Research on earthquake damage prediction of stone structure in southern Fujian based on fuzzy comprehensive evaluation

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Abstract. Based on fuzzy mathematics method, earthquake damage prediction of stone structure houses in Southern Fujian is studied. The subsets of earthquake damage affecting factors applicable to stone structures and their fuzzy relation with earthquake damage levels are established. Furthermore, the earthquake damage prediction model of stone structure houses in southern Fujian is developed based on fuzzy comprehensive evaluation method. Taking the two-storey stone structure house as an example, the model is applied to predict and evaluate the damage state of the two-storey stone structure house after earthquake damage. The results show that, according to the fuzzy comprehensive prediction and evaluation model, the stone structure house suffers serious damage degree in the earthquake damage, the evaluation grade of earthquake damage is C, and the evaluation result is consistent with the actual damage state. The model of earthquake damage prediction is clear and easy to calculate, which provides a theoretical basis for earthquake damage prediction and reinforcement and maintenance of stone structure houses in southern Fujian.

1. Introduction

In Southern Fujian, due to the rich stone resources, mining convenient and low price. As a special form of masonry structure, stone structure houses exist in abundance. Fujian southern region is located in the southeast of China, the Ring of the Pacific seismic belt, seismic activity is frequent, and the damage to houses caused by the earthquake was more serious. Especially the southern region of fujian stone structure houses generally used stones as wall, floor and roof bearing component and lack of necessary seismic connection measures, and most of the stone houses without design structure, s is relatively long, use condition is bad, the integrity of the building and its seismic capability of severity shortage, never even the region seismic fortification standards, as long as reached the level of earthquake magnitude, housing may damage and collapse[1]. In the earthquake disaster, it is urgent to carry out reasonable earthquake damage evaluation and reinforcement and maintenance. Therefore, it is of great practical significance to study the seismic damage evaluation method of stone structure houses in Southern Fujian.

The research methods of earthquake damage prediction are empirical analysis and theoretical analysis. Wang Qiang et al. [2] carried out research on earthquake damage prediction of brick and wood houses in rural areas. Based on the analysis, statistics and summary of a large number of earthquake damage data, they obtained the relationship between earthquake damage prediction indexes and earthquake damage levels, and then predicted the earthquake damage of brick and wood buildings in rural areas. Li Lingjiao et al. [3, 4] predicted earthquake damage of a large number of existing ancient buildings with brick and stone structures and wooden structures in China through earthquake damage data, theoretical analysis and model test combined with fuzzy mathematics theory. Although the research
methods of earthquake damage prediction have been advanced and applied, the research data, methods and application scope of all kinds of prediction methods have their limitations. At present, there are few researches on earthquake damage prediction of stone structure houses. Zhou Wenqi et al. [5] studied the seismic performance of group buildings in southern Fujian, counted the earthquake damage distribution of various structure types under different intensification, obtained the corresponding vulnerability matrix, and predicted and evaluated the earthquake damage situation within the region. Although this evaluation method is simple and feasible, it is still dominated by traditional empirical method, and the results are subjective and not accurate enough. In this paper, stone structure houses in Southern Fujian are selected as the research object, based on the earthquake damage data and existing research results, the corresponding relationship between the impact factor of earthquake damage and the earthquake damage index is established, and the earthquake damage prediction model of stone structure houses in southern Fujian is given by using fuzzy comprehensive evaluation method. It provides a more reasonable and reliable method for earthquake damage assessment of stone structure houses in southern Fujian.

2. Related Work

2.1. Fuzzy comprehensive evaluation theory

Fuzzy comprehensive evaluation method is a practical application method based on fuzzy mathematics theory. The basic idea is to select the main factors related to the evaluated object, use the membership function to transform the qualitative evaluation of single factor into quantitative evaluation, and make a reasonable comprehensive evaluation according to the membership degree identification principle. The specific steps are as follows:

Set \( U = \{u_1, u_2, \ldots, u_n\} \) as \( n \) factors or indicators, and establish \( m \) kinds of evaluation index sets \( V = \{v_1, v_2, \ldots, v_m\} \).

According to the result of single factor evaluation, a single factor evaluation matrix was established:

\[
R = \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1m} \\
    r_{21} & r_{22} & \cdots & r_{2m} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{n1} & r_{n2} & \cdots & r_{nm}
\end{bmatrix}
\]  

(1)

Where, \( r_{nm} \) is the membership degree of the influencing factor \( u_i \) to the evaluation set \( v_j \).

Further calculate the weight of each factor as follows:

\[
W^\tau = (w_1, w_2, \ldots, w_n) = a^\tau = (a_1, a_2, \ldots, a_n)
\]  

(2)

And then, a comprehensive evaluation result can be obtained through a certain type of synthesis operation:

\[
B = W^\tau \cdot R = (w_1, w_2, \ldots, w_n) \cdot \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1m} \\
    r_{21} & r_{22} & \cdots & r_{2m} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{n1} & r_{n2} & \cdots & r_{nm}
\end{bmatrix} = (b_1, b_2, \ldots, b_n)
\]  

(3)

Finally, according to the principle of membership identification, a reasonable comprehensive evaluation is made.

2.2. Earthquake damage prediction and assessment of buildings

In the earthquake damage prediction and evaluation of buildings, there are usually five earthquake damage grades: basically intact, slight damage, medium damage, serious damage and collapse. The
earthquake damage itself is a fuzzy event in earthquake disaster prediction and evaluation. Therefore, the research method of earthquake damage prediction based on fuzzy comprehensive evaluation method is reasonable for dealing with such fuzzy events.

In this paper, it is assumed that the earthquake damage index is:

\[ V = \{v_1, v_2, \ldots, v_m\} = \{0, 0.1, 0.2, \ldots, 1.0\} \]  \( (4) \)

The fuzzy subset of earthquake damage grade \( V \) is expressed as follows:

\[ A_j = a_1 / v_1 + a_2 / v_2 + \ldots + a_j / v_j + a_{11} / v_{11} \]  \( (5) \)

Where, \( v_j \) is the earthquake damage index grade, \( a_j \) is the subordinate degree of earthquake damage of buildings to earthquake damage grade \( v_j \).

Combined with the fuzzy comprehensive evaluation theory and the maximum membership principle, the earthquake damage grade of buildings can be evaluated and determined. According to reference [5-7], the corresponding relationship between earthquake damage level and failure state of stone structure buildings in South Fujian Province is shown in Table 1.

| Assessment Level | State of destruction | maintenance measures |
|------------------|----------------------|----------------------|
| A                | basically intact,    | minor repair         |
|                  | slight damage        |                      |
| B                | medium damage        | medium repair        |
| C                | serious damage       | capital repair       |
| D                | collapse             | Rescue protection    |

### 3. Earthquake damage prediction and evaluation of stone structure buildings in South Fujian

#### 3.1. Earthquake damage influence factors and grade evaluation standards

For the stone structures in Southern Fujian, the following five seismic damage factors are selected by analyzing the influencing factors of seismic performance and seismic damage characteristics [5-7].

1. Evaluation standard of seismic intensity

Seismic intensity is the intensity of the impact of earthquake on the surface and engineering buildings. Therefore, seismic intensity can be used to evaluate the degree of earthquake damage to buildings. Based on a large number of historical seismic damage data of stone structure buildings in Southern Fujian (see reference [5]), the seismic damage matrix of stone structure buildings in the area of VII ~ IX is obtained, as shown in Table 2. The prediction results of earthquake intensity and damage are shown in Table 3.

| Earthquake intensity | basically intact, slight damage | medium damage | serious damage | collapse |
|----------------------|---------------------------------|---------------|----------------|---------|
| VII degrees          | 21.30                           | 63.90         | 11.38          | 3.41    |
| VIII degrees         | 0.00                            | 48.78         | 36.75          | 14.47   |
| IX degrees           | 0.00                            | 0.00          | 41.14          | 58.86   |

| Earthquake intensity | (0.2,0.7,1.0,0.7) |
|----------------------|------------------|
| VII degrees          |                  |
| VIII degrees         | (0.0,2.0,7,1.0)   |
| IX degrees           | (0.0,0,2.0,7)     |

2. Evaluation standard of cracks in stone masonry structure buildings

Different damage states of stone masonry structure corresponding to seismic damage assessment grade. Grade A corresponds to no obvious cracks, grade B corresponds to a small number of cracks in
minor parts, and grade C corresponds to that there are not many cracks but in important parts, grade D
 corresponds to many cracks and are in important parts.

(3) Evaluation standard for surface damage of masonry buildings

The failure state of stone masonry structure corresponding to grade A is no obvious damage, grade B
 corresponds to minor damage, grade C corresponds to small damage, but in important parts, grade D
 corresponds to large damage and important parts.

(4) Evaluation standard for completion time of stone masonry buildings

The completion time reflects the quality of the building and the degree of old and new. It reflects the
 property that the seismic capacity of the building decreases with the increase of service time. Obviously,
 the new house with intact structure has better seismic performance than the old one. The construction
 time of stone masonry structure corresponding to grade A is less than 30 years, that of grade B is 30-60
 years, that of grade C is 60-90 years, and that of grade D is more than 90 years.

(5) Evaluation standard for connection structure of stone masonry building

Based on the statistical analysis of earthquake damage data and existing studies, the evaluation
 standard for the connection structure of stone masonry structure was given in reference [1, 7]. The
 evaluation grades A, B, C and D are determined based on the following aspects: whether the building
 structure is properly standardized, whether the building materials are properly matched, whether the
 connection mode meets the requirements of the code, and whether the construction meets the
 requirements of the code.

3.2. Membership function of each single index

For the quantitative factors such as building age, the smaller the better type, the smaller descending
 ridge distribution is adopted. For qualitative factors such as cracks, connection structure and surface
 damage, the membership function can be established by analogy method [4].

3.3. Determination method of weight coefficient of each influence factor

The weight value reflects the role of each factor in the comprehensive evaluation, and directly affects
 the results of comprehensive decision-making, which is very important to the decision-making result of
 fuzzy comprehensive evaluation. Analytic hierarchy process (AHP) is an effective method to determine
 the weight value, but it does not consider the impact of single factor changes on the decision-making
 results in the process of determining the weight. In this paper, the improved AHP method is adopted.

Assuming that the performance levels of the influencing factors are balanced, that is \( W^T = a^T \).

The weight vector is obtained by analytic hierarchy process:

\[
a^T = (a_1, a_2, ..., a_n) \tag{6}
\]

According to the principle that the worse the performance of influence factors is, the greater the
 weight is:

\[
\beta^T = (\beta_1, \beta_2, ..., \beta_n) \tag{7}
\]

Finally, the final weight vector is obtained:

\[
W^T = (w_1, w_2, ..., w_n) \tag{8}
\]

Where, \( w_i = a_i \beta_i / (\alpha^T \beta^T) \).

By distributing the weight questionnaire to experienced experts, the importance assignment of each
 factor of stone structure is obtained. According to table 4, the weight coefficient vector of the five
 seismic damage factor indexes of the stone structure building can be obtained as follows: \( W = [0.484, 0.157, 0.101, 0.157, 0.101]^T \).

| the same | Slightly stronger | strong | Very strong | Slightly weaker | weak | Very weak |
|---------|------------------|-------|-------------|----------------|------|-----------|
| 1       | 3                | 5     | 7           | 1/3            | 1/5  | 1/7       |
4. Application Studies

In order to effectively verify the rationality of the method, a two-story stone structure building in Southern Fujian was selected as an example. The building age was about 80 years ago, and the seismic fortification was grade VIII. There are two rooms on the floor, with 3.6m Bay and 4.8m depth. The width of single corridor corridor is 1m, the cornice height is 6.0m, the width and height of door opening are 0.8m and 2.1m, and the width and height of window are 0.9m and 1.2m. The wall is made of dry masonry with gasket. The thickness of the wall is 370mm. There are stone columns and stone lintels. The connection between the vertical and horizontal walls is good.

The earthquake damage prediction of the house is as follows:

The seismic fortification of the stone structure buildings in Southern Fujian. According to table 3, the membership vectors of the prediction results of earthquake intensity and damage are as follows: (0,0.2,0.7,1.0).

In the earthquake disaster, there are different degrees of cracks in the walls of the two-story stone structure building. Most of the cracks are X-shaped, and there are vertical cracks with a length of 1 m in the top floor. According to the analogy method and evaluation standard, the membership vectors of cracks are: (0,0.3,0.7,0).

According to the analogy method and evaluation standard, the membership vector of surface damage is: (0,0,0.8,0.2).

According to the analogy method and table 4, the membership vectors are: (0,0.4,0.6,0).

According to the records, this two-layer stone structure was built in Qing Dynasty, and has a history of 80 years. According to the treatment and evaluation standard of small-scale descending ridge distribution, the construction time rating vector is: (0,0,1,0).

Therefore, the evaluation grade vector of the two-story stone structure building can be obtained:

\[
B = W^T \cdot R = \begin{bmatrix}
0 & 0.2 & 0.7 & 1.0 \\
0 & 0.3 & 0.7 & 0 \\
0 & 0 & 0.8 & 0.2 \\
0 & 0.4 & 0.6 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix} \times \begin{bmatrix}
0.484 \\
0.157 \\
0.101 \\
0.157 \\
0.101
\end{bmatrix}
= \begin{bmatrix}
0.2067 \\
0.7247 \\
0.5047
\end{bmatrix}
\]

According to the principle of maximum membership degree, the maximum value of 0.7247 falls into the C level in Table 1, then the earthquake damage prediction and evaluation grade of the two-story stone structure building is grade C. It shows that the building is seriously damaged, the main structure is seriously damaged, the wall has cracks of different degrees, the top stones falls and local collapse, so rescue protection should be carried out.

5. Conclusion

(1) Based on the fuzzy mathematics theory, the evaluation model of earthquake damage status of stone structure houses in southern Fujian is established, and the specific evaluation method of the model is given.

(2) Taking two-story stone structure houses in southern Fujian province as an example, this evaluation model is applied to evaluate the damage degree of stone structure houses in earthquake disasters. The evaluation results are basically consistent with the actual situation, which verifies the correctness of this model. At the same time, it also shows that the intensity of earthquake plays a decisive role in the destruction of stone structures.

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