Seismic Performance of Non-Engineered Residential Buildings in the 2014 Mae Lao Earthquake

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ABSTRACT: Non-engineered residential buildings, namely reinforced concrete frame, have been widely used for housing construction in Thailand over the last few decades. Most one- and two-story single-family RC frame dwellings did experience substantial damage due to the M_w 6.1, 5 May 2014 Mae Lao earthquake, with the exception of a few timber dwellings of pre-1970 vintage, which suffered moderate damage. Several infill wall three- and four-story non-engineered reinforced concrete frame buildings suffered extensive damage, and two of these buildings collapsed. The key damage patterns and the causes of damage are discussed in the paper. The extent of damage observed in the field was correlated with calculated vulnerability indices. The findings of averaged damage level as a function of peak ground acceleration (PGA) seems to correlate well with observed damage. The averaged damage level seems to getting larger if estimated PGA exceeds 0.2g based on three different ground motion prediction equations (GMPEs).

1 INTRODUCTION

In many countries, there are many non-engineered buildings, which are extremely vulnerable to earthquakes. The loss of life and property caused during an earthquake are mostly limited by the number of people present in this kind of structures, which is poor in many different aspects such as low quality materials, irregular building configuration, brittle failure, poor construction quality, etc. Seismic risk increases as earthquake-prone regions become increasingly urbanized with low building control. It is quite apparent that these types of construction are dangerous even for a relatively small earthquake based on past experience. However, due to, economic constraint coupling with lacking of knowledge, it is quite difficult to do away with this kind of construction, and lesson learned from any damaging earthquakes to these non-engineered buildings would prove to be valuable and improved scientific knowledge.

The Mw 6.1 earthquake hit Mae Lao on 5 May 2014 at 18:08 Thai local time with its epicentre located inside Thailand focal depth of 7 km as reported by USGS and Thai Metrological Department (TMD). Soon after, the extensive damage in epicentral area start to emerge with reports of one casualty and many injured victims, total structural collapse, corresponding to Modified Mercalli Intensity (MMI) about VIII in Mae Lao and Pan districts. Despite severe damage to infrastructure and residential houses in these local area, the observed damage in Chiang Rai city centre, which locating around 30 km from the epicenter, are relatively less intense with no casualty; however, there are reports of cracking inside buildings, there is no report of building collapse (MMI VI; Ornthammarath and Warnitchai, 2015).

Few days after earthquake origin time, damage data surveyed was performed by a group of local authorities and volunteered engineers for the purpose of prioritized assistance and release of relief fund. Three damage classes had been assigned for each building. The damage classification was separated in to insignificant or no damage (green class), moderate (yellow class), and heavy (red class). The field assessment was carried out at the most affect region including Mae Lao, Pan, Chiang Rai, and Mae Suai few days after mainshock. The findings indicate that structures that have been constructed in compliance with the latest seismic codes and standards, engineered buildings, will be more resistant to earthquake damage. Poorly built structures that were constructed under less-effective

construction quality, non-engineered buildings, and not retrofitted to meet modern standards are likely to experience more damage.

The database of damaged RC buildings was then analyzed to find the relationship between the damage level and estimated ground motion parameters. For non-engineered residential buildings in Thailand, a preliminary vulnerability curve was developed for risk analysis or scenario simulation.

2 NON-ENGINEERED BUILDINGS

Non-engineered buildings in Thailand can be explained as: 1) Using cheap and low quality materials, 2). Using easy construction technique, 3). Using less construction time, and 4). Suiting traditional culture and usage. A majority of buildings affected by the 5 May 2014 earthquake can be classified as resident buildings. Masonry infill wall with reinforced concrete (RC) frame is the most popular housing construction technology in Thailand. Northern part of country has been considered as a seismic region; however, due to low restriction of building code, lacking of earthquake awareness and knowledge, leading to inevitable conclusion in which seismic design has never really been considered for local people. Consequently large building stocks contain inadequate seismic resistant structures. Therefore unless specifically noted, the buildings reported herein fall into this category.

Ornthammarath and Warnitchai (2015) discussed and categorized earthquake damaged structures due to 2014 Mae Lao earthquake into four main types based on their seismic performance, which are listed in Table 1 with construction details for each type of observed buildings. However, only brief information would be provided in order to explain the failure mechanism for each class of structures.

Table 1. Structural classifications of residential buildings in the affected region.

Type	Description
1). Lightly RC frame with heavy cement bricks (LRC)	Non-engineered lightly reinforced concrete or wooden frame with heavy cement block walls, low-quality mortar, and light steel metal roof.
2). Elevated lightly RC frame with heavy concrete bricks (ELRC)	Non-engineered lightly reinforced concrete or wooden frame with elevated first floor, heavy cement block walls in the second story, low-quality mortar, and light steel metal or heavy tile roof.
3). Reinforced concrete (RC)	Non-engineered reinforced concrete frame with adobe infill wall, low-quality mortar, and heavy tile roof.
4). Wooden-frame (W),	Wooden buildings with elevated first floor. Wooden structure in the second floor with light roof.

For structural type I, these buildings generally feature small non ductile precast columns. The number of column stirrups typically provided is small e.g., 6-mm-diameter bars at 150–200 mm spacing for 150×150 mm^2 or 200×200 mm^2 columns. Infill, unreinforced masonry panels, generally 70-100 mm thick, is extensively used as nonstructural elements, with a small number of dowel bars connecting the panels and the boundary RC frames. The ultimate compressive strength of concrete in buildings is normally on the order of 18 MPa, or lower. The specified yield strength of reinforcing bars is usually 240 MPa for plain bars and 300 MPa for deformed ones. Bricks and mortar are of extremely low quality, since they are used as nonstructural elements. This type of structures is quite common for low income family and is vulnerable to earthquake. Many such buildings have collapsed in past earthquakes resulting in the loss of lives, (Ornthammarath, 2013; Ornthammarath and Warnitchai, 2015).

The typical red class damage of this kind of building type is a partial or full out-of-plane failure of heavy cement block walls. This wall is generally fixed on the ground with little or no connection to column, which could be referred as free-standing wall. The out-of-plane inertia force acting on the mass of the wall tends to overturn it. Clearly this failure mechanism generally not fulfils life safety performance level. The seismic resistance of the wall is by virtue of its weight and tensile strength of mortar, which is obviously very small. The typical wall height are about 3.0-4.0 m, and the wall slenderness ratio are about 30 – 40. For yellow class damage level, large bending cracks would be

observed as a vertical crack at the edge of the wall since the walls are subjected to the inertia force acting on their own mass. Significant numbers of yellow class damage would generally be observed for walls with cement mortar on both surfaces.

Figure 1 a). Typical characteristic of type I structure b) partial or full failure of infill wall (red class damage) c). Bending crack observed on infill wall (yellow class damage)

Type II buildings constitute the most vulnerable to earthquake (Figure 2). Their ground story is left open with elevated first floor. Typical column heights are between 1.5 m and 2 m. The second story is generally made of cast-in-place concrete beam. Due to their heavy concrete floor and cement block walls in the second story, large inertia forces are induced during earthquakes. The column on the first floor is either lightly reinforced concrete column as Type I structure or wooden frame. The main problem in this type of building is the incompatibility of the materials used for different stories and their improper connection to each other. All of these factors leading to a soft story failure pattern. Partial out-of- plane collapse of second-story walls or full collapses of the unit are mostly founded. Figure 2 displays a typical collapse of type II building with failure due to soft story effect and poor beam-to-column joint reinforcing details. Clearly this failure mechanism generally not fulfils life safety performance level. For yellow class damage level, large bending cracks would be observed as a horizontal crack at the edge of the column since the columns are subjected to the inertia force acting on upper floor.

Type III buildings have generally better seismic performance than previous two types since their larger column cross section between 200 mm and 250 mm with at least four 12-mm diameter of longitudinal bars and 6-mm diameter bars with stirrup spacing at 150-200 mm, properly placed horizontal bond beams, relatively better corner connections, and better vertical alignment of openings. This type of building is not earthquake resistant but can withstand earthquakes of moderate intensity since some basic rules of thumb have been considered during construction. The typical failure modes of this type of buildings are variable such as, short column, out-of-plane and in-plane failure of non-structural walls, soft story. For buildings of this type, if there are elevated floors between 0.3 m and 0.5 m,

severe shear failure of column with vertical bar buckling occurred due to short column failure type is quite common.

Nevertheless, severe damage of type III buildings could also been found if these structures are extended to 3 or 4 story heights, in which the ground story is kept opening without partition walls. The story height of the first floor is almost 25 % more than the upper stories. Consequently, soft and weak stories caused heavy structural damages. For yellow class damage level, damage would be observed at some parts of structure such as short column due to small openings, as a horizontal crack at the edge of the column since the columns are subjected to the inertia force acting on upper floor. Another typical but severe damage of buildings in this type is due to non-structural partition walls made of briquette. These non-structural walls formed compression struts and induced forces in adjacent columns near joints. This led to shear failure of columns, as shown in Figure 19. Buckling of longitudinal bars also occurred, indicating loss of gravity-load-carrying capacity.

Type IV buildings are traditional Thai house, Figure 4. Wooden columns, beams, and slabs are the loading members to resist both the lateral and gravity loads. Wooden house with elevated first floor is less damaged comparing to type II buildings since it is light and more flexible. However, the older buildings of this type the more vulnerable could be expected since the quality of wooden is deteriorated over time. Leaning to one side or partial failure of roof are the most common damage (yellow class damage) pattern of type IV buildings; however, total collapse case has not been reported.

Figure 2 a). Typical characteristic of type II structure b) partial or full failure of infill wall (red class damage) c). Bending crack observed on infill wall (yellow class damage) d). Bending crack observed on precast column (yellow class damage)

Figure 3 a). Typical failure characteristic of type III structure b) soft story failure of 3 story RC frame (red class damage) c). Short column failure due to openings (yellow class damage) d). Bending crack observed on infill wall (yellow class damage)

Figure 4 a). Typical characteristic of type IV structure b) partial failure of roof (yellow class damage)

3 OBSERVED GROUND MOTION

No recorded ground motions are available within 10 km of the epicenter, and therefore no direct comparison between damage patterns and ground motion recordings can be made. However, liquefaction was widely observed within epicentral area, and the nearest free-field seismic station was located at 25 km distance. This station is equipped with a seismometer, operated by Department of Mineral Resources (DMR). The observed ground motion has been analyzed with saturated velocity time history. After conversion this velocity trace to acceleration time history, it was found out that the peak ground acceleration (PGA) is 0.13g, which is similar to what is usually expected. So the PGA in the epicentral area should be at least 0.2g but it is quite clear that the PGA should not be substantially high since the large numbers of building stocks within epicentral area are still intact and local infrastructure could be resumed within few days after earthquake. Ornthammarath and Warnitchai (2015) compared observed ground motion with Sadigh et al. (1997); Boore and Atkinson (2008), BA08; and Boore et al. (2014), BSSA14, and the observed PGA values generally exhibit no significant biases over the applicable distance range from 0 to 200 km; however, larger underestimation of Sadigh et al. (1997) could be observed. BA08 median curves for stiff and soft soils seem to provide better fit to recorded data than that of BSSA14, suggesting that the BA08 model well captures the attenuation rate for this event.

4 VULNERABILITY CURVE OF NON-ENGINEERED BUILDINGS

Every district might consist of different building typologies (e.g. Lightly RC frame, Elevated lightly RC frame, Non-engineered RC structure, and wooden frame). Vulnerability curves are usually derived for each material type structures where finally a single vulnerability curve is assigned to each district probability weighted by the structure type contribution. A single curve per District is employed in the current study primarily for the simplicity reason and due to the fact that it reduces the computational effort by one-fifth, giving the same results as obtained using class-by-class vulnerability curves. As the foregoing discussion indicates, damage is related to the locations of buildings in an epicentral area. In this study, the distance from the epicentre and each village are used as parameters to characterize the expected ground motion parameters on buildings. Each damage level, D, is quantified as shown in Table 2. It is worth to note that further study in relating the damage levels to the retrofitting per rebuilding cost could be easily applied for more precise loss assessment for different building types.

The averaged damage level, $\bar{D}$, is computed according to the following equation:

$$\bar{D} = \frac{0.33n_2 + 0.67n_3 + 1.00n_4}{n_1 + n_2 + n_3 + n_4}$$

where n_1 is the number of building with no damage (green class), n_2 is the number of buildings with moderate damage (yellow class), n_3 is the number of buildings with heavy damage (red class), and n_4 is the number of collapsed buildings. The averaged damage level is weighted according to the values in Table 2. The computed averaged damaged level is ranged from 0.0 to 1.0, in which the 1.0 would mean total collapsed structures in considered area. Figure 5 shows the number of buildings in earthquake affected area with respect to the estimated peak ground acceleration (PGA) and epicentral distance. In total, there are 51,212 buildings included in this analysis. The data is uniformly distributed with distance; however, only 15,688 structures located within zone with PGA greater than 0.2g.

Table 2. Damage level and its assigned values

Damage level (D)	Value
Insignificant or no damage (green class).	0.00
Moderate (yellow class)	0.33
Heavy (red class),	0.67
Collapse	1.00

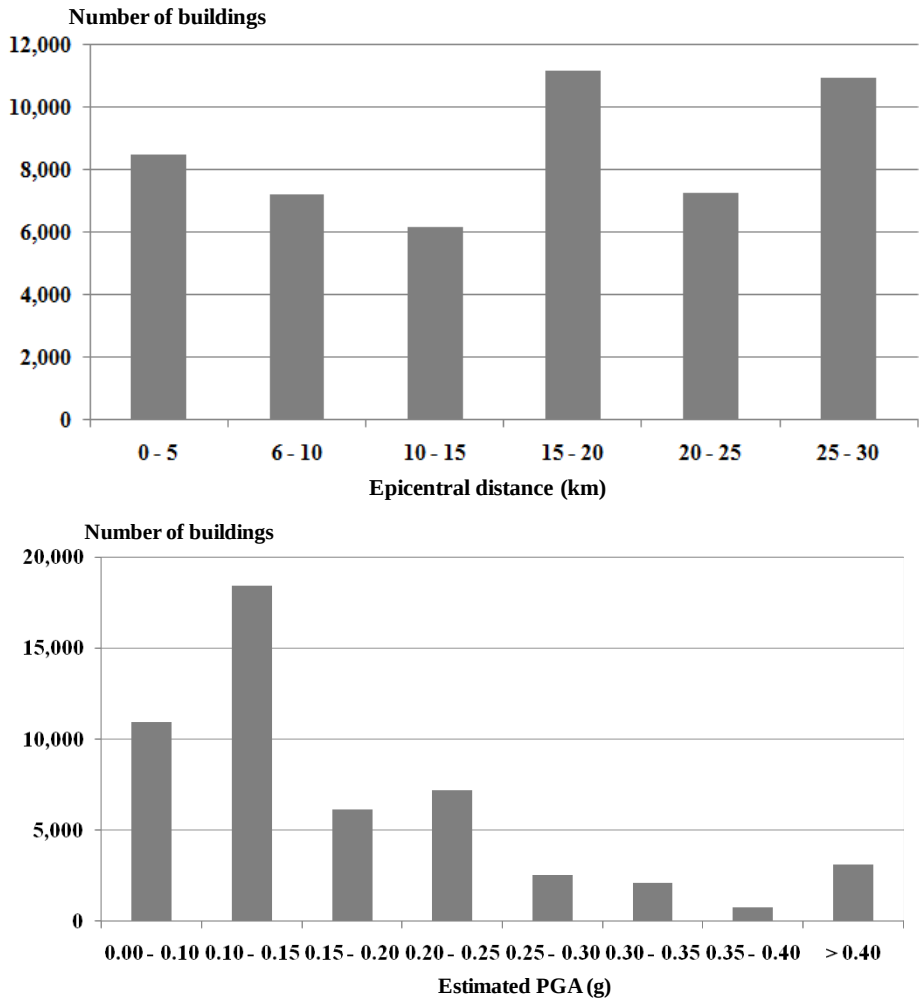

Figure 5 a). The number of buildings in earthquake affected area with respect to the epicentral distance and b) estimated peak ground acceleration (PGA) based on BA08.

Figure 6 displays the relation between the averaged damage level with estimated PGA and epicentral distance. The averaged damaged level tends to decrease as the distance increase. PGA values seem to correlate well with observed damage this is might due to the fact that most dwellings in affected area are one to two story buildings. The maximum averaged damage level is 0.11. Within relatively small area, for 10 km long, the averaged damage level is in range of 0.01 – 0.11 conforming to field investigation that large numbers of buildings within Mae Lao are still intact with minimal structural damage. In addition, the averaged damage level seems to significantly change if PGA exceeds 0.2g, 0.3g, and 0.4g based on BA08, Sadigh et al. (1997), and BSSA14, respectively. It is worth to note that similar damage patterns in this region have been observed in the previous Mw 6.8 Tarlay earthquake on 24 March 2011, in which the recorded ground motion PGA is 0.2g, Ornthammarath (2013).

5 CONCLUSION

The M_w 6.1 Mae Lao earthquake damage was the most destruction in Thai modern history, causing one fatality, several injured people, and collapsed structures. The economic loss was estimated to be around 30 million USD. A unique aspect of the earthquake damaged investigation were collected and presented. The damaged of non-engineered structures highlighted the need for further investigation to develop seismic mitigation strategy of these easy-to-construct dwellings. In addition, on the basis of the survey data, the relations between the damage level and a) the estimated PGA and b) the distance from the epicentre were studied. The damage level tends to increase significantly for the estimated PGA 0.2g, which is well consistent to previous observed damaged.

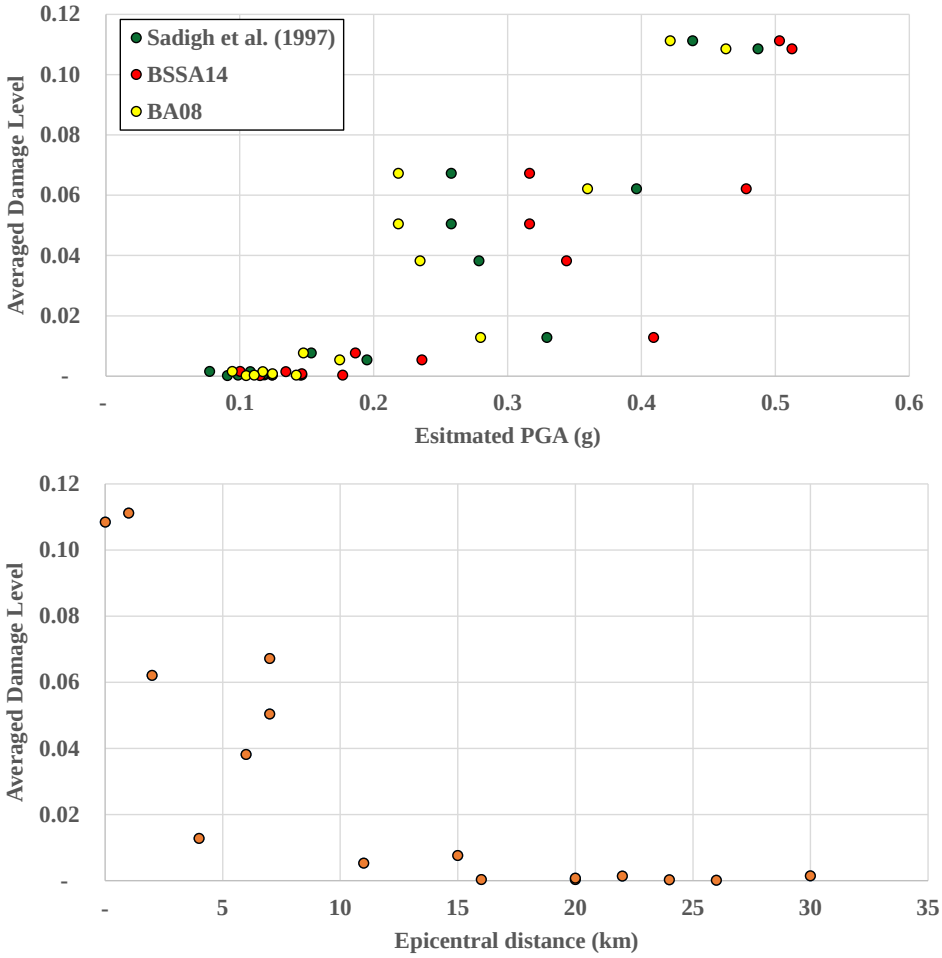

Figure 6 a). Averaged damage level in earthquake affected area with respect to estimated peak ground acceleration (PGA) based on BA08, BSSA14, and Sadigh et al. (1997) and b) the epicentral distance.

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