Learning from Earthquakes

The M_w 6.3 Java, Indonesia, Earthquake of May 27, 2006

This report presents the observations of two reconnaissance teams that assessed the earthquake damage. The geotechnical and engineering information came from Bigman Hutapea, Sindhu Rudianto, F. X. Toha, and Hartono of the Indonesian Society for Geotechnical Engineering; Agus Darmawan Adi of Gajah Mada University; and Juan Chavez of ABS Consulting.

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Overview

On May 27, 2006 at 5:54 am local time, a M_w 6.3 earthquake struck the island of Java, Indonesia, about 20 km from Yogyakarta. The affected area is a densely populated mix of urban and rural communities on the southern slope of Mt. Merapi, an active volcano. Yogyakarta is an intellectual and cultural center of Indonesia, home of many universities, historical sites, and small to medium-scale enterprises, such as handicraft producers.

The latest casualty figures stand at 5,176 killed and over 40,000 injured. An estimated 600,000 people or more are currently without permanent shelter. The total amount of damage and loss caused by this earthquake is estimated at US $3.1 billion (CGI 2006), making it one of the most costly natural disasters in a developing country in the last ten years.

Dwellings were hit the hardest by the earthquake, accounting for over half of the total damage: an estimated 154,000 houses were completely destroyed, and 260,000 suffered some damage. More houses were affected in this earthquake than in the December 26, 2004, Sumatra earthquake and tsunami and the March 28, 2005, Nias earthquake combined.

Most heavily damaged were the Bantul district in Yogyakarta Special Province (DIY), in which 47,000 houses were destroyed, and the Klaten district in Central Java Province, in which 66,000 houses were destroyed. It is estimated that 4.1 million cubic m of debris resulted from the quake (CGI 2006).

Epicenter and Strong Ground Motion

According to the U.S. Geological Survey, the epicenter of the earthquake was onshore at latitude 7.962° and longitude 110.458°, with a fairly shallow focal depth (± 10 km).

Figure 1 shows the seismicity of Java, which relates mostly to the subduction of the Australian plate under the Sunda plate (on which Java sits). However, it is thought that the earthquake was not due to subduction, but rather to a secondary effect of subduction that compresses the Sunda plate in a N-S direction, and puts strain on local faults, especially those trending NE-SW.

It was reported by a local newspaper (*Kompas* 2006) that the earthquake was caused by a rupture of the Opak fault; indeed, this correlates with the damage intensities in nearby villages (Figure 2). However, there is some debate among local seismologists and geologists about the location of the fault and the area of fault rupture.

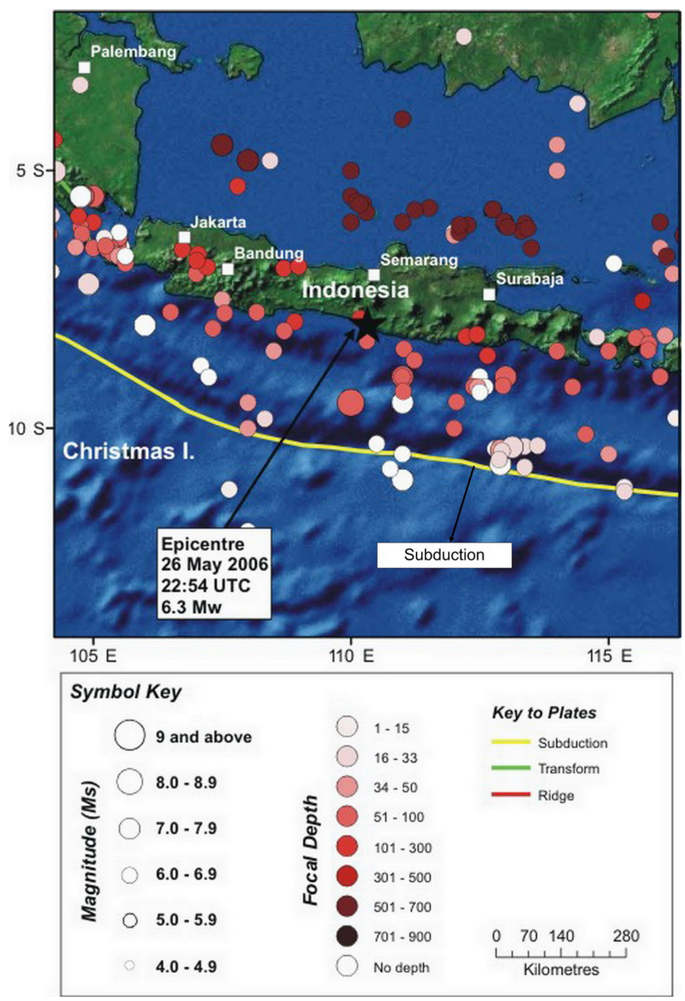

Figure 1. *Seismicity map of Java, Indonesia (magnitudes above 6.0) since 1903 (British Geological Survey)*

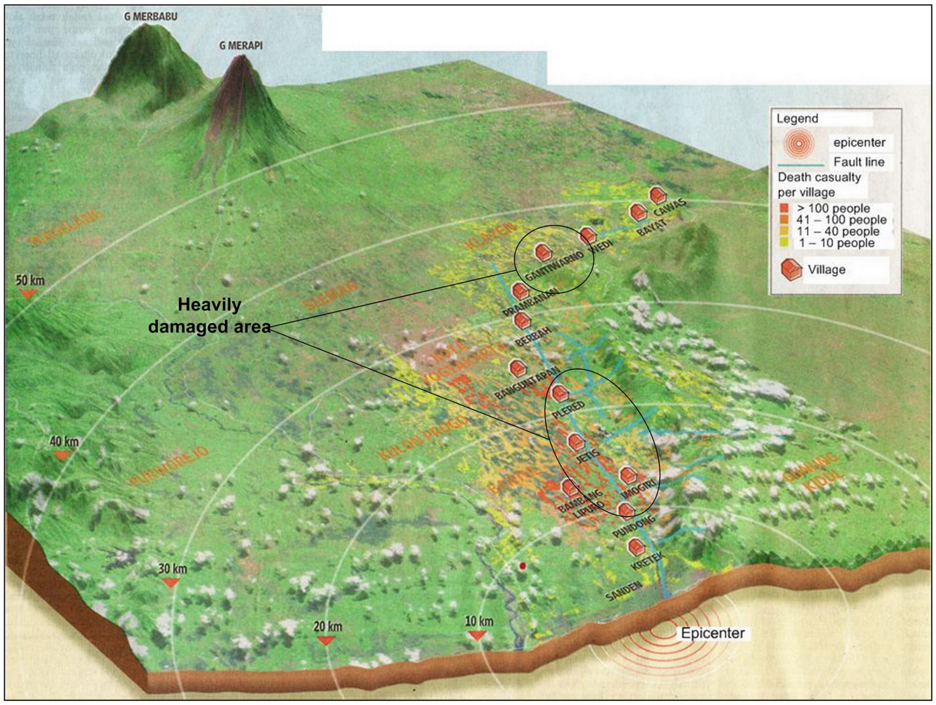

Figure 2. *Reported Opak fault and damage to nearby villages (Kompas 2006).*

Dr. Dwikorita Karnawati, head of the Geology Department at Gadjah Madah University, and her students have been mapping ground ruptures and cracking in an effort to find surface expression of fault rupture. The Indonesian geology and seismology community expects to release its results in August.

During the main shock, there was only one strong motion record from Mt. Merapi, approximately 55 km from the epicenter. There is at least one other instrument in Yogyakarta, but it was not turned on. Right after the main shock, a few seismometers were deployed near the epicenter to monitor the aftershocks. The Mt. Merapi recording and the aftershock records have not yet been made available to the public.

Several people interviewed in the heavily affected areas (Imogiri, Bantul) reported a distinct vertical motion followed by strong horizontal shaking. Preliminary discussions with local structural engineers also substantiated the high vertical component of the ground shaking.

Geotechnical Aspects

In the heavily damaged areas (Imogiri, Bantul, Plered) the subsurface is underlain by young volcanic deposits from Mt. Merapi up to 200 m in thickness. These deposits consist of undifferentiated tuff, ash, breccia, agglomerates and lava flows. Their weathering products, mainly from the lower slopes and the plain extending to the south, are largely alluvial deposits of volcanic debris reworked by small streams from initial deposits on upper slopes.

Preliminary information from a few soil borings in Yogyakarta indicates the subsurface consists of 10-15 m of loose to medium-dense volcanic fine sand underlain by over 10-20 m of dense to very dense sand and silty sand. The groundwater was found approximately 4-5 m below the surface.

From a geotechnical perspective, the most pronounced effects of the earthquake are associated with directivity and soil amplification. Figure 2 shows the heavily damaged zones concentrated in two distinct areas: one near the epicenter (Imogiri, Bantul, Plered), and other further northeast (Gantiwarno). It appears that directivity (and proximity to the fault rupture zone), topography, local site conditions, and the vulnerability of older unreinforced masonry homes (addressed later in this report) affected the severity of the damage. These effects, however, cannot be confirmed until the detailed study on

Figure 3. *Lateral spread at Muhammadiyah University (7.8108°S, 110.3210°E) (photo Hartono).*

Figure 4. *Ground cracking, settlement and lateral deformation toward stream channel (7.9464°S, 110.2974°E) (photo Hausler).*

geology and seismology is completed and the fault rupture location and orientation are confirmed.

The other distinct geotechnical phenomenon was ground cracking associated with lateral spreading, settlement, permanent deformations, dynamic densification, or a combination. Lateral spreading of embankment fill soil led to the failure of a section of stone masonry retaining wall around a pond at Muhammadiyah University campus (Figure 3). At the same location, a stairway supported on a pad footing over clayey fill settled about 2 inches. No evidence of sand boils or liquefaction was found in the site vicinity.

Figure 4 shows ground cracking and settlement due to permanent deformation along a road shoulder. This road runs parallel to a small stream along which stone masonry retaining walls failed at several locations along its length, in some places settling as much as 20 cm. The same phenomenon was observed along several bridge approaches with poorly compacted fills and river embankments through the region.

Dynamic densification caused lateral and vertical displacement of the Brahma temple, one of the 9th Century Hindu temples located in Prambanan village (Klaten). Lateral ground movement was observed between the tower pad and surrounding soils, and the tower tilted about 2 inches. There were reports of sand and water boils in some rice fields in Bantul, but these reports were not confirmed. Muddy fine sand was observed that caused minor damage to one of the inner roads near Klaten, confirming that sand boils and liquefaction did occur.

A rock fall occurred in the hills near Imogiri, southeast of Yogyakarta and probably very close to the fault rupture area (Figure 5). Some natural slopes along river banks near the Sriharjo Bridge also failed during the shaking. There were no other reports of landslides. There were no reported dams, port structures, or facilities on improved ground affected by the earthquake.

Housing

Houses were severely affected by this earthquake, with over 7% of the housing stock lost in the six most affected districts (CGI 2006). In some villages, 70-90% of the

Figure 5. *Rock fall near epicenter (7.8789°S, 110.3955°E) (photo Hausler).*

Figure 6. *Destroyed unreinforced masonry houses, Pleret (Bantul) (S7.83686° E110.41552°).*

Figure 7. *Typical unreinforced masonry bricklaying, Sumbermilo (Bantul).*

houses were completely destroyed. The houses can be divided into three general categories: 1) unreinforced masonry—older houses (pre-1990) consisting of unreinforced fired clay brick masonry walls with flexible, pitched or hipped timber truss or bamboo roofs with clay tiles; 2) confined or partially confined masonry—newer houses (post-1990) built of reinforced concrete confined or partially confined brick, solid concrete block or stone masonry in cement mortar walls with flexible, pitched or hipped timber truss or bamboo roofs covered by clay tiles; and 3) timber frame—less common and often with some masonry walls.

Unreinforced Masonry: Unreinforced masonry houses were ubiquitous throughout the affected area and the most severely damaged (Figure 6). The collapse of such buildings was responsible for most of the deaths and injuries. URM failures were associated with poor quality materials and lack of wall integrity in the transverse direction for out-of-plane forces: no mechanical connection between the top of the wall and the roof or floor, and inadequate out-of-plane strength due to a lack of reinforcement. No steel reinforced concrete foundation beams, columns, or ring beams were used in older houses.

Wood-fired clay bricks were laid in sand-clay mortar or weak cement-sand-lime mortar. In many cases, the mortar crumbled under finger pressure. The walls of the oldest masonry houses were approximately 25 cm wide, built with full brick bonding (English bond). The bricks used in the oldest houses tended to be longer (25cm x 11cm x 4cm) than their modern counterparts (22 cm x 11cm x 4 cm). Full brick wide bonding is not possible with the shorter bricks, so common practice transitioned to a 17 cm wide bond in which two bricks were laid in the plane of the wall and one brick turned on its side (see Figure 7).

Confined or Partially Confined Masonry: Many newly built con-

Figure 8. *Well-designed and built confined brick masonry house, edge of heavily damaged Pleret (Bantul) (S7.83686° E110.41552°).*

Figure 9. *Partially confined stone masonry house with timber ring beam, Platar Somopuro, Jokonalan (Klaten) (S7.75478°, E110.53557°).*

Figure 10. *Beam column connection detailing in posters distributed by CEEDEDS.*

fined masonry houses performed well due to their reinforced concrete tie columns and bond beams at the plinth and roof levels. Examples of good performance of confined fired brick, solid concrete block, and stone masonry were scattered throughout the heavily affected areas (Figures 8 and 9). Columns were typically cast after the masonry wall was built, flush with the wall, and thus the same width as a brick or block (10 or 11 cm). Smooth reinforcing steel was common, typically 6 or 8mm in diameter with stirrups ranging from 3 to 6mm in diameter. Stirrups were often spaced at 15 to 20 cm intervals.

Prior to the earthquake, three houses were built in Wonokromo, Pleret (Bantul) under the supervision and direction of Professor Sarwidi of the Center for Earthquake Engineering, Dynamic Effect, and Disaster Studies (CEEDEDS) at Universitas Islam Indonesia. These confined masonry houses used connection detailing shown in the posters distributed by CEEDEDS (Figure 10). The houses performed very well in the earthquake, with only hairline cracks, and in one case, minor damage to a masonry gable wall.

Although confined masonry houses performed fairly well, many collapsed or were severely damaged, for various reasons:

1) Insufficient connections between reinforced concrete tie columns and bond beams, and between tie columns and masonry walls (Figure 11). Typical reinforcement in the heavily damaged houses terminates in the joint with a poorly made hook.

Figure 11. *(left) Confined masonry house under construction, insufficient connections, and (right) zoom-in view of ring beam–column connection, Pleret (Bantul) (S7.87574°, E110.40703°).*

Figure 12. *Masonry gable wall overturning, Keputren, Pleret (Bantul) (S7.86905° E110.40272°).*

Figure 13. *Collapse of masonry wall (note absence of reinforced concrete plinth and ring beams).*

2) Tall, slender poorly confined masonry walls. Newer houses use running bond for the masonry wall, resulting in a half-brick wide wall (13 cm with plaster, 10-11 cm without) that is often over 3 m tall. Gables add another 1–2 m to the height. Damage and failure to masonry gable walls were widespread throughout the affected region and plagued both new and older houses with and without reinforced concrete ring beams (Figure 12). In most cases, gable masonry was neither properly confined nor properly connected to the roof. Cross-bracing between gables was not common. Offset gables, a popular architectural style that accommodates a larger living room and terrace, were also damaged.

3) Absence of plinth beams and ring beams. Many newer houses had reinforced concrete tie columns but no reinforced concrete plinth or ring beams (Figure 13).

4) Insufficient connections between walls or columns and roof. Column steel was often wrapped around a timber beam which functioned as a ring beam in some cases. Timber beams were generally 8 cm by 12 cm and made from coconut trees, local hardwood, or hardwood from Kalimantan. Bamboo is also common for roof structures. Some older houses were a mix of structural systems, in which part of the roof load was carried by timber posts infilled with masonry. A typical timber truss is shown in Figure 14.

5) Use of reinforced concrete trusses. Reinforced concrete trusses were seen in a few of the houses, all of which had nonductile failures at the beam-column con-

Figure 14. *Typical timber truss with steel plates reinforcing the joints, Kasongan, Kasihan (Bantul) (S7.84512° E110.33534°).*

Figure 15. *House/shop with reinforced concrete truss, Bebekan Mulyodadi, Bambang Lipuro (Bantul) (S7.93460° E110.32194°).*

Figure 16. Transitional house in Pleret (Bantul) (S7.83686° E110.41552°).

Figure 17. First floor collapse of building on STIE Campus, Yogyakarta (S7.82733° E110.36789°) (photo Chavez)

nections (Figure 15). These single-story buildings were mixed use: the rear part was used for storage or living area, and the front for a shop. The front was typically an open frame (no shear wall).

Housing Reconstruction: Tents were distributed in some areas, as were hammers, shovels and other tools to support debris clearing and recycling. Many families with destroyed houses had already rebuilt transitional one- or two-room shelters on the foundation of their destroyed houses (Figure 16). Transitional shelters use a mix of recycled timber, bamboo, and window and door frames, and new plastic tarps, plywood and corrugated galvanized iron sheets. Also, many families were continuing to live in houses that were damaged beyond repair and vulnerable to collapse in aftershocks.

The Indonesian Government has announced a plan to allocate Rp. 33 million (US $3,700) to rebuild each destroyed house. It is not clear whether the funds will be given directly to homeowners, or channeled through government-hired contractors. Yogyakarta is not a center of heavy industry; although fired bricks are produced locally, many building materials must be brought in by highway from other cities. A price survey done during the reconnaissance indicated that materials prices are already at a level consistent with prices in tsunami-devastated Aceh. In Aceh, materials and labor for a two-bedroom, $36m^2$ reinforced concrete confined masonry house with septic tank and electrical wiring are in the range of Rp. 52-60 million (US $5,800-6,700).

Commercial and Public Buildings

Reinforced Concrete Frame: A number of buildings in the area are nonductile reinforced concrete structures with unreinforced masonry infill. The infill masonry consists primarily of solid bricks, although in some cases concrete blocks are used. The floor diaphragm consists of beams and slab construction supported by columns. Smooth bars are commonly used for the longitudinal reinforcement of beams and columns because of their lower cost compared to deformed bars. Roof structures are flat or pitched having, in many cases, a steel framing and tiled roofing. The anchorage of the infill wall to the roof system is poor or nonexistent.

Many of these buildings collapsed or were seriously damaged. Structural damage can be attributed to 1) nonductile detailing, 2) insufficient confinement reinforcement in columns, 3) lack of lateral resisting system, and 4) poor quality construction. Short-column effect and soft-story actions contributed to the damage in some of the buildings. Nonstructural damage in the infill walls was observed in various low-rise buildings, especially at the lower floors.

Several buildings on the STIE (Sekolah Tinggi Ilmu Ekonomi) University campus were severely damaged. One building partially collapsed (Figure 17) due to poor detailing, insufficient splicing length, and insufficient spacing and number of ties. In addition, there was brittle failure of columns at the first floor (Figure 18), and the infill created vulnerable short columns at the second floor.

The south wing of the BPKP (Badan Pengawasan Keuangan Dan Pembangunan: Indonesian Finance and Development Committee) governmental building collapsed due to poor detailing and insufficient confinement reinforcement (Figure 19). Flexural hinging of the columns near the joint led to buckling of longitudinal reinforcement. A soft story mechanism also appears to have contributed to the failure of this building.

Lack of a lateral resisting system was another cause of building col-

***Figure 18.** Brittle failure of columns at the first floor of the STIE building, Yogyakarta (S7.82733° E110.36789°) (photo Chavez).*

lapse. Figure 20 shows a two-story reinforced concrete furniture shop and warehouse, where concrete columns and concrete beams are used for the framing at the interior of the buildings. Unreinforced solid concrete block masonry confined by RC columns is used as the lateral system at the exterior of the building. The concrete blocks and masonry work are of poor quality and not tied to the floor diaphragm, creating an incomplete load path. Once the exterior URM walls failed, only slender columns were left to support the building.

Steel Structures: Some steel industrial facilities in the affected region performed well, while others experienced minor to moderate structural damage. Loss of diagonal bracing in the roof diaphragm and, in one case, fracture of vertical diagonal bracing was noted. Several diagonal cracks were noted on URM infill walls.

Lifelines: In general, lifelines sustained relatively little damage compared to houses. Steel transmission towers were mostly unaffected. Bridges experienced minor cracking in the concrete abutment. Cracking in the underside due to pounding between the steel truss and the expansion joints was found in a steel bridge in the Pleret village. The separation between two sections of the bridge appears to indicate the effect of the directionality of the earthquake.

Building Codes and Practices

The current seismic code in Indonesia (2002) is based on the UBC 1997. It considers Yogyakarta as a Seismic Zone 3 among 6 seismic zones. The expected peak ground acceleration for Zone 3 varies between 0.18g and 0.3g, depending on the soil type. The previous seismic code (1987) was based on the New Zealand Code. Although the Indonesian seismic code includes ductility detailing requirements, these were not satisfied in many of the damaged multistory RC buildings. Ductile detailing was rarely observed, and in some cases large buildings appeared to have been designed without the assistance of qualified engineers.

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***Figure 19.** Collapse of the south wing of the BPKP building, Yogyakarta (S7.84497° E110.36131°) (photo Chavez).*

***Figure 20.** Collapse of a two-story RC frame building. Unreinforced masonry concrete block is the main lateral resisting system, Baturetno (S7.84450° E110.41048°) (photo Chavez).*