Cascading Failures in Urban Infrastructure Systems Towards Resilience: A Review and Prospects

ZHANG Changchun, HE Lei, FAN Tingjun

Abstract: The increasing frequency of extreme disasters driven by global climate change has underscored cascading-failure risks caused by complex interdependencies among urban infrastructure systems, making them a pivotal challenge for disaster-resilient urban planning. Existing studies remain constrained by three limitations. The identification of infrastructure interdependencies is limited by data availability and methodological tools, producing a narrow set of recognized categories. The refined identification of critical facilities often overlooks social systems and residents' behavior, resulting in incomplete simulation frameworks. Resilience-improvement strategies still focus mainly on single-system responses and emergency countermeasures, while collaborative multi-system planning remains underdeveloped. Against the background of rapid progress in artificial intelligence, this paper proposes research directions and technical pathways: using multisource heterogeneous data and large language models to improve the granularity and precision of interdependency identification; developing facility-society-population coupled cyber-physical simulation models to characterize urban spatial vulnerability; and formulating intelligent, multi-system collaborative recovery strategies to accelerate the restoration of urban service capacity. The study provides theoretical guidance and feasible technical approaches for key issues in disaster-resilient planning.

Keywords: urban infrastructure; cascading failures; disaster-resilient planning; artificial intelligence; literature review

Global climate change has increased the frequency and intensity of extreme meteorological disasters, exposing highly built-up Chinese megacities to severe waterlogging and flooding. Recent heavy rainstorms in Zhengzhou, Beijing, and Shenzhen caused major losses and social impacts and revealed the vulnerability of urban systems. The Zhengzhou July 20 extraordinary rainstorm is a typical case: cascading failures triggered by the failure of a single infrastructure facility caused large-scale functional paralysis, and the recovery of public services lagged markedly [1].

In response, China has attached growing importance to disaster resilience and infrastructure renewal. Over the past five years, a series of national policy documents have been issued, including the Opinions on Promoting New Urban Infrastructure Construction and Building Resilient Cities issued in December 2024. These documents require local governments to enhance resilience to extreme disasters and improve comprehensive urban disaster-prevention capacity. In practice, Beijing resilient city spatial planning, Shanghai comprehensive disaster prevention and reduction planning, and national technical procedures for territorial spatial comprehensive disaster-prevention planning have all defined frameworks, processes, and core contents. Yet scientific understanding of multi-system interactions and precise regulatory techniques remains insufficient.

At its root, the built environment contains complex coupling relations among multiple elements. These relations create the conditions and pathways for failure propagation, allowing secondary disasters triggered by primary hazards to spread and expand within the built environment [2-3]. Urban and rural planning is a core means of coordinating multi-system spatial layouts and construction sequences in the built environment, but the lack of systematic research and precise regulation for multi-hazard and multi-system interactions limits the effect of disaster-prevention planning [4-8]. This paper therefore reviews current limitations in disaster-prevention planning, summarizes cascading-failure studies of interconnected infrastructure from interdependency identification, failure simulation, and resilience-restoration strategy, and proposes prospects and innovation pathways based on new technologies.

1 Coupling risks in urban infrastructure systems

The city is a dynamic system that depends heavily on infrastructure functions during operation. Seemingly independent systems form an interdependent functional transmission network that supports daily life and urban functions [9]. As shown in Fig. 1, power, communications, transportation, water supply and other lifeline systems have close internal supply-support relationships. They also provide essential guarantees for public service facilities such as hospitals and material reserves. These facilities, through infrastructure networks and road transport systems, meet residents' daily needs and stabilize urban operation.

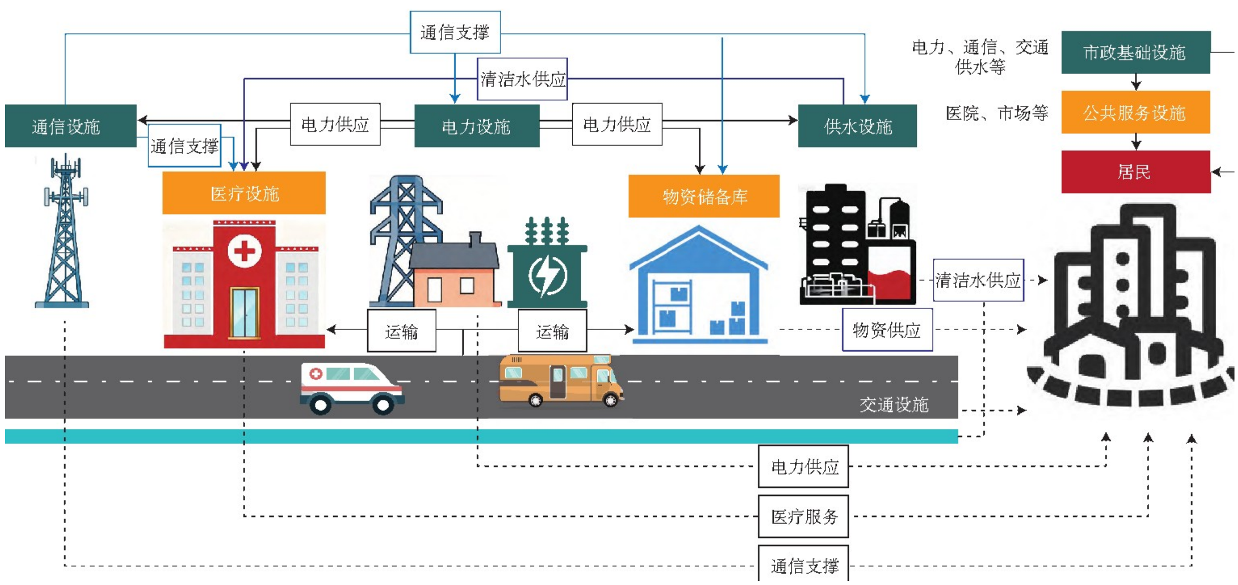

Fig. 1 Interdependencies among urban infrastructure subsystems.

This association is a result of planning and design. The form and organization of the built environment are shaped by planning decisions, and interdependency relations, spatial layouts, and functional linkages among infrastructure systems are designed to improve overall operating efficiency. As connections and coupling density increase, service efficiency improves but systemic vulnerability also grows [10-11]. When a critical node or subsystem is disturbed, the effect can spread rapidly through dependency chains and cause multi-system paralysis. The 2003 North American blackout triggered failures in water supply, transportation, and communications; in the 2021 Zhengzhou July 20 rainstorm, damage to power facilities caused difficulties in water supply and communications [1].

Interconnections among infrastructure systems mean that damage to a single facility may trigger cascading failures, weaken urban service capacity, and cause chain damage to residents' daily life and the urban economy. Under China's intensive effort to build disaster-resilient cities, reducing cascading impacts, intervening efficiently in limited facilities, parcels, and systems, and improving urban service capacity are key tasks for resilient city construction.

2 Research progress in urban infrastructure disaster-prevention planning

Traditional disaster-prevention planning around urban infrastructure has developed mainly in two directions. The first is single-system facility optimization. Existing studies focus on optimized design of single facilities such as road infrastructure, rainwater detention tanks, water-supply pipelines, green infrastructure, and pumping stations, often using physical or numerical models to minimize postdisaster losses and improve the effectiveness of emergency plans [12-15]. This line of work is useful for local engineering optimization but is generally limited to a single facility and does not fully consider feedback between multiple systems or spatial coupling.

The second direction is system protection and planning. From a system perspective, studies identify infrastructure resilience and propose strategies in areas such as integrated management, refined full-process control, and regular maintenance [16-17]. Recent work on urban resilience has increasingly recognized that interdependencies among infrastructures determine urban vulnerability and postdisaster recovery speed. Scholars have proposed planning guidance from the coupling of municipal infrastructure and disaster-prevention systems [18], called for the incorporation of exposure, vulnerability, and hazard analysis into the disaster-prevention planning evaluation system [20], and argued that resilient planning must coordinate single-system robustness with multi-system cascading-failure prevention [19-21].

Overall, resilience-oriented disaster-prevention planning must move from facility-level engineering experience to cross-system coordination. Its task is to identify vulnerable links in complex networks, understand cascading-failure mechanisms and amplification effects, and translate them into operable planning controls. The process can be organized around three core links: interdependency identification, failure simulation, and recovery strategy (Fig. 3).

3 Research progress on key technologies for cascading failures in interconnected urban infrastructure

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城市关联基础设施各子系统通过物
质、能量与信息交互形成有机整体，极

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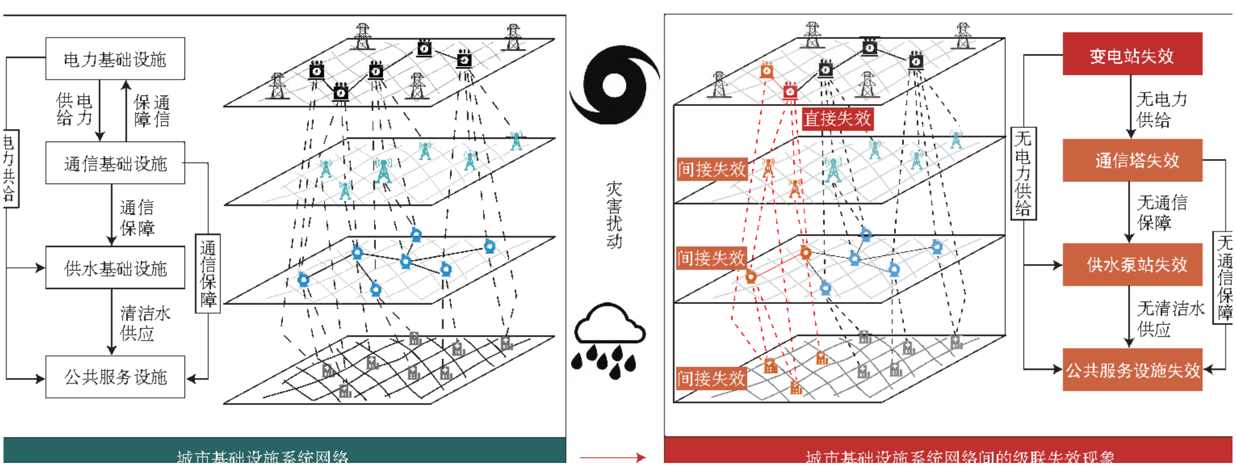

Fig. 2 Cascading failures of urban infrastructure systems.

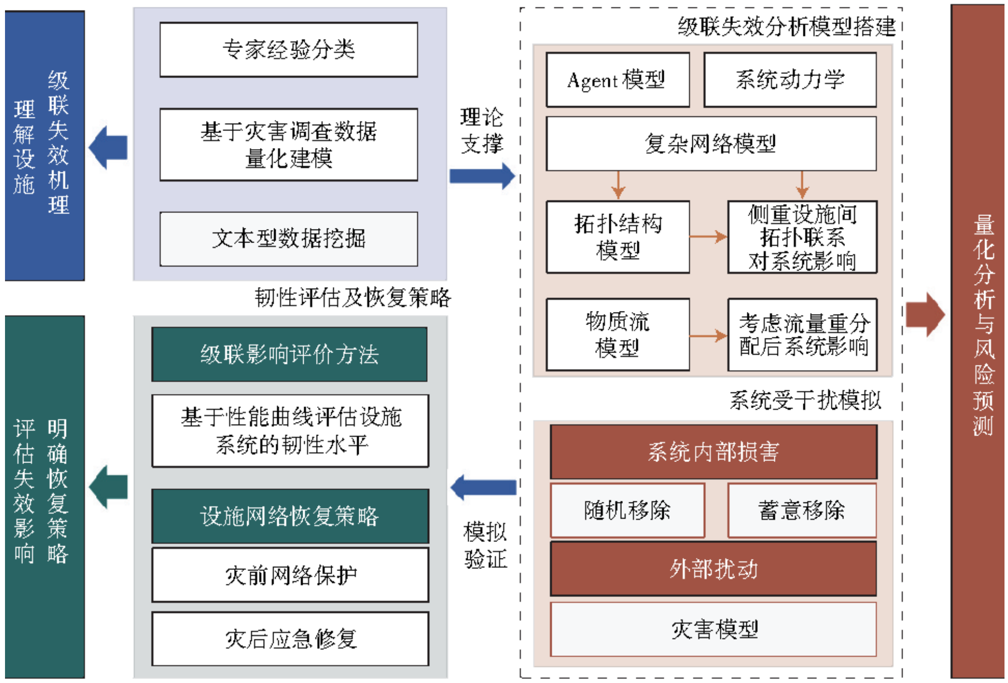

图3 城市基础设施级联失效关键技术研究概况

Fig. 3 Literature review on key technologies for mitigating cascading failures in urban infrastructure.

Urban infrastructure subsystems form organic entities through the exchange of matter, energy, and information. Under extreme disturbance, local failures can spread along dependency chains and escalate into cascading failures, threatening urban operation and resident safety. The analysis of this problem should follow a system-flow logic of mechanism analysis, risk deduction, active intervention, and resilience assessment. The following review focuses on interdependency identification, failure-model simulation, and resilience countermeasures.

3.1 Identification of interdependencies among interconnected infrastructure

Rinaldi et al. classified interdependencies among infrastructure into physical, cyber, geographic, and logical categories, focusing on power, water supply, communications, energy, and transport systems [9]. Later studies expanded this classification from different perspectives by adding policy dependence, social dependence, and economic dependence [22]. Early work was often based on expert judgment and concentrated on a few sectors such as power and water supply, with limited support from empirical data.

Subsequent studies shifted toward data-driven dependency identification. Methods based on disaster investigation records quantify interdependencies from postevent data. Mendonca and Wallace identified correlations in postdisaster infrastructure restoration after the 2001 World Trade Center attack [24]. Monsalve and de la Llera estimated interdependency coefficients and strengths from restoration-rate fitting [25]. Zorn and Shamseldin derived dependency direction and intensity using assistance-recovery relations [26]. Report and news mining has also been used to extract dependency events from public records and media, constructing more diverse textual evidence for interdependency recognition [27-29].

Data-driven research remains exploratory. Many studies rely on single-modal text mining, lack cross-validation of multisource data, and usually identify interdependency types such as geographic adjacency or administrative decision support. They remain insufficient for revealing complex dependence mechanisms among associated infrastructure.

3.2 Simulation of cascading failures in interconnected infrastructure

Cascading failures among infrastructure occur through complex interdependency and functional dependence. Realistic simulation is therefore essential for understanding failure mechanisms and identifying key facilities. Existing research mainly addresses modeling methods, disturbance forms, and dynamic deduction under faults.

3.2.1 Modeling methods for interconnected infrastructure networks

Owing to differences in research perspective and data availability, three types of modeling methods are widely used. Agent-based modeling treats infrastructure components as entities with decision and behavioral attributes and simulates interactions between systems [31-32]. System-dynamics methods examine feedback between disturbance and network response, analyzing long-term effects of failures [33-34]. Network-analysis methods abstract components as nodes, physical or dependency connections as edges, and directional relationships as weights, thereby identifying reliability and service-flow transmission across systems [35-36].

3.2.2 Forms of failure disturbance in infrastructure networks

Infrastructure networks are exposed to internal and external disturbances. Internal disturbances include random removal and malicious attacks on nodes or components, which are used to simulate interruptions caused by aging equipment, operational failure, or targeted damage [45-47]. External disturbances include natural hazards, accidents, and malicious attacks. They have significant spatiotemporal heterogeneity and geographic correlations, and studies often combine hazard-process models with infrastructure-network models to simulate component failure under disaster action [48-51]. However, existing disturbance models still have limited capacity to capture dynamic spatial evolution and cross-system response processes under complex disasters.

3.3 Infrastructure-resilience strategies under cascading-failure impacts

On the basis of cascading-failure mechanisms, studies have assessed infrastructure resilience and restoration strategies to ensure service stability during extreme weather. Resilience evaluation commonly uses performance curves to quantify system condition before, during, and after failure [51]. Restoration studies focus on network protection before disaster and resource allocation after disaster, including identification of key components, optimization of network operating modes, resource allocation, and protection measures [52-54]. Emergency-recovery studies examine task sequencing and resource allocation under limited repair resources and behavior constraints [55-56].

Existing strategy research has made progress in identifying key components, improving network protection, and optimizing repair-resource allocation, but it still focuses mainly on infrastructure networks themselves. The effects of resident-service accessibility, social operation behavior, and spatial coordination on resilience are often not fully considered.

3.4 Review of research progress

3.4.1 Research objects: insufficient multi-system integration

Current studies are mostly concentrated on single infrastructure systems or internal cascading failures among a small number of systems. They have not yet formed a framework that starts from the overall city, integrates multiple types of infrastructure, and evaluates their effects on resident service capacity. Research content remains dominated by transport and drainage facilities, while the functional failure effects of social infrastructure such as hospitals, material reserves, and emergency-service facilities receive inadequate attention. Since failure of these facilities may directly and indirectly affect postdisaster recovery, the object system of research needs to be expanded.

3.4.2 Mechanism exploration: identification precision remains limited

Studies of failure mechanisms are often based on qualitative judgment or structured data analysis. Data-driven dependency identification and transmission-law discovery remain weak. Many studies rely on authoritative documents or single information extraction, lack cross-validation and integrated analysis of multisource heterogeneous data, and provide insufficient characterization of complex dependencies among interlinked infrastructure.

3.4.3 Model simulation: insufficient depiction of physical mechanisms and social effects

Existing simulation models can describe facility physical failure processes to some extent, but they tend to focus on facility-level damage. They often lack comprehensive analysis of residents' service accessibility and social-operation effects. Since the core goal of urban resilience is to safeguard daily resident needs and service continuity, models must introduce dimensions such as resident accessibility and service supply to realize a transformation from functional interruption to social-impact assessment.

3.4.4 Strategy level: regulation remains concentrated on engineering repair

Current recovery strategies concentrate on engineering repair and protective reinforcement and have not yet formed a systematic recovery framework that integrates spatial and temporal coordination. Engineering measures can mitigate local infrastructure failure, but they are insufficient for addressing cascading impacts across multiple systems. Future planning should build integrated mechanisms for spatial layout optimization, facility redundancy, and governance coordination, supporting coordinated recovery and rapid restoration of resident service capacity.

4 Prospects for cascading-failure studies under new technologies

Given the problems of incomplete interdependency identification, insufficient refined simulation of critical facilities, and weak multi-system collaborative planning strategies, artificial intelligence offers new research pathways. This paper proposes three directions: improving the precision of infrastructure dependency identification with large language models, building cyber-physical multisystem dependency models for scenario simulation and risk assessment, and realizing intelligent disaster-resilient planning under multiple objectives.

4.1 Using large language models to improve infrastructure interdependency identification

Current interdependency analysis focuses mainly on physical connections, and the exploration of hidden dependencies among systems such as communications, transport, and social infrastructure remains insufficient. Large language models can be used to mine multisource data, including historical disaster reports, news, expert knowledge, remote-sensing imagery, sensor monitoring, and social-media information. Text data help reveal infrastructure dependencies under normal operation and unusual disaster conditions, sensor data capture traffic and facility operating states, and remote sensing interprets spatial distribution and physical connections.

On this basis, large language models can conduct semantic analysis, knowledge extraction, and knowledge-graph construction, creating an interdependency knowledge map and making dependency structures storable and visualizable. Through structured storage and visual representation, the model can support the identification of latent and nonintuitive dependencies and provide a stronger evidence base for planning decisions (Fig. 4).

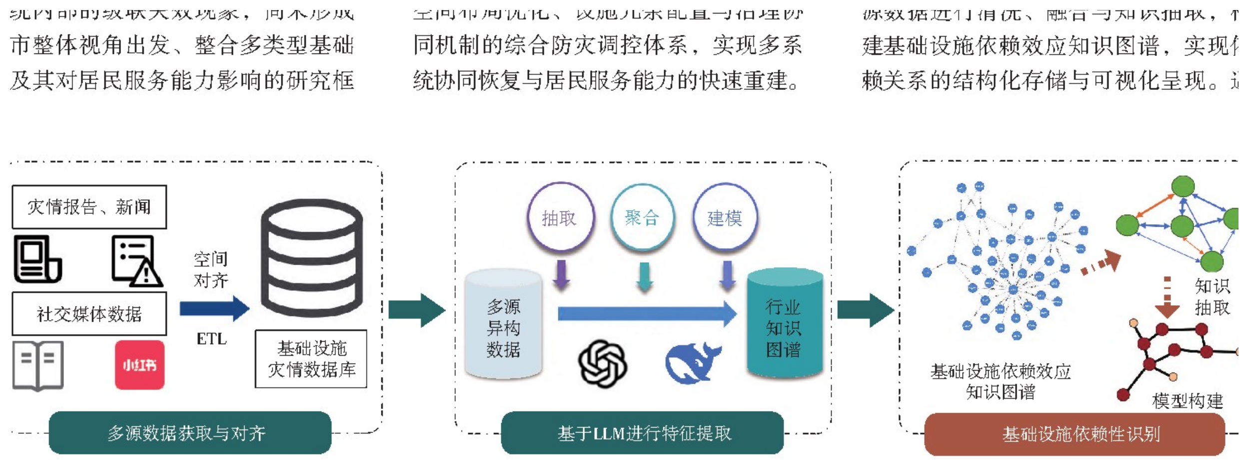

Fig. 4 Enhancement of infrastructure interdependency identification through multisource data and large language models.

4.2 Building cyber-physical urban multisystem dependency models for scenario simulation and risk assessment

For disaster-resilient planning, modeling cascading failures in multiple systems is a central challenge. Purely digital models can efficiently deduce macroscopic system responses, but they have difficulty reproducing fine-grained mechanisms and simplifying model assumptions may bias failure thresholds and transmission paths. Physical models can restore real processes, but their coverage of large-scale complex scenarios is limited. A cyber-physical dependency model can combine the advantages of both.

The model consists of multisystem dependency simulation and physical-experiment modules. The simulation module takes single-layer infrastructure networks as the basis and completes coupling construction according to dependency rules, including simplified topology and modeling of core networks such as power, water supply, and transportation, and defining flow laws, dependency types, key attributes, and core parameters. The physical-experiment module verifies digital-simulation results under controlled environments. Measurements from wind tunnels, tanks, and other experiments can correct supply-and-demand relations, mechanical parameters, and vulnerability parameters under extreme loads, improving the accuracy of microscopic failure mechanisms and providing evidence for multiscale model calibration.

4.3 Realizing intelligent disaster-resilient planning under multiple objectives

Existing planning largely relies on experience-driven deduction and model-based analysis. Under extreme disasters, urban multi-system cascading failures require a planning framework that integrates intelligent algorithms and multiobjective decision making, shifting from passive response to active prevention. As shown in Fig. 5, the core is to build an integrated loop of mechanism mining, simulation, and decision optimization. In mechanism mining, infrastructure dependencies, functional associations, and coupling paths are identified. In simulation, multi-system models are used for theoretical construction, empirical validation, scenario simulation, and risk assessment. In decision optimization, multiobjective algorithms generate optimal intervention sequences under objectives such as minimum disruption, lowest investment, and optimal fairness.

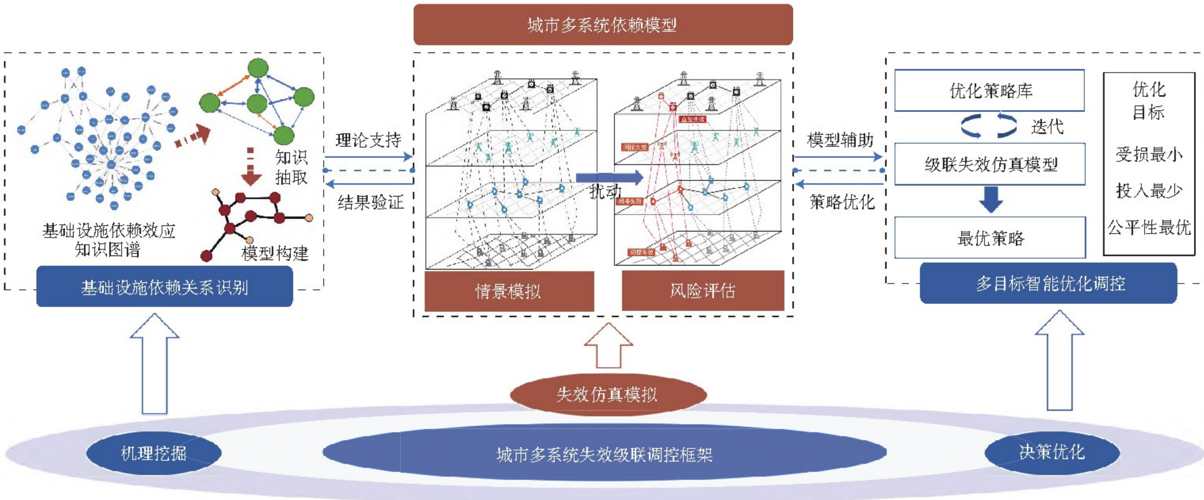

Fig. 5 Planning and regulatory approaches for urban multi-system cascading failures.

This framework helps address two core problems in current disaster-prevention planning: the absence of sufficient multi-system interaction mechanisms and the lack of quantitative, precise, and flexible controls. It can support risk identification, functional recovery, and spatial intervention and promote disaster-resilient planning toward intelligence and refined upgrading.

5 Conclusion

This paper reviews research progress on cascading failures in infrastructure systems for disaster-resilient city planning. It systematically summarizes three core links, namely interdependency identification, failure-model simulation, and recovery-strategy formulation, and analyzes cascading mechanisms and prevention pathways for infrastructure under disaster disturbance. Accurate identification of multidimensional dependencies is the basis for understanding cascading-failure mechanisms; scenario simulation and evaluation systems are the scientific basis for formulating targeted recovery strategies and improving overall system resilience.

The review also finds clear limitations in current studies. They insufficiently understand multi-system collaborative failure mechanisms, underrepresent social functions and service impacts, and pay limited attention to spatial coordination in engineering repair. To overcome these problems, future research should use multisource heterogeneous data and large language models to build infrastructure dependency knowledge graphs; construct cyber-physical simulation platforms that integrate digital simulation and physical experiments; and develop multiobjective decision models for resource allocation and resilient intervention. As data environments improve and intelligent methods become more deeply integrated, infrastructure-resilience research will play an increasingly important role in urban safety governance and sustainable development.

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