Empirical seismic vulnerability curve for mortality: case study of China

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Received: 9 October 2014 / Accepted: 6 January 2015 / Published online: 21 January 2015
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Abstract Most seismic casualty estimations are based on the vulnerability of various categories of structure and facilities in the region concerned. These approaches require detailed inventory database of the structures and facilities in the region. In China, however, the data is not always available, especially for some underdeveloped regions. This motivates the development of empirical models that use historical casualty data for earthquakes and provide a country- or region-specific earthquake death rate as a function of ground shake. However, diminishing divergences in fitting method and obtaining higher accuracy are still a great challenge. Building on the findings of previous research, the present paper employs vulnerability curves to express the relation between seismic intensity and mortality. From data of the death rate by intensity, curves are established for the whole of China and western China. Some methodological improvements are also discussed. To validate the curves, data from four recent strong earthquakes occurred in western China are used, and the best curves for estimation are selected and compared with similar models. Results indicate that the established curves for western China give a better estimation for the four earthquakes and the logistic functions show higher accuracy. They can be used to clarify the magnitude of seismic deaths in western China when structure and facility data are unavailable. Uncertainties and the application of the models are also analyzed and discussed in the conclusion.

Keywords Earthquake · Mortality estimation · Vulnerability curve · Empirical model

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1 Introduction

Earthquakes are major natural disasters that result in heavy casualties and property losses (Ma 1990; Alexander 1993; Chen and Shi 2007; Wong 2014). The United States Geological Survey (USGS) estimated that there are millions of earthquakes around the world each year (USGS 2013). Most earthquakes are of small magnitude or strike in remote oceans and thus cannot be felt by people. However, strong earthquakes that strike in densely populated areas result in losses of property and life.

China is an earthquake-prone country. Half of its territory is prone to earthquakes with seismic intensity¹ of VII or higher; this area includes 23 provincial capitals and two-thirds of the nation's large cities with a population of more than one million inhabitants (CEA 2013). In the twentieth century, half of the deaths caused by earthquakes around the world were in China, and half of the deaths caused by natural disasters in China since 1950 were due to earthquakes (CEA 2013). In recent years, the Chinese mainland has been hit by a number of severe earthquakes, including the Wenchuan earthquake in 2008, the Yushu earthquake in 2010 and the Lushan and Dingxi earthquakes in 2013. These earthquakes had different degrees of property losses and casualties.

The estimation of risk in terms of seismic mortality has drawn much attention from the scientific community because of the severe loss of life in earthquake disasters. Disaster risk refers to the potential losses of life, health status, livelihoods, assets and service systems in a disaster (UNDP 2004), emphasizing possible events and possible losses (Blaikie et al. 1994; Li et al. 2012; Selva 2013).

Over the past 20 years, there have been important advances in seismic science and engineering relating to the probabilistic estimation of seismic hazards and early warning, but there are uncertainties regarding source initiation, rupture phenomena and the accuracy of the timing and magnitude of earthquake occurrence that seem difficult to overcome (Kossobokov 2013). Estimation of possible losses, such as seismic mortality, is another important aspect of risk assessment. When an earthquake strikes, a proper estimation of possible mortalities is necessary to understand the magnitude of expected seismic losses and to facilitate decision making in relief operations.

To effectively estimate mortality in the event of an earthquake, a number of models at local or regional levels have been established, with most being based on the vulnerability of various categories of structure and facilities in the region concerned (Okada 1992; Coburn et al. 1992; Weimin 2002; Cheng and Yang 1993; Yin 1995). These models are also widely used by governments in earthquake loss evaluation systems, such as the HAZUS system developed by the Federal Emergency Management Agency (FEMA) and the PAGER system developed by the USGS. However, these models require a detailed inventory database of structures and facilities, which is not always readily available in many regions of the world (Jaiswal et al. 2011). In China, for example, the gathering of relevant complex structural parameters is not easy for two reasons. (1) In the past several decades, the socioeconomic development of different regions in China has been uneven. The buildings in cities and rural areas thus differ greatly in structure and materials, and even buildings of the same material have different seismic resistance. (2) With rapid economic growth in China, buildings are reconstructed frequently, and data on buildings cannot be updated in a timeframe suitable for modeling.

¹ In this paper, intensity data on Chinese earthquakes are based on the China Seismic Intensity Scale (CSIS), which classifies seismic impacts into 12°.

Empirical models have been developed because of the lack of structure and facility data in some regions. These models use historical earthquake casualty data and provide a country- or region-specific earthquake death rate as a function of the ground shake. They need fewer parameters and can help responders understand the scale of disasters more quickly. There have been many studies in this field since the twentieth century (Jaiswal et al. 2011; Samardjieva and Oike 1992; Samardjieva and Badal 2002; Nichols and Beavers 2003). As a typical empirical model, Jaiswal et al.'s (2011) model was used within the PAGER system of the USGS. The model uses seismic intensity as a key parameter and employs a two-parameter lognormal cumulative distribution function to characterize the relationship between seismic intensity and mortality. Li et al. (2012) produced separate models for western and eastern China by modifying the parameters of Jaiswal et al.'s model. Chen et al. (1998) proposed a method of assessing seismic losses based on macroeconomic and social indicators and applied it around the world. Taking the same approach, Liu et al. (2006) established models based on seismic intensity and corresponding death rates and applied them at a regional level. Other studies established models based on maximum intensity and the total number of deaths (Xiao 1991; Liu et al. 2012; Liu and Lin 2012). However, differences in the fitting methods used and the accuracy achieved pose a great challenge.

The present paper employs vulnerability curves to express the relation between seismic intensity and mortality. Data of the death rate by intensity are collected for 157 earthquakes between 1989 and 2004 in China and grouped by region. Curves are established using different regression methods and validated using data for the latest four severe earthquakes that struck China. The best three curves in the estimation are finally selected and compared with similar models. Results indicate that the curves established in this paper provide improved estimations of death rates and can feasibly be used to clarify the magnitude of seismic deaths in western China when structure and facility data are unavailable.

2 Methods and data

2.1 Methods

Ground-shake parameters mainly include the earthquake magnitude, seismic intensity and spectral acceleration. Seismic intensity is always taken as a main parameter because it has been demonstrated to have a strong association with the death rate (Liu et al. 2011) and intensity maps can be generated within several minutes of an earthquake through rapid estimations of ground motion (David et al. 2006, 1999; Lind et al. 1996). Maximum intensity at the epicenter and the total death rate are often used in empirical models (Chan et al. 1998; Liu et al. 2012; Liu and Lin 2012). However, it should be noted that the severity of an earthquake in most affected areas is not as high as that in the epicentral area, and damage is therefore less.

The paper thus considers such differences and retraces the death rate according to the distribution of intensity, taking the “death rate by intensity” as a key parameter which can be defined as the ratio of the deaths to the population of affected areas with the same intensity. The equation is:

$$DRI_i = DI_i/PI_i \quad (1)$$

where DRI_i is the death rates in intensity i , DI_i is the deaths in intensity i , and PI is the population of the affected areas affected by the intensity i , $i = 1, 2, 3, 4, 5, 6, \dots, 12$. By

using regression methods, functional relationship between seismic intensity (i) and the death rate by intensity (DRI_i) can be established, which is the vulnerability curve for mortality:

$$\text{DRI}_i = f(i) \quad (2)$$

When earthquake strikes, if we can approximately know the number of population by intensity (PI_i), the total death (TD) can be estimated as follows:

$$\text{TD} = \sum_1^i (\text{DRI}_i \times \text{PI}_i) \quad (3)$$

Considering death rate divergence at same intensity, this study established curves based on “observed death rate” and “mean death rate” separately. Mean death rate is the mean value of observed death at same intensity. Differences in curve fitting are also compared.

In addition, China is a country of vast territory, where the geological structures, seismic zones and socioeconomic development differ markedly among regions. Such differences are distinct between western and eastern China. Moreover, earthquakes frequently strike western China. To improve the accuracy and applicability of the model, vulnerability curves both for the nation and for western regions are established. The western regions cover Yunnan Province, Sichuan Province, Gansu Province, Qinghai Province, the Xizang (Tibet) Autonomous Region and the Xinjiang Uygur Autonomous Region. These regions are divided into two groups, namely western region I (comprising Yunnan, Sichuan, Gansu and Xinjiang) and western region II (comprising Qinghai and Xizang) according to natural and socioeconomic differences.

2.2 Data

The data of death rate by intensity are mainly taken from Liu (2006), who collected detailed data for 157 earthquakes that struck Mainland China from 1989 to 2004, including the distribution of intensity, fatalities by intensity and corresponding population. The data on fatalities by CSIS intensity are a collection of official publications based on on-site recording and loss assessment. The number of population within areas of same intensity is computed in geographical information system (GIS) environment by using seismic intensity map and administrative unit map.

Taking the 1996 Lijiang earthquake data for example, the earthquake totally claimed 309 lives and the epicentral intensity is IX. Table 1 gives the area, population and deaths by intensity in the earthquake. The area of intensity IX is about 1,393.91 km²; the population and deaths in this area are 61,250 and 158. Then, the death rates by intensity (DRI)

Table 1 Catalog of data (taking the 1996 Lijiang earthquake as an example)

CSIS intensity (i)	Areas/km ²	Population by intensity (PI) (persons)	Deaths by intensity (DI) (persons)	Death rates by intensity (%) (DRI)
IX	1,393.91	61,250	158	2.58
VIII	2,243.07	97,390	76	7.80×10^{-2}
VII	4,179.26	192,860	52	2.70×10^{-2}
VI	10,591.10	498,980	23	4.61×10^{-3}

can be calculated by Eq. (1), and Fig. 1 shows the scatter plot of actual death rates by intensity in Mainland China, central and eastern China and western China.

To validate the vulnerability curves derived in this paper, data on the dead or missing for four strong earthquakes that struck western China in recent years were collected from official publications (Zheng et al. 2010, 2011; SBSP 2013; SBGP 2013). The four earthquakes were the Wenchuan earthquake (May 12, 2008), Yushu earthquake (April 14, 2010), Lushan earthquake (April 12, 2013) and Dingxi earthquake (July 22, 2013). Table 2 shows the maximum intensity and total deaths in the earthquakes, missing persons are also taken into account.

The number of population by CSIS intensity (PI) in the four earthquakes was collected from the relevant studies (Xu et al. 2008; Fan 2010; Yu 2010) (Table 3).

3 Establishment of seismic vulnerability curves

A vulnerability curve describes the functional relationship between the intensity of the hazard and the loss caused (Shi 2010); in this paper, it describes the functional relationship between seismic intensity and the death rate by intensity. The vulnerability curve for mortality may rise with intensity in three stages, i.e., the curve initially rises slowly, then rapidly, and finally slowly again while approaching a peak level (where the peak death rate is 1 in this paper). Theoretically, as shown in Fig. 2, weak hazards (weak earthquakes) cause no death and are seldom taken into account. Meanwhile, there are almost no records of extreme hazards having almost 100 % death rates since they rarely occur. Therefore, the middle part of the curve is mainly taken for fitting.

In this paper, different functions are applied for fitting. These functions can be categorized into three groups by shape. Type 1 comprises quadratic and cubic functions, type 2 comprises linear, logarithmic and reciprocal functions, and type 3 comprises composite, power, growth and exponential functions and S curves and logistic curves (Fig. 3, based on national data). The first two categories of functions have negative values in the fitting range and are not suitable. The significance level of type 3 curves is lower than 0.05, and the composite function overlaps with growth and exponential functions. Therefore, composite and power functions and S curves and logistic curves are used for fitting; the composite function can be replaced by a growth or exponential function. Such functions require there

Fig. 1 Observed death rates by intensity

Table 2 Total deaths in four earthquakes

Cases	Maximum intensity	Total deaths (persons)
Wenchuan earthquake	XI	87,150
Yushu earthquake	IX	2,968
Lushan earthquake	IX	217
Dingxi earthquake	VIII	95

Table 3 Population by CSIS intensity (PI) in the four earthquakes (persons)

CSIS intensity cases	VI	VII	VIII	IX	X	XI
Wenchuan earthquake	71,100,600	19,696,400	4,327,300	913,500	233,900	189,400
Yushu earthquake	197,441	54,997	59,483	16,200	–	–
Lushan earthquake	1,093,600	544,900	153,000	61,800	–	–
Dingxi earthquake	915,000	525,000	108,000	–	–	–

Fig. 2 Theoretical model of the vulnerability curve for mortality

to be no “zero-death” values (i.e., the Y-axis value should not be zero), which means zero-death cases should be excluded. The data set has 78 cases meeting this requirement.

3.1 Vulnerability curves based on national data

The paper fit the vulnerability curves based on “observed death rate” and “mean death rate” separately (Fig. 4). According to the regression equations, estimated death rates in each intensity are calculated; Table 4 shows the equations and the estimated death rates when intensity is from VI to XI.

3.2 Vulnerability curves for western China

For national data, the standard deviation of death rate shows large divergence at same intensity and increases substantially with intensity. When intensity is VI, the standard deviation of death rate data is 0.044, and when intensity reaches IX, the standard deviation exceeds 7 (Table 5). To improve the accuracy and applicability of the model, the paper

Fig. 3 Fitting results of different functions (national). *Note* Cubic and quadratic functions have similar curves. The linear function overlaps considerably with logarithmic and reciprocal functions. There are also overlaps between composite, growth and exponential functions and the logistic curve. For easy interpretation, only five curves are shown in the figure: the composite function, quadratic function, power function, S curve and linear function

Fig. 4 Four types of vulnerability curves based on national data. (The Y axis is the observed death rate in the left figure and the mean death rate in the right figure)

Table 4 Estimated death rate by intensity (DRI_i) (national) (%)

Intensity	6 (VI)	7 (VII)	8 (VIII)	9 (IX)	10 (X)	11 (XI)
Based on observed death rate versus intensity						
Composite function ($\text{DRI}_i = 2.441 \times 10^{-7} \times 5.064^i$)	4.117×10^{-3}	2.085×10^{-2}	1.056×10^{-1}	5.346×10^{-1}	2.707	13.709
Power function ($\text{DRI}_i = 4.400 \times 10^{-12} \times i^{11.495}$)	3.875×10^{-3}	2.280×10^{-2}	1.058×10^{-1}	4.097×10^{-1}	1.375	4.114
S curve [$\text{DRI}_i = e^{(7.757-80.148/i)}$]	3.694×10^{-3}	2.490×10^{-2}	1.042×10^{-1}	3.172×10^{-1}	7.726×10^{-1}	1.601
Logistic curve [$\text{DRI}_i = 1/(0.01 + 4.284 \times 10^6 \times 0.196^i)$]	4.117×10^{-3}	2.100×10^{-2}	1.071×10^{-1}	5.439×10^{-1}	2.714	12.461
Based on mean death rate versus intensity						
Composite function ($\text{DRI}_i = 4.068 \times 10^{-7} \times 5.790^i$)	1.533×10^{-2}	8.874×10^{-2}	5.138×10^{-1}	2.975	17.225	99.734
Power function ($\text{DRI}_i = 1.452 \times 10^{-12} \times i^{12.834}$)	1.409×10^{-2}	1.018×10^{-1}	5.652×10^{-1}	2.563	9.908	33.667
S curve ($\text{DRI}_i = e^{(11.003-91.983/i)}$)	1.320×10^{-2}	1.796×10^{-1}	6.096×10^{-1}	2.187	6.078	14.026
Logistic curve [$\text{DRI}_i = 1/(0.01 + 2.691 \times 10^6 \times 0.170^i)$]	1.539×10^{-2}	9.047×10^{-2}	5.298×10^{-1}	3.038	15.563	52.020

i represents seismic intensity, and DRI_i represents the death rate by intensity. The same symbolic representation is used hereafter

Table 5 Data and standard deviation at different intensities (western region I vs. national)

	VI		VII		VIII		IX	
	Sample size	Standard deviation	Sample size	Standard deviation	Sample size	Standard deviation	Sample size	Standard deviation
Nationwide	23	0.044	27	0.130	21	0.551	4	7.277
Western region I	17	0.003	21	0.008	17	0.275	3	1.070

establishes vulnerability curves for west regions. West regions are also frequently stricken by earthquakes these years.

Considering natural and socioeconomic differences, this work divides western China into two parts: western region (I) and western region (II). Take the death rate data of western region (I) for instance, when intensity is VI, the data's standard deviation is 0.003 and when intensity reaches IX, the standard deviation is 1.070 (Table 5). The standard deviation for “western region (I)” is lower than that for the “National” thus help the improvement in the curves' accuracy and applicability. Since there are no recent seismic cases available for validation in central and eastern regions, these regions are not discussed further.

3.2.1 Western region (I)

The western region of China comprises 12 provinces, municipalities and autonomous regions. These areas are underdeveloped and differ greatly from central and eastern regions in terms of socioeconomic development. Since the validation data are mainly for Sichuan, Gansu, Yunnan, Qinghai, Xinjiang and Xizang, western region (I) in this study mainly refers to Sichuan, Gansu, Yunnan and Xinjiang. Qinghai and Xizang are discussed separately for their special natural and socioeconomic backgrounds. Figure 5 shows vulnerability curves for mortality in western region (I). According to the regression equations, estimated death rates in each intensity are calculated; Table 6 shows the equations and the estimated death rates when intensity is from VI to XI.

3.2.2 Western region (II)

Most of Qinghai and Xizang are within the seismic zone of the Qinghai–Xizang Plateau. There is frequent seismic activity in this zone, but in most cases, there are fewer deaths owing to the low population density. However, when earthquakes strike in counties with relatively dense population, the death rate is somewhat high because of improperly designed or unreinforced buildings, vulnerable lifelines and infrastructure and the severe environment of plateaus (Liu et al. 2010). Figure 6 shows the vulnerability curves for mortality in the case of Qinghai and Xizang. According to the regression equations, estimated death rates in each intensity are calculated; Table 7 shows the equations and the estimated death rates when intensity is from VI to XI.

4 Validation of vulnerability curves

All four severe earthquakes mentioned in Sect. 2 struck western region (I) and western region (II) and can thus be used to validate the established curves. Meanwhile, three similar curves established by other researchers are selected for comparison.

Fig. 5 Four types of vulnerability curves for western region I. (The Y axis is the observed death rate in the left figure and the mean death rate in the right figure)

4.1 Evaluation with earthquake data

The total deaths (TD) of the four earthquakes are estimated from Eq. (3), where the death rates by intensity (DRI_i) are the estimation results of different curves in Sect. 3 (Tables 4, 6, 7); populations by intensity (PI) are from Table 3. Because Wenchuan, Lushan and Dingxi earthquakes occurred in western region (I), the national curves and west region (I) curves are used for estimation. Yushu earthquake occurred in western region (II); the national curves and west region (II) curves are used for estimation. The results are shown in Table 8 and reveal the following:

1. There are definite differences in seismic mortalities among regions, and the curve fitting using regional data provides better results. Vulnerability to earthquakes varies among regions in China, and the vulnerability curves established by data for western regions are more suitable for estimating losses in earthquakes striking those regions.
2. The curves based on the observed death rate and mean death rate have different characteristics, especially for western region (I). When the maximum intensity is no higher than 9, such as for the earthquakes in Lushan and Dingxi, the curves based on the observed death rate provide a better estimation than the curves based on the mean death rate. When the maximum intensity exceeds 9, such as for the Wenchuan earthquake, the curves based on the mean death rate give a better estimation than the curves based on the observed death rate.
3. The estimation of the logistic curve is closest to the actual losses. The three-stage growth and the feature of convergence echo the theoretical model of the vulnerability curve. Therefore, the following curves are selected in this study to estimate mortality due to earthquakes in western China.

Western region (I):

when maximum intensity ≤ 9

$$\text{DRI}_i = 1 / (0.01 + 4.186 \times 10^7 \times 0.165^i) \quad (4)$$

Table 6 Estimated death rate by intensity (western region I) (%)

Intensity	6 (VI)	7 (VII)	8 (VIII)	9 (IX)	10 (X)	11 (XI)
Based on observed death rate versus intensity						
Composite function ($DRI_i = 2.410 \times 10^{-8} \times 6.060^i$)	1.194×10^{-3}	7.233×10^{-3}	4.383×10^{-2}	2.656×10^{-1}	1.610	9.755
Power function ($DRI_i = 1.327 \times 10^{-13} \times i^{12.763}$)	1.133×10^{-3}	8.107×10^{-3}	4.457×10^{-2}	2.004×10^{-1}	7.689×10^{-1}	2.595
S curve [$DRI_i = e^{(8.016 - 88.994/i)}$]	1.096×10^{-3}	9.119×10^{-3}	4.468×10^{-2}	1.538×10^{-1}	4.134×10^{-1}	9.283×10^{-1}
Logistic curve [$DRI_i = 1/(0.01 + 4.186 \times 10^7 \times 0.165^i)$]	1.184×10^{-3}	7.174×10^{-3}	4.347×10^{-2}	2.628×10^{-1}	1.572	8.826
Based on mean death rate versus intensity						
Composite function ($DRI_i = 6.625 \times 10^{-9} \times 7.670^i$)	1.349×10^{-3}	1.035×10^{-2}	7.935×10^{-2}	6.086×10^{-1}	4.668	35.804
Power function ($DRI_i = 3.462 \times 10^{-15} \times i^{14.846}$)	1.235×10^{-3}	1.218×10^{-2}	8.843×10^{-2}	5.082×10^{-1}	2.428	9.996
S curve [$DRI_i = e^{(10.905 - 105.987/i)}$]	1.160×10^{-3}	1.447×10^{-2}	9.600×10^{-2}	4.184×10^{-1}	1.358	3.560
Logistic curve [$DRI_i = 1/(0.01 + 1.534 \times 10^8 \times 0.130^i)$]	1.351×10^{-3}	1.039×10^{-2}	7.985×10^{-2}	6.110×10^{-1}	4.515	26.673

Fig. 6 Four types of vulnerability curve for western region II. (The Y axis is the observed death rate in the left figure and the mean death rate in the right figure)

when maximum intensity >9

$$DRI_i = 1 / (0.01 + 1.534 \times 10^8 \times 0.130^i) \quad (5)$$

Western region (II):

$$DRI_i = 1 / (0.01 + 5.263 \times 10^6 \times 0.136^i) \quad (6)$$

4.2 Comparison of similar curves

4.2.1 Three models are selected for comparison

Curve 1 is a global empirical model used in the USGS PAGER system and is expressed by a two-parameter lognormal cumulative distribution function (Jaiswal et al. 2011). Using the model, Chinese scholars have produced curves for western and eastern China separately (Li et al. 2012).

$$\text{For eastern regions: } V(S) = \Phi \left[\frac{1}{0.1231} \ln \left(\frac{S}{11.2924} \right) \right] \quad (7)$$

$$\text{For western regions: } V(S) = \Phi \left[\frac{1}{0.1065} \ln \left(\frac{S}{11.4571} \right) \right] \quad (8)$$

where Φ is the standard normal distribution function, and S is seismic intensity.

Curve 2 is established from the death rate by intensity (Liu 2006) and is expressed by a power function where R is the death rate and I is seismic intensity. When the gross domestic product (GDP) per capita (at constant prices in 2000) in the affected area is no $<2,700$ yuan, Formula (9) is used. When the GDP per capita (at constant prices in 2,000) is $<2,700$ yuan, Formula (10) is used.

Table 7 Estimated death rate by intensity (western region II) (%)

Intensity	6 (VI)	7 (VII)	8 (VIII)	9 (IX)	10 (X)	11 (XI)
Based on observed death rate versus intensity						
Composite function ($DRI_i = 3.044 \times 10^{-7} \times 6.581^i$)	2.473×10^{-2}	1.627×10^{-1}	1.071	7.048	46.384	–
Power function ($DRI_i = 4.976 \times 10^{-13} \times i^{13.683}$)	2.210×10^{-2}	1.821×10^{-1}	1.132	5.673	23.982	88.360
S Curve ($DRI_i = e^{(12.329-97.375/i)}$)	2.024×10^{-2}	2.056×10^{-1}	1.170	4.525	13.350	32.354
Logistic curve [$DRI_i = 1/(0.01 + 4.509 \times 10^6 \times 0.145^i)$]	2.386×10^{-2}	1.643×10^{-1}	1.122	7.259	35.056	78.826
Based on mean death rate versus intensity						
Composite function ($DRI_i = 2.651 \times 10^{-7} \times 6.971^i$)	3.042×10^{-2}	2.121×10^{-1}	1.478	10.305	71.839	–
Power function ($DRI_i = 2.493 \times 10^{-13} \times i^{14.195}$)	2.771×10^{-2}	2.471×10^{-1}	1.645	8.754	39.059	–
S curve [$DRI_i = e^{(13.300-101.750/i)}$]	2.578×10^{-2}	2.906×10^{-1}	1.788	7.348	22.760	57.397
Logistic curve [$DRI_i = 1/(0.01 + 5.263 \times 10^6 \times 0.136^i)$]	3.000×10^{-2}	2.203×10^{-1}	1.598	10.665	46.745	86.585

Table 8 Estimation of total deaths (TD) in four earthquakes using different curves. Values in bold are the estimations of the three selected curves, which are Eqs. (4)–(6)

	Wenchuan earthquake	Yushu earthquake	Lushan earthquake	Dingxi earthquake
National curves				
Observed death rate versus intensity				
Composite F	48,781	169	650	261
Power F	26,575	149	582	269
S curve	19,778	134	532	277
Logistic curve	46,616	171	659	264
Mean death rate versus intensity				
Composite F	306,975	867	3,276	1,161
Power F	164,884	835	3,158	1,274
S curve	119,763	808	3,072	1,398
Logistic curve	214,372	887	3,350	1,188
Western region (I) curves				
Observed death rate versus intensity				
Composite F	28,837	–	284	96
Power F	12,875	–	249	101
S curve	8,638	–	225	106
Logistic curve	26,930		281	95
Mean death rate versus intensity				
Composite F	72,360	–	784	280
Power F	40,204	–	766	307
S curve	29,505	–	752	338
Logistic curve	73,122		571	153
Western region (II) curves				
Observed death rate versus intensity				
Composite F	–	1,917	–	–
Power F	–	1,736	–	–
S curve	–	1,582	–	–
Logistic curve		1,981		
Mean death rate versus intensity				
Composite F	–	2,726	–	–
Power F	–	2,587	–	–
S curve	–	2,465	–	–
Logistic curve		2,858		
Actual death	87,150	2,968	217	95

$$R = 9 \times 10^{-15} I^{14.977} \quad (9)$$

$$R = 6 \times 10^{-11} I^{9.849} \quad (10)$$

GDP per capita of 2,700 yuan is taken as a threshold in the selection of curves for different regions; this threshold was set to identify poverty-stricken counties in China in 2002. In 2008, however, the average per capita GDP of the 592 national-level poverty-

stricken counties exceeded 8,771 yuan (Xie and Xu 2011), and few counties had a per capita GDP of <2,700 yuan. Therefore, Formula (9) is mainly used here for comparison.

Curve 3 is based on the maximum intensity and total death rate of 257 earthquakes that caused human losses in China between 1900 and 2009 (Liu et al. 2012). The curve is expressed by an exponential function, where y is the death rate and x is the maximum intensity.

$$y = 3 \times 10^{-5} e^{0.8185x} \quad (11)$$

The three curves are selected because they have important similarities and differences with the curves derived in this study. Curve 1 is similar in that it considers regional division. Curve 2 is similar in that it takes the death rate by intensity as a key parameter and is different in that it uses a single economic indicator (per capita GDP of 2,700 yuan) as the threshold. Curve 3 is different in that it takes the maximum intensity and total death rate as the main parameters.

Table 9 shows that the logistic curves established in this paper have a mean relative error of 0.12 in estimating deaths of the four earthquakes. The logistic curves have the smallest mean relative error among the four curves and can provide a better estimation.

5 Discussion and conclusion

Using data of the death rate by CSIS intensity, seismic vulnerability curves for mortality in China were established at both national and regional levels. Additionally, seismic loss data were used to validate the curves. The following conclusions are drawn from the results obtained.

1. The relationship between seismic intensity and mortalities is nonlinear for earthquake disasters in China. A logistic curve better describes such a relationship.
2. There are definite differences in seismic mortalities among regions. Fitting with regional data provides better results. These results were confirmed using data for recent earthquakes.
3. The vulnerability curves derived from death rate data by intensity provide a better estimation than those derived from the total death rate and maximum intensity.
4. The curves established in this paper provide improved estimations of fatalities. The results also suggest that with incomplete loss data for earthquakes around the world, a

Table 9 Comparison of the four curves in deaths estimation (persons). Values in bold are the estimations and mean relative error of the logistic curves built in this study

	Wenchuan earthquake	Yushu earthquake	Lushan earthquake	Dingxi earthquake	Mean relative error ^a
Curve 1	104,967	217	1,310	42	1.68
Curve 2	127,441	495	2,411	578	4.12
Curve 3	676,819	3,326	15,453	10,836	190.16
Logistic curves (in this study)	73,122	2,858	281	95	0.12
Actual death	87,150	2,968	217	95	–

^a Relative error = $(\text{estimated deaths} - \text{actual deaths}) / \text{actual deaths}$

collection of detailed information, such as loss by intensity, is important not only to vulnerability studies but also to emergency rescue in the future.

5. Data on high-intensity events are limited because there are few severe earthquakes, which affects the curve stability. Curves might be improved using more data, especially data on high-intensity events in the future. It should also be noted that the uncertainties in intensity map estimation will result in uncertainties in rapid death estimation. A number of contributing factors affect the accuracy of a given intensity map (Lin et al. 2005), to quantify the intensity map uncertainties can also help the improvement of death estimation (David et al. 2006).

Earthquake-caused deaths are also affected by other multiple uncertain factors. The first factor is the specific time of the earthquake occurrence. The time determines the possibility of human activities and thus the extent of casualties. The second factor is the structure and materials of buildings, which are related to property losses and casualties directly or indirectly. The third factor is individual characteristics, including socioeconomic status (income, political power and prestige), gender, age, education and cultural background (Zebardast 2013; Gabriela and Lisa 2012). These individual characteristics are related to the reaction of people when facing disasters. It is still a great challenge to fully understand how these factors relate earthquakes to disasters, and the combination of so many factors surely leads to a high level of uncertainty.

Given the approximate nature of empirical models, the models are needed more in developing regions where little is known of the structural properties and seismic resistance of local building types (Spenc et al. 2011), and the models can also provide a useful benchmark for calibrating losses taking both hybrid and analytical approaches (Jaiswal et al. 2011). In future work, by collecting more data and improving interpretation, better vulnerability curves can be developed. New parameters such as the time of earthquake occurrence can also be considered in modifying the curves and improving stability.

Acknowledgments This study is supported by the National Science and Technology Support Program of China (Grant No. 2013BAK05B04). We greatly appreciate the anonymous reviewers for their insightful comments, which led to significant improvement in the manuscript.

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