PRELIMINARY RESEARCH ON THE EARTHQUAKE-INTENSITY ASSESSMENT USING THE MEAN DAMAGE INDEX OF BUILDINGS WITH EARTHQAKE-RESISTANT DESIGN

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ABSTRACT:

The buildings referred in China Intensity Scale are those without earthquake-resistant design. With the development of the economy of China, the number of the buildings without earthquake-resistant design is decreasing. Assessment of earthquake intensity based on the damage state of buildings with earthquake-resistant design is urgently needed. In terms of the relations between seismic damage matrix and the mean damage index, also based on the seismic damage matrix of the frame structure and masonry structure, the authors fit the curves of seismic design intensity-the mean damage index, then establish the evaluation standards of the seismic intensity according to the damage state of the frame structure and masonry structure. The earthquakes in the past few years verify the method. This paper can offer some earthquake disaster datum and certain experience for the assessment of the earthquake intensity.

KEY WORDS: earthquake intensity，the frame structure and masonry structure，the mean damage index

1. INTRODUCTION

Earthquake intensity is an index of the local destructive effect in a limited area after an earthquake (Hu,Y.X., 1989).The term earthquake intensity has been used for more than 170 years. Its usage includes the following three aspects. Firstly, it can be as a simple measure of earthquake damage. Secondly, it can be as a simple macroseismic scale for the strength of earthquake motion for seismologists. Thirdly, it can be as a rough but convenient index to sum up experience on earthquake engineering construction and to depict zones of seismic hazard. The assessment of earthquake intensity has practical significance. Firstly, the term earthquake intensity is the most suitable index for describing the destructive effect. Secondly, earthquake intensity with the distribution map of the isoseismal line is a simple way to show the general damage of an earthquake. Thirdly, it is very useful for rough but simple indication to guide emergency disaster relief planning or national investment.

The basis of the assessment of the earthquake intensity is the intensity scale. At present, the commonly used intensity scales are the Abridged MM scale, European Macroseismic Scale (EMS98), China Intensity Scale GB/T17742-1999 and Japanese Intensity Scale. China Intensity Scale includes two parts, one is the description of macroseismic phenomena, and the other is the feature of earthquake ground motion, such as PGA and PGV. There are four categories of macroseismic phenomena: human feeling, damage to artificial structures, response of objects and change in natural conditions. According to the regulations in GB/T17742-1999, when the earthquake intensity is between Ⅰ and Ⅴ, it is measured through feeling and other macroseismic phenomena chiefly, meanwhile, when the earthquake intensity is between Ⅺ and Ⅻ, the major measure to assess the earthquake intensity is the damage in natural conditions, also, when the earthquake intensity is between Ⅵ and Ⅹ,it is mainly measured by the damage to artificial structures. As an important index of evaluation of earthquake intensity, artificial structures are big in quantity and distributed widely. In addition, in some sense, buildings can be regard as the most practical seismograph.

The buildings referred in China Intensity Scale are brick-wood structure or masonry structure without earthquake-resistant design or reinforcement, not including the mordent buildings with earthquake-resistant design as frame structure. With the development of the economy of China, the number of the buildings without earthquake-resistant design is decreasing. Assessment of earthquake intensity based on the damage state of buildings with earthquake-resistant design is urgently needed.

At present, there is no standard based on the damage of the modern structures to assess the earthquake intensity. Up to now, the related work laid particular stress on the seismic damage prediction and the vulnerability of structure. For example, Yin, Z.Q. calculated the seismic damage index of the different structures according to the datum of the investigation of the buildings in 2000 or so all over the country. Wen, Z.P. calculated the fragility curves of the frame structure and masonry structure. Ye, L.Y. and Ge, X.L. etc. provided the investigation datum of buildings with different-level earthquake-resistant design in Lijiang earthquake, Gengma earthquake, Wuding earthquake. The authors collected the seismic damage appraisal report in Ninger earthquake .Based on the datum of the damage to modern buildings; the authors provide a method to assess the earthquake intensity using the mean damage index of the frame structure and masonry structure. As one of the indexes to assess the earthquake intensity, the damage to buildings with other macroseismic phenomena, the authors define the indices of the intensity scale.

2. METHOD OF THE MEAN DAMAGE INDEX

2.1Definition of The Mean Damage Index

In 1970s, in order to measure the earthquake intensity and the classification of damage to buildings and improve the precision of assessment, the mean damage index is defined based on the investigation of the structures. It can be regard as the standard in quantities to assess earthquake intensity. The damage grades and their corresponding mean damage indices are defined in table 2.1.

Table2.1 The definition of the mean damage index

Damage grade (*j*)	Macroseismic phenomena	Definition of mean damage index (d_j)
1.Negligible damage	Various structural members without any damage, or slight damage in unstructured members.	0.0
2.Slight damage	Some structural members with obvious damage and some individual unstructured members with heavier destruction, but there is no obvious effect on bearing capacity and normal usage.	0.2
3.Moderate damage	The unstructured members are damaged generally, some individual structural members, which can be used after local repair or reinforcement, suffer heavy destruction.	0.4
4.Heavy damage	The structural members are damaged generally which can be used after major repair or reinforcement merely, or the cost of repairing is too large.	0.7
5. Destruction	Whole or partial structural members collapse almost and there is no value of repair.	1.0

According to the definition in GB/T17742-1999, the mean damage index λ_i for the buildings of class *i* can be written as

$$\lambda_i = \sum_j \left[d_{i,j} \frac{S_{i,j}}{\sum_j S_{i,j}} \right] \tag{2.1}$$

where $d_{i,j}$ is the mean damage index of the buildings of class *i* which suffer damage of grade *j*; $S_{i,j}$ is the acreage of the damaged buildings of class *i* which suffer damage of grade *j*.

On seismic site investigation, the seismic disastrous area is divided into several enumeration districts. The number of types of structures is N in an enumeration districts. Use equation (2.1) to simulate the mean damage index λ_i (i=1,2,…N). At present, the method to simulate the mean damage index $\bar{I}$ of an enumeration district is calculating the weighted average of the mean damage index of each types of structure:

$$\bar{I} = \sum_i \left[\lambda_i \frac{\sum_j S_{i,j}}{\sum_i^N \sum_j S_{i,j}} \right] \tag{2.2}$$

Where $\sum_j S_{i,j}$ is the acreage of the damaged buildings of class i in the investigation area; $\sum_i^N \sum_j S_{i,j}$ is the acreage of all the buildings in the investigation area.

The shortcoming of this method is that it is ignored the differences in seismic capacity of different structures, and it is obvious in the area in which most buildings are with earthquake-resistant design. For example, the seismic fortification intensity of a city is Ⅷ,in which most buildings are designed with earthquake-resistant, such as reinforced concrete structures with earthquake-resistant design. On the effect of an earthquake with intensity Ⅶ,the earthquake damage to reinforced concrete is less heavier. If assessors use the equation (2.2) to simulate the mean damage index to assess the earthquake intensity, the earthquake hazard degree will be underestimated. In fact, the mean damage index of the buildings with earthquake-resistant design should be conversed to the mean damage index of brick-wood structure or masonry structure without earthquake-resistant design or reinforcement, then calculate the weighted average of each kind of structures(Hu,Y.X., 1977).

2.2 Relations Between Seismic Damage Matrix and The Mean Damage Index

Structural vulnerability is a measure of the seismic strength or capacity of a structure. Due to the differences in buildings materials and the construction quality, the seismic capacity of the buildings in the same area with the identical defense level can make a great difference. According to the investigation to the masonry structure buildings before 1980s, more than 1000 statistical data was given the test. The results showed that, the masonry structure resistance follows lognormal distribution. The resistance of reinforced concrete frame also follows lognormal distribution, but the average value and variation coefficient on RC frame are different (Yin, Z.Q. 1995). Under certain earthquake action, the rate of surpass the designed strength (E) is defined as equation 2.3

$$E = \frac{Q_s}{V_s} = \frac{Q_s/W}{V_s/W} = \frac{\alpha}{a_y} \tag{2.3}$$

Where V_s is the shear strength of the building; Q_s is the seismic shear force; W is the weight of the building; α is the acceleration table value of the actual seismic input; α_y is the yield acceleration of the building. The yield acceleration of the reinforced concrete frame building is defined as equation 2.4

$$a_y = 1.64\alpha'(1+\sum c_k) \tag{2.4}$$

Where α' is the designed response spectrum; c_k is the correction coefficient of the structural resistance. The yield acceleration of the S_{th} floor in a masonry structure is defined as equation 2.5

$$a_{sy}=\frac{\overline{V}_s}{\overline{w}}=0.325\frac{F_s}{A_s\cdot d}R_\tau(1+\sum_{1}^{k}c_i) \qquad (2.5)$$

$$d=3.6\frac{F_s}{A_s}+0.35 \qquad (2.6)$$

$$R_\tau=0.8\sqrt{R_k{}^2+0.5(n-s+1)R_k} \qquad (2.7)$$

Where F_s is the sectional area of the longitudinal cross wall at the S$_{\mathrm{th}}$ story without deducting the opening hole in the wall (m^2); A_s is the building area of the S$_{\mathrm{th}}$ story (m^2); d is the correction coefficient of the representative value of the gravity, defined as equation 2.6; R_τ is the standard shear strength of the masonry (N/cm^2),defined as equation 2.7; R_k is the standard shear strength of the masonry without anti-seismic design (N/cm^2);n is the number of stories; s is the story which is calculated; c_i is the correction coefficient of the masonry strength with earthquake-resistant design.

According to the statistics to the damage state of structures which suffered the damage of earthquake, the relationship between the damage state and E can be given in table 2.2.

Table2.2 Relationship between the damage state and E

Damage grade	Negligible damage	Slight damage	Moderate damage	Heavy damage	Destruction
RC structure	$E\le1.00$	$1.00<E\le2.00$	$2.00<E\le3.00$	$3.00<E\le4.00$	$E>4.00$
Shear wall structure	$E\le1.00$	$1.00<E\le1.40$	$1.40<E\le2.20$	$2.20<E\le3.00$	$E>3.00$
Masonry structure with structural column	$E\le1.00$	$1.00<E\le1.35$	$1.35<E\le2.10$	$2.10<E\le2.50$	$E>2.50$

The seismic damage matrix is the probability distribution of the damage state under the effect of certain earthquake; it can be defined as equation 2.8

$$P[D_j|\alpha]=\int P\left[D_j|a_y,\alpha\right]f(a_y)da_y \qquad (2.8)$$

Where $f(a_y)$ is the probability density function of the yield acceleration which follows lognormal distribution. If a_y is the yield acceleration of the building and α is the acceleration table value of the earthquake input, the probability of the building will suffer damage of grade j is given as equation 2.9

$$P[D_j|a_j\le a_y<b_j,\alpha]=\Phi(\frac{\ln b_j-\mu}{\zeta_j})-\Phi(\frac{\ln a_j-\mu}{\zeta_j}) \qquad (2.9)$$

Where $\mu=\ln\overline{a}_y-\frac{1}{2}\zeta^2$, it is the mean value of the lognormal distribution; $\zeta^2=\ln(1+\frac{\sigma^2}{\overline{a}_y^2})$, it is the variance of the lognormal distribution; $\Phi(\bullet)$ is the integral function of the standard normal distribution; $\overline{a}_y$ is the mean value of the yield acceleration; σ is the variance of the yield acceleration; a_j, b_j is the taking interval value of a_y when the building suffers damage of grade j.

2.3 Relations Between Damage Index and Earthquake Intensity of RC

Used function (2.9), Yin,Z.Q.（1995） deduced the damage probability matrices of the RC structure buildings，Used function (2.10), calculated the mean damage index of the RC structure buildings.

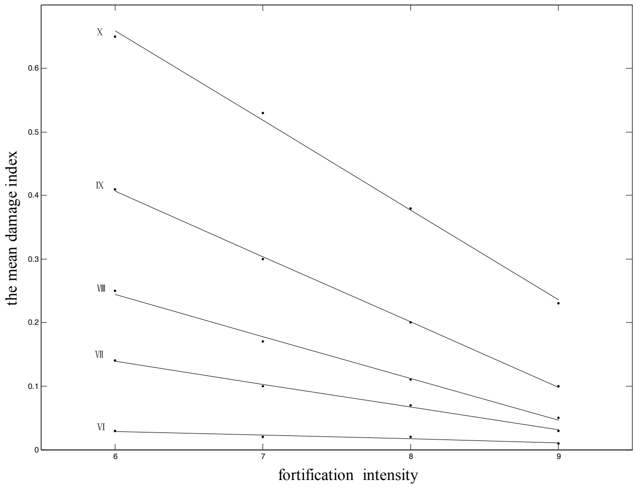

Figure 1 the curves of FI-MDI of RC structure

Figure 1 shows the relationship between fortification intensity (FI) and the mean damage index (MDI) under different earthquake action. With the increasing of intensity, the mean damage index is decreasing, and it is on linear relationship between FI and MDI. Fit the curves of seismic design intensity-mean damage index, and deduce the negative slopes of the fitting straight lines as follow, 0.01 if intensity is Ⅵ, 0.04 if intensity is Ⅶ, 0.07 if intensity is Ⅷ, 0.10 if intensity is Ⅸ, 0.14 if intensity is Ⅹ. The negative slopes of the fitting straight lines are the decrement of the mean damage index when the earthquake intensity increases one under the same earthquake action. Table 2.3 shows the range of the mean damage index of RC structure, which is defined based on the damage index regulated in GB/T17742-1999.

Table2.3 The range of mean damage index of RC on different earthquake action

FI	Earthquake intensity				
	Ⅵ	Ⅶ	Ⅷ	Ⅸ	Ⅹ
FI=6	0.00-0.09	0.10-0.26	0.27-0.43	0.44-0.60	0.61-0.76
FI=7	0.00-0.08	0.09-0.22	0.23-0.36	0.37-0.50	0.51-0.62
FI=8	0.00-0.07	0.08-0.18	0.19-0.29	0.30-0.40	0.41-0.48
FI=9	0.00-0.06	0.07-0.14	0.15-0.22	0.23-0.30	0.31-0.34

2.4 relations between damage index and earthquake intensity of masonry structure

With the development of the economy of China, the number of the buildings without earthquake-resistant design is decreasing. The reinforced brick multistory building is the most popular structure in the city at present. To this type of structure, brick walls are the supporting members. In the influence of climate, the thickness of the brick wall has influence on the structural resistance. Class the country into three region, the first region is on the north of 43°north latitude, the thickness of the brick wall is commonly 49_{cm}; the second region is the area from 35°N to 43°N, the thickness of the brick wall is commonly 37_{cm}; the third region is the area southward from 35°N, the thickness of the brick wall is commonly $24_{cm.}$Similar to the method used to analysis the RC structure, Fit the curves of seismic design intensity-mean damage index, as given in figure 2, and deduce the negative slopes of the fitting straight lines, as given in table 2.4.

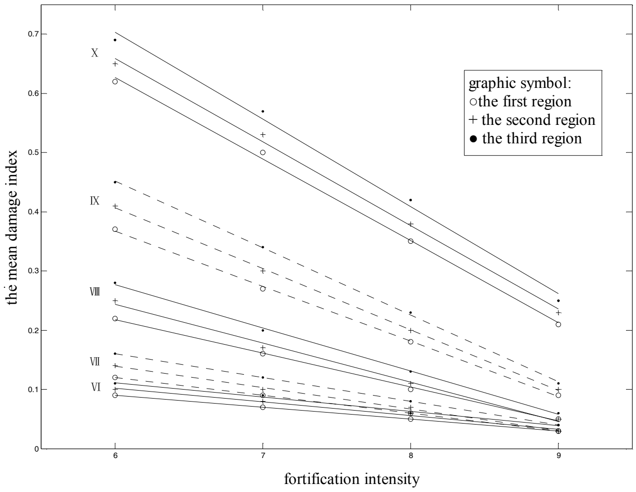

Figure 2 the curves of FI-MDI of masonry structure

The negative slopes of the fitting straight lines are the decrement of the mean damage index when the earthquake intensity increases one under the same earthquake action. Table 2.5, table2.6 and table 2.7 show the range of the mean damage index of masonry structure.

Table 2.4 Negative slopes of the fitting straight lines of masonry structure

District classification	Earthquake intensity				
	Ⅵ	Ⅶ	Ⅷ	Ⅸ	Ⅹ
first region(Ⅰ)	0.02	0.03	0.06	0.09	0.14
second region(Ⅱ)	0.02	0.04	0.07	0.10	0.14
third region(Ⅲ)	0.02	0.04	0.07	0.11	0.15

Table 2.5 The mean damage index of masonry structure in the first region

FI	Earthquake intensity				
	Ⅵ	Ⅶ	Ⅷ	Ⅸ	Ⅹ
FI=6	0.00-0.08	0.09-0.27	0.28-0.44	0.45-0.61	0.61-0.76
FI=7	0.00-0.06	0.07-0.24	0.25-0.38	0.39-0.52	0.51-0.62
FI=8	0.00-0.04	0.05-0.21	0.22-0.32	0.33-0.43	0.41-0.48
FI=9	0.00-0.02	0.03-0.18	0.19-0.26	0.27-0.34	——

Table 2.6 The mean damage index of masonry structure in the second region

FI	Earthquake intensity				
	Ⅵ	Ⅶ	Ⅷ	Ⅸ	Ⅹ
FI=6	0.00-0.08	0.09-0.26	0.27-0.43	0.44-0.60	0.61-0.760
FI=7	0.00-0.06	0.07-0.22	0.23-0.36	0.37-0.50	0.51-0.62
FI=8	0.00-0.04	0.05-0.18	0.19-0.29	0.30-0.40	0.41-0.48
FI=9	0.00-0.02	0.03-0.14	0.15-0.22	0.23-0.30	0.31-0.34

Table 2.7 The mean damage index of masonry structure in the third region

FI	Earthquake intensity				
	Ⅵ	Ⅶ	Ⅷ	Ⅸ	Ⅹ

FI=6	0.00-0.08	0.09-0.26	0.27-0.43	0.44-0.59	0.6-0.75
FI=7	0.00-0.06	0.07-0.22	0.23-0.36	0.37-0.48	0.49-0.60
FI=8	0.00-0.04	0.05-0.18	0.19-0.29	0.30-0.37	0.38-0.45
FI=9	0.00-0.02	0.03-0.14	0.15-0.22	0.23-0.26	0.27-0.30

3. Verifications to The Method of The Mean Damage Index

In this paper, the earthquakes are collected which occurred in China mainland in about 2000. The investigation datum to the earthquakes is in detail, such as Lijiang earthquake in 1996.2, Baotou earthquake in 1996.5, Yaoan earthquake in 2000.1, Shidian earthquake in 2001.4, Yongsheng earthquake in 2001.10,Dayao earthquake in 2003.7,Dayao earthquake in 2003.10,Ludian earthquake in 2004.8 and Ninger earthquake in 2007.6.

On the basis of the range of the mean damage index induced in this paper, calculate the mean damage index of buildings, which are damaged in the earthquakes referred above paragraph. The buildings are classified according to the structure form. The comparisons between this method and site assessment are given in table 3.1 and table 3.2.

Table 3.1 Verification to RC structure

Earthquake site	Earthquake occurring time	FI	MDI	Site assessment	Result of this method
Lijiang	1996.2	8	0.22	Ⅷ	Ⅷ
Baotou	1996.5	8	0.21	Ⅷ	Ⅷ
Yaoan	2000.1	7	0.33	Ⅷ	Ⅷ
Yaoan	2000.1	7	0.19	Ⅶ	Ⅶ
Yaoan	2000.1	7	0.07	Ⅵ	Ⅵ
Shidian	2001.4	8	0.12	Ⅶ	Ⅶ
Shidian	2001.4	8	0.07	Ⅵ	Ⅵ
Yongsheng	2001.10	8	0.07	Ⅶ	Ⅶ
Yongsheng	2001.10	8	0.02	Ⅵ	Ⅵ
Dayao	2003.7	7	0.08	Ⅶ	Ⅶ
Dayao	2003.10	7	0.20	Ⅶ	Ⅶ
Ludian	2004.8	7	0.05	Ⅵ	Ⅵ
Ninger	2007.6	7	0.26	Ⅷ	Ⅷ

Table 3.2 Verification to masonry structure

Earthquake site	Earthquake occurring time	FI	MDI	Region classification	Site assessment	Result of this method
Lijiang	1996.2	8	0.28	III	Ⅷ	Ⅷ
Baotou	1996.5	8	0.23	II	Ⅷ	Ⅷ
Yaoan	2000.1	7	0.26	III	Ⅷ	Ⅷ
Yaoan	2000.10	7	0.21	III	Ⅶ	Ⅶ
Shidian	2001.4	8	0.33	III	Ⅷ	Ⅸ
Shidian	2001.4	8	0.13	III	Ⅶ	Ⅶ
Yongsheng	2001.10	8	0.08	III	Ⅶ	Ⅶ
Yongsheng	2001.10	8	0.04	III	Ⅵ	Ⅵ
Dayao	2003.10	7	0.11	III	Ⅶ	Ⅶ
Dayao	2003.7	7	0.32	III	Ⅷ	Ⅷ

Dayao	2003.7	7	0.12	III	Ⅶ	Ⅶ
Ludian	2004.8	7	0.31	III	Ⅷ	Ⅷ
Ludian	2004.8	7	0.17	III	Ⅶ	Ⅶ
Ninger	2007.6	7	0.28	III	Ⅷ	Ⅷ

4. CONCLUSION

As shown in table 3.1 and table 3.2, the intensity according to this method is consistent with the result based on site assessment, except for the masonry structure damaged in Shidian earthquake in 2001.4. The intensity according to this method is consistent with the result based on site assessment in generally. The method in this paper can surmount the disadvantage of inconsideration to the variation of the seismic capacity, and ensure the consistence and furtherance of the intensity assessment. According to the seismic capacity follows lognormal distribution, calculate the mean damage indices of frame structure and masonry structure by the seismic damage matrix. The mean damage index decreases linearly with the improvement of anti-seismic ability. The intensity assessment according to the mean damage index method is consistent with the site evaluation. Certainly, the final results depends on the comprehensive phenomena, the damage to the buildings with seismic resistant design is one of the main index, and this paper can offer some earthquake disaster datum and certain experience for the assessment of the earthquake intensity.

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