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Review

Resilience of Critical Infrastructure Systems: A Systematic Literature Review of Measurement Frameworks

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Abstract: Critical infrastructures such as transportation, power, telecommunication, water supply, and hospitals play a vital role in effectively managing post-disaster responses. The resilience of critical infrastructures should be incorporated in the planning and designing phase based on the risk assessment in a particular geographic area. However, the framework to assess critical infrastructure resilience (CIR) is variably conceptualised. Therefore, the objective of this study was to critically appraise the existing CIR assessment frameworks developed since the adoption of the Sendai Framework in 2015 with the hazard focus on earthquakes. The preferred reporting items for systematic reviews and meta-analyses (PRISMA) method was used for the selection of the 24 most relevant studies, and these were analysed to delineate existing frameworks, models, and concepts. The study found that there are wide-ranging disparities among the existing frameworks to assess the infrastructure resilience, and it has become a key challenge to prioritise resilience-based investment in the infrastructure sector. Furthermore, key attributes such as performance indicators, emergency aspects, and damage assessment need to be considered for different disaster phases—ex-ante, during, and ex-post—to improve the long-term resilience of critical infrastructure. Subsequently, an integrated and adaptable infrastructure resilience assessment framework is proposed for proper critical infrastructure planning and resilience-based investment decision making.

Keywords: critical infrastructure; disaster; earthquake; infrastructure resilience; indicators

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1. Introduction

In 1950, only 30% of the world's population lived in urban areas, which grew to 55% by 2018 and will be 68% by 2050 [1]. As urbanisation increases, people rely more on resilient infrastructure systems to access essential resources and facilities during and after a disaster [2,3]. Hence, strategic investments in infrastructure make it capable of withstanding multiple disasters and climate change risks are vital [4]. However, the impact of disasters may vary geographically due to differences in vulnerability, exposure, and capacity of the communities [5].

Disasters such as earthquakes, tsunamis, cyclones, floods, and landslides have negative consequences on a society and may trigger social, political, and economic instability [6–8]. Rapid onset disasters such as earthquakes have the potential to cause catastrophic infrastructure failures, which may result in fatalities and functional losses [9] compared to other slow onset disasters such as droughts. Although large magnitude earthquakes are not frequent (magnitude 8.0 or higher) [10], they can have a catastrophic impact on human lives, potentially resulting in fatalities and cascading disasters [11]. Therefore, building socioeconomic, infrastructure, and institutional resilience are crucial to preventing accumulated damages and ensuring the safety of communities [12,13].

In recent years, several frameworks, tools, strategies, and policies have been developed by researchers, policy makers, and key stakeholders in disaster management to support earthquake preparedness measures and to ensure the recovery of communities after earthquakes [14]. The resilience of infrastructure systems and critical services during crises needs to be assured by using measures such as safety margins in engineering design codes and guidelines [15]. In times of crisis, necessary services such as electricity, energy sources, transportation, telecommunication, water, and healthcare are usually interrupted [6]. These services are defined as critical needs that are provided by critical or lifeline infrastructure systems [16]. The term "infrastructure resilience" has no unified definition, and the definition varies depending on the key attributes used in the studies. Nonetheless, the primary consideration remains the same: to provide critical services to the people [17]. Typically, infrastructure resilience is defined as the ability of a critical infrastructure system (CIS) to withstand and recover from a potentially disruptive event [18].

Critical infrastructures play a key role in a nation's and a community's economic prosperity and have direct consequences on social development, civic participation, and environmental sustainability. Hence, their resilience to emerging disaster risks need to be strengthened [19]. Nevertheless, CISs are complex and often interconnected to one another [6]. This requires the CIS to be properly planned and designed to build a disaster-resilient community [20], which becomes the key priority for national and local governments [21].

Numerous approaches for qualitative and quantitative evaluations of a CIS have been employed to assess infrastructure resilience. Forcellini [22] used a quantitative method to reduce the earthquake risk to bridges through a geotechnical seismic isolation technique. The resilience of infrastructure systems and infrastructure interdependencies and the damage assessments are carried out with virtual city models for different seismic scenarios [23]. Some other frameworks have assessed the functionality of the critical infrastructure during and after disasters through performance-based design [24], a Bayesian network [25–28], fragility functions [27–38], and restoration curves [29]. Furthermore, a qualitative assessment can be carried out to assess the functionality of the critical infrastructures [39,40]. In general, many of the frameworks were developed with a geographic focus (for a specific county/region/city/community/coast) and in a specific socioeconomic setting. Despite the fact that these frameworks were successful in their application within the scope of a geographic region, they have limited application and replication potential in multiple contexts due to a lack of inclusive and adaptable indicators to different settings [12,13,41,42]. Such a framework with adaptable indicators is needed for consistent operationalisation in multiple contexts, which will then be helpful for making effective resilience investment decisions. Therefore, an integrated framework is required to assess the resilience of critical infrastructure using a set of potentially adaptable indicators in multiple geographic contexts and hierarchical levels (from a community to a national level).

In this study, an attempt has been made to critically appraise the available frameworks developed to assess CIR and to conceptualise a framework applicable in multiple contexts. Subsequently, a systematic critical review methodology using preferred reporting items for systematic reviews and meta-analyses (PRISMA) was adopted to select the relevant past studies. Consequently, 24 frameworks to assess critical/lifelines infrastructure for earthquake hazard that were analysed for their method of development and the indicators outlined were selected. A set of commonalities and differences between the frameworks such as geographic-specific and various hierarchical levels were studied. Finally, this study proposes an integrated and adaptable framework that can be used in different settings with proper contextualisation by key disaster management stakeholders at the policy, practice, and research levels.

2. Infrastructure Resilience in the Context of Seismic Hazards

2.1. Types of Critical Infrastructure

The degree of criticality of the infrastructure is measured by its effect on society in the event of its failure [6,43]. Protection and mitigation are two key CIR strategies [44]. Protection refers to the "necessity to protect the infrastructure from its collapse", and mitigation means "necessity to reduce loss of life and damage to the property by lessening the impact due to disasters" [44] (p.33). Furthermore, most of the schools and community buildings are used as temporary shelters [45], which makes the performance analysis of these structures in the event of an earthquake essential.

2.2. Critical Infrastructure Resilience (CIR)

The resilience of infrastructure systems largely depends on the potential failure rate and the residual/restoration performance measure of infrastructure elements. The level of resilience can be primarily expressed with the robustness and rapidity components [28]. However, the '4R' concept of resilience proposed by Bruneau et al. [46] and Tierney and Bruneau [47] is a good basis for assessing infrastructure resilience for earthquakes. The '4Rs' include robustness (ability to withstand hazards without suffering the loss of functions), redundancy (capability of satisfying functional needs during disasters), resourcefulness (ability to use the resources), and rapidity (capable of recovery).

The resilience of the infrastructure depends on the robustness interval where critical infrastructure can provide the services without any interruption after an occurrence [46]. The functionality failure of critical infrastructure can vary according to the type and intensity of the hazards. Meanwhile, critical infrastructures can perform better/worse than the expected performance [28,48]. A performance-based infrastructure resilience curve for critical infrastructure is shown in Figure 1 for different phases of a disaster [ex-ante, during, and ex-post].

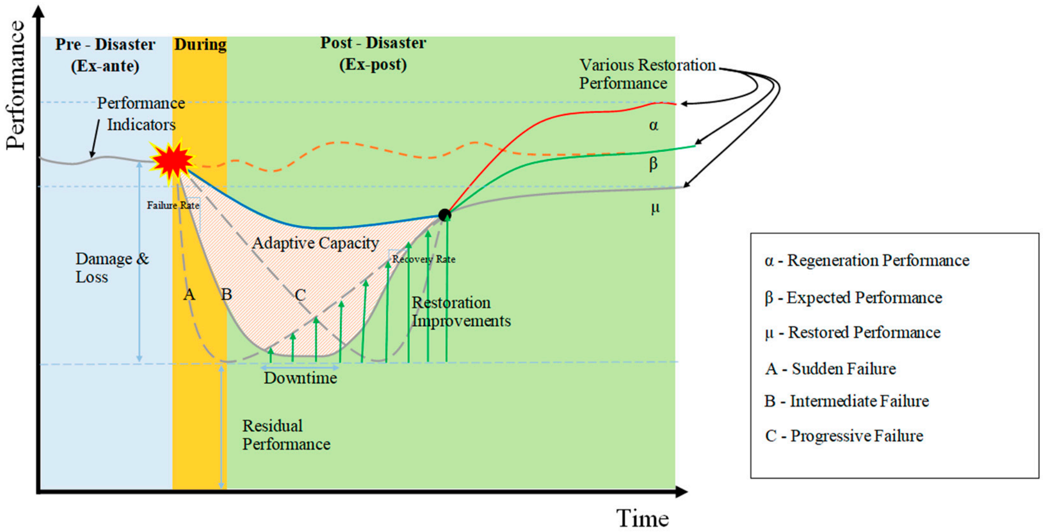

Figure 1. Performance based resilience components of a CIS (adapted from Refs. [28,48]).

The performance of infrastructure can be dropped to a level lower than the targeted level or the preperformance level (β line) immediately after a disaster. The failure can occur in terms of functionality and serviceability as a sudden or progressive failure depends on the disaster intensity and the resilience to that disaster event (A, B, and C). The restoration performance of the infrastructure can be expected at different levels such as restored performance (α), expected performance (β), and regeneration performance (μ-higher performance than expected). The resilience of a critical infrastructure can be assessed with the key performance indicators such as functionality and serviceability. [49].

Cutter and Sherifi [12,50] evaluated many different community resilience assessment frameworks in which infrastructure resilience is one of the five key community dimensions. Marasco et al. [23] studied seismic resilience and vulnerability of critical infrastructures built at the urban level using large virtual models in which the recovery stage was not considered (ex-post phase). A number of disaster resilience assessment frameworks extantin the literature were developed in a multi-dimensional resilience context in which the infrastructure was one of the critical dimensions. There is still a gap in the knowledge and necessity to critically examine the distinct infrastructure resilience assessment frameworks developed in a disaster context. This critical analysis assists researchers in understanding the key attributes/indicators to assess infrastructure resilience that can be used in multiple contexts without much time and cost in conceiving such a framework.

2.3. Critical Infrastructure Resilience (CIR) in the Context of Seismic Hazards

The studies related to CIR in the context of earthquakes have been increasing in academic and policy studies [51,52]. The impact on the critical infrastructure from earthquakes is considerably high [9], leading to massive casualties and economic losses [53,54] compared to other disasters. Earthquakes are the most lethal natural disasters, killing almost 720,000 people worldwide between 2000 and 2018 [55] and causing significant damage to critical infrastructures around the world.

The resilience of systems to seismic hazards such as earthquakes is a measure mainly based on three attributes: the threat to a site; the vulnerability of people, structures, and infrastructure that makes them vulnerable to damage; and exposure to potential loss [56]. For example, the seismic risk of urban road networks included the study of land use, network connectivity and demands patterns [57]. The probability of road blockage by liquefaction and building collapse was assessed in Taiwan, based on direct and indirect damages during an earthquake [33]. In another study, the earthquake safety assessment was carried out for the reinforced buildings to check the applicability of rapid visual screening (RVS) methods in Turkey [58]. Similarly, Miles and Chang [59,60] studied the urban recovery of lifeline infrastructure during earthquakes using a conceptual framework and computer-based modelling. The currently available research on CIR have focused on specific places, whereas resilience standards relevant to specific regions have not demonstrated adaptability to other locations [58]. Hence, an adaptive and integrated framework to assess the CIR in the different phases of earthquakes is necessary.

The studies that focused on the impact of critical infrastructure due to earthquakes highlighted above addressed the recovery of lifeline services and planning, mitigation, and decision-making strategies. However, an integrated framework that can be used to assess the resilience of different infrastructure systems to earthquakes should be able to be practically operationalised in multiple contexts with consistent attributes. Although the probability of an earthquake may be low, the consequences of an earthquake are severe [7] and have the potential to trigger cascading disasters such as landslides, tsunamis, and fire. Therefore, much attention needs to be paid to assess the resilience of multiple CISs due to earthquakes, which is the key focus of this study.

3. Methodology

A systematic literature survey was performed in this study to critically analyse the extant frameworks for assessing infrastructure resilience to disasters. Research articles published in scholarly journals after 2015 were selected to analyse the development of the frameworks after the adoption of the Sendai Framework for Disaster Risk Reduction 2015–2030 [61]. The PRISMA method was used for the final selection of studies that proposed or applied infrastructure resilience frameworks in a disaster context [41] (Figure 2). PRISMA is an established method for guiding the systematic review of scholarly literature and is based on four key steps: (1) identification, (2) screening, (3) eligibility, and (4) inclusion. The process of the PRISMA includes:

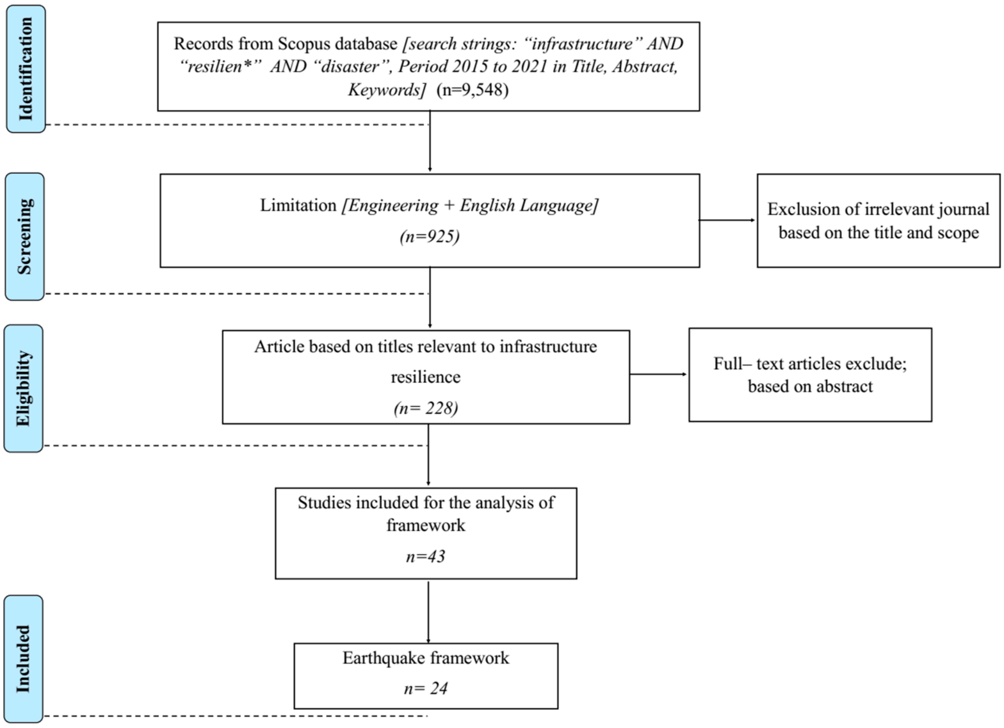

Figure 2. PRISMA flowchart to identify and select studies relevant to infrastructure resilience frameworks.

Step 1: Identification phase—In this process, the keywords "infrastructure", "resilien*", and "disaster" were used to classify all relevant research and review publications on infrastructure resilience. The 'AND' Boolean search method was used for relevant studies [18]. In the identification step of this study, the search for relevant research articles published in peer-reviewed and indexed journals on infrastructure resilience in disaster management was conducted in the Scopus database [18] which is the world's largest scholarly publication and citation database for peer-reviewed literature [62]. The search was conducted in title, abstract, and keywords, and the search yielded 9548 studies for initial analysis.

Step 2: Screening phase—The limiters were used again in this phase to further filter the database on the most specific area as engineering and the language as English. In this screening phase, 925 studies were found to be most relevant for more detailed analysis (Supplementary Table S1 in the supplementary information).

Step 3: Eligibility check—At this step, the 925 studies that were selected in Step 2 were further screened to exclude irrelevant articles and journals that are out of the scope of this review. The titles of the studies that were more relevant to the assessment of infrastructure resilience in a disaster context were sort listed. This process resulted in 228 more relevant studies for full-text analysis (Supplementary Table S2 in the supplementary information).

Step 4: Inclusion stage—By analysing the abstracts and conclusion sections, 43 articles were included (refer Supplementary Tables S3 and S4) for detailed content analysis to critically review the frameworks developed for assessing infrastructure resilience in disaster management. Among those articles, 24 studies were finally selected for critical review that focused on earthquake-hazard-specific infrastructure resilience assessment as shown in Table 1 (full details are given in Supplementary Table S5). The aim of this study is to analyse each of the 24 frameworks in detail as opposed to some reviews that aim to provide a macroview of the selected papers such as [63,64].

Table 1. Infrastructure Resilience Frameworks Assessed in this study.

#	Author (Year)	Framework	Country	Hazard	Method Adopted	Disaster Phase	Ref.
1	Nozhati (2021)	Optimisation formulation-based framework	USA	Earthquake	Parallel rollout method, dynamic programming algorithms along with heuristics and case study	Post disaster	[31]
2	Iuliis et al. (2020)	Probabilistic approach	Global	Earthquake	Literature study, experts' opinions	Post-disaster	[27]
3	Devendiran et al. (2020)	Integrated approach Hydrological model	USA	Flood and Earthquake	model simulations in conjunction with a macro-scale hydrological model and bridge structural components (case study)	Post-disaster	[32]
4	Lo et al. (2020)	Complete model building type (Combined probabilistic)	Taiwan	Earthquake	Cascade failure due to soil liquefications and building collapse, peak ground motions, and fragility curve evaluation	During the disaster	[33]
5	Harirchian and Lahmer (2020)	Index-based framework	Turkey	Earthquake	Rapid visual screening (RVS) Type-2 fuzzy system, fragility functions, and vulnerability index	Pre- and post-disaster	[65]
6	Tomar et al. (2020)	Discrete-event simulation framework (probabilistic-based framework)	USA	Earthquake	Pipe damage and repair (napa water system) and case study	Post-disaster	[66,67]
7	Kammouh et al. (2020)	Probabilistic-based framework	Brazil	Natural and Manmade	Expert knowledge	All phase	[26]
8	Aslani et al. (2020)	4R based framework	Iran	Earthquake	Literature study, analytical hierarchy process (hybrid approach), experts' opinions and case study (analytical maps), SWOT analysis	All phase	[68]
9	Whitworth et al. (2020)	UN Resilience Scorecard	Nepal	Earthquake	Disaster cycle, operational capacity, and resilience of the society	Pre-disaster	[69]
10	Merschman et al. (2020)	Decision framework	USA	Natural Hazard	Functional, topological, and social measures	post disaster	[70]
11	Ranjbar and Naderpour(2020)	Seismic resilience index (Index-based framework)	USA	Earthquake	Case study, seismic hazard analysis, dynamic analysis (fragility and vulnerability functions)	Pre- and post-disaster	[36]
12	Chen et al. (2020)	Residents' perceptions and intended evacuation behaviours (Static-based framework)	USA	Tsunami and earthquake	Survey data, bivariate chart, intercorrelation table, and regression analyses	Post-disaster	[71]

Table 1. *Cont.*

#	Author (Year)	Framework	Country	Hazard	Method Adopted	Disaster Phase	Ref.
13	Mazumder et al. (2020)	Damage-based framework	USA, Italy Bangladesh	Earthquake	Scenario-based seismic damage analysis, Python-based open-source libraries, SeismoPi	During and post-disaster	[34]
14	Kameshwar et al. (2019)	Probabilistic decision support	USA	Multi-hazard	Performance goals, case study, hazard models, and system topology	Pre- and post-disaster	[28]
15	Koc et al. (2019)	medium articulation graph index (Probability-based framework)	Global	Earthquake	Polynomial equations, hypothetical water distribution systems	Post-disaster	[72]
16	Hayat (2019)	Reconstruction conceptual framework	Indonesia	Earthquake and tsunami	Literature, empirical evidence (structured interviews), and case studies	Post-disaster	[73]
17	Sun et al. (2019)	Agent-based modelling framework	Global	Earthquake	Parametric investigation and virtual system and case study	Post-disaster	[74]
18	Yu et al. (2019)	Seismic resilience assessment framework	China	Earthquake	Fault tree analysis and case studies	Post-disaster	[37]
19	Anwar et al. (2019)	Performance-based probabilistic framework	China	Earthquake	Three-dimensional inelastic fibre-based numerical modelling approaches	All phase	[35]
20	Wang et al. (2017)	Conceptual model of the role of built environment	China	Earthquake	Triangulation method was utilized for collecting data, drones field trips, lesson learned	During and post-disaster	[75]
21	Rowell and Goodchild (2017)	Travel demand model	USA	Earthquake	Community-based disaster recovery planning	Post-disaster	[76]
22	Liu et al. (2016)	Decision support framework	England	Earthquake	experiences and lesson learned	Post-disaster	[29]
23	Hadigheh et al. (2016)	Resilience-based design framework (RBD)	Australia	Earthquake	Capacity spectrum method and retrofitting methods	Pre-disaster	[24]
24	Farahmandfar et al. (2016)	Resilience and optimisation framework	USA	Earthquake	Node degree formulation and demand	During the disaster	[38]

4. Key Findings and Discussion

The existing frameworks for assessing infrastructure resilience to earthquakes can be analysed in different ways in terms of geographic aspects, method of framework/model development, application of frameworks in different disaster phases (ex-ante, immediately after the disaster, or ex-post), and type of critical infrastructure focus. Table 1 shows the details of the 24 frameworks selected for assessing infrastructure resilience to earthquakes from 2015 to 2021. The details of the 24 frameworks are given in chronological order that includes the name of the framework, country developed, method adopted for developing the framework and the different phases of a disaster.

As shown in Figure 3, the majority of the frameworks focused on the housing and building infrastructure (32%). Other frameworks focused on transportation (26%), electricity and power (23%), water (11%), and telecommunication (8%) sectors.

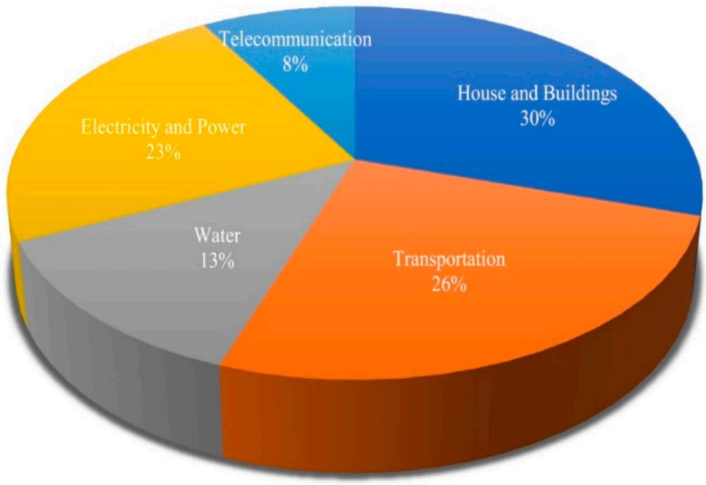

Figure 3. The summary of studies evaluated based on the infrastructure types.

The analysis of the year of publication of the study shows that more than 50% of the frameworks were published in 2020 and 25% in 2019 (Figure 4). The number of frameworks developed in 2015 was only 4%, 8% in 2016, and 9% in 2017. The trend shows that there has been increasing interest in developing and applying different infrastructure resilience assessment frameworks. As shown in Table 1 (Supplementary Table S5 for the details of earthquake-based critical infrastructure resilience assessment frameworks), the number of frameworks that considered the post-disaster phase is comparatively higher than the pre-disaster phase. Furthermore, the method of analysis and the indicators selected for the analysis also varied based on pre- and post-disaster phases. In addition, the analysis showed that most of the frameworks were compensated with the probabilisticbased study [25,27,28,33].

4.1. Types of Infrastructure Resilience Frameworks Evaluated in this Study

The frameworks to assess infrastructure resilience can be classified in many different ways. There are stand-alone frameworks [31,32,77,78] to assess infrastructure resilience. However, some other frameworks are multi-dimensional frameworks [25–27,79] in which the infrastructure resilience assessment is one among key resilience dimensions such as social, economic, ecological, and institutional. A number of stand-alone infrastructure resilience frameworks used different methods for their development. These included rapid visual screening [65], UN resilience scorecard [69], reconstruction conceptual framework [73], decision support framework [28,29,31], and probabilistic-based framework [25,26,28,35,36,79]. However, some frameworks have used multiple methods such as fragility functions and decision-making strategies [28,29]. Figure 5 summarises the approaches to develop infrastructure resilience frameworks and includes common indicators/attributes, sectors that used specific indicators, and context-specific indicators such as geography-focused or hazard-specific indicators.

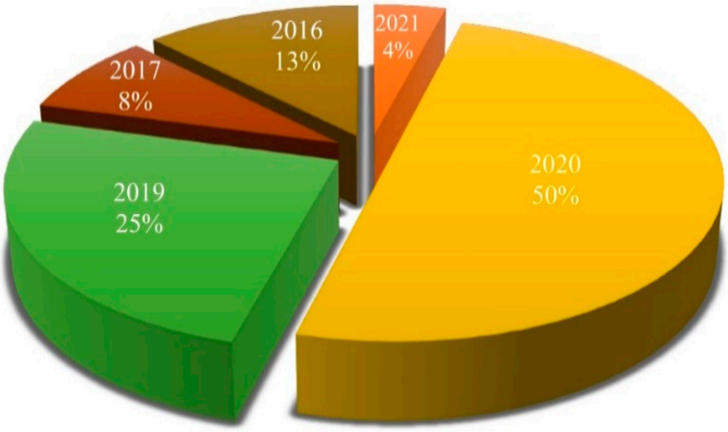

Figure 4. The summary of studies evaluated by the year of publication.

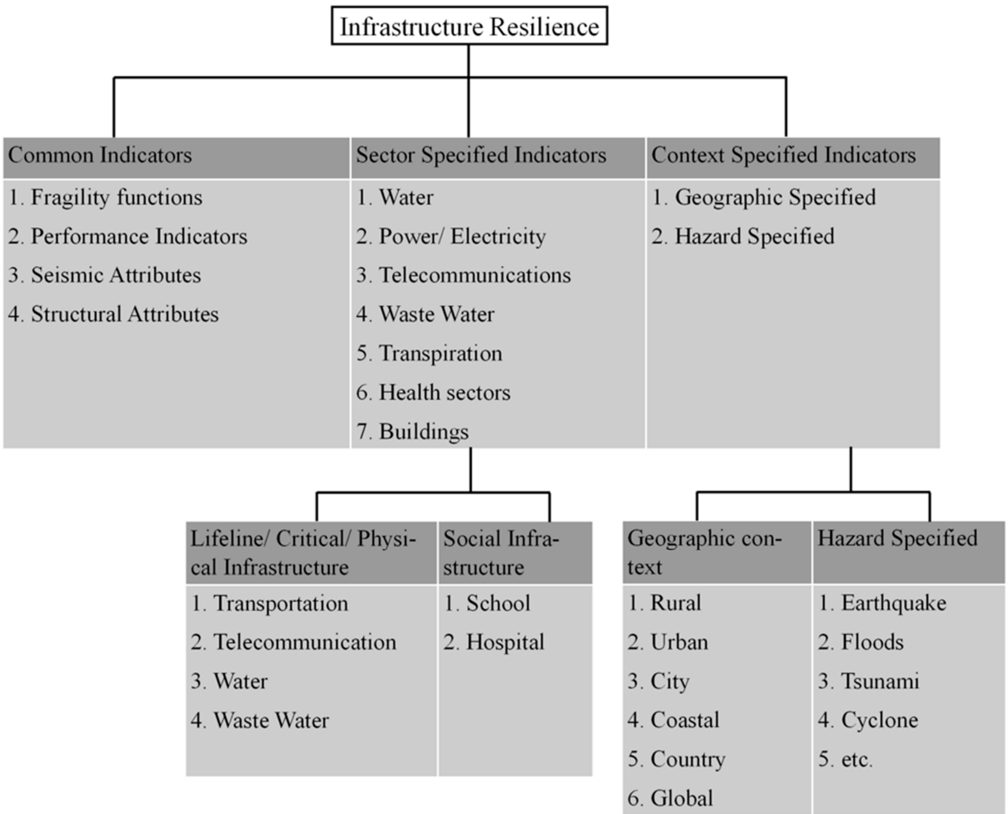

Figure 5. Summary of infrastructure resilience framework development approaches.

The frameworks that focused on the resilience of housing and building infrastructures analysed the structural reliability during the earthquake, where they used time–history analysis and fragility functions to validate the frameworks [24,27,29,32,33,79]. Transportation, water, electricity, and power infrastructure resilience frameworks focused on the dependability of the road networks during unforeseen events and the reliability of the bridges [70,71,76,80–82]. However, some frameworks focused on more than one infrastructure [28,31,69], and some other frameworks used interconnectivity/interdependencies of infrastructure systems [23,28,37,74].

Each framework has its own set of constraints and methods of implementation. The analysis focused on different aspects such as geographic features, indicators used, and interdependencies of critical infrastructure. The variation of geographic scope includes community, city, region, country, and global-level frameworks as well as urban, rural, and coastal regions. The key differences between the existing frameworks are the number of variables used to assess infrastructure resilience and the method of their development/application. A wide range of methods were used to develop frameworks such as Bayesian networks, decision support frameworks, and damage modelling [26–28,83].

4.2. Frameworks Developed for a Specific Geographic Context

Most of the frameworks evaluated in this study were developed with a specific geographic focus, such as regional frameworks, rural/urban resilience frameworks, community frameworks, and coastal resilience frameworks. Figure 6 illustrates the number of frameworks developed in each country. Notably, a large number of frameworks (11) were developed with the focus on the United States of America (USA), whereas 3 among the 24 frameworks were general without any specific geographic focus.

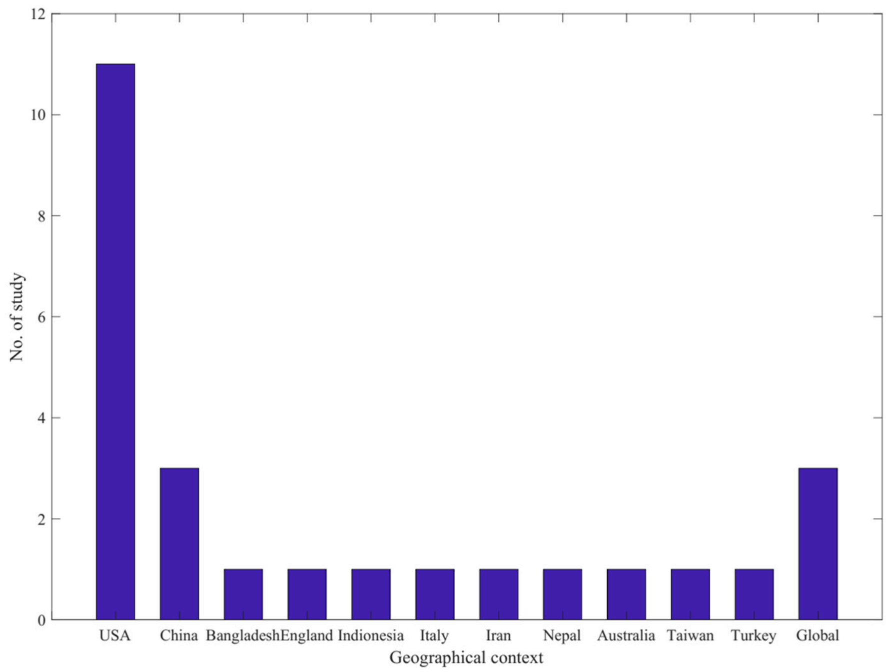

Figure 6. The geographic scope of the infrastructure resilience frameworks evaluated.

Table 2 summarises the similarities and differences between various geographic-focused frameworks such as Global, USA, and China with probabilistic, decision support and conceptual model frameworks, respectively. The earthquake specification in terms of intensity, mitigation strategies, infrastructure specifications, guidelines of particular geographic context and community resilience are similar for different geographic contexts. However, the differences in resilience characteristics for different geographies include the selected infrastructure, their codes, and models. Furthermore, Kameshwar et al. [28] used the Cascadia Subduction zone (coastal zone) in the USA which is a specific area to assess infrastructure resilience.

Table 2. Example of key infrastructure resilience characteristics developed for specific geographic scope.

Framework	Key Infrastructure Resilience Characteristics		Authors	Geographic Scope
	Similarities	Differences		
Probabilistic model	Infrastructure specifications, earthquake specification, human resources/available resources, type of recovery technology	Lifeline infrastructure (power and telecommunication), hierarchical model, anti-seismic technology of structure	Iuliis et al. [27]	Global
Decision-support framework	Community-planning guidelines/standards, specification of the infrastructure, earthquake specifications, performance-based guidelines	Critical infrastructure (interconnectivity) seaside, economic damages, restoration goals.	Kameshwar et al. [28]	United Status of America
Conceptual model	Planning and natural hazard resilient technologies, assessment of hazards, rural community mitigation.	Lesson-learned techniques, setting appropriate design codes, construction process management	Wang et al. [75]	China

Table 3 shows the similarities and differences in the example frameworks analysed with similar geographic context (three frameworks developed in USA regions). All the frameworks included fragility functions as an infrastructure resilience characteristic. The fragility curves can be empirical or analytical [36]. In addition, hazard specifications such as intensity and past records were considered seismic specifications. The differences are generally based on the infrastructure considered for the analysis. For example, Ranjbar and Naderpour [36] and Devendiran [32] focused on only one critical infrastructure: hospitals and bridges, respectively. Therefore, infrastructure-specific characteristics were used in the resilience assessments.

Table 3. The similarities and differences in the framework with similar geographic scope.

Framework	Key Infrastructure Resilience Characteristic		Authors	Geographic Scope
	Similarities	Differences		
Decision-support framework	Community planning guidelines/standards, specification of the infrastructure, earthquake specifications, performance based-guidelines, fragility curve	Critical infrastructure (electricity, water, and transportation) located in seaside, economic damages.	Kameshwar et al. [28]	USA
Probability model	Seismic specifications, hospital structural details, fragility curve	Hospital building, dynamic analysis, vulnerability curve	Ranjbar and Naderpour [36]	USA
Integrated approach	Ground motions, bridge structural details, seismic demand parameters, guidelines, fragility curve	Bridge seismic vulnerability in flood-induced scour, flood inundation details, ripraps	Devendiran et al. [32]	USA

4.3. Approaches in Framework Development/Application

Subsequently, the review revealed that different approaches were used in the development/application of the framework. Kameshwar et al. [28] studied the resilience of critical infrastructure for earthquakes using a decision support framework that included Bayesian networks with performance-based indicators and guidelines for building, transportation, water, and electricity infrastructures in the coastal areas. Rowell and Goodchild [76] focused on the impact on road networks from pre- and post-disasters (earthquake and tsunami) perspectives, using travel demand models to predict passenger and forestry freight travel differences. This model suggested the key regional transportation centre. Liu et al. [29] investigated the wastewater services system losses after an earthquake using performance indicators to generate the decision support framework. This framework was primarily concerned with functional impacts, physical damage, and serviceability restoration modules. Farahmandfar et al. [38] examined the performance of water supply networks after hazards using primary indicators such as estimated network topology, hazard intensity, and pipeline response. The study proposed an optimisation framework to enhance the water network system after earthquakes.

Table 4 summarises the method or approach used in the development of the framework to assess infrastructure resilience to earthquakes (Supplementary Tables S6 and S7 in supplementary information provide details of the sectors/type of critical infrastructure and methods used for development). Many of the frameworks used probabilistic models, decision support models, Bayesian networks, damage modelling, and fragility curves for assessing infrastructure resilience. Some frameworks used more than one method/tool to create the framework [25–28,79]. For example, Hayat [73] evaluated infrastructure resilience using the literature and empirical evidence, semi-structured interviews and expert opinions.

The key factor considered in the assessment of CIR was the impact related to damage or failure to the infrastructure. Furthermore, it is essential to assess interdependencies of infrastructure systems so that the cascading effects of infrastructure failures can also be forecast/assessed [84]. If one or more critical elements of the infrastructure failed to provide services during and after the event, entire systems may fail, even if an alternative exists [28,31]. For instance, if there is an alternate arrangement for water (by truck) and the transport infrastructure fails, then other systems also collapse [28]. Moreover, the restoration process of critical services in the aftermath of hazards is important for providing effective performance for the other critical infrastructure [66,67].

The assessment frameworks of CIR can be categorised based on a specific context (i.e., geographic/hazard-specific); however, they may not take into account the time factors [41]. The challenges during the CIR may arise in terms of cooperation and communications between stakeholders, understanding of the system, and the involvement of citizens in resilience building [85]. In addition, evaluating and understanding the inter-dependencies of infrastructure is quite challenging [86], and mitigation of interdependencies of critical infrastructure is necessary to avoid cascade failures of other critical infrastructure services [87].

4.3.1. Decision-Based Framework/Models

The decision-based frameworks were used by Nozhati et al. [31], Liu et al. [29], Kameshwar et al. [28], and Merschman et al. [70]. These frameworks focused on the post-disaster consequences and decision-making strategies. They used the progress of restoration of critical infrastructure after the disaster [28]. Figure 7 summarises the key aspects of the decision-based frameworks/models. The key findings were categorised based on social and serviceability measures, functional impact measures, indicators, and methods used.

Although the serviceability and functionality measures of the decision-based frameworks have similar attributes, the indicators used in these frameworks vary considerably. It is mainly due to the type of infrastructure focused on and the hazard specifications. The serviceability measures that were used in these frameworks include infrastructure interdependencies, response strategies based on lesson learned, and restoration functions. The functionality measures include mitigation strategies, short- and long-term restoration strategies, and functionality of interdependent infrastructure components. The assessment of system functionality included the key attributes of infrastructure such as materials, age, and construction method.

Table 4. Methods/approaches used to develop the infrastructure resilience frameworks 4.3.1 Decision-based framework/models.

#	Reference	Integrated Approach	Decision-Based	Damage Based	Fragility Based Evaluation	Probabilistic Model	4R	Static-Based	Reconstruction	Index-Based	Resilience Assess-ment	Travel Demand Model	Optimisation Based	Conceptual Model	Agent-Based Model
1	Nozhati [31]		×										×		
2	Iuliis et al. [27]				×	×									
3	Devendiran et al. [32]	×			×										
4	Lo et al. [33]				×	×									
5	Harirchian and Lahmer [65]									×					
6	Tomar et al. [66,67]					×									
7	Kammouh et al. [26]					×									
8	Anwar et al. [35]				×	×									
9	Aslani et al. [68]						×								
10	Whitworth et al. [69]														
11	Merschman et al. [70]		×												
12	Ranjbar and Naderpour [36]				×					×					
13	Chen et al. [71]							×							
14	Kameshwar et al. [28]		×	×	×	×									
15	Koc et al. [72]					×				×					
16	Mazumder et al. [34]			×	×										
17	Hayat [73]								×					×	
18	Sun et al. [74]														×
19	Yu et al. [37]				×						×				
20	Wang et al. [75]													×	
21	Rowell and Goodchild [76]											×			
22	Liu et al. [29]		×		×										
23	Hadigheh et al. [24]			×							×				
24	Farahmandfar et al. [38]				×						×		×		

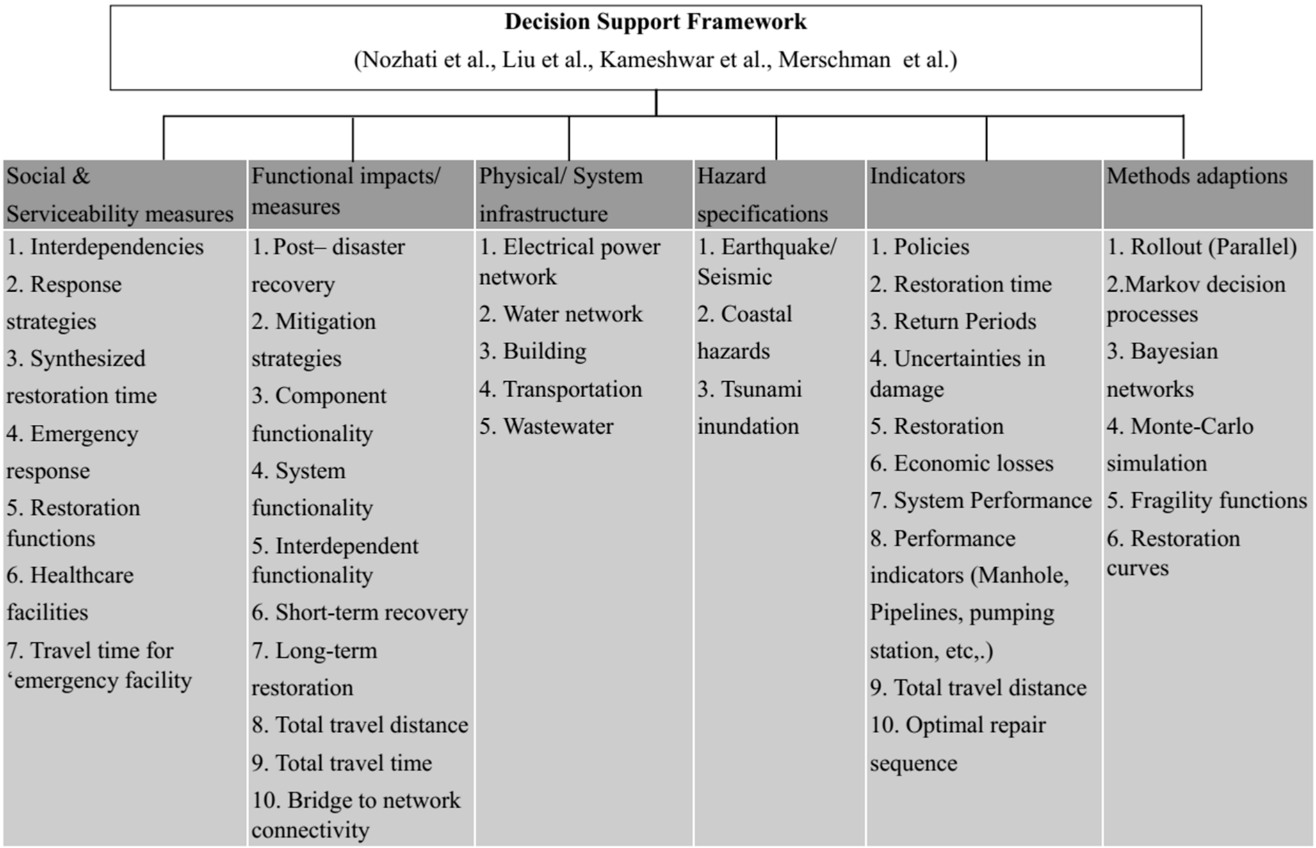

Figure 7. Attributes of the decision-based framework from past studies in terms of social, functional, and physical metrics, taking into account the indicators and methodology used.

4.3.2. Probabilistic Models/Frameworks

Probabilistic models are more applicable in real life because they are better at forecasting uncertainty and interdependencies. [26,88]. Generally, the probabilistic-based hazard analysis was carried out in four different approaches: generation of the seismic hazard curve (ground motion intensity measures), use of structural response analysis, damage assessment/measures, and use of decision variables [42]. The probabilistic frameworks analysed in this study mainly used Bayesian networks/Bayesian Belief network [26–28], the Monte Carlo method [28,35,72,78] and the Markov chain model [78].

Figure 8 shows the key features of infrastructure resilience assessment frameworks developed using probabilistic models. The social/serviceability measures primarily focused on policies, early warning systems, disaster preparedness, and interdependencies, whereas the functionality measures focused on human resources, socioeconomic factors, damage analysis, and sustainability concerns. Discrete and continuous variables were used to analyse the downtime of power and telecommunication by Iuliis et al. [27] (Discrete variable is defined as the finite number such as earthquake intensity, and continuous variable is defined as the infinite element such as exposed structures and infrastructure types).

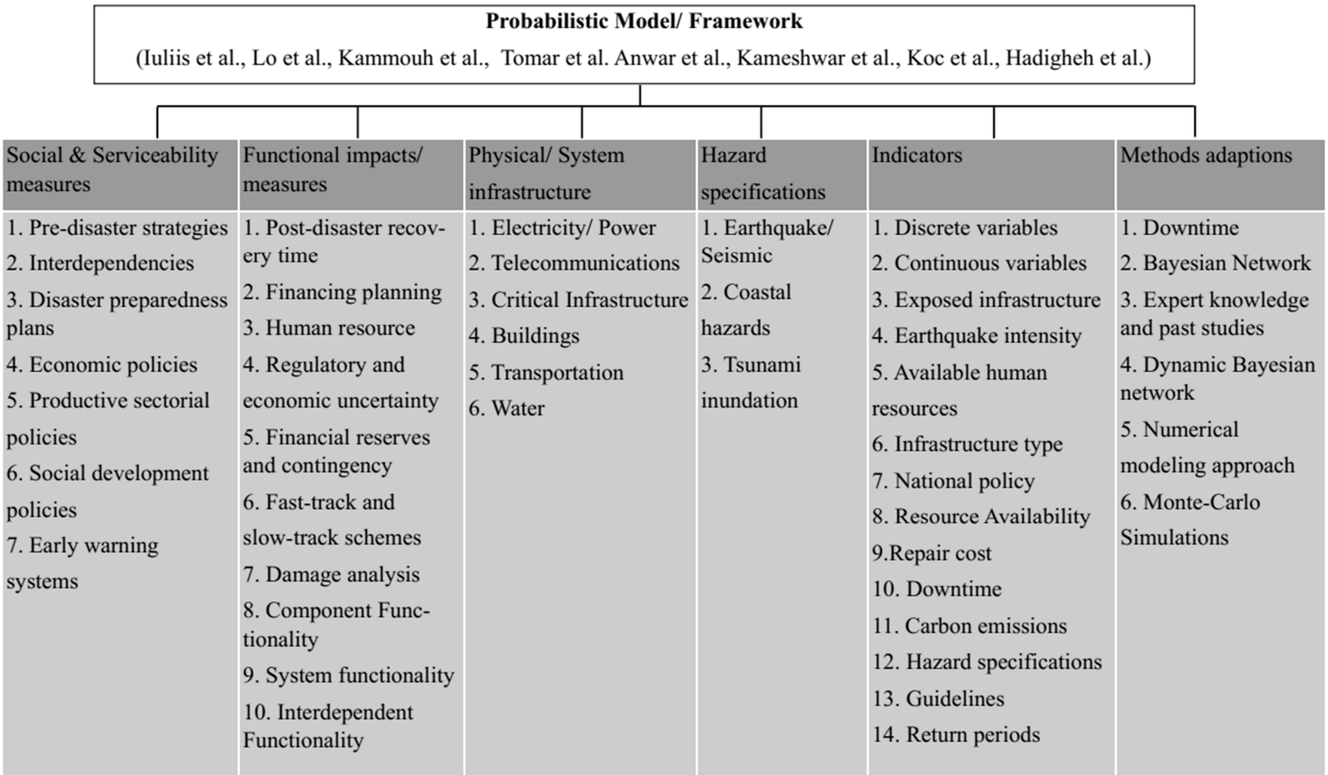

Figure 8. Attributes of the probabilistic-based framework from past studies in terms of social, functional, and physical metrics, taking into account the indicators and methodology used.

4.3.3. Damage-Modelling/Analysis Framework

As infrastructure systems are highly dependent on each other, the damage propagation on a particular infrastructure can have a direct or indirect impact on the other facilities [42]. One of the key aspects in this framework was the use of a fragility curve to estimate the various limit state/conditional probability. Most of the frameworks used the fragility functions to evaluate the fragility of the structures [27–29,31–38]. Figure 9 shows the key attributes of serviceability and functionality in the damage-modelling or damage analysis frameworks.

The damage analysis frameworks were specifically used for the pipeline networks and buildings. For example, Mazumder et al. [30] studied the damage assessment of pipelines during earthquakes using corrosion and seismic damage of pipelines. The significant social/serviceability measure was performed based on the time of occurrence of the event, societal response, life safety, and resources. The key attributes such as retrofitting methods, damage-based functionality, renewable strategies, and recovery functions were preliminary considerations in the analysis/modelling. In addition, building codes, design factors, and guidelines were used as key indicators in the damage modelling/analysis frameworks.

4.4. Analysis of Infrastructure Resilience Assessment Indicators

The selection of the most appropriate indicators to assess risk in critical infrastructure is critical [44]. In the assessment of infrastructure resilience, indicators represent the key components of the subject of assessment, such as functionality return time, redundancy, and resistance [89]. The selection of the indicators typically relies on the framework developed, and the reliability of the infrastructure systems in a disaster context needs to be analysed with the most relevant indicators [27]. The indicator analysis will provide benchmarks against the uncertainties and help to pre-determine the baseline status [7,89].

Damage Modeling/ Analysis Framework
(Mazumder et al., Hadigheh et al., Kameshwar et al.)

Social & Serviceability measures	Functional impacts/ measures	Physical/ System infrastructure	Hazard specifications	Indicators	Methods adaptions
1.Time of occurrence of event	1. Recovery function/time (linear)	1. Electricity/ Power	1. Earthquake/ Seismic	1. Building codes	1. Performance-based design approach
2. Preparedness	2. Retrofitting methods	2. Buried water pipe-lines	2. Coastal hazards	2. Retrofitting methods	2. Bayesian Network
3. Resources	3. Resilience values	3. Rehabilitated buildings (hospital)	3. Tsunami inundation	3. Time of occurrence of event	3. Numerical modeling
4. Societal response	4. Damage-economic loss relations	4. Buildings		4. Specification of the buildings	4. Fragility functions
5. Immediate occupancy	5. Damage-restoration time	5. Transportation		5. Seismic response	
6. Life safety	6. Damage functionality relations	6. Water		6. Design loads	
7. Collapse prevention	7. Repair rate			7. Discrete variables	
8. Corrosion deterioration of pipelines	8. Component functionality			8. Hazard specifications	
	9. System functionality			9. Guidelines	
	10. Interdependent functionality			10. Pipelines network	
	11. Renewal strategy of pipelines			11. Corrosion	
				12. Seismic repair rate	
				13. Characteristics of an earthquake	

Figure 9. Attributes of the damage-analysis-based framework from past studies in terms of social, functional, and physical metrics, taking into account the indicators and methodology used.

Resilience indicators should also be assessed in accordance with industry or system professionals for each specific industry [7]. Specific indicators and matrices can be developed for the specified critical infrastructure to investigate the risk to critical infrastructure, and they need to be validated for each organization by a particular sector and experts [44]. However, Petrović et al. [90] considered generic resilience indicators based on the criteria that the indicators should not be related to a specific hazard or specified critical infrastructure to enhance critical infrastructure interconnectivity. Increasing the number of indicators improves the coverage, but it becomes complex. During a disaster, it is assessed that humans can handle about three indicators [91].

In the frameworks analysed in this study, 140 variables/indicators were found, and they were iteratively categorised to appropriate sub-dimensions. As a result, a number of indicators were rejected, either because they were irrelevant or because they overlapped with other indicators [92]. For example, building components such as the number of stories, dimensions of the buildings/infrastructure, material usage, and building type, as well as pipe diameter and connectivity in the water network, were considered as infrastructure specifications. As a result, 24 indicators were selected to evaluate the seismic resilience of critical infrastructure (Supplementary Table S7 in the supplementary information for the results of indicator analysis).

Figure 10 shows the resulting map of the thematic analysis of critical infrastructure indicators used in the frameworks. In this study, two steps were followed to perform the word clustering: (1) The frequency of indicators and their associations were determined using the word link programme WORDij 3.0 [93,94]. WORDij is a content analysis software, and it was used to create the co-occurrence between the variables [95]. (2) The mapping was carried out using Gephi 0.9.2 software. Gephi is open source software, and the indicators created can be imported, analysed, specialised, filtered, and exported in a variety of networks [96,97]. The interconnection between the indicators is depicted by the arrow, and the size of the circle represents the frequency with which the indicators were mostly used in previous studies.

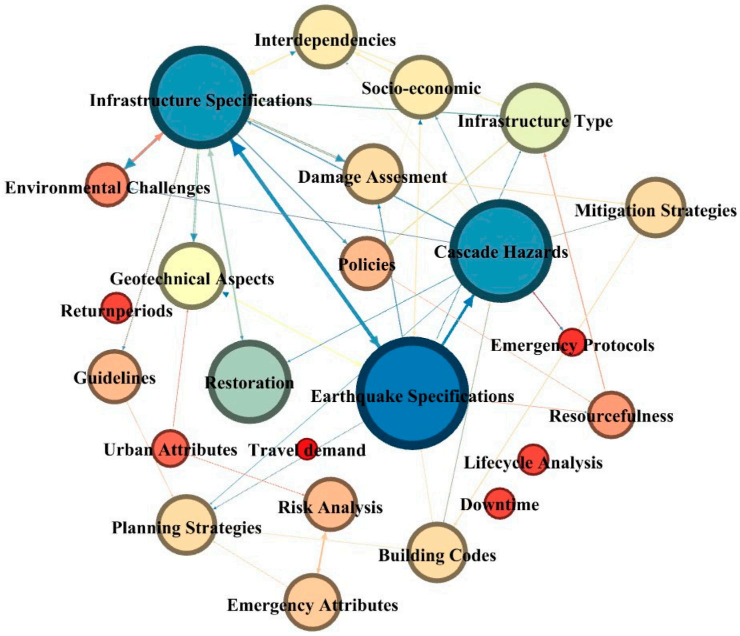

Figure 10. CIR indicators/variables map view The arrows represent the correlation between the indicators, while the size indicates the importance of the indicators used to measure critical infrastructure resilience.

As shown in Figure 10, the size of the circle denotes the scalar values of the indicators used in the study [98]. It is also necessary to define the connections between the elements required for the analysis, as well as their characteristics in terms of direction and weight [92]. In this study, the mixed method of analysis was selected to evaluate correlations between critical infrastructure [86]. Moreover, a variable can be categorised as directed or undirected based on the graph theory [92]. The majority of the frameworks prioritised infrastructure specifications such as building type, number of stories in buildings, and distribution components in power infrastructure (e.g., distribution circuits and pole distribution) as well as seismic specifications such as seismic intensity, seismic cycling, and wave arrival time. In terms of connectivity in the analysis, the interdependencies are connected to infrastructure specifications, cascading hazards, socioeconomic factors, and infrastructure type (e.g., water networks, power networks, and transportation networks). Moreover, the indicators utilised in this study can help analyse various types of critical infrastructure as stated in the novel and adaptive framework (see Figure 11). The water network infrastructure can be analysed in different attributes: national guidelines and policies, geotechnical aspects (e.g., soil parameters), damage assessment (e.g., corrosion), interdependencies, specification of infrastructure (e.g., pipe diameter, distribution network, etc..), and emergency attributes (e.g., availability of water resources).

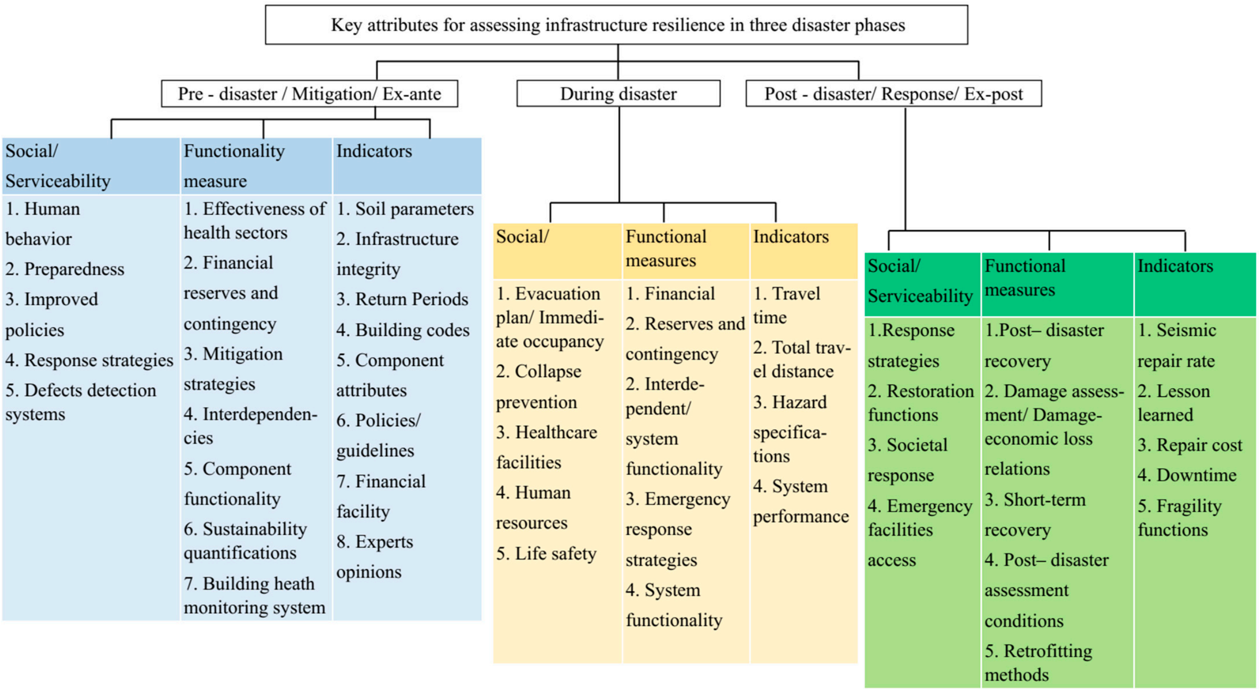

Figure 11. Key features for assessing infrastructure resilience in different phases of a disaster (pre-, during, and post-disaster) to develop an integrated and adaptable framework.

5. An Integrated and Adaptable Framework for Assessing Infrastructure Resilience

The critical analyses have shown that there is a need for an integrated and adaptable framework for global context for measuring resilience of infrastructure systems to earthquakes. The existing frameworks to assess seismic resilience of critical infrastructure were mostly based on a specific infrastructure network with limited assessment of indicators, specific phase of a disaster, and a specific spatial context. However, developing a context-specific framework is a time- and resource-intensive process [41]. To develop an adaptable and integrated framework, the similarities and differences in frameworks extant in the literature were analysed as highlighted in Section 4. Figure 11 shows a summary of the findings for different phases of a disaster—pre (ex-ante), during, post (ex-post), and the key factors/attributes are categorised under the key sections such as serviceability attributes, functionality measures, and key indicators.

As shown in Figure 11, the proposed framework will be focused on the different phases of hazards with key attributes of serviceability and functionality. There are two methodologies for assessing system performance: interconnectivity study and serviceability analysis [99]. In addition, the functionality of critical infrastructure also was focused on as other attributes. Throughout the content analysis of the 24 studies considered, the total numbers of attributes were classified as social/serviceability and functional measures. In the pre-disaster phase, the mitigation strategies and existing reliability of critical infrastructure were focused on as primary attributes. Moreover, interdependencies that lacked focus in past studies related to three different phases of a disaster were included as the other key feature in this framework. Emergency attributes and resourcefulness were also focused on during the disaster phases in our framework. In addition, system/interdependent functionality was added as an additional key attribute. The damage assessment and response strategies in the post-disaster phase were initially focused on restoring the critical infrastructure facility in a short period of time. As a result, the long-term restoration of the critical infrastructure can be achieved.

Proposed Integrated and Adaptable Framework

Based on the critical analysis of existing frameworks, an integrated and adaptable framework for assessing the resilience of critical infrastructures for earthquakes has been developed in this study (Figure 12). This framework is aligned with the three key phases of a disaster (ex-ante, during, and ex-post), as shown in Figure 1. In this framework, the serviceability and functionality measures in different phases of earthquake risk were considered as key attributes. “The serviceability is expressed as the ratio of the available demand to required demand corresponding to a seismic damage scenario” [100] (p. 07). Moreover, the focus on the pre-disaster serviceability measures is necessary due to the post-disaster scenario causing high demand for critical infrastructure services [101]. The decrease in resilience is deemed equivalent to the degeneration of the infrastructure throughout the period of recovery [102]. The functionality measures define the degree of functionality and service life required by stakeholders [103]. Furthermore, infrastructure resilience depends on the capacities of facilities and systems to maintain a sufficient degree of functionality during and after the disruptions and to recover full functionality within a specified time frame [104].

As shown in Figure 1 (Section 2.2), the ‘during’ disaster time phase is very short for earthquakes [105], despite the fact that the impacts are severe in the aftermath of the disaster. As a result of such a crisis, it is necessary to investigate the attributes in the pre-disaster phase for mitigation [106]. In this proposed framework, the resilience of critical infrastructure before an earthquake (ex-ante) will be evaluated based on the interdependencies between CISs and their connectivity as a functionality attribute. It is necessary to assess the interdependencies in the early stage (pre-disaster) to provide continued services during and after (ex-post) the disasters [3,105] and with the cascade hazards/failures of critical infrastructure [107]. Moreover, sevaluating critical infrastructure interdependencies resilience at the regional level would yield reliable results for serviceability and functionality losses [108]. The evaluation of proactive and reactive requirements of interdependencies between infrastructures is necessary [23,109]. The risk and reliability analysis will also need to be carried out based on the critical infrastructure’s risk assessment in the ex-ante phase. The critical infrastructure’s existing risk management policies, design aspects, and mitigation/improving structural reliability will be evaluated in this attribute. The critical infrastructure should be able to continue offering services during and after a disaster. For instance, corrosion in the water pipe line distribution system will be severely impacted by an earthquake [34]. Moreover, the recovery of critical infrastructure, such as transportation, from an interruption will help enhance performance [17,110].The results will exhibit the existing critical infrastructure’s performance, improvement techniques, and mitigation strategies such as early warning systems.

During the disaster phase, emergency attributes, applications of the safety protocols, resourcefulness, and contingencies will be assessed. The contingencies [111] and resourcefulness [112] are primary attributes to ensure the functionality of critical infrastructure during earthquakes. In the immediate aftermath of an earthquake, financial conditions will be critical [113], and it is also important the government/private sector to allocate funds for critical infrastructure to withstand economic impacts of disasters [14]. Furthermore, efficient resource allocation will improve the resilience of critical infrastructure for a quick recovery [114]. In this phase, the availability of human resources, alternative essential needs (for example, alternative power supply systems after the loss of power), temporary housing facilities (e.g., schools and house of worship), and food services will be considered as major resources. Furthermore, the destruction of infrastructure has a significant influence on local emergency response, resulting in a shortfall of rescue resources for disaster relief [75]. The emergency attributes and safety protocols of system efficiency have to be evaluated throughout the disaster phase to assess the effectiveness of the emergency services (fire services, rescue services, and armed forces).

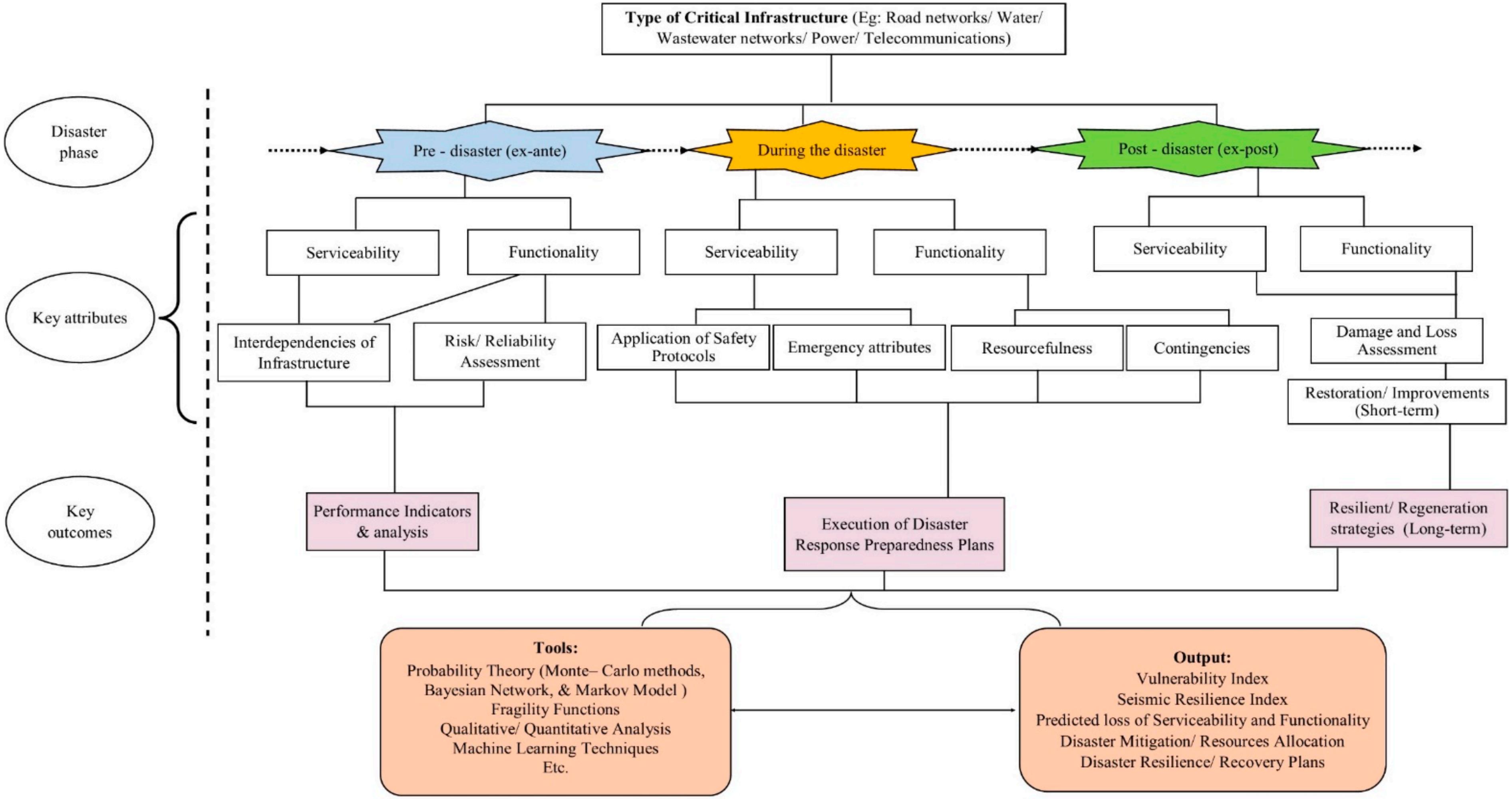

Figure 12. An overview of an integrated and adaptive framework for assessing infrastructure resilience for earthquake hazards.

Damage assessment has to be carried out and should progress to allow critical infrastructure to recover quickly to provide services. The infrastructure can then be further improved in the longer-term recovery as depicted in the Figure 1 (Section 2.2) (α-curve line). Moreover, the applications of safety protocols must be restudied as lessons learned to ensure the adequate performance of designed safety systems. Subsequently, the long-term CIR for earthquakes in terms of the concept of restoration [46] and regeneration [48] has to be assessed to improve performance and services. Another aspect of the ex-post phase is to plan an earthquake debris management strategy to improve long-term performance [115]. In each phase of the analysis, the stakeholders, engineers, architects, and decision makers need to select appropriate tools to perform the analysis needed for the specific stage of the disaster. For example, they need to improve the mitigation strategies (e.g., retrofitting and health monitoring systems) in pre-disaster phases. During the hazard phase, they need to focus on emergency management plans (e.g., short-recovery, warning systems, and temporary shelters). Finally, during the post-disaster phase, they should focus on short-term and long-term recovery of critical infrastructure services [31,48,67,116,117]. Thus this proposed framework is adaptable for the user to select the most appropriate tool and a method for application based on the user requirements [118,119].

6. Summary and Conclusions

This paper proposes an adaptive and integrative framework for assessing critical infrastructure and buildings in the event of an earthquake. To assess the seismic resilience of critical infrastructure, an integrated and adaptable framework with possible indicator applications is necessary. A total of 24 infrastructure resilience assessment frameworks developed for earthquake risks were critically reviewed using the PRISMA methodology. The frameworks were selected from the articles published in the Scopus database between 2015 and January 2021, which is the period coinciding with the implementation of the 2015 Sendai framework for disaster risk reduction (SFDRR). The critical assessment conducted in this study revealed the following key findings:

- There is a lack of systematic configurations to assess CIR for seismic hazards. It is mostly due to the fact that the majority of the frameworks were primarily focused on a specific context such as within a geographic scope or in a selected community. Therefore, it is challenging to use one of these frameworks as a general, but adaptable tool for assessing seismic risks in any other context. This research gap needs to be addressed by developing an integrated and adaptable infrastructure resilience assessment framework. Such a framework will provide a consistent approach to develop a uniform method to make resilience investment decisions.
- The serviceability and functionality of critical infrastructure are the key attributes to provide uninterrupted services during a disaster. Therefore, it is vital that any disaster framework establishes a set of key resilience performance indicators. Such performance indicators can be relied upon in different phases of a disaster to consistently measure progress before, during, and after earthquakes and to make well informed resilience investment decisions for future risks.
- The frameworks evaluated in this study emphasise risk/reliability assessment in the ex-ante phase, resourcefulness as disaster impact mitigation strategies, and short/long-term restoration strategies of critical infrastructure in the ex-post phase. In contrast, the proposed framework focuses on the socioeconomic and emergency protocols during and after the disasters. Therefore, governments should maintain contingencies for unforeseen events. Policymakers and stakeholders can use the framework to reduce the vulnerability of critical infrastructures and ensure community safety before, during, and after disasters. The seismic hazard level has the greatest influence on the robustness of critical infrastructure networks immediately after the disasters occur.
- An integrated and adaptive framework for assessing critical infrastructure for earthquake hazards was developed based on the key findings of a critical evaluation of the 24 selected frameworks develop over the past five years. This framework is helpful

for policy makers, engineers/practitioners, and other key stakeholders involved in developing critical infrastructure in earthquake risk-prone geographic areas.

However, this framework only focuses on the preliminary attributes of seismic resilience, which can be further expanded by taking into account the interconnectivity of critical infrastructures and the cascading failures/hazards. The proposed conceptual framework needs to be validated in all three key phases of a disaster—pre, during, and post disaster phases and needs to be tested in various geographic settings.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/infrastructures7050067/s1, Table S1: Scopus-Extracted; Table S2: Screening Stage-01; Table S3: Screening Stage-02; Table S4: Multiple Haz IR frameworks; Table S5: Seismic IR Framework detail; Table S6: Sectors of infrastructure; Table S7: Framework type and content.

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