Learning from Earthquakes

The M_w 7.6 Western Sumatra Earthquake of September 30, 2009

From October 9th to 18th, a team organized by the EERI investigated the effects of the Western Sumatra Earthquake. The team was led by Gregory Deierlein of Stanford University, and included Nick Alexander of Degenkolb Engineers, Veronica Cedillos of GeoHazards International, Louise Comfort of the University of Pittsburgh, Tim Hart of Forell/Elsesser Engineers, Inc., Elizabeth Hausler of Build Change, Scott Henderson and Kelly Wood of the Stanford Chapter of Engineers for a Sustainable World, Sindhu Rudianto of Geo-Optima, Inc., and Sugeng Wijanto of PT. Gistama Intisemesta. Others who contributed to this report include Walter Mooney and Art McGarr of the USGS, Carlos Cabrera of Risk Management Solutions, Inc., Andrew Kizzee of Food for the Hungry, Harkunti Rahayu, Syahril Kusuma, and Anin Utami of the Institute of Technology Bandung, Kerry Sieh of Nanyang Technical University, and Gina Sandoval, Richard Franco, and Brian DiBarnaba of Degenkolb Engineers.

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Introduction

On Wednesday September 30, 2009, at 5:16 p.m., an M_w 7.6 earthquake struck the west coast of Sumatra, affecting an area with a population of about 1.2M people, including 900,000 in Padang and 80,000 in Pariaman. Padang is the capital of West Sumatra, situated on the coast of the Indian Ocean between the Sumatra fault and the Sunda Trench fault (Figure 1).

The earthquake caused 1,195 deaths and significant damage to about 140,000 houses and 4,000 other buildings (Satkorlak, 2009). The casualties (383 deaths, 431 serious injuries) in Padang were mostly due to building damage and collapse. These numbers would likely have been higher had the earthquake struck earlier, when schools and offices were in session.

Landslides in the outlying rural mountain areas buried several villages, damaged roads, and caused over 600 deaths. That the earthquake did little damage to roads and bridges in and around Padang facilitated the restoration of power, communications and infrastructure to most regions within a week.

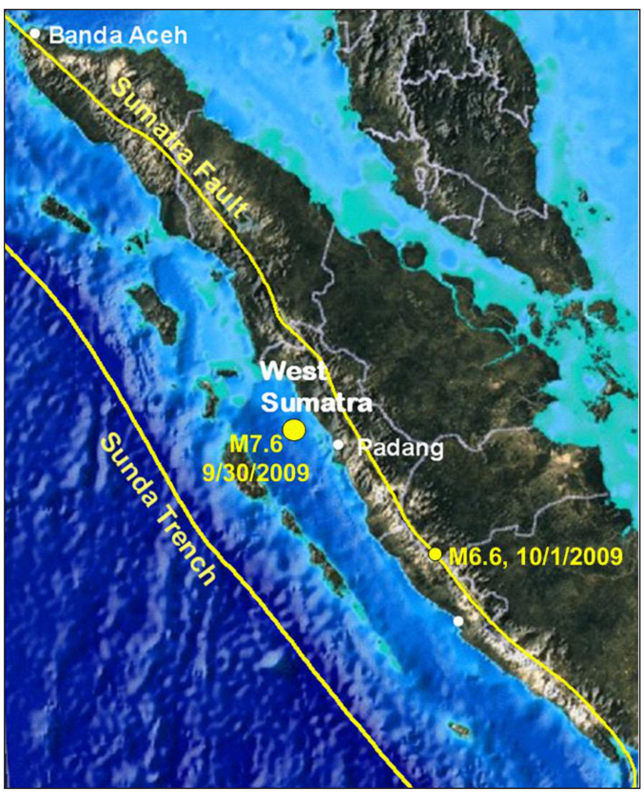
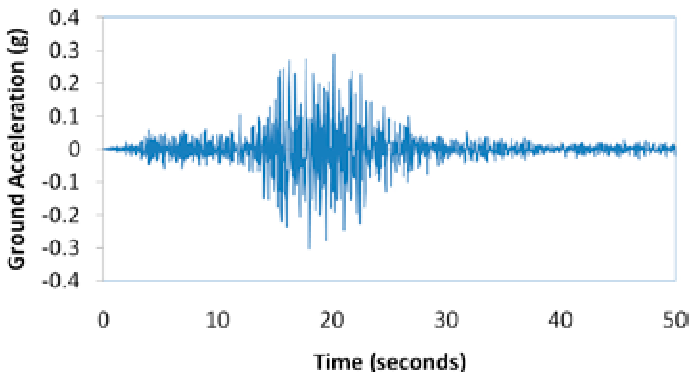


Figure 1. *Location of the September 30 and October 1 earthquake epicenters on the Sunda thrust fault and Sumatra strike-slip faults (Sieh 2009).*

Figure 2. *Padang and the Batang Arau River viewed from the mountains to the east.*



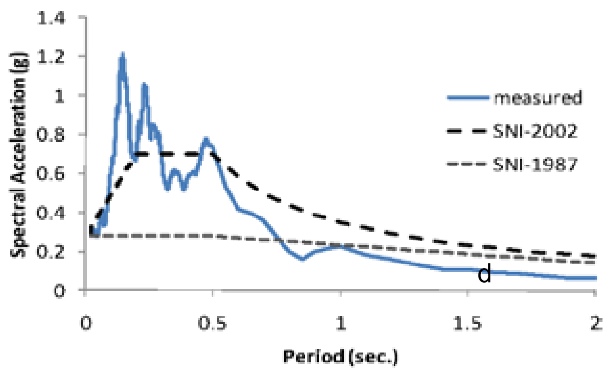


Figure 3. *Ground acceleration and response spectra (N-S component) and design earthquake spectra (BMKG/USGS, 2009).*

Figure 4. *Siti Nurbaya Bridge south approach ramp.*

The low-lying coastal regions of Padang and the surrounding west coast of Sumatra have one of the highest risks in the world from a tsunami, specifically one generated by a large earthquake on the Sunda Trench, since it has a seismic gap (Sieh, 2009). Padang is bordered on the south by the Batang Arau River and on the south and east by mountains; over time the city has developed to the north along the coast (Figure 2). When strong ground shaking was felt on September 30, most people in Padang attempted to evacuate inland to higher ground, but with limited success due to traffic congestion. Fortunately, the earthquake was caused by a deep fault rupture that did not trigger a tsunami.

The cities of Padang and Pariaman and the surrounding region face a major building reconstruction effort. The widespread damage to buildings raises questions about the effectiveness of design and construction practices, as well as building code enforcement. The earthquake also highlights the need for improved emergency response, tsunami evacuation strategies, and coorination of relief efforts for future disasters.

Seismicity and Ground Motions

Earthquakes are abun- abundant at the megathrust boundary between the subducting oceanic Indo-Australian plate and the overriding Sunda plate, which includes the island of Sumatra. The subduction zone surrounding this event has not had a megathrust earthquake since a very large event (est. >M 8.5) in 1797. However, the M_w7.6 quake was neither a megathrust event nor did it generate a tsunami of any significance. It was located at a depth of about 80 km within the oceanic slab of the Indo-Australian plate, with its epicenter located offshore about 60 km WNW of Padang.

The rupture zone of the earthquake is remarkably compact, with a nearly circular shape with a radius of only 15 km. In terms of its high-frequency ground motion, this earthquake was similar to intra-slab earthquakes, at intermediate depth and comparable magnitude, in other locations such as the west coast of South America. However, its focal mechanism — thrust faulting on planes striking at high angles to the trend of the subduction zone off Sumatra — is quite unusual. The thrust faulting source mechanism indicates that it was due to compression and internal buckling of the oceanic lithosphere. A slip model developed by the USGS indicates a maximum slip within the rupture zone of about 9 m. This, in conjunction with the seismic moment (about $2.6x10^{20}$ N-m), suggests a high maximum slip rate, as well as strong radiated energy. As with typical subcrustal earthquakes (60-170 km depth), the earthquake produced only a few aftershocks, most soon after the M7.6 main shock. On October 1, the area experienced shaking from a M6.6 earthquake, which was not an aftershock, but instead originated on the Sumatra fault about 215 km south east of Padang (see Figure 1).

There is only one strong ground motion record from the region (BMKG/USGS 2009), which shows about 20 seconds of strong shaking with a peak ground acceleration (PGA) of 0.3g (Figure 3). The spectral accelerations in the short period ranged from 0.5g-1.2g and dropped off at longer periods. Since the instrument site was located at the base of the mountains, about 12 km in from the coast and on stiff soil, the ground motions in the center of Padang, on softer deeper soil deposits, are likely to have been larger. Superimposed with the measured spectral accelerations are design earthquake spectra, described later. Median PGA values from attenuation models for

Figure 5. *First-story column damage and residual drifts in public works building.*

subduction earthquakes for M7.6, R=60km, and H=80km yield PGA of 0.4g to 0.6g for soil sites (Young et al., 1997; Zhao et al., 2006; Atkinson et al., 2003), which are consistent with the strong motion recording.

Geotechnical Aspects and Landslides

Geotechnical conditions and ground deformation: According to the geologic maps of the Geological Survey of Indonesia (Kastowo et al., 1973), the coastal plains of Padang and Pariaman are underlain by quaternary alluvium deposits, consisting of silt, sand, gravel and remnants of pumice tuff.

Preliminary information from soil borings in Padang shows the subsurface consisting of medium dense to dense silty sand and stiff to very stiff silt with relatively low ground water levels. In areas next to the Batang Arau River (Figure 2), the site conditions include undocumented fills consisting of loose, saturated fine sand, which were placed as part of the site development.

Despite severe damage to many buildings, ground cracking and foundation damage did not appear to be significant, except in few areas next to the Bantang Arau River, where there was ground cracking up to several hundred meters in from the river front.

The Siti Nurbaya bridge (in Figure 2) is one of the few bridges outside of the mountain areas that suffered earthquake damage. It is an important link between the low-lying old town of Padang and high ground located to the south, and the bridge approach had ground cracking due to settlement and dynamic densification of fills within the reinforced earth ramp (Figure 4).

Under a four-story public works building, located 100 m away from the river front, there was liquefaction that may have contributed to the building damage. The building configuration concentrated lateral deformations and residual drift in the first story (Figure 5). Adjacent to the building, fine beach sand spouted out of ground cracks, indicating that liquefaction may have caused foundation movement and increased the demands on the structure. There was ground deformation under several other smaller buildings along the river front and in other isolated parts of Padang.

Landslides: At Lubuk Lawe, northeast of Padang and Pariaman, extensive landslides and mud flows buried hundreds of people and demolished at least five villages (Figure 6). Observations of the spoil site showed that the pumiceous tuff originating from late eruptions of the Maninjau caldera was light and porous and had little cohesion. Heavy rain over several days before the earthquake is likely to have saturated the ground, increasing the driving force and weakening the soil resistances, causing the slope to be marginally stable. The flat lands below the hills at the toe of the hills, consisting mainly of loose silt, sand and gravel mixtures, may have also lost lateral support and

Figure 6. *Shallow slope failures and debris flows in rural areas northeast of Padang.*

contributed to the massive landslides and debris and mud flows. In highland areas the heavy rain and earthquake shaking caused near-surface loose colluvium to slide.

Seismic Design and Building Behavior

Typical construction and building performance: Most multi-story buildings in Padang are reinforced concrete frames with unreinforced solid clay brick infill walls. The frames are designed as the primary lateral force-resisting system; the stiffness and strength from the brick infill walls are not typically considered in design.

Story collapses, often in the first story, were observed in many buildings. These were due primarily to a combination of weak columns, strength and stiffness irregularities created by discontinuous or failed infill walls, and deficiencies in concrete reinforcement detailing and construction. Collapses were more prevalent in concrete buildings constructed prior to about 2002, before Indonesia revised its building codes with higher seismic base shears and more stringent design requirements. Particularly in older buildings, the concrete frame member sizes appeared smaller than required to resist the ground motion demands. In such cases, the infill walls tended to improve the performance initially, up to the point that the walls failed, then led to a concentration of deformations that could cause collapse.

Deficiencies observed are similar to those seen in older reinforced concrete buildings in the United States and in developing regions throughout the world. Concrete spalling and failure revealed (a) absence of column stirrups in beam-column joints, (b) use of plane, as opposed to deformed, reinforcing bars, (c) insufficient column ties (large spacing, small diameter) with 90 degree hooks with minimal overlap, and (d) concrete with rounded river stone aggregates and low bond/compressive strengths. Beyond the structural system, infill walls and other architectural finishes (drywall partitions, glass facades, plaster coatings) were damaged extensively by the deformations of the flexible concrete frames.

Building code seismic design provisions: The first earthquake loading code in Indonesia was published in 1970 (Indonesian Loading Guidelines N.I.-18), where the design accelerations for Padang were 0.1g for use with working stress design. In 1987, the seismic design requirements were changed to incorporate inelastic response modification factors and more stringent detailing requirements. Modeled after the New Zealand and ACI-318 codes (SNI 03-1726-1987), the 1987 standard divided the Indonesian region into six seismic zones, Zone 1 being the highest and Zone 6 the lowest seismic hazard, and specified two soil conditions (soft or hard). Padang and the surrounding region were classified as Zone 2, with design PGA of 0.28g (hard soil in the hills) to 0.36g (soft soil in the downtown area).

In 2002 the code was updated to the Earthquake Resistant Design Standard (SNI-1726-2002), which was adapted from the 1997 UBC and the 1999 ACI-318 concrete design provisions. This code revised the seismic zone designations, with Zone 1 now being the lowest and Zone 6 the highest seismic hazard, expanded the soil designations to three, and modified the design spectra in the short period range.

As shown in Figure 3, in the short period range, the elastic design spectra for the 2002 code are comparable to the spectral accelerations of the measured ground motions, whereas the values from the 1987 code are much smaller. The elastic design spectra shown in Figure 3 are both for hard soil sites; for the softer soil sites in downtown Padang, the spectral values are

Figure 7. *Padang city government buildings, including a collapsed 3-story building (left) and newer 4-story building (right) with extensive nonstructural damage.*

Figure 8. *First-floor collapse in 3-story office of the Provincial West Sumatra Planning Building, constructed in 1983.*

about 30% larger, and the transition period shifts to 1 second.

In response to several large recent earthquakes, work is currently underway on a new Earthquake Resistant Design Standard modeled after the ASCE 7-05, IBC-2009, and related standards. It is expected to be published in 2010. Probabilistic hazard studies, conducted by ITB University and USGS, suggest that the PGA design values on soft soil sites in Padang should be increased to about 0.4 to 0.5 g (Peterson et al., 2004).

Enforcement of building codes: Based on the EERI team's observations and interviews with engineers, enforcement of building codes and construction quality assurance is lacking in Padang. While the national building code standards have been strengthened, the extent to which these have been implemented in Padang is unclear. Enforcement problems are most serious with smaller buildings and renovations, which are often not reviewed by city building department officials, leading to deficiencies in both the design engineering and construction quality assurance.

Government buildings: Government buildings in Padang, Pariaman, and West Sumatra Province had significant earthquake damage and many collapsed. The EERI team visited ten government buildings, of which all were closed, and six suffered a first-story collapse. With the exception of a few older masonry buildings, most buildings were multi-story concrete frames with brick exterior walls and infill partitions. The newer buildings tended to have more glass on the exterior and combinations of infill brick and dry wall interior partitions.

The Padang City Government headquarters consists of several buildings, including an old 2-story masonry building that houses the mayor's office and two concrete buildings that house administrative offices. The masonry building, constructed by the Dutch in 1906, had moderate damage to the masonry walls, including a couple that failed out-of-plane. The 3-story city planning office, constructed in 1977, had a first-story collapse due to a combination of weak columns and seismically deficient steel reinforcement (Figure 7, left). This building had been moderately damaged during an earthquake in 2007, but no investigation or retrofit followed. The office staff had left for the day and the building was unoccupied when the earthquake struck. A newer 4-story office building survived the earthquake with only minor damage to the concrete frame, but with extensive damage to the façade, interior partitions, and the third-floor ceiling (Figure 7, right). Damage to the third-floor ceiling and walls was exacerbated by the steel roof truss that provided limited diaphragm stiffness.

The first story collapsed in the 3-story office of the West Sumatra Planning Department (Figure 8), built in 1983. The inward taper to the façade and concrete walls created a weak first story that collapsed with about 250 mm of lateral displacement (6% drift). Large river rock aggregate (up to 120 mm) in the concrete had limited bond to the cement and sand matrix. According to security personnel, 80 people were in the building during the earthquake, two of whom died while evacuating from the 2nd floor.

Schools: According to Indonesian government sources (Satkorlak, 2009), about 1,100 schools were damaged, affecting 3,200 classrooms. The schools include both multi-story concrete buildings and single-story masonry buildings. Most schools were not in session at the time of the earthquake, but there were some notable exceptions, such as schools that hosted late afternoon language tutoring and special education programs. The EERI team visited eight damaged school buildings, including five that had partial or full collapse.

The SMK Negeri 9 high school is located in downtown Padang across the street from the damaged

Figure 9. *Partially collapsed SMK 9 Negeri High School.*

Ambacang Hotel. In the largest of the three buildings, a 3-story concrete frame with brick infill walls built in 1996, interior brick partitions failed (Figure 9) and the third floor collapsed partially. School officials reported that 200 students were present at the time of the earthquake and that most escaped by running out of the building. Two people died and five others were injured. Displaced classes were being held in a tent, and workers were in the process of building a temporary wood building to house classes until the permanent buildings were reconstructed.

The 4-story STBA Prayoga Language College building (Figure 10) was located close to the coast and had been identified for vertical tsunami evacuation. Constructed in 2001, the building consisted of two structures, separated by an expansion joint, one of which collapsed completely. A class of 15 people was in session at the time of the earthquake, 13 of whom perished. According to the survivors, the students were on the 2nd floor and attempted escape from exits at opposite sides of the building before being trapped by the collapse. The portion of the building left standing revealed a concrete frame with tall story heights, deep beams and slender columns, which made the building prone to a multistory sideway collapse. Pounding between the adjacent buildings may also have contributed to the collapse.

Hospitals: The EERI team visited four of nine hospitals in Padang that had sustained significant damage. While three of the four hospitals were open at the time of the team's visit, hospital capacities for patient care were significantly reduced. The M. Djamil Hospital is the largest medical facility in the Padang area, with over 800 patient beds. The hospital campus includes 13 separate buildings, of which the one housing outpatient services collapsed. An adjacent building that housed the labs sustained substantial structural damage and was closed. The remaining buildings, including the critical care areas of the hospital, appeared to sustain only minor damage and remained in service. The outpatient building, constructed in 1982, was comprised of a 3-story cross-shaped core section with 2-story wings at each corner. The entire 3-story core and one of the 2-story wings suffered a 1st-story collapse (Figure 11). The column failure appeared to result from inadequate strength and reinforcing bar details, combined with horizontal and vertical framing irregularities.

The Yos Sudarso Hospital, a 14-building, 145-bed campus, is the second largest hospital in Padang.

Figure 10. *Before and after pictures of 4-story STBA Prayoga school building.*

Figure 11. *Collapsed outpatient building of the M. Djamil Hospital.*

The original three-building core was constructed from 1971-1973, and three more central structures were added in 1990. Additional buildings outside the core included a nurse's dormitory building (1988), a pediatric and patient care building (2003), and a senior care and housing facility (1985-1994).

The primary damage was to one of the core buildings and a corridor connecting the buildings. There was extensive column damage in the second story, which appeared to be the result of incompatible deformations and pounding across the expansion joints between the interconnected core buildings. Remarkably, the area below the second floor was undamaged, and the first floor was still in use, even during the demolition and removal of the upper stories.

The concrete frame and infill walls of the nurse's dormitory were damaged extensively, and the building is likely to be demolished. Damage to other buildings was mostly limited to localized concrete spalling, cracking of brick infill walls, and damage to contents and equipment. Major radiology equipment did not have visible damage, but some of it is not operational. Though it lost 60% of its pre-earthquake capacity, the hospital continued to serve patients immediately following the earthquake, with the help of tents, an on-site emergency generator, and on-site well-water supply.

Commercial buildings: Padang was a Dutch colonial trading center in the 17th century. Evidence of this period is found along the Batang Arau River, where there are a number of 100-300 year old buildings from the Dutch era (Figure 12). While most of the old Dutch buildings survived, significant repairs will be necessary to restore them. Padang is still an active trading port, with large cement and coal producing facilities. Modern commercial buildings are characterized by large department stores, hotels, shopping centers, private offices, and bank buildings. Home-shop buildings, known locally as rukos, are very common; in them, ground level commercial spaces are combined with residential living areas on the second story.

The typical ruko layout includes an open store front and large window openings at the front elevation, with concrete frames and exterior brick infill walls on all sides and interior brick infill walls between units (Figure 13, top). The brick infill wall layout causes the buildings to be stiff in the transverse direction and flexible along the front elevation. While the majority of these buildings showed no signs of structural damage, there were a number with significant residual drift and hinging at the top of the first-story columns. A number of collapsed rukos were observed, almost exclusively caused by a first-story mechanism and column failure (Figure 13, bottom). In many cases, they had been renovated to add ad-

Figure 12. *Masonry building constructed by the Dutch in 1908.*

Figure 13. *▲ Damage to home shops that are common in Padang. ▼*

ditional floors without any seismic design or strengthening.

Commercial shopping districts in Padang consist of both new shopping centers and older traditional market buildings. When the EERI team was there, all but one (Damar Plaza) of the six largest shopping centers in Padang were closed due to damage. This damage is particularly significant since many of the buildings had been identified for tsunami vertical evacuation, which would require better performance than observed. The Sentral Plasa Raya, a 3-story structure built in 2005, suffered significant brick infill wall damage on all four sides and major nonstructural damage to ceilings and equipment (Figure 14). The rear corner of the structure collapsed, while adjacent columns were damaged at the beam-column joint but remained standing. On the roof above the collapsed area, several large tanks and a penthouse may have caused torsional behavior that contributed to the collapse. While the column reinforcing ties were closely spaced, the ties had 90 degree hooks all aligned along one corner; that conduced to unzipping the ties up the column.

Approximately half of Padang's large multi-story hotels suffered significant damage and were closed after the earthquake, which limited accommodations for visiting aid organizations. Collapse or partial collapse was more prevalent in the older hotels, especially those that had renovations and additions. Some of the newest hotels sustained extensive damage to nonstructural components, including architectural cladding, ceilings and partitions.

The collapsed Ambacang Hotel received extensive media coverage because of the large number of trapped guests and fatalities; unconfirmed media reports had 200 people dying in the collapse. The original portion of the building was a 2-story concrete frame with masonry infill, constructed in the early 1900's. Recently, three new floors were added on top of the original two, with a combination of structural steel and concrete framing. A separate 6-story steel framed structure was built adjacent to the original building. The second story of the original building and the lower stories of the new 6-story building collapsed.

Just down the street from the Ambacang Hotel, another new 5-story steel-framed addition to the Mariani Hotel collapsed. As these two buildings were among the few new steel buildings in Padang, their collapses suggest a need to improve Padang's seismic design practice for steel construction.

Bank Indonesia is a large bank office complex consisting of three concrete frame buildings with brick and glass infill. Two original buildings were built in 1975 and the third was added in 2003. One of the older buildings had structural and nonstructural damage, while the other two had minor to moderate nonstructural damage.

◄ ***Figure 14.*** ▲
Collapsed portion of three-story Sentral Plasa Raya.

Services at the bank were interrupted by the earthquake; however, most ATMs were functional within two days of the earthquake and normal operations resumed within five days.

The Bank Indonesia building offers an attractive tsunami refuge site, owing to its large size and high elevation (on a large outdoor terrace 20 meters above sea level), and it had been designated by the Padang government as a tsunami evacuation site. However, according to a security guard, not only did the outside population not seek refuge in the bank, but most of the bank employees evacuated the site in search of higher ground inland.

Residential Housing

According to Indonesian government reports, up to 140,000 houses were damaged in Padang, Pariaman, and the surrounding areas. Most of the housing is unreinforced masonry, although there are a significant number of timber houses with masonry skirt walls, and a growing number of confined masonry houses.

In contrast to the significant damage to masonry houses, the timber frame houses performed well due to their lighter weight and proportionally higher strength. Calculation-based design requirements for masonry and other house construction are not covered in the regular building code; rather, there are guidelines with recommended construction details and requirements.

Unreinforced masonry: Single-story unreinforced masonry (URM) houses are typically supported by a shallow river stone masonry strip footing, and the walls are either fired brick masonry (Figure 15) or rounded river cobble masonry (Figure 16).

Bricks common to rural areas are hand-molded, fired in outdoor kilns. Their quality and strength can vary considerably, depending on the type of clay used, duration of firing, and placement in the kiln.

Figure 15. *Unreinforced brick masonry house with both in-plane and out of plane wall failures.*

Figure 16. *Unreinforced river stone masonry house with hipped roof, Padang Bintungan.*

Houses typically use running bond for the masonry wall, resulting in walls a half-brick thick (about 100 mm). Cobble stone masonry walls are approximately 200 mm thick.

Hipped and pitched roofs are both common, consisting of timber trusses supporting lightweight corrugated galvanized iron sheets or the less common asbestos sheets.

Single-story URM houses were damaged for a number of reasons:

1) poor quality materials and workmanship in the masonry wall, including weak mortar, poor bonding between bricks or stones;
2) lack of sufficient stiffness in the in-plane direction of the front wall, due to the many large openings at the front of the house;
3) lack of structural integrity due to renovations and phased construction — some older homes were built with a timber frame above an unreinforced masonry skirt wall and later renovated to replace the timber with a masonry wall;
4) use of masonry columns or lack of confinement by reinforced concrete elements, leading to out-of-plane failure; and
5) overturning out-of-plane failure of masonry gable walls.

Confined masonry: Confined masonry is commonly used for new houses in rural areas of Indonesia, although it was less prevalent in areas affected by this earthquake. Observed damage to confined masonry was less severe than to unreinforced masonry houses. In one confined masonry house (Figure 17) where damage was observed, the out-of-plane wall failure was attributed to the lack of anchors between the concrete columns and brick infill, and deformations induced by foundation settlement. With proper detailing, such failures should be avoidable.

Performance of Lifelines, Port, and Industrial Facilities

Water systems and electrical power were badly damaged in Padang. Other lifelines such as the transportation and shipping networks, fuel supplies, and waste disposal system suffered less damage and did not cause lasting business interruption. Outside of Padang, landslide damage to transportation networks had more serious effects

Figure 17. *Out-of-plane collapse of confined masonry wall, exacerbated by foundation settlement, Lansano, Kampong Dalam.*

on rural villages that were cut off from Padang and could not receive aid quickly. Cell phone service was also disrupted, though some landlines were in service and cell phone text messaging was possible. Phone service returned to normal within about a week of the earthquake.

The largest water treatment facility demonstrated the benefits of redundancy in the production process. In this plant, water was supplied by two pipes, a subterranean pipe from the 1970s and a newer aboveground pipe from the 1980s. The older pipe broke and could not be used, but the newer pipe suffered no damage and enabled the facility to continue functioning. There were two distillation tanks at the facility, one of which ruptured and was non-operational; the other had only minor damage and was quickly repaired. Within two weeks of the earthquake, the three water treatment facilities that serve Padang were able to supply 60% of the city's water demand.

Various facility managers interviewed indicated that the earthquake caused city-wide electrical outages, primarily due to transformer damage. The National Electric Company responded quickly to fix the transformers. Within five days, only 20% of the electricity service was restored, but by three days later it was fully restored in Padang.

The main port facilities for Padang — Teluk Bayur Port and Bungus Fishing Port — are located south of the city and did not appear to suffer significant damage to buildings or infrastructure. As there was little damage reported to single-story homes in the port vicinity, it appears that the level of seismic shaking there was less severe than in Padang. This is despite the fact that the port site is underlain by thick soft clay deposit (≈ 30 m deep).

The largest industrial facility near Padang is a cement plant located at the highland area and constructed in the early 1980's on a mat foundation. This facility did not appear to suffer any structural damage either to the main facilities or the mine pits.

Emergency Response and Coordination

The government response to the earthquake tested the extensive planning that had been done in Indonesia in the nearly five years since the 2004 Sumatran earthquake and tsunami. Following the massive destruction in Aceh Province, the Indonesian National Government identified Padang as one of six cities in which to make a focused investment of resources, planning activities, and public education. While there was substantial evidence that the disaster preparedness planning and training for tsunamis had a positive effect in Padang, the earthquake taught new lessons for disaster planning and response, some of which are critical to protecting lives, property, and continuity of operations.

Initial response and communication: The strong ground motion shaking served as immediate notification of danger to all residents of the city. Consistent with prior training and preparedness plans, the principal officers responsible for emergency operations in the city contacted each other by radio, and within five minutes the mayor activated the emergency plan for the Padang. The principals met first at the Radio Station of RRI, since the station had a back-up generator and they could communicate a rapid assessment of the situation to the public.

Since the City Hall building had been damaged, the mayor established the Emergency Operations Center at his residence, which was undamaged and could accommodate the many organizations engaged in response operations. Communication was limited as the earthquake had damaged electrical power, cell phone, and landline telephone communications.

Coordination among response agencies and governmental jurisdictions: In most important respects, prior training improved coordination in response operations among agencies within the city, within the province of West Sumatra, and among provinces across the nation. However, key elements of the response bear re-examination. The preparedness exercises in the years 2005-2008 that emphasized tsunami warning and evacuation led to spontaneous mass evacuation by city residents, including emergency response personnel and their families.

The absence of key personnel from response operations in the first crucial hours after the earthquake hampered the overall response and coordination. Most critical was the absence of police to direct the traffic for evacuation, and to clear roads so fire personnel could respond to the 36 fires that broke out following the earthquake. Coordination was further limited by damage to the City Hall buildings, where GIS mapping resources were lost (Figure 7).

Community Earthquake and Tsunami Preparedness

As part of the preparedness effort initiated by the Indonesian government, school children and community members were taught the "duck, cover and hold" response to earthquake shaking and were instructed to evacuate only when the shaking stops. Nevertheless, many people disregarded this training and ran out of buildings as soon as they felt the ground shake. In light of the many buildings that collapsed, and the many people who escaped unharmed by running out, the safety response training should be re-evaluated and repeated.

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. The city evacuation plan is currently based on a map that divides the city 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 (>15 meters).

According to a local government official, over 90% of people living in the Red Zone (about 500,000) evacuated after the earthquake, mostly by car or motor bike. The spontaneous evacuation led to massive traffic congestion, hindered in part by building collapse debris on streets. A small number of people evacuated vertically to nearby multi-story buildings, since they recognized that they could not reach safe ground in time. The evacuation required several hours, several times longer than the estimated travel time of 20 minutes for a near-source tsunami to reach Padang.

The process of stopping the evacuation process was very difficult. The mayor of Padang received a report from the BMKG (Agency for Meteorology, Climatology and Geophysics) within 5-7 minutes of the earthquake that no tsunami had been generated. He broadcast this message to the public and, within 20 minutes, efforts to stop the evacuation were underway, but the task of reversing this flow of evacuees through crowded streets took hours.

The government has tried to promote use of buildings as evacuation sites by requiring all buildings over two stories tall to be open for evacuation during a tsunami. However, based on observations after the quake, most people are either unaware of the option or unwilling to utilize vertical evacuation.

Several groups, including Indonesian and international government agencies and universities, have worked to identify buildings that are well suited for vertical tsunami evacuation. About 30 of these tsunami evacuation buildings were visited by the EERI team (including ones described previously in this report), and the team observed that about 80% of them had sufficient damage to be closed after the earthquake, including about 35% that were severely damaged or collapsed.

In cases where the structural system remained intact, the nonstructural damage was often severe enough that people felt unsafe and evacuated the buildings. The government may want to change the criteria it uses to identify such buildings.

Final Remarks

Damage to older concrete buildings is not unexpected, since they were designed and constructed to codes with insufficient seismic loading requirements and without ductile reinforcing bar details. On the other hand, the damage to newer buildings was greater than expected and demonstrates the needs for more training for engineers and contractors, and for more rigorous enforcement of building code provisions. While the Indonesian government has aggressive goals to rebuild quickly, the reconstruction should not bypass the needed improvements to the planning, design and construction practices that will result in safer buildings.

The earthquake is a reminder of the serious future seismic threats faced by Padang and West Sumatra. The number of casualties in collapsed and damaged buildings would have been larger had the earthquake occurred earlier in the day, and a tsunami would have caused more fatalities, as tens of thousands of people did not evacuate quickly enough.

The evacuation demonstrated that horizontal evacuation routes will not accommodate the large population in low-lying areas. Without an improved evacuation infrastructure (wider roads, better directions, improved coordination) and more effective vertical evacuation (designing better new buildings, and assessing and retrofitting existing buildings), many people will remain in harm's way.

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