ΕΓΕ 2019
15th International Congress of the Geological Society of Greece
Athens, 22-24 May, 2019 | Harokopio University of Athens, Greece
Bulletin of the Geological Society of Greece, Sp. Pub. **7** Ext. Abs. GSG2019-343

Primary and secondary effects of the September 2018 Mw 7.5 Palu (Sulawesi Island, Indonesia) earthquake and their impact on the natural and built environment of Palu Bay area

S. Mavroulis[1], M. Gogou[1], E. Lekkas[1], P. Carydis[2]

(1) Section of Dynamic Tectonic Applied Geology, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, Panepistimiopolis, 15784, Athens, Greece, smavroulis@geol.uoa.gr
(2) National Technical University of Athens, Athens, Greece

On September 28, 2018, at 10:21 UTC [18:02:44, WITA (Indonesia Central Standard Time)], an earthquake occurred in the western part of Sulawesi Island (Indonesia) and more specifically on the coastal Lende area. It was assessed as M 7.5 [United States Geological Survey (USGS)] or M 7.7 [Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG)]. The main shock is located onshore at a distance of 61 km north of Palu city and at depths of about 10 km.

It was preceded by a foreshock with magnitude M 6.1 generated at 07:00 UTC [15:00, WITA (Indonesia Central Standard Time)] and located 55 km NNW of Palu at a depth of about 18 km (USGS). The fault plane solutions of the main shock demonstrated an almost N-S striking left lateral strike slip fault (USGS, GCMT, CPPT, IPGP, GFZ) in the very complex tectonic environment of the Southeastern Asia. Based on the spatial distribution of aftershocks, it is estimated that the fault length was over 150 km (Sassa and Takagawa, 2018).

The affected Sulawesi Island is a K-shaped island located within the highly seismic active triple junction area between the Australian, Philippine and Sunda plates, which is composed of small rotating blocks bounded by active faults (Socquet et al., 2006). It is composed of four rapidly rotating crustal blocks: (1) the Makassar block, located in the southwestern part of Sulawesi, (2) the North Sula block, located in the northeastern part of Sulawesi, (3) the East Sulawesi block is pinched between the Makassar block and the North Sula block and (4) the Manado block, located at the northeastern end of the island (Socquet et al., 2006).

14 earthquake-induced tsunamis were recorded for Sulawesi Island between 1820 and 1982 (Soloviev et al., 1992). Since 1927, the Makassar Strait sustained the destructive effects of seven tsunamis (Prasetya et al., 2001). They are attributed to earthquakes involving main tsunamigenic tectonic structures comprising the Palu-Koro fault, which constitutes part of the Central Sulawesi fault system (Prasetya et al., 2001). In the case of the September 2018 earthquake, the most affected area was the Palu depression (Lekkas et al., 2018), along the boundary between the Makassar and the North Sula blocks. The most affected parts of Palu depression included the coastal areas of the Palu Bay and more specifically the onshore Palu valley, in the east of the Palu-Koro fault, which is considered as the causative fault based on the primary EEE observed on the field (Lekkas et al., 2018) and the analysis of teleseismic data and synthetic-aperture radar and satellite optical images (Bao et al., 2019).

The environmental effects induced by the 2018 Palu earthquake are classified into primary and secondary effects (Lekkas et al., 2018). The primary earthquake environmental effects (EEE) include coseismic surface ruptures in the Palu City area, while the secondary EEE included tsunami waves, liquefaction phenomena and ground cracks in the Palu Bay area (Lekkas et al., 2018).

The coseismic surface ruptures directed parallel and in an en echelon arrangement to the causative fault and resulted in deformation and destruction of the road network and buildings respectively. The deformed asphalt pavements as well as the adjacent damaged buildings along with the perimeter walls and railings reveal left lateral offset, which is in coincidence with the causative Palu-Koro fault.

The liquefaction phenomena occurred in Balaroa and Petobo districts and along a riverbed south of Bilomaru, located SE of Palu City. They comprised liquefaction- and lateral spreading-initiated flow that have resulted the total destruction of Balaroa and Petobo neighborhoods in Central Palu, which were swallowed up in a wave of mud resulting in thousands of dead, injured and missing people.

The ground cracks were observed as tension cracks close to sites with gravitational movements and lateral spreading and are attributed to the ground shaking.

Among the most impressive EEE, the 2018 Palu earthquake triggered a tsunami that struck the western coastal part of the Central Sulawesi Province extending from Magapa area to Palu Bay located north and south of the earthquake epicenter respectively. The tsunami struck several settlements along the aforementioned coastal area with the Palu Bay being the worst affected area. The coastal part of Palu City was devastated. The destructive waves arrived up to 10 minutes after the generation of the earthquake. This fact allowed little to no time for early warning and left no time to the local population for early evacuation resulting in many fatalities and huge economic damage. The evacuation started as soon as the tsunami approached the coast.

With inundation depth ranging from 2 to 5m locally and inundation distance of hundreds of meters, the waves devastated the Talise beach in Palu City, the Dongala village at the western tip of the Palu bay as well as all many villages along the coast of Palu bay claiming the life of thousands and resulting in heavy impact on buildings, infrastructures, mobile objects and the environment. It is mainly attributed to the synergy of coseismic seabed displacement, submarine landslides and liquefied gravity flow within Palu bay. Factors enhancing the tsunami destructive characteristics and losses along the coastal areas of Palu Bay include: (a) the close proximity of the affected area to the epicenter of the main shock and to tsunamigenic source resulting in tsunami arrival times shorter than 10 minutes, low dispersion and cause extreme run-up, (b) the local bathymetry and seabed morphology, which is characterized by a very steep rise from the seafloor of North Makassar Straits with water depth of about 2500 m to the western coast of the Central Sulawesi province, (c) the coastal configuration of the affected area, which is composed of gulfs and a gently concave coastline that created a wave-guide, funneling effects on the tsunami wave energy, amplification of tsunami height and run up and enhanced damage along the coast of Palu Bay, (d) both local bathymetry and coastal configuration resulted in wave refraction and reflection.

As regards the earthquake impact on the building stock, the earthquake caused non-structural and structural damage mainly in Palu city. Multistory reinforced concrete (R/C) hotels and malls suffered heavy structural damage resulting in partial or total collapse. The ground floor of the buildings collapsed, while the upper floors behaved as rigid bodies, resulting in toppling of the damaged structures. In contrast, wooden and steel-frame buildings suffered mainly non-structural damage by the earthquake ground motion. Severe structural damage were observed in monumental structures such as mosques.

In the liquefaction-affected areas, the level of building destruction was almost complete with many buildings of all types being compressed together and wrecked into a soil and debris zone resulting in significant loss of life.

In the tsunami affected areas, all wooden structures founded along the coastal front were totally washed away by the wave pressure and only their concrete foundations were left in place. In villages along the western coast of Palu Bay, some wooden structures with wooden foundation were detached from their foundations and transferred inland but not destroyed.

The R/C buildings suffered typical tsunami-induced damage in the ground floor and in the first floor due to tsunami water pressure and impact with floating debris. Punching failure of brick infill walls under out-of-plane tsunami pressures were observed in the form of large circular openings in infill walls. Flexural failures of columns within their midheights are attributed to impact forces generated by floating debris.

Based on our field survey on the tsunami affected area and on all already published official reports on the tsunami impact, the Integrated Tsunami Intensity Scale (ITIS 2012) is applied for the Palu tsunami. Tsunami quantities and the impact on humans, mobile objects, coastal infrastructure, the natural environment and buildings were taken into account for the tsunami intensity assessment. The maximum assigned intensity is XII.

Acknowledgements

This study was partially funded by the Environmental, Disaster and Crises Management Strategies Post graduate Program of the Department of Geology and Geoenvironment of the National and Kapodistrian University of Athens.

References

Bao, H., Ampuero, J.-P., Meng, L., Fielding, E.J., Liang, C., Milliner, C. W. D., Feng, T., Huang, H. (2019). Early and persistent supershear rupture of the 2018 magnitude 7.5 Palu earthquake. Nature Geoscience, 12, 200-205, https://doi.org/10.1038/s41561-018-0297-z

Lekkas, E., Carydis, P., Mavroulis, S. (2018). The September 2018 Mw 7.5 Palu (Sulawesi Island, Indonesia) earthquake and tsunami disaster – Scientific Report (Version 1.0). Newsletter of Environmental, Disaster and Crisis Management Strategies, 9. Available at https://edcm.edu.gr/images/docs/2018/Newsletter_2018_9_Indonesia_EQ.pdf

Prasetya, G.S., de Lange, W.P., Healy, T.R., 2001. The Makassar Strait Tsunamigenic Region, Indonesia. Natural Hazards, 24, 295-307, https://doi.org/10.1023/A:1012297413280

Socquet, A., Simons, W., Vigny, C., McCaffrey, R., Subarya, C., Sarsito, D., Ambrosius, B., Spakman, W., 2006. Microblock rotations and fault coupling in SE Asia triple junction (Sulawesi, Indonesia) from GPS and earthquake slip vector data. Journal of Geophysical Research, 111, B08409, http://doi.org/10.1029/2005JB003963

Soloviev, S.L., Go, C.N., Kim, K.S., 1992. Catalog of tsunamis in Pacific. Academy of Sciences of the USSR, Moscow, Translated by Amerind Publishing Co. Pvt. Ltd., New Delhi