Intensity Based Casualty Models: Case Study Of Bhuj and Latur Earthquake in India

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15 WCEE
LISBOA 2012

SUMMARY:
Casualty data from Latur (1993) and Bhuj (2001) earthquakes in India are analyzed to study the relationship of death rates with shaking intensity. A strong correlation is noted between intensity and death rates (correlation coefficient ~0.77). The expected (median) death rates are 0.31%, 1.77%, and 19.45% for intensity VII, VIII and IX in case of Latur, and 0.0029%, 0.049%, 1.92% and 4.92% for intensity VII, VIII, IX and X in case of Bhuj. The significantly higher death rates in Latur are due to building typologies and the time of the event. Thus, there is a factor of ~100 for intensity VII and a factor of ~10 for intensity IX, indicating that the empirical casualty models should be area specific and not country specific. A two-parameter empirical model has been proposed.

Keywords: Intensity, Casualty, Earthquakes, Bhuj, Latur.

1. INTRODUCTION

Deaths during earthquakes may be caused by structural collapse, tsunamis, fires, rock falls, landslides and other secondary hazards. However, the main cause of fatalities is usually the structural collapse. Structural collapse depends mainly upon the type and quality of constructions and the shaking intensity. The number of casualties depends on structural response, type of constructions, time (and season) of the earthquake, and on rescue and relief. Generally, construction typologies may be divided into three broad categories: (a) engineered (for seismic loads), (b) engineered (for gravity loads), and (c) non-engineered. Many developing countries like India have a large percentage of category (b) and (c) type constructions. Such construction typologies cause huge loss of life during strong shaking. Therefore, earthquake casualty estimations are useful for local administration for preparedness and management of disasters. Three approaches are used for casualty estimation (Jaiswal *et. al.*, 2009a): analytical, semi-empirical and empirical. In analytical approach, loss estimates are made based on seismic hazard assessment and structural analysis, e.g., FEMA (2006). Semi-empirical approaches are based on seismic intensity instead of engineering parameters for damage and hence the loss estimation, e.g., Coburn *et. al.* (1989), Shiono *et. al.* (1991), Yamazaki *et. al.* (1996), and Shakhramanian *et. al.* (2000). Empirical approaches are useful for direct estimation of losses based on regression analysis of casualties in past seismic events. Using the parameters like magnitude and seismic intensity, Ohta *et. al*. (1983) developed empirical relationship to assess casualties based on the number of destroyed houses. Models based on earthquake magnitude have also been used to estimate the earthquake fatalities, e.g., Oike (1991), and Samardjieva and Badal (2002). Nichols and Beavers (2003) have proposed a bounding function based on fatality count and earthquake magnitude. Badal *et. al.* (2005) proposed casualty estimates for various intensity ranges.

Shaking intensity is a spatially varying parameter and is a more direct measure of damage as compared to any other parameter like earthquake magnitude or peak ground motion parameters. An area exposed to higher shaking intensity is expected to have higher losses. Recently, Jaiswal *et. al.* (2009b) developed a parametric cumulative distribution function model that provides earthquake fatality rate as a function of shaking intensity, where the distribution function parameters are country-specific. This model is utilized in PAGER (Prompt Assessment of Global Earthquakes for Response) system used by United States Geological Survey (USGS) for post earthquake fatality estimation. Jaiswal *et. al.*

(2009b) have used the historical earthquake data in the form of total shake-related deaths and the associated population exposure at different shaking intensities and have given country specific death rates.

In many developing countries, the casualty data of desired quality and quantity is difficult to obtain. However, in two major earthquakes in India (1993 M6.2 Latur and 2001 M7.7 Bhuj), reliable data on number of deaths is available. In case of Latur earthquake, casualty data is available for about 50 villages, while in case of Bhuj earthquake the data is available for 73 talukas. A taluka consists of several villages. Therefore, within a single taluka intensity may vary considerably. The present work considers these two Indian earthquakes to study the casualty pattern vis-a-vis seismic intensity. Isoseismal maps reported by Geological Survey of India are used for assigning the seismic intensity to which a particular village or taluka was exposed. A regression analysis has been carried out to study and develop casualty models.The present study is expected to give a better insight for intensity based casualty assessment as compared to the earlier studies.

2. CASUALTY DATA

2.1. Latur earthquake

The Latur earthquake of 1993 (M6.2) occurred at 3.53 AM and killed 7,635 persons in 52 villages in the state of Maharashtra. This being a winter night time, most people were sleeping indoors at the time, which caused high casualty rates. Being a shallow focus earthquake, the affected area was rather small. The earthquake intensity in affected region ranged upto IX on the MSK scale of intensity. Due to some ambiguity in the data collected from two villages, only 50 villages have been used here for the analysis. Distribution of the casualty data from Latur earthquake is given in Table 2.1.1.

Table 2.1.1. Casualty data from Latur earthquake

Intensity wise distribution			**Distribution of total death toll**		**Distribution of death rates (per 10,000)**	
Intensity	No. of Villages	Death rate range (per 10,000)	No. of deaths	No. of Villages	Death rates (per 10,000)	No. of Villages
			1-10	18	1-10	2
VII	17	3-340	10-100	16	10-100	19
VIII	19	15-2022	100-1000	14	100-1000	16
IX	14	855-3280	1000-10000	2	1000-10000	13

It may be noted that the 50 villages are evenly affected by intensity VII, VIII, and IX (34%, 38% and 28%, respectively). Maximum death rates of 3.4%, 20% (about one-fifth of the population), and 33% (about one third of the population) are observed in zones affected by intensity VII, VIII, and IX shaking, respectively. Almost one third villages had more than 100 deaths. 58% villages had death rate of more than 1% deaths while approximately 45% of them observed more than 10% deaths.

2.2. Bhuj earthquake

The Bhuj earthquake of 2001 (M7.7) occurred at 8:46 AM and killed 13,805 persons in a much larger area in the state of Gujarat. The timing of the earthquake was quite favorable with many people outdoors. The earthquake intensity in the affected region ranged up to X on the MSK scale of intensity. Distribution of casualty data from Bhuj earthquake is given in Table 2.2.1. Out of 73 talukas, 59 talukas (about 81%) experienced intensity VII. One taluka experienced intensity VIII, while in the remaining talukas shaking intensity varied. Maximum death rate of 0.03% and 0.11% are observed due to intensity VII and VIII, respectively. 90% of the talukas had death rates less than 0.10%.

It is clear from the above discussion that the death rate for a given shaking intensity was much higher in Latur earthquake as compared to that in the Bhuj earthquake. Range of death rates for Latur earthquake is 3 to 3280 deaths per 10,000 population while for Bhuj earthquake death rate ranges between 0.06 to 420 deaths per 10,000 population. This is due to two main reasons: a) much higher vulnerability of dwellings in the affected area of the Latur earthquake, and b) more unfavorable timing of the Latur earthquake which occurred when most persons were sleeping indoors.

Table 2.2.1. Casualty data from Bhuj earthquake

Intensity wise distribution			**Distribution of total death toll**		**Distribution of death rates (per 10,000)**	
Intensity	No. of Talukas	Death rate range (per 10,000)	Death range	No. of Talukas	Death rates (per 10,000)	No. of Talukas
VII	59	0.06-3.43	1-10	51	0.01-0.1	10
VIII	1	11.36			0.1-1	42
VII & VIII	7	0.23-10.26	10-100	15	1-10	14
VIII & IX	1	57.94				
IX & X	1	419.84	100-1000	4	10-100	4
VII,VIII & IX	1	2.56				
VII,VIII & X	1	46.17	1000-10000	3	100-1000	3
VIII, IX & X	1	215.40				
VII,VIII,IX & X	1	111.90				

3. SHAKING INTENSITY AND DEATH RATES

3.1. Correlation analysis

Even though death rates are expected to be higher for higher seismic intensity, it is of interest to see how strong such a correlation may be. Latur casualty data set gives the correlation coefficient as 0.77 between death rates (per 10,000 populations) and seismic intensity (numerical values are considered as 7, 8, and 9 for intensity VII, VIII and IX, respectively). In order to gain confidence in the correlation between death rates and intensity, bootstrapping method is used. Bootstrapping is a simulation technique based on repetition of data from the actual sample. A bootstrap sample thus obtained may have one or more villages more than once, while some of the villages may not be there in the sample such that the sample size remains the same. Fig. 3.1.1 shows the histogram of correlation coefficient between death rates and seismic intensity for 10,000 bootstrapped samples. The correlation coefficient ranges from 0.50 to 0.88, with an average value of 0.77 and standard deviation of 0.03, indicating a rather strong correlation between shaking intensity and death rates.

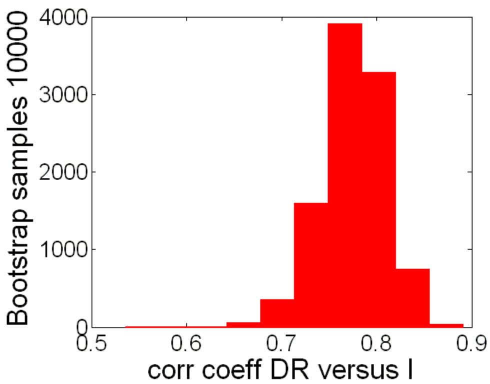


Figure 3.1.1. Correlation coefficient between death rates and seismic intensity for Latur earthquake

3.2. Distribution analysis

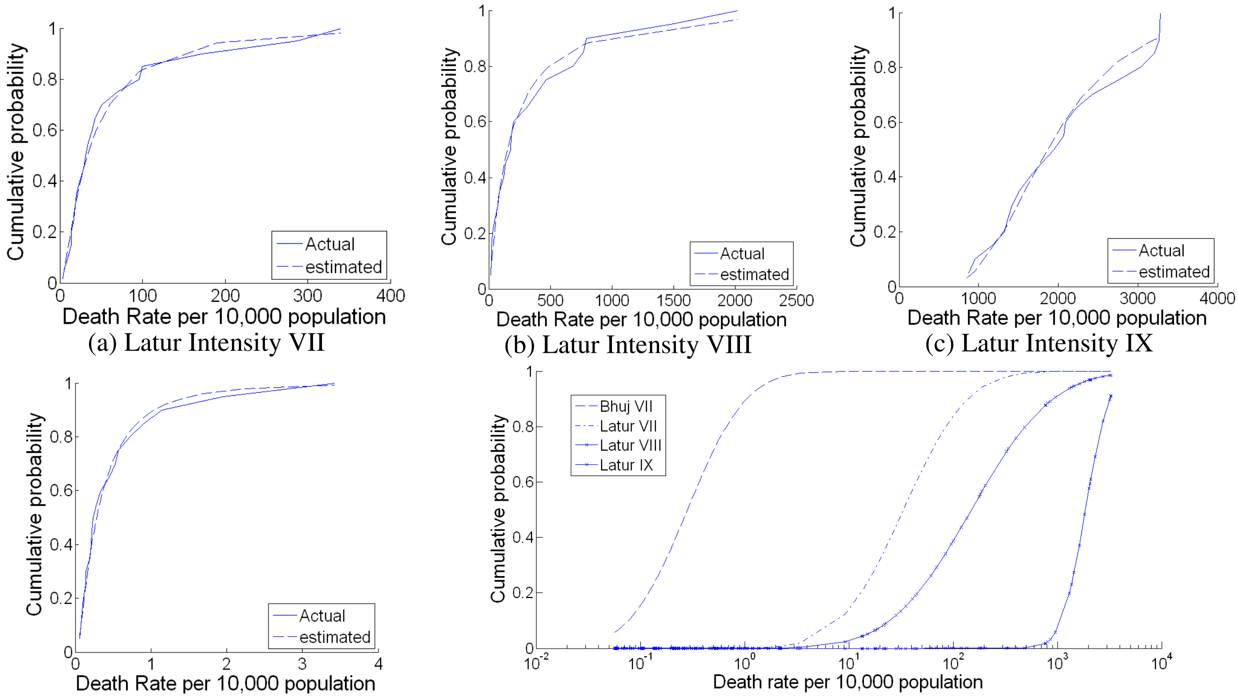
The casualty data for intensity VII, VIII, IX from Latur earthquake and intensity VII from Bhuj earthquake are found to follow log-normal distribution with all the four cases passing 5% significance level chi-square test (Table 3.2.1). The distribution of the casualty data may therefore be represented by the following standard equation of log-normal distribution (e.g., Hines *et. al.*, 2009).

$$f(DR) = \frac{1}{\beta \times DR \times \sqrt{2\pi}} \exp\left[-\frac{(\ln(DR)-\emptyset)^2}{2\beta^2}\right] \tag{3.2.1}$$

Where, *DR* is the death rate per 10,000 population and *f*(*DR*) is the probability distribution function of death rates. Φ and β are distribution parameters and are representative of arithmetic mean and standard deviation of the natural logarithm of death rates. Higher values of Φ indicate higher death rates. It may be noted that e^{Φ} and e^{β} will be equal to the geometric mean and geometric standard deviation of death rates, respectively. For lognormal distributions, geometric mean represents the median. Using maximum likelihood approach, parameters Φ and β are determined and are shown in Table 3.2.1.

Table 3.2.1. Chi-square test results and distribution parameters

Event	Seismic Intensity	Chi-square value (observed)	Chi-square value (5% significance level)	No. of Talukas/ Villages	Distribution Parameters	
					Φ	β
Latur	VII	0.47	3.84	17	3.51	1.11
	VIII	2.42	3.84	19	5.01	1.41
	IX	1.68	3.84	14	7.53	0.42
Bhuj	VII	3.05	9.49	59	-1.26	1.02



(a) Latur Intensity VII (b) Latur Intensity VIII (c) Latur Intensity IX

(d) Bhuj Intensity VII (e) Comparative

Figure 3.2.1. Actual and proposed cumulative probability distribution of death rates (per 10,000 population) for (a) Intensity VII, (b) Intensity VIII, and (c) Intensity IX of Latur earthquake, (d) Intensity VII of Bhuj earthquake, and (e) Comparative plot of all the distributions

Geometric mean (or median) of death rates (e^{Φ}) for the four cases (VII, VIII, and IX Latur; VII Bhuj) is 33, 150, 1863, and 0.28, respectively. Geometric standard deviation of death rates (e^{β}) for these four cases is 3.0, 4.1, 1.5, and 2.8, respectively. This indicates that the intensity IX data is comparatively less dispersed about its median. Log-normal distribution is positively skewed with skewness coefficient for these four cases as 2.58, 2.53, 0.33, and 2.75, respectively. Except intensity IX (Latur), rest of the data are equally and significantly skewed. Figs. 3.2.1 (a), (b), (c), and (d) are the cumulative probability distribution curves for death rates for intensity VII, VIII, and IX Latur earthquake and intensity VII Bhuj earthquake, respectively. Fig. 3.2.1(e) shows the comparison between the four cases.

The proposed log-normal distribution matches well with the actual distribution of the data which is prepared based on rank-percentile analysis. Comparative study of the distribution patterns shows a nearly constant geometric increment in the death rates with increasing shaking intensity for Latur earthquake in the range of 65% to 85% confidence level values. However, geometric increment reduces with intensity at confidence levels higher than 85% and increases with intensity at confidence levels lower than 65%.

3.3. Variation of death rates with intensity

In the case of Latur earthquake mean, median, and standard deviations of death rates are determined for intensities VII, VIII, and IX (see Table 3.3.1). Bhuj earthquake casualty data is not large enough for intensities other than VII. Therefore, Table 3.3.1 shows the mean, median, and standard deviation of death rates for intensity VII only for Bhuj earthquake. 90% confidence level values are also derived from log-normal distribution parameters as shown in Table 3.2.1. It may be mentioned here that the mean death rate may be useful for overall death toll assessment for entire region while the median death rate (50% confidence level value) may be more useful for casualty assessment for an individual village.

Table 3.3.1. Statistical properties of death rates of Latur and Bhuj earthquakes

Event	Seismic Intensity	Mean Death Rate (per ten thousand populations)	Median Death Rate (per ten thousand populations)	Standard Deviation	90% Confidence level values of Death Rates
Latur	VII	63	31	85	139
	VIII	351	177	485	913
	IX	2020	1945	831	3192
Bhuj	VII	0.49	0.23	0.62	1.05

Mean death rates are consistently higher than the median death rates due to skewed nature of log-normal distribution of the death rate data. It is also observed that the difference between mean and median death rates is rather low for intensity IX as compared to the other cases because of considerably low skewness of the distribution for intensity IX. Coefficient of variation, which is a measure of dispersion of the data in relation with its mean and is given by the ratio of standard deviation to mean, for the four cases (VII, VIII, IX Latur; and VII Bhuj) is 1.4, 1.4, 0.4, and 1.3, respectively. Data from intensity IX (Latur) show significantly low variance as compared to that for lower intensities.

As compared to Latur earthquake, death rates are significantly lower in case of Bhuj earthquake. For intensity VII and 90% confidence level, Bhuj earthquake had about 1.05 deaths per 10,000 population as against 139 deaths per 10,000 population in Latur earthquake.

Further, in Latur earthquake mean death rate goes up by 5.61 and 5.75 times, from intensity VII to VIII and VIII to IX, respectively, while median death rate goes up by 5.63 and 11.00 times, from intensity VII to VIII and VIII to IX, respectively. It is assumed that when intensity goes up by one unit, the death rate goes up by a certain factor say ‘α’. Based on death rates corresponding to intensity VII, VIII, IX and X, the value α can be determined using several possible ratios like VIII to VII, IX to VIII, square root of X to VIII and so on. However, it is proposed that the ratio based on the two limiting intensities (highest and lowest) would provide an average ratio by which the death rates go up multiplicatively with intensity. Based on this definition the value ‘α’ for Latur earthquake casualty data is 5.68, 7.87, and 4.80 for mean, median and 90% confidence level death rates, indicating that with every unit increment in intensity, death rates go up by 5 to 8 times.

A taluka consists of several villages and during the Bhuj earthquake, 13 talukas have experienced mixed intensity, e.g., a part of taluka has intensity VII while the other part has VIII. When the intensity varies within a taluka, it is assumed that the population is uniformly distributed over the geographical area of the taluka and the population exposed to a particular intensity is proportional to the geographical area affected by that intensity. If $P_{VII,}$ $P_{VIII,}$ $P_{IX,}$ and P_X are the populations exposed to intensities VII, VIII, IX and X, respectively, and their corresponding death rates (per 10,000 population) are $DR_{VII,}$ $DR_{VIII,}$ $DR_{IX,}$ and $DR_{X,}$ then total number of deaths *'D'* can be given as,

$$\frac{DR_{VII} \cdot P_{VII} + DR_{VIII} \cdot P_{VIII} + DR_{IX} \cdot P_{IX} + DR_X \cdot P_X}{10{,}000} = D \qquad (3.3.1)$$

The total number of deaths in different talukas (*D*) is known and we need to estimate death rates ($DR_{VII,}$ $DR_{VIII,}$ $DR_{IX,}$ and DR_X) in Eqn. 3.3.1. Linear regression analysis is performed by four different approaches L1 norm, L2 norm, G norm and L2G norm minimization. L1 norm, L2 norm and G norm, respectively, are the summation of absolute differences, squared differences and squared logarithmic differences between the estimated and actual values of *D* in Eqn. 3.3.1. L2G norm is the combination of L2 and G norms. L1 norm considers absolute residuals and hence may not be much useful. L2 norm gives more emphasis to the higher death rates minimization. G norm reduces the contribution of higher death rates in total error term and gives more emphasis to the lower death rates. Results of the four methods are as shown in Table 3.3.2.

Table 3.3.2. Estimated death rates (per 10,000 population) for Bhuj earthquake

Intensity	L1 Norm	L2 Norm	G Norm	L2G Norm
VII	0.39	1.69	0.28	0.29
VIII	5.10	9.42	4.63	4.91
IX	221.69	192.33	48.31	192.21
X	711.90	492.39	636.12	492.38

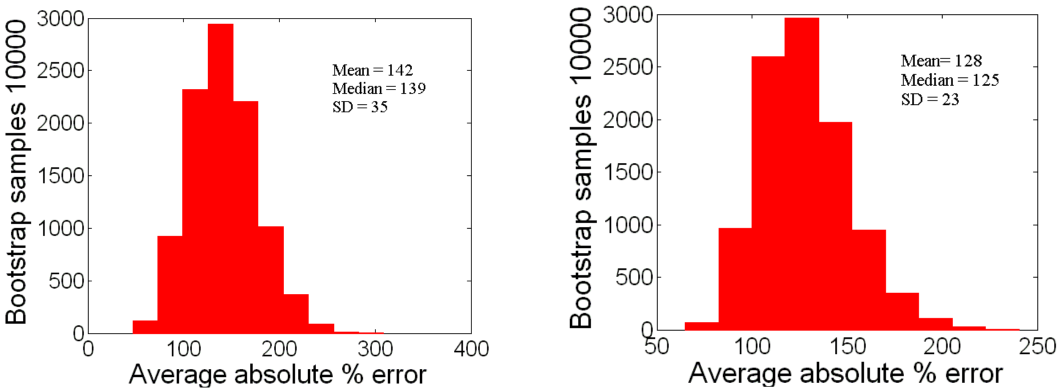
L2 norm significantly overestimates the death rate of intensity VII and gives a value which is more than 90% confidence value (see Table 3.3.1). Value estimated by G norm seems to be much smaller for intensity IX. Therefore, as also suggested by Jaiswal *et. al.* (2009b), L2G norm is used which combines the benefits of both L2 and G norms. It can be observed that the estimate made by L2G norm for intensity VII is very close to the median of the actual data set. Hence, values obtained by L2G norm minimization approach are considered for further analysis and discussion. From the Table 3.3.2, it can be seen that on an average casualties go up 12 times for each unit increment in the intensity as per estimated death rates based L2G norms.Table 3.3.3 shows expected (median) death rates in Latur and Bhuj earthquake, and the estimates made by Jaiswal *et. al.* (2009b) for India in case of seismic intensity VII, VIII, IX, and X.

Table 3.3.3. Comparison of expected death rates per 10,000 population

Intensity	Latur Earthquake	Bhuj Earthquake	Jaiswal et. al. (2009b)
VII	31	0.29	2
VIII	177	4.91	45
IX	1945	192.21	384
X	--	492.38	1546

Death rates vary by a factor of 107, 36, and 10 between Bhuj and Latur earthquakes for intensity VII, VIII, and IX, respectively. At low intensity shaking, there may not be many collapses of low vulnerability building stock. That is, the gap between the death rates in high (Latur) and low (Bhuj) vulnerability regions is much higher at low intensity levels than at the high intensity levels. The huge variation in casualty rates in two earthquakes within the same country depending on construction practices, time of earthquake, etc. must be clearly recognized. The general model for the entire country as proposed by Jaiswal *et. al.* (2009b) falls in between the two values but may highly over or under estimate the casualties for a particular earthquake, particularly when shaking intensity is low. For instance, the actual casualty numbers in case of Latur earthquake will be 16, 4, and 5 times higher for intensity VII, VIII, and IX, respectively, while in Bhuj earthquake 7, 9, 2, and 3 times lower for intensity VII, VIII, IX, and X, respectively, as compared to the model proposed by Jaiswal *et. al.* (2009b) for India.

To determine the variation of actual number of casualties in different villages/talukas as compared to the expected death rates (Table 3.3.3) for Latur and Bhuj earthquake, average absolute error of 142% and 128%, respectively, was obtained. To gain further confidence on these values bootstrapped analysis is carried out on average absolute percentage errors (Fig. 3.3.1), which gives an average of 142% and 128% error, respectively, with standard deviation of 35% and 23%, respectively. It can therefore be concluded that any empirical casualty model based on intensity can at best be expected to give results ±150%.



(a) (b)

Figure 3.3.1. Average absolute % errors in the actual expected death rates for (a) Latur and (b) Bhuj earthquake

3.4. Proposed model

Based on the above observations, an empirical relationship between death rates per 10,000 population (*DR*) and corresponding seismic intensity (*I*) is proposed as,

$$Log\ (DR) = A_0 + A_1(I) \tag{3.4.1}$$

Where, A_0 and A_1 are the regression parameters and '*I*' is the numerical value of seismic intensity. It is worth mentioning here that this relationship is based on the assumption of constant geometric increment of death rates with intensity. A_1 is the measure of jump (α) in the death rate between two intensity levels while A_0 represents the vulnerability associated with the affected region and seismic event. The proposed model does not use any other parameter except seismic intensity. Therefore, it is expected that the regression parameters (A_0 and A_1) will account for the remaining parameters including earthquake timing, geographical location, building typologies, quality of rescue and relief available, and other factors which may affect the loss of life during earthquakes.

When the casualty data is unevenly distributed among various intensities, accumulation of data from a particular intensity may cause bias in the parameter estimation through regression analysis. In view of this, the death rate data is screened such that there is equal representation of death rate data from each of the intensity levels. In case of Latur earthquake, the base-10 logarithms of the death rates corresponding to intensity VII, VIII, and IX are arranged in the decreasing order. Then, for each of the intensity, data corresponding to 100, 95, 90… and, 5-percentile is obtained. This screening provides 20 data points from each of the intensity levels which are then used in the regression analysis. In case of Bhuj earthquake, the death rate estimates based on L2G norm (Table 3.3.2) are utilized for the regression analysis of the proposed model. Table 3.4.1 shows the values of the parameters along with their standard errors.

Table 3.4.1. Parameters of the proposed model

Data set	A_0	A_1	Range of α
Latur earthquake	-4.48 ±0.56	0.86 ±0.07	6.17–8.51
Bhuj earthquake	-8.31 ±1.45	1.13 ±0.17	9.12–19.95

Higher value of parameter A_0 represents higher vulnerability and hence the value is much higher for Latur earthquake as compared to that for Bhuj earthquake. This vulnerability parameter (A_0) can be mathematically expressed in terms of the population out of which 1 death is expected for hypothetical zero seismic intensity event. Smaller that population, higher would be the vulnerability. This population is 302 million and 2040 billion for Latur and Bhuj earthquakes, respectively. Parameter A_1 is a measure of relative vulnerability among various intensities for a given seismic event. Value of A_1 is higher for Bhuj earthquake than for Latur earthquake indicating that vulnerability (death rate) increases more rapidly in case of Bhuj earthquake. Further, it may be noted that A_1 is higher for region where A_0 is lower, that is, higher vulnerability regions observe lower increment in death rates with intensity. At high intensity levels (e.g., intensity IX to X), the death rate tends to saturate in case of highly vulnerable constructions while it continues to grow in case of low vulnerability buildings. Therefore, less vulnerable (smaller A_0) regions are expected to have higher increment (higher A_1) in death rates with intensity and vice-versa. Fig. 3.4.1 shows the proposed model of death rates for Latur and Bhuj earthquakes.

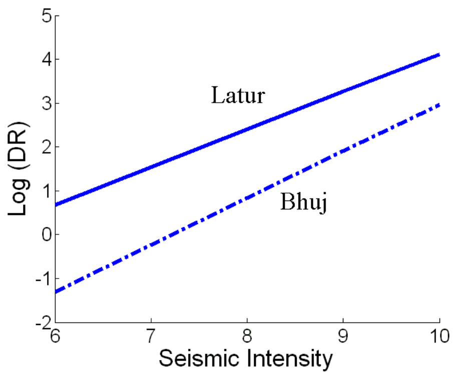


Figure 3.4.1. Death rate (per 10,000 population) versus seismic intensity: proposed models for Latur and Bhuj earthquake

Using the estimated parameters (Table 3.4.1) of the proposed model, death rates per 10,000 population are estimated for the two data sets. It is seen that the estimated values for Latur earthquake are in close agreement with the median values and are smaller than the mean values. Death rate values for intensity IX and X in case of Bhuj earthquake are underestimated by 62% and overestimated by 98%, respectively. This may be attributed to lack of sufficient explicit data from intensities VIII, IX, and X from Bhuj earthquake.

Table 3.4.2. Estimated and actual observed number of deaths per 10,000 populations

Intensity	Latur (Observed Mean)	Latur (Observed Median)	Latur (Estimated)	Bhuj (regression analysis)	Bhuj (Estimated)
VII	63	31	35	0.29	0.40
VIII	351	177	251	4.91	5.37
IX	2020	1945	1820	192.21	72.44
X	--	--	--	492.38	977.24

Figs. 3.4.2 (a) and (b) show the histogram of average absolute percentage error in estimates using the proposed model (Table 3.4.1) as compared to actual death rates in the villages/talukas using 10,000 bootstrapped samples. The mean of average absolute percentage error is around 186%, and 158% for Latur and Bhuj earthquake, respectively, with standard deviation value of 49% and 22%, respectively. This, when compared with 142% and 128% reported in the previous section appears quite reasonable.

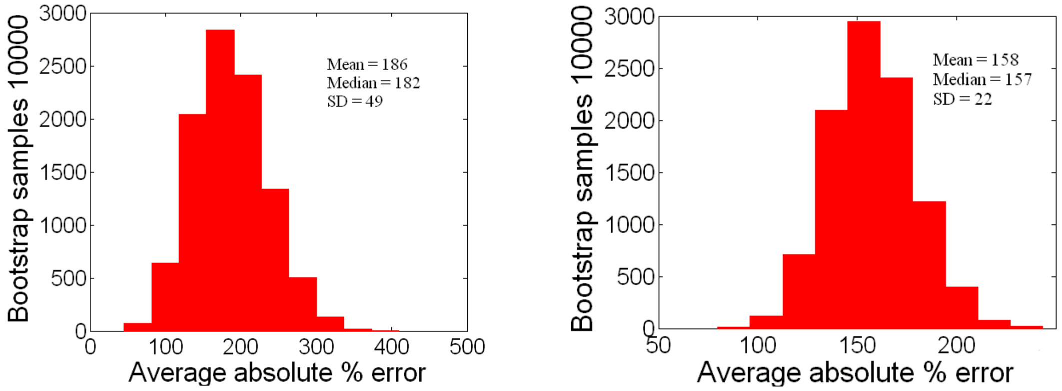


Figure 3.4.2. Average absolute % errors in the proposed death rates for (a) Latur and (b) Bhuj earthquake

4. SUMMARY AND CONCLUSIONS

For pre-earthquake preparedness and immediate post-earthquake management, it is useful to estimate the expected number of casualties in a given village, town or region. Constructions in the developing countries tend to have huge variation in quality and most often do not follow the building codes. Hence, for casualty estimation in such countries, empirical approach, based on past earthquakes, may provide a much better option as compared to analytical and semi-empirical methods. In this paper, casualty data from Latur (1993) and Bhuj (2001) earthquakes in India are analyzed to study the relationship of casualty with seismic intensity. Latur earthquake occurred in a region with very highly vulnerable constructions (random rubble masonry in mud mortar, with heavy roofs) and at a time when most people were sleeping indoors. Bhuj earthquake on the other hand occurred in a region with better constructions (even though still far inferior to what the codes require) and at a time when many people were outdoors. As a result, Latur earthquake caused significantly higher death rates as compared to Bhuj earthquake.

The Latur data shows that a strong correlation exists between intensity of shaking and death rates (correlation coefficient ~0.77) for a given region. It is observed that the death rates for a particular seismic intensity are log-normally distributed. The expected (median) death rates are 0.31%, 1.77%, and 19.45% for intensity VII, VIII and IX in case of Latur, and 0.0029%, 0.049%, 1.92% and 4.92% for intensity VII, VIII, IX and X in case of Bhuj. Thus, there is a factor of ~100 for intensity VII and a factor of ~10 for intensity IX between Latur and Bhuj, indicating that the empirical casualty models should be area specific keeping in view the construction typologies and the time of the earthquake, and that a common model for the entire country can lead to huge overestimation or underestimation in number of casualties.

It is observed that with every unit increment in the intensity level, death rates increase by about 5 and 12 times, respectively, for Latur and Bhuj earthquakes. Assuming a constant geometric increment in death rates with increasing intensity levels, a two-parameter empirical model has been proposed to obtain death rate with intensity of shaking as $\mathrm{Log(DR)}=A_0+A_1(I)$ for a given earthquake. Here A_0 represents vulnerability of the region and A_1 indicates geometric increment. Expected values of A_0 are -4.48 and -8.31 while for A_1 these are 0.86 and 1.13 in case of Latur and Bhuj earthquake, respectively. These parameters are expected to depend mainly upon construction typologies, time of the day, seismic event, and geographical location. Further, it is noticed that the highly vulnerable building stock (higher A_0) shall reflect lower geometric increment (smaller A_1) due to saturation of death rates in higher intensities. For same seismic event, the error in estimated death rates is observed to range ±150% to ±200% using the proposed model. It will be worthwhile to carry out similar studies with casualty data from other earthquakes as well to validate the results of this study.

ACKNOWLEDGEMENT

The authors are thankful to Gujarat State Disaster Management Authority (GSDMA) for providing the casualty data for Bhuj earthquake and to the Government of Maharashtra for Latur earthquake casualty data.

REFERENCES

Badal, J., Vázquez-Prada, M. and González, A. (2005). Preliminary Quantitative Assessment of Earthquake Casualties and Damages. *Natural Hazards* **34:3,** 353-374.

Coburn, A.W., Pomonis, A. and Sakai, S. (1989). Assessing strategies to reduce fatalities in earthquakes. In *proc. of International Workshop on Earthquake Injury Epidemiology for Mitigation and Response*, *The Johns Hopkins University, Baltimore, USA*. 107-132.

FEMA. (2006). HAZUS-MH MR2 Technical Manual, Federal Emergency Management Agency, Washington, DC, USA. (*http://www.fema.gov/plan/prevent/hazus/hz_manuals.htm).*

Jaiswal, K.S., Wald, D.J., Earle, P.S., Porter, K.A. and Hearne, M. (2009a). Earthquake Casualty Models within the USGS prompt Assessment of Global Earthquakes for Response (PAGER) system. *Second international workshop on disaster casualties*, *University of Cambridge, UK*, 8 pp.

Jaiswal, K., Wald, D. J. and Hearne, M. (2009b). Estimating Casualties for Large Earthquakes Worldwide Using an Empirical Approach. U.S. Geological Survey Open-File Report-2009-1136.

Hines, William W., Montgomery, Douglas C., Goldsman, David M. and Borror Connie M. (2009). Probability and Statistics in Engineering, John Wiley & Sons, Inc., Delhi, India.

Nichols, J.M. and Beavers, J.E. (2003). Development and calibration of an earthquake fatality function. *Earthquake Spectra* **19:3**, 605-633.

Ohta, Y., Goto, N. and Ohashi, H. (1983). An empirical construction of equations for estimating number of victims by earthquakes. *Zisin II* **36**, 463-466.

Oike, K. (1991). A discussion on the relation between magnitude and number of deaths by earthquakes. In *proc. of the Int. Seminar on Earthquake and Hazard Mitigation Technology, Tsukuba, Japan.* 333-341.

Samardjieva, E. and Badal, J. (2002). Estimation of the expected number of casualties caused by strong earthquakes. *Bulletin of the seismological society of America* **92:6**, 2310-2322.

Shakhramanian, M.A., Larionov, V.I., Nigmetov, G.M. and Sutschev, S.P. (2000). Assessment of the seismic risk and forecasting consequences of earthquakes while solving problems on population rescue (Theory and Practice). *Russian Civil Defense and Disaster Management Research Institute*, *Moscow*. 180pp.

Shiono, K., Krimgold, F. and Ohta, Y. (1991). A method for the estimation of earthquake fatalities and its applicability to the global macro-zonation of human casualty risk. In *proc. of 4th International Conference on seismic zonation, Stanford, California.* **Vol. III**: 277-284.

Yamazaki, F., Nishimura, A. and Ueno, Y. (1996). Estimation of human casualties due to urban earthquakes. In *proc. of the 11th World Conference on Earthquake Engineering*. Paper No. 443.