China Probabilistic Seismic Risk Model - Part 1 Hazard and Exposure

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ABSTRACT :

The potential financial and social loss due to earthquakes in China has increased significantly over the past decades due to the country's rapid growth and increase in exposure concentration in major cities. In order to quantify the dynamically changing seismic risk, a probabilistic seismic risk model of China has been developed as a joined effort between the Institute of Engineering Mechanics (IEM) in Harbin and Risk Management Solutions, Inc. (RMS) in California. This paper is the first of two papers presenting the study and its results and focuses on the hazard quantification and the exposure development. The second paper focuses on vulnerability curves development and probabilistic loss estimation. This paper presents the parameters describing the seismic risk: the delineation of seismic sources, the magnitude distribution, rate of earthquake occurrence and upper magnitude truncation. Soil classification and liquefaction potential are estimated from high resolution geologic maps. Western and Eastern Chinese elliptical spectra based attenuation functions are adopted and calibrated against historical events. Over 85,000 simulated events are included based on the seismic source model to quantify the seismicity. The outputs of this effort are peak ground acceleration and spectral acceleration maps for selected return periods. The paper further presents the development of the exposure for the whole country at the district/county level by lines of businesses based on national census, industry statistics and market information. For each province, a detailed review of the exposure was performed to reach this high level of resolution. In order to properly estimate the vulnerability of the exposure a detailed inventory classification was developed including the building class, construction material and design philosophy, age of structure, number of stories and seismic zone requirements. More than ten such inventories were derived going from "central business district" to "rural" environment. This information is used as the input for the second paper that addresses the loss estimation.

KEYWORDS: Earthquake Hazard, Exposure, Loss Estimation, China Earthquake Risk, Attenuation

1. INTRODUCTION

Earthquakes are naturally resulted from the release of earth's energy accumulated by the plate movement. The casualty, economic loss as well as business interruption caused by a large earthquake often result in a continuous impact on the society, economy and the country for a long time, in cases even to the connected world economy. After thousands' of years in defending against the threat of potential earthquake damage, human beings have realized that there are essentially three different but correlated types of things they can do to reduce the impact of an earthquake. The first type is for things that are related to preparedness relatively long before the occurrence of an earthquake. This type of tasks includes building earthquake resistant engineering structures, educating general public on the background information as well as preparing on a daily basis for an upcoming earthquake.

The second type of tasks includes earthquake monitoring and prediction right before and after an earthquake. If an accurate prediction on exact time, location and magnitude of an earthquake can be issued, an emergency evacuation can be implemented to avoid human casualty. Whereas, even with accurate prediction of earthquake and evacuating in time to save people's lives, the engineering structures will still suffer damage if not properly designed and built. The third type of tasks includes emergency response, search and rescue after the occurrence of a damaging earthquake. This type of tasks is designed to compensate what has been left in the previous two types of tasks. Because of the limited knowledge human beings have on earthquakes, an effective earthquake disaster reduction would probably have to combine efforts from all the above three types of tasks.

One key component in all the above three types of tasks is the earthquake risk quantification. Without knowing about the earthquake risk level, we would not be able to decide the appropriate level for earthquake resistance design. Without proper knowledge on earthquake risk, it is difficult to predict the extent of the impact of an earthquake. Without proper knowledge on earthquake risk, there is no way to deploy appropriate troops and professional staff in a timely fashion for search and rescue and emergency response activities, especially in remote areas where transportation and communication become difficult right after an earthquake. Therefore, a reasonably accurate quantification method for earthquake risk is required for effective earthquake disaster reduction programs.

There have been many ways on how to quantify an earthquake risk with various uncertainty, accuracy, and reliability. Similar to the approaches taken for any other science and engineering research, studies on earthquake risk research also started with empirical formulae derived from statistic analysis of historical data and information. The most important part was mostly concentrated on estimating consequences given the fact that an earthquake has occurred. The key component here is the so called vulnerability relationship, which is the relationship between a given seismic parameter and a given consequence indicator. The seismic parameter can be the magnitude of the earthquake, which is then evolved into intensity and to most recently the acceleration, velocity, displacement or even response spectra. The consequence indicator can take various forms as well, in the forms such as damage ratio, GDP loss ratio, different levels of casualty rate, or even time lost for business interruption.

With the accumulation of knowledge on our understanding of earthquake risk, it gradually becomes clear to us that a deterministic approach is good for scenario analysis, that is, for case study during which we can perform different types of what-if analysis. Given the fact that we have not fully understood the mechanism of earthquake occurrence, the extent of consequence given an earthquake and the impact of the consequences, it is often appropriate to describe the mean value and the variance of the estimate. Therefore, a probabilistic approach is better in describing the earthquake risk.

Although there could be different variations on how to model earthquake risk probabilistically, there are always three key components in the analysis, that is, the earthquake hazard, the vulnerability and the exposure or the inventory. Christopher Rojahn and Roland L. Sharpe (1985) in their ATC-13 document provided not only the methodology but also the data for earthquake loss estimation for California. A majority of the current methods in earthquake risk modeling were based on their work. Therefore, we will not go into detail for describing the exact framework in earthquake risk modeling. Interested readers are encouraged to read ATC-13 document for details.

RMS has over the time developed a more robust earthquake risk modeling methodology to estimate earthquake loss and casualty. Its products have been widely used in the insurance and financial industry. Zifa Wang (2006) described the key components of the earthquake risk modeling methodology framework and expanded its application in earthquake resistance design practice. In 2006, Institute of Engineering Mechanics (IEM), China Earthquake Administration partnered with RMS, Inc. on applying the RMS methodology for earthquake risk analysis in China. The final product was released in March, 2007 which is currently used by a handful of international insurance clients.

This is the first of the two papers describing the application of the methodology in China. This paper concentrates on earthquake hazard, exposure and inventory while the second paper, which is written by Mohsen Rahnama, etc. (2008), concentrates on vulnerability and loss estimation.

2. Earthquake Hazard

In our probabilistic earthquake risk modeling, earthquake hazard is expressed as the ground motion at any given site. Ground motion is the excitation on the ground resulted from energy dissipated from the epicenter of an earthquake. To estimate the ground motion, we need to know the following information, the parameters of seismic sources that cause the earthquake which are often expressed as the potential location, the maximum magnitude, the rate of occurrence and the depth, the attenuation of the excitation due to wave propagation in the earth's media and the local site condition that affects excitation and input to engineering structures and infrastructures.

As described above, four things need to be decided for seismic sources: the location, the maximum magnitude, the rate of occurrence and the depth of the fault. Fortunately, China has a long history of earthquake catalogs. The earliest earthquake record in China literature can date back to more than 2000 B.C. (Ziqun Min， 1995), but the Chinese earthquake catalog usually includes earthquake started from 780 B.C. Figure 1 shows the epicenters of historical earthquakes from 780 B.C. to October, 2006 with a magnitude of 5 or above.

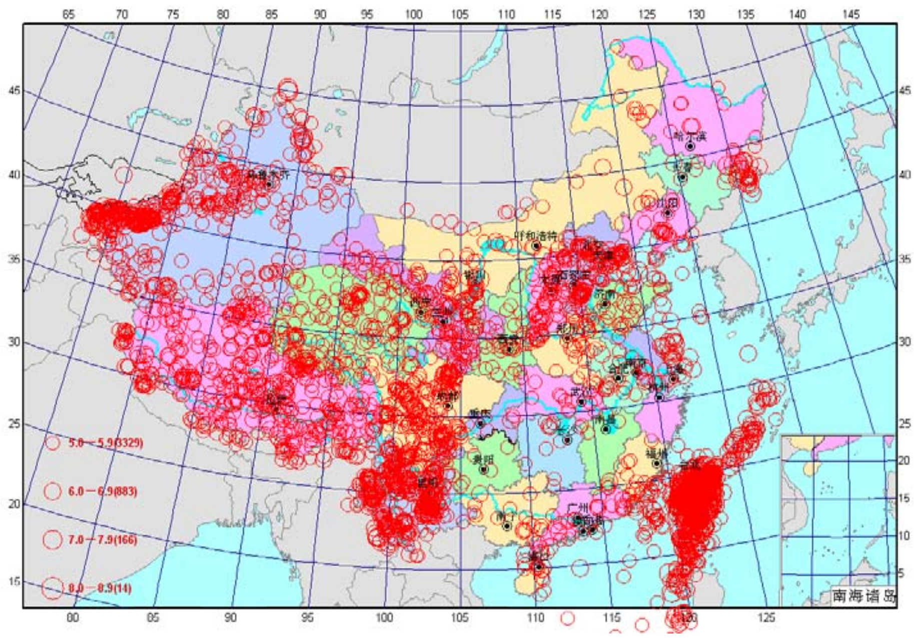


Figure 1 Epicenter of M5 or above earthquakes in China (780B.C. ~ October, 2006)

From Figure 1, we can clearly see that the historical earthquakes concentrated in certain areas. To correlate with historical study on seismicity in China, we started with the seismic sources which were used in China Seismic Ground Motion Zonation Map (China Earthquake Administration, 2001). In this version of seismic sources, as many others used in China, the whole Chinese territory in terms of seismicity is divided into 7 seismic regions and 4 sub-regions. These regions and sub-regions are then further divided into 20 seismic belts. To account for new findings after that study before 2001, we have modified the seismic source based on new knowledge coming from active fault detection, recent seismic activity and latest research results on seismicity and source parameter determination. In our earthquake risk modeling, in order to calculate the probabilistic occurrence of all the potential earthquakes in China, we have divided the seismic belts into line sources for simplicity of modeling. In order to model the earthquakes that happened outside the seismic belts, such as the 2005 Jiujiang earthquake in Jiangxi Province, we have added in background seismic sources covering all China. Maximum magnitude for these background events can be up to 5.5. Figure 2 (Zifa Wang et al, 2008) shows the divided line sources and the background sources used in our model. For the purpose of modeling all the possible occurrence of earthquakes, we divided the seismic belts into approximately 9,000 line sources, and the background sources contributed another 6,000 line sources. Altogether, we used close to 85,000 events from these 15,000 line sources to model all the possible combination of earthquake occurrence.

Associating with the 85,000 earthquake events, we need to estimate the rate of occurrence for each and every possible earthquake. Rate is calculated based on the historical earthquakes in the seismic regions and then distributed among belts based on their area size. Figure 3 shows the result for a typical G-R curve for the Tancheng-Lujiang belt, which is one of the longest and most active belts in the east part of the country. From this relationship, we can easily calculate the rate of occurrence for different magnitude bins, which can then be correlated back to the 85,000 modeled events. In Figure 3 we also show the plots from the result for zoning map and that from the catalog. From the figure we can conclude that the curve used in the model lies in between the catalogue and that used for the zoning map. The modification is based on new data that was recorded after year 2001, especially the small and medium size earthquakes, and new findings on active faults as well as the geologic study on return periods for large events.

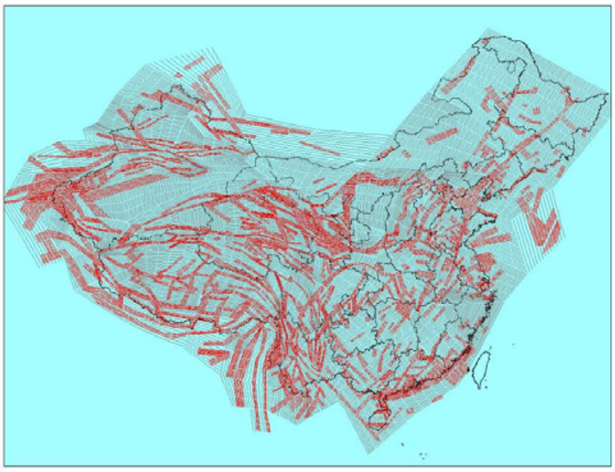


Figure 2 Seismic sources in China with background sources

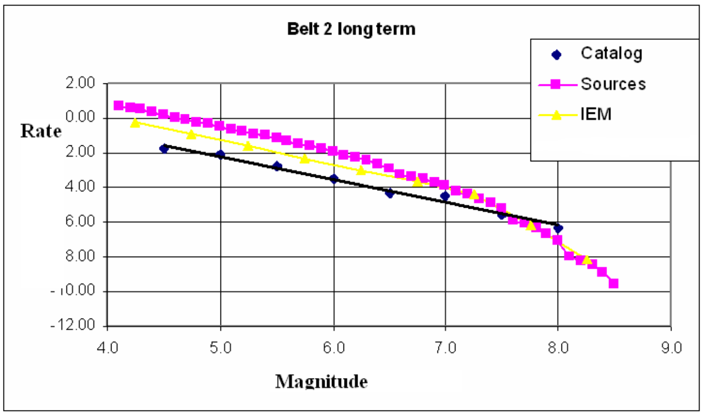


Figure 3 Seismicity map for Tancheng-Lujiang belt

The ground motion at a given site for hard soil can be calculated based on the following attenuation equation (China Earthquake Administration, 2001):

$$\text{Long axis: } \ln Y = 6.0805 + 0.5438M - 1.1924\ln(R+20) \tag{1a}$$

$$\text{Short axis: } \ln Y = 4.7868 + 0.5715M - 1.0727\ln(R+5) \tag{1b}$$

To account for the effect of local site conditions, we also obtained the digital soil map with resolution up to 1:200,000. RMS soil classification method is used to determine the soil types, which is a value between 0-7 and the liquefaction potential for all areas within China. These values can be further used to calculate the site amplification and potential liquefaction effect for any given site.

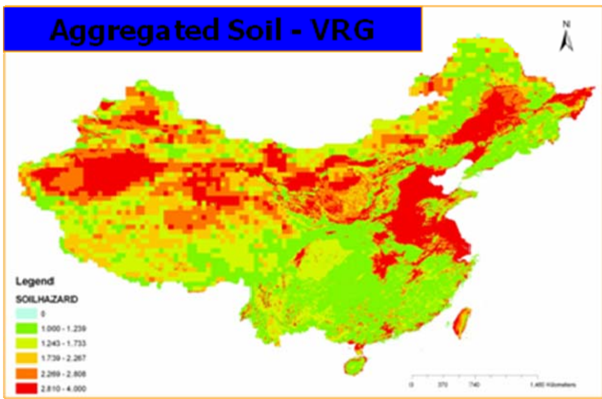


Figure 4 Soil types for China

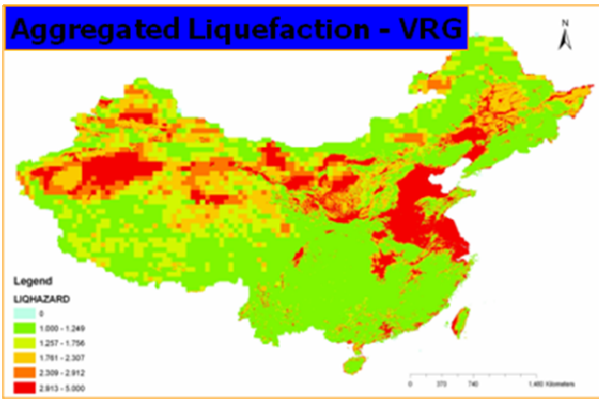


Figure 5 Liquefaction potential in China

3. Exposure and Inventory

Exposure is the value exposed to the potential threat of future earthquakes. Inventory is the distribution within and composition of exposure by different types of engineering structures and lines of business. It is very difficult to estimate the exact value of exposure and the inventory for every administrative district, so we tried to group China's inventory into the following 11 types considering the current economic condition and expansion in the country. These 11 types are as follows.

1. Beijing Type: for mega cities like Beijing and Shanghai;
2. Shenyang Type: for large cities like Shenyang, Harbin, etc.;
3. Tianjin Type: for medium cities like Tianjin;
4. Developed District Level City Type: for cities at the district level in the developed regions;
5. Developing District Level City Type: for cities at the district level in the developing regions;
6. Developed County Type: for counties along the east coast of developed regions;
7. Urban County Type: for counties near large cities or relatively developed counties;
8. Regular County type: for counties farther away from a large city or a medium developed counties;
9. Western County Type: for counties in the West or developing counties;
10. Tangshan Type: for new cities like Tangshan and Shenzhen, which were newly constructed;
11. Hong Kong Type: for Hong Kong and Macao.

For distribution within inventory, we consider two main aspects. One is the building classification, and the other is the occupancy types or lines of business. For building classification, we consider building types, the year of built, and the height of the building. Building material is the main factor in determining different building types, thus we only consider wood, adobe and brick, RC and steel structures in building classification. For year built, we believe that the impact from design code is much important than any other factor, therefore, we determined the year bins according to the issuance of new seismic design codes in China. Considering the actual situation in China, we used 5 height bins to group all the structures, that is, single story, 2-3 stories, 4-7 stories, 8-14 stories and 15stories or higher. For occupancy types, we only have three groups: residential, commercial and industrial. Based on census data and the year book for all the provinces in 2004, we can allocate absolute value amount to all the counties within China, which solves the exposure issue. For inventory, we sent students to cities like Shenyang of Liaoning Province and Sanya of Hainan Provinces to investigate and count the buildings on the site. This information is then used to extrapolate for cities we did not send people to. Figure 6 shows the distribution of a typical city in terms of height, year, and material for the engineering structures.

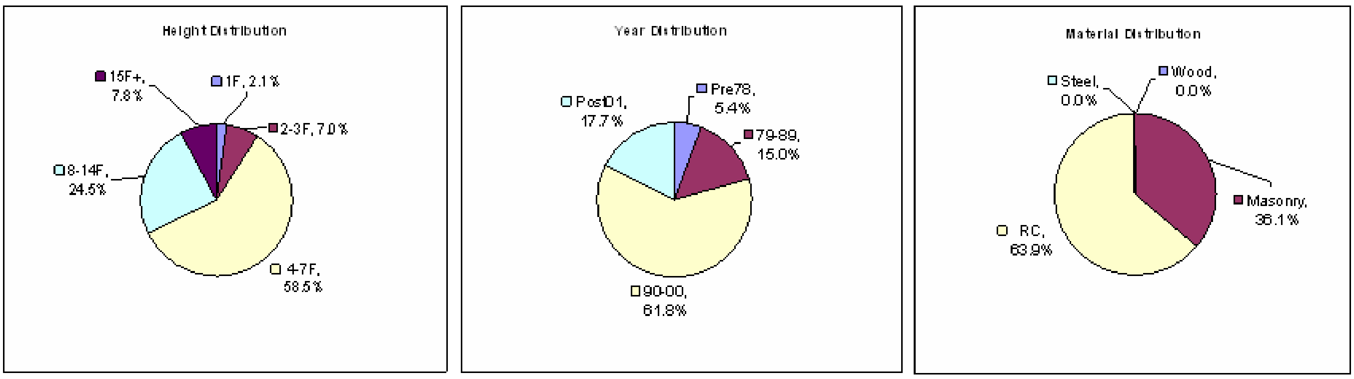


Figure 6 Typical inventory information for Shenyang-type city by height, year and building materials

4. Validation and Application

The second paper of this series by Mohsen Rahnama et al (2008) has provided a detailed report on the calibration of the earthquake risk model we have developed for China. Altogether we used six events to validate the proposed model, which are listed in table 1. These events represent the major earthquakes which occurred in China between 1975 and 2005 with detailed loss report, especially for Tangshan event, for which we had 6 volumes of data collected and analyzed. Therefore, Tangshan earthquake was the key event we calibrated our model against and the validation result looked promising, as shown in Table 1. In table 1, the modeled value is the amounted calculated using our model. The estimated value is the result of historical intensity with current exposure to reflect the current status of the modeling.

Name	Estimated	Modeled	Mod/Est
Tangshan 1976 M7.8	120,951	133,971	1.11
Haicheng 1975 M7.3	22,168	19,397	0.87
Lijiang 1996 M7.0	968	1,177	1.22
Baotou 1996 M6.4	2,572	2,229	0.87
Datong 1989 M6.1	182	203	1.12
Jiujiang 2005 M5.7	943	726	0.77
Six Event Combined	**147,784**	**157,703**	**1.07**

Table 1 Six selected events for validation

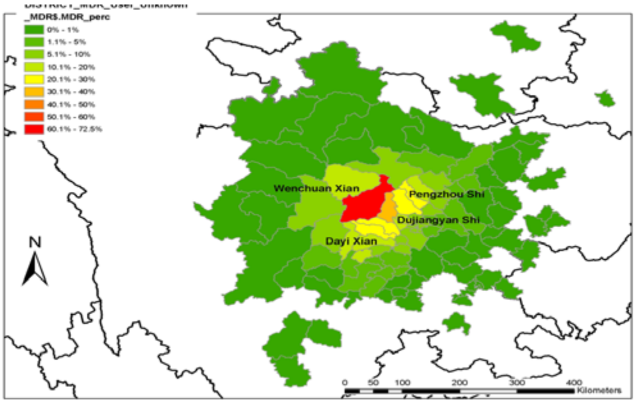
From table 1, it can be inferred that the proposed model can well simulate the recurrence of historical loss data. While there is a variation of less than 23% difference for a single event, the overall difference is only 7% with some events over-estimated and other events under-estimated. The variation demonstrated the good balance that a probabilistic model should achieve and verified the reasonable estimation from the developed model.

On May 12, 2008, a disastrous event with a magnitude of 8 struck Wenchuan area in Sichuan Province. Although the Chinese government responded with an unprecedented speed for emergency response, search and rescue, the consequence was still alarming. By July 10, 2008, there were already 69,197 people died and there were still 18,377 people missing with over 374,176 injured. Although the total direct economic loss has not be publicly reported, based on the feedback from IEM's staff to the field, the final number will be well ahead of 100 billion USDs, making it the worst event in China's history in terms of economic loss (Zifa Wang, 2008).

Institute of Engineering Mechanics, China Earthquake Administration, as the only national non-profit research institute on earthquake engineering, responded quickly by sending its staff within hours from the occurrence of the earthquake. IEM then continued to dispatch its staff to the field and at the peak time it had close to 70 staff on the field. 2 months after the event, IEM sent back another 50-plus member team, joined with people from other universities and research institutes, to collect valuable data from the earthquake damages for future research on earthquake engineering which includes calibration of the newly developed China earthquake risk model.

Within hours of the earthquake occurrence, RMS and IEM responded quickly with running the China earthquake risk model in the hope to estimate the extent of the damage from the event. Given the fact that at the time the only information available was the magnitude (7.8 at the time) and the location of the event, the model still gave an estimate that was far closer to the final number than that from most of the other models on the market. The initial estimates for direct loss and casualty for buildings only were around 15billion USD for loss and 22,000 for fatal casualty. This number was reported to CEA personnel on the field and was then relayed to the Premier on the site, which helped the Chinese government to make the decision to mobilize another 100,000 troops for emergency response, search and rescue efforts.

Figure 7 shows the modeled damage ratio and Figure 8 shows the estimated fatality distribution of the Wenchuan Earthquake. Using the exposure and inventory we developed in section 3, the final number for building loss was estimated to be close to 15billion USDs. Using the same dataset with population, the estimated fatal casualty from the Wenchuan Earthquake was around 22,000. Although both of the numbers were much lower than the final actual number, these estimates were the best ones at the time, with most of other estimates put the number at around 1/10 of our estimates. Another point we can infer from the modeled result is the distribution of loss and fatality among different counties. Our model estimated a much severe damage on the right side of the fault, which correlated well with the actual damage. There are a number of reasons why our estimates were off. 1) Our exposure data is only at county level, therefore, the distribution within the county could not be considered which could potentially have a huge impact because of fast attenuation in ground motion from the fault. 2) We only considered building loss and building damage induced casualty while in this particular event, lifeline loss and geotechnical failure contributed a large portion in the final result.



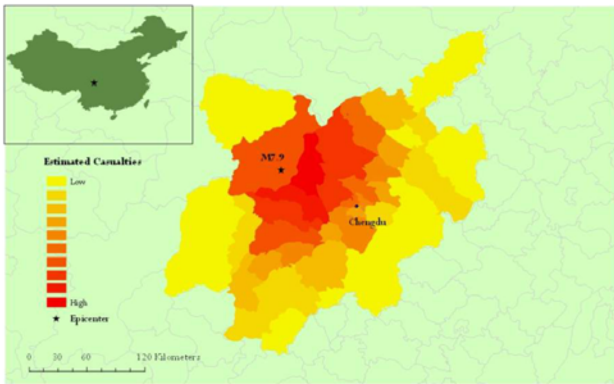


Figure 7 Building damage ratio for Wenchuan Earthquake   Figure 8 Casualty distribution of Wenchuan Earthquake

The developed model was also applied to predict the earthquake loss for the recurrence of both 1976 Tangshan and 1679 Sanhe-Pinggu earthquake. The total loss for the two events is estimated to be 414billion and 1.31 trillion RMB, respectively, making them the 3rd and worst event in China's history before Wenchuan Earthquake. The residential damage ratio distribution from Sanhe-Pinggu event is shown in Figure 9. From Figure 9 we can clearly see the impact of the event to especially the eastern side of the city. Please note that this number was based on the 2004 census data in China, and given the fast growth rate of GDP and vast increase of real estate price in Beijing, the actual loss could be much larger if such as event really repeats today.

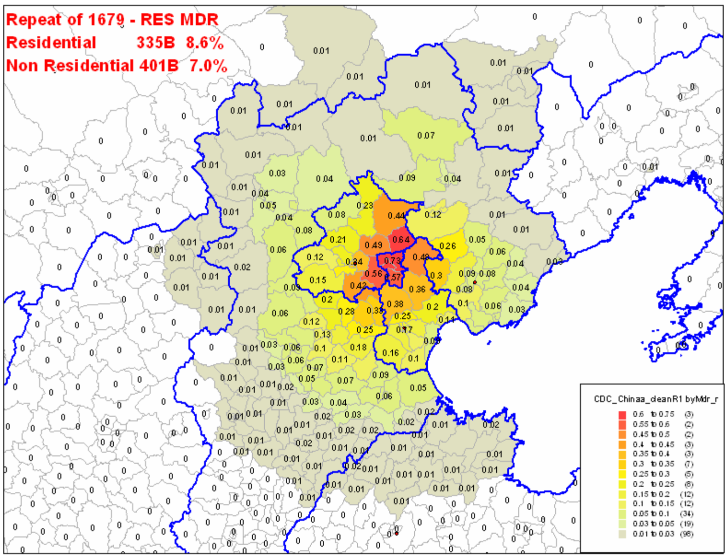


Figure 9 Residential loss for 1679 Sanhe-Pinggu Earthquake

5. Conclusions

Earthquake risk modeling is essential in earthquake disaster reduction. This paper, as part 1 of the reports, summarized the earthquake hazard, exposure and inventory for China earthquake risk analysis. With a long history of earthquake records in China, the seismic sources were well documented and the parameters were estimated based on historical events. Two attenuation equations were used to consider the effect of fault rupture and the latest digital maps on surface soil were used to determine the site amplification as well as the potential of occurring liquefaction. 11 types of inventory were proposed to account for the complex geographic distribution of exposure in China and the inventory proposed accounted for the difference of building material, year built, and the height of the building. The lines of business were also considered in the inventory for a better estimation. The proposed model was calibrated against 6 historical earthquakes in China with detailed damage and loss report. The calibrated model was then applied in China, especially for estimating the loss and casualty a few hours after occurrence of the May 12, 2008 great Wenchuan Earthquake. The fast estimates, although a little bit off from the final numbers, provided a good basis for government officers to make decisions on emergency response, search and rescue. This again validates the importance of an earthquake risk model from a non-traditional angle and thus provides a good opportunity to expand the application of the proposed China earthquake risk model.

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