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A multi-hazard risk assessment of buildings in Padang city

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Abstract

The main purpose of an earthquake risk assessment is to assess the potential loss of buildings in earthquake prone regions and to provide enough information to employ suitable mitigation strategies. The M_w 9.1 great Sumatra earthquake in 2004 and the M_w 9.0 Japan earthquake in 2011 have highlighted the importance of a multi-hazard risk assessment framework that includes the effects of both earthquake and its associated hazards such as tsunami. The multi-hazard risk assessment of buildings requires several stages including earthquake and tsunami hazard analyses, the vulnerability analysis of buildings, building inventory as well as the risk estimation of buildings in the investigated area, which are discussed in this paper. The method on how to incorporate these stages into a multi-hazard risk assessment framework is also presented. The developed risk assessment framework is then used for the city of Padang that has a considerably high earthquake and tsunami hazard with great exposure to population and infrastructures. The estimated risk obtained in this study is expressed in terms of Pure Risk Premium (PRP) for different building categories commonly found in Padang including unreinforced brick masonry (UBM), confined brick masonry (CBM), reinforced concrete frame with masonry infill (RCI) and steel structures. The earthquake PRP(s) obtained in this study are comparable with the latest insurance rates released by MAIPARK. MAIPARK is an insurance company specialized in earthquake reinsurance, which also provides earthquake statistics and sets a benchmark for earthquake insurance pricing in Indonesia. Tsunami PRP(s) for different building categories in the area are also presented in this paper; however, no comparison can be made due to the unavailability of tsunami insurance premium data for Indonesia. Based on the results, it can be concluded that building risk associated with tsunami in Padang is considerably lower than that of earthquake, due to infrequent occurrence of tsunamis in the area. The earthquake and tsunami risk of buildings in Padang is predicted to be £54.5 million and £30.8 million per annum, respectively.

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Keywords: earthquake; tsunami; seismic hazard; risk assessment; building

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1. Introduction

The territory of Sumatra lies within the Pacific Ring of Fire, where some of mega magnitude earthquakes in the world have occurred. The seismicity of Sumatra is mostly contributed by the Sumatran Fault and the Sumatra subduction zone. The Sumatra fault zone runs from the north to the south of Sumatra Island for about 1900 km. The oblique convergence between Indian-Australian and Eurasian Plates of the Sumatra subduction zone creates the strike slip fault with dextral movement. The slip rates across the Sumatra fault zone are around 6 mm/year near Sunda strait, 25 mm/year close to the equator and 50 mm/year near the Andaman sea [1]. A highly segmented fault and a wide step-over had limited the areas of slip ruptures in the Sumatra fault, which consequently produced lower magnitude earthquakes. Historical records showed that this fault was capable of producing earthquakes with magnitude up to M_w 7.5 [2].

Another important seismic source for Sumatra is the Sumatra subduction zone. The subduction zone formed as a result of a coalition between the Australian plate and the overriding Eurasian plate, which lies along the Sunda Trench. The dip angle of the Sumatra subduction zone is about 13°-15°[3] with the velocity of the relative motion varies depending on the region. The velocity between the Australian and Eurasian plates is around 52 mm per year at the northern part of Sumatra and at 62 mm per year at the southern part [4]. The subduction zone in Sumatra is known for producing mega-thrust earthquakes such as the M_w 8.8-9.2 in 1833, the M_w 8.3-8.5 in 1861, the M_w 9.0-9.3 in December 2004, the M_w 8.7 in March 2005 and the M_w 8.4 in September 2007.

Moreover, the Sumatran subduction zone is also known of producing tsunamigenic earthquakes. In the last decade, there were few tsunami events occurring in the region including the 2010 tsunami in Mentawai, the 2007 tsunami in Bengkulu, the 2005 tsunami in Nias and the 2004 Indian Ocean tsunami. At least 6 countries were hardly affected in the latter event, which killed more than 200,000 people in the vicinity of the Indian Ocean. In addition, the Indian Ocean tsunami had caused a great economic loss reaching $10 million[5], mostly due to the damaged infrastructures such as buildings.

It can be concluded that the Sumatran region, particularly on the western part, is highly prone to both earthquake and tsunami hazards. For such region, risk assessment needs to be conducted to evaluate the potential loss in the area due to both earthquakes and earthquake associated hazards such as tsunami. This paper presents a practical multi-hazard risk assessment framework to include earthquake and tsunami associated hazards (ETRA Framework), which is suitable for the Sumatran region. The efficiency of the framework is demonstrated for a case study region in Padang City, West Sumatra.

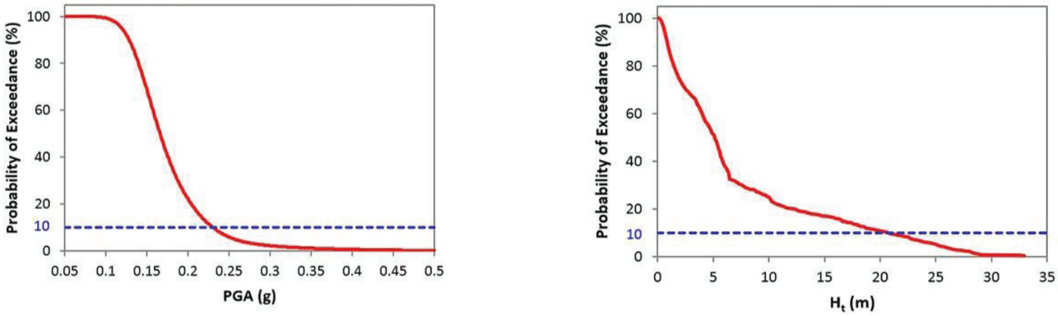
2. A multi-hazard risk assessment framework (ETRA-Framework)

Coppola [6] suggested a four phase approach for a comprehensive disaster management, which consisted of mitigation, preparedness, response and recovery. Risk assessment is part of the mitigation phase that helps to identify the likelihood of hazard and its consequence to the exposed elements (i.e. human, buildings, social and economic, etc.). Mulyani [7] highlighted the importance of a multi-hazard risk assessment framework in seismic mitigation process considering the massive consequences caused by earthquake associated hazards in the past events. The multi-hazard risk assessment method for earthquake and tsunami developed by Mulyani [7] is adopted in this study, which contains few elements as discussed in the following sections.

2.1. Earthquake and tsunami hazard analyses

The initial stage of the Earthquake and Tsunami Risk Assessment Framework (ETRA-Framework) developed in this study involves earthquake and tsunami hazard analyses. The main aim of the hazard analyses is to estimate the level of earthquake and tsunami hazards in the examined area. In this study, the parameter of earthquake hazard is expressed in terms of Peak Ground Acceleration (PGA), while tsunami run-up height (H_t) is selected to represent the level of tsunami hazard. An integrated quantification of earthquake and tsunami hazards is challenging due to mathematical and computational problems as well as limited available data [7]. To analyse earthquake and tsunami hazards in this study, a practical method is adopted which generates synthetic events based on historical earthquake and tsunami catalogues in the area under study [7].

For earthquake hazard analysis, the PGA levels were quantified using ground motion attenuation relationships developed by Youngs, Chiou [8] for the Sumatra subduction zone and attenuation relationships by Sadigh, Chang [9] for the Sumatran fault. For tsunami hazard analysis, the tsunami run-up heights were estimated using a relationship between earthquake moment magnitude and tsunami run-up height, specially developed for Sumatra region [7]. The outcomes of earthquake and tsunami hazard analyses utilized in the ETRA Framework are expressed in terms of hazard curves as shown in Fig. 1



(a) (b)

Fig. 1. (a) Earthquake hazard curve for Padang city for 50 years (bed rock); (b) Tsunami hazard curve for Padang city for a 50 year period

2.2. Vulnerability curves of buildings

Vulnerability curves for each type of structures in Padang are required to determine earthquake and tsunami risk. The vulnerability curves correlate the expected ground motions (or tsunami heights) with the mean damage ratio of the existing building stock in the region. For earthquake risk assessment, this study adopts vulnerability curves proposed by GESI [10] that includes data from many countries including Indonesia and also provides flexibility in selecting the class of construction in terms of design, quality and material. The GESI vulnerability curves comprise four damage states: (1) none, slight or moderate; (2) extensive; (3) partial collapse; and (4) complete collapse. The earthquake vulnerability curves that represent building stock in Padang are shown in Fig. 2 (a). For tsunami hazard assessment, the vulnerability curves proposed by Tinti et al. [11] are used in this study.

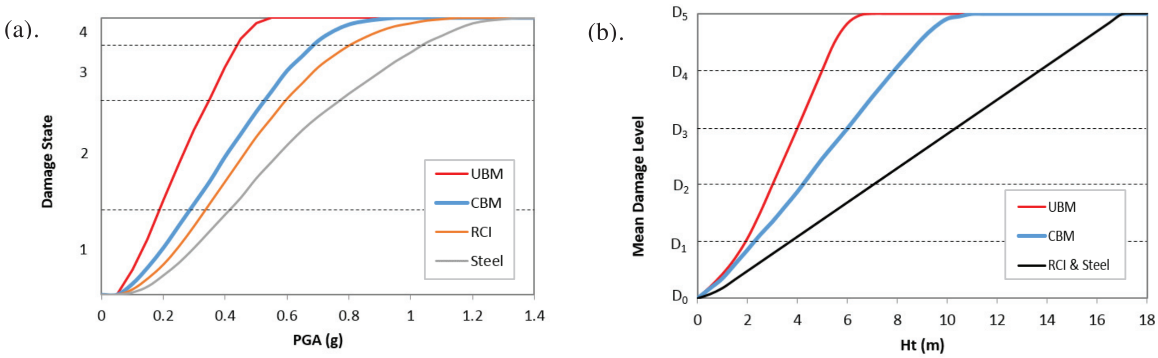


Fig. 2. (a) Earthquake vulnerability curves for different type of structures [10];
(b)Tsunami vulnerability curves for different type of structures [11]

The tsunami vulnerability curves were developed as part of the SCHEMA project (a consortium of 11 organisations in the European Union, Turkey and Morocco) aiming to build up tsunami hazard, vulnerability and impact damage maps for Europe and Mediterranean countries. The project used post tsunami data from Banda Aceh (Sumatra, Indonesia) after the Indian Ocean tsunami in 2004 [12]. Therefore, the vulnerability curves are perfectly applicable for this study. The adopted tsunami vulnerability curves are shown in Fig. 2 (b). The tsunami vulnerability curves used in this study consist of 6 damage levels: (1) no damage, D_0; (2) light damage, D_1; (3) important damage, D_2; (4) heavy damage, D_3; (5) partial failure, D_4; and (6) Collapse, D_5.

2.3. Building inventory

Building inventory for Padang was obtained from a digital map produced by PT. Exsa International in collaboration with BAKORSURTANAL (the Indonesian government agency for surveying and mapping). The map contains a layer with the plans of buildings in the region, but it does not provide the number of storeys for each building as well as the typology of the structures.

A field survey by the EEFIT team revealed that the structures in Padang mainly consisted of unreinforced masonry, confined masonry and reinforced concrete (RC) frames with masonry infill [13-15]. The region had approximately 203,450 residential houses, of which 20% were classified as semi-permanent (wood and unreinforced masonry constructions). The other 80% were generally constructed with either brick with reinforced columns (confined masonry) or RC frames with masonry infills and typically had 1 or 2 storeys. The city had about 1,572 buildings for public or commercial purposes, which were mainly constructed from RC frames with masonry infills. The use of steel structures was limited and generally found in large commercial buildings or industrial facilities.

To estimate the distribution for each type of structures in the investigated area, visual inspections from satellite imagery [16] were performed. The Padang area was characterised into 4 categories such as residential, commercial, industrial, and combinations of residential and commercial areas as seen in Fig. 3. Then, the Padang region was subdivided into small rectangular grids and a category was assigned to each grid. The percentage of each type of structure for every category was determined and averaged as shown inFig. 4. In this study, the risk assessment is performed considering four building categories: unreinforced brick masonry (UBM), confined brick masonry (CBM), reinforced concrete frame structures with masonry infill (RCI) and steel structures (steel). The assigned building category for each grid is shown in Fig. 4(a). The "NA" category in the figure denotes an area with limited or no observed building stock. The estimated area of buildings for each grid in Padang city is shown inFig. 4(b). The figure shows that the building density is higher along the coastal area of Padang.

Table 1. Composition of buildings in Padang based on the land use of the areas.

Category		% UBM	% CBM	% RCI	% Steel
1.	Rural residential area (R-1)	17.3	69.0	13.6	0.1
2.	Residential area in the city (R-2)	13.1	52.2	34.6	0.1
3.	Residential and commercial area at the outskirt of the city (RC-1)	6.7	26.6	66.5	0.2
4.	Residential and commercial area in the city (RC-2)	1.5	6.1	92.0	0.4
5.	Residential and industrial area (RI)	11.6	46.6	27.2	14.6
6.	Residential, commercial and industrial area (RCI)	3.0	12.1	80.4	4.5

Residential Area — Commercial Area — Industrial Area — Residential and Commercial Area

Fig. 3. Typical satellite imagery for residential, commercial and industrial areas in Padang city [16]

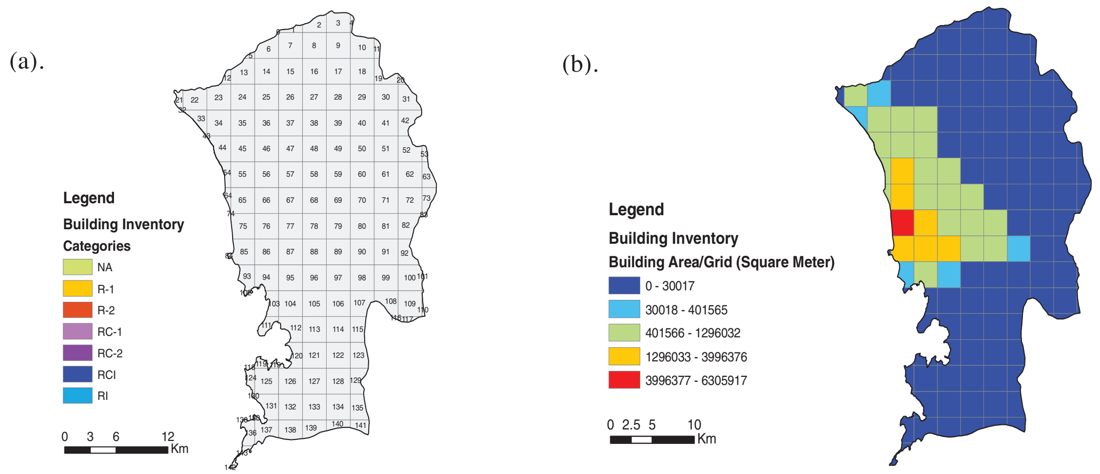


Fig. 4. (a). Distribution of structural categories within the Padang area; (b). Estimated areas of buildings (m2) for each grid in Padang city

3. Risk assessment of buildings in Padang City

3.1. Earthquake Risk

Padang is a major city in the West Sumatra province of Indonesia and is home to almost one million people. The city is exposed to high earthquake risk due to the high level of seismic hazard, high vulnerability of the existing building stock and large exposure. It is assumed that most of the existing building stock in Padang is substandard with poor seismic performance, as observed during the EEFIT field survey [13, 14]. However, some seismically designed buildings are also present in the area. The risk model in this study estimates that the earthquake risk in Padang could reach £54.5 million per annum, which can be attributed to the high seismicity of the area and poor building quality.

The outcomes of the risk assessment in this study are expressed in terms of pure risk premium (PRP). The PRP denotes estimated loss per mil (building value). The average values of the PRP and total insurance premiums of all building categories in this study are summarised inTable 2. The table shows higher insurance rate for the existing UBM and CBM buildings of about 36.4‰ and 16.6‰, respectively. Better quality UBM and CBM buildings can reduce the insurance rate to 8.1‰ and 3.1‰, respectively. As it is expected, the seismically designed RCI and steel structures provide better seismic resistance, resulting in significantly lower earthquake insurance rates (up to 90% less).

Table 2. Average earthquake and tsunami pure rate premium (PRP) and total insurance premium (TP) for all building categories in Padang

Building Category	Non-seismically Designed Building Stock				Seismically Designed Building Stock			
	Earthquake		Tsunami		Earthquake		Tsunami	
	PRP (‰)	TP (‰)	PRP (‰)	TP (‰)	PRP (‰)	TP (‰)	PRP (‰)	TP (‰)
1. Unreinforced brick masonry (UBM) structures	21.9	36.4	7.03	11.72	4.8	8.1	5.27	8.78
2. Confined brick masonry (CBM) structures	9.9	16.6	5.93	9.88	1.9	3.1	4.80	8.00
3. Reinforced concrete frame with masonry infill (RCI) structures	4.8	8.1	4.20	7.00	0.8	1.4	2.68	4.47
4. Steel frame structures	1.9	3.1	4.20	7.00	0.2	0.3	2.68	4.47

Earthquake insurance premiums obtained in this study are compared with the insurance rates of two insurance companies in Indonesia, ACA and MAIPARK. The latter insurance company was established from the Indonesian Earthquake Reinsurance Pool in 2003 and is specialized in earthquake reinsurance. MAIPARK provides earthquake statistics and sets a benchmark for earthquake insurance pricing in Indonesia [17]. ACA insurance has applied a flat rate of 3‰ for all building categories in Sumatra [18]. MAIRPARK [19] initially assigned a maximum earthquake insurance rate of 3.3‰ for other than RC and steel frame structures in Zone III as the highest risk zone in the area. This tariff was then increased to 4.7‰ in 2010. Unlike the former tariff, the new policy considered an identical rate for steel, wood and RC frame structures and categorised the Indonesian region into five zones. The Padang city was categorised into Zone V (the highest risk). The insurance rates obtained in this study are compared with those given by ACA [18], MAIPARK 2007 [19] and MAIPARK 2011 [20] in Fig. 5. The figure implies that, in most cases, the MAIPARK and ACA insurance rates are lower than those estimated for the existing building stock in Padang. However, the MAIPARK insurance premium rates are in general consistent with the risk obtained for seismically design structures.

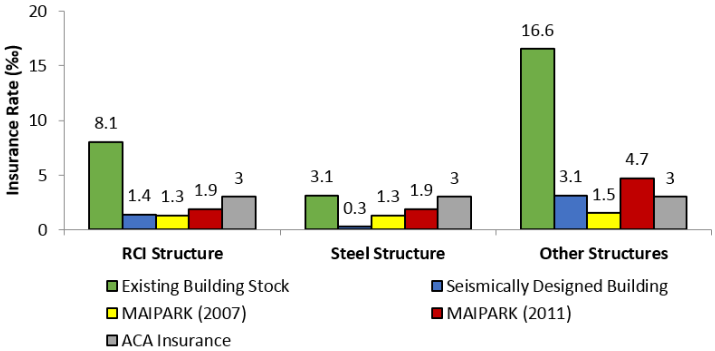


Fig. 5. Comparison between insurance rates obtained in this study (existing and seismically design buildings) and the insurance rates applied by two insurance companies (MAIPARK and ACA insurance) for Padang city

3.2. Tsunami Risk

Tsunami occurrence in Padang is infrequent due to the long return period of tsunamigenic earthquakes in the region. However, the impact of a tsunami can be immensely devastating, as demonstrated by the 2011 tsunami of Japan. Based on the results of this study, the tsunami risk in Padang is predicted to be £30.8 million per annum. The risk is lower than the predicted earthquake risk, which reaches £54.5 million per annum. The existing UBM structures are the most vulnerable buildings with a maximum PRP of 11‰. A comparable maximum PRP is obtained for CBM structures. The RCI and steel structures show a comparable risk since an identical vulnerability curve is assigned to both building categories. A maximum tsunami risk of 3‰ per annum is predicted for the existing RCI and steel structures, and the risk decreases by 36% for the seismically designed structures.

The tsunami insurance premium rates for Padang city are summarised in Table 2. The highest insurance rate applies to UBM buildings and then followed by CBM, RCI and steel structures. Equal tsunami insurance rate is estimated for RCI and steel structures. Tsunami premium data from insurance companies in Indonesia is not available, and thus, no comparison can be performed.

4. Conclusion

- Earthquake and tsunami risk assessments are conducted for Padang city for four building categories. It is found that the existing unreinforced brick masonry buildings are the most vulnerable, followed with the confined brick masonry, reinforced concrete structures with masonry infill and steel structures. The earthquake risk decreases considerably (about 80%), if the buildings are designed according to modern seismic design standards. Tsunami risk for seismic design buildings is about 25% lower than that of the existing buildings with poor seismic performance.
- The earthquake risk obtained in this study is compared with earthquake risk premium charged by 2 insurance companies in Indonesia. It is observed that the earthquake insurance tariffs are consistent with the risk obtained for seismically design structures. For RCI buildings, the total premiums obtained in this study are 8.1‰ and 1.4‰ for the existing and the seismically designed buildings, respectively. Estimated rates for steel structures are 3.1‰

for the existing building stock and 0.3‰ for buildings with good seismic performance. For other types of structures, the total premiums are estimated to be 16.6‰ and 3.1‰ for the existing and the seismically designed buildings, respectively. ACA Insurance applies a flat rate of 3‰ for all building types, while MAIPARK Insurance charges 1.9‰, 1.9‰ and 4.7‰ for RCI, steel and other structures, respectively.

- Tsunami insurance premiums for Padang are obtained. For the existing building stock, the recommended premium rates are 7‰ for RCI/steel structures and 9.9‰ for other building types. For seismically designed buildings, insurance rates of 4.5‰ and 8‰ are suggested for RCI/steel structures and other types of buildings, respectively.
- Building risk associated with tsunami in Padang is lower than that of earthquake due to infrequent occurrence of tsunamis in the area. The earthquake and tsunami risk for buildings in Padang is predicted to be £54.5 million and £30.8 million per annum, respectively.

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