# Local and indigenous knowledge in disaster risk reduction: Analysing multi-hazard housing reconstruction strategies in the Philippines

by

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# Thesis Abstract

The place-based ("local") and cultural ("indigenous") knowledge of communities developed out of their embeddedness in their environments has provided them with time-tested approaches for disaster risk reduction (DRR). However, current DRR interventions often disregard local and indigenous knowledge (LIK) that could contextualise better responses to disaster impacts among affected populations. This thesis examined LIK in housing reconstruction in multi-hazard settings. First, it reviewed the state of knowledge of LIK in DRR scholarship through a systematic literature search, identifying the trajectories of its application to manage disaster impacts. Second, based on a case study in Itbayat, Batanes in the Philippines, structural housing performance was quantified among the post-disaster dwellings built by Indigenous households in response to multi-hazard events. First-generation fragility functions were derived for Batanes Province contributing to more localised housing risk assessments in the country. Third, the socio-technical factors influencing multi-hazard housing reconstruction were elicited through interviews and focus group discussions. Factors such as the urgency of reconstruction, risk perceptions, financial capacities, and regulatory barriers on resource extraction affect how households build their dwellings, offering contextual shelter recovery insights. Finally, this thesis culminates with a proposed approach (as applied to the case study) to analyse collective safer construction practices of a residential building portfolio in multi-hazard settings while considering the socio-technical circumstances of the Indigenous community. This approach facilitates multi-hazard housing reconstruction decision-making useful for policymakers to enact safer construction interventions. Overall, this thesis highlights blending local capacities and resources with technical approaches to understand and improve the multi-hazard housing trajectories among Indigenous communities.

## Statement of Originality

This is to certify that, to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work, and all the assistance received in preparing this thesis and the sources have been acknowledged.

Arvin Hadlos

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This work is far from being the product of my sole effort. Like raising a child, it took a village for this to come to fruition. The more I think of the people who have helped me in one way or another, the more I realise that expansively writing their names and articulating their respective contributions would always be insufficient relative to the amount of support I received from them. From my family and friends' encouragement to my supervisors' unwavering guidance to the Indigenous people in Batanes who welcomed me to their ancestral domain, this work has been rallied by a community of good-hearted folks.

This page is kept half-empty and the next empty to symbolically reflect the endless list of people in my head who have given their magnanimous support along my journey. Let these blank spaces be a reminder that words are insufficient to articulate my gratitude for you and that these spaces mark your special place in this scholarly endeavour.

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## Authorship Attribution Statement

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Author contributions:
I wrote the main manuscript text, conducted the data collection and analysis. Aaron Opdyke (A.O.) provided primary supervision while Ali Hadigheh (S.A.H.) provided secondary supervision. A.O. and I edited the manuscript. All authors conceptualised the project and reviewed the manuscript.

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Author contributions:
I wrote the main manuscript text, conducted the field visits, data collection, and analysis. A.O. provided primary supervision while S.A.H. provided secondary supervision. A.O. and I edited the manuscript. All authors conceptualised the project and reviewed the manuscript.

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I wrote the main manuscript text, conducted the field visits, data collection, and analysis. A.O. provided primary supervision while S.A.H. provided secondary supervision. Charmaine Gato

(C.G.) helped in the project administration and investigation. A.O. and I edited the manuscript. A.O., S.A.H., and I conceptualised the study. All authors reviewed the manuscript.

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I wrote the main manuscript text, conducted data collection and analysis. A.O. provided primary supervision while S.A.H. provided secondary supervision. A.O. and I conceptualised the study. All authors edited and reviewed the manuscript.

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As supervisor for the candidature upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

Dr Aaron Opdyke

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## List of Abbreviations

| | |
|---|---|
| ATC | Applied Technology Council |
| CGI | corrugated galvanised iron |
| DRR | disaster risk reduction |
| DS | damage state |
| DVF | desirability, viability, and feasibility |
| EDP | engineering demand parameter |
| FEMA | Federal Emergency Management Agency |
| GEM | Global Earthquake Model |
| HAZUS | Hazards US |
| IPCC | Intergovernmental Panel on Climate Change |
| IP(s) | Indigenous people(s) |
| km/h | kilometres per hour |
| LIK | local and indigenous knowledge |
| LW-A | lightweight with wooden posts |
| LW-B | lightweight with steel posts |
| MDRRMO | Municipal Disaster Risk Reduction and Management Office |
| mm | millimetre/s |
| MMI | Modified Mercalli Intensity |
| MPDO | Municipal Planning and Development Office |
| $M_w$ | magnitude |
| NCIP | National Commission on Indigenous Peoples |
| PAGASA | Philippine Atmospheric, Geophysical, and Astronomical Services Administration |
| PEIS | PHIVOLCS Earthquake Intensity Scale |
| PGA | Peak Ground Acceleration |
| PHIVOLCS | Philippine Institute of Volcanology and Seismology |
| PHP | Philippine peso |
| PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |
| RC | reinforced concrete |
| RC-A | reinforced concrete with lightweight roof |
| RC-B | reinforced concrete with slab roof |

| | |
|---|---|
| RP | return period |
| RQ | research question |
| RSB | reinforcing steel bar |
| s | second |
| SAW | Simple Additive Weighting |
| SC-A | semi-concrete with steel posts |
| SC-B | semi-concrete with reinforced concrete posts |
| UNESCO | United Nations Educational, Scientific, and Cultural Organisation |
| URM | unreinforced masonry |
| USD | United States dollar |
| WPM | Weighted Product Method |

# Chapter 1

# Introduction

## 1 Background

Disasters bring considerable damage to communities prompting calls, such as from the Sendai Framework, to adopt local and national disaster risk reduction (DRR) strategies to systematically minimise losses to lives and assets [1]. From 2000 to 2019, there were 7,348 natural hazard-related disasters recorded globally which affected 4.03 billion people and resulted in 1.23 million deaths and US$2.97 trillion economic losses [2]. Scaling DRR efforts competes with the increasing number of disaster events and can be further complicated by the multi-hazard exposure of certain areas. The term multi-hazard can be defined as the spatial or temporal overlap of at least two (natural) hazards, either with or without dependence on each other [3–6]. In this thesis, the context of multi-hazard is viewed as the spatial overlap of natural hazards at a particular location where the exposed populations deal with the impacts of at least two independently occurring hazards. De facto DRR strategies have historically relied on single-hazard approaches [7] responding to each hazard impact in isolation, thus lacking the synergy to address the complicated nature of multi-hazard events. Re-classified disaster records from 1900 to 2023 suggest that 19% of the 16,535 disaster events are considered multi-hazard, contributing to 59% of global economic loss [8].

Mainstream DRR strategies have mainly relied on scientific approaches such as the use of contemporary technology which have enabled more comprehensive disaster risk assessments, safer building practices, and hazard forecasts. However, prior to or alongside the establishment of these scientific approaches, the place-based (“local”) and culturally linked (“indigenous”) knowledge bases of communities borne out of their interaction with their environments have shaped context-dependent means to manage disaster risk [9–14]. While scientific knowledge catapults DRR through its methodological approach, local and indigenous knowledge (LIK) relies on experiential learning of those living in hazard-affected regions. However, the technocracy in DRR agencies, organisations, and institutions risks the displacement of LIK as an important knowledge sphere to reduce disaster impacts [15–20]. This institutional technocracy brings forth a trajectory that continues to favour scientific knowledge over LIK. As a result, this situation creates a gap between the two knowledge spheres (LIK and scientific) instead of informing ways to integrate them for more robust risk intervention strategies. The global frameworks guiding DRR efforts – from the Yokohama Strategy in 1994 [21] to the Hyogo Framework in 2005 [22] to the current Sendai Framework [23] – have acknowledged LIK alongside scientific and technical capacities to bolster DRR efforts. Significant challenges nonetheless remain to implement the inclusion of LIK in formal DRR practice [15] with prevailing barriers such as the dominance of a science-based stance in risk management [17,18]. In 2022, the United Nations Office for Disaster Risk Reduction (UNDRR) crafted a guidance instrument for integrating LIK and scientific knowledge through knowledge co-production [24]. This initiative not only helps translate the provisions of the Sendai Framework to implementable actions pertaining to LIK for DRR but also reinforces the genuine interest in renewing focus on its inclusion in practice and policy realms.

A core component of LIK is the vernacular construction systems of communities developed intergenerationally [24] and the prevailing local construction practices learnt informally [25]. These building practices emerge from the ingenious use of locally available materials, dictated or assimilated by societal norms of construction, and experientially refined based on frequent triggers of building performance to the impacts of hazards. Reflective of these construction systems are the housing assets built by local populations and Indigenous communities which are among their highly valued possessions but these also tend to be frequently affected by natural hazards [26]. From 2021 to 2040, it is projected that the escalating climate crisis will damage 167 million houses globally [27], signifying the need for strategies to improve risk reduction efforts through safeguarding housing assets. In post-disaster settings, rebuilding housing assets impacted by hazards not only helps re-establish a sense of normality in the aftermath of disasters but is also a vital phase linked to disaster mitigation, providing opportunities to build more resilient assets [23]. While external aid plays a role in assisting communities to recover in these settings, most disaster-affected populations in low- and middle-income countries resort to using their resources in a process called self-recovery [28–32].

Given that LIK – inclusive of local or vernacular construction practices – is developed experientially based on communities' frequent encounters with hazards, its limitation can become apparent in the occurrence of rare but high-magnitude events. A dilemma emerges when communities' response capacities historically rely on frequent hazards but there are other impending hazards requiring different response dynamics. This multi-hazard exposure poses challenges in safeguarding structural assets, most especially in navigating the trade-offs in building resilient dwellings considering the competing hazard impacts [33,34]. For example, frequent wind events may require heavier materials such as masonry, but this can be highly susceptible to seismic impacts. Guidance instruments to support communities navigating multi-hazard housing reconstruction are sparse, especially within informal construction settings. For instance, (most) building codes are exclusionary to vernacular construction methods and rarely provide frameworks to encompass those assets built informally by communities. Thus, there is a need to understand local capacities (e.g., construction skills and practices) for housing (re)construction, especially in multi-hazard contexts, to inform more resilient housing trajectories among disaster-affected populations.

This thesis focuses on the context of the Philippines. The country is a constant frontrunner in the World's Risk Index [35,36], with at least 60% of its geography exposed to multi-hazard impacts [37]. The archipelago is home to a significant number of Indigenous peoples (IPs) estimated to comprise 10% to 20% of the national population of 101 million in 2015 [38]. The Indigenous Peoples' Rights Act of 1997 promotes the protection of the cultural artefacts of the IPs, which include their vernacular construction systems [39]. However, there are gaps in understanding how IPs adapt these building technologies at the interface of multi-hazard events and housing reconstruction processes. In 2010, the country adopted the Disaster Risk Reduction Management Act which institutionalises DRR efforts from national to community level [40]. This was an essential step in the devolution of decision-making, especially among minority groups who (still often) rely on LIK to reduce disaster risks. However, significant roadblocks remain in understanding and leveraging how local capacities can be bolstered to tackle multi-hazard problems. An imperative arises to focus on the granular understanding of DRR at a local level to collectively inform more refined approaches to diverse groups. This knowledge will contribute to more sensible and grounded national strategies to tackle multi-hazard housing (re)construction strategies.

## 2 Aims and scope

This thesis investigates how LIK is mobilised in DRR in housing reconstruction in response to multi-hazard events (see Figure 1.1). Previous studies have distinctly focused on either local and indigenous capacities for DRR (e.g., [9]) or multi-hazard housing reconstruction strategies (e.g., [33]), but not at the intersection of these two important agendas. This thesis seeks to answer the overarching question, “How do local and Indigenous households navigate housing reconstruction amid multi-hazard events?” It aims to, first, characterise how LIK is studied in the (broad) DRR scholarship. Second, using a case analysis or field-based study (see Section 3), this thesis then quantifies the housing performance of post-disaster dwellings built by Indigenous households in response to multi-hazard events. Third, it aims to elicit the socio-technical factors influencing multi-hazard housing reconstruction. Lastly, this thesis culminates with a proposed approach to analyse collective safer construction practices of a residential building portfolio in multi-hazard settings while embedding the socio-technical capacities of an Indigenous community. Table 1.1 shows the disaggregated knowledge gaps and research questions per the thesis structure.

This thesis contributes to the renewed interest for the greater inclusion of LIK in formal DRR interventions, mobilising locally grounded knowledge as a critical component in substantiating the predominant technical stance in managing disaster impacts. While engineering (as a field linked to science) has helped advance DRR interventions, the prevailing approach in the discipline is most often devoid of the socio-technical contexts where these interventions are based or introduced. This thesis explores the integration of technical thinking to that of the socio-technical realities impacting how disaster-affected populations – especially among minorities with intrinsic capacities and resources – navigate housing reconstruction. It focuses on how these groups apply and adopt existing and new construction methodologies as foundational aspects to inform collective community-wide efforts to reduce multi-hazard housing risk. Thus, this thesis more broadly aims to influence discourses relating to closing the divide between LIK and scientific knowledge, lobbying for knowledge co-production rather than examining the dichotomy of the two knowledge spheres in DRR scholarship.

**Table 1.1.** Research gaps and research questions per thesis chapter.

| Chapter | Research gaps | Research questions |
|---|---|---|
| 2 | Lack of a holistic synthesis of LIK in DRR scholarship hampering a collective understanding of its merits in formal DRR interventions | (1) What forms of LIK appear in disaster literature? |
| | | (2) How has the research focus of LIK in disaster scholarship evolved over time? |
| | | (3) What are the priorities of the Sendai Framework (not) being captured in the current understanding of LIK in the DRR body of knowledge? |
| 3 | Limited effort and resources to conduct structural housing performance assessments accounting for the granularity of housing characteristics at a local level, especially in rural and resource-constrained settings facing the consequences of multi-hazard events | (1) How can housing performance be analysed in multi-hazard, resource-constrained settings (e.g., in rural areas in the Philippines)? |
| 4 | Inadequate insights on how Indigenous populations navigate housing reconstruction considering the impacts of multi-hazard events | (1) What factors affected how Indigenous households in the Philippines reconstructed their dwellings? |
| | | (2) How did these factors lead to the housing outputs that households chose to build? |
| 5 | Lack of an approach to collectively analyse the trade-offs of multi-hazard housing reconstruction at a community level, especially where housing assets are highly variable | (1) How can a heterogeneous housing stock be optimised against multi-hazard direct economic losses? |

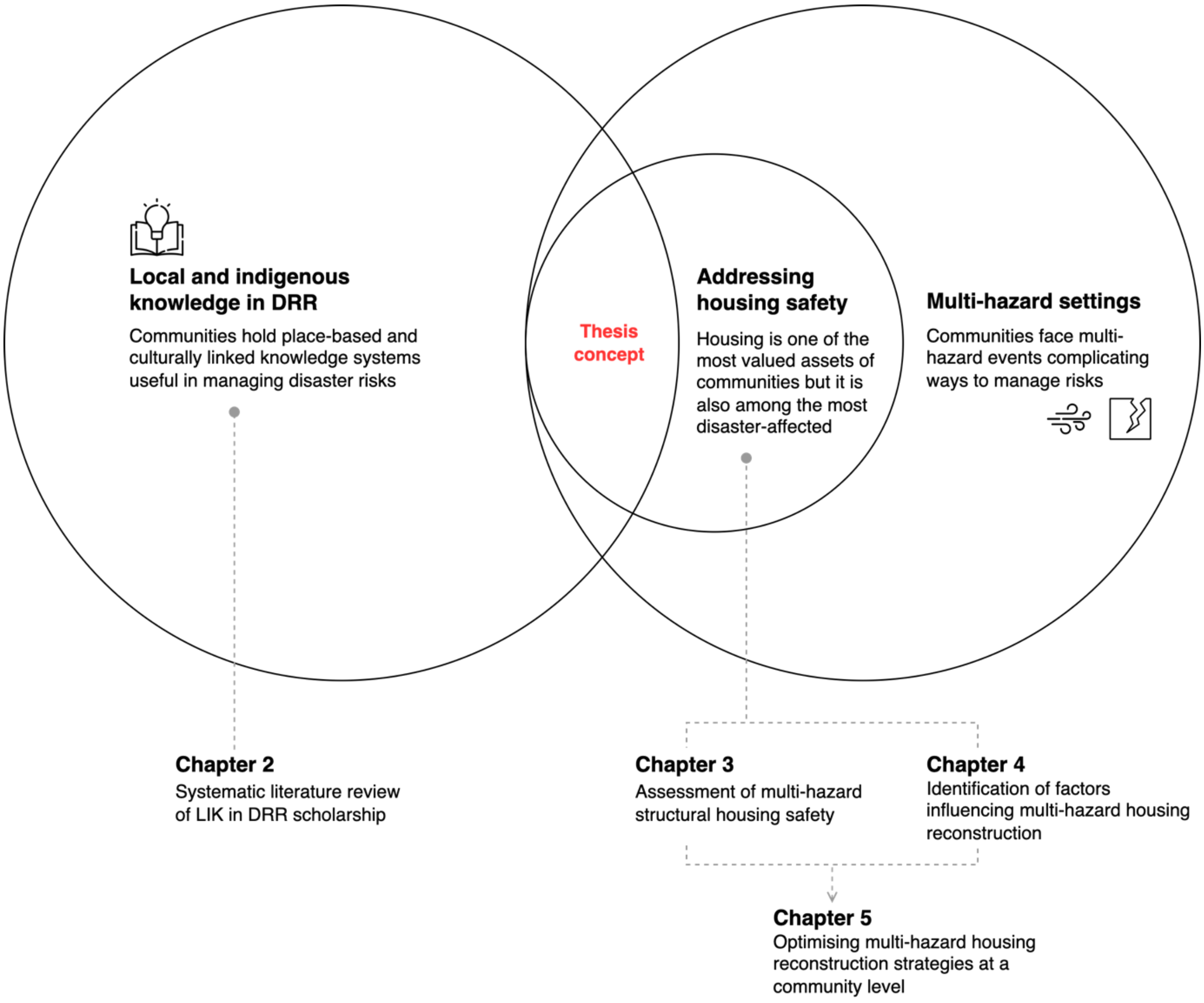


**Figure 1.1.** Thesis framework

## 3 Research setting

Chapters 3 to 5 of this thesis are based on the case of Itbayat, Batanes in the Philippines. Itbayat is the Philippines' northernmost municipality comprising a collective of islands, islets, atolls, and outcrops, with the mainland (Itbayat Island) being the only landform inhabited (see Figure 1.2). It is among the six municipalities of the Province of Batanes located between the Balintang Channel and Bashi Channel known to be frequent typhoon passages [41]. Itbayat also experiences seismic impacts consistent with the country's exposure to tectonic activities [42]. Wind and seismic hazards are, therefore, the two major hazards experienced in the area, with the former occurring more frequently than the latter. In 2016, Super Typhoon Ferdie (Meranti) hit Itbayat with at least 252 kilometres per hour (km/h) peak gust [43], making it one of the strongest storms experienced in the municipality. Three years later, a series of earthquakes in 2019 affected the island with the strongest ground shaking recorded at Intensity VII (“destructive”) of the PHIVOLCS Earthquake Intensity Scale (PEIS) [44,45].

Itbayat is primarily reliant on a fishing and farming economy. The municipality is an ancestral domain of the Ivatans, the IPs of Batanes, protected by the provisions of the Indigenous Peoples’ Rights Act of 1997 [39]. The culture of the Ivatans has been shaped by the frequent wind events in the area, with the most tangible representation of this cultural adaptation being their stone-and-lime vernacular dwellings assimilated in the 19th century from the construction systems of Spanish colonisers [46]. Given the geographical remoteness of the island municipality from mainland Batanes, typhoon events usually cut access to the area, rendering disaster response challenging. As a result, self-reliance has emerged to define the community’s coping capacity to frequent impacts brought by wind events. However, disaster response and mitigation related to earthquakes are not well inculcated in the disaster sub-culture of the community due to the rarity of seismic events. Thus, safeguarding assets from both the impacts of wind and seismic hazards has become an agenda for building resilience within the community that has primarily coped with wind events.

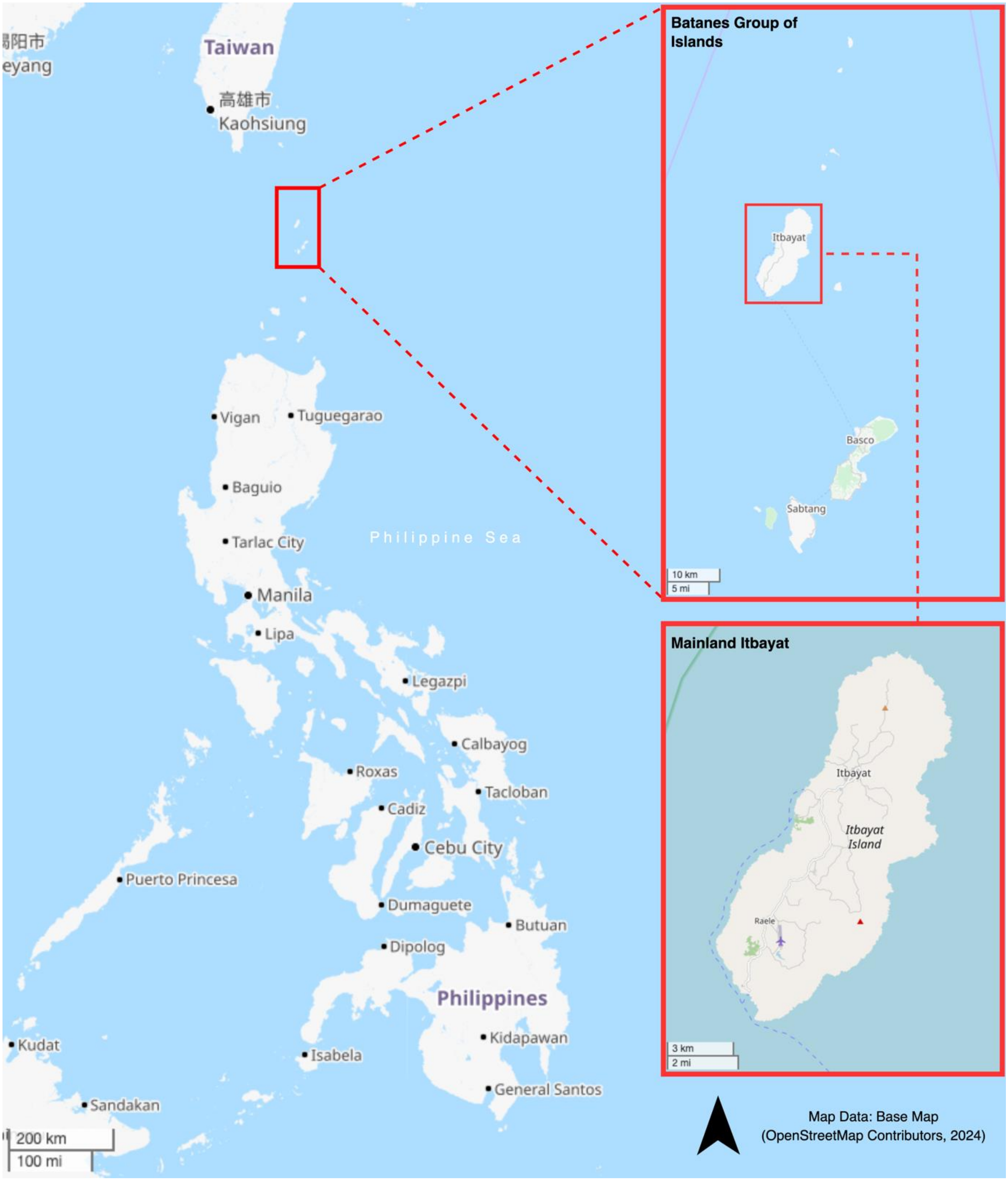


**Figure 1.2.** Map of Itbayat, Batanes in the Philippines.

## 4 Research methods

Chapter 2 of this thesis reviews the application of LIK in DRR. Through a systematic literature review [47], 325 research articles were screened from a pool of 613 documents sourced from the Scopus database using a predefined search string. Qualitative coding – leading to both inductive and deductive thematic analysis – was then implemented to (1) characterise the DRR practices related to LIK, (2) identify the general patterns of how LIK has been studied in DRR scholarship, and (3) align how the current state of knowledge aligns with the Sendai Framework. This chapter sets the backdrop of the field-based analyses in the succeeding chapters, providing a framework for corroborating theoretical views to practical insights.

Chapter 3 quantifies the structural housing performance of the post-disaster dwellings built by Indigenous households in Itbayat in response to wind and seismic hazards. Structural housing performance was assessed through the derivation of fragility functions which estimate the probability of a structural asset reaching or exceeding a certain damage state under varying hazard intensities. Rapid visual surveys were conducted in January 2023 to identify the prominent housing typologies households chose to build after the 2019 earthquakes. Experts' opinions were then solicited from seven local experts and 11 specialists to estimate housing damage states against wind and seismic hazards, following the method proposed by the Applied Technology Council [48,49]. This chapter provides the structural housing characteristics fundamental to examine the socio-technical factors of housing reconstruction in Chapter 4. Additionally, this chapter generates the data (e.g., housing typologies) needed to analyse disaster losses of housing assets in Chapter 5.

Chapter 4 identifies the socio-technical factors influencing multi-hazard housing reconstruction in Itbayat after the 2019 earthquakes. This was conducted using semi-structured interviews (n = 20 heads of households; n = 10 representatives of local government agencies and organisations) and six focus group discussions among cohorts of local builders of vernacular houses, contemporary construction workers, local government officers, heads of households, and council of elders or the trusted village leaders within the community. Insights from interviews and focus groups were complemented by data obtained through immersion (field notes). Qualitative coding was conducted in NVivo to identify the socio-technical factors based on the interview and focus group discussion transcripts. The identified factors were then visually mapped through the key relationship types framework [50,51] to portray the cohesive network of housing reconstruction triggers and influences. This chapter informs the adoption of the desirability, viability, and feasibility (DVF) framework [52] in Chapter 5 to contextualise housing reconstruction strategies and pathways.

Finally, in Chapter 5, collective safer construction practices on a community level were analysed through scenario-based simulations of direct economic losses of the residential building stock in Itbayat against wind and seismic hazards. Eleven thousand six hundred twenty-eight (11,628) hypothetical scenarios were identified representing the different ratios of housing typologies (identified in Chapter 3) in the community. Using Monte Carlo simulation, the loss estimates for each building stock scenario were then calculated under two cases of paired extreme hazard intensity thresholds. Based on the loss outputs per case, Pareto optimal solutions were then identified, representing those scenarios that simultaneously minimise losses to both wind and seismic impacts. These optimal solutions were further analysed against the DVF framework to account for the socio-technical factors that would determine the practicality of the scenarios.

## 5 Thesis format

This thesis is structured such that each chapter is written as a standalone journal article, while Chapter 1 and Chapter 6 are intended to bookend the whole thesis and bind the collective thought across the chapters. Some minor duplication of text is thus evident across the chapters to re-introduce context and enable each chapter to be independent. Additional supporting materials are provided as appendices. Appendix A contains the experts' solicitation form used to derive the fragility functions in Chapter 3. Appendix B provides the interview and focus group discussion guides used in Chapter 4. Lastly, Appendix C contains the procedures of construction cost estimates and the complete Pareto optimal results of the loss simulation conducted in Chapter 5.

## 6 References

[1] C. Wamsler, Å. Johannessen, Meeting at the crossroads? Developing national strategies for disaster risk reduction and resilience: Relevance, scope for, and challenges to, integration, International Journal of Disaster Risk Reduction 45 (2020) 101452. https://doi.org/10.1016/j.ijdrr.2019.101452.

[2] CRED, UNDRR, The human cost of disasters: an overview of the last 20 years (2000-2019), 2020.

[3] S. De Angeli, B.D. Malamud, L. Rossi, F.E. Taylor, E. Trasforini, R. Rudari, A multi-hazard framework for spatial-temporal impact analysis, International Journal of Disaster Risk Reduction 73 (2022) 102829. https://doi.org/10.1016/j.ijdrr.2022.102829.

[4] A. Tilloy, B.D. Malamud, H. Winter, A. Joly-Laugel, A review of quantification methodologies for multi-hazard interrelationships, Earth-Science Reviews 196 (2019) 102881. https://doi.org/10.1016/j.earscirev.2019.102881.

[5] B. Liu, Y.L. Siu, G. Mitchell, Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment, Nat. Hazards Earth Syst. Sci. 16 (2016) 629–642. https://doi.org/10.5194/nhess-16-629-2016.

[6] J.C. Gill, B.D. Malamud, Reviewing and visualizing the interactions of natural hazards: Interactions of Natural Hazards, Rev. Geophys. 52 (2014) 680–722. https://doi.org/10.1002/2013RG000445.

[7] P.J. Ward, J. Daniell, M. Duncan, A. Dunne, C. Hananel, S. Hochrainer-Stigler, A. Tijssen, S. Torresan, R. Ciurean, J.C. Gill, J. Sillmann, A. Couasnon, E. Koks, N. Padrón-Fumero, S. Tatman, M. Tronstad Lund, A. Adesiyun, J.C.J.H. Aerts, A. Alabaster, B. Bulder, C. Campillo Torres, A. Critto, R. Hernández-Martín, M. Machado, J. Mysiak, R. Orth, I. Palomino Antolín, E.-C. Petrescu, M. Reichstein, T. Tiggeloven, A.F. Van Loon, H. Vuong Pham, M.C. De Ruiter, Invited perspectives: A research agenda towards disaster risk management pathways in multi-(hazard-)risk assessment, Nat. Hazards Earth Syst. Sci. 22 (2022) 1487–1497. https://doi.org/10.5194/nhess-22-1487-2022.

[8] R. Lee, C.J. White, M.S.G. Adnan, J. Douglas, M.D. Mahecha, F.E. O'Loughlin, E. Patelli, A.M. Ramos, M.J. Roberts, O. Martius, E. Tubaldi, B. Van Den Hurk, P.J. Ward, J. Zscheischler, Reclassifying historical disasters: From single to multi-hazards, Science of The Total Environment 912 (2024) 169120. https://doi.org/10.1016/j.scitotenv.2023.169120.

[9] G.P. Cuaton, Y. Su, Local-indigenous knowledge on disaster risk reduction: Insights from the Mamanwa indigenous peoples in Basey, Samar after Typhoon Haiyan in the Philippines, International Journal of Disaster Risk Reduction 48 (2020). https://doi.org/10.1016/j.ijdrr.2020.101596.

[10] A. Agrawal, Dismantling the Divide Between Indigenous and Scientific Knowledge, Development and Change 26 (1995) 413–439. https://doi.org/10.1111/j.1467-7660.1995.tb00560.x.

[11] M.B. Khalil, B.C. Jacobs, N. Kuruppu, Grassroots Technologies and Community Trust in Climate Change Adaptation: Learning from Coastal Settlements of Bangladesh, 2016. https://doi.org/10.1007/978-3-319-25814-0_21.

[12] IPCC, Annex I: Glossary. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, 2019.

[13] J. Mercer, I. Kelman, L. Taranis, S. Suchet-Pearson, Framework for integrating indigenous and scientific knowledge for disaster risk reduction, Disasters 34 (2010) 214–239. https://doi.org/10.1111/j.1467-7717.2009.01126.x.

[14] UNESCO, Local and Indigenous Knowledge Systems (LINKS), UNESCO (2018). https://en.unesco.org/links (accessed July 14, 2021).

[15] R. Šakić Trogrlić, M. Duncan, G. Wright, M. van den Homberg, A. Adeloye, F. Mwale, C. McQuistan, External stakeholders' attitudes towards and engagement with local knowledge in disaster risk reduction: are we only paying lip service?, International Journal of Disaster Risk Reduction 58 (2021). https://doi.org/10.1016/j.ijdrr.2021.102196.

[16] S.J. Lambert, J.C. Scott, International disaster risk reduction strategies and indigenous peoples, International Indigenous Policy Journal 10 (2019). https://doi.org/10.18584/iipj.2019.10.2.2.

[17] M. Mawere, Indigenous knowledge for disaster risk management in Africa: Some showcases from Zimbabwe, in: Between Rhetoric and Reality: The State and Use of Indigenous Knowledge in Post-Colonial Africa, 2015: pp. 19–38. https://muse.jhu.edu/book/40075.

[18] R. Howitt, O. Havnen, S. Veland, Natural and Unnatural Disasters: Responding with Respect for Indigenous Rights and Knowledges, Geographical Research 50 (2012) 47–59. https://doi.org/10.1111/j.1745-5871.2011.00709.x.

[19] K.M. Allen, Community-based disaster preparedness and climate adaptation: Local capacity-building in the Philippines, Disasters 30 (2006) 81–101. https://doi.org/10.1111/j.1467-9523.2006.00308.x.

[20] B.R. Cook, Disaster management culture in bangladesh: The enrolment of local knowledge by decision makers, in: Cultures and Disasters: Understanding Cultural Framings in Disaster Risk Reduction, 2015: pp. 193–207. https://doi.org/10.4324/9781315797809.

[21] IDNDR, Yokohama Strategy and Plan of Action for a Safer World, 1994.

[22] UNISDR, Hyogo Framework for Arction 2005 - 2015, 2005.

[23] UNISDR, Sendai Framework for Disaster Risk Reduction 2015 - 2030, 2015.

[24] UNDRR, Words into Action guidelines: Using traditional and indigenous knowledges for disaster risk reduction, UNDRR, 2022.

[25] A. Charleson, A. Nonoguchi, A. Maeshima, C. Villacis, C. Minowa, G. Zamani, H. Imai, K. Okazaki, K. Yamaguchi, R. Shaw, S. Fukushima, S. Kita, S. Saito, S. Matsuzaki, S. Ando, S. Yasukawa, T. Narafu, T. Yokoi, T. Hanazato, Y. Ishiyama, Towards resilient non-engineered construction: guide for risk-informed policy-making, United Nations Educational, Scientific, and Cultural Organisation, 2016.

[26] I. Ahmed, An overview of post-disaster permanent housing reconstruction in developing countries, International Journal of Disaster Resilience in the Built Environment 2 (2011) 148–164. https://doi.org/10.1108/17595901111149141.

[27] ShelterBox, Climate crisis to destroy 167 million homes in next 20 years, ReliefWeb (2021). https://reliefweb.int/report/world/climate-crisis-destroy-167-million-homes-next-20-years (accessed December 3, 2024).

[28] J. Twigg, E. Lovell, H. Schofield, L.M. Morel, B. Flinn, S. Sargeant, T. Dijkstra, V. Stephenson, A. Albuerne, T. Rossetto, D. D'Ayala, Self-recovery from disasters: An interdisciplinary perspective, Overseas Development Institute, 2017.

[29] L. Harriss, C. Parrack, Z. Jordan, Building safety in humanitarian programmes that support post-disaster shelter self-recovery: an evidence review, Disasters 44 (2020) 307–335. https://doi.org/10.1111/disa.12397.

[30] J. Twigg, The evolution of shelter "self-recovery": adapting thinking and practice for post-disaster resilience, JBA 9s8 (2021) 5–22. https://doi.org/10.5871/jba/009s8.005.

[31] B. Flinn, Defining 'Better' Better: Why Building Back Better Means More than Structural Safety, Journal of Humanitarian Affairs 2 (2020) 35–43. https://doi.org/10.7227/JHA.032.

[32] C. Parrack, B. Flinn, M. Passey, Getting the Message Across for Safer Self-Recovery in Post-Disaster Shelter, OHI 39 (2014) 47–58. https://doi.org/10.1108/OHI-03-2014-B0006.

[33] M.C. de Ruiter, J.A. de Bruijn, J. Englhardt, J.E. Daniell, H. de Moel, P.J. Ward, The Asynergies of Structural Disaster Risk Reduction Measures: Comparing Floods and Earthquakes, Earth's Future 9 (2021). https://doi.org/10.1029/2020EF001531.

[34] Y. Li, A. Ahuja, J.E. Padgett, Review of Methods to Assess, Design for, and Mitigate Multiple Hazards, J. Perform. Constr. Facil. 26 (2012) 104–117. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000279.

[35] Bündnis Entwicklung Hilft / IFHV, WorldRiskReport 2024, Bündnis Entwicklung Hilft, Berlin, 2024.

[36] Bündnis Entwicklung Hilft / IFHV, WorldRiskReport 2023, Bündnis Entwicklung Hilft, Berlin, 2023.

[37] GFDRR, Country Profile: Philippines, (2016). https://www.gfdrr.org/sites/default/files/publication/PHILIPPINES2016.pdf (accessed August 7, 2022).

[38] International Work Group for Indigenous Affairs, The Indigenous World 2023: Philippines, (2023). https://www.iwgia.org/en/philippines/5132-iw-2023-philippines.html (accessed October 21, 2024).

[39] Congress of the Philippines, An Act to Recognize, Protect and Promote the Rights of Indigenous Cultural Communities/Indigenous Peoples, Creating a National Commission on Indigenous Peoples, Establishing Implementing Mechanisms, Appropriating Funds Therefor, and for Other Purposes, 1997.

[40] Congress of the Philippines, Philippine Disaster Risk Reduction and Management Act of 2010, 2010.

[41] Britannica, T. Editors of Encyclopaedia, Batan Islands, Encyclopedia Britannica (2024). https://www.britannica.com/place/Batan-Islands (accessed October 22, 2024).

[42] Philippine Institute of Volcanology and Seismology, Philippine Earthquake Model, 2017.

[43] R. Paciente, Tropical Cyclone Passage Report, Typhoon Committee, 2016. https://typhooncommittee.org/docs/Passage%20Reports/2016/1614-MERANTE-Philippines.pdf (accessed July 12, 2023).

[44] International Federation of Red Cross and Red Crescent Societies, Philippines: Batanes Earthquake, 2020.

[45] J. Perez, K. Vitto, P. Sawi, J. Blacer, R. Tiglao, M. Pagtalunan, J.R. Danganan, A. Garil, Impacts of the 27 July 2019 Magnitudes (Mw) 5.4, 5.9, and 5.8 Itbayat, Batanes Earthquakes, Department of Science and Technology - Philippine Institute of Volcanology and Seismology, 2019.

[46] F. Hornedo, Traditional Ivatan Shelter and Architecture, Part Two, The Classic Traditional Ivatan House: Emergence and Prospects, Ivatan Studies Journal XIII–XIV (2015) 39–112.

[47] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, R. Chou, J. Glanville, J.M. Grimshaw,

A. Hróbjartsson, M.M. Lalu, T. Li, E.W. Loder, E. Mayo-Wilson, S. McDonald, L.A. McGuinness, L.A. Stewart, J. Thomas, A.C. Tricco, V.A. Welch, P. Whiting, D. Moher, The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ (2021) n71. https://doi.org/10.1136/bmj.n71.

[48] K. Porter, R. Kennedy, R. Bachman, Creating Fragility Functions for Performance-Based Earthquake Engineering, Earthquake Spectra 23 (2007) 471–489. https://doi.org/10.1193/1.2720892.

[49] P.K. Porter, R. Kennedy, R. Bachman, Developing Fragility Functions for Building Components for ATC-58, Applied Technology Council, Redwood City, CA, 2006.

[50] L.M. Tutty, M.A. Rothery, R.M. Grinnell, Qualitative research for social workers, Allyn and Bacon, Boston, 1996.

[51] M. Rabinovich, L. Kacen, Advanced relationships between categories analysis as a qualitative research tool, J Clin Psychol 66 (2010) 698–708. https://doi.org/10.1002/jclp.20693.

[52] D. Bland, A. Osterwalder, Testing Business Ideas, John Wiley & Sons, Inc., Hoboken, NJ USA, 2020.

# Chapter 2

# Where does local and indigenous knowledge in disaster risk reduction go from here? A systematic literature review

## Abstract

The embeddedness of local and indigenous communities in their environments has led them to develop time-tested knowledge and practices to prepare for, mitigate, respond to, and recover from the impacts of natural hazards. Collectively, these are referred to as local and indigenous knowledge (LIK) and have gained a niche in disaster risk reduction (DRR) scholarship. We conducted a systematic literature review, identifying 325 articles that were qualitatively coded to identify what practices constitute LIK, patterns in how it has been studied, and how current understanding of LIK fits to the Sendai Framework. We found a plethora of strategies that communities mobilise, from hazard forecasts to livelihood-based adaptation, with the study of these concentrated in middle- and high-income countries. Efforts to integrate knowledge (LIK and scientific) and power spheres (top-down and bottom-up) are increasingly prominent themes in disaster scholarship. There is a recognition of LIK in the Sendai Framework priority areas, although still embryonic, which we link to the existing body of knowledge in literature. Our synthesis pieces together a holistic understanding of LIK to offer a more concrete appreciation of what LIK is and how it can be further relevant for DRR efforts.

## 1 Introduction

The World Meteorological Organisation (WMO) [1] reports a five-fold increase in the number of disasters in the past fifty years. Meanwhile, the International Federation of Red Cross and Red Crescent Societies (IFRC) [2] states there was a 35% surge of disasters since 1990s alongside an increase in their intensities. This trend has seen an accompanying rise in scholarship in disaster studies [3]. In most instances, the scholarship has been shrouded by contested and conflicting ideologies on which knowledge system best fits for risk reduction. Consequently, a growing number of scholars have since advanced the idea that local communities' embeddedness in their environments has led them to develop time-tested knowledge, coping practices, and adaptation strategies to prepare for, mitigate, respond to, and recover from the impacts of disasters [4–9]. The strategies and practices developed and used by communities to reduce disaster risks form the basis of cultural adaptation [10], giving rise to what scholars call as "culture of disaster" [11,12] or "disaster subculture" [13,14]. Communities gain and develop these strategies and practices as they are considered the "zero-order responders" in dealing with the frequent disruptions of hazards affecting them [15]. In the existing literature on disaster risk reduction (DRR), such strategies and practices emerge as products of what is conjunctively referred to as local and indigenous knowledge (LIK).

When taken independently, the term "local knowledge" is derived from a community's place-based relationship with the local environment while "indigenous knowledge" is gained from long-term cultural ties or traditional ownership of a place [16,17]. Similarly, the Intergovernmental Panel on Climate Change (IPCC) [18] characterises the former to be the understandings and skills specific to where people live, while the latter is developed out of longstanding interaction with the natural environment. Distinctions between the two exist in literature. However, in reality, blurred lines emerge in demarcating what is local or indigenous since communities often use varied sources of knowledge concurrently [19,20].

The importance of LIK in the general developmental sense has been emphasised as early as the 1970s [10]. In the aftermath of the 2004 Indian Ocean earthquake and tsunami, the relevance of LIK to DRR was put into the limelight when the coping strategies of indigenous communities were widely publicised [21]. The oral story of the Simeulue people reminded how inherited knowledge can serve as an early warning system to save lives [22,23]. Literature on LIK has since gained a niche in disaster scholarship with broader implications on the field. A myriad of different terms has emerged from the way scholars have attributed harnessing local capacities such as "community-based", "participatory", "multi-stakeholder", "grassroots-level", "people-centred", among others. In the Sendai Framework for Disaster Risk Reduction, the current global framework guiding efforts to reduce disaster risk, LIK is acknowledged as an essential complement to scientific knowledge in the assessment of disaster risks and the development and implementation of policies and programmes [24].

The existing scholarship on LIK in disaster studies is extensive. However, the DRR body of knowledge on LIK is primarily constructed from case studies. To date, there has been limited effort to synthesise what we understand about LIK more collectively. There have been some studies that have reviewed LIK in specific DRR contexts. These include the adaptation of indigenous Taiwanese communities to climate shocks [25], the integration of indigenous and scientific knowledge for flood risk reduction [26], the development of local knowledge for disaster preparedness [27], the inclusion of communities in early warning systems [28,29], and the state of integrated, multi-scale disaster research [30]. These reviews deal with LIK in specific parameters, but a more holistic synthesis of LIK in DRR in the broadest sense – unrestrictive of affinity to a country, hazard, disaster phase, or timeline – is missing. How then does LIK stand more holistically especially within the disaster discourse that is still being polarised by the dichotomy of what knowledge system best fits for DRR? This systematic review is conceptualised as a “reflective pause” to assess the landscape and current state of LIK in DRR literature.

While a systematic literature review can serve a critical role in providing synthesis to identify research priorities and gaps [31], we further posit that such synthesis gains relevance if analysed against a backdrop of policy frameworks. Hence, by reviewing LIK in DRR, we endeavour not just to provide the current state of knowledge but also to give guidance to both scholars and policymakers to progress the Sendai Framework, of which the use of LIK is part of its advocacy [24]. We draw on three research questions (RQs) as the bases for this review:

(RQ1) What forms of LIK appear in disaster literature?
(RQ2) How has the research focus of LIK in disaster scholarship evolved over time?
(RQ3) What are the priorities of the Sendai Framework (not) being captured in the current understanding of LIK in the DRR body of knowledge?

In the following sections, we first provide a theoretical orientation of LIK in DRR. We then present our methods, including the review search strategy, document selection and screening, and coding process and thematic analysis. Our findings are presented in three sub-sections aligned with the research questions that focus on the identification and classification of LIK in the current body of knowledge, research themes on how LIK has been studied over time, and how these themes fit to the Sendai Framework. Finally, we discuss implications for future research and emerging gaps.

# 2 Theoretical Orientation

LIK has sometimes been interchangeably referred to as “traditional ecological knowledge,” “indigenous technical knowledge,” and “endogenous knowledge” [21] apart from other associated terms such as “ethnic,” “folk”, and “vernacular”. The breadth of literature on this topic has resulted in diverging characterisations among scholars. While, on the one hand, the divergence may imply a comprehensive understanding, on the other, it signals continued contestation. For example, Matti & Ögmundardóttir [32] use “local knowledge” over “indigenous” or “traditional” since the former is restrictive to non-indigenous local knowledge, while the latter has static connotations implying that such form of knowledge is not evolving. Meanwhile, Mercer et al. [33] assemble several literatures to define indigenous knowledge as “a body of knowledge existing within or acquired by local people over a period of time through the accumulation of experiences, society-nature relationships, community practices and institutions, and by passing it down through generations” (p. 217). Similarly, Cuaton & Su [7] aggregated local and indigenous knowledge as “a body of different types of knowledge and practices of societies accumulated through a continuous interaction with their natural surroundings” (p. 2). The characterisation that is gaining wider acceptance from scholars is perhaps best stated by UNESCO [34] which defines LIK as “the understandings, skills, and philosophies developed by societies with long histories of interaction with their natural surroundings”.

The burgeoning permutations of how LIK is characterised in disaster studies merit a simple but encompassing definition to be inclusively representative of the different ideas and connotations across the breadth of literature. Therefore, insofar as this study is concerned, LIK is collectively referred to as the developed understandings (perceptions, beliefs, philosophies) and self-help measures (inherent skills, local ways of doing things, traditional practices) used by communities to prepare for, mitigate, respond to, and recover from the impacts of natural hazards. This definition is in line with Dekens’ [27] people-centred characterisation that focuses on “what the residents know about natural hazard risks and what they believe and do about them in a given situation” (p. 5). By borrowing the term “self-help measures” from Plate [35], it is implied herein that knowledge manifests when communities use their efforts and resources on the ground with little to no reliance from others. Such knowledge can be developed over many generations and handed down, dynamic due to the influences within and outside a community [27], or used concurrently with other complementary forms of knowledge in the community [19,20] ascribing to a trend called “cognitive polyphasia” [36]. While Agrawal [16], Gaillard [37], and Griffin & Barney [19] caution adhering to a LIK and scientific knowledge dichotomy, we distinguish the two for clarity and operationalisation. LIK is acquired experientially, grounded in the sociocultural context of the need to address issues of everyday living [26]. It arises from context-specific and outcomes-based understanding of the natural realities [38]. On the other hand, scientific knowledge is developed through a formal evidence-based technical systematisation of information to carefully provide explanations of phenomena [39]. We further operationalise “community” to mean being a part of any urban, rural, culturally and socially distinct (e.g., indigenous, tribal, ethnic), homogenous, or heterogeneous groups where LIK emanates. Such characterisation broadly encompasses the diverse contexts and complexities of how community can be defined in the developmental and DRR-related work [40]. Regardless of community structures, residents do have the understandings and self-help measures at their disposal in the face of hazards.

Across past and current global DRR frameworks, the recognition of LIK which forms part of community capacity for risk reduction has mostly been juxtaposed with scientific knowledge. In the Yokohama Strategy and Plan for Action in 1994, traditional methods of reducing disaster impacts were recognised to be “supplemented” and “reinforced” with scientific knowledge [41]. In the Hyogo Framework for Action in 2005, incorporation of LIK was supported to provide understandable risk information, albeit alongside more generous emphasis to strengthen scientific and technical DRR capacity [42]. Such adjunct representations of LIK have been carried over in the Sendai Framework, where LIK is presented to “complement” scientific knowledge in risk assessments and policy developments [24]. Across the development of these three global frameworks, Tozier de la Poterie & Baudoin [43] draw attention to how communities went from being regarded as valued partners to aid recipients alongside a significant shift to support technological solutions for DRR.

The need to holistically review the literature on LIK stems from the phenomenon that a science-based stance still dominates the disaster discourse. Reasons include the persistent technocratic bias in disaster management and the dominant influence of scientific thinking in scholarship which favours more technical and formal means towards DRR. Generally, a paradox exists because LIK remains underutilised in the actual practice of DRR, yet it is widely praised in academic literature and policy environment [44]. One potential barrier for its underutilisation could be that we have fragmented thinking of LIK, which is reflected by the contested and inconsistent terminologies that surface in literature. But the fragmentation goes beyond naming conventions, as ideally, there should be a unified understanding of what constitutes the characteristics of LIK, but still none exists despite the breadth of literature. With the sustained academic and policy attention of LIK in DRR, how can we translate diverging understandings to an integrated and more collective view of what we know about LIK from past studies? We conducted this systematic review to piece together knowledge about LIK to establish a more holistic perspective to assist scholars, practitioners, and policymakers appreciate what LIK is and how it can be (further) relevant for DRR efforts.

## 3 Methods

This study aimed to identify what forms of LIK appear in DRR literature (RQ1), themes in the longitudinal evolution of LIK (RQ2), and to what extent current and past foci fit to the Sendai Framework (RQ3). The following sub-sections present the search strategy, document selection and screening, and the coding process and thematic analysis. We followed recommended best practices for systematic literature reviews [45,46] to enhance the rigour in synthesising the extensive body of knowledge on LIK. A visual summary of the document selection and screening process is presented in Figure 2.1 following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram. PRISMA is a reporting guideline for systematic reviews instigating transparency in the identification, selection, appraisal, and synthesis of studies [31].

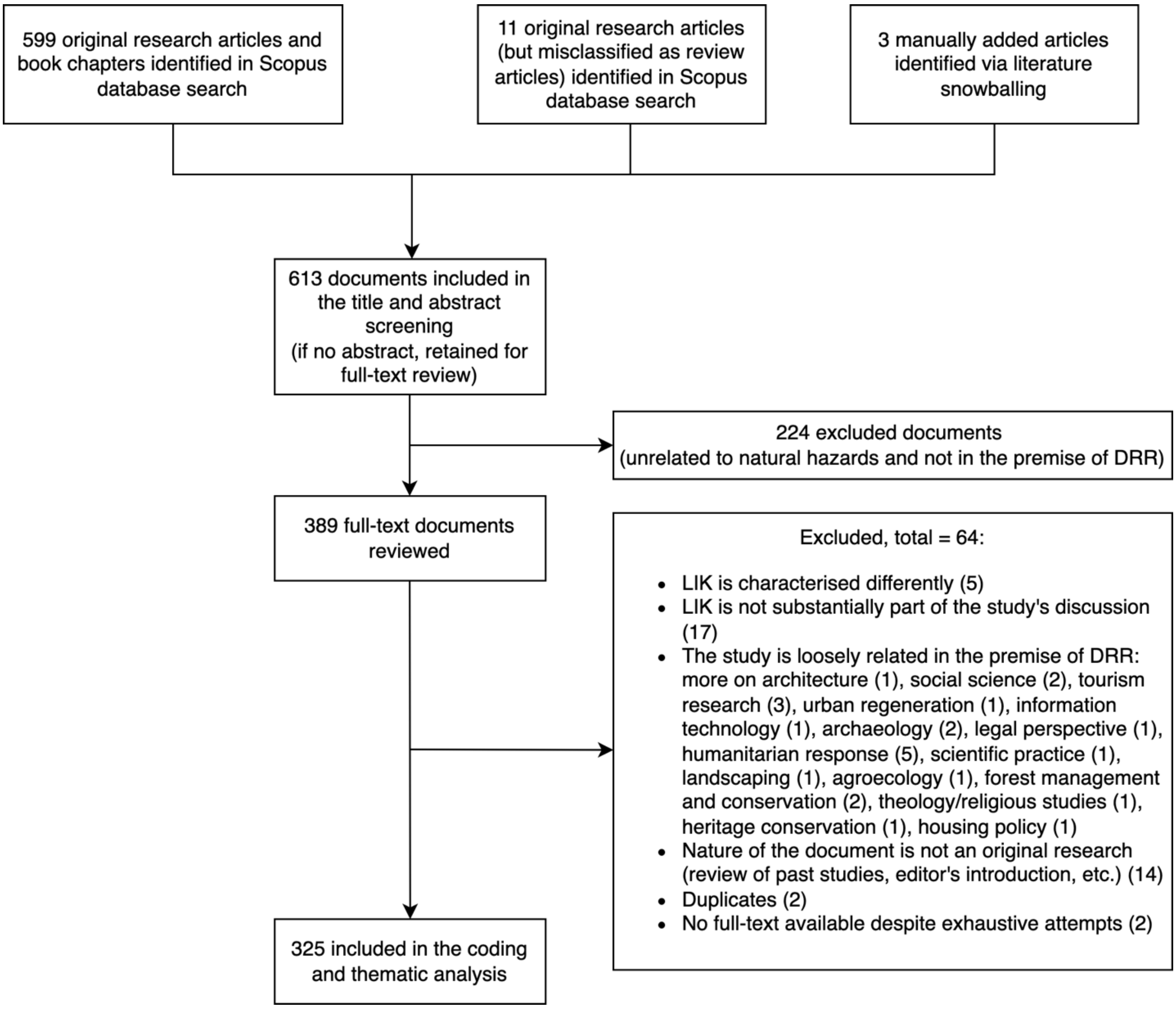


**Figure 2.1.** Document selection and exclusion PRISMA diagram

### *3.1 Search strategy*

Our search was bounded to the Scopus database to identify documents included in the systematic literature review. Scopus is one of the largest abstract and citation databases for peer-reviewed literature. As a point of comparison, it indexes 66% more unique journals than Web of Science [47]. Additionally, Scopus is preferred since it has extensive quality assurance processes in indexing data elements monitored by an independent Content Selection and Advisory Board [48]. An initial keyword search was conducted to determine the coverage and relevance when using the combination of the following principal words: “local,” “indigenous,” “knowledge,” and “disaster”. The resulting items were then used to inform the final advanced document search. On top of the initial keywords used, additional search operators were utilised, including Boolean (“OR”, “AND”), proximity (“W/*n*”), and wildcard (“*”). The final combination of words and operators (“search string”) was as follows:

**TITLE-ABS-KEY ((local* OR indigenous OR traditional W/5 knowledge) AND disaster*)**

The search string implies that any of the words “local” (including any other variations such as “locals’,” “locally-known,” etc. as denoted by the asterisk), “indigenous,” or “traditional” should be within a distance of five words from “knowledge”. The word “traditional” was included as this was found to be used synonymously in many articles in the initial search. The proximity operator of a distance of five words reasonably narrowed the search's intended focus. It was also a conservative and inclusive assumption that allowed to capture phrases such as “…locals’ or the community’s knowledge…”. Additionally, “disaster” was used to confine the focus of LIK to disasters. If the word combinations matched with any of the texts from a document’s title, abstract, or keywords (“TITLE-ABS-KEY”), then such document was included.

The search string yielded 599 document results on 5 August 2021 inclusive of original research articles and book chapters in the English language. Conference papers and review articles were excluded since the former often represent works in progress for most fields of relevance, while review articles would have created redundancy in the reporting of themes. An additional eleven (11) documents were included in the pool of items screened, which Scopus misclassified as review articles. We also manually added three (3) articles of relevance [13,22,49] identified via literature snowballing. Also known as backward search, this technique includes relevant works cited in the articles being reviewed but were not captured by the search string. Overall, 613 documents were included in the title and abstract screening.

### *3.2 Document selection and screening*

To be included in the next round of review (full-text review), the following criteria were used to filter the documents: (i) the context of “disaster” must have been related to natural hazards (e.g., meteorological, geophysical) or environmental threats such as climate change (e.g., sea-level rise, drought); and, (ii) LIK should have been in the premise of DRR (mitigation, preparedness, response, and recovery and rehabilitation). As such, studies dealing with disasters in the context of biological hazards (disease outbreaks), chemical (oil spill, contaminations), technological (nuclear), societal (civil unrest, armed conflicts, fire due to arson), or those that explored LIK in the context of traditional medicine, forest management, and other topics not explicitly related to disasters were excluded. By default, if a document did not have an abstract, it was automatically carried over for full-text review. A total of 389 documents qualified and were included in the full-text review, of which 13 items did not have abstracts.

Each document was thoroughly reviewed before coding for themes. A total of 64 documents were removed at this stage for the following reasons: (i) LIK was characterised differently, e.g., local expertise of formal disaster actors rather than that of communities' (*n* = 5); (ii) LIK was not substantially part of the study's discussion (*n* = 17); (iii) the general premise of the study was loosely related to DRR (*n* = 24); (iv) the nature of the document was not original research but more closely a review of past studies (*n* = 14); (v) duplicate articles (*n* = 2); and, (vi) no full text available despite exhaustive attempts (*n* = 2). The remaining 325 documents were systematically coded using thematic analysis.

### *3.3 Coding process and thematic analysis*

Coding is the derivation of a summative thought from words, phrases, or sentences ("codes") which represent the meaning of a portion of a data [50]. In this study, the process was facilitated using NVivo 12 software, and preference was given to ideas developed in the findings, discussion, and conclusions that form part of the core arguments of the documents. Prior to coding, the documents reviewed were classified either as fieldwork- or non-fieldwork-based studies. We considered a study to be fieldwork-based if it deliberately articulated any form of interaction with communities in gathering data, therefore we made it the basis for eliciting LIK as practised on the ground (see RQ1). Otherwise, documents were classified as non-fieldwork if there was no interaction with communities in the primary data collection (e.g., comments, desk research, and theoretical frameworks). Thematic analysis was then employed across all the codes (regardless if from fieldwork- or non-fieldwork-based studies) to identify the patterns of meaning – herein more formally referred to as *themes.*

Thematic analysis groups the derived codes to represent bigger picture ideas. We followed the six-step process for theme identification pioneered by Braun & Clarke [51] which can be summarised to include data familiarisation, data coding, and theme development and revision.

While often used in qualitative research, there have been doubts about how scholars have adopted thematic analysis rigorously and methodically in their research methods [52,53]. In this light, we have also considered the protocols suggested by Nowell et al. [53] and Castleberry & Nolen [52]. Some of these protocols include aligning the data collection methods with the research questions, as well as peer debriefing to crosscheck the analysis with a co-researcher who knows a substantive area of the inquiry.

A hybrid of deductive and inductive approaches was used to identify themes. The former develops themes under existing or preconceived concepts and ideas, while the latter is directed by the content of the data to generate common themes [51]. The inductive approach was applicable in answering RQ1 and RQ2 since one of the objectives was to understand emergent themes that have surfaced in literature. On the other hand, the deductive approach was applicable in answering RQ3 since we wanted to analyse how the identified themes in literature fit within the four priority areas of the Sendai Framework. During the theme development, multiple themes could be extracted from a single document. Hence, there is no implied congruence regarding the frequency of themes to the number of documents reviewed.

## 4 Findings and Discussions

To advance the recognition of LIK in DRR, we first present a synthesis of how scholarship has, to date, characterised LIK in fieldwork-based studies. We found seven forms attributed to how LIK is used in DRR, from hazard forecasts to livelihood-based adaptation (RQ1) (see Section 4.1). We then present the six identified themes derived from all the documents reviewed from both fieldwork- and non-fieldwork-based studies (see Section 4.2). Emergent themes such as exploring the nexus of LIK and scientific knowledge link to the research foci of how this research agenda has been studied in scholarship (RQ2). Lastly, these themes are then analysed to the Sendai Framework to understand what priority areas are (not) captured in the current understanding of LIK in the DRR body of knowledge (RQ 3) (see Section 4.3).

### *4.1 LIK on the ground: Encounters from fieldwork-based studies*

Communities mobilise a plethora of LIK which highlights their ingenuity to come up with self-help measures to protect themselves and their assets in the face of hazards. While the literature gains an appreciation of natural hazards and their impacts and often highlights LIK in a positive light, we also found that in some instances, this knowledge emerges to counteract the absence of institutional support. However, the greater picture remains obscure since, based on the documents reviewed, low-income countries receive a meagre 5% share of fieldwork-based studies compared to middle- and high-income countries which receive 73.5% and 21.5%, respectively (see Figure 2.2). The same trend also exists with non-fieldwork-based studies: 1.6% in low-income countries, 50.8% in middle-income countries, and 47.5% in high-income countries (see Figure 2.3). This geographical skewness can mirror the publishing bias in academia to disproportionately give less attention to data-scarce communities. One potential reason of this skewness may also be that some countries (or group of countries) receive more attention due to their higher hazard exposure. Clearly, however, there remain challenges in the practice and policy environments of DRR to gain balanced and more diversified representations about grassroot capacities of low-income countries to manage risk reduction efforts.

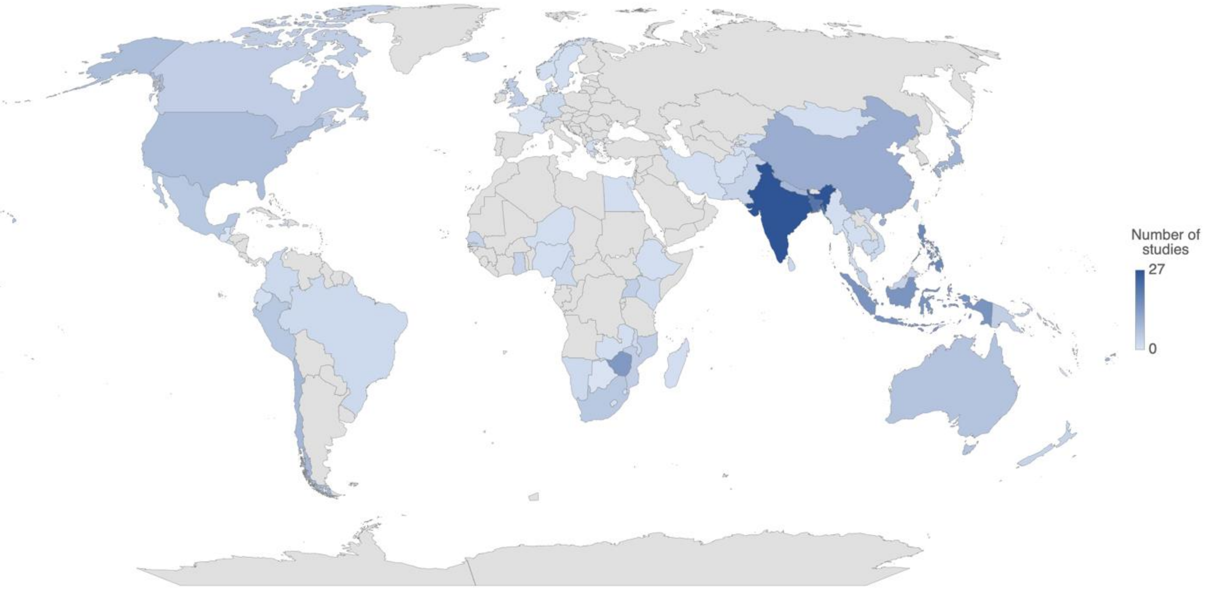


**Figure 2.2**. Geographical distribution of fieldwork-based studies. (Note: Some studies are conducted in more than one fieldwork location.)

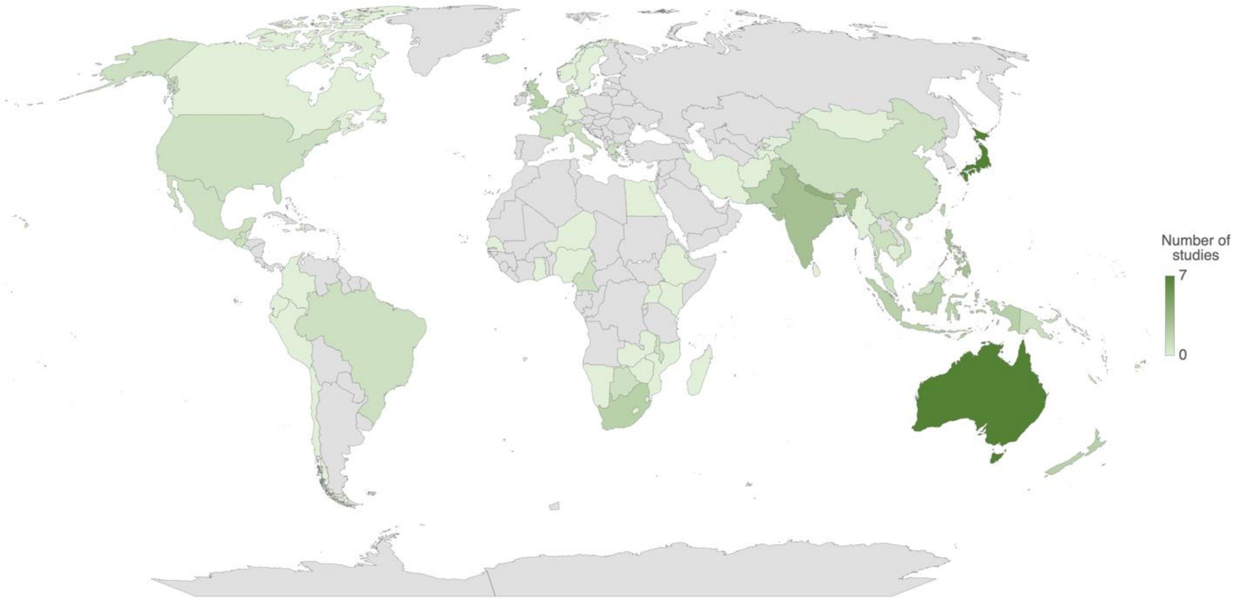


**Figure 2.3.** Geographical distribution of non-fieldwork-based studies. (Note: Country associations with non-fieldwork studies are based on the location a study focuses (e.g., a study discussing the state of LIK in Australia is counted for Australia). Some studies are associated with more than one location, while others do not represent specific locations.)

In the following sub-sections, we discuss characteristics of LIK extracted from fieldwork-based studies. Early warning systems and risk knowledge and perception influence the precautionary and adaptation strategies that communities use in response to hazards, and these are shaped by belief systems and community dynamics, such as social cohesion (see Figure 2.4). We move away from presenting the use of LIK in the typical disaster cycle paradigm as we acknowledge that these practices do not occur very linear or cyclical ([see 54]), but instead, there are overlaps and overarching instances when these are used when disasters unfold. Hence, we are not limiting *when* LIK occurs against a predefined disaster phase as there is a continuum of ways communities use their knowledge and practices for disaster response.

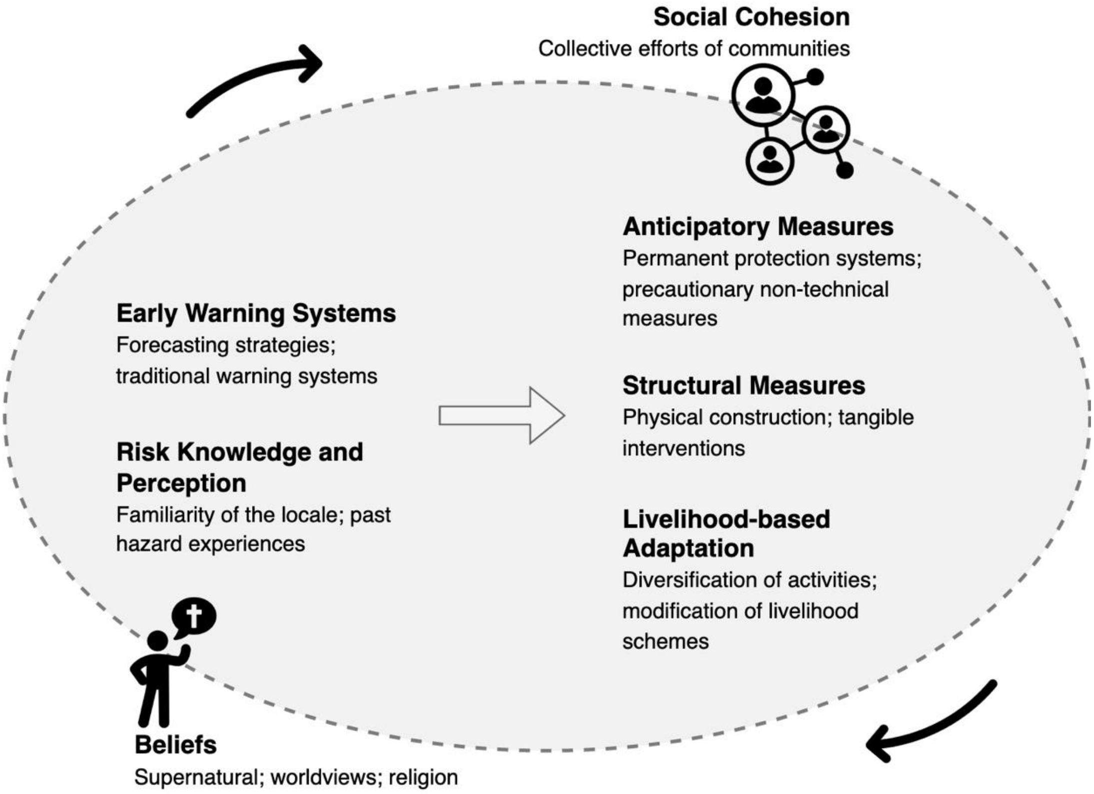


**Figure 2.4.** The interconnectedness of the different forms of LIK as derived from the synthesis of fieldwork-based studies

#### *4.1.1 Early warning systems*

Early warning systems which include, but are not limited to, alarms, news, and warning signs, provide information for populations exposed to hazards for them to be receptive, be prepared, and consequently take action [55]. It is the continuous interactions between communities and their surroundings that enable them to identify signs and signals from nature that can indicate impending hazards. Some scholars, however, note that these environmental cues are becoming less reliable due to climate variability [4,9,56–58] and environmental degradation [9,59]. Regardless, communities still hold and use these practices, and they will continue to do so as long as these practices aid in reducing risk.

Forecasting, the first stage in more general warning processes [35], is common among local and indigenous communities. Flooding forecasts in Cambodia [58] and Malawi [9], for example, are based on the direct observation of clarity, speed, and sound of water. In Sri Lanka, predicting landslides is based on the assessment of unusual earth cracks and understanding the impact of heavy rainfall on the water table [8]. Meanwhile, drought forecasts in Lesotho and Eswatini are based on the changing rainfall patterns and strong winds blowing in particular directions [60]. A myriad of examples exists in literature regarding the flora- and fauna-based forecasting strategies that depend on the phenology of plants and the behaviour of animals to foretell both general weather conditions and occurrence of hazards. Some examples include: whales swimming in particular directions to signal approaching storms in India [61]; an abundance of sea urchins and starfish along shorelines to foreshadow impending typhoons in the Philippines [62]; and, night-flowering jasmine to predict the onset of heavy rainfall in India [63]. To relay forecasts, some communities also use local technologies to disseminate information or trigger alarms, such as using bamboo slit drums and mosque loudspeakers in Indonesia [64] and community drums and indigenous loudspeakers in Afghanistan [65].

Apart from the wealth of examples on forecasting strategies that we found in literature, we also saw an uptick in attention highlighting how communities informally integrate traditional forecasts with more technical sources of hazard information such as from televised meteorological forecasts. For example, Balay-As et al. [4] noticed how radio forecasts serve as confirmation when traditional signs of dark-coloured sky hint an approaching rain as observed from an indigenous group in the northern Philippines. The hybridisation of different knowledge sources (see Section 4.2.2) happens then as more communities – especially from low- and middle-income communities with heavy reliance on LIK – begin to gain access to technologies. This hybridisation can be positive, helping communities better prepare for disasters by integrating sources of hazard information. Inversely, however, such integration of knowledge systems often still sees a dominant narrative in favour of scientific knowledge. This implicit overshadowing can lead to the eventual disregard of LIK resulting to the overreliance to the technicalities of scientific knowledge.

### *4.1.2 Risk knowledge and perception*

The awareness and judgement of communities to environmental threats are baseline conditions for disaster preparedness. Risk knowledge and perception are developed when communities are embedded in or hold understanding about their environment, as day-to-day encounters teach them what these hazards can bring, why and how they occur, and how to cope with them. We identified two ways how risk knowledge and perception are gained. The first is through familiarity of the locale, while the second mechanism is through accumulation of past hazard experiences.

One’s familiarity with a place provides insights into local conditions and environmental elements, such as in Nepal where villagers are aware that landslides affecting their farmlands occur due to weak geology exacerbated by water table conditions and impact of heavy rainfall [66]. In the typhoon-prone Philippines, the structure of storms is well understood by some communities and they can explain the concept of storm surges without scientific translation [67]. Similarly, in Australia, communities have developed a more intimate understanding of cyclones and these are recalled as sensory experiences with specific elements and characteristics [68]. In a community bushfire mapping activity, also in Australia, communities’ spatial awareness of their environment enabled them to identify areas of increased risk, such as dense bushland as well as routes for safe evacuation [69]. Communities residing around the base of active volcanoes in Indonesia have developed localised terminologies to the hazardous elements brought by phreatic eruptions and this is one of the ways to understand their vulnerabilities [70]. These examples highlight that familiarity of place transcends beyond spatial knowing but also entails an understanding of the elements and conditions that affect a place. In most instances, this understanding of place results in localised views which lead to the development of context-dependent knowledge systems helpful for communities to prepare for disasters.

Past hazard experiences are also sources of risk knowledge and perception among communities. Lessons are absorbed from past events and are applied. The 1977 flood in Mozambique, for example, served as the maximum benchmark providing a flood line defining acceptable risk for communities [71] while in the Philippines, the impacts or severity of past flood events are remembered through anthropometric measurements such as knee, waist, and hip depths [72]. Households’ experiences with landslides in Peru were vital in understanding the hazard’s occurrence and reactivations (dates, magnitudes, and damages) which were used for hazard mapping [73]. There are also increasing efforts to preserve these past experiences and ensure transfer between generations, such as in Japan. In some museums, disaster encounters are conveyed as stories to pass local knowledge for future DRR in line with the *kataribe* tradition of sharing lessons and experiences [74]. Generally, while such past hazard experiences provide historically grounded accounts on what to expect or what can possibly happen, extreme events can sometimes overthrow the relevance of these experiences [75–78].

Such has been demonstrated, for example, during the 2000 floods in Mozambique [71]. The maximum flood level benchmark left by the 1977 flood has been surpassed, leaving communities uncertain of the thresholds of what could now be risky or safe as they anticipate related hydrological events.

### *4.1.3 Anticipatory measures: Mitigation and preparedness*

To reduce risk in the face of hazards, communities take early actions which can either be through permanent protection systems and strategies (“mitigation”) or precautionary non-technical measures (“preparedness”) [35]. Due to their forecasting strategies and prior knowledge of local hazards, communities become receptive and develop safety-seeking anticipatory measures. In Sri Lanka, mitigation measures undertaken for landslides include planting and reserving tree belts near houses, terrace cultivation, and adoption of a land utilisation pattern where the upper areas are retained as forest reserves, the middle portions as housing areas, and the lowest portions as paddy fields [8]. Similarly, in India, land use strategies are in place to prepare for landslides such as: avoiding flood- or landslide-prone locations when building a house; converting hillsides into level terraces (including managing water flows between terraces); stabilising slopes with trees; and managing slow rainwater runoff by creating a network of ponds [79]. To mitigate the impacts of flooding, certain housing adjustments are undertaken by many communities across countries (see Section 4.1.4).

In terms of preparedness measures, communities in the Philippines adopt strategies for impending typhoons and typhoon-induced flooding: securing roofs with ropes and cutting down tall and decaying trees [67]; reinforcing wooden or thatched houses by tying with wires, nailing down walls and windows, and putting heavy items (sandbags, tyres) on top to protect roofing [72]; and practising a tradition which involves replacing old thatched roofs with newer ones to make sure that these can withstand heavy rains and winds [4]. Food preservation is also a common preparedness strategy to ensure food security in times of disaster. Examples include traditional fermentation of terrestrial and marine food in Tuvalu [80] and keeping food within pots and burying them underground as practised in Bangladesh [81]. All these anticipatory measures attest to the general notion in disaster discourse that communities are indeed not helpless as they can proactively prepare for forthcoming hazards. Hence, communities should not be merely regarded as passive victims and recipients of external aid but active agents for DRR measures [15,72,82].

### *4.1.4 Structural measures*

According to UNDRR [83], “Structural measures are any physical construction to reduce or avoid possible impacts of hazards, or the application of engineering techniques or technology to achieve hazard resistance and resilience in structures or systems”. The most common structural interventions captured from the documents reviewed were those that are adopted by communities in response to flooding. These include raising houses either on piles, stilts, platforms, or plinths [6,79,84,85], on higher grounds [9,86], or elevating room levels through earth-filling [72]. Additionally, still in response to flooding, sandbags are used [87,88], retaining walls around farmlands are constructed [6], and walls and foundations of houses are strengthened using local materials [9].

Other structural measures are embodied in the different seismic-resistant housing construction techniques. One of the best examples is India’s *Dhajji-diwari* style in the Himalayan belt wherein the technique uses stones for lower storeys and a combination of bricks and timber for upper storeys [89]. To prevent landslides in Sri Lanka, locally developed stone walling techniques and the use of Pawatta plant as live fences are employed [8]. In Senegal, agricultural yields are optimised through the invention of micro dams – a hydroagricultural innovation by the communities that can retain water and impede drought for a few weeks [90]. In China, traditional settlements were built to be protected from storms through windbreaks, dense-alley patterns, courtyards, strengthened exterior walls, and local roof technologies [91].

Structural measures are a product of understanding the impact of disasters and identifying the physical remedies to counteract such impact to mitigate risks. As these measures are developed out of locally understood scientific principles in the absence of more formal ways of learning, aptly, these are local technologies that have shaped risk reduction strategies prior to more technical approaches. Similar to the hybridisation of early warning systems discussed in the previous section, the same phenomenon has also been observed for structural measures. Some discussions on LIK now include the integration of local and indigenous building techniques with contemporary strategies. For example, in Pakistan, a post-disaster reconstruction initiative relied on traditional character and form of structures but strengthened them with formal engineering interventions [92].

### *4.1.5 Livelihood-based adaptation*

Disasters threaten not only the safety of communities but also their livelihoods. Scholarship on LIK presents a vast array of examples specific to agriculture. The most common agricultural practices across countries in response to different hazards include: crop selection based on the resistance to risks [6,60,93,94]; introducing new and/or diversifying crop options to optimise yield [79,85,90,93,95,96]; altering cropping patterns and structure [85,93,94]; relocating planting areas away from high-risk areas [9,66,90]; improving irrigation and water management systems [85,93,94,96]; and adjusting planting schedules [9,93,95,96]. Additionally, other farming schemes have been developed or adopted such as market gardening in rainy conditions alternating according to the seasons in Senegal [90] and floating agriculture to adapt to the persistent flooding in Bangladesh [85]. In Taiwan, communities release water in the fish farms and set up surrounding nets to prevent water and fish overflow for aquaculture-based adaptation strategies in response to flooding [6].

Communities also practice livelihood diversification – a strategy to secure more than one source of subsistence to sustain a living in the face of dynamic risks which threaten the primary source of livelihood. In Sri Lanka, fishers engage in collecting honey, rice cultivation, selling fruits, among others, to reduce main reliance on aquaculture-based activity and increase income options in adverse conditions [97]. Similarly, in the Philippines, some Aetas rely on combining and switching activities (cultivation, animal husbandry, etc.) while repeatedly changing their locations as a coping mechanism after the 1991 Mt. Pinatubo eruption [98].

The scholarship on LIK clearly points to livelihood-based strategies that are as dynamic as the risks communities face. It is evident from the examples that adjustments happen through living with these risks while finding ways to secure livelihoods rather than eliminating the risks upfront to revert to the usual livelihood setup under normal conditions. When lands are submerged, people innovate to farm on the floodwaters; when crops are susceptible to damages, farmers diversify their planting options. As hazards impact sources of subsistence, communities come up with livelihood innovations reflecting their resourcefulness amid disasters. These innovations happening on the ground reflect the complex socio-economic responses that they need to undertake to thrive and survive in altered conditions.

### *4.1.6 Social cohesion*

Transcending beyond individual actions are collective efforts by communities to pool their knowledge and resources in the face of hazards, either within established organisations or through informal social linkages and networks. We present social cohesion as an intangible asset that is activated in times of crisis [99], whether as an inherent part of a culture or existing within the day-to-day concept of sense of community. The common denominator lies on how different community members ultimately work together to prepare for or recover from disasters.

In terms of social cohesion imbibed within a culture, an example is from the *Sahis* of Puri, India. Communities rely on mutual cooperation to address communal problems, such as working together in response to calamities regardless of differences in economic status or social position (caste) [100]. Disaster recovery of a community in Bangladesh is being propelled by the help of *samaj*. It is a local-level traditional institution that bonds like-minded community members governed by customs and norms, apart from supports of other community organisations such as *madrasha* management committees, schools, etc. [86]. Beyond formally established community organisations like committees and traditional institutions, knowledge and practices still make their way through social ties and tight-knit networks. In preparation for flooding in Malawi, social networks are utilised to help community members stabilise houses, relocate livestock, seek temporary shelters, and rely on warning information from traditional leaders during community meetings [9]. In Japan, motivations for evacuation during the 2017 torrential rain in Kyushu were based on community discussions – made possible by good neighbourhood relationships – in lieu of timely disaster information due to power outages [101].

A breadth of other examples exists affirming how social cohesion manifests across communities, from customary support and resource sharing systems ([see 56]) to neighbourhood-driven rescue operations ([see 82]). From this review, we have observed the roles cultural settings and good neighbourhood relations play in activating this intangible asset. While these two are not the only precursors to social cohesion, they are prominent factors contributing to building a safety net to combat risks for communities undertaking collective actions.

### *4.1.7 Beliefs*

The truths that communities believe in and hold as valid significantly shape their understanding of risks and hazards and thereby affect how they respond to disasters [102]. Discourse on beliefs linked to DRR prominently presents the idea that disasters are a form of punishment for transgressions, such as in Zimbabwe where the occurrence of hazards is attributed to being sinful or abandoning one's culture [12]. Beyond the concept of punishment, von Vacano & Schwarz [103] present related religious framings of disasters – admonishment and divine test. The former seeks to remind to improve one's faith, while the latter challenges the belief of a person to be proved through coping of the disaster. Meanwhile, in some communities, a divine entity is considered as the source of protection whom they can seek safety from hazards [104] and ask for guidance to recover after disasters [86]. Beliefs are also attributed to supernatural forces such as a case in Peru where a landslide is believed to be caused by a bull pushing the earth downslope [73], and in the Philippines where volcanic activity is associated with spirits [98].

We can see from these examples that beliefs can either give a sense of fatality among communities (with the worldview that someone is in control of everything, including the occurrence of disasters) or a sense of psychological safety (as faith to a central figure can give support and guidance in surviving disasters). This observation is consistent with the two impact pathways of Sun et al. [102] where they explain that beliefs have both constructive and harmful impacts. The former is believed to foster and promote disaster resilience individually and collectively as a social unit while the latter can inhibit the initiative of communities to cope with disaster.

## *4.2 Themes: Foci on how LIK has been studied in DRR*

In this section, we present the foci of how LIK in DRR has been given attention in scholarship. The focus on LIK for risk reduction efforts started to spike during the mid-2000s. Such finding is consistent with Hiwasaki et al. [21] who note that scholars became interested in the potential use of LIK in DRR after communities used their indigenous knowledge and coping practices during the 2004 Indian Ocean earthquake and tsunami. Unsurprisingly, most interest on this topic has been dedicated to understanding the knowledge and practices, including how they are used for DRR and how can they further be leveraged. Figure 2.5 shows how primary LIK themes have flourished, and we discuss each of these themes in the following sub-sections.

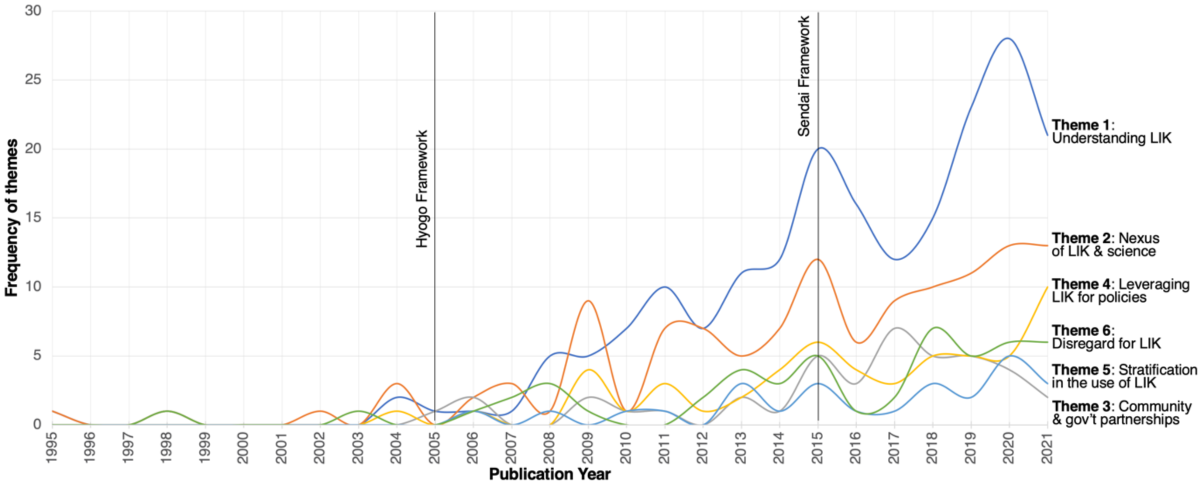


**Figure 2.5**. Trend across the themes identified based on the frequency of publication reviewed in each year

### *4.2.1 Theme 1 – Understanding LIK: Knowledge construction, identification, and points of leverage*

Risk can be understood by communities differently and may provide varied motivations to respond [67]. Several studies have explored how LIK is constructed as a form of knowledge for DRR. For instance, Swee [68] focused on the Australian tropics to understand how local cyclone knowledge is "assembled" and found that it comprises of heterogeneous parts – which include other knowledge sources apart from that of community's own risk perception – and are integrated in an ad hoc and complex manner. Every community interprets disasters in a localised way, and Bongo et al. [12] associate the varied interpretations to the concept of a "script" that needs to be well understood within local priorities and knowledge systems. Interactions of communities with their environment give rise to LIK. Examples include how bushfire risk perception emanates from the interaction of people, landscape, and objects [105] and how local practices of flood management in Myanmar have been shaped by the hydrosocial relationship among residents, institutions, and settlements [106]. Similarly, close relationships between fisher communities and their environment result in what Mulvany [61] call "flood imaginary" or the traditional mechanisms to understand and cope with the impacts of seasonal flooding in India.

To further understand LIK and gain insights into its role in DRR, there is a growing consensus among scholars to document the knowledge and practices, even to the extent of emphasising it as a clarion call [81]. Mutasa [107] argues that unless LIK is documented and preserved, its marginalisation will continue. Recognition of LIK helps sectors involved in DRR management acknowledge its importance [62] and preservation [108]. Documentation is also the first step to understand the principles behind how these local practices work in their own context to be more readily accepted and understood by others [21,109]. From here, points of leverage to maximise the use and recognition of LIK can be inferred. For example, Sharma [110] promotes capitalising on the local technologies of communities while Baumwoll & Krishnamurthy [111] suggest extracting common principles and transferrable elements from documented LIK to apply them as strategies to help vulnerable communities. If there is a prime association with how scholars have understood LIK, it is on the idea that since these assets are homegrown and have been used by communities over time, these knowledge and practices can help to enhance local-level resilience [6,100,112–115]. But documentation comes with risks as well, including how it can strip the contextual aspects of LIK [116]. When exposed to external stakeholders, the practices can also be taken advantage of. To this extent, LIK has been legally protected in some societies like in the Philippines where it is considered an intellectual property ([see 7]).

#### *4.2.2 Theme 2 – Nexus of LIK and science: Integration, validation, and management*

DRR agenda have tendencies to juxtapose LIK with scientific knowledge. The former is understood in this study to be developed locally from community resources (e.g., disaster experiences, lessons handed down by elders, and local materials), while the latter is a knowledge sphere acquired through a formal evidence-based technical systematisation of information. Garcia et al. [117] explain that LIK alone is insufficient to reduce disaster risk, while scientific knowledge is devoid of the holistic picture to understand the local vulnerability context. Combining the two knowledge bases renders more precise information useful for decision making [117]. Additionally, communities with low literacy levels may find it challenging to understand technical concepts moulded on scientific principles and they may resort to customary knowledge [44,118]. Conversely, outsiders might encounter loss of translation when understanding LIK [58] because such knowledge systems are contextually embedded in a community's cultural setting. Scholars should thus continue to advocate for the potential benefit of combining LIK and science to create more robust systems ([see 21,33,59,119]).

Several studies have focused on deliberate efforts to incorporate and integrate community risk perceptions and local spatial knowledge into geospatial technology – such as Geographic Information System (GIS) and Remote Sensing (RS) – to create hazard maps, vulnerability indices, and resilience assessments (see [58,66,72,73,120–136]). Other means of integration happen in post-disaster reconstruction where traditionally built structures are strengthened with engineering interventions. Examples include the "Building Back Safer with Vernacular Methodologies" initiative in Pakistan [92], the adoption of stabilised compressed earth blocks to traditional construction systems in India [110], and the material modifications introduced to *quincha* – a traditional structure in Peru – to improve its seismic performance [137].

Comparison and validation of the two knowledge bases have also attracted attention among scholars. The most popular focus is analysing how LIK of weather and climate trends conform with meteorological data [63,94,107,138–142]. There are also attempts to validate LIK through experiments. For example, Zhang & Nakagawa [143] examined the hydraulics and morphodynamics of *Bandal* structure, a traditional flood and erosion control technology, to understand how the design idea can have the potential to be integrated into contemporary engineering. In comparing the two knowledge spheres, Malone et al. [49] suggest the concept of "cross-validation" where it allows the two knowledge bases to converge and diverge, and where the limitations of each other can be addressed by strengths in the other.

However, the school of thought that LIK is inherently hybridised – that it co-develops with other knowledge sources – is gaining popularity. Lin & Chang [144], for instance, argue that LIK absorbs other knowledge sources instead of rejecting them, forming an involuted knowledge. Meanwhile, Lauer [20] explains that even isolated indigenous communities draw on the intersection of many knowledge systems which allow them to innovate. For example, in the Philippines, communities adopt typhoon warnings from broadcasted meteorological information combined with traditional forecasts based on environmental signs [4,145]. The reliance on the integrated sources of knowledge to gain insight into impending hazards has also been observed in Malawi [9], Indonesia [19], Zimbabwe [146], Fiji, and Tonga [147]. These are evidences that even when there is no deliberate effort to integrate both knowledge spheres, LIK and scientific knowledge are already being informally combined on the ground by local and indigenous people. Such evidences support calls, like that by Pascua [148], to reject the artificial compartmentalisation of LIK and scientific knowledge bases.

#### *4.2.3 Theme 3 – Community and government partnerships for appraising LIK*

While communities have internally developed capacities to handle disasters, they still, however, need external assistance at times [149]. This need for external support can arise from limitations of local capacities. Thus, there is a need to integrate top-down (government-driven) with bottom-up (community-based) approaches [150] in responding to disasters, striking a balance between inputs from administrative authorities and insights from communities [15]. When government-initiated disaster management lacks sensitivity to local-level conditions, affected communities transform policies to respond to disasters better suited to their own circumstances [144].

To foster partnerships between communities and the government, McDonnell et al. [151] present the idea of "managed participation" as evident in the state-led, public post-disaster planning in the aftermath of Superstorm Sandy in New York. In this idea, integration exists between intra-community social ties ("horizontal") and extra-community relations with policy institutions and agencies ("vertical"). Ingham & Redshaw [152], meanwhile, encourage a paradigm shift from rescuer-victim dichotomy and instead embrace the concept that responding to disasters is a "shared responsibility". Vallance [153] sees local government as a recovery agent and an "architecture of engagement" – which pertains to the broad social connections being foundations of a rebuilding process – as an enabler to see both opportunities and needs of the affected residents. However, partnerships can be a challenge especially in communities where their traditional cultural fabric remains intact. In this case, communication and coordination with traditional leaders, village chiefs, or seniors can serve as the gateway to a meaningful rapport [154,155].

Examples of partnerships between community and government include: the establishment of village-level disaster committees in India [110,156] and Nepal [157] comprising of local leaders who partake in disaster risk planning and management; the transdisciplinary community-based DRR approach undertaken in China to complement the existing top-down system of the government [158]; the co-managed flood early warning system in Indonesia where it serves as a platform of interaction between the community and the government [64]; and, the inclusion of LIK by DRR authorities in tackling the risks imposed by an Icelandic glacier [32].

#### *4.2.4 Theme 4 – Leveraging LIK for policy recommendations, programme development, and lessons learned*

Acknowledgement of LIK is not sufficient to leverage it for DRR. There needs to be an impetus to translate ideals well presented in literature into practice. This theme presents those that leverage the merits of LIK for policies, programmes, lessons, and other insights which can transform theory to practice. For instance, Dube [125] proposes an inclusive, multilevel wildland fire management in Botswana and recommends drawing upon LIK to co-determine temporal risk assessments. In analysing external stakeholders' attitudes towards engaging LIK to DRR, Šakić Trogrlić et al. [44] present enhancement pathways suggested by formal DRR practitioners. These include improvement of community engagement, documentation, validation, and dissemination of LIK, integration of LIK with science, and empowerment of communities to use their LIK. Meanwhile, Griffin & Barney [19] recommend that when knowledge sharing between experts and communities already exists, there should be a departure from dividing between knowledge systems, and instead focus on balanced sharing and identifying existing rapport.

Projects and programmes have also been devised to leverage the merits of LIK for DRR. For example, to enhance disaster prevention capabilities among children and assist engagement in the reconstruction after the Kumamoto earthquake in Japan, an educational programme was developed wherein knowledge based on the local historical experiences served as a starting point [159]. In devising evacuation operations, agility that could save more lives was achieved by incorporating local knowledge that provides contextualised information such as the shortest routes [160]. There have also been projects that draw on historical lessons to commemorate disaster events, such as installing plaques that can positively reinforce disaster awareness [161].

Leveraging LIK for policies, programmes, and projects provides a conduit on how the knowledge assets can be mobilised in the developmental realm. However, as LIK is place-based and is emergent within a localised context in which it belongs, there are considerations when extracting their value for risk reduction purposes. Generally, these considerations can be echoed from Kelman et al.'s [162] principal takeaways in appraising LIK, which include: (i) understanding the context and (non)transferability of the knowledge system; (ii) fostering trust and self-help by working with the knowledge that is already acceptable to the community; and (iii) acknowledging heterogeneity as differences do exist within communities.

#### *4.2.5 Theme 5 – Stratification in the use and access of LIK*

With LIK having social, economic, political, and environmental dimensions, its access and use are expected to be "nonlinear" and stratified. Hence, discussions of LIK in DRR should not discount such dimensions. Trogrlić et al. [9] explain that due to intergenerational and gendered differences, there remains an unequal distribution and access of LIK within communities. This theme highlights the stratifications of LIK that are emergent in scholarship. We focus on presenting how demographic factors affect the use and access of the knowledge system, and not about the inequities that these factors bring to communities.

Due to the traditional roles associated with men and women in most societies, gender continues to be a significant factor in the stratification of the use and access of LIK. Women are known to have a wide grasp of LIK due to their exposure to daily activities [59] and, alongside seniors and traditional leaders, are regarded as custodians of the knowledge system [163]. In Gauteng, South Africa, mothers are known to transmit local knowledge and techniques to their children revealing their foundational role in the promotion of LIK and its awareness [163]. Women have also been mostly known to help ensure food security in preparation for disasters in some communities as they are usually more familiar with indigenous food preservation techniques [4,164]. In some cases, women have been shown to have a higher level of risk perception or disaster awareness compared to men [120,165]. In other contexts, men perceive climate variability better as it impacts the crop yields that they attend to [141].

Age also stratifies access to LIK for the apparent reason that senior members of a community have more disaster experiences and have often gone through several hazard events allowing them to acquire firsthand knowledge [166,167]. Social class has also been shown to affect disaster awareness with less privileged community members exhibiting lower risk perception [168] though this can be the result of societal marginalisation. Meanwhile, urban residents tend to have lower levels of local knowledge compared to rural residents who have most likely developed a sense of community and place attachment [169]. Lastly, occupation informs access to specific LIK, such as when fishers become familiar to forecast hazards based on water behaviour due to their close interaction with the environment [166,167].

#### *4.2.6 Theme 6 – Disregard for the potential use of LIK*

Lambert & Scott [170] have emphasised that as early as the mid-1990s, LIK was already acknowledged in disaster-related multilateral agreements but DRR strategies focused on the resources and assets of indigenous people remain challenging to implement. Among the contributing factors include state-sponsored or endorsed racism, historical isolation, ongoing marginalisation, and institutional inertia. This disregard for the potential use of LIK for effective DRR remains pronounced and can be explained by two broad and dominant influences: the persistence of scientific hegemony and the inherent technocracy among institutions and governing bodies.

With influential practitioners from global DRR organisations mostly being educated in scientific-based institutions [171], the mindset that science is more equipped than LIK in preventing risks continues to infiltrate DRR practice. According to Howitt et al. [172], “key institutional structures continue to privilege discourses based on scientific and administrative expertise over locally contextualised knowledges, and to discount or dismiss social and cultural dimensions of risk…” (p. 52). The perception that outside, expert-led knowledge is superior disempowers communities and may damage their local institutions [173]. Ironically, the development community – which has boosted the appraisal of LIK in literature – implicitly conveys a general attitude that LIK is a backward form of knowledge, hence its effectiveness is questionable [44]. Similarly, practitioners often advocate the value of LIK whilst maintaining a dominant science-based stance to improve their image and avoid criticism [174]. Outright examples of disregard for LIK have been demonstrated. For example, in the Philippines, the Department of Science and Technology’s preference is (somewhat obviously) science-based DRR strategies as LIK is a challenge to be incorporated into programmes when a technical working group is comprised of scientific experts [7]. Similarly, in Chile, the social memory and local historical records have been rejected by the Scientific Technical Committee due to their un-scientific nature in diagnosing a seismic crisis [175].

Technocracy has also contributed to the disregard of LIK. Disaster management carried out by governments, external institutions, and other organisations tends to exclude communities [73,133,144,176–179]. This approach has exacerbated community’s exclusion with barriers such as weak capacity among community members to uphold their LIK at district and national levels, and the lack of institutional support to maintain a rapport between LIK holders and formal DRR practitioners [133]. As a result, technical-solution-oriented development is commonplace and the social, political, and cultural contexts of disasters have been taken out of context [113,180], sidelining the knowledge of locals and indigenous people for effective disaster management. In worst cases, some NGOs have been observed to abuse relationships with communities to leverage their objectives [60] or they operate within predefined frameworks thereby excluding potential contributions of communities [166].

### *4.3 LIK within the global DRR framework*

The Sendai Framework for Disaster Risk Reduction seeks to advance local, national, regional, and global efforts to prevent new risks, reduce existing risks, and increase resilience, replacing the Hyogo Framework for Action in 2015 [24]. The Sendai Framework promotes LIK to *complement* scientific knowledge in disaster risk assessment and policy and programme development. However, the word "complement" alone implicitly discounts how other sources and interpretations of knowledge can be at par with more formal ways of knowing and understanding risk reduction measures. We refer to this as an embryonic recognition of LIK, which is unsurprising since there has been an observed shift away from valuing local community input towards technological advancements across the most recent global frameworks [43] (see Section 2).

In this study, we progress the Sendai Framework by analysing how the priority areas of action are captured in the current understanding of LIK in the DRR body of knowledge (see Figure 2.6). In doing so, we endeavour to understand how the priority areas coincide with attention in scholarship, or the lack thereof. We discuss below each of the four Sendai Framework priority areas along with how the extracted themes from the review align to these. From here, we offer our recommendations based on the common messages conveyed across the literature to help realise the implementation of the global framework's priority areas.

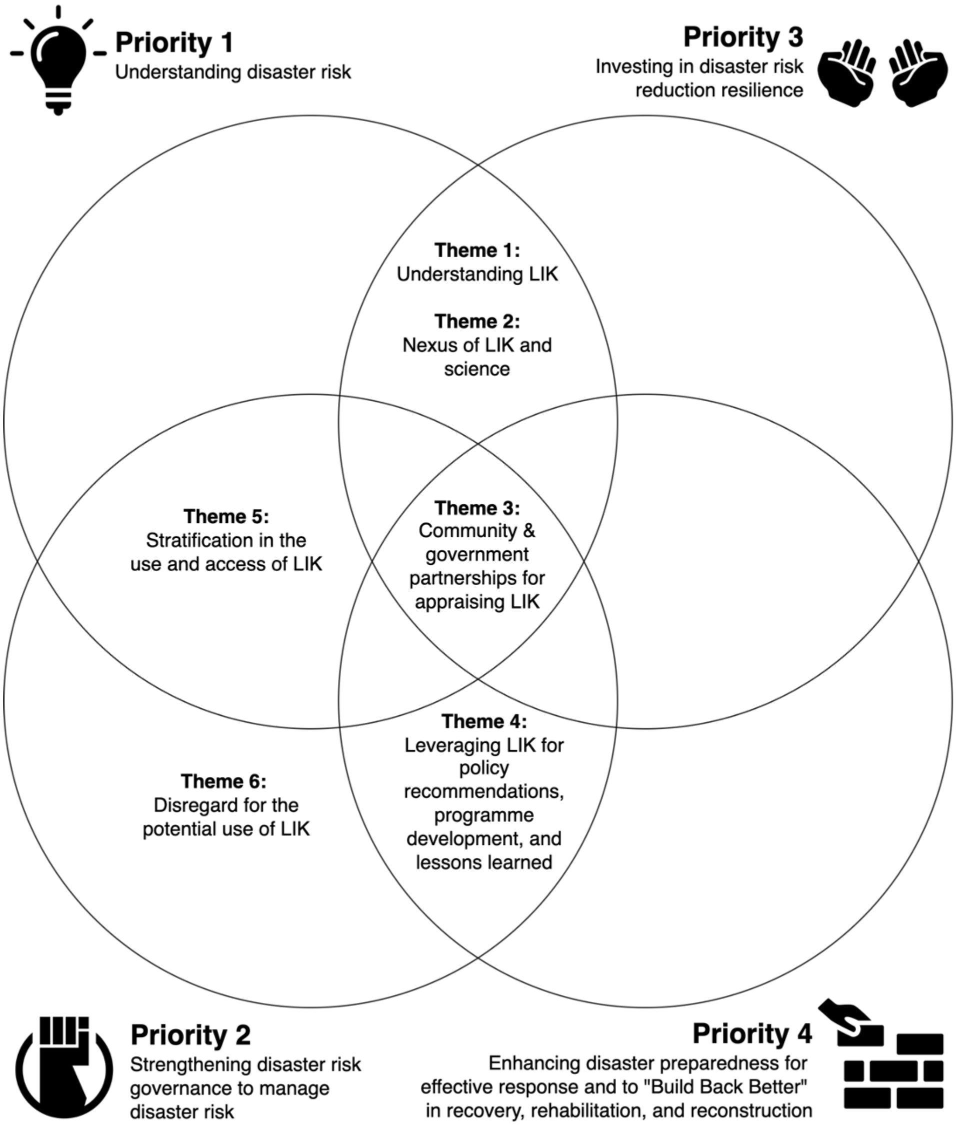


**Figure 2.6.** Themes within the Sendai Framework

### *4.3.1 Priority 1: Understanding disaster risk*

Priority 1 of the Sendai Framework focuses on understanding the multi-dimensional characteristics of disaster risk [24]. To achieve this at the national and local levels, the framework suggests disseminating disaster risk information in appropriate formats to decision-makers and at-risk communities. The need to understand LIK (Theme 1) thus has relevance to how communities take actions autonomously or in partnership with stakeholders. Priority 1 further promotes that LIK should complement scientific knowledge for risk assessments, policymaking, and programme development (Theme 2). Numerous studies have adopted the integration of LIK with geospatial technology and this is well aligned with the Sendai

Framework goal to "enhance measurement tools, and the collection, analysis, and dissemination of data without sidelining each of the knowledge spheres". Cross-sectoral collaboration, cooperation, and dialogue in understanding risk are also well highlighted under Priority 1 and this can be linked to the partnerships discussed in Theme 3. Risk, being multi-dimensional, co-exists within a broader social fabric and those who are directly affected should not just be the sole actors to address it. While there is much alignment of the Sendai Framework with literature, absent is nuance in who holds LIK. The framework adequately draws attention to the need to disaggregate social and demographic factors (such as age and gender) but falls short of recognising that LIK is stratified and not homogenous (Theme 5). These shortcomings discount acknowledging the dynamics in how different members of a community use and access their knowledge resources.

### *4.3.2 Priority 2: Strengthening disaster risk governance to manage disaster risk*

Priority 2 promotes the effective and efficient management of disaster risk based on clear vision, plans, competence, guidance, and cross-sectoral coordination [24]. If understanding risk requires partnerships, risk governance should forge them. The role of government to help local and indigenous communities to realise their knowledge assets has been highlighted in Theme 3. While governments are not the only institutions that support the implementation of instruments relevant to DRR, policy recommendations that arise from LIK presented in Theme 4 will remain unutilised unless there is motivation to advance these within legal frameworks. Strengthening risk governance should also consider the problems that exacerbate the vulnerability of communities. Unequal access to knowledge within communities (Theme 5) is one such dilemma for capacity building efforts outlined in the Sendai Framework. There have also been both deliberate and unconscious efforts by technocratic bodies to disregard the potential use of LIK for DRR (Theme 6). Tacitly, technical-solution-oriented developments remain to be the dominant approach in "reducing risks" and these most often ignore how communities respond to and prepare for disasters.

### *4.3.3 Priority 3: Investing in DRR for resilience*

Priority 3 emphasises the need to invest in both structural and non-structural measures to prevent and reduce disaster risks [24]. As highlighted in Theme 1, there are a plethora of locally developed strategies that communities use to face hazards which include those that are intangible (e.g., forecasting abilities, risk perceptions, social cohesion) and tangible (e.g., seismic-responsive dwellings, soil erosion and flooding technology). These "homegrown" strategies are investments that DRR practitioners can utilise. These assets are readily available and acceptable to communities. However, while these measures are promising, they are not without limitations. Integrating these into the scientific domain (Theme 2) can be a way to emphasise the strengths of these practices and advance cooperation among academic, scientific, and research entities in developing risk reduction interventions. Under this priority, there is again a need to echo the importance of community and government partnerships (Theme 3) as it is understood that to leverage such investments to reduce risks and mainstream related activities, governmental support will substantiate these efforts.

### *4.3.4 Priority 4: Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation, and reconstruction*

Priority 4 highlights strengthened disaster preparedness for response, actions to anticipate events, and capacities for response and recovery. Additionally, Priority 4 emphasises "building back better" as an opportunity in the recovery, rehabilitation, and reconstruction phases [24]. The concept of building back *better* references lessons learned from past actions. Under Theme 4 developed in this study, extensive literature points to enhancing preparedness and capacities to build back better by leveraging the knowledge assets of communities. However, the mention of "adoption of policies, plans, and programmes" again shows a need for community and government partnerships (Theme 3). The Sendai Framework underscores a need for guidance instruments (e.g., codes and standards) to support coordinated action for disaster preparedness and response as well as to facilitate exchange of information for policy practice and programmes for post-disaster reconstruction.

## 5 Limitations

While this study aimed to be as inclusive and comprehensive as possible to capture all pertinent documents to reflect the state of knowledge, we acknowledge that some documents of interest may not have been captured by the search string. Due to the plurality of terms in DRR literature, some authors may have discussed LIK and disasters but used different, less common terminologies. Additionally, these terms could have also been implicitly represented in other discussions. The criterion to exclude non-English documents does omit important insights but was necessary in favour of what we can only interpret. This is potentially shown in the skewed geographical representation of the included studies, with fewer documents from low-income countries. Lastly, we only focused on peer-reviewed articles to understand the scholarly attention. Thus, the exclusion of grey literature misses how organisations and institutions might have depicted LIK in their technical reports, working papers, and other non-scholarly documents.

## 6 Conclusions

The discourse on LIK highlights a plethora of practices that communities possess and use to prepare for, mitigate, respond to, and recover from the impacts of disasters caused by natural hazards. We systematically reviewed 325 documents that were qualitatively coded to identify what practices constitute LIK, patterns in how it has been studied, and how our current understanding of the knowledge system fits to the Sendai Framework.

We elicited a wide range of LIK developed on the ground, from hazard forecasts to anticipatory measures, which is shaped by social cohesion and belief systems. From both fieldwork- and non-fieldwork-based studies, we found that low-income countries are less represented in the scholarship compared to middle- and high-income countries. We also found deliberate attempts to forge knowledge and power spheres, such as the acknowledgement of the hybridisation of both LIK and scientific knowledge in understanding risks, or the collaborative efforts between experts and local communities in mapping hazards. In the Sendai Framework, the general recognition of LIK is still embryonic, although we see how the current understanding of LIK in scholarship aligns within the priority areas of the framework.

So, where does LIK in DRR go from here? First, our holistic synthesis hints the geographical skewness of where LIK has been (under)studied. While numerous strategies and practices emerged from publications, other vulnerable communities holding a great amount of LIK from less popular regions do not share the limelight. We encourage shifting focus to these less represented groups to understand how they manage the impacts of disasters in lieu of access to formal DRR support which are beyond their reach in most cases. Second, we welcome the hybridisation of knowledge and power spheres as they strengthen risk reduction measures by relying on various sources of knowledge and information. However, we are compelled to mention how LIK can be at risk of being exploited at this amalgamation of knowledge systems due to how they could be misunderstood and misused when taken out of their place-based and cultural contexts. Thus, there should be institutional safeguards to when these are being used in conjunction with other knowledge bases. Third, our framing of LIK to the Sendai Framework priority areas identifies alignment and ongoing gaps in LIK applications in DRR. Along this, we challenge future policymakers to consider crafting the position of LIK in future global frameworks as a knowledge system existing on its own right, and not just adjunct to scientific knowledge as how it is currently being represented. Last, the sustained scholarly attention of LIK should inform a collective identity of the knowledge system out of the rich and vast representations in DRR literature. Such identity strengthens its character in the DRR practice and policy environments useful to further progress its recognition and protection amid threats such as rapid urbanisation and persistent technocracy.

## 7 References

[1] World Meteorological Organization, WMO Atlas of Mortality and Economic Losses from Weather, Climate and Weather Extremes (1970 - 2019), 2021.

[2] IFRC, World Disasters Report: Come Heat or High Water., Intl Fed of Red Cross, Geneva, 2020.

[3] Elsevier, Global Outlook in Disaster Science, 2017.

[4] M. Balay-As, J. Marlowe, J.C. Gaillard, Deconstructing the binary between indigenous and scientific knowledge in disaster risk reduction: Approaches to high impact weather hazards, Int. J. Disaster Risk Reduct. 30 (2018) 18–24. https://doi.org/10.1016/j.ijdrr.2018.03.013.

[5] F.M. Camacho, C.I. Matus, Towards situated practices for disaster risk reduction (DRR): Indigenous counter-mapping in Saavedra, Chile, Int. J. Disaster Risk Reduct. 60 (2021) 102306. https://doi.org/10.1016/j.ijdrr.2021.102306.

[6] T.-L. Chen, H.-W. Cheng, Applying traditional knowledge to resilience in coastal rural villages, Int. J. Disaster Risk Reduct. 47 (2020). https://doi.org/10.1016/j.ijdrr.2020.101564.

[7] G.P. Cuaton, Y. Su, Local-indigenous knowledge on disaster risk reduction: Insights from the Mamanwa indigenous peoples in Basey, Samar after Typhoon Haiyan in the Philippines, Int. J. Disaster Risk Reduct. 48 (2020) 101596. https://doi.org/10.1016/j.ijdrr.2020.101596.

[8] U. Dasanayaka, Y. Matsuda, A study on local knowledge in adaptation to landslide disasters in Sri Lanka, Eng. J. 23 (2019) 501–509. https://doi.org/10.4186/ej.2019.23.6.501.

[9] R.Š. Trogrlić, G.B. Wright, M.J. Duncan, M.J.C. van den Homberg, A.J. Adeloye, F.D. Mwale, J. Mwafulirwa, Characterising local knowledge across the flood risk management cycle: A case study of Southern Malawi, Sustain. Switz. 11 (2019). https://doi.org/10.3390/su11061681.

[10] A. Oliver-Smith, Disaster risk reduction and applied anthropology, 2016. https://doi.org/10.1111/napa.12089.

[11] G. Bankoff, Cultures of disaster society and natural hazards in the Philippines, RoutledgeCurzon, London, 2003.

[12] P.P. Bongo, P. Chipangura, M. Sithole, F. Moyo, Dynamics of configuring and interpreting the disaster risk script: Experiences from Zimbabwe, Jamba J. Disaster Risk Stud. 5 (2013). https://doi.org/10.4102/jamba.v5i2.93.

[13] J.-C. Gaillard, E. Clavé, O. Vibert, Azhari, Dedi, J.-C. Denain, Y. Efendi, D. Grancher, C.C. Liamzon, D.R. Sari, R. Setiawan, Ethnic groups' response to the 26 December 2004 earthquake and tsunami in Aceh, Indonesia, Nat. Hazards 47 (2008) 17–38. https://doi.org/10.1007/s11069-007-9193-3.

[14] H. Granot, Disaster subcultures, Disaster Prev. Manag. 5 (1996) 36–40. https://doi.org/10.1108/09653569610127433.

[15] F. Briones, R. Vachon, M. Glantz, Local responses to disasters: recent lessons from zero-order responders, Disaster Prev. Manag. Int. J. 28 (2019) 119–125. https://doi.org/10.1108/DPM-05-2018-0151.

[16] A. Agrawal, Dismantling the Divide Between Indigenous and Scientific Knowledge, Dev. Change 26 (1995) 413–439. https://doi.org/10.1111/j.1467-7660.1995.tb00560.x.

[17] M.B. Khalil, B.C. Jacobs, N. Kuruppu, Grassroots Technologies and Community Trust in Climate Change Adaptation: Learning from Coastal Settlements of Bangladesh, 2016. https://doi.org/10.1007/978-3-319-25814-0_21.

[18] IPCC, Annex I: Glossary. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, 2019.

[19] C. Griffin, K. Barney, Local disaster knowledge: Towards a plural understanding of volcanic disasters in Central Java's highlands, Indonesia, Geogr. J. 187 (2021) 2–15. https://doi.org/10.1111/geoj.12364.

[20] M. Lauer, Oral traditions or situated practices? Understanding how indigenous communities respond to environmental disasters, Hum. Organ. 71 (2012) 176–187. https://doi.org/10.17730/humo.71.2.j0w0101277ww6084.

[21] L. Hiwasaki, E. Luna, Syamsidik, R. Shaw, Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities, Int. J. Disaster Risk Reduct. 10 (2014) 15–27. https://doi.org/10.1016/j.ijdrr.2014.07.007.

[22] B.G. McAdoo, L. Dengler, G. Prasetya, V. Titov, Smong: How an Oral History Saved Thousands on Indonesia's Simeulue Island during the December 2004 and March 2005 Tsunamis, Earthq. Spectra 22 (2006) 661–669. https://doi.org/10.1193/1.2204966.

[23] Syafwina, Recognizing Indigenous Knowledge for Disaster Management: Smong, Early Warning System from Simeulue Island, Aceh, Procedia Environ. Sci. 20 (2014) 573–582. https://doi.org/10.1016/j.proenv.2014.03.070.

[24] UNISDR, Sendai Framework for Disaster Risk Reduction 2015 - 2030, 2015.

[25] M.M. Bayrak, Y.-Y. Hsu, L.-S. Hung, H.-M. Tsai, T. 'E Vayayana, Global climate change and indigenous peoples in Taiwan: A critical bibliometric analysis and review, Sustain. Switz. 13 (2021) 1–27. https://doi.org/10.3390/su13010029.

[26] B. Bwambale, M. Nyeko, M. Muhumuza, M. Kervyn, Questioning knowledge foundation: What is the best way to integrate knowledge to achieve substantial disaster risk reduction?, Int. J. Disaster Risk Reduct. 51 (2020) 101850. https://doi.org/10.1016/j.ijdrr.2020.101850.

[27] J. Dekens, Local knowledge for disaster preparedness: a literature review, International Centre for Integrated Mountain Development, Kathmandu, 2007.

[28] V. Marchezini, F.E.A. Horita, P.M. Matsuo, R. Trajber, M.A. Trejo-Rangel, D. Olivato, A Review of Studies on Participatory Early Warning Systems (P-EWS): Pathways to Support Citizen Science Initiatives, Front. Earth Sci. 6 (2018) 184. https://doi.org/10.3389/feart.2018.00184.

[29] S. Sufri, F. Dwirahmadi, D. Phung, S. Rutherford, A systematic review of Community Engagement (CE) in Disaster Early Warning Systems (EWSs), Prog. Disaster Sci. 5 (2020) 100058. https://doi.org/10.1016/j.pdisas.2019.100058.

[30] M. Gall, K.H. Nguyen, S.L. Cutter, Integrated research on disaster risk: Is it really integrated?, Int. J. Disaster Risk Reduct. 12 (2015) 255–267. https://doi.org/10.1016/j.ijdrr.2015.01.010.

[31] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, R. Chou, J. Glanville, J.M. Grimshaw, A. Hróbjartsson, M.M. Lalu, T. Li, E.W. Loder, E. Mayo-Wilson, S. McDonald, L.A. McGuinness, L.A. Stewart, J. Thomas, A.C. Tricco, V.A. Welch, P.

Whiting, D. Moher, The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ (2021) n71. https://doi.org/10.1136/bmj.n71.

[32] S. Matti, H. Ögmundardóttir, Local knowledge of emerging hazards: Instability above an Icelandic glacier, Int. J. Disaster Risk Reduct. 58 (2021) 102187. https://doi.org/10.1016/j.ijdrr.2021.102187.

[33] J. Mercer, I. Kelman, L. Taranis, S. Suchet-Pearson, Framework for integrating indigenous and scientific knowledge for disaster risk reduction, Disasters 34 (2010) 214–239. https://doi.org/10.1111/j.1467-7717.2009.01126.x.

[34] UNESCO, Local and Indigenous Knowledge Systems (LINKS), UNESCO (2018). https://en.unesco.org/links (accessed July 14, 2021).

[35] E.J. Plate, Disaster prevention, in: Earth Syst. Sci. Anthr., 2006: pp. 87–111. https://doi.org/10.1007/3-540-26590-2_9.

[36] K. Yamori, A historical overview of social representation of earthquake risk in Japan: Fatalism, social reform, scientific control and collaborative risk management, 2013. https://doi.org/10.1007/978-94-007-6184-1_5.

[37] J.-C. Gaillard, The Invention of Disaster; Power and Knowledge in Discourses on Hazard and Vulnerability, Routledge, 2022.

[38] B. Bwambale, M. Muhumuza, T.T. Kahigwa, S.M.B. Baluku, H. Kasozi, M. Nyeko, M. Kervyn, Foundations of indigenous knowledge on disasters from natural hazards: lessons from the outlook on floods among the Bayira of the Rwenzori region, Disasters (2021) disa.12529. https://doi.org/10.1111/disa.12529.

[39] B. Hepburn, H. Andersen, Scientific Method, Stanf. Encycl. Philos. (2021). https://plato.stanford.edu/archives/sum2021/entries/scientific-method/.

[40] A. Titz, T. Cannon, F. Krüger, Uncovering ‘Community’: Challenging an Elusive Concept in Development and Disaster Related Work, Societies 8 (2018) 71. https://doi.org/10.3390/soc8030071.

[41] IDNDR, Yokohama Strategy and Plan of Action for a Safer World, 1994.

[42] UNISDR, Hyogo Framework for Arction 2005 - 2015, 2005.

[43] A. Tozier de la Poterie, M.-A. Baudoin, From Yokohama to Sendai: Approaches to Participation in International Disaster Risk Reduction Frameworks, Int. J. Disaster Risk Sci. 6 (2015) 128–139. https://doi.org/10.1007/s13753-015-0053-6.

[44] R. Šakić Trogrlić, M. Duncan, G. Wright, M. van den Homberg, A. Adeloye, F. Mwale, C. McQuistan, External stakeholders’ attitudes towards and engagement with

local knowledge in disaster risk reduction: are we only paying lip service?, Int. J. Disaster Risk Reduct. 58 (2021) 102196. https://doi.org/10.1016/j.ijdrr.2021.102196.

[45] L. Berrang-Ford, T. Pearce, J.D. Ford, Systematic review approaches for climate change adaptation research, Reg. Environ. Change 15 (2015) 755–769. https://doi.org/10.1007/s10113-014-0708-7.

[46] Y. Xiao, M. Watson, Guidance on Conducting a Systematic Literature Review, (2017) 20.

[47] V.K. Singh, P. Singh, M. Karmakar, J. Leta, P. Mayr, The journal coverage of Web of Science, Scopus and Dimensions: A comparative analysis, Scientometrics 126 (2021) 5113–5142. https://doi.org/10.1007/s11192-021-03948-5.

[48] J. Baas, M. Schotten, A. Plume, G. Côté, R. Karimi, Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies, Quant. Sci. Stud. 1 (2020) 377–386. https://doi.org/10.1162/qss_a_00019.

[49] A. Malone, P. Santi, Y.C. Cabana, N.M. Smith, J. Manning, E.Z. Zeballos, W. Zhou, Cross-validation as a step toward the integration of local and scientific knowledge of geologic hazards in rural Peru, Int. J. Disaster Risk Reduct. 67 (2022) 102682. https://doi.org/10.1016/j.ijdrr.2021.102682.

[50] J. Saldaña, The coding manual for qualitative researchers, 2nd ed, SAGE, Los Angeles, 2013.

[51] V. Braun, V. Clarke, Using thematic analysis in psychology, Qual. Res. Psychol. 3 (2006) 77–101. https://doi.org/10.1191/1478088706qp063oa.

[52] A. Castleberry, A. Nolen, Thematic analysis of qualitative research data: Is it as easy as it sounds?, Curr. Pharm. Teach. Learn. 10 (2018) 807–815. https://doi.org/10.1016/j.cptl.2018.03.019.

[53] L.S. Nowell, J.M. Norris, D.E. White, N.J. Moules, Thematic Analysis: Striving to Meet the Trustworthiness Criteria, Int. J. Qual. Methods (2017) 13.

[54] L. Bosher, K. Chmutina, D. van Niekerk, Stop going around in circles: towards a reconceptualisation of disaster risk management phases, Disaster Prev. Manag. Int. J. 30 (2021) 525–537. https://doi.org/10.1108/DPM-03-2021-0071.

[55] R. Yore, J.F. Walker, Early warning systems and evacuation: rare and extreme versus frequent and small-scale tropical cyclones in the Philippines and Dominica, Disasters 45 (2021) 691–716. https://doi.org/10.1111/disa.12434.

[56] B. Iticha, A. Husen, Adaptation to climate change using indigenous weather forecasting systems in Borana pastoralists of southern Ethiopia, Clim. Dev. 11 (2019) 564–573. https://doi.org/10.1080/17565529.2018.1507896.

[57] D. Madhanagopal, S. Pattanaik, Exploring fishermen's local knowledge and perceptions in the face of climate change: the case of coastal Tamil Nadu, India, Environ. Dev. Sustain. 22 (2020) 3461–3489. https://doi.org/10.1007/s10668-019-00354-z.

[58] N. Pauli, M. Williams, S. Henningsen, K. Davies, C. Chhom, F. van Ogtrop, S. Hak, B. Boruff, A. Neef, "Listening to the Sounds of the Water": Bringing Together Local Knowledge and Biophysical Data to Understand Climate-Related Hazard Dynamics, Int. J. Disaster Risk Sci. 12 (2021) 326–340. https://doi.org/10.1007/s13753-021-00336-8.

[59] M. Masinde, An innovative drought early warning system for sub-saharan Africa: Integrating modern and indigenous approaches, Afr. J. Sci. Technol. Innov. Dev. 7 (2015) 8–25. https://doi.org/10.1080/20421338.2014.971558.

[60] J.K. Kamara, K. Agho, A.M.N. Renzaho, Combating recurrent hazards: evidence from rural Lesotho and Eswatini–a qualitative study, Environ. Hazards 19 (2020) 421–441. https://doi.org/10.1080/17477891.2019.1614430.

[61] A. Mulvany, From resilience to reliance. State disruption of traditional flood mitigation strategies, Nar. Umjet. 49 (2012) 23–40.

[62] J.A.L. Reyes, K.A.R. Ayo, M.P.M. Baluyan, A.S.R.B. Balaguer, Indigenous Knowledge in Disaster Risk Reduction: The Tales of Three Islands (San Miguel, Camotes and Alabat) in the Philippines, Cph. J. Asian Stud. 37 (2020) 103–132. https://doi.org/10.22439/CJAS.V37I1.5908.

[63] S. Acharya, Prediction of rainfall variation through flowering phenology of night-flowering jasmine (Nyctanthes arbor-tristis L.; Verbenaceae) in Tripura, Indian J. Tradit. Knowl. 10 (2011) 96–101.

[64] A.D. Sari, N. Prayoga, Enhancing citizen engagement in the face of climate change risks: A case study of the flood early warning system and health information system in Semarang city, Indonesia, 2018. https://doi.org/10.1007/978-3-319-65003-6_7.

[65] A. Mohanty, M. Hussain, M. Mishra, D.B. Kattel, I. Pal, Exploring community resilience and early warning solution for flash floods, debris flow and landslides in conflict prone villages of Badakhshan, Afghanistan, Int. J. Disaster Risk Reduct. 33 (2019) 5–15. https://doi.org/10.1016/j.ijdrr.2018.07.012.

[66] K. Sudmeier-Rieux, S. Jaquet, M.-H. Derron, M. Jaboyedoff, S. Devkota, A case study of coping strategies and landslides in two villages of Central-Eastern Nepal, Appl. Geogr. 32 (2012) 680–690. https://doi.org/10.1016/j.apgeog.2011.07.005.

[67] I.Z. Ponce de Leon, A portrait of contrasts in disaster risk response: A post-haiyan study of coron, Philippines, Weather Clim. Soc. 13 (2021) 511–523. https://doi.org/10.1175/WCAS-D-20-0093.1.

[68] H. Swee, Assembling local cyclone knowledge in the Australian tropics, Nat. Cult. 12 (2017) 8–26. https://doi.org/10.3167/nc.2017.120102.

[69] B. Haworth, J. Whittaker, E. Bruce, Assessing the application and value of participatory mapping for community bushfire preparation, Appl. Geogr. 76 (2016) 115–127. https://doi.org/10.1016/j.apgeog.2016.09.019.

[70] S. Andreastuti, E. Paripurno, H. Gunawan, A. Budianto, D. Syahbana, J. Pallister, Character of community response to volcanic crises at Sinabung and Kelud volcanoes, J. Volcanol. Geotherm. Res. 382 (2019) 298–310. https://doi.org/10.1016/j.jvolgeores.2017.01.022.

[71] R. Brouwer, J. Nhassengo, About bridges and bonds: Community responses to the 2000 floods in Mabalane District, Mozambique, Econ. Outlook 30 (2006) 234–255. https://doi.org/10.1111/j.0361-3666.2006.00317.x.

[72] G. Peters-Guarin, M.K. Mccall, C. van Westen, Coping strategies and risk manageability: Using participatory geographical information systems to represent local knowledge, Disasters 36 (2012) 1–27. https://doi.org/10.1111/j.1467-7717.2011.01247.x.

[73] J. Klimeš, A.M. Rosario, R. Vargas, P. Raška, L. Vicuña, C. Jurt, Community participation in landslide risk reduction: a case history from Central Andes, Peru, Landslides 16 (2019) 1763–1777. https://doi.org/10.1007/s10346-019-01203-w.

[74] E. Maly, M. Yamazaki, Disaster museums in Japan: Telling the stories of disasters before and after 3.11, J. Disaster Res. 16 (2021) 146–156. https://doi.org/10.20965/jdr.2021.p0146.

[75] D. Hilhorst, J. Baart, G. van der Haar, F.M. Leeftink, Is disaster “normal” for indigenous people? Indigenous knowledge and coping practices, Disaster Prev. Manag. 24 (2015) 506–522. https://doi.org/10.1108/DPM-02-2015-0027.

[76] E. Mavhura, S.B. Manyena, A.E. Collins, D. Manatsa, Indigenous knowledge, coping strategies and resilience to floods in Muzarabani, Zimbabwe, Int. J. Disaster Risk Reduct. 5 (2013) 38–48. https://doi.org/10.1016/j.ijdrr.2013.07.001.

[77] S.K. Paul, J.K. Routray, Flood proneness and coping strategies: The experiences of two villages in Bangladesh, Disasters 34 (2010) 489–508. https://doi.org/10.1111/j.1467-7717.2009.01139.x.

[78] S.K. Srivastava, Managing indigenous and scientific knowledge for resilience building: Case studies from disaster-prone regions of India, J. Adv. Manag. Res. 9 (2012) 45–63. https://doi.org/10.1108/09727981211225644.

[79] A. Pareek, P.C. Trivedi, Cultural values and indigenous knowledge of climate change and disaster prediction in Rajasthan, India, Indian J. Tradit. Knowl. 10 (2011) 183–189.

[80] A. Resture, Utilising indigenous knowledge for building disaster resilience in Tuvalu, in: Indig. Knowl. Disaster Risk Reduct. Pract. Policy, 2009: pp. 255–270.

[81] M. Haque, Indigenous knowledge and practices in disaster management: Experiences of the coastal people of Bangladesh, in: Disaster Risk Reduct. Community Resil. Responses, 2018: pp. 59–72. https://doi.org/10.1007/978-981-10-8845-2_4.

[82] J. Moreno, A. Lara, M. Torres, Community resilience in response to the 2010 tsunami in Chile: The survival of a small-scale fishing community, Int. J. Disaster Risk Reduct. 33 (2019) 376–384. https://doi.org/10.1016/j.ijdrr.2018.10.024.

[83] UNDRR, Structural and non-structural measures, (2021). https://www.undrr.org/terminology/structural-and-non-structural-measures (accessed September 16, 2021).

[84] J. Newton, An Assessment of Coping with Environmental Hazards in Northern Aboriginal Communities, Can. Geogr. Géographe Can. 39 (1995) 112–120. https://doi.org/10.1111/j.1541-0064.1995.tb00406.x.

[85] M.A. Sattar, A.A.A. Biswas, M.T. Islam, M.A. Hossain, M. Siddeqa, M.A. Rahim, M.N. Amin, M. Touhiduzzaman, M.A. Rahman, S. Aktar, Disaster vulnerability and mitigation of humanitarian issues in coastal Bangladesh: Local evidence and knowledge gaps, Prog. Disaster Sci. 8 (2020). https://doi.org/10.1016/j.pdisas.2020.100138.

[86] M.S. Uddin, C.E. Haque, D. Walker, M.-U.-I. Choudhury, Community resilience to cyclone and storm surge disasters: Evidence from coastal communities of Bangladesh, J. Environ. Manage. 264 (2020). https://doi.org/10.1016/j.jenvman.2020.110457.

[87] K.R. Aryal, Disaster vulnerability in Nepal, Int. J. Disaster Risk Reduct. 9 (2014) 137–146. https://doi.org/10.1016/j.ijdrr.2014.05.009.

[88] S. Forrest, E.-M. Trell, J. Woltjer, Civil society contributions to local level flood resilience: Before, during and after the 2015 Boxing Day floods in the Upper Calder Valley, Trans. Inst. Br. Geogr. 44 (2019) 422–436. https://doi.org/10.1111/tran.12279.

[89] K. Mitra, Design for resilience: Traditional knowledge in disaster resilience in the built environment, 2020. https://doi.org/10.1007/978-3-030-25879-5_9.

[90] G. Tremblay, Adaptation strategies in the valley of the senegal river: A social approach to dealing with climate change in senegal, in: Agric. Adapt. Clim. Change, 2016: pp. 185–198. https://doi.org/10.1007/978-3-319-31392-4_12.

[91] J. Tao, D. Xiao, Q. Qin, X. Zhuo, J. Wang, H. Chen, Q. Wang, Climate-adaptive Design of Historic Villages and Dwellings in a Typhoon-prone Region in Southernmost Mainland China, Int. J. Archit. Herit. (2020). https://doi.org/10.1080/15583058.2020.1753262.

[92] M. Nanavati, Developing tradition: A case of heritage foundation of pakistan, 2018. https://doi.org/10.1007/978-3-319-57937-5_7.

[93] M.T.B. Lirag, A.B. Estrella, Adaptation measures of farmers in response to climate change in Bicol Region, Philippines, Int. J. Adv. Sci. Eng. Inf. Technol. 7 (2017) 2308–2315. https://doi.org/10.18517/ijaseit.7.6.4325.

[94] W. Shijin, Q. Dahe, Mountain inhabitants perspectives on climate change, and its impacts and adaptation based on temporal and spatial characteristics analysis: A case study of Mt. Yulong Snow, Southeastern Tibetan Plateau, Environ. Hazards 14 (2015) 122–136. https://doi.org/10.1080/17477891.2014.1003776.

[95] W. Lunga, C. Musarurwa, Exploiting indigenous knowledge commonwealth to mitigate disasters: From the archives of vulnerable communities in Zimbabwe, Indian J. Tradit. Knowl. 15 (2016) 22–29.

[96] J. Vermaak, D. van Niekerk, Disaster risk reduction initiatives in South Africa, Dev. South. Afr. 21 (2004) 555–574. https://doi.org/10.1080/0376835042000265487.

[97] E.K. Galappaththi, J.D. Ford, E.M. Bennett, Climate change and adaptation to social-ecological change: the case of indigenous people and culture-based fisheries in Sri Lanka, Clim. Change 162 (2020) 279–300. https://doi.org/10.1007/s10584-020-02716-3.

[98] S. Seitz, Coping strategies in an ethnic minority group: The Aeta of Mount Pinatubo, Disasters 22 (1998) 76–90. https://doi.org/10.1111/1467-7717.00076.

[99] D.P. Aldrich, M.A. Meyer, Social Capital and Community Resilience, Am. Behav. Sci. 59 (2015) 254–269. https://doi.org/10.1177/0002764214550299.

[100] A.K. Surjan, R. Shaw, “Eco-city” to “disaster-resilient eco-community”: A concerted approach in the coastal city of Puri, India, Sustain. Sci. 3 (2008) 249–265. https://doi.org/10.1007/s11625-008-0051-3.

[101] A. Nonomura, K. Fujisawa, M. Takahashi, H. Matsumoto, S. Hasegawa, Analysis of the actions and motivations of a community during the 2017 torrential rains in northern kyushu, Japan, Int. J. Environ. Res. Public. Health 17 (2020). https://doi.org/10.3390/ijerph17072424.

[102] L. Sun, Y. Deng, W. Qi, Two impact pathways from religious belief to public disaster response: Findings from a literature review, Int. J. Disaster Risk Reduct. 27 (2018) 588–595. https://doi.org/10.1016/j.ijdrr.2017.10.004.

[103] M. von Vacano, S. Schwarz, The Religious Dimension of Coping: The Roles of Cosmologies and Religious Practices, in: M. Zaumseil, S. Schwarz, M. von Vacano, G.B. Sullivan, J.E. Prawitasari-Hadiyono (Eds.), Cult. Psychol. Coping Disasters, Springer New York, New York, NY, 2014: pp. 245–264. https://doi.org/10.1007/978-1-4614-9354-9_12.

[104] R.M. Johnson, E. Edwards, J.S. Gardner, A.P. Diduck, Community vulnerability and resilience in disaster risk reduction: an example from Phojal Nalla, Himachal Pradesh, India, Reg. Environ. Change 18 (2018) 2073–2087. https://doi.org/10.1007/s10113-018-1326-6.

[105] R. Beilin, K. Reid, It’s not a “thing” but a “place”: Reconceptualising “assets” in the context of fire risk landscapes, Int. J. Wildland Fire 24 (2015) 130–137. https://doi.org/10.1071/WF14035.

[106] V. Lamb, Hydrosocial practice in an urbanising floodplain: Local management and dilemmas of beneficial flooding, Int. Dev. Plan. Rev. 42 (2020) 315–335. https://doi.org/10.3828/idpr.2019.5.

[107] M. Mutasa, Knowledge apartheid in disaster risk management discourse: Is marrying indigenous and scientific knowledge the missing link?, Jamba J. Disaster Risk Stud. 7 (2015). https://doi.org/10.4102/jamba.v7i1.150.

[108] A. Siambombe, Q. Mutale, T. Muzingili, Indigenous knowledge systems: A synthesis of batonga people’s traditional knowledge on weather dynamism, Afr. J. Soc. Work 8 (2018) 46–54.

[109] R. Bordoloi, A.U. Muzaddadi, Indigenous technical knowledge associated with disaster management and fisheries related activities in the highest flood affected district (Dhemaji) of Assam, India, Indian J. Tradit. Knowl. 14 (2015) 407–415.

[110] A. Sharma, Rebuilding after disaster: People, processes, and five percent technology, in: Routledge Handb. People Place 21st-Century City, 2019: pp. 263–272. https://doi.org/10.4324/9781351211543-29.

[111] J. Baumwoll, R.R. Krishnamurthy, Indigenous knowledge and disaster reduction in coastal areas, in: Indig. Knowl. Disaster Risk Reduct. Pract. Policy, 2009: pp. 27–44.

[112] S.E. Cho, S. Won, S. Kim, Living in harmony with disaster: Exploring volcanic hazard vulnerability in Indonesia, Sustain. Switz. 8 (2016). https://doi.org/10.3390/su8090848.

[113] I. Chowdhooree, Indigenous knowledge for enhancing community resilience: An experience from the south-western coastal region of Bangladesh, Int. J. Disaster Risk Reduct. 40 (2019). https://doi.org/10.1016/j.ijdrr.2019.101259.

[114] S.Z. Janif, P.D. Nunn, P. Geraghty, W. Aalbersberg, F.R. Thomas, M. Camailakeba, Value of traditional oral narratives in building climate-change resilience: Insights from rural communities in Fiji, Ecol. Soc. 21 (2016). https://doi.org/10.5751/ES-08100-210207.

[115] H. Takakura, Local agricultural knowledge as time manipulation: Paddy field farmers after the great east japan earthquake of 2011, Asian Ethnol. 77 (2018) 257–284.

[116] A. Agrawal, Indigenous knowledge and the politics of classification, Int. Soc. Sci. J. 54 (2002) 287–297. https://doi.org/10.1111/1468-2451.00382.

[117] C. Garcia, J. Blahut, M. Angignard, A. Pasuto, The importance of the lessons learnt from past disasters for risk assessment, 2014. https://doi.org/10.1007/978-94-007-6769-0_9.

[118] J. Garai, Qualitative analysis of coping strategies of cyclone disaster in coastal area of Bangladesh, Nat. Hazards 85 (2017) 425–435. https://doi.org/10.1007/s11069-016-2574-8.

[119] Z. Wang, J. Liu, N. Xu, C. Fan, Y. Fan, S. He, L. Jiao, N. Ma, The role of indigenous knowledge in integrating scientific and indigenous knowledge for community-based disaster risk reduction: A case of Haikou Village in Ningxia, China, Int. J. Disaster Risk Reduct. 41 (2019). https://doi.org/10.1016/j.ijdrr.2019.101309.

[120] B. Ahmed, P. Sammonds, N.M. Saville, V. Le Masson, K. Suri, G.M. Bhat, N. Hakhoo, T. Jolden, G. Hussain, K. Wangmo, B. Thusu, Indigenous mountain people's risk perception to environmental hazards in border conflict areas, Int. J. Disaster Risk Reduct. 35 (2019). https://doi.org/10.1016/j.ijdrr.2019.01.002.

[121] M.E. Andrews Deller, Space technology for disaster management : Data access and its place in the community, 2007. https://doi.org/10.1144/SP283.14.

[122] K. Brandt, L. Graham, T. Hawthorne, J. Jeanty, B. Burkholder, C. Munisteri, C. Visaggi, Integrating sketch mapping and hot spot analysis to enhance capacity for community-level flood and disaster risk management, Geogr. J. 186 (2020) 198–212. https://doi.org/10.1111/geoj.12330.

[123] L. Canevari-Luzardo, J. Bastide, I. Choutet, D. Liverman, Using partial participatory GIS in vulnerability and disaster risk reduction in Grenada, Clim. Dev. 9 (2017) 95–109. https://doi.org/10.1080/17565529.2015.1067593.

[124] J. Cools, P. Vanderkimpen, G. El Afandi, A. Abdelkhalek, S. Fockedey, M. El Sammany, G. Abdallah, M. El Bihery, W. Bauwens, M. Huygens, An early warning system for flash floods in hyper-arid Egypt, Nat. Hazards Earth Syst. Sci. 12 (2012) 443–457. https://doi.org/10.5194/nhess-12-443-2012.

[125] O.P. Dube, Challenges of wildland fire management in Botswana: Towards a community inclusive fire management approach, Weather Clim. Extrem. 1 (2013) 26–41. https://doi.org/10.1016/j.wace.2013.08.001.

[126] H.-C. Hung, C.-Y. Yang, C.-Y. Chien, Y.-C. Liu, Building resilience: Mainstreaming community participation into integrated assessment of resilience to climatic hazards in metropolitan land use management, Land Use Policy 50 (2016) 48–58. https://doi.org/10.1016/j.landusepol.2015.08.029.

[127] N.S. Hutton, T.R. Allen, The role of traditional knowledge in coastal adaptation priorities: The pamunkey indian reservation, Water Switz. 12 (2020). https://doi.org/10.3390/w12123548.

[128] Y. Isoda, A. Muranaka, G. Tanibata, K. Hanaoka, J. Ohmura, A. Tsukamoto, Strengths of exaggerated tsunami-originated placenames: Disaster subculture in Sanriku Coast, Japan, ISPRS Int. J. Geo-Inf. 8 (2019). https://doi.org/10.3390/ijgi8100429.

[129] S. Kienberger, Participatory mapping of flood hazard risk in Munamicua, District of Búzi, Mozambique, J. Maps 10 (2014) 269–275. https://doi.org/10.1080/17445647.2014.891265.

[130] S. Kienberger, P. Zeil, A. Castellano, When disaster strikes⋯, GEO Connex. 10 (2011) 38–41.

[131] S. Kubisch, J. Guth, S. Keller, M.T. Bull, L. Keller, A.C. Braun, The contribution of tsunami evacuation analysis to evacuation planning in Chile: Applying a multi-perspective research design, Int. J. Disaster Risk Reduct. 45 (2020). https://doi.org/10.1016/j.ijdrr.2019.101462.

[132] S. Murshed, D.J. Paull, A.L. Griffin, M.A. Islam, A parsimonious approach to mapping climate-change-related composite disaster risk at the local scale in coastal Bangladesh, Int. J. Disaster Risk Reduct. 55 (2021). https://doi.org/10.1016/j.ijdrr.2021.102049.

[133] C. Reichel, U.U. Frömming, Participatory Mapping of Local Disaster Risk Reduction Knowledge: An Example from Switzerland, Int. J. Disaster Risk Sci. 5 (2014) 41–54. https://doi.org/10.1007/s13753-014-0013-6.

[134] G. Thongs, Integrating risk perceptions into flood risk management: Trinidad case study, Nat. Hazards 98 (2019) 593–619. https://doi.org/10.1007/s11069-019-03720-2.

[135] P. Tran, R. Shaw, G. Chantry, J. Norton, GIS and local knowledge in disaster management: A case study of flood risk mapping in Viet Nam, Disasters 33 (2009) 152–169. https://doi.org/10.1111/j.1467-7717.2008.01067.x.

[136] P.J. Zweig, Collaborative risk governance in informal urban areas: The case of Wallacedene temporary relocation area, Jamba J. Disaster Risk Stud. 9 (2017). https://doi.org/10.4102/jamba.v9i1.386.

[137] T. Schilderman, Adapting traditional shelter for disaster mitigation and reconstruction: Experiences with community-based approaches, Build. Res. Inf. 32 (2004) 414–426. https://doi.org/10.1080/0961321042000250979.

[138] B. Chisadza, M.J. Tumbare, W.R. Nyabeze, I. Nhapi, Validation of local knowledge drought forecasting systems in the Limpopo River Basin in Southern Africa, Disaster Prev. Manag. 23 (2014) 551–566. https://doi.org/10.1108/DPM-02-2014-0032.

[139] B. Chisadza, M.J. Tumbare, W.R. Nyabeze, I. Nhapi, Linkages between local knowledge drought forecasting indicators and scientific drought forecasting parameters in the Limpopo River Basin in Southern Africa, Int. J. Disaster Risk Reduct. 12 (2015) 226–233. https://doi.org/10.1016/j.ijdrr.2015.01.007.

[140] E.S. Galacgac, C.M. Balisacan, Traditional weather forecasting for sustainable agroforestry practices in Ilocos Norte Province, Philippines, For. Ecol. Manag. 257 (2009) 2044–2053. https://doi.org/10.1016/j.foreco.2009.01.002.

[141] C. Li, Y. Tang, H. Luo, B. Di, L. Zhang, Local farmers' perceptions of climate change and local adaptive strategies: A case study from the Middle Yarlung Zangbo River Valley, Tibet, China, Environ. Manage. 52 (2013) 894–906. https://doi.org/10.1007/s00267-013-0139-0.

[142] Y. Uprety, U.B. Shrestha, M.B. Rokaya, S. Shrestha, R.P. Chaudhary, A. Thakali, G. Cockfield, H. Asselin, Perceptions of climate change by highland communities in the

Nepal Himalaya, Clim. Dev. 9 (2017) 649–661. https://doi.org/10.1080/17565529.2017.1304886.

[143] H. Zhang, H. Nakagawa, Validation of indigenous knowledge for disaster resilience against river flooding and bank erosion, in: Sci. Technol. Disaster Risk Reduct. Asia, Elsevier, 2018: pp. 57–76. https://doi.org/10.1016/B978-0-12-812711-7.00005-5.

[144] P.-S.S. Lin, K.-M. Chang, Metamorphosis from local knowledge to involuted disaster knowledge for disaster governance in a landslide-prone tribal community in Taiwan, Int. J. Disaster Risk Reduct. 42 (2020). https://doi.org/10.1016/j.ijdrr.2019.101339.

[145] K.T. Ton, J.C. Gaillard, J.R. Cadag, A. Naing, It takes two to tango: integrating meteorological knowledge and actions for disaster risk reduction, Clim. Dev. 9 (2017) 479–492. https://doi.org/10.1080/17565529.2016.1174658.

[146] B. Chisadza, M.J. Tumbare, I. Nhapi, W.R. Nyabeze, Useful traditional knowledge indicators for drought forecasting in the Mzingwane Catchment area of Zimbabwe, Disaster Prev. Manag. Int. J. 22 (2013) 312–325. https://doi.org/10.1108/DPM-10-2012-0109.

[147] I. Johnston, Traditional warning signs of cyclones on remote islands in Fiji and Tonga, Environ. Hazards 14 (2015) 210–223. https://doi.org/10.1080/17477891.2015.1046156.

[148] L. Pascua, The question of ‘knowledge’ about disaster risk reduction in sustainability education, in: Issues Teach. Learn. Educ. Sustain. Theory Pract., 2019: pp. 73–84. https://doi.org/10.4324/9780429450433-6.

[149] J.C. Gaillard, J. Mercer, From knowledge to action: Bridging gaps in disaster risk reduction, Prog. Hum. Geogr. 37 (2013) 93–114. https://doi.org/10.1177/0309132512446717.

[150] L. Le Dé, T. Rey, F. Leone, D. Gilbert, Sustainable livelihoods and effectiveness of disaster responses: a case study of tropical cyclone Pam in Vanuatu, Nat. Hazards 91 (2018) 1203–1221. https://doi.org/10.1007/s11069-018-3174-6.

[151] S. McDonnell, P. Ghorbani, C. Wolf, M.J. Cruz, D.M. Burgy, S. Desai, D. Berkovits, R. Silberblatt, A Managed-Participatory Approach to Community Resilience: The Case of the New York Rising Community Reconstruction Program, Am. Rev. Public Adm. 49 (2019) 309–324. https://doi.org/10.1177/0275074018804663.

[152] V. Ingham, S. Redshaw, Connecting community organisations for disaster preparedness, Int. J. Saf. Secur. Eng. 7 (2017) 52–64. https://doi.org/10.2495/SAFE-V7-N1-52-64.

[153] S. Vallance, An Evaluation of the Waimakariri District Council's Integrated and Community-Based Recovery Framework Following the Canterbury Earthquakes: Implications for Urban Resilience, Urban Policy Res. 33 (2015) 433–451. https://doi.org/10.1080/08111146.2014.980401.

[154] S.Z. Bonye, J.S. Godfred, Traditional coping mechanisms in disaster management in the Builsa and Sissala districts of Northern Ghana, Eur. J. Soc. Sci. 25 (2011) 204–218.

[155] D. Manalu, T.B. Soesilo, F.S.S.E. Seda, Socio-ecological aspects informing community resilience in a disaster-prone area: A Case Study of the Traditional Koa community in East Nusa Tenggara province of Indonesia, in: Sustain. Future Hum. Secur. Soc. Cities Gov., 2017: pp. 351–367. https://doi.org/10.1007/978-981-10-5433-4_24.

[156] P.D. Chakrabarti, Indigenous knowledge on disaster risk reduction and decision making in India, in: Indig. Knowl. Disaster Risk Reduct. Pract. Policy, 2009: pp. 431–444.

[157] I. Watson, Resilience and disaster risk reduction: reclassifying diversity and national identity in post-earthquake Nepal, Third World Q. 38 (2017) 483–504. https://doi.org/10.1080/01436597.2016.1159913.

[158] S.I.M. Timothy, L. Dominelli, L.A.U. Jocelyn, A Pathway to Initiate Bottom-up Community-Based Disaster Risk Reduction Within a Top-down System: The Case of China, Int. J. Saf. Secur. Eng. 7 (2017) 283–293. https://doi.org/10.2495/SAFE-V7-N3-283-293.

[159] R. Machida, H. Shimojima, J. Machida, N. Honda, Development of the disaster prevention and minimization educational program for reconstruction after the kumamoto earthquake, Int. J. GEOMATE 19 (2020) 28–35. https://doi.org/10.21660/2020.71.9190.

[160] O. Rodríguez-Espíndola, S. Despoudi, P. Albores, U. Sivarajah, Achieving agility in evacuation operations: an evidence-based framework, Prod. Plan. Control (2021). https://doi.org/10.1080/09537287.2020.1834132.

[161] E. Garnier, Lessons learned from the past for a better resilience to contemporary risks, Disaster Prev. Manag. Int. J. 28 (2019) 778–795. https://doi.org/10.1108/DPM-09-2019-0303.

[162] I. Kelman, J. Mercer, J. Gaillard, Indigenous knowledge and disaster risk reduction, Geography 97 (2012) 12–21.

[163] M.A. Masoga, Fires, burning and flames narratives: Reflections on some african indigenous perspectives, in: Biomass Burn. Sub-Sahar. Afr. Chem. Issues Action Outreach, 2020: pp. 121–141. https://doi.org/10.1007/978-94-007-0808-2_10.

[164] M.A. Rakib, S. Islam, I. Nikolaos, M. Bodrud-Doza, M.A.H. Bhuiyan, Flood vulnerability, local perception and gender role judgment using multivariate analysis: A problem-based "participatory action to Future Skill Management" to cope with flood impacts, Weather Clim. Extrem. 18 (2017) 29–43. https://doi.org/10.1016/j.wace.2017.10.002.

[165] A.B. Ponce-Pacheco, D.A. Novelo-Casanova, I.N. Agustin-Ortíz, A.B. Garduño-González, Risk perception in Unión Juárez, Chiapas, Mexico, Nat. Hazards 106 (2021) 855–879. https://doi.org/10.1007/s11069-020-04494-8.

[166] M.-U.-I. Choudhury, C. Emdad Haque, A. Nishat, S. Byrne, Social learning for building community resilience to cyclones: Role of indigenous and local knowledge, power, and institutions in coastal bangladesh, Ecol. Soc. 26 (2021). https://doi.org/10.5751/ES-12107-260105.

[167] S.K. Paul, J.K. Routray, An Analysis of the Causes of Non-Responses to Cyclone Warnings and the Use of Indigenous Knowledge for Cyclone Forecasting in Bangladesh, 2013. https://doi.org/10.1007/978-3-642-31110-9_2.

[168] K. Burningham, J. Fielding, D. Thrush, "It'll never happen to me": Understanding public awareness of local flood risk, Disasters 32 (2008) 216–238. https://doi.org/10.1111/j.1467-7717.2007.01036.x.

[169] D.K. Bird, G. Gísladóttir, D. Dominey-Howes, Different communities, different perspectives: Issues affecting residents' response to a volcanic eruption in southern Iceland, Bull. Volcanol. 73 (2011) 1209–1227. https://doi.org/10.1007/s00445-011-0464-1.

[170] S.J. Lambert, J.C. Scott, International disaster risk reduction strategies and indigenous peoples, Int. Indig. Policy J. 10 (2019). https://doi.org/10.18584/iipj.2019.10.2.2.

[171] M. Mawere, Indigenous knowledge for disaster risk management in Africa: Some showcases from Zimbabwe, in: Rhetor. Real. State Use Indig. Knowl. Post-Colon. Afr., 2015: pp. 19–38. https://muse.jhu.edu/book/40075.

[172] R. Howitt, O. Havnen, S. Veland, Natural and Unnatural Disasters: Responding with Respect for Indigenous Rights and Knowledges, Geogr. Res. 50 (2012) 47–59. https://doi.org/10.1111/j.1745-5871.2011.00709.x.

[173] K.M. Allen, Community-based disaster preparedness and climate adaptation: Local capacity-building in the Philippines, Disasters 30 (2006) 81–101. https://doi.org/10.1111/j.1467-9523.2006.00308.x.

[174] B.R. Cook, Disaster management culture in bangladesh: The enrolment of local knowledge by decision makers, in: Cult. Disasters Underst. Cult. Fram. Disaster Risk Reduct., 2015: pp. 193–207. https://doi.org/10.4324/9781315797809.

[175] J. Marin, J. Cortés, E. Aliste, J. Campos, Scientific controversy as a disaster risk factor: The 2007 seismic crisis in Patagonia, Chile, Int. J. Disaster Risk Reduct. 49 (2020). https://doi.org/10.1016/j.ijdrr.2020.101639.

[176] D. Botha, D. van Niekerk, Views from the frontline: A critical assessment of local risk governance in South Africa, Jamba J. Disaster Risk Stud. 5 (2013). https://doi.org/10.4102/jamba.v5i2.82.

[177] C. Choi, J. Choi, Distribution and application of community-based disaster risk information: Lessons from Shiga prefecture in Japan, J. Distrib. Sci. 16 (2018) 15–23. https://doi.org/10.15722/jds.16.6.201806.17.

[178] P.-S. Liu, N.W. Chan, The Malaysian flood hazard management program, Int. J. Emerg. Manag. 1 (2003) 205–214. https://doi.org/10.1504/IJEM.2003.003303.

[179] L. Saum-Manning, Best Practices and Lessons Learned from Community Engagement and Data Collection Strategies in Post-Hurricane Maria Puerto Rico, J. Homel. Secur. Emerg. Manag. (2021). https://doi.org/10.1515/jhsem-2020-0075.

[180] M.-F. Fan, Disaster governance and community resilience: reflections on Typhoon Morakot in Taiwan, J. Environ. Plan. Manag. 58 (2015) 24–38. https://doi.org/10.1080/09640568.2013.839444.

# Chapter 3

# Deriving expert-driven seismic and wind fragility functions for non-engineered residential typologies in Batanes, Philippines

## Abstract

Natural hazards inflict significant damage to dwellings in the Philippines where housing is often the most valued asset of households. Residential fragility functions estimate structural damage to mitigate risk but these are challenging to derive when empirical and analytical data are lacking, as is common in rural areas. Too often, conventional fragility estimates overlook the characteristics of informally built or non-engineered dwellings common in rural areas. We used a heuristic alternative of deriving fragility functions relying on experts' judgements to understand the housing performance of non-engineered residential typologies in the Province of Batanes in the Philippines. Drawing on field surveys in the Municipality of Itbayat, we identified and defined seven prominent typologies. Based on the Applied Technology Council's expert-driven method of deriving fragility functions, 18 experts estimated the damage states of these typologies against the impacts of earthquakes and typhoons which are the two most prominent hazards in the region. Our findings provide first-generation fragility functions for Batanes as a step towards more localised risk assessment in the Philippines. More broadly, these functions can be used for typologies identified beyond Batanes where similar structural characteristics are prevalent.

## 1 Introduction

Building back safer after disasters has been a consistent mantra for post-disaster reconstruction efforts under the Sendai Framework for Disaster Risk Reduction [1]. Dwellings in low- and middle-income countries are the most valued assets of households but these also tend to be the most disaster-affected [2]. To safeguard these assets, it is imperative to understand their structural performance against the impacts of hazards. The derivation of fragility functions captures structural performance of a building when it is subjected to an environmental excitation [3–6]. Fragility functions, often depicted graphically as a series of fragility curves, appraise risk by quantifying the relationship between a hazard intensity (e.g., seismic intensity or wind speed) and the probability of a component or structure reaching or exceeding a certain damage state [3–6].

The availability of fragility functions can support modelling natural hazard impacts and more informed targeting of structural safety programs. For example, deriving these functions can reveal vulnerable structural typologies in a building stock leading to risk prioritisation interventions. Hence, risk and loss estimation methods are usually anchored on deriving these functions, such as those developed by the United States Federal Emergency Management Agency (FEMA) [4,7–9]. However, in the context of resource-constraint communities, the limited data on past disaster damage and unregulated construction practices inhibit the derivation of fragility functions. While these functions are a foundational tool to understand structural safety and are useful for disaster preparedness, they are too often lacking in hazard-prone regions where they are critically important [10].

In rural areas in low- and middle-income countries, dwellings built informally by residents are common. These are either patterned from longstanding vernacular practices, borne out of the immediate need to have shelter (e.g., urgent reconstruction due to disaster impacts), or as a compromise to rising construction costs. In these cases, the construction of dwellings is usually non-engineered, with the absence or limited oversight of qualified building professionals [11]. As a result, housing typologies often exhibit a high variance of characteristics compared to conventional building typologies designed and constructed based on prevailing building codes and standards. While these non-engineered structures are not prejudiced to be deficient in structural safety and may, in fact, reveal sound locally developed building practices [12], their structural performance is less documented and certain. Furthermore, the exposure of dwellings to multiple natural hazards hinders our understanding of their performance when assessed against competing impacts on structures. Building-level disaster risk reduction (DRR) measures have shown how multi-hazard trade-offs and asynergies complicate building more resilient dwellings. That is, where construction practices may reduce the impact of risk to one hazard, such can exacerbate the risk to another hazard [13,14].

Depending on the available sources of damage data, fragility functions can be derived in various ways [5,15]. When documented post-disaster damage data is available, empirical methods can be used. If resources allow for the simulation or modelling of structural typologies, analytical methods can be employed. When both resources are lacking, a heuristic alternative is to solicit experts' opinions to derive the functions. A fourth approach is a hybrid of at least two methods. Further discussion about these four methods, including an overview of past studies using specific approaches, can be found in Maio & Tsionis et al. [16] and Rossetto et al. [17]. Previous attention to deriving these functions has primarily focused on a structure's performance to a single hazard. Recently, there has been a growing emphasis in academic, policy, and practice environments to incorporate multi-hazard approaches to realise effective DRR strategies [14,18,19].

Hazards impact a structure differently thereby requiring a combination of strategies and approaches to reduce or mitigate risk [13,14]. Deriving multi-hazard fragility functions can therefore offer insights on how to optimise trade-offs in construction decisions. The scarcity of data and technical resources are, however, roadblocks in rural contexts in low- and middle-income countries. The expert-driven approach is often the only possible method in the absence of empirical and analytical data [16,20–22]. Elicitation of experts' opinions has been used in various disciplines to produce the fragility functions of components of interests, extending from structural engineering [20,23–25], hydrology [10,22], and civil engineering [26]. The ATC-58 project of the Applied Technology Council (ATC) aimed to develop next-generation seismic design assessment standards, and the expert-driven method is adopted among other approaches to derive fragility functions as formalised through a proposed method of solicitation and aggregation of experts' opinions [27,28]. The main strength of this approach is that experts can include in their assessment all factors affecting the response of a structure against hazards, unlike empirical and analytical methods where these are limited to the quantity and quality of available data [15]. The major drawback of expert-driven methods is the subjectivity associated with experts' experience and trust in their judgement [15]. However, when dealing with non-engineered residential typologies, experts' experience is beneficial to capture the varied structural performance arising from the inherent variability of the design and construction of these building classes.

The objective of this study was to derive fragility functions for non-engineered residential typologies in the Province of Batanes – the storm-battered northernmost part of the Philippines. We drew on field surveys in the Municipality of Itbayat to identify relevant typologies for the Province of Batanes. The remote island municipality of Itbayat was home to vernacular stone-and-lime houses, like elsewhere in Batanes, built out of tradition to withstand typhoon impacts.

Unfortunately, these dwellings were extensively damaged following the series of destructive earthquakes (magnitudes ($M_w$) 5.4, 5.9, 5.8) in 2019 [29,30]. These disasters redefined the construction practices in the area with a departure from the stone-and-lime character of the building stock. We surveyed the existing building stock three years later and identified the most prominent typologies that households chose to build to replace these vernacular dwellings. Based on the expert-driven approach of deriving fragility functions developed in ATC-58, a pool of experts estimated the seismic and wind performance of both the vernacular and replacement typologies.

The rest of the paper is structured as follows. The Methods section characterises the research procedures and protocols undertaken for this study. Next, under the Results section, we present the identified housing typologies and the derived fragility functions. The Discussion section then provides insights gleaned in using the expert-driven approach in deriving fragility functions. Lastly, in the Conclusion section, we summarise the theoretical and practical implications of this study.

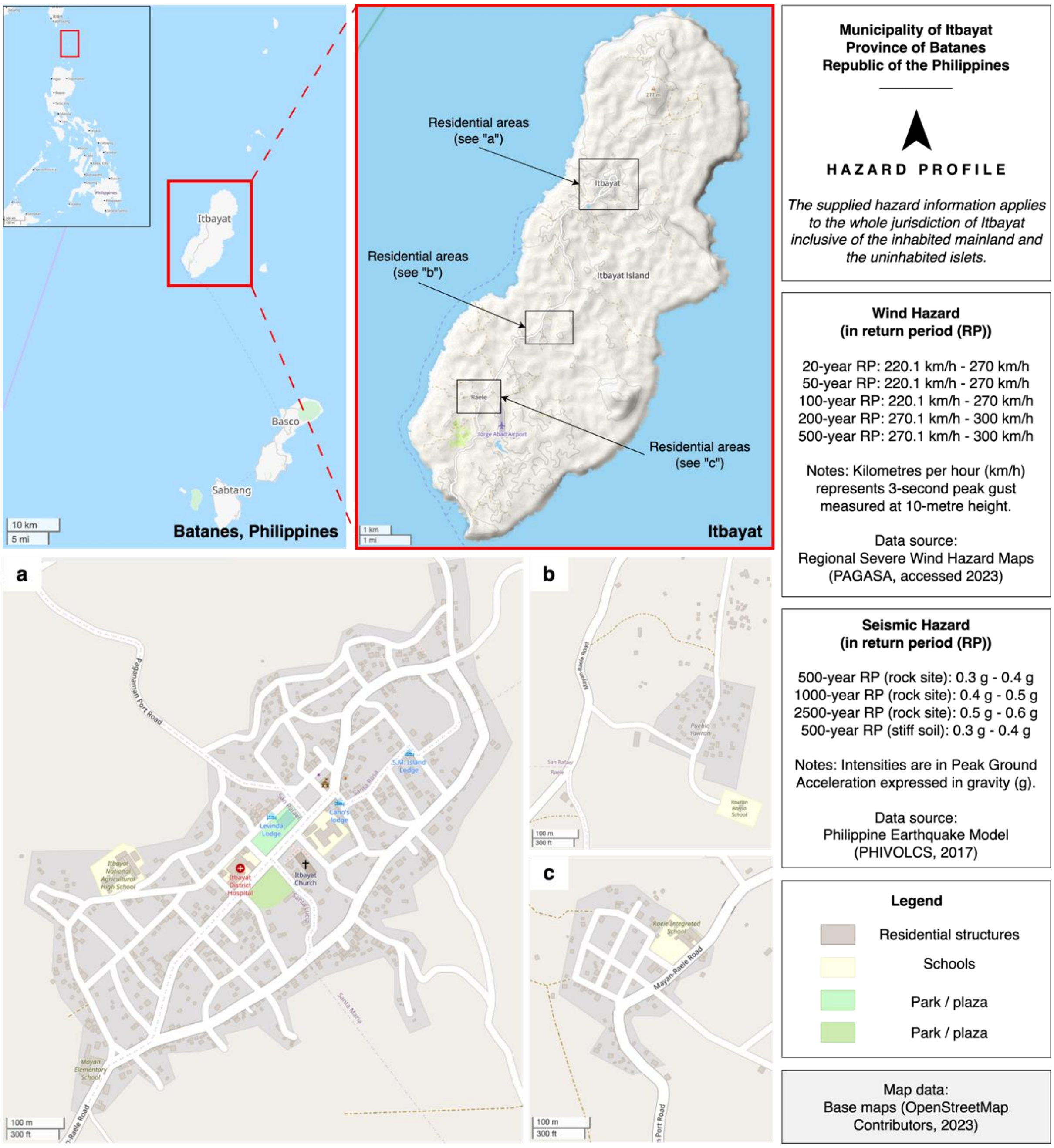
## 2 Methods

Below, we outline how we surveyed the housing typologies, followed by the process of soliciting and aggregating experts' estimates. We then present how we derived the fragility functions. Lastly, we provide information on the research ethics protocols and permits obtained for this study.

### *2.1 Identification of housing typologies*

Identifying a building typology is the first step in building-level risk estimation as this serves as the object of analysis for fragility functions. A typology, usually labelled with a taxonomy (string), characterises a building class from attributes posing vulnerability to the impacts of natural hazards [4,31]. For example, for earthquake risk, structures are classified according to the (i) type of lateral load-resisting system, (ii) material of lateral load-resisting system, (iii) building height, and (iv) seismic code level (or the period of construction of a structure vis-à-vis the enforcement of seismic regulations). Such attributes are the core parameters used in risk analysis by many organisations, such as FEMA for HAZUS [7] and the Global Earthquake Model (GEM) [31]. For typhoon risk, the same set of attributes are relevant, but with wind-induced damage concentrated on walls and roofs [32,33], building envelope materials and roof profile are usually considered in conjunction [34]. In this study, we used all these attributes – except for the seismic code level – to inform the development of a rapid visual survey to assess the attributes of a building stock. The seismic code level was omitted because the housing typologies surveyed were non-engineered, with formal seismic regulations having limited applicability to these types of structures.

The rapid visual surveys were conducted in January 2023 using the five building attributes as the parameters of the assessment. For lateral load-resisting systems, we referred to the expanded classifications and definitions of the GEM taxonomy [35] since their database accounts for the structural characteristics of non-engineered construction [31]. The field study aimed to understand the housing reconstruction strategies of households after the 2019 earthquakes in the Municipality of Itbayat, located in the Province of Batanes in the Philippines (see Figure 3.1). Hence, we focused the surveys on the emergent (or replacement) typologies constructed by households who were living in vernacular stone-and-lime houses before the earthquakes but were forced to rebuild due to the extensive damage to this typology. This pre-earthquake typology was also surveyed. Out of the 153 households identified from the joint report of the Municipal Disaster Risk Reduction Office (MDRRMO) and the Municipal Planning and Development Office (MPDO) in Itbayat, we were able to survey 101 structures. The remaining houses were not surveyed due to the unavailability of households despite multiple attempts at the time of the survey (n = 35) or where households did not reconstruct their houses and have either migrated to a different municipality or living with relatives (n = 17). In surveying the attributes of the stone-and-lime housing typology, we relied on households’ recollection about the features of their past dwelling. We also triangulated these features via archival research (e.g., photo documentation from the National Commission on Indigenous Peoples (NCIP)), desk research (e.g., publications [36–40]), and field visits to a few standing archetypes in the municipality. For the emergent housing typologies after the earthquakes, these were surveyed as all the necessary information was observable onsite.



**Municipality of Itbayat**
**Province of Batanes**
**Republic of the Philippines**

**HAZARD PROFILE**

*The supplied hazard information applies to the whole jurisdiction of Itbayat inclusive of the inhabited mainland and the uninhabited islets.*

**Wind Hazard**
**(in return period (RP))**

20-year RP: 220.1 km/h - 270 km/h
50-year RP: 220.1 km/h - 270 km/h
100-year RP: 220.1 km/h - 270 km/h
200-year RP: 270.1 km/h - 300 km/h
500-year RP: 270.1 km/h - 300 km/h

Notes: Kilometres per hour (km/h) represents 3-second peak gust measured at 10-metre height.

Data source:
Regional Severe Wind Hazard Maps
(PAGASA, accessed 2023)

**Seismic Hazard**
**(in return period (RP))**

500-year RP (rock site): 0.3 g - 0.4 g
1000-year RP (rock site): 0.4 g - 0.5 g
2500-year RP (rock site): 0.5 g - 0.6 g
500-year RP (stiff soil): 0.3 g - 0.4 g

Notes: Intensities are in Peak Ground Acceleration expressed in gravity (g).

Data source:
Philippine Earthquake Model
(PHIVOLCS, 2017)

**Legend**

▨ Residential structures
▨ Schools
▨ Park / plaza
▨ Park / plaza

Map data:
Base maps (OpenStreetMap Contributors, 2023)

**Figure 3.1**. Map of Itbayat, Batanes in the Philippines.

## *2.2 Solicitation of experts' opinion*

After identifying the predominant housing typologies, we selected a pool of experts to estimate the damage states of these typologies. In qualifying "expertise", we recognised both the inputs of those who are locally based ("local experts") and those who are not but with relevant insights on the housing performance of non-engineered typologies in the country ("specialists"). Local experts included the municipal engineers for all six municipalities in Batanes and district engineers at the provincial level. These roles assume building regulatory responsibilities in the targeted jurisdictions encompassing extensive experience with local damage impacts from past earthquakes and typhoons in Batanes.

For the specialists, their expertise was sought because of their familiarity with the dynamics of the typologies of interest. While the impacts of hazards vary in different geographical contexts, the specialists' judgements were considered reliable if they were acquainted with the common damage mechanisms or expected performance of these structures in the Philippine setting. We relied on academic publications and technical reports focused on seismic and wind field assessments as the basis for identifying specialists. We identified documents on Google Scholar and Scopus employing a permutation of the following keywords: "housing", "damage", "Philippines", "disaster", "shelter", "assessment", "wind OR typhoon", and "seismic OR earthquake". From this query, we shortlisted relevant documents, and then conducted literature snowballing to trace other documents not captured by the keyword search. The authors of these documents were then compiled. Finally, we shortlisted those with civil, structural, or construction engineering backgrounds.

Porter et al. [27] developed a method to systematically solicit and aggregate experts' opinions to derive fragility functions. This is among the methods of damage analysis developed for the ATC for its next-generation probabilistic assessment of structures adapted from the Pacific Earthquake Engineering Research Centre [27]. Unlike behavioural means of aggregating experts' opinions wherein participants interact with each other and arrive at a consensus, this proposed method uses a mathematical approach to consolidate distinct inputs of participants [17]. Consultation with experts and combining their individual judgements provide a worthwhile basis for assessment [41] since consensus-based approaches might reflect mere conformity among experts rather than genuine agreement [24]. While developed for seismic applications, the expert-driven method for ATC explicitly focuses on aggregating experts' opinions. It can therefore be adaptable if the required information on component types, damage states, and engineering demand parameters (EDPs) are contextualised to the impacts of hazards of interest. Hence, we used this method in deriving both the fragility functions against the impacts of earthquakes and typhoons. The procedure asks experts to estimate the (median and lower-bound) values of a specified EDP with respect to the presented component type and damage states, alongside their self-assessed level of expertise. The use of EDP, however, is less relevant when the components of interest are low-rise non-engineered housing typologies. For example, inter-story drift ratio, being one of the most common EDPs [42,43], is best suited for multi-story components because of the need to analyse relative translational displacement of floor levels. In this regard, it was imperative to substitute EDP with the intensity measure of a hazard.

A survey form adapted from Porter et al. [27] was developed for this study. For earthquakes, we used the Philippine Institute of Volcanology and Seismology (PHIVOLCS) Earthquake Intensity Scale (PEIS) as the intensity measure, ranging from numeral I (weakest, “scarcely perceptible”) to X (strongest, “completely devastating”) [44]. This intensity scale, developed by PHIVOLCS, considers the common building construction types in the Philippines and the population’s perception of shaking strength, thus making it the official intensity scale in the country since 1996 [45]. PEIS is comparable to the widely used Modified Mercalli Intensity (MMI) scale in that intensities I to VII represent the same effect of ground shaking, while PEIS VIII is similar to MMI VIII – IX; PEIS IX to MMI X – XI; and PEIS X to MMI XII [45,46]. We opted to use earthquake intensity instead of Peak Ground Acceleration (PGA) because the local engineers surveyed were more familiar with damage relationships with instrumental intensities. This is due to the lack of localised seismic hazard maps until recently and the limited use of PGA as a design parameter in the current National Structural Code of the Philippines. In addition, instrumental intensities can be converted to PGA when conversion equations of intensities and ground motion become available [47] with applicability to the geographical context of interest. With the absence of such conversion equations for the Philippines for the time being, using PEIS is logical since building damageability has been long attributed to instrumental intensities within the country. Forcing the use of PGA considering such context would introduce significant, and in our view – unjustified, uncertainty in the fragility functions.

The damage states defined by FEMA for earthquake loss estimation [4,7] were used after contextualising them to the structural properties of the identified typologies. We used these damage states because of their specificity in describing structural conditions. Thus, these well-delineated descriptions of structural failure for each damage state helped eliminate ambiguity in assessing stages of structural failure [6]. These are categorised within five damage states (DS), namely: no/very minor (DS1), minor (DS2), moderate (DS3), extensive (DS4), and complete (DS5) (see Table 3.1).

For typhoons, we used 3-second peak gust wind speed in kilometres per hour (km/h) as the intensity measure, ranging from 0 km/h to 400 km/h. The maximum value was capped at 400 km/h – a reasonable and realistic upper bound based on the intensity ranges of the strongest typhoons recorded in the country. For example, Typhoon Haiyan (Yolanda), one of the strongest typhoons to hit the country, had an estimated peak gust of 324 km/h to 378 km/h [48]. The damage states for wind impacts were based on FEMA [8,9] for the same reason that they have specific delineations of structural conditions. The damage states are categorised into five, namely: no/very minor (DS1), minor (DS2), moderate (DS3), extensive (DS4), and complete (DS5) (see Table 3.1).

**Table 3.1**. Damage states for earthquake and typhoon impacts. Adapted from Kircher et al. [4], FEMA [7], FEMA [8], and Vickery et al. [9].

| Damage State (DS) | Earthquake | Typhoon |
|---|---|---|
| **DS1 – No/very minor damage** | None or very minor damage | None to very minor damage. Roof cover loss of less than 2% with no or limited water penetration. |
| **DS2 – Minor damage** | Small (≤1/8 inch or ≤ 3 mm) cracks or hairline cracks at corners of doors, windows, wall ceiling intersections, connections (e.g., on welds, beam and column joints, etc.), wall surfaces; spalling at a few locations (for typologies with concrete components) | Roof cover loss of 2% to 15% of the roof area but can be temporarily covered to prevent water seepage. Roof structure remains intact. Maximum of one window/door failure. No failure of wall structure but marks/dents are visible which can be repaired by painting/patching. |
| **DS3 – Moderate damage** | Large (>1/8 inch or > 3 mm) cracks at corners of doors and windows, connections (e.g., on welds, beam and column joints, etc.), wall surfaces; permanent rotation at connections are likely; spalling at wall ends (for typologies with concrete components) | Roof cover loss of above 15% to 50% of the roof area. Roof structure remains intact. Moderate window breakage. Water penetration causes some interior damage to the structure. No failure of wall structure. |
| **DS4 – Extensive damage** | Partial collapse, characterised by failed connections/critical elements, permanent lateral movement of floors, roof, beams, etc., extensive large/through-the-wall cracks (for concrete/masonry components) or out-of-plane failure | Roof cover loss of more than 50%. Roof structure remains intact. Major window damage. Water penetration causes extensive damage to the interior of structure. No failure of wall structure. |
| **DS5 – Complete damage** | Total collapse, or in imminent danger of collapse, due to failed lateral-load resisting system | Complete roof failure and/or failure of wall structure. |

The content of the expert survey form was divided into three parts: (1) information on the housing typologies, (2) earthquake assessment, and (3) typhoon assessment. For the first part, actual images of the typologies taken onsite were provided, alongside descriptions of the type and materials of their lateral load-resisting systems, building height, wall materials, and roof profile. For the second part, information about the recorded intensities of the 2019 earthquakes in Itbayat (and the felt intensities in surrounding municipalities) [30] was provided to help orient the respondents about the intensity measure used. Similarly, for the third part, information about the known intensities of Typhoon Ferdie (Meranti) in 2016 and Typhoon Yolanda (Haiyan) in 2013 was supplied with a sample of the regional wind hazard map of the Philippines. For both the second and third part, the respective damage states were presented, leading to the assessment section. The experts were asked to estimate what PEIS intensity (for earthquake) and 3-s peak gust wind speed (for typhoon) will yield each of the damage states (DS1 to DS5) for each of the typologies. The experts were asked to provide both median and lower-bound intensities, following the method of Porter et al. [27,28]. We explained the median as, "What hazard intensity can bring the specified damage state to *50%* of the residential structures having the same typology?" For the lower bound, it was explained as, "What hazard intensity can bring the specified damage state to *10%* of the residential structures having the same typology?" Lastly, experts were also asked to rate their level of confidence with the range of estimates they provided for each typology, ranging from 1 (low) to 5 (high). Note that we used the term level of confidence instead of level of expertise to emphasise that we were interested in the trust in their estimates and not with their professional standing as this was pre-assessed before invitation using the methods described above.

The surveys were conducted online from May 2023 to July 2023. In total, we sent 57 survey invites to the roster of local experts and specialists we identified earlier. Eighteen (18) agreed to participate, five declined, and 34 did not respond. The respondents comprised seven local experts and 11 specialists. Two local experts decided to provide a single response while two specialists expressed confidence in answering only either the earthquake or typhoon assessment. We therefore collected 16 unique responses per assessment. In using expert judgement to quantify scientific uncertainty, it is suggested that 8 – 15 experts are reasonable, with diminishing returns becoming evident from having 20 or more participants [49]. Recent studies that used expert judgement for engineering applications have relied on this range of the number of experts involved [10,20,24]. Additionally, comprehensive insights of experts can be derived despite a limited size of cohort if and when participants are selected systematically based on their expertise aligning with the context of the assessment [49]. Finally, in the method utilised for this study, fragility functions derived through experts' estimates are considered to be of medium quality (the highest benchmark specified) when at least three experts have $\geq 3$ level of confidence [27,28].

### 2.3 Aggregation of experts' opinion

The median and lower-bound values of experts' estimates of hazard intensities and the corresponding levels of confidence were used as inputs for Equations 1 to 3 which are part of the method developed by Porter et al. [27,28]. These equations are based on probability encoding and expert qualification and a full transcript of their derivation is found in Porter et al. [28].

$$x_m = \frac{\sum_{i=1}^{N} w_i^{\alpha} x_{mi}}{\sum_{i=1}^{N} w_i^{\alpha}} \tag{1}$$

$$x_l = \frac{\sum_{i=1}^{N} w_i^{\alpha} x_{li}}{\sum_{i=1}^{N} w_i^{\alpha}} \tag{2}$$

$$\beta = \frac{\ln\left(\frac{x_m}{x_l}\right)}{1.28} \tag{3}$$

If Equation 3 produces $\beta < 0.4$, either justify the $\beta$, or use Equation 2 and Equation 4:

$$\begin{aligned} \beta &= 0.4 \\ x_m &= 1.67 x_l \end{aligned} \tag{4}$$

where:

$N$ = number of experts providing judgment about a value

$i$ = index of experts, $i$ {1, 2,…$N$}

$x_{mi}$ = estimated median intensity measure of expert $i$

$x_{li}$ = estimated lower-bound intensity measure of expert $i$

$w_i$ = level of expertise of expert $i$

$\alpha$ = 1.5

These equations weight experts' estimates based on their levels of confidence. The constant value of $\alpha$ renders that estimates with an assigned level of confidence of 3 are weighted five times more than just a confidence of 1, while a confidence of 5 is weighted around twice as much as 3. The constant values in Equation 3 and 4 anchor the dispersion between the median and lower-bound values to suggest a reasonable range within these. For this study, we did not use Equation 4 and instead just used the calculated $\beta$. At least for the context of this assessment, there is no plausible argument to have a definitive threshold to maintain a reasonable gap between the solicited median and lower-bound values. For example, a difference of just 1 PEIS intensity can have pronounced implications for housing damage, as with a 0.5 difference, depending on how these structures are built. For wind speeds, a difference of 10 km/h might already bring lower-bound and median probabilities of damage to certain typologies, while for others, higher wind speeds bring more pronounced housing damage.

### *2.4 Plotting of fragility functions*

Fragility functions define the probability of a damage state *ds* being exceeded or reached for a component, given a particular value of intensity measure *im*, such that P[DS ≥ ds | IM = im]. In this expression, lowercase notations indicate particular values of the uppercase variables. Fragility functions are most commonly idealised through a lognormal cumulative distribution function [5,6,50] (see Equation 5). Each fragility function needs a median value ($x_m$) of the intensity measure representing the threshold and the variability of a damage state, and a logarithmic standard deviation ($\beta$) describing the total variability of the damage states [4].

$$P[DS \geq ds \,|IM = im] \;=\; \phi\left(\frac{\ln(im/x_m)}{\beta}\right) \tag{5}$$

where:

$ds$ = specific damage state

$im$ = particular value of intensity measure

$\phi$ = standard normal cumulative distribution function

$x_m$ = median value of distribution (as derived in Equation 1)

$\beta$ = logarithmic standard deviation (as derived in Equation 3)

In plotting the fragility functions, we used the *plnorm()* function in RStudio which idealises the lognormal cumulative distribution function. We used the calculated $x_m$ and $\beta$ values from Equation 1 and Equation 3. For the $x_m$ inputs, we first calculated their lognormal values to standardise on the log scale before feeding them into the function. For one typology (LW-B), we encountered a minor crossing of two functions (damage states). Crossing of curves implies a meaningless negative probability and this was addressed using Equation 6 and Equation 7 to adjust $x_m$ and $\beta$ values as proposed by Porter et al. [27,28]. Where functions $i$ and $j$ cross having medians $x_{mj} > x_{mi}$ and $\beta_i \neq \beta_j$, the adjusted values $x'_{mi}$ and $\beta'_i$ were calculated.

$$\beta'_i = \frac{1}{N}\sum_{i=1}^{N}\beta_i \;\; for\ all\ i \tag{6}$$

$$x'_{mi} = \exp(1.28(\beta' - \beta_i) + \ln x_{mi}) \tag{7}$$

### *2.5 Ethics and inclusion statement*

All procedures performed involving human subjects were in accordance with the Human Research Ethics Committee of The University of Sydney under the approved protocol 2022/705. The field study site was located on the ancestral domain of the Indigenous people of Itbayat. A free prior-informed consent was obtained from the National Commission on Indigenous Peoples under Certificate of Precondition R2-IKSP-2022-12-21.

# 3 Results

## *3.1 Identified housing typologies*

### *3.1.1 Unreinforced masonry*

Before the series of earthquakes in 2019, unreinforced masonry ("URM") dwellings were the vernacular housing archetype in the municipality of Itbayat like elsewhere in the province of Batanes. This typology is characterised by thick (0.80 m – 1 m in width) coral limestone walls bounded by quicklime mortar and roofed with layered cogon. Unique in Batanes, this typology is of Spanish colonial influence adapted by the Ivatans in response to frequent typhoons [38,40]. With wind-induced damages common in this context, features to safeguard the structure include solid wooden panels with shutters to cover openings, a low stature of the structure for better wind resistance, and a blank wall facing the direction where wind blows strongest. Whilst responsive against wind impacts as per locals' experience, this typology proved vulnerable to ground shaking – evident on the extensive damage experienced following the maximum intensity of PEIS VII from the 2019 earthquakes [30]. A conservative estimate based on field data suggests that there are fewer than ten structures remaining of such typology in Itbayat, though much can still be seen in most municipalities in Batanes. Post-earthquake, the household-led reconstruction resulted in a departure from the vernacular construction styles. New typologies emerged due to regulatory restrictions affecting traditional resource extraction of building materials (e.g., hardwood, limestones, and cogon), the favourability of contemporary construction methods, and the presence of modern shelter materials donated by organisations. Six prominent housing typologies were identified replacing URM which account for 91% of the surveyed building stock. These include variations of lightweight, semi-concrete, and reinforced concrete (RC) dwellings (see Figure 3.2 and Figure 3.3).

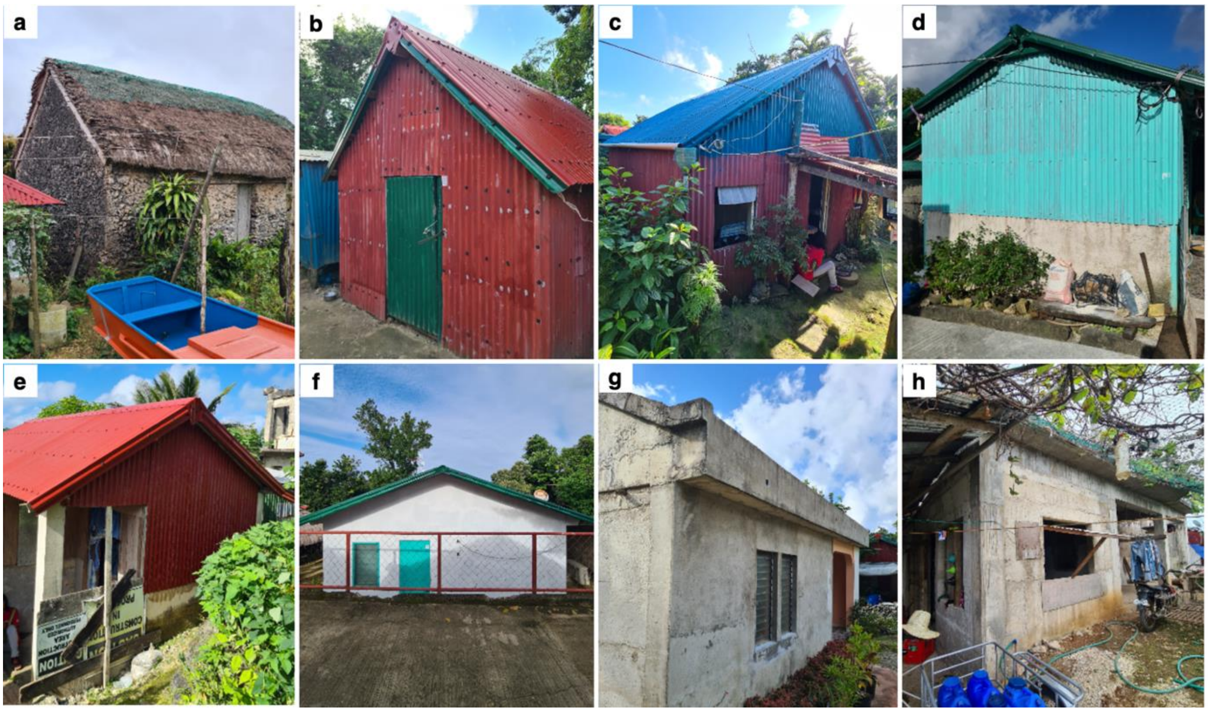


**Figure 3.2.** The surveyed housing typologies in Itbayat. **(a)** Unreinforced masonry (URM). **(b)** Lightweight with wooden posts (LW-A). **(c)** Lightweight with steel posts (LW-B). **(d)** Semi-concrete with steel posts (SC-A). **(e)** Semi-concrete with RC posts (SC-B). **(f)** RC structure with lightweight roofing (RC-A) where in some instances, inside gutters are common to conceal the edges of roofing sheets as shown in **(g)**. **(h)** RC structure with RC slab roofing (RC-B).

**Figure 3.3.** Structural details documented across the typologies surveyed. **(a)** Roof-to-wall connection where thick logs are embedded in stone walls and **(b)** layered thatch (cogon) roofing with reed matting are features of URM. **(c)** Improvised rubber washers for nail fasteners are used for typologies with CGI sheets. For LW-A, common post-and-beam connections are **(d)** bolted, **(e)** hooked with reinforcing steel bars, and **(f)** nailed. For LW-B and SC-A, common post-and-beam connections are **(g)** bolted, **(h)** notched and clipped, and **(i)** hooked with reinforcing steel bars. For SC-B, typical post-and-beam connections are **(j, k)** dowels wrapped around beams and roof members. For RC-A, **(l)** roof-to-wall connections are common to be via dowels from reinforcing steel bars wrapping the wooden roof members. For RC-B, **(m)** beams and columns are reinforced concrete supporting the slab roof.

### *3.1.2 Lightweight*

Two variations of lightweight structures were identified, both having post-and-beam lateral load-resisting systems. The first variation ("LW-A") features timber beams and timber columns for primary (corner) posts, where the columns do not have footings and are only driven underground. The beam-to-column connections vary with the use of bolts, nails, and improvised hooks made from reinforcing steel bars (RSB). The second variation ("LW-B") of lightweight structures has primary (corner) posts made of 4-inch to 5-inch diameter steel pipes with RC footing and with timber beams. These components are connected via bolts, improvised hooks made from RSB, and in some instances, the beams are notched and clipped inside the steel pipes. Both lightweight typologies are one-story structures having gable roof profiles, where their roof eaves rarely exceed 300 millimetres (mm). Roof and walls are enveloped by corrugated galvanised iron (CGI) sheets fastened every other one or two corrugations on wooden frames using common wire nails with improvised rubber washers. Additional timber posts as intermediate supports are used. CGI or plywood covers for door openings are common and the same for windows alongside jalousie (louvred) glass. Of the surveyed residential building stock, 17% and 25% account for LW-A and LW-B, respectively.

### *3.1.3 Semi-concrete*

For semi-concrete structures, two variations were surveyed, both having hybrid lateral load-resisting systems. These typologies have post-and-beam systems in combination with half-height RC walls at the base of the structure providing additional lateral stiffness. The first variation of semi-concrete structure ("SC-A") has primary (corner) posts made of 4-inch to 5-inch diameter steel pipes with RC footing and with timber beams. The beam-to-column connections vary with the use of bolts, improvised hooks made from RSB, and in some instances, the beams are just notched and clipped inside the steel pipes. The second variation ("SC-B") has RC columns with RC footing. The columns have dowels on top used to wrap and fasten the timber beams (and sometimes together with roof members). Both semi-concrete typologies are one-story structures having gable roof profiles, where their roof eaves rarely exceed 300 mm. Roof and walls are enveloped by CGI sheets fastened every other one or two corrugations on wooden frames using common wire nails with improvised rubber washers. Additional timber posts as intermediate supports are used. CGI or plywood covers for door openings are common and the same for windows alongside jalousie (louvred) glass. SC-A has a 17% share of the surveyed building stock, while SC-B has 14%.

### *3.1.4 Reinforced concrete*

Two types of RC structures were identified – one with lightweight roofing ("RC-A") and the other one with RC slab roofing ("RC-B"). RC-A has a gable roof configuration with eaves rarely exceeding 300 mm. The CGI roof panels are fastened to wooden roof members using common wire nails with improvised rubber washers. Meanwhile, RC-B has a flat slab with eaves typically exceeding 300 mm. Both RC typologies are one-story structures having RC posts (including footings), beams, and walls. As such, these are considered to have hybrid lateral load-resisting systems characterised by their moment frame connections in combination with RC walls providing additional lateral stiffness. CGI or plywood covers for door openings are common and the same for windows alongside jalousie (louvred) glass. Of the surveyed residential building stock, 9% are RC-A and 9% are RCB.

All the typologies identified in this study are considered non-engineered due to limited regulatory building oversight. For URM, building codes and standards were not yet in place, or perhaps limited, when these structures were constructed (circa ~1900s). In 2019 after the earthquakes, the housing reconstruction phase coincided with the typhoon season, and although the need for a building permit was not explicitly waived, the sense of urgency dictated the thrust of the household-led rebuilding influenced by the resources available to households. For example, those who chose to build LW-A and LW-B initially envisioned these as temporary, intending to build more permanent dwellings later, but financial limitations precluded this from happening. Nevertheless, building materials were carefully selected in some instances. For example, local hardwood was favoured over commercial timber for main structural elements such as rafters and beams. For those who chose to build concrete typologies, imported commercial aggregates from mainland Luzon were desired for their quality. However, since the importation of materials would inflate building costs, households used local aggregates (crushed coral limestones) for walls while commercial aggregates were used for beams and columns.

## *3.2 Fragility functions*

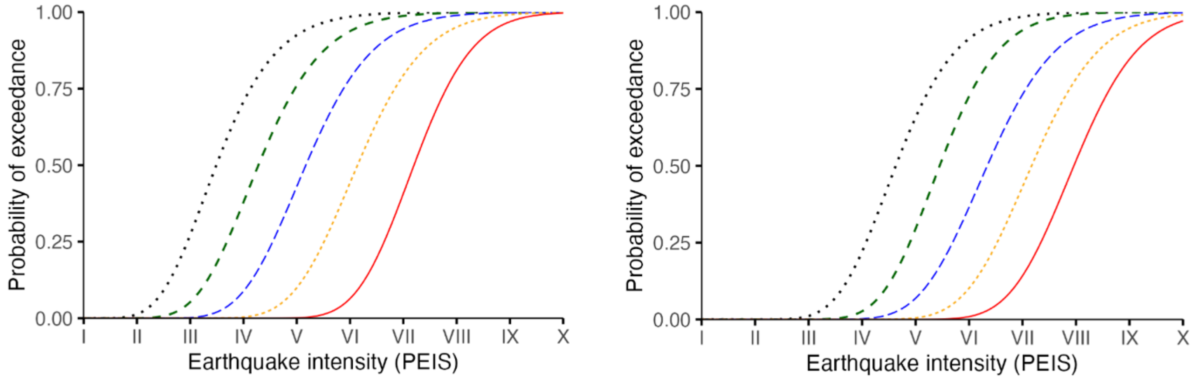
The fragility functions derived in this study, presented in Figure 3.4 and Figure 3.5, are based on the calculated $x_m$ and $\beta$ values shown in Table 3.2. For seismic impacts, URM has a 27% probability of reaching or exceeding very minor damage (DS1) at PEIS III. This intensity is of weak shaking comparable to the vibration of a passing light truck. The rest of the typologies have negligible probabilities (almost 0%) to any damage state at this intensity. At PEIS V, described as strong shaking with a rocking effect on buildings, all typologies except for URM show a 45% to 69% probability of meeting or exceeding DS1 and a likelihood of $\leq 30\%$ of DS2 (minor damage) and DS3 (moderate damage). Meanwhile, at a very destructive shaking (PEIS VIII) where many well-built buildings are expected to be considerably damaged, URM structures have a 95% probability of reaching or exceeding DS4 (extensive damage) and 81% for complete damage (DS5). For lightweight typologies, there are 78% (LW-A) and 75% (LW-

B) probabilities of meeting or exceeding DS4, and 52% (LW-A) and 33% (LW-B) likelihood for DS5. For semi-concrete typologies, still considering PEIS VIII, there is 76% (SC-A) and 81% (SC-B) probabilities of reaching or exceeding DS4, and 33% (SC-A) and 42% (SC-B) probabilities for DS5. For RC typologies, DS4 has 70% (RC-A) and 76% (RC-B) chances of being reached or exceeded, while 25% (RC-A) and 42% (RC-B) for DS5. Generally, URM tends to be the most vulnerable typology to seismic impacts while the other typologies perform better, either because of low structure weights (LW-A, LW-B), more robust lateral force resisting systems (RC-A, RC-B), or a combination of these features (SC-A, SC-B).

While URM might be vulnerable to seismic impacts, it generally tends to perform better against wind alongside RC typologies. At 100 km/h 3-s peak gust, URM has a 2% likelihood of reaching or exceeding DS1, RC-A has a 3% probability and RC-B has a negligible probability. At the same wind intensity, lightweight typologies show 41% (LW-A) and 30% (LW-B) probabilities of meeting or exceeding DS1, while semi-concrete typologies show 13% (SC-A) and 11% (SC-B) probabilities of exceedance. Considering a 200 km/h peak gust, URM, RC typologies, and SC-B have very low to negligible probabilities of reaching or exceeding DS5 unlike LW-A, LW-B, and SC-A where there are 22%, 17%, and 8% chances of meeting or exceeding DS5, respectively. This wind intensity corresponds roughly to an estimated 20-year return period in the Province of Batanes, meaning that it has a 5% possibility to happen in a given year, based on the regional severe wind hazard maps for the Philippines [51]. At 300 km/h, corresponding to a 500-year return period (0.2% chance to happen in a given year), URM structures have 87% and 65% probabilities of reaching or exceeding DS4 and DS5, respectively. RC-A is expected to perform similarly with 87% and 69% probabilities of DS4 and DS5, respectively. Meanwhile, RC-B shows an 11% probability of reaching or exceeding DS4 and a 3% probability for DS5. For lightweight typologies, DS4 has a likelihood of 97% (LW-A and LW-B), while DS5 corresponds with 92% (LW-A) and 91% (LW-B). For semi-concrete typologies, DS4 shows 92% (SC-A) and 89% (SC-B) probabilities of exceedance, and 81% (SC-A) to 74% (SC-B) for DS5. At 400 km/h, all typologies have > 99% probability of exceedance for DS5, except for RC-B having a 79% likelihood of reaching or exceeding this damage state.

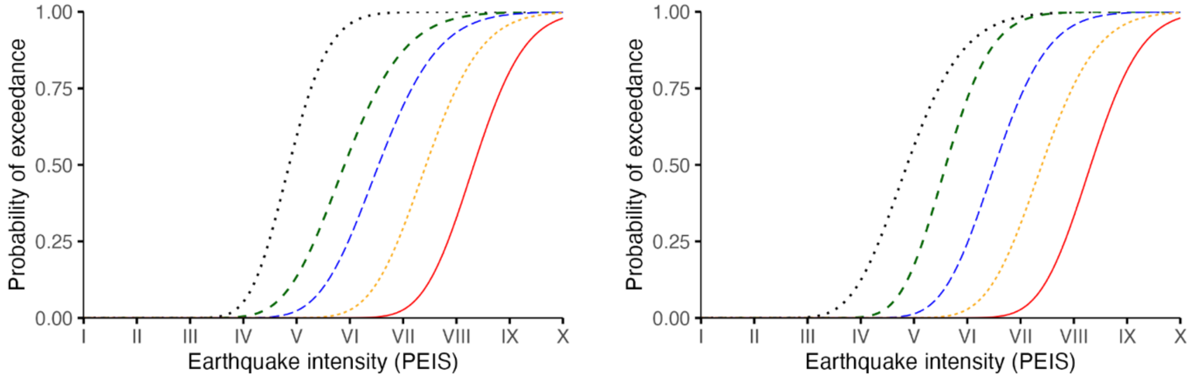
**Table 3.2.** $x_m$ and $\beta$ values of the fragility functions.

| Typology | Earthquake | | | | | Typhoon | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | DS1 | DS2 | DS3 | DS4 | DS5 | DS1 | DS2 | DS3 | DS4 | DS5 |
| **URM** | $x_m$: 3.49 | 4.28 | 5.17 | 6.14 | 7.20 | $x_m$:136.87 | 177.26 | 222.60 | 256.70 | 285.18 |
| | $\beta$: 0.25 | 0.22 | 0.19 | 0.16 | 0.12 | $\beta$: 0.16 | 0.15 | 0.15 | 0.14 | 0.13 |
| **LW-A** | $x_m$: 4.63 | 5.45 | 6.34 | 7.17 | 7.96 | $x_m$:104.12 | 130.13 | 158.80 | 201.53 | 230.30 |
| | $\beta$: 0.19 | 0.16 | 0.16 | 0.14 | 0.12 | $\beta$: 0.18 | 0.14 | 0.18 | 0.21 | 0.19 |
| **LW-B** | $x_m$: 4.86 | 5.90 | 6.54 | 7.43 | 8.33 | $x_m$:110.18 | 137.59 | 165.86 | 207.47 | 236.83 |
| | $\beta$: 0.12 | 0.15 | 0.14 | 0.11 | 0.09 | $\beta$: 0.18 | 0.14 | 0.20 | 0.20 | 0.18 |
| **SC-A** | $x_m$: 4.87 | 5.60 | 6.52 | 7.40 | 8.32 | $x_m$:122.14 | 149.67 | 178.05 | 222.68 | 256.26 |
| | $\beta$: 0.17 | 0.12 | 0.12 | 0.11 | 0.09 | $\beta$: 0.18 | 0.14 | 0.21 | 0.21 | 0.18 |
| **SC-B** | $x_m$: 4.62 | 5.43 | 6.16 | 7.26 | 8.17 | $x_m$:125.02 | 157.52 | 190.12 | 243.92 | 270.10 |
| | $\beta$: 0.16 | 0.15 | 0.10 | 0.11 | 0.11 | $\beta$: 0.18 | 0.18 | 0.17 | 0.17 | 0.16 |
| **RC-A** | $x_m$: 5.11 | 5.89 | 6.82 | 7.59 | 8.43 | $x_m$:145.23 | 181.70 | 210.73 | 255.46 | 281.16 |
| | $\beta$: 0.16 | 0.13 | 0.12 | 0.10 | 0.08 | $\beta$: 0.20 | 0.17 | 0.17 | 0.14 | 0.13 |
| **RC-B** | $x_m$: 4.85 | 5.55 | 6.42 | 7.36 | 8.18 | $x_m$:230.27 | 266.00 | 298.31 | 338.73 | 366.65 |
| | $\beta$: 0.17 | 0.14 | 0.14 | 0.12 | 0.11 | $\beta$: 0.08 | 0.12 | 0.12 | 0.10 | 0.11 |



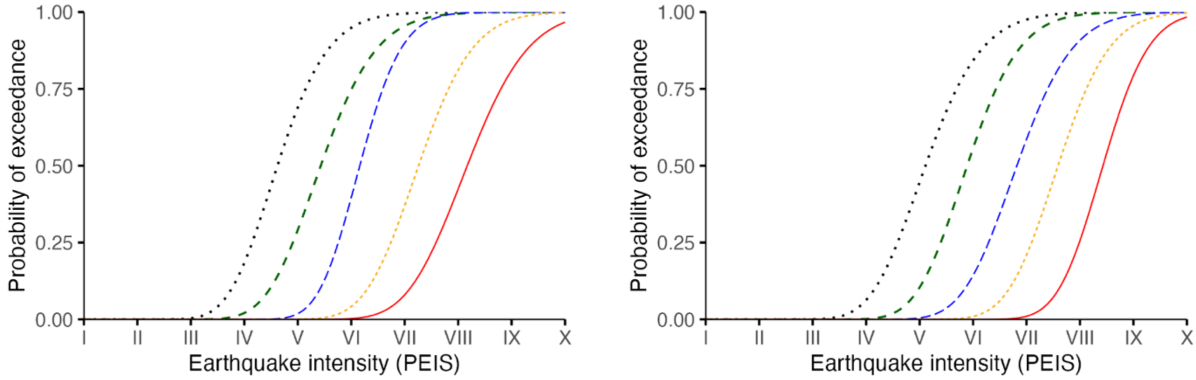
**(a) Unreinforced masonry [URM]**

**(b) Lightweight with wooden posts [LW-A]**



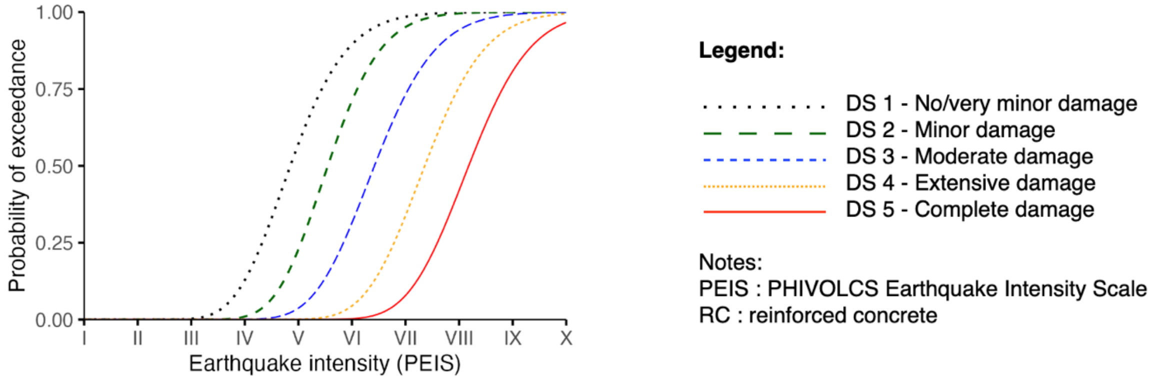
**(c) Lightweight with steel posts [LW-B]**

**(d) Semi-concrete with steel posts [SC-A]**



**(e) Semi-concrete with RC posts [SC-B]**

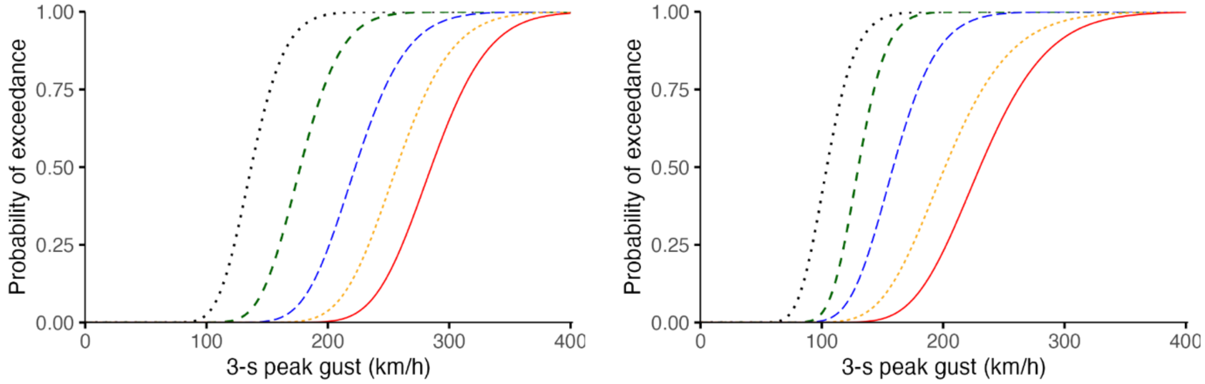
**(f) RC structure with lightweight roof [RC-A]**



Notes:
PEIS : PHIVOLCS Earthquake Intensity Scale
RC : reinforced concrete

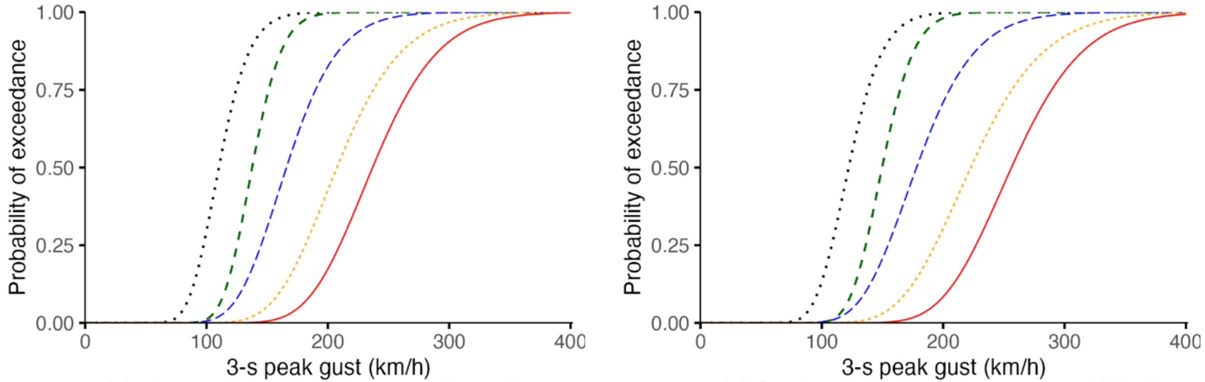
**(g) RC structure with slab roof [RC-B]**

**Figure 3.4.** Fragility functions against seismic impacts derived from experts' estimates.



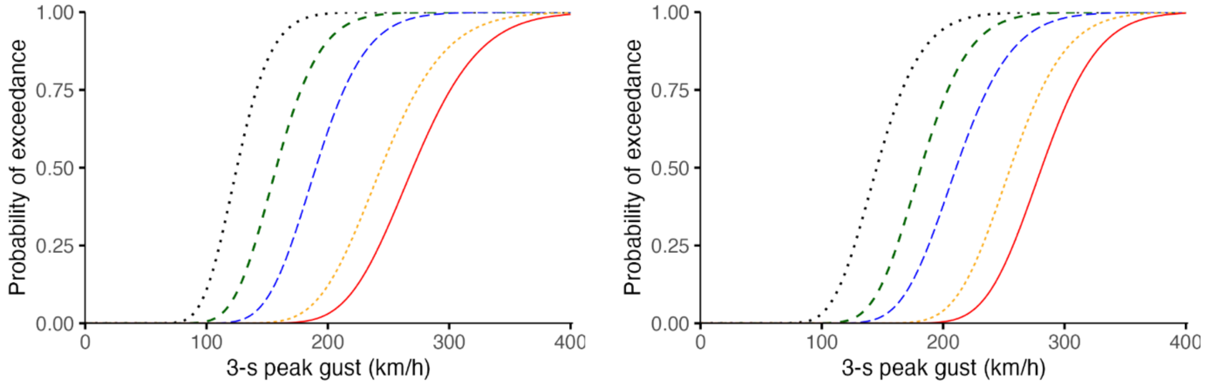
(a) Unreinforced masonry [URM]

(b) Lightweight with wooden posts [LW-A]



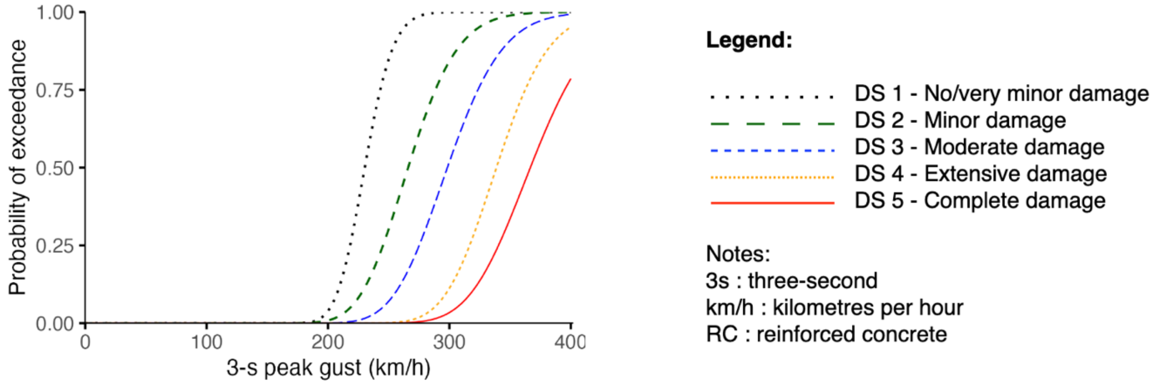
(c) Lightweight with steel posts [LW-B]

(d) Semi-concrete with steel posts [SC-A]



(e) Semi-concrete with RC posts [SC-B]

(f) RC structure with lightweight roof [RC-A]



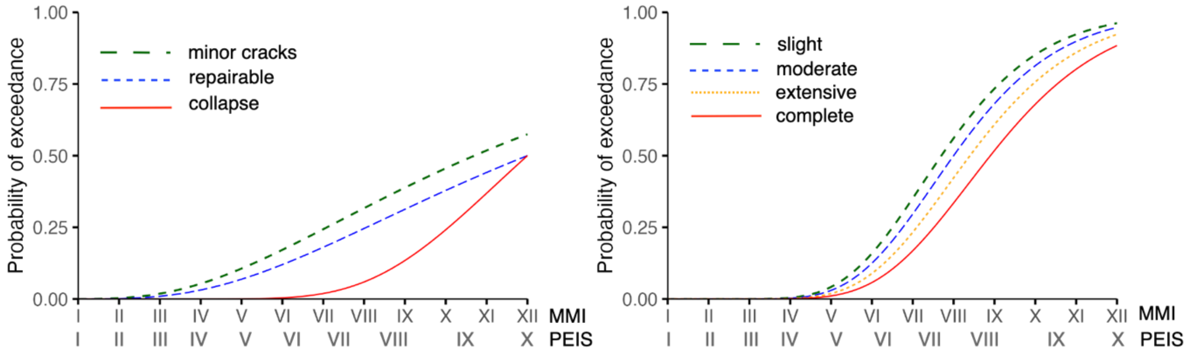
(g) RC structure with slab roof [RC-B]

Notes:
3s : three-second
km/h : kilometres per hour
RC : reinforced concrete

**Figure 3.5.** Fragility functions against wind impacts derived through experts' estimates.

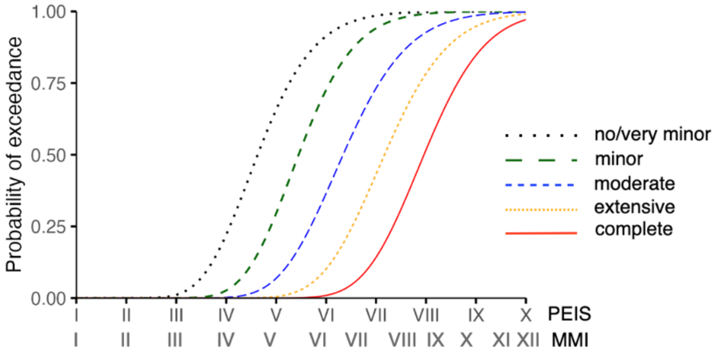
Studies on the derivation of fragility functions in the Philippines are presently very limited. Cross-comparison of our functions to the available studies is challenging given the differences of how typologies and damage states are characterised including the nuanced assumptions considered in deriving these functions. Given these limitations, we were only able to draw comparisons to the works of Pacheco et al. [52] and Naguit et al. [53] on the fragility functions derived for lightweight, wooden-framed structures. This typology is comparable to LW-A (lightweight with wooden posts) in this study characterised by wooden post and beam systems. Other typologies from these studies exhibit different structural characteristics from the ones we surveyed. For example, low-rise concrete-framed typologies described by both studies cannot be used for direct comparison since in their works, these are described as concrete moment-framed structures with (hollow block) masonry walls whereas those surveyed in this study were concrete moment-framed structures with RC walls, adding lateral stiffness to the structure. Pacheco et al. [52] derived their functions using a hybrid approach (computational and heuristic) while Naguit et al. [53] generated their functions using empirical methods using data collected by communities.

Comparing seismic fragilities of lightweight wooden structures (see Figure 3.6), our functions provide higher probabilities for complete damage or collapse. Whereas Naguit et al.'s [53] functions estimate ~ 50% probabilities of exceedance for collapse and Pacheco et al.'s [52] functions estimate ~ 85% for complete damage at the maximum seismic intensity possible (PEIS X / MMI XII), our functions assume complete damage at this intensity close to 100% probability of exceedance. Our functions also indicate that slight damage may start to manifest between Intensities II and III, close to Naguit et al.'s [53] which suggest minor cracks starting to manifest around Intensity II. Meanwhile, Pacheco et al.'s [52] functions indicate slight damage starting to become possible at Intensity IV. For wind comparisons (see Figure 3.7), both our functions and Pacheco et al.'s [52] suggest > 75% probabilities of exceedance for complete damage for wind speeds greater than 350 km/h. For both functions, slight/minor and moderate damage start to arise around 100 km/h but ours have steeper curves suggesting a more rapid change in probabilities with the increase of wind speed. In comparing functions, caution should be taken since differences can emanate from the varied characterisations adopted by authors. For example, the use three-tier damage scale (e.g., Naguit et al. [53]) can result to a different set of functions when applying more granular observations to visualise or represent five damage states.



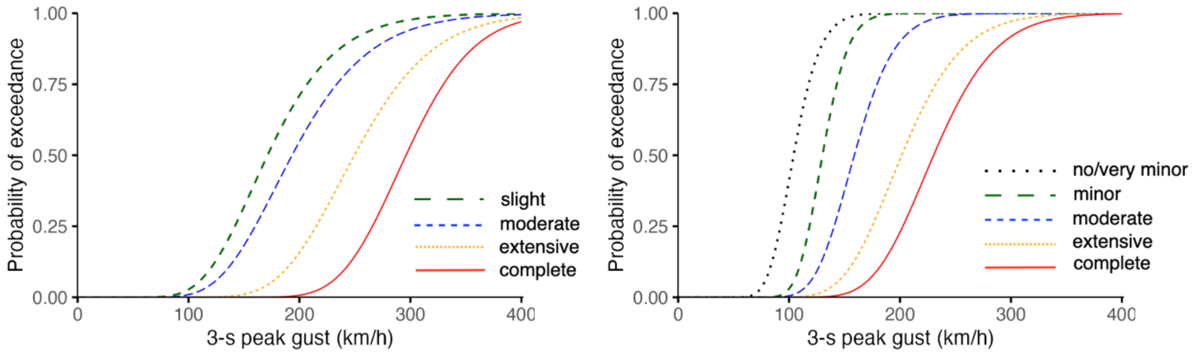
**(a) Wood, light frame [Naguit et al., 2017]**

**(b) Wood, light frame [Pacheco et al., 2014]**



**(c) Lightweight with wooden posts [LW-A in this study]**

**Figure 3.6.** Comparison of seismic fragility functions to other studies for lightweight, wooden-framed typology. (Note: PEIS stands for PHIVOLCS Earthquake Intensity Scale while MMI stands for Modified Mercalli Intensity.)



**(a) Wood, light frame [Pacheco et al., 2014]**

**(b) Lightweight with wooden posts [LW-A in this study]**

**Figure 3.7.** Comparison of wind fragility functions to other studies for lightweight, wooden-framed typology.

Benchmarking the accuracy of the functions derived in this study is difficult as these are the first to be derived for this geographical context. In the interim, these functions can be considered as medium quality having satisfied the criteria of Porter et al. [27,28] to have at least three experts whose confidence ratings are ≥ 3. For the expert-driven approach in ATC-58, only low and medium-quality benchmarks are provided in reporting on the quality of the derived functions. At least 68% of the responses for every typology for each hazard received confidence ratings of 3 or greater (out of 5). As shown in Table 3.3, there was variation in experts' confidence in their assessments. The median of confidence level for wind assessments for each typology is 3 across all typologies. Meanwhile, for seismic assessments, heavier typologies (URM, RC-A, and RC-B) have a median confidence rating of 4 while the rest, which are the lighter weight counterparts, have a median confidence level of 3. Considering experts' unweighted (or raw) inputs, standard deviations across damage states for earthquake intensities range from PEIS 0.83 – PEIS 1.54, while for typhoon wind speeds, they range from 43.29 km/h – 105.65 km/h. The minimum and maximum values of the consolidated estimates from both local experts and specialists are presented in Table 3.3 and these values show the variation of inputs solicited for this assessment.

To summarise, respondents were more confident in their assessments of heavier typologies for both hazards. However, for typhoon hazards, variance of responses increased from light to heavy typologies, suggesting wider variation in expert assessments. In general, we argue that the variability of experts' inputs should be considered an advantage for the context of this assessment because such variability encompasses the broad scenario-based observations of housing performance. This consideration is beneficial most especially where construction resources are used less prescriptively against building codes and standards requiring less straightforward appraisal of housing performance.

**Table 3.3.** Ranges of consolidated experts' estimates shown through minimum and maximum values, including the median.

| | | | **Earthquake Intensity (PEIS)** | | | | | | | **Typhoon Intensity (km/h)** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **URM** | **LW-A** | **LW-B** | **SC-A** | **SC-B** | **RC-A** | **RC-B** | **URM** | **LW-A** | **LW-B** | **SC-A** | **SC-B** | **RC-A** | **RC-B** |
| Confidence levels* | | Min | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | | Max | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | | Median | 4 | 3 | 3 | 3 | 3 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **DS 1** | Median IM** | Min | 2 | 1 | 3 | 2 | 2 | 4 | 3 | 50 | 30 | 30 | 60 | 60 | 45 | 70 |
| | | Max | 6 | 4 | 8 | 8 | 7 | 7 | 7 | 300 | 225 | 225 | 300 | 300 | 300 | 400 |
| | | Median | 3 | 3 | 5 | 4 | 4 | 5 | 4.5 | 100 | 100 | 100 | 100 | 100 | 120 | 150 |
| | Lower bound IM | Min | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 30 | 20 | 25 | 50 | 55 | 30 | 60 |
| | | Max | 5 | 7 | 8 | 7 | 6 | 6 | 5 | 250 | 200 | 200 | 250 | 250 | 250 | 400 |
| | | Median | 2 | 3 | 4 | 3 | 3 | 4 | 4 | 80 | 60 | 70 | 80 | 80 | 100 | 130 |
| **DS 2** | Median IM | Min | 3 | 3.5 | 4 | 3 | 2.5 | 4.5 | 3 | 70 | 40 | 40 | 75 | 80 | 55 | 90 |
| | | Max | 6 | 8 | 8 | 8 | 8 | 8 | 8 | 325 | 250 | 250 | 325 | 325 | 325 | 400 |
| | | Median | 4 | 5 | 6 | 5 | 5 | 5.75 | 5.5 | 150 | 120 | 126 | 135 | 140 | 150 | 200 |
| | Lower bound IM | Min | 2 | 2 | 3 | 2 | 1 | 2 | 2 | 40 | 25 | 30 | 60 | 70 | 45 | 70 |
| | | Max | 5 | 7 | 8 | 8 | 7 | 7 | 6 | 275 | 225 | 225 | 275 | 275 | 275 | 400 |
| | | Median | 3 | 4 | 5 | 4 | 4 | 5 | 5 | 120 | 100 | 100 | 100 | 100 | 125 | 155 |
| **DS 3** | Median IM | Min | 3 | 4 | 4.5 | 3.5 | 3 | 5 | 4 | 75 | 60 | 60 | 90 | 90 | 75 | 160 |
| | | Max | 7 | 9 | 9 | 9 | 8 | 9 | 8 | 350 | 275 | 275 | 350 | 350 | 350 | 400 |
| | | Median | 5 | 6 | 6.75 | 6 | 6 | 7 | 6.75 | 180 | 155 | 155 | 160 | 180 | 200 | 300 |
| | Lower bound IM | Min | 2 | 3 | 4 | 3 | 2 | 4 | 2 | 50 | 40 | 45 | 60 | 60 | 50 | 100 |
| | | Max | 6 | 8 | 8 | 8 | 8 | 8 | 7 | 300 | 250 | 250 | 300 | 300 | 300 | 400 |
| | | Median | 4 | 5 | 5.5 | 5 | 5 | 6 | 5.5 | 160 | 115 | 120 | 125 | 145 | 150 | 200 |
| **DS 4** | Median IM | Min | 4 | 5 | 6 | 4 | 4 | 6 | 5 | 80 | 90 | 90 | 140 | 140 | 90 | 220 |
| | | Max | 8 | 10 | 10 | 9 | 9 | 10 | 9 | 375 | 300 | 300 | 375 | 375 | 375 | 400 |
| | | Median | 6 | 7 | 7.25 | 7 | 7 | 7.5 | 7.5 | 200 | 200 | 200 | 200 | 205 | 240 | 350 |
| | Lower bound IM | Min | 3 | 3 | 4 | 3 | 2 | 4 | 3 | 70 | 80 | 90 | 100 | 100 | 75 | 160 |
| | | Max | 7 | 9 | 9 | 8 | 9 | 9 | 8 | 325 | 275 | 275 | 325 | 325 | 325 | 400 |
| | | Median | 5 | 6 | 6.25 | 6 | 6 | 7 | 6.5 | 175 | 150 | 150 | 150 | 175 | 200 | 300 |
| **DS 5** | Median IM | Min | 5 | 6 | 6.5 | 5 | 5 | 7 | 6 | 90 | 110 | 110 | 150 | 150 | 100 | 250 |
| | | Max | 9 | 10 | 10 | 10 | 10 | 10 | 10 | 400 | 325 | 325 | 400 | 400 | 400 | 400 |
| | | Median | 7 | 8 | 8 | 8 | 8 | 8 | 8 | 250 | 245 | 250 | 250 | 240 | 260 | 400 |
| | Lower bound IM | Min | 4 | 5 | 6 | 4 | 3 | 5 | 5 | 60 | 90 | 100 | 100 | 100 | 85 | 180 |
| | | Max | 8 | 9 | 9 | 9 | 9 | 10 | 9 | 375 | 300 | 300 | 350 | 350 | 350 | 400 |
| | | Median | 6.5 | 7 | 7.25 | 7 | 7 | 7.5 | 7.25 | 200 | 180 | 185 | 200 | 200 | 222.5 | 325 |

*Confidence levels are ordinal ratings from 1 to 5.

**IM stands for intensity measure. For earthquake, it is expressed in PHIVOLCS Earthquake Intensity Scale (PEIS). For typhoon, it is expressed in kilometres per hour (km/h).

## 4 Discussion

In conducting the expert-driven approach of deriving fragility functions, we gleaned three insights to consider when using this heuristic alternative for damage analysis. These insights include how disaster sub-culture influences experts' estimates, some caveats to be aware of when relying on hazard intensities published by agencies, and the logistical challenges of soliciting experts' opinions.

In areas like Batanes where people have perennial encounters with hazards, disaster preparedness practices instinctively emerge to become part of their disaster sub-culture. For example, before a typhoon hits, houses are tied up with ropes to secure their envelopes (a practice called *kap'yakuyakut* in Itbayat and *kapanpet* in mainland Batanes). Meanwhile, windows are covered with an additional layer of improvised shutters (*tapangko*). During the solicitation of experts' opinions, a local expert commented that his estimates were guided by how the houses perform in conjunction with these prevailing disaster preparedness practices in the area. These considerations provide a layered understanding of housing performance embedded in local settings – and why the development of localised fragility functions is important. Conventional approaches to damage analysis would suggest equal, unifying assumptions for assessments. However, understanding these local practices requires context and nuance not captured by decoupling building elements and preparedness activities. Commanding local experts to "disregard" such considerations is counterintuitive given that the core basis of their estimates is on actual observations. Beyond the expert-driven approach, there is an opportunity to consider these types of non-traditional measures in computational fragility modelling done experimentally. These disaster preparedness practices will also have an impact on future empirical data collected in Batanes since housing damage will likely be reflective of the housing performance in conjunction with such practices.

Damage estimates based on experts' opinions are guided by actual observations of housing performance based on past disaster events. These observations are most likely referenced with impactful hazard intensities as broadcasted by agencies. Since damage estimates are relative or "framed" within agency-interpreted intensities, any errors, limitations, or discrepancies in how these intensities are interpreted affect the experts' estimates. On the survey forms, we provided information sheets that contained ranges of hazard intensities of notable disaster events in the Philippines from different data sources to guide respondents in situating their estimates. The intention was to confine their estimates within reasonable hazard intensities that were actually recorded. However, in some instances, there is no definite historical upper bound of hazard intensities for wind events due to previous data limitations. For example, recorded peak gusts of Typhoon Meranti (Ferdie) in 2016 are unavailable in Itbayat where it made landfall [54]. Likewise, peak gusts of Typhoon Haiyan (Yolanda) were not recorded across some weather stations in the Visayas region due to the damage sustained by the weather instruments [48,55,56]. To compensate for such limitations, intensity readings of neighbouring international weather agencies were used. Additionally, estimated intensities evident from impact signs to infrastructure as derived in some studies were referenced [55–57]. However, without officially recorded intensity readings of some of the largest typhoons in the Philippines, estimates will always be confined within the proxied or assumed values. For seismic impacts, a factor to consider as raised by one specialist is the possibility of circular logic between PEIS intensities and damage states. That is, PEIS ground shaking is at least partly pegged to certain descriptors of building damage.

On the use of the expert-driven approach as a viable alternative where analytical and empirical data are currently impractical to acquire, we realise that expertise can also be a rare commodity. Local expertise might be limited at a municipal level especially in small, geographically remote areas. We have addressed this issue by broadening the jurisdiction to the provincial level where district engineers compensated for this limitation. Additionally, while there is a reasonable number of specialists who could be prospective respondents, their availability was not guaranteed, and response rates mainly dictated the sampling of the respondents. Therefore, robustly qualifying who gets involved was the priority more than reaching a certain quota of respondents with a focus on quality over quantity of participant selection.

These three insights guided our derivation of the first-generation fragility functions in Batanes. The non-engineered nature of the typologies surveyed makes it a challenge to definitively assess the variability inherent to this building stock. This study, however, advanced this pursuit by acknowledging the nuanced characteristics of non-engineered typologies, which could have otherwise been categorised within existing generic taxonomies. In the Philippines, previous efforts to generate fragility or vulnerability functions for residential typologies have been conducted for Greater Metro Manila Area [52], Bohol [53], and Cebu [58], with contributions in the GEM database. This study branched out further north to consider the rural context of a small island geography which has been pressured to address multi-hazard housing safety due to the competing impacts of extreme events. The functions derived are fundamental tools for practitioners to understand the vulnerability of non-engineered structures and offer targeted structural mitigation and preparedness programmes contextualised in the area. It is suggested that when more empirical data becomes available, the possibility of combining new and existing functions should be explored [50,59].

## 5 Conclusion

Using fragility functions in risk assessments is fundamental to model anticipated structural housing damage against the impacts of natural hazards. We used an expert-driven approach to derive wind and seismic fragility functions for the Province of Batanes. Theoretically, this study provides new estimates of the performance of non-engineered housing in the Philippines, which would traditionally be discounted by conventional fragility assessments relying on generic building taxonomies. This region-specific evaluation is a step to advance more localised risk assessments. Practically, the set of fragility functions derived in this study is seen to assist practitioners in exploring risk preparedness and mitigation measures applicable in Batanes. On a national scale, we fill gaps on the lacking representation of building archetypes in rural and remote areas as most attention to understanding building-level risk reduction has, to date, focused in urban centres where data are more accessible. Our functions lay a foundation for more holistic and contextualised approaches to risk modelling nationwide considering the inclusion of neglected geographic areas. As new damage data and analysis emerge in the future, our functions can aid hybrid approaches to generate the next generation of fragility estimates.

## 6 References

[1] UNISDR, Sendai Framework for Disaster Risk Reduction 2015 - 2030, 2015.

[2] I. Ahmed, An overview of post-disaster permanent housing reconstruction in developing countries, International Journal of Disaster Resilience in the Built Environment 2 (2011) 148–164. https://doi.org/10.1108/17595901111149141.

[3] A. Kaynia, I. Iervolino, F. Taucer, U. Hancilar, Guidelines for deriving seismic fragility functions of elements at risk: buildings, lifelines, transportation networks and critical facilities., Publications Office of the European Union, LU, 2013. https://data.europa.eu/doi/10.2788/19605 (accessed December 18, 2022).

[4] C.A. Kircher, R.V. Whitman, W.T. Holmes, HAZUS Earthquake Loss Estimation Methods, Nat. Hazards Rev. 7 (2006) 45–59. https://doi.org/10.1061/(ASCE)1527-6988(2006)7:2(45).

[5] C. Negulescu, P. Gehl, Mechanical Methods: Fragility Curves and Pushover Analysis, in: P. Gueguen (Ed.), Seismic Vulnerability of Structures, John Wiley & Sons, Inc., Hoboken, NJ USA, 2013: pp. 63–110. https://doi.org/10.1002/9781118603925.ch2.

[6] K. Porter, A Beginner's Guide to Fragility, Vulnerability, and Risk, in: M. Beer, I.A. Kougioumtzoglou, E. Patelli, I.S.-K. Au (Eds.), Encyclopedia of Earthquake Engineering, Springer Berlin Heidelberg, Berlin, Heidelberg, 2021: pp. 1–29. https://doi.org/10.1007/978-3-642-36197-5_256-1.

[7] FEMA, Hazus Earthquake Model Technical Manual, 2020.

[8] FEMA, Hazus Hurricane Model Technical Manual, 2021.

[9] P.J. Vickery, P.F. Skerlj, J. Lin, L.A. Twisdale, M.A. Young, F.M. Lavelle, HAZUS-MH Hurricane Model Methodology. II: Damage and Loss Estimation, Nat. Hazards Rev. 7 (2006) 94–103. https://doi.org/10.1061/(ASCE)1527-6988(2006)7:2(94).

[10] G.L. Pita, B.S. Albornoz, J.I. Zaracho, Flood depth-damage and fragility functions derived with structured expert judgment, Journal of Hydrology 603 (2021) 126982. https://doi.org/10.1016/j.jhydrol.2021.126982.

[11] A. Charleson, A. Nonoguchi, A. Maeshima, C. Villacis, C. Minowa, G. Zamani, H. Imai, K. Okazaki, K. Yamaguchi, R. Shaw, S. Fukushima, S. Kita, S. Saito, S. Matsuzaki, S. Ando, S. Yasukawa, T. Narafu, T. Yokoi, T. Hanazato, Y. Ishiyama, Towards resilient non-engineered construction: guide for risk-informed policy-making, United Nations Educational, Scientific, and Cultural Organisation, 2016.

[12] A. Hadlos, A. Opdyke, S.A. Hadigheh, Where does local and indigenous knowledge in disaster risk reduction go from here? A systematic literature review, International Journal of Disaster Risk Reduction 79 (2022) 103160. https://doi.org/10.1016/j.ijdrr.2022.103160.

[13] M.C. de Ruiter, J.A. de Bruijn, J. Englhardt, J.E. Daniell, H. de Moel, P.J. Ward, The Asynergies of Structural Disaster Risk Reduction Measures: Comparing Floods and Earthquakes, Earth's Future 9 (2021). https://doi.org/10.1029/2020EF001531.

[14] Y. Li, A. Ahuja, J.E. Padgett, Review of Methods to Assess, Design for, and Mitigate Multiple Hazards, J. Perform. Constr. Facil. 26 (2012) 104–117. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000279.

[15] T. Rossetto, A. Elnashai, Derivation of vulnerability functions for European-type RC structures based on observational data, Engineering Structures 25 (2003) 1241–1263. https://doi.org/10.1016/S0141-0296(03)00060-9.

[16] R. Maio, G. Tsionis, Seismic fragility curves for the European building stock: review and evaluation of existing fragility curves, Publications Office, Luxembourg, 2015.

[17] T. Rossetto, D. D’Ayala, I. Ioannou, A. Meslem, Evaluation of Existing Fragility Curves, in: K. Pitilakis, H. Crowley, A.M. Kaynia (Eds.), SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk, Springer Netherlands, Dordrecht, 2014: pp. 47–93. https://doi.org/10.1007/978-94-007-7872-6_3.

[18] S. De Angeli, B.D. Malamud, L. Rossi, F.E. Taylor, E. Trasforini, R. Rudari, A multi-hazard framework for spatial-temporal impact analysis, International Journal of Disaster Risk Reduction 73 (2022) 102829. https://doi.org/10.1016/j.ijdrr.2022.102829.

[19] M.S. Kappes, M. Keiler, K. von Elverfeldt, T. Glade, Challenges of analyzing multi-hazard risk: a review, Nat Hazards 64 (2012) 1925–1958. https://doi.org/10.1007/s11069-012-0294-2.

[20] K. Jaiswal, D. Wald, D. Perkins, W. Aspinall, A. Kiremidjian, Estimating structural collapse fragility of generic building typologies using expert judgment, in: G. Deodatis, B. Ellingwood, D. Frangopol (Eds.), Safety, Reliability, Risk and Life-Cycle Performance of Structures and Infrastructures, CRC Press, 2014: pp. 879–886. https://doi.org/10.1201/b16387-130.

[21] K.S. Jaiswal, W.P. Aspinall, D. Perkins, D. Wald, K.A. Porter, Use of Expert Judgment Elicitation to Estimate Seismic Vulnerability of Selected Building Types, in: Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 2012.

[22] M.V. Martello, A.J. Whittle, H.R. Lyons-Galante, Depth-damage curves for rail rapid transit infrastructure, J Flood Risk Management (2022). https://doi.org/10.1111/jfr3.12856.

[23] Applied Technology Council, ATC-13 Earthquake Damage Evaluation Data for California, Redwood City, CA, 1985.

[24] I. Ioannou, W. Aspinall, D. Rush, L. Bisby, T. Rossetto, Expert judgment-based fragility assessment of reinforced concrete buildings exposed to fire, Reliability Engineering & System Safety 167 (2017) 105–127. https://doi.org/10.1016/j.ress.2017.05.011.

[25] H. Miura, S. Midorikawa, K. Fujimoto, B.M. Pacheco, H. Yamanaka, Earthquake damage estimation in Metro Manila, Philippines based on seismic performance of

buildings evaluated by local experts' judgments, Soil Dynamics and Earthquake Engineering 28 (2008) 764–777. https://doi.org/10.1016/j.soildyn.2007.10.011.

[26] M.G. Winter, J.T. Smith, S. Fotopoulou, K. Pitilakis, O. Mavrouli, J. Corominas, S. Argyroudis, An expert judgement approach to determining the physical vulnerability of roads to debris flow, Bull Eng Geol Environ 73 (2014) 291–305. https://doi.org/10.1007/s10064-014-0570-3.

[27] K. Porter, R. Kennedy, R. Bachman, Creating Fragility Functions for Performance-Based Earthquake Engineering, Earthquake Spectra 23 (2007) 471–489. https://doi.org/10.1193/1.2720892.

[28] P.K. Porter, R. Kennedy, R. Bachman, Developing Fragility Functions for Building Components for ATC-58, Applied Technology Council, Redwood City, CA, 2006.

[29] International Federation of Red Cross and Red Crescent Societies, Philippines: Batanes Earthquake, 2020.

[30] J. Perez, K. Vitto, P. Sawi, J. Blacer, R. Tiglao, M. Pagtalunan, J.R. Danganan, A. Garil, Impacts of the 27 July 2019 Magnitudes (Mw) 5.4, 5.9, and 5.8 Itbayat, Batanes Earthquakes, Department of Science and Technology - Philippine Institute of Volcanology and Seismology, 2019.

[31] V. Silva, S. Brzev, C. Scawthorn, C. Yepes, J. Dabbeek, H. Crowley, A Building Classification System for Multi-hazard Risk Assessment, Int J Disaster Risk Sci 13 (2022) 161–177. https://doi.org/10.1007/s13753-022-00400-x.

[32] C. Venable, A. Javernick-Will, A.B. Liel, M.A. Koschmann, Revealing (mis)alignments between household perceptions and engineering assessments of post-disaster housing safety in typhoons, International Journal of Disaster Risk Reduction 53 (2021). https://doi.org/10.1016/j.ijdrr.2020.101976.

[33] C. Venable, A.B. Liel, T. Kijewski-Correa, A. Javernick-Will, Wind Performance Assessment of Postdisaster Housing in the Philippines, Nat. Hazards Rev. 22 (2021) 04021033. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000491.

[34] G. Sevieri, C. Galasso, D. D'Ayala, R. De Jesus, A. Oreta, M.E.D.A. Grio, R. Ibabao, A multi-hazard risk prioritisation framework for cultural heritage assets, Nat. Hazards Earth Syst. Sci. 20 (2020) 1391–1414. https://doi.org/10.5194/nhess-20-1391-2020.

[35] GEM Foundation, Glossary for GEM Taxonomy, (2023). https://taxonomy.openquake.org/ (accessed February 11, 2023).

[36] F. Adami, The Traditional Ivatan House in Barangay Itbud Today, Ivatan Studies Journal II, III, IV (1998) 216–231.

[37] R. Fernandez, A Visual Dictionary on Filipino Architecture, University of Santo Tomas Publishing House, Manila, 2015.

[38] F. Hornedo, Traditional Ivatan Shelter and Architecture, Part Two, The Classic Traditional Ivatan House: Emergence and Prospects, Ivatan Studies Journal XIII–XIV (2015) 39–112.

[39] National Historical Commission of the Philippines, Ivatan Traditional House: A Construction and Maintenance Manual, National Historical Commission of the Philippines, Manila, 2018.

[40] National Historical Commission of the Philippines, Vahay: Documenting the Story of the Ivatan House, National Historical Commission of the Philippines, Manila, 2018.

[41] R.T. Clemen, R.L. Winkler, Combining Probability Distributions From Experts in Risk Analysis, Risk Analysis 19 (1999) 187–203. https://doi.org/10.1111/j.1539-6924.1999.tb00399.x.

[42] J. Moehle, G. Deierlein, A Framework Methodology for Performance-Based Earthquake Engineering, in: Vancouver, B.C., Canada, 2004.

[43] D.A. Skolnik, J.W. Wallace, Critical Assessment of Interstory Drift Measurements, J. Struct. Eng. 136 (2010) 1574–1584. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000255.

[44] Philippine Institute of Volcanology and Seismology, PHIVOLCS Earthquake Intensity Scale (PEIS), (n.d.). https://www.phivolcs.dost.gov.ph/index.php/earthquake/earthquake-intensity-scale (accessed July 10, 2023).

[45] M. Lasala, H. Inoue, R. Tiglao, Z. Fan, B. Bautista, I. Narag, Establishment of Earthquake Intensity Meter Network in the Philippines, J. Disaster Res. 10 (2015) 43–50. https://doi.org/10.20965/jdr.2015.p0043.

[46] Japan International Cooperation Agency, Pacific Consultants International, OYO International Corporation, PASCO Corporation, Earthquake Impact Reduction Study for Metropolitan Manila, Republic of the Philippines, 2004.

[47] G. Cua, D.J. Wald, T.I. Allen, D. Garcia, C.B. Worden, M. Gerstenberger, K. Lin, K. Marano, “Best Practices” for Using Macroseismic Intensity and Ground Motion Intensity Conversion Equations for Hazard and Loss Models in GEM1, GEM Foundation, Pavia, Italy, 2010.

[48] Q. Yang, R. Gao, F. Bai, T. Li, Y. Tamura, Damage to buildings and structures due to recent devastating wind hazards in East Asia, Nat Hazards 92 (2018) 1321–1353. https://doi.org/10.1007/s11069-018-3253-8.

[49] W.P. Aspinall, R.M. Cooke, Quantifying scientific uncertainty from expert judgement elicitation, in: J. Rougier, S. Sparks, L.J. Hill (Eds.), Risk and Uncertainty Assessment for Natural Hazards, 1st ed., Cambridge University Press, 2013: pp. 64–99. https://doi.org/10.1017/CBO9781139047562.005.

[50] D. Lallemant, A. Kiremidjian, H. Burton, Statistical procedures for developing earthquake damage fragility curves, Earthquake Engng Struct. Dyn. 44 (2015) 1373–1389. https://doi.org/10.1002/eqe.2522.

[51] Philippine Atmospheric, Geophysical, and Astronomical Services, Regional Severe Wind Hazard Maps, (n.d.). https://www.pagasa.dost.gov.ph/products-and-services/severe-wind-maps (accessed July 17, 2023).

[52] B. Pacheco, J. Hernandez Jr., P.P. Castro, E.A.J. Tingatinga, R. Suiza, L.R.E. Tan, R.E. Longalong, M.C. Veron, D.H. Aquino, R. Macuha, W. Mata, I.B.O. Villalba, M.C. Pascua, U. Ignacio Jr., F. Germar, J.R. Diño, G.P. Reyes, J.L. Tirao, M.A. Zarco, Development of Vulnerability Curves of Key Building Types in the Greater Metro Manila Area, Philippines, Institute of Civil Engineering, University of the Philippines Diliman, Quezon City, Philippines, 2014.

[53] M. Naguit, P. Cummins, M. Edwards, H. Ghasemi, B. Bautista, H. Ryu, M. Haynes, From Source to Building Fragility: Post-Event Assessment of the 2013 M7.1 Bohol, Philippines, Earthquake, Earthquake Spectra 33 (2017) 999–1027. https://doi.org/10.1193/0101716eqs173m.

[54] R. Paciente, Tropical Cyclone Passage Report, Typhoon Committee, 2016. https://typhooncommittee.org/docs/Passage%20Reports/2016/1614-MERANTE-Philippines.pdf (accessed July 12, 2023).

[55] J.C. Agar, W.L. Mata, J. Hernandez Jr., Estimating Typhoon Haiyan's Wind Speeds Using Windicators, Philippine Engineering Journal 39 (2018) 29–42.

[56] R.E. Aquino, W. Mata, J.J. Valdez, Brief Report on Observed Wind Damages in Leyte and Samar due to Typhoon Yolanda of 2013, 2014.

[57] J. Hernandez Jr., R.E. Aquino, B. Pacheco, E. Cruz, Damage Caused by Typhoon Haiyan in the Philippines, Review of Structural Regulations and Practice, and Research Developments in Wind Engineering, Wind Engineers, JAWE 40 (2015) 270–274.

[58] J.C. Agar, J.J.C. Gumaro, T.J. Acosta, J.P.G. Alvarez, M.N.C. Ereno, J.Y. Hernandez Jr, J.S. Pacer, D.A.D. Plamenco, L.R.E. Tan, J. Baniqued, E.A.J. Tingatinga, J.K.B. Musico, P.E.B. Quinay, I.B.O. Villalba, H.O. Bisa, Component-based Severe Wind Vulnerability Analysis of Wooden Buildings in the Philippines, AEJ 12 (2022) 219–225. https://doi.org/10.11113/aej.v12.17463.

[59] K. Jaiswal, D. Wald, D. D'Ayala, Developing Empirical Collapse Fragility Functions for Global Building Types, Earthquake Spectra 27 (2011) 775–795. https://doi.org/10.1193/1.3606398.

# Chapter 4

# Pathways of multi-hazard post-disaster housing reconstruction among Ivatan Indigenous households

## Abstract

Most disaster-affected populations face the complex task of reconstructing their dwellings with minimal or no external support. However, not much is known about the self-initiated reconstruction pathways of households, especially among Indigenous groups needing to address the competing impacts of multiple hazards. We conducted a case study analysis based in Itbayat, Batanes in the Philippines to understand the housing reconstruction trajectories of the Ivatan Indigenous households after the 2019 earthquakes that redefined their typhoon-resilient construction practices. Using interviews and focus group discussions, factors affecting the reconstruction process were elicited. Then, using concept maps, we explored the linkages of these factors leading to the adoption of the emergent housing outputs. We found that the emergence of new housing typologies that displaced the vernacular architecture was influenced by the compounded urgency to reconstruct houses, perceptions of housing safety influenced by the seismic events, the nature of aid provided alongside households' financial capacity, and the regulatory barriers affecting traditional resource extraction. To achieve structural housing safety, this study demonstrates the need for policies that enable and guide reconstruction in emergency contexts, as well as systems to channel aid to provide equitable opportunities to build back safer. Additionally, the role of local governance is shown to leverage the use of existing indigenous construction practices salient for rebuilding. This study builds upon the heightened imperatives in the disaster risk reduction practice and policy environments to focus on the multi-hazard realities affecting communities and the use of local and indigenous knowledge to reduce disaster impacts.

## 1 Introduction

Households impacted by disasters are active decision-makers in the process of housing reconstruction [1,2]. Self-recovery, or when affected populations rebuild impacted properties using their available resources, has been acknowledged as an inevitable and immediate process following disasters [1–5]. This process enables agency among affected populations to prioritise their needs in the reconstruction of their dwellings [1,3,4]. With varying priorities come diverging outcomes, resulting in a plethora of pathways in how households choose to rebuild their dwellings. Most often, demographics influence households' priorities, such as social and economic classes affecting access to critical resources for reconstruction [6]. Among culturally distinct communities like Indigenous populations, constructing a house is usually rooted in tradition [7], and their customary building practices can therefore play a more significant role in the reconstruction process. These groups have relied on longstanding vernacular practices for their building technology in response to natural hazards. However, they are challenged in addressing the impacts of low-frequency but high-impact events.

Housing outcomes are heavily influenced by the available building resources which are contested in post-disaster settings [8–11]. While the management of resources among independently recovering households is not a new point of inquiry (e.g., [12]), what is least understood is how the management of resources influences emergent housing outputs in post-disaster settings. To achieve structurally sound housing outputs, the attention is primarily focused on building code compliance. While housing reconstruction has been predominantly labelled as a technical task, underlying non-technical factors (e.g., politics and finances) are posited to have as much influence in the construction of sound structures [13]. As active decision-makers, households are at the forefront of dealing with these factors to reconstruct their dwellings. Understanding how Indigenous peoples manage the process of rebuilding their houses is important given that their concept of housing is cultural and is often excluded in normative construction guidelines [7]. Moreover, as the cultures of Indigenous peoples are exposed to external influences, their knowledge systems become more blended [14,15]. However, disaster practitioners aiming to support Indigenous peoples often remain indifferent to such a circumstance, leading to the adoption – or aptly, "imposition" – of mainstream risk reduction approaches that discount the (evolving) cultural contexts crucial to sensibly support these groups. In such technocratic scenarios, local resources and capacities usually remain underutilised which could be of benefit to communities and have the potential to reduce external reliance (e.g., aid dependence).

Indigenous peoples have historically been sidelined in the practice and policy environments of disaster risk reduction despite possession of central skills and knowledge systems useful to reduce risks [16]. An in-depth analysis of how Indigenous groups approach housing reconstruction is important with the Sendai Framework for Disaster Risk Reduction emphasising that their experiential knowledge contributes to context-appropriate development and post-disaster reconstruction efforts [17]. Case studies among these groups are a way to elicit a tailored understanding of the cultural requirements in housing reconstruction, particularly in situations where their coping capacities are pressured to incorporate measures to address extraordinary events. Through a community-level understanding of housing reconstruction pathways, evidence-based findings can inform and contextualise better policies, approaches, and strategies to support these groups. Additionally, the insights derived from such studies can contribute to the collective empirical evidence in disaster risk reduction scholarship critical to upscaling the visibility of indigenous knowledge systems in national- and global-level policy environments.

In this study, we examine how Indigenous Ivatan households in the Philippines navigated the reconstruction process after the 2019 earthquakes in Itbayat, located in the province of Batanes. The seismic events crumbled the traditional stone-and-lime dwellings which were regarded as typhoon-resilient. With the pressure to address both wind and seismic impacts in reconstruction, the vernacular construction practices in the area have been redefined. In this regard, we sought to answer the following research questions (RQ):

> RQ1. What factors affected how households reconstructed their dwellings?
> RQ2. How did these factors lead to the housing outputs that households chose to build?

In the following sections, we present a background of post-disaster housing reconstruction, followed by our research methods. Answers to the research questions are presented next in the results section, succeeded by the discussion section which highlights the policy implications of our research inquiry. We summarise our findings and future research directions in the conclusion section.

## 2 Background

Overlapping factors, such as the nature and extent of a disaster, the geographical context, and cultural values, make post-disaster housing reconstruction necessarily a local process [18]. Managing post-disaster housing is therefore a complex task that transcends mere emphasis on the provision of construction materials but should also consider the contexts and environments where these projects are conceived. For example, resource availability is a critical dimension in post-disaster rebuilding, but can be influenced by policies and economic environments [10]. Behind good intentions to produce structurally resilient dwellings unfolds socio-political agendas of stakeholders affecting (unjust) housing outcomes [13]. Despite the reality that most disaster-affected populations face the task of complex rebuilding with minimal or no external support, thorough investigation into the *self-initiated* reconstruction pathways at a household level remains obscure in present post-disaster narratives.

Post-disaster housing studies have however focused in recent years on identifying challenges, influences, and new insights into household-led reconstruction. Such trends are in line with the increased motivation to achieve resilient post-disaster housing especially amidst the plurality of characterising what is considered resilient housing [19]. For example, households' perception of housing safety has been investigated to promote alignment and integration with formal engineering knowledge towards reconstruction [20]. Studies have highlighted what inhibits or enables the adoption of safer construction practices among recovering households, emphasising the crucial role of technical assistance [21] and hazard-resistant communication [22]. Barriers affecting household recovery are also discussed in literature, providing evidence of a myriad of factors inhibiting capacities to rebuild, such as the power dynamics of grant provision [23]. It has also been emphasised how social norms and networks can shape the decision-making processes of households undertaking incremental housing approaches [24,25]. All these studies reinforce the complexity of conceptualising and managing the construction of dwellings. Exploring the emergent links among these factors is important to grasp the web of systems and trail of considerations that steer housing reconstruction decisions among households.

An additional layer of complexity in post-disaster reconstruction is the need to address multi-hazard housing safety. Geographies like the Philippines are inherently exposed to the impacts of more than one hazard, like typhoons and earthquakes, which vary in their frequencies and impacts. Addressing multi-hazard safety can complicate the construction of structurally safe dwellings, such that reducing risk for one hazard may increase the vulnerability of a structure to another hazard [26,27]. Building codes provide guidance for this dilemma, but enforcement is yet to be fully institutionalised in rural areas. Local construction knowledge and building practices informally learned and adopted by communities are therefore important in these settings [7,16]. Indigenous populations, for example, are known to have construction practices generated, used, and transmitted intergenerationally [7,16]. These culture-based knowledge systems have been a tenet for Indigenous peoples to meet housing needs while considering the impacts of disasters frequent in their locale. However, as culture is dynamic, these practices change and assimilate to internal and external influences among communities [14,15]. In post-disaster settings for example, the introduction of contemporary donor-provided construction materials can redefine the longstanding vernacular architecture of communities [13]. Amid such influences and the necessity to address multi-hazard housing safety, how local and Indigenous peoples cope with their building practices to address these needs and pressures has been relatively less understood.

## 3 Methods

This study sought to analyse the pathways of multi-hazard post-disaster housing reconstruction using a case study of the Ivatan Indigenous households in Itbayat, Batanes in the Philippines. We first provide an overview of the selected case study site followed by the data collection processes involving interviews and focus group discussions. We then describe how we analysed the data through qualitative coding to identify factors affecting the reconstruction pathways, and the use of concept maps to draw linkages among the identified factors.

### *3.1 Case study site*

Itbayat is a geographically isolated municipality in the northern Philippines (see Figure 4.1). The natives of Batanes are called the Ivatans, an Indigenous group whose hallmark is their vernacular stone-and-lime houses traditionally built in response to strong winds and typhoons that frequent the area. These dwellings are of Spanish influence characterised by thick quicklime-bounded stone walls, roofed with layers of thatch (cogon) roofing. These dwellings are often complemented with hardwood window shutters, a low stature, and sometimes window-less walls on some sides to further protect the structure from harsh wind impacts [28,29] (Figure 4.1). In 2019, a series of earthquakes (magnitudes ($M_W$) 5.4, 5.9, 5.8) hit Itbayat [30] becoming the single most impactful seismic activity in the municipality based on the recollection of the people in the community. The vernacular wind-resilient houses crumbled, highlighting the need to address multi-hazard housing safety in reconstruction. We have thus chosen Itbayat as a case study to understand the pathways in how Indigenous households navigated reconstruction processes that required balancing wind and seismic considerations. Housing trajectories after the 2019 earthquakes have yet to be documented to offer lessons in tailoring more effective support for (similar) Indigenous groups. Little is currently understood regarding the factors and motivations influencing how Indigenous groups decide to rebuild their dwellings. Such merits an inquiry to appraise contextually relevant policies and programs at the nexus of traditional and contemporary construction practices.

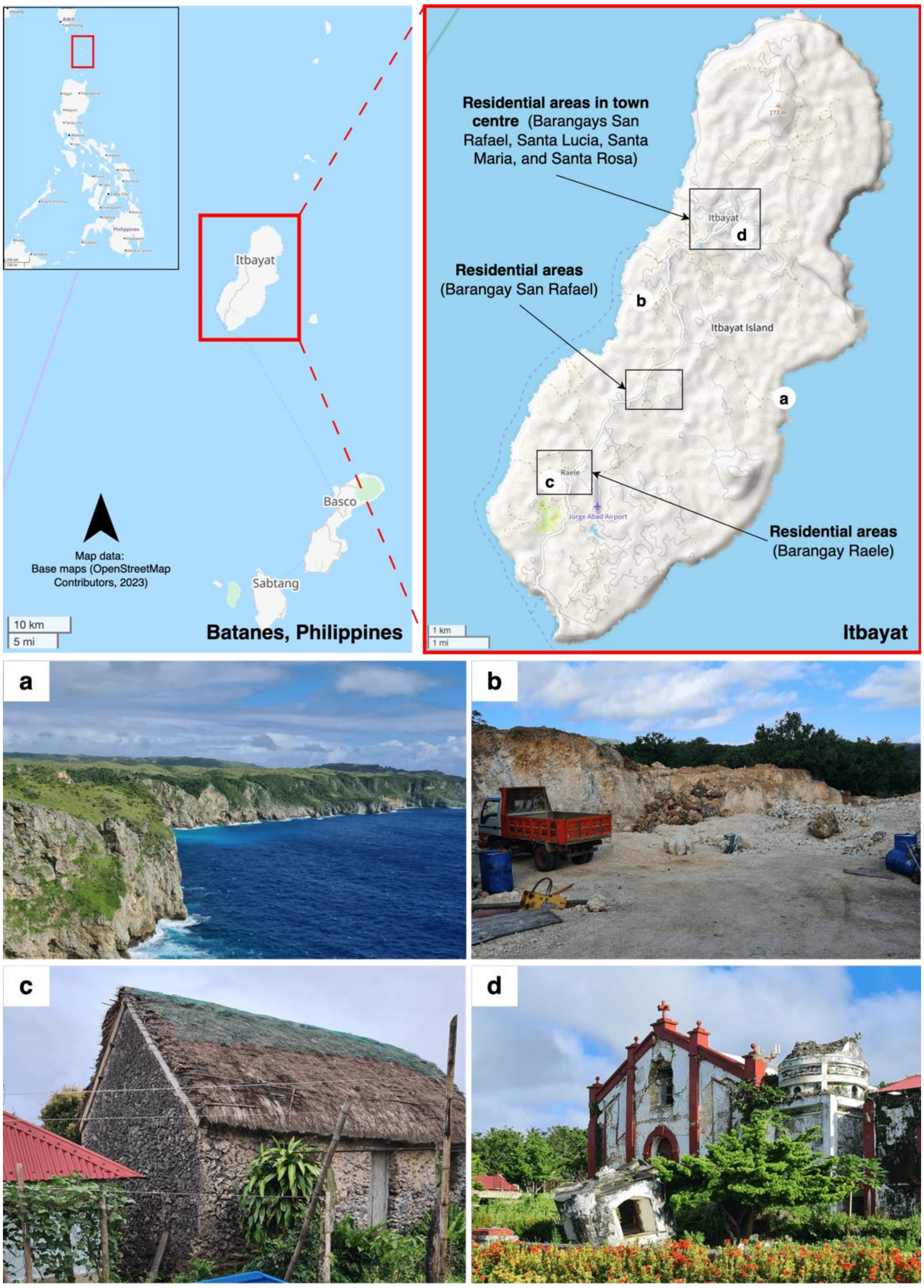


**Figure 4.1.** Location map of Itbayat, Batanes in the Philippines. **(a)** The island was formed via coral uplift characterised by its cliffside topography and limestone geology. **(b)** One of the limestone quarry areas on the island where local aggregates are sourced for construction. **(c)** A stone-and-lime vernacular house in Barangay Raele – one of the only few traditional houses that survived the 2019 earthquakes.

**(d)** A stone-and-lime church in the town centre of Itbayat which was extensively damaged during the 2019 earthquakes.

### *3.2 Data collection*

To capture and understand factors that influenced housing reconstruction in Itbayat after the 2019 earthquakes, we conducted 30 semi-structured interviews and six focus group discussions. The first author spent three months, from January 2023 to March 2023, in the municipality for data collection concurrent with efforts to survey the post-earthquake building stock in the area and evaluate structural housing safety (see [31]). This time duration enabled immersion in the community and was a critical aspect to complement the data formally gathered. All data collection conformed to the approved protocol 2022/705 granted by the Human Research Ethics Committee of The University of Sydney. Additionally, since the study was conducted among the Indigenous people of Itbayat, free, prior, and informed consent was obtained from the National Commission of Indigenous Peoples under Certificate of Precondition R2-IKSP-2022-12-21.

#### *3.2.1 Interviews*

We conducted semi-structured interviews among heads of households (n = 20) whose vernacular stone-and-lime houses were extensively damaged during the 2019 earthquakes. The participants were determined based on the damage assessment report provided by the Municipal Disaster Risk Reduction Office (MDRRMO) and the Municipal Planning and Development Office (MPDO) in Itbayat which identified 153 households with totally damaged vernacular dwellings. We selected this cohort since they were the most affected in terms of structural housing damage. The interview participants were part of an earlier group who had their reconstructed houses surveyed for structural assessment (see [31]), and these households expressed interest in being included in the interviews. Saturation of new emergent themes guided the sample size which means that the number of interviews was already capped off when new information was no longer being elicited. Interview questions focused on the traditional building practices in the area (e.g., *Can you share the indigenous construction practices in Itbayat that you know and how they help against the impacts of typhoons?*), experiences with post-earthquake reconstruction (e.g., *What made you decide to use a certain material in rebuilding your house after the earthquakes?*), and considerations of addressing housing safety against the impacts of earthquakes and typhoons (e.g., *How do you think your present house will perform against earthquakes and typhoons?*). We were interested in narratives on how households rebuilt their homes and how they balanced multi-hazard trade-offs when making housing reconstruction decisions.

We also conducted interviews (n = 10) among representatives of three municipal government offices, five provincial agencies, and two private organisations who participated in the reconstruction efforts in Itbayat. At the municipal level, the interviewees included the planning and department officer, an Indigenous peoples officer, and an environment committee member. At the provincial level, the interviewees comprised district and provincial engineers, the Indigenous peoples cultural officer, the head of the environment department, and the former disaster risk reduction officer. Interviewees representing private organisations were from a volunteer group and a heritage advocacy group. These participants had stakes during the post-earthquake reconstruction in Itbayat with them either having exercised mandated administrative functions or had provided financial, material, or technical assistance to the affected households. Participants were identified in consultation with the administrative authorities of the local government of Itbayat. The number of participants was determined by the availability of key informants. Interview questions for these personnel focused on their roles and contribution towards housing reconstruction (e.g., *Can you share what type of assistance you provided and why you chose to provide them?*), and their reflections on the challenges faced by households during reconstruction (e.g., *How do you think your organisation influenced the progress of the reconstruction process?*).

All interviews for both households and representatives of offices or agencies lasted for around 30 - 45 minutes. The interviews were mostly conducted in Filipino since participants were fluent in the national language (including the lead author). When Itbayaten, the local language, was spoken by the participants, translation was provided by a research assistant who spoke the local language and assisted in the data collection. All interviews were audio recorded, translated from Filipino to English, and then transcribed for analysis.

### *3.2.2 Focus group discussions*

While interviews are a good source of in-depth insights, focus group discussions elicit reflections arising from the interaction among participants [32]. Thus, we conducted focus groups to complement the interviews and triangulate themes. We sought priming groups with similar backgrounds (or roles) to obtain their insights emanating from their shared circumstances. We conducted six focus groups comprising six to ten participants who were involved in the reconstruction process, including local builders of vernacular houses (n=2), contemporary construction workers (n=1), local government officers (n=1), heads of households (n=1), and council of elders or the trusted village leaders within the community (n=1). The discussion for each cohort centred on their knowledge of the indigenous building practices in the area (e.g., *How are the indigenous construction practices observed today? Are they still relevant?*), their observations or experiences during the housing reconstruction (e.g., *Why do you think the households built differently after the earthquakes?*), and perceptions of the multi-hazard housing performance of the rebuilt houses (e.g., *How do you think the contemporary houses will perform against earthquakes and typhoons?*). These discussions lasted for around 60 minutes and were conducted in Filipino. These were facilitated by the lead author with the help of a research assistant from the area who provided translation from Itbayaten when needed during the discussions. Audio recordings were translated from Filipino to English and were transcribed prior to analysis.

### *2.2.3. Field notes*

Complementing the interviews and focus group discussions were data obtained through field immersion out of the first author's three-month stay in the island municipality. Day-to-day conversations with community members provided supplementary information which not only provided context to the formally gathered data but also substantiated and triangulated themes. These conversations occurred in natural settings whereby community members voluntarily shared their experiences and stories with the first author imparting his research purpose. Informal conversations are favoured in qualitative research for their ease of communication producing naturalistic data [33]. Information from these conversations was recorded via field notes alongside other means of record-keeping, such as photo documentations, sketches, and note-taking from observations. Locally produced documents (e.g., ancestral domain books, land use maps, ordinances, etc.) were also reviewed to source additional information.

### *3.3 Data analysis*

We drew on case study methods to describe the post-disaster housing reconstruction trajectories of the Indigenous households in Itbayat. Beyond a mere description of the dynamics of the chosen setting [34], we aimed to use the case as a basis to develop theory inductively [35]. First, we analysed the focus groups and interview transcripts through qualitative coding to identify and group constructs relevant to the rebuilding processes. Then, we reviewed these constructs to identify linkages using a key relationship types framework which identifies patterns of connections within the transcripts. Finally, we integrated these linkages via concept maps to portray a holistic picture representing the complexities of housing reconstruction endeavours leading to pathways of building a dwelling.

### 3.3.1 *Theme identification*

Qualitative coding identifies relevant words, phrases, and sentences that represent thoughts – or themes – within texts [36]. In this study, we used inductive coding where the content of the data dictated how themes were coded rather than having pre-defined criteria as the basis of coding. To ensure the consistency of this process, a coding dictionary was created guiding the derivation of themes based on clearly defined sets of terms and words representative of those themes. For example, we described "logistical challenges" as "challenges in importation, sourcing out, or delivering materials for housing construction or aid in general". As such, words and statements related to the transportation of materials, landed costs, and availability of materials were coded under this theme. The interview and focus group transcriptions were coded in NVivo 12.

### *3.3.2 Identifying relationships between themes*

Codes within the identified themes were reviewed (i) to find constructs indicative of factors affecting the housing reconstruction process, and (ii) to map the relationships between or among these constructs. To aid in the pattern and relationship analysis in interpretative research, Tutty et al. [37] propose three key relationship types (see Figure 4.2) to establish the links between constructs which provided a framework for our analysis in this study. The first type is called *contained relationships* where one or several constructs with shared features are grouped into one larger category. For example, we identified three construction delivery modes – (a) household-led reconstruction, (b) contract package, and (c) daily wages setup – which we then grouped as "labour schemes". The second type is *temporal relationships* where one category is a precursor to another, like that of when participants noted "approaching typhoons" which would immediately succeed the traditional practice of "tying houses". The third type is *causal relationships* where one category is the reason for another. This can be cautiously demonstrated not on a cause-and-effect basis, but intuitively when a category can be a factor for another to exist (e.g., "mass reconstruction" influenced "high demand of labour").

Rabinovich & Kacen [38] define additional relationship types to be considered in conjunction with Tutty et al.'s [37] in analysing relationships between constructs. These relationship types (see Figure 4.2) provide associative links rather than causal relationships, hence allowing the examination of the meaning of constructs from a participant's own perspective. The first type is *bilateral relationships* where one construct recurs frequently together with another in their statements, thus revealing the conjunctive association inherent between these. For example, mention of "reinforced concrete construction" was regularly equated with "durable or sturdy construction". The second type is *trilateral relationships* where one category links two other categories. This is where two bilateral relationships are joined by a common category, such as the "emergency situation of reconstruction" being associated with "eased acquisition of building permits" and the "moratorium of tree cutting permit". The third type is *quadrilateral relationships* where instead of having one common construct like that of the trilateral, it has a pair of associated opposite constructs. For example, "financial capacity" and "limited or no financial capacity" are opposing constructs, where the former was linked to "capacity to build concrete-based houses" while the latter was associated with "construction of lightweight houses".

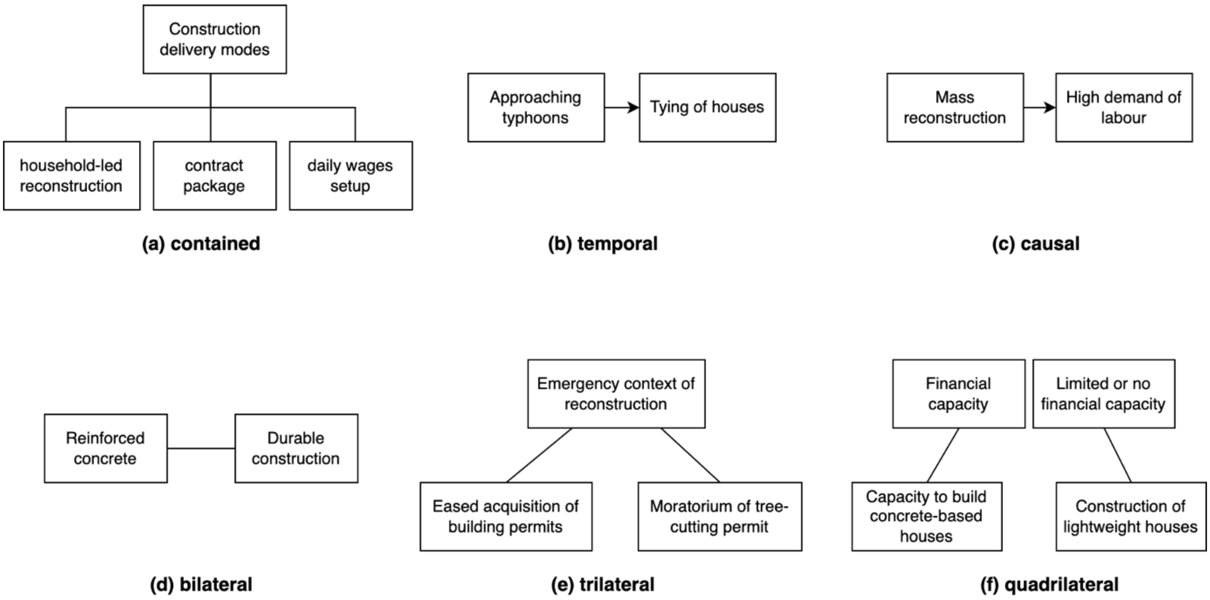


**Figure 4.2.** Examples of relationship patterns based on the key relationship types framework of Tutty et al. [37] and Rabinovich & Kacen [38].

We visualised the identified relationships using the concept maps in NVivo 12 which allowed us to draw connections among constructs. Overall, the identified relationships using the six key relationship types provided emergent patterns that served as the basis of our theoretical construction of the housing trajectories among households. To integrate these patterns into a web or network of constructs, we next used iterative diagramming.

### *3.3.3 Mapping the network of constructs*

Visual mapping facilitates the discovery of the logic of relationships and is therefore among the methods proposed to achieve integration among constructs [38]. In this study, we further used the concept maps feature in NVivo 12 to connect the individual relationship patterns identified earlier to make a cohesive network of constructs representing a community-level case of housing reconstruction in Itbayat. We looked for the commonalities across constructs (which have been earlier mapped with relationship patterns) and merged them. Additionally, we juxtaposed associated constructs to congregate them. For example, “reliance on relatives’ remittances, personal savings, or loans” was joined with “cash assistance from donors” to provide a node of “financial assets”. The first author undertook this process of integration guided by his field immersion insights and his technical background in housing construction. In case study research, supplementing insights from multiple sources substantiates theory building [34,35]. The network of constructs was then reviewed by the rest of the research team for appraisal. The second and third authors supported the external validity of identified constructs and linkages in line with their engineering and disaster management backgrounds. Meanwhile, the fourth author gave an insider’s perspective being an Indigenous community member in Itbayat, the former incident command manager during the 2019 earthquakes, and presently a local government officer. Feedback was incorporated and the diagram was iteratively refined.

## 4 Results

As a geographically isolated municipality, self-reliance is a tenet of all life aspects in Itbayat including recovery from disaster impacts. The logistics of importing aid is challenging with the frequent weather disturbances affecting the air and ocean transportation modes. Stories of previous reconstruction circumstances on the island (e.g., after Typhoon Meranti (Ferdie) in 2016) point to how the community used their available resources to rebuild with limited dependence on external aid. As how one participant remarked during a focus group discussion:

> "[…] right after [typhoons we already start] to fix things. At the same time, *bayanihan* [or helping each other out] is still very much alive. […] Because if [your house] was damaged, the others will help you. It's either in the form of labour or wood. Your neighbour is ready to help. [We are] not the kind to just rest and wait for the help of the government. The wind is still there but the people fixing are already up, for every family."

During the 2019 earthquakes, however, the dynamics of housing reconstruction was challenged due to the extensive structural damage. While not new to the process of rebuilding, addressing seismic impacts in reconstruction was a foreign concept to communities who historically needed to primarily cope with wind-induced damage from frequent typhoons. As a result, emergent housing outputs (see Figure 4.3) replaced the vernacular building stock (see also [31] for the detailed structural characteristics of these typologies). Four impetuses or stimuli affecting this reconstruction phenomenon were identified, namely (i) compounded sense of urgency, (ii) perceptions of housing safety, (iii) nature of aid vis-à-vis financial capacity, and (iv) regulatory barriers. The interrelatedness of these impetuses is depicted in Figure 4.4, and a simplified diagram of this interrelatedness is presented in Figure 4.5 to demonstrate the housing reconstruction pathways.

**Figure 4.3.** Emergent housing outputs. **(a)** Archetype of stone-and-lime vernacular house. Post-earthquake, the vernacular houses were damaged and were replaced with **(b)** lightweight, **(c)** semi-concrete, and **(d)** reinforced concrete typologies.

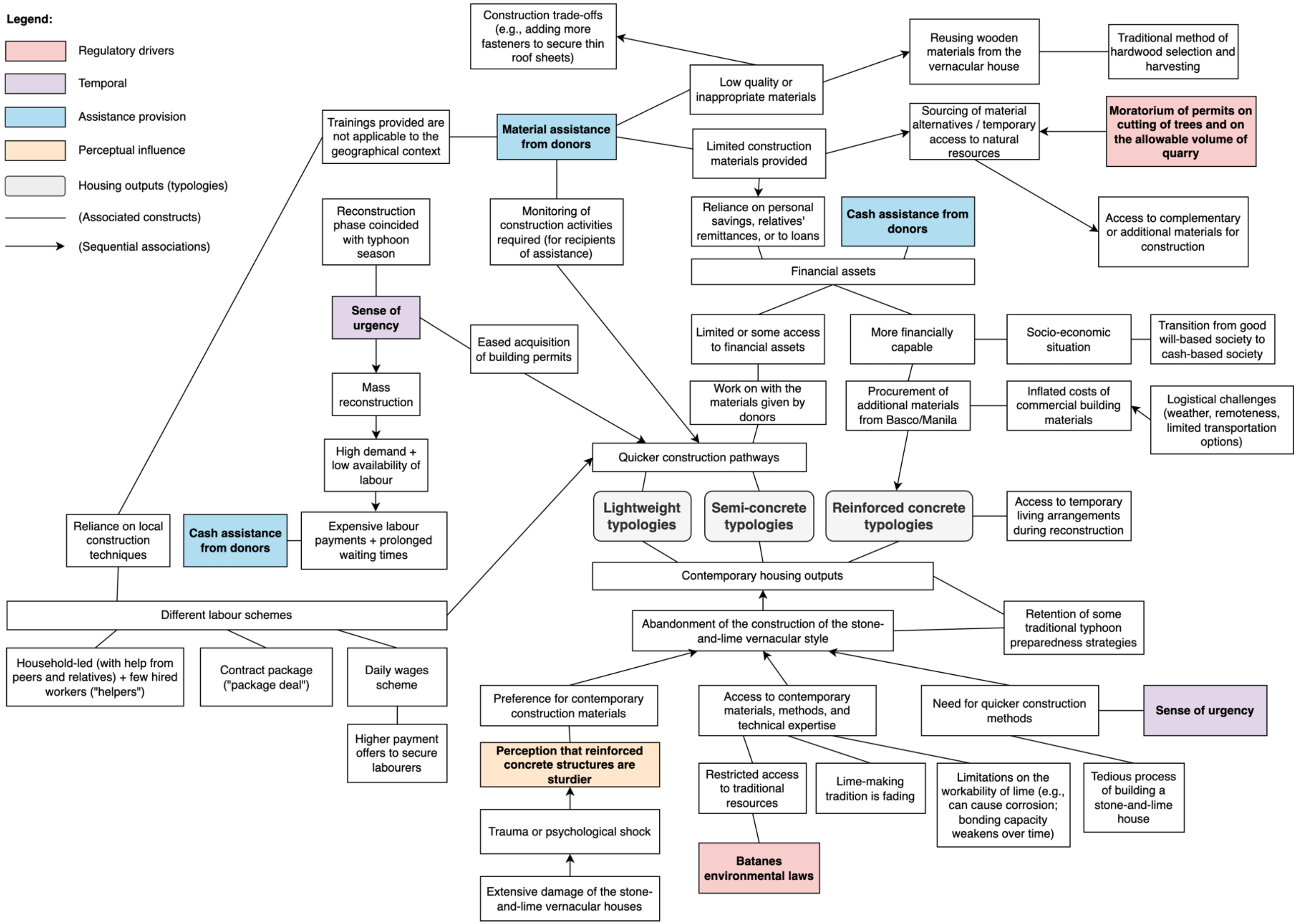


**Figure 4.4.** Network of constructs showing the influences that affected the housing trajectories of households.

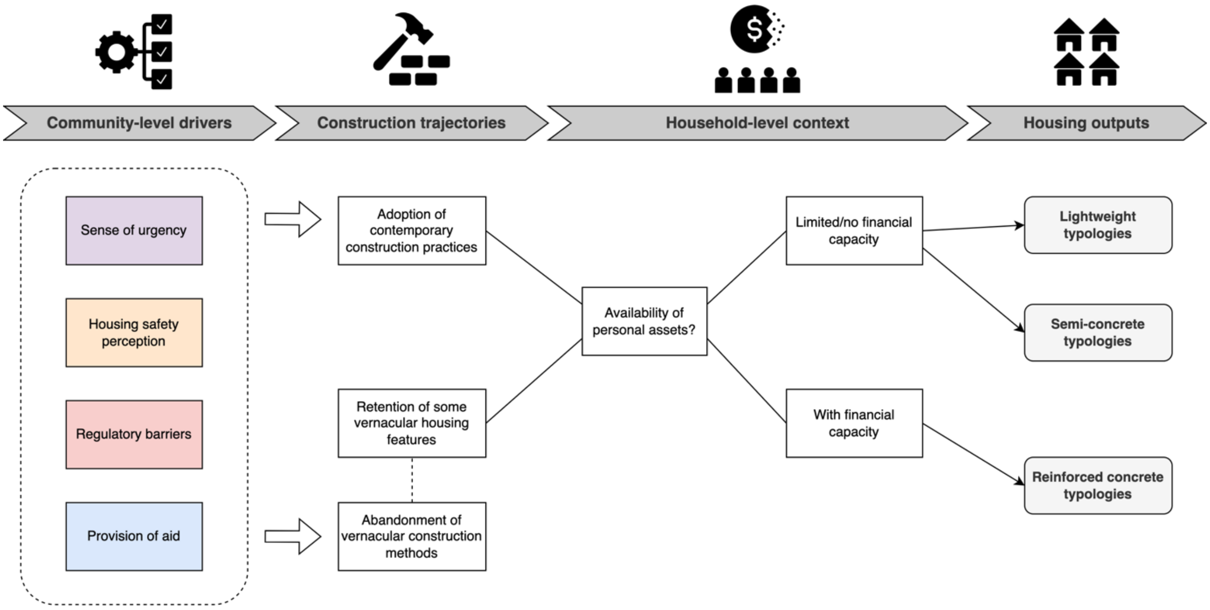


**Figure 4.5**. Diagram showing housing reconstruction pathways.

### *4.1 Compounded sense of urgency*

Time compression is a key characteristic in post-disaster environments where increased activities and demand for resources render urgency in the rebuilding process [39]. Sense of urgency became one of the main drivers in housing reconstruction in Itbayat, with two dominant factors having dictated the need to build houses as quickly as possible. First, the reconstruction phase coincided with the typhoon season. Affected households were evacuated to the plaza (an open space public square) under tents where heavy downpours and strong winds worsened the temporary living conditions, including limited access to sanitary facilities. Reconstruction began after two weeks when directives from authorities allowed households to return to their properties. By this time, some assistance provided by various government agencies and non-government organisations had already been channelled through identified recipients. The second factor—which also seemingly compounded the sense of urgency—was the conditions imposed alongside aid. Donors from both government and non-government organisations required monitoring and documentation, which pressured the households to reconstruct quickly to show rebuilding progress. Households stated how provided materials, when not immediately used, would be reallocated to others. As explained by one participant:

> "[…] [the construction of the house] should be quick because within how many months, you should have already built your house, because [the donors] are afraid that the assistance given [to us] will be deviated to other purposes. […] I'm not sure if it was here

> in our area or in others, [but] they said instead of using it to construct the house, [someone] bought a motorcycle. [If the assistance provided] will be forfeited[,] it would be embarrassing to those who donated."

From the local and provincial administrative authorities, the imposed condition was a way to instil immediate housing reconstruction to address the concern that delayed rebuilding during the typhoon season would cause further casualties. However, this donor-induced pressure intersected with other ongoing pressures (e.g., time, resource constraints, etc.) which warranted a heavily tangible-based assessment of reconstruction progress, potentially missing an opportunity to further rethink multi-hazard housing construction strategies.

Given the emergency situation, reductions of regulatory requirements were put in place, including the easing (or bypassing) of building permit stipulations to reduce construction delays. The reconstruction also resulted in a high demand but low availability of labour which consequently raised costs and prolonged waiting times for construction. Three different labour schemes emerged to address this situation. The first scheme saw household members leading the construction of their houses alongside neighbours, relatives, and one or two hired unskilled labourers. The second scheme was based on a contract led by skilled workers where a labour deal was set to complete the construction of a house. On some occasions, households reported giving all the donor-provided materials they received to builders with any lacking materials shouldered by the builders. The third was a daily wages scheme that required higher worker wages to secure. These labour schemes, together with the reduced regulatory guidelines of construction, brought quicker construction pathways for households – at least for resultant lightweight and semi-concrete housing typologies. During aid disbursement, building construction workshops were a prerequisite to receiving material assistance as imposed by some organisations to communicate building back safer messages and upskill labour. However, the workshops were discounted by households who stated that while the methods taught seismic safety, limited emphasis was given to typhoons. This resulted in a default patronage of the prevailing local carpentry methods believed to be more superior for wind safety based on the community's experiences. As expressed by participants:

> "[…] we are the ones living here, [and they] taught how to build what they [said was] a sturdy house, but the materials that they brought are weaker than the materials that we are using. At the same time, their teachings [were] something applicable to the mainland,

> in Manila. But here, I think […] [the]methods they [taught] in building houses [won't pass]."

> "[…] why the design of [the training provided by the organisation] was like that because their response here was for the earthquake. […] But the people here are more experienced with typhoons. That's why they built more securely [against wind impacts] compared to [what was demonstrated to them]. I think [the organisation was] thinking of it as a response to the earthquake."

### *4.2 Perceptions of housing safety*

The extensive damage sustained by the vernacular houses greatly influenced the construction material preferences of households. Due to the unreinforced nature of stone-and-lime houses, the irreparable state of these dwellings due to ground shaking brought trauma and shock to the community. This discouraged households from considering rebuilding this style, and instead, they opted for more resilient options, with reinforced concrete structures being the most desirable goal. Additionally, the access to contemporary building materials reinforced the notion of a construction "trend" that can be adopted more conveniently. The disaster impacts brought a sense of fatalism and some remarked that the event was a divine sign for households to replace the vernacular housing typology being seismically vulnerable, serving as a challenge to construct more robust structures. The time-consuming process of building using vernacular methods – which can take years starting from the process of burning lime – was also unsuited to the need for quicker construction alternatives to address immediate shelter needs. Additionally, the vernacular house-making craftsmanship is now a fading tradition. The greater access to building professionals with expertise in modern construction techniques has become a more favourable option. While advocates vied for workarounds to prioritise and retain the heritage character of vernacular houses in reconstruction, cost became an issue, and there was an absence of a framework to blend heritage preservation efforts with disaster management.

Despite a trajectory that abandoned the vernacular construction archetype in favour of contemporary housing typologies, retention of some local and indigenous construction and disaster preparedness practices is evident (see Figure 4.6). For example, roof framing methods were carried over in the reconstructed houses, characterised by rafter systems that utilise hardwood. The tradition of tying houses, known as *kap'yakuyakut,* remains a community-level effort to secure lightweight building envelopes. In vernacular houses, window panels were of hardwood locked from the inside with a horizontal bar called *vavangtal* to prevent wind intrusion. This feature has evolved as *tapangko*, now placed outside to cover windows especially those made of glass which can be prone to wind-borne impacts. In some instances, preference for hardwood window panels led some households to recycle those from their previous vernacular houses. Lastly, roof eaves of the reconstructed houses remain relatively short – as is with the vernacular archetype – to minimise wind uplift.

**Figure 4.6.** Retained construction and typhoon preparedness practices. **(a)** Indigenous roof framing system of a stone-and-lime house. **(b)** The indigenous roof framing system as applied to a new housing typology. **(c)** A steel anchor embedded on a concrete wall of a contemporary house which is used to secure ropes or ties as part of the continued practice of tying houses in preparation for typhoons. **(d)** From the inside of a vernacular stone-and-lime house, a horizontal bar (*vavangtal*) is used to secure windows and prevent wind and rainwater intrusion. **(e, f)** This concept has now evolved and is used

from the outside to protect glass windows common with contemporary housing typologies. **(g, h)** Recycling hardwood from damaged vernacular houses is common, such that window and door panels made from hardwood are preferred over glass.

## *4.3 Nature of aid vis-à-vis financial capacity*

The materials provided by government and non-government organisations dictated the characteristics of the emergent housing typologies after the earthquakes. Households whose houses were completely destroyed received a combination of corrugated galvanised iron sheets, steel pipes, lumber, nails, and cement in varying quantities, enabling contemporary construction. Cash aid was also disbursed and was predominantly used to procure lacking materials and as labour payments. Additionally, access to relatives' remittances, personal savings, or loans augmented financial assets which were linked to households' socio-economic situations. Being mostly an agricultural and fishing economy, income opportunities on the island do not easily match the high cost of living exacerbated by geographical isolation. Thus, this situation restricted economic freedom for some, if not most, to finance reconstruction activities. Historically, community transactions in Itbayat have largely been based on goodwill including the exchange of goods and commodities. With the present context already transitioning to a monetary-based economy, this situation saw an increased influence on whether households had the required capacity to build back safer.

Households with limited financial assets were forced to use donated materials to reconstruct their houses, resulting in lightweight and semi-concrete typologies. The cuboid form of these typologies was assimilated from vernacular houses – a design input lobbied by the provincial government alongside the aid disbursement. Additionally, the prominence of steel posts as corner posts in these typologies was an input to expedite construction and address the lack of hardwood access. These typologies were intended to be temporary, with the vision of incremental improvements as more resources became available to households. However, more than three years after the earthquakes, these typologies remained as unchanged dwellings. Households with more financial capacity were able to procure additional materials (specifically cement, reinforcing steel bars, and aggregates) from Basco or mainland Luzon, which enabled them to build reinforced concrete structures. Due to the geographical isolation of Itbayat, logistical challenges of importation inflate material costs. For example, the price of cement is double compared to mainland Luzon, while aggregates can be six times more expensive. For those who built reinforced concrete, access to either temporary living arrangements with relatives or secondary shelters was required during the construction since construction timelines took longer compared to the lightweight typologies.

### *4.4 Regulatory barriers*

In 2000, Republic Act 8991, otherwise known as the Batanes Protected Area Act, was enacted to conserve, protect, and preserve the environmental and cultural assets of the Batanes Group of Islands [40]. While well-intended to safeguard the environment, its stringent mandates on resource extraction have become misaligned to the needs of the Indigenous people who cultivate and own the ancestral domain. Restrictive environmental policies have become a contributory factor to the abandonment of building a vernacular stone-and-lime house, as resources such as coral limestones and hardwood are heavily policed. As how one participant from a government agency explained this situation:

> "Can you imagine, a community like Itbayat where resources are scarce, commercially expensive and for centuries the people claimed this island as their own, but [then] the government came in [to regulate natural] resource use? Everything has become so restricted. Imagine, you planted trees for you to use in building your houses, but you don't get access to it. So now, [the Ivatans] are being deprived. […] [T]he implementation of very stringent policies in the protected area [is depriving] these people from making use of what is supposed to be theirs to build a more resilient house. […] So many layers of bureaucracy. […] These agencies sometimes have become irrelevant to the needs of the community considering the urgency [of reconstruction]. […] It seems that the government is protecting so much of the resources, but not the welfare of the people. It is so focused on the preservation of those resources that they didn't consider that these resources were cultivated [and] planted for [the Indigenous people's] use. But now, [the people] rely on the commercial lumbers, so in just a whiff of the wind, [these materials become] too weak."

House building is central to the Ivatan culture where resources are cultivated or sourced for this endeavour. In building a timber house, for example, the local terms for framing components are attributed to structural functions which serve as a basis for sourcing the best type of wood to be used (see Figure 4.7). For example, when someone is tasked to find materials for *pangoraywanan* (corner post), specific hardwood types of the sturdiest make (e.g., *Vuxos*, *Aryaw*, and *Murni*) are sought. The existing regulations restricting access to hardwood are, however, affecting this practice.

After the 2019 earthquakes, a moratorium on the prohibition of hardwood cutting (via a special permit) was issued to allow hardwood to be used for housing reconstruction. This diverted households from using the softwood provided in the material assistance as structural components, which were instead used as door and window frames. Reusing hardwood salvaged from the damaged vernacular houses was also practised by most households. The moratorium lasted for three months, but the extraction of resources within this duration was not maximised due to local cultural practices. Apart from the careful selection of wood species, the Ivatans are also known to practice lunar harvesting. Trees are preferred to be cut from full moon to last quarter for moisture considerations which can affect the durability of wood (especially against wood boring insects). The lunar cycles were not accounted for when the moratorium was conceived, and households needed to apply for separate individual permits after the moratorium lapsed. Individual permit processing can take some time as this needs to be approved by the regional office (located in mainland Luzon). A copy of lot titles is required with the application, and this became a barrier for most households due to the pending legal status of lot ownership.

**Figure 4.7.** The indigenous method of timber construction comes with local names for the parts of the framing system. (Note: The structure shown is constructed for a shed, but the framing system is generic for residential construction.)

## 5 Discussion

Apart from being a conduit for achieving a sense of normalcy after disasters, housing reconstruction is also seen as an opportunity to address underlying structural and social vulnerabilities [41]. Thus, "building back safer" has become the mainstream slogan in post-disaster rebuilding efforts [42]. Most often, the provision of construction material aid and training assistance is the de facto modality of government and non-government donors to leverage such pursuits. However, without careful thought in understanding the complex factors shrouding the trajectories of housing reconstruction, outside interventions risk offering band-aid solutions precluding sustainable and contextually appropriate outcomes. As demonstrated in the case of Itbayat, addressing structural housing safety against wind and seismic impacts involved a web of cultural, environmental, regulatory, and socio-economic considerations. Unfortunately, default interventions still linger in aid (such as the one-time blanket provision of shelter kits) without deliberate effort to understand their impact and relevance within the wide network of factors affecting housing reconstruction. Below, we reflect on multi-faceted policy implications of the issues affecting the capacity of households to have safer dwellings after disasters.

### *5.1 Construction oversight during disasters*

Building code compliance through the issuance of building permits ensures that the planning, design, and construction of structures conform to technically approved building practices. However, as how our case study has shown, existing legislation does not provide special guidance for housing construction oversight during emergency situations where time and resources are contested by the affected populations. As a result, building regulations are often neglected or bypassed by affected households. This circumstance presents an unaccounted risk in achieving housing safety since it sits at the nexus of balancing the urgency to have a shelter and easing requirements that would have addressed sound housing construction and planning. Furthermore, building practices have generally been rooted in independent approaches to dealing with the impacts of individual hazards. Trade-offs aim to optimise housing safety amid the various and often competing hazard impacts. However, without appropriate technical guidance, risk emerges when communities are left to make decisions without adequate information to inform multi-hazard safety.

The majority of legislation (such as in our case site) was crafted without consideration of emergency contexts [43]. In post-disaster rebuilding, legislation plays a vital role in shaping a robust regulatory framework for building back safer [44]. Two modes are posited for viable implementation – first, regulation needs to support construction standards (“legislation for compliance”) and second, policy to simplify processes to reconstruct quicker in such emergency contexts (“legislation for facilitation”) [44]. While existing building codes satisfy legislation for compliance, technical guidance on multi-hazard rebuilding is yet to be incorporated. Multi-hazard studies are increasingly becoming prominent but their inclusion in legislation and policies is still limited. Legislation for facilitation (e.g., [45]) also lags, and its enactment is critical to complement the former. One of the main problems in managing post-disaster reconstruction is that despite the acknowledgement that resources are compromised, customary legislation unsuited for high-pressure post-disaster environments is still being proxied for use in these contexts [43]. In our case study, we have seen that with the lack of legislation for facilitation, households navigated their own reconstruction, and this put uncertainty in satisfying the merits of legislation for compliance due to its unregulated nature. Further, uncertainty in achieving housing safety was compounded by the lack of technical guidance on multi-hazard construction as it should have ideally been part of legislation for compliance. To improve construction oversight in the aftermath of disasters, the synergies between legislative compliance and facilitation should be achieved with special consideration to the unique challenges of post-disaster environments.

### *5.2 Rethinking the landscape of aid*

The culture of aid-giving in Itbayat only materialised when social media started to routinely publicise the perennial struggles of the community to natural hazards, especially typhoons. Before this occurrence, the island's isolation – both geographically and logistically – inculcated self-reliance among the people. During the 2019 earthquakes, a much different post-disaster landscape emerged characterised by superfluous aid coupled with the heightened attention and demand of donors to flock to the island. This situation overwhelmed the community. The throngs of donors and personnel deployed to the area to disburse the aid threatened the carrying capacity of the island with the increased demand for necessities paralysing the already fragile and limited resources. As a result, entry restrictions to the island were imposed to further prevent unwanted consequences. In post-disaster situations, the crowding of donors is usually a familiar scene whereby the lack of coordination among themselves in channelling aid can result in an overall inefficient operation in supporting affected populations [46,47]. Enhancing coordination in humanitarian responses proves to be a challenge where the operating environments and the organisational structures where humanitarian actors are part of usually fail to promote inter-organisational cooperation [48].

Both *what* is provided to support recovering communities and *how* it is distributed can impact the capacity to build safer dwellings. The literature is vast on how inappropriate materials can have consequences for longer-term recovery and risk reduction. For example, in Nepal, the reconstruction efforts after the 2015 Gorkha earthquake resulted in the adoption of concrete houses which displaced vernacular construction technologies and have produced dwellings that are unresponsive to the climate and to the needs of the households [13]. However, what is not highlighted in literature is how communities exercise trade-offs as coping mechanisms to tackle the provision of what can be argued as inappropriate (material) aid. For example, in our study, if the quality of donated materials did not meet households' expectations (e.g., softwood), efforts were undertaken to source better alternatives (e.g., salvaged hardwood from previous dwellings) to satisfy perceived structural soundness. Where households are left to use what is given (e.g., being forced to use donated lightweight material envelopes due to financial limitations), we observed attempts to increase construction safety using workarounds (e.g., introducing closely spaced fasteners to secure building envelopes). Aid-providing organisations can learn from these trade-offs to rethink how aid is mobilised and to strategise how to upscale interventions.

The manner of aid distribution is just as impactful in meeting safer housing objectives. In the case of Itbayat, it was remarked that various organisations targeted specific households, relying only on *barangay*- or village-level beneficiary assessments without coordination with the local municipal government. This situation presented loopholes for nepotistic and cronyistic intentions to divert or duplicate the aid being received. The result was non-equitable aid distribution exacerbated by the lack of checks and balances. When this happens, other households are deprived of reconstructing safer dwellings, which demonstrates a classic example of how the political environment can impact the achievement of housing safety in post-disaster settings. Aid distribution and management are critical when the affected population contests for reconstruction resources. Our case study contributes by showing how power dynamics in post-disaster settings impact housing reconstruction outputs (see, for example, [23]).

### *5.3 Harmonisation of laws*

The conflicting and overlapping provisions of laws are affecting the opportunities of the Indigenous people to build structurally safer houses. While the Indigenous Peoples Rights Act of 1997 promotes the rights of cultural communities over the ownership of their ancestral domains [49], environmental laws like the Batanes Protected Act of 2000 [40] complicate implementation. The Ivatans, whose traditional resource extraction practices have long relied on natural materials for house building (e.g., locally grown hardwood), are now pressured to rely on (costly) commercial construction materials. The most economically disadvantaged households are then left behind in this conundrum, restricting their opportunities to build back safer. While government mandates aim to protect both the environment and the interests of the Indigenous peoples, it becomes the case of one interest being upheld while inhibiting the other.

A policy review is thus needed to better align existing laws. Tackling complex societal challenges has been linked to building policy synergies which look into “the interactions of policy elements shaping outcomes and impacts which could otherwise not be achieved by a policy working on its own” [50] (p. 2). Three entry points are proposed to achieve policy synergies: (i) building on existing policy architecture focusing on opportunities like overarching frameworks guiding administrative activities towards shared objectives; (ii) investing in multi-stakeholder decision-making and action spaces to understand how issues are perceived, thus impacting how these are addressed; and, (iii) co-developing integrative capacity of policy actors through strategies like improving social relationships and bringing in together different sources of knowledge to shape collective decision-making and action [50]. These entry points would support a more participative approach to legislation, drawing on the grounded experiences of grassroots constituents and the leadership of administrative actors. In post-disaster reconstruction, this integration of intra-community social ties and extra-community relations has the potential not just to foster partnerships but also to manage reconstruction outcomes [51].

### *5.4 Investing in local and indigenous knowledge*

The adoption of contemporary building practices in Itbayat did not mean the total abandonment of local and indigenous interventions in rebuilding houses. The retention of some traditional building practices resonates with patronage to tried and tested experiential measures, now used alongside modern construction techniques. This adds to the growing evidence in literature on the blending of local, indigenous and scientific means to reduce risks [16]. This nexus offers opportunities to institutionalise these practices. For example, in April 2023, the local government of Itbayat started a knowledge-sharing and skills enhancement training among the youth focused on the practice of tying houses in preparation for typhoons to instil the relevance of this practice and create inter-generational knowledge transfer. Additionally, beyond securing the house, a municipal ordinance was adopted in October 2023 to institutionalise the indigenous disaster preparedness practices of food stockpiling (e.g., *kapan'tachip, kapan'inalis*, etc.) and evacuation (*kapachihbeng*) [52].

There has been an increasing awareness and recognition of the importance of local and indigenous knowledge for risk reduction [16]. However, its culture-specific and heterogeneous nature makes it challenging to formally include it in a national agenda where interventions are expected to be easily upscaled and mainstreamed across a multitude of contexts [7]. An insight gleaned from the case of Itbayat is the potential to downscale policies through local ordinances to support mainstreaming risk reduction practices based on local and indigenous knowledge. This becomes possible with the presence of an enabling administrative environment at a local level to pioneer legislation in culturally rooted risk reduction practices. However, this locally supportive context is not a panacea, as some mandates are normatively crafted at a national level. For example, building codes are enacted nationally in the Philippines and thus assume general applicability across a country. Where indigenous construction methods are used in localities, guidance on their enforcement and regulation is limited, if not lacking. Most often, building codes only have contemporary construction guidelines, thus risking the displacement of long-practised indigenous construction systems.

## 6 Conclusion

Most disaster-affected populations face the complex task of reconstructing their dwellings with minimal or no external support. However, there is a need to further understand the self-initiated reconstruction pathways of households, especially among Indigenous groups, who need to address the competing impacts of multiple hazards. We presented a case study in Itbayat, Batanes in the Philippines to understand the housing reconstruction trajectories of the Ivatan Indigenous households after the 2019 earthquakes that redefined their typhoon-resilient construction practices. Using interviews and focus group discussions, factors affecting the reconstruction process were elicited. Then, using concept maps, we explored the linkages of these factors leading to the adoption of the emergent housing outputs. We found that the emergence of new housing typologies that displaced the vernacular architecture was influenced by the compounded urgency to reconstruct houses, perceptions of housing safety influenced by the seismic events, the nature of aid provided alongside households' financial capacity, and the regulatory barriers affecting traditional resource extraction.

Indigenous households in Itbayat mobilised both indigenous and modern construction approaches to rebuild their dwellings. This adheres to the concept of "involuted disaster knowledge" proposed by Lin and Chang [14] alongside others who empirically observed how knowledge systems are inherently hybridised on-the-ground (see [16]). We theoretically advance that such hybridisation is being heightened with the intersecting personal (e.g., socio-economic background and housing safety perceptions), circumstantial (e.g., emergency context), and institutional (e.g., regulatory barriers and presence of donors) influences. For example, households exercised construction trade-offs to cope with the provision of modern material aid adapting their local construction practices within the contemporary context of rebuilding. We further advance the idea that these influences impose explicit and implicit decisions on households, with the concept of trade-offs representing their coping capacities in navigating both decisions they have direct and indirect control. On a broader perspective, the trade-offs highlighted in this case study are attributed to the phenomenon of social-ecological resilience where societies are observed to continually innovate (sometimes in an unplanned and unpredictable ways) in the face of disturbances such as disasters [53].

On a practical note, our case study provides relevance for policy insights. First, the central role of legislation has been emphasised as a platform to initiate multi-hazard housing reconstruction. Whereby policies exist, reforms are needed when contradictions among mandates complicate the achievement of objectives that enable the capacities of constituents to build back safer. Second, a system of channelling aid is critical to ensure that aid distribution grants equitable access to resources during post-disaster reconstruction. The need for a system is further heightened in geographically isolated and environmentally protected areas like Itbayat, where construction resources are limited due to challenging logistics and stringent environmental laws. Lastly, among Indigenous communities, local governance has the potential to pioneer the continued relevance of using local and indigenous disaster mitigation practices. By downscaling policies through the enactment of local ordinances, institutionalising and mainstreaming indigenous practices for disaster risk reduction become feasible. These insights intend to guide the appraisal of contextually relevant policies and programs at the nexus of traditional and contemporary construction practices considering emergency contexts.

## 7 References

[1] L. Harriss, C. Parrack, Z. Jordan, Building safety in humanitarian programmes that support post-disaster shelter self-recovery: an evidence review, Disasters 44 (2020) 307–335. https://doi.org/10.1111/disa.12397.

[2] J. Twigg, The evolution of shelter “self-recovery”: adapting thinking and practice for post-disaster resilience, JBA 9s8 (2021) 5–22. https://doi.org/10.5871/jba/009s8.005.

[3] B. Flinn, Defining ‘Better’ Better: Why Building Back Better Means More than Structural Safety, Journal of Humanitarian Affairs 2 (2020) 35–43. https://doi.org/10.7227/JHA.032.

[4] C. Parrack, B. Flinn, M. Passey, Getting the Message Across for Safer Self-Recovery in Post-Disaster Shelter, OHI 39 (2014) 47–58. https://doi.org/10.1108/OHI-03-2014-B0006.

[5] J. Twigg, E. Lovell, H. Schofield, L.M. Morel, B. Flinn, S. Sargeant, T. Dijkstra, V. Stephenson, A. Albuerne, T. Rossetto, D. D’Ayala, Self-recovery from disasters: An interdisciplinary perspective, Overseas Development Institute, 2017.

[6] M.T. Tafti, M. Bashiri, Navigating transition: post-disaster housing pathways of households, J Hous and the Built Environ 37 (2022) 1745–1767. https://doi.org/10.1007/s10901-021-09918-w.

[7] UNDRR, Words into Action guidelines: Using traditional and indigenous knowledges for disaster risk reduction, UNDRR, 2022.

[8] E. Jordan, A. Javernick-Will, K. Tierney, Post-tsunami recovery in Tamil Nadu, India: combined social and infrastructural outcomes, Nat Hazards 84 (2016) 1327–1347. https://doi.org/10.1007/s11069-016-2489-4.

[9] Y. Chang, S. Wilkinson, R. Potangaroa, E. Seville, Donor-driven resource procurement for post-disaster reconstruction: Constraints and actions, Habitat International 35 (2011) 199–205. https://doi.org/10.1016/j.habitatint.2010.08.003.

[10] Y. Chang, S. Wilkinson, R. Potangaroa, E. Seville, Identifying factors affecting resource availability for post-disaster reconstruction: a case study in China, Construction Management and Economics 29 (2011) 37–48. https://doi.org/10.1080/01446193.2010.521761.

[11] Y. Chang, S. Wilkinson, R. Potangaroa, E. Seville, Resourcing challenges for post-disaster housing reconstruction: a comparative analysis, Building Research & Information 38 (2010) 247–264. https://doi.org/10.1080/09613211003693945.

[12] M.T. Tafti, Housing assistance distribution after disasters: does it enable affected households to recover?, Environmental Hazards 14 (2015) 361–377. https://doi.org/10.1080/17477891.2015.1080655.

[13] J. Karki, S. Matthewman, J.H. Grayman, Nayã Ghar (A new house): Examining post-earthquake housing reconstruction issues in Nepal, International Journal of Disaster Risk Reduction 78 (2022) 103116. https://doi.org/10.1016/j.ijdrr.2022.103116.

[14] P.-S.S. Lin, K.-M. Chang, Metamorphosis from local knowledge to involuted disaster knowledge for disaster governance in a landslide-prone tribal community in Taiwan, International Journal of Disaster Risk Reduction 42 (2020). https://doi.org/10.1016/j.ijdrr.2019.101339.

[15] M. Lauer, Oral traditions or situated practices? Understanding how indigenous communities respond to environmental disasters, Human Organization 71 (2012) 176–187. https://doi.org/10.17730/humo.71.2.j0w0101277ww6084.

[16] A. Hadlos, A. Opdyke, S.A. Hadigheh, Where does local and indigenous knowledge in disaster risk reduction go from here? A systematic literature review, International Journal of Disaster Risk Reduction 79 (2022) 103160. https://doi.org/10.1016/j.ijdrr.2022.103160.

[17] UNISDR, Sendai Framework for Disaster Risk Reduction 2015 - 2030, 2015.

[18] A.K. Jha, J.D. Barenstein, P.M. Phelps, D. Pittet, S. Sena, Safer Homes, Stronger Communities, The World Bank, 2010.

[19] O. Ladipo, G. Reichard, A. McCoy, A. Pearce, P. Knox, M. Flint, Attributes and metrics for comparative quantification of disaster resilience across diverse performance mandates and standards of building, Journal of Building Engineering 21 (2019) 446–454. https://doi.org/10.1016/j.jobe.2018.11.007.

[20] C. Venable, A. Javernick-Will, A.B. Liel, M.A. Koschmann, Revealing (mis)alignments between household perceptions and engineering assessments of post-disaster housing safety in typhoons, International Journal of Disaster Risk Reduction 53 (2021) 101976. https://doi.org/10.1016/j.ijdrr.2020.101976.

[21] E. Hendriks, M. Stokmans, Drivers and barriers for the adoption of hazard-resistant construction knowledge in Nepal: Applying the motivation, ability, opportunity (MAO) theory, International Journal of Disaster Risk Reduction 51 (2020) 101778. https://doi.org/10.1016/j.ijdrr.2020.101778.

[22] E. Hendriks, A. Opdyke, Knowledge adoption in post-disaster housing self-recovery, DPM 29 (2020) 849–864. https://doi.org/10.1108/DPM-01-2020-0025.

[23] H. Schofield, E. Lovell, B. Flinn, J. Twigg, Barriers to urban shelter self-recovery in Philippines and Nepal: lessons for humanitarian policy and practice, JBA 7 (2019) 83–107.

[24] S. Merrill, E. Markel, A. Scarampi, M. Bolden, S. Yoder, Beyond building: how social norms and networks shape mason construction practices in incremental homebuilding, EDM 32 (2021) 161–178. https://doi.org/10.3362/1755-1986.21-00014.

[25] J. Talbot, C. Poleacovschi, S. Hamideh, C. Santos-Rivera, Informality in Postdisaster Reconstruction: The Role of Social Capital in Reconstruction Management in Post–Hurricane Maria Puerto Rico, J. Manage. Eng. 36 (2020) 04020074. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000833.

[26] M.C. de Ruiter, J.A. de Bruijn, J. Englhardt, J.E. Daniell, H. de Moel, P.J. Ward, The Asynergies of Structural Disaster Risk Reduction Measures: Comparing Floods and Earthquakes, Earth's Future 9 (2021). https://doi.org/10.1029/2020EF001531.

[27] Y. Li, A. Ahuja, J.E. Padgett, Review of Methods to Assess, Design for, and Mitigate Multiple Hazards, J. Perform. Constr. Facil. 26 (2012) 104–117. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000279.

[28] F. Hornedo, Traditional Ivatan Shelter and Architecture, Part Two, The Classic Traditional Ivatan House: Emergence and Prospects, Ivatan Studies Journal XIII–XIV (2015) 39–112.

[29] National Historical Commission of the Philippines, Vahay: Documenting the Story of the Ivatan House, National Historical Commission of the Philippines, Manila, 2018.

[30] J. Perez, K. Vitto, P. Sawi, J. Blacer, R. Tiglao, M. Pagtalunan, J.R. Danganan, A. Garil, Impacts of the 27 July 2019 Magnitudes (Mw) 5.4, 5.9, and 5.8 Itbayat, Batanes Earthquakes, Department of Science and Technology - Philippine Institute of Volcanology and Seismology, 2019.

[31] A. Hadlos, A. Opdyke, S.A. Hadigheh, Deriving expert-driven wind and seismic fragility functions for non-engineered residential typologies in Batanes, Philippines, Scientific Reports 13 (2022). https://doi.org/10.1038/s41598-023-49398-2.

[32] D.W. Seal, L.M. Bogart, A.A. Ehrhardt, Small Group Dynamics: The Utility of Focus Group Discussions as a Research Method, Group Dynamics: Theory, Research, and Practice Vol. 2 (1998) 253–266.

[33] J. Swain, B. King, Using Informal Conversations in Qualitative Research, International Journal of Qualitative Methods 21 (2022) 160940692210850. https://doi.org/10.1177/16094069221085056.

[34] K.M. Eisenhardt, Building Theories from Case Study Research, The Academy of Management Review 14 (1989) 532–550.

[35] K.M. Eisenhardt, M.E. Graebner, Theory Building From Cases: Opportunities And Challenges, AMJ 50 (2007) 25–32. https://doi.org/10.5465/amj.2007.24160888.

[36] J. Saldaña, The coding manual for qualitative researchers, 2nd ed, SAGE, Los Angeles, 2013.

[37] L.M. Tutty, M.A. Rothery, R.M. Grinnell, Qualitative research for social workers, Allyn and Bacon, Boston, 1996.

[38] M. Rabinovich, L. Kacen, Advanced relationships between categories analysis as a qualitative research tool, J Clin Psychol 66 (2010) 698–708. https://doi.org/10.1002/jclp.20693.

[39] R.B. Olshansky, L.D. Hopkins, L.A. Johnson, Disaster and Recovery: Processes Compressed in Time, Nat. Hazards Rev. 13 (2012) 173–178. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000077.

[40] Congress of the Philippines, An Act to Establish the Batanes Group of Islands and Islets as a Protected Area, and Its Peripheral Waters as Buffer Zones, Providing for Its Management and for Other Purposes, 2001.

[41] T.A. Tran, Post-disaster housing reconstruction as a significant opportunity to building disaster resilience: a case in Vietnam, Nat Hazards 79 (2015) 61–79. https://doi.org/10.1007/s11069-015-1826-3.

[42] A. Opdyke, Z. Wang, Prioritising build back safer messages for humanitarian shelter, International Journal of Disaster Risk Reduction 64 (2021) 102475. https://doi.org/10.1016/j.ijdrr.2021.102475.

[43] J.L. Masurier, J.O.B. Rotimi, S. Wilkinson, A Comparison Between Routine Construction and Post-Disaster Reconstruction with Case Studies from New Zealand, in: Proceedings 22nd Annual ARCOM Conference, Association of Researchers in Construction Management, Birmingham, UK, 2006: pp. 523–30.

[44] S. Mannakkara, S. Wilkinson, Post-Disaster Legislation for Building Back Better, Construction Law Journal (2013).

[45] Disaster Management Centre, Mainstreaming Disaster Risk Reduction into approval permits of development activities in the coastal areas of Sri Lanka, (2011).

[46] H. Safarpour, S. Fooladlou, M. Safi-Keykaleh, S. Mousavipour, D. Pirani, A. Sahebi, H. Ghodsi, I. Farahi-Ashtiani, A. Dehghani, Challenges and barriers of humanitarian aid management in 2017 Kermanshah earthquake: a qualitative study, BMC Public Health 20 (2020) 563. https://doi.org/10.1186/s12889-020-08722-5.

[47] E. Safapour, S. Kermanshachi, A. Pamidimukkala, Post-disaster recovery in urban and rural communities: Challenges and strategies, International Journal of Disaster Risk Reduction 64 (2021) 102535. https://doi.org/10.1016/j.ijdrr.2021.102535.

[48] M. Stephenson Jr., Making humanitarian relief networks more effective: operational coordination, trust and sense making: Making Humanitarian Relief Networks More

Effective, Disasters 29 (2005) 337–350. https://doi.org/10.1111/j.0361-3666.2005.00296.x.

[49] Congress of the Philippines, An Act to Recognize, Protect and Promote the Rights of Indigenous Cultural Communities/Indigenous Peoples, Creating a National Commission on Indigenous Peoples, Establishing Implementing Mechanisms, Appropriating Funds Therefor, and for Other Purposes, 1997.

[50] E. Carmen, I. Fazey, A.M. Bergseng, E.S. Om, Building policy synergies: A case of community resilience, climate change and community empowerment policies in Scotland, Environmental Science & Policy 150 (2023) 103579. https://doi.org/10.1016/j.envsci.2023.103579.

[51] S. McDonnell, P. Ghorbani, C. Wolf, M.J. Cruz, D.M. Burgy, S. Desai, D. Berkovits, R. Silberblatt, A Managed-Participatory Approach to Community Resilience: The Case of the New York Rising Community Reconstruction Program, American Review of Public Administration 49 (2019) 309–324. https://doi.org/10.1177/0275074018804663.

[52] LGU Itbayat, An Ordinance Establishing Guidelines on the Declaration and Enforcement of Pre-Emptive and Forced Evacuation During Emergency Situations Caused by Natural and/or Man-Made Disasters in the Municipality of Itbayat, 2023.

[53] C. Folke, R. Biggs, A.V. Norström, B. Reyers, J. Rockström, Social-ecological resilience and biosphere-based sustainability science, E&S 21 (2016) art41. https://doi.org/10.5751/ES-08748-210341.

# Chapter 5

# Optimising housing typology distributions for multi-hazard loss reductions in resource-constrained settings

## Abstract

Disaster loss estimations are valuable risk reduction tools but rarely consider the loss trade-offs when a building stock is subjected to multi-hazard impacts. Here, we developed an approach to simulate direct economic losses of a housing stock and explore loss reduction across scenarios of housing typology distributions. We used multi-objective optimisation to model wind and seismic losses in Itbayat, Batanes, Philippines. Using Monte Carlo simulation, 11,628 housing stock scenarios were modelled under two cases of paired extreme hazard intensity thresholds, identifying Pareto optimal solutions that were further analysed against a socio-technical framework. We show that the current housing stock distribution can sustain lower multi-hazard losses by achieving more optimal combinations of lightweight and reinforced concrete typologies. However, transitioning to this desired stock distribution becomes a trade-off of not just wind-seismic loss reductions but also of socio-technical considerations such as households' risk perceptions. Our study advances risk reduction strategies by streamlining loss estimations to inform collective and safer multi-hazard construction practices.

## 1 Introduction

Disaster losses serve as an important metric to assess the toll that natural hazards take on societies. In 2023, global disaster losses were estimated to be USD 250 billion [1,2], conveying the extensive economic impacts of disaster events worldwide. A sub-component of disaster losses is direct economic loss, which represents the monetary consequences of natural hazards inflicting damage to physical assets (e.g., infrastructures and buildings) [3,4]. Hence, direct economic loss is crucial in understanding the value or cost of structural repairs, rebuilding efforts or required investments to mitigate potential losses. In the United Nations Sendai Framework for Disaster Risk Reduction, the reduction of direct economic losses is among the seven global targets contributing to the overall goal of substantially reducing global disaster risks [4].

In 2023, the series of earthquakes in Türkiye and Syria [5] was the single most impactful disaster event, causing USD 50 billion in damages [1,2]. However, the majority of direct economic losses (76%) in that year were from weather events such as typhoons and hurricanes [1,2]. While some natural hazards can be less frequent and have high impacts, others accumulate losses over their frequent occurrence. Many communities globally are exposed to multi-hazard impacts which complicate strategies to prevent property damage. *Multi-hazard* can be defined as the presence of at least two hazards that overlap spatially or temporally, either with or without dependence on each other (see [6–9]). In this study, we focus on the spatial overlap of natural hazards over a geographical location, implying the exposure of communities to at least two independently occurring hazards. In the Philippines, for example, 60% of the country's total land area experiences multiple hazards (such as typhoons and earthquakes), and 74% of its population is vulnerable to their impacts [10]. Often, the competing impacts of hazards mean that addressing one hazard may increase the vulnerability of assets to the other and vice versa [11,12]. Identifying optimal solutions is thus foundational to inform strategies to simultaneously address impacts from two or more hazards that often have diverging requirements.

Traditionally, disaster risk reduction (DRR) has long relied on a single-hazard approach where hazard impacts are assessed or analysed in isolation from other hazards [13]. The attention to understanding multi-hazard impacts has gained traction, acknowledging their compounding consequences for communities [14,15]. Of the 16,535 global disaster records from 1900 to 2023, 19% can be (re)classified as multi-hazard events (considering the spatial or temporal overlaps of hazards), constituting 59% of total economic losses [16]. In addressing multi-hazard impacts, necessary trade-offs are required as a compromise to satisfy diverging and conflicting requirements. For example, in past research analysing building-level risk reduction against both floods and earthquakes in Afghanistan, optimal structural measures were found to vary spatially in that some districts could reduce disaster risk by investing more in flood measures compared to seismic mitigation, and vice versa [11]. The concept of optimality thus emerges as a necessary strategy to analyse trade-offs amid conflicting requirements of reducing disaster risks. Adherence to a single-hazard approach in a multi-hazard context is insufficient for holistic risk reduction and is counterintuitive. Due to the differing dynamics of counteracting multiple hazards, investments towards structural risk reduction against only one hazard can create risk to other hazards.

Present guidance instruments to reduce structural risks, such as building codes, are mostly tailored to a single hazard outlook. The design of structures is (usually) governed by the effects of the hazard that dominates [17,18]. This approach overtly assumes that satisfying the load demands of the dominant hazard also addresses the load requirements of its non-dominant counterpart/s. However, this assumption can be problematic. Structures subjected to different loads, such as seismic and wind loads, can potentially have up to twice the risk of exceeding limit states compared to only considering risks associated with a single hazard that dominates, as is usually prescribed in code provisions [19]. The need to understand the synergy in multi-hazard design (see [20]) thus emerges, motivating a need to acknowledge structural impacts from all known hazards, whether they dominate or not [17,18,21]. This is critical in multi-hazard settings where structural risks are being complicated by the exposure of assets to independently occurring hazards having different dynamics, frequencies, and impacts, obscuring straightforward pathways towards risk reduction.

An integrated analysis of the impacts of spatially overlapping natural hazards has implications for a more holistic understanding of their collective consequences to physical assets eventually influencing construction decisions in a specific geographical area. Multi-objective optimisation is well established in the field of engineering. Still, its applications for multi-hazard analysis have primarily been concentrated on the trade-offs pertinent to specific structural components (e.g., [18,21,22] ) or at an individual building level (e.g., [23,24]). Community-wide applications in past studies have used multi-objective optimisation to model the trade-offs among direct economic loss, population dislocation (e.g., [25]), and post-disaster repair times (e.g., [26]). So far, multi-objective optimisation has yet to be capitalised to analyse the trade-offs of structural impacts to physical assets at a community level (e.g., a building stock) against multiple hazards. Addressing this gap has significant potential to transform how we reduce risk especially in building stocks with highly variable (or "heterogeneous") physical assets. This larger unit of analysis is poised to support community efforts towards risk reduction through the potential regulation of structural typologies in heterogeneous building stocks susceptible to multi-hazard exposure. While DRR efforts have focused on the repair and retrofit of (existing) structural assets as practical solutions to strengthen physical assets, these measures can be insufficient considering that structural characteristics of typologies can govern vulnerability [27,28]. Within informal construction markets, addressing deeply seated vulnerabilities to multiple hazards requires more significant changes which we position can be more practically achieved through changes to building typologies. Thus, in a heterogeneous building stock, there is an opportunity to achieve optimal combinations of different building typologies to minimise multi-hazard impacts to safeguard the collective structural assets of a community.

Localised disaster events experienced by remote and rural communities contribute significantly to disaster losses, but these often remain unreported because they do not generate attention on national and global scales [29]. From 1990 to 2013, 99.7% of all disasters were localised or small-scale events, constituting less than 30 deaths and less than 5000 houses destroyed [30]. Disaster data – and presumably risk analysis – has been biased towards high-impact disaster events, often in urban areas and regions with higher asset values where “reportable” disaster loss values are larger [29,31,32]. In resource-constrained settings typical in low- and middle-income countries, dwellings tend to be non-engineered houses built informally by households or local construction workers without oversight from built environment professionals such as engineers and architects [33]. A heterogeneous housing stock emerges in such an instance characterised by a high variance of housing typologies. In this case, regulating safer construction practices becomes challenging and usual repair and retrofit strategies have limitations because the characteristics of housing typologies can become the main drivers of vulnerability to hazards. Thus, a broader and more collective view of understanding multi-hazard impacts of housing assets on a community scale is crucial for more encompassing prevention of damage to assets. This study focused on the context of a municipal-level assessment of direct economic losses of a housing stock in a geographically remote and small island community. Factoring in the intricacies of navigating the competing impacts of wind and seismic hazards and acknowledging the intrinsic characteristics of the local residential portfolio, we ask the question: *How can a heterogeneous housing stock be optimised against multi-hazard direct economic losses?*

The main objective of this study is to explore transitions towards more optimal housing stock distributions which simultaneously minimise direct economic losses from both wind and seismic hazards. Mitigating the impacts of both hazards usually requires trade-offs because of their potentially incongruent structural requirements. For example, ductile performance is essential for a structure in seismic regions  but this is less significant for wind load design [17]. This trade-off requires Pareto optimal solutions [34] representing candidate solutions that somehow satisfy the conflicting requirements of various objectives. Our study is based in Itbayat, Batanes – a frequent typhoon passage in the northern Philippines. The exposure of this municipality to wind impacts has greatly influenced the historical construction of heavy, masonry dwellings [35,36] but these were destroyed after a series of earthquakes in 2019 [37,38]. New housing typologies emerged thereafter [39,40] but with limited knowledge of their wind and seismic performance. We focused on wind and seismic hazards because they are the most prominent hazards and the only known hazards that inflict significant damage to housing assets in the selected municipality.

For this study, we explored different hypothetical housing stock distributions (referred to as “scenarios”) to identify what concentrations and ratios of the emergent housing typologies can minimise multi-hazard direct economic losses. These typologies are described in Figure 5.1 and Table 5.1. We generated 11,628 housing stock scenarios based on the assumption that for a given housing stock, each typology would constitute at least 5% of the overall stock distribution. We then simulated the loss outputs for each scenario using Monte Carlo simulation, considering two cases of paired extreme hazard intensity thresholds. Seismic intensities are based on the PHIVOLCS Earthquake Intensity Scale (PEIS) which is the nationally developed earthquake intensity measurement in the Philippines [41]. PEIS range from Intensity I (scarcely perceptible; approximate peak ground acceleration (PGA) of < 0.0005 g; equivalent to Modified Mercalli Intensity (MMI) I) to Intensity X (completely devastating; approximate PGA of > 1.39 g; equivalent to MMI XII) (see [41–44]). Meanwhile, wind intensities are expressed in kilometres per hour (km/h) and represent a 3-second peak gust measured 10 m above ground [45]. The first case of our analysis represents occasional hazard occurrences (PEIS VII and 270 km/h) pertaining to hazard levels below the maximum projected thresholds. The second case is rare hazard occurrences (PEIS VIII and 300 km/h) which represents the projected maximum hazard intensities. For both cases, Pareto optimal solutions were identified and then ranked using a multi-attribute decision-making method called the R-method [46]. Finally, acknowledging the socio-technical factors influencing residential construction in resource-constrained settings, the Pareto optimal solutions were contextualised against the desirability, viability, and feasibility (DVF) framework. We adopted this framework to qualitatively discuss whether potential solutions align with the households’ preferred mode of construction (“desirability”), suitable for the community in the long term (“viability”), and realistically achievable (“feasibility”). We assessed the DVF criteria based on field study insights of housing reconstruction trajectories of the households in Itbayat. For the entire data analysis procedures of this study, see “Methods” section.

Our main findings suggest that the current housing stock distribution can be improved to sustain lower wind and seismic losses by achieving a more optimal combination of lightweight and reinforced concrete typologies at varying proportions within the building stock. This result instils a paradigm shift in understanding structural safety as an aggregate system of the physical assets of disaster-affected communities, safeguarding these assets more collectively. However, transitioning to this desired stock distribution becomes a trade-off of not just loss reduction between the two natural hazards but, more importantly, of socio-technical factors such as households' risk perceptions, local appropriateness of solutions, and availability of resources. Our study contributes to advancing risk reduction strategies by offering an approach that not only streamlines multi-hazard loss estimations and trade-offs but also contextualises these based on the capacities of constituents. This approach is useful for policymakers to inform collective safer construction practices in multi-hazard settings.

**Table 5.1.** Characteristics of the different housing typologies. For detailed structural descriptions such as post-to-beam connections, see Hadlos et al. [39].

| **Housing typology** | **Characteristics** |
|---|---|
| Lightweight with wooden posts (LWA) | One story; timber beams and columns (no footings); corrugated galvanised iron (CGI) sheets as building envelopes; gable roof profile |
| Lightweight with steel posts (LWB) | One story; 4-inch to 5-inch diameter steel pipes as posts (with reinforced concrete (RC) footings) and timber beams; CGI sheets as building envelopes; gable roof profile |
| Semi-concrete with steel posts (SCA) | One story; 4-inch to 5-inch diameter steel pipes as posts (with RC footings) and timber beams; half-height RC walls at the base with remaining CGI walls for the upper half; gable roof profile with CGI sheets |
| Semi-concrete with reinforced concrete posts (SCB) | One story; RC posts (with RC footings) and timber beams; half-height RC walls at the base with remaining CGI walls for the upper half; gable roof profile with CGI sheets |
| Reinforced concrete with lightweight roof (RCA) | One story; RC posts (with RC footings) and beams; RC walls; gable roof profile with CGI sheets |
| Reinforced concrete with slab roof (RCB) | One story; RC posts (with RC footings) and beams; RC walls; RC slab roof |

**Figure 5.1.** Predominant housing typologies in Itbayat, Batanes, Philippines. **(a)** A lightweight typology that can either have timber posts and beams (LWA) or steel posts and timber beams (LWB). **(b)** A semi-concrete typology that can either have steel posts and timber beams (SCA) or RC posts and timber beams (SCB). **(c)** An RC typology with lightweight roof (RCA). **(d)** An RC typology with RC slab roof (RCB).

## 2 Results

### *2.1 Case 1 (Occasional hazard occurrences) – PEIS VII and 270 km/h*

Sixty-five (65) Pareto optimal solutions were identified from the 11,628 scenarios for Case 1 (see Figure 5.2; refer to Appendix C for the list of Pareto optimal solutions). The two top-ranked solutions (tied at first rank) based on the R-method lie on the extreme ends of the Pareto frontier. This means that either a housing stock dominated by 75% LWB or 75% RCB is the most optimal solution to reduce losses among the rest of the non-dominated solutions. However, such a result is heavily based on the "polarity" of the impacts of wind and seismic hazards made pronounced when we specified equal ranks for each hazard. The polarity infers that heavier typologies will incur significant losses to seismic, and lighter typologies will have more losses to wind impacts. This yielded extreme results where a tandem of losses of PHP 331M for seismic and PHP 195M for wind was identified as an equally superior solution alongside losses of PHP 162M for seismic and PHP 385M for wind. Practically, between these two solutions, there is no merit in picking one over the other as it would substantially skew loss prevention to either hazard. Thus, alternatives can be explored along the Pareto frontier which strike the balance of minimising losses for both hazards.

The baseline scenario or the current housing stock distribution in the community is characterised by a spread of 10% to 25% of each typology, with an estimated loss of PHP 199M for seismic and PHP 382M for wind (see Figure 5.3). The current baseline is distant from the Pareto frontier, confirming that shifts in the distribution of housing typologies would result in improvement to minimise losses for both hazards. The closest Pareto optimal solution from the baseline is the most immediate option along the Pareto frontier which reduces the losses against both hazards from the current baseline losses. This scenario constitutes a majority of lightweight structures (50% LWA & 20% LWB) and an increase to 15% fully concrete houses (RCB), with the remainder of typologies at 5%. This scenario offers a slight reduction in seismic losses at PHP 191M and a significant decrease in wind losses at PHP 330M (see Figure 5.3). Along the Pareto frontier, a scenario with balanced losses for both hazards is a housing stock dominated by a combination of 40% LWA and 40% RCB (with the rest of the typologies at 5%). The losses for this scenario are estimated to be PHP 251M for seismic and PHP 269M for wind. However, moving from the baseline scenario to here would drastically exacerbate seismic losses but will notably reduce wind losses.

The transition from the baseline scenario is not only a concern of the extent to which losses are reduced but also of the socio-technical factors necessary to support and manage such transition. Adopting the 75% LWB distribution significantly reduces seismic losses and offers almost no reduction to wind losses, and this scenario compromises the desirability criteria in that concrete-based structures are heavily favoured by the community more than lightweight houses. Additionally, while this scenario is feasible cost-wise, the social acceptance of these as permanent dwellings needs to be factored in with additional attention to how their longevity could be improved given that these tend to be less durable than concrete structures. On the other hand, the 75% RCB distribution is desirable and viable, but the transition would not be financially feasible, and it only reduces losses significantly to wind and greatly exacerbates losses to seismic. The 40% LWA and 40% RCB distribution is potentially the best candidate solution that balances the conflicting demands of the desirability, viability, and feasibility criteria although with a compromise in preventing seismic losses considering the baseline. While the closest optimal solution to the baseline might not be desirable given that it is predominantly lightweight, this scenario is the most practical trajectory to lessen multi-hazard losses.

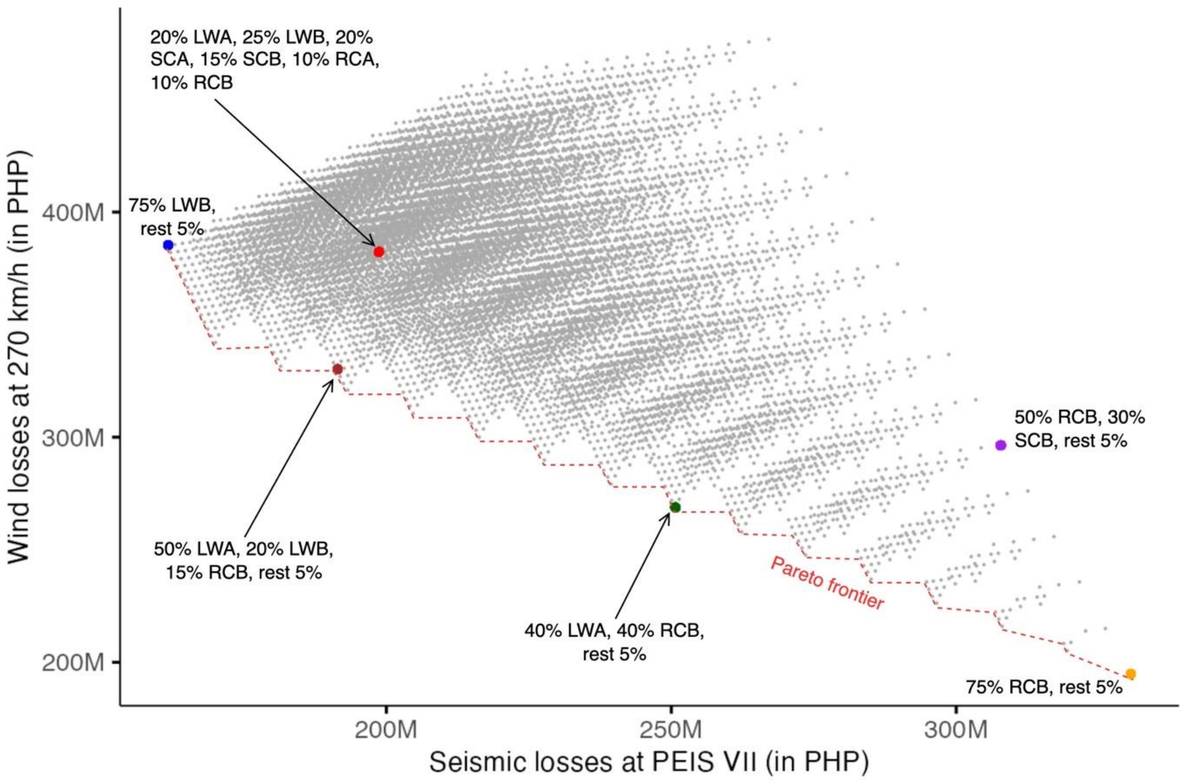
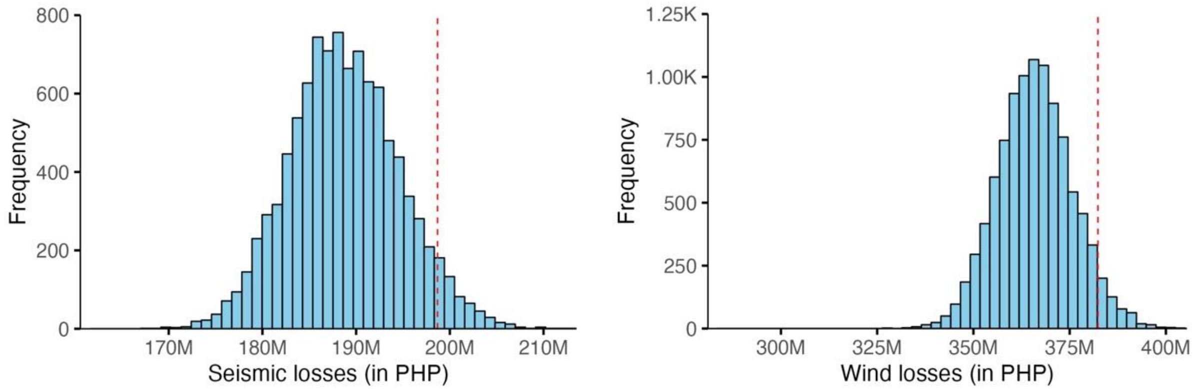
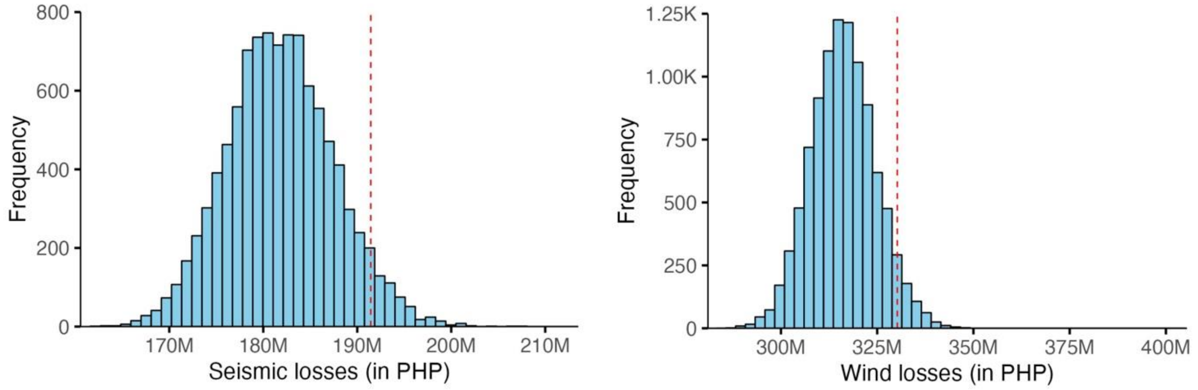


**Figure 5.2**. Pareto optimal graph for Case 1. The grey points represent the 11,628 scenarios simulated for seismic and wind losses at PEIS VII and 270 km/h, respectively. The red, broken line shows the Pareto frontier where the non-dominated (Pareto optimal) solutions lie. The superimposed coloured points show the important scenarios. The red point is the baseline representing the current housing stock distribution. The blue and orange points are the first-ranked solutions. The brown point is the solution closest to the baseline. The green point is the solution that yields the most balanced minimal losses for both hazards while the purple point represents the most balanced maximal losses. (Note that the values are based on the 95th percentile of the resulting probability distribution for each scenario. Losses are in Philippine peso (PHP).)



**(a)** Losses for baseline scenario



**(b)** Losses for the Pareto optimal solution closest to the baseline scenario

**Figure 5.3**. Simulated losses for Case 1 (PEIS VII and 270 km/h) considering the baseline scenario and Pareto optimal solution closest to the baseline scenario. The red, broken line indicates the 95th percentile value.

## *2.2 Case 2 (Rare hazard occurrences) – PEIS VIII and 300 km/h*

Fifteen (15) Pareto optimal solutions were identified from the 11,628 scenarios for Case 2 (see Figure 5.4; refer to Appendix C for the list of Pareto optimal solutions). Similar to Case 1, the two top-ranked solutions (tied at first ranks) based on the R-method lie on the extreme ends of the Pareto frontier, reinforcing the polarity of wind and seismic impacts in a heterogeneous housing stock comprised of fully lightweight to fully concrete typologies. The first-ranked solutions estimate PHP 629M losses for seismic and PHP 331M for wind if the distribution is 75% RCB; PHP 311M losses are estimated for seismic and PHP 403M for wind if the distribution is 75% LWA. Direct economic loss estimates are partly dependent on construction costs. When considering a heterogenous housing stock under extraordinary hazard intensities, it follows that more expensive typologies will incur more losses while the least expensive ones incur fewer. This is under the assumption that extreme hazard intensities overthrow the disparate housing performance among the typologies. Under such circumstances of extreme events, mitigation strategies should at least aim for collapse prevention to reduce casualties, problematising at what level of construction investment is commensurate to adhere to this housing performance in resource-constraint settings.

The baseline scenario – of which the typologies are spread within 10% to 25% distributions – yields PHP 386M losses for seismic and PHP 474M for wind (see Figure 5.5). Losses can be further minimised from the baseline by transitioning to a scenario with 70% LWA, 10% RCB, and the rest of the typologies at 5%. With such a transition, the reduction of losses is estimated at PHP 334M for seismic and PHP 398M for wind (see Figure 5.5). This is the most ideal trajectory when considering significant improvements to both losses. Alternatively, when opting for balanced losses for both hazards, transitioning to a housing stock with 60% LWA, 20% RCB, and rest at 5% would incur losses of PHP 380M and PHP 388M for seismic and wind, respectively. This trajectory also reduces losses for both hazards compared to the baseline, although it is more significantly towards wind loss reduction and not so for seismic.

Similar to Case 1, the Pareto solutions on the extreme ends of the Pareto frontier are likely neither the most pragmatic solutions in that they highly prevent losses for one hazard but to a significant detriment of loss reduction to the other hazard. When factoring in the DVF criteria, their extremities are further stretched considering that one becomes a highly desirable and viable option but not feasible, and vice versa. To this end, the most practical trajectories are the transitions that improve loss reduction for both hazards compared to the baseline, albeit to the compromise of some of the criteria in the DVF framework. For example, the significant loss reduction to both hazards by transitioning to either 70% or 60% LWA is promising to manage multi-hazard impacts but raises potential conflict with the desirability and viability criteria. Transitioning to a housing stock with more lightweight structures is more plausible given that financial limitations might override the aspirational aspects of desired construction trajectories among households. However, the technical standpoint of endorsing lightweight typologies needs further evaluation in a storm-battered region with more frequent wind events than seismic activities.

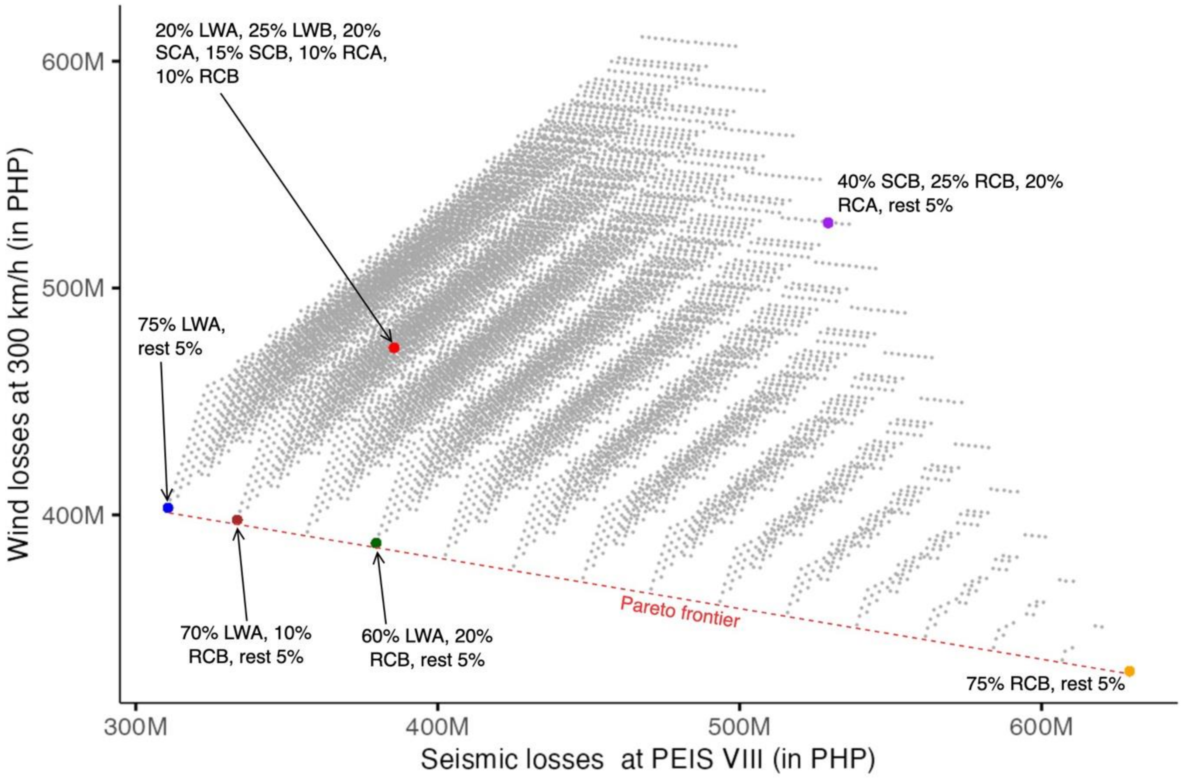
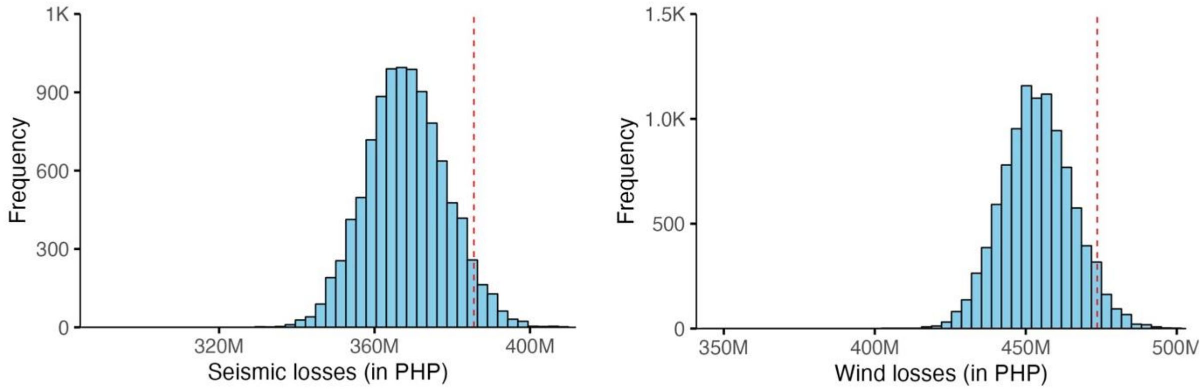
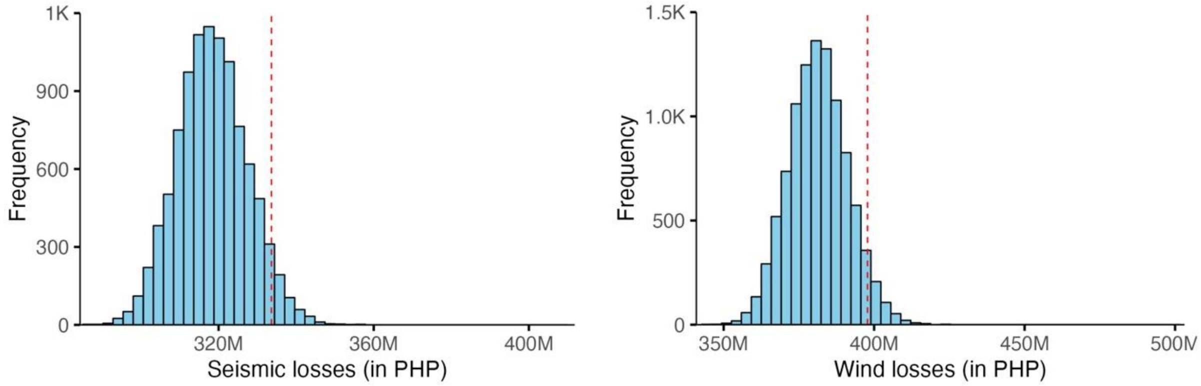


**Figure 5.4**. Pareto optimal graph for Case 2. The grey points represent the 11,628 scenarios simulated for seismic and wind losses at PEIS VIII and 300 km/h, respectively. The red, broken line shows the Pareto frontier where the non-dominated (Pareto optimal) solutions lie. The superimposed coloured points show the important scenarios. The red point is the baseline representing the current housing stock distribution. The blue and orange points are the first-ranked solutions. The brown point is the solution closest to the baseline. The green point is the solution that yields the most balanced minimal losses for both hazards while the purple point represents the most balanced maximal losses. (Note that the values are based on the 95th percentile of the resulting probability distribution for each scenario. Losses are in Philippine peso (PHP).)



**(a)** Losses for baseline scenario



**(b)** Losses for the Pareto optimal solution closest to the baseline scenario

**Figure 5.5**. Simulated losses for Case 2 (PEIS VIII and 300 km/h) considering the baseline scenario and the Pareto optimal solution closest to the baseline scenario. The red, broken line indicates the 95th percentile value.

## 3 Discussion

The housing stock-level analysis of optimising typologies within a building portfolio against multi-hazard losses, as demonstrated in this study, offers a new way to approach structural risk reduction. This analysis is crucial in settings like Itbayat where "experimental" and non-engineered housing typologies emerged due to the immediate need for households to shelter themselves using their available resources following disaster impacts. The heterogeneity of the housing stock – arising from the plurality of how households constructed their dwellings – poses challenges for individual structural housing risk mitigation. This circumstance necessitates a more collective appraisal of the characteristics of the housing stock in the community to leverage substantial risk reduction efforts. Under very high to extreme hazard intensities, usual repair and retrofit schemes can have limitations in addressing structural safety, and construction of or adherence to specific typologies might offer more effective pathways to reduce hazard impacts. Therefore, the stock-level methodology of optimising housing typology distribution used in this study aims to streamline a robust and wider coverage risk assessment beyond the individual housing level. This methodology can provide community-level guidance into strategies to mitigate structural losses by increasing or decreasing concentrations of certain typologies which can be achieved by the entry points discussed below. The endorsement of optimised housing typology distributions not only yields anticipated lower economic losses in the event of disasters but will also potentially decrease the number of casualties and reduce the length of repair times for impacted assets.

Our application of multi-objective optimisation to a collective approach for structural risk reduction complements and further substantiates insights into engineering optimisation models currently concentrated on building-level components of assets (e.g., [18,21–24]). Given the escalating global impacts of multi-hazard events that complicate DRR efforts, a paradigm shift is needed to understand structural safety as an aggregate system of the physical assets of disaster-affected communities. If, for example, a housing stock is perceived as an aggregate system and not just a composition of individual dwellings, the implications can be far-reaching. These include instigating equitable distribution of building resources in a socio-demographically diverse community to having a more cohesive outlook in planning agendas (e.g., zoning reforms) in multi-hazard geographies. Our study has also highlighted – and challenged – the concept of optimality in resource-constrained settings. With the notion of optimal solutions in engineering often limited to the knowledge of material performance trade-offs of assets, we extended our analysis to account for the socio-technical factors that explain the social realities impacting realistic pathways to prevent multi-hazard losses. Thus, our approach adds a layer to an otherwise tangible view of trade-off analysis, guiding future applications in the pragmatic assessment of disaster losses for similar contexts.

The housing stock transitions proposed in this study can be implemented through the variable increase and decrease of housing typology quantities (based on the prescribed ratio of housing stock combinations). This is a longitudinal process due to the dynamic housing needs influenced by the (expected) demographic changes over time, such as shifts in population, household sizes, and living setups or preferences. As such, this is a sustained effort that can be championed by planning and engineering officials to work towards optimal stock distributions within their jurisdictions as a form of disaster mitigation. Increasing certain typology quantities means encouraging new construction or incremental housing modifications towards desired typologies, all while controlling or inhibiting the construction of other typologies (thus "decreasing" their ratios relative to the uptake of the new construction or housing modifications). In practice, a starting point for this to happen is through having community-wide construction guidelines enforceable through development approvals and permitting processes. It must be noted that housing stock transitions in resource-constrained settings are not straightforward processes [47] because construction assets might not be accrued easily due to socio-demographic circumstances. Below, we outline some practical strategies for housing transitions to take place realistically.

In the context of new construction, the transition to the ideal ratios of housing stock distributions can be achieved through the following entry points. First, the construction of better-performing typologies can be encouraged by providing incentives to households intending to build dwellings (either in post-disaster settings or under normal situations). In areas like Itbayat where financial capacities greatly influence the typology households plan to build, the availability of "template" construction drawings could be a starting point to mainstream their adoption. Not only will this reduce the costs for engineering and architectural services, but it will also potentially embed the community-wide practice of adhering to endorsed construction specifications for such typologies. In the long term, this can then become the status quo of construction within the locale, with previous research showing that households can easily conform to construction trends to ultimately decide/aspire for how they will build their house [48,49]. These recommendations can inform municipal shelter recovery plans as promoted in the Post-disaster Shelter Recovery Policy Framework of the Philippines [50] or could be additionally enforced through the regulation of building permit approvals. In anticipation of the New Philippine Building Act that would allow municipal governments to legislate their own building laws [51], these recommendations can then be formally enacted through local building ordinances.

Second, in times of disaster, donors aiming to provide shelter kits and construction materials to impacted households can tailor their donations to the materials needed to construct targeted housing typologies. This also includes designing trainings contextualised locally (see [49]). For example, in Itbayat, the community has long practised timber construction as part of their cultural ways of house-making, but the adoption of concrete construction needs further technical guidance to avoid common defects (e.g., honeycomb). Donor agencies and organisations can design trainings appropriate in such instances to carry forward both familiar and foreign construction methodologies in housing (re)construction.

Housing stock transition considering existing housing assets can be accomplished through incremental upgrades as realistic pathways to achieve ideal concentrations of housing typologies within a community. For example, a semi-concrete house can be developed over time into a fully concrete structure given the suitable materials and expertise. Incremental upgrades should, however, be approached with caution to avoid creating new vulnerabilities that can arise through mixing materials, such as masonry infill wall upgrades to timber-framed homes. A fully concrete house will most likely not be downgraded to a lighter-weight version given the financial investments made and its desirability in the setting we have studied. The incorporation of lightweight typologies within the general housing stock distribution is then only possible with new construction to adhere to the ideal ratios. This may be feasible given how lightweight typologies are the least expensive to construct, and while they are perceived to be less desirable, it is more likely the case that financial feasibility is the main determinant driving construction in remote settings. Given the frequency of wind events in the region, the endorsement of lightweight typologies might seem counterintuitive, but ways to safeguard these assets have traditionally been practised in the area (e.g., tying of houses) (see [40]). Additionally, while the results of our simulation yield specific ratios among the typologies, further insights can be explored to understand whether the nuances of the structural characteristics between similarly classed typologies (e.g., LWA vs LWB for the lightweight class) have commensurate differences in their housing performance to that of their differential cost.

This study did not incorporate site exposure multipliers (e.g., hazard impacts on hilly locations, proximity to coastlines, soil-structure relationships) which can further potentially impact housing performance. However, our study sparks conversation on the importance of the spatial spread of housing typologies within a community and the role of land use planning as an instrument to reduce multi-hazard losses. Given the heterogeneity of the housing stock that assures some typologies are better off against wind than seismic, and vice versa, there is a potential to regulate the construction of susceptible typologies to identified areas with higher exposure to a specific hazard. For example, no-build zones can be enforced where wind exposure is the strongest and seismic codes can be reviewed where they benefit soil-structure relationships while considering wind-seismic trade-offs accordingly towards decision-making.

Additionally, the heterogeneity of the housing stock can be an advantage to intersperse typologies so that heavier typologies can act as wind buffers protecting lighter-weight counterparts. Our study focused only on the ratios of the housing stock distribution; thus, we envision our assessment to be the first layer of analysis with the most refined outputs possible once site exposure multipliers are considered.

Our study has several limitations. The direct economic loss estimation in this study is based on first-generation fragility functions [39] specifically derived for the field study site which used an expert opinion-based approach. Loss estimates can be refined if hybrid functions are considered where inputs from empirical and analytical data can provide complementary insights into housing performance. This was not done due to the lack of empirical or analytical functions developed for the area. Additionally, we have used generic structural repair cost ratios given that none has yet been developed for the Philippine context. While we posit that these are reasonable proxies, the nuances of how these ratios can vary in specific geographical contexts are worth factoring into future loss estimations once these become available. Our study dealt with housing stock distributions, but our analysis did not incorporate site exposure multipliers. This is because it is uncertain where houses will be built, and we assumed that these are household decisions that cannot be accurately predicted. This uncertainty in the spatial distribution of the houses also inhibited us from modelling the spatial correlations of wind speeds and structural fragilities among the housing units within the building portfolios (see [52]). These limitations are encouraged to be explored for future work.

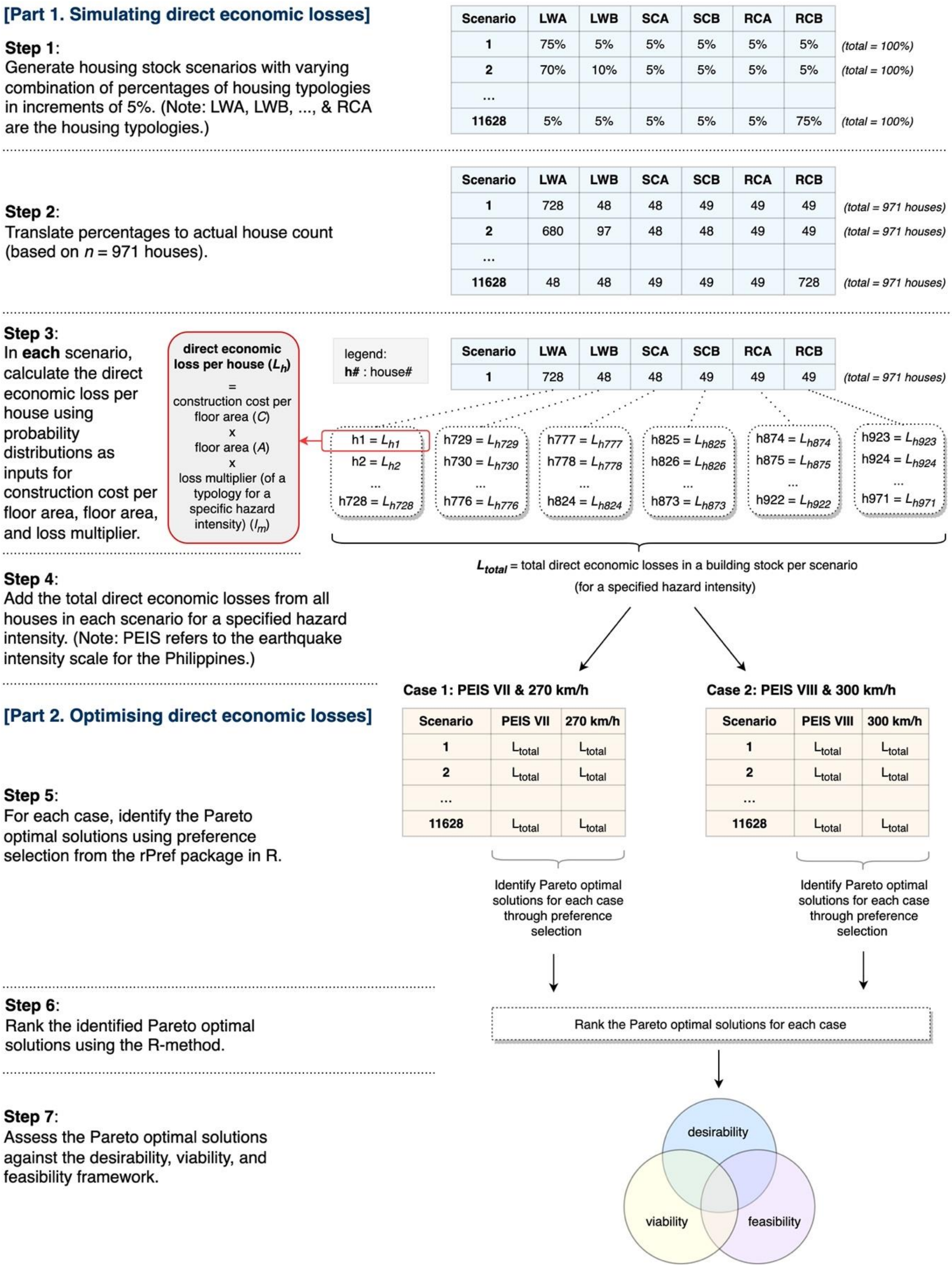
## 4 Conclusion

Direct loss estimations are crucial to anticipate hazard impacts, but these are rarely conducted on a community level where localised disaster events bring a stream of significant losses. The multi-hazard realities that people experience in these settings further complicate strategies to mitigate disaster impacts. In this study, we applied multi-objective optimisation to simulate direct economic losses of a housing stock against wind and seismic impacts based in Itbayat, Batanes, in the Philippines. Monte Carlo simulations were used to explore multiple housing stock scenarios to identify the ideal concentration of housing typologies that would minimise losses for both hazards. Two cases were analysed concerning extreme hazard intensity thresholds. For both cases, results demonstrate that the baseline (or the current) housing stock distribution can be improved to sustain lower wind and seismic losses by achieving a combination of lightweight and reinforced concrete typologies at varying proportions. A set of Pareto optimal solutions were identified from the optimisation inquiry. These candidate solutions were then consequently analysed against the desirability, viability, and feasibility framework to situate their practicality in the field.

Our use of multi-objective optimisation at a housing stock level on a local scale opens opportunities to collectively analyse damage impacts while incorporating granular data that refines loss estimates contextualised for a specific area. This contributes to refining national-level loss estimates usually based on general parameters. Additionally, our analysis of the Pareto optimal solutions against the socio-technical indicators instils broader conversation among stakeholders on the concept of optimality in resource-constrained settings. The trade-offs highlighted in this study went beyond the quantified losses for both hazards, but also considered the trade-offs arising from risk perceptions, local appropriateness of solutions, and availability of resources. Most often, these considerations are neglected when policymakers and technical stakeholders decide on optimal interventions. Overall, our study contributes to advancing risk reduction strategies by offering an approach to streamline and contextualise multi-hazard loss estimates.

## 5 Methods

Our methods are divided into two broad sections. The first part describes the simulation of direct economic losses against wind and seismic impacts under different housing stock scenarios. The second part sets out the identification of the scenarios or optimal solutions that yield minimal losses considering both hazards. The flowchart of the overall methods is presented in Figure 5.6. This study utilised data from previous field investigations (see [39,40]) compliant with protocol 2022/705 issued by the Human Research Ethics Committee at the University of Sydney and the Certificate of Precondition R2-IKSP-2022-12-21 issued by the National Commission on Indigenous Peoples of the Philippines.



**[Part 1. Simulating direct economic losses]**

**Step 1**:
Generate housing stock scenarios with varying combination of percentages of housing typologies in increments of 5%. (Note: LWA, LWB, ..., & RCA are the housing typologies.)

| Scenario | LWA | LWB | SCA | SCB | RCA | RCB | |
|---|---|---|---|---|---|---|---|
| 1 | 75% | 5% | 5% | 5% | 5% | 5% | *(total = 100%)* |
| 2 | 70% | 10% | 5% | 5% | 5% | 5% | *(total = 100%)* |
| ... | | | | | | | |
| 11628 | 5% | 5% | 5% | 5% | 5% | 75% | *(total = 100%)* |

**Step 2**:
Translate percentages to actual house count (based on $n = 971$ houses).

| Scenario | LWA | LWB | SCA | SCB | RCA | RCB | |
|---|---|---|---|---|---|---|---|
| 1 | 728 | 48 | 48 | 49 | 49 | 49 | *(total = 971 houses)* |
| 2 | 680 | 97 | 48 | 48 | 49 | 49 | *(total = 971 houses)* |
| ... | | | | | | | |
| 11628 | 48 | 48 | 49 | 49 | 49 | 728 | *(total = 971 houses)* |

**Step 3**:
In **each** scenario, calculate the direct economic loss per house using probability distributions as inputs for construction cost per floor area, floor area, and loss multiplier.

**direct economic loss per house ($L_h$)** = construction cost per floor area ($C$) x floor area ($A$) x loss multiplier (of a typology for a specific hazard intensity) ($I_m$)

legend:
**h#** : house#

| Scenario | LWA | LWB | SCA | SCB | RCA | RCB | |
|---|---|---|---|---|---|---|---|
| 1 | 728 | 48 | 48 | 49 | 49 | 49 | *(total = 971 houses)* |

$L_{total}$ = total direct economic losses in a building stock per scenario (for a specified hazard intensity)

**Step 4**:
Add the total direct economic losses from all houses in each scenario for a specified hazard intensity. (Note: PEIS refers to the earthquake intensity scale for the Philippines.)

**Case 1: PEIS VII & 270 km/h**

| Scenario | PEIS VII | 270 km/h |
|---|---|---|
| 1 | $L_{total}$ | $L_{total}$ |
| 2 | $L_{total}$ | $L_{total}$ |
| ... | | |
| 11628 | $L_{total}$ | $L_{total}$ |

**Case 2: PEIS VIII & 300 km/h**

| Scenario | PEIS VIII | 300 km/h |
|---|---|---|
| 1 | $L_{total}$ | $L_{total}$ |
| 2 | $L_{total}$ | $L_{total}$ |
| ... | | |
| 11628 | $L_{total}$ | $L_{total}$ |

**[Part 2. Optimising direct economic losses]**

**Step 5**:
For each case, identify the Pareto optimal solutions using preference selection from the rPref package in R.

Identify Pareto optimal solutions for each case through preference selection

Identify Pareto optimal solutions for each case through preference selection

**Step 6**:
Rank the identified Pareto optimal solutions using the R-method.

Rank the Pareto optimal solutions for each case

**Step 7**:
Assess the Pareto optimal solutions against the desirability, viability, and feasibility framework.

**Figure 5.6.** Flowchart of the methods.

## *5.1 Simulating direct economic losses*

To simulate the direct economic losses from seismic and wind hazards, we first estimated the average construction costs of the housing typologies through quantity surveying. Next, we derived scenarios of hypothetical housing stock distributions. Finally, we quantified and aggregated the housing stock-level direct economic losses.

### *5.1.1 Construction cost estimates*

Estimating the value of the (undamaged) housing stock was first needed before inferring direct economic loss calculations. We conducted quantity surveying for each of the six post-earthquake housing typologies surveyed in an earlier study (see [39]) representing the construction archetypes that are now ubiquitous in the municipality of Itbayat. These typologies are lightweight, semi-concrete, and concrete (see Figure 5.1), and their characteristics are described in Table 5.1. The first author conducted the quantity surveying, having inspected the housing typologies on site which provided familiarity with the housing characteristics. The procedures of the construction cost estimates, together with the resulting bill of quantities, are presented in Appendix C.

### *5.1.2 Deriving hypothetical scenarios of housing stock distribution*

We explored different possible combinations of the six typologies to inform hypothetical housing stock distributions (hereon referred to as "scenarios") which were later assessed for their optimal performance in reducing multi-hazard losses. In deriving these scenarios, we used the partitions package in R which uses combinatorial mathematics to enumerate all the possible combinations of integers [53]. We assumed that for a given housing stock, each typology would constitute at least 5% of the overall stock distribution. The idea of representing every typology in the stock distribution across all scenarios is grounded on the observed heterogeneity of the present housing stock, implying that each of the typologies will likely be adopted or constructed by households. Additionally, due to the various socio-economic factors affecting how households build their dwellings [40], we posit that the transition to a purely homogeneous housing stock is unlikely in the future. The 5% assumption, which returned 11,628 scenarios, allowed us to have a reasonable number of stock distributions to analyse without having to deal with excessive computational efforts for the simulation in the next steps. We translated the 11,628 scenarios, initially expressed in percentages for each typology present in the housing stock, to counts of housing units. We extrapolated the percentages of each typology in the housing stock based on a total of 971 households – the latest data on the total number of households in the municipality was obtained from the local government as of May 2024. A "baseline" scenario was identified from the 11,628 scenarios to represent the current housing stock distribution in the community based on the distribution of the residential portfolio after the 2019 earthquakes. This baseline scenario was used in comparisons to potential future distributions.

### *5.1.3 Quantifying direct economic losses*

To quantify direct economic losses, we first simulated the losses per house ($L_h$) for each typology in every scenario using Equation 1 based on the loss estimation methods of Lin & Wang [54] (adopted from HAZUS [55]). We carried out Monte Carlo simulations in R where the number of simulations corresponds to the quantity of houses specified per scenario. All simulations (based on a standard of 10,000 iterations) were probabilistic to account for uncertainties in the loss estimates. We therefore used probability distributions as inputs for Equation 1 to generate a resulting probability distribution for $L_h$. This method is referred to as uncertainty propagation where the uncertainties in the inputs "propagate" into the simulation results [56].

$$L_h = C * A * l_m \tag{1}$$

where:
$L$ = direct economic loss per house, in Philippine peso (PHP)
$C$ = construction cost of a house per square metre, in PHP
$A$ = floor area of a house, in square metre
$l_m$ = loss multiplier

The construction cost of a house per square metre ($C$) was based on the quantity surveying discussed in "Construction cost estimates" section. We used a triangular distribution common in probabilistic construction cost estimates which can intuitively account for a range of cost values based on the mode, the minimum, and the maximum estimates [57]. We used the estimated construction cost as the mode and +/- 10% for the maximum and minimum values. The 10% assumption is based on a common rule of thumb in residential project estimation in the Philippines accounting for contingencies of estimates and the inherent uncertainties with the construction market. The floor area of a house ($A$) was based on data from the Philippine Statistics Authority [58,59]. In Region 2, where Itbayat is located, the floor areas of houses approximate a lognormal distribution with most of them having 30 sqm to 49 sqm [58,59]. In our simulation, we bounded the values between 5 sqm and 200 sqm to represent realistic total floor sizes. Less than five sqm was considered too small to be habitable, while more than 200 sqm is rare within the residential portfolio of Itbayat.

The loss multiplier ($l_m$) was derived using Equation 2. Specific hazard intensities are required in this calculation representing the triggers incurring losses in relation to housing performance of particular typologies. For this study, we described the selection of these hazard intensities in "Selecting cases for Pareto optimal solutions" section.

$$l_m = \sum_{ds2}^{ds5} (P_{dsx} * R_{dsx}) \tag{2}$$

where:
$l_m$ = loss multiplier
$ds2{:}ds5$ = damage state (ds) 2 to 5
$P_{dsx}$ = probability of a housing typology in each damage state
$R_{dsx}$ = structural repair cost ratio of a housing typology in each damage state

The probabilities of a typology reaching or exceeding a damage state ($P_{dsx}$) were based on the fragility functions derived specifically for the context of Itbayat (see [39]). These functions – derived through an expert-driven approach – account for wind and seismic housing performance of the housing typologies constructed after the 2019 earthquakes. (For the parameters of these fragility functions, see [39].) For the structural repair cost ratios ($R_{dsx}$), none have been developed yet specific to the Philippine context which could have contextualised the loss-to-repair dynamics of the different construction archetypes within the country. Therefore, we used the default values of structural repair cost ratios from HAZUS which are used as proxies for both wind and seismic loss estimations [55,60,61]. These are 0.02 for minor damage (damage state (ds) 2), 0.10 for moderate (ds3), 0.50 for extensive (ds4), and 1.00 for complete (ds5). It is assumed that no repair costs are required for very minor damage (ds1); thus, it was omitted from the calculation. We used the same repair cost ratios for all the typologies given that the default values are generic. A triangular distribution was adopted for the simulation where the calculated $l_m$ under the specified hazard intensity was the mode. For seismic, the minimum and maximum values are the corresponding $l_m$ by +/- one PEIS intensity. For wind, the minimum and maximum values are the $l_m$ by +/- 50 kilometres per hour – an assumption based on expert judgement to establish a reasonable threshold for wind damage.

Finally, the losses per house were aggregated to quantify the total direct economic losses incurred by a housing stock in each scenario. This was calculated using Equation 3.

$$L_{total} = (\textstyle\sum_{i=1}^{n} i = L_h)_{LWA} + (\sum_{i=1}^{n} i = L_h)_{LWB} + (\sum_{i=1}^{n} i = L_h)_{SCA} + (\sum_{i=1}^{n} i = L_h)_{SCB} + (\sum_{i=1}^{n} i = L_h)_{RCA} + (\sum_{i=1}^{n} i = L_h)_{RCB} \qquad (3)$$

where:

$L_{total}$ = total direct economic losses in a housing stock per scenario (for a specific hazard intensity), in PHP

$L_h$ = direct economic losses per house for a specific hazard intensity, in PHP

$n$ = number of houses for a typology in each scenario

$_{LWA,\ LWB,\ \ldots\ RCB}$ = housing typologies

## *5.2 Optimising direct economic losses*

Pareto optimality describes a situation wherein the achievement of one objective compromises compliance with the other objective/s [34]. This is a common concept in multi-objective optimisation where the inherently conflicting requirements of various objectives warrant consideration of candidate solutions that *somehow* satisfy all the required objectives. In this study, we employed Pareto optimality to identify which scenarios simultaneously yield the least direct economic losses, considering a tandem of predefined seismic and wind intensities. Building a dwelling to resist both seismic and wind impacts is an example of a multi-objective problem requiring Pareto optimal solutions due to the competing impacts of these hazards. In the following sections, we describe how we selected hazard intensities for the Pareto optimal analysis, followed by how we identified and ranked the Pareto optimal solutions. Lastly, we present how we incorporated a framework to analyse these solutions against socio-technical indicators.

### *5.2.1 Selecting cases for Pareto optimal solutions*

The calculation of direct economic losses is based on specific hazard intensities as earlier shown in Equation 2. In this study, we chose two (2) pairs of wind and seismic intensities (hereon referred to as “cases”) where Pareto optimal solutions were analysed. Each case represents the objectives of the inquiry in that we aim to simultaneously minimise the direct economic losses incurred by a housing stock respective to the specified intensities. The selection of the pairs of intensities does not imply the simultaneous co-occurrence of these. Rather, we selected the cases as thresholds where losses to housing assets are anticipated, guided by the performance-based design matrix [62,63] (see Figure 5.7). The cases were based on hazard levels, with the pairing of intensities drawn from the corresponding return periods. Our analysis is geared towards life safety and collapse prevention – the performance level requirements for residential dwellings (standard occupancy) when these are subjected to occasional and rare hazard intensities. The return periods are probabilistic estimates from the Philippine Earthquake Model [64] and the Regional Severe Wind Hazard Maps of the Philippines [45]. Seismic intensities are based on the PHIVOLCS Earthquake Intensity Scale (PEIS) which is the nationally developed earthquake intensity measurement in the Philippines [41]. Meanwhile, wind intensities are expressed in kilometres per hour (km/h) and represent a 3-second peak gust measured 10 m above ground [45].

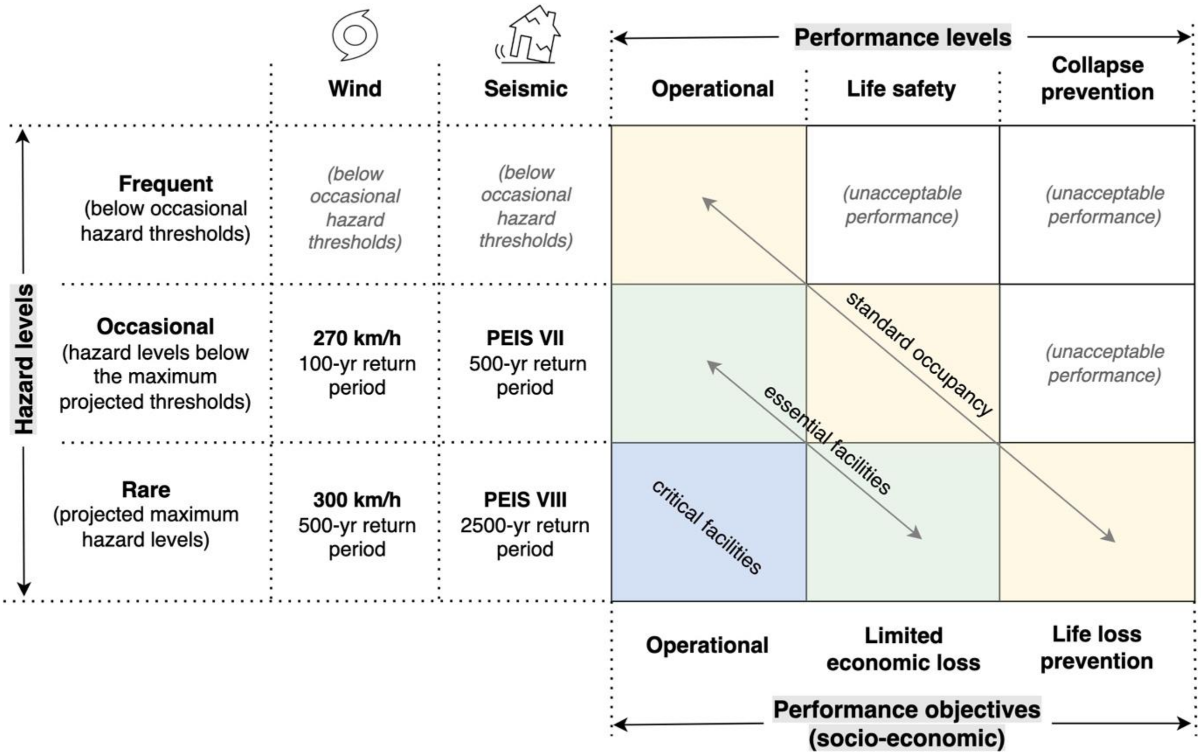


**Figure 5.7**. Performance-based design matrix adapted from Elnashai & Di Sarno [62] and Tsompanakis [63]. The return periods for Itbayat, Batanes are probabilistic estimates from the Philippine Earthquake Model [64] and the Regional Severe Wind Hazard Maps of the Philippines [45].

The first case is PEIS VII and 270 km/h representing occasional hazard intensities. "Occasional" in this context implies hazard levels below the threshold of the most extreme hazard intensities projected. A 270 km/h wind speed has a probability of 1% (100-year return period) to 5% (20-year return period) of occurring in a given year [45]. Meanwhile, a peak ground acceleration of 0.3 g to 0.4 g (approximately PEIS VII (see [42–44])) has a probability of 0.2% occurring annually (500-year return period) [64]. These intensities align with significant recent disasters experienced in the community. In 2016, Typhoon Ferdie (Meranti) hit mainland Batanes with a gustiness of up to 252 km/h, then made landfall in Itbayat where its intensity (was believed to) peaked but no official records are available due to limitations of weather instruments [65] (potentially reaching ~ 270 km/h). In 2019, a series of earthquakes struck the island, and the majority of the residential areas were exposed to the impacts of PEIS VII [37,38]. Thus, these intensities can also be referred to as the experiential maximums – a threshold that will likely inform policies of disaster mitigation based on the first-hand encounters of local constituents.

The second case is PEIS VIII and 300 km/h representing rare hazard intensities. "Rare" in this context implies the anticipated maximum hazard levels in the probabilistic hazard maps. The projected maximum wind speed that can be experienced in Itbayat is 300 km/h simulated to have a 0.2% likelihood to occur in any given year (500-year return period) [45]. Meanwhile, the maximum peak ground acceleration expected is 0.6 g (approximately PEIS VIII (see [42–44])) which has a 0.04% likelihood in a given year (2500-year return period) [64]. No official records can confirm if these wind and seismic intensities have been experienced historically in Itbayat. These projections of intensities – being the theoretical maximums in our analysis – are useful to anticipate the vulnerability of structural assets of the residential building portfolio under extraordinary circumstances.

### *5.2.2 Identifying and ranking Pareto optimal solutions*

The Pareto optimal solutions were identified for each case by determining the scenarios that simultaneously yield the least direct economic losses for both wind and seismic hazards. To do this, we used the preference selection (*psel*) function in rPref package in R [66]. The *psel* function evaluates a preference from a given data set. In this study, the preference was to identify the scenarios with the least losses considering both hazards, returning a set of non-dominated solutions (or Pareto optimal solutions) that satisfy this preference. The process of deriving these non-dominated solutions involves an algorithm that iteratively evaluates all possible outcome combinations and returns the best solutions being those that are not dominated by any other possible solutions. The loss outputs from Equation 3 are probability distributions, thus the 95th percentile values for these distributions were selected for the preference selection analysis. We used the 95th percentile value being more stringent and conservative considering the high-risk consequences that could possibly arise from underreporting potential worst-case outcomes in probabilistic loss analysis.

The Pareto optimal solutions identified for each case were then ranked to filter the top solutions. We used the multi-attribute decision-making method proposed by Rao and Lakshmi [46] called the R-method. This method has been demonstrated to outperform widely used multi-attribute decision-making tools such as the simple additive weighting (SAW), weighted product method (WPM), among others [46]. The first step in using the R-method is to rank the objectives according to perceived importance. Here, we assigned a 1.5 rank (average of 1st and 2nd ranks) for both the wind and seismic objectives implying their equal importance because impacts from both hazards do bring significant damage to structural assets. Next, the Pareto optimal solutions are ranked for each hazard. Since the goal is to minimise losses, the solution with the lowest direct economic loss was ranked 1st and the highest was ranked last. The ranks for both objectives and solutions were then converted to their corresponding weights using Equation 4. Examples of deriving these weights can be found in Rao and Lakshmi [46].

$$w_j = \frac{\left(\frac{1}{\sum_{k=1}^{j}\left(\frac{1}{r_k}\right)}\right)}{\sum_{j=1}^{n}\left(\frac{1}{\sum_{k=1}^{j}\left(\frac{1}{r_k}\right)}\right)} \tag{4}$$

where:

$w_j$ = weight of objective/solution $j$ ($j$ = 1, 2, 3, …, n)

$r_k$ = rank of objective/solution $k$ ($k$ = 1, 2, 3, …, j)

$n$ = number of objectives/solutions

The weights of the solutions were then multiplied by the weight of their corresponding objective. The products of these were summed up across each scenario to create a composite score where the score with the highest value/s represent/s the top solution/s.

### *5.2.3 Contextualising the Pareto optimal solutions against the DVF framework*

The Pareto optimal solutions represent the candidate scenarios that best address the objectives of simultaneously minimising direct economic losses against wind and seismic impacts. However, these solutions might not be pragmatically applicable without analysing them against the socio-technical factors affecting the residential construction context. Hence, we contextualised the Pareto optimal solutions against the desirability, viability, and feasibility (DVF) framework. The DVF framework is used in design thinking and business disciplines to evaluate whether proposed innovations will be desirable to users, viable for organisations, and technically and financially feasible [67]. We adapted this framework for this study to evaluate whether the characteristics of the housing stock distributions of the Pareto optimal solutions align with the households' preferred mode of construction ("desirability"), suitable for the community in the long term ("viability"), and realistically achievable ("feasibility") (see Figure 5.8). Our assessment was qualitative with the aim to generally appraise potential solutions within practical considerations. This qualitative assessment was based on primary data from an earlier study in the same field study site which used field immersion, interviews, and focus group discussions to understand the socio-technical factors of housing reconstruction within the selected community (see [40]). Note that desirability, viability, and feasibility are dynamic lenses influenced by circumstances, such that households' perceptions can change or new technologies or increased financial capacities can shift what is viable and/or feasible.

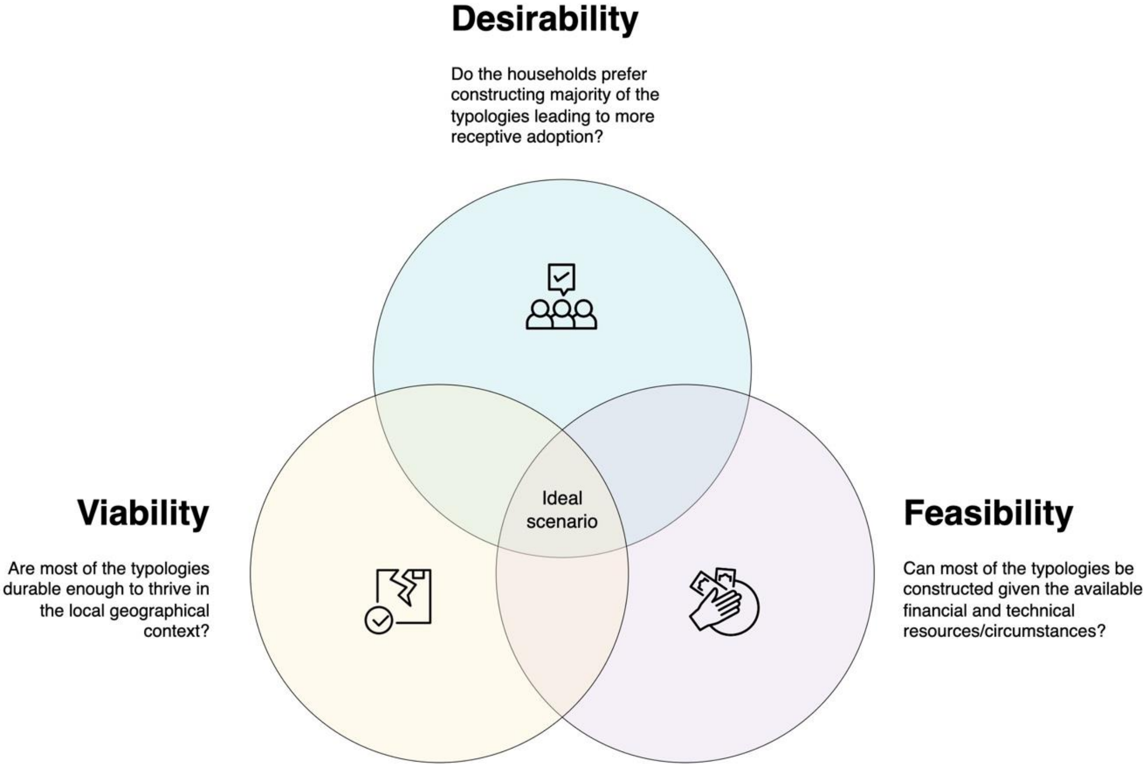


**Figure 5.8**. Desirability, viability, and feasibility (DVF) framework.

We posit that concrete structures are favoured most by households in Itbayat based on a previous study where households increasingly seek to construct heavier, reinforced typologies following the seismic events in 2019 and the noticeably intensifying wind hazards [40]. Restrictions on cutting and sourcing hardwood grown on the island have also forced households to use commercially available alternatives which raised scepticism about whether alternative timber materials are as durable as the local species of wood they commonly used before. Hence, we assessed scenarios as desirable if most houses are concrete-based typologies (SC-A, SC-B, RC-A, RC-B). Desirability is a critical aspect as previous studies in different contexts have shown how households' perception of housing safety greatly influences the adoption of (and receptiveness to) certain construction archetypes [48,68]. Factoring in desirability also eliminates the risk of endorsing (and eventually imposing) unwanted solutions common in the developmental context.

We assessed viability based on the idea of permanence associated with lesser maintenance requirements and inherent longevity of typologies. Lightweight typologies tend to incur maintenance more frequently than concrete structures and can be less durable when exposed to extreme environmental conditions [69]. For example, corrugated galvanised iron sheets used as the main wall cladding for lightweight houses can eventually be prone to rusting due to sea breeze (Itbayat being an island) on top of their susceptibility to physical damage. Additionally, (untreated) wooden materials can easily become structurally compromised when exposed to damp conditions. We thus have considered scenarios with less lightweight houses to be more viable.

Feasibility was assessed on economic and technical bases. Cost-wise, the heavier the typologies become, the costlier they are to construct. On average, the differential cost of building a fully lightweight and a fully concrete house in Itbayat is ~ PHP 600,000 (USD 10,700) – a cost not commensurate to be easily funded (without formal subsidies) when most of the households rely on fishing and farming for their livelihoods. The high construction costs on the island have been primarily due to the logistical challenges of importing materials and the regulatory barriers affecting the extraction of locally available materials forcing locals to rely on costly commercial alternatives [40]. On a technical basis, local building expertise in Itbayat has historically been focused on wooden construction systems, with the majority of the available construction labour on the island more well-versed in timber construction. Given these considerations, we assessed a scenario to be more feasible if fewer houses are of full or partial concrete construction.

## 6 Data and code availability

A supplementary file is attached as Appendix C. The code used in this study is available at https://github.com/arvinhadlos/loss-estimation.git.

## 7 References

[1] Munich Re, Natural disasters in 2023, 2024.

[2] UNDRR, Uncounted costs - Data gaps hide the true human impacts of disasters in 2023 | UNDRR, (2023). https://www.undrr.org/explainer/uncounted-costs-of-disasters-2023 (accessed October 3, 2024).

[3] B.N. Porfir’ev, E.A. Makarova, Economic evaluation of damage from natural disasters, Her. Russ. Acad. Sci. 84 (2014) 395–406. https://doi.org/10.1134/S1019331614060136.

[4] United Nations General Assembly, Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction, 2016.

[5] C. Galasso, E.A. Opabola, The 2023 Kahramanmaraş Earthquake Sequence: finding a path to a more resilient, sustainable, and equitable society, Commun Eng 3 (2024) 24. https://doi.org/10.1038/s44172-024-00170-y.

[6] S. De Angeli, B.D. Malamud, L. Rossi, F.E. Taylor, E. Trasforini, R. Rudari, A multi-hazard framework for spatial-temporal impact analysis, International Journal of Disaster Risk Reduction 73 (2022) 102829. https://doi.org/10.1016/j.ijdrr.2022.102829.

[7] A. Tilloy, B.D. Malamud, H. Winter, A. Joly-Laugel, A review of quantification methodologies for multi-hazard interrelationships, Earth-Science Reviews 196 (2019) 102881. https://doi.org/10.1016/j.earscirev.2019.102881.

[8] B. Liu, Y.L. Siu, G. Mitchell, Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment, Nat. Hazards Earth Syst. Sci. 16 (2016) 629–642. https://doi.org/10.5194/nhess-16-629-2016.

[9] J.C. Gill, B.D. Malamud, Reviewing and visualizing the interactions of natural hazards: Interactions of Natural Hazards, Rev. Geophys. 52 (2014) 680–722. https://doi.org/10.1002/2013RG000445.

[10] GFDRR, Country Profile: Philippines, (2016). https://www.gfdrr.org/sites/default/files/publication/PHILIPPINES2016.pdf (accessed August 7, 2022).

[11] M.C. de Ruiter, J.A. de Bruijn, J. Englhardt, J.E. Daniell, H. de Moel, P.J. Ward, The Asynergies of Structural Disaster Risk Reduction Measures: Comparing Floods and Earthquakes, Earth's Future 9 (2021). https://doi.org/10.1029/2020EF001531.

[12] Y. Li, A. Ahuja, J.E. Padgett, Review of Methods to Assess, Design for, and Mitigate Multiple Hazards, J. Perform. Constr. Facil. 26 (2012) 104–117. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000279.

[13] C. Galasso, J. McNair, M. Fujii, Z. Dong, Resilient infrastructure, Commun Eng 1 (2022) 27. https://doi.org/10.1038/s44172-022-00032-5.

[14] P.J. Ward, J. Daniell, M. Duncan, A. Dunne, C. Hananel, S. Hochrainer-Stigler, A. Tijssen, S. Torresan, R. Ciurean, J.C. Gill, J. Sillmann, A. Couasnon, E. Koks, N. Padrón-Fumero, S. Tatman, M. Tronstad Lund, A. Adesiyun, J.C.J.H. Aerts, A. Alabaster, B. Bulder, C. Campillo Torres, A. Critto, R. Hernández-Martín, M. Machado, J. Mysiak, R. Orth, I. Palomino Antolín, E.-C. Petrescu, M. Reichstein, T. Tiggeloven,

A.F. Van Loon, H. Vuong Pham, M.C. De Ruiter, Invited perspectives: A research agenda towards disaster risk management pathways in multi-(hazard-)risk assessment, Nat. Hazards Earth Syst. Sci. 22 (2022) 1487–1497. https://doi.org/10.5194/nhess-22-1487-2022.

[15] S. Hochrainer-Stigler, R. Šakić Trogrlić, K. Reiter, P.J. Ward, M.C. De Ruiter, M.J. Duncan, S. Torresan, R. Ciurean, J. Mysiak, D. Stuparu, S. Gottardo, Toward a framework for systemic multi-hazard and multi-risk assessment and management, iScience 26 (2023) 106736. https://doi.org/10.1016/j.isci.2023.106736.

[16] R. Lee, C.J. White, M.S.G. Adnan, J. Douglas, M.D. Mahecha, F.E. O'Loughlin, E. Patelli, A.M. Ramos, M.J. Roberts, O. Martius, E. Tubaldi, B. Van Den Hurk, P.J. Ward, J. Zscheischler, Reclassifying historical disasters: From single to multi-hazards, Science of The Total Environment 912 (2024) 169120. https://doi.org/10.1016/j.scitotenv.2023.169120.

[17] S. Kwag, A. Gupta, J. Baugh, H.-S. Kim, Significance of multi-hazard risk in design of buildings under earthquake and wind loads, Engineering Structures 243 (2021) 112623. https://doi.org/10.1016/j.engstruct.2021.112623.

[18] A. Chulahwat, H. Mahmoud, A combinatorial optimization approach for multi-hazard design of building systems with suspended floor slabs under wind and seismic hazards, Engineering Structures 137 (2017) 268–284. https://doi.org/10.1016/j.engstruct.2017.01.074.

[19] D. Duthinh, E. Simiu, Safety of Structures in Strong Winds and Earthquakes: Multihazard Considerations, J. Struct. Eng. 136 (2010) 330–333. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000108.

[20] C. Crosti, D. Duthinh, E. Simiu, Risk Consistency and Synergy in Multihazard Design, J. Struct. Eng. 137 (2011) 844–849. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000335.

[21] F.A. Potra, E. Simiu, Optimization and Multihazard Structural Design, J. Eng. Mech. 135 (2009) 1472–1475. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000057.

[22] H. Mahmoud, A. Chulahwat, Multi-Hazard Multi-Objective Optimization of Building Systems with Isolated Floors Under Seismic and Wind Demands, in: P. Gardoni, J.M. LaFave (Eds.), Multi-Hazard Approaches to Civil Infrastructure Engineering, Springer International Publishing, Cham, 2016: pp. 141–164. https://doi.org/10.1007/978-3-319-29713-2_8.

[23] D.H. Zelleke, S.K. Saha, V.A. Matsagar, Reliability-Based Multi-Hazard Design Optimization of Base-Isolated Buildings, Engineering Structures 301 (2024) 117242. https://doi.org/10.1016/j.engstruct.2023.117242.

[24] Y.-J. Yin, Y. Li, Probabilistic loss assessment of light-frame wood construction subjected to combined seismic and snow loads, Engineering Structures 33 (2011) 380–390. https://doi.org/10.1016/j.engstruct.2010.10.018.

[25] W. Zhang, C. Nicholson, A multi-objective optimization model for retrofit strategies to mitigate direct economic loss and population dislocation, Sustainable and Resilient Infrastructure 1 (2016) 123–136. https://doi.org/10.1080/23789689.2016.1254995.

[26] H.S. Gupta, T. Adluri, D. Sanderson, A.D. González, C.D. Nicholson, D. Cox, Multi-objective optimization of mitigation strategies for buildings subject to multiple hazards, International Journal of Disaster Risk Reduction 100 (2024) 104125. https://doi.org/10.1016/j.ijdrr.2023.104125.

[27] C.A. Kircher, R.V. Whitman, W.T. Holmes, HAZUS Earthquake Loss Estimation Methods, Nat. Hazards Rev. 7 (2006) 45–59. https://doi.org/10.1061/(ASCE)1527-6988(2006)7:2(45).

[28] V. Silva, S. Brzev, C. Scawthorn, C. Yepes, J. Dabbeek, H. Crowley, A Building Classification System for Multi-hazard Risk Assessment, Int J Disaster Risk Sci 13 (2022) 161–177. https://doi.org/10.1007/s13753-022-00400-x.

[29] UNDRR, Closing Climate and Disaster Data Gaps: New challenges, new thinking, (2023).

[30] UNDRR, Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future, Geneva, 2022.

[31] K. Tennakoon, S. Serrao-Neumann, C. Hanna, Examining the incorporation of small-scale recurring disasters in emergency management frameworks: Insights from Aotearoa – New Zealand, International Journal of Disaster Risk Reduction 66 (2021) 102595. https://doi.org/10.1016/j.ijdrr.2021.102595.

[32] M.E. Brennan, S. Danielak, Too small to count? The cumulative impacts and policy implications of small disasters in the Sahel, International Journal of Disaster Risk Reduction 68 (2022) 102687. https://doi.org/10.1016/j.ijdrr.2021.102687.

[33] A. Charleson, A. Nonoguchi, A. Maeshima, C. Villacis, C. Minowa, G. Zamani, H. Imai, K. Okazaki, K. Yamaguchi, R. Shaw, S. Fukushima, S. Kita, S. Saito, S. Matsuzaki, S. Ando, S. Yasukawa, T. Narafu, T. Yokoi, T. Hanazato, Y. Ishiyama,

Towards resilient non-engineered construction: guide for risk-informed policy-making, United Nations Educational, Scientific, and Cultural Organisation, 2016.

[34] J.S. Arora, Multi-objective Optimum Design Concepts and Methods, in: Introduction to Optimum Design, Elsevier, 2012: pp. 657–679. https://doi.org/10.1016/B978-0-12-381375-6.00017-6.

[35] N. Uy, R. Shaw, Shaped by Wind and Typhoon: The Indigenous Knowledge of the Ivatans in the Batanes Islands, Philippines, in: Indigenous Knowledge for Disaster Risk Reduction: Good Practices and Lessons Learned from Experiences in the Asia-Pacific Region, UNISDR, 2008: pp. 59–63.

[36] F. Hornedo, Traditional Ivatan Shelter and Architecture, Part Two, The Classic Traditional Ivatan House: Emergence and Prospects, Ivatan Studies Journal XIII–XIV (2015) 39–112.

[37] International Federation of Red Cross and Red Crescent Societies, Philippines: Batanes Earthquake, 2020.

[38] J. Perez, K. Vitto, P. Sawi, J. Blacer, R. Tiglao, M. Pagtalunan, J.R. Danganan, A. Garil, Impacts of the 27 July 2019 Magnitudes (Mw) 5.4, 5.9, and 5.8 Itbayat, Batanes Earthquakes, Department of Science and Technology - Philippine Institute of Volcanology and Seismology, 2019.

[39] A. Hadlos, A. Opdyke, S.A. Hadigheh, Deriving expert-driven wind and seismic fragility functions for non-engineered residential typologies in Batanes, Philippines, Scientific Reports 13 (2022). https://doi.org/10.1038/s41598-023-49398-2.

[40] A. Hadlos, A. Opdyke, S.A. Hadigheh, C. Gato, Pathways of multi-hazard post-disaster housing reconstruction among Ivatan Indigenous households, Journal of Building Engineering 91 (2024) 109636. https://doi.org/10.1016/j.jobe.2024.109636.

[41] Philippine Institute of Volcanology and Seismology, PHIVOLCS Earthquake Intensity Scale (PEIS), (n.d.). https://www.phivolcs.dost.gov.ph/index.php/earthquake/earthquake-intensity-scale (accessed July 10, 2023).

[42] United States Geological Survey, 3.5. Representing Macroseismic Intensity on Maps, ShakeMap Documentation (n.d.). https://usgs.github.io/shakemap/manual4_0/ug_intensity.html (accessed March 29, 2025).

[43] C.B. Worden, M.C. Gerstenberger, D.A. Rhoades, D.J. Wald, Probabilistic Relationships between Ground-Motion Parameters and Modified Mercalli Intensity in

California, Bulletin of the Seismological Society of America 102 (2012) 204–221. https://doi.org/10.1785/0120110156.

[44] M. Lasala, H. Inoue, R. Tiglao, Z. Fan, B. Bautista, I. Narag, Establishment of Earthquake Intensity Meter Network in the Philippines, J. Disaster Res. 10 (2015) 43–50. https://doi.org/10.20965/jdr.2015.p0043.

[45] Philippine Atmospheric, Geophysical, and Astronomical Services, Regional Severe Wind Hazard Maps, (n.d.). https://www.pagasa.dost.gov.ph/products-and-services/severe-wind-maps (accessed July 17, 2023).

[46] R.V. Rao, R.J. Lakshmi, Ranking of Pareto-optimal solutions and selecting the best solution in multi- and many-objective optimization problems using R-method, Soft Computing Letters 3 (2021) 100015. https://doi.org/10.1016/j.socl.2021.100015.

[47] L. Babister, A. Opdyke, A. Hadlos, C. Parrack, B. Flinn, Constructive Ambiguity: Supporting Recovery from Humanitarian Crises, in: Shelter Projects, 9th Edition, International Organisation for Migration, 2023: pp. 185–188.

[48] Habitat for Humanity, Beyond Building: How Social Norms Shape Low-Income Home Construction, 2019.

[49] A. Opdyke, A. Javernick-Will, M. Koschmann, Household construction knowledge acquisition in post-disaster shelter training, International Journal of Disaster Risk Reduction 28 (2018) 131–139. https://doi.org/10.1016/j.ijdrr.2018.02.038.

[50] The World Bank, Post-disaster Shelter Recovery Policy Framework: Building a Responsive System to Support Resilient and Equitable Recovery in the Philippines, (2022). http://documents.worldbank.org/curated/en/579231642696271929/Post-Disaster-Shelter-Recovery-Policy-Framework-Building-a-Responsive-System-to-Support-Resilient-and-Equitable-Recovery-in-the-Philippines (accessed October 28, 2024).

[51] F.M. Cervantes, House pushes for climate proofing reforms, Philippine News Agency (2023). https://www.pna.gov.ph/articles/1207529 (accessed October 28, 2024).

[52] D. Zeng, H. Zhang, C. Wang, Modelling correlated damage of spatially distributed building portfolios under scenario tropical cyclones, Structural Safety 87 (2020) 101978. https://doi.org/10.1016/j.strusafe.2020.101978.

[53] R.K.S. Hankin, partitions: Additive Partitions of Integers, (2006) 1.10-7. https://doi.org/10.32614/CRAN.package.partitions.

[54] S.-Y. Lin, C.-H. Wang, Life cycle cost analysis of seismic retrofit policy at the city scale, Journal of Building Engineering 80 (2023) 107917. https://doi.org/10.1016/j.jobe.2023.107917.

[55] FEMA, Hazus Earthquake Model Technical Manual, 2020.

[56] S.P. Rayjada, J. Ghosh, M. Raghunandan, Assessment, quantification and propagation of uncertainty in seismic life-cycle cost analysis, Structure and Infrastructure Engineering (2024) 1–20. https://doi.org/10.1080/15732479.2024.2391037.

[57] N. Wang, Y.-C. Chang, A.A. El-Sheikh, Monte Carlo simulation approach to life cycle cost management, Structure and Infrastructure Engineering 8 (2012) 739–746. https://doi.org/10.1080/15732479.2010.481304.

[58] Philippine Statistics Authority, Housing Characteristics in the Philippines (2020 Census of Population and Housing), 2023. https://psa.gov.ph/content/housing-characteristics-philippines-2020-census-population-and-housing (accessed October 4, 2024).

[59] Philippine Statistics Authority, Occupied Housing Units by Floor Area and Region: 2020, (2023). https://psa.gov.ph/content/housing-characteristics-philippines-2020-census-population-and-housing (accessed October 4, 2024).

[60] FEMA, Advanced Engineering Building Module (AEBM), Technical and User's Manual, (n.d.).

[61] FEMA, Hazus Hurricane Model Technical Manual, 2021.

[62] A.S. Elnashai, L. Di Sarno, Fundamentals of Earthquake Engineering, 1st ed., Wiley, 2008. https://doi.org/10.1002/9780470024867.

[63] Y. Tsompanakis, Earthquake Return Period and Its Incorporation into Seismic Actions, in: M. Beer, I.A. Kougioumtzoglou, E. Patelli, I.S.-K. Au (Eds.), Encyclopedia of Earthquake Engineering, Springer Berlin Heidelberg, Berlin, Heidelberg, 2014: pp. 1–35. https://doi.org/10.1007/978-3-642-36197-5_116-1.

[64] Philippine Institute of Volcanology and Seismology, Philippine Earthquake Model, 2017.

[65] R. Paciente, Tropical Cyclone Passage Report, Typhoon Committee, 2016. https://typhooncommittee.org/docs/Passage%20Reports/2016/1614-MERANTE-Philippines.pdf (accessed July 12, 2023).

[66] P. Roocks, rPref: Database Preferences and Skyline Computation, (2014) 1.4.0. https://doi.org/10.32614/CRAN.package.rPref.

[67] D. Bland, A. Osterwalder, Testing Business Ideas, John Wiley & Sons, Inc., Hoboken, NJ USA, 2020.

[68] B. Goldwyn, A. Javernick-Will, A.B. Liel, Multi-Hazard Housing Safety Perceptions of Those Involved with Housing Construction in Puerto Rico, Sustainability 14 (2022) 3802. https://doi.org/10.3390/su14073802.

[69] I. Besarra, A. Opdyke, D.H. Aquino, J. Santiago, J.E. Mendoza, A.M.F.A. Lagmay, Flood fragility and vulnerability functions for residential buildings in the Province of Leyte, Philippines, J Flood Risk Management (2024) e13043. https://doi.org/10.1111/jfr3.13043.

# Chapter 6

# Conclusion

## 1 Synthesis

This thesis analysed how Indigenous communities affected by multi-hazard events navigate housing reconstruction using their knowledge and resources to reduce disaster risk. First, an extensive review was conducted to examine the application of LIK in DRR scholarship, which revealed a myriad of risk reduction strategies that communities mobilise, often discussed at the nexus of the integration of knowledge (LIK and scientific) and power spheres (top-down and bottom-up approaches). Second, a field-based investigation was carried out in Itbayat, Batanes in the Philippines to quantify housing performance against wind and seismic hazards of the post-disaster dwellings built by Indigenous households. An expert-driven approach was used to derive fragility functions to assess the housing performance of these dwellings, revealing the extent of structural responses of the different housing typologies. These typologies range from lightweight to reinforced concrete; some reflect the blending of contemporary and traditional construction practices. Third, an inquiry into the factors affecting how households rebuilt their dwellings showed the network of socio-technical considerations leading to a plurality of housing reconstruction pathways. These considerations were influenced by the urgency to have shelter, perceptions of housing safety, the nature of aid channelled to households vis-à-vis their financial situations, and the policies that affect access to locally available building materials. Lastly, to analyse collective safer housing construction practices at a community level, this thesis developed an approach to evaluate the trade-offs of building resilient dwellings amid wind and seismic impacts through multi-objective optimisation. In resource-constraint settings like Itbayat, it becomes apparent that transitioning to a more resilient housing stock considering multi-hazard impacts is not only a matter of structural considerations of housing characteristics. The trade-offs intrinsically faced in these settings extend to socio-technical aspects such as households' risk perceptions, local appropriateness of solutions, and availability of resources.

## 2 Research contributions

This thesis broadly contributes to examining the application of LIK alongside scientific knowledge to manage disaster risk. By analysing local capacities, this people-centred approach is a step towards connecting technical knowledge to behavioural and cultural patterns critical to tackle sustainable development challenges usually undertaken technocratically. Disaster studies are inextricably linked to the behavioural and cultural dynamics of people in hazard-affected regions. However, default DRR interventions usually impose solutions on communities devoid of the “human element” for these to work on the ground. Moreover, this thesis contributes to the school of thought in decolonising the engineering practice (see [1]). By incorporating local perspectives in the conception of products and approaches that assist underserved communities, this work rethinks the incessant quest for new technologies to address problems, and instead it examines how local engagement plays a role in identifying contextual and sensible solutions.

The specific chapter contributions of this thesis are as follows. In Chapter 2, the review of the LIK in DRR scholarship offers a blueprint providing future directions for where this important agenda is headed. It assessed the blind spots (e.g., where LIK is geographically understudied) and trajectories (e.g., alignment to the Sendai Framework priority areas) of this agenda for more refined practice and policy applications. For example, the blending of LIK and scientific knowledge is becoming a prominent approach to reduce disaster risks. However, low-income nations are disproportionately underrepresented in empirical LIK studies and thus we lack a grasp on their knowledge systems, potentially inhibiting pathways to incorporate them in formal DRR interventions. The review also underscores the vastness of LIK as a rich asset in managing disaster risks which is useful towards a more collective understanding of its strengths, limitations, and the threats to its implementation in the DRR space. Overall, this chapter delivers a holistic synthesis of LIK in DRR scholarship, potentially paving the way for its more dedicated inclusion in DRR practice and policy environments (see [2–4]).

In Chapter 3, the housing performance assessment of non-engineered dwellings is (among) the first to extrapolate the expert-driven approach of deriving fragility functions to consider understudied housing typologies in a high-risk setting like the Philippines. Through the application of heuristic methods, opportunities open to more localised and streamlined risk assessments of housing assets by capturing the nuances and granularity of their structural characteristics. Additionally, the resulting fragility functions derived in this chapter are the first-generation functions developed for Batanes, Philippines, which can also be used in other contexts where similar structural housing characteristics prevail. These functions are fundamental in catastrophe modelling but are usually lacking in high-risk settings where they are critically needed [5]. The derivation of these fragility functions contributes to databases and resources for global risk modelling, such as that of the Global Earthquake Model (GEM) [6]. In countries like the Philippines where housing characteristics greatly vary across the region (see [7]), the focus on municipal-level housing assessments aid in a more refined approach of understanding local-level risks which are (often) generalised in macro-level assessments [8]. This chapter contributes to new structural housing performance assessments that account for the granular characteristics of local residential portfolios in disaster-prone and resource-constrained settings.

In Chapter 4, the elicitation of socio-technical factors affecting housing reconstruction contributes to the contextual understanding of shelter recovery in multi-hazard settings [9,10], specifically among communities who had primarily coped with the impacts of a single hazard. The field-based study informs policy suggestions based on the nuanced understanding of the intrinsic challenges in the context of the Indigenous communities in Itbayat. Additionally, it also expands a proposition that attaining safer construction practices can largely be dependent on the socio-cultural climate within a community (see [9–13]). While the general school of thought is that building safer dwellings is a technical (engineering) task (see [14]), insights from the case study demonstrate otherwise, shedding light on the socio-technical factors that make housing reconstruction more than an engineering problem. This thesis thus influences discourses on effectively delivering safer housing projects. Overall, this chapter uncovers how Indigenous populations navigate housing reconstruction under the impacts of multi-hazard events.

In Chapter 5, the developed building stock-level approach to optimise multi-hazard housing reconstruction strategies contributes to facilitating decision-making considering the conflicting demands of multiple hazards. This approach also instils a paradigm shift in understanding housing safety as an aggregate or collective system of the physical assets of disaster-affected communities. Much of the application of multi-objective optimisation in engineering literature has been on the trade-offs of multi-hazard performance of structural components and parts [15–17] or at an individual building level [18,19]. Thus, applying this method to a residential building stock extends mainstreaming to this unit of analysis, informing more collective safer construction practices in communities. Central to the approach developed for this chapter is the addition of a socio-technical analysis of the identified optimal solutions. This contributes to a more pragmatic appraisal, in both practice and policy environments of DRR, of what optimality looks like considering the trade-offs of not just housing performance but also of the capacities of constituents and the circumstances allowing for intended reconstruction propositions to take place. This chapter addresses the lack of an approach to collectively analyse the trade-offs of multi-hazard housing reconstruction at a community level, considering the structural performance of physical assets and the prevailing socio-technical circumstances.

## 3 Research implications

### *3.1 Local or municipal level*

On a local or municipal level, this thesis provides insights into potential policy reforms and program development to advance the multi-hazard resilience of housing assets. Identifying prevailing housing typologies and assessing their respective performance offers a clearer understanding of the capacity of the studied residential building portfolio. Given this information, the Comprehensive Land Use Plan in Itbayat can be updated to reflect the distribution of housing typologies within the built-up areas. This can serve as useful baseline inventory for critical DRR activities like structural retrofitting programs or housing upgrades, rapid damage and needs assessments, and risk-based residential zoning considering site-exposure multipliers vis-à-vis the characteristics of housing assets. Such potential applications can guide the formulation of a municipal housing recovery plan as promoted in the Post-disaster Shelter Recovery Policy Framework of the Philippines [20]. Additionally, these potential applications can also inform local building ordinances, especially in anticipation of the New Philippine Building Act (House Bill 8500), which would allow municipal governments to legislate their own building laws [21].

The attempts to understand and codify the local construction practices in Itbayat also support the cultural upkeeping of important building methodologies in the area, aiding in the intergenerational transfer of these assets. In July 2024, the Local Culture and the Art Council and the municipal legislators of Itbayat recognised Chapter 3 of this thesis as among the documentations that helps promote the heritage of the municipality (see [22]). This acknowledgement is timely in the pursuit of understanding LIK in DRR amid the factors that threaten its existence, such as rapid urbanisation and persistent technocracy in DRR management. Finally, this thesis highlights how the lack of policy synergies creates a cascading effect on the ability of Indigenous communities to build resilient dwellings. Presently, an ongoing effort calls for a policy review of environmental laws such as the Batanes Protected

Area Act of 2000 [23] and how it conflicts with the Indigenous Peoples' Rights Act of 1997 [24]. This thesis provides substantial insights on this agenda, informing potential policy refinements that would eventually benefit the Indigenous communities in Batanes and across the country.

### *3.2 National level*

On a national level, this thesis encourages localised risk assessments in the advancement of country-wide assessments of the vulnerability of housing typologies pertinent to their (multi-)hazard exposure. While housing characteristics already form part of the national census conducted by Philippine Statistics Authority and that national hazard exposure databases are publicly available (e.g., [25]), there still remains a gargantuan task to understand the resilience of the housing stock in the country. The focus on local case analysis or field-based studies sets an approach to identify housing vulnerability hotspots at a municipal level nationwide, eventually bringing a more refined understanding of housing resilience in the Philippines. This approach prompts the national government to support every municipality in producing detailed risk assessments as building blocks towards a robust national housing evaluation. The importance of localised risk assessment also instils the need to complement macro-level assessments with granular data at the community level because generalised assumptions might under- or over-estimate risk projections [8]. These insights can build the momentum for greater inclusion of or investment in localised risk assessments in the National Disaster Risk Reduction Management Plan of the Philippines, setting forth a clearer agenda or framework for institutionalising these assessments.

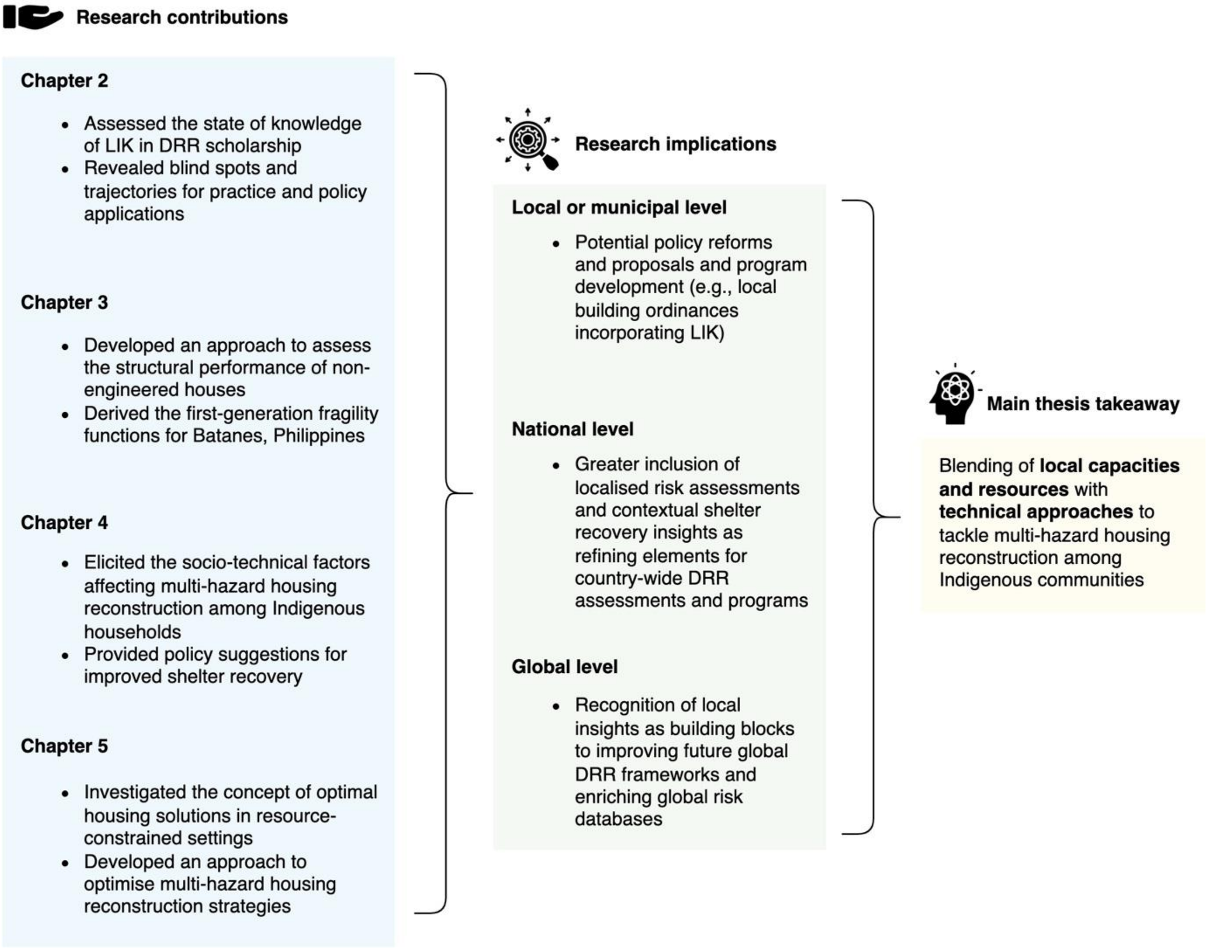
The dynamics of housing reconstruction among Indigenous households presented in this thesis supports the mandate of the Post-disaster Shelter Recovery Policy Framework of the Philippines [20]. Specifically, this policy framework underscores the importance of housing self-recovery to address the shelter deficit problem in the country through leveraging local knowledge and practices of communities. This thesis gives clearer directions to this policy framework with the presented case study bringing self-recovery insights which can be used as a rationale in crafting the implementing rules and regulations of such policy. Additionally, with the limited insights on the housing performance of self-built or non-engineered houses across the country, this thesis encourages further analysis for these types of structures and for them to have a certain degree of guidance in the National Building Code and the National Structural

Code of the Philippines. The passing of the New Philippine Building Act would be a timely entry point for this endeavour as it would repeal the decades-old and obsolete building laws [26], additionally lobbying for climate-proofing and strengthened risk reduction measures of structural assets in the Philippines [21,27].

### *3.3 Global scale*

On a global scale, this thesis adheres to the Sendai Framework on using LIK in DRR across the four priority areas of understanding risk, strengthening risk governance, investing in disaster risk reduction resilience, and enhancing reconstruction capacities to build back better. Insights from local case studies are the building blocks to better understand the contextual nuances of advancing these priority areas. These local insights guide future global DRR frameworks in continually refining strategies and policies to support the worldwide response of substantially reducing losses to lives and assets. The importance of case studies for global application has been demonstrated in light of the development of a complementary guidance instrument for translating the Sendai Framework into implementable actions on advancing the use of LIK in DRR (see [2]). By showcasing the field-based insights of this thesis to a global readership, it influences the dynamics of how DRR practitioners worldwide can learn from and support Indigenous populations in multi-hazard settings.

The survey of local housing typologies and the generation of the fragility functions in this thesis are foundational in the global efforts to understand the worldwide snapshot of disaster risk based on more locally grounded, refined assessments. This setup has implications for more robust global loss estimates, helping in closing the gap of underreported disaster impacts, especially in rural or remote areas [28]. This will eventually render the true extent of the toll that disasters take globally and potentially enhance the vision for more equitable allocation or distribution of aid/resources in disaster settings.



**Research contributions**

**Chapter 2**

- Assessed the state of knowledge of LIK in DRR scholarship
- Revealed blind spots and trajectories for practice and policy applications

**Chapter 3**

- Developed an approach to assess the structural performance of non-engineered houses
- Derived the first-generation fragility functions for Batanes, Philippines

**Chapter 4**

- Elicited the socio-technical factors affecting multi-hazard housing reconstruction among Indigenous households
- Provided policy suggestions for improved shelter recovery

**Chapter 5**

- Investigated the concept of optimal housing solutions in resource-constrained settings
- Developed an approach to optimise multi-hazard housing reconstruction strategies

**Research implications**

**Local or municipal level**

- Potential policy reforms and proposals and program development (e.g., local building ordinances incorporating LIK)

**National level**

- Greater inclusion of localised risk assessments and contextual shelter recovery insights as refining elements for country-wide DRR assessments and programs

**Global level**

- Recognition of local insights as building blocks to improving future global DRR frameworks and enriching global risk databases

**Main thesis takeaway**

Blending of **local capacities and resources** with **technical approaches** to tackle multi-hazard housing reconstruction among Indigenous communities

**Figure 6.1.** Summary of research contributions, research implications, and main thesis takeaway.

## 4 Future directions

This thesis highlights a context where local capacities become a critical dimension to manage disaster impacts, suggesting a course of action that should instate a people-centred view in improving (blanket) DRR interventions. While technologies aid in disaster management, focusing on the behavioural and cultural patterns among disaster-affected populations can provide as much benefit and outcome for risk reduction. This thesis supports this position through the blending of LIK and scientific thinking to address DRR challenges. From here, an imperative arises for future work to adopt this paradigm of knowledge co-production which can eventually transform the persistent and technocratic status quo in managing disaster impacts. Additionally, the people-centred view adapts to the dynamic outlook of the disaster-affected populations of continually innovating their coping strategies in the face of disturbances. Thus, instating a people-centred view in DRR guides future work in ensuring the relevance of strategies and actions in the ever-changing disaster space.

This thesis focused on one Indigenous community in the Philippines to provide a contextual understanding of the intrinsic housing reconstruction strategies in this area. The approaches adopted in this thesis – namely, (i) the quantification of housing performance through expert-driven method, (ii) the socio-technical analysis of housing reconstruction factors, and (iii) the multi-hazard housing reconstruction analysis – can be scaled for application in similar contexts in the Philippines. By doing so, an opportunity arises to create a national database of localised housing risk assessments. While this is an enormous task in an archipelago of more than 7000 islands, this shall set forth the underlying corpus of understanding or building local resilience of assets in the country. Beyond the Philippines, these approaches can also be undertaken and refined in other contexts especially in areas where multi-hazard circumstances complicate reconstruction strategies. Additionally, this thesis only explored the structural aspect of risk reduction. Other loss parameters including the anticipated casualties and recovery times are not incorporated and can therefore be adopted in future studies.

## 5 References

[1] S. Mitra, S. Sarkar, A. Ganguli-Mitra, On the need for an anticolonial perspective in engineering education and practice, Nat Commun 14 (2023) 8453. https://doi.org/10.1038/s41467-023-43952-2.

[2] UNDRR, Words into Action guidelines: Using traditional and indigenous knowledges for disaster risk reduction, UNDRR, 2022.

[3] T.J. Jones, H. Nyce, Y. Le Moigne, G. Williams-Jones, D. Nyce, Rethinking natural hazards research and engagement to include co-creation with Indigenous communities, Npj Nat. Hazards 1 (2024) 34. https://doi.org/10.1038/s44304-024-00034-7.

[4] L. Hiwasaki, E. Luna, Syamsidik, R. Shaw, Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities, International Journal of Disaster Risk Reduction 10 (2014) 15–27. https://doi.org/10.1016/j.ijdrr.2014.07.007.

[5] G.L. Pita, B.S. Albornoz, J.I. Zaracho, Flood depth-damage and fragility functions derived with structured expert judgment, Journal of Hydrology 603 (2021) 126982. https://doi.org/10.1016/j.jhydrol.2021.126982.

[6] GEM Foundation, Global Earthquake Model Foundation, (n.d.). https://www.globalquakemodel.org (accessed October 23, 2024).

[7] S. Lloyd, J. Gray, S. Healey, A. Opdyke, Social vulnerability to natural hazards in the Philippines, International Journal of Disaster Risk Reduction 79 (2022) 103103. https://doi.org/10.1016/j.ijdrr.2022.103103.

[8] M.L.P. Bautista, B. Bautista, I.C. Narag, A.D. Aquino, K. Papiona, et al., Enhancing Risk Analysis Capacities for Flood, Tropical Cyclone Severe Wind and Earthquake for Greater Metro Manila Area, 2014.

[9] B. Goldwyn, A. Javernick-Will, A.B. Liel, Multi-Hazard Housing Safety Perceptions of Those Involved with Housing Construction in Puerto Rico, Sustainability 14 (2022) 3802. https://doi.org/10.3390/su14073802.

[10] C. Venable, A. Javernick-Will, A.B. Liel, Perceptions of Post-Disaster Housing Safety in Future Typhoons and Earthquakes, Sustainability 12 (2020) 3837. https://doi.org/10.3390/su12093837.

[11] C. Venable, A. Javernick-Will, A.B. Liel, M.A. Koschmann, Revealing (mis)alignments between household perceptions and engineering assessments of post-disaster housing safety in typhoons, International Journal of Disaster Risk Reduction 53 (2021). https://doi.org/10.1016/j.ijdrr.2020.101976.

[12] Habitat for Humanity, Beyond Building: How Social Norms Shape Low-Income Home Construction, 2019.

[13] S. Merrill, E. Markel, A. Scarampi, M. Bolden, S. Yoder, Beyond building: how social norms and networks shape mason construction practices in incremental homebuilding, EDM 32 (2021) 161–178. https://doi.org/10.3362/1755-1986.21-00014.

[14] C.B. Brown, D.G. Elms, R.E. Melchers, Assessing and achieving structural safety, Proceedings of the Institution of Civil Engineers - Structures and Buildings 161 (2008) 219–230. https://doi.org/10.1680/stbu.2008.161.4.219.

[15] A. Chulahwat, H. Mahmoud, A combinatorial optimization approach for multi-hazard design of building systems with suspended floor slabs under wind and seismic hazards, Engineering Structures 137 (2017) 268–284. https://doi.org/10.1016/j.engstruct.2017.01.074.

[16] F.A. Potra, E. Simiu, Optimization and Multihazard Structural Design, J. Eng. Mech. 135 (2009) 1472–1475. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000057.

[17] H. Mahmoud, A. Chulahwat, Multi-Hazard Multi-Objective Optimization of Building Systems with Isolated Floors Under Seismic and Wind Demands, in: P. Gardoni, J.M. LaFave (Eds.), Multi-Hazard Approaches to Civil Infrastructure Engineering, Springer

International Publishing, Cham, 2016: pp. 141–164. https://doi.org/10.1007/978-3-319-29713-2_8.

[18] D.H. Zelleke, S.K. Saha, V.A. Matsagar, Reliability-Based Multi-Hazard Design Optimization of Base-Isolated Buildings, Engineering Structures 301 (2024) 117242. https://doi.org/10.1016/j.engstruct.2023.117242.

[19] Y.-J. Yin, Y. Li, Probabilistic loss assessment of light-frame wood construction subjected to combined seismic and snow loads, Engineering Structures 33 (2011) 380–390. https://doi.org/10.1016/j.engstruct.2010.10.018.

[20] The World Bank, Post-disaster Shelter Recovery Policy Framework: Building a Responsive System to Support Resilient and Equitable Recovery in the Philippines, (2022). http://documents.worldbank.org/curated/en/579231642696271929/Post-Disaster-Shelter-Recovery-Policy-Framework-Building-a-Responsive-System-to-Support-Resilient-and-Equitable-Recovery-in-the-Philippines (accessed October 28, 2024).

[21] F.M. Cervantes, House pushes for climate proofing reforms, Philippine News Agency (2023). https://www.pna.gov.ph/articles/1207529 (accessed October 28, 2024).

[22] Office of the Sangguniang Bayan, Itbayat, Batanes, Resolution Acknowledging the Published Documentations of History and Culture of Itbayat, Batanes in Different Media Platforms, 2024.

[23] Congress of the Philippines, An Act to Establish the Batanes Group of Islands and Islets as a Protected Area, and Its Peripheral Waters as Buffer Zones, Providing for Its Management and for Other Purposes, 2001.

[24] Congress of the Philippines, An Act to Recognize, Protect and Promote the Rights of Indigenous Cultural Communities/Indigenous Peoples, Creating a National Commission on Indigenous Peoples, Establishing Implementing Mechanisms, Appropriating Funds Therefor, and for Other Purposes, 1997.

[25] GeoRisk Philippines, GeoRisk Philippines Initiative, (n.d.). https://georisk.gov.ph/ (accessed October 28, 2024).

[26] D. de Leon, House OKs new code to repeal decades-old, “obsolete” building law, RAPPLER (2023). https://www.rappler.com/philippines/house-representatives-approves-new-code-repeal-decades-old-obsolete-building-law-august-2023/ (accessed October 28, 2024).

[27] Manila Bulletin Editorial, Time to revamp the National Building Code, Manila Bulletin (2023). https://mb.com.ph/2023/8/14/time-to-revamp-the-national-building-code (accessed October 28, 2024).

[28] UNDRR, Closing Climate and Disaster Data Gaps: New challenges, new thinking, (2023).

# Appendix A

## Experts' solicitation form (Chapter 3)

**Objective.** This survey aims to solicit your judgement on what **intensity of earthquake and typhoon** can bring a certain damage state to a particular **housing typology**. Your inputs will be used to derive fragility functions – a fundamental tool in assessing how a particular housing typology can withstand different hazard intensities. The study in general is based in Itbayat, Batanes, Philippines and we aim to help households understand the vulnerability of their houses against wind and seismic impacts. We are relying on the judgement of experts and specialists because analytical and empirical data are currently impractical to acquire. We invite you to take part in this assessment because of your familiarity with the typologies of interest and/or the damage states.

**Outline.** This document contains the following:

- **Page 2 – 5**: Descriptions of the seven (7) housing typologies, which include:
    - Typology 1 – Unreinforced masonry
    - Typology 2 – Lightweight with wooden posts
    - Typology 3 – Lightweight with steel posts
    - Typology 4 – Semi-concrete with steel posts
    - Typology 5 – Semi-concrete with reinforced concrete (RC) posts
    - Typology 6 – RC structure with lightweight roof
    - Typology 7 – RC structure with flat slab
- **Page 6 – 7**: Earthquake assessment (includes the answer sheet, information on the intensity measure, and damage states)
- **Page 8 – 9**: Typhoon assessment (includes the answer sheet, information on the intensity measure, and damage states)

**General instructions.** Please provide an estimated **earthquake and typhoon intensity** that will yield the specified damage extent to the seven (7) housing typologies described in the succeeding pages. Note that these typologies maybe constructed with variability in design and construction (especially because of their non-engineered nature), so there might not be a precise threshold. To reflect this uncertainty, we need you to estimate two values – a median and a lower bound – for each damage measure for every typology. We also need you to assess your level of confidence in the estimates you provided.

- **Median intensity** – "What intensity can bring the specified damage state to **50%** of residential structures having the same typology?" (see example below)
- **Lower-bound intensity** – "What intensity can bring the specified damage state to **10%** of residential structures having the same typology?" *(Note: Judge the lower-bound carefully. Make an initial guess and consider conditions that will affect your estimate, then revise accordingly. Without careful thought, distinction between the lower-bound and median estimates might not be pronounced so think twice and do not be afraid to show uncertainty.)* (see example below)
- **Level of confidence** – How confident are you in your estimates? Provide an answer from 1 to 5, where 1 means low confidence (not so sure of your estimates) and 5 means highly confident (or very sure about your estimates). (see example below)

**Instructions for answering the earthquake assessment.** "PEIS" refers to the earthquake intensity scale used in the Philippines – this is described fully in Page 6 including the damage states for seismic impact.

**For example:** If you answer this, then you are implying that when there is an intensity VI (or 6) earthquake, **50%** of unreinforced masonry structures will experience extensive damage (damage state 4).

| Typology | | Damage states | | | | | Con-fidence level |
|---|---|---|---|---|---|---|---|
| | | 1 (None/very minor damage) | 2 (Minor damage) | 3 (Moderate damage) | 4 (Extensive damage) | 5 (Complete damage) | |
| **1 – Unreinforced masonry** | Median intensity (PEIS Intensity) | PEIS: III | PEIS: IV | PEIS: V | PEIS: VI | PEIS: VII | 4 |
| | Lower-bound intensity (PEIS Intensity) | PEIS: II | PEIS: III | PEIS: IV-V (or 4.5) | PEIS: V-VI (or 5.5) | PEIS: VI-VII (or 6.5) | |

(Note: Fill all the blanks in the table. These inputs are for illustrative purposes only.)

**For example:** If you answer this, then you are implying that when there is an intensity V-VI (or 5.5) earthquake, **10%** of unreinforced masonry structures will experience extensive damage (damage state 4).

**For example:** If you answer this, you are expressing that you are almost very sure about the estimates you provided.

**Instructions for answering the typhoon assessment.** "3-second peak gust" is the intensity measure for wind impact – this is described fully in Page 8 including the damage states for wind impacts.

**For example:** If you answer this, then you are implying that when there is a 320 km/h 3-second peak gust wind speed, **50%** of unreinforced masonry structures will experience extensive damage (damage state 4).

| **Typology** | | **Damage states** | | | | | **Con-fidence level** |
|---|---|---|---|---|---|---|---|
| | | **1 (None/very minor damage)** | **2 (Minor damage)** | **3 (Moderate damage)** | **4 (Extensive damage)** | **5 (Complete damage)** | |
| **1 – Unreinforced masonry** | Median intensity (3-sec peak gust) | 70 km/h | 95 km/h | 210 km/h | 320 km/h | 375 km/h | 1 |
| | | (Note: Fill all the blanks in the table. These inputs are for illustrative purposes only.) | | | | | |
| | Lower-bound intensity (3-sec peak gust) | 65 km/h | 80 km/h | 150 km/h | 275 km/h | 350 km/h | |

**For example:** If you answer this, then you are implying that when there is a 275 km/h 3-second peak gust wind speed, **10%** of unreinforced masonry structures will experience extensive damage (damage state 4).

**For example:** If you answer this, you are expressing that you are not very sure about your estimates.

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**Housing typologies.** Please refer to the images and descriptions of housing typologies below for reference.

**Housing typology 1 – Unreinforced masonry**

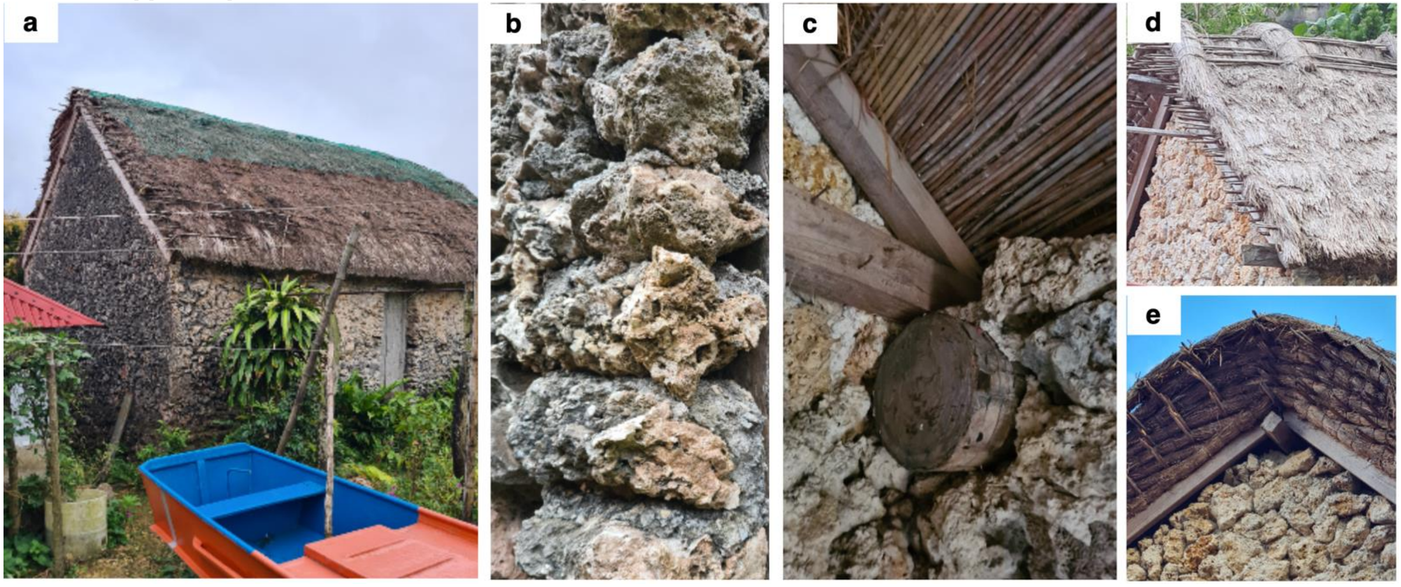


**Figure 1. (a)** An archetype of an unreinforced masonry structure. **(b)** Coral limestones as walling material bounded by quicklime mortar. **(c)** Typical roof-to-wall connection where thick logs are embedded in stone walls. **(d, e)** Layered thatch (cogon) roofing with reed matting.

| **Typology 1** | **Unreinforced masonry** (see Figure 1) |
|---|---|
| Building height | One story |
| Type of lateral load-resisting system (LLRS) | Wall system |
| Material of LLRS | Thick walls (0.80 metre to 1 metre **wide**) made of coral limestones bounded by quicklime ("slaked") mortar (see image "b"). With wall foundation of the same material. |
| Wall material | Thick walls (0.80 m to 1 m wide) made of coral limestones bounded by quicklime ("slaked") mortar (see image "b"). Openings are covered with solid wood panels. |
| Roof profile | Gable roof configuration. Layered thatch (cogon) roofing tied to wooden roof members (see image "c") using native (plant-based) tying materials (or most recently with commercially available materials like nylon). Roof eaves/overhangs follow just the thickness of the thatch roofing (see image "d", and "e"). |

### Housing typology 2 – Lightweight with wooden posts

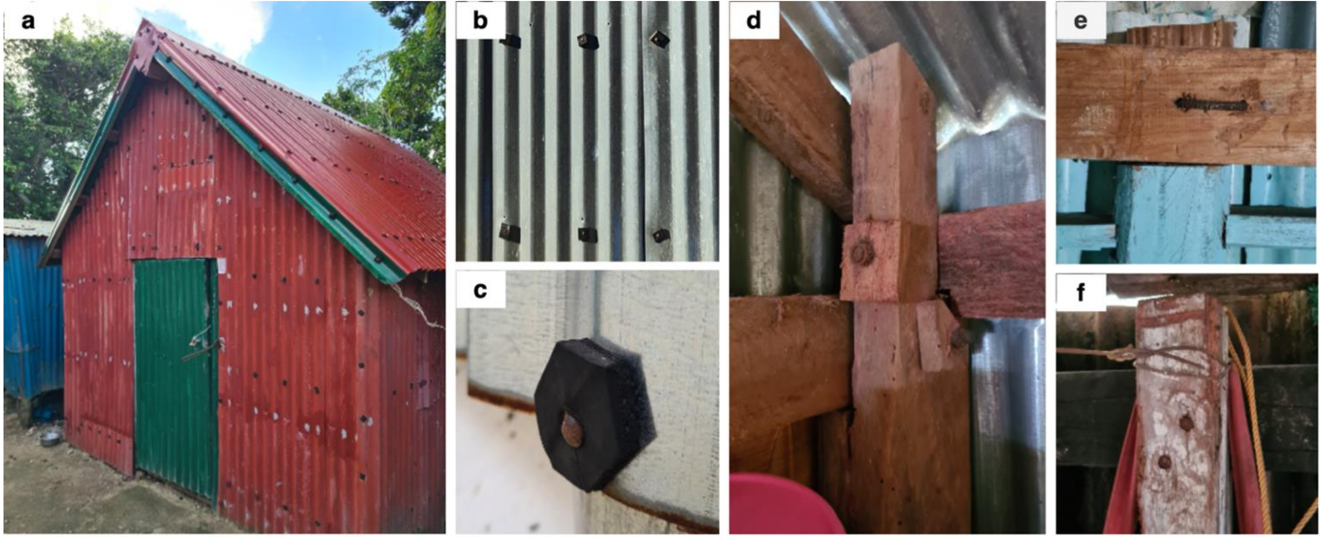


**Figure 2.** **(a)** An archetype of a lightweight structure with wooden posts. **(b)** Roof/wall sheets are common to be fastened every one or two corrugations. **(c)** Improvised rubber washers for nail fasteners. Common post and beam connections are **(d)** bolted, **(e)** hooked with reinforcing steel bars, and **(f)** nailed.

| **Typology 2** | **Lightweight with wooden posts** (see Figure 2) |
|---|---|
| Building height | One story |
| Type of lateral load-resisting system (LLRS) | Post and beam system |
| Material of LLRS | Primary (corner) posts are made of wood (see image "d", "e", and "f") driven on ground but **without** foundation. Additional wooden posts as intermediate supports are common. Timber beams are used. |
| Wall material | Corrugated galvanised iron (CGI) sheets nailed on wooden frames, fastened every other one or two corrugations (see image "b"). Nails are common to have improvised rubber washers (see image "c"). Jalousie glass windows or window/door panels made from CGI/plywood are common. |
| Roof profile | Gable roof configuration. CGI roofing sheets nailed on wooden roof members. Nails are common to have improvised rubber washers (see image "c"). Roof eaves/overhangs rarely exceed 30 cm. |

### Housing typology 3 – Lightweight with steel posts

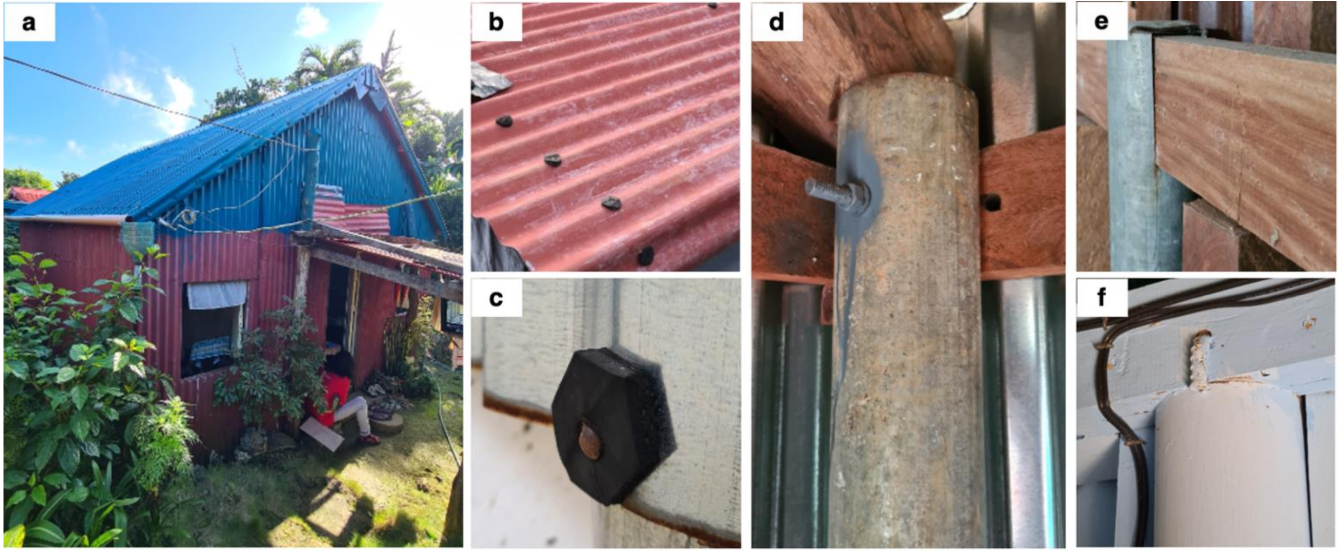


**Figure 3.** **(a)** An archetype of a lightweight structure with steel posts. **(b)** Roof/wall sheets are common to be fastened every one or two corrugations. **(c)** Improvised rubber washers for nail fasteners. Common post and beam connections are **(d)** bolted, **(e)** notched and clipped, and **(f)** hooked with reinforcing steel bars.

| **Typology 3** | **Lightweight with steel posts** (see Figure 3) |
|---|---|
| Building height | One story |
| Type of lateral load-resisting system (LLRS) | Post and beam system |
| Material of LLRS | Primary (corner) posts are made of 4-inch to 5-inch (100-mm to 127-mm) diameter steel pipe (see image "d", "e", and "f") **with** reinforced concrete (RC) foundation. Wooden posts as intermediate supports are common. Timber beams are used. |
| Wall material | Corrugated galvanised iron (CGI) sheets nailed on wooden frames, fastened every other one or two corrugations (see image "b"). Nails are common to have improvised rubber washers (see image "c"). Jalousie glass windows or window/door panels made from CGI/plywood are common. |
| Roof profile | Gable roof configuration. CGI roofing sheets nailed on wooden roof members. Nails are common to have improvised rubber washers (see image "c"). Roof eaves/overhangs rarely exceed 30 cm. |

## Housing typology 4 – Semi-concrete with steel posts

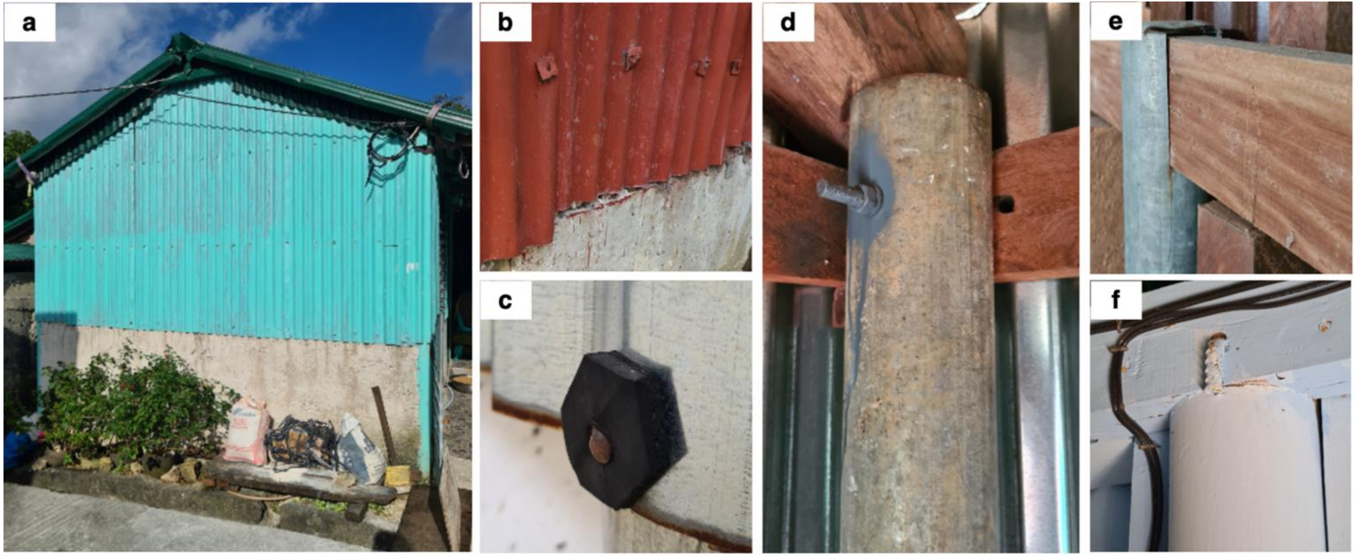


**Figure 4.** **(a)** An archetype of a semi-concrete structure with steel posts. **(b)** Roof/wall sheets are common to be fastened every one or two corrugations. **(c)** Improvised rubber washers for nail fasteners. Common post and beam connections are **(d)** bolted, **(e)** notched and clipped, and **(f)** hooked with reinforcing steel bars.

| **Typology 4** | **Semi-concrete with steel posts** (see Figure 4) |
|---|---|
| Building height | One story |
| Type of lateral load-resisting system (LLRS) | Hybrid: Post and beam system with lower half reinforced concrete (RC) wall providing additional lateral stiffness |
| Material of LLRS | Primary (corner) posts are made of 4-inch to 5-inch (100-mm to 127-mm) diameter steel pipe (see image "d", "e", and "f") **with** RC foundation. Wooden posts as intermediate supports are common. Timber beams are used. |
| Wall material | Lower half: RC walls. Upper half: corrugated galvanised iron (CGI) sheets nailed on wooden frames, fastened every other one or two corrugations (see image "b"). Nails are common to have improvised rubber washers (see image "c"). Jalousie glass windows or window/door panels made from CGI/plywood are common. |
| Roof profile | Gable roof configuration. CGI roofing sheets nailed on wooden roof members. Nails are common to have improvised rubber washers (see image "c"). Roof eaves/overhangs rarely exceed 30 cm. |

## Housing typology 5 – Semi-concrete with reinforced concrete (RC) posts

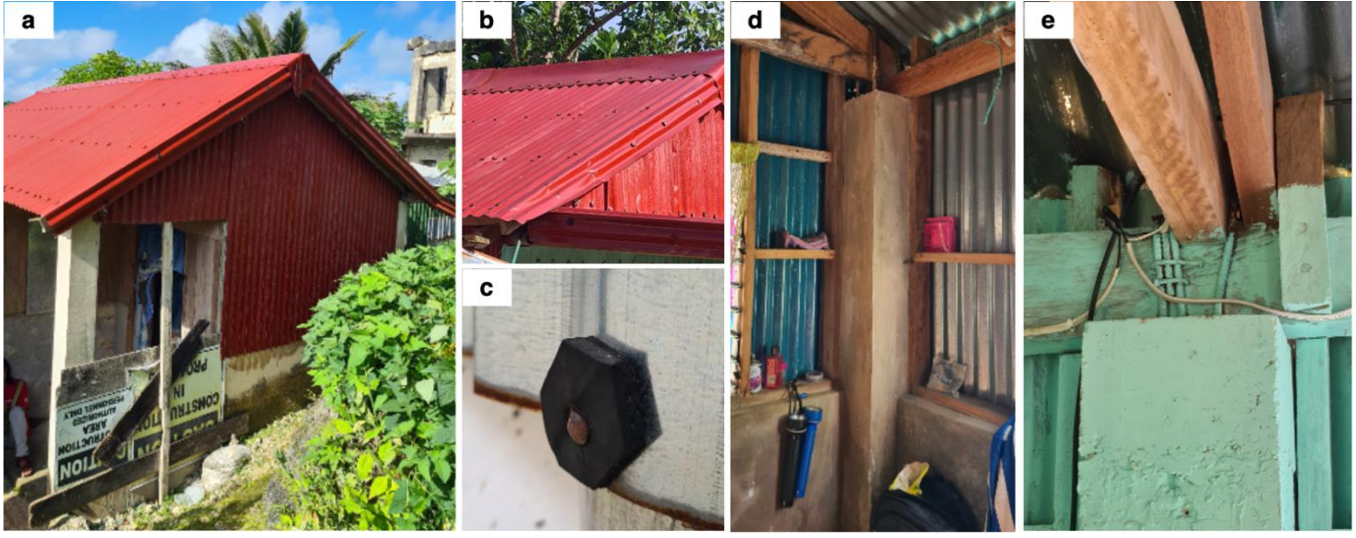


**Figure 5.** **(a)** An archetype of a semi-concrete structure with RC posts. **(b)** Roof/wall sheets are common to be fastened every one or two corrugations. **(c)** Improvised rubber washers for nail fasteners. Common post and beam connections are **(d, e)** dowels wrapped around beams and roof members.

| **Typology 5** | **Semi-concrete with reinforced concrete (RC) posts** (see Figure 5) |
|---|---|
| Building height | One story |
| Type of lateral load-resisting system (LLRS) | Hybrid: Post and beam system with lower half reinforced concrete (RC) wall providing additional lateral stiffness |
| Material of LLRS | Primary (corner) posts are made of RC (see image "d" and "e") **with** RC foundation. Timber beams are used. |
| Wall material | Lower half: RC walls. Upper half: corrugated galvanised iron (CGI) sheets nailed on wooden frames, fastened every other one or two corrugations. Nails are common to have improvised rubber washers (see image "c"). Jalousie glass windows or window/door panels made from CGI/plywood are common. |
| Roof profile | Gable roof configuration. CGI roofing sheets nailed on wooden roof members. Nails are common to have improvised rubber washers (see image "c"). Roof eaves/overhangs rarely exceed 30 cm. |

### Housing typology 6 – Reinforced concrete (RC) structure with lightweight roof

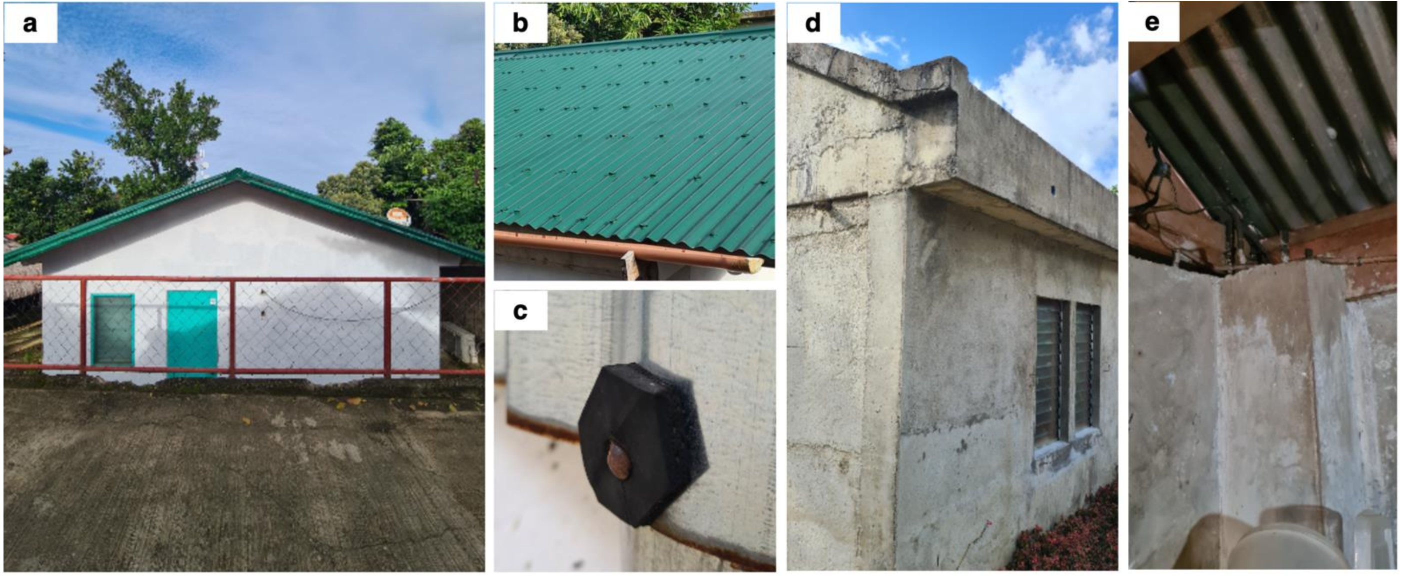


**Figure 6.** (**a**) An archetype of a reinforced concrete structure with lightweight roof. (**b**) Roof sheets are fastened every one or two corrugations. (**c**) Nails as fasteners come with improvised rubber washers. (**d**) In some structures, inside gutters are common to conceal the edges of roofing sheets. (**e**) Roof-to-wall connections are common to be via dowels from reinforcing steel bars wrapping the wooden roof members.

| **Typology 6** | **Reinforced concrete (RC) structure with lightweight roof** (see Figure 6) |
|---|---|
| Building height | One story |
| Type of lateral load-resisting system (LLRS) | Hybrid: moment frame, with reinforced concrete (RC) walls providing additional lateral stiffness |
| Material of LLRS | Primary (corner) posts, foundations, and beams are made of RC. Walls are made of RC. |
| Wall material | Reinforced concrete (RC) walls. Jalousie glass windows or window/door panels made from CGI/plywood are common. |
| Roof profile | Gable roof configuration. Corrugated galvanised iron (CGI) roofing sheets nailed on wooden roof members (see image "b"). Nails are common to have improvised rubber washers (see image "c"). Roof eaves/overhangs rarely exceed 30 cm. In some structures, edges of roofing sheets are concealed with inside gutters (see image "d"). |

### Housing typology 7 – Reinforced concrete (RC) structure with slab roof

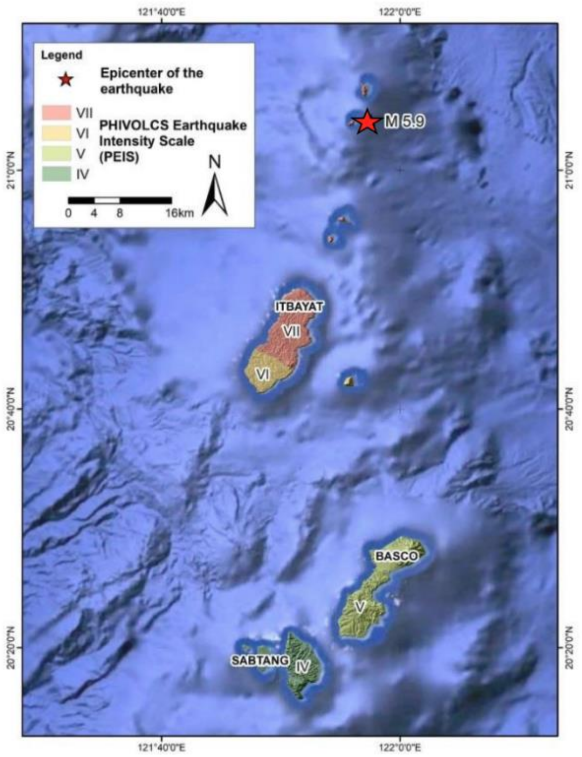
**Figure 7.** (**a**) An archetype of a reinforced concrete structure with slab roof. (**b**) Reinforced concrete slab overhangs typically exceed 30 cm. (**c**) All beams and columns, including exterior walls, are reinforced concrete.

| **Typology 7** | **Reinforced concrete (RC) structure with slab roof** (see Figure 7) |
|---|---|
| Building height | One story |
| Type of lateral load-resisting system (LLRS) | Hybrid: moment frame, with reinforced concrete (RC) walls providing additional lateral stiffness |
| Material of LLRS | Primary (corner) posts, foundations, and beams are made of RC. Walls are made of RC. |
| Wall material | RC walls. Jalousie glass windows or window/door panels made from CGI/plywood are common. |
| Roof profile | Flat RC slab roof configuration. Slab eaves/overhangs typically exceed 30 cm. |

**Earthquake intensity measure.** **PHIVOLCS Earthquake Intensity Scale (PEIS)** is developed and used by the Philippine Institute of Volcanology and Seismology (PHIVOLCS) for the Philippine setting. It is a ten-range scale and considers the impact of shaking to people, structures, and other immediate objects.

| PEIS | Shaking | Description |
|---|---|---|
| I | Scarcely perceptible | Perceptible to people under favourable circumstances. Delicately balanced objects are disturbed slightly. Still water in containers oscillates slowly. |
| II | Slightly felt | Felt by few individuals at rest indoors. Hanging objects swing slightly. Still water in containers oscillates noticeably. |
| III | Weak | Felt by many people indoors especially in upper floors of buildings. Vibration is felt like one passing of a light truck. Dizziness and nausea are experienced by some people. Hanging objects swing moderately. Still water in containers oscillates moderately. |
| IV | Moderately strong | Felt generally by people indoors and by some people outdoors. Light sleepers are awakened. Vibration is felt like a passing of heavy truck. Hanging objects swing considerably. Dinner, plates, glasses, windows and doors rattle. Floors and walls of wood framed buildings creak. Standing motor cars may rock slightly. Liquids in containers are slightly disturbed. Water in containers oscillate strongly. Rumbling sound may sometimes be heard. |
| V | Strong | Generally felt by most people indoors and outdoors. Many sleeping people are awakened. Some are frightened, some run outdoors. Strong shaking and rocking felt throughout building. Hanging objects swing violently. Dining utensils clatter and clink; some are broken. Small, light and unstable objects may fall or overturn. Liquids spill from filled open containers. Standing vehicles rock noticeably. Shaking of leaves and twigs of trees are noticeable. |
| VI | Very strong | Many people are frightened; many run outdoors. Some people lose their balance. motorists feel like driving in flat tires. Heavy objects or furniture move or may be shifted. Small church bells may ring. Wall plaster may crack. Very old or poorly built houses and man-made structures are slightly damaged though well-built structures are not affected. Limited rockfalls and rolling boulders occur in hilly to mountainous areas and escarpments. Trees are noticeably shaken. |
| VII | Destructive | Most people are frightened and run outdoors. People find it difficult to stand in upper floors. Heavy objects and furniture overturn or topple. Big church bells may ring. Old or poorly-built structures suffer considerable damage. Some well-built structures are slightly damaged. Some cracks may appear on dikes, fish ponds, road surface, or concrete hollow block walls. Limited liquefaction, lateral spreading and landslides are observed. Trees are shaken strongly. (Liquefaction is a process by which loose saturated sand lose strength during an earthquake and behave like liquid). |
| VIII | Very destructive | People are panicky. People find it difficult to stand even outdoors. Many well-built buildings are considerably damaged. Concrete dikes and foundation of bridges are destroyed by ground settling or toppling. Railway tracks are bent or broken. Tombstones may be displaced, twisted or overturned. Utility posts, towers and monuments mat tilt or topple. Water and sewer pipes may be bent, twisted or broken. Liquefaction and lateral spreading cause man- made structure to sink, tilt or topple. Numerous landslides and rockfalls occur in mountainous and hilly areas. Boulders are thrown out from their positions particularly near the epicentre. Fissures and faults rapture may be observed. Trees are violently shaken. Water splash or stop over dikes or banks of rivers. |
| IX | Devastating | People are forcibly thrown to ground. Many cry and shake with fear. Most buildings are totally damaged. bridges and elevated concrete structures are toppled or destroyed. Numerous utility posts, towers and monument are tilted, toppled or broken. Water sewer pipes are bent, twisted or broken. Landslides and liquefaction with lateral spreadings and sandboils are widespread. the ground is distorted into undulations. Trees are shaken very violently with some toppled or broken. Boulders are commonly thrown out. River water splashes violently on slops over dikes and banks. |
| X | Completely devastating | Practically all man-made structures are destroyed. Massive landslides and liquefaction, large scale subsidence and uplifting of landforms and many ground fissures are observed. Changes in river courses and destructive seiches in large lakes occur. Many trees are toppled, broken and uprooted. |

**Table 1.** The PHIVOLCS Earthquake Intensity Scale (PEIS). Source: https://www.phivolcs.dost.gov.ph/index.php/earthquake/earthquake-intensity-scale



For context, the 5.9-magnitude earthquake in the province of Batanes, Philippines (epicentre in Itbayat) that occurred on 29 July 2019 at 7 AM had recorded the following PEIS intensities:

- **VII** (Destructive)
  – Northern part of Itbayat, Batanes (Barangays Santa Maria, Santa Lucia, Santa Rosa, and San Rafael)
- **VI** (Very strong)
  – Southern Itbayat, Batanes (Barangay Raele)
- **V** (Strong)
  – Municipalities of Basco, Ivana, and Mahatao, Batanes
- **IV** (Moderately strong)
  – Municipalities of Uyugan and Sabtang, Batanes

**Figure 8.** Map of Batanes, Philippines with the PEIS intensities of the 5.9 magnitude earthquake in 2019. Source: Perez et al., 2019 / DOST-PHIVOLCS.

**Earthquake damage states.** Please refer to the damage states below.

- **Damage state 1 (No or very minor damage)** – None or very minor damage
- **Damage state 2 (Minor damage)** – Small (≤1/8 inch or ≤ 3 mm) cracks or hairline cracks at corners of doors, windows, wall ceiling intersections, connections (e.g., on welds, beam and column joints, etc.), wall surfaces; spalling at a few locations (for typologies with concrete components)
- **Damage state 3 (Moderate damage)** – Large (>1/8 inch or > 3 mm) cracks at corners of doors and windows, connections (e.g., on welds, beam and column joints, etc.), wall surfaces; permanent rotation at connections are likely; spalling at wall ends (for typologies with concrete components)
- **Damage state 4 (Extensive damage)** – Partial collapse, characterised by failed connections/critical elements, permanent lateral movement of floors, roof, beams, etc., extensive large/through-the-wall cracks (for concrete/masonry components) or out-of-plane failure
- **Damage state 5 (Complete damage)** – Total collapse, or in imminent danger of collapse, due to failed lateral-load resisting system

**Answer sheet.** Please provide an estimated **PEIS Intensity** that will yield the specified damage extent to the seven (7) housing typologies described above. The meaning of median intensity, lower-bound intensity, and level of confidence is explained in Page 1.

Note:

1. In estimating the PEIS intensity, provide a numeral/number from **I to X**, or **1 to 10**. If you wish to input value in between the numbers/numerals, do so by providing "0.5" for the number, or a range for the numeral (e.g., 5.5 or V-VI). If you think that a certain typology will not succumb or exhibit a certain damage state even at PEIS Intensity X, put **N/A** – short for "not applicable" which means that such typology can withstand the most severe ground shaking possible. Please fill out all the blanks in the table.
2. You can fill out this table either digitally or manually (via a printout). Please return a copy of the answered sheet to arvin.hadlos@sydney.edu.au

| **Typology** | | **Damage states** | | | | | **Con-fidence level** |
|---|---|---|---|---|---|---|---|
| | | **1 (None/very minor damage)** | **2 (Minor damage)** | **3 (Moderate damage)** | **4 (Extensive damage)** | **5 (Complete damage)** | |
| **1 – Unreinforced masonry** | Median intensity (PEIS Intensity) | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | _____ |
| | Lower-bound intensity (PEIS Intensity) | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | |
| **2 – Lightweight with wooden posts** | Median | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | _____ |
| | Lower-bound | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | |
| **3 – Lightweight with steel posts** | Median | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | _____ |
| | Lower-bound | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | |
| **4 – Semi-concrete with steel posts** | Median | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | _____ |
| | Lower-bound | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | |
| **5 – Semi-concrete with RC posts** | Median | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | _____ |
| | Lower-bound | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | |
| **6 – RC structure with lightweight roof** | Median | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | _____ |
| | Lower-bound | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | |
| **7 – RC structure with slab roof** | Median | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | _____ |
| | Lower-bound | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | PEIS: _____ | |

**Typhoon intensity measure. 3-second peak gust wind speed**, expressed in kilometres per hour (km/h), refers to the highest average wind speed over a three-second interval measured at 10 meters above ground. "Gust" – as defined by the Philippine Atmospheric, Geophysical, and Astronomical Services (PAGASA) – is the brief and sudden increase in wind speed followed by a lull or slackening of the wind speed.

Please note that meteorological data of typhoon wind speed in the Philippines as communicated by PAGASA are based on a 10-minute sustained wind speed. We need estimates of 3-sec peak gust in this assessment since this measure has more impact when considering building damage.

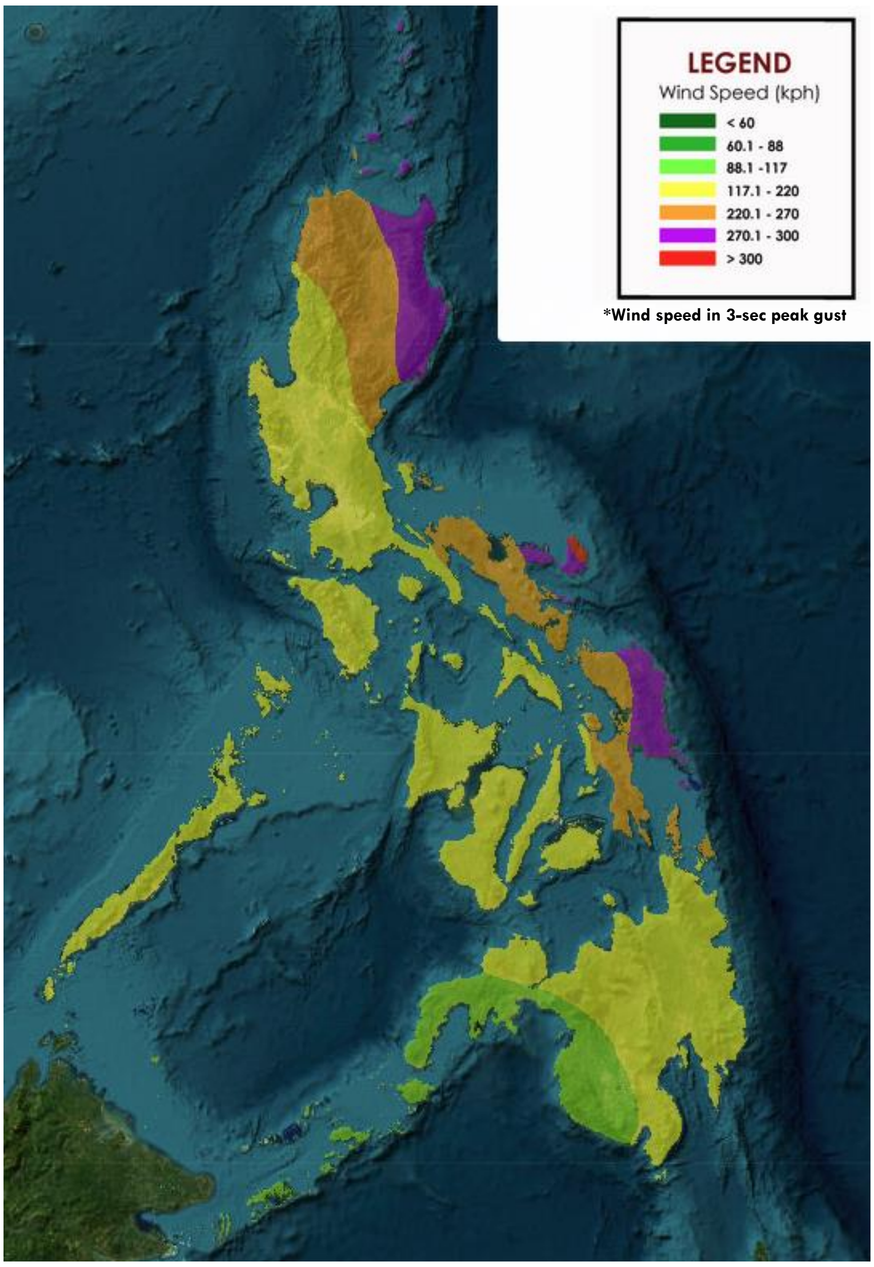


**Figure 9.** Regional severe wind hazard maps of the Philippines representing a 500-year return period (0.2% chance that the indicated wind speed will happen in a given year). Note that the wind speed represents 3-sec peak gust. Source: PAGASA, https://www.pagasa.dost.gov.ph/products-and-services/severe-wind-maps

For context, here are some of the gustiness of the recent strongest typhoons in the Philippines. Note that the peak gust of a typhoon varies from location to location along its track.

- **Typhoon Ferdie (Meranti) in 2016**
  – A gustiness of up to 252 km/h was recorded in Basco, Batanes although no record is available for Itbayat, Batanes where it directly passed near its peak intensity.

- **Typhoon Yolanda (Haiyan) in 2013**
  – In Tacloban City, 3-sec peak gust of 252 km/h was estimated evident on bent rebars due to wind impacts. In Roxas, Capiz, peak gust of 205 km/h was recorded. Note that other data are not provided because weather instruments were affected during the onslaught of the typhoon. International weather agencies provided higher estimates of the 3-sec peak gust such as 324 km/h and 378 km/h.

For additional context, PAGASA's regional severe wind hazard maps provide estimates of the 3-sec peak gust wind speed that will likely affect the Philippines (see, for example, Figure 9).

**Typhoon damage states.** Please refer to the damage states below.

- **Damage state 1 (No or very minor damage)** – None to very minor damage. Roof cover loss of less than 2% with no or limited water penetration.
- **Damage state 2 (Minor damage)** – Roof cover loss of 2% to 15% of the roof area but can be temporarily covered to prevent water seepage. Roof structure remains intact. Maximum of one window/door failure. No failure of wall structure but marks/dents are visible which can be repaired by painting/patching.
- **Damage state 3 (Moderate damage)** – Roof cover loss of above 15% to 50% of the roof area. Roof structure remains intact. Moderate window breakage. Water penetration causes some interior damage to the structure. No failure of wall structure.
- **Damage state 4 (Extensive damage)** – Roof cover loss of more than 50%. Roof structure remains intact. Major window damage. Water penetration causes extensive damage to the interior of structure. No failure of wall structure.
- **Damage state 5 (Complete damage)** – Complete roof failure and/or failure of wall structure.

**Answer sheet.** Please provide an estimated **3-second peak gust wind speed** that will yield the specified damage extent to the seven (7) housing typologies described above. The meaning of median intensity, lower-bound intensity, and level of confidence is explained in Page 1.

Notes:

1. In estimating the 3-second peak wind speed, provide any speed from **0 km/h to 400 km/h**. If you think that a certain typology will not succumb or exhibit a certain damage state even at 400 km/h, put **N/A** – short for "not applicable" which means that such typology can withstand the most severe wind impact possible. Please fill out all the blanks in the table.
2. You can fill out this table either digitally or manually (via a printout). Please return a copy of the answered sheet to arvin.hadlos@sydney.edu.au

| **Typology** | | **Damage states** | | | | | **Con-fidence level** |
|---|---|---|---|---|---|---|---|
| | | **1 (None/very minor damage)** | **2 (Minor damage)** | **3 (Moderate damage)** | **4 (Extensive damage)** | **5 (Complete damage)** | |
| **1 – Unreinforced masonry** | Median intensity (3-sec peak gust) | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ |
| | Lower-bound intensity (3-sec peak gust) | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | |
| **2 – Lightweight with wooden posts** | Median | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ |
| | Lower-bound | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | |
| **3 – Lightweight with steel posts** | Median | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ |
| | Lower-bound | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | |
| **4 – Semi-concrete with steel posts** | Median | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ |
| | Lower-bound | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | |
| **5 – Semi-concrete with RC posts** | Median | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ |
| | Lower-bound | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | |
| **6 – RC structure with lightweight roof** | Median | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ |
| | Lower-bound | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | |
| **7 – RC structure with slab roof** | Median | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ |
| | Lower-bound | _____ km/h | _____ km/h | _____ km/h | _____ km/h | _____ km/h | |

# Appendix B

## Interview and focus group discussion guides (Chapter 4)

## Key Informant Interviews (KII) Guide

**Introduction**

_________________________ (local greetings). My name is Arvin Hadlos from The University of Sydney conducting my PhD thesis about housing reconstruction after the 2019 earthquakes in Itbayat, Batanes. I am joined by my research assistant, _______________, who will be taking notes. Your responses will contribute insights and lessons learned on how the community can build back safer in future disasters.

We are going to ask you several questions about your opinion, experiences, and observations during the time when the community was rebuilding houses. Your participation in this interview is voluntary. You may withdraw at any time and will not impact your relationship to us or to whoever are affiliated with this study.

If you do not know the answer to a question or do not want to answer, we can skip the question. The focus group should last around one hour. Your individual views will remain confidential and your name and identifying information will be redacted in any final reports. There are no right or wrong answers to the questions. We will be taking notes, and we would like to record your responses to each question to be sure that we capture all the information that is shared today.

Do you have any questions?
*[Facilitator to confirm that all individual consent to participate]*

**Questions for heads of households:**

**(Opening questions)**

1. Introduce yourself and describe how your house was affected by the earthquake.
2. What assistance, if any, did you receive from the government or any other organisations in rebuilding your house?

**Itbayat indigenous building practices**

3. Itbayat is known for traditional building practices for typhoon-proofing. Can you share the practices that you know and how they help against the impacts of typhoons?
4. How are these practices observed today? Are they still relevant?

**Post-earthquake reconstruction**

5. After the July 2019 earthquakes, households with previous stone-and-lime houses decided to build differently. Why is this so?
6. Currently, houses in the community are made of GI sheet walls, or semi-concrete/semi-lightweight, and entirely concrete. What made you decide to use a certain material in rebuilding their houses?
7. How did you secure labour/manpower in rebuilding their houses?
8. Were there guidelines or orders that you needed to follow in rebuilding their houses? If yes, please discuss them.
9. What were the resource limitations, if any, that affected the outcome of your rebuilt house? Please explain.
10. While your house now look different from the stone-and-lime dwelling, were the Itbayat traditional building practices considered during the housing reconstruction? Why or why not?

**Multi-hazard safety**

11. How do you think your present house will perform against earthquakes and typhoons?

**(Overall assessment)**

12. If you received any form of assistance from organisations, how did that assistance influence the outcome of your present house?
13. Between your past and present house, which do you like better? Why?
14. Given your current house, are there improvements you wish to introduce to strengthen it?

**Questions for representatives from organisations:**

**(Opening questions)**

1. Describe your role during the reconstruction process.
2. From your observations, how did households start rebuilding their house?

**Assistance**

3. Did you provide any form of assistance to the households in rebuilding their houses? If yes, were those:
   a. Financial,
   b. In-kind,
   c. Technical assistance?
   Please share why you provided such form/s of assistance.
4. How did you identify recipients of such assistance? Why did you choose this/these group/s?
5. Were there conditions that the recipients should observe alongside the assistance you provided? Please explain.
6. Did your organisation appropriate the form of assistance to the local conditions? Why or why not?
7. How did the recipients perceive the assistance you provided to them?

**Challenges & opportunities in reconstruction**

8. From your observations, did the households struggle at some point in rebuilding their houses? Please explain at what point and why.
9. The Ivatans are known to have developed local building practices. Were these useful in rebuilding their houses? Why or why not.

**(Overall assessment)**

10. Do you think the households built back safer following the earthquakes?
11. How do you think your organisation influenced the progress of the household reconstruction process?
12. What were the main lessons learned from your programming after the earthquakes?

## Focus Group Discussion (FGD) Guide

**Introduction**

________________________ (local greetings). My name is Arvin Hadlos from The University of Sydney conducting my PhD thesis about housing reconstruction after the 2019 earthquakes in Itbayat, Batanes. I am joined by my research assistant, _______________, who will be taking notes. Your responses will contribute insights and lessons learned on how the community can build back safer in future disasters.

We are going to ask you several questions about your opinion, experiences, and observations during the time when the community was rebuilding houses. Your participation in this focus group is voluntary. You may withdraw at any time and will not impact your relationship to us or to whoever are affiliated with this study.

If you do not know the answer to a question or do not want to answer, we can skip the question. The focus group should last around one hour. Your individual views will remain confidential and your name and identifying information will be redacted in any final reports. There are no right or wrong answers to the questions. We will be taking notes, and we would like to record your responses to each question to be sure that we capture all the information that is shared today.

Do you have any questions?
*[Facilitator to confirm that all individual consent to participate]*

### Questions for heads of households:

*(same as KII questions)*

**(Opening questions)**

1. Introduce yourself and describe how your house was affected by the earthquake.
2. What assistance, if any, did you receive from the government or any other organisations in rebuilding your house?

**Itbayat indigenous building practices**

3. Itbayat is known for traditional building practices for typhoon-proofing. Can you share the practices that you know and how they help against the impacts of typhoons?
4. How are these practices observed today? Are they still relevant?

**Post-earthquake reconstruction**

5. After the July 2019 earthquakes, households with previous stone-and-lime houses decided to build differently. Why is this so?
6. Currently, houses in the community are made of GI sheet walls, or semi-concrete/semi-lightweight, and entirely concrete. What made you decide to use a certain material in rebuilding their houses?
7. How did you secure labour/manpower in rebuilding their houses?
8. Were there guidelines or orders that you needed to follow in rebuilding their houses? If yes, please discuss them.
9. What were the resource limitations, if any, that affected the outcome of your rebuilt house? Please explain.

10. While your house now look different from the stone-and-lime dwelling, were the Itbayat traditional building practices considered during the housing reconstruction? Why or why not?

**Multi-hazard safety**

11. How do you think your present house will perform against earthquakes and typhoons?

**(Overall assessment)**

12. If you received any form of assistance from organisations, how did that assistance influence the outcome of your present house?
13. Between your past and present house, which do you like better? Why?
14. Given your current house, are there improvements you wish to introduce to strengthen it?

## Questions for village leaders, local builders, municipal employees, and council of elders:

**(Opening questions)**

1. Introduce yourself and your role in the community.

**Itbayat indigenous building practices**

2. Itbayat is known for traditional building practices for typhoon-proofing. Can you share the practices that you know and how they help against the impacts of typhoons?
3. How are these practices observed today? Are they still relevant?

**Post-earthquake reconstruction**

4. After the July 2019 earthquakes, households with previous stone-and-lime houses decided to build differently. Why is this so?
5. Currently, houses in the community are made of GI sheet walls, semi-concrete/semi-lightweight, and entirely concrete. What do you think made the households decide to use a certain material in rebuilding their houses?
6. How did households secure labour/manpower in rebuilding their houses?
7. Were there guidelines or orders that the households needed to follow in rebuilding their houses? If yes, please discuss them.
8. From your observations, what were the resource limitations, if any, that affected the outcome of their rebuilt houses? Please explain.
9. While houses now look different, were the Itbayat traditional building practices considered during the housing reconstruction? Why or why not?

**Multi-hazard safety**

10. How do you think the present houses in the community will perform against earthquakes and typhoons?

**(Overall assessment)**

11. As a/n *(insert role here)*, are there improvements in the present houses of households that you wish to introduce to strengthen them?

//end

# Appendix C

## Construction cost estimates and Pareto optimal solutions (Chapter 5)

Supplementary File

# Optimising housing typology distributions for multi-hazard loss reductions in resource-constrained settings

## 1 Construction cost estimates

In this study, the construction cost for the typologies includes both material and labour costs. To estimate the material costs, we assumed a one-story five-meter by seven-meter (5m X 7m) housing configuration having a floor to top-of-beam height of 2.70 m. These assumptions conform to the prevailing characteristics of the typologies surveyed (via rapid visual assessment) in January 2023. Whereby required details for the estimates were not documented due to the limitation of direct visual observations, standard construction details were applied to derive the estimates. For example, we used the standard rebar spacing for residential projects (i.e., 0.40 m both ways for slabs/flooring). Conventional construction procedures were also assumed, such as the use of 1:2:4 proportion for cement-sand-gravel mixture typical for residential projects in the Philippines. We referred to the construction estimate guidelines by Fajardo [1] which provide detailed procedures for estimating construction material quantities applicable to the Philippine context. For the material prices, these were sourced from hardware stores in Itbayat representative of the actual prevailing market prices as of March 2024.

Meanwhile, to derive the labour costs, we projected the construction duration for each typology using activity-on-node diagrams (see Figure S1 to S6) considering a labour workforce of three skilled and three unskilled workers. We then used the standard construction wage in Itbayat (as reported by some construction workers as of March 2024) to inform the total labour cost based on the estimated construction duration for each typology. The resulting bill of quantities based on material and labour costs are shown in Table S1 to S6.

Abbreviations and notations

| | |
|---|---|
| ” | inches |
| CGI | corrugated galvanised iron |
| FTB | footing tie beam |
| GI | galvanised iron |
| kg. | kilogram |
| pcs. | pieces |
| RC | reinforced concrete |

## *1.1 Activity-on-node diagrams*

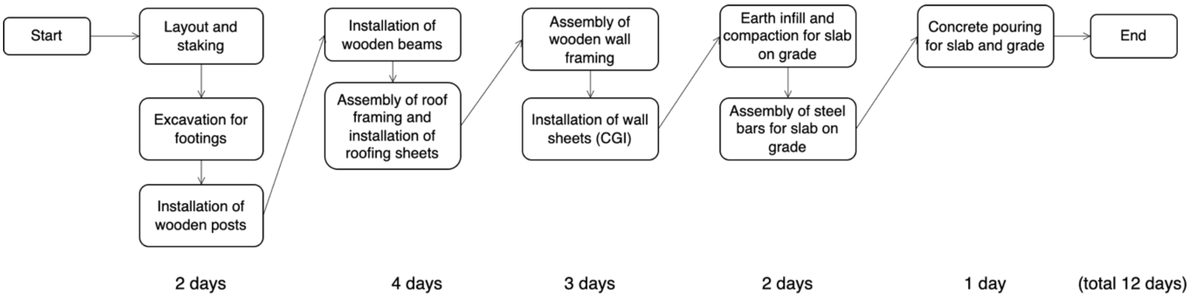


**Figure S1.** Activity-on-node diagram for LW-A.

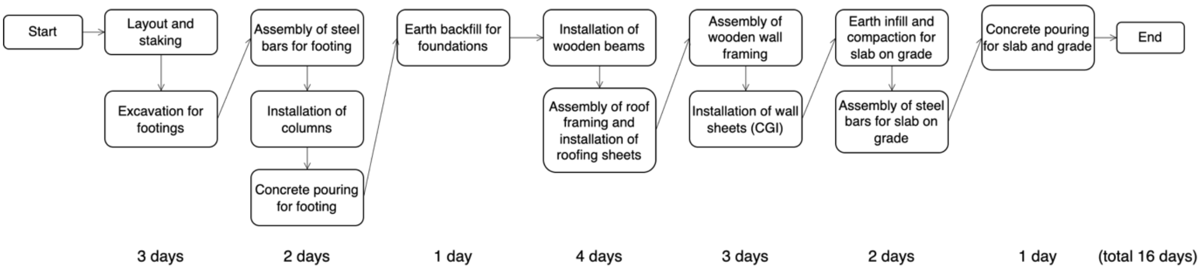


**Figure S2.** Activity-on-node diagram for LW-B.

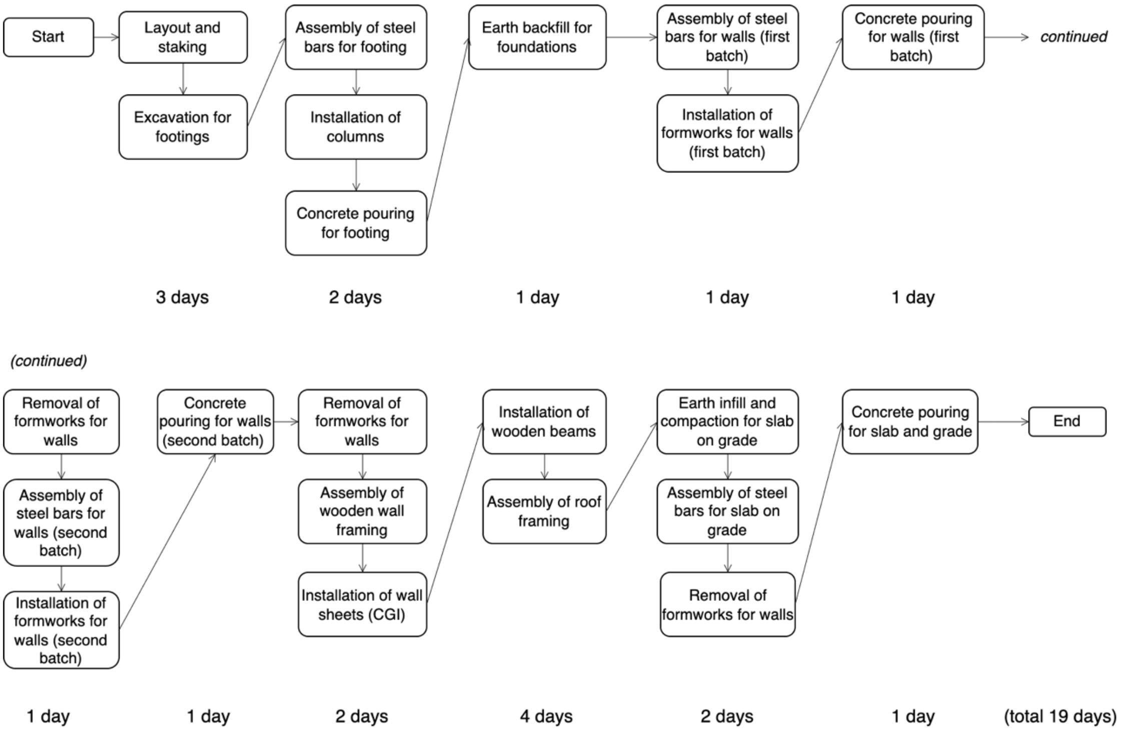


**Figure S3.** Activity-on-node diagram for SC-A.

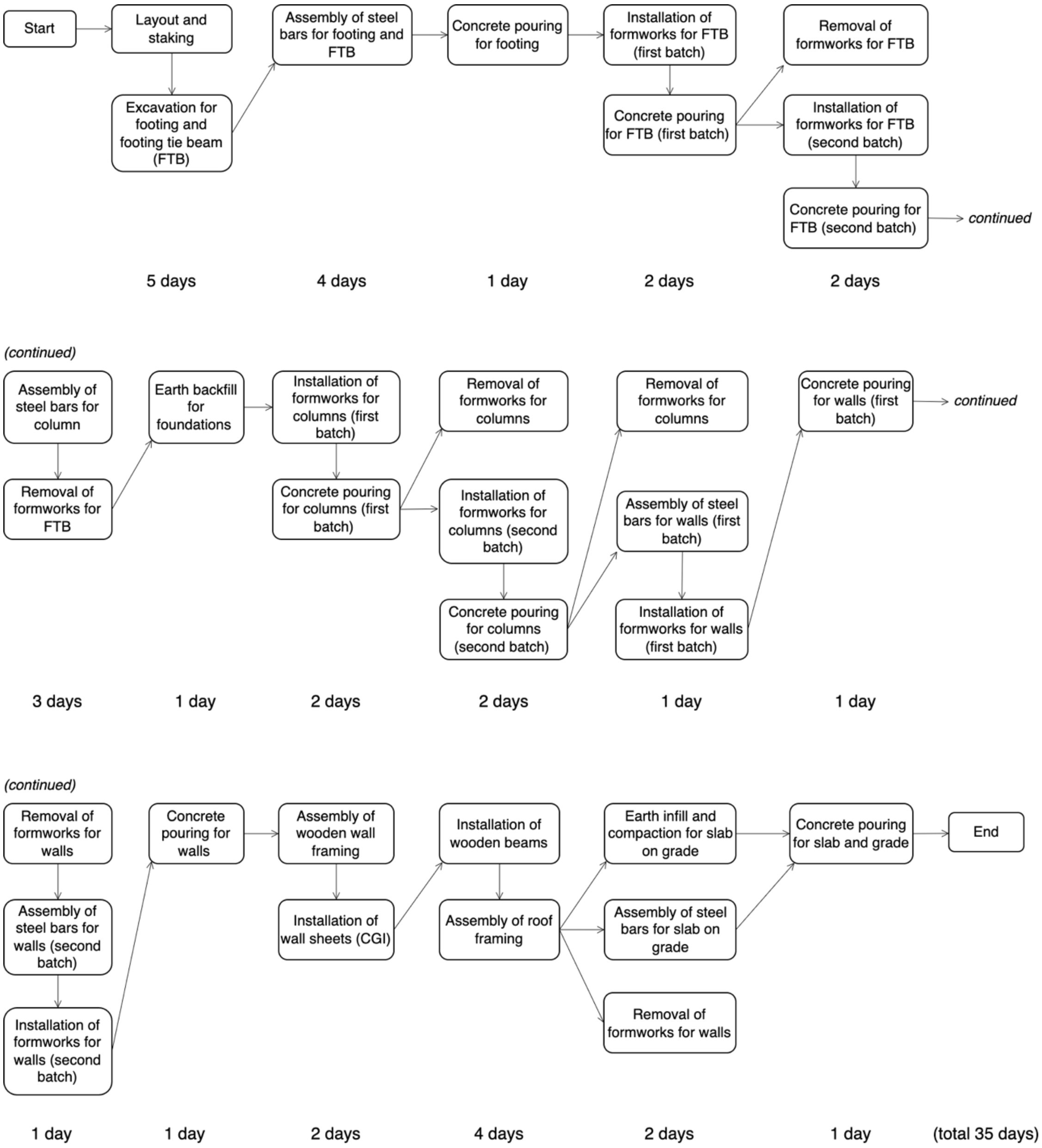


**Figure S4.** Activity-on-node diagram for SC-B.

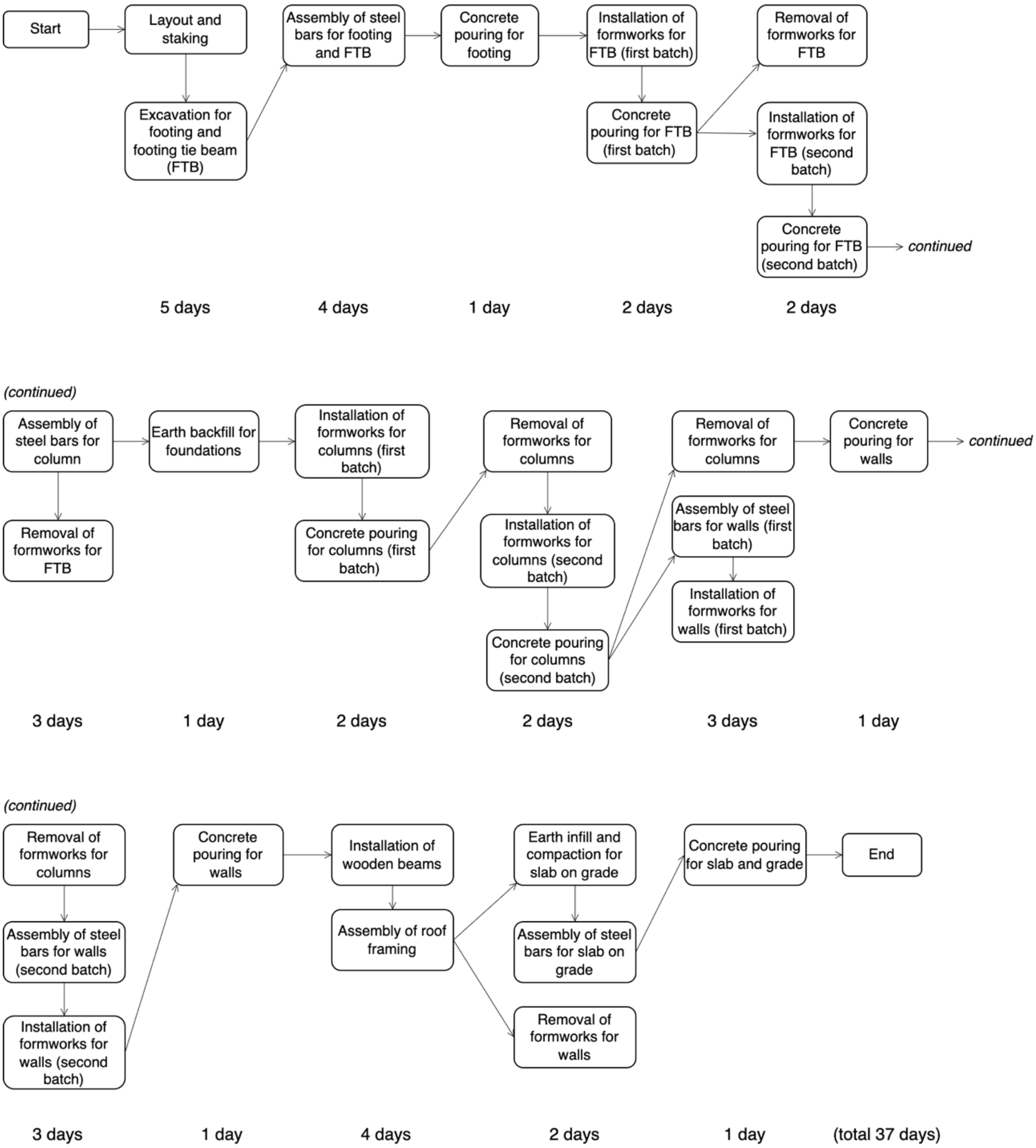


**Figure S5.** Activity-on-node diagram for RC-A.

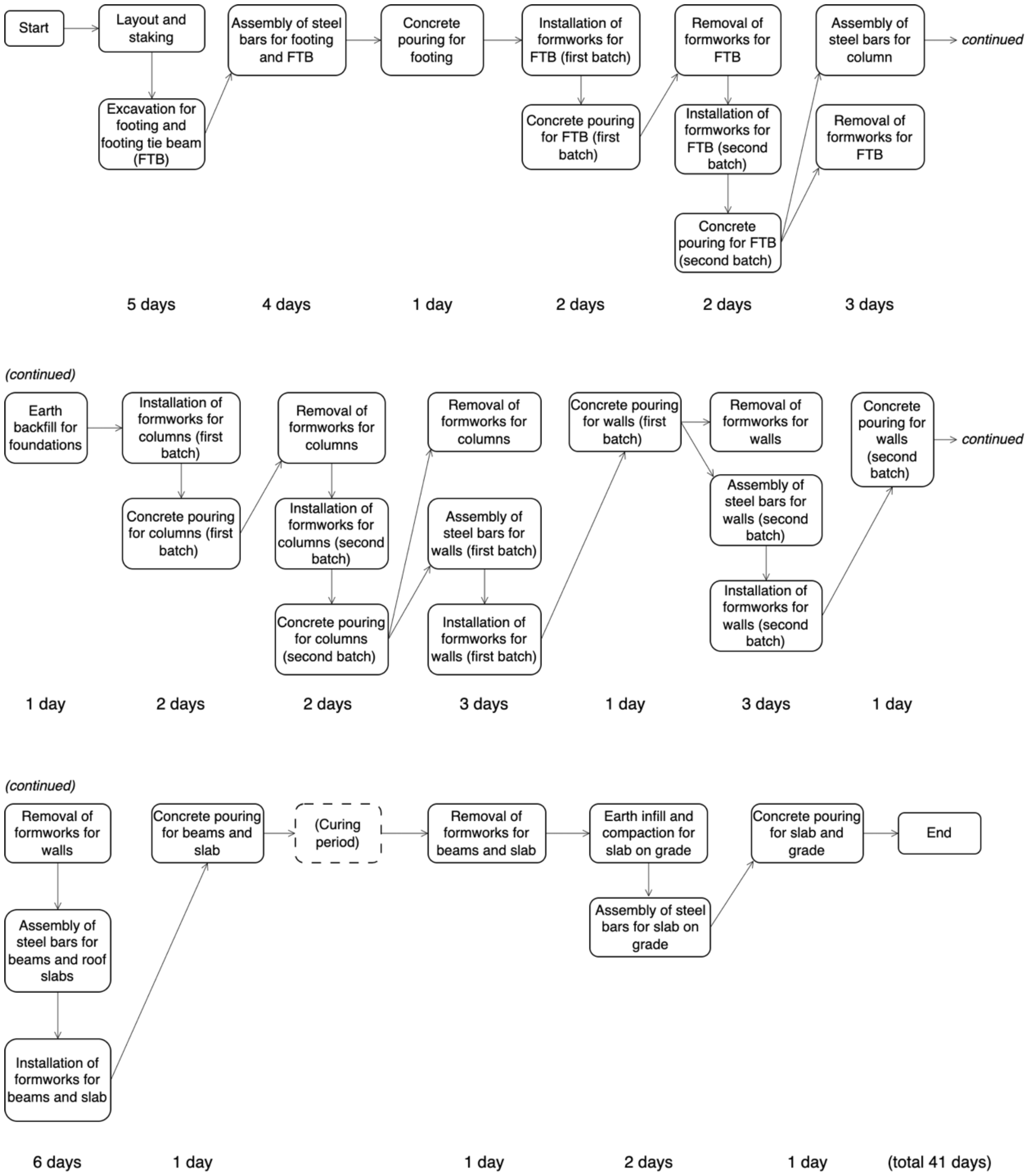


**Figure S6.** Activity-on-node diagram for RC-B.

## *1.2 Bill of quantities*

**Table S1.** Bill of quantities for LW-A (lightweight with wooden posts).

| **Construction cost estimates for LW-A (lightweight with wooden posts)** | | | | |
|---|---|---|---|---|
| *Summary* | | | | |
| Total cost (₱): | **294,255.00** | | | |
| Cost per square metre (₱): | **8,407.29** | | | |
| | | | | |
| **Detailed breakdown** | | | | |

|  | quantity | unit | unit price (₱) | total cost (₱) |
|---|---|---|---|---|
| **Lateral load-resisting system** |  |  |  |  |
| timber posts (4"X4") | 8 | pcs. | 810 | 6,480.00 |
| timber beams (2"X4") | 10 | pcs. | 550 | 5,500.00 |
| 5" common wire nail | 1 | kg. | 120 | 120.00 |
|  |  |  |  |  |
| **Roof framing** |  |  |  |  |
| timber rafter (2"X4") | 22 | pcs. | 550 | 12,100.00 |
| timber purlins (2"X2") | 33 | pcs. | 415 | 13,695.00 |
| fascia board (2"X6") | 9 | pcs. | 700 | 6,300.00 |
| 5" common wire nail | 10 | kg. | 120 | 1,200.00 |
|  |  |  |  |  |
| **Wall framing** |  |  |  |  |
| 2”X4” wood | 49 | pcs. | 550 | 26,950.00 |
| 5" common wire nail | 3.25 | kg. | 120 | 390.00 |
|  |  |  |  |  |
| **Wall envelope** |  |  |  |  |
| Gauge 24 CGI sheet (3 metres) | 36 | pcs. | 1,300 | 46,800.00 |
| 5" common wire nail | 17.75 | kg. | 120 | 2,130.00 |
|  |  |  |  |  |
| **Roof envelope** |  |  |  |  |
| Gauge 24 CGI sheet (3 metres) | 30 | pcs. | 1,300 | 39,000.00 |
| Plain GI | 3 | pcs. | 2,600 | 7,800.00 |
| 5" common wire nail | 14.75 | kg. | 120 | 1,770.00 |
|  |  |  |  |  |
| **Flooring** |  |  |  |  |
| 40 kgs. cement | 32 | bags | 550 | 17,600.00 |
| sand | 1.75 | cu.m. | 8,000 | 14,000.00 |
| 3/4" gravel | 3.5 | cu.m. | 7,000 | 24,500.00 |
| 10 mm diameter steel bars | 75 | pcs. | 280 | 21,000.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
|  |  |  |  |  |
| **Labour** |  |  |  |  |
| foreman | 12 | days | 700 | 8,400.00 |
| skilled | 12 | days | 700 | 8,400.00 |
| skilled | 12 | days | 700 | 8,400.00 |
| unskilled (helper) | 12 | days | 600 | 7,200.00 |
| unskilled (helper) | 12 | days | 600 | 7,200.00 |
| unskilled (helper) | 12 | days | 600 | 7,200.00 |
|  |  |  |  |  |
|  |  |  | **Grand total** | **294,255.00** |

**Table S2.** Bill of quantities for LW-B (lightweight with steel posts).

| **Construction cost estimates for LW-B (lightweight with steel posts)** | | | | |
|---|---|---|---|---|
| *Summary* | | | | |
| Total cost (₱): | **361,495.00** | | | |
| Cost per square metre (₱): | **10,328.43** | | | |
| | | | | |
| **Detailed breakdown** | | | | |
| | **quantity** | **unit** | **unit price (₱)** | **total cost (₱)** |
| **Lateral load-resisting system** | | | | |
| 5" diameter steel pipes | 4 | pcs. | 6,450 | 25,800.00 |
| timber beams (2"X4") | 10 | pcs. | 550 | 5,500.00 |
| 40 kgs. cement | 14 | bags | 550 | 7,700.00 |
| sand | 0.75 | cu.m. | 8,000 | 6,000.00 |
| 3/4" gravel | 1.5 | cu.m. | 7,000 | 10,500.00 |
| 16 mm diameter steel bars | 10 | pcs. | 800 | 8,000.00 |
| 5" common wire nail | 1 | kg. | 120 | 120.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
| | | | | |
| **Roof framing** | | | | |
| timber rafter (2”X4”) | 22 | pcs. | 550 | 12,100.00 |
| timber purlins (2”X2”) | 33 | pcs. | 415 | 13,695.00 |
| fascia board (2”X6”) | 9 | pcs. | 700 | 6,300.00 |
| 5" common wire nail | 10 | kg. | 120 | 1,200.00 |
| | | | | |
| **Wall framing** | | | | |
| 2”X4” wood | 49 | pcs. | 550 | 26,950.00 |
| 5" common wire nail | 3.25 | kg. | 120 | 390.00 |
| | | | | |
| **Wall envelope** | | | | |
| Gauge 24 CGI sheet (3 metres) | 36 | pcs. | 1,300 | 46,800.00 |
| 5" common wire nail | 17.75 | kg. | 120 | 2,130.00 |
| | | | | |
| **Roof envelope** | | | | |
| Gauge 24 CGI sheet (3 metres) | 30 | pcs. | 1,300 | 39,000.00 |
| Plain GI | 3 | pcs. | 2,600 | 7,800.00 |
| 5" common wire nail | 14.75 | kg. | 120 | 1,770.00 |
| | | | | |
| **Flooring** | | | | |
| 40 kgs. cement | 32 | bags | 550 | 17,600.00 |
| sand | 1.75 | cu.m. | 8,000 | 14,000.00 |

|  |  |  |  |  |
|---|---|---|---|---|
| 3/4" gravel | 3.5 | cu.m. | 7,000 | 24,500.00 |
| 10 mm diameter steel bars | 75 | pcs. | 280 | 21,000.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
|  |  |  |  |  |
| **Labour** |  |  |  |  |
| foreman | 16 | days | 700 | 11,200.00 |
| skilled | 16 | days | 700 | 11,200.00 |
| skilled | 16 | days | 700 | 11,200.00 |
| unskilled (helper) | 16 | days | 600 | 9,600.00 |
| unskilled (helper) | 16 | days | 600 | 9,600.00 |
| unskilled (helper) | 16 | days | 600 | 9,600.00 |
|  |  |  |  |  |
|  |  |  | **Grand total** | **361,495.00** |

**Table S3.** Bill of quantities for SC-A (semi-concrete with steel posts).

| **Construction cost estimates for SC-A (semi-concrete with steel posts)** |  |  |  |  |
|---|---|---|---|---|
| *Summary* |  |  |  |  |
| Total cost (₱): | **421,945.00** |  |  |  |
| Cost per square metre (₱): | **12,055.57** |  |  |  |
|  |  |  |  |  |
| **Detailed breakdown** |  |  |  |  |
|  | **quantity** | **unit** | **unit price (₱)** | **total cost (₱)** |
| **Lateral load-resisting system** |  |  |  |  |
| 5" diameter steel pipes | 4 | pcs. | 6,450 | 25,800.00 |
| timber beams (2”X4”) | 10 | pcs. | 550 | 5,500.00 |
| 40 kgs. cement | 14 | bags | 550 | 7,700.00 |
| sand | 0.75 | cu.m. | 8,000 | 6,000.00 |
| 3/4" gravel | 1.5 | cu.m. | 7,000 | 10,500.00 |
| 16 mm diameter steel bars | 10 | pcs. | 800 | 8,000.00 |
| 5" common wire nail | 1 | kg. | 120 | 120.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
|  |  |  |  |  |
| **Roof framing** |  |  |  |  |
| timber rafter (2”X4”) | 22 | pcs. | 550 | 12,100.00 |
| timber purlins (2”X2”) | 33 | pcs. | 415 | 13,695.00 |
| fascia board (2”X6”) | 9 | pcs. | 700 | 6,300.00 |
| 5" common wire nail | 10 | kg. | 120 | 1,200.00 |
|  |  |  |  |  |
| **Wall framing** |  |  |  |  |
| 2”X4” wood frame | 35 | pcs. | 550 | 19,250.00 |

| | | | | |
|---|---|---|---|---|
| 40 kgs. cement | 22 | bags | 550 | 12,100.00 |
| sand | 1.2 | cu.m. | 8,000 | 9,600.00 |
| 3/4" gravel | 2.4 | cu.m. | 7,000 | 16,800.00 |
| 10 mm diameter steel bars | 23 | pcs. | 280 | 6,440.00 |
| 5" common wire nail | 2.25 | kg. | 120 | 270.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
| | | | | |
| **Wall envelope** | | | | |
| Gauge 24 CGI sheet (3 metres) | 22 | pcs. | 1,300 | 28,600.00 |
| 5" common wire nail | 11 | kg. | 120 | 1,320.00 |
| | | | | |
| **Roof envelope** | | | | |
| Gauge 24 CGI sheet (3 metres) | 30 | pcs. | 1,300 | 39,000.00 |
| Plain GI | 3 | pcs. | 2,600 | 7,800.00 |
| 5" common wire nail | 14.75 | kg. | 120 | 1,770.00 |
| | | | | |
| **Flooring** | | | | |
| 40 kgs. cement | 32 | bags | 550 | 17,600.00 |
| sand | 1.75 | cu.m. | 8,000 | 14,000.00 |
| 3/4" gravel | 3.5 | cu.m. | 7,000 | 24,500.00 |
| 10 mm diameter steel bars | 75 | pcs. | 280 | 21,000.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
| | | | | |
| **Formworks** | | | | |
| 2" X 2" wood | 34 | pcs. | 415 | 14,110.00 |
| 1/2" fibre cement board | 9 | pcs. | 1,800 | 16,200.00 |
| 2" common wire nail | 2 | kg. | 105 | 210.00 |
| | | | | |
| **Labour** | | | | |
| foreman | 19 | days | 700 | 13,300.00 |
| skilled | 19 | days | 700 | 13,300.00 |
| skilled | 19 | days | 700 | 13,300.00 |
| unskilled (helper) | 19 | days | 600 | 11,400.00 |
| unskilled (helper) | 19 | days | 600 | 11,400.00 |
| unskilled (helper) | 19 | days | 600 | 11,400.00 |
| | | | | |
| | | | **Grand total** | **421,945.00** |

**Table S4**. Bill of quantities for SC-B (semi-concrete with RC posts).

| **Construction cost estimates for SC-B (semi-concrete with RC posts)** | | | | |
|---|---|---|---|---|
| *Summary* | | | | |
| Total cost (₱): | **627,755.00** | | | |
| Cost per square metre (₱): | **17,935.86** | | | |
| | | | | |
| **Detailed breakdown** | | | | |
| | **quantity** | **unit** | **unit price (₱)** | **total cost (₱)** |
| **Lateral load-resisting system** | | | | |
| timber beams (2”X4”) | 10 | pcs. | 550 | 5,500.00 |
| 40 kgs. cement | 48 | bags | 550 | 26,400.00 |
| sand | 2.61 | cu.m. | 8,000 | 20,880.00 |
| 3/4" gravel | 5.22 | cu.m. | 7,000 | 36,540.00 |
| 16 mm diameter steel bars | 62 | pcs. | 800 | 49,600.00 |
| 10 mm diameter steel bars | 57 | pcs. | 280 | 15,960.00 |
| 5" common wire nail | 1 | kg. | 120 | 120.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
| | | | | |
| **Roof framing** | | | | |
| timber rafter (2”X4”) | 22 | pcs. | 550 | 12,100.00 |
| timber purlins (2”X2”) | 33 | pcs. | 415 | 13,695.00 |
| fascia board (2”X6”) | 9 | pcs. | 700 | 6,300.00 |
| 5" common wire nail | 10 | kg. | 120 | 1,200.00 |
| | | | | |
| **Wall framing** | | | | |
| 2”X4” wood frame | 35 | pcs. | 550 | 19,250.00 |
| 40 kgs. cement | 22 | bags | 550 | 12,100.00 |
| sand | 1.2 | cu.m. | 8,000 | 9,600.00 |
| 3/4" gravel | 2.4 | cu.m. | 7,000 | 16,800.00 |
| 10 mm diameter steel bars | 23 | pcs. | 280 | 6,440.00 |
| 5" common wire nail | 2.25 | kg. | 120 | 270.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
| | | | | |
| **Wall envelope** | | | | |
| Gauge 24 CGI sheet (3 metres) | 22 | pcs. | 1,300 | 28,600.00 |
| 5" common wire nail | 11 | kg. | 120 | 1,320.00 |
| | | | | |
| **Roof envelope** | | | | |
| Gauge 24 CGI sheet (3 metres) | 30 | pcs. | 1,300 | 39,000.00 |
| Plain GI | 3 | pcs. | 2,600 | 7,800.00 |
| 5" common wire nail | 14.75 | kg. | 120 | 1,770.00 |

| | | | | |
|---|---|---|---|---|
| **Flooring** | | | | |
| 40 kgs. cement | 32 | bags | 550 | 17,600.00 |
| sand | 1.75 | cu.m. | 8,000 | 14,000.00 |
| 3/4" gravel | 3.5 | cu.m. | 7,000 | 24,500.00 |
| 10 mm diameter steel bars | 75 | pcs. | 280 | 21,000.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
| | | | | |
| **Formworks** | | | | |
| 2" X 2" wood | 116 | pcs. | 415 | 48,140.00 |
| 1/2" fibre cement board | 19 | pcs. | 1,800 | 34,200.00 |
| 2" common wire nail | 2 | kg. | 105 | 210.00 |
| | | | | |
| **Labour** | | | | |
| foreman | 35 | days | 700 | 24,500.00 |
| skilled | 35 | days | 700 | 24,500.00 |
| skilled | 35 | days | 700 | 24,500.00 |
| unskilled (helper) | 35 | days | 600 | 21,000.00 |
| unskilled (helper) | 35 | days | 600 | 21,000.00 |
| unskilled (helper) | 35 | days | 600 | 21,000.00 |
| | | | | |
| | | | **Grand total** | **627,755.00** |

**Table S5**. Bill of quantities for RC-A (reinforced concrete with lightweight roof).

| **Construction cost estimates for RC-A (reinforced concrete with lightweight roof)** | | | | |
|---|---|---|---|---|
| *Summary* | | | | |
| Total cost (₱): | **677,725.00** | | | |
| Cost per square metre (₱): | **19,363.57** | | | |
| | | | | |
| **Detailed breakdown** | | | | |
| | **quantity** | **unit** | **unit price (₱)** | **total cost (₱)** |
| **Lateral load-resisting system** | | | | |
| timber beams (2”X4”) | 10 | pcs. | 550 | 5,500.00 |
| 40 kgs. cement | 48 | bags | 550 | 26,400.00 |
| sand | 2.61 | cu.m. | 8,000 | 20,880.00 |
| 3/4" gravel | 5.22 | cu.m. | 7,000 | 36,540.00 |
| 16 mm diameter steel bars | 62 | pcs. | 800 | 49,600.00 |
| 10 mm diameter steel bars | 57 | pcs. | 280 | 15,960.00 |
| 5" common wire nail | 1 | kg. | 120 | 120.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |

| | | | | |
|---|---|---|---|---|
| **Roof framing** | | | | |
| timber rafter (2”X4”) | 22 | pcs. | 550 | 12,100.00 |
| timber purlins (2”X2”) | 33 | pcs. | 415 | 13,695.00 |
| fascia board (2”X6”) | 9 | pcs. | 700 | 6,300.00 |
| 5" common wire nail | 10 | kg. | 120 | 1,200.00 |
| | | | | |
| **Wall framing/envelope** | | | | |
| 40 kgs. cement | 52 | bags | 550 | 28,600.00 |
| sand | 2.84 | cu.m. | 8,000 | 22,720.00 |
| 3/4" gravel | 5.68 | cu.m. | 7,000 | 39,760.00 |
| 10 mm diameter steel bars | 49 | pcs. | 280 | 13,720.00 |
| GI tie wire | 2 | kg. | 120 | 240.00 |
| | | | | |
| **Roof envelope** | | | | |
| Gauge 24 CGI sheet (3 metres) | 30 | pcs. | 1,300 | 39,000.00 |
| Plain GI | 3 | pcs. | 2,600 | 7,800.00 |
| 5" common wire nail | 14.75 | kg. | 120 | 1,770.00 |
| | | | | |
| **Flooring** | | | | |
| 40 kgs. cement | 32 | bags | 550 | 17,600.00 |
| sand | 1.75 | cu.m. | 8,000 | 14,000.00 |
| 3/4" gravel | 3.5 | cu.m. | 7,000 | 24,500.00 |
| 10 mm diameter steel bars | 75 | pcs. | 280 | 21,000.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
| | | | | |
| **Formworks** | | | | |
| 2" X 2" wood | 144 | pcs. | 415 | 59,760.00 |
| 1/2" fibre cement board | 30 | pcs. | 1,800 | 54,000.00 |
| 2" common wire nail | 4 | kg. | 105 | 420.00 |
| | | | | |
| **Labour** | | | | |
| foreman | 37 | days | 700 | 25,900.00 |
| skilled | 37 | days | 700 | 25,900.00 |
| skilled | 37 | days | 700 | 25,900.00 |
| unskilled (helper) | 37 | days | 600 | 22,200.00 |
| unskilled (helper) | 37 | days | 600 | 22,200.00 |
| unskilled (helper) | 37 | days | 600 | 22,200.00 |
| | | | | |
| | | | **Grand total** | **677,725.00** |

**Table S6**. Bill of quantities for RC-B (reinforced concrete with slab roof).

| **Construction cost estimates for RC-B (reinforced concrete with slab roof)** | | | | |
|---|---|---|---|---|
| *Summary* | | | | |
| Total cost (₱): | **881,395.00** | | | |
| Cost per square metre (₱): | **25,182.71** | | | |
| | | | | |
| **Detailed breakdown** | | | | |
| | **quantity** | **unit** | **unit price (₱)** | **total cost (₱)** |
| **Lateral load-resisting system** | | | | |
| 40 kgs. cement | 64 | bags | 550 | 35,200.00 |
| sand | 3.48 | cu.m. | 8,000 | 27,840.00 |
| 3/4" gravel | 6.96 | cu.m. | 7,000 | 48,720.00 |
| 16 mm diameter steel bars | 90 | pcs. | 800 | 72,000.00 |
| 10 mm diameter steel bars | 87 | pcs. | 280 | 24,360.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
| | | | | |
| **Roof framing/envelope** | | | | |
| 40 kgs. cement | 57 | bags | 550 | 31,350.00 |
| sand | 3.15 | cu.m. | 8,000 | 25,200.00 |
| 3/4" gravel | 6.3 | cu.m. | 7,000 | 44,100.00 |
| 10 mm diameter steel bars | 78 | pcs. | 280 | 21,840.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
| | | | | |
| **Wall framing/envelope** | | | | |
| 40 kgs. cement | 46 | bags | 550 | 25,300.00 |
| sand | 2.52 | cu.m. | 8,000 | 20,160.00 |
| 3/4" gravel | 5.04 | cu.m. | 7,000 | 35,280.00 |
| 10 mm diameter steel bars | 43 | pcs. | 280 | 12,040.00 |
| GI tie wire | 2 | kg. | 120 | 240.00 |
| | | | | |
| **Flooring** | | | | |
| 40 kgs. cement | 32 | bags | 550 | 17,600.00 |
| sand | 1.75 | cu.m. | 8,000 | 14,000.00 |
| 3/4" gravel | 3.5 | cu.m. | 7,000 | 24,500.00 |
| 10 mm diameter steel bars | 75 | pcs. | 280 | 21,000.00 |
| GI tie wire | 1 | kg. | 120 | 120.00 |
| | | | | |
| **Formworks** | | | | |
| 2" X 2" wood | 265 | pcs. | 415 | 109,975.00 |
| 1/2" fibre cement board | 61 | pcs. | 1,800 | 109,800.00 |
| 2" common wire nail | 6 | kg. | 105 | 630.00 |

| | | | | |
|---|---|---|---|---|
| | | | | |
| **Labour** | | | | |
| foreman | 41 | days | 700 | 28,700.00 |
| skilled | 41 | days | 700 | 28,700.00 |
| skilled | 41 | days | 700 | 28,700.00 |
| unskilled (helper) | 41 | days | 600 | 24,600.00 |
| unskilled (helper) | 41 | days | 600 | 24,600.00 |
| unskilled (helper) | 41 | days | 600 | 24,600.00 |
| | | | | |
| | | | **Grand total** | **881,395.00** |

## 2 Pareto optimal solutions

**Table S7**. Pareto optimal solutions for Case 1 (PEIS VII & 270 km/h).

| Scenario # | Direct economic losses (in PHP) | | Scores for Pareto optimal ranking | | | Building stock distribution | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | PEIS VII | 270 km/h | PEIS VII | 270 km/h | Composite score | LWA | LWB | SCA | SCB | RCA | RCB |
| 11628 | 330,643,889 | 194,809,277 | 0.005673246 | 0.02700054 | 0.032673786 | 5% | 5% | 5% | 5% | 5% | 75% |
| 15 | 161,719,217 | 385,296,870 | 0.02700054 | 0.005673246 | 0.032673786 | 5% | 75% | 5% | 5% | 5% | 5% |
| 11623 | 319,468,398 | 205,180,265 | 0.005691644 | 0.01800036 | 0.023692004 | 10% | 5% | 5% | 5% | 5% | 70% |
| 14 | 162,130,218 | 382,028,657 | 0.01800036 | 0.005691644 | 0.023692004 | 10% | 70% | 5% | 5% | 5% | 5% |
| 11624 | 318,852,908 | 208,356,401 | 0.005710453 | 0.014727567 | 0.02043802 | 5% | 10% | 5% | 5% | 5% | 70% |
| 13 | 162,723,840 | 378,799,591 | 0.014727567 | 0.005710453 | 0.02043802 | 15% | 65% | 5% | 5% | 5% | 5% |
| 11608 | 308,051,879 | 216,001,788 | 0.005729688 | 0.012960259 | 0.018689947 | 15% | 5% | 5% | 5% | 5% | 65% |
| 12 | 163,333,090 | 375,785,701 | 0.012960259 | 0.005729688 | 0.018689947 | 20% | 60% | 5% | 5% | 5% | 5% |
| 11609 | 307,468,066 | 219,223,797 | 0.005749366 | 0.011825054 | 0.01757442 | 10% | 10% | 5% | 5% | 5% | 65% |
| 11 | 163,957,401 | 372,703,382 | 0.011825054 | 0.005749366 | 0.01757442 | 25% | 55% | 5% | 5% | 5% | 5% |
| 11610 | 306,868,700 | 222,332,970 | 0.005769506 | 0.011020629 | 0.016790135 | 5% | 15% | 5% | 5% | 5% | 65% |
| 10 | 164,672,020 | 369,770,738 | 0.011020629 | 0.005769506 | 0.016790135 | 30% | 50% | 5% | 5% | 5% | 5% |
| 11573 | 296,565,843 | 226,277,475 | 0.005790127 | 0.010413431 | 0.016203558 | 20% | 5% | 5% | 5% | 5% | 60% |
| 9 | 165,104,516 | 366,513,292 | 0.010413431 | 0.005790127 | 0.016203558 | 35% | 45% | 5% | 5% | 5% | 5% |
| 11574 | 295,778,659 | 229,245,878 | 0.005811249 | 0.009934496 | 0.015745744 | 15% | 10% | 5% | 5% | 5% | 60% |
| 8 | 165,873,869 | 363,660,877 | 0.009934496 | 0.005811249 | 0.015745744 | 40% | 40% | 5% | 5% | 5% | 5% |
| 7 | 166,292,994 | 360,397,559 | 0.009544306 | 0.005832893 | 0.0153772 | 45% | 35% | 5% | 5% | 5% | 5% |
| 11575 | 295,182,952 | 232,435,456 | 0.005832893 | 0.009544306 | 0.0153772 | 10% | 15% | 5% | 5% | 5% | 60% |
| 6 | 167,038,511 | 357,491,529 | 0.009218448 | 0.005855084 | 0.015073531 | 50% | 30% | 5% | 5% | 5% | 5% |
| 11576 | 294,796,288 | 235,696,945 | 0.005855084 | 0.009218448 | 0.015073531 | 5% | 20% | 5% | 5% | 5% | 60% |
| 5 | 167,472,726 | 354,198,684 | 0.008940939 | 0.005877845 | 0.014818784 | 55% | 25% | 5% | 5% | 5% | 5% |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11503 | 285,064,184 | 236,938,396 | 0.005877845 | 0.008940939 | 0.014818784 | 25% | 5% | 5% | 5% | 5% | 55% |
| 4 | 168,071,741 | 351,051,812 | 0.00870084 | 0.005901202 | 0.014602042 | 60% | 20% | 5% | 5% | 5% | 5% |
| 11504 | 284,437,175 | 240,075,052 | 0.005901202 | 0.00870084 | 0.014602042 | 20% | 10% | 5% | 5% | 5% | 55% |
| 3 | 168,668,524 | 348,016,025 | 0.008490379 | 0.005925184 | 0.014415562 | 65% | 15% | 5% | 5% | 5% | 5% |
| 11505 | 283,745,624 | 242,936,879 | 0.005925184 | 0.008490379 | 0.014415562 | 15% | 15% | 5% | 5% | 5% | 55% |
| 2 | 169,246,530 | 344,963,082 | 0.008303867 | 0.005949819 | 0.014253686 | 70% | 10% | 5% | 5% | 5% | 5% |
| 11506 | 283,288,837 | 246,252,129 | 0.005949819 | 0.008303867 | 0.014253686 | 10% | 20% | 5% | 5% | 5% | 55% |
| 1 | 169,982,214 | 342,009,468 | 0.008137033 | 0.00597514 | 0.014112173 | 75% | 5% | 5% | 5% | 5% | 5% |
| 11377 | 273,557,925 | 247,624,032 | 0.00597514 | 0.008137033 | 0.014112173 | 30% | 5% | 5% | 5% | 5% | 50% |
| 3064 | 179,706,197 | 340,867,610 | 0.007986603 | 0.00600118 | 0.013987783 | 55% | 20% | 5% | 5% | 5% | 10% |
| 11378 | 272,918,403 | 250,754,293 | 0.00600118 | 0.007986603 | 0.013987783 | 25% | 10% | 5% | 5% | 5% | 50% |
| 3063 | 180,168,810 | 337,549,713 | 0.007850015 | 0.006027976 | 0.013877991 | 60% | 15% | 5% | 5% | 5% | 10% |
| 11379 | 272,320,370 | 253,891,151 | 0.006027976 | 0.007850015 | 0.013877991 | 20% | 15% | 5% | 5% | 5% | 50% |
| 3062 | 180,863,829 | 334,652,767 | 0.007725238 | 0.006055566 | 0.013780803 | 65% | 10% | 5% | 5% | 5% | 10% |
| 11380 | 271,751,401 | 256,979,382 | 0.006055566 | 0.007725238 | 0.013780803 | 15% | 20% | 5% | 5% | 5% | 50% |
| 3061 | 181,453,337 | 331,501,319 | 0.007610632 | 0.006083993 | 0.013694625 | 70% | 5% | 5% | 5% | 5% | 10% |
| 11167 | 262,352,399 | 257,953,971 | 0.006083993 | 0.007610632 | 0.013694625 | 35% | 5% | 5% | 5% | 5% | 45% |
| 5444 | 191,440,238 | 330,220,789 | 0.007504862 | 0.006113301 | 0.013618163 | 50% | 20% | 5% | 5% | 5% | 15% |
| 11168 | 261,755,450 | 261,129,624 | 0.006113301 | 0.007504862 | 0.013618163 | 30% | 10% | 5% | 5% | 5% | 45% |
| 5443 | 191,882,978 | 326,940,752 | 0.007406827 | 0.00614354 | 0.013550367 | 55% | 15% | 5% | 5% | 5% | 15% |
| 11169 | 260,995,447 | 264,039,989 | 0.00614354 | 0.007406827 | 0.013550367 | 25% | 15% | 5% | 5% | 5% | 45% |
| 5442 | 192,461,239 | 323,821,432 | 0.007315607 | 0.006174762 | 0.013490369 | 60% | 10% | 5% | 5% | 5% | 15% |
| 11170 | 260,598,584 | 267,304,627 | 0.006174762 | 0.007315607 | 0.013490369 | 20% | 20% | 5% | 5% | 5% | 45% |
| 5441 | 193,225,689 | 320,931,695 | 0.007230432 | 0.006207023 | 0.013437454 | 65% | 5% | 5% | 5% | 5% | 15% |
| 10837 | 250,697,562 | 268,818,308 | 0.006207023 | 0.007230432 | 0.013437454 | 40% | 5% | 5% | 5% | 5% | 40% |
| 7264 | 202,962,510 | 319,945,851 | 0.007150646 | 0.006240385 | 0.013391031 | 45% | 20% | 5% | 5% | 5% | 20% |
| 10838 | 250,060,355 | 271,930,672 | 0.006240385 | 0.007150646 | 0.013391031 | 35% | 10% | 5% | 5% | 5% | 40% |
| 7263 | 203,536,208 | 316,856,009 | 0.007075691 | 0.006274915 | 0.013350606 | 50% | 15% | 5% | 5% | 5% | 20% |
| 10839 | 249,495,353 | 275,091,799 | 0.006274915 | 0.007075691 | 0.013350606 | 30% | 15% | 5% | 5% | 5% | 40% |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7262 | 204,124,781 | 313,836,584 | 0.007005086 | 0.006310686 | 0.013315771 | 55% | 10% | 5% | 5% | 5% | 20% |
| 10840 | 248,900,698 | 278,175,787 | 0.006310686 | 0.007005086 | 0.013315771 | 25% | 20% | 5% | 5% | 5% | 40% |
| 7261 | 204,701,301 | 310,576,712 | 0.006938415 | 0.006347776 | 0.013286191 | 60% | 5% | 5% | 5% | 5% | 20% |
| 10342 | 239,430,991 | 279,231,186 | 0.006347776 | 0.006938415 | 0.013286191 | 45% | 5% | 5% | 5% | 5% | 35% |
| 8629 | 214,536,724 | 309,266,738 | 0.006875316 | 0.006386274 | 0.013261589 | 40% | 20% | 5% | 5% | 5% | 25% |
| 10343 | 238,842,242 | 282,281,368 | 0.006386274 | 0.006875316 | 0.013261589 | 40% | 10% | 5% | 5% | 5% | 35% |
| 8628 | 214,929,525 | 306,087,444 | 0.006815472 | 0.006426273 | 0.013241745 | 45% | 15% | 5% | 5% | 5% | 25% |
| 10344 | 238,113,201 | 285,296,294 | 0.006426273 | 0.006815472 | 0.013241745 | 35% | 15% | 5% | 5% | 5% | 35% |
| 8627 | 215,726,723 | 303,119,163 | 0.006758605 | 0.006467878 | 0.013226483 | 50% | 10% | 5% | 5% | 5% | 25% |
| 10345 | 237,651,045 | 288,516,143 | 0.006467878 | 0.006758605 | 0.013226483 | 30% | 20% | 5% | 5% | 5% | 35% |
| 8626 | 216,299,312 | 300,007,584 | 0.006704469 | 0.006511204 | 0.013215673 | 55% | 5% | 5% | 5% | 5% | 25% |
| 9627 | 227,719,722 | 289,836,563 | 0.006511204 | 0.006704469 | 0.013215673 | 50% | 5% | 5% | 5% | 5% | 30% |
| 9628 | 227,081,804 | 292,913,126 | 0.006556378 | 0.006652845 | 0.013209223 | 45% | 10% | 5% | 5% | 5% | 30% |
| 9630 | 225,900,540 | 299,076,682 | 0.006652845 | 0.006556378 | 0.013209223 | 35% | 20% | 5% | 5% | 5% | 30% |
| 9629 | 226,479,311 | 296,019,937 | 0.006603539 | 0.006603539 | 0.013207079 | 40% | 15% | 5% | 5% | 5% | 30% |

**Table S8**. Pareto optimal solutions for Case 2 (PEIS VIII & 300 km/h).

| Scenario # | Direct economic loss (in PHP) | | Scores for Pareto optimal ranking | | | Building stock distribution | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **PEIS VIII** | **300 km/h** | **PEIS VIII** | **300 km/h** | **Composite score** | **LWA** | **LWB** | **SCA** | **SCB** | **RCA** | **RCB** |
| 11628 | 629,185,361 | 331,094,944 | 0.022957675 | 0.076178823 | 0.099136498 | 5% | 5% | 5% | 5% | 5% | 75% |
| 1 | 310,680,271 | 403,105,449 | 0.076178823 | 0.022957675 | 0.099136498 | 75% | 5% | 5% | 5% | 5% | 5% |
| 11623 | 606,842,199 | 336,037,316 | 0.023428376 | 0.050785882 | 0.074214258 | 10% | 5% | 5% | 5% | 5% | 70% |
| 3061 | 333,613,205 | 397,793,439 | 0.050785882 | 0.023428376 | 0.074214258 | 70% | 5% | 5% | 5% | 5% | 10% |
| 11608 | 584,101,527 | 341,513,574 | 0.023954597 | 0.041552085 | 0.065506683 | 15% | 5% | 5% | 5% | 5% | 65% |
| 5441 | 356,828,476 | 392,520,890 | 0.041552085 | 0.023954597 | 0.065506683 | 65% | 5% | 5% | 5% | 5% | 15% |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11573 | 561,560,277 | 346,509,750 | 0.024548389 | 0.036565835 | 0.061114224 | 20% | 5% | 5% | 5% | 5% | 60% |
| 7261 | 379,581,182 | 387,564,025 | 0.036565835 | 0.024548389 | 0.061114224 | 60% | 5% | 5% | 5% | 5% | 20% |
| 11503 | 538,837,184 | 351,494,598 | 0.0252258 | 0.033362988 | 0.058588789 | 25% | 5% | 5% | 5% | 5% | 55% |
| 8626 | 402,568,525 | 382,454,594 | 0.033362988 | 0.0252258 | 0.058588789 | 55% | 5% | 5% | 5% | 5% | 25% |
| 9627 | 425,172,974 | 377,485,899 | 0.031093397 | 0.026008757 | 0.057102154 | 50% | 5% | 5% | 5% | 5% | 30% |
| 11377 | 515,893,516 | 356,979,231 | 0.026008757 | 0.031093397 | 0.057102154 | 30% | 5% | 5% | 5% | 5% | 50% |
| 10342 | 448,141,503 | 372,270,392 | 0.029380262 | 0.026928129 | 0.056308392 | 45% | 5% | 5% | 5% | 5% | 35% |
| 11167 | 493,479,698 | 361,862,506 | 0.026928129 | 0.029380262 | 0.056308392 | 35% | 5% | 5% | 5% | 5% | 45% |
| 10837 | 470,679,801 | 367,346,345 | 0.028029002 | 0.028029002 | 0.056058004 | 40% | 5% | 5% | 5% | 5% | 40% |

# 3 References

[1] M. Fajardo, Jr., *Simplified Construction Estimate*, 2000 Edition. 2000.