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AN EVALUATION OF INFRASTRUCTURE FOR TSUNAMI EVACUATION IN PADANG, WEST SUMATRA, INDONESIA

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ABSTRACT

Padang, West Sumatra, Indonesia is considered to have one of the highest tsunami risks in the world. Currently, the strategy to prepare for a tsunami in Padang is focused on developing early warning systems, planning evacuation routes, conducting evacuation drills, and educating the public about its tsunami risk. Although these are all necessary efforts, they are not sufficient. Padang is located so close to the Sunda Trench and has such flat terrain that a large portion of its populace will not be able to reach safe ground in the interval—less than 30 minutes—between the time the earthquake shaking stops and the tsunami arrives at the shore. It is estimated that over 100,000 inhabitants of Padang will be unable to evacuate in that time, even if they head for safe ground immediately following the earthquake. Given these circumstances, other means to prepare for the expected tsunami must be developed. With this motivation, GeoHazards International and Stanford University partnered with Indonesian organizations—Andalas University in Padang, the Laboratory for Earth Hazards (LIPI), and the Ministry of Marine Affairs and Fisheries (KKP)—in an effort to evaluate the need for and feasibility of developing Padang's tsunami evacuation infrastructure. This project team designed and conducted a course at Stanford University, undertook several field investigations in Padang, and participated in a reconnaissance trip following the September 30, 2009 earthquake. The team concluded that: 1) the tsunami-generating earthquake is still a threat, despite the recent M7.6 earthquake; 2) Padang's tsunami evacuation capacity is currently inadequate, and evacuation structures need to be implemented as part of an effective evacuation plan; 3) it is likely that previous estimates of the number of people unable to evacuate in time are grossly low; and 4) a more engineering-based approach is needed to evaluate the appropriateness of existing buildings to serve as evacuation sites.

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Introduction

This paper is a product of the GeoHazards International (GHI) and Stanford University study, conducted in collaboration with Indonesian partners, which began in the fall of 2008. Several of the team members also participated in the Earthquake Engineering Research Institute (EERI) reconnaissance trip following the September 30, 2009 earthquake near Padang. That trip was a crucial factor in reaching the conclusions presented in this paper. This study is an ongoing effort, and both GHI and Stanford University are currently working on continuing tsunami risk reduction efforts in Padang.

Tsunami Risk in Padang

In 2004, the Great Indian Ocean Tsunami devastated northern Sumatra and in particular, Sumatra's northernmost city, Banda Aceh. That tsunami killed more than half the population in Banda Aceh and changed the geography of the area. Padang, West Sumatra, Indonesia faces a similar hazard from the same fault that generated the 2004 tsunami. Unfortunately, Padang has almost four times the population of pre-tsunami Banda Aceh. Padang, the capital of West Sumatra Province and the most populated city in that province, is now recognized as having one of the highest risks of tsunamis in the world. Padang has a high tsunami hazard due to the offshore megathrust fault–the Sunda Trench–and has a particularly high exposure to this hazard.

Tsunami Hazard in Padang

Starting in 2004, a series of tsunami-generating earthquakes has occurred on the Sunda Trench. As can be seen in Figure 1, a seismic gap exists along the northern segment of the Mentawai patch, which is located directly offshore Padang. This particular segment of the Sunda Trench is believed to generate a tsunami approximately every 200 years, with the last supercycle in 1797 (5-10 m tsunami in Padang) and 1833 (3-4 m tsunami in Padang) (Natawidjaja 2006). Scientific studies, including paleoseismic data, GPS measurements, and sediment deposits, support this conclusion (Sieh 2008). It is estimated that the tsunami-generating earthquake can measure up to M8.8 and will occur sometime within the next few decades (Sieh 2008). The tsunami wave will arrive roughly 20 minutes after the earthquake and will reach its maximum wave height at 30 minutes (Natawidjaja 2006).

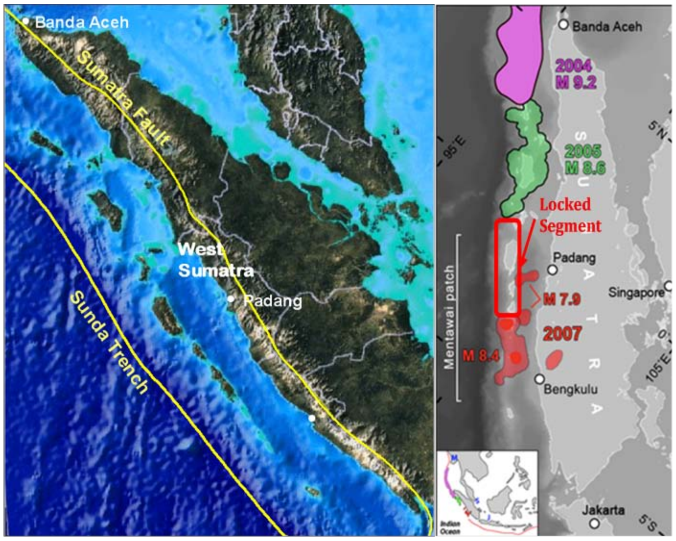

Figure 1. (Left) Map of Sumatra illustrating the offshore Sunda Trench and inland Sumatra Fault. (Right) Map showing locations of recent events along the Sunda Trench offshore Sumatra. Note that the northern segment of the Mentawai patch remains locked, creating a seismic gap directly offshore Padang. Image Source: K. Sieh.

Exposure in Padang

Padang literally means "field" in Bahasa Indonesia, the national language. Its terrain reflects its name: Padang has 3-4 km of flat land, before rising toward hills further inland. As with many coastal towns, Padang's major roads run parallel to the coast, making evacuation inland difficult. Several parts of the city, and numerous areas along West Sumatra's coast, have bodies of water that run parallel to the coast and that therefore impede people from evacuating inland. Most of these areas have few bridges, and the earthquake-resistance of existing bridges is questionable; they might not be usable immediately after an earthquake, when people are trying to evacuate from the approaching tsunami.

In addition to its vulnerable terrain, Padang's population density and distribution make the situation even more concerning. Padang is a city of 900,000 people, half of whom live close to the coast and within a five-meter elevation above sea level. Many of the people living right at the coast are poor fishermen, making relocation a difficult alternative, because these families depend upon the ocean for their survival. Padang's city center, located along the south end of the city, is a bustling shopping area filled with shops and offices. The population density in this region is about 9,000 people per km^2, a population density similar to Mexico City. The population density and distribution, in combination with the terrain, make Padang particularly vulnerable to tsunamis.

Preparedness Efforts in Padang

Padang was designated one of six cities in Indonesia to undertake earthquake and tsunami risk reduction activities, after the tsunami of 2004. In Padang, many of those efforts have focused on developing tsunami early warning systems, planning evacuation routes, educating the local people about their risk, and conducting tsunami evacuation drills. The early warning systems consist of a network of buoys offshore and of seismometers that collect data, in order to immediately determine an earthquake's characteristics and whether or not it could generate a tsunami. People are also being taught to evacuate immediately, if the natural signs of a potential tsunami are present. These include ground shaking that: 1) lasts more than one minute; 2) is so strong that it is difficult to stand; and 3) causes visible building damage. Evacuation routes have been developed, but several studies indicate that the current road and bridge system is grossly insufficient to evacuate the entire city.

Numerous tsunami inundation maps of Padang have been developed by expert scientists, both internationally and within Indonesia. Unfortunately, each map was developed using different assumptions, models and data, which has resulted in inundation maps that vary significantly. The complexity of determining the "best" map has resulted in the city simply using a topography map to plan its evacuation. The city is currently divided into different levels of tsunami vulnerability, according to elevation above sea level: Red Zone (0-5 meters), Yellow Zone (5-10 meters), and Green Zone (>10 meters).

Although all these efforts are necessary, they are unfortunately not sufficient. It is estimated that over 100,000 people would still be unable to evacuate in time, if a tsunami were to occur today. This number, in fact, might be a lower bound, since the simulations used to generate this estimate made questionable assumptions about people's behavior during evacuation and did not account for post-earthquake conditions, such as road blockages due to building debris.

Evacuation Structures

There are several ongoing efforts to incorporate tsunami evacuation structures into Padang's evacuation plan, in order to address the inadequacy of the current plan. Tsunami evacuation structures can be generalized into the following categories:

- *Refuge structures* can be any type of structure that is designed to rise above the expected tsunami inundation level and to withstand the expected earthquake and tsunami forces. These types of structures provide what is referred to as "vertical evacuation." The options for refuge structures can vary widely: they can be new or existing buildings, evacuation towers, soil berms, elevated highways or pedestrian overpasses. Examples of these can be seen in Figure 2.

- *Bridge structures* only need to be earthquake-resistant and to serve as an element of an evacuation route. These structures facilitate what is referred to as "horizontal evacuation." They can help people to evacuate inland or to high ground, as shown in Figure 2.

Figure 2. Examples of tsunami evacuation structures. (Top left) Tsunami evacuation building in Banda Aceh, built after the 2004 tsunami. This building's secondary purpose is to serve as a community center. (Bottom Left) Pre-fabricated structure in Japan with the sole purpose of serving as an evacuation site during a tsunami. (Top right) Aerial photo of a bridge in Padang that provides access to high ground from the city center. (Bottom Right) A soil berm in Japan that provides refuge during tsunamis. Image sources: ATC-64.

New Government Regulation

The local government in Padang passed a law after the 2004 tsunami, indicating that all buildings that are over two stories high can be used as evacuation sites during a tsunami event. Although this law is a good start, several problems remain. First, this regulation has not been communicated well to the public and to building owners. Most people remain unaware of this regulation. Second, it is questionable whether most two-story buildings in Padang could actually serve as safe evacuation sites. The structural integrity of many buildings in Padang is likely insufficient to withstand tsunami forces, let alone the earthquake forces prior to the tsunami.

Existing Building Surveys

There have been recent efforts to evaluate existing buildings, in order to identify those that would be adequate for vertical evacuation. This is especially crucial in Padang, because the government has limited resources, and using structures that are currently available is more economically feasible than building new evacuation structures. There have been several studies to date on the suitability of existing buildings in Padang to serve as evacuation structures. A brief description of each study follows.

- Provincial Government List. This is a list of "important, tall buildings in Padang" that was compiled by the provincial government sometime around 2006. No other evaluations were conducted.

- Andalas University List. This building survey was carried out in collaboration with a German organization. The survey "graded" 513 buildings under four categories–earthquake-resistance, tsunami-resistance, accessibility, and liquefaction potential–by conducting quick visual assessments and by taking some measurements of element sizes and material strength. In this survey, only three buildings received good scores for all four categories.
- Ministry of Marine Affairs and Fisheries (KKP) List. This list of recommended buildings was compiled using the two lists described above and following a similar procedure to the Andalas University List. However, this list also excluded: 1) buildings within 200 meters of the coast; 2) buildings with two floors within 500 meters of the coast; 3) private company buildings; 4) warehouses; 5) home-shops (rukos); 6) hospitals/clinics; and 7) houses. This list has a total number of 44 recommended buildings.
- German-Indonesian Tsunami Early Warning System (GITEWS) List. The recommended buildings on this list were included as preliminary candidates for evacuation on evacuation maps developed in 2009. These recommendations were based on past building surveys conducted by KKP and Andalas University.
- Laboratory of Earth Hazards (LIPI) List. This building survey was being initiated in the summer of 2009 and is currently incomplete. The survey follows a similar procedure to that of the Andalas University List. No building recommendations have yet been made by LIPI.
- GHI-Stanford Survey. This survey was conducted during the summer of 2009; buildings were chosen based on the lists described above. This study focused more on determining building seismic deficiencies when compared to the previous surveys. No building recommendations have been developed yet from this survey.

These building surveys provide a good start towards identifying existing buildings that could serve as evacuation sites; however, much work remains to be done. The surveys are quick assessments and do not adequately address potential seismic deficiencies of the buildings, which is crucial to determining whether or not they are appropriate as evacuation structures.

September 30, 2009 Earthquake and Evacuation

On September 30, 2009 at 5:16 PM, a M7.6 earthquake struck Indonesia approximately 50 km W–NW of Padang. The earthquake occurred within the Indian-Australian plate but was too deep (80 km) to generate a tsunami. This earthquake had relatively few aftershocks, but on the next day, a M6.6 earthquake occurred on the inland Sumatran fault located 215 km southeast of Padang. Unfortunately, only one strong motion sensor collected data. This equipment, which was located at the foothills and further inland, recorded a peak ground acceleration of 0.3g. However, most of Padang sits closer to the coast and on soft soil, so it is expected that the ground motion there was probably closer to 0.4 – 0.6g.

Tsunami Evacuation

Tsunami education efforts have definitely spread throughout Padang, and most people now know that strong earthquake shaking is a natural warning of a potential tsunami. According to a government official, over 90% of the people in the high inundation area evacuated after the earthquake. However, there were still numerous problems with the evacuation plan. People are taught to evacuate immediately after earthquake shaking, a procedure people do follow during evacuation drills. However, people did not do this during the earthquake. They delayed evacuating for various reasons–to help injured people or people under trapped buildings, and/or to go home to check on their families. Most people also used their vehicles, although they had been told not to do so during an evacuation. This caused people to be stuck in massive traffic jams for 1-2 hours. Some people in traffic became so frustrated that they abandoned their cars and fled on foot, making the traffic congestion even worse. This is especially concerning when one considers that, had a tsunami occurred, it would have arrived in Padang 20-30 minutes after the earthquake.

There was very little evidence of vertical evacuation, with one exception. Andi Syukri, an Andalas University student, evacuated to Masjid Taqwa, one of the major mosques in Padang, right after the earthquake and indicated that about 100 people evacuated to the mosque in fear of a tsunami.

Performance of Evacuation Structures

Roads and Bridges

The roads and bridges leading to “safe ground” (either inland or to high ground) did not suffer heavy damage, but the already narrow roads became even more constricted, due to building debris. A recent study by Professor Febrin from Andalas University showed that the evacuation demand on these roads is too high, even if the roads are clear of debris. One of the major bridges connecting part of the dense area of the city to high ground did suffer some damage. As can be seen in Figure 3, the damage is in the approach to the bridge and not to the bridge structure itself. Although this bridge will need substantial repair, the damage was not sufficient to have presented major problems with evacuation, had a tsunami occurred.

Figure 3. (Left) Map indicating location of one of the major bridges connecting the dense city

center to high ground. (Right) Photos of earthquake damage to the south end of the bridge approach. Image source: EERI.

Buildings

Buildings that had been previously recommended as potential tsunami evacuation sites varied in performance. Many suffered heavy structural and nonstructural damage, while a few completely collapsed. This wide spectrum of performance demonstrates the need for a more thorough analysis of buildings, before any are recommended as evacuation sites. Although some of the building's structural system remained intact, nonstructural damage was so intense that most people would have felt unsafe going inside. Therefore, their use as evacuation sites remained ineffective. Of the 31 potential evacuation buildings visited by the EERI reconnaissance team, 1/3 were found to have collapsed or were heavily damaged, and roughly ¾ of the buildings had sufficient damage still to be closed two weeks after the earthquake. Figure 4 shows before and after photos of some of these buildings.

Figure 4. Before and after photos of buildings that had been recommended as evacuation sites. From left to right: Four story mall, partial collapse on the 4th floor and fire; 4-story language school, collapse of first 2 stories; 4-story junior college, complete collapse. Image source: EERI.

Good Candidates for Evacuation Sites

After the earthquake, there were few structures that could have served well as evacuation sites had a tsunami occurred. Below are two examples.

Bank Indonesia

Bank Indonesia is a bank office complex with three concrete frame buildings. It is a good candidate for tsunami evacuation, because the complex is large, located on an elevated site, and has an outdoor terrace that is 20 meters above sea level. The complex also has on-site security, ensuring that access during a tsunami could be arranged. Two of the newer buildings suffered only minor to moderate nonstructural damage due to the earthquake. This building was designated by the Padang government as a tsunami evacuation site. However, according to a security guard, the general population did not seek refuge in the bank complex, and most people who were inside the building during the earthquake evacuated and tried to go inland.

Masjid Taqwa

Masjid Taqwa is a large, three-story mosque that was constructed around 1979. The mosque is located near the central market in the heart of the city center. There was no visible structural damage to the building after the earthquake, only minor non-structural damage, chiefly to the minaret and parapets. Roughly 100 people evacuated to the mosque following the earthquake, because they were afraid that a tsunami might strike.

In general, large, multi-story mosques are good candidates for tsunami evacuation sites, because: 1) they have a large, open prayer area that can accommodate a large number of people; 2) they tend to have a lot of columns, making them redundant structures; 3) they tend to be of better construction quality than other structures; 4) they are designed to be accessible to a large number of people; and 5) people tend to go to mosques after disasters, due to the religious nature of the culture.

Conclusions

The following is a summary of conclusions drawn, based on observations and lessons learned from the GHI-Stanford study and from the September 30, 2009 Earthquake reconnaissance trip:

1) A tsunami-generating earthquake is still a threat. The recent earthquake was too deep to cause a tsunami and did not release accumulated stress on the Sunda Trench.
2) Padang’s tsunami evacuation capacity is currently inadequate, and evacuation structures need to be incorporated into the evacuation plan. As past studies have concluded and as the recent earthquake demonstrated, horizontal evacuation is not sufficient for the city of Padang. Therefore, it is crucial to develop other means of evacuation.
3) It is likely that previous estimates of the number of people who will be unable to evacuate are grossly low, given that most of these studies did not account for the real, post-earthquake conditions demonstrated during the September 30 event. Past models/simulations did not account for debris in the road and lack of visibility from dust and particles from collapsed buildings. Those models/simulations also assumed that: a) people would not use their vehicles for evacuation; b) people would evacuate immediately following the earthquake; and c) people could use certain buildings for evacuation, many of which proved to be inadequate under earthquake loading alone.
4) A more engineering-based approach is needed to evaluate the appropriateness of existing buildings to serve as evacuation sites. The wide spectrum of performance of potential evacuation buildings during this recent earthquake demonstrates the need for a more thorough analysis of buildings, before they are recommended as evacuation sites.

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