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Concepts, models, and indicator systems for urban safety resilience: A literature review and an exploration in China

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ABSTRACT

Safety resilient city is a frontier concept of urban safety development and a hot topic in the field of urban safety research. In this paper, the relevant research results of domestic and foreign scholars are reviewed from the perspectives of concepts and models, the evaluation indicator system of urban safety resilience is compared in terms of risk types, evaluation objects, evaluation dimensions and quantitative methods, and the development of international standards for resilient cities is discussed. Based on the literature review, the connotation of the triangular theoretical model of urban safety resilience is explained, and an urban safety resilience evaluation index system applicable to Chinese cities is proposed, which provides support for the development of the national standard "Guide for safety resilient city evaluation" (GB/T 40947-2021). It is applied to six representative cities as examples for evaluation to explore the direction of Chinese urban safety resilience improvement. The pathway for improving the safety resilience of Chinese cities is discussed.

1. Introduction

Cities are an important symbol and the primary carriers of modern civilization, and urbanization is a defining historical process in the development of human society. The 2020 World Cities Report released by UN–Habitat revealed that the world urbanization rate is expected to reach 56.2% in 2020 and 62.5% by 2035 [1]. Safety is a primary prerequisite for cities to function dynamically. As the built environment expands and urban operational systems and vital signs become more complex, the safety risks faced by cities continue to rise, with frequent natural disasters and man-made accidents causing severe damage and threatening their survival.

In recent years, the concept of "resilience" has gradually become a hot topic in the safety discipline. In 2015, ISO/TC 292 expanded from "Security" to "Security and Resilience." The third UN World Conference on Disaster Risk Reduction, the third UN Conference on Housing and Sustainable Urban Development, and the sixth session of the Global Platform for Disaster Risk Reduction regarded "resilience" as an important concept [2–5]. The Rockefeller Foundation and Arup launched the "Global 100 Resilient Cities" initiative [6]. New York, Tokyo, London, Paris, Rotterdam, and Singapore have launched the construction of resilient cities in succession [7–12].

As an underdeveloped concept, the connotations and extensions of resilience are ambiguous. To understand urban safety resilience, the concepts and models of urban safety resilience must be systematically sorted based on the background of urban safety research. The evaluation of urban safety resilience is an important link to turning theory into practice. Thus, identifying the key factors of a comprehensive evaluation of urban safety resilience and developing an evaluation method with Chinese characteristics is crucial in China.

The remainder of this paper is structured as follows. Section 2 reviews the concept of urban safety resilience to analyze the development and evolution of this concept and to refine its core connotation. Section 3 analyzes relevant theoretical models and existing index system evaluation methods to clarify the key issues in the comprehensive evaluation of urban safety resilience. Section 4 elaborates on the connotation of the triangular theoretical model of urban safety resilience, proposes an urban safety resilience evaluation index system applicable to Chinese cities, and analyzes strategies for improving urban safety resilience in China based on the six selected Chinese cities using an empirical approach. Section 5 summarizes the core ideas of this study.

2. Concept of urban safety resilience

2.1. Evolutionary history

The etymology of resilience is derived from the Latin word "resilio," which originally meant "to spring back to its original state," and was

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later adopted in French and English [13]. The concept of resilience was originally used in physics and mechanics when referring to an object's ability to recover after being deformed by an external force [14]. In 1973, the concept of resilience was introduced in the context of ecology to describe an ecosystem's ability to restore its balance. Since then, it has been promoted in engineering and sociology.

As the concept's scope of application has expanded and people's understanding of the system's perspective has shifted, the connotation of resilience has evolved in practice. Currently, in the field of engineering, the main views on the understanding of resilience are engineering, ecological, and evolutionary resilience [13]. Each revision of the concept reflects a new perspective on resilience. Engineering resilience is the first of the three perspectives and is most similar to traditional physical and mechanical concepts; thus, it is called engineering resilience. Engineering resilience refers to a system's ability to return to equilibrium after disturbance [14]. In 1996, Holling proposed a change in the definition of resilience, arguing that resilience should emphasize the magnitude of disturbance that a system can absorb before structural change, and emphasized the existence of multi-stability of the system [15]. With further understanding of the system, Walker et al. proposed the theory of adaptive cycles, which gave rise to the concept of evolutionary resilience, in which the system does not exist in a steady state, and resilience places greater emphasis on the system's ability to adapt and transform in a constantly changing environment [16].

In the 1980s and 1990s, the concept of resilience was introduced in the safety discipline in research related to post-disaster recovery [17–20]. It emphasized a society's ability to absorb and recover from disasters. As an international topic, resilience was introduced by the Local Government Environmental Action Council (LGEA) and the United Nations International Strategy for Disaster Reduction (UNISDR) [21]. The Hyogo Framework for Action, adopted by the Second World Conference on Disaster Reduction in 2005, incorporated resilience into the UN resolution document and called for enhancing the resilience of countries and regions by strengthening their disaster reduction and management capacities [22]. Since then, the concept of resilience has attracted increasing academic attention and its understanding is not limited to the management of social response to disasters. Risk factors have been broadened from natural disasters to include accidents, public health events, and social safety events [23–30]. The subjects involved range from government departments to various physical facilities and a wide range of social subjects [31–41]. Management processes extend from prevention and recovery to emergency management [42–45].

2.2. Representative discourses

The concept of "resilience" has been widely used in various aspects of systems science to emphasize the continuity of system functions and the existence of system identity. Although disasters frequently cause the decline, collapse, and even destruction of system functions, the concept fits well with the science of safety management and disaster prevention. Cities are the primary targets for safety management and disaster prevention. Therefore, this study focuses on urban safety research, proposes the concept of urban safety resilience, and distinguishes it from other relevant concepts, such as environmental, economic, and ecological resilience. The discussion on resilience in this study focuses on urban safety resilience.

Despite extensive discussion and a wide range of research objects, purposes, and scenarios, as well as the evolving and deepening understanding of safety resilience theory in academia, no consensus has been reached on the concept of safety resilience [46–48]. The UNISDR defines resilience as the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate, and recover timely and efficiently from the effects of hazards, including the preservation and restoration of essential basic structures and functions [2]. The International Organization for Standardization Committee on Security and Resilience defines urban resilience as the ability of an urban system, to anticipate, prepare for, respond to, and absorb shocks, as well as positively adapt and transform in the face of stresses and challenges in a changing environment, while facilitating inclusive and sustainable development [49]. The World Bank defines resilience to natural shocks as a stronger, faster, and more inclusive post-disaster reconstruction [50]. Other research institutions and researchers have also proposed corresponding definitions of resilience on the basis of the characteristics of their research work, and numerous definitions exist for the concept of safety resilience [51]. Some representative definitions are summarized in Table 1.

Table 1 exhibits that the early definitions of safety resilience focused on maintaining stability and restoring the system to its original state in the face of risks and perturbations, mainly as a reflection of the engineering resilience perspective. Over time, system adaptation and transformation in unknown changing environments have been increasingly discussed. Although no consensus has been reached on the definition of safety resilience, this process of change reflects a general trend in the scholarly understanding of safety resilience from an engineering resilience perspective to an ecological and evolutionary resilience perspective. In terms of understanding, safety resilience is considered a resilience or intrinsic property of a system in the face of risk factors, a safe state in which the system is located in a risky environment, or the process by which the system exerts resilience to achieve a safe state under risk pressure.

Different definitions of urban safety resilience have distinct emphases, but the ability to respond, recover, and adapt is necessary for a city's survival during catastrophic events. A city that performs well in the process of responding, recovering, and adapting will reach a safe state during disasters. Thus, safety-resilient cities are able to respond, recover, and adapt to catastrophic events.

3. Model and evaluation system methodology of urban safety resilience

3.1. Model of urban safety resilience

Few systematic theories exist on safety-resilient city characterization models. ISO/TC 292 Security and Resilience proposed a framework for urban resilience that characterizes the elements of urban resilience in terms of people, assets, and processes, where local governments and stakeholders can enhance the resilience of cities in the face of shocks, stresses, and challenges through activities such as plans, actions, and initiatives [49]. Fan et al. proposed the triangle theoretical model of public safety, which forms a basic theoretical framework for public safety science from three dimensions: emergencies, disaster carriers, and emergency management [82]. Fang et al. proposed the "three-dimensional space" system theory, which elaborates on the connotation of urban safety resilience under the interaction of subsystems based on the perspective of physics, society, and information [77].

Many researchers and research institutions have proposed corresponding safety-resilient city research dimensions to characterize the relevant elements of a safety-resilient city. For example, the Multidisciplinary Earthquake Engineering Research Center proposed the "PEOPLES" resilience model to characterize the elements of resilient cities from seven perspectives: people and demographics, environment and ecosystem, government organization services, physical infrastructure, lifestyle and community competitiveness, economic development, and socio-cultural capital [83]. The model outlines the elements of urban safety resilience explored at various spatial scales. Rockefeller Foundation and Arup summarized the elements of urban safety resilience from four dimensions: leadership and strategy; health and well-being; infrastructure and ecosystems; and economy and society. These dimensions are used in the evaluation and creation of activities of the 100 Resilient Cities Program [6]. Bruneau et al. suggested that resilience should include four interrelated dimensions: technological, organizational, social, and economic resilience [84]. Jha et al. proposed that urban resilience

Table 1
Representative discourses of safety resilience.

Institution/ Author	Year	Definition of safety resilience
Wildavsky	1988	Resilience is the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back [52].
Mileti	1999	A locality can tolerate and overcome damage, diminished productivity, and reduced quality of life from an extreme event without significant outside assistance [53].
Abel and Langston	2001	Resilience is the ability to persist through future disturbances [54].
Pelling	2003	Resilience is the ability to adapt to difficult situations [55].
Klein et al.	2003	It is recommended that resilience only be used in a restricted sense to describe specific system attributes concerning (i) the amount of disturbance a system can absorb and still remain within the same state or domain of attraction and (ii) the degree to which the system is capable of self-organization [56].
Godschalk	2003	A resilient city is a sustainable network of physical systems and human communities. During a disaster, the physical systems and the community networks must be able to survive and function under extreme stresses [57].
Ahmed et al.	2004	We define community resilience as including those features of a community that in general promote the safety of its residents and serve as a specific buffer against injury and violence risks, and more generally, adversity [58].
Bodin and Wiman	2004	The dynamic behavior of the system as it strives (if at all) to return to equilibrium, i.e., the extent to which, and the speed with which return occurs [59].
Walker et al.	2004	Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks [60].
UNISDR	2005	Resilience is the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions [2].
Adger et al.	2005	By resilience, we mean the capacity of linked social-ecological systems to absorb recurrent disturbances, such as hurricanes or floods so as to retain essential structures, processes, and feedbacks [61].
Cutter et al.	2008	Resilience is the ability of a social system to respond and recover from disasters and includes those inherent conditions that allow the system to absorb impacts and cope with an event, as well as post-event, adaptive processes that facilitate the ability of the social system to reorganize, change, and learn in response to a threat [62].
Norris et al.	2008	Community resilience is a process linking a network of adaptive capacities (resources with dynamic attributes) to adaptation after a disturbance or adversity [63].
Resilience Alliance	2010	Resilience refers to the magnitude of change or disturbance that a system can experience without shifting into an alternate state that has different structural and functional properties and supplies different bundles of the ecosystem services that benefit people [64].
Ernstson	2010	Resilience is the ability of urban governance to maintain a certain dynamic regime in the face of uncertainty and changing transitions [65].
Ahern	2011	Resilience is the capacity of systems to reorganize and recover from change and disturbance without changing to other states—in other words, systems that are “safe to fail” [66].
Tyler and Moench	2012	Resilience is about encouraging practitioners to consider innovation and change to aid recovery from stresses and shocks that may or may not be predictable [67].
Lhomme et al.	2012	Resilience is the ability of a city to absorb disturbances and recover its own functions after a disturbance [68].
CARRI	2013	Community resilience is the capability to anticipate risk, limit impact, and bounce back rapidly through survival, adaptability, evolution, and growth in the face of turbulent change [69].
Desouza	2013	Resilience in terms of cities generally refers to the ability to absorb, adapt and respond to changes in an urban system [70].
Wamsler and Flanery	2013	A disaster resilient city can be understood as a city that has managed to successfully support measures to strengthen individuals, communities and institutions to: (a) Reduce or avoid current and future hazards; (b) reduce current and future susceptibility to withstand hazards; (c) establish functioning mechanisms and structures for disaster response; and (d) establish functioning mechanisms and structures for disaster recovery [71].
Romero-Lankao and Gnatz	2013	Resilience denotes a capacity of urban populations and systems to endure a wide array of hazards and stresses [72].
Fan Weicheng	2016	Resilience is the ability of a city to withstand, adapt and recover quickly in an inverted environment [73].
Meerow et al.	2016	Urban resilience refers to the ability of an urban system—and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales—to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity [74].
Zhou Limin	2016	A resilient city is one that can quickly reorganize and resume life and production even after a disaster shock [75].
World Bank	2017	Resilience to natural shocks is stronger, faster, and more inclusive post-disaster reconstruction [50].
Bozza et al.	2017	Resilience identifies the capability to recover, absorb shocks, and restore equilibrium after a perturbation [76].
Fang et al.	2017	Urban resilience is the ability of urban systems and their various subsystems to maintain or rapidly recover their functions when disturbed and to better cope with future uncertainty through adaptation [77].
González et al.	2018	Resilience are the capacities of a system, person, community or country exposed to a threat of natural origin, to anticipate, resist, absorb, adapt and recover from its effects in a timely and effective manner, to achieve the preservation, restoration and improvement of its structures, basic functions and identity [78].
Marchese et al.	2018	Resilience was viewed as the ability of a system to prepare for threats, absorb impacts, recover and adapt following persistent stress or a disruptive event [79].
Saja et al.	2018	Social resilience is defined as the ability of social entities and mechanisms to anticipate, absorb, and adapt to disasters along with the ability to undertake recovery activities to reduce future disruptions and their impact [80].
ISO/TC 292	2019	Urban resilience is the ability of any urban system, with its inhabitants, in a changing environment, to anticipate, prepare, respond to and absorb shocks, positively adapt and transform in the face of stresses and challenges, while facilitating inclusive and sustainable development [49].
Convertino and Valverde	2019	A type of resilience is arrived at by minimizing the frequency and magnitude of undesired system effects, via instruments oriented towards anticipation, sensing/monitoring, learning, and adaptation [81].

includes four dimensions: infrastructural, institutional, economic, and social [85].

3.2. Evaluation system methodology for urban safety resilience

Overall, two main types of methodologies exist in the field of urban safety resilience assessment: the model simulation and index evaluation system. At present, the model simulation methodology relies primarily on the resilience curve model [86]. This methodology describes the dynamic change process of system resilience. However, owing to the high requirements of the model and database, comprehensively considering various evaluation elements of urban safety resilience is difficult. The evaluation methodology based on the index system is systematic and flexible, and it allows for the comprehensive consideration of various elements of urban resilience in conjunction with city characteristics. This methodology is practical and concise for city application. This methodology selects a set of indicators that can reflect the safety resilience characteristics of the system and characterizes, qualitatively or quantitatively, the system composition, management mode, functional characteristics, and other aspects. The advantages of this methodology include its applicability, systematicity, expandability, and flexibility. When designing an index system, the researcher can set the evaluation indicators in a targeted manner according to the evaluation objects and objectives. The number of evaluation indicators is generally not limited; thus, they can comprehensively reflect the key characteristics of the evaluation objects. The same set of indicator systems and evaluation methods can be used to evaluate the safety resilience of similar objects. The evaluation indicators can be adjusted flexibly, making them easy to maintain or update.

When evaluating urban safety resilience using this approach, designing an urban safety resilience evaluation indicator system that supports assessment methods is necessary. Among the core issues are the types of risk of concern, the spatial scale of the assessment object, the assessment dimensions of safety resilience, the quantification tools, and the method of determining indicator weights. Due to the diversity of research objects, research purposes, and research support conditions, specific research works should take distinct approaches to the aforementioned issues. The corresponding main approaches are presented in Table 2.

Given that the evaluation system methodology for urban safety resilience is more inclusive and suitable for organizing researchers from different fields working under the same framework, the approach is widely used in the standardization efforts for urban safety resilience, for example, the International Organization for Standardization Technical Committee 268 (ISO/TC 268)—Sustainable Cities and Communities published an international standard—ISO 37123:2019 Sustainable cities and communities—Indicators for resilient cities [112].

3.3. International standards for resilient cities

The development of international standards reflects the process of consensus formation in various academic areas. Two main international standard technical committees are working on resilient cities: ISO/TC 292—Security and Resilience and ISO/TC 268—Sustainable Cities and Communities.

ISO/TC 292—Security and Resilience is responsible for the standardization of security and resilience at the national, community, industry, organization, and citizen levels. This technical committee develops standard documents in various themes, including security and resilience guidance documents, business continuity management, emergency management, authenticity, integrity, and trust for products and documents, community resilience, security management systems, protective security, organizational resilience, and urban resilience.

On April 28, 2017, the technical committee established a fundamental working project "Frameworks and principles for urban resilience" in the urban resilience theme to provide basic prerequisites for the development of international standards in security and resilience. The project produced two versions of the technical report for the voting phases on February 21, 2018 and April 10, 2019 [49,113]. The technical report contained the technical committee's definition and understanding of urban resilience. Comparing the content of the two versions of the technical report, the 2018 version of the technical report defines urban resilience as the measurable ability of an urban system to absorb and recover quickly from the impact of any plausible hazard and maintain the continuity of its functions [113]. The 2019 version of the technical report defines urban resilience as the ability of any urban system, with its inhabitants, in a changing environment, to anticipate, prepare, respond to, and absorb shocks, as well as positively adapt and transform in the face of stresses and challenges, while facilitating inclusive and sustainable development [49]. These two statements demonstrate that ISO/TC 292 has paid attention to cities' ability to deal with risks while maintaining the continuity of urban functions. As for the difference between them, ISO/TC 292 recognizes that urban resilience should also include the ability to adapt and transform, in addition to maintaining stability.

In the field of urban safety, the ISO/TC 268—Sustainable Cities and Communities collaborates with ISO/TC 292 while gearing toward maintaining and improving urban services and enhancing the quality of human habitats.

In the field of urban resilience, this technical committee formed a working draft of the standard "Sustainable development in communities—Indicators for resilient cities" on March 2, 2018 [114]. This standard was published in December 2019 and renamed "ISO 37123:2019 Sustainable cities and communities—Indicators for resilient cities" [112]. The 2018 working draft of the standard defines a resilient city as "a city that is able to manage, adapt, maintain and ensure city services and enhance quality of life in the face of hazards, shocks and stresses" [114]. The officially released standard in 2019 interprets it as a "city able to prepare for, recover from and adapt to shocks and stresses" [112]. As for the difference between them, ISO/TC 268 realized that urban resilience should include adaptive capacity.

Although some international standards for safety-resilient cities are being promoted or have been implemented, national standards for safety-resilient cities in China remain few. The primary step in promoting the development of safety-resilient cities in China is to establish an evaluation methodology applicable to Chinese cities. However, China began evaluating the resilience of urban safety a bit later than other countries. The lack of a systematic evaluation system has become a restrictive factor in China's practice of constructing safety-resilient cities. Based on the above reasons, this study proposes a triangular theoretical model of urban safety resilience, builds an urban safety resilience evaluation system considering the characteristics of Chinese cities, and conducts empirical research in Section 4. This work also leads to the formulation of the "Guide for safety resilient city evaluation" (GB/T 40947–2021).

4. Comprehensive evaluation of urban safety resilience: the case of China

4.1. Triangular theoretical model of urban safety resilience

The triangle theoretical model of public safety is the consensus foundation theory of the public safety discipline [82]. The model considers emergencies, disaster carriers, and emergency management as the three edges, with disaster elements serving as the nodes linking the three edges, revealing the fundamental components of public safety science.

When conducting research in the field of safety resilience, it is necessary to construct a theoretical model that reflects the basic elements of safety-resilient cities. Taking into account the characteristics and trends of safety and resilient city research, this study applies the triangle theoretical model of public safety to the field of safety-resilient city research and focuses on public safety incidents, urban disaster-bearing systems,

Table 2
Core issues and key practices in comprehensive urban safety and resilience evaluation methodology.

Core issues	Key practices	Features	Typical cases
Types of risks of concern	Non-specific risks	Practices of this kind emphasize the general safety resilience properties of cities to various types of risks and consider the impact of various types of risk elements holistically. They usually suit different regions better.	Disaster Resilience Scorecard for Cities [87], City Resilience Index [88]
	Specific risks	This type of practice focuses on one or a certain type of major risk factors faced by the assessment target and makes more targeted considerations on the basis of specific risk types. They usually highlight localized features.	SPUR Methodology [89], Coastal Community Resilience Index [90]
Spatial scale of the evaluation object	Community scale	Based on urban primary organizations and governance units, practices on this scale focus on strengthening neighborhood connectivity and resource sharing, as well as adaptive preparedness and response to common risks.	IFRC Framework for Community Resilience [91], Communities Advancing Resilience Toolkit [92]
	Regional scale	Based on areas with relatively clear administrative boundaries, practices on this scale can easily obtain administrative statistics and seek decision support, and evaluations typically focus on multiple perspectives, such as physical, spatial, cultural, and management.	Disaster Resilience Scorecard for Cities [87], City Resilience Index [88]
	National scale	Practices on this scale easily obtain support from country-level macro data. They focus on measuring a country's comprehensive level of risk response to achieve sustainable economic and social development.	Resilience Analysis of Countries under Disasters [93]
Assessment dimensions of safety resilience	Subsystems	Practices of this kind divide the object of evaluation into different subsystems of physical, social, and economic aspects according to their characteristics, and thus conduct safety resilience evaluation.	City Resilience Index [88], Baseline Resilience Indicators for Communities [94]
	Intrinsic abilities	Practices of this kind assess urban safety resilience in terms of its capabilities for emergencies, such as coping, recovery, and adaptive abilities.	Disaster Resilience Scorecard for Cities [87], The Australian Natural Disaster Resilience Index [95–97]
Quantification tools	"Top-down" style	Practices of this kind obtain data from statistics or databases published by government departments or institutions. They are usually characterized by easy access and reliable data, and are mostly used to make horizontal and vertical comparisons of similar objects. The quantification tools are mostly in the form of data-based indicators.	Community Disaster Resilience Index [98], PEOPLES Framework [99], Resilient City Evaluation System based on the Post-disaster Recovery Process [100]
	"Bottom-up" style	Practices of this kind usually obtain relevant data from the object itself and from stakeholders. They can take a targeted design based on the characteristics of the subject, are better suited for public participation, and are mostly used for small-scale spatial or sectoral assessments, such as communities and sectors. The quantification tools they use are in the form of questionnaires, evaluation scorecards, evaluation checklists, engineering analysis tools, and so on.	Conjoint Community Resilience Assessment Measurement [101], The City Water Resilience Approach [102]
Way of determining indicator weights	No weights	Rather than an integrated representation of the results of each indicator by an index, this approach is oriented toward the individual results of each indicator and is designed to identify problems and guide the city toward overall improvement.	Community Disaster Resilience Toolkit [103,104], Rural Resilience Index [105]
	Equal weights	This approach integrates the evaluation results of each indicator through a composite index but does not distinguish the levels of importance among indicators, thus avoiding problems caused by the judgment of the relative importance of indicators. This approach can provide a reference for the horizontal comparison between evaluation objects and the vertical improvement of the same object.	A Validation of Metrics for Community Resilience to Natural Hazards and Disasters [106], DS3 Model [107]
	Different weights	This approach uses subjective methods, such as Delphi and hierarchical analysis, and importance ranking or objective methods, such as factor analysis and entropy weighting, to assign different weights to each indicator in order to utilize the expert experience and data characteristic for an accurate assessment. However, this approach has problems, such as being more subjective and over-emphasizing the differences among indicators.	Community Based Resilience Analysis [108, 109], Resilience Inference Measurement Model [110], Evaluation System of Urban Community Resilience from the Perspective of Seismic Disaster Prevention [111]

and safety-resilient management as the basic framework. The triangle theoretical model of public safety, in which the three edges are linked by disaster elements, reflects the focus on the principles of disaster mechanisms in the public safety discipline. Greater emphasis should be placed on applied research that guides practice in the field of safe cities. To link the three edges, other suitable elements that can reflect the features of the safety-resilient city field must be identified. The three key characteristics—response, recovery, and adaption—are the behavior patterns of urban disaster-bearing systems in the face of public safety incidents and the management process of safety resilience for public safety incidents. Therefore, these three key characteristics can be used as resilient stages to organically link the three edges.

This study develops a triangle theoretical model of public safety by constructing a triangle theoretical model of urban safety resilience, which considers public safety incidents, urban disaster-bearing systems, and safety resilient management as the three edges and the key characteristics of a safety resilient city—response, recovery, and adaption—as the resilient stages to link the edges, as shown in Fig. 1.

The connotations of each key element of the triangular theoretical model of urban safety resilience are as follows. Public safety incidents are direct factors that impact and damage urban systems with suddenness, uncertainty, and chain and coupling effects, and include natural disasters, accidents, public health and social security events, and other types of emergencies that may occur in cities. Urban disaster-bearing systems are the carriers of public safety incidents and include physical urban entities, such as buildings and infrastructure, people, and the economic and information society generated by human behaviors. Safety-resilient management is a measure for urban disaster systems that comprises public safety incidents and urban disaster-bearing systems. This can reduce the impact or damage caused by public safety incidents on the urban disaster-bearing system and enhance the safety resilience of cities. It involves many aspects, such as leadership, coordination, resource guarantee, and emergency response. The resilient stages encompass the entirety of the urban safety resilience construction and improvement process, including the three steps of response, recovery, and adaptation. These stages are also a key link for safety-resilient management. Resilient stages are key components of safety resilience

Fig. 1. Triangular theoretical model of urban safety resilience.

management. The urban disaster-bearing system will undergo the above resilient stages in the face of public safety incidents, and safety resilient management can optimize this process to minimize damage to the urban disaster-bearing system.

4.2. Development of China's urban safety resilience evaluation index system and national standard

4.2.1. Framework of the urban safety resilience evaluation index system applicable to Chinese cities

Determining the evaluation dimensions is the premise of constructing an urban safety resilience evaluation index system, which is also the basis for evaluating urban safety resilience using an index system. The dimensions of the current evaluation index systems for safety-resilient cities are mostly determined on the basis of empirical judgment or target setting, and no definite division method exists. This study derives, from the basic theoretical models of academia, professionals, and international standards, a model to determine the evaluation dimensions scientifically and obtain reliable research findings.

The triangular theoretical model of urban safety resilience constructed here was derived from the triangle theoretical model of public safety, which is the basic theory of public safety science. Based on this model, among the three edges, the urban disaster-bearing system and safety-resilient management constitute the internal factors of the urban system, while public safety incidents are exogenous disturbances to urban systems. As safety resilience is a systemic capacity and an intrinsic property of cities, attention should be paid to the internal factors of the urban system.

The MMEM, also called the 4M model, is a guiding theoretical model for the risk management profession [115]. It contains four dimensions: humans, machines, environment, and management. According to this model, environment is the external factor, whereas humans, machines, and management are the internal factors of the risk management system. If the evaluation process of urban safety resilience is carried out based on this theory, it can be analyzed through the above-mentioned three internal factors.

In terms of international standards, the framework for urban resilience proposed by ISO/TC 292 is a theoretical model for the underlying work on urban safety resilience [49]. This framework focuses on the description of urban ontology and outlines the functions and systems of the city in three dimensions: assets, people, and processes.

The comparison of the three theoretical models above revealed that they are logically consistent with one another. The triangular theoretical model of urban safety resilience and the MMEM model include external and internal factors. In terms of internal factors, both consider management as an important dimension, and MMEM summarizes internal physical factors as humans and machines, which can be covered by the urban disaster-bearing system dimension of the triangular theoretical model of urban safety resilience. The two internal factors of the ISO/TC 292 urban resilience framework are assets and people, which correspond to the two factors of the MMEM theoretical model of machines and people, and the two factors can also be covered by the edge of the urban disaster-bearing system of the triangular theoretical model of urban safety resilience. The management is reflected in the process factor of the ISO/TC 292 urban resilience framework.

Integrating the three theoretical models and the characteristics and needs of urban safety resilience index evaluation, this study takes three evaluation dimensions—safety resilience of urban facilities, safety resilience of urban people, and safety resilience of urban management—as the three Tier 1 indicators of the urban safety resilience evaluation index system. This division highlights the attributes of the inner urban system and conforms to the framework of the above three theoretical models. The specific relationship is shown in Fig. 2.

Based on the three Tier 1 indicators of safety resilience—urban facilities, people, and management—Tier 2 indicators can be refined by analyzing the connotation of each Tier 1 indicator.

When evaluating from the perspective of safety resilience of urban facilities, consideration should be given to infrastructure that has a significant impact on urban functions, including building projects, transportation facilities, lifeline engineering facilities, and industrial enterprises, in addition to monitoring, early warning, and emergency safety facilities that have a significant impact on the continuity of urban functions in emergency situations. When conducting evaluations from the perspective of the safety resilience of urban people, the vulnerability and motivation of personnel should be analyzed, and the Tier 2 indicators should include the basic attributes of the population, readiness for social participation, and sense of safety and safety culture. The safety resilience of urban management should encompass top-level design, emergency response processes, management effectiveness, support measures, and so on. The Tier 2 indicators in this dimension include management system construction, prevention and response, risk control level, and support and safety input.

The three Tier 1 indicators and thirteen Tier 2 indicators reflect the overall dimensions and refined areas for conducting a comprehensive evaluation of urban safety resilience, which constitute the framework of the urban safety resilience evaluation index system, as shown in Fig. 3.

4.2.2. Indicators of the urban safety resilience evaluation index system applicable to Chinese cities

To enhance the applicability of the evaluation index system to Chinese cities, based on research on specific evaluation indicators of urban safety resilience, this study considers the national public safety planning objectives in China, assessment indicators of Chinese government departments, and the relevant research results, and draws on the indicators from the "Evaluation Rules for National Model Cities for Safety Development" proposed by the Office of the Safety Commission of the State Council [116]. An urban safety resilience evaluation index system applicable to Chinese cities is proposed on the basis of the above principles, of which 71 Tier 3 indicators are selected on the basis of the framework of the urban safety resilience evaluation index system, considering the accessibility and authority of data. The three key characteristics of urban safety resilience—the ability of response, recovery, and adaptation—are reflected in each of the indicators.

To evaluate the ability of response, recovery, and adaption, this study considers the characteristics of each tier of the three indicators, with the ability of response, recovery, and adaption corresponding to the indicators, and each indicator focusing on one or more of the three key characteristics. Tier 3 indicators can be quantitative or qualitative. The results of quantitative indicators can be quantified by specific numbers, whereas the results of qualitative indicators can be quantified at a hierarchical level through description and judgment. Tier 3 indicators can also be classified according to their direction and may be positive or negative indicators. Among them, the positive indicators reveal better urban safety resilience with greater results, whereas the negative

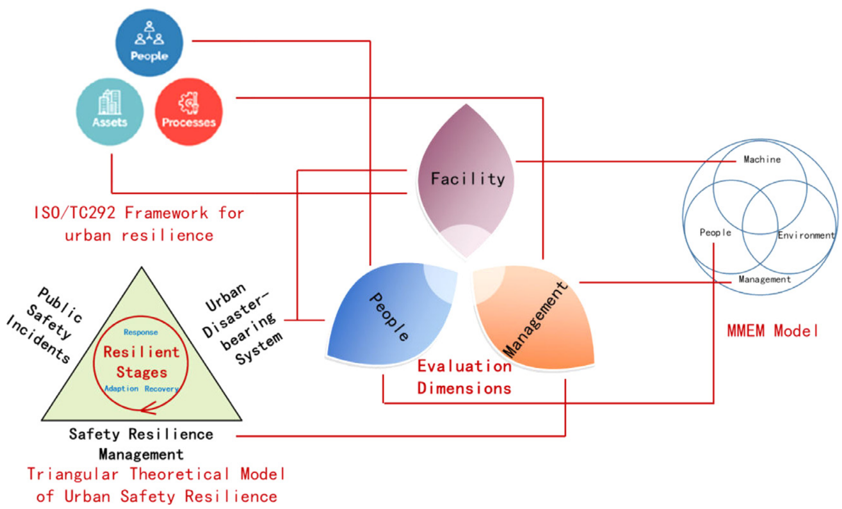

Fig. 2. Evaluation dimensions of the urban safety resilience evaluation index system.

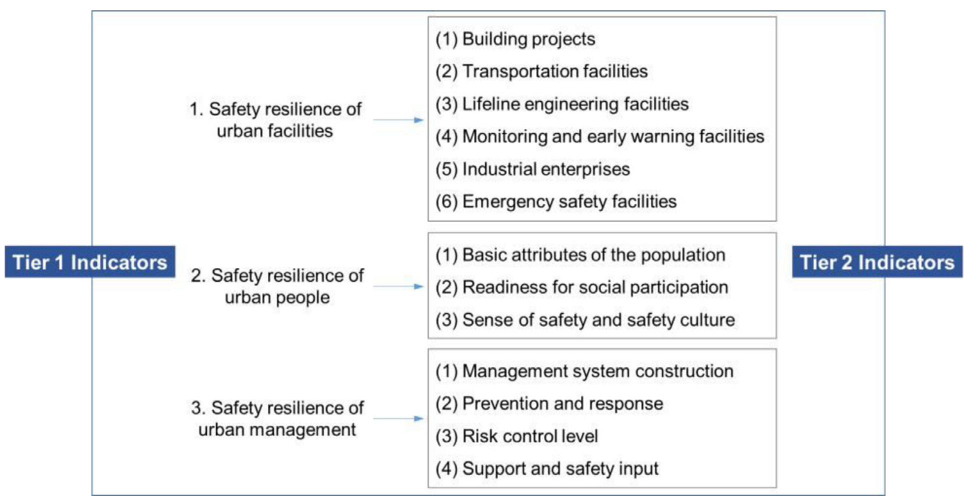

Fig. 3. Framework of the urban safety resilience evaluation index system.

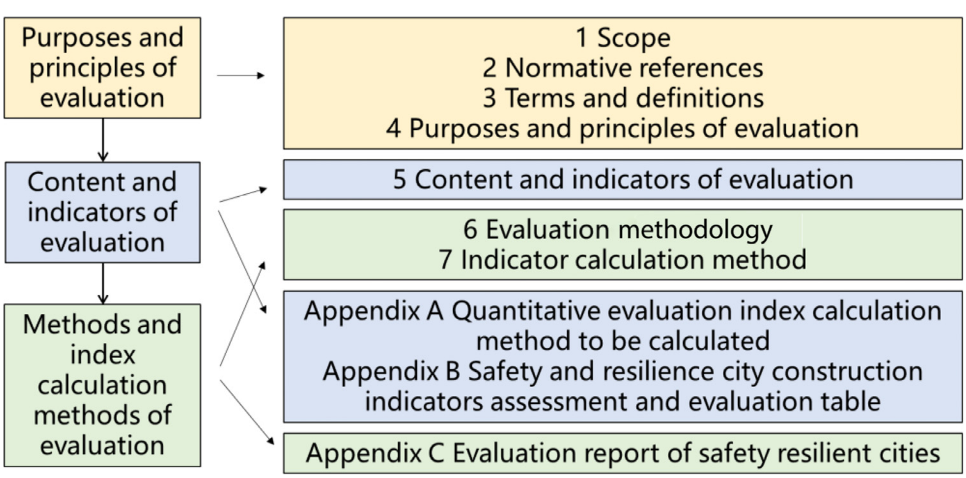

Fig. 4. Content structure of "Guide for safety resilient city evaluation" (GB/T 40947–2021).

indicators reveal worse urban safety resilience with greater results. A detailed urban safety resilience evaluation index system is presented in Table 3.

4.2.3. Development of the national standard "Guide for safety resilient city evaluation" (GB/T 40947–2021)

On the basis of the urban safety resilience evaluation index system, the China National Institute of Standardization and Tsinghua University developed the first national standard in the field of urban safety resilience evaluation, the Guide for safety resilient city evaluation (GB/T 40947–2021) [117]. The framework of this standard includes the purposes and principles of urban safety resilience evaluation, content and indicators of evaluation, and evaluation methods and processes. This standard can be used by governments at all levels, relevant management departments, and third-party organizations to conduct urban safety resilience evaluations. The structure of the standard is depicted in Fig. 4.

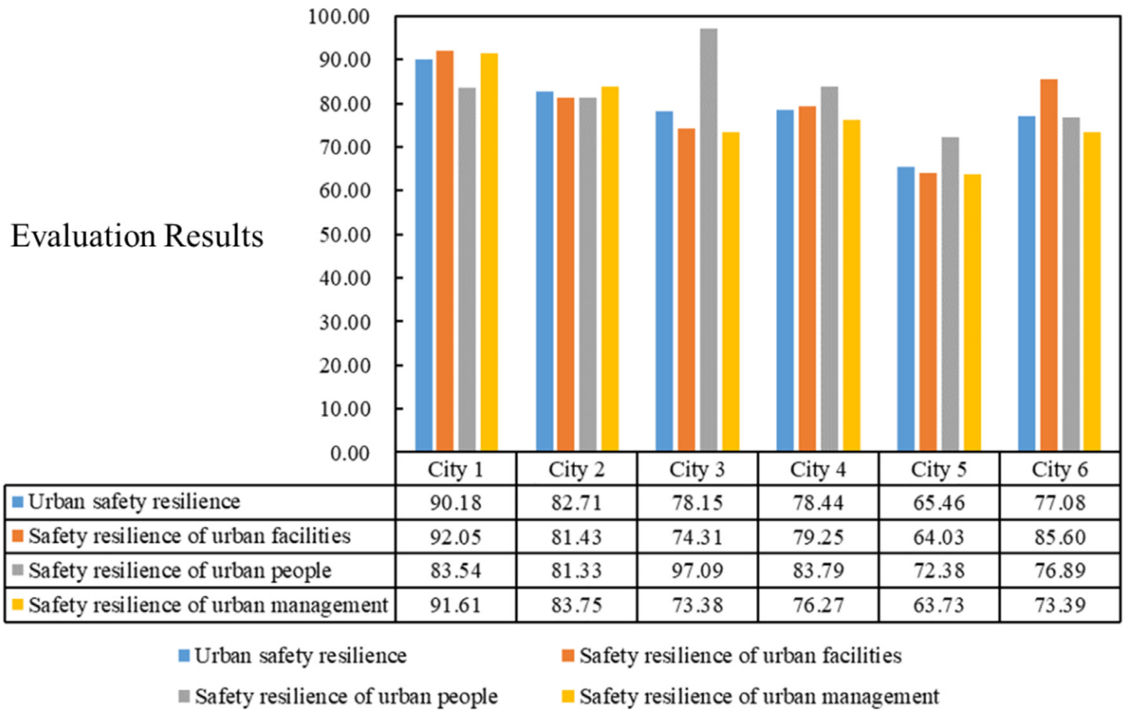

Fig. 5. Overall urban safety resilience results and urban safety resilience results by dimensions of each city.

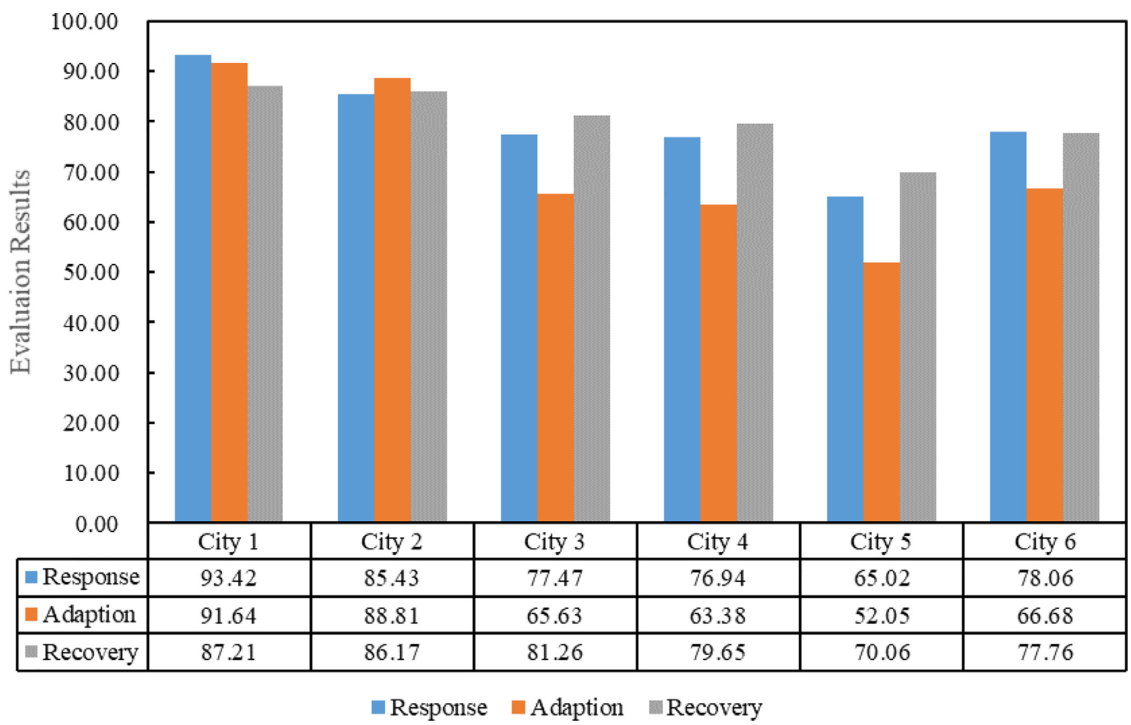

Fig. 6. Urban safety resilience results by characteristics of each city.

4.3. Application and result analysis of urban safety resilience evaluation in China

Six major cities in China were selected as evaluation objects, and the 2018 data of the Tier 3 indicators in the urban safety resilience evaluation index system were collected. The comprehensive weights of the indicators were determined by combining the indicator weights obtained by two methods: a subjective method, the importance discrimination method; and an objective method, the entropy weight method. The overall urban safety resilience and urban safety resilience results were evaluated on the basis of the dimensions and characteristics.

The overall urban safety resilience and urban safety resilience results based on the dimensions of each measured city are shown in Fig. 5. Regarding the overall urban safety resilience results, City 1 received the highest score (90.18) and was ranked 1st, City 2 (82.71) was ranked 2nd, Cities 4 (78.44), 3 (78.15), and 6 (77.08) had similar scores and were ranked 3rd–5th. City 5 had the lowest score (65.46).

Table 3
Urban Safety Resilience Evaluation Index System.

Tier 1 Indicators	Tier 2 Indicators	Tier 3 Indicators	Indicator Type	Indicator Direction	Indicator Characteristics
F_1 Safety resilience of urban facilities	S_1 Building projects	T_1 Proportion of buildings that basically meet seismic protection requirements;	Quantitative	Positive	Response
		T_2 Proportion of land area in safety vulnerable areas;	Quantitative	Negative	Response
		T_3 Land development intensity	Quantitative	Negative	Adaption
	S_2 Transportation facilities	T_4 Road area per capita;	Quantitative	Positive	Response, adaption
		T_5 Highway bridge safety and durability level;	Qualitative	Positive	Response
		T_6 Number of intercity material delivery lanes	Qualitative	Positive	Response, adaption
	S_3 Lifeline engineering facilities	T_7 Number of days that a backup gas supply can provide basic service;	Quantitative	Positive	Response, recovery
		T_8 Shared backup capacity in the event of a power outage;	Quantitative	Positive	Response, recovery
		T_9 Average annual power outage duration for households;	Quantitative	Negative	Response, recovery
		T_{10} Average annual water outage duration for households;	Quantitative	Negative	Response, recovery
		T_{11} Mobile phone penetration rate;	Quantitative	Positive	Response, adaption
		T_{12} Fixed broadband household penetration	Quantitative	Positive	Response, adaption
	S_4 Monitoring and early warning facilities	T_{13} Surveillance coverage of public areas in urban areas;	Quantitative	Positive	Response, recovery
		T_{14} Public coverage of weather disaster monitoring and forecasting warning information;	Quantitative	Positive	Response, adaption
		T_{15} Intelligent monitoring and management rate of municipal pipeline network pipelines	Quantitative	Positive	Response
	S_5 Industrial enterprises	T_{16} Management of operational safety risks in hazardous chemical enterprises;	Qualitative	Positive	Response
		T_{17} Tailings storage and sludge receiving site operational risk management;	Qualitative	Positive	Response
		T_{18} Risk management in construction operations	Qualitative	Positive	Response
	S_6 Emergency safety facilities	T_{19} Shelter area per capita;	Quantitative	Positive	Response, adaption
		T_{20} Green coverage;	Quantitative	Positive	Adaption
		T_{21} Storage space for disaster relief agencies per 10,000 people;	Quantitative	Positive	Response, recovery
		T_{22} Fire station construction;	Qualitative	Positive	Response
		T_{23} Number of beds in health care facilities per 100,000 people	Quantitative	Positive	Recovery
F_2 Safety resilience of urban people	S_7 Basic attributes of the population	T_{24} Population age structure index;	Quantitative	Negative	Response
		T_{25} Percentage of population with disabilities;	Quantitative	Negative	Response
		T_{26} Density of resident population in built-up areas;	Quantitative	Negative	Adaption
		T_{27} Percentage of transient population;	Quantitative	Negative	Adaption
		T_{28} Basic health insurance coverage;	Quantitative	Positive	Recovery, adaption
		T_{29} Proportion of employed population with higher education;	Quantitative	Positive	Adaption
	S_8 Readiness for social participation	T_{30} Number of health technicians per 10,000 persons;	Quantitative	Positive	Response, recovery
		T_{31} Number of police officers per 10,000 persons;	Quantitative	Positive	Response, recovery
		T_{32} Number of firefighters per 10,000 persons;	Quantitative	Positive	Response, recovery
		T_{33} Number of emergency response teams;	Quantitative	Positive	Response, recovery
		T_{34} Proportion of registered volunteers;	Quantitative	Positive	Response, recovery, adaption
	S_9 Sense of safety and safety culture	T_{35} Safety production liability insurance coverage;	Quantitative	Positive	Recovery
		T_{36} Citizen safety awareness and satisfaction;	Qualitative	Positive	Adaption
		T_{37} Business insurance density;	Quantitative	Positive	Recovery
		T_{38} Number of urban safety culture education experience bases or venues;	Quantitative	Positive	Response, recovery, adaption
F_3 Safety resilience of urban management	S_{10} Management system construction	T_{39} Urban leadership responsibilities of urban safety of party committees and governments at all levels;	Qualitative	Positive	Response, recovery, adaption
		T_{40} Responsibility for urban safety supervision of departments at all levels;	Qualitative	Positive	Response, recovery, adaption

(*continued on next page*)

Table 3 (*continued*)

Tier 1 Indicators	Tier 2 Indicators	Tier 3 Indicators	Indicator Type	Indicator Direction	Indicator Characteristics
		T_{41} Urban master plan, disaster prevention, mitigation plan, and other special plans;	Qualitative	Positive	Response, recovery, adaption
		T_{42} Plans or enhancement programs for a resilient city;	Qualitative	Positive	Response, recovery, adaption
		T_{43} Development of a city-level recovery plan;	Qualitative	Positive	Recovery
		T_{44} Emergency preparedness system;	Qualitative	Positive	Response, recovery
		T_{45} Emergency drills conducted;	Qualitative	Positive	Response, recovery
		T_{46} Urban community safety grid;	Qualitative	Positive	Adaption
	S_{11} Prevention and response	T_{47} Urban safety risks investigation; and correction	Qualitative	Positive	Response
		T_{48} Comprehensive urban risk assessment;	Qualitative	Positive	Response
		T_{49} Meteorology and flood monitoring;	Qualitative	Positive	Response
		T_{50} Earthquake and potential geological hazard monitoring;	Qualitative	Positive	Response
		T_{51} Hazardous chemicals operational safety risk monitoring	Qualitative	Positive	Response
		T_{52} Construction operations safety risk monitoring	Qualitative	Positive	Response
		T_{53} Urban lifeline and elevator safety risk monitoring	Qualitative	Positive	Response
		T_{54} Urban traffic safety risk monitoring;	Qualitative	Positive	Response
		T_{55} Safety risk monitoring of bridges, tunnels, and houses;	Qualitative	Positive	Response
		T_{56} Density of major hazard sources;	Quantitative	Negative	Response
		T_{57} Minimum limit of total annual runoff control rate;	Quantitative	Positive	Response
		T_{58} Integrated application platform for urban emergency management;	Qualitative	Positive	Response, recovery
		T_{59} Average time for emergency response and rescue personnel to reach the scene following an alarm	Quantitative	Negative	Response, recovery
	S_{12} Risk control level	T_{60} Disaster-related death rate per million population;	Quantitative	Negative	Response
		T_{61} Direct economic losses due to disasters as a percentage of regional GDP;	Quantitative	Negative	Response
		T_{62} Safety accident death rate per 100 million yuan of gross regional product;	Quantitative	Negative	Response
		T_{63} Safety accident death rate for 100,000 persons employed in industry, mining, and trade;	Quantitative	Negative	Response
		T_{64} Ratio of direct economic loss to regional GDP for particularly significant accidents;	Quantitative	Negative	Response
		T_{65} Death rate per 100,000 people from legally classified Classes A and B infectious diseases;	Quantitative	Negative	Response
		T_{66} Proportion of people affected by disasters in a year;	Quantitative	Negative	Response
		T_{67} Fire fatalities per 10,000 persons;	Quantitative	Negative	Response
		T_{68} Criminal case incidences per 10,000 persons;	Quantitative	Negative	Response
	S_{13} Support and safety input	T_{69} Percentage of financial expenditure on public safety;	Quantitative	Positive	Response, recovery, adaption
		T_{70} Percentage of financial expenditure on health care;	Quantitative	Positive	Response, recovery, adaption
		T_{71} Research and development in safety science and technology and the promotion of the use of results, technologies, and products	Qualitative	Positive	Response, recovery, adaption

Table 4
Evaluation Results of Urban Safety Resilience by Dimensions and Characteristics for Each City.

Evaluation Dimension	Key Characteristics	Cities					
		City 1	City 2	City 3	City 4	City 5	City 6
Safety resilience of urban facilities	Response	92.47	77.70	75.04	76.82	57.99	84.00
	Recovery	100.00	93.49	49.13	50.57	40.97	90.91
	Adaption	83.73	96.01	87.15	88.22	82.42	91.62
Safety resilience of urban people	Response	92.03	91.10	93.63	83.88	78.94	80.64
	Recovery	92.09	95.40	94.49	83.99	66.09	74.12
	Adaption	76.06	77.30	96.31	78.98	73.52	76.52
Safety resilience of urban management	Response	94.06	87.64	75.55	75.73	65.43	75.10
	Recovery	88.51	84.31	58.99	58.99	49.88	54.95
	Adaption	98.63	87.16	65.07	74.69	59.28	69.88

Overall, the evaluation results of the three dimensions of safety resilience of urban facilities, people, and management were generally consistent with the overall urban safety resilience results, and their scores fluctuated around the overall results, but the features of the results for the three dimensions differed among cities. For example, compared with the other two dimensions, City 1 had a lower score on the safety resilience dimension of urban people, whereas City 3 had a higher score. City 3 had significantly different scores on the three dimensions, whereas City 2 had a more consistent score on the three dimensions.

The evaluation results for the urban safety resilience characteristics of response, recovery, and adaptation are shown in Fig. 6. It demonstrates that the overall level of the evaluation results of urban safety resilience characteristics of each city was roughly in line with the overall results of urban safety resilience, with City 1 having the highest evaluation scores on the three key characteristics, followed by City 2, Cities 3, 4, and 6 having similar scores, and City 5 having the lowest scores. A comparison of the scores of the three key characteristics of the same city in terms of recovery features, except for Cities 1 and 2, revealed that the scores of urban ability to recover from the other four cities were significantly lower than the other two key characteristics, indicating that Chinese cities, in general, must be strengthened in terms of recovery ability.

The detailed evaluation results of urban safety resilience based on the dimensions and characteristics are shown in Table 4.

5. Summary

In this study, the concepts, models, evaluation systems, and international standards for urban safety resilience were reviewed, and an urban safety resilience evaluation index system applicable to Chinese cities, containing 3 Tier 1 indicators, 13 Tier 2 indicators, and 71 Tier 3 indicators, was constructed. This system provides developmental support for the national standard “Guide for safety resilient city evaluation” (GB/T 40947–2021). Six major cities in China were selected as evaluation objects for urban safety resilience. The results of urban safety resilience, including the overall results and results by dimensions and characteristics of the six cities, were presented. The results were employed to provide a basis for evaluating the safety resilience of Chinese cities and identifying directions for improving urban safety resilience in China. Overall, strengthening the ability of Chinese cities to recover from public safety incidents is a priority to improve urban safety resilience.

Declaration of Competing Interest

The authors declare no conflict of interest.

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