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LESSONS LEARNED FROM BUILDING DAMAGE CAUSED BY PADANG EARTHQUAKE, SEPTEMBER 30, 2009

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ABSTRACT

The huge destruction of the 7.6 and 6.2 M_W earthquake in Padang, West Sumatra, Indonesia on September 30, 2009 caused widespread death of more than 1,200 people and destruction to the heavily populated and relatively prosperous region. In this paper a summary of earthquake effects to structural damage on buildings during the earthquake were identified based on direct field observation at several districts, i.e. the city of Padang, Padang Pariaman, Pariaman and Agam. The earthquakes destroyed thousands non-engineered buildings i.e. masonry houses, hospitals, schools and shop buildings, and few engineered buildings (mainly reinforced concrete structures). The non-engineered building were found to collapse and suffer major structural damage probably due to non compliance of minimum requirement of earthquake resistant building code and low quality of construction materials. The causes of building damage in terms of building structural design and material quality are discussed. Integrated risk assessment of existing buildings has been recommended in order to evaluate the hazard risks due to earthquake event in the future.

Keywords: Padang earthquake, building deterioration, structural damage, RC building

INTRODUCTION

On September 30, 2009 Padang (West Sumatra, Indonesia) earthquake occurred with a magnitude of 7.6 M_W. The earthquake caused more than 1,200 fatalities and 3,000 injuries including damage to more than 100,000 structures, with losses estimated at USD 2.3 billion reported from an official report by Indonesian National Disaster Management Agency. The origin of the earthquake was located in the subduction zone of Indo-Australian and Eurasia plate. However, the earthquake intensity was reported at level of VII-VIII MMI (Modified Mercalli Intensity) in Padang city and at V-VI MMI in Padang Pariaman, Agam and Pariaman. Sengara et al. (2009) reported that the peak ground acceleration (PGA) at the Andalas University, Padang, was approximately 0.295g which resulted in relatively high ground acceleration. Most of the losses were caused by damage to infrastructures, especially housing and road networks.

The aim of this paper is to highlight the results of reconnaissance surveys from the Padang earthquake, on buildings in the city of Padang, Padang Pariaman, Pariaman and Agam in West Sumatra, Indonesia (Figure 1). Analyses of earthquake effects were carried out based on observation and evaluation on the degree of damage collected from various sources and field work in observed areas.

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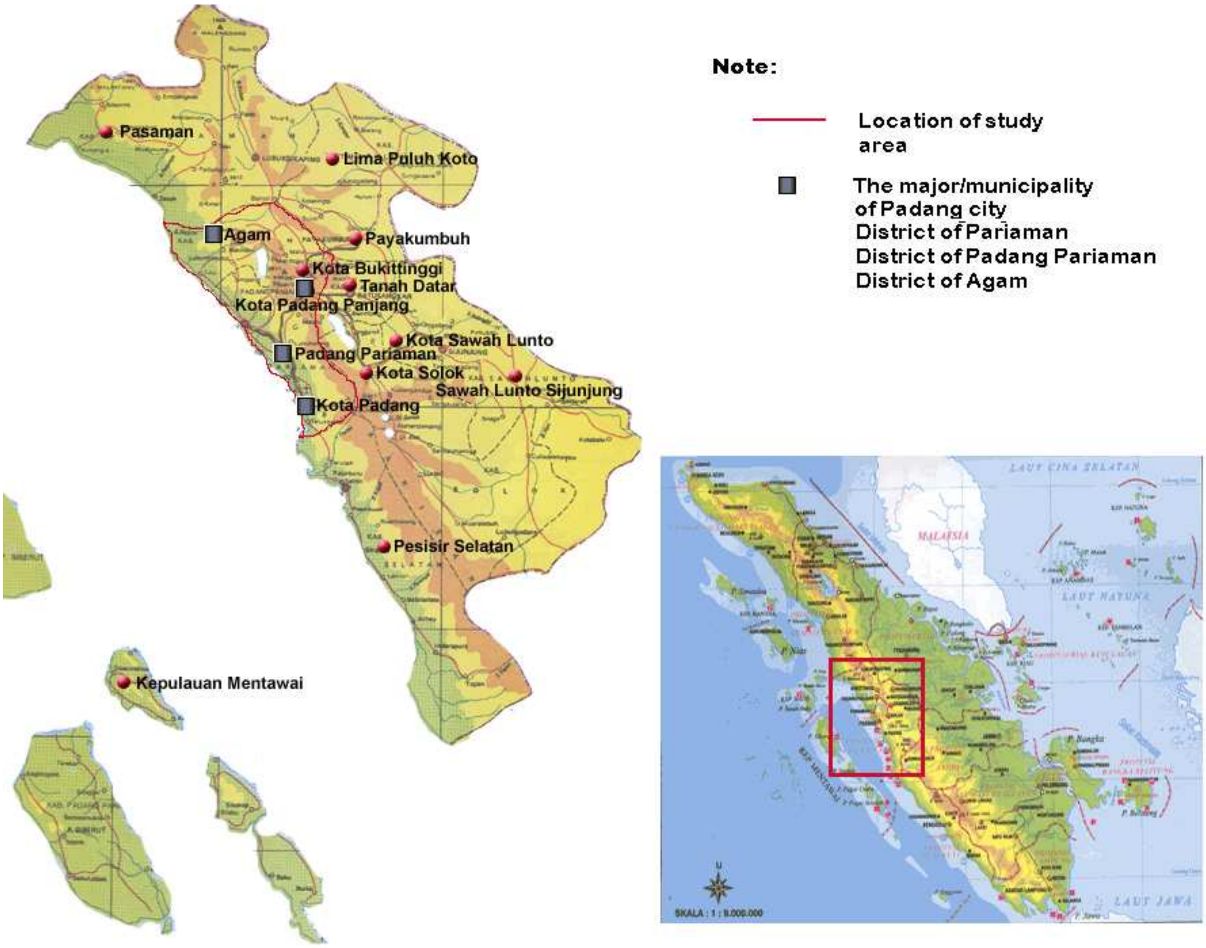


Figure 1. Location of study: city of Padang, Pariaman, Padang Pariaman and Agam district.

EARTHQUAKE EVENT AND SEISMICITY

An earthquake of 7.6 M_W struck the city of Padang and nearby areas on September 30, 2009, occurred at 17.16 local time (West Indonesian Time) with the epicenter of 57 kilometers off the coast northwest of Pariaman at 0.84^o longitude and 99.65^o latitude (BMKG/the Meteorology, Climatology and Geophysics Agency Indonesia) or at 0.73^o longitude and 99.86^o latitude (USGS). The depth of the earthquake was measured at around 71 km (BMKG) or 81 km (USGS).

The main earthquake resulted in maximum peak ground acceleration at the bedrock reaching 0.24 to 0.33g at Padang city. Sengara et al. (2009) estimated the spatial distribution of the ground shaking based on the attenuation analysis of Youngs's intra-slab (Youngs et al. 1997). Based on their calculations, the earthquake propagation may have produced peak ground acceleration at the bedrock ranging between 0.25-0.3g. Considering the spatial variability of the local geological and geotechnical characteristics of

Padang and nearby districts, the seismic amplifications in these locations are estimated to be in the range of 1.2-1.5 times the peak ground acceleration, which could have produced a relatively high ground acceleration in the range of 0.3-0.35g.

According to the USGS, the earthquake occurred due to oblique-thrust faulting near the subduction interface plate boundary between the Australian and Sunda plates. The Australia plate moves towards the north-northeast with the respect to the Sunda plate at about 60 mm/year. However, based on the mechanism of the fault and the epicenter of earthquake (70 to 81 km of depth), it shows that this earthquake may be a result of activities within the subducting Australian Plate rather than on the plate interface itself. According to McCloskey et al. (2010), the earthquake probably ruptured the mantle of the Australian plate. No tsunami was reported although a warning was issued for several minutes following the main earthquake event due to the absence of the sea bed deformation. On the same day, a major 6.2 MW aftershock occurred at 17.38 local time with an epicenter at a depth of 110 kilometers and located 22 km southwest of Pariaman at 0.72^{o} longitude and 99.94^{o} latitude.

GEOLOGY OF STUDY AREA

Geology of Padang City and Nearby Area

Padang city area is classified as complex geological structure formed by the combination of metamorphic rocks, sedimentary rocks, volcanic rocks, intrusive rock and alluvial deposits formation (Figure 2). Kastowo et al. (1996) and Prawiradisastra et al. (2009) explained that these rock formations are from Paleozoic to Quarterany age. The older rock formations are located in the eastern part of Padang city area. Rock formation distribution may also be interpreted from the morphological condition of area. Morphology of flat area found surrounding Padang city is formed by alluvium deposit which consists of silt, sand and gravel. In addition, marsh deposit is also found located in the northern part of area.

In general, Padang basin may be divided into three areas of geological formations (Prawiradisastra et al. 2009). The first, known as the formation of “Kipas Aluvial” (alluvial fan), located in the south of Padang city, while in the eastern part of area, the formation known as multicycle alluvial is widely found in which consists of consolidated flufiovulcanic with lava deposit, tuff and volcanic andesite. The alluvial formation is covered by Pleistocene coarse sand layer with a thickness ranging from 5 to 10 m. The second formation is known as "Timbunan Pasir Pantai" (coastal sand hill) which consists of 15 sand hills with about 3 km of wide. This pleistocene deposit covers the northern area of Padang basin and along the coastal area. The final formation is the "Rawa Belakang" lagoon sand deposits which consists the mud to clayey sand (Prawiradisastra et al. 2009).

Geology of Pariaman, Agam and Padang Pariaman District Area

Geological conditions in the Pariaman and Padang Pariaman district are much different than the geological structure in Padang city. Study by Kastowo et al. (1996) showed that the rock formation in the southern part of the formation Pariaman is covered by surficial deposit with characteristics similar to alluvial deposits in the city of Padang. Whereas, the eastern and northern area, the rock formations are found very complex. Major rock formation is classified as volcanic rock consisting of pumiceous tuff and andesite (basalt) in which locally consists of quartz-rich sand, as well as layers of gravel consisting of pebbles and cobbles of quartz, volcanic rocks and limestone. In nearby areas, the rock was formed from hornblende hypersthene pumiceous tuff consisting of almost entirely of pumice lapili, commonly ranging from 2 to 10 cm in diameter which have slightly consolidated hornblende, hypersthene and biotite. This formation is quite compact and located on a floating rock and andesit which stretches until close to the Maninjau Lake hilly area (Agam district). According to Westerveld (1953), these tuffaceous deposits may represent either late eruptions from Maninjau caldera or fissure eruptions related to the Great Sumatran Fault zone. Important physical property obtained from the pumiceous tuff and andesite formation is that the formation contains unconsolidated layers of loose sand and gravel. These layers may cause settlement and liquefaction due to earthquake event.

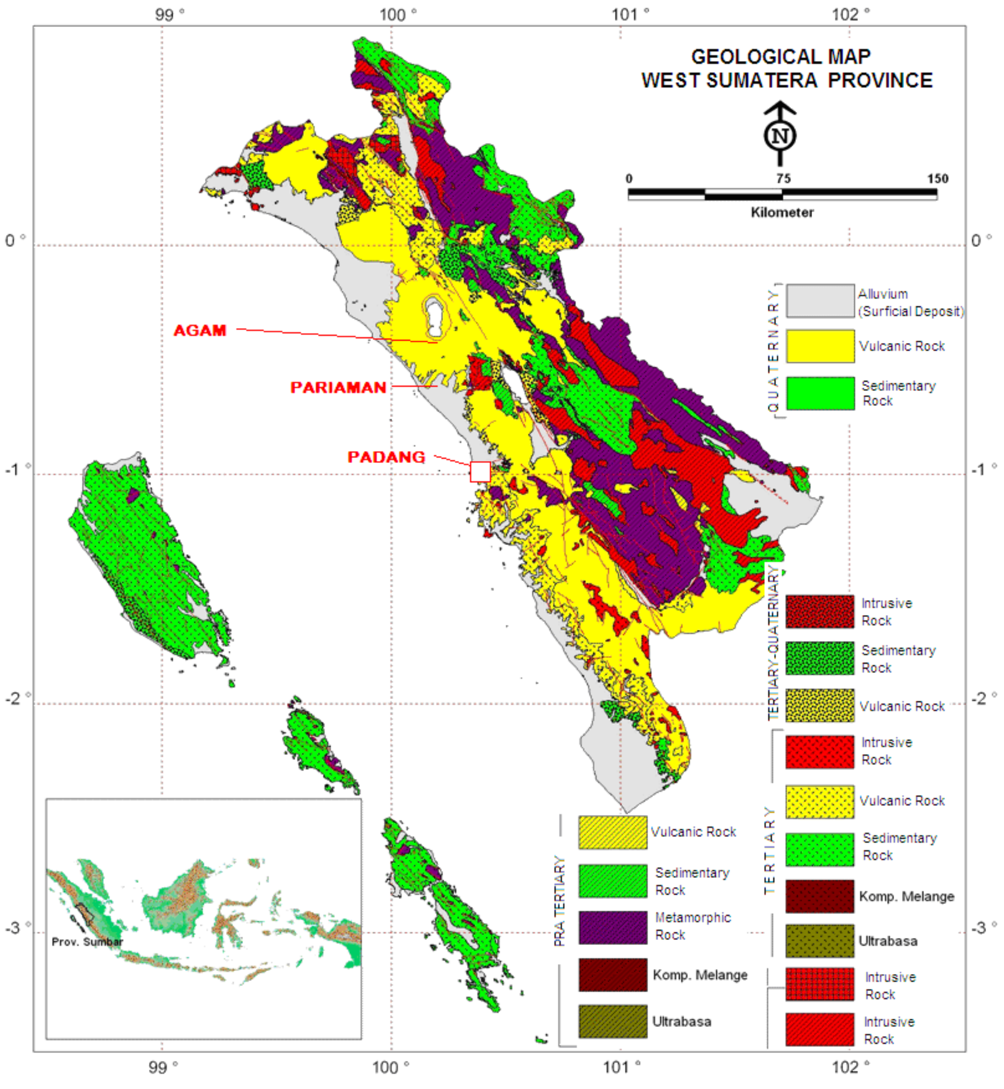


Figure 2. Geology map of location of study: city of Padang, Pariaman, Padang Pariaman and Agam district

RESULT OF RECONNAISSANCE SURVEYS

Building damage classification

The buildings in study areas can be classified as masonry and reinforced concrete (RC). From the field investigations recorded by the Government Disaster Management Unit (Satkorlak Penanggulangan Bencana, Indonesia), more than 269,683 buildings were damaged in which 132,186 houses had severe damage (28 %) and the rest suffered low to moderate damage with about 49 % and 23 %, respectively.

Thousands of non-engineered buildings, i.e., simple masonry houses, schools, and 1 to 2 stories buildings, were totally collapsed. In addition, many RC buildings were also reported to suffer low to severe levels of damage. The non-engineered building was dominantly residential houses. Damage to residential structures were not widespread, with the most severe damage concentrated in certain areas of Padang city and towns in Pariaman and Padang Pariaman district. Residential structures here are predominantly one- to two-storey high buildings constructed of confined masonry.

Types of damage

The non-engineered building term used henceforth is referred to Suhendro (2008) which is defined as a building in which no civil engineers involved during design as well as construction of the building commonly built from the relatively low qualities of material. In addition, the structural system usually does not meet the minimum requirements of the earthquake resistant building code. There are two types of non-engineered masonry building found in Padang and nearby districts, i.e., masonry building with brick plaster and masonry building with reinforced simple concrete frame.

Masonry buildings with brick plaster or known as unreinforced masonry (URM) is the most totally collapsed non-engineered building type which was found in city of Padang, Padang Pariaman and Pariaman districts. Typical structural system of the URM consists of simple stone foundation, one thick brick wall, brick plasters, and roof supporting trusses (Suhendro, 2008). From our observation, it is found that this type of building structure was constructed with low quality materials and improperly anchored among the structural elements particularly from roof to the wall. Even after the government had issued the earthquake resistance building code in 2002, this type of building is still exist due to the lack of enforcement of building code and low economical status of the owners. Typical damage observed on collapsed masonry buildings with brick plaster could be described as follows: (a) roof tends to separate from the supporting wall and fell down (Figure 3a), (b) walls tend to tear apart (Figure 3b), (c) walls tend to diagonally crack in its own plane due to in-plane component of earthquake forces (Figure 3c), (d) walls tend to fall out of plane due to face loading (out of plane component as shown in Figure 3d), and (e) walls tend to separate from its supporting foundation (Figure 4).

(a)

(b)

(c)

(d)

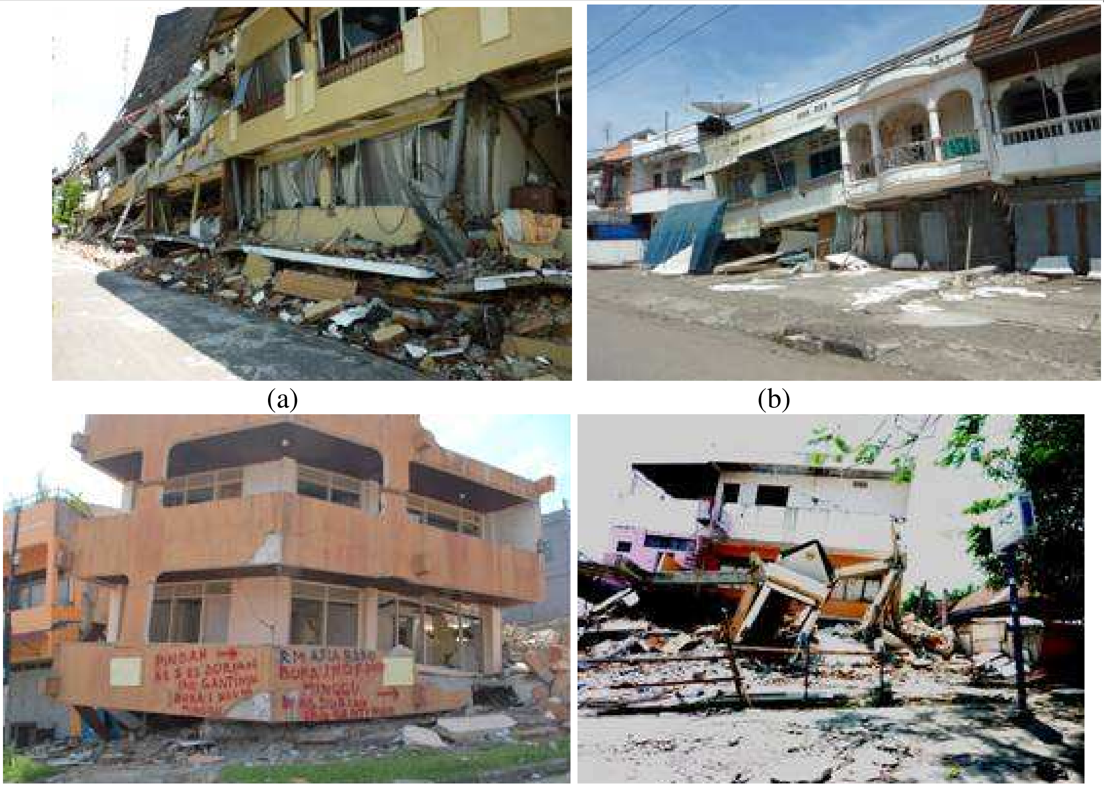
Figure 3. Typical damage on unreinforced masonry residential house and school in Pariaman, Padang Pariaman and Agam district.

Figure 4. Collapsed school building in Koto Tinggi, Padang Pariaman district due to walls which tend to separate from the supporting foundation

Another type of masonry buildings are made of brick wall framed with simple reinforced concrete frame system consisting of tie beam, column, and ring beam. Most these buildings might survive the earthquake compared to URM buildings. Some commonly minor to major structural damage such as diagonal cracks on the wall, vertical or horizontal cracks on the column/beam, significant out of plane deformation of brick walls, falling roof, significant dilatation damage and deformation, were found. However, there were some engineered buildings which totally collapsed probably due to the either low quality of design or material (Figure 5).

Figure 5. Collapsed and severe damage masonry building with simple reinforced concrete frame system in Padang Pariaman and Padang city district due to low quality of building design or material

Engineered buildings of moment-resistant frames of reinforced concrete (RC) is commonly used for multi storey houses, government buildings, school buildings, university campuses, offices, hospitals, hotels, plaza, malls, shopping centers, and etc. Typically, the main structural system consist of foundation, tie beams, columns, beams, slabs, roof supporting trusses, and sometime shear wall or core, which are monolithically connected to each other for structural integrity and provide strength, stiffness, stability, and serviceability of a structure. Some buildings survived the earthquake and only suffered minor to major structural damage as well as nonstructural deteriorations. However, a significant number of engineered buildings particularly distributed in Padang city and Padang Pariaman totally collapsed and had significant structural damage (Figure 6). The predominant failure mechanism of RC structures was soft storey failure, i.e., collapsed of lower storey of a building which was less strong than the upper structure as shown in Figure 6a, 6b and 6c. Figure 6a shows the structure of the ground floor of Inna Muara Hotel in the city of Padang which was relatively less resistant to lateral earthquake motion than the upper floors. Thus a disproportionate amount of the building's overall side-to-side drift was focused on that floor. Subjected to disproportionate lateral stress, and less able to withstand the forces, the floor became a weak point that suffered structural damage or complete failure, which in turn results in the collapse of the entire building. The collapsed of 2 to 4 storey shop houses (used for both home and store) is shown in Figure 6b. The first floor is usually used as a store/shop and the second floor as residential house. Many of these buildings have public access at the street level. This access involved large openings for garage or commercial space and if not properly designed can lead to pancake-style collapses to the ground floor. Another cause of RC building damage was low material quality or poor reinforcement particularly in the column and beam joints (Figure 6d).



(a) (b) (c) (d)

Figure 6. Collapsed reinforce concrete buildings in Padang city district due to low quality material and incorrect construction methods or design code

Typical damage observed on survived reinforced concrete buildings are divided into two, i.e. (1) non structural damage: diagonal cracks on the wall, vertical or horizontal cracks on the interface between column/beam, spilling of the mortar of the wall cover surface, small size broken or falling ceiling, broken or falling roof, significant out of plane deformation of brick walls and large size broken or falling roof, (2) structural damage: dilation damage and significant torsional deformation. Even though the RC building suffers only non-structural damage, the consequence could be very risky for people underneath, since the broken parts may fall down any time.

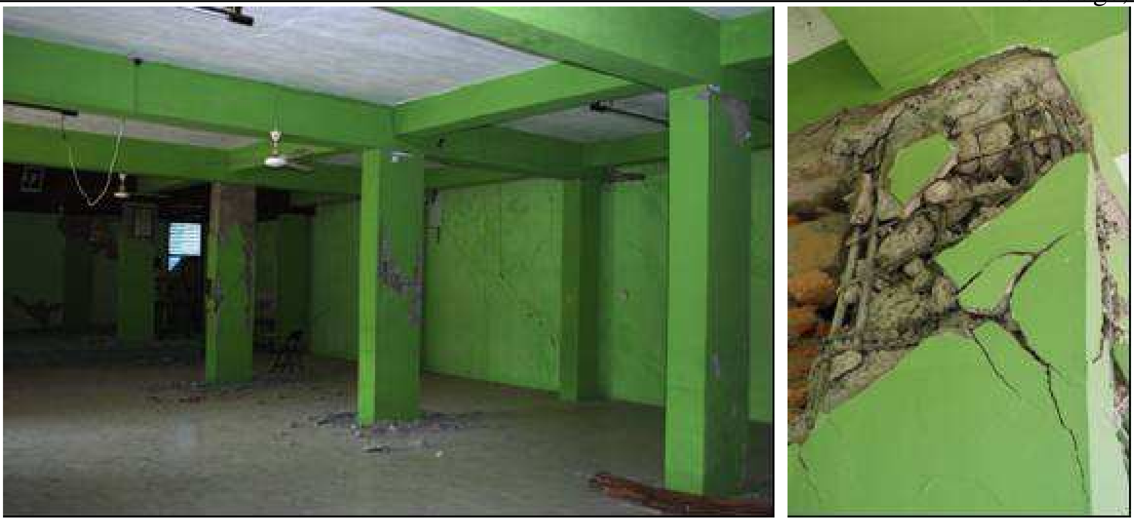
Figure 7 shows another case of the structural damage in a building with a show room in the city of Padang. The damage on RC column (Figure 7b) indicates that inadequate column detailing, i.e., inadequate column lap splices for main flexural reinforcement and a lack of adequate transverse reinforcement within the column. In addition, the column lap splices were short compared to the requirement of modern codes.

(a) (b)

Figure 7. Severe damage on reinforce concrete buildings in Padang city due to poor column detailing

Figure 8 shows the structural damage of another RC building in the city of Padang. It indicate that the structural damage in the columns were due to the poor quality of concrete material or strength. The column reinforcement bars were still in place without any structural damage. However, the poor concrete material used caused reduction of column capacity.

Field investigation also indicate that some RC building located on relatively strong ground condition, and/or close to occurrences of ground settlement, fractures and sufficient confinement suffered low to severe level foundation damage due to the inadequate construction detailing. The building columns/walls were not supported with the reinforced concrete ring beam which is used to enhance the flexural strength and stiffness of the foundation structure. Thus the structure system is became brittle in nature causing transverse cracks or even burst of foundation. In addition, based on our interview with building owners, some RC buildings were constructed since 1960-1970 period in which insufficient soil information was used for foundation construction.



(a) (b)

Figure 8. Severe damage on reinforce concrete buildings in Padang city due to low quality of concrete strength in column

Geotechnical failures resulting in building damage

Soil settlements were the most common phenomenon of damage induced by Padang earthquake. Settlement of soft soil might have been caused by inadequate soil compaction for foundations. Figure 9 shows typical settlement and severe cracks on walls and floors found in several buildings in Padang. Damage to the soil subgrade and foundation was also found in the city of Padang with heavy ejection of water and sand in the high intensity earthquake zones. Geotechnical condition of soil subgrade and foundation comprise of medium to dense silty sand layers. Liquefaction occurred in some areas with these layers particularly close to the shoreline in which saturated loose to medium dense silty sand exists (Sengara et al. 2009).

Another geotechnical failure resulting in building damage by the earthquake was landslide. Most landslides were concentrated in the Pariaman district where residential buildings and other infrastructures such as road networks, drainage, electrical power lines, etc in some villages were totally demolished. A huge landslide totally demolished one village in this area in which hundreds of people were buried alive as shown in Figure 10a. Other landslides occurred at many nearby locations which destroyed road networks and buildings as shown in Figure 10b. As a result, it cause difficulties in rescue efforts and aids deliverance.

Topography of Pariaman is classified as the hilly area which is part of the Barisan mountain range. These areas are dominantly covered by volcanic frozen rocks, i.e., tuff, pumis and andesite and metamorphic rocks. The original topography of these hilly areas is formed by the Sumatra fault system (SFS). Thus, in fault zone, the rock hill is usually disjointed by cracking rocks with brittle nature. As a result, when the earthquake occurred, many slopes became unstable and caused landslides and rock falls from the cliff. In addition, the material of the Pariaman hills, particularly in surface layers, consists of volcanic deposits of unconsolidated rock with dominant deposits of loose tuff and andesite. These materials have high collapse potential during earthquake or heavy rain.

Figure 9. Typical damage on buildings due to soil settlement

(a) (b)

Figure 10. (a) Huge landslides which destroyed one village in Pariaman, (b) Buildings and road network was totally collapsed due to landslide in Pariaman

Landslides with collateral debris flow were found at the hilly area of Maninjau Lake, Agam district. The earthquake resulted in slope failures and landslides at the top of the hill, therefore, debris flows occurred after heavy rainfall. Many hamlets have been exposed to this risk during rainy season. Several buildings collapsed and road segments became inaccessible as it was covered by debris materials (Figure 11).

(a)

(b)

Figure 11. (a) Debris flow destroyed some residential houses in Maninjau Lake, Agam district, Sumatera, (b) road network was totally covered by mud from debris flow.

Generally, seismic performance of UMR, confined masonry (CM) and RC frame buildings was quite poor even when subjected to earthquakes below the design level prescribed by code. One of the underlying reasons is the absence of an effective mechanism for code enforcement by the local government and related authorities. This deficiency in governmental oversight is linked to several related factors, such as the lack of technical control and supervision, problems with the legal framework, low engineering fees, and improper regional construction practices. When one or more such factors were present during construction, it is highly possible that the built structure could not have complied with many aspects of the design. As a result, its seismic resistance becomes inadequate with the consequence that unpredictable damage or failure results when subjected to loads below the code-prescribed levels. Currently, seismic assessment procedures and revised building code of 2010 are well established. For existing CM and RC structures located in high seismic risk area are being evaluated and retrofitted. A comprehensive seismic building assessment has been recommended for development of seismic evaluation and retrofitting techniques for all building structures.

CONCLUSIONS

The earthquake of September 30, 2009, in the city of Padang and nearby areas in West Sumatra, Indonesia, seriously damaged thousands of houses and caused the lives of over 1200 people. Many buildings and road infrastructures also suffer low to severe damage level. A summary of typical structural as well as non-structural damage on non-engineered and engineered building structures during the earthquake was compiled based on field observation Padang city and Pariaman study areas. Low quality material, lack of building code requirement in design and incorrect construction methods were identified as the main reasons for the damage. Soft storey effect was also observed in several RC buildings mostly in Padang city and Padang Pariaman. A comprehensive risk assessment of buildings on observed locations has been recommended in order to evaluate the future hazard risks.

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