RECENT EARTHQUAKES IN INDONESIA AND JAPAN: OBSERVED DAMAGE AND RETROFIT SOLUTIONS

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ABSTRACT :

Damage from two earthquakes that occurred in 2007 was surveyed. The 2007 Sumatra earthquake struck Indonesia. The results were typical of damage observed in developing countries from this magnitude event. Due to questionable detailing and inadequate construction practices, there was significant structural damage, including thousands of collapsed structures. The damage exceeded what is expected from this level of shaking. To mitigate such damage in future events, cost-effective and robust retrofits are proposed. Implementing such program would greatly reduce casualties and structural damage in the next earthquake. The 2007 Niigata earthquake struck a part of Japan that had experienced several major earthquakes since 1960's. This was a moderate event. Since in Japan, most modern buildings use the current seismic code design and there is good construction quality, the structural damage was minor to moderate. However, there was significant nonstructural, including equipment, damage. This caused business interruptions and significant loss of operation for many industrial buildings. To alleviate such economic loss in future earthquakes, it is recommended that structural engineers increase their scope of activity and work with architects and owners and develop better detailing and installation practices for building equipment

KEYWORDS: Sumatra earthquake, Niigata earthquake, non-ductile concrete, nonstructural damage, seismic retrofit, business interruptions

1. INTRODUCTION

1.1. Overview

Two major earthquakes occurred in 2007: the West Sumatra earthquake in Indonesia and the Niigata event in Japan. Both these events caused casualties, damage, and financial losses. The damage in Indonesia was concentrated on structural systems using nonductile detailing in concrete frame or unreinforced masonry wall. For many structures, a clear load path was not defined. In Japan, the financial loss was primarily due to damage to nonstructural components. Inadequate bracing and anchorage caused shutdown of industrial facilities and loss of operations. Both types of damage have been observed in previous earthquake and there are reliable and cost-effective retrofits available. Similar structural and nonstructural components have performed very well when properly retrofitted prior to the event.

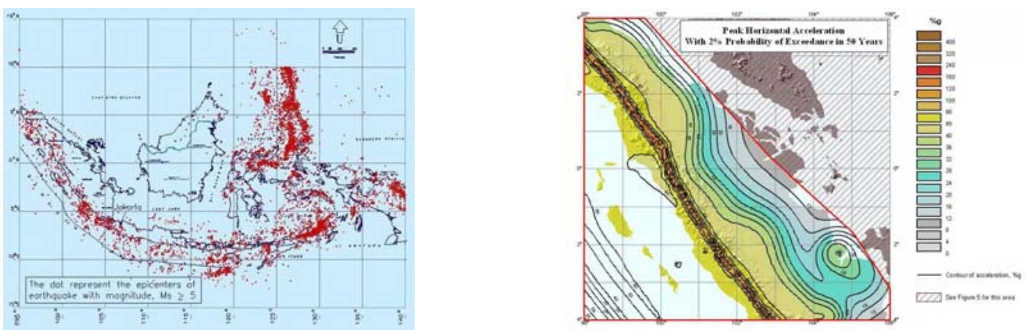
2. 2007 WEST SUMARTA (INDONESIA) EARTHQUAKE

2.1. Overview

On March 6, 2007, a powerful earthquake hit the Indonesian island of Sumatra and 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 US$180 million, which is a large sum for this area. The quake had a moment magnitude of 6.3/6.4 and struck close to the city of Padang in the west part of the island, at 10:49 a.m. local time. Its epicentral depth is estimated at 30 km located approximately 49 km north-northeast of Padang, Sumatra, Indonesia. 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 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 (Miyamoto 2007a).

2.2. Seismicity of the Area

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. 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's Aceh province.



a. History of earthquakes in Indonesia

b. Earthquake hazard maps of Western Sumatra

Figure 1. Seismicity of Indonesia (BIT, 2007)

2.3. Building Structures

Most commercial, retail, and residential buildings at the earthquake site consist of three types of structures: unreinforced masonry (URM) walls, with and concrete "bond" beams and columns; wood framing, and concrete moment frame structures with URM infills. There are very few industrial facilities in this area. Nearly 44,000 structures sustained damage. The damage was considered medium and heavy for approximately 60% of these buildings, resulting in more than 135,000 people being displaced.

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 are small and lightly reinforced with smooth bars. They have minimal transverse reinforcement, use poor joint detailing, and do not confine 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 2 shows typical modes of failure observed from this event. They consist of:

a) Soft story collapse when the first floor lateral-story stiffness and strength were significantly less than those of the upper floors.
b) Out-of-plane failure of URM walls due to lack of adequate floor diaphragms and poor anchorage of the

walls to perimeter concrete bond beams and columns.

c) Captive column shear failure resulting from the URM infill reducing the clear height of the columns from story height to the height between solid infill and preventing development of full flexural capacity and inducing brittle shear failure.
d) Beam-to-column joint failure due to the lack of ductile detailing (the reinforcement steel not extending sufficiently into the joint, not having adequate development length, and joint not confined).

a. Soft-story collapse

b. Out of plane failure of URM walls

c. Short column shear failure

d. Beam-to-column joint failure

Figure 2. Residential and commercial building damage

The earthquake caused substantial damage to school buildings. These buildings used URM wall framing and thus experienced many of the failure modes observed in residential structures. URM school buildings are the most vulnerable structures. More than 700 school buildings were damaged, including more than 300 collapsed buildings. Of these, over 65% of damage was classified as either major or moderate. Foreshocks saved many students' lives. However, two teachers were killed. School buildings sustained structural and nonstructural damage. Figure 3a shows out-of-plane collapse of URM walls. 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. School buildings also sustained nonstructural damage. Some school buildings did not sustain any structural damage, however, the ceiling and soffit collapsed due to the lack of proper design and anchorage and caused life-safety hazards.

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. Had the quake occurred during prayer time, it would have resulted in substantial casualties. Spalling of concrete from tall, slender column at the first-story level and shear failure of the interior URM wall were common failures. Figure 3b shows the collapse of a mosque. The URM walls on the extreme edges of the building collapsed due to the torsional motion.

2.4. Lifelines

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 two-lane steel bridge close to the epicenter had slid off its bearings at the abutments. The superstructure did not sustain any damage. However, the bridge had an inadequate transverse shear key, and its abutment bearings had insufficient movement capacity. The steel members in this bridge appeared to be undamaged. A three-span concrete bridge close to the epicenter was near collapse after the earthquake. Figure 3c 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 brittle shear failure in one bent and rocking at another. This bridge is near collapse, and traffic has been redirected.

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.

None of the hospitals was severely damaged during the earthquake. However, a fire station sustained significant damage; see Figure 3d. This one-story building had URM infill and concrete bond beam framing. Because of the damage, the firefighters had to erect tents for shelter.

a. Damage to school | b. Collapsed mosque | c. Concrete bridge failure | d. Fire station building

Figure 3. Observed damage to schools, mosques, and lifelines

2.5. 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 120 km long with a subduction zone offshore. The earthquake caused a rupture along a 200-m section, and three segments slipped. A large landslide was caused by the earthquake and it buried four houses. The earthquake also caused noticeable ground rupture both horizontally and vertically.

2.6. 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 the URM infills and concrete bond beams, it is recommended to strengthen the beam-to-column joints. 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. For bridges that are supported at the abutments on inadequate bearing pads, seismic isolation pads provide an attractive replacement alternative. 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.

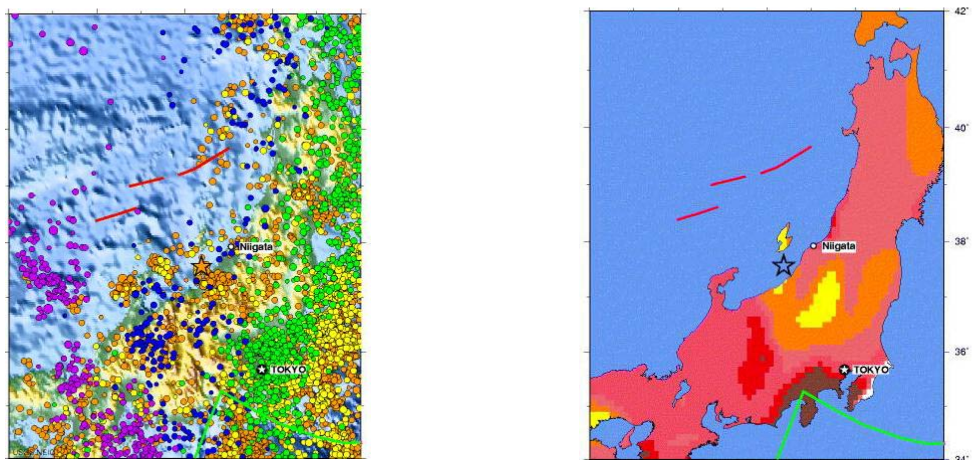
3. 2007 NIIGATA (JAPAN) EARTHQUAKE

3.1. Overview

On 16 July 2007, a magnitude 6.6 shallow earthquake occurred near the west coast of Honshū Japan. It was followed hours later by a deep magnitude 6.8 event. The first event was caused by deformation associated with the boundary between the Amur plate and the Okhotsk plate. The second quake, however, was the result of faulting associated with the subducted Pacific plate (USGS 2007). Two days after the initial earthquakes, an aftershock of magnitude 4.0 occurred. More than 70 smaller aftershocks rattled the Niigata Prefecture and its vicinity over the next few days. 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 6.6 event is classified as having an intensity of VIII. This earthquake caused structural and significant nonstructural damage leading to revenue loss and business interruptions (Miyamoto 2007b).

3.2. Seismicity of the Area

Japan is one of the world's most earthquake-prone countries, with tremors occurring frequently, as shown in Figure 4a. Large destructive events with peak ground accelerations in excess of 0.5g is expected in Japan, see Figure 4b. Most damage is from earthquakes for which the ground acceleration is at or exceeds 0.5g. Earthquakes are common in Japan because the country lies at the junction of four major tectonic plates that shift. About 20 percent of the world's most powerful earthquakes take place in Japan. The last major earthquake to hit Niigata occurred in October 2004, with a magnitude of 6.8. It killed 65 people, injured more than 300, and caused $30 billion in losses. It was the deadliest quake in Japan since a magnitude 7.3 tremor hit the city of Kobe in 1995, killing more than 6,400 people and with economic losses in excess of $100 billion. The 2007 Niigata Chuetsu-Oki Earthquake killed several people, and economic losses are expected to be around $5 billion.



a. History of earthquakes in Japan b. Earthquake hazard maps of Japan

Figure 4. Seismicity of Japan (USGS 2007)

3.3. Building Structures

Many industries are based in Niigata. A number of industrial facilities, including one very large manufacturing plant, were affected by the earthquake. Structural, nonstructural, and equipment damage caused some facilities to shut down and lose revenue. Direct damage to facilities was a small percentage of the overall financial loss to the industrial sector, however. Most of the loss was caused by business interruption (BI).

The Riken production facility is located in the city of Kashiwazaki and manufactures piston rings and transmission seals for major Japanese automakers, including Toyota and Honda. The structural damage to the facility was minimal. There was significant equipment damage at the site, however; the primary cause of damage was the inadequate anchorage of equipment to the floor; 1,240 out of 1,840 pieces of heavy machinery equipment (about 70 percent) slid or toppled during the earthquake due to large accelerations at the site. The plant was shut down for two weeks after the earthquake.

The Paltac industrial building is a major chemical distribution center. The building is located approximately 30 km from the epicenter. There was no structural damage to the building. The unbraced suspended ceiling system at the third floor sustained significant damage, see Figure 5a. The lay-in acoustic panel fell; the grid system buckled; and connections came loose.

The sake factory is also located in Kashiwazaki. It is one of the major sake breweries in Japan and consists of a main building, a production facility, and a storage building. The main plywood building and the modern production facility performed well during the earthquake, with little structural damage. In the production building, much of the equipment was anchored and performed well. The equipment that was not anchored did sustain damage. As shown in Figure 5b, the storage tanks slid off their supports. Piping and catwalks also were extensively damaged. Many crates of sake tipped over, and full bottles broke. Structural and equipment damage at this facility caused the brewery to lose 50 percent of its production capacity for the remainder of 2007.

The stack of the Kashiwazaki Municipal Recycling Plant building sustained a complete failure, as shown in Figure 5c. This tower is approximately 60 m tall. It has a hollow 4.5-m wide, reinforced concrete, square cross-section. The wall thickness varies from 370 mm at the bottom to 80 mm at top. This industrial facility was constructed in the 1980's using modern Japanese reinforced concrete design. The tower sustained complete fracture at approximately one-third of its height. This is the location of the lap splice for longitudinal reinforcement. The likely cause of failure is the inadequate splice length for the lapped reinforcement.

a. damaged suspended ceiling b. Slide of un-braced tanks c. Pounding at school building

Figure 5. Structural and nonstructural damage to industrial buildings

Approximately 1,000 houses totally collapsed because of the earthquake. Most of the collapses were the older, traditional Japanese wood structures (Figure 6) or buildings with soft stories (Figure 7) at the first floor created by a garage or storefront. The damage to modern residential buildings was not extensive. Traditional Japanese wood-frame construction is of post and beam construction, no shear walls, or braces are provided, and, as a result, these structures have been severely damaged in every significant earthquake.

School buildings in the affected region did not have major structural damage. This outcome was true especially for buildings retrofitted with shear walls. One type of observed damage was pounding of buildings against adjacent units. This type of damage was worse when adjacent structures had floor slabs located at different elevations (Figure 8). This type of pounding can damage building columns and compromise a structure's gravity and lateral-load capacity. Following the current building code recommendations and providing either an adequate seismic gap or continuity between adjacent buildings can mitigate pounding.

Figure 6. Collapsed house

Figure 7. Soft-story failure

Figure 8. School building

3.4. Lifelines

The most significant damage to bridges occurred on the Toyota Bridge. This three-span concrete structure is supported on isolation bearings at abutments and piers. Following the earthquake, the isolation system experienced large longitudinal and transverse inelastic deformations, as shown in Figure 9. The deformations resulted from soil failure that caused large movement of abutments. For the Nagomi Bridge, the reinforced expansion joint at the abutments closed, and the joint filler material was extruded. Niigata Airport temporarily closed its runways immediately after the quake to check for damage, according to airport officials. Bullet trains stopped services in northern Japan temporarily after the earthquake. East Japan Railway Company temporarily halted train service on the Tohoku, Joetsu, and Nagano Shinkansen lines. Derailments of local and freight trains occurred, but no one was injured. Many cracks and ruptures were detected on the Hokuriku Expressway and other local roads (Figure 10). The road failures are attributable to the poor underlying soil conditions.

The quake halted gas, electricity, and water service, and it interrupted telephone service. Substations generally fared well during the earthquake, the transformers, bushings, and other components performed well. Earthquake damage to substations and distribution towers was typically caused by the settlement of underlying soils. The Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP) is the world's largest nuclear power generation facility. It is along the coast of the Sea of Japan, which is used to obtain the plant's cooling water, see Figure 11. The plant is owned and operated by the Tokyo Electric Power Company (TEPCO), the world's third largest electric utility company. The plant consists of seven reactors and the electric output of the plant is more than 8,200 MW; sufficient for approximately 30 percent of Japanese households. The earthquake was the largest seismic event ever to hit a nuclear power plant. During the earthquake, the strong-motion sensors recorded peak rock acceleration of over 0.5 g nearly twice the ground shaking considered in design. The only observed damage was nonstructural. It consisted of the following: damage to equipment systems outside the safety-related areas of the plant; one of the transformers caught fire, which was quickly extinguished; damage to a. ceiling crane in the No. 6 nuclear reactor building; and damaged suspended ceilings in one of the office buildings. TEPCO had initially reported that there was no radiation leak, but later the company said that contaminated water reached the Sea of Japan, with no effect on the environment. The amount of contaminated water was estimated at 1,200 liters. The company also said that a small amount of radioactive matter had been emitted into the atmosphere.

Figure 9. Toyota Bridge

Figure 10. Ruptured roadway

Figure 11. KKNP Power Plant

3.5. Geotechnical Damage

Much of this region of Japan is situated on poor, liquefiable, sandy soil. Major liquefaction in earthquakes in both 1964 and 2004 led to extensive damage. The poor soil condition also caused damage during the 2007 event. Figure 12a shows liquefaction boil. The landslide was extensive and affected residential buildings as well as a major roadway. Slope instability caused damage to and closure of a major transportation artery in this area. The largest building in the affected area had an unusual concrete mat foundation that was severely damaged; see Figure 12b. Differential soil settlement caused structural damage to many buildings. In many cases, there was no major superstructure damage, but the underlying soil had settled significantly. Figure 12c shows a building supported on a pile foundation. Note that the building columns supported on piles have not settled. The adjacent area, however, experienced settlement of 300 mm or more.

3.6. Retrofit

Most modern buildings that were affected by the earthquake had moderate damage, despite the very high accelerations experienced. However, there was significant damage to the ground around typical buildings, including some stunning failures of surrounding fills and backfills. The damage caused extensive business interruption for commercial buildings. Given the poor and liquefiable soil in this area, two options are feasible for important structures: either use pile supports that extend to competent soil below, or the underlying soil should be strengthened to avoid this type of damage. The nonstructural damage can be mainly attributed to lack of adequate bracing and anchorage. Adding proper anchorage is a cost-effective mean of reducing damage and the resulting BI.

a. Soil liquefaction and boil

b. Abutment sliding

c. Soil settlement

Figure 12. Geotechnical and foundation damage

4. SUMAMRY, CONCLUSIONS AND RECOMMENDATIONS

Post-earthquake reconnaissance of the West Sumatra region found widespread damage. The extent of the damage was identified as being excessive for this intensity of earthquake, with many destroyed or heavily damaged buildings. 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 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.

The 2007 Niigata Chuetsu-Oki Earthquake provides lessons that have been taught repeatedly by past earthquakes. Loss of life and building collapse were avoidable. This is especially true given the generally good design criteria provided in Japan's current building code. Unfortunately, the presence of a good building code does not guarantee good performance of buildings and contents. It is critical to have adequate detailing, good construction quality, and independent design review and construction inspection. Seismic design and retrofit programs do work, and the impacts of earthquakes can be minimized. Aggressive pursuit of incremental upgrades of structures and nonstructural components can provide significant return in earthquakes. Business interruption can be minimized through adequate seismic strengthening of equipment.

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