resources and to improve the speed and quality of recovery.

Optimizing resilience recovery strategies should consider several key factors. The first is data-driven decision support. Through the collection and analysis of real-time post-disaster data, precise information on recovery needs and priorities can be provided to assist decision makers in making scientific and reasonable adjustments at different points in time. The second is efficient scheduling and allocation of resources. In the aftermath of an earthquake, the limited availability of materials, equipment, and personnel needs to be reasonably allocated through an intelligent scheduling system to ensure that critical facilities and key areas are prioritized for restoration. In addition, strategy optimization should also take into account time constraints and social impacts, i.e., ensure the speed of restoration while minimizing the long-term negative impacts on social life and economic activities.

In the actual resilience recovery process, the implementation of recovery strategies needs to maintain flexibility and the ability to adjust dynamically. Recovery programmes should be implemented in phases based on vulnerability assessments and risk identification of post-disaster infrastructure systems, and early emergency recovery needs to be coordinated with mid- and late-stage system optimization. In the early phase, the focus is on restoring critical lifeline systems, such as transportation, power, water and communication networks, in response to the extent of infrastructure damage. Based on this, subsequent phases implement more in-depth structural reinforcement and system optimization through continuous disaster monitoring and performance assessment to ensure the long-term stable operation of the infrastructure. The dynamic implementation strategy also allows for continuous adjustments through feedback mechanisms to ensure that the objectives of each phase are met in a timely manner.

The optimization and implementation of resilience recovery strategies not only rely on technical means and system design, but also require close multisectoral collaboration and extensive social participation. Effective collaboration among government departments at all levels, infrastructure management units, relief agencies and social organizations can ensure the sharing of resources and information in the post-disaster recovery process, avoiding redundancy and waste of resources. At the same time, the active participation of the public is also an important part of the implementation of the strategy. Through community self-help, volunteer action and public education, the speed and breadth of the recovery work can be effectively increased to enhance the overall disaster recovery capacity of the city. Such cross-sectoral collaboration and public participation can provide a strong guarantee for the successful implementation of resilience recovery strategies.

5. Conclusion

This study centers on resilience recovery strategies for urban infrastructure systems under seismic effects, and clarifies the importance and urgency of resilience recovery by analyzing the impacts of earthquakes on urban infrastructure. We explore the core concepts and evaluation indexes of resilience, and propose the necessity of optimizing recovery strategies through system vulnerability assessment and risk identification. Meanwhile, by analyzing the technology selection and strategy implementation for resilience recovery, we clarify the key roles of diverse technology applications, phased recovery, and cross-sector collaboration in enhancing recovery efficiency. Ultimately, the optimization and implementation of resilience recovery strategies not only rely on advanced technologies, but also incorporate scientific resource allocation, dynamic feedback mechanisms, and extensive public participation, in order to rapidly restore urban functions and reduce social and economic losses after a disaster.

Future urban infrastructure resilience construction needs to further integrate these strategies into daily planning and management, in order to enhance the adaptability and resilience of urban systems in the face of natural disasters, and to truly realize sustainable development and disaster resilience. This not only provides theoretical support for the current urban disaster prevention work, but also lays a solid foundation for dealing with more complex disaster challenges in the future.

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