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DEVELOPMENT AND VERIFICATION OF THE JAVA EXPOSURE MODEL FOR USE IN PSRA

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Abstract: *The island of Java in Indonesia is the most populated island in the world, with over 150 million residents. Java is located in a complex tectonic setting and frequently experiences damaging earthquakes. In Java, many buildings are non-engineered and built with limited or no seismic design provisions. This has led to poor quality construction and materials being used, particularly in residential houses, with the housing sector often sustaining the highest economic losses in Indonesia. Despite this high hazard, high exposure, and high vulnerability there is limited seismic risk information available for Java. This is in part due to poor data availability to develop exposure and vulnerability models to verify them. This study has focussed on developing a village scale exposure model for Java from multiple sources and understanding the uncertainty in this process. This new exposure model harmonises multiple eras of census data, government reports, the Global Human Settlement building height model, OpenStreetMap, post-disaster surveys and other published literature to develop an exposure model that includes residential, commercial, and industrial buildings, and schools. The model shows spatial variation in the seismic resilience of buildings based on the relative wealth, region (rural, urban or city) and population density. Model performance was then assessed through scenario damage analysis of several recent earthquakes in Java.*

A reliable exposure model is a critical input to a Probabilistic Seismic Risk Assessment (PSRA) that would help Indonesia mitigate the threat earthquakes pose to communities and infrastructure. However, the scenario damage analyses highlighted two key issues that must be addressed before conducting a PSRA. Firstly, it identified that the ground motion models used in recent Indonesia PSHAs do not accurately represent the ground motion, particularly in areas with active volcanism. Secondly it identified that the performance of the exposure model varies across Java, but the reason for this variation is difficult to elucidate without a better understanding of the uncertainty in the exposure model. To assess this uncertainty, a suite of alternate mapping schema was developed for the exposure model. The result of this study is a detailed fine scale exposure model with uncertainty that can be used as an input for PSRA to support decision making in Java, Indonesia.

1 Introduction

Indonesia is one of the most seismically active countries in the world and has experienced many damaging earthquakes in the past. The island of Java is the most populous island in Indonesia, with a population of over 150 million people and a population density of up to 15 900 people/km^2 in Jakarta (BPS, n.d.). The megacity of Jakarta is in Java and there are around 30 million people in the greater metropolitan area of Jakarta alone. Despite the high population and the known high seismic hazard, little is known about the seismic risk in Java, or elsewhere in Indonesia. One of the limiting factors in the development of risk models and analyses in Java is the absence of a detailed exposure model. There are a few studies which have developed exposure models for small locations (Aulady and Fujimi, 2019; Lambang-Goro *et al.*, 2022) or as part of a global model (Silva *et al.*, 2020), but there are no studies that consider all of Java in detail, and no studies which attempt to validate the exposure model or address the uncertainty in the model. Therefore, this study focuses on developing a *desa* (village) scale exposure model for Java including residential, commercial, industrial buildings, schools, and hospitals. The uncertainty in the input datasets is discussed, the exposure model is validated using historical events, and alternate mapping schema are developed to account for the uncertainty in the exposure model. The resulting model can support future seismic risk assessments and scenario damage assessments for Java.

1.1 Background

Buildings in Indonesia are often described as being of poor quality or not seismically resilient (e.g., Pribadi et al., 2022). In past events it has been observed that there was more damage than expected given the intensity of ground shaking experienced (Bappenas, 2006; BNBP, 2009). This has been attributed to several factors: the prevalence of non-engineered buildings particularly in residential buildings, the use of poor quality materials in construction, and the apparent poor enforcement of the building code (Boen, 2006; Boen and Pribadi, 2007; Idham *et al*., 2010; Pribadi *et al.*, 2021). Whilst these factors are well known and have been confirmed through multiple post disaster damage surveys across the archipelago (e.g., EERI, 2009, 2007, 2006), very limited efforts have been put into understanding the exposure in Indonesia. This is an issue that has been highlighted by Pribadi et al. (2021) who states that lessons have not been learnt from previous events and construction practices have not improved. Given the high hazard in Java and the known poor quality of the building stock, it is important to understand the seismic risk to inform disaster management and policy development.

The next logical step is to develop an exposure model, but like many other countries exposure data is not readily available in Indonesia (Silva *et al.*, 2020, Yepes-Estrada *et al.*, 2023). In locations without exposure data secondary data sources, such as census and land use data, are commonly relied on for exposure model development (Yepes-Estrada *et al.*, 2017). In Indonesia, secondary data sources can also be difficult to access. There are often issues with data access, or language barriers for non-Bahasa speakers. Many sources of information are online pdf documents which need to be digitised, and data availability is not consistent across Java. There are other sources of data that can be accessed for Indonesia including: OpenStreetMap (OSM, n.d.), which has extensive coverage in key cities in Java; various Global Human Settlement Layer (Schiavina *et al.*, 2022) datasets, data from the Council of Tall Buildings and Urban Habitat (CTBUH, 2023) and real estate websites. There are also frequent smaller household surveys (SUSENAS) conducted in Indonesia (e.g., BPS, 2013), which have additional data on building material, but are not freely accessible. For non-residential buildings there are various Government of Indonesia (GoI) websites which have data on the number and location of buildings, but coverage and quality is not uniform. These challenges are formidable and have largely stymied attempts to integrate this data to develop detailed exposure data for Java or elsewhere in Indonesia.

The most comprehensive exposure data for Indonesia is that in the recently updated global exposure model (Yepes-Estrada *et al.*, 2023). This model has been developed as part of a global scale model and is not intended to support sub national decision making or policy development. At the other end of the spectrum, a very detailed model has been developed for West Jakarta by Lambang-Goro et al. (2022) utilising building data that is only available for Jakarta. This model is suitable for fine grain decision making and is not possible to develop for a larger area without extension of the underlying dataset by the Indonesian Government. Others have developed small scale exposure models to support various vulnerability studies using combinations of census data, household survey data and field data (Saputra *et al.*, 2017; Aulady and Fujimi, 2019). These studies cover very small areas and can be used to provide information on the types of buildings present, but not substantive data that can be integrated into an exposure model. Thus, there is a need for more detailed exposure information that can be developed consistently across a large area of Indonesia, such as Java, which can support sub-national decision making and policy development.

2 Exposure model development

The exposure model in this study has been developed at the desa scale, the smallest administrative division with population of household data. The model has been developed through the integration of several decades of census data, as well as other secondary sources. Due to data limitations the model does not include government buildings, religious buildings, universities, monuments, or sporting venues. The exposure model includes night and day occupancy of buildings, structural value, and mapping to fragility functions. Socioeconomic data has been used to inform the selection of fragility functions for buildings across the island, as it is often highlighted that buildings in Indonesia have poor seismic performance and it is the poorer population which is least likely to afford seismically resilient buildings (BNBP, 2009). The data available differs for each type of building and thus the method and resulting model for category of buildings considered in this study is shown in the following sections.

2.1 Residential buildings

Residential buildings comprise the majority of the of the building stock in Java. Residential buildings include houses, apartments (low-rise, tower developments, skyscrapers) and group accommodation (institutions, boarding schools, military, and other barracks). We have integrated the data from multiple decades of census data, household surveys, Government of Indonesia (GoI) reports, and open-source data to generate the residential component of the exposure model. Table 1 shows a summary of the parameters in the exposure model and the data used to determine these parameters.

Table 1. Input datasets for parameters in the exposure model.

Parameter	Data Sources	References
Age	1980 Census, 1990 Census, 2000 Census, 2010 Census, 2020 Census	IPUMS (2021a, b, c), BPS (2010a, 2020)
Height and Floors	Susenas 2010, CTBUH database, GHSL building heights dataset, GoI reports	BPS (2010b), CTBUH (https://www.ctbuh.org/), (Schiavina *et al.*, 2022), Perumnas (2007, 2008, 2009, 2010)
Construction Materials	Susenas 2010 (we assume all construction post 2010 is masonry)	BPS (2010b)
Occupancy	2010 Census, real estate websites, GoI reports	BPS (2010a), rumah.com, floqk.com, Perumnas (2007,2008,2009,2010)
Structural Value	Construction handbook 2019, literature, post-disaster reports	Arcadis Indonesia (2019), Lambang-Goro et al. (2022), Aulady and Fujimi (2019), BNPB (2009), BAPPENAS (2006)
Floor Area	2010 Census, 2020 Census	BPS (2010a), BPS (2020)
Building Type	Peer-reviewed literature, post-disaster surveys, GoI reports	EERI (2009a, 2009b, 2007, 2006) BNPB (2009), BAPPENAS (2006) (Boen, 2006; Sengara *et al.*, 2010; Teguh, 2014; Saputra *et al.*, 2017; Idham *et al.*, 2018; Aulady and Fujimi, 2019)
Location	Census 2010, Census 2020	BPS (2010a) BPS (2020)
Number of Buildings	Census 2010, Census 2020, OSM, satellite imagery	BPS (2010a), BPS (2020), the OpenStreetMap Community(https://www.openstreetmap.org), Google Earth
Setting (urban/rural/kota)	Census 2010	BPS (2010a)
Poverty Decile	SMERU poverty map	SMERU (2015)

Indonesians have a strong preference for living in individual houses (Firman, 2004; Idham, Numan and Mohd, 2010) which is also easily observable from satellite imagery and building height data. According to the Housing Censuses, the floor area of these houses can be very small (<40sqm) (BPS, 2010). It is therefore assumed that each household in the census represents an individual house unless there is evidence to the contrary. We systematically check for the presence of multi-dwelling buildings in each desa by using the census data, GoI reports on tower developments (Perumnas, 2008) and the Public Works (PU) database on social housing apartments (data.pu.go.id), analysis of the building height profile to determine whether there are enough low-rise (1 to 4 storey) buildings to accommodate the number of households in houses, and analysis of the population density to determine whether there is sufficient land to accommodate the number of households as houses. In the case of the documented instances of apartments, households are assigned to these based on the number of apartments in the building that is recorded or estimated from the size of the building. Whereas for the locations identified through analysis of the building profile and population density, satellite imagery is used to inspect each desa and identify additional apartments and estimate the number of households in these. This results in an exposure model that has predominantly small footprint individual houses, with apartment buildings that are predominantly located in Jakarta. This is reflective of the available literature on housing preferences and architecture for Java (e.g., Firman, 2004). The exposure model for residential buildings in Java is shown in Figure 1.

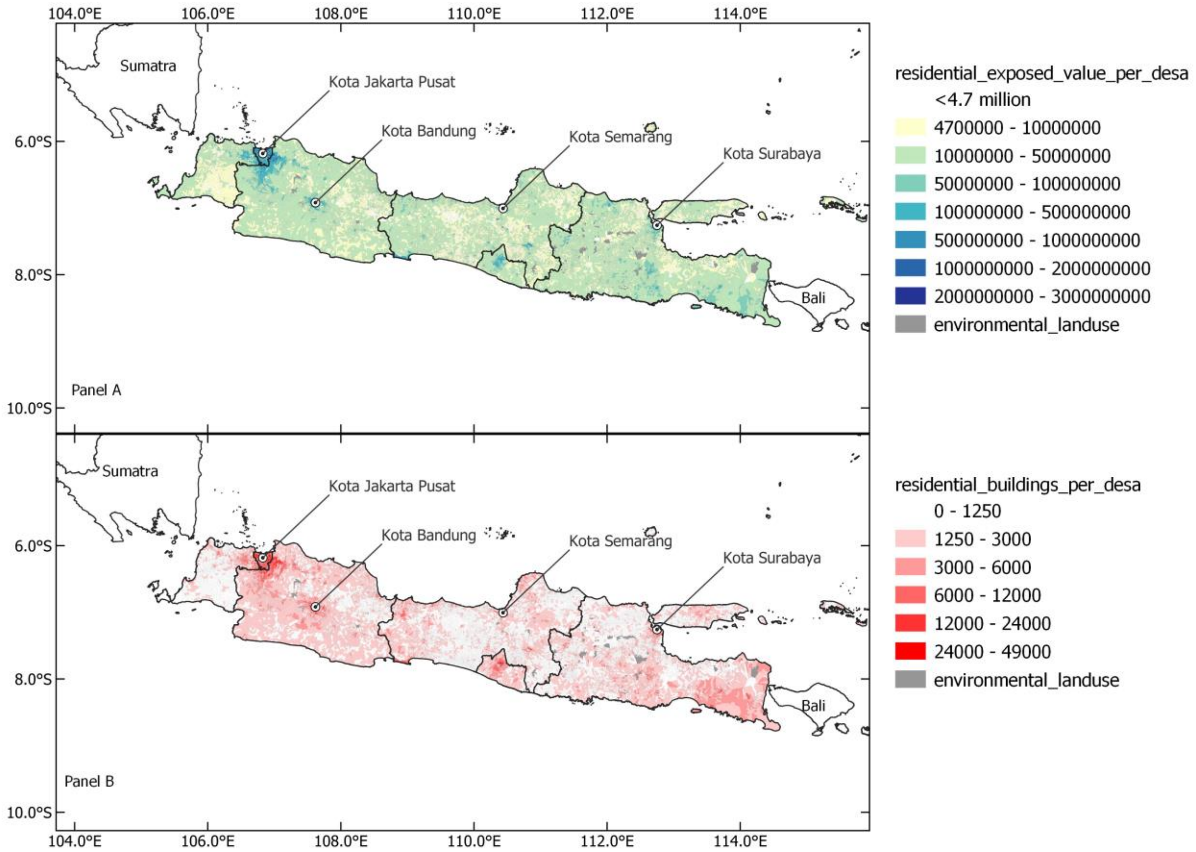

Figure 1. The 2020 residential building exposure model for Java, Indonesia at the desa scale. Panel A is the exposed value, an estimate of the structural replacement cost. The exposed value is in 2020 USD. Panel B is the total number of residential buildings.

Tall buildings (>12 stories) are assumed to have been constructed to the building code and of sufficient seismic resilience for the active seismic setting. Shorter buildings and houses have been assigned building types based on the available literature, the known changes in masonry construction practices through time in Indonesia, as well as the relative poverty of a desa, and whether the desa is classified as rural, urban or a *kota* (city). The mapping schema for residential houses has been developed using two alternative but critical assumptions:

1. That all houses constructed prior to 1990 were unreinforced masonry (URM), regardless of the relative wealth or the setting (kota, urban, rural). URM houses can be up to four storeys high. Other masonry houses are assigned based on setting and relative wealth.
2. The construction of unreinforced masonry houses was phased out over time based on the relative wealth and the setting of an administrative area. It also assumes that URM houses are only 3 storeys high.

This results in two alternate mapping schemas for residential houses in Java. From preliminary testing on several past events we ascertained that global fragility functions developed by Martins and Silva (2020) are suitable to describe the fragility of houses in Indonesia, with the exception of unreinforced masonry (URM) houses. The fragility of URM houses was found to be variable and the HAZUS URM (FEMA, 2020), which is more fragile than the global URM functions, is more suitable in some locations. These two mapping schema and the alternate fragility functions for URM are tested in each scenario in section 5. The main difference in the resulting models using these alternate mapping schemas is the prevalence of URM houses versus the more seismically resilient confined masonry houses. The breakdown in buildings by province for each alternate mapping schema is shown in Figure 2. Masonry houses account for 75% of the residential buildings in Java, the breakdown of the remaining 25% of residential buildings is shown in Figure 3.

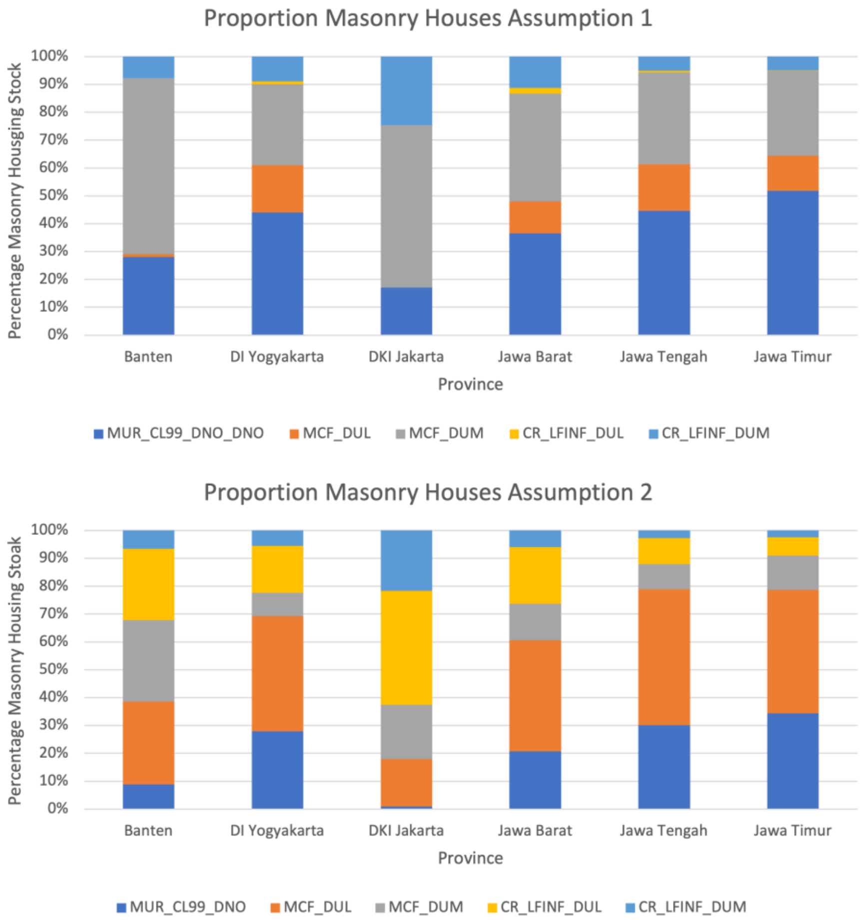

Figure 2. The top graph shows the proportions of the different types of masonry houses by Province using assumption one. The bottom graph shows the proportions of the different types of masonry houses by Province using assumption two. These form the basis of the two alternate mapping schemas for residential houses. The additional two mapping schema are based on the fragility function used for URM houses, HAZUS (FEMA, 2020) or Martins and Silva (2020), applied to both assumptions.

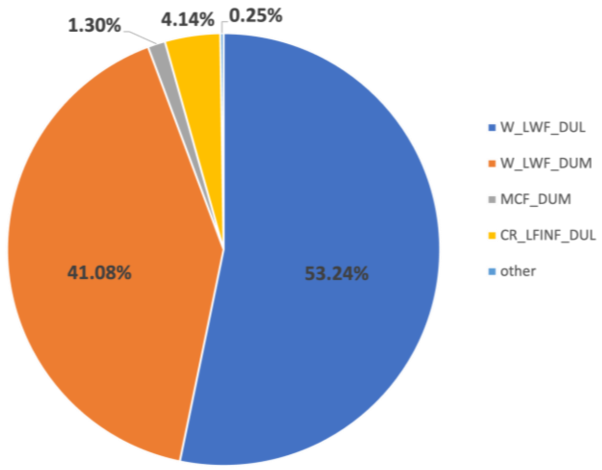

Figure 3. The distribution of building classes of the 25% of residential buildings in the 2020 Java residential exposure model that are not masonry houses. The other category includes mainly apartment buildings which are reinforced concrete with a dual wall system. The buildings were classified using the GEM taxonomy (Silva *et al.*, 2022).

2.2 Non-residential buildings

Commercial and industrial buildings are the next biggest category of buildings after residential buildings. There is significantly less information available for these buildings and thus a different approach was taken to develop this component of the exposure model. The 2016 Establishment Survey (BPS, 2016) has the most detailed information on commercial and industrial buildings, but the scale of the data is at the kabupaten (administrative 2) level. This data was integrated with the GHSL Morphological Settlement Zone dataset (Pesaresi and Panagiotis, no date) to distribute the businesses to individual desa. The types of buildings are allocated based on the type and size of the business from what is known about these types of buildings in Indonesia and in other locations in the world. Data from OSM and CTBUH are used to improve the accuracy for this class of buildings. It is acknowledged that the available data used is for 2016, and there have likely been changes in the number of businesses and associated buildings between 2020 and 2016 and this likely results in a small underestimation for this class of buildings. It should be noted that commercial buildings do not include non-permanent structures such as roadside stalls or temporary markets. Shop-houses are prevalent in Indonesia; these are not counted here as they are already addressed in the residential exposure model.

Schools are a relatively small category of non-residential buildings. These buildings are typically not included in exposure models (Rodgers, 2012) as there is often insufficient information to characterise them. This is also the case in Indonesia. However, due to the known poor construction practices used in schools in Indonesia and the fact that a very large proportion of the youth population is inside these buildings during the day, we have tried to characterise these buildings for inclusion in our exposure model. Data on the location and occupancy of schools is available at the kecamatan (administrative level 3) scale from the Ministry of Education, Culture, Research and Technology school database (MoECRT; https://dapo.kemdikbud.go.id/). There are almost 98 000 schools – elementary (SD), middle (SMP) and high school (SMA and SMK) – in Java and just over 5% of these are mapped in OSM and named in a way that the data can be linked to the GoI data. The OSM data was used in conjunction with the building height data from GHSL to characterise the mapped buildings. This was then linked with the GoI data to create typical schools based on Province, number of students, year level, and type of school (state or private). This was then used to characterise all schools in Java and population data was used to distribute these schools to the desa scale. There is sufficient information on the construction materials of schools, which are the same as masonry houses, to allow schools to be characterised by construction type and fragility. This component of the model does not include other education institutions such as day-care centres, kindergartens, universities and colleges, for which there is limited data available.

Hospitals are the final type of non-residential building that are included in the exposure model. There are 1568 hospitals in Java and the exact location of these are known from the Ministry of Health RSOnline database (https://sirs.kemkes.go.id/fo/). OSM and GHSL are used as they were with schools to characterise these buildings in terms of floor area and the number of stories. There is very minimal information available on the construction materials, quality, and standards of hospitals in Indonesia. No reports have been found of damage to hospitals in past earthquake events in Indonesia. Hospitals are divided into four categories (A, B, C, D) in Indonesia (RSOnline, n.d.). It is assumed that category A and B hospitals which tend to be mid to high rise buildings (Florczyk *et al.*, 2019) are well constructed and seismically resilient. It is assumed that category C and D hospitals, which tend to be low-rise buildings (Florczyk *et al.*, 2019) are similar in construction to houses and schools. This component of the model does not include other health facilities such as *Puskemas* (local health clinics).

There is significantly more uncertainty associated with the non-residential component of the model. This is because of the scale of the input data, the lack of studies addressing these types of buildings, and the minimal instances of these types of buildings being considered in post-disaster damage surveys. This could be improved with field surveys and government data collection that focussed on this class of buildings. Although there are significantly less non-residential buildings compared with residential buildings, the day occupancy of these buildings is quite high. The non-residential exposure model in terms of the number of buildings and exposed value is shown in Figure 4. The proportion of the types of buildings that this includes, broken down by province is shown in Figure 5. It should be noted that government buildings, places of worship, and historical monument have not been considered in our non-residential exposure model due to insufficient data.

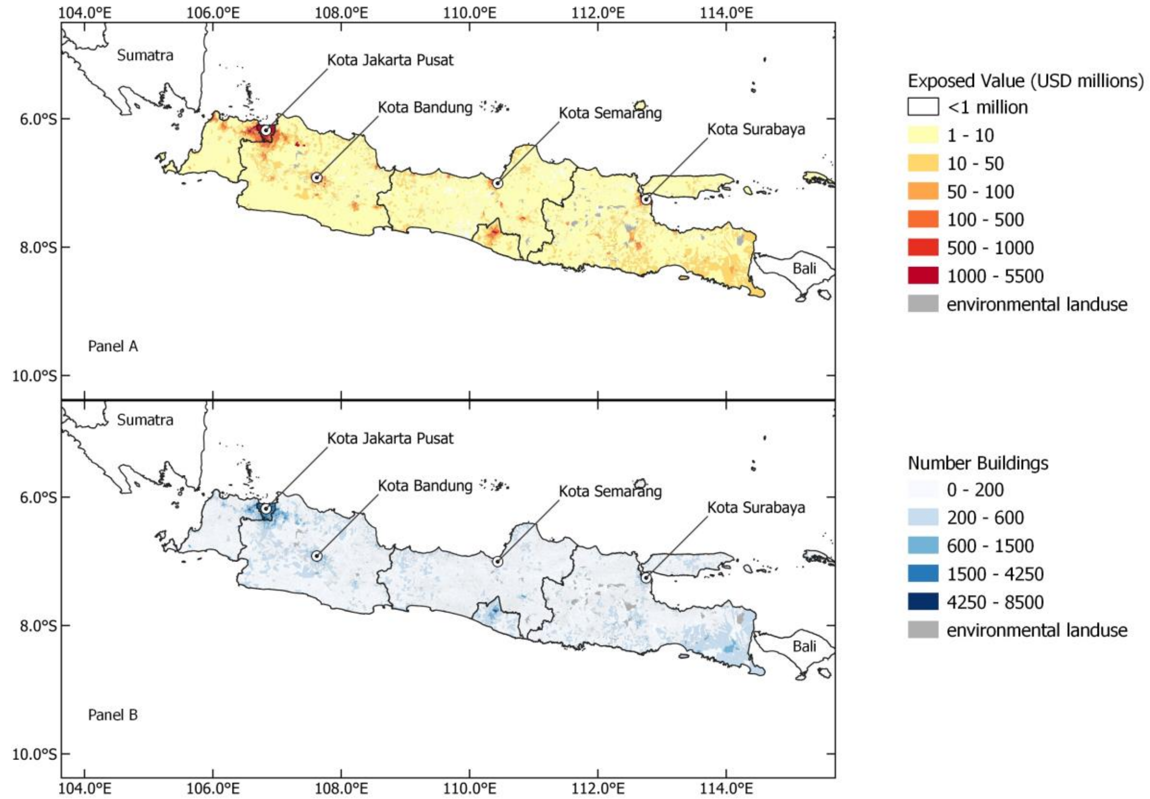

Figure 4. The 2020 non-residential building exposure model for Java, Indonesia at the desa scale. Panel A is the exposed value, an estimate of the structural replacement cost. The exposed value is in 2020 USD. Panel B is the total number of non-residential buildings.

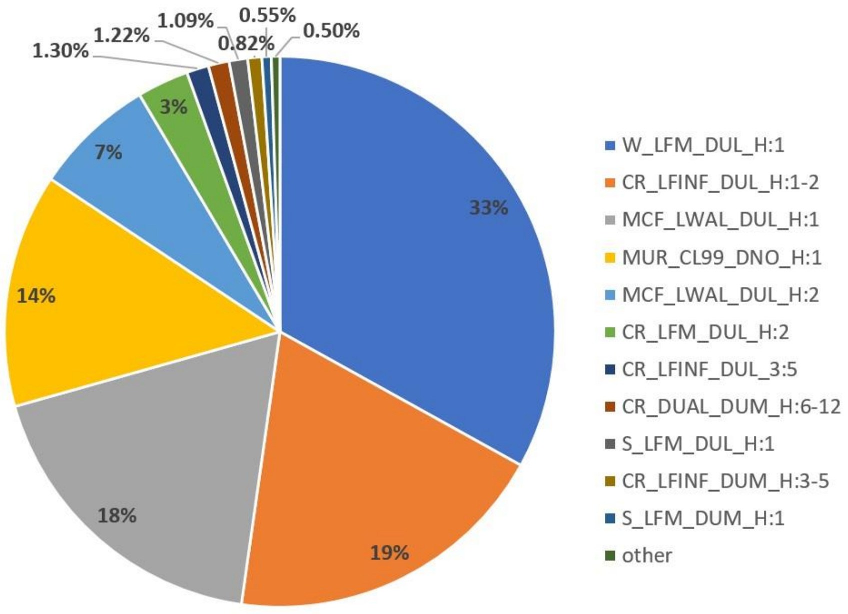

Figure 5. The distribution of building classes of the 2020 Java non-residential exposure model. The 'other' category mainly includes high-rise buildings that are reinforced concrete with a dual wall system The buildings were classified using the GEM taxonomy (Silva *et al*., 2022).

3 Exposure model uncertainty

There is significant uncertainty in each of the input datasets which have been used to develop the exposure model. The uncertainty is the highest for commercial and industrial buildings in all facets of this model. This is due to a lack of data on these building types and the uncertainty could be reduced through collection of field data. Schools have more certainty in location, height, floor area and construction styles. The uncertainty in residential buildings really hinges on the categorisation of masonry houses in the census data. The construction materials are quite well established and in general are quite homogeneous with clay fired brick and clay tile roofing dominating housing materials (Boen, 2006; Boen and Pribadi, 2007; Idham, 2019). However, we have much less information the distribution of specific construction types and thus mapping these houses to unreinforced masonry, confined masonry, or reinforced concrete, and determining the level of ductility is much less certain. In cities we also have additional uncertainty in the height of the houses, as the height data includes so many other types of buildings. However, in rural areas we have more certainty on the heights due to the homogeneous height data indicating mainly one storey buildings, which is expected for Java.

The uncertainties can be classified as epistemic uncertainties, such as the proportions of buildings in each building type, or aleatory uncertainties, such as the construction cost per square metre (Crowley *et al.*, 2020). Epistemic uncertainty can be reduced through data collection. Data collection in a densely populated location such as Java would require extensive resources which are outside the scope of this study. The development of the alternate mapping schemas for residential houses in this study allows for the propagation of this uncertainty to damage and risk calculations using logic trees. Uncertainty can be further reduced through verification of the model using damage data from past earthquake events. This was performed for residential houses and discussed in the following section.

4 Exposure model verification with scenario damage analyses

Verification of the exposure model was performed using scenario damage analyses of recent past earthquakes that occurred on Java, for which damage data are available. The events selected represent all of the damaging earthquakes within the time frame of 2017-2022 and include active shallow crust, intraslab and interface events. The quality of the damage data available for verification varies from location to location, and is only suitable for residential houses. Thus, the other building types in the exposure model cannot be verified using this method. The historical events selected were modelled using OpenQuake V13.16, using 1000 ground motion simulations to converge on a ground motion solution. The scenarios were modelled four times using the two alternate mapping schema and the two alternate fragility functions for URM houses. There is insufficient ground motion data to guide selection of ground motion prediction equations (GMPEs) for most events and there are no GMPEs specific to Indonesia. GMPEs were selected that account for the presence of active volcanism in Java and that best matched the observed damage pattern. A summary of the modelled events and the GMPEs used are shown in Table 2. Figure 6 shows the location of these events in Java and highlights the impacted kabupaten.

Table 2: Recent earthquake event with damage data used for verification of the residential houses component of the Java exposure model. Damage compiled from multiple sources (BNPB,n.d. https://dibi.bnpb.go.id/xdibi*;* Muhari *et al.*, 2021*;BNPB,2022a;BPNB,2022b).*

Event	Setting	Reference	GMPE selected	Damage Data Scale
East Java, Mw6.1, 10/4/21	Intraslab	Supendi et al., 2022	Zhao et al. (2016)	Total damaged sustained
Banten, Mw6.9, 2/8/2019	Intraslab	Gunawan et al., 2022	Abrahamson et al. (2016)	kabupaten
Tasikmalaya, Mw6.5, 15/12/2017	Interface	Sirait et al., 2020	Abrahamson et al. (2016)	kabupaten
Lebak, Mw5.9, 23/1/2018	Interface	Sirait et al., 2020	Abrahamson et al. (2016)	kabupaten
Cianjur, Mw5.6, 21/11/2022	Active Shallow Crust	BMKG, BG and GCMT	Chiou and Youngs (2014) optimised for Japan	Total damaged sustained

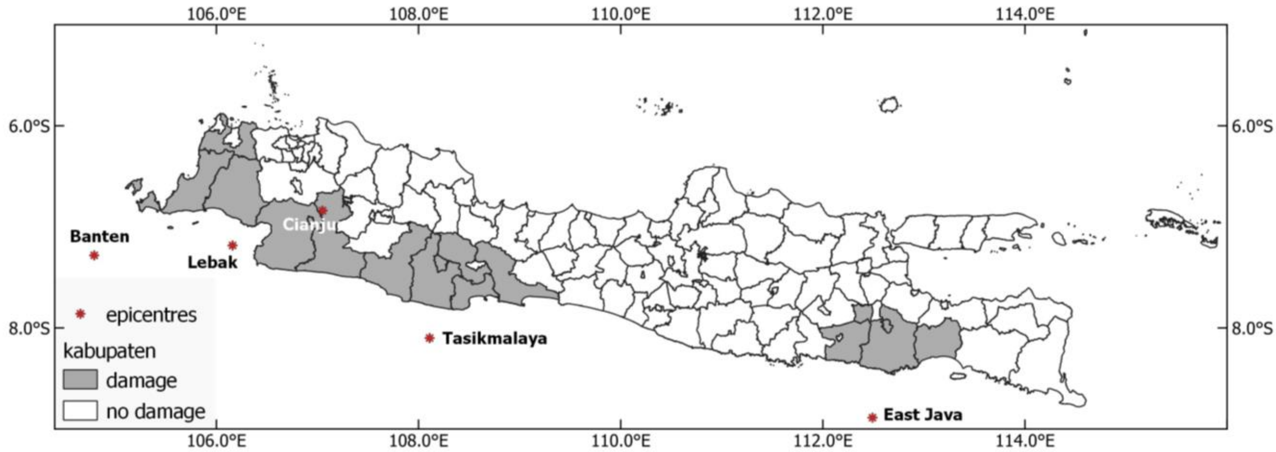

Figure 6. Locations of recent damaging earthquakes used to verify the residential houses in the Java 2020 exposure model. The kabupaten that sustained damage are highlighted in grey.

Figure 7 shows the results for each event that gives the best agreement with the recorded damage data. There are simulations which give good agreement for the heavy and moderate damage states for each scenario, or the recorded damage data lies between the values of two scenarios using different mapping schema. In most cases it is not possible to replicate the slight damage that was recorded, with simulations mostly significantly over estimating the slight damage. This is likely due to issues with the recording of the actual slight damage data in the field and the difficulties in recording damage that is internal to a building. It may also be associated with the GMPEs not being bespoke to Indonesia and the seismic wave not attenuating at a fast enough rate for the Indonesian site conditions. Further study is required to determine whether this varies in a predictable manner or not. These scenarios indicate that the exposure model is performing well and that multiple mapping schemas are indeed required to capture the uncertainty in the exposure model.

These scenarios only cover part of Java, and there is therefore more confidence in our assessment of uncertainty in these locations of the exposure model than there is in locations which have not experienced a recent damaging earthquake and therefore had no scenario damage analyses undertaken on them. Thus in the modelled locations we can pick which exposure mapping is most appropriate and use that for future studies, however, in the rest of Java which has not had scenario analyses undertaken we do not know which exposure mapping is most relevant. Therefore, we recommend that any damage or risk analyses use a logic tree approach with the alternate mapping schemas to account for the uncertainty in the exposure model. We also propose for risk studies that additional GMPEs are considered instead of the GMPEs that have been used in the recent Indonesia PSHA (Irsyam *et al.*, 2020), particularly to account for the presence of active volcanism to ensure that the damage is not overestimated.

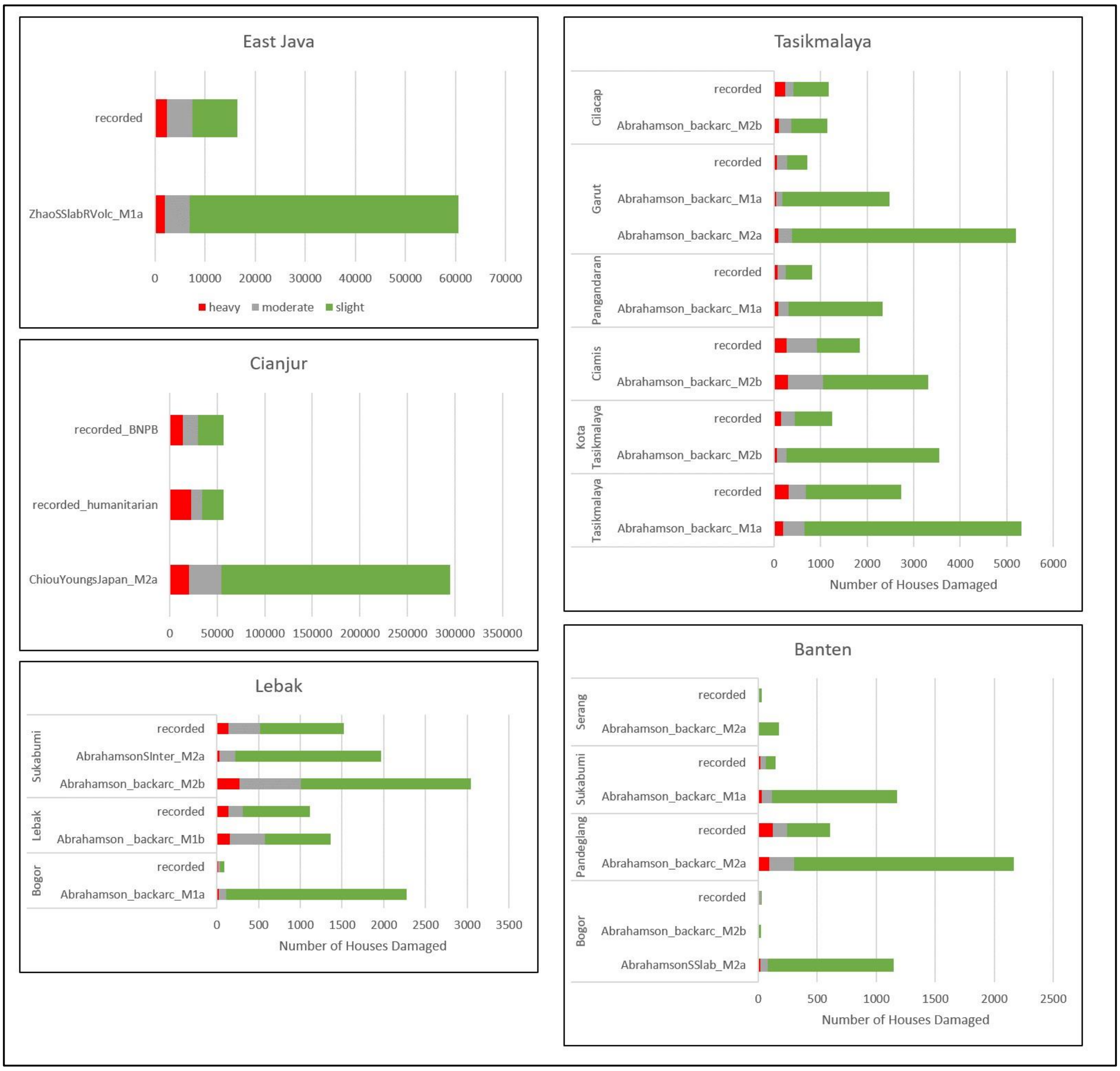

Figure 7. The results of the comparison of observed damage data to the simulated damage data for each of the 5 events. ***M1*** *and* ***M2*** *are based on assumption 1 and 2 in Figure 2,* ***a*** *is URM fragility – MUR_CL99_DNO – from Martins and Silva (2020),* ***b*** *is the URM fragility – URML – from HAZUS (FEMA,2020).*

5 Conclusions

There are many uncertainties associated with the development of an exposure model, particularly with the use of secondary sources. This study has integrated data from multiple sources to develop a desa scale model for Java, Indonesia for residential, commercial, industrial, school and hospital buildings. The exposure model includes day and night occupancy as well as estimates of structural value. Residential buildings, in particular houses, comprise most of the buildings in the exposure model. The residential houses component of the model has been verified through scenario damage analyses of recent events which were compared to the officially recorded damage data. Alternate mapping schema for the exposure model were developed to account for uncertainty, and the scenario damage analyses confirm that multiple mapping schema are required to get agreement with recorded damage. The mapping schema required vary from kabupaten to kabupaten in an unpredictable fashion. These alternate mapping schemas primarily impact the proportion of unreinforced masonry houses and confined masonry houses that are in the model. There is a significant difference in the fragility of these two types of houses, and it is expected this would significantly influence impact loss and risk calculations. The development of these alternate mapping schema allows for this uncertainty to be captured in future studies.

6 References

Abrahamson, N., Gregor, N. and Addo, K. (2016). BC hydro ground motion prediction equations for subduction earthquakes, *Earthquake Spectra*, 32(1): 23–44.

Arcadis Indonesia (2019). *Construction Cost Handbook Indonesia 2019*. 5th Ed. Arcadis Indonesia

Aulady, M.F.N. and Fujimi, T. (2019). Earthquake loss estimation of residential buildings in Bantul regency, Indonesia, *Jamba: Journal of Disaster Risk Studies*, 11(1):1–10.

Bappenas (2006). Preliminary Damage and Loss Assessment Yogyakarta and Central Java Natural Disaster.

BAPPENAS (2006). *Yogyakarta (Kota) Preliminary Damage and Loss Assessment*.

BNBP, B. (2009). *West Sumatra and Jambi Natural Disasters: Damage, Loss and Preliminary Needs Assessment*.

BNPB (n.d.) https://dibi.bnpb.go.id/xdibi. Last accessed 7/6/2023

Boen, T. (2006). Yogya Earthquake 27 May 2006, Structural Damage Report, pp. 1–22.

BNPB (2022a). Press Release 25/11/2022. Accessed at: https://www.bnpb.go.id/berita

BNPB (2022b). Press Release 10/12/2022. Accessed at: https://www.bnpb.go.id/berita

Boen, T. and Pribadi, K.S. (2007). Engineering the Non Engineered Houses for Better Earthquake Resistance in Indonesia. *Proceedings of the DRH Contents Meeting-EDM-NIED 2007*, Kobe, Japan.

BPS (2010a). Census Data, 2010 (District level): Village level information. ANU Dataverse. https://doi.org/doi/10.26193/BN3KCP

BPS (2010b). Indonesian Susenas, 2010. ANU Dataverse. Available at: https://doi.org/doi/10.26193/1EZ5JP.

BPS, (2016). Sensus Ekonomi 2016. https://se2016.bps.go.id/umkumb/. Last accessed 10/10/2023

BPS, (2020). Sensus Penduduk 2020. https://sensus.bps.go.id/main/index/sp2020. Last accessed 1/10/2023.

Chiou, B.S.J. and Youngs, R.R. (2014) Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra, *Earthquake Spectra*, 30(3):1117–1153.

Crowley, H., Despotaki, V., Rodrigues, D., Silva, V., Toma-Danila, D., Riga, E., Karatzetzou, A., Fotopoulou, S., Zugic, Z., Sousa, L., Ozcebe, S. and Gamba, P. (2020). Exposure model for European seismic risk assessment, *Earthquake Spectra*, 36(1):252–273.

EERI (2006). *The M w 6. 3 Java, Indonesia, Earthquake of May 27, 2006*, *EERI Special Earthquake Report*,

EERI (2007). *Observations on the Southern Sumatra Earthquakes of September 12-13, 2007*.

EERI (2009a). The M7.3 September 2, 2009, West Java quake', *EERI Newsletter*, 43(10):4

EERI (2009b). *The Mw7.6 Western Sumatra Earthquake of September 30,2009*.

FEMA (2020). *HAZUS. Earthquake Model, Technical Manual*, Federal Emergency Management Agency, Washington DC.

Firman, T. (2004). New town development in Jakarta Metropolitan Region: A perspective of spatial segregation, *Habitat International*, 28(3), pp. 349–368.

Florczyk, A.J., Corabne, C., Ehrlich, D., Freire, S., Kemper, T., Maffenini, L., Melchiorri, M., Pesari, M., Schiavina, M., Sabo, F., and Zanchetta, L. (2019). *GHSL Data Package 2019 Public release*. JRC Technical Report. European Commission.

Idham, N.C. and Mohd, (2018). Eartquake Vulnerability Level of Reconstructed Houses, Lesson Learned after Ten Years Java Eartquake 2006, *SHS Web of Conferences*, 41(October 2020), p. 06004.

Idham, N.C. (2019). Earthquake Failures on Buildings and the Role of Architect on Building Safety, *DIMENSI (Journal of Architecture and Built Environment)*, 45(2):153-164

Idham, N.C., Numan, I. and Mohd, M. (2010) *Changes of quality in Javanese houses*, *Open House International*. Available at: https://doi.org/10.1108/ohi-03-2010-b0003.

IPUMS (2020a)**.** Minnesota Population Center. Integrated Public Use Microdata Series, International: Version 7.3 Indonesia Census 1980. Minneapolis, MN https://doi.org/10.18128/D020.V7.2

IPUMS (2020b). Minnesota Population Center. Integrated Public Use Microdata Series, International: Version 7.3 Indonesia Census 1990. Minneapolis, MN https://doi.org/10.18128/D020.V7.2

IPUMS (2020c)**.** Minnesota Population Center. Integrated Public Use Microdata Series, International: Version 7.3 Indonesia Census 2000. Minneapolis, MN https://doi.org/10.18128/D020.V7.2

Irsyam, M., Cummins, P., Asrurifak, M., Faizal, L., Natawidjaja, D., Widiyantoro, S., Meilano, I., Triyoso, W., Rudiyanto, A., Hidayati, S., Ridwan, M., Hanifa, N. and Syabana, A. (2020). Development of the 2017 national seismic hazard maps of Indonesia, *Earthquake Spectra*, 36:112–136.

Lambang-Goro, G., Irsyam, M., Asrurifak, M. and Meilano, I. (2022). Earthquake Risk Study on Residential Buildings in West Jakarta using the Event-Based Risk Analysis Method, *IOP Conference Series: Earth and Environmental Science*, 1065(1):012011.

Martins, L. and Silva, V. (2020). Development of a fragility and vulnerability model for global seismic risk analyses, *Bulletin of Earthquake Engineering*, 19:6719-6745.

Muhari, A., Harjito, T., Irawan, F. and Utomo, A. (eds) (2021) *Data Bencana Indonesia 2021*. Indonesia: Pusat Data Informasi dan Komunikasi Kebencanaan, BNPB.

OSM (n.d.) OpenStreetMap Contributors. 2021 download accessed at: https://www.openstreetmap.org

Perumnas (2007). *Laporan Tahun 2007 Annual Report.* Perumnas

Perumnas (2008). *Laporan Tahun 2008 Annual Report*. Perumnas.

Perumnas (2009). *Laporan Tahun 2009 Annual Report.* Perumnas

Perumnas (2010). *Laporan Tahun 2100. Annual Report.* Perumnas

Pesaresi, M. and Panagiotis, P. (no date) 'GHS-BUILT-C R2023A - GHS Settlement Characteristics, derived from Sentinel2 composite (2018) and other GHS R2023A data'. http://data.europa.eu/89h/3c60ddf6-0586-4190-854b-f6aa0edc2a30.

Pribadi, K.S., Abduh, M., Wirahadikusumah, R., Hanifa, N., Irsyam, M., Kusumanngrum, P. and Puri, E. (2021). Learning from past earthquake disasters: The need for knowledge management system to enhance infrastructure resilience in Indonesia, *International Journal of Disaster Risk Reduction*, 64: 102424.

Rodgers, J.E. (2012). Why Schools are Vulnerable to Earthquakes, *Proceedings of the 15th WCEE*, Lisbon, Portugal.

Saputra, A., Rahardianto, T., Revindo, M., Delikostidis, I., Hadmoko, D., Sartohadi, J. and Gomez, C. (2017) Seismic vulnerability assessment of residential buildings using logistic regression and geographic information system (GIS) in Pleret Sub District (Yogyakarta, Indonesia), *Geoenvironmental Disasters*, 4:11.

Schiavina, M., Melchiorri, M., Pesaresi, M., Politis, P., Freire, S., Maffenini, L., Florio, P., Ehrlich, D., Goch, K., Tommasi, P. and Kemper, T. (2022). *GHSL Data Package 2022-Public Release*, JRC Scientific Information Systems and Databases Report, European Commission.

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

Silva, V., Amo-Oduro, D., Calderon, A., Costa, C., Dabbeek, J., Despotaki, V., Martins, L., Pagani, M., Rao, A., Simionato, M., Vigano, D., Yepes-Estrada, C., Acevedo, A., Crowley, H., Horspool, N., Jaiswal, K., Journeay, M. and Pittore, M. (2020). Development of a global seismic risk model, *Earthquake Spectra*, 36:372–394.

Silva, V., Brzev, S., Sawthorn, C., Yepes, C., Dabbeek, J. and Crowley, H. (2022). A building classification system for multi-hazard risk assessment. *International Journal of Disaster Risk Science*,13:161-177.

Teguh, M. (2014). Earthquake resistant construction practices in Indonesia: a reconnaissance on vulnerable built-conventional houses for sustainable development, *Proceedings Third International Conference on Sustainable Built Environment*, 9-24.

Yepes-Estrada, C., Silva, V., Valcarcel, J., Acevedo, A., Tarque, N., Hube, M., Coronel, G. and Hernan Santa, M. (2017). Modeling the Residential Building Inventory in South America for Seismic Risk Assessment', *Earthquake Spectra*, 33(1):299–322.

Yepes-Estrada, C., Calderon, A., Costa, C., Crowley, H., Dabbeek, J., Hoyos, M., Martins, L., Paul, N., Rao, A. and Silva, V. (2023). Global building exposure model for earthquake risk assessment, *Earthquake Spectra*, 0(0).

Zhao, J.X., Jiang, F., Shi, P., Xing, H., Huang, H., Hou, R., Zhang, Y., Yu, P., Lan, X., Rhoades, D., Somerville, P., Irikura, K. and Fukushima, Y. (2016). Ground-Motion Prediction Equations for Subduction Slab Earthquakes in Japan Using Site Class and Simple Geometric Attenuation Functions, *Bulletin of the Seismological Society of America*, 106(4):1535–1551.