Damages to the 9th century Prambanan temple caused by the 2006 Yogyakarta earthquake (Java, Indonesia)

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Abstract: *An M 6.5 earthquake hit Yogyakarta on May 26, 2006. The region, considered aseismic, suffered high damages: 155,000 houses were destroyed. The Prambanan temple complex was among the severely damaged masonry buildings. Location and direction of damages have been investigated: displacement and falling directions of masonry blocks were surveyed. We reconstructed the direction of strong motion responsible for the damages. It is parallel to the strike of the causative fault (30°-210°).*

Key words*: archaeoseismology, Java, Indonesia, Middle Ages.*

INTRODUCTION

There was an M 6.5 earthquake on 26 May 2006 at dawn in Yogyakarta sultanate on Java island, Indonesia (Fig. 1). The city of 4 million did not suffer considerable damage, but 150,000 houses collapsed in the surrounding rural area and further 200,000 were severely damaged. Six thousand people died.

The earthquake occurred in a sector of Java which have been considered aseismic (Luehr et al., 2008). There was no surface rupture and the causative fault could not be identified with any of the known faults (Setijadji et al., 2008). Twelve temporary seismic stations were operated for three months to record aftershocks (Walter et al., 2007). Engineering geological mapping provided explanation for the great damage caused: thick, loose succession of repeated mudflows, lahars, derived from nearby Merapi volcano amplified the shaking (Walter et al., 2008).

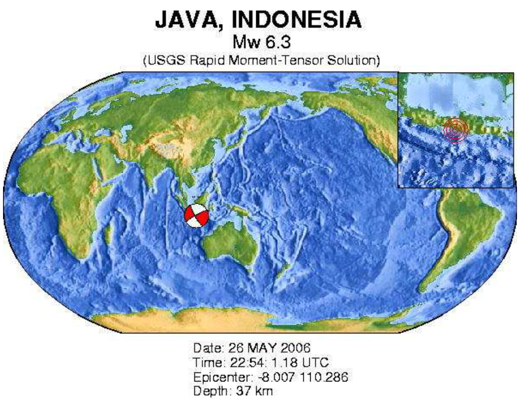

Fig. 1: Location and focal mechanism of the May 26, 2006 Yogyakarta earthquake

We carried out an archaeoseismological survey three year after the earthquake, supposing that Medieval Hindu masonry temples in the region preserved earthquake-induced damages. The displacements – if caused by an earthquake of known focal mechanism – will be suitable for calibration of archaeoseismological studies, where the mechanism is unknown. The largest temple complex, Prambanan, suffered heavy damages in 2006. Restoration was in progress, and we were allowed to study the shrines before repairs covered the damages.

Fig. 2: Aerial view of the Prambanan temple complex.

PRAMBANAN

The Loro Jonggran temple complex (mentioned by the better-known name of the village Prambanan where it is located) was probably built during the first half of the 9th century (*Fig. 2*). The pervasive Hindu cultural influence and rule erected a multitude of temples at that time, including the UNESCO World Heritage site Borobudur 35 km to the NW. Prambanan has been a site for cultural and religious tourism (Jordaan, 1996) since its discovery by Sir Thomas Raffles, the then British governor of Java during the Napoleonic wars (Raffles, 1817). Excavation and surveying started at that time has been going on for two centuries (Tiffin, 2009): old temples are restored and long-forgotten ones are excavated from below thick volcano-sedimentary succession.

A modern restoration of Prambanan satisfying the needs of the tourist industry followed the grandiose aims set for Borobudur nearby. That, financed by UNESCO in the 1960s, was completely dismantled and re-built again, supported by a reinforced concrete structure (Soekmono, 1976). Therefore nothing can be seen on Borobudur which could offer any information on its twelve-century history in earthquake-stricken Indonesia. Fortunately, Prambanan's reconstruction was made in a financially less successful environment: only the external, carved stones were removed, a reinforced concrete layer constructed, and the carved stones replaced on select portions.

METHODS

Visibly recent damages on several buildings of the temple complex, considered to be made by the 2006 earthquake by Mr. Darmojo, the master builder, have been surveyed by compass and measuring tape, and documented on photographs. Restoration documentation prepared at various times was studied, commented by Mr. Darmojo. A manuscript map recording the surface deformations right after the 2006 earthquake was seen as well. Although the fallen masonry have mostly been removed by the time we visited the site, a few major pieces were located and their falling direction recorded. Observed damage features are also named as Earthquake Archaeological Effects (EAE - Rodríguez-Pascua et al., 2011), and are correlated to the intensity scale of Rodríguez-Pascua et al. (2013). We determined the shifting directions of masonry blocks as well. Recorded features were interpreted as parts of a strong-motion field. and principal directions were determined graphically (Angelier, 1984).

EARTHQUAKE ARCHAEOLOGICAL EFFECTS

The Shiva shrine of the Prambanan complex has excellent foundations: 8 m deep white tuff blocks, underlain by compacted sand down to 14 m. Groundwater level is at 11 m depth (Suryolelono, 2008).

Various damages were surveyed to determine the direction of the strong motion responsible for the displacement. The tip of the 14 m high Apit Utara shrine fell towards 120° for 7.7 m (*Fig. 3*) (EAE: impact block mark, I = VI-). The largest shrine, the 60 m high Shiva temple has a reinforced concrete mantle at the middle and upper levels, while the lower level has not been restored extensively. This unreinforced lower part suffered horizontal extension in 20-200° directon (*Figs 4-5)* (EAE: displaced masonry blocks in walls, I = IX-).

Fig. 3: Tip of Apit Utara temple fell towards 120° for 7.7 m.

Fig. 4: Shiva temple, sanctuary level. 45 mm shift towards 20°

Lower part of the Brahma temple was enclosed in reinforced concrete, while the middle and upper parts were left intact. There are centimetre-sized left-lateral displacements across several rows of masonry in the unreinforced level,. We suggest that these are surface features of a left-lateral displacement zone, which runs diagonally across the monument (EAE: penetrative fracture of masonry blocks, I = VII-).

Tip of the Brahma temple fell towards 215° for 15 metres. (EAE: impact block mark, I = VI-).

Ground fissure

A 20 m long, several centimetre wide fissure extended in 15°-195° direction near Brahma temple. Further ground fissures were mapped regionally by Pramumijoyo and Sudarno (2008). Was there a a higher water table, this ground fissure would have yielded liquefaction and sand volcano (EAE: liquefaction, I = VIII-).

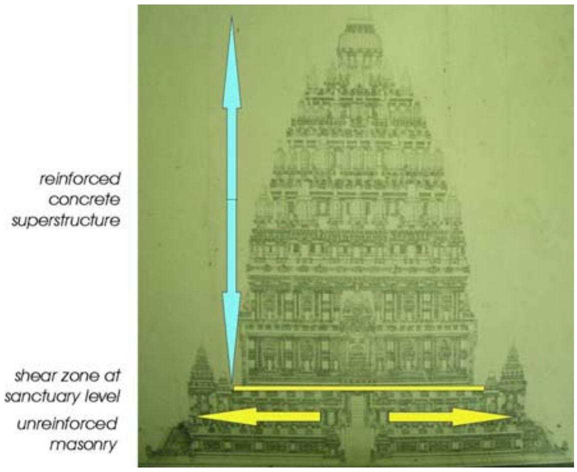

Fig. 5: Shiva temple as seen from the west (photo of an architectural drawing). A horizontal shear plane was formed between the top part containing a reinforced concrete core and the unreinforced bottom part. Horizontal arrows indicate the location of 10 cm extension due to seismic shaking

Fig. 6: Brahma temple: a NW-SE left-lateral fault cross-cutting the temple diagonally. A reinforced concrete wall surrounds the level below this floor. There was 4 mm left-lateral displacement.

DISCUSSION

Displacements are plotted in a single plot describing the strong motion stress field of the 2006 earthquake. Descriptors are falling directions, displacement of walls and ground fissures. The best descriptors are those damages, where the displacement direction is the least constrained by the geometry of the building. Additionally, evidence of damages affecting major buildings are considered stronger than those affecting minor constructions (Fig. 8).

The least constraints are those which affected the falling directions of the tips of the Apit Utara and Brahma temples, both temples close to being centrally symmetrical. The top part can fall in any direction as dictated by shaking. Their falling direction is perpendicular to each other; i.e. both regular components of strong motion directions could affect them *(Fig. 7)*.

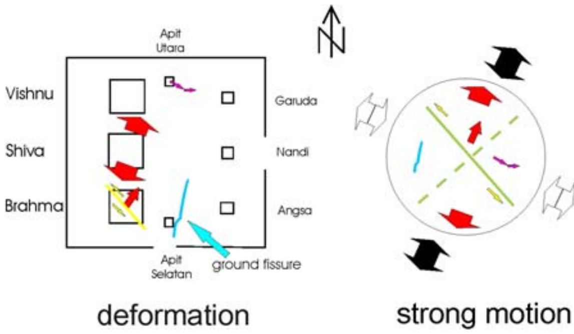

Fig. 7: Strong motion directions (black and white arrows) reconstructed from damaged temples

Tha causative fault of the 2006 Yogyakarta earthquake is a left-lateral strike-slip fault. Epicentre was at the SW termination, from where fracture spread towards NE, probably as far as indicated by the hypocentres of the aftershocks (*Fig. 9*). Prambanan complex is approximately at the hypothetical northeastern extension of the fault; this explains its major damage as compared to other temples nearby. Possibly the P-waves caused the extension of the unreinforced lower level of the Shiva temple. S-waves caused the jumping of the tip decorations off their tenons and subsequent fall.

Left-lateral strike-slip faulting of Brahma temple is also caused by P waves: these created the diagonal fracture across the building according to the Mohs planes. The left lateral displacement has no particular meaning: the shaking stopped at this particular moment. If stopped another second the displacement would have been right-lateral.

These suggestions serve a better understanding of the multitude of damage data recorded by archaeological monuments.

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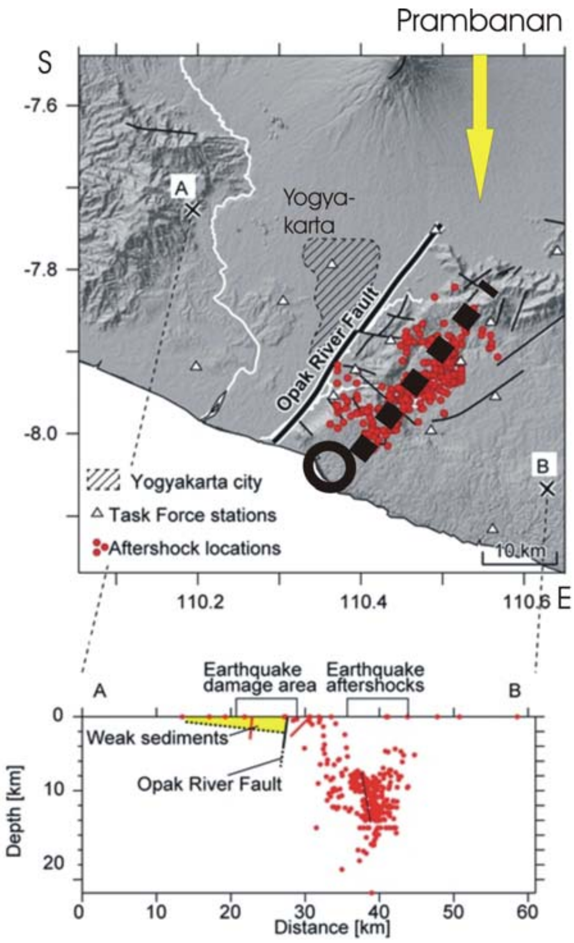

Fig. 8: Map of post-seismic activity after the May 26, 2006 earthquake (after Walter, 2008, modified). Black circle – epicentre. Hatched – Yogyakarta city. Triangles – temporary seismic stations. Small circles: epicentres of post-seismic activity. Hatched line: supposed azimuth of the causative fault. Prambanan is to the NE. Faults after Rahardjo et al. (1977). A-B profile: hypocentres of post-seismic activity compared to the location of the greatest damage. Unconsolidated sediments of the Opak River valley are mostly from lahars of Mt. Merapi volcano.

References

Angelier, J., (1984). Tectonic analysis of fault data sets. *Journal of Geophysical Research* 89, 5835-5846.

Jordaan, R. (ed.) (1996). *In Praise of Prambanan: Dutch Essays on the Loro Jonggrang Temple Complex*. KITLV Press, Leiden,p 259

Luehr, B.-G., Walter, Th., Wassermann, J., Wang, R., Wagner, D., Anggraini, A., Parolai, S., Zschau, J., Prih Harjadi, P. J., Kirbani Sri Brotopuspito, (2008). The surprising Mw 6.5 Bantul earthquake 2006. *Geophysical Research Abstracts* 10, EGU2008-A-03153.

Pramumijoyo, S., Sudarno, I., (2008). Surface cracking due to Yogyakarta earthquake 2006. In: *The Yogyakarta Earthquake of May 27, 2006*. Karnawati, D., Pranumijoyo, S., Anderson, R., Husein, S. (eds). Star Publishing Company, Belmont, CA, pp. 6-1 – 6-5.

Raffles, T.S., (1817). *The History of Java*. London: Black, Parbury and Allen and John Murray, 2 vols.

Rahardjo, Sukandarrumidi, W., Rosidi, H., (1977). *Geologic map of the Yogyakarta quadrangle, Java,* scale 1:100,000, 8 pp., Geological Survey of Indonesia, Ministry of Mines, Jakarta.

Rodríguez-Pascua, M.A., Pérez-lópez, R., Giner-Robles, J.L., Garduño-Monroy, V.H., Reicherter, K. (2011). A comprehensive classification of Earthquake Archaeological Effects (EAE) in archaeoseismology: Application to ancient remains of Roman and Mesoamerican cultures. *Quaternary International* 242, 20-30.

Rodríguez-Pascua, M.A., Silva, P.G., Pérez-López, R., Giner-Robles, J., Martín-González, F., Perucha, M.A. (2013). Preliminary intensity correlation between macroseismic scales (ESI07 and EMS98) and Earthquake archaeological effects (EAEs). In: PATA days – Seismic Hazard, Critical Facielities and Slow Active Faults. *4th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA*), Grützner, C., Rudersdorf, A., Pérez-López, R., Reicherter, K. (eds.), 9-14 October 2013, Aachen, Germany, pp. 221-224.

Setijadji,L . D., Barianto, D. H., Watanabe, K., Fukuoka, K., Ehara, W., Sudarno, I., Shimoyama, S., Susilo, A. Itaya, T., (2008). Searching for the active fault of the Yogyakarta earthquake of 2006 using data integration on aftershocks, Cenozoic geohistory and tectonic geomorphology. In: *The Yogyakarta Earthquake of May 27, 2006*. Karnawati, D., Pranumijoyo, S., Anderson, R., Husein, S. (eds.). Star Publishing Company, Belmont, CA, pp. 4-1 – 4-23.

Soekmono, (1976). *Chandi Borobudur – A Monument of Mankind.* Van Gorcum, Assen-Amsterdam, The UNESCO Press, Paris, 60 p.

Suryolelono, K.B., (2008). Investigation of the Prambanan temple after the May 27, 2006 Yogyakarta earthquake. In: *The Yogyakarta Earthquake of May 27, 2006*. Karnawati, D., Pranumijoyo, S., Anderson, R., Husein, S. (eds.). Star Publishing Company, Belmont, CA, pp. 16-1 – 16-9.

Tiffin, S., (2009). Java's ruined *candi*s and the British picturesque ideal. – *Bulletin of SOAS* 72 (3), 525-558.

Walter, T.R., Lühr, B., Sobiesiak, M., Grosser, H., Wang, R., Parolai, S., Wetzel, H.-U., Zschau, J., Milkereit, C., Günther, E., Wassermann, J., Behr, Y., Anggraini, A., Sri Brotopuspito, K., Harjadi, P., (2007). Soft volcanic sediments compound 2006 Java earthquake disaster. *Eos, Transactions, American Geophysical Union* 88 (46), p. 486.

Walter, T.R., Wang, R., Luehr, B.-G., Wassermann, J., Behr, Y., Parolai, S., Anggraini, A. Günther, E., Sobiesiak, M., Grosser, H., Wetzel, H.-U., Milkereit, C., Sri Brotopuspito, P.J.K., Harjadi, P., Zschau, J., (2008). The 26 May 2006 magnitude 6.4 Yogyakarta earthquake south of Mt. Merapi volcano: Did lahar deposits amplify ground shaking and thus lead to the disaster? *Geochemistry, Geophysics, Geosystems* 9 (5), Q05006, doi:10.1029/2007GC001810.

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