CHINA PROBABILISTIC SEISMIC RISK MODEL
PART 2 – BUILDING VULNERABLITY AND LOSS ESTIMATION

M. Rahnama[1] Z. Wang[2] C. Mortgat[1], M. Masuda[1], F. Ahmad[1], L. Zhang[2]

[1] *Risk Management Solutions, Inc., Newark, CA, USA*

[2] Institute of Engineering Mechanics (IEM) *Harbin, China*

Email: mohsenr@rms.com

ABSTRACT:

In order to quantify the seismic risk of China, a probabilistic seismic risk model 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 second of two that focuses on vulnerability function development, building inventory and economic exposure development and probabilistic loss estimation. The first paper focuses on hazard quantification.

This paper describes procedures adopted in order to develop and implement building vulnerability functions to relate damage ratio (defined as dollar loss / replacement value) to spectra acceleration for individual building and building portfolio loss assessment. The Performance Based Engineering framework developed by the PEER researchers is implemented through the use of Incremental Dynamic Analyses (IDA) to develop the building vulnerability functions. Nine structure models, which represent a mix of Chinese building inventory, were designed using the Chinese building code. These structure models were subjected to roughly four hundred Chinese ground motions to perform non-linear dynamic analysis. The maximum inter-story drift of each story from time-history analysis is computed and related to a damage state and an associated damage ratio for both structural and non-structural components. In the development of fragility functions uncertainty associated with structural parameters and building damage thresholds were considered. This paper also highlights building inventory and exposure development, as well as the model calibration and validation process using key historical events such as the 1976 Great Tangshan earthquake for which good damage data is available.

KEYWORDS: Building Vulnerability, Fragility, Damage Assessment, Loss estimation

1. INTRODUCTION

In portfolio loss assessment, a vulnerability function quantifies the mean damage ratio (i.e., the average loss / replacement value) experienced by a "class" of buildings for a given intensity of ground motion. A class of buildings is defined using a broad set of building characteristics; e.g., number of stories, structural lateral system and construction materials. Further classification may be introduced based on the locality of the construction practices (e.g., design seismic zones) and the vintage of the building code (e.g., post 1976). These additional qualifiers allow the effect of regional and temporal variation of design and construction practices to be incorporated.

When vulnerability functions are developed using analytical methods such as IDA (Vamvatsikos and Cornell, 2001) [3] , it is customary to perform the analyses on a "typical" building model for that class that incorporates the variability due to material properties and damage thresholds. However, if the vulnerability functions are to be applicable to a class of buildings as it is used in portfolio loss assessment, the effect of many other contributors to vulnerability, such as the effect of structural geometry (e.g., number of bays and variation in story height), the variation of strength and stiffness over the height, and the relative proportioning of member strengths, need to be incorporated. A series of buildings were designed with different permutations of the parameters of interest using the provisions of different Chinese building codes. Analytical models of these buildings were subjected to a suite of ground motions to predict the transient maximum inter-story drifts and maximum floor accelerations used to quantify both structural and non-structural (drift- and acceleration-sensitive) damage.

Another key element of the portfolio loss assessment is the development of the regional building inventory and economic exposure, which is required for the reconstruction of historical events as part of the model calibration/validation process. The regional building inventory represents the Central Business District (CBD), urban, sub-urban and rural regions developed in collaboration with the IEM researchers. Also, the economic exposure for the different line of business that includes residential single and multi family, commercial and industrial was developed. Several recent earthquake events of different sizes were considered in the model calibration process.

The seismic risk profiles consist of exceedance probability losses, average annual losses and loss cost by region and line of business. These results provide insight to the key drivers of risk across the country. The model introduced in the paper can generate critical benchmarks for the insurance industry and will be a powerful simulation tool for the central and local governments in emergency response and risk mitigation strategy planning.

2. FRAMEWORK FOR EARTQUAKE LOSS ASSESSMENT METHODOLOGY

During the last few years, significant advances have been made to link building performance to ground motion characteristics and to both qualitatively and quantitatively describe the building performance at different hazard levels. Structural element capacity data and seismic demand parameters such as inter-story drift are used to describe the building performance for different hazard levels. Most importantly, these guidelines document information related to the damage threshold capacities of various structural elements corresponding to different levels of seismic performance. For the China model, building specific damage thresholds were provided for different construction classes by the IEM researchers using Chinese data. Probabilistic seismic demand estimates, along with information on capacities of elements and structures can be used to determine probabilities that exceed certain performance levels. The Pacific Earthquake Engineering Research (PEER) center has developed a framing equation (Cornell and Krawinkler, 2000) [2] for the performance evaluation of buildings. In the present study, the PEER framework is utilized for economic loss assessment based on building performance at the level of a single site as well as at a regional scale.

An accurate assessment of the seismic response of buildings is a complex problem due to the significant number of parameters that affect building performance during an earthquake. These parameters are also subject to uncertainty – for example, arising from the evaluation of material properties from tests, from simplified analytical modeling of building, from the effects of nonstructural components, from definition of building damage thresholds, and finally from inherent variability in ground motion characteristics. In this study, the PEER framework has been adopted for seismic Performance-Based Loss Assessment (PBLA) of buildings from an insurance perspective for site-specific as well as portfolio analysis. The details of the PEER approach have been addressed in many publications and its implementation in portfolio type analysis was discussed by Rahnama and Seneviratna (2004) [5].

In the software implementation, loss computations are performed using a vulnerability module and a hazard module. The hazard module computes the hazard at each building location using a set of predefined events, taking into account the effects of attenuation, surface geology and soil condition. The vulnerability module contains a set of pre-computed vulnerability functions for different types of construction and coverage. These functions express the probability of exceeding a given damage ratio (*DR*) for specified level of spectral acceleration (*SA*), i.e. $P\left[DR > dr \middle| SA = sa\right]$. This can be computed as:

$$P[DR > dr \mid SA = sa] = \sum_{i=1}^{m} \int P[DR > dr \mid DS = ds_i] P[DS = ds_i \mid IDR = idr] \mid dP[IDR > idr \mid SA = sa] \mid$$

in which $P\left[DS = ds_i \middle| IDR = idr\right]$ is the conditional probability of being in the damage state ds_i given that the maximum inter-story drift demand is *idr*.

In the IDA procedure, the structure is subjected to a series of time histories of increasing intensity. The hazard parameter chosen for this study, spectral acceleration at the fundamental period, is used to scale the ground motions to different levels of intensity. The total number of unscaled records at each level of spectral acceleration is insufficient; hence, scaling of the ground motions is necessary to be able to evaluate the seismic performance of buildings for the different intensity levels. The effects of scaling of ground motion records using PGA as well as $S_a(T_1)$ have been examined by several researchers, and the extent of scaling and its limitations depend on the characteristics of the ground motions (i.e., taking into consideration near-source effects, directivity, soil conditions, etc.) as well as on structural properties (such as period and strength). Therefore, careful review of the scaled ground motions is necessary to ensure that important characteristics of the unscaled ground motions such as frequency content are preserved.

3. DEVELOPMENT OF VULNERABILITY FUNCTIONS

3.1. Earthquake Ground Motions

For the time history analysis approximately 400 Chinese ground motions including 280 records from Taiwan with PGA equal to or greater than 0.10g at different soil conditions were selected. These ground motions were grouped by distance to the source (i.e., <15km, 15-50 km, >50km) and soil type. The normalized elastic strength demand spectra for these ground motions as well as mean and mean $+\sigma$ spectra are shown in Figure 1.

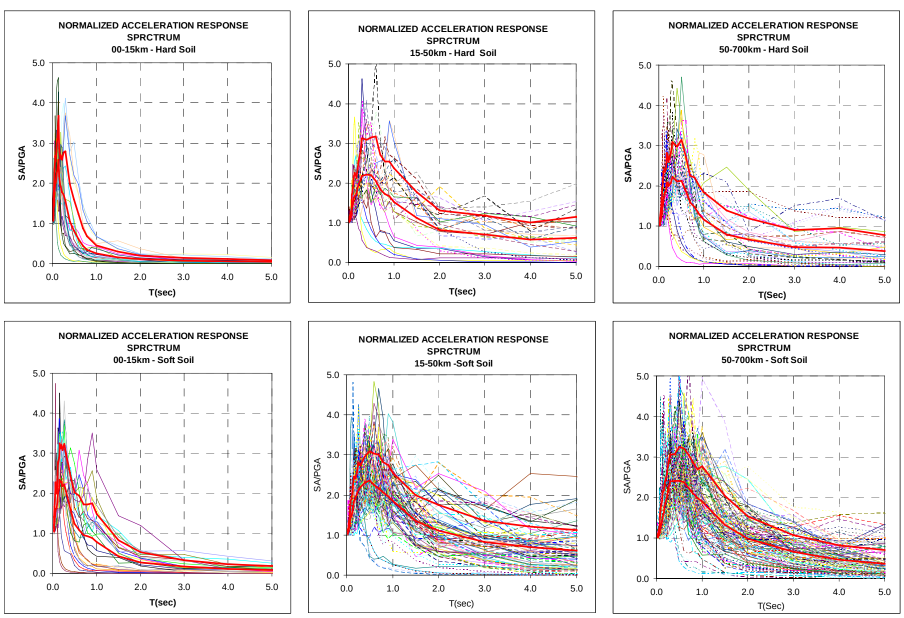

Figure 1 Normalized Elastic Strength Demand Spectra

3.2. Structural Models for the Incremental Dynamic Analyses

The first building code that addressed the design for seismic resistance of buildings in China was published in 1955. It was a translation of the seismic design code of the former Soviet Union. In 1959, the first required seismic design code was published. The code has undergone a series of revisions over time due to better understanding of the structural performance of buildings during the significant earthquake events during the last four decades. A major upgrade to the code took place as a result of the 1976 earthquake and it covered a wide spectrum of the code's scope. The seismic design code enforcement is implemented in cities, but not in villages, small towns or rural areas.

The regional building inventory includes a mix of different building characteristics such as construction, year built, and number of stories. For this study nine typical Chinese reinforced concrete and steel structure buildings with 2, 6, 12 and 20-stories were designed using different versions of the Chinese building code to represent old and new buildings in the regions. The Drain-2DX analysis program was used to perform a comprehensive set of the nonlinear time history analyses using Chinese specific ground motions and structure models. Approximately 400 ground motions were used for the time history analyses at each scaled level of spectral acceleration. Additionally, for each ground motion considered, permutations on the structural properties were introduced to account for uncertainty associated with the capacity evaluation of the structural elements.

3.3. Building Fragility Functions

The economic loss assessment in earthquake events is based on a probabilistic approach that takes into consideration inherent uncertainties in the prediction of ground motions, seismic demands on buildings, and damage assessment of the buildings. The probabilistic relationship between structural damage and seismic demands is characterized by a fragility function, which expresses, for example, how a building damage ratio is related to the intensity of the ground motion.

Fragility curves express the probability of reaching or exceeding specific structural damage states as a function of seismic demand parameters such as spectral acceleration, displacement, or the inter-story drift ratio. Building fragility curves for any damage state are obtained by evaluating the conditional probabilities of being in, or exceeding that damage state, given different levels of the seismic demands. The computed fragility curves take into account variability and uncertainty associated with the ground motions, with the structural elements' capacity evaluations, and with the selected thresholds that define the building damage states. In this study, four discrete damage states (corresponding to slight, moderate, extensive, and complete damage) are utilized to characterize the physical condition and state of the building damage.

These seismic demands are utilized along with the specifed performance criteria to define the building damage states and subsequently measure the performance of structural and nonstructural components in the buildings. Many research publications and guidelines/standards from different countries provide recommendations regarding building damage thresholds expressed in terms of inter-story drift ratios, plastic rotations, and other seismic demands to characterize building performance. These structural and nonstructural damage thresholds have generally been based on results from experimental tests on building components as well as from observations during post-earthquake building surveys.

Several thousand nonlinear analyses were performed in order to take into account the variability of the ground motions, the structural response, and the defined damage thresholds while developing the fragility functions. These fragility curves are then used to develop building vulnerability functions, which express the expected losses (normalized by the total replacement value) in terms of ground motion intensity.

Figure 3 illustrates fragility functions for the 6 story reinforced concrete frame building. This *CDF* describes the probability of non-exceedance of a

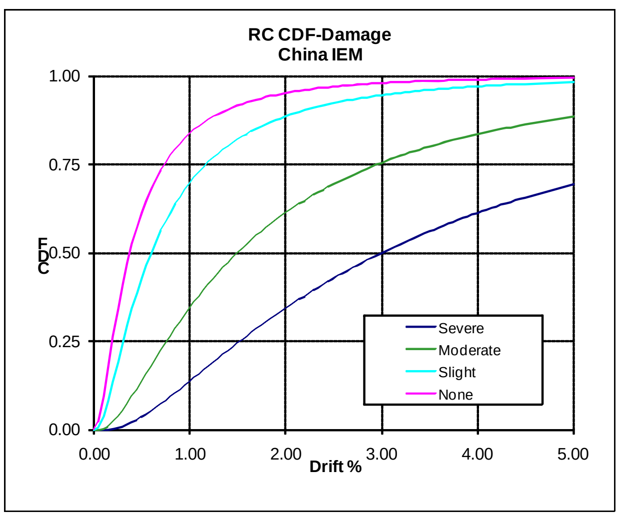

Figure 3. Fragility functions of 6-story RC Structure

given damage state, which is computed using the maximum inter-story drift as a measure of the story damage.

In order to investigate whether simplified MDOF stick models might be adequate for the development of building vulnerability functions, similar types of MDOF stick model analyses were carried out with the actual complete structure model. The MDOF stick model structures were then subjected to the same set of scaled ground motions and the same damage thresholds were utilized to develop the fragility functions and, subsequently, the building vulnerability functions. The MDOF stick model and actual frame model vulnerability functions for the 6-story reinforced concrete buildings are shown in Figure 4. The plots show the mean structural damage ratio expressed as a function of spectral acceleration. As indicated in the figure, the MDOF stick model based damage ratios are very similar to the actual frame analysis results. The use of the MDOF stick model is computationally much faster than the actual frame model, which enables performing extensive number of analyses to account for all sources of model uncertainty (i.e., structural capacity, damage thresholds, ground motions, etc.).

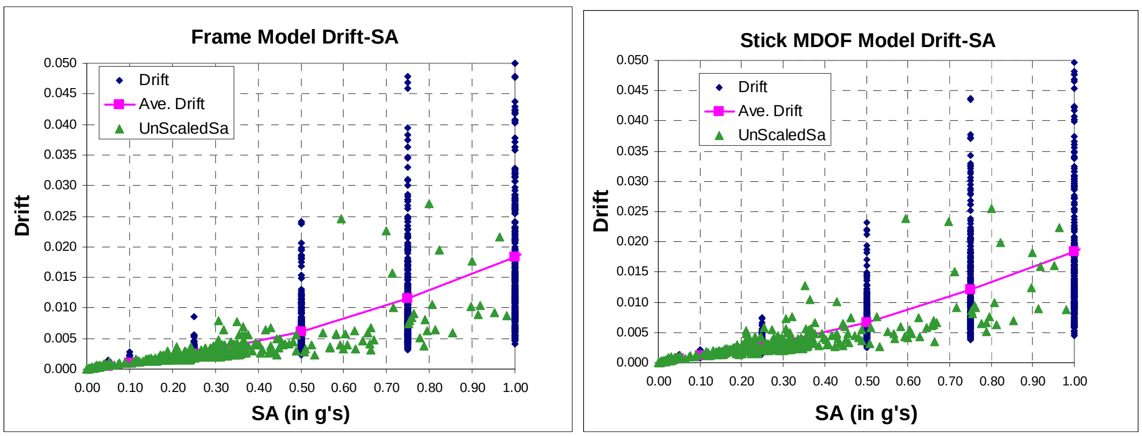

Figure 4 Building vulnerability functions for 6-story reinforced concrete buildings

4. BUILDING INVETORY AND EXPOSURE DEVELOPMENT

The building inventory database in China was derived from a combination of societal, economic, housing and population statistics. The inventory distribution is designed to develop composite vulnerability curves based on the building material, year built and height distribution for a given region and occupancy. Eleven different inventory regions were introduced to account for characteristics of the regional building stocks, which represent five central business districts, two medium sized cities and four rural areas. Figure 5 shows the typical inventory

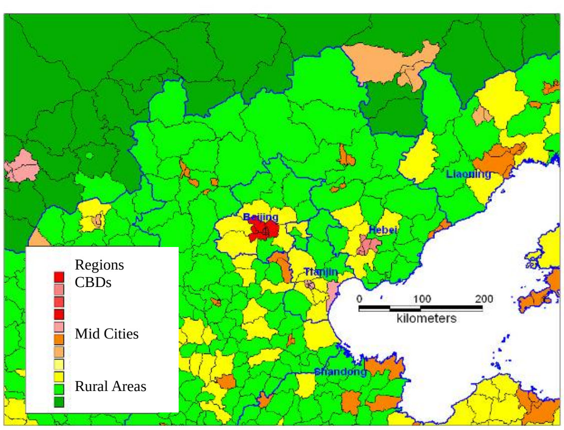

Figure 5 District level inventory mapping (Beijing and vicinity)

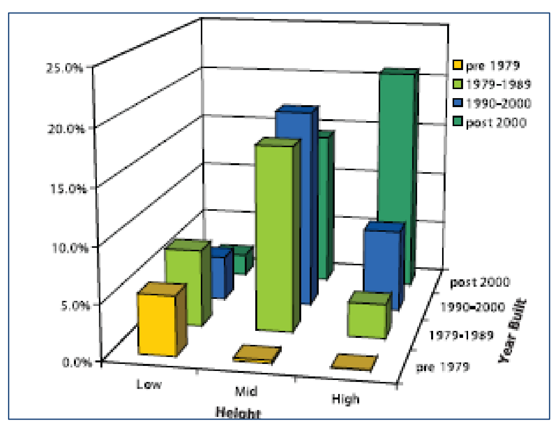

Figure 6 Commercial exposure breakdown in Beijing urban region

mapping in the vicinity Beijing and Figure 6 represents the breakdown of commercial exposure by year built and height in the urban area of Beijing.

The exposure database was developed primarily based on census and construction year books. The building values for each district per occupancy are estimated using total floor areas in the region associated average construction costs for a given occupancy. Content values were also estimated based on occupancy classes. Thus, the exposure represents combined value of buildings and contents for residential, commercial and industrial exposure. A detailed discussion of the exposure development is given in part one of this paper [8].

5. MODEL CALIBRATION VALIDATION

After the completion of the economic exposure and vulnerability functions development and the implementation of the ground motion attenuation function and soil amplification model, the next step is the overall model calibration and validation process. This process involves collecting the damage surveys from past events, which include number of damaged and collapsed buildings, published intensity maps, ground motions footprints, economic loss data and reconnaissance reports. For the historical earthquake event reconstructions for the China model, several recent major as well as small events where the detailed damage survey was available were used. The highlights of 1976 Great Tangshan earthquakes calibration process are discussed below.

1976 Great Tangshan Earthquake

The Tangshan earthquake with magnitude 7.5 M_w was initiated at a shallow depth (11 km) below the city, with the rupture extending to northeast and southwest along the fault system for a total of approximately 100 km. An extensive evaluation of the levels of damage and ground shaking was completed to determine the extent of ground motion intensities. Damage to brick smokestacks, water tanks, and various types of buildings, as well as observed ground failure were used to determine these intensities. According to the Chinese Seismic Intensity Scale (approximately consistent with Modified Mercalli Intensity Scale), maximum intensities exceeded X throughout downtown Tangshan and caused irreparable damage. Overall, the earthquake was felt in twelve provinces or autonomous regions and in the cities of Tianjin and Beijing. The earthquake was felt for at least 800 km in all directions. Intensities reached IX in small portions of Tianjin with most of the city intensity level VII. In Beijing, intensities were primarily VI with localized areas reaching VIII relating to soil liquefaction.

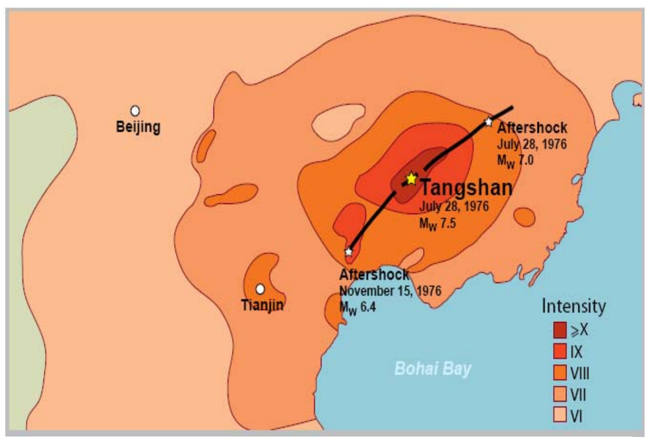

Figure 7 Intensity map of 1976 Tangshan earthquake

At the time of the earthquake, the area encompassing Beijing, Tianjin, and Tangshan in northern China was heavily developed. In these regions in general, buildings constructed before 1949 sustained more damage than those built after this date, as the study of earthquake resistance design did not begin in China until the 1950s. However, while there was improvement in the design code over time, the seismic design code in force at the time of the earthquake (the 1974 code) designated the Tangshan area as a low seismicity region. Structures were built according to design intensity VI with no consideration for earthquake resistances. Many residential unreinforced masonry buildings collapsed due to the lack of proper connections between the walls and roof, as did many reinforced concrete and masonry industrial buildings with heavy roofs.

Figure 8 shows the residential damage ratio footprint using 5km uniform grids due to the 1976 Tangshan earthquake. Damage ratio at the epicentre regions is 70%, which is very high due to the poor performance of the masonry and non-seismic design buildings. Damage ratios by distance decay due to decrease in the ground motion intensity. Figure 9 illustrates the building damage ratio comparison between the model and estimated actual loss ratios by distance.

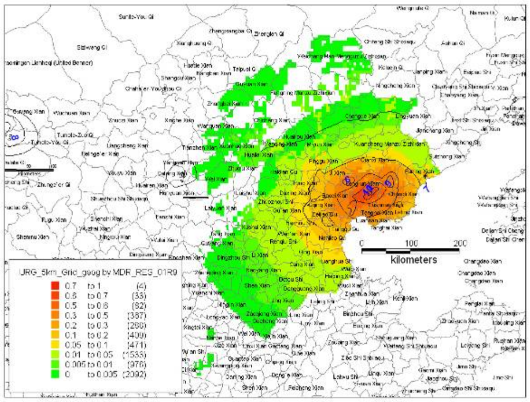

Figure 8 Damage ratio footprint for Tangshan M7.8 earthquake

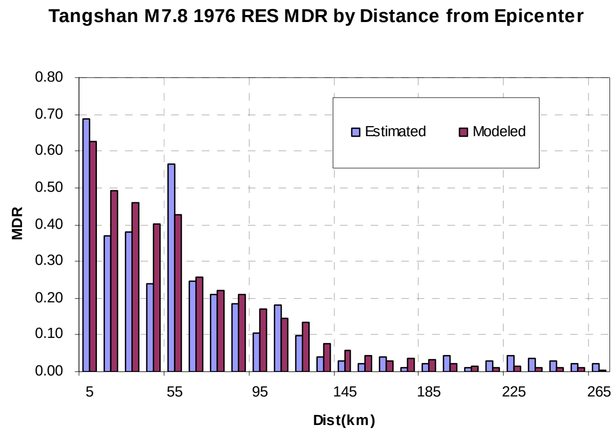

Figure 9 Damage ratios comparison by distance

The Tangshan earthquake highlights the extraordinary potential for loss of life and economic disruption when a major earthquake occurs directly beneath a large city. However, there are two main points that must be highlighted about a repeat of this event: the expected recurrence and the building stock. First, given the release of strain associated with the earthquake, a repeat of a similar event on the Tangshan fault has an extremely low probability. The same is not true for other parts of China as was shown recently in the May 2008 M_w 7.9 Eastern Sichuan earthquake. Second, given the nearly total reconstruction of Tangshan city after 1976, the quality and vintage of the building stock today is unique in the Chinese landscape as compared to other cities. The area affected by the Tangshan earthquake included the Hebei province, which contains Tangshan, as well as Beijing, Tianjin and several counties of the Liaoning province. According to government statistics, the total population in 2006 in the Hebei province, Beijing and Tianjin is over 89 million. The population of Tangshan is 2.96 million, nearly three times the population in 1976. After the event, the zoned intensities were adjusted to VIII in Tangshan, Beijing and Tianjin, and earthquake resistance building designs were widely used in these areas. If a similar event were to recur today, the performance of the building in Tangshan would be much better than the old building stock. In particular, the reinforced concrete structures designed according to the newer codes would be much less vulnerable to damage and collapse.

The direct economic loss from the Tangshan earthquake has been estimated at around 28 billion RMB or $10 billion USD (1976 dollars). If the event would to recur today, this figure would be significantly higher due to the increase in building and population density despite the fact that the seismic resistance of buildings has improved. At today's values and rapidly expanded building stock, it is expected that the economic loss from a repeat of the earthquake would be comparable to the loss following the 1995 Kobe Japan earthquake, in range of $100 billion USD.

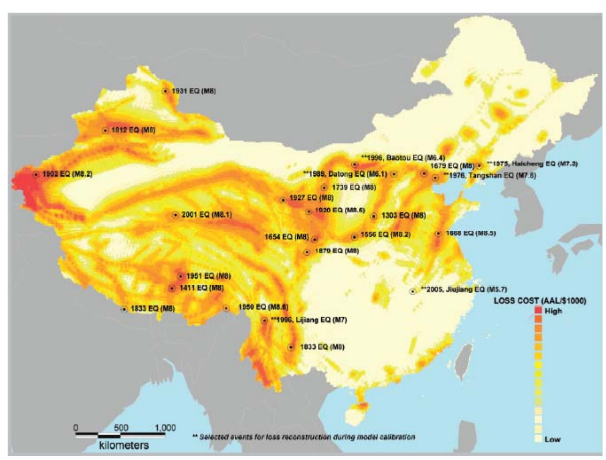

Figure10 Earthquake risk map of mainland China

Figure 10 shows the earthquake risk map of mainland China, in terms of the loss cost (average annual loss ALL per US$1000 exposure) for the residential building stock, based on the RMS China Earthquake Model. The hot color regions represent the area with the highest seismicity. Basically, since the map is in normalized form, it represents the seismicity or hazard map of China.

6. CONCLUSIONS

Over the past decade, China has undergone significant economic development. According to the Ministry of Construction, between 2001 and 2005, the country built 2.7 billion square meters of new housing for urban residents, along with equivalent amounts of commercial and industrial development. The repeat of major historical events such as 1679 Sanhe-Pinggu could cause catastrophic damage and significant casualties. A clear example of such a scenario is the May 2008 M_w 7.9 Eastern Sichuan earthquake, which killed about 80,000 people and destroyed a significant number of buildings and infrastructures. Therefore, it is essential to develop a model than can be used to quantify the risk throughout the country for emergency response, risk mitigation, strategy planning, and risk assessment. The China model introduced in this paper is a powerful simulation tool which can generate critical benchmarks for decision making by central and local governments, as well as industry to better understand the earthquake risk.

The paper discussed the methodology for developing building vulnerability functions using Chinese structure models and ground motions. The incremental nonlinear dynamic analysis approach is used to compute the seismic demands for increasing levels of intensity to develop vulnerability functions. The performance based loss assessment methodology for developing building vulnerability functions, which links ground motion characteristics (hazard) to the building response (vulnerability), is a very transparent approach and permits an objective evaluation of building performance. In order to account for the uncertainty related to the structural properties, building response evaluation, and building damage thresholds, a significant number of simulations were performed to capture all the variability in developing the building vulnerability functions.

As part of this study, a detailed building inventory and economic exposure were developed in collaboration with the IEM researches. For the model calibration, several recent earthquake events of different sizes, such as the Tangshan 1976 M7.8 and Jiujiang 2005 M5 were utilized. Also, as part of the model development process repeat of major historical events, such as 1679 Sanhe-Pinggu, were studied in great details.

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