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Modeling the Potential Risk of Building Vulnerability towards Tsunami Hazard in Ulak Karang and Pasir Jambak Sub-District, Padang

Leli Honesti[a,b*], Muhd Zaimi Abd Majid[a], Nazwar Djali[c], Meli Muchlian[d]

[a]Department of Structure and Material, Faculty of civil engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Department of Civil Enginering, Faculty of Civil Enginering and Design, Institut Teknologi Padang, Indonesia
[c]Department of Civil Enginering, Faculty of Civil Enginering and Design, Bung Hatta University, Indonesia
[d]Post Graduate Physics, Andalas University, Indonesia
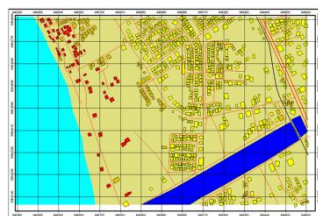
*Corresponding author: leli.honesti@yahoo.com

Graphical abstract

Abstract

Padang was destroyed by tsunamis generated by the earthquakes in the history of Padang. As an area located in a coastal region, its buildings in Padang face major vulnerability against a tsunami. The objectives of this study are to develop the potential impact model of building vulnerability toward tsunami hazard and to compare the building damage levels based on water inundation, internal, and external factors in Ulak Karang and Pasir Jambak sub-districts. The objective of this research is also to give recommendation to government in making planning strategies for reducing and managing the tsunami risk on building vulnerability. There are three stages of modeling; first stage in this study is simulating an eartquake model for two study areas to estimate the maximum inundation. The second stage of modeling is implementing the spatial analysis of building vulnerability based on the field surveys and GIS. The third stage to conlude is developing the Relative Vulnerability Index (RVI) scores of buildings by mapping the building vulnerability toward tsunami hazard and giving several alternatives to develop a risk management plan in a coastal community. The result shows that Ulak Karang sub-district is determined to be more vulnerable than Pasir Jambak sub-district because many buildings near the coastline of Ulak Karang sub-district are made of timber and are arranged close to each other. Moreover, many buildings in Ulak Karang sub-district, especially along the river, are made of traditional brick. Although near Pasir Jambak coastline many buildings are made of timber, but the buildings are not close to each other. There are several alternatives to increase resilience of buildings in a coastal zone, namely: 1) regulation for buildings that have RVI: 4 and 5; 2) building codes; 3) vertical evacuation structures; 4) land use zones; 5) sea walls along the coastlines; 6) natural barriers and 7) early warning system.

Keywords: Tsunami simulation; building vulnerability; potential risk zonesl risk management

◼1.0 INTRODUCTION

West Sumatra was badly affected by a tsunami originating from a near field tsunami of southern Mentawai islands on September 12, 2007. Many villages and buildings were affected by the tsunami, which reached from 100 to 200 m of Bengkulu coastlines and as far as 300 m into the Mentawai coastlines with tsunami height from 2.15 to 3.6 m [1].

On October 25, 2010, Mentawai earthquake, with a magnitude 7.8 Mw, ruptured the shallow portion of the subduction zone seaward of Mentawai islands, off-shore of Sumatra, generating from 3 to 9 m tsunami run-up along the southwest coast of Pagai island that took at least 431 lives [2]. The local tsunamis originated from location along Mentawai megatrust.

Padang being a populous region, is very vulnerable to the seismic because the location is near the earthquake source in Mentawai islands. The total 856,815 population of Padang and 694.96 square kilometres of land area yields a density of 1233 people per square kilometres [3].

Sumatran fault region is a subduction zone between Indo–Australia and Eurasia plates. Rates of subduction are typically centimetres per year, with the average rate of convergence being approximately 5-7 centimetres per year. A total of 1833 great earthquakes were recognized as the worst case generated from this fault and was identified to have possibilities of repetition every 200 years [4]. Based on the historical seismicity data, the tsunami in 1833 caused the run-up of around 4-5 m in land and destroyed the buildings in the coastal areas of Padang [4], [5].

Ulak Karang and Pasir Jambak are located along the Padang coast in 2 sub-districts. These areas lie at 0.9125–0.9158 south latitude and 100.3425–100.3541 east longitude for Ulak Karang and at 0.8608–0.8641 south latitude and 100.3283–100.3450 east

longitude for Pasir Jambak and face with the Mentawai islands. Two types of these coastal zones are sandy beach and low-lying areas. Those types extend along the coast of Padang. The highest tsunami inundation generally occurs in sandy coastal area [6]. The communities in Ulak Karang and Pasir Jambak sub-districts have densely populated areas and different kind of buildings. The population of these areas is approximately 12.5% of the total population of the Padang city.

Because most residents live in coastal communities of Ulak Karang and Pasir Jambak sub-districts work as a fisherman, many community activities and public services are available, such as Padang State University, Bung Hatta University, Schools and Markets. These coastlines are very vulnerable to earthquakes and tsunamis, causing extensive damage to the buildings and infrastructures.

The first objective of this research is to develop a model for assessing and developing the potential risk of building vulnerability agaits tsunami hazard. The second objective of this study is to compare the potential risk of building vulnerability toward tsunami hazard based on Relative Vulnerability Index (RVI) scores between Ulak Karang and Pasir Jambak sub-districts. This research noted which one is more vulnerable between Ulak Karang and Pasir Jambak sub-districts based on RVI scores. RVI distribution of two maps can be used to assess and develop the potential building risk levels toward a tsunami. An important thing as the last of this objective is to give recommendation about the result of RVI score maps that can be used by government to mitigate the potential risk of building vulnerability toward tsunami hazard in coastal areas of Ulak Karang and Pasir Jambak sub-districts.

The hazard consists of water inundation factor and the building vulnerability comprises of internal and external building factors. The three main factors of the hazard and the vulnerability, expressed in a scale, are called the Relative Vulnerability Index (RVI) scores. By comparing the potential risk of building vulnerability to tsunami hazard based on Relative Vulnerability Index (RVI) scores in Ulak Karang and Pasir Jambak sub-districts, then, the distribution of building vulnerability can be obtained.

An important thing to give recommendation about the result of RVI scores are that those can be used by government to mitigate the potential risk of building vulnerability toward tsunami hazard in coastal areas of Ulak Karang and Pasir Jambak sub-districts. Mitigation strategies for tsunami effects may be exposed to minimize future tsunami forces.

■2.0 METHOD

A study about tsunami run-up for West Sumatra has been done by Joce C. Borrero, Kerry Sieh, Mohamed Chlieh and Coctas E.Synolakis [7] that was published by National Academy of Science of USA in 2006. Based on the characteristic earthquake models from historical tsunami events of 1797 and 1833, the potential tsunami source regions were identified from western Mentawai islands by using MOST (Method of Splitting Tsunami). At that time, the tsunamis hit along the coastlines of West Sumatra Province. The maximum height has reached almost 5 m and the travel times were 30 minutes in average. In 2007, McCloskey *et al.* [8] found that in the all the numerical simulations of near-field tsunami in Mentawai islands, West Sumatra, the tsunami inundation generated at same time of arrival time. Furthermore, their studies modeled that maximum tsunami wave heights were directly proportional to the earthquke parameters.

An enormous amount of energy is released when a tsunami reaches the coast and it has impact to the buildings along the coastal zones. Modified after Dall' Osso *et al.* [9], the amount of internal factors of a building is determined by a number of factors. These

include: 1) kinds of material; 2) number of stories; 3) soil condition; 4) basement; 5) ground floor construction and foundation; 6) preservation condition; 7) ground floor and 8) orientation of building. Furthermore, external factors of a building are defined by a number of components. These include: 1) movable objects; 2) building rows; 3) height of concrete fence; 4) natural barrier; 5) distance from coastline; 6) distance from river; 7) obstacle islands and 8) gap between buildings.

The terms of research can be seen as follow:
1. The tsunami is modeled by using TURMINA [10] model with a Mw 9.0 earthquake and a potential tsunami from region of Pagai megathrust block that is located in western Mentawai islands (see Figure 1). The simulation uses a 10 km depth of hypocenter, which result tidal gauges and inundation water elevations in around Ulak Karang and Pasir Jambak sub-districts. Bathymetric data is derived from General Bathymetric Chart of the Oceans (GEBCO) and topographic data is obtained from Shuttle Radar Topography Mission (SRTM).
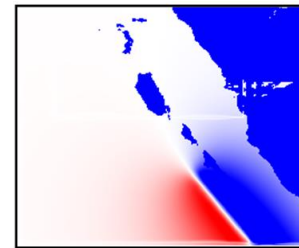
Mw	Xl	Yl	H
9	157950	381510	10

Figure 1 Tsunami source zone model at Pagai megathrust block

2. Tsunami inundation maps are required for assessing and developing the water elevation in around Ulak Karang and Pasir Jambak sub-districts.
3. The buildings in this study area are digitized using Arc View 10. Then, the results of digitization and field condition are compared by field study data. The inputs of field study data require internal and external building factors.
4. Building materials distribution maps for both study areas are used as the information of the material kinds.
5. To assess the potential risk of an existing building vulnerability due to tsunami hazard, this study develops a formulation of International Strategy for Disaster Reduction [11] as follow :

$$R = H \times V$$

where R is risk level; H is hazard level and V is vulnerability level. The concept is used to simplify the logic of risk calculation, where, 2 elements are essential in formulation of risk. In the context of Relative Vulnerability Index (**RVI**) as a risk level measure, the every building score is given by a formulation [9]:

(1/3) x tsunami inundation factor + (1/3) x internal factors + (1/3) x external factors

Using the two factors, hazard and vulnerability, the risk levels of each building can be computed. Table 1 (a, b & c) [12] are indicators for the potential risk of building vulnerability to tsunami hazard. Relative Vulnerability Index (RVI) scores of a potential risk of building vulnerability due to tsunami hazard are described in RVI score maps in Ulak Karang and Pasir Jambak sub-districts.

Table 1 (a, b & c) Factors for building vulnerability toward tsunami hazard (modified from Dall'Osso *et al.* 2009)

a.   Internal factors

No	Factors	Weight (%)	Very high risk	Score	High risk	Score	Medium risk	Score	Low risk	Score	Very low risk	Score
1	Kind of material	30	timber	5	timber+concrete	4	traditional brick with RC-column	3	RC with brick infill walls	2	concrete + steel	1
2	Number of stories	15	1 story	5	2 stories	4	3 stories	3	4 stories	2	>5 stories	1
3	Soil condition	20	impermeable soil	5		4	medium soil	3		2	permeable soil	1
4	Basement	5	no	5		4		3		2	Yes	1
5	GF const. & found.	5	> 40 years	5		4	20-40 years	3		2	0-20 years	1
6	Preservation condition	5	very poor	5	poor	4	average	3	good	2	very good	1
7	Ground floor	5	not open plan	5	not open plan but many windows	4	50% open plan	3	open plan & windows	2	open plan	1
8	Orientation of building	15	long sides parallel to the shoreline	5	long side forming angle > 30 shoreline	4	long side angel <60 and > 30 shoreline	3	long side forming angle > 60 shoreline	2	long sides perpendicular the shoreline	1
	Total weight	100										

b. External factors

No	Factors	Weight (%)	Very high risk	Score	High risk	Score	Medium risk	Score	Low risk	Score	Very low risk	Score
1	Movable objects	5	extreme	5	high	4	average	3	moderate	2	minimum	1
2	Building rows	15	0	5	1-2 row	4	3-4-5 row	3	6-7-8-9 row	2	>9 row	1
3	Height of concrete fence	15	0-20%	5	20-40%	4	40-60%	3	60-80%	2	80-100%	1
4	Natural barrier	10	no protection	5	moderate	4	average	3	high	2	very high protection	1
5	Distance from coastline	25	0-200 m	5	200-500 m	4	500-1000 m	3	1000- 1500 m	2	>1500 m	1
6	Distance from river	15	0-100 m	5	100-200 m	4	200-300 m	3	300-500 m	2	>500 m	1
7	Obstacle islands	5	no	5		4	small	3		2	big	1
8	Gap between buildings	10	a house	5	3/4 house	4	1/2 house	3	1/4 house	2	close	1
	Total weight	100										

c. Tsunami inundation factor

No	Component	Weight (%)	Very high risk	Score	High risk	Score	Medium risk	Score	Low risk	Score	Very low risk	Score
1	Inundation	100	$h \geq 2$	5	$1.5 \leq h < 2$	4	$1 \leq h < 1.5$	3	$0.5 \leq h < 1$	2	$h < 0.5$	1
	Total weight	100										

■3.0 RESULTS AND DISCUSSION

Domain maps display buildings, roads and river distribution. The maps are created from digitized maps and collected data. The maps show that buildings in Ulak Karang sub-district have more density than buildings in Pasir Jambak sub-district. In Ulak Karang sub-district, distribution of population is almost everywhere in the land. Population who lives near the coastline of Ulak Karang is fisherman. The building distribution in the middle area is the economical center such as Ulak Karang market and some private offices. Furthermore, the eastern sub-district is residential buildings with dense population.

In general, along the coast of Ulak Karang sub-district most building materials distribution is timber and the buildings are close to each other. At least 200 m from this coastline, the building materials distribution is traditional brick with RC columns. In the other side facing to the east, the dominant buildings are RC with brick infill walls. Description of building materials distribution in Ulak Karang sub-district can be seen in Figure 2.

The next is the building distribution in domain of Pasir Jambak sub-district. Ulak Karang sub-district is more residential buildings than Pasir Jambak sub-district. Based on the building materials distribution (Figure 3), most buildings are concentrated in the central region. In a western region of Pasir Jambak sub-district, the buildings are not far apart and they generally are a timber residential area of fisherman. The southern region is bounded by the river that flows into the ocean. The eastern area is an economic center (market, shops) and most building materials distribution is RC with brick infill walls. The second most building materials distribution is traditional brick with RC-Columns. Timber type is rarely in this area.

Based on the maximum tsunami heights and travel times of tsunami generated from a potential tsunami source along the Pagai megathrust to coastal areas of Ulak Karang and Pasir Jambak sub-districts, it can be seen that the bigger earthquake magnitudes generate the higher tsunami waves and shorter travel times of tsunami. But, influence of tsunami height and arrival times with earthquake source depth is different. Tsunami source depths are not proportional with tsunami heights.

A shallow megathrust earthquake source model of 9.0 Mw and at 10 km depth is located at the western Pagai Block. In general situation, the beginning of tsunami waves are characterized by decreasing of mean sea level of 35 minutes after earthquake. Before arriving to study areas, tsunami waves are crushed by western Mentawai islands that directly face to tsunami source. Figure 4 is mean sea level (MSL) of tsunami in Ulak Karang and Pasir Jambak sub-districts. When more detail investigation conducted in both study areas, the water height decrease at the same time (35 minutes after the earthquake model). Tsunami heights on MSL in both study areas are different. MSL in Pasir Jambak sub-district is 7.08 m and in Ulak Karang sub-district is 6.22 m. The topography of both areas are different, Ulak Karang sub-district is more vulnerable than Pasir Jambak sub-district because the topography of Ulak Karang area is more sloping and higher than Pasir Jambak area. As the consequence, tsunami inundation only reaches 200 m from coastline of Pasir Jambak sub-district. Figure 5 and Figure 6 describe the tsunami inundation maps for Ulak Karang (Figure 5) and Pasir Jambak (Figure 6) sub-districts.
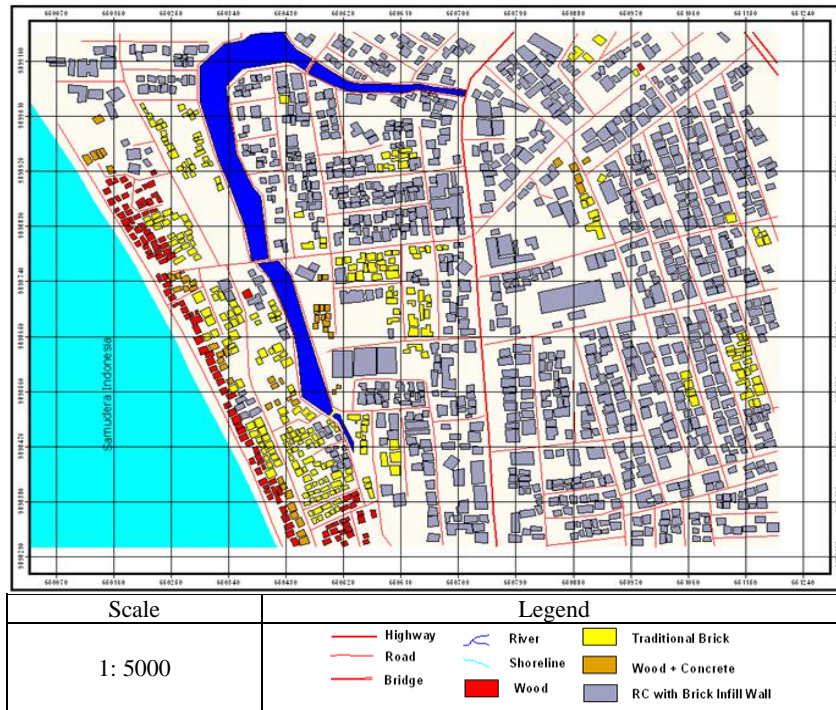
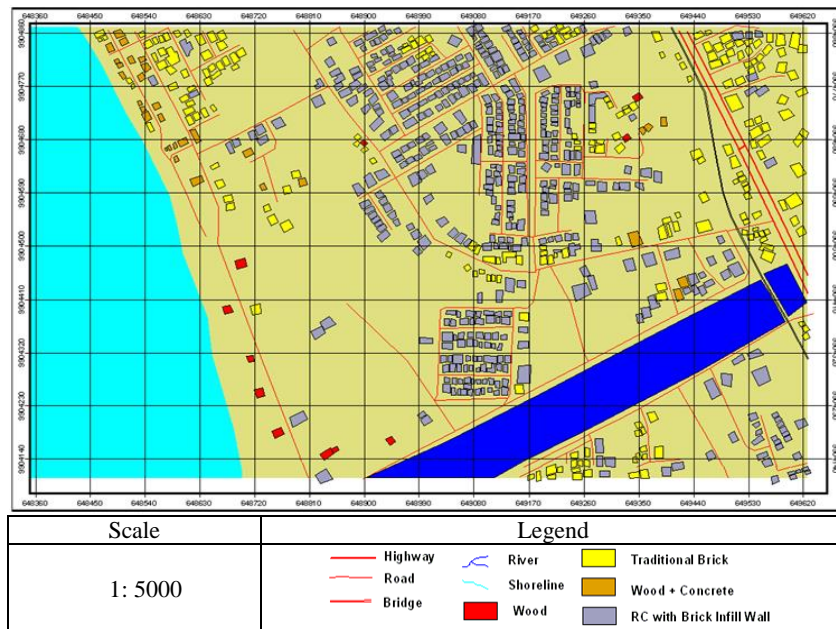**Figure 2** Building distribution in Ulak Karang sub-district

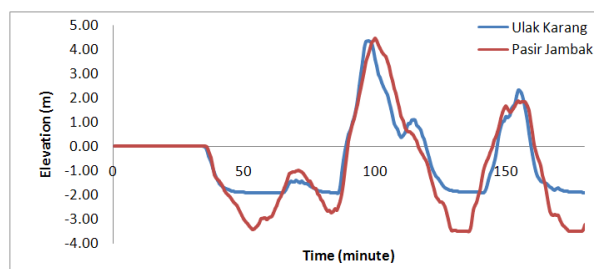**Figure 3** Building distribution in Pasir Jambak sub-district
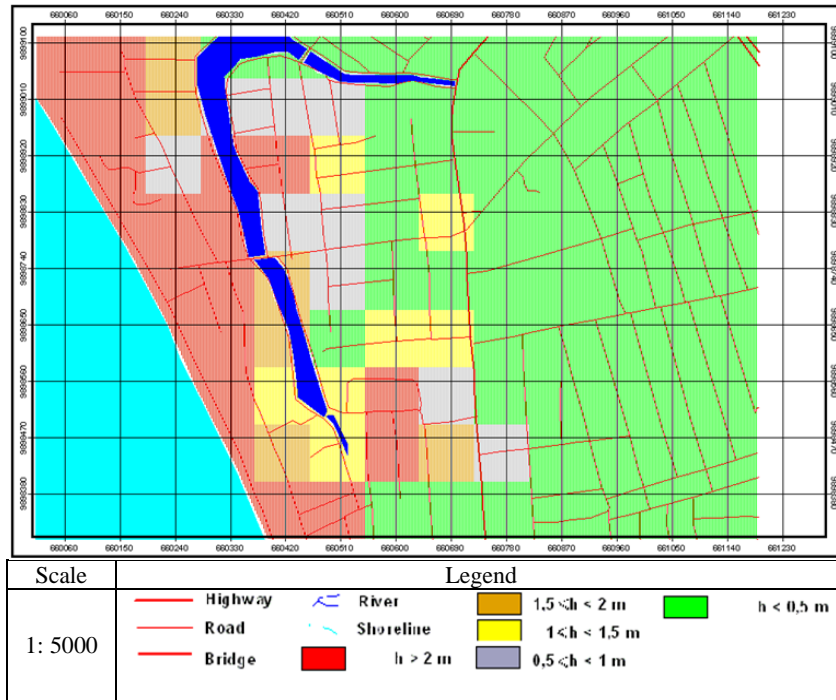

Figure 4 Water elevation caused by a tsunami

Scale	Legend					
1: 5000	Highway / Road / Bridge	River / Shoreline	$1.5 \leq h < 2$ m	$1 \leq h < 1.5$ m	$0.5 \leq h < 1$ m	$h > 2$ m / $h < 0.5$ m

Figure 5 Distribution of tsunami inundation in Ulak Karang sub-district

Scale	Legend					
1: 5000	Highway / Road / Bridge	River / Shoreline	$1.5 \leq h < 2$ m	$1 \leq h < 1.5$ m	$0.5 \leq h < 1$ m	$h > 2$ m / $h < 0.5$ m
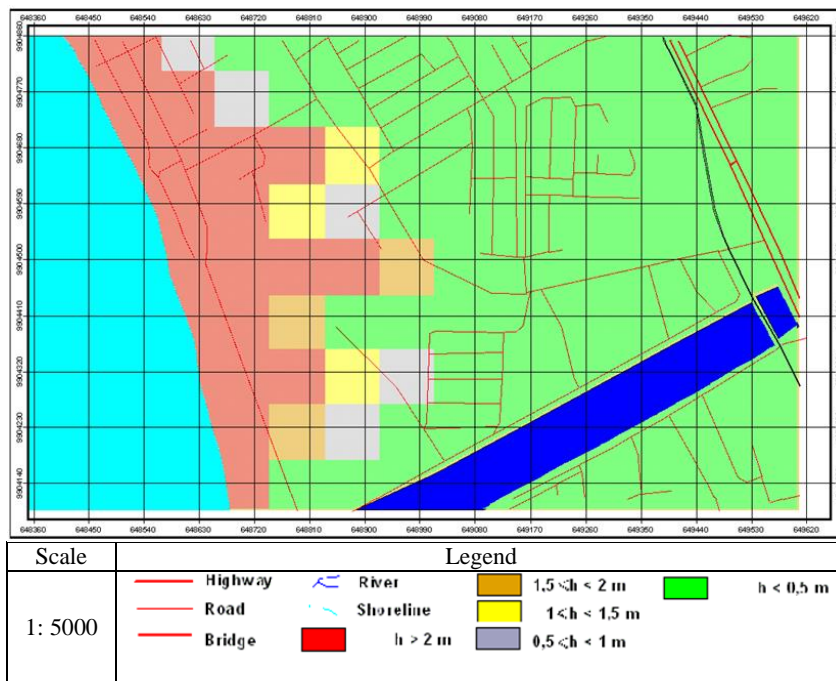
Figure 6 Distribution of tsunami inundation in Pasir Jambak sub-district

Scale	Legend			
1: 5000	─── Highway ── Road	──= Bridge ⌇ River ■ RVI 5	⌇ Shoreline	▦ RVI 4 ▦ RVI 3
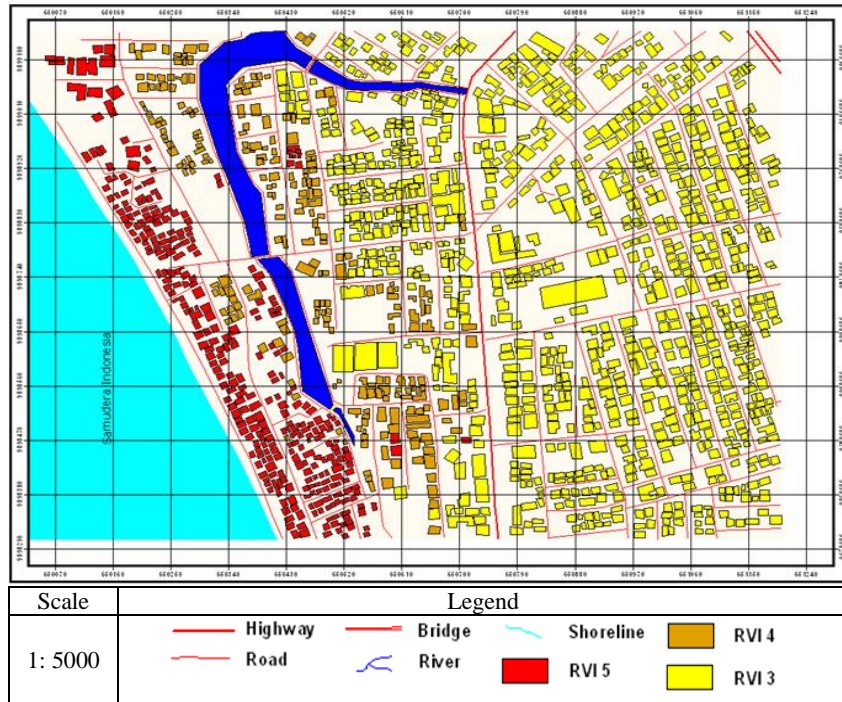
Figure 7 The RVI scores of buildings in Ulak Karang sub-district

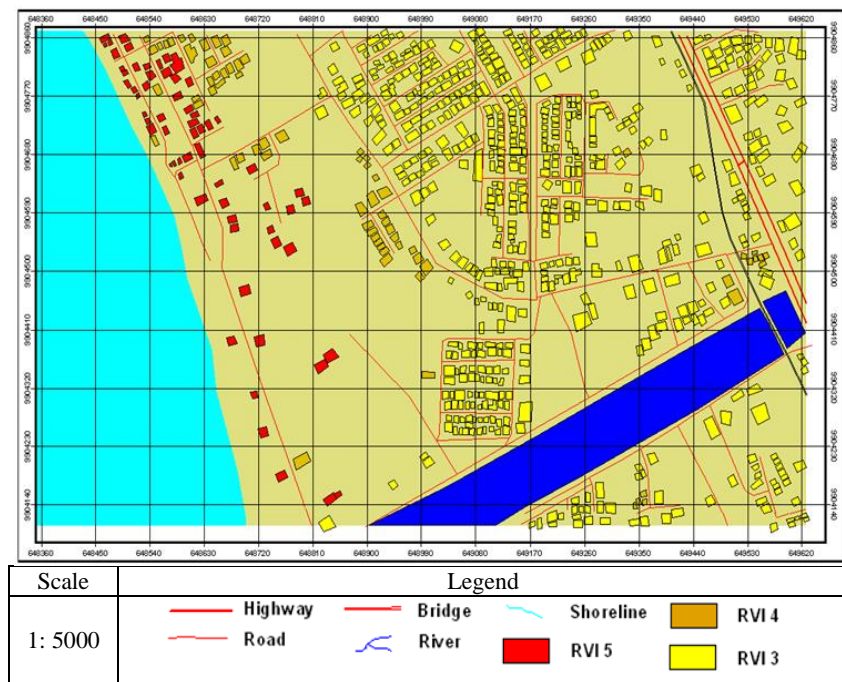| Scale	Legend			
1: 5000	─── Highway ── Road	──= Bridge ⌇ River ■ RVI 5	⌇ Shoreline	▦ RVI 4 ▦ RVI 3

Figure 8 The RVI scores of buildings in Pasir Jambak sub-district

■4.0 CONCLUSIONS

Based on buildings susceptibility toward tsunamis along the coastal areas, the Relative Vulnerability Index (RVI) scores of buildings in Ulak Karang and Pasir Jambak sub-districts are from 3 to 5 (from medium to very high risk), as exposed in Figure 7 for Ulak Karang sub-district and Figure 8 for Pasir Jambak sub-district. The values imply extremely vulnerable to tsunami and unsafe.

To compare these two field study areas, the buildings in area of Ulak Karang sub-district are more vulnerable to tsunami inundation than in Pasir Jambak sub-district because the topography of Ulak Karang sub-district is more sloping than Pasir Jambak sub-district. Moreover, the buildings in Ulak Karang sub-district are close to each other compared to buildings in Pasir Jambak sub-district. Tsunami inundations only touch the land of Pasir Jambak sub-district at least 200 m from the coastline. The consequence, the buildings in Ulak Karang sub-district is more vulnerable than in Pasir Jambak sub-district.

Coastal areas have always been a favorite place for settlement houses. Because of devastating tsunami events, the buildings in coastal communities in Padang have to be developed continually with several alternatives included: 1) regulation for buildings that have 4 and 5 of Relative Vulnerability Index (RVI) scores; 2) building codes; 3) land use zones; 4) sea wall along the coastlines; 5) natural barrier; 6) design and build the vertical evacuation structures, and 7) early warning system.

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