

Research on the Evaluation Method for Key Buildings Based on Seismic Damage Index Modification—Taking the Yangzonghai Area Seismic Fortification Planning of Kunming City as an Example

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Abstract: This article focuses on the evaluation of key buildings in seismic mitigation planning, based on the modified seismic damage index. In the evaluation process, a computational model for key building evaluation is proposed, including the coefficients for model modification. The weights of the model modification coefficients are quantitatively calculated, followed by the application of the model for evaluation and conclusion derivation. Taking the "Yangzonghai Regional Seismic Design Planning" as an example, in the key building evaluation section of the specific mitigation planning, the average seismic damage index of group buildings in Yunnan Province's zone of VIII degree is used as the basis for calculation. The average seismic damage index of group buildings is adjusted with weighted factors such as building structure, construction year, site type, compliance with regulations, and adoption of seismic isolation technology. The factors are further adjusted using expert scoring. Finally, the seismic damage index for each important building is calculated. By referring to the corresponding building damage level associated with the seismic damage index, the potential damage levels that each important building may experience during a seismic event of the designated design level are determined. This study provides preliminary guidance for the renovation and improvement of important buildings and serves as an initial reference for decision-making by relevant government departments.

Keywords: Seismic Damage Index, Seismic Damage Matrix, Key Buildings, Analytic Hierarchy Process, Modification Coefficients, Yangzonghai.

1. Introduction

China is one of the countries most severely affected by earthquake disasters. Yunnan Province, located in the southeastern part of the Qinghai-Tibet Plateau, is situated in the collision zone between the Indian Plate and the Eurasian Plate. It experiences intense tectonic deformation and seismic activity, characterized by high frequency, strong intensity, wide distribution, and shallow seismic sources. The losses incurred in terms of human life and property during seismic events are immeasurable, with the majority of secondary disasters being triggered by the destruction of buildings. However, the consequences of seismic damage to buildings vary significantly due to factors such as building type and location, making it difficult to achieve consistent and accurate evaluations and judgments of their seismic performance. This is particularly critical for large public buildings, such as healthcare facilities, educational institutions, major public infrastructure, as well as administrative and lifeline engineering structures that impact disaster relief efforts. These important buildings require thorough evaluations of their seismic performance and damage assessment [1]. In order to enhance urban seismic disaster prevention and mitigation capabilities and provide reasonably accurate assessments of key buildings, thereby offering rational urban redevelopment recommendations, the method of modifying the seismic damage index for group buildings can be employed within the framework of seismic disaster prevention and mitigation planning. This approach ensures the convenience, rationality, and instructiveness of seismic damage evaluations for key urban buildings.

Seismic damage prediction in China has gradually evolved since the 1980s. Currently, the methods predominantly used in seismic mitigation planning require detailed physical and mechanical parameters of buildings, necessitating extensive surveys and statistical analysis of the structures. This approach incurs significant manpower and resource costs, as it contradicts the principle of simplicity and efficiency in seismic damage prediction within the planning framework [2]. To address these challenges, this study proposes a method for assessing key buildings through the modification of seismic damage indices for group buildings. By considering the regional average seismic damage index and factors such as building structure type, construction era, and building location, a combined quantitative and qualitative approach is employed using expert scoring and weighting. This approach enables the prediction of the seismic damage indices of individual important buildings on a larger scale. The method is primarily used for seismic damage prediction of key buildings within seismic planning. By utilizing a relatively simple model, it scales up the prediction of potential damage to important buildings under designated design levels, providing preliminary forecasting results. These results can guide subsequent re-evaluations of key buildings, as well as offer initial recommendations for renovation and improvement [3].

2. Evaluation Method Based on Revised Seismic Damage Index

2.1 Evaluation Method and Process

Seismic damage prediction for key buildings refers to the assessment of buildings that are critical for continuous functionality during earthquakes or have the potential to cause significant casualties and major disasters, considering the seismic conditions corresponding to the designated design levels in urban areas [4]. In the prediction of seismic damage for key buildings, the first step is to determine the average seismic damage index corresponding to the designated intensity level in the evaluation area. Then, based on factors such as building structure type, construction era, site classification, seismic measures adopted, and compliance with regulations, correction coefficients for the five major seismic damage indices are established. The Analytic Hierarchy Process (AHP) is then employed to establish a weight matrix for these correction coefficients. The corresponding weight values for each correction coefficient are calculated, taking into account expert ratings obtained through consultation with a certain number of experts. By combining the expert ratings and calculated weight values for each coefficient, the final values for each type of correction coefficient are determined. Subsequently, the seismic damage index for each key building is calculated using the resulting list of correction coefficients. Based on the seismic damage index of each individual key building, an overall evaluation is conducted to determine the building's damage level, and corresponding recommendations are provided [5]. The basic workflow for seismic damage prediction of key buildings is illustrated in Figure 1.

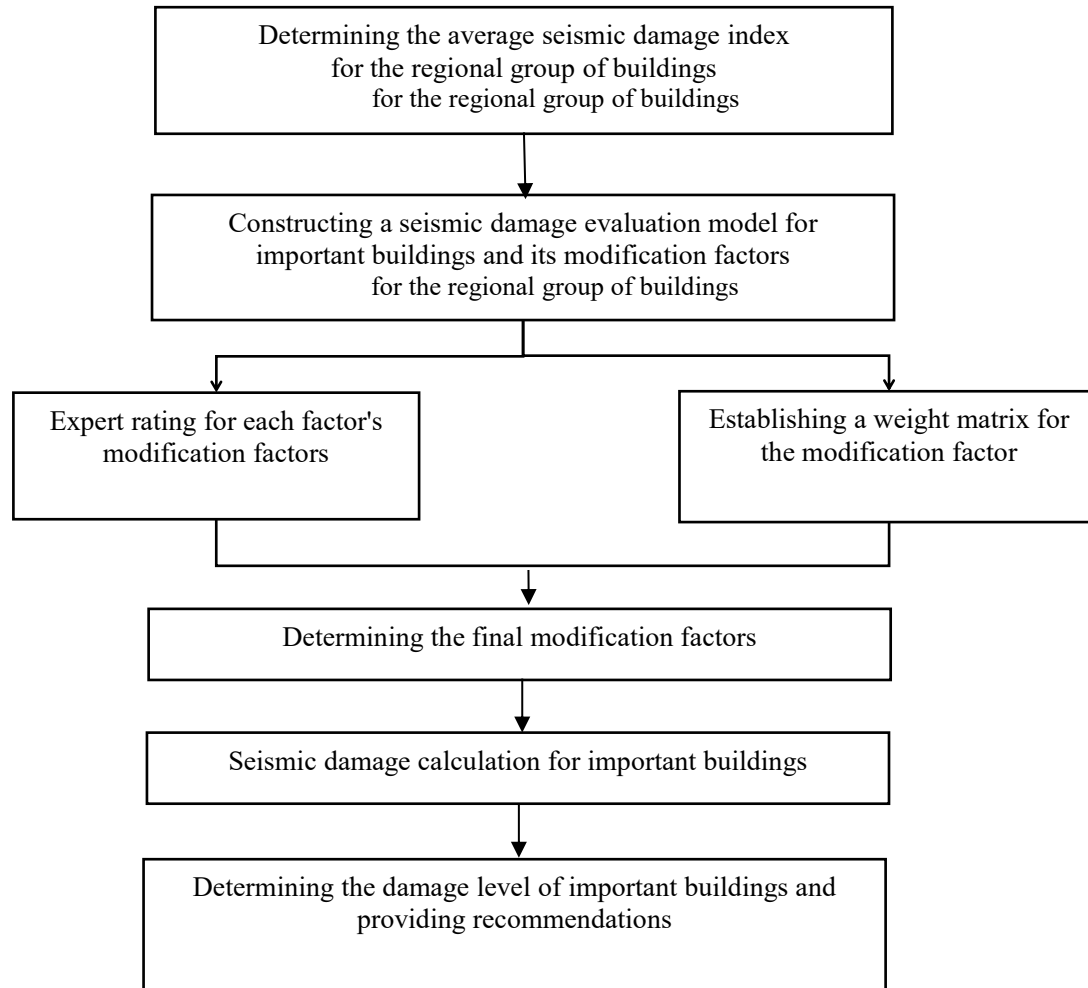


Figure 1: Basic Workflow for Seismic Damage Prediction of Key Buildings

2.2 Model Research for Revised Seismic Damage Index

According to the "Classification of Seismic Damage Levels for Buildings" (GB/T 24335-2009), the damage degree of surveyed buildings is divided into five levels: essentially intact, slight damage, moderate damage, severe damage, and collapse. The relationship between the building's damage level and the seismic damage index, as per the "Chinese Earthquake Intensity Scale," is shown in Table 1. The higher the numerical value, the more severe the seismic damage.

Table 1: Corresponding Seismic Damage Index and Upper/Lower Limits for Building Damage Levels (Chinese Earthquake Intensity Scale, GB/T 17742-2008)

Damage Level	Seismic Damage Index	Seismic Damage Index Range
Essentially Intact	0.05	$D \leq 0.10$
Slight Damage	0.20	$0.10 < D \leq 0.30$
Moderate Damage	0.45	$0.30 < D \leq 0.55$
Severe Damage	0.70	$0.55 < D \leq 0.85$
Destroyed	0.90	$D > 0.85$

The seismic damage index used is applicable to group buildings and can reflect the damage levels of a certain group of buildings. However, it overlooks factors such as regional variations and individual building characteristics, including construction era, structural features, and adopted seismic measures, which can significantly affect the impact of disasters [6]. Therefore, it is necessary to revise the seismic damage index based on existing building data and survey results. In this study, when evaluating the seismic performance of individual key buildings, factors related to

individual performance and correction coefficients are established, taking into account the building's structural type, construction era, site conditions, compliance with regulations, and adopted seismic technologies. By applying these factors, the seismic damage index for key buildings is corrected to obtain a more accurate assessment of individual building performance [7].

The seismic damage index of a building is primarily influenced by factors such as seismic defense measures, construction era, building structure, site type, and usage conditions [8]. As the construction era becomes more distant, buildings are more prone to damage in earthquakes due to prolonged lack of maintenance or changes in material characteristics. Different structural types exhibit varying capacities to withstand seismic events. The soil conditions and usage patterns of construction sites have a significant and noticeable impact on buildings. Even buildings with the same construction era, structural type, and site type can have different seismic performance depending on whether they comply with regulations and utilize seismic technologies [9]. Therefore, in the assessment and seismic damage prediction of significant individual buildings, the average seismic damage index of the structures is adjusted through the application of a formula based on the construction era, structural type, site conditions, compliance with the prevailing architectural design regulations at the time, and the utilization of seismic isolation technology [10]. The adjustment calculation is performed using the following formula:

$$D(I)' = i_1 i_2 i_3 i_4 i_5 D(I)$$

In the equation:

$D(I)'$ - Seismic damage index of the building;

i_1 - Modification coefficient for structural type of the building;

i_2 - Modification coefficient for construction era of the building;

i_3 - Modification coefficient for site type of the building;

i_4 - Modification coefficient for compliance with contemporary architectural design regulations of the building;

i_5 - Modification coefficient for utilization of seismic isolation technology in the building;

$D(I)$ - Average seismic damage index.

In the assessment of significant buildings within seismic disaster prevention and mitigation planning, the revised seismic damage index $D(I)'$ is used to correspond to the seismic damage index and upper and lower limit values of the corresponding damage levels of the buildings in Table 1. This is done to determine the damage level and seismic performance of the important individual buildings under the intensity of urban seismic defense [11].

2.3 Quantification of Model Modification Factor Weights

To ensure a more scientifically and logically determined set of modification factors, the weights of each factor are quantified using the Analytic Hierarchy Process (AHP) alongside expert ratings. The methodology involves constructing judgment matrices for the five modification factors in Equation (1) using the AHP 1-9 scale. By performing calculations and passing consistency tests on these matrices, relative weight values for each factor indicator are determined. These calculated results are then combined with expert ratings to determine the final modification factors for each factor. Once the modification factors are determined, they are incorporated into the previous equation to calculate the specific seismic damage index for individual significant buildings. This allows for the prediction of seismic damage scenarios and the formulation of corresponding strategies under the designated seismic defense intensity in the area [12].

3. Construction of Seismic Damage Model and Evaluation for Important Buildings in the Yangzonghai Region

3.1 Overview of the Yangzonghai Region

The Yangzonghai region is located in the central part of Yunnan Province, southeast of Kunming City, adjacent to the main urban area of Kunming. It is situated 10 kilometers from the Chenggong New District and 18 kilometers from the central area of Kunming. The region is also within a short drive from Kunming International Airport and Kunming International Logistics Center, making it a crucial hub in the core economic zone of central Yunnan. It serves as an important gateway from Yunnan to coastal areas, Southeast Asia, and South Asia, as well as a key transportation stronghold connecting Kunming to the southeast of Yunnan. In terms of geological structure, the Yangzonghai region is located in a developed section of the Xiaojiang Fault Zone, with its western branch passing through the center of the region. The Xiaojiang Fault Zone is a relatively immature fault zone, containing multiple secondary faults that are arranged in a parallel and complex manner. The fault zones are characterized by numerous fault levels, steep fault planes, and frequent changes in direction. These areas are often in a locked state, and intense stress concentration can lead to strong earthquakes. Since 1500, more than ten earthquakes with a magnitude greater than 6 have occurred along the Yunnan section of the Xiaojiang Fault, including the Songming-Yiliang 8.0 magnitude earthquake in 1833. Therefore, the Yangzonghai region has higher seismic defense requirements, with a seismic defense intensity of 8 degrees, a design basic earthquake acceleration of 0.3, and it falls under the third seismic design category. Seismic disaster prevention planning and seismic damage prediction are particularly important for this area [13]. The "Seismic Disaster Prevention and Mitigation Planning for the Yangzonghai Region (2020-2035)" utilizes the modified seismic damage index model for scale-based preliminary prediction and evaluation of seismic damage for key buildings. This paper takes the aforementioned special planning as an example to illustrate the research process of seismic damage prediction and evaluation for important buildings.

3.2 Establishment of Seismic Damage Prediction Model

The first step is to determine the average seismic damage index. With a seismic defense intensity of 8 degrees in the Yangzonghai region, the average seismic damage index can be obtained from the "Seismic Damage Matrix for House Buildings in Yunnan Region" (Zhou Guangquan, Tan Wenhong, et al., 2007, China Earthquake, 23(2), 115-123). According to the statistical values of seismic damage indices for different types of house buildings at various intensities in Yunnan region, the average seismic damage index for the 8-degree zone is 0.35%.

Next, we determine the modification factors for each element. In the seismic disaster prevention and mitigation planning for the Yangzonghai region, the modification factors for structural factors are obtained directly by calculating the statistical values of seismic damage indices for different types of house buildings under the 8-degree defense condition, as presented in Table 2 of "Seismic Damage Matrix for House Buildings in Yunnan Region" by Zhou Guangquan et al. Additionally, the modification factors for other factors are determined through a combination of weighted calculations and expert ratings [14]. The modification factor for building structure types in the 8-degree zone of Yunnan is calculated by combining the average seismic damage index values for each structure type in Table 2 with the average seismic damage index value of 0.35. The calculated results are shown in List 3.

Table 2: Statistical values of seismic intensity indices for different types of buildings in areas with different intensities in Yunnan Province, China (%)

Structural type Intensity		Frame structure	Brick-concrete structure	Brick-wood structure	civil structure	Average seismic intensity index
IX	Range	0.27~0.27	0.41~0.41	0.48~0.51	0.48~0.56	0.44~0.46
	Average	0.27	0.41	0.50	0.52	0.45
VIII	Range	0.20~0.33	0.21~0.42	0.31~0.45	0.28~0.49	0.28~0.45
	Average	0.25	0.31	0.36	0.38	0.35
VII	Range	0.04~0.24	0.08~0.25	0.11~0.28	0.12~0.30	0.09~0.30
	Average	0.11	0.14	0.18	0.19	0.17
VI	Range	0.01~0.09	0.02~0.09	0.02~0.11	0.05~0.17	0.03~0.10
	Average	0.05	0.06	0.07	0.09	0.07

Table 3: Modification Coefficients of Building Structure Types in District VIII

Structure Type	Modification coefficient
Frame/Shear wall	0.71
Brick-concrete	0.89
Brick-wood	1.03
Masonry	1.09

Finally, the average seismic intensity index and various modification coefficients are brought into the formula $D(I)' = \frac{1}{n} \sum_{i=1}^n D(I)_i$, completing the modeling of seismic hazard prediction for important buildings.

3.3 Quantification of Model Modification Coefficient Weights

Except for building structure factors, the influence of other factors on building seismic capacity is first scored by more than 10 experts to obtain the average score of each factor. Then, the remaining four factors are constructed with a 1-9 scale judgment matrix using the hierarchy analysis method to determine the relative weight values of the factor indices. This paper sets the construction year of the building as Factor A, the type of building site as Factor B, whether the building meets the building design codes at that time as Factor C, and whether seismic retrofitting technology is adopted as the modification coefficient Factor D. According to the actual seismic hazard rules and expert opinions, the four-factor judgment matrix is constructed:

$$T = \begin{bmatrix} 1 & 1/1.2 & 1 & 1/1.1 \\ 1.2 & 1 & 1.2 & 1.2/1.1 \\ 1 & 1/1.2 & 1 & 1/1.1 \\ 1.1 & 1.1/1.2 & 1.1 & 1 \end{bmatrix}$$

Calculating the judgment matrix T yields the maximum eigenvalue $\lambda_{\max} = 4.00$. At this time, the average random consistency index RI can be found to be 0.94 by looking up the table. The consistency of the maximum eigenvalue is tested by calculating the consistency index $CI = 0.00$. The consistency ratio $CR = 0.00 < 0.1$ meets the consistency requirement, indicating that the judgment matrix is logically sound without errors and acceptable. Therefore, the corresponding characteristic vector is $\omega = (0.93, 1.12, 0.93, 1.02)$. After normalization, the weight values are shown in Table 4.

Table 4: Weights of Four Factors

Factor Weight	A	B	C	D	Weight
A	1	1/1.2	1	1/1.1	0.2326

B	1.2	1	1.2	1.2/1.1	0.2791
C	1	1/1.2	1	1/1.1	0.2326
D	1.1	1.1/1.2	1.1	1	0.2558
Note 1: $\lambda_{\max} = 4.00$; $CI = 0.00$, $RI = 0.94$, $CR = 0.00 < 0.1$.					
Note 2: A refers to the year of building construction. B refers to the building site type. C refers to whether the building meets the building design code at that time. D refers to whether the building adopts seismic mitigation technology.					

During the expert scoring process for "Seismic Reinforcement in Yangzhonghai Region", a lower seismic intensity index indicates lower destructive power, so the scoring was carried out in descending order - the greater the negative impact, the higher the score, with a maximum of 6 points. Experts determined the score ranges for different sub-factors based on experience. The scoring result was the average of the individual expert scores. After weighted calculation, the modification coefficient for each factor was obtained.

Among them, when the experts scored the construction year of buildings, each expert comprehensively considered the impact on seismic resistance of buildings in the Yangzhonghai area based on factors such as the promulgation of the "Code for Seismic Design of Buildings" and the revision time nodes of the "Seismic Zonation Map of China", and divided the years into four stages: the first stage is before 1990, the second stage is 1990-2000, the third stage is 2001-2010, and the fourth stage is 2010 and later. The final determined modification coefficients are shown in Table 5.

Table 5: Average Expert Scores of Building Construction Year

Year	Expert Rating	Weight	Modification Coefficient
After 2010	3.87	0.2326	0.9
2001-2010	4.3		1
1990-2000	3.87		0.9
Before 1990	5.59		1.3

The types of urban land plots are divided into four categories: advantageous plots, general plots, disadvantageous plots, and dangerous plots. The modification coefficients calculated after expert scoring and weighted scoring are shown in Table 6. Among them, dangerous plots cannot be built on. The destruction rate of buildings on dangerous plots during seismic hazards can reach 100%. Therefore, no modification is made for them, and a single veto system is adopted. If there are important buildings distributed in dangerous plots, the important building evaluation and prediction in the seismic reinforcement planning universally recommend relocating and rebuilding at another site.

Table 6: Modification Coefficients of Building Site Types

Site Type	Expert Rating	Weight	Modification coefficient
Favorable site	2.9	0.2791	0.8
General site	3.2		0.9
Unfavorable site	3.6		1
Hazardous site	Not scored		

For buildings that do not meet the building design codes at that time, which belong to relatively dangerous buildings, the scoring is set as meeting and not meeting the codes. When scoring, the experts also gave corresponding scores to meeting and not meeting, respectively. Combined with the weight calculation, the modification coefficient is shown in Table 7.

Table 7: Modification Coefficients of Whether Buildings Meet Building Design Codes at That Time

Compliance with building design codes at that time	Expert Rating	Weight	Modification coefficient
Yes	3.87	0.2326	0.9
No	5.16		1.2

Whether seismic technology was adopted for buildings, and the seismic technology is further divided into seismic retrofitting technology and seismic isolation technology, which have different influences on the seismic performance of buildings. When scoring, the experts scored according to whether seismic technology was adopted and the impact of adopting seismic retrofitting or isolation technology on the seismic resistance of buildings, and then obtained the modification coefficient by combining with the weight values. The modification coefficients for whether seismic retrofitting or isolation technology was adopted are shown in Table 8.

Table 8: Modification Coefficients of Whether Buildings Adopt Seismic Mitigation Technologies

Adoption of seismic mitigation technology	Expert Rating	Weight	Modification coefficient
No	3.9	0.2558	1
Damping	3.7		0.95
Isolation	2.9		0.75

After determining the modification coefficients of each factor based on Tables 3, 5, 6, 7 and 8, bringing the average seismic intensity index of 0.35 and the modification coefficients into the formula $D(I)=i_1 i_2 i_3 i_4 i_5 D(I)$, the seismic intensity indices of various important buildings can be calculated through lookup.

3.4 Important Building Seismic Hazard Prediction and Evaluation Analysis

A total of 126 important buildings were collected in the "Yangzhonghai Region Seismic Disaster Reduction Planning". These important buildings are distributed throughout the jurisdiction, and the layout of important buildings is shown in Figure 2. Among these buildings, there are 6 buildings built before 1990; 76 buildings built between 1990 and 2010; and 53 buildings built after 2010.

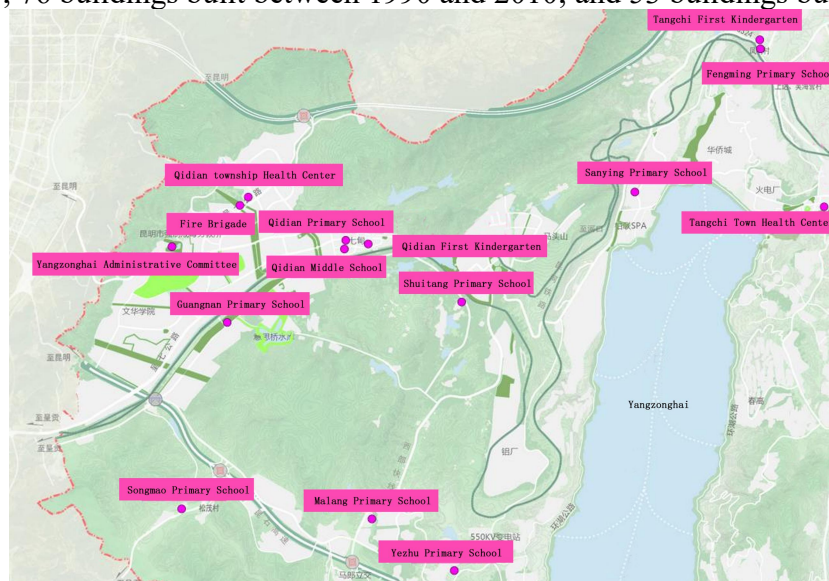


Figure 2: Layout of Key Buildings

The seismic intensity indices were calculated to predict the degree of damage of individual important buildings in the Yangzhonghai region under the designed intensity level of seismic fortification, while the corresponding planning recommendations were given. See According to the above evaluation method, the seismic hazard prediction of important buildings in the Yangzhonghai area showed 122 buildings with minor damage, 6 buildings with moderate damage, and 7 buildings located in potential dangerous plots. For those buildings included in the special fortification class and key fortification class, the building seismic quality pre-estimation control can refer to the evaluation conclusions. For important buildings predicted to have more severe damage or located in potential dangerous plots, the seismic performance identification of these buildings should be initiated immediately to determine the seismic fortification capacity of each building, screen strengthening buildings, demolishing and reconstructing buildings, and selecting alternative sites for new construction, so as to improve the integrated seismic disaster relief capacity of towns[15].

Seismic retrofitting shall be carried out on buildings that do not meet seismic requirements according to the seismic fortification requirements of new projects, to ensure normal use during earthquakes. Priority should be given to adopting new seismic retrofitting technologies such as seismic isolation and damping, and new design concepts based on functions, to ensure the safety requirements of important buildings. For buildings with longer service life, priority should be given to renovation or demolition and reconstruction[16].

4. Conclusion

This paper takes the "Yangzhonghai Region Seismic Disaster Reduction Planning (2020-2035)" as an example to evaluate the seismic performance of important urban buildings through the seismic intensity index modification method. In the modification of seismic intensity index, the analytic hierarchy process was first used to quantitatively calculate the weights of modification coefficients in the calculation model, and the modification coefficients of different factors were obtained. Finally, the modification coefficient values were brought into the model formula to calculate the predicted seismic intensity values of different important buildings, and the corresponding damage levels could be predicted according to the hazard index values. Eventually, the corresponding evaluation conclusions and suggestions on seismic construction and reform of important individual buildings were drawn. This prediction method is relatively simple and easy to operate. It has been successfully applied in seismic disaster reduction planning projects such as the Yangzhonghai Region Seismic Disaster Reduction Planning. The seismic disaster reduction planning in Yunnan Province can re-calculate the weights based on different intensities seismic matrices and average seismic intensity indexes in Yunnan Province after expert scoring, and bring them into the model formula for simple calculation according to different situations[17]. Other regions can also modify and apply it based on relevant seismic intensity indexes and different expert scoring to provide preliminary opinions for the seismic retrofitting and regulation of important buildings in urban seismic disaster reduction planning, and provide reference opinions for government decision-making.

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