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Research on an Evaluation Model of Urban Seismic Resilience Based on System Dynamics: A Case Study of Chengdu, China

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Abstract: In response to the frequent occurrence of earthquakes in Chengdu, which poses a great threat to the economy, social development, production, and people's lives, in this study, we construct an index evaluation system and a system dynamics model for urban seismic resilience based on an analysis of the interaction between earthquake disasters and the urban system. Four types of schemes, namely, the current continuity type, economic development type, government intervention type, and resilience construction type, were designed, and the dynamic evaluation and simulation prediction of Chengdu's seismic resilience capacity under each scheme were conducted. The research results show that, compared with the other three schemes, the resilience construction type has better universality and expansibility in terms of improving Chengdu's seismic resilience. Therefore, it is necessary to maintain a certain level of economic development, to attach importance to the construction of monitoring and warning systems, and to strive to improve emergency rescue capabilities and disaster awareness education. The model and evaluation indicators have strong applicability, and the research results can provide a theoretical reference for the evaluation of seismic resilience in Chengdu.

Keywords: public safety; resilience; urban system; system dynamics; earthquake disaster; simulation

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1. Introduction

During the process of urban development, cities have always been faced with a significant number of natural disasters, technological disasters, and human-made disasters. There are more than 5 million earthquakes occurring worldwide each year, of which approximately 11 result in significant damages [1]. According to statistics, since the 21st century, 35% of earthquakes with a magnitude of 7 or higher have occurred in China [2]. Due to the suddenness and strong destructive nature of earthquakes, the disasters caused by them are particularly severe. To prevent earthquake disasters from causing more serious damage due to the high concentration of urban populations and increasingly complex urban environments, exploring and evaluating methods to enhance the seismic resilience of cities has important theoretical and practical significance for promoting China's urbanization process.

Urban seismic resilience is currently a research hotspot which is based on the further deepening and development of performance-based seismic design, providing a new and comprehensive way of thinking for urban seismic planning and design. Chang et al. [3]. established an evaluation framework for community resilience based on an earthquake loss estimation model, and used the water supply system in Memphis as an example with which to compare the reactions of two reinforcement methods and an unreinforced system under earthquake conditions through Monte Carlo simulation. Cimellaro et al. [4] quantitatively studied the resilience capabilities of the power supply, water supply, gas supply, and other lifeline systems in 12 cities after the 2011 Japan earthquake, and analyzed the interrelationships between them based on actual statistical data on the recovery process.

In 2013, Arup released the "Resilience-based Earthquake design initiative for the Next Generation of Buildings" report, proposing design recommendations for resilient cities and buildings based on the duration for which they can maintain their functionality [5] Zhang [6]. Using traffic flow analysis to evaluate the seismic resilience of transportation networks, Liu [7] evaluated the seismic resilience of water supply networks using hydraulic analysis and described the entire process, from the initial loss of system function to gradual recovery during earthquakes. Cao Xu-Yang [8] proposed a consistent seismic hazard and fragility framework, considering combined capacity–demand uncertainties, in light of the probability density evolution method (PDEM). V squez A [9] studied the response and resilience of healthcare networks in earthquakes, while tudied t [10] quantified the resilience of water supply systems in seismic contexts. Domaneschi M [11] and others investigated the seismic resistance of bridge systems. Currently, research on urban seismic resilience mainly focuses on improving individual structures and conducting simulation assessments, with little practical application research focusing on the entire urban system. Currently, research on urban seismic resilience mainly focuses on the improvement of individual structures and simulation-based evaluation, with limited practical applications.

2. The Establishment of Chengdu's Seismic Resilience Model

2.1. The Construction of Urban Seismic Resilience

The construction of urban seismic resilience refers to the ability of the urban system to resist, adapt to, and quickly recover from the impact of disasters when they occur. Urban seismic resilience refers to the resistance, adaptability, and recovery ability of urban systems in the face of earthquake disasters. The relevant national standards and regulations are also considered [12–14], as well as existing relevant research both at home and abroad [15–18]. Mature and recognized indicators were selected as often as possible, and through the objectivity of the evaluation, quantifiable indicators were chosen as often as possible. Finally, a city seismic resilience evaluation index system was obtained, including 3 dimensions, 7 field levels, and 22 indicators, as shown in Table 1. Subjective weights were determined using the improved G1 method [19] based on data collected from the China Statistical Yearbook and government department reports, and objective weights were determined using the rank-order method [20]. The final weight was obtained by integrating the two features using the multiplication integration method [21]. By considering the impact of resistance, adaptability, and recovery on the level of urban seismic resilience, an assessment model for urban seismic resilience was constructed, as shown in Formula (1):

$$USR = A + B + R = \sum_{i=1}^{7} C_i \omega_i \tag{1}$$

The equation shows that USR represents the level of urban seismic resilience; A, B, and R represent resistance, adaptation, and recovery, respectively; C_i represents monitoring and early warning capabilities, personnel seismic resistance, physical facility seismic resistance, self-help and mutual aid capabilities, emergency rescue capabilities, medical service capabilities, and physical facility recovery capabilities; and ω_i represents their corresponding weights.

Table 1 of the index system still requires further clarification in some cases.

C22: the severity of personnel casualties.

Calculations were based on the method for estimating casualties and injuries based on seismic intensity in Appendix A of the "Emergency Evaluation of Earthquake Disaster GB/T 30352-2013" [22].

Table 1. Evaluation index system for urban seismic resilience.

Resilience	Domain Layer	Indicator Layer	Indicator Description (Unit)	Weight
Resistance (A)	Monitoring and Early Warning Capability (C1)	Seismic monitoring capability (C11)	Number of seismic stations (units)	0.068
		Information dissemination capability (C12)	Per capita number of internet users (households/person)	0.043
		Information security capability (C13)	TV program coverage rate (percentage of population)	0.060
	Personnel Earthquake Resistance Ability (C2)	Population size (C21)	Population density in urban areas (ppl/km^2)	0.045
		Degree of personal injury (C22)	Estimated number of casualties (ppl)	0.044
	Physical Facility Earthquake Resistance Ability (C3)	Building system security capability (C31)	Building density (%)	0.059
		Transportation system security capability (C32)	Per capita road area (m^2/person)	0.038
		Water supply system security capability (C33)	Per capita length of urban water supply network (m/person)	0.032
		Gas supply system security capability (C34)	Gas penetration rate (%)	0.027
		Power supply system security capability (C35)	Per capita electricity consumption (kW·h/person)	0.041
Adaptability (B)	Self-help and Mutual Assistance Ability (C4)	Age structure (C41)	Proportion of population aged 15–64 in urban areas (%)	0.075
		Educational level (C42)	Proportion of illiterate population aged 15 and above (%)	0.028
		Shelter capacity (C43)	Per capita area of shelter (m^2/person)	0.046
	Emergency Rescue Ability (C5)	Emergency rescue experience (C51)	Number of earthquake disasters (occurrences)	0.026
		Social rescue capability (C52)	Density of social organizations (units/10,000 ppl)	0.034
		Emergency management capability (C53)	Per capita public safety expenditure (RMB/person)	0.064
Recovery Ability (R)	Medical Service Capability (C6)	Medical level (C61)	Percentage of health hxpenditure in GDP	0.057
		Medical service personnel (C62)	Number of technical health personnel per 1000 of total population (%)	0.049
		Medical security capability (C63)	Number of hospital beds per 1000 of total population (%)	0.056
	Physical Facility Recovery Capability (C7)	Government financial strength (C71)	Per capita GDP (RMB/person)	0.053
		Scale of related talents (C72)	Proportion of employees in the construction industry (%)	0.044
		Living security capability (C73)	Proportion of employees in electricity, gas, and water production and supply (%)	0.011

Estimated number of deaths:

$$N_D = \sum_{j=6}^{I_{max}} A_j \rho R_j \tag{2}$$

Estimated number of injured:

$$N_I = \sum_{j=6}^{I_{max}} A_j \rho W_j \tag{3}$$

In the above formula, N_D represents the number of deaths in units of persons; N_I represents the number of injuries in units of persons; I_{max} represents the seismic intensity in the extremely strong seismic zone; A_j represents the area of the j intensity value distribution in units of square kilometers (km^2); ρ represents the population density in units of persons per square kilometer (persons/km^2); and R_j and W_j denote the mortality rate and injury rate corresponding to the intensity level, which can be referred to in Table 2. In this study, it was assumed that the entire administrative area of the city experienced the same intensity level, which was determined based on the seismic design intensity for the city's earthquake resistance.

Table 2. Statistical relationship between fatality rate, injury rate, and intensity.

Intensity	City	
	Fatality Rate	**Injury Rate**
VI	0.14×10^{-4}	5.40×10^{-4}
VII	3.10×10^{-4}	53.00×10^{-4}
VIII	48.00×10^{-4}	460.00×10^{-4}
IX	680.00×10^{-4}	4000.00×10^{-4}

2.2. The System Flow and Main Feedback Relationships of Seismic Resilience in Chengdu City

The system dynamics method was proposed by Professor Forrester in the 1950s for the purpose of understanding the decision-making processes regarding complex systems. Initially applied in industry, it was originally known as industrial dynamics. The system dynamics method is a computer-assisted and theoretical tool used for analyzing dynamic and complex systems with features of mutual feedback and interdependence. System dynamics is a simulation model technology based on systems' thinking. It describes complex systems based on complexity, interconnection, and dynamic behavior over time. Due to its analytical advantages in uncertain and dynamic complex systems, the system dynamics method has gained widespread recognition in the past decade. Nowadays, the system dynamics method is used in multiple research fields [23–25], and some scholars have already begun to apply it to the study of urban resilience [26].

When using system dynamics (SD) to study the resilience capacity of a city against earthquakes, the system boundaries must first be defined and specific goals must be established to determine the most effective system structure and optimal design parameters. Next, the important elements of the system and their relationships must be identified to conduct accurate quantitative analyses. Based on this, a system flow chart can be established and an SD model can be built for simulation experiments.

The city's seismic resilience system dynamics model was constructed using Vensim software (vensim PLE 7.3.5) in this study. Vensim software, developed by Ventana Corporation in the United States, enables the creation of causal loop diagrams and system dynamics flowcharts. It is a visual modeling tool that allows for simulation, prediction, and analysis. The entire scope of the urban seismic resilience model is selected as the boundary of the system dynamics model. From the three dimensions of resilience resistance, adaptation, and recovery, seven subsystems are established to analyze the level of urban seismic resilience and the dependencies and constraints among subsystems. These seven subsystems are monitoring and warning capabilities, personal seismic resistance, physical facility seismic resistance, self-help and mutual aid capabilities, emergency rescue capabilities, medical service capabilities, and physical facility recovery capabilities. The feedback relationships are shown in Figure 1.

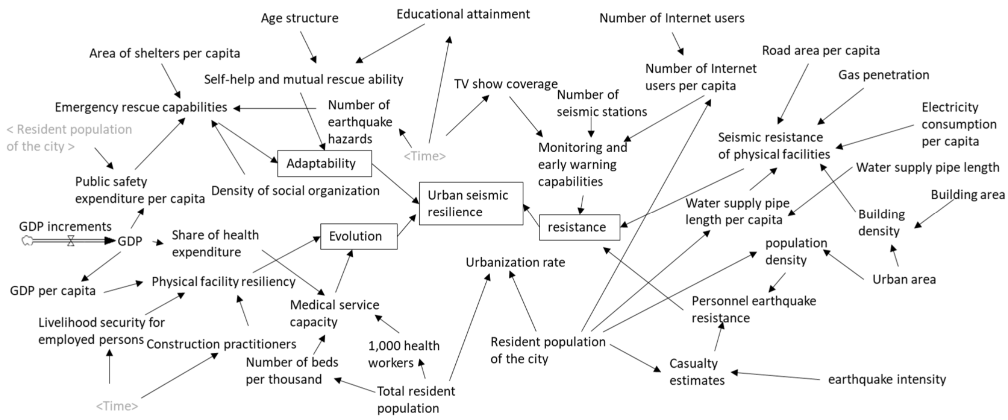

Figure 1. City seismic resilience system dynamics flowchart.

(1) Subsystem of monitoring and early warning capability: The main variables of the monitoring and early warning capability subsystem include earthquake monitoring capability, information dissemination capability, and information security capability. Changes in the number of seismographs, the number of internet users per capita, and the comprehensive population coverage of television programs will affect the changes in earthquake monitoring capability, information dissemination capability, and information security capability, thereby affecting the monitoring and early warning capability.

(2) Subsystem of personnel seismic resistance capability: The personnel seismic resistance capability subsystem consists of population size and the possible degree of injury to personnel. Population density is directly related to population size, which in turn affects personnel seismic resistance capability.

(3) Subsystem of physical infrastructure seismic resistance capability: The physical infrastructure includes building systems, transportation systems, water supply systems, gas supply systems, and power supply systems. The density of buildings, per capita road area, per capita length of water supply pipeline, gas penetration rate, and per capita electricity consumption, respectively, affect the changes in each physical facility.

(4) Subsystem of self-help and mutual aid capability: The success rate of self-help and mutual aid is closely related to the basic composition characteristics, quality, and other factors of the residents in disaster-stricken areas. Age structure and education level were selected as evaluation indicators.

(5) Subsystem of emergency rescue capability: The main variables of the emergency rescue capability subsystem include emergency management capability, emergency rescue experience, professional rescue forces, social rescue forces, and the scale of refuge.

(6) Subsystem of medical service capability: Personnel rescue mainly depends on the city's medical service capability. The medical service capability subsystem is composed of medical level, medical service personnel, and medical security capability, mainly including the number of health personnel per thousand people, the number of beds per thousand people, and the proportion of health expenditures.

(7) Subsystem of physical infrastructure recovery capability: Per capita GDP, the number of livelihood employees, and the number of building industry employees affect the physical infrastructure recovery capability, which in turn affects the government's financial strength and the scale of related talents.

There are four types of equations in system dynamics, including state equations, rate equations, auxiliary equations, and constant equations.

(1) The state equation is an equation that describes changes in the stock variables of the model, as shown in Formula (4).

$$\text{Stock}(t) = \text{Stock}(t_0) + \int_{t_0}^{t} (Inflow(\tau) - Outflow(\tau))d\tau \tag{4}$$

In the equation, Stock(t) represents the value of stock at time t, while $Inflow(\tau)$ and $Outflow(\tau)$ represent the inflow and outflow of the stock, respectively.

(2) The rate equation is an equation that shows the law of flow rate change and controls the state of stock change. It is generally expressed as a function of stock, constant, and some auxiliary variables.

$$flow = f(\text{Stock}, \text{Constant}) \tag{5}$$

(3) The auxiliary equation is an equation that reflects the quantitative relationship between variables in the model. It is generally determined based on actual situations or real data, such as urban population density equals urban population divided by urban area.

(4) The constant equation refers to the values that are basically unchanged in the system dynamics model. These constants usually play an important role in determining other variables in the model.

The system dynamics equation's construction methods in system dynamics include multivariate statistical regression, linear interpolation, table function, etc. This article includes three types of parameters: constant, table function, and initial value, and the assignment method used is as follows:

(1) Fill in missing data:

$$x_j = \frac{x_i - x_0}{i} * j \tag{6}$$

In the equation, x_j represents the value of the missing item; j represents the order of the missing item in the data column; and x_1 and x_i represent the values of the first and last data points, respectively.

(2) Assign horizontal variables:

As shown in Table 3. The assign horizontal variables are reproduced as follows.

Table 3. Assign horizontal variables.

Horizontal Variable	Increment	Initial Value
GDP (100 million yuan)	1182.72	5889.46
Permanent population (10,000 people)	68.92	1405.5
Urban permanent population (10,000 people)	72.59	924.1
Per capita road area (m^2/person)	0.48	14.89
Length of urban water supply network (km)	1571.46	5194
Gas coverage rate (%)	0.56	94.42
Per capita electricity consumption (kW·h/person)	151.52	1925.46
15–64 year-old population as a percentage of urban population (%)	0.51	66.97
Number of social organizations (units)	778	5311
Per capita refuge area (m^2/person)	0.138	13.21
Health expenditure (10,000 yuan)	128,074.9	427,439
Building area (km^2)	15.21	154.43
Number of earthquake monitoring stations (units)	14.7	12
Number of internet users (10,000 households)	287.6	100

(3) Table function

For indicators that have no mutual relationship with other variables and whose own trends are not obvious, such as the TV program population coverage rate, illiteracy rate, earthquake disaster frequency, construction industry employment proportion, and social security employment proportion, they can be processed in the form of a table function, which means directly using the original data collected for the indicator for analysis.

(4) Assign constant term

In the simulation of the Chengdu seismic resilience system dynamics, SPSS software was used to calculate the constant term in the model based on the relationship between the indicators, as shown in Table 4.

Table 4. Constant term assignment.

Constant Term	Horizontal Value
Public safety expenditure as a percentage of total GDP (%)	0.797%
Number of technical health personnel per 1000 of total population (%)	0.590%
Number of hospital beds per 1000 of total population (%)	0.525%
Urban area (km^2)	1602
Earthquake intensity level	7

The data collected from China Statistical Yearbook, Sichuan Statistical Yearbook, Chengdu Statistical Yearbook, and various government reports between 2010 and 2020 were processed using the methods mentioned above. The Vensim software was used to construct the seismic resilience system dynamics model for Chengdu. The input parameter equations are shown in Table 5.

Table 5. The SD model of main variables and design concept.

Variable Name	Design Thought
GDP	INTEG (1182.72, 5889.46)
Resident population	INTEG (68.92, 1405.5)
Urban resident population	INTEG (72.59, 924.1)
Per capita road area	INTEG (0.48, 14.89)
Urban water supply network length	INTEG (1571.46, 5194)
Gas coverage rate	INTEG (0.56, 94.42)
Per capita electricity consumption	INTEG(151.52, 1925.46)
Proportion of population aged 15–64 in urban areas	INTEG (0.51, 66.97)
Number of social organizations	INTEG (778, 5311)
Per capita shelter area	INTEG (0.138, 13.21)
Health expenditure	INTEG (128,074.9, 427,439)
Building area	INTEG (15.21, 154.43)
Number of seismological stations	INTEG (14.7, 12)
Number of internet users	INTEG (287.6, 100)
Public security expenditure	0.797% × GDP
Number of health technical personnel per 1000 people	0.590% × Urban resident population
Number of hospital beds per 1000 people	0.525% × Urban resident population
Estimated number of casualties	IF THEN ELSE(Earthquake intensity = 6, 5.54 × urban population; Earthquake intensity = 7, 56.1 × urban population; Earthquake intensity = 8, 508 × urban population; Earthquake intensity = 9, 4680 × urban population)
Proportion of illiterate population aged 15 and above	WITH LOOKUP (TIME) LOOKUP([(2010, 0)–(2020, 10)], (2010, 5.44), (2011, 7.21), (2012, 6.85), (2013, 6.67), (2014, 7.18), (2015, 8.22), (2016, 8.22), (2017, 7.05), (2018, 7.49), (2019, 6.81), (2020, 4.74))
TV program audience coverage rate	WITH LOOKUP (TIME) LOOKUP([(2010, 90)–(2020, 100)], (2010, 98.47), (2011, 97.82), (2012, 99.19), (2013, 98.53), (2014, 98.53), (2015, 98.42), (2016, 99.77), (2017, 96.59), (2018, 96.91), (2019, 98.35), (2020, 100))
Number of earthquake disasters	WITH LOOKUP (TIME) LOOKUP([(0, 0)–(3000, 10)], (2010, 2), (2011, 2), (2012, 0), (2013, 7), (2014, 3), (2015, 1), (2016, 2), (2017, 2), (2018, 2), (2019, 8), (2020, 2))
Proportion of employees in the construction industry	WITH LOOKUP (TIME) LOOKUP([(0, 0)–(3000, 10)], (2010, 0.158), (2011, 0.163), (2012, 0.162), (2013, 0.163), (2014, 0.151), (2015, 0.163), (2016, 0.156), (2017, 0.151), (2018, 0.148), (2019, 0.142), (2020, 0.141))
Proportion of employees in the social security sector	WITH LOOKUP (TIME) LOOKUP([(0, 0)–(3000, 10)], (2010, 0.003), (2011, 0.004), (2012, 0.003), (2013, 0.014), (2014, 0.005), (2015, 0.006), (2016, 0.005), (2017, 0.004), (2018, 0.004), (2019, 0.01), (2020, 0.005))

3. Application of the Chengdu Earthquake Resilience Model

Chengdu is located in the central part of Sichuan Province, with two fault zones, Longmenshan and Longquan Mountain, passing through it, which results in a high risk of earthquake disasters. It has jurisdiction over 23 districts (cities, counties), with a total area of 14,335 square kilometers. Chengdu is a key earthquake monitoring and defense zone designated by the State Council, as shown in Figure 2.

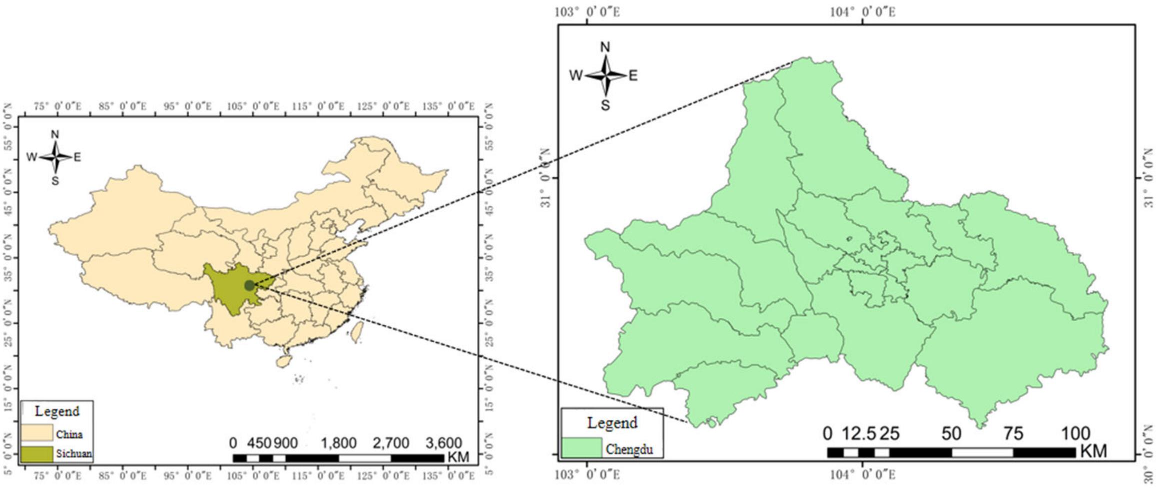

Figure 2. Location of the study area.

3.1. Historical Validation of the Model

The system dynamics model needs to undergo both realism and historical testing during operation to verify the degree of conformity between the model's data and reality. The testing methods include intuitive testing, historical relative error testing, and sensitivity testing. In this paper, extreme testing was first adopted. The economic indicator "GDP", which is widely used in the model and is closely related to the level of urban seismic resilience, was selected for extreme testing. The GDP increment was adjusted to 0 and 5000, and the results of the system dynamics model operation are shown in Figure 3.

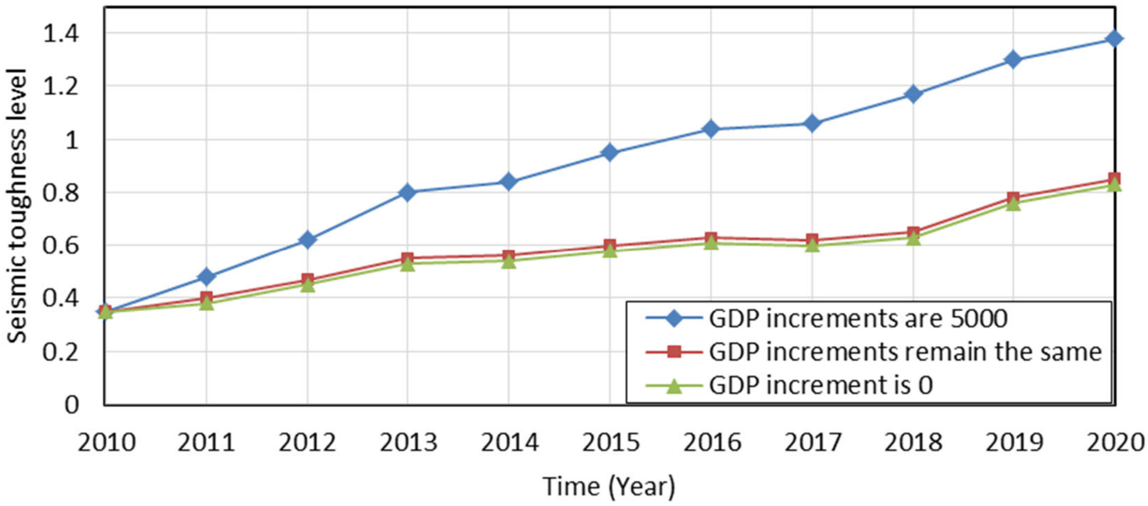

Figure 3. The seismic resilience levels of cities with changes in GDP increment.

Based on Figure 3, it can be seen that when the GDP increment increased, the rate of improvement in urban seismic resilience also increased. The faster the socio-economic development, the faster the improvement in urban seismic resilience. This is consistent with the actual situation, indicating that the model's simulation is effective and robust.

Historical data verification involves comparing the model's simulation results with actual historical data to assess the accuracy of the model. The model's accuracy is determined based on the magnitude of the error, where a larger relative error indicates lower model accuracy and a smaller relative error indicates higher model accuracy. The calculation formula was as follows:

$$\delta = \frac{x' - x}{x'} \tag{7}$$

In the equation, δ represents the relative error, x represents the historical data, and x' represents the model's simulation results. Historical data on "GDP", "urban resident population", and "total resident population" were used for the historical data test. The actual values of historical variables were compared with the simulation values obtained from the model, and the test results are shown in Table 6.

Table 6. Historical test results.

Year	GDP			Urban Permanent Population			Total Resident Population		
	Actual Value	Simulated Value	Relative Error	Actual Value	Simulated Value	Relative Error	Actual Value	Simulated Value	Relative Error
2010	5889.46	5889.46	0.000	924.1	924.1	0.000	1405.5	1405.5	0.000
2011	7345.32	7072.18	−0.039	974.5	996.69	0.022	1457.5	1474.42	0.011
2012	8619.6	8254.9	−0.044	1030.1	1069.28	0.037	1510.9	1543.34	0.021
2013	9450.66	9437.62	−0.001	1091.1	1141.87	0.044	1564.3	1612.26	0.030
2014	10,368.43	10,620.3	0.024	1155.9	1214.46	0.048	1619.8	1681.18	0.037
2015	10,662.31	11,803.1	0.097	1230.4	1287.05	0.044	1685.3	1750.1	0.037
2016	11,874.07	12,985.8	0.086	1375.3	1359.64	−0.012	1858.2	1819.02	−0.022
2017	13,931.39	14,168.5	0.017	1444.7	1432.23	−0.009	1918.8	1887.94	−0.016
2018	15,698.94	15,351.2	−0.023	1517.7	1504.82	−0.009	1981.3	1956.86	−0.012
2019	17,010.66	16,533.9	−0.029	1591.9	1577.41	−0.009	2040.9	2025.78	−0.007
2020	17,716.67	17,716.7	0.000	1650	1650	0.000	2094.7	2094.7	0.000

According to the test results, the simulation values of GDP, urban permanent population, and total permanent population in Chengdu from 2010 to 2020 had an error of less than 5% compared to the actual values, indicating a good fit and a scientifically reasonable structure of the constructed system dynamics model. Therefore, the model can reflect the actual situation of each subsystem in the system, and can be further used to predict the development trend of Chengdu's seismic resilience.

3.2. Simulation Results

After verifying the model through the aforementioned validation methods, the constructed system dynamics model of Chengdu was found to be reliable. Through simulation using Vensim software, the results of the evaluation of the city's seismic resistance, adaptability, and recovery capacity could be obtained, as shown in Figure 4. As seen from Figure 4, Chengdu's resistance, adaptability, and recovery capacity all showed upward trends from 2010 to 2020. Furthermore, the growth rate of the recovery capacity and resistance were similar, while the adaptability increased at a faster rate than the other two.

This is because the factors affecting resistance include monitoring and warning capabilities, people's seismic resistance capabilities, and physical facilities' seismic resistance capabilities. The recovery capacity is determined by medical service capabilities and physical facility recovery capabilities. Except for monitoring and warning capabilities, all these factors are closely related to the city's own development, and people have long realized their importance to the city's seismic resistance. Therefore, at the beginning of the study period, the city's recovery capacity and resistance had already achieved a certain baseline level.

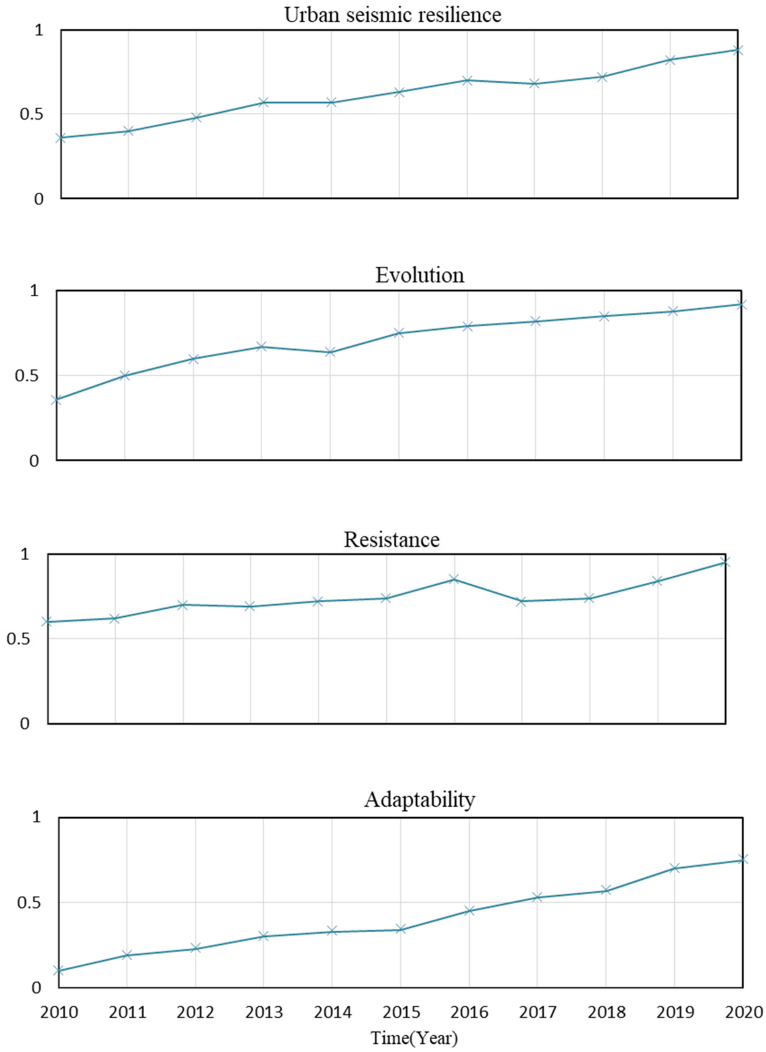

Figure 4. Development trend of urban seismic resilience level.

Adaptability reflects self-help and mutual aid capabilities, as well as emergency rescue capabilities. After the "5.12" Wenchuan earthquake, Chengdu began to increase its seismic resistance construction efforts. Some districts and counties, such as Qingbaijiang, Longquanyi, and Jintang, established earthquake prevention and disaster reduction bureaus. As of the end of 2009, Chengdu had a total of 106 emergency rescue teams with a total of 2414 people. Currently, Chengdu has 54 social professional rescue teams and has started to organize the Chengdu Brigade of the National Earthquake Rescue Team, combined with normal earthquake comprehensive exercises, to train emergency rescue teams.

Therefore, Chengdu's adaptability level was relatively low in 2010, but developed at a fast pace. The model's results are consistent with the actual situation.

3.3. Design and Analysis of the Scheme

In designing the development plan, the specific situation of Chengdu's seismic resilience was taken into account, and the decision variables of total population, GDP, number of seismograph stations, TV program coverage rate, public safety expenditure, and number of social organizations were selected and combined to determine the development plan. By changing the values, the changes in Chengdu's seismic resilience were simulated. The plan description and parameter settings are listed in Tables 7 and 8, respectively.

Table 7. Description of the seismic resilience plan for Chengdu city.

Simulation Scheme	Scheme Description
Status quo continuation scheme	Continues to develop according to existing steps.
Economic development scheme	This scenario focuses on economic development and uses GDP to represent the level of urban economic development in the model. In this scenario, the GDP will be increased by 50%. Considering that rapid economic development can lead to an increase in urban population, the urban population increment will also be increased by 50%. Other parameters in the model will remain unchanged.
Government intervention scheme	A development scheme oriented towards improving emergency response and monitoring and early warning capabilities is reflected in the model by increasing the television program coverage, public safety expenditure, and number of social organizations by 50%, while keeping the other parameters unchanged.
Resilient construction scheme	The resilience-building approach typically takes into account multiple aspects of urban development, including resistance, adaptation, and recovery. Therefore, during the simulation prediction of the resilience-building scheme, the GDP increment and urban resident population increment were both increased by 30%, and the earthquake monitoring stations and social organization quantity were increased by 50%. Other parameters remained unchanged.

Table 8. Control parameters and plans for enhancing seismic resilience in Chengdu.

Indicator	Persistence-Oriented Type	Economic Development-Oriented Type	Government Intervention-Oriented Type	Resilience-Building Type
Total population	1.0	1.5	1.0	1.3
GDP	1.0	1.5	1.0	1.3
Number of seismological stations	1.0	1.0	1.0	1.5
TV program coverage	1.0	1.0	1.5	1.0
Public safety expenditure	1.0	1.0	1.5	1.0
Number of social organizations	1.0	1.0	1.5	1.5

As seen from Figure 5, for the Current Situation Continuation scenario, the urban seismic resilience level in 2030 was 1.26557, higher than the 2020 value of 0.877809. This indicates that the urban seismic resilience level in Chengdu will continue to improve under the current development situation, and that this development plan is relatively reasonable. However, compared with the other scenarios, the seismic resilience level of the Current Situation Continuation scenario was still relatively low, suggesting the possibility of further improving the current seismic development model.

For the Economic Development scenario, the urban seismic resilience level in 2020 was 0.986888, which is not much different from the Current Situation Continuation scenario. However, the value for 2030 was 1.45436, which is much higher than the level of development under the current plan. This is because the improvement in the economic development level will promote the development of multiple indicators, such as medical service capacity and physical facility recovery ability.

The government intervention plan had a city seismic resilience level of 1.01053 in 2020, higher than the other three plans, but in 2030, it ranked only third, with a level of 1.42339. This indicates that government intervention measures can effectively improve the city's seismic resilience level, but there is insufficient follow-up, resulting in slower growth rates when other indicators remain unchanged.

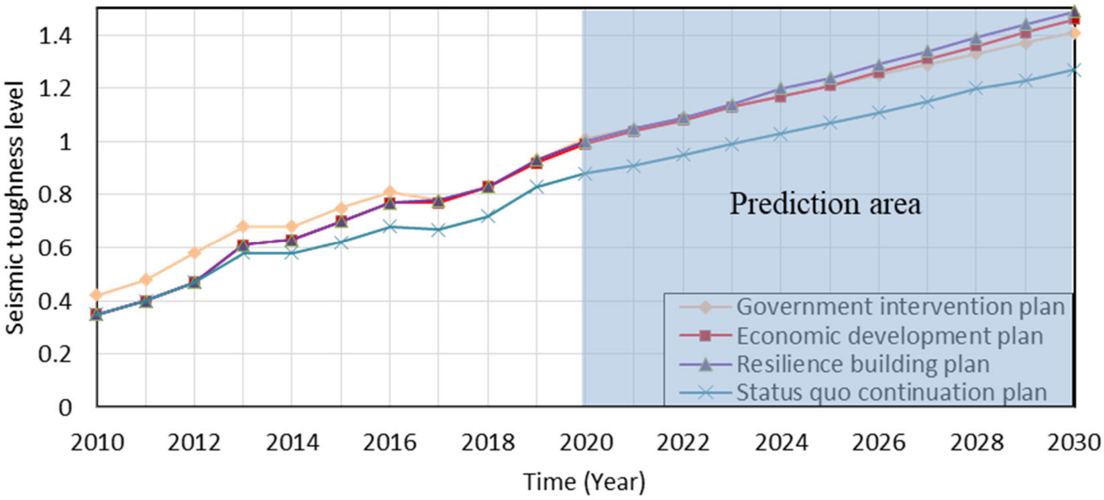

Figure 5. Simulation results for the 4 development scenarios.

The resilience-building plan had a seismic resilience level of 1.47863 for 2030, higher than the other three plans. The city's seismic resilience level increased by 47.9%, the highest increase among all plans. Therefore, Chengdu can consider conducting seismic resilience construction for the city according to the entire process of facing earthquake disasters, comprehensively considering the city's resistance, adaptability, and recovery and jointly constructing a seismic resilience city in the social space, physical space, and information space of the urban system.

4. Conclusions

(1) Based on the establishment of the urban seismic resilience assessment indicator system, the causal relationships among various indicators in the urban seismic resilience system were analyzed using the system dynamics method, and a system dynamics model was constructed to dynamically evaluate the urban seismic resilience. This can provide a reference for urban seismic resilience assessment.

(2) Taking Chengdu City as an example, reliable model operation results were provided using Vensim software. The analysis of the model operation results showed that from 2010 to 2020, Chengdu City's seismic resilience level remained in an upward trend, which is basically consistent with the actual situation of Chengdu's seismic development.

(3) According to the simulation prediction results, urban seismic resilience should be comprehensively considered in terms of urban resistance, adaptability, and recovery. It is necessary to maintain a certain level of economic development, to attach importance to the construction of monitoring and warning systems, and to improve emergency rescue capabilities and disaster propaganda and education levels as much as possible.

The urban seismic resilience assessment index system constructed in this study included three dimensions, seven domain layers, and twenty-two indicators. This index system was based on existing data surveys. However, due to the limited availability of public data, future research should further supplement and improve the index system in ways such as including data on military forces in the emergency response capacity. In order to achieve a finer spatial scale model, the next step in the research can focus on constructing seismic resilience assessment models for specific regions, or even communities, within the city. This will help us to explore regional differences and identify areas where urban seismic resilience needs improvement.

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