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Applicability of Regional Evaluation for Rapid Assessment Models of Earthquake Disaster Life Loss – A case study of Gansu Province

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Abstract

In this paper, typical earthquake disaster life loss assessment models are applied to verify and calculate the historical earthquake cases in the Gansu Province since 1966. The assessment accuracy and applicability of various models in the Gansu Province are studied by means of actual earthquake cases. Results show that: (1) For Ms<5.5 and 5.5≤Ms≤6.0, a life loss assessment model is based on population density, another model based on epicentral intensity proposed, and the national earthquake disaster emergency assessment model are relatively accurate and basically included in the reasonable range; for Ms>6.0, characteristics of the assessed regions, such as physical geography and social economy, should be analyzed to correct the model calculation results and to receive comprehensive assessment results, so as to support emergency decisions. (2) Earthquake disaster life loss assessment models are regionalized and the assessment results are obviously regional. Assessment results of the earthquakes occurred in Hedong Region are not accurate for Hexi Region of Gansu Province.

Keywords: Gansu Province; earthquake; life loss model; rapid assessment; applicability evaluation

1. Introduction

China is one of the countries that suffer the severest earthquake disasters all over the world (Fu, 1994), and as Gansu Province is located on the north segment of the south-north seismic belt, it is one of the multi-earthquake provinces in China. It is recorded that Gansu Province has ever had the earthquakes of Ms≥8.0 for four times, resulting in mass casualties, wherein Haiyuan had an earthquake of Ms=8.5 in 1920, resulting in death toll of 273,465±9,700 (Liu, 2003); Gulang had an earthquake of Ms=8.0 in 1927, resulting in death toll of 41,471. In recent years, Gansu Province and its surrounding areas have increased seismic activities. For example, Wenchuan of Sichuan Province had an earthquake of Ms=8.0, Jiuzhaigou of Sichuan Province had an earthquake of Ms=7.0, Minxian County and Zhangxian County of Gansu Province had an earthquake of Ms=6.6, and Menyuan of Qinghai had an earthquake of Ms=6.4, etc. Since earthquakes are characterized in instantaneity and suddenness, violent earthquakes often lead to serious loss of life.

According to the Chinese *Rules for Natural Disaster Relief*, “people first” is the primary principle (the State Council of the P.R.C., 2010). Besides, in actual earthquake emergency response, response level is in direct proportion to relief materials. If emergency response level is too high, it will lead to mass waste of relief materials; if emergency response level is too low, it goes against disaster relief. As a key factor, “casualties” directly determines the earthquake emergency response start level of the government (National Earthquake Emergency Plan, 2012). Rapid assessment of earthquake

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disaster life loss is a scientific problem to be solved in actual earthquakes. Studies on rapid assessment models of life loss can provide technical support for instant emergency command and decision-making of the governments, thus have very important scientific and practical significance. In this paper, typical earthquake disaster life loss assessment models are applied to verify and calculate the historical earthquake cases of Gansu Province since 1966. Assessment accuracy, applicability and existing problems of different models by means of actual earthquake cases are discussed.

2. Research progress

At present, the life loss risk assessment oriented to earthquake emergency is mainly focused on probabilistic risk assessment and deterministic risk assessment. There are mainly two assessment directions: One is the earthquake-caused human mortality rate model obtained through building vulnerability analysis. This generally contains seismic damage matrix method based on historical data and experts' experience and vulnerability analysis method based on performance. For example, Yin (1991) proposed seismic vulnerability classification method for buildings and facilities, vulnerability analysis method for various building structures, and earthquake-caused loss prediction method; He (2005) obtained the house building vulnerability matrix in different parts of Sichuan Province through the empirical statistics of ten earthquake cases in Sichuan Province; FEMA commissioned the National Institute of Building Sciences (NIBS) for theoretical research and demonstration and launched a set of standardized methods HAZUS99 for earthquake-caused loss prediction in 1999 (FEMA, 1999). The former does not require much on the detail level of the data about the disaster-affected carriers, but gives a relative rough classification for building types, therefor the accuracy and reliability of the seismic damage matrix may be affected by the limitation of the local seismic history conditions; the latter fully considers the influence of structure types and post-earthquake damage state on mortality and systematically conducts calculations for earthquake-caused mortality. However, it requires detailed classification and careful investigation of the buildings in the area, establishment of a detailed database about buildings, and a large number of numerical calculations and statistical analyses (Li, 2014). The other is the empirical formulae of human mortality rate and number based on seismic parameters (i.e., magnitude, intensity, etc.) obtained by regression analysis of historical seismic damage data without consideration of the damage to buildings. The first category is based on population density. For example, Samardjieva et al. (2002) conducted research on earthquake cases which occurred since 1990. They, based on population density (respectively below 25 people/km^2, 25 people/km^2 to 50 people/km^2, 50 people/km^2 to 100 people/km^2, 100 people/km^2 to 200 people/km^2, and above 200 people / km^2), obtained the empirical formulae about earthquake-caused mortality number and earthquake magnitude for the earthquakes occurring in 1900 to 1950 and 1950 to 1999 on a global scale; On this basis, Badal et al. (2005), by means of magnitude, people density and other related indicators, constructed a human mortality assessment model and used it to assess the human mortality number in eight Spanish cities hypothetically hit by 6.0-magnitude and 6.5-magnitude earthquakes. The second category is based on time. For example, Chen (2005) conducted a research on the earthquake cases which occurred in China from 1980 to 2000. He classified the earthquake occurrence time by day and night, and obtained the empirical formulae related to human mortality number and earthquake intensity based on time. The third category is based on per capita GDP. For example, Chen et al. (1999) researched 207 earthquake cases occurred in China from 1989 to 2004. He set CN ¥2,700 Yuan – the per capita GDP represented by constant price in 2000 – as the classification threshold, and obtained the relationship between life loss rate and earthquake intensity; Liu Jifu et al (Liu, 2009), based on the previous research on macroscopic vulnerability, allotted population and GDP according to actual earthquake intensity, and established an earthquake-related life vulnerability model that is more similar to the real earthquake situations. The empirical formulae based on seismic parameters under statistical laws are dependent highly on historical data, so the selection of different historical data sets imposes great influence on the establishment of calculation methods. The selection of major influencing factors is the main cause of the difference in the assessment results from various models. Simple parameter obtaining is more applicable for rapid post-earthquake human mortality assessment.

3. Data source

Considering the reliability and integrity of earthquake disaster data, the earthquake disaster loss assessment reports of Gansu Province having officially have field investigation of earthquake damage and loss assessment since 1966. They include earthquake-caused loss data in Gansu and were collected from the Compilation of Earthquake Disaster Loss Assessment in Mainland China for 1966-1989, 1990–1995, 1996–2000, 2001–2005, 2006–2010, and 2011–2015 (China Earthquake Administration, 1996; 2000; 2010; 2015); besides, the data of towns, townships and sub-districts according to the population census of Gansu Province in 2010 as well as statistical yearbooks of Gansu Province over the years are also collected. Upon data analysis, 16 earthquake cases of Ms≥6.0 are selected to verify the earthquake disaster life loss assessment models and take corresponding earthquake parameters, including the earthquake date, earthquake time, latitudinal and longitudinal coordinates, magnitude (because the China Seismological Network uses the surface wave magnitude Ms, this magnitude is used in the rest of the paper), and mortality number.

The intensity maps of the 16 earthquakes were scanned one by one. Thereafter, the ArcGIS software developed by ESRI was used to register and digitize the intensity maps to obtain the area and distribution range of each intensity zone of an earthquake. In some previous studies, population data are distributed in macroscopic epicentral intensity (the highest intensity), which is quite different from the actual condition of earthquake; besides, actual life loss distribution is closely related to the distribution of population in intensity map. In this paper, the actual intensity area is used as the allocation unit. According to the township population involved in each intensity area during the earthquake, the number of people in the area of each intensity area is converted into the population of the intensity zones.

4. Method

When collecting and collating the earthquake-caused life loss assessment models published since 2000, the author finds that different models stem from different sources, employ different expressions, and have different applicable spatial ranges and time periods. In the case of earthquake emergency response, the human mortality assessment method based on building vulnerability requires more accurate classification of buildings and collapse rate of earthquake-affected buildings. In addition, the construction of earthquake-caused life loss risk assessment model requires the following principles: the model is simple and easy to popularize, the parameters are easy to obtain, the human judgment-based factors are less, and the assessment results are relatively reliable. In view of this, the author finally determines four earthquake risk models (which are named after the researchers' names) of two types, respectively deterministic risk assessment models and probabilistic risk assessment models.

1) Nonlinear regression model based on population intensity

The author selects the morality assessment model based on magnitude, population density and other related indicators, which was constructed by Badal et al. (2005). The formula is:

$$\log N_k(D) = a(D) + b(D)M \qquad (1)$$

where M is the magnitude, D is the population density, and $N_k$is the predicted mortality number. The population is divided by population density: <25 people/km^2, 25–50 people/km^2, 50–100 people/km^2, 100–200 people/km^2, and >200 people/km^2. The values of a and b differ for different population density levels.

2) Probabilistic model based on macro-economic indicator

Liu et al. (2009), based on the previous research on macroscopic vulnerability, set CN ¥2,700 Yuan – the per capita GDP represented by constant price in 2000 – as the classification threshold, and divided all the statistical data into two groups for regression statistics:

$$R_{MDF} = CAI^B \qquad (2)$$

where R_{MDF} represents life loss rate; I is seismic intensity; A and B are coefficients; C is correction coefficient. The model is used to assess life loss rate. In practical application, the earthquake-caused mortality number can finally be obtained only after the affected population is obtained.

3) Nonlinear regression model based on epicenter intensity

Liu et al. (2012), based on the data samples of the destructive earthquakes causing mortality in China from 1990 to 2006 along with several major earthquakes damage data in China, found out the main mortality-affecting factors. Through Gaussian function fitting and regression analysis; they obtained a mortality prediction model with epicenter intensity as a main parameter and magnitude and population density as auxiliary parameters for correction. The final mortality model is shown below:

$$\mathrm{D} = e^{12.2\alpha_{den}\alpha_m \cdot e^{-(\ln(\ln t)-2.445)^2/0.3^2}} \quad (3)$$

where D represents mortality number; $\ln t$ represents epicenter intensity; α_m is magnitude correction coefficient; α_{den} is population density correction coefficient.

4) Earthquake damage assessment method stated in the national standard GB/T 30352-2013

The author selects the mortality assessment method stated in the normative appendix of the *Earthquake Damage Assessment* promulgated on December 31, 2013 and implemented in July 1, 2014 (China Earthquake Administration, 2014). The formula is as follows:

$$N_D = \sum_{j=6}^{I_{max}} A_j \rho R_j \quad (4)$$

Where N_D is mortality number; I_{max} is the intensity of meizoseismal zone (it is the highest intensity zone of earthquake.); A_j is the distribution area of the jth intensity value; ρ is population density; R_j is the mortality rate corresponding to the jth intensity value, and the statistical relationship of mortality rate and intensity is hereby given.

5. Applicability Evaluation

5.1. *Comparison between predicted value and actual value of death toll*

Based on the four types of assessment models, this paper assesses the death toll of the selected 16 earthquakes with epicentral intensity of Ⅵ and above, and compares the results with the actual death toll. For the convenience of statistics, these 16 earthquakes are sampled and numbered. The evaluation results are shown in Table 1.

Table 1. Comparison between the Assessment Results of Four Models and the Actual Death Tolls

ID	Date	Magnitude	Name of Meizoseismal Area	Death Toll/Person	Liu Jifu	Badal	GB/T30352-2013	Liu Jinlong
1	19840106	5.5	Tianzhu	0	1	2	0	1
2	19870108	5.9	Diebu	0	34	5	2	2
3	19871025	5	Lixian County	0	14	4	0	1
4	19881122	5.7	Su’nan	0	0	2	0	1
5	19901020	6.2	Tianzhu	1	26	9	2	9
6	19920112	5.4	Su’nan	0	2	2	0	1
7	19950722	5.8	Yongdeng	12	117	11	14	12
8	19960601	5.4	Tianzhu - Gulang	0	30	6	1	2
9	19990415	4.7	Wenxian County - Wudu	1	9	2	0	1
10	20000606	5.9	Jingtai	0	11	9	2	10
11	20021214	5.9	Yumen	2	16	5	1	2
12	20031025	6.1	Minle - Shandan	10	553	26	117	13
13	20031113	5.2	Minxian County - Lintan	1	133	14	31	16
14	20040907	5	Minxian County - Zhuoni County	1	37	6	2	2
15	20060621	5	Wudu - Wenxian County	1	7	3	0	1
16	20130722	6.6	Minxian County - Zhangxian County	95	4132	52	864	15

It can be concluded from the assessment results that relative error values of the four models fluctuate obviously; predicted death tolls fluctuate greatly; results of some cases are consistent with the actual results, but results of some cases basically don't belong to the same order of magnitude and are obviously different. In order to further verify accuracy of the overall assessment results of the four models, mean relative error and root-mean-square error are applied to measure the deviation between estimated value and truth value, as shown in Table 2. In terms of overall accuracy, the earthquake damage life loss assessment model proposed by Badal and Liu performs well in the verification of historical examples in Gansu Province.

Table 2. Mean Relative Error & Root-Mean-Square Error of the Assessment Results of the Four Models

Model	Liu Jifu	Badal	GB/T30352-2013	Liu Jinlong
Mean Relative Error	96%	81%	142%	96%
Root-Mean-Square Error	1019.46	12.58	194.18	20.70

5.2. *Applicability evaluation*

After analysis and comparison of the above predicted and actual values of death toll, it is found that:

(1) These earthquakes are divided into three magnitude levels, and root-mean-square error is applied to measure the relative difference degree between predicted and actual values of the death toll, as shown in Table 3. As to $Ms < 5.5$ and $5.5 \leq Ms \leq 6.0$, the life loss assessment model based on population density proposed by Badal, the life loss assessment model based on epicentral intensity proposed by Liu Jinlong, and the national earthquake disaster emergency assessment model are relatively accurate, so that they have reference significance when determining earthquake emergency response level and provide scientific support to emergency decision-making and deployment. However, assessment result gained from the life loss assessment model based on GDP per capita and the actual value basically don't have the same order of magnitude and the value is relatively large in general. This model might be not applicable for Gansu Province as per the division standard of GDP per capita, resulting in noticeable error of assessment result. Generally speaking, when assessing actual earthquake death toll, macroscopic life loss research method might be not applicable for some regions in Gansu Province.

As to $Ms > 6.0$, assessment results are obviously not as accurate as those of $Ms \leq 6.0$. The difference between some assessment and actual results even exceeds 1.5 times with big contingency. The reason for such obvious difference might be that with the rise of magnitude, the factors that impact earthquake deaths increase or a certain factor is enhanced, so that special earthquake cases need to be assessed by the models of specific applicable range. As to the assessment of death toll after actual occurrence of earthquake, it can be concluded as per experts' experience on the basis of model assessment.

Table 3. Assessment Result Error Comparison of the Four Models under Different Magnitude Levels

Magnitude Level	Root-Mean-Square Error			
	Liu Jifu	Badal	GB/T30352-2013	Liu Jinlong
$Ms<5.5$	53.34	6.09	11.49	5.79
$5.5 \leq Ms \leq 6.0$	45.44	4.44	1.61	4.39
$Ms>6.0$	2352.04	26.79	448.10	46.57

(2) Earthquake disaster casualties are regionalized in Gansu Province to a certain extent. As Hedong Region is mountainous with high mountains and deep valleys, it often suffers post-earthquake disasters (landslip, landslide and debris flow), so that the casualties there are higher than Hexi Region (Pei, 2015). For example, the earthquake of M6.6 occurred in Minxian County and Zhangxian County in 2013 caused death toll of 95, including 14 deaths due to secondary disasters of earthquake. In this paper, this earthquake case is divided into two regions: Hedong Region and Hexi Region. After calculating root-mean-square error of the assessment results of the four models respectively and verifying the accuracy, it is found that accuracy of model assessment results of the earthquakes occurred in Hedong Region is quite different from Hexi Region, as shown in Figure 1. The reason for such obvious difference is the increase in regional impact factors for the

earthquake with casualties where the earthquake magnitude is generally in direct proportion to casualties. But some earthquakes may be different due to earthquake occurrence site, and main impact factors might include population density, geographical environment, origin time, building structure, etc.

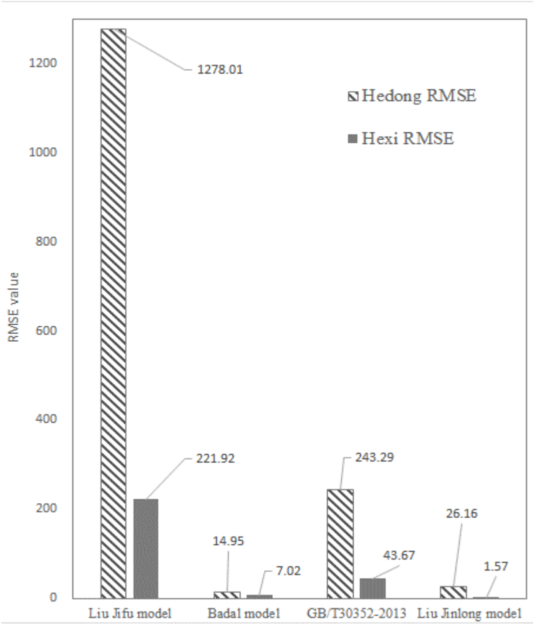

Figure 1. Root-Mean-Square Error Comparison of the Assessment Results of Four Models of the Two Regions in Gansu Province

Based on the above analysis, it is found that earthquake casualties are of great uncertainty and it is really hard to make the assessment results totally the same. Thus, comparison in order of magnitude between the assessment results and the actual death toll is considered at the same time, as shown in Table 4. Earthquake assessment results of the models at Hexi Region are obviously better than those of Hedong District. Assessment results of the model proposed by Badal and the model proposed by Liu are of the same order of magnitude, so that such results can provide accurate basis for the determination of emergency response level when an earthquake occurs. Thus, when making life loss assessment in Gansu Province, regional characteristics of Hedong Region and Hexi Region need to be considered and assessment conclusions should be given combining experts' experience. In the studies of earthquake disaster life loss assessment models, it is especially important to build typical assessment models targeted on regional earthquake life loss characteristics.

Table 4. Consistency Comparison in Order of Magnitude between Predicted Values and Actual Values of Death Toll of the Four Models

Model	Verified Earthquake Cases	Same Order of Magnitude		Different Orders of Magnitude	
		Hedong	Hexi	Hedong	Hexi
Liu Jifu's model	16	20%	50%	80%	50%
Badal's model	16	80%	100%	20%	0%
GB/T30352-2013	16	80%	83%	20%	17%
Liu Jinlong's model	16	70%	100%	30%	0%

6. Conclusion and Discussion

6.1. *Conclusion*

After destructive earthquakes, the primary task of post-earthquake rescue and relief is to make timely, efficient and orderly rescue and to reduce casualties. As the emergency relief strength input is closely related to casualties, it is of important research significance and practical value to finish rapid assessment of the death toll after earthquake and clarify credibility of results. In this paper, with applicability comparison of the earthquake disaster life loss assessment models as research objects, conclusions are drawn below:

(1) From the theoretical point of view, the empirical formula based on earthquake parameters follows statistical laws and relies highly on historical data. Selection of different historical data sets will have great impacts on the establishment of computing methods. But simple parameters acquisition is applicable for the demand of rapid assessment for post-earthquake casualties. Thus, empirical formula for casualty assessment is a relatively ideal model for rapid assessment of post-earthquake casualties.

(2) From the perspective of practical application, casualties of 16 earthquakes at Gansu Province are assessed with the four earthquake disaster life loss assessment models and the death tolls concluded from assessment are compared with the actual values. Results show that:

① As to $Ms < 5.5$ and $5.5 \leq Ms \leq 6.0$,, the life loss assessment model based on population density proposed by Badal, the life loss assessment model based on epicentral intensity proposed by Liu Jinlong and the national earthquake disaster emergency assessment model are relatively accurate, so that they have reference significance when determining earthquake emergency response level and have important support to emergency decision-making and deployment. As to $Ms >$ 6.0, due to less data of such earthquake cases, the number of statistical fitting samples is small, resulting in discrete fitting and error. Thus, obvious characteristics in physical geography, social economy, specific customs and other relevant aspects are analyzed to receive comprehensive assessment results, so as to support emergency decisions.

② Even though the formulas and methods given by these models basically meet the requirements of regression fit and research results can be concluded from statistical analysis, most models are limited by certain applicable range or input condition. Assessment results are obviously regional: accuracy of the model assessment results for the earthquakes occurred in Hedong Region is not as good as that of Hexi Region in Gansu Province. In the studies of earthquake disaster life loss assessment models, it is especially important to build typical assessment models targeted on regional earthquake life loss characteristics.

6.2. *Discussion*

From the perspective of practical application, earthquake life loss rapid assessment models are important parts of earthquake emergency relief decision-making and deployment. At present, many types of assessment models have been studied, but few of them are actually applied in relevant earthquake departments, such as earthquake emergency center. The reason is that such assessment models involve too many parameters and limits, so that it is really hard to apply these models in actual conditions. When any destructive earthquake occurs, China Earthquake Networks Center and the provincial earthquake bureau of the earthquake location will release three elements (time, place and magnitude) of the earthquake to the public in about ten minutes and report the possible earthquake disaster affection to the government. The government will start the earthquake emergency relief of rapidly according to earthquake disaster level. It is an urgent scientific problem to input less estimated parameters, reduce subjective factors and improve credibility of earthquake life loss rapid assessment results at present. However, assessment models are often built on the basis of accurately knowing the hardest-hit area, hit area, epicentral intensity and hit population, which leads to higher requirements for deployment of the entire earthquake emergency command technology system.

In order to improve the accuracy of earthquake disaster life loss assessment models to better serve earthquake disaster emergency command decision-making of the governments at all levels, it should be studied from the following three aspects: ①Essential data should be collected about the disaster situation in an affected zone. A comprehensive collection and classification of management standards should be established. Standards for the collection of essential data about disaster situation and effective information resource sharing mechanisms should be established. ② Post-earthquake life vulnerability models involve many life loss influencing factors. It is impossible to consider all influencing factors and collect the relations between casualties and all factors so as to obtain a universal empirical statistical formula. According to actual demands, based on the space-time characteristics of earthquake disaster life losses in details, regional assessment models are developed to improve or solve the problems related to the accuracy of assessment models, such as building regional models or building assessment models in different magnitude levels; ③ Existing models of high accuracy have complex parameters and require much for assessed data, so that it is really hard to collect and update relevant data in practical application, resulting in poor practicability. The life vulnerability models suitable for practical application should be characterized by few parameter input, easy collection and update of basic data with scientific and reasonable model assessment results. It needs further study to build simple and practical life vulnerability models.

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