THE 2007 WEST SUMATRA EARTHQUAKE: SEISMIC HAZARD MITIGATION IN DEVELOPING COUNTRIES

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Abstract

Seismic hazard mitigation in developing countries is critical since even moderate earthquakes adversely affect many lives. On March 6, 2007, a magnitude 6.3 earthquake hit the Indonesian island of Sumatra. This moderate event caused 70 fatalities and 500 casualties, caused 130,000 displaced people, and severe damage or collapse of nearly 15,000 buildings. The total damage from the earthquake is estimated at over $180 million, which is a very large sum for this area. Indonesia, the world's largest archipelago, is prone to earthquakes due to its location on the Pacific "Ring of Fire". In December 2004, a large earthquake with a magnitude of 9.0 off Sumatra triggered a tsunami that killed over 230,000 people in a dozen Indian Ocean countries, including over 160,000 in Indonesia alone. The reconstruction effort in Sumatra has been slow. Shortly after the 2007 West Sumatra Earthquake, the Indonesian government invited the authors to survey the damage. The investigators found widespread damage to commercial, residential, and public buildings, and bridges. The majority of damaged buildings used unreinforced masonry (URM) walls and non-ductile concrete frames to resist lateral loading. The extensive damage is attributed to the engineering details and construction quality. Cost-effective, simple-to-implement engineering solutions to mitigate this type of damage in future events were proposed.

Introduction

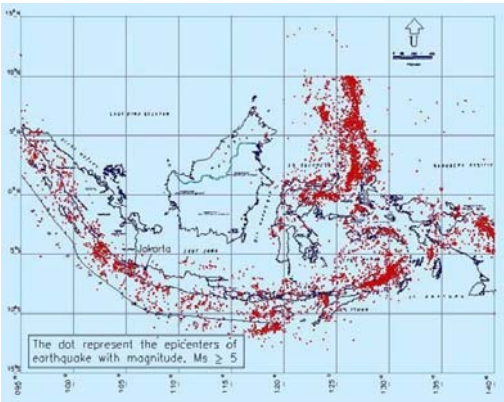
On March 6, 2007, a powerful earthquake hit the Indonesian island of Sumatra; see Figure 1. It resulted in 66 fatalities, 500 injured, and severe damage or collapse of nearly 15,000 buildings. The total damage from the earthquake is estimated at over $180 million, a large sum for this area. The quake had a moment magnitude of 6.3 and struck close to the city of Padang in the west part of the island, at 10:49 a.m. local time. The quake was preceded by two tremors, magnitude 4.8 and 4.9, which caused panic. As a result, people fled their homes and buildings, and this, in turn, reduced the number of casualties from the main shock. The main shock was followed by many aftershocks. The damage from the earthquake was substantial and included collapse of industrial buildings, mosques, homes, schools, and businesses. As distressing as the human loss and economic consequences are, the effects could have been much worse. A large population inhabits the area alongside the Sumatra Fault. Cost-effective and reliable retrofit methods need to be developed to prepare this area for the next earthquake.

On March 17, a reconnaissance team led by Miyamoto International surveyed the impacted area and investigated the earthquake damage (Miyamoto and Gilani 2007). Following the on-site investigations, the group formulated cost-effective and simple-to-implement retrofit strategies. The purpose of these strategies is to reduce future potential casualties and structural damage in this seismically vulnerable region.

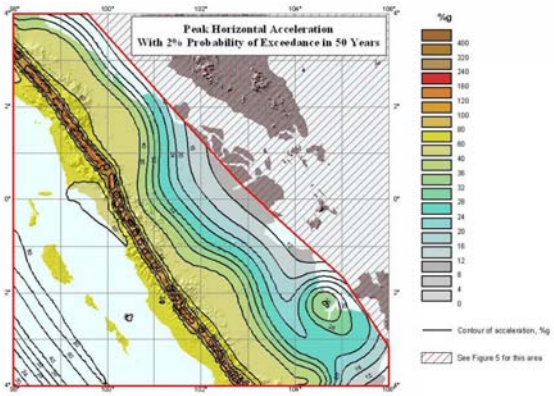
Seismicity of Indonesia

Indonesia, the world's largest archipelago, is prone to earthquakes due to its location on the so-called Pacific "Ring of Fire," an arc of volcanoes and fault lines encircling the Pacific Basin. Indonesia is located close to many major faults, and, as shown in Figure 1a, many major tremors have hit the country. Figure 1b shows the 2,500-year return events and their expected peak ground accelerations for Indonesia. Note that at Sumatra, and near the site of the March 2007 earthquake, large accelerations are to be

expected. In particular, for the 2,500-year event, the peak ground acceleration is well over 150% of gravity, and as such, it is expected that large earthquakes will occur and that these hazards will place large seismic demand on the structural systems. Table 1 lists some of the major seismic events in the past ten years. Padang, in Sumatra, is one of several Indonesian cities where a tsunami warning system exists. In December 2004, a powerful magnitude 9.1 earthquake, off Sumatra, triggered a tsunami that killed more than 250,000 people in a dozen Indian Ocean countries, including more than 160,000 in Indonesia.



a. History of earthquakes in Indonesia



b. Earthquake hazard maps of Western Sumatra, 2500-year event

Figure 1. Seismicity of Indonesia (Courtesy of Institute of Technology, Bandung, Indonesia)

Table 1. Partial List of Major Earthquakes in Indonesia, 1976 to 2007 Earthquake Details (USGS 2007)

Year	*Location*	*Magnitude*	*Fatalities*
2000	Southern Sumatra	7.9	
2002	Northern Sumatra	7.5	
2004	Southern Sumatra	7.3	
2004	Sumatra	9.1	283,106
2005	Northern Sumatra	8.6	1,313
2006	South of Java	7.7	730
2007	Sumatra	6.4	70

Earthquake Details

The main tremor had a magnitude of 6.4 and occurred on March 6, 2007 at 10:49:41 a.m. local time, with an epicenter located at 0.536S, 100.498E, and approximately 49 kilometers north-northeast of Padang, Sumatra, Indonesia. The quake had an epicentral depth of 30 kilometers. This quake is classified as a VI to VIII event on the MMI scale. This MMI corresponds to strong, shaking, and moderately heavy damage. The estimated peak ground acceleration (PGA) for this quake is approximately 30%g. The main tremor was preceded by several foreshocks and many aftershocks. On March 6, 468 shocks measuring between 4.4 and 5.8 on the Richter scale were recorded. These shocks were followed by 355 shocks of magnitude 3.0 to 4.5 on the day after and by 114 shocks greater than magnitude 3.0 in the next two days.

Damage to Civil Structures

Religious Facilities Indonesia is the world's most populated Muslim country. Mosques are common in Indonesia. Typical mosque structures use concrete framing consisting of tall, slender columns. URM infills are placed on one (back) side of the building. As such, these buildings experience torsional-translational coupled response. More than 950 mosques were damaged in the earthquake. Approximately

65% of these buildings sustained medium or heavy damage; see Figure 3. Had the quake occurred during prayer time, it would have resulted in substantial casualties.

Figure 2a shows typical mosque construction. Note the slender exterior concrete columns. This building was constructed in the mid-1990s. Figure 2b show spalling of concrete from tall, slender column at the first-story level and shear failure of the interior URM wall. Note that URM walls are placed on the backside only, and thus the building is torsionally irregular.

a. Concrete spalling of slender columns

b. URM failure

Figure 2. Failure of religious facilities

Commercial and Residential Buildings. Most commercial, retail, and residential buildings at the earthquake site consist of three types of structures: (1) unreinforced masonry (URM) walls, with one withe, and concrete "bond" beams and columns; (2) wood framing, and (3) concrete moment frame structures with URM infills. There are very few industrial facilities in this area; therefore, there was no reportable major damage to industrial structures. Nearly 44,000 structures sustained damage. The damage was considered medium and heavy for approximately 60% of these buildings. As a result, more than 135,000 people were displaced. It appears that 20% of the total residential structures have collapsed or have sustained significant damage.

URM buildings performed poorly and sustained severe damage and collapse. Concrete bond beams and columns typically occur on the two ends and top of URM infill walls. These concrete members usually have a small cross-section and are lightly reinforced with longitudinal smooth bars. They have minimal transverse reinforcement, use poor joint detailing, and do not provide confinement to the infill URM. The URM walls do not have out-of-plane connections to roof or floor diaphragms. The wood-frame buildings fared relatively well because they are a lightweight building system. The major issue for wood construction was collapse induced by soft-story response of the first story. Reinforced concrete moment frame structures exhibited shear failure, spalling, and failure at the joints.

Figure 3 presents the types of damage observed to commercial and residential buildings. The commercial/residential structure of Figure 3a used URM framing. The lateral-story stiffness and strength were significantly less for the upper floors and resulted in a soft-story collapse of the first story. Figure 3b shows out-of-plane failure of URM walls. The URM buildings do not have adequate floor diaphragms, and URM walls are not positively connected to the perimeter bond beams and columns. As such, they are not restrained against out-of-plane failure. As seen in Figure 3c, the presence of URM infill dramatically alters the seismic response of concrete frames. The infills reduce the clear height of the columns from story height to the height between solid infills. This short-column effect prevents development of full flexural capacity and induces brittle shear failure. The beam-to-column joints for the concrete moment frames do not use ductile detailing; see Figure 3d. The reinforcement steel does not extend sufficiently

into the joint, nor does it have adequate development length. Furthermore, the joints are not confined and hence are susceptible to shear failure.

a. Soft story collapse

b. Out-of-plane failure of URM wall

c. Short column effect

d. Beam-to-column joint failure

Figure 2. Failure modes of commercial/residential building, with URM and reinforced concrete framing

Schools. The 2007 earthquake caused substantial damage to school buildings. These buildings use URM wall framing, and experienced similar failures previously noted for residential structures. URM school buildings are the most vulnerable structures. These buildings must be retrofitted immediately, because many children's lives are in danger. More than 700 school buildings were damaged, including more than 300 collapsed buildings; see Figure 4. Of these, over 65% of damage was classified as either major or moderate. Foreshocks saved many students' lives. However, two teachers were killed.

Figure 4a shows unreinforced retaining wall failure of a school building. Note the diagonal shear cracks on the URM walls at the side of the building. The out-of-plane collapse of URM walls is shown in Figure 4b. The walls were not adequately anchored to the foundation or roof diaphragm to restrain the URM walls. The Sumatra Fault is shown in the near distance. The roof diaphragm, perimeter concrete beam, and columns were weak. Figures 4c and 4d show nonstructural damage to a school building. This building did not sustain any structural damage. However, the ceiling and soffit collapsed. Unless these elements are properly designed and anchored, they are life-safety hazards. For this school building, ceiling panels collapsed in the classrooms, and roof soffit panels dislodged.

a. Soft story collapse

b. Out-of-plane failure of URM wall

c. Soffit failure

d. Ceiling damage

Figure 4. Damage to schools

Bridges. In this part of Indonesia, many bridges cross the Great Sumatra Fault. Bridges are very important lifelines. After earthquakes, operational bridges are required for emergency access. A three-span concrete bridge close to the epicenter was near collapse after the March earthquake. Another two-lane steel bridge also close to the epicenter had slid off its bearings at the abutments.

Figure 5 shows failure of piers for the concrete bridge. A heavy deck and bents contribute to high seismically induced force experienced by the bridge, which caused the rocking failure in one bent; Figure 5a, and brittle shear failure at another; Figure 5b. This bridge is near collapse, and traffic has been redirected. Figure 5c shows a steel truss bridge located in the earthquake-impacted area. The superstructure did not sustain any damage. However, the bridge had an inadequate abutment bearings (Figure 5c) and transverse shear key (Figure 5d), and its had insufficient movement capacity. The steel members in this bridge appeared to be undamaged. During the earthquake, the bridge slid off its bearings. The bearing pads did not have adequate width and/or restraint to allow or resist the seismic movement.

a. Rocking failure

b. Shear failure

c. Transverse movement off bearing pad

d. Shear key failure

Figure 5. Damage to schools

Lifelines. Immediately after the earthquake, the power was disconnected. Post-earthquake investigation showed that one of the bushings had tipped over. The bushing was not damaged. It was re-erected in the upright position, and electricity was restored within two days. The water and wastewater facilities were not damaged. The telephone lines were operational.

Emergency Facilities. None of the hospitals were damaged severely during the earthquake. However, a fire station sustained significant damage. This one-story building had URM infill and concrete bond beam framing. Because of the damage, the firefighters had to erect tents for shelter.

Ground Failure. The Great Sumatra Fault is a large fault with several modes of ground failure that were observed following the earthquake. There was liquefaction near the site, close to a lake. The epicenter of the fault was situated on sandy soil. Additionally, there were large areas of landslide and ground failure.

The Sumatra Fault is an inland slip fault and is 120 kilometers long with a subduction zone offshore. The earthquake caused a rupture along a 200-meter section, and there were three segments that slipped. A large landslide caused by the earthquake is shown in Figure 6a. Note the roadway at the bottom of the landslide. This slide buried four houses. As shown in Figure 6b, the earthquake also caused noticeable ground rupture both horizontally and vertically.

a. large landslide

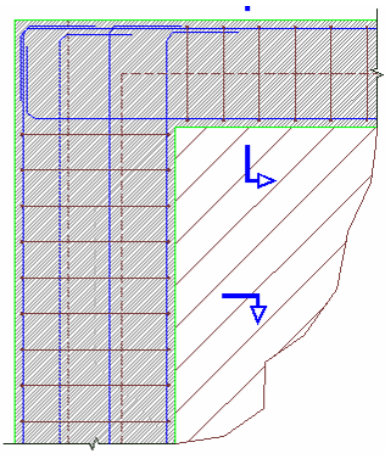
b. Ground failure

Figure 6. Ground failure

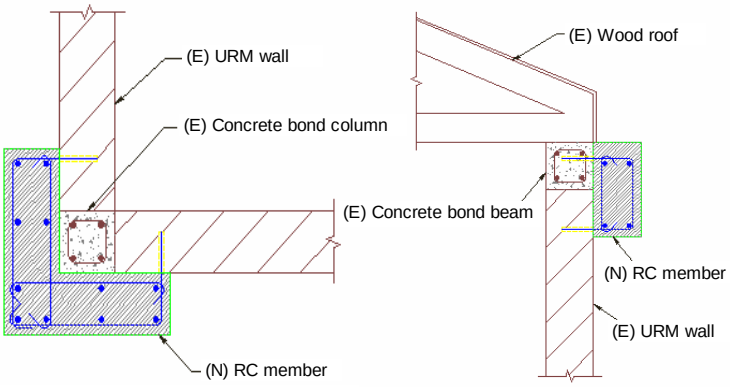
Proposed Seismic Retrofits

Because this area experiences frequent large earthquakes and because many buildings are constructed near or on the fault line, it is imperative to develop rapid, reliable, and cost-effective seismic retrofit strategies for the typical buildings. Conceptual recommendations are outlined here.

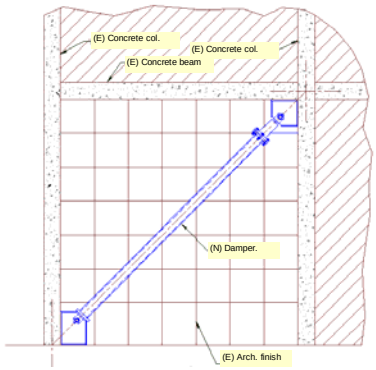
For URM infills and concrete bond beams, it is recommended to strengthen the beam-to-column joints; see Figures 7a and 7b. This will avert the brittle shear failure at the joints and will allow the concrete elements to provide some confinement to infills. Most importantly, they will carry the gravity loading and mitigate the building collapse. To alleviate soft-story and torsional response of mosques and other commercial buildings, either braces or dampers can be added to the first floor of the building; See Figure 7c. For bridges that are supported at the abutments on inadequate bearing pads, seismic isolation pads provide an attractive replacement alternative; Figure 7d. This isolation system will serve to reduce the inertial forces transferred to the substructure. Additionally, a well-designed system with adequate transverse shear keys would prevent the type of failures observed during this earthquake.



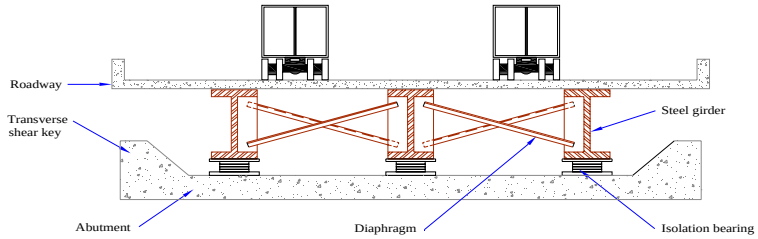
a. RC frame repair



b. Details



c. Soft story mitigation



d. Steel bridge abutment

Figure 7. Proposed seismic retrofit

Conclusions and Recommendations

Post-earthquake reconnaissance of the West Sumatra region found widespread damage to residential buildings, schools, mosques, bridges, and industrial buildings. Damage was anticipated after two magnitude 4.8 and 4.9 events, which were quickly followed by the main event of magnitude 6.3 some two hours later. The extent of the damage, however, was quickly identified as being excessive for this intensity of earthquake, with many destroyed or heavily damaged buildings. Sadly, 66 people lost their lives, and more than 500 were injured. The misery was compounded by the total destruction of more than 700 schools, 950 damaged mosques (65% of them heavily damaged), and nearly 15,000 severely damaged or collapsed buildings. More than 135,000 people were left homeless. The total damage is estimated at over $180 million. This event was a "near miss." If the magnitude 6.3 quake had hit first, mid-morning, then all the schools would not have been evacuated, and a collapse could easily have killed thousands of children in the area.

Most of the damage seen could have been either mitigated or reduced by incorporating sound seismic design, known standard construction practices, and good quality control. Such approaches can both save lives and protect structures. It is important to understand that these practices are not difficult to implement; they are simple and cost-effective. All parties who assisted in this earthquake reconnaissance urgently suggest that such efforts be undertaken, because the failure to do so in this volatile seismic area could result in more devastation and unnecessary loss of life when the next earthquake hits Sumatra, or any of the risk areas of Indonesia. It is recommended that a seismic risk mitigation strategy be organized for both West Sumatra and other potentially hazardous areas of Indonesia. The highest priority should be given to schools, mosques, and bridge structures, because these groups of structures are extremely vulnerable to earthquake damage and impact large populations.

References

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Miyamoto, H.K., and Gilani, A., 2007, "Reconnaissance Report for the 2007 Sumatra Earthquake," Proceedings of the 2007 SEAOC convention, Structural Engineers Association of California, Squaw Creek, CA.