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Seismic Loss Estimation and Reduction after Structural Rehabilitation in Chiang Rai City

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Abstract

Chiang Rai is located in the North of Thailand. The city is in a seismic risk region in which many buildings have inadequate building code enforcement. This paper presents a spatial study of the seismic performance of buildings in Chiang Rai city to establish an earthquake scenario with an assumed magnitude of 5 on the Richter scale. The results of the building damage show that areas that suffer the most occur in a high density building zone. The extent of building damage in the area was about 400,000 m^2 in every 1 km^2, or 24.79 % of the entire area. The number of human losses was calculated for 2 different times; there were about 712 deaths during the nighttime (at 2:00 AM), and 1,027 during the daytime (at 2:00 PM). Finally, the earthquake risk mitigation team was able to initiate the rehabilitation of some important existing structures to improve their seismic performance, which was carried out under moderate-seismic activity. The important buildings considered here were hospital/emergency services buildings, schools, and government offices, which resulted in the highest consequences. The reduction of the complete damage of those buildings was more than 49 %, and human losses were reduced 75 % during the nighttime and 70.85 % during the daytime. As a result, this information is a good source for government officers to use as a tool to initiate preparation plans against a repeat of this kind of disaster.

Keywords: Loss estimation, earthquake, rehabilitation, Chiang Rai, building damage

Introduction

Ground shaking induced by earthquakes, if large enough, can result in huge losses of life, mainly caused by building collapse. Hence, appropriate building design methods for earthquake resistance have been intensively developed. However, many buildings were constructed before the emergence of the best earthquake knowledge. In other words, the earthquake resistive building design methods have been developed based on what has been learnt from past earthquakes. Especially for the moderate seismicity areas, in which earthquake preparation measures are limited, many buildings were constructed without seismic consideration. Northern Thailand has long been considered as a non-seismic area and, therefore, many of the buildings in the area are vulnerable to structural damage, as the structure has inadequate seismic code enforcement. Chiang Rai province is one of the highest earthquake risk areas, consisting of the Mae Chan - Chiang Saen fault and the Phayao fault, and can cause earthquakes of magnitude 6.0 - 6.5 on the Richter scale [1]. The maximum peak ground acceleration area from the earthquake, every 475 year period, is approximately 0.2 g on solid rock [2-4]. The recent big Mae Lao earthquake, with a magnitude of 6.3, occurred on May 5, 2014, and caused approximately $28 million in damage (**Figure 1**). The epicenter of the earthquake was about 7.4 kilometers underground in Dong-Mada Sub-District, south of Mae Lao District and 27 kilometers southwest of Chiang Rai city, Thailand [5]. The earthquake was recorded as being strong, shaking both Northern Thailand and neighboring Myanmar. It was the strongest earthquake ever recorded in Thailand, according to the National Disaster Warning Center of Thailand [6]. Although the country has long been considered as having low seismicity, the present historical seismicity has resulted in the city being classified as a moderate risk zone [7].

As an earthquake involves rapid shaking, there is no prior warning. It is well recognized that the best way to manage this kind of disaster is to establish adequate preparedness. With the trend of providing preparedness, there have been a number of researchers concerned with earthquake loss estimation. Yeh *et al.* [8], Molina *et al.* [9], Reza *et al.* [10], and Wood *et al.* [11] developed analysis modules in order to make an early loss estimation system. A Taiwanese city earthquake loss estimation was performed and a mitigation plan was proposed based on their results. In the work of Nordenson *et al.* [12], the earthquake loss estimation for New York City was conducted, providing a better understanding of how businesses and agencies create an effective mitigation plan to reduce potential damage and losses to life from future earthquakes.

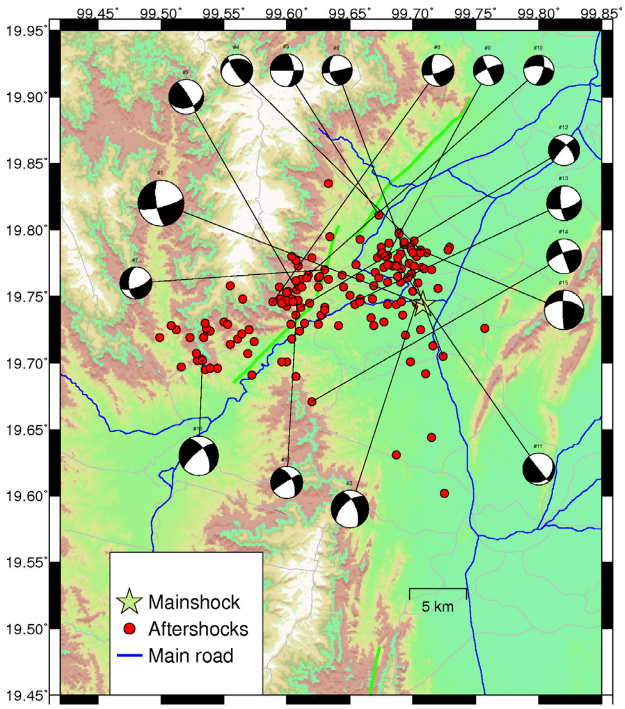

Figure 1 Mainshock and aftershock characteristics within 24 h on 5 May 2014, Pananont *et al*. [13].

Most damage and deaths caused by earthquakes are directly or indirectly as a result of ground shaking induced building collapse. This study focuses on a spatial study of the seismic performance of buildings in Chiang Rai city, to establish an earthquake scenario with a magnitude of 5.0 that can lead to corresponding seismic scenarios. While the HAZUS [14] approach is attractive, it is tailored so intimately to U.S. situations that is difficult to apply it to other environments and geographical regions. In this study, GIS-based software (e.g., ArcGis), using the computational scheme of HAZUS, was used, in conjunction with local information, as a tool for this spatial analysis. The results of the study will enable forecasting capabilities, which would be useful in anticipating the consequences of future earthquakes, and for developing plans and strategies for reducing risk. The collapse of buildings was first estimated, and the number of death caused by the building collapse was approximated. Much research in the past has resulted in earthquake scenarios, to encourage building rehabilitation, but it has not shown the measures needed for loss reduction. This study developed earthquake scenarios in Chiang Rai city to estimate the seismic losses and changes after upgrading some of important buildings. The aim of this study was to make people aware of, and show them the benefits of, upgrading some selected important buildings for seismic loss reduction.

Methodology

The work for this study was divided into 3 steps. The first step was to estimate the level of building damage. Secondly, with the building damage estimation completed, loss of life was approximated. Finally, loss estimation was developed for the structural upgrading of a select number of important buildings.

Building damage estimation

The building damage estimation in this study was based on the concept of the Capacity-spectrum method. This method combines the ground motion input in terms of the response spectra (spectral acceleration versus spectral displacement, as shown in **Figure 2**) with the building's specific capacity curve, varying in building type, construction quality, and local building regulations. Using the assumption of similar structural performances, the capacity curves for 36 US building types developed by FEMA [15,16] were used in this study. The curves have been adopted in earthquake damage estimation in a HAZUS analysis. It is noted that structural performance of the existing buildings were assumed to comply with pre-seismic code construction regulations.

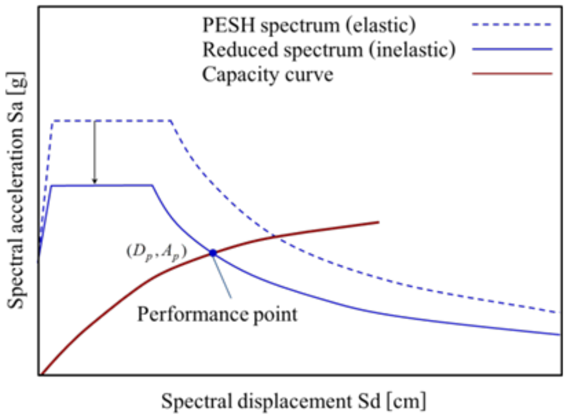

Figure 2 Capacity-spectrum curves [15,16].

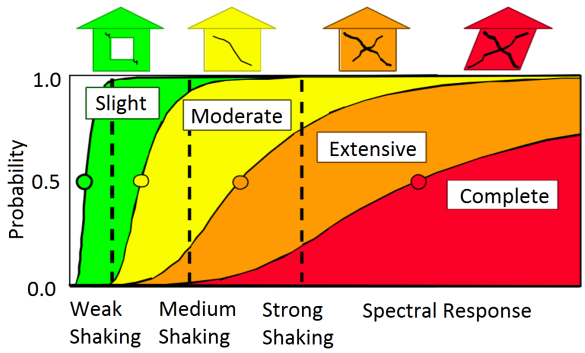

Figure 3 Fragility curve [15,16].

For each given building type, and considering the performance points (**Figure 2**), displacements induced by an earthquake can be defined, and the values used to compute the probability of damage in each of the 4 damage states (slight, moderate, extensive, and complete), as seen in **Figure 3**. This probability is subsequently used in spatial analysis to express the results in terms of a damaged area.

The first step to perform loss estimation was to select the study area. Building inventory in the area was classified to allow identification of an appropriate capacity curve. The generation of demand curve, magnitude, and epicenter location of scenario earthquakes was selected based on the records from historical earthquakes in the study area. In order to evaluate the ground shaking intensity and peak ground acceleration, the local soil condition and attenuation were computed.

Approximation of number of deaths

The number of people in the study area was first estimated, based on the building occupancy rate. The calculation of the number of human casualties basically follows the HAZUS approach (**Figure 4**). The number of casualties due to direct structural damage for any given structure type, which does not consist of non-structural damage, level of building damage, or injury severity, can be calculated by Eqs. (1) - (2). However, the loss model applied here considered the level of severity as meaning those instantaneously killed or mortally injured.

$$P_{killed} = P_A \times P_E + P_B \times P_F + P_C \times P_G + P_D \times (P_H \times P_J + P_I \times P_K) \tag{1}$$

$$EN_{Occpants\ killeds} = N_{occupants} \times P_{killed} \tag{2}$$

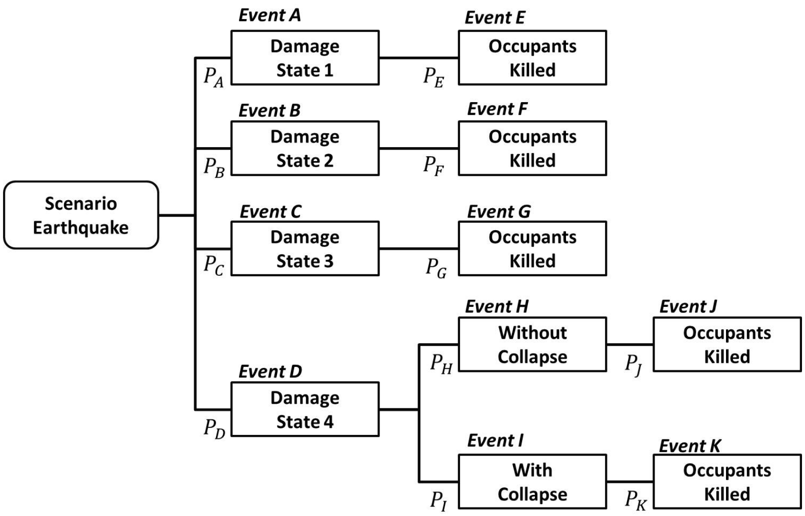

Figure 4 Casualty event tree model [17,18].

Due to the different activities during one day, the numbers of casualties were computed for 2 different times, e.g., nighttime (at 2:00 AM), and daytime (at 2:00 PM), respectively. At nighttime, people usually stay at home. However, during the daytime, people are assumed to be working outside, and are more likely to be in densely packed public and assembly buildings.

Re-estimation of losses after structural upgrading

The same methodology for estimating buildings damaged and numbers of casualties, mentioned above, were re-applied after the rehabilitation of a selected number of existing structures to improve their seismic performance. Buildings of higher importance, such as hospital/emergency services, schools, and government offices, were selected for rehabilitation. The performance of the rehabilitated buildings that were required to conform with regulations for moderate-seismicity is not mentioned here, but the rehabilitation method required more sophisticated study. **Figure 5** shows the performance comparisons between the existing and upgraded buildings.

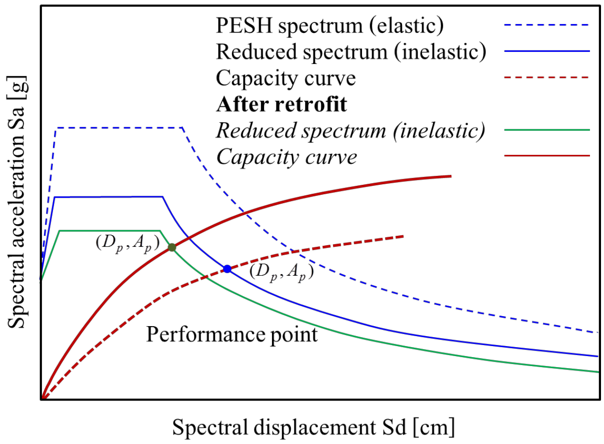

Figure 5 Capacity-spectrum curves after rehabilitation.

Site description and scenario earthquakes

The study area was Chiang Rai municipality. To perform spatial analysis, the area was divided into 1,379 census tracts (size 250×250 m^2), over an area of about 79.3 km^2, as shown in **Figure 6**.

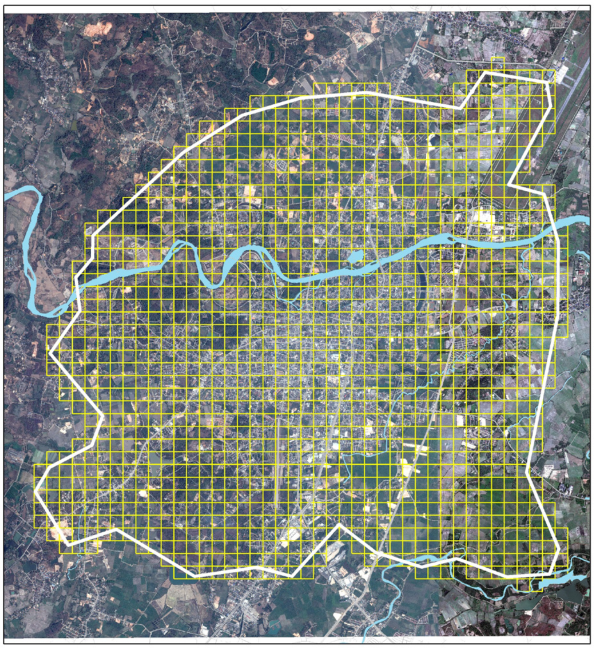

Figure 6 Study area showing the positioning of the 1,379 Census tracts.

Building classification

Building regulations for seismic design in Thailand commenced in 1996. It can therefore be said that most buildings in Chiang Rai have been designed without consideration of seismic effect. Therefore, a pre-seismic design level was assumed for the analysis. **Table 1** shows the structural type of buildings in Chiang Rai city. The structural type was defined according to the NEHRP Handbook for the Seismic Evaluation of Buildings - A Prestandard [19]. Most of them were classified as C3, or Low-rise reinforced concrete frames with unreinforced masonry, infilled walls, and within the residential building category type. **Figures 7 and 8** show the spatial distribution of structural types of the buildings and the building categories. Based on the building occupancy, the number of people in the analyzed buildings was roughly estimated. The estimated number of people in the area was 276,688 during the daytime, and 195,194 during the nighttime.

Table 1 Structural type of buildings in the study area.

Building type	Structural type											Grand Total
	C1	C2	C3	S1	S2	S3	URM	W1	W1C3	W2	W2C3	
Assembly	9		38	2								49
Commercial	122	160	5,515	17	12	10		126	49	8	3	6,022
Emer. Services	12	10	223					5				250
Government	28	4	622	3				42	6	6		711
Historic	21		301				24	18	58		7	429
Hotel	2	24	185	1				1	1	3		217
Industrial	48	1	348	19	8	12		15	7	2		460
Office	20	18	277	6		1	1	2	7			332
Other	116		2,180	9	1	3	5	146	29	2		2,491
Residential	1,140	86	30,372	79	9	5	4	2,155	1,193	201	6	35,250
School	25	26	434					3	62	1	13	564
Grand total	1,543	329	40,495	136	30	31	34	2,513	1,412	223	29	46,775

where
- C1 is concrete moment-resisting frame buildings
- C2 is concrete shear-wall buildings
- C3 is concrete frame buildings with unreinforced masonry infill walls
- S1 is steel moment-resisting frame buildings
- S2 is braced frame buildings
- S3 is light metal buildings
- URM is unreinforced masonry bearing-wall buildings
- W1 is light wood-frame buildings smaller than or equal to 464.52 m^2 (or 5,000 ft^2)
- W2 is light wood-frame buildings larger than 464.52 m^2 (or 5,000 ft^2)
- W1C3 is combination structure light wood-frame and concrete frame buildings with unreinforced masonry infill walls smaller than or equal to 464.52 m^2 (or 5,000 ft^2)
- W2C3 is combination structure light wood-frame and concrete frame buildings with unreinforced masonry infill walls larger than 464.52 m^2 (or 5,000 ft^2)

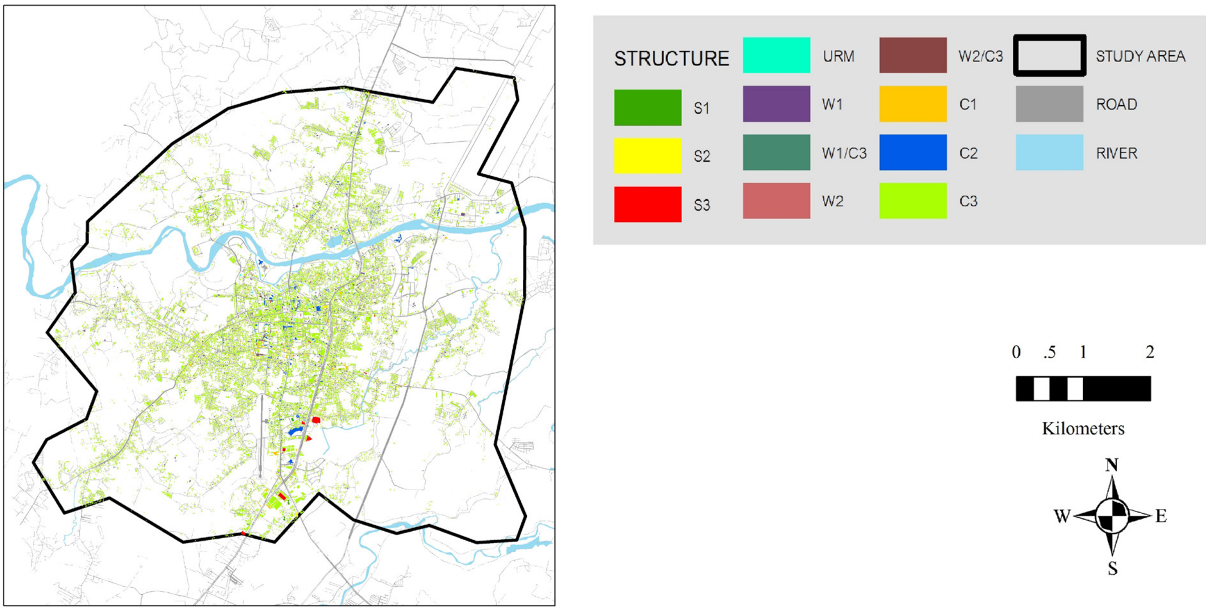

Figure 7 Distribution of structural types of buildings.

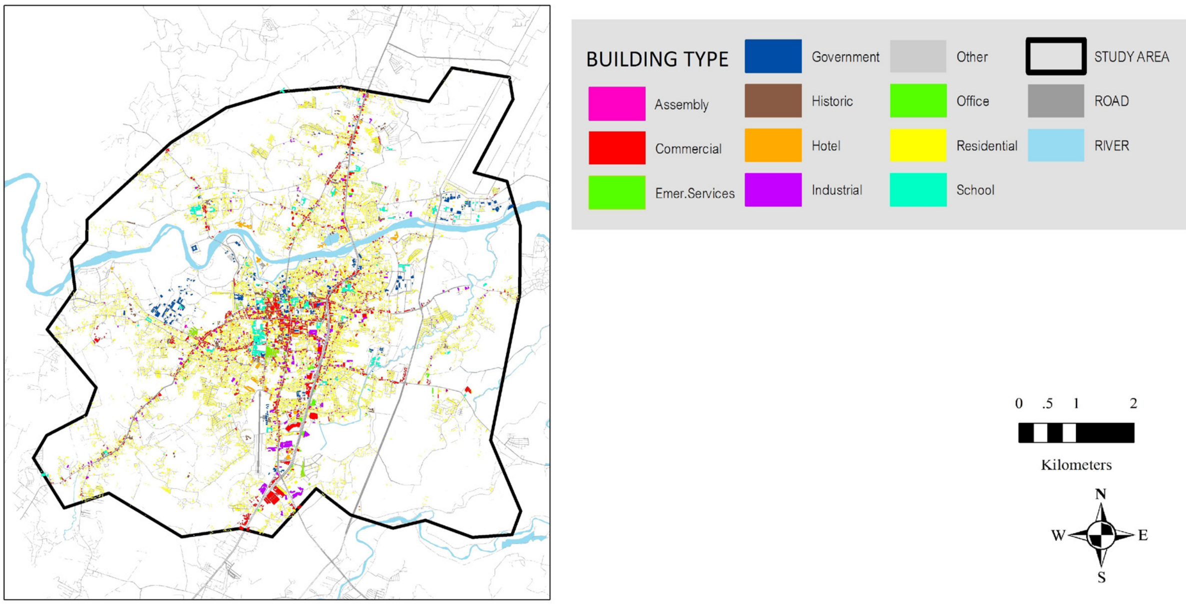

Figure 8 Distribution of building types.

Soil classification

The ground motion at a specific site may be amplified through its soil profile, depending on the soil conditions. By using shear velocity, the soil conditions at a site can be classified as A through E [20]. In this study, based on soil investigations, most of the area can be classified as D class, or Stiff soil, with shear velocity between 180 and 360 m/s, and was used in the analysis.

Attenuation relationship

Attenuation laws are typically used to determine the level of earthquake intensity at the bed rock depth for the considered sites. Through the attenuation model, the peak ground acceleration, velocity, and displacement at the considered sites can be estimated. Although, currently, numerous attenuation laws have been published and are available to use, the one that is most appropriate for the site conditions and ground motion type must be carefully selected. In this study, based on the fault moving mechanism, the earthquake intensity for the study area was estimated through the attenuation model as proposed by Youngs *et al*. [21,22]. Youngs' attenuation relationship is expressed in detail below;

$$\ln(SD) = A_{IF}G_{IF} + A_{IS}G_{IS} + 1.414M + b(10-M)^3 + c\ln(R + 1.782e^{0.554M}) + 0.00607H \tag{3}$$

where SD is the average peak ground acceleration or spectrum acceleration
M is the Earthquake magnitude (Mw, Moment magnitude)
R is source (epicenter) to site distance (km)
A_{IF}, A_{IS} is the multiplication factor for the mechanism of the earthquake generation, which is interface or intraslab.

Assumed earthquake event

For the study area, an earthquake event considered for loss estimation, with an epicenter magnitude of 5, as shown in **Figure 9**. The earthquake is on Mae Lao fault line, which is located 3.71 km away from downtown to the north-west of Chiang Rai city. According to past records, earthquakes have occurred in the selected location.

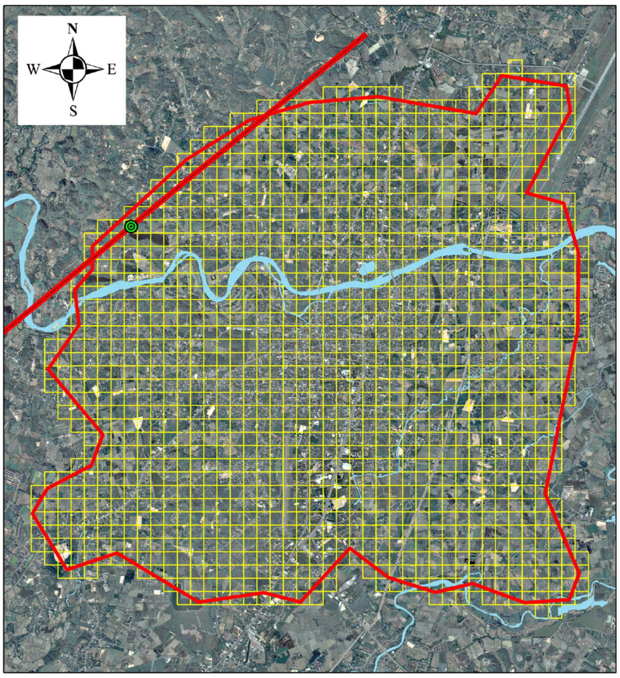

Figure 9 Epicenter of the earthquake scenario with magnitude of 5.

Results and discussions

Peak ground acceleration

For the assumed earthquake event and the attenuation model, **Figure 10** shows the peak ground acceleration contour for the study area. The acceleration was in the range of 0.104 to 0.241 g in the earthquake scenario, which is in the same intensity range as past research in the area (Warnitchai *et al.* [23]).

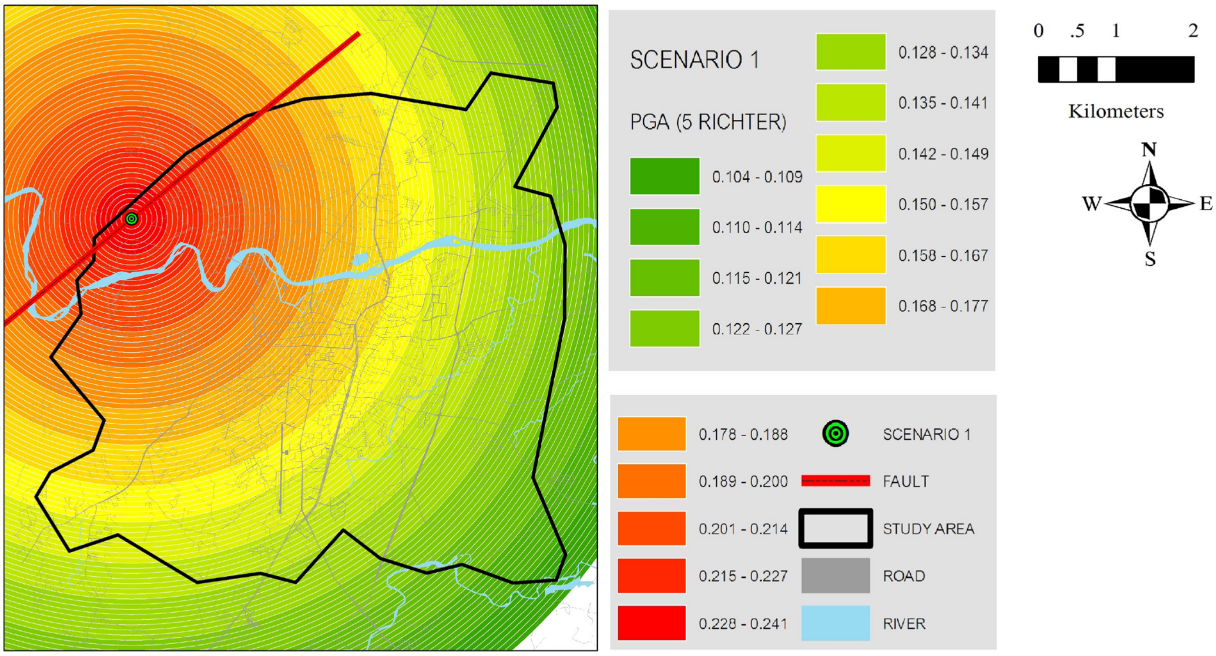

Figure 10 Peak ground acceleration contour.

Building losses (Complete level)

Figure 11 shows the distribution of the complete damage (collapse) of buildings in Chiang Rai city when subjected to the earthquake scenario. It illustrates the maximum damage occurring at the central part of the study area, with a complete damage area of about 2,633,947.92 m^2 (400,000 m^2 in every 1 km^2), or 24.79 % of the entire building area.

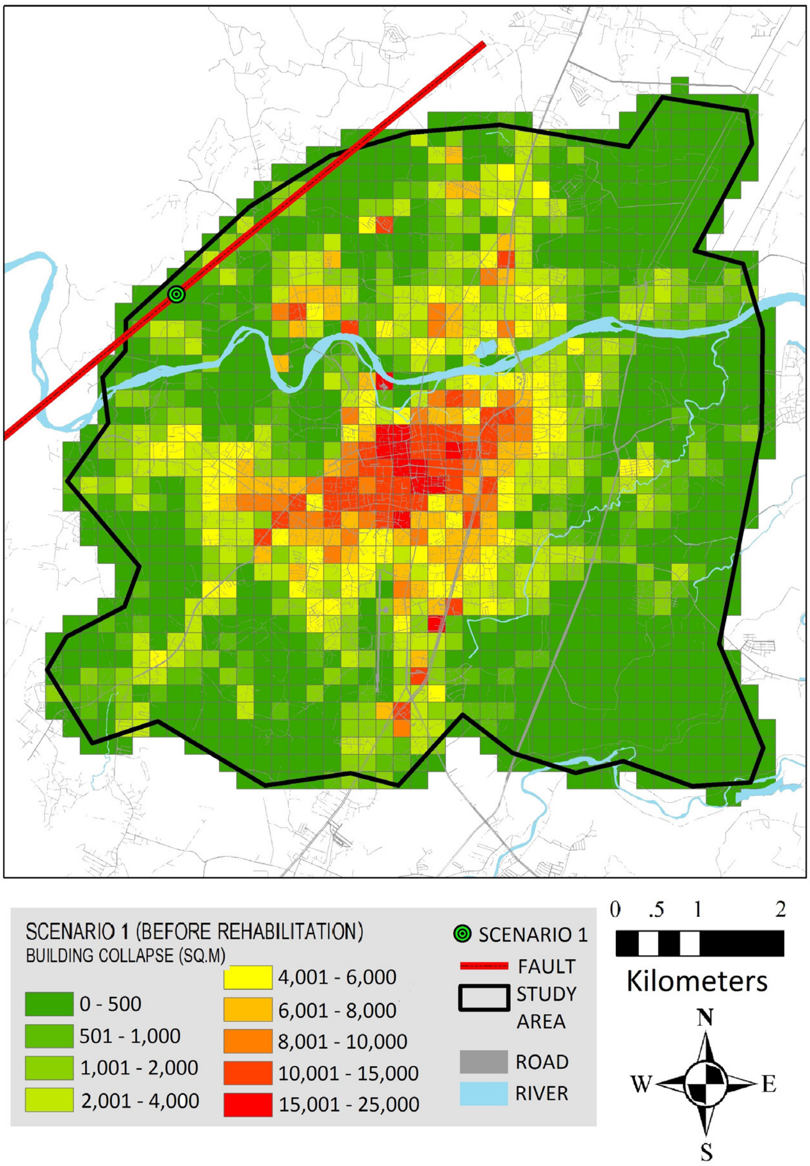

Figure 11 Complete damage (collapse) of the buildings in the study area.

Human losses

The numbers of human deaths were calculated for the 2 different times, as shown in **Figure 12**. During the nighttime, the level of severity of those instantaneously killed was about 712 people and 1,027 during the daytime, equivalent to 0.365 and 0.371 percent for nighttime and daytime, respectively, of the total number of people living in the buildings.

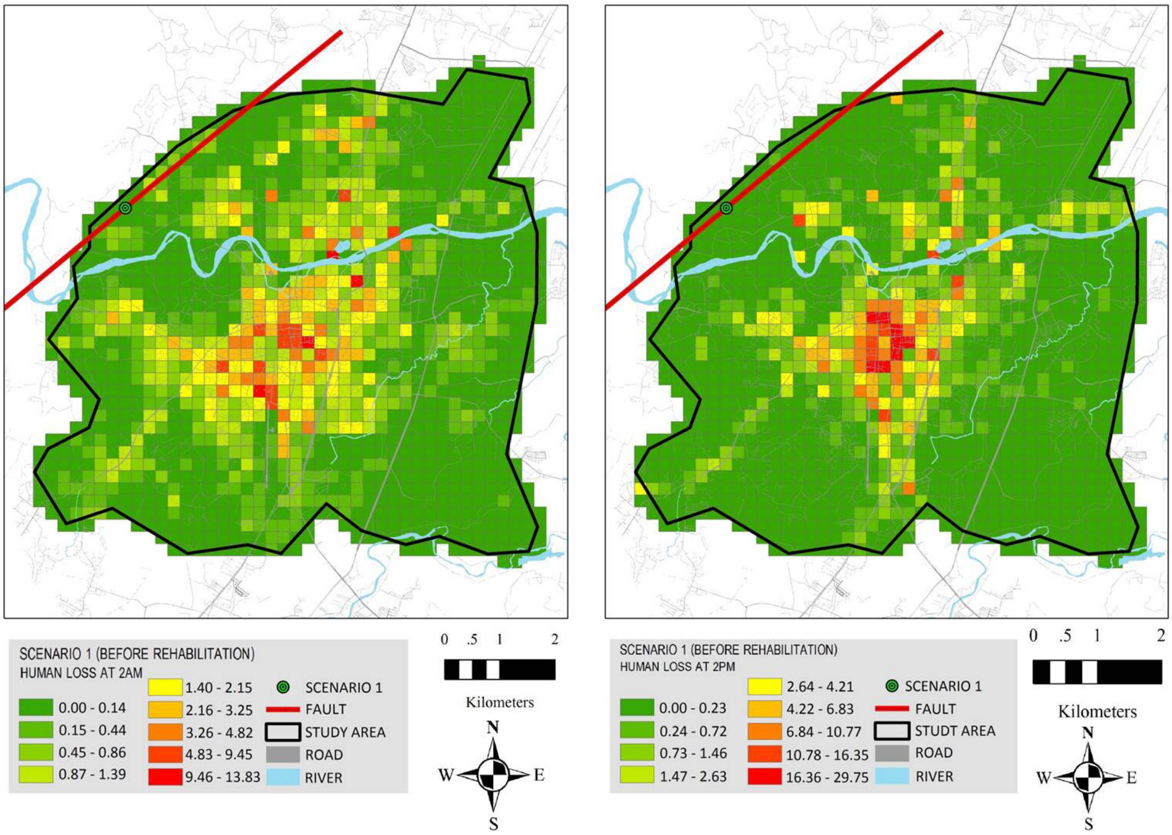

Figure 12 Distribution of human casualties; 2AM (left), 2PM (right).

Building damage after rehabilitation

Figure 13 shows the distribution of the building damage after rehabilitation of the selected buildings. The selected important buildings comprise 564 school buildings, 96 hospital buildings, 154 emergency services buildings, and 711 government offices. The complete damage of those buildings, before the rehabilitation, covered about 225,587.35 m^2, which was reduced to about 115,043.34 m^2 after rehabilitation to a moderate seismic design level standard. The reduction of the damage area can account for more than 49 %. Overall, it illustrates that the complete damage area was reduced from 2,633,947.92 m^2 to 2,440,244.88 m^2, or 7.35 % of the entire building area.

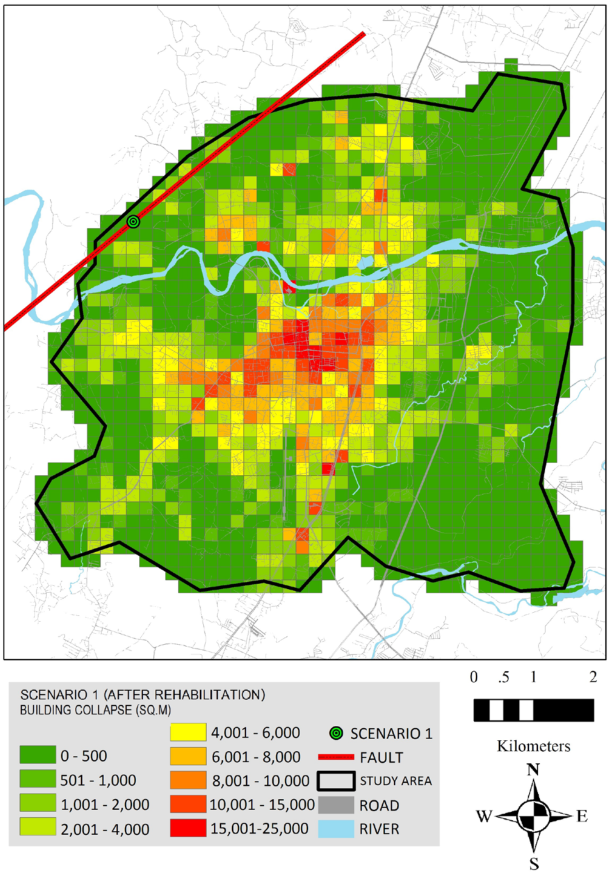

Figure 13 Complete damage after rehabilitation.

Human losses after rehabilitation

As the upgrading led to less building damage, the numbers of casualties were also reduced accordingly. However, with a limitation on budget and time, incremental upgrading focusing on important buildings has been only generally considered. For this study, the numbers of human fatalities during the nighttime in the upgraded buildings were reduced from 4 deaths before to 1 death after the rehabilitation. It is evident that in the daytime, with high occupancy, the numbers of deaths were reduced from 295 persons to 86 persons after the rehabilitation. In proportion, the reduction in the numbers of deaths was about 75 % for the nighttime and 70.85 % for the daytime. **Table 2** shows the number of people and deaths before and after the rehabilitation of important buildings.

Table 2 Number of people and deaths before and after rehabilitation.

	Building Occupancy	Population		Losses Before Rehab.		Losses After Rehab.	
		2:00 AM	**2:00 PM**	**2:00 AM**	**2:00 PM**	**2:00 AM**	**2:00 PM**
Highly Important	Hospital & Emergency Services	430	20,883	2	80	0.5	24
	Government Offices	499	24,253	2	86	0.5	23
	Schools	0	33,957	0	129	0	39
	Sub-Total	**929**	**79,093**	**4**	**295**	**1**	**86**
Less Important	Other Buildings	194,265	197,595	708	732	708	732
	Grand Total	**195,194**	**276,688**	**712**	**1,027**	**709**	**818**

Figure 14 shows the numbers of human deaths after the rehabilitation of existing structures for the 2 different times. In the nighttime, in all areas of the study, the numbers of human casualties that were instantaneously killed were about 709 and 818 in the nighttime and daytime, respectively.

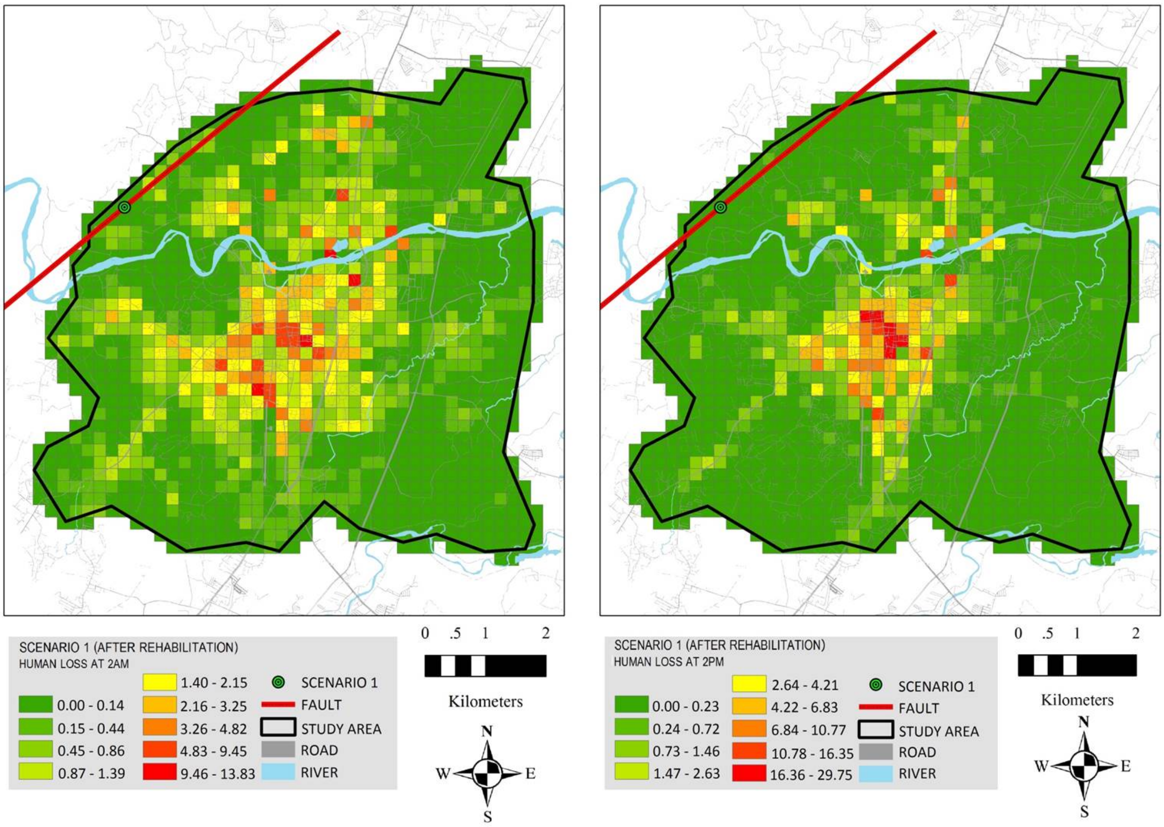

Figure 14 Distribution of human casualties after rehabilitation of existing structures; 2AM (left), 2AM (right).

Conclusions

This paper presents a spatial study on the seismic performance of buildings in Chiang Rai city to establish an earthquake loss scenario in a magnitude 5.0 event, and the changes to earthquake losses after upgrading some select important buildings. To conduct this loss estimation, building data, population distribution, and seismicity were spatially collected, and GIS-based software was utilized. The results of the building damage showed that the area that suffered the most was a high dense building stock zone. In the seismic scenario, the damage to the buildings was about 400,000 m^2 in every 1 km^2, or 24.79 % of the entire building area. The numbers of human losses were about 712 persons during the nighttime and 1,027 persons during the daytime. To simulate loss reduction, some selected buildings, of high importance to the community, comprising 564 school buildings, 96 hospital buildings, 154 emergency service buildings, and 711 government offices, were structurally rehabilitated to the required moderate seismicity standards. The complete damage to those buildings before the rehabilitation was about 225,587.35 m^2, which was reduced to about 115,043.34 m^2 (49 %) after rehabilitation. The numbers of human losses after rehabilitation in the selected important buildings were about 1 person during the nighttime and 86 people during the daytime. Compared with the numbers of deaths of 4 persons during the nighttime and 295 persons during the daytime before the upgrading, the human losses in the scenario would be reduced by 75 % during the nighttime and 70.85 % during the daytime. As a result, this information is a good source of help to government officers to use as a tool to develop a preparedness plan in the event of this kind of disaster happening again.

Acknowledgement

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