Earthquake Scenario-based Assessment for Empirical Seismic Fragility Functions:
A Case Study of the Mw7.1 Bohol Philippines Earthquake

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Abstract

A damage assessment has been conducted for the 2013 Mw7.1 Bohol Philippines earthquake. The aftermath of this event is dominated by strong ground shaking which damaged over 70,000 buildings. An extensive survey was conducted leading to a robust description of over 25,000 exposed structural systems in the island. This exposure/damage database represents a mix of construction types at various inferred intensity levels, in urban and rural settings. Using an empirical approach, the seismic fragility functions of typical building units emerging from this database have been constrained. A significant step in the process is the correlation of earthquake ground motion estimates with building damage. For the earthquake source model, the rupture process is characterized by jointly inverting available seismic and geodetic data. This produced a finite fault model extending along the NW portion of the island from which an intensity distribution has been extrapolated. On the other hand, the building population representing pre-defined damage thresholds are aggregated and used as statistical inputs in the analysis. This analysis allows us to validate building fragility functions already in use in the Philippines. Through consultation with local engineers and contractors, we also validated the corresponding vulnerability models for different building types. This assessment further corroborates the significance of building an empirical database in evaluating the seismic performance of buildings, thereby improving knowledge on building resilience.

Keywords: building fragility, vulnerability, exposure/damage database, Bohol Philippines earthquake

1 INTRODUCTION

The 2013 Bohol Philippines earthquake presents an important opportunity in improving knowledge of building fragility and vulnerability, not only for the Philippines but for other countries in the region as well. Because of the extensive damage and the wide spread of intensities deemed to have shaken the island of Bohol, this event is a good candidate for impact estimation wherein the earthquake performance of structures are evaluated.

A key component highlighted in this research is the use of empirical data in validating the seismic fragility and vulnerability models. The process involves the assessment of seismic risk factors like hazard, exposure and vulnerability to correlate the earthquake source model with a reliable statistical description of building damage.

1.1 Hazard: The Mw7.1 Bohol Philippines Earthquake

The Philippines being one of the seismically active regions in the globe features a complex tectonic setting consisting of subduction zones and trenches, while surrounded by major tectonic plates. A few of the primary tectonic structures that fire up the earthquake activity in the Philippines include the Manila Trench on its western boundary, the Philippine Trench along its eastern side and the Philippine Fault System traversing the central part of the country (Yumul *et al.*, 2008).

However, the occurrence of the Mw7.1 Bohol earthquake in the morning of 15 October 2013 was not associated with a major plate boundary or any of the mapped active faults for that matter. This inland quake is linked with the rupture along a newly-discovered thrust fault named as the *North Bohol Fault* (EMI, 2014).

The prominent geomorphic features observed on site include a 6km surface rupture with vertical offsets measured from 0.1 to 5m in NW Bohol and the coastal uplift in the SW which shifted the shoreline at least 50m seawards (PPDO,2014). The SAR-inferred crustal deformation (Kobayashi, 2014) revealed these physical features and may have pointed out the extent of the fault plane, much longer in length than the observed rupture. In addition, the distribution of aftershocks recorded by the Philippine Institute of Volcanology and Seismology (PHIVOLCS), being the local seismic monitoring agency, is mostly concentrated on the northern part of the island suggesting a fault zone that may extend even up to 100km (Punongbayan *et al.*, 2014).

1.2 Exposure: Core Elements at Risk

The main elements exposed to this seismic hazard include the people and the buildings. Bohol being the 10^{th} largest island in the Philippines has a total area estimated at 4,821 sq km and a population of 1.255M. It has one capital city and 47 municipalities, which are further divided into 1,109 villages representing the smallest administrative units in the country, locally termed as *barangays.* Geologically, around 80% of Bohol is covered in limestone and its topography ranges from flat to steeply sloping with an elevation up to 870m (EMI, 2014).

Based on recent census, Bohol has approximately 260,000 housing units. For the occupied housing units, at least 34% utilized concrete, brick or stone in its outer walls. On the other hand, approximately 26% were made up of bamboo, cogon or nipa while 22% employed a combination of these structural materials (EMI, 2014).

1.3 Vulnerability: Structural Damage

The intense ground shaking has a tremendous impact in Bohol's physical environment and structures, as depicted in Figure 1. Indeed, the Bohol earthquake tested the structural integrity of buildings and infrastructures not only within the island but the neighbouring provinces as well. Around 58,000 houses incurred partial damage while at least 15,000 were rendered completely damaged. Several historic churches, which were standing for hundreds of years since the Spanish Colonial Era, were reduced into rubble (EMI, 2014).

Figure 1.The impact of intense ground shaking on Bohol's built environment

2 DEVELOPMENT OF THE EXPOSURE/DAMAGE DATABASE

A post-event survey has been conducted consisting of two components: [1] interviews with the local officials and health workers to gain insights on the structural attributes; and [2] interviews with the engineers and contractors to elicit expert opinion on associated costs of repair and reconstruction. A total of 100 *barangays* were selected, in urban and rural areas, located at various earthquake intensity levels.

This extensive exposure/damage database is an inventory of the location and attributes describing over 25,000 damaged and undamaged structures spread throughout the island – the main elements related to its development are depicted in Figure 2. Majority of the buildings in the database are of residential dwellings, with one or two storeys, housing four to seven people. A huge proportion of these housing units were built in flat terrain. The structural materials utilized for these buildings include confined masonry, wood, concrete hollow blocks or combination thereof for the walls, light materials for the roofing and concrete slab for the flooring. In addition, this database features a good variation in construction vintage and damage states.

From the mix of construction types present in the database, four predominant building stocks emerged: [1] wood with light frame (**W1**); [2] confined masonry (**C1**); [3] concrete hollow blocks (**CHB**); and [4] concrete hollow blocks with wood or light metal (**MWS**). The buildings were categorized with reference to the typological system developed by the local engineers (UPD-ICE, 2013).

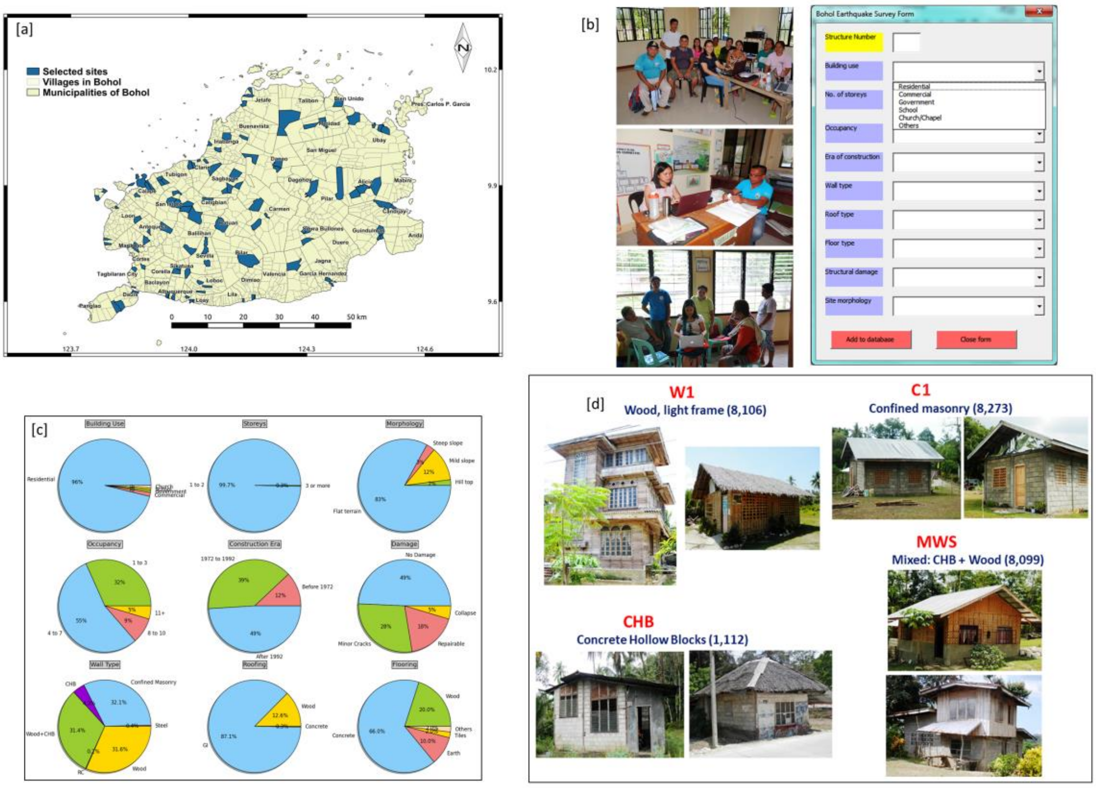

Figure 2. [a] Strategic locations of villages in Bohol where the post-event interviews were conducted; [b] Interviews with the locals & the survey form showing the structural attributes; [c] Summary of the exposure/damage database; and [d] Typical building types in the database

3 CORRELATION OF EARTHQUAKE SOURCE MODEL TO DAMAGE OBSERVATIONS

The joint inversion of SAR and tele-seismic broadband seismic data resulted to a finite fault model, with most of the slip confined in the upper half of the fault. With this fault geometry, ground motions were simulated using a computer algorithm called the EXtended finite-fault SIMulation or EXSIM (Motazedian and Atkinson, 2005). This code offers a stochastic approach in estimating the ground motions by calibrating the parameters pertaining to the source, path and site of the scenario being considered.

Upon simulating the corresponding ground motions at pre-defined reference sites, the simulated peak ground accelerations (PGA) and spectral accelerations were converted to Modified Mercalli Intensity (MMI) using empirical equations (Worden *et al.*, 2012). Hence, the source model is translated into ground motion inputs in the form of earthquake intensity, and thereby calibrated to the exposure/damage database, as demonstrated in Figure 3.

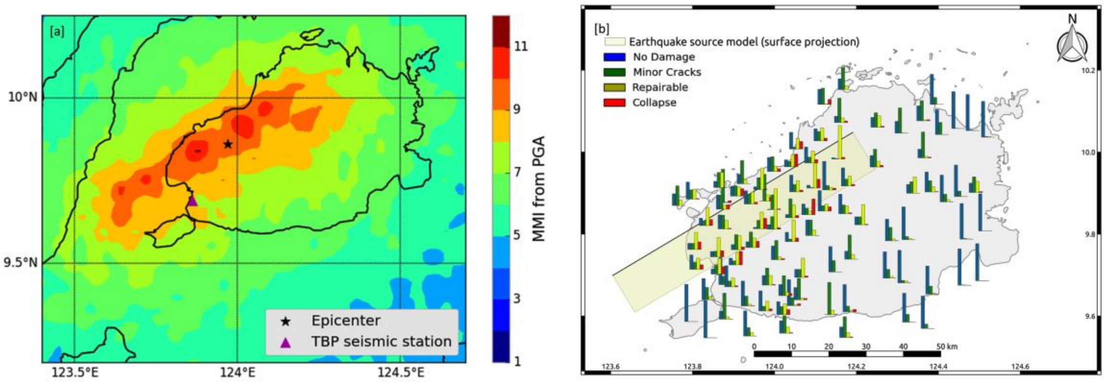

Figure 3. [a] Distribution of intensity levels based on the estimates of PGA in EXSIM; and [b] Distribution of damage in selected sites and the surface projection of our fault model

4 APPLICATION TO SEISMIC FRAGILITY & VULNERABILITY MODELS

Fragility models represent the probability of exceeding a certain damage state as a function of ground motion like earthquake intensity or PGA, among others (Abo-El-Ezz *et al.*, 2013). Linked with building fragility, the vulnerability models exhibit the loss ratios for a given measure of ground shaking, which consider the repair and reconstruction cost as damage index (Sengara *et al.*, 2010).

In this research, the seismic fragility and vulnerability models proposed by the engineers from the University of the Philippines Diliman-Institute of Civil Engineering (UPD-ICE, 2013) are validated and constrained. The hybrid fragility curves by UPD-ICE were developed by applying either the (1) *computational/analytical method* wherein structural models for each building type were numerically simulated or (2) the *heuristic method* wherein inputs and engineering judgment from experts were utilized. The proposed UPD-ICE vulnerability models for CHB and MWS, although not succinctly reported, adopted the *empirical method* using compiled field reports from historical earthquakes, whereas *heuristic* and *computational* methods were used to derive the models for W1 and C1 respectively.

From the assembled exposure/damage database, the severity of damage is expressed in four damage states: (1) *No Damage* which covers minor tilting for wooden structures and no visible cracks for concrete buildings; (2) *Minor Cracks* (equivalent to *Slight* for UPD-ICE) denote slight cracks in structures but no need for repair; (3) *Repairable* (*Moderate to Extensive* for UPD-ICE) wherein the structure is still standing but it has suffered extensive damage, thereby requiring reparation; and (4) *Collapse* (*Complete* for UPD-ICE) wherein the structure is rendered uneconomic to repair and require total reconstruction.

Results indicated conservative UPD-ICE fragility models at Moderate to Extensive/ Repairable and Complete/Collapse damage states while estimated probabilities for Slight/Minor Cracks were generally comparable although W1 yielded smaller estimates, as shown in Figure 4. For the vulnerability models, the computed loss ratios were lower than the UPD-ICE, as depicted in Figure 5. In general, for all building types, a trend in probability estimates has been established in the scatter plots of actual damage observations. And for all damage states, the fragilities and loss ratios tend to increase with increasing intensity.

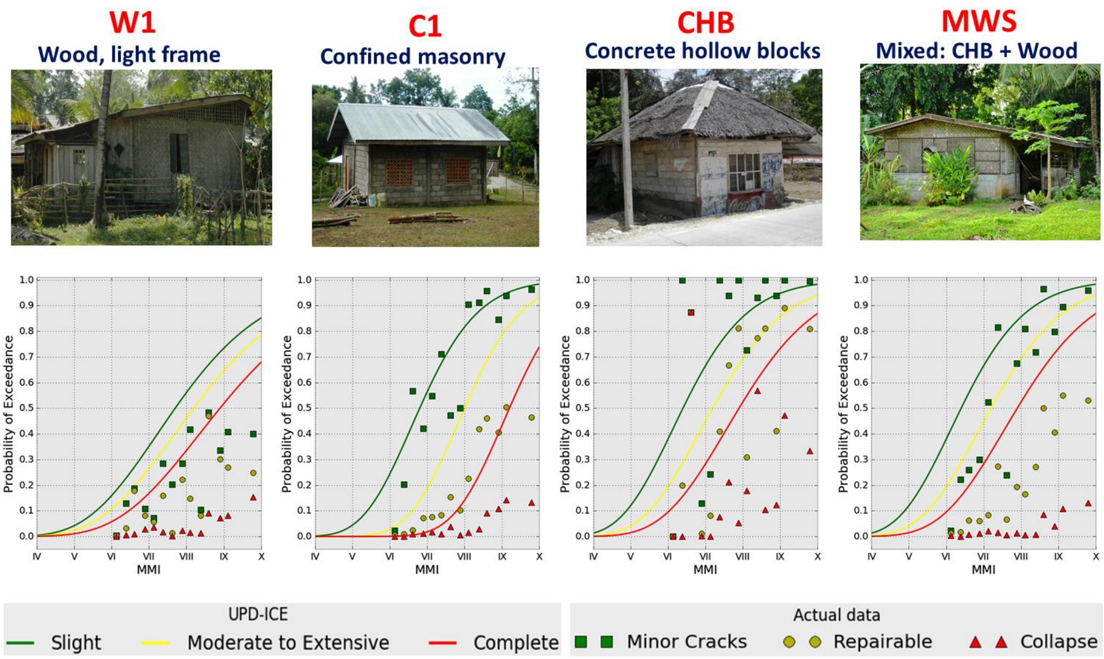

Figure 4.Validation of seismic fragility models

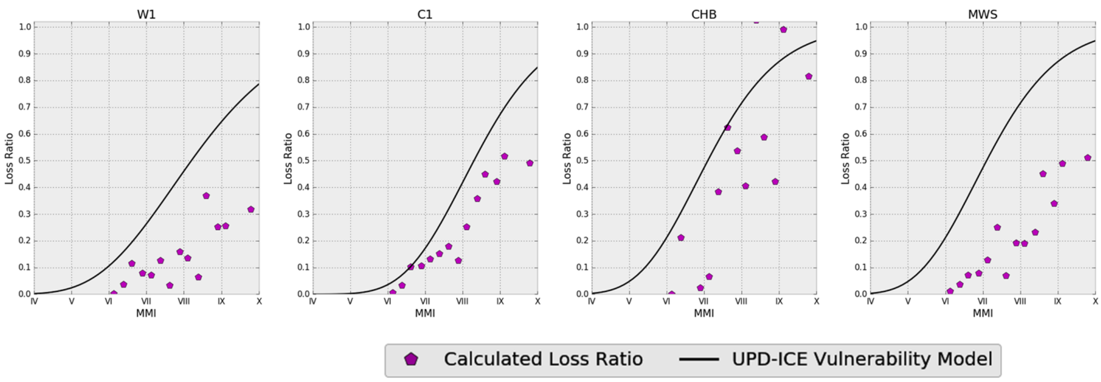

Figure 5.Validation of seismic vulnerability models

For the earthquake performance of these building stocks, W1 appears to be the most resilient against earthquake excitation as it returned lower probabilities of exceeding the damage states. C1 and MWS have comparable performance wherein a huge proportion of structures need repair and endured minor cracks. CHB has poor performance with large number of structures in the collapsed and repairable condition. W1 appears to establish a clear dependence with respect to age category as the fraction of buildings with no damage increases over time, which is not the case for C1, CHB and MWS. Further assessment did not indicate a strong difference in earthquake performance between urban and rural structures, perhaps indicating uniformity in construction practices and building code implementation.

5 KEY MESSAGES & FUTURE DIRECTION

With the immense damage and the variation of intensities associated with the Mw7.1 Bohol Philippines earthquake, this event offers a significant opportunity in constraining and validating the seismic fragility and vulnerability models for predominant building types in Bohol. The developed earthquake source model led to a reliable estimate of ground motion intensities while the statistical building survey resulted in a well sampled representation of damaged and undamaged structures located throughout the island. Correlating various facets of building components and construction to corresponding seismic intensity inputs quantified how fragile and vulnerable selected building types were when exposed to seismic hazard.

In this empirical approach, the source model complements the exposure/damage database. For future work, a sensitivity analysis will demonstrate the variability of earthquake source models as ground motion inputs in fragility and vulnerability modelling. Also, further work on the fragility and vulnerability can improve and enhance the existing models.

REFERENCES

Abo-El-Ezz, A., Nolle, M. and Nastev, M. (2013). Seismic fragility assessment of low-rise stone masonry buildings, Journal of Earthquake Engineering and Engineering Vibration, Vol 12, No. 1, pp 87-97.

EMI (2014). The Mw7.2 15 October 2013 Bohol, Philippines Earthquake, Technical Report from the Earthquake & Megacities Initiative, Quezon City, Philippines.

Kobayashi, T. (2014). Remarkable ground uplift and reverse fault ruptures for the 2013 Bohol earthquake (Mw7.1), Philippines, revealed by SAR pixel offset analysis, Geoscience Letters, Vol 1, pp 1-10.

Motazedian, D. and Atkinson, G. (2005). Stochastic Finite-fault Modelling Based on a Dynamic Corner Frequency, Bulletin of the Seismological Society of America, Vol. 95, No. 3, pp.995-1010.

PPDO (2014). Post-Great Bohol Earthquake Rehabilitation Plan, Technical Report from the Provincial Planning and Development Office, Bohol, Philippines.

Punongbayan, BJ., Kumagai, H., Pulido, N., Bonita, J., Nakano, M., Yamashina, T., Maeda, Y., Inoue, H., Melosantos, A., Figueroa, M., Alcones, P., Soriano, K., Narag, I. and Solidum, R. (2014). Development and Operation of a Regional Moment Tensor Analysis System in the Philippines: Contributions to the Understanding of Recent Damaging Earthquakes, Journal of Disaster Research, Vol 10, No 1, pp 25-34.

Sengara, I., Suarjana, M., Beetham, D., Corby, N., Edwards, M., Griffith, M., Wehner, M. and Weller, R. (2010). The 30th September 2009 West Sumatra Earthquake Padang Region Damage Survey, Technical Report from Geoscience Australia, Canberra, Australia, Record 2010/44, 201pp.

UPD-ICE (2013). Development of vulnerability curves of key building types in the Greater Metro Manila Area, Technical Report from the University of the Philippines, Institute of Civil Engineering, Diliman, Quezon City, Philippines.

Worden, C., Gerstenberger, M., Rhoades, D. and Wald, D. (2012). Probabilistic Relationships between Ground-Motion Parameters and Modified Mercalli Intensity in California, Bulletin of the Seismological Society of America, Vol. 102, No 1, pp 204-221.

Yumul, G., Dimalanta, C., Maglambayan, V. and Marquez, E. (2008). Tectonic setting of a composite terrane: A review of the Philippine island arc system, Geosciences Journal, Vol 12, No 1, pp 7-17.