Research on Evaluation Models and Empirical Analysis of Earthquake Disaster Losses in China

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Earthquake disasters occurred very frequently in China. As a result, to evaluate the losses has important social value and economic effect. This paper focuses on the assessment of economic losses of earthquake disasters which is divided into two parts: direct economic loss and indirect economic loss. First, the Kolmogorov–Smirnov (KS) test is used to determine the distribution of the earthquake losses per year in China, fitting the frequency of earthquake that happened per month in China. Second, the grey clustering method and principal component analysis (PCA) are applied, respectively, for direct economic loss rating and indirect economic loss rating. Finally, the economic loss generated by the earthquakes which happened from 2006 to 2009 in China is evaluated, and eight earthquakes are rated based on the comprehensive economic loss.

Key words: Earthquake Disaster; Economic Loss Rating; Grey Relation-Cluster Analysis; Principal Component Analysis; Evaluation Models.

1. Introduction

China is one of the countries which have the most earthquake disasters in the world. Analysis and assessment on the damage of an earthquake is a basic content of disaster physics and disaster geoscience. Also, it is the inevitable requirement of disaster prevention and mitigation. It has great meaning for a sustainable development of economy and society.

At present, there is no uniform standard or methods for the classification of the earthquake disaster loss in the world. From the perspective of social economic loss, Mitchem used a principal component analysis to select the natural and social vulnerability indexes for assessing the impact of disasters [1]; Zi-Qian Yin studied on prediction methods of earthquake disaster and its direct losses based on probability [2]. In China, Axing Zhao and Zong-Jin Ma proposed the concept of disaster degrees which shows the extend of the damage caused by disasters [3]; Qing-Dong Yu and Rong-Fang Shen established a classfication model for absolute status of loss on the grey cluster method [4]; Lu-Chuan Ren put forward the concept of fuzzy disaster degree and the measurement method of fuzzy disaster degree applied in classification of loss [5]; Qing-Dong Yu and Rong-Fang Shen proposed the index system and single-index grading criteria for rating the comprehensive situation of natural disasters [6]; Guo-Min Mao et al. constructed a factor analysis-principal component-equamax rotation (FAPE) classification model and a hierarchical cluster-ward method-seuclid (HCWS) gradation model and divided disasters into eight classes and five grades [7]; Xiang-Quan Chang et al. used the factor analysis to construct a index system for earthquake disaster loss assessment [8]; based on this, Xin Gu et al. construted the measurement method of neural network [9]; Lei Tong did a grey relation analysis for economic loss factors which obtained a quantative result [10].

The research above focuses on the assessment of direct economic losses of earthquakes. However, few scholars did research on the indirect economic losses for the complexity of qualifying the time, space, and chain reaction. First, this paper attempts to combine multivariate statistical analysis and the grey system theory with fuzzy mathematics to study the indirect economic losses primarily. Second, we apply the assessment model constructed in the first part to the national economy losses caused by earthquake damage, and rate the earthquake disasters happened from 2006 to 2009 in China.

2. Distribution of Chinese Earthquake Disaster Losses

Since the beginning of the 21st century, severe earthquakes have occurrened frequently in the circum-pacific seismic belt and the southeastern part of the Eurasian seismic zone, that is the Qinghai-Xizang-Yunan-Burma-Indonesia (QXYBI) eta-type tectonic system, that the world has entered into a catastrophe cluster period which will definitly have a significant influence on China mainland [11 – 13]. According to statistics, the number of strong earthquakes in China is about 1/3 of that in the world. Also, 60% of the country's area is locate in the VI intensity zone [14]. Two $M \geq 8$ earthquakes (the 2001 Kunlunshan *M8.1* earthquake and the 2008 Wenchuan *M8.0* earthquake) and two $M \geq 7$ earthquakes (the 2008 Hetian *M7.3* earthquak and the 2010 Yushu *M7.3* earthquake) occurred from 2001 to 2010 in west China [15 – 17]. Besides, many $M \geq 6$ strong earthquakes occurred in China Mainland during the 11th Five-Year Plan period, such as in Wenchuan, Mianyang, and so on. To forecast earthquakes, it is necessary to determine the distribution of earthquake losses first. This article collects the latest data to analyse the annual earthquake losses and the number of earthquake disasters per year. In this way, the distribution of Chinese earthquake disaster losses can be determined.

2.1. Distribution of Chinese Earthquake Losses per Year

This paper selects the annual direct economic losses caused by the earthquake disasters in China during 2000 – 2009 as the sample data. All of them are from China statistical yearbook. The statistical analysis of the data reveals that the sample distribution function is not compatible with existing forms, such as normal distribution, exponential distribution, and uniform distribution. After calculating the logarithm value, use statistical product and service solutions (SPSS) software software to draw the probability-probability (PP) plot shown in Figure 1. Most of the data is closely around the 45 degrees line in the figure, which means it basically subjects to the lognormal distribution. At the same time, we used the KS test for the lognormal distribution test [18].

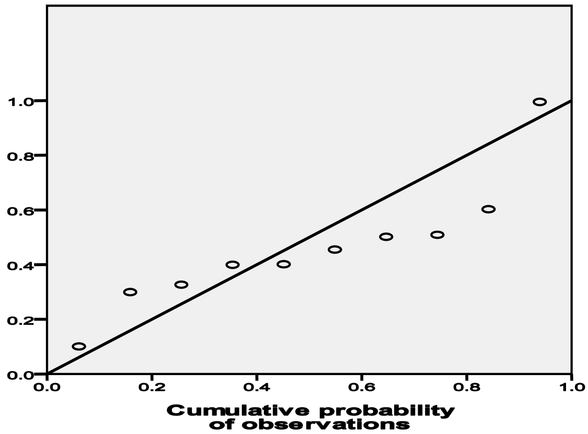

Fig. 1. Lognormal PP figure for direct loss of earthquake disaster.

The KS test statistic value is 0.941, P value is 0.338, with 0.05 level of significance through the test. In summary, the loss of earthquake in China is subjected to the lognormal distribution with mean 12.4695 and standard deviation 2.2451. Namely, $\ln z \sim N(12.4695, 2.2451)$.

2.2. Fitting Frequency of Earthquake Disasters

Frequency of earthquake disasters itself is a random variable with probability characteristics. From the database of 2006–2009, all of the earthquakes which occurred in the inland of China (Taiwan Province is not included) are regarded as sample data x. All of their magnitudes are equal or greater than 3.0. Assume that the occurrence of earthquakes per month obey the Poisson distribution with the parameter λ.

From the mathematical statistics, we know that $\hat{\lambda} = \bar{x} = 4.2857$. We make use of the KS test method for hypothesis testing. Let v_i be the real frequency of the sample that falls into the ith interval. Table 1 shows the statistics of earthquakes ($M \geq 3.0$) per month in Chinese mainland during 2006 to 2010.

The KS test shows that the test statistic value is 1.126, P value is 0.159, the number of earthquakes per

Table 1. Frequency of earthquakes ($M \geq 3.0$) per month in Chinese mainland during 2006 to 2010.

i	0	1	2	3	4	5	6
v_i	6	12	14	11	2	3	4
i	7	8	9	10	11 – 30	31 – 50	>50
v_i	1	1	2	0	3	0	1

month is subjected to the Poison distribution with parameter 4.2857.

3. Analysis on the Earthquake Economic Loss Factors

3.1. Analysis on the Factor Index

The direct losses of earthquakes result from the original earthquake phenomenon. This is the most significant reason of earthquake casualties, lifeline damage, and social economic losses. Also, the indirect earthquake losses are the consquences of breaking the pre-balanced nature or pre-normal social order by earthquake disasters. On the one hand, the direct economic losses mainly reflect the losses of agriculture, forestry, animal husbandry and fishery fields, casualties and property losses of the city, which can be measured by quantity units. However, these indexes should be normalized first. On the other hand, for its influence on all walks of life, the indirect losses are difficult to be shown by data only. As a result, this paper selects the representative indexes as the basis for measuring the indirect losses. According to the content of the earthquake disaster losses, Table 2 shows the index system of evaluating economic losses of earthquake disaster.

3.2. Normalized Index

To reflect fully the direct impact on social economy by earthquake disasters, nine factors are choosen as the indexes of direct economic losses including the number of deaths and injured. However, different factors have no unified units, which will result in a wrong assessment. To overcome this shortcoming, we clasify the standards of rating the indexes and unify them first.

According to the existing 'disaster level' concept and rating standards, the traditional classification will be divided into five levels: catastrophe, great-disaster, medium-disaster, small-disaster, and micro-disaster. In order to consider about the direct economic losses and indirect economic losses together, some changes should be made for the classification above. However, the direct economic loss only is involved in the current losses, which is different from the indirect one

Table 2. Index system of evaluating economic losses of earthquake disaster.

Target layer	Rule layer	Index layer
Economic loss of earthquake disaster	Indexes of direct economic loss	the number of deaths the number of injured area of the houses damaged seriously area of the houses damaged slightly losses of agriculture losses of forestry losses of animal husbandry losses of fishery cost of emengency
	Indexes of indirect economic loss	Loss of time spread Loss of area spread

Table 3. Classification table of disaster loss.

Classfication index	micro disaster	small disaster	medium disaster	great disaster	catastrophe
number of deaths	$(0, 10]$	$(10, 10^2]$	$(10^2, 10^3]$	$(10^3, 10^4]$	$(10^4, +\infty)$
number of injured	$(20, 2\times10^2]$	$(2\times10^2, 2\times10^3]$	$(2\times10^3, 2\times10^4]$	$(2\times10^4, 2\times10^5]$	$(2\times10^5, +\infty)$
area of the houses damaged seriously	$(10^2, 10^3]$	$(10^3, 10^4]$	$(10^4, 10^5]$	$(10^5, 10^6]$	$(10^6, +\infty)$
area of the houses damaged slightly	$(10^3, 10^4]$	$(10^4, 10^5]$	$(10^5, 10^6]$	$(10^6, 10^7]$	$(10^7, +\infty)$
losses of agriculture	$(5\cdot10^4, 5\cdot10^5]$	$(5\cdot10^5, 5\cdot10^6]$	$(5\cdot10^6, 5\cdot10^7]$	$(5\cdot10^7, 5\cdot10^8]$	$(5\cdot10^8, +\infty)$
losses of forestry	$(5\cdot10^4, 5\cdot10^5]$	$(5\cdot10^5, 5\cdot10^6]$	$(5\cdot10^6, 5\cdot10^7]$	$(5\cdot10^7, 5\cdot10^8]$	$(5\cdot10^8, +\infty)$
losses of animal husbandry	$(5\cdot10^4, 5\cdot10^5]$	$(5\cdot10^5, 5\cdot10^6]$	$(5\cdot10^6, 5\cdot10^7]$	$(5\cdot10^7, 5\cdot10^8]$	$(5\cdot10^8, +\infty)$
losses of fishery	$(5\cdot10^4, 5\cdot10^5]$	$(5\cdot10^5, 5\cdot10^6]$	$(5\cdot10^6, 5\cdot10^7]$	$(5\cdot10^7, 5\cdot10^8]$	$(5\cdot10^8, +\infty)$
cost of emergency	$(10^4, 10^5]$	$(10^5, 10^6]$	$(10^6, 10^7]$	$(10^7, 10^8]$	$(10^8, +\infty)$

Table 4. Classification table of disaster.

Classification of economic loss	micro disaster	small disaster	medium disaster	great disaster	catastrophe
value of transfer function	(0,0.2]	(0.2,0.4]	(0.4,0.6]	(0.6,0.8]	(0.8,1.0]

related to the time. And this makes it difficult to synchronize the two parts for rating. So this paper classfies the earthquakes into five levels first based on the direct economic loss. And then make the indexes of indirect economic loss as the second index level to do the classfication another time.

Based on the previous research [10], five more indexes are added, including the losses of agriculture, forestry, animal husbandry and fishery fields, and the cost of emengency. The improved index system is shown in Table 3.

Define x_j $(j = 1, 2, \dots, 9)$ as the factors of direct economic loss of earthquake disasters. Among them, x_1 is the number of death people, x_2 the number of injuried, x_3 the area of houses damaged seriously (unit: m^2), x_4 the area of the houses damaged slightly (unit: m^2), x_5 the loss of agriculture (unit: yuan); x_6 the loss of forestry (unit: yuan), x_7 the loss of animal husbandry (unit: yuan), x_8 the loss of fishery (unit: yuan), and x_9 the cost of emengency. Define $V_j(x)$ as the value of transfer function. The functions for x_j $(j = 1, 2, \dots, 9)$ are as follows:

$$\text{Function for } x_1\text{: } V_1(x) = \begin{cases} 1 & x > 10^5, \\ 0.2\lg x & 1 < x \le 10^5, \\ 0 & x \le 1, \end{cases} \tag{1}$$

$$\text{Function for } x_2\text{: } V_2(x) = \begin{cases} 1 & x > 2\times 10^6, \\ 0.2\lg(x/20) & 20 < x \le 2\times 10^6, \\ 0 & x \le 20, \end{cases} \tag{2}$$

$$\text{Function for } x_3\text{: } V_3(x) = \begin{cases} 1 & x > 10^7, \\ 0.2\lg(x/100) & 10^2 < x \le 10^7, \\ 0 & x \le 10^2, \end{cases} \tag{3}$$

$$\text{Function for } x_4\text{: } V_4(x) = \begin{cases} 1 & x > 10^8, \\ 0.2\lg(x/10^3) & 10^3 < x \le 10^8, \\ 0 & x \le 10^3, \end{cases} \tag{4}$$

$$\text{Function for } x_5, x_6, x_7, x_8\text{: } V_i(x) = \begin{cases} 1 & x > 10^9, \\ 0.2\lg(x/5\times 10^4) & 10^4 < x \le 10^9 \\ 0 & x \le 10^4, \end{cases} \quad, (i = 5, 6, 7, 8), \tag{5}$$

$$\text{Function for } x_9\text{: } V_9(x) = \begin{cases} 1 & x > 10^9, \\ 0.2\lg(x/10^4) & 10^4 < x \le 10^9, \\ 0 & x \le 10^4. \end{cases} \tag{6}$$

Through calculating the functions above, the new classification standard is obtained in Table 4.

4. Disaster Assessment Model

4.1. Direct Economic Losses Assessment

Due to the difficulty of investing and collecting data after an earthquake, it is impossible to access all related information. As a consquence, we evaluated the direct economic losses using the grey system [19]. In the first place, we determined the factors influencing the direct economic losses to get their relationship order by the grey relation method. In the second place, we rated different earthquakes by the grey-cluster model, according to the assessment indexes identified above.

4.1.1. Grey Relation Analysis

First, we introduce the grey-relation analysis model. Assume $y_0 = \{y_0(1), y_0(2), \ldots, y_0(n)\}$ as original sequence, $y_i = \{y_i(1), y_i(2), \ldots, y_i(n)\}, \quad (i = 1, \ldots, m)$ as sub-sequences.

Step 1: pre-initialization. Each number in the sequence is divided by the first one first. Let $x_0(k) = y_0(k)/y_0(1)$. Therefore we get:

$$x_0 = \{x_0(1), x_0(2), \ldots, x_0(n)\},$$
$$x_i = \{x_i(1), x_i(2), \ldots, x_i(n)\}, \quad (i = 1, \ldots, m) .$$

Step 2: calculate the absolute difference. Make $\Delta_i = |x_0(k) - x_i(k)|$, $\Delta_{\min} = \min\limits_i \min\limits_k \Delta_i$, $\Delta_{\max} = \max\limits_i \max\limits_k \Delta_i$.

Step 3: calculate the correlation coefficient. $\xi_i(k) = \frac{\Delta_{\min} + \rho\, \Delta_{\max}}{\Delta_i + \rho \Delta_{\max}}$, where $0 < \rho < 1$ and $\rho = 0.5$, usually.

Step 4: obtain grey correlation. $R_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k)$.

Step 5: determine the relation order. According to the value of the correlations, get the order named $\{x\}$, which reflects the relationship between the sub-sequences and the original sequence.

While the sum of direct economic loss is taken as the parent sequence, some appropriate factors are selected as sub-sequences. According to [10], existing studies usually choose the following factors as the comparative sequences: earthquake magnitude, focal depth, occurrence time, the number of affected villages and towns, and the affected population. Based on the research, two factors are added in: the the gross domestic product (GDP) per capita in the region last year and the topography of the region. So the following factors are selected as the comparative sequences: earthquake magnitude (y_1), focal depth (y_2), occurrence time (y_3), the number of affected villages and towns (y_4), the affected population (y_5), the GDP per capita in the region last year (y_6), and the main topography of the region (y_7). However, y_3 belongs to a state factor, which is classified as four periods: 05-08, 08-18, 18-23 and 23-05 o'clock, values for 1, 2, 3, 4, respectively. Also, y_7 is another state factor just as y_3. It can be divided into five categories: mountain, plateau, basin, hill, and plain. Respectively, the corresponding value is 1, 2, 3, 4, and 5. By this approach, these factors can be quantified, calculated their relevance, and compared by the outcome.

4.1.2. Grey Cluster Classification

Based on the nine indexes, the grey cluster model is used to rate the direct economic loss of earthquakes. According to the proof in paper [20], its better to make $k \pm 0.5$ as interval point to determine the grey cluster to which the integrated cluster coefficient belongs. In consequence, the improved integrated grey cluster method is used to rate the economic influences here.

Assume there are n objects, m indicators, and s different grey classes. x_{ij} is the observation on the indicator j $(j = 1, 2, \ldots, m)$ of the object i $(i = 1, 2, \ldots, n)$.

Step 1: Determine the function $f_j^k(*)$ of the indicator j on the grey class k $(k = 1, 2, \ldots, s)$.

Step 2: Determine the clusting weight η_j^k, which is the indicator j on the grey class k, by the formular $\eta_j^k = \lambda_j^k / \sum_{j=1}^{m} \lambda_j^k$, where λ_j^k is the threshold of the indicator j on the grey class k

Step 3: Calculate the clustering coefficient σ_i^k by the formular $\sigma_i^k = \sum_{j=1}^{m} f_j^k(x_{ij})\cdot$

Step 4: Calculate the normalized clustering coefficient δ_i^k by the formular $\delta_i^k = \sigma_i^k / \sum_{k=1}^{s} \sigma_i^k$, where $\delta_i = \left(\delta_i^1, \delta_i^2, \ldots, \delta_i^s\right)$, $i = 1, 2, \ldots, n$, is the normalized clustering coefficient vector of the object i.

Step 5: Calculate the comprehensive clustering coefficient ω_i of the object i by the formular $\omega_i = \delta_i \cdot \eta$, where $\delta_i = \left(\delta_i^1, \delta_i^2, \ldots, \delta_i^s\right)$, $i = 1, 2, \ldots, n$, is the normalized clustering coefficient vector of the object i, and $\eta = (1, 2, \ldots, s-1, s)^{\mathrm{T}}$ is the threshold vector of the comprehensive clustering coefficient.

Step 6: Divide $[1,\ s]$, the value interval of ω_i, into s parts: $[1,\ 1.5], [1.5,\ 2.5], \ldots, [k-0.5, k+0.5], \ldots, [s-0.5, s]$, and classfy the object i. If $\omega_i \in [1,\ 1.5]$, then the object i belongs to the first grey class; if $\omega_i \in [k-0.5,\ k+0.5]$, $(k \neq 1,\ k \neq s)$, then the object i belongs to the kth grey class; if $\omega_i \in [s-0.5,\ s]$, the object i is classfied into the sth grey class.

4.2. Indirect Economic Losses Assessment

The indirect economic losses mainly fall into two parts: time spread loss and regional spread loss. For simplicity, this paper selects the appropriate indexes to reflect the extent of indirect losses and makes use of principal component analysis for evaluating the indirect economic losses each time.

4.2.1. Indirect Economic Losses Index

Time spread loss is the sum of money for the value reduction and reconstruction during recovery time. It can be divided into lifeline losses and related industry losses. According to statistical data and indexes, some representative industry indexes are selected as follows: total production of energy (w_1), total output value of construction (w_2), freight traffic (w_3), total retail sales of consumer goods (w_4), total value of imports and exports (w_5), earnings from international tourism (w_6), and education expenditure (w_7).

With improvement, the industry indexes above can be taken for indirect economic loss assessment. Set $w_i^{'}$ $(i = 1, 2, \ldots, 7)$ as the ith index of indirect economic loss, and we get the following equation:

$$w_i^{'} = 1 - \frac{w_{it}/(G_{it} - w_{it})}{w_{i(t-1)}/\left(G_{i(t-1)} - w_{i(t-1)}\right)} ,$$

where w_{it} is the value of the ith indirect economic loss index of the affected area of this year, $w_{i(t-1)}$ the value of the ith indirect economic loss index of the affected area of the previous year, G_{it} the value of the ith index of the country of this year, and $G_{i(t-1)}$ the value of the ith index of the country of the previous year.

To show the regional spread losses, the size of the affected area by the earthquake is chosen and set as $w_8^{'}$.

Now use the principal component analysis for these indexes and calculate the composite scores. The higher the score, the more the loss.

4.2.2. Principal Component Analysis Model [21, 22]

The theory of principal components (PCs) states that every symmetrical covariance or correlation matrix relating p random variables $X_1, X_2, \ldots, X_n$ can be transformed into particular linear combinations by rotating the matrix into a new coordinate system. This rotation is produced by multiplying each of the original data variables by their appropriate weighting coefficients. For each component, these weights comprise a vector called an eigenvector, and the variance is ‘explained’ by its eigenvalue. The original matrix is rotated such that the axis defined by the first principal component (PC1) is aligned in the direction of greatest variance, hence maximizing the eigenvalue. To obtain the second component (PC2) the matrix is rotated around the PC1 axis to obtain a second eigenvector which again contains the greatest possible amount of remaining variance. This procedure is repeated until a set of N orthogonal (uncorrelated) components is obtained, arranged in descending order of variance. In this transformation, none of the information contained within the original variables is lost, and the derived components can be statistically manipulated in the same way as the original variables. Moreover, the transformation is useful because most of the significant total variance (i.e. correlated neuronal information) is concentrated within the first few uncorrelated PCs, while the remaining PCs mainly contain ‘noise’ (i.e. uncorrelated neuronal information). The first few PCs not only provide a simpler and more parsimonious description of the covariance structure, they also concentrate the information which is normally spread across multiple variables (neurons) into a single, more statistically useful ‘factor’.

The squares of these weighting coefficients represent the correlations of each variable (neuron) with the PC. Since each component is apportioned some fraction of the total variance of the neuron, the sum of squared coefficients across each row must equal 1.0. A further constraint is that the sums of squared coefficients for each component must also equal 1.0. Thus the total variance contained in the ensemble can be represented either in terms of the combination of neurons, or the combination of principal components.

4.3. Integrated Economic Loss Classification

After receiving the assessment of the direct and indirect economic loss for the earthquake disasters, the classification of the integrated economic loss should be followed by combing the two above together. First, the principal component scores should be converted into classifications.

The higher the score is, the larger the economic loss will be. So this paper classifies the indirect economic loss into three types: ‘A’, ‘AA’, and ‘AAA’. Where, ‘A’ means that the indirect economic loss is small, ‘AA’

Table 5. Classification table of indirect economic loss.

classification	A	AA	AAA
Value of PC	$(-\infty, 0]$	$(0, 0.5]$	$(0.5, +\infty)$

Table 6. Relational degree of each factor and their sort.

factor	Earthquake magnitude	focal depth	occurrence time	number of affected villages and towns	affected population	GDP per capita in the region last year	Main topography
Correlation values	0.8697	0.8714	0.8704	0.8725	0.8743	0.8735	0.8705
Order	7	4	6	3	1	2	5

means that the loss is medium, and 'AAA' represents that the loss is huge. The classification standards will be shown in Table 5.

Take three examples as follows. If an earthquake disaster is classified as '1-AAA', it means both the direct and the indirect economic loss is enormous, which not only leads quickly to a disaster relief, but also adjusts the long-term economic planning. If a disaster is treated as '5-AAA', it shows that the direct economic loss caused by the earthquake is not too much. However, the impact on the related industries is so huge that the government should not ignore it. If an earthquake is ranked as '1-A', it represents that the government should pay full attention on disaster relief at the moment because there is little indirect economic loss.

5. Chinese Earthquake Economic Losses Assessment During 2006 – 2009

According to [23 – 27], 29 earthquake disasters during 2006 – 2009 are selected to evaluate their losses.

5.1. Grey Relation Analysis

First, the grey correlation between each factor and direct economic loss is calculated by the grey-relation analysis. Table 6 shows their values and their order.

From the result, we find that the affected population affects the disaster the most. It can be explained by two reasons as follows. First, large population means high density which will lead to serious loss and many casualties. What is more, more population will involve much more material property. Consequently, the suffered material loss will be larger.

Secondly, the GDP per capita in the region last year has a great influence on the direct economic loss. The GDP of last year is a representation of the level of wealth accumulation of the region. With a high level of social economic development, the region must be affected great by the disaster. Also, the level of urbanization is measured by the number of affected villages and towns, which shows the level of regional economic development too. So it ranks third in the relationship order.

Earthquake magnitude, focal depth, occurrence time, and the main topography of the region are the basic parameters of the earthquake. The correlation between direct loss and focal depth is usually negative. General speaking, the more shallow the source is, the greater the damage will be. The impact of the main topography is mainly reflected in two aspects: whether there is follow-up disaster and the local original economy. Different topography will result in different follow-up disaster. And it is also a factor of affecting the level of local economic development. The occurrence time of the earthquake has a certain link to the direct economic loss. The main reason is that it will make an impact on the number of casualties. Since it will increase the difficulties for people to flee and get help, the direct economic loss caused by an earthquake occurring at night is larger than that during daytime. The magnitude comes in the last one, indicating that there is no positive correlation between the loss and itself. In summary, the loss is determined by more than one factor.

The grey correlation order is as follows: the affected population > the GDP per capita in the region last year > the number of affected villages and towns > focal depth > the main topography of the region > occurrence time > earthquake magnitude.

5.2. Direct Economic Losses Classification

We apply the grey cluster model for rating direct economic losses of 29 earthquake disasters. Assume $f_j^k(u_{ij})$ is the function for the jth cluster index of the cluster object i.

When $k = 1$,

$$f_j^1(u_{ij}) = \begin{cases} 0 & u_{ij} \le 0.6, \\ \dfrac{u_{ij} - 0.6}{0.2} & 0.6 < u_{ij} \le 0.8, \\ 1 & 0.8 < u_{ij} \le 1.0. \end{cases} \tag{7}$$

Table 7. Rating table for direct loss of earthquake disaster.

Area	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$	Classification result
Yushu	0	0.0805	0.5	0.2966	0.4	3
Shunchang	0	0	0.1344	0.25	0.8656	5
Ninger	0.51	0.4551	0.1151	0.3693	0.4198	1
Tekesi	0.0318	0.5	0.4165	0	0.4	2
Changning	0	0	0	0	1	5
Yutian	0.0751	0.2955	0.4249	0.2045	0.5	5
Yingjiang	0	0.1684	0.4374	0.3316	0.5626	5
Zhushan	0	0	0	0.139	1	5
Sunan	0	0.174	0.5	0.326	0.4	3
Yumin	0.0163	0.4455	0.4838	0.0545	0.5	3
Sunana	0	0.1099	0.5	0.3901	0.4	3
Wenchuan	1	0.0399	0	0	0	1
Elunchun	0	0	0.2288	0.25	0.7713	5
Yingjiang	0.2979	0.5	0.2021	0.378	0.5	2
Renhe	0.6185	0.3625	0.3291	0.5	0.1709	1
Hejing	0	0.0313	0.494	0.4688	0.506	5
Wuqia	0	0.1921	0.5	0.3079	0.4	3
Dangxiong	0.0225	0.5	0.4775	0.3693	0.5	2
Haixi	0	0	0.076	0.346	0.924	5
Zigui	0	0	0.2379	0.25	0.7621	5
Ruili	0	0.2143	0.4203	0.2961	0.5798	5
Yili	0	0.2795	0.5	0.2205	0.4	3
Akesu	0.0031	0.381	0.4969	0.119	0.5	5
Aheqi	0	0.2398	0.5	0.2603	0.4	3
Atushi	0	0.1526	0.4853	0.3474	0.5148	5
Chuxiong	0.4823	0.3071	0.0851	0.25	0.4326	1
Rongchang	0	0	0	0.0753	1	5
Haixi	0	0	0.369	0.5	0.631	5
Dali	0.0099	0.4699	0.4901	0.0778	0.5	5

Note : '1' represents catastrophe, '2' represents great disaster, '3' represents medium disaster, '4' represents small disaster, and '5' represents micro disaster.

When $k = 2,3,4$,

$$f_j^k(u_{ij}) = \begin{cases} \dfrac{u_{ij}-u_k+0.2}{0.2} & u_k-0.2 < u_{ij} \le u_k, \\ 1 & u_k < u_{ij} \le u_k+0.2, \\ \dfrac{u_k+0.4-u_{ij}}{0.2} & u_k+0.2 < u_{ij} \le u_k+0.4, \\ 0 & \text{else}, \end{cases} \tag{8}$$

where u_k is the lower limit of the index for kth disaster, $u_2 = 0.6$, $u_3 = 0.4$, $u_4 = 0.2$.

When $k = 5$,

$$f_j^5(u_{ij}) = \begin{cases} 1 & 0 < u_{ij} \le 0.2, \\ \dfrac{0.4-u_{ij}}{0.2} & 0.2 < u_{ij} \le 0.4, \\ 0 & u_{ij} > 0.4. \end{cases} \tag{9}$$

As part of the index data cannot be obtained now, only four indexes can be used for grey cluster rating. First, use conversion functions to convert the value of the indexes. Second, calculate $f_j^k(u_{ij})$ and the clustering coefficients. Namely, the clustering vectors can be obtained. Third, follow the principle of maximum membership degree to get the classfication result shown in Table 7.

After grey cluster rating, the Ning'er earthquake in Yunnan Province in 2007, the Wenchuan earthquake in Sichuan Province in 2008, the Renhe earthquake in Sichuan Province in 2008, and the Chuxiong earthquake in Yunnan Province in 2009 are classfied as 'catastrophe', which means huge direct economic loss. The Tekesi earthquake in Xinjiang Province in 2007, the Yingjiang earthquake in Yunnan province in 2008, and the Dangxiong earthquake in Xizang province in 2008 are classfied as 'great disaster'. The Yushu earthquake in Qinghai Province in 2006, the Sunan earthquake in Gansu Province in 2008, the Yumin earthquake in Xinjiang Province in 2008, the Wuqia earthquake in Xinjiang Province in 2008, the Yili earthquake in Xinjiang Province in 2009, and the Aheqi earthquake in Xinjiang Province in 2009 are classfied as 'medium disaster'. The rest are classfied as 'micro disaster'; there is no 'small disaster'.

The rating result above meets the objective reality of China. According to [25], the magnitude of the Ning'er earthquake in Yunnan Province in 2007 was 6.4 and the casualties and the property losses account for 94% of all of those caused by the disasters in 2007. That is nearly 2.5 times the total loss of the ten earthquake disasters in 2006. According to [26], the Wenchuan earthquake in 2008 whose magnitude was 8.0 has caused a loss of 852.3 billion yuan and that is the worst natural disaster since 30 years in China. The Renhe earthquake in 2008 caused the direct economic loss of 4.46 billion yuan. According to [27], 2.154 billion yuan in direct economic loss is caused by the Chuxiong earthquake in 2009. Note that these data show that the four disasters should be classfied as 'catastrophic' for their enormous impact on economic. The loss of the three disasters which are classfied as 'great disaster' is between 1 to 15 million yuan. What is more, the loss of the rest are more than 100 million yuan, in addition to the Haixi earthquake in 2008 and the Ruili earthquake in 2008. This demonstrates that the accuracy of the grey cluster method is very high.

5.3. Indirect Economic Losses Classificstion

Based on the model above, the indirect economic loss indexes of different regions should be used for the principal component analysis to calculate their scores. Due to the unobtained index value of counties and villages, the affected provinces are regarded as study sample. This article integrates a classification for those provinces which have only one earthquake disaster a year.

$$\begin{aligned}
\text{prin}_1 &= 0.1327w_1 - 0.3571w_2 + 0.01w_3 \\
&- 0.5486w_4 + 0.137w_5 - 0.2365w_6 \\
&+ 0.6009w_7 + 0.3435w_8, \\
\text{prin}_2 &= 0.457w_1 + 0.4467w_2 + 0.444w_3 \\
&- 0.0214w_4 + 0.5851w_5 + 0.0617w_6 \\
&- 0.0863w_7 + 0.201w_8, \\
\text{prin}_3 &= 0.309w_1 - 0.0741w_2 - 0.5167w_3 \\
&- 0.0925w_4 + 0.2627w_5 + 0.659w_6 \\
&+ 0.1806w_7 - 0.2961w_8, \\
\text{prin}_4 &= 0.2693w_1 - 0.4097w_2 - 0.0802w_3 \\
&+ 0.4683w_4 - 0.0966w_5 + 0.2142w_6 \\
&- 0.1534w_7 + 0.6747w_8.
\end{aligned}$$

Table 8. Rating table of principal component score.

object	prin1	prin2	prin3	prin4	PC score	classification
2006Qinghai	0.60486	0.22558	0.79602	−0.69563	0.357594	AA
2007Fujian	−0.58957	−0.18314	−1.89301	−1.56358	−0.87574	A
2007Yunnan	−0.98714	0.76929	0.21377	−0.95954	−0.22946	A
2007Xinjiang	−0.61202	0.96777	0.39722	−1.09648	−0.01483	A
2008Sichuan	1.93391	1.0843	−1.25238	0.97225	0.898282	AAA
2008Xinjiang	1.06274	2.85627	1.38976	0.79962	1.610436	AAA
2008Yunnan	−0.21157	−1.47587	0.6091	0.07453	−0.3662	A
2008Hubei	−0.22793	0.14996	0.4787	−0.5215	−0.01303	A
2008Gansu	1.87797	−1.21994	−1.53071	0.29394	0.064485	AA
2008Neimenggu	0.11423	−2.48815	1.98503	0.28877	−0.22307	A
2008Qinghai	1.04435	−0.88621	−0.41517	0.81452	0.155386	AA
2009Qinghai	−4.00984	0.20013	−0.77835	1.59311	−1.36386	A

Note : 'A' represents small indirect economic loss, 'AA' represents much indirect economic loss, 'AAA' represents great indirect economic loss.

Table 9. Rating of the comprehensive economic loss.

object	Comprehensive classification	object	Comprehensive classification
2006Yushu	3-AA	2008Wenchuan	1-AAA
2007Shunchang	5-A	2008Sunan	3-AA
2007Ninger	1-A	2008Elunchun	5-A
2007Tekesi	2-A	2009Haixi	5-AA

Note :'A' represents small indirect economic loss, 'AA' represents much indirect economic loss, 'AAA' represents great indirect economic loss. '1' represents catastrophe, '2' represents great disaster, '3' represents medium disaster, '4' represents small disaster, and '5' represents micro disaster.

With the scores of every PC, the variance contributions of themselves are made as weights to calculate their value of linear combination. Then we achieved the rating result shown in Table 8.

5.4. Comprehensive Economic Losses Classification

We evaluated the sample with only one earthquake disaster a year and rated the comprehensive economic loss. The result is shown in Table 9.

6. Conclusion and Discussion

(i) According to the KS test, the loss of earthquakes in China is subjected to the lognormal distribution with mean 12.4695 and standard deviation 2.2451. Also, the number of earthquakes per month is subjected to the Poison distribution with parameter 4.2857.

(ii) The correlation of each factor and direct economic loss can be obtained by the grey relation analysis. The grey correlation order is as follows: the affected population $>$ the GDP per capita in the region last year $>$ the number of affected villages and towns $>$ focal depth $>$ the main topography of the region $>$ occurrence time $>$ Earthquake magnitude.

(iii) The grey cluster model and principle component analysis are used for economic loss classification of eight earthquakes during 2006 – 2009. The result is accurate in line with the reality of China.

(iv) As the lack of historical data and the grey fuzzy identity of the indirect economic loss itself, some important indicators and seismic samples cannot be tested and applied. For example, the index representing the loss of the regional spread could be improved. At the same time, two reasons make the time spread loss ignoring the long-term influence. First, the duration of the negative impact by disaster cannot be measured. Second, most negative impact may be overshadowed by the rapid Chinese economy development. Therefore the classification system can be improved in the future.

(v) As one of the countries which have the most earthquake disasters in the world, China should pay full attention on the early warning of disaster and the research and application of disaster evaluation. In addition, increasing the ability in respond to serious natural disasters to make a contribution to earthquake relief.

[1] J. D. Mitchem, Place Vunerability to Tornadoes in the United States: A Multi-Scale Assessment. University of South Carolina 2004.
[2] Z. Q. Yin, Prediction Methods of Earthquake Disaster and its Losses. in: Researches Album on Prediction of Chinese Earthquake Losses, Part 4 (in Chinese). (Ed. Department of Earthquake Disaster Prevention, China Earthquake Administration), Seismological Press, Beijing 1996, p. 201.
[3] A. X. Zhao and Z. J. Ma, J. Natural Disasters (in Chinese) **2**, 1 (1993).
[4] Q. D. Yu and R. F. Shen, Systems Engineering-Theory Methodology Application (in Chinese) **4**, 47 (1995).
[5] L. C. Ren, J. Natural Disasters (in Chinese) **5**, 13 (1996).
[6] Q. D. Yu and R. F. Shen, J. Catastrophology (in Chinese) **12**, 12 (1997).
[7] G. M. Mao, J. H. Gu, and X. Y. Wu, Acta Seismologica Sinica (in Chinese) **29**, 426 (2007).
[8] X. Q. Chang, J. X. Han, and B. Zhang, Statistics and Decision-Making (in Chinese) **1**, 46 (2009).
[9] X. Gu, X. Q. Chang, and J. X. Han, Statistics and Decision-Making (in Chinese) **10**, 45 (2009).
[10] L. Tong, Research on the Gray Model of Earthquake Disaster and Decision Making (in Chinese). Hohai University, Nanjing 2005.
[11] D. Y. Xu and W. P. Sun, J. Geomech. (in Chinese) **17**, 64 (2011).
[12] D. Y. Xu, The Consideration of the Clustering Period of Great Disasters During the Beginning of 21 Century and its Prediction Significance. in: The Chinese Geophysics 2010 (in Chinese). Seismological Press, Beijing 2010, pp. 384 – 385.
[13] K. Men, China Eng. Sci. (in Chinese) **11**, 82 (2009).
[14] X. S. Ren and H. M. Ling, World Earthquake Eng. (in Chinese) **22**, 99 (2006).
[15] K. Men and W. J. Liu, Z. Naturforsch. **66a**, 363 (2011).
[16] K. Men, Z. Naturforsch. **66a**, 681 (2011).
[17] K. Men, Z. Naturforsch. **67a**, 308 (2012).
[18] W. J. Conover, Practical Nonparametric Statistics. 3rd Ed. Wiley, New York 1999.
[19] S. F. Liu, Y. G. Dang, and Z. G. Fang, Grey System Theory and its Application. 3rd Ed (in Chinese). Science Press, Beijing 2004.
[20] F. Y. Dong, J. J. Liu, and B. Liu, System Sciences and Comprehensive Studies in Agriculture (in Chinese) **26**, 478 (2010).
[21] T. W. Anderson, An Introduction to Multivariate Statistical Analysis. 2nd Ed. Wiley, New York 1984.
[22] A- C. Rencher, Methods of Multivariate Analysis. Wiley, New York 2002.

[23] National Bureau of Statistics of China. China Statistical Yearbook (in Chinese). China Statistics Press, Beijing 2007 – 2010.

[24] C. T. Du, W. Q. Li, and N. Lu, Technol. Earthquake Prevention (in Chinese) **1**, 371 (2006).

[25] H. L. Mi, Y. Li, and J. S. Hou, Recent Developments in World Seismology (in Chinese) **2**, 41 (2008).

[26] T. Y. Zheng, Y. Li, and J. S. Hou, J. Catastrophology (in Chinese) **25**, 112 (2010).

[27] T. Y. Zheng, Y. Li, and J. S. Hou, J. Catastrophology (in Chinese) **25**, 96 (2010).