Probabilistic Seismic Risk Assessment for Pacific Island Countries

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SUMMARY:
A fully probabilistic earthquake risk assessment study was carried out for fifteen Pacific Island Countries (PICs): Cook Islands, Fiji, Kiribati, Republic of Marshall Islands, Federated States of Micronesia, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste, Tonga, Tuvalu and Vanuatu. This article presents an overview of the assets exposed to risk and the main findings of the study. The seismic hazard component of the study is discussed in a companion paper (Rong et al., 2012). The risk is measured both in terms of impact on population (casualties and fatalities) and on direct economic losses to residential, commercial, industrial and public buildings and to major infrastructure assets. These country-specific earthquake risk profiles can support multiple applications that benefit both public and private stakeholders, such as urban development planning, community-based earthquake risk management and mitigation, post-disaster damage assessments, and disaster risk financing.

Keywords: seismic hazard and risk assessment, Pacific Island Countries, asset exposure, seismic vulnerability

1. INTRODUCTION

The Pacific Region is prone to frequent earthquakes (Figure 1) that threaten the inhabitants of the Pacific Island Countries and cause significant damage to the built environment, with consequent large economic losses that harshly impact the relatively fragile economies in the region. In last two decades alone (1990-2009), earthquakes have caused at least 300 million USD in losses and 2,500 deaths in these countries (NGDC/WDC, 2012). As part of the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) project funded by the World Bank and supported by other agencies, such the Asian Development Bank (ADB) and the Applied Geoscience and Technology Division (SOPAC) of the Secretariat of the Pacific Community (SPC), AIR Worldwide developed country-specific seismic risk assessment models for fifteen Pacific Island Countries (PICs): Cook Islands (CK), Fiji (FJ), Kiribati (KI), the Republic of Marshall Islands (MH), the Federated States of Micronesia (FM), Nauru (NR), Niue (NU), Palau (PW), Papua New Guinea (PG), Samoa (WS), Solomon Islands (SB), Timor-Leste (TL), Tonga (TO), Tuvalu (TV), and Vanuatu (VU). The seismic risk models are part of a larger study that also included risk models for the perils of earthquake-induced tsunami and tropical cyclone. The impact of these additional perils is not discussed here.

In this study the seismic risk is measured both in terms of impact on population and of direct economic losses to residential, commercial, industrial and public buildings and to major infrastructure. An overview of the exposure database of building and infrastructure assets is presented here. Although not discussed herein, a crop exposure database was also developed for use in the tsunami and tropical cyclone risk models. The exposure database assembled in this study can be considered the most comprehensive for this part of the world to date. The article follows with a discussion on the vulnerability of buildings, infrastructure, and population to the seismic threat, and shows the earthquake ground shaking risk profiles that were computed for the 15 PICs.

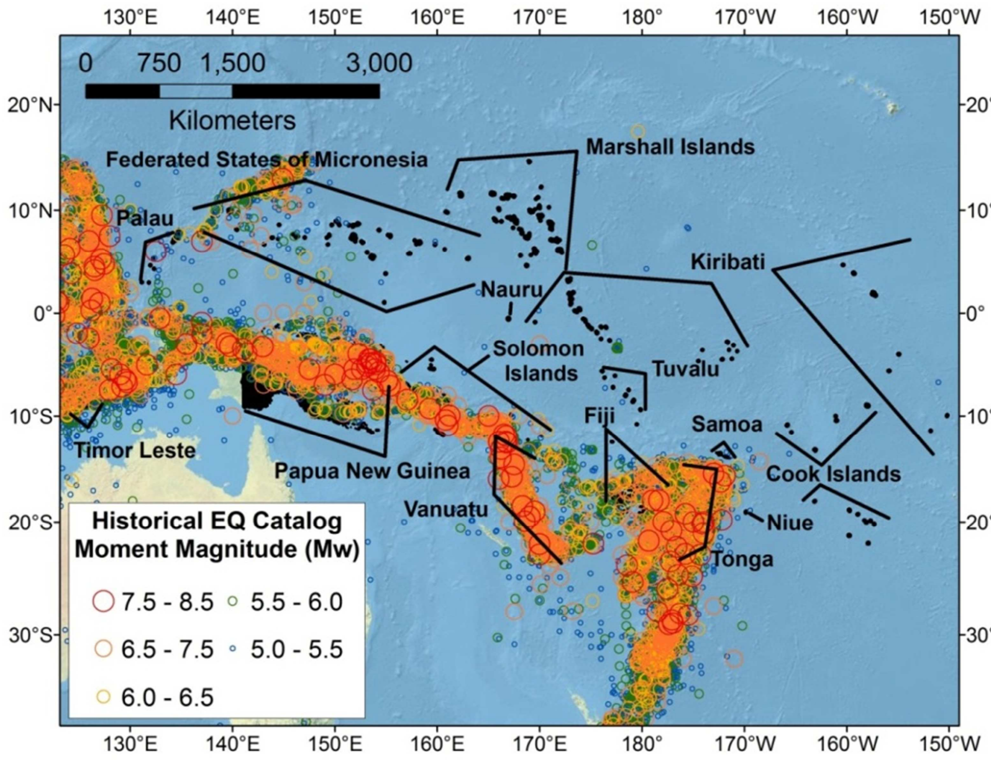

Figure 1. Historic earthquake activity in the Pacific Island Countries (1768 to 2009)

2. EXPOSURE DATABASE

Census and economic data for the 15 PICs were collected, processed and trended, when necessary, to 2010 values (see Table 1). The 2010 estimated population and nominal GDP values of the 15 PICs are 9.73 million people and 16.6 trillion USD, respectively. It is estimated that about 3.5 million residential and non-residential buildings exist in the 15 PICs countries with an estimated replacement cost of 94 billion USD. In addition, it is estimated that the PICs contain about 15 billion USD in major infrastructure assets. A breakdown of the number of buildings and replacement costs by country is shown in Table 1. An example profile of the exposure database for Papua New Guinea, which is by far the largest of these 15 PICs, is shown in Figure 2.

Table 1. Summary of Exposure data for the 15 PICs

Country	Abbreviation	2010 Population	2010 Nominal GDP (million USD)	Replacement Cost (million USD)		Number of Buildings per Extraction Method					
				Buildings	Infrastructure	Level 1	Level 2	Level 3	Level 4	Level 5	Total
Cook Islands	CK	19,826	244.1	1,296.8	117.6	5,044	4,889	100	357	212	10,602
Fiji	FJ	846,842	3,009.4	18,865.2	3,093.9	18,622	79,545	8,214	158,436	1,323	266,140
Federated States of Micronesia	FM	111,567	287.4	1,729.0	312.8	1,008	15,802	-	15,158	20	31,988
Kiribati	KI	101,403	151.2	1,006.1	164.2	746	12,137	2,139	12,562	5	27,589
Marshall Islands	MH	54,827	155.8	1,404.1	285.9	-	7,684	151	5,031	28	12,894
Nauru	NR	10,824	34.5	410.6	42.0	-	2,745	-	-	10	2,755
Niue	NU	1,479	15.8	173.8	74.0	-	1,105	-	-	3	1,108
Papua New Guinea	PG	6,405,599	9,480.0	39,509.0	6,639.1	11,821	122,674	24,398	2,228,935	5,451	2,393,279
Palau	PW	20,503	169.7	1,338.5	159.9	1,283	4,206	-	84	146	5,719
Solomon Islands	SB	547,540	678.6	3,058.7	420.3	12,268	23,150	381	131,574	1,739	169,112
Timor-Leste	TL	1,066,582	701.0	17,881.3	2,160.6	-	96,539	-	300,791	1,355	398,685
Tonga	TO	103,352	357.5	2,525.2	259.4	10,082	17,622	-	6,957	90	34,751
Tuvalu	TV	9,960	32.0	229.3	39.7	956	1,258	-	804	-	3,018
Vanuatu	VU	245,864	729.0	2,858.4	420.0	10,661	21,883	-	66,782	1,420	100,746
Samoa	WS	182,901	565.2	2,147.9	467.4	6,517	42,221	-	-	93	48,831
Total	**-**	**9,729,069**	**16,611**	**94,434**	**14,657**	**79,008**	**453,460**	**35,383**	**2,927,471**	**11,895**	**3,507,217**

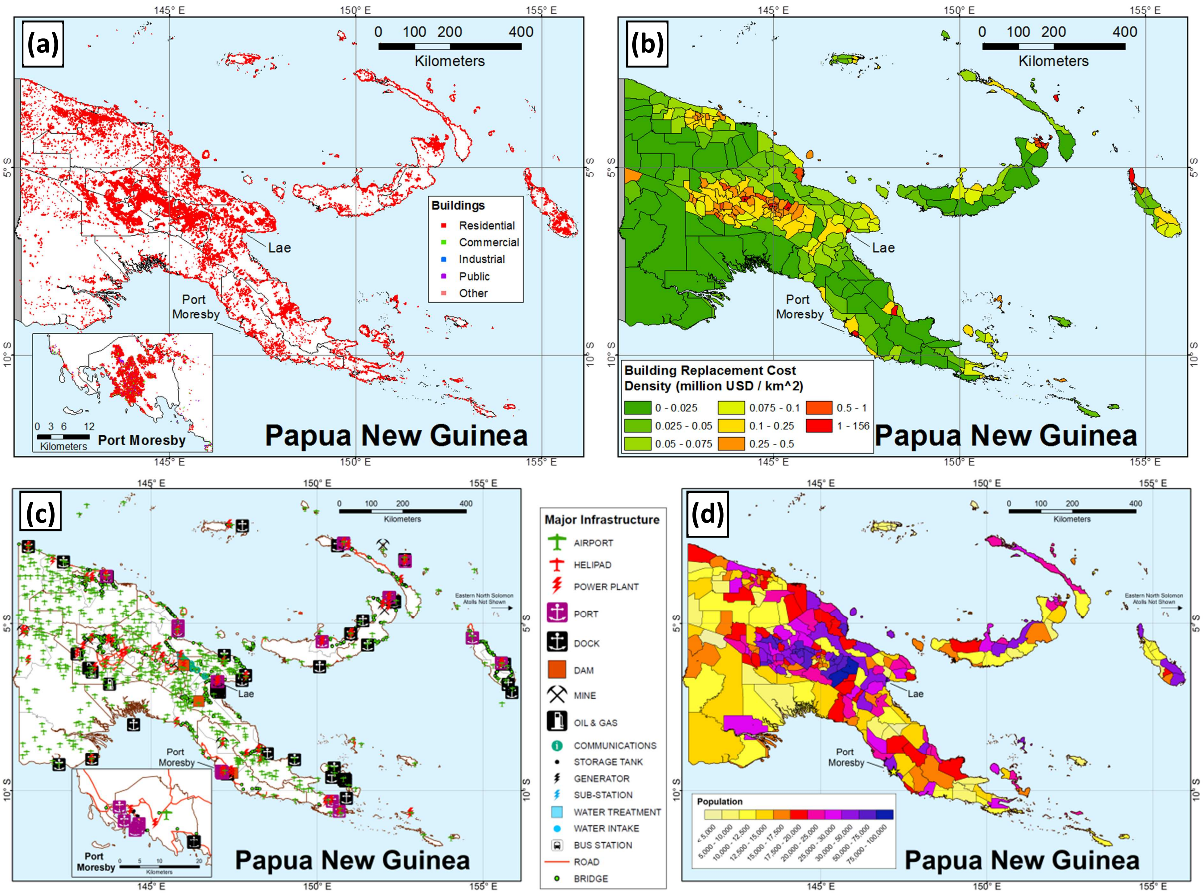

Figure 2. Example profile of the exposure database for Papua New Guinea: (a) location of buildings (b) density of building replacement cost (c) location of infrastructure (d) total population

Building and infrastructure assets with their characteristics, replacement costs, and location were assembled in a geo-referenced database for each on the 15 PICs. The building exposure database includes information such as building location (i.e., latitude and longitude), occupancy type (e.g., residential or commercial), construction type (e.g., timber frame), number of stories, building footprint area, replacement cost, and several structural and non-structural attributes (e.g., foundation type or roof type) that affect the building's vulnerability to the effects of natural events. In addition, a geocoded infrastructure database was developed which comprises an extensive inventory of major infrastructure assets with basic attributes and estimated replacement costs.

2.1 Building Location

The PICs contain thousands of inhabited islands and large sparsely populated land masses (especially in PG) spread over an immense geographic area throughout the Pacific Ocean. The locations of buildings were determined by methods that balance accuracy and economy. In general, buildings were either (Level 1) manually digitized from high-resolution satellite imagery and surveyed in the field (about 80,000 buildings in 11 PICs); (Level 2) manually digitized from high-resolution satellite imagery but not field verified (about 450,000 buildings in all 15 PICs); (Level 3) delineated from clusters of buildings outlined and manually enumerated with moderate to high-resolution imagery (about 35,000 buildings in 6 PICs); (Level 4) inferred using image processing techniques and/or census data (about 3 million buildings in 12 PICs); or (Level 5) extracted from ancillary datasets acquired from government and other sources (e.g., the location of education and health facilities in SB and PG) (about 12,000 buildings in 14 PICs). Table 1 shown previously indicates the number of buildings per country processed using the five different levels of building extraction methods.

Buildings in specified locations of 11 out of the 15 PICs were homogeneously field surveyed by teams of inspectors. Field visits in eight countries (PG, TO, VU, TV, SB, WS, CK, and FJ) were conducted by SOPAC, GNS Science and the Pacific Disaster Center (PDC) under the auspices of both the PCRAFI project and of a sister project financed by the Asian Development Bank. In addition, SOPAC conducted additional field surveys in three countries (KI, PW, and FM). For each surveyed building, photographs and several attributes were collected using a common format (Vocea, 2010). No field surveys were conducted in NR, NU, MH, and TL. In NR and NU, which are very small countries (less than 10,000 inhabitants each), building attribute data was assigned by local experts. Building characteristic data for TL and MH was collected only from high resolution satellite imagery and public sources.

A collection of high-resolution satellite images with pixel resolution of four meters or less were acquired, geo-referenced and manually processed to extract building footprints according to the Level 1 and Level 2 methods. In general, buildings were manually digitized by tracing polygons around the image of the building perimeter with GIS software. The digitization was conducted in a unified and consistent manner for all countries. Generally, roof footprints were digitized as polygons for buildings approximately larger than 30 m^2, whereas buildings smaller than 30 m^2 were usually digitized as points. Most of the major urban areas of the 15 PICs were fully digitized; the entire countries of WS, NR, and NU, and virtually all buildings (over 95%) for PW and CK were fully digitized. Overall, as mentioned above, more than 530,000 buildings were manually digitized, which represents about 15% of all the estimated buildings in the PICs.

Buildings in several second-tier urban areas, as well as those in urban areas with no coverage of high-resolution imagery (especially in PG) and remote islands (especially western Fiji), were interpreted using moderate resolution imagery. Under this Level 3 method, clusters of buildings were outlined by polygons and enumerated manually. The locations of buildings in large polygons were distributed over a 100 meter grid within the polygon boundary. A land use analysis was used to develop the building occupancy classification in these areas.

The Level 4 building extraction method involved computer image processing techniques and was applied mainly in rural areas of the PICs (especially TL, FJ, PG, SB, and VU). A residential building inference was conducted using a three-step process:

1. Low and moderate-resolution satellite imagery was analyzed using computer-aided image processing techniques to identify areas where buildings are most likely to be located. The detection algorithm is primarily based on anomalies of brightness and color with respect to neighboring areas. Image-processing software identified pixels with such anomalies, and adjacent identified pixels were grouped into larger “cells” (either on a 50 or 100 meter grid, depending on the size of the country). Each identified cell is assigned a weighting-factor proportional to the brightness of the associated pixel group.

2. Trended 2010 population counts from a high-resolution regional population database developed for this study are used to estimate the number of people within detected settlements.

3. The average number of persons per dwelling, collected from census data, was used to estimate the number of dwellings and consequently the number of residential buildings (by assuming an average of two buildings per dwelling, as empirically determined in this study).

The Level 4 method was supplemented with ancillary data including land use/land cover (LULC) maps, data sets that indicate village locations, additional census data, and Defence Imagery and Geospatial Organisation (DIGO) data from the Australian Government. Several issues with the automated building detection procedure were identified and corrected (e.g., clouds which falsely indicate built-up areas, the occurrence of unrealistically large number of dwellings per cell, etc.). The image detection parameters were tuned over several iterations and results were spot-checked with high resolution satellite imagery. When image detection was not possible (e.g., cloud cover or forest canopy), building locations were aggregated to the centroid of respective administration areas, and the number of buildings was inferred from population counts. Only about 20,000 dwellings (15,000 in PG) could not be located and were aggregated to the centroids of about 3,000 administration areas, resulting in less than seven dwellings per point location, on average.

The Level 4 building inference method is based on census data which only enumerates residential dwellings. Location and counts of non-residential buildings, including commercial, industrial, and public buildings, are inferred from residential buildings. Data from several sources investigated in this study indicate that 80% to 97% of the total buildings in many given areas in the PICs are used for residential purposes. For rural areas, the ratio is slightly higher, with 88% to 97% of the total buildings used for residential purposes. Thus, for the Level 4 building detection method in rural areas, extra buildings were added randomly among the locations of the detected settlement cells, so that approximately 5% of the buildings are designated as non-residential (e.g., commercial, industrial, public).

2.2 Basic Characteristics and Detailed Attributes of Buildings

Joint statistics of basic characteristics of buildings (e.g., occupancy type, construction type, and number of stories) were determined from the field surveys, local expertise, census data, and other sources. Of the approximately 3.5 million buildings enumerated in the PICs, 4.4% have verified basic characteristic data (e.g., occupancy type and/or construction type) and 2.0% have verified detailed attribute data (e.g., full building attributes collected from the field surveys).

The basic characteristics of remaining buildings were simulated using a Monte Carlo approach based on the empirical data collected. In particular, the construction type of buildings was simulated conditional on the occupancy type. Despite the paucity of field data from rural environments (i.e., 1,500 buildings surveyed in the village of Auki in the Solomon Islands), the empirical distributions of building types in rural and urban environments were differentiated, mainly with the aid of census data. In fact, for single family homes, construction type statistics are well supported by recent census data (generally no earlier than 2000) from each country. The census data usually included statistics of the wall and roof material, along with other data, which was used to infer the construction type. The resolution of census data is generally different for each country. For example, construction data from the census is available for 43 different regions in Samoa, while similar statistics for PG and TL were distinguished only by rural or urban areas. Nevertheless, the construction type of single family houses, which represents more than 90% of all the estimated buildings, were accurately represented (in a statistical sense) at a high resolution for each country. This level of detail allows for an accurate representation of the regional differences within each country. For example, 74% of dwellings in rural areas of PG have traditional style construction, as opposed to 10% in urban areas.

The detailed attributes of all the un-surveyed buildings were also statistically assigned using the same simulation approach based on country-specific distributions of building attributes conditional on occupancy type and building type. These distributions were derived, again, from the field surveyed data and, when available, detailed information from census data. Examples of the distribution of three building attributes for all buildings in PNG are shown in Table 2. In general, when the sample size of the available datasets was large enough, building attributes were simulated from country-specific data. When the sample size was low, attributes were instead simulated from data aggregated from all PICs combined.

Note that distributions of building characteristics and attributes for MH and TL, where field surveys were not conducted, were inferred from statistics extracted from buildings in FM and PG, respectively, as it was felt that the building stock in those countries were reasonably similar due to their close proximity.

Table 2. Empirically based distributions of construction type, foundation type, and roof type conditional on urban and rural areas for buildings in Papua New Guinea.

Construction Type	Urban	Rural	Foundation Type	Urban	Rural	Roof Type	Urban	Rural
Combination Masonry/Concrete & Timber Frame	5.3%	1.2%	Concrete Slab	69.4%	44.3%	Concrete	0.4%	0.1%
Masonry/Concrete	7.6%	1.7%	Load Bearing Wall	0.2%	0.7%	Metal Sheet	88.6%	27.5%
Open Walled	3.6%	0.4%	Pole (>1.0 meter)	9.5%	15.4%	Traditional	8.1%	71.5%
Steel Frame	4.4%	0.8%	Post (<1.0 meter)	14.0%	19.5%	Complex/Other	2.9%	0.8%
Timber Frame	54.2%	18.3%	None	2.9%	13.5%			
Traditional	7.4%	71.3%	Complex/Other	4.0%	6.6%			
Uninhabitable or Poor Construction	15.4%	5.8%						
Other	2.0%	0.5%						

A special note on the building area attribute is in order. The floor area of digitized buildings was assumed to be on average 84% of the roof area to account for the overhang of the roof as per suggestions from the field inspections. For buildings that were not digitized, the floor area was simulated using truncated log-normal probability distribution whose parameters were empirically derived from the survey data and the digitized footprints. These derived distributions are conditional to a given occupancy type.

2.3 Building Replacement Costs

For the risk analysis preformed in this study, the economic losses from direct building damage are computed as a fraction of the replacement cost of the buildings. Country-specific replacement cost values for different construction and occupancy types were collected from a variety of sources, including a construction cost management firm subcontracted for this project (Rawlinsons Jenkins Ltd. based in Suva, Fiji), governmental reports, interviews with local experts, and disaster reports. This information was processed to determine distinct country-specific replacement cost ranges for every building type considered in this study, including those with different occupancy classes, construction classes, and those located in urban or rural areas. Note that, in general, it is difficult to obtain accurate quotes of the building costs for rural areas and for some countries (e.g., Timor-Leste), where the construction industry is generally not well developed. The replacement cost data is expressed in 2010 USD per square meter of the building floor area. The total replacement cost of buildings is simply calculated as the product of the replacement cost, floor area, and number of stories.

2.4 Infrastructure Assets

In addition to residential and non-residential buildings, a detailed inventory of major infrastructure assets (e.g., airports, ports, docks, power plants, dams, mines, major roads, bridges, etc.) was assembled, which comprises their location, type, and characteristics. These parameters allow a categorization of these assets in different vulnerability classes, and replacement cost. Data regarding the location, characteristics, and replacement costs were collected and processed from a wide variety of sources, including the field surveys in 11 of the 15 PICs discussed earlier, manual inspection of high-definition satellite imagery, remote sensing techniques, GIS-based data distributed by SOPAC and GNS Science, DIGO data, publically available databases (e.g., http://carma.org for power plants and http://www.worldaerodata.com for airports), AIR Worldwide's proprietary data, government data, publically available industrial data, and several publications available in the literature. While the infrastructure database cannot be considered exhaustive, it contains a comprehensive inventory of major infrastructure facilities, with a higher level of detail in major urban centers.

Several methods were used to estimate the replacement costs of the infrastructure assets. For example, relative airport costs were estimated from the length and condition (paved/unpaved) of the runway. Similarly, the relative replacement cost of bridges was derived from the length and material of the span. For power plants, replacement costs were estimated based on the energy output as listed by the Carbon Monitoring for Action (CARMA) database. Since major infrastructure assets are typically built to higher standards than residential structures, it is assumed that their quality is similar throughout the entire region. Therefore, average estimates of the unit replacement costs of infrastructure assets are applied to all 15 PICs.

3. DAMAGE FUNCTIONS AND LOSS VALIDATION

The severity of the physical damage experienced by buildings and infrastructure assets from ground shaking is represented by damage functions (DFs) that statistically estimate the loss an asset is expected to suffer when subject to different levels of ground motion intensities. The degree of loss is represented by the damage ratio (DR), which is defined as the ratio of the cost to repair the asset over the total replacement value of the asset. The intensity of the ground motion is gauged by the maximum horizontal peak ground acceleration (PGA) or by the maximum horizontal 5%-damped elastic spectral acceleration (Sa) at oscillator periods of 0.3 and 1.0 seconds. The intensity measures are determined at each asset location. Note that other effects such as landslides, liquefaction, and fire-following earthquake are not explicitly considered.

In addition to construction type and number of stories, several building attributes (e.g., building defect, foundation type, foundation bracing type, roof material, and wall material) were considered in the damage estimation of buildings. These "secondary modifiers" differentiate the vulnerability of buildings within the same construction class. For example, a building with a tall, unbraced, stilt-like foundation (e.g., those common in PG) would be considerably more vulnerable to ground shaking than a similar building with a slab foundation. The effects on the expected losses for buildings that have characteristics related to more than one modifier are cumulative. The extent of the increase or decrease in the vulnerability due to each modifier is based on extensive analytical analyses (and supported, when available, by empirical data) that AIR has conducted mostly outside the scope of this project.

The damage functions for typical buildings in each construction class are primarily developed from AIR's proprietary vulnerability model for building structures. An in-depth study of the characteristics of the buildings in the PICs was used to judiciously select and tune existing DFs from AIR's vulnerability database that were developed for buildings of similar characteristics in other countries with similar construction practices (e.g., Indonesia). The selected DFs were compared and, when appropriate, calibrated using historic building damage data collected from various sources, including a damage reconnaissance study for the 2009 M7.6 Padang Earthquake that struck offshore West Sumatra in Indonesia (Institut Teknologi Bandung, 2010), a disaster report of the 1970 M7.0 Madang Earthquake in Papua New Guinea (Port Moresby Dept. of Lands, Surveys, and Mines, 1973), and an assessment report of the 2002 M7.2 Port Vila Earthquake in Vanuatu (Garaebiti et al., 2002). Average DFs were developed for the entire PIC region, and the relative vulnerability of like buildings in different countries is generally accounted for by the country-specific differences in the distributions of the secondary modifiers.

The losses estimated using the resulting DFs were then compared against the observed losses for several historical events in the region. Comparisons of the modeled economic ground-up losses and reported losses are shown for earthquake events in Figure 3 (the historic losses are trended low and high values reported from several sources, such as NGDC/WDC, 2012). In general, there is a good agreement between the modeled losses and the observed losses. However, some discrepancy between modeled and reported losses for historical events is to be expected mainly for three reasons: firstly, the location of the fault rupture, which may be hundreds of kilometers long in some instances, is highly uncertain given that for many of these events only the epicenter is known with some certainty; secondly, there are virtually no ground motion recordings at any of the sites hit by these earthquakes; and finally, there is usually a significant degree of uncertainty in what the observed or reported losses account for.

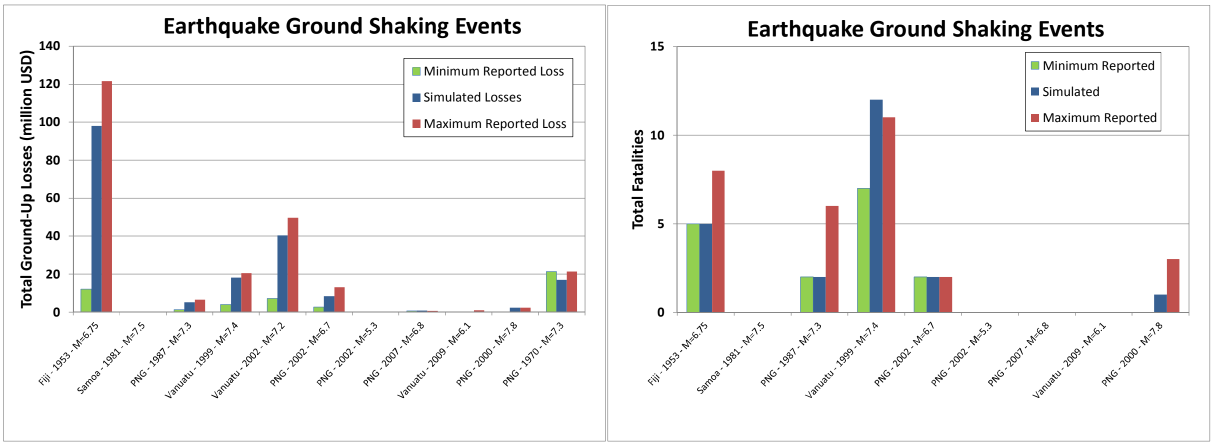

Figure 3. Comparison of reported and simulated economic losses (left panel) and fatalities (right panel) for historical earthquakes

The development of DFs for infrastructure assets follows a similar approach as that described for buildings, except that the DFs are developed for typical assets in each vulnerability class and secondary modifiers are not considered. Infrastructure damage functions use the same input ground motion intensity measures as those mentioned for buildings. The development of infrastructure damage functions is based on AIR's proprietary vulnerability model and, therefore, a detailed description is omitted. These infrastructure damage functions were calibrated and validated with historical data, when available.

4. CASUALTY MODEL

A casualty model was developed to assess the impact on population, i.e., the number of fatalities and injuries (casualties) due to ground shaking from earthquake events. The earthquake fatality model methodology is based primarily on USGS's PAGER system (Wald et al., 2010), which uses empirical methods to estimate fatalities as a function of the shaking intensity and the number of people exposed to such intensities. Specifically, the fatality model for this project uses the same values of the empirical parameters reported by Wald et al. (2010) for the PIC region. At each asset location, the fatality rate is calculated as a function of the PGA intensity. For simplicity, our casualty model assumes that all the population resides in residential dwellings at the time when the earthquake strikes. Figure 3 (right panel) shown previously compares the simulated number of fatalities to reported numbers for some historical earthquakes (i.e. fatalities due to ground shaking only). In addition to the fatality model, an empirical injury model was developed specifically for this project. This model assumes that, on average, there are nine injuries for each fatality caused by ground shaking only. This proportion is empirically derived from data on reported injuries caused by earthquake ground shaking in the region. The simplicity of the injury model is mainly due to the limited amount of injury data.

5. EARTHQUAKE RISK CALCULATION

As discussed, the adverse consequences of earthquakes are measured in terms of ground-up, economic losses to buildings and infrastructure and by the number of casualties among the affected population. The likelihood of future casualty and economic losses due to earthquake ground shaking has been estimated via a probabilistic approach. For each of the 7.6 million M5.0 or greater events in the stochastic catalog which represents 10,000 possible realizations of next year earthquake activity (see companion paper by Rong et al., 2012), the hazard model computes the random fields of ground motion intensities in the affected region. Given the extremely large number of earthquakes considered, the simulated ground motion fields are correlated only via the inter-event error term of the ground motion prediction equation, which is kept constant in each simulation. For each simulated ground motion field, the loss at each building or infrastructure asset was simulated from the corresponding damage function. The losses simulated for each asset are then summed to estimate the total loss caused by the event. This exercise is repeated for all the events in the catalog and the resulting losses are then ranked from the highest to the lowest. An estimate of the loss that has an annual rate of been reached or exceeded 1/10,000 is the highest value. The second highest value has an annual rate of exceedance of 2/10,000, and so on. Alternatively and equivalently, these losses can be thought as having a mean return period (MRP) of exceedance of 10,000 years, 5,000 years, etc. These ranked losses and corresponding annual rates of exceedance (or MRP) can be arranged in what is customarily but somewhat improperly called annual Exceedance Probability curve or EP curve for short. Note that annual rates and annual probabilities are not identical but are numerically very close for small values, which correspond to large loss levels that are usually of most interest. To achieve some higher level confidence in estimates of the losses corresponding to different annual rates of exceedance, the loss simulation procedure explained above has been repeated 100 times, leading to 100 statistically consistent, possible representations of the true, but unknown, EP curve.

As an example, Figure 4 (left panel) shows the median EP curve empirically derived from these 100 simulations for ground-up monetary losses for all the 15 PICs combined, as well as individually for the top five most vulnerable PICs. For a more transparent country-to-country comparison of the risk, the EP curves are normalized by the corresponding 2010 nominal GDP values. As shown in Figure 4, the 15 PICs are expected to collectively suffer a loss due to earthquake ground shaking exceeding about 6% of the total nominal GDP, which corresponds to one billion USD on average, once every 400 years. Figure 4 (right panel) shows the EP curves for casualties for the PICs. The 15 PICs are expected to collectively suffer casualties (injuries plus fatalities) due to earthquake ground shaking exceeding about 5,000 on average, once every 200 years.

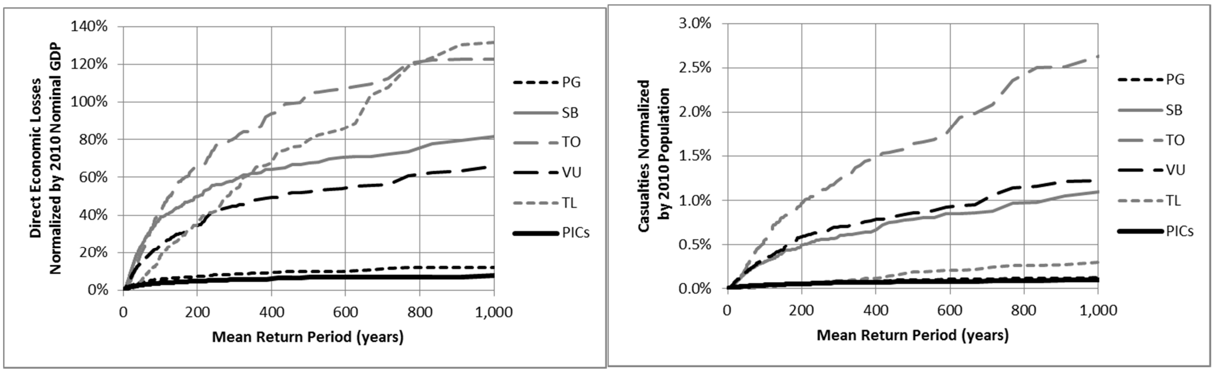

Figure 4. Normalized seismic risk profiles for the PICs: direct economic losses (left panel) and casualties (right panel)

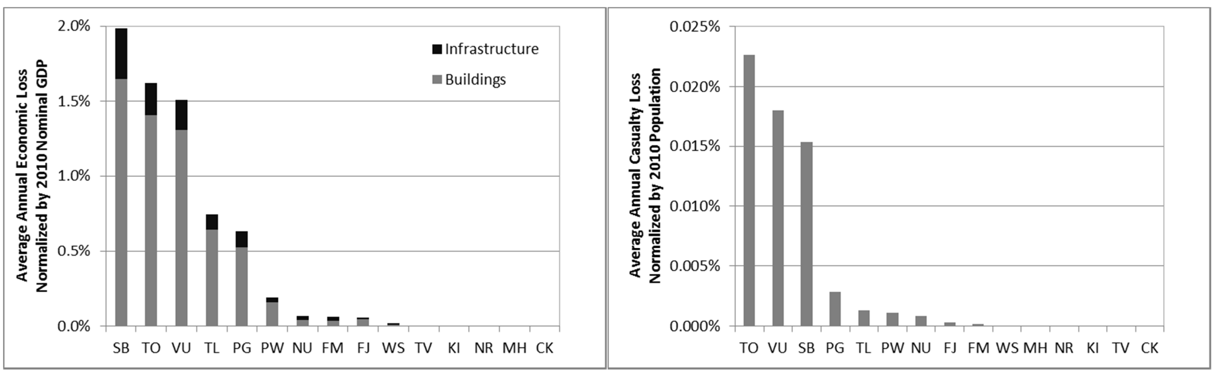

Figure 5. Seismic risk profiles for the 15 PICs measured in terms of normalized average annual loss: direct economic losses (left panel) and casualties (right panel)

As expected, the risk of the countries that are located close or on top of the boundaries of the tectonic plates (e.g., Tonga or Vanuatu) where most of the seismicity occurs (Figure 1) is significantly higher than the risk of others that are farther away (e.g., Cook Islands or Tuvalu). This can be appreciated from Figure 5, which provides an average, long term view of the seismic risk expressed in terms of the average annual loss caused by earthquakes in each country. Although not shown here, EP curves and average annual metrics can also be computed for the losses incurred by assets in different resolutions of administration boundaries for each country (e.g., see Figure 2 such boundaries in PG) as opposed to all assets in the entire country. Note that some countries (e.g., Samoa), are susceptible to catastrophic losses due to earthquake-induced tsunami. Although not presented here, similar quantitative tsunami risk estimates were also determined for each of the 15 PICs for this project.

5. CONCLUSIONS

This article presents a brief overview of a massive effort that lead to the earthquake risk assessment of 15 Pacific Islands Countries. The effort also included the assessment of tropical cyclone and earthquake-induced tsunami; these two additional perils are omitted in this article. The risk profiles computed in this study are, to the authors' knowledge, the first of their kind developed for these 15 PICs.

The country risk profiles can support multiple applications that benefit both public and private stakeholders. In urban and development planning, planners can use the risk profile information to identify the best location of new development areas, evaluate how earthquakes may shape their development, and to assess whether the benefits of reducing the risk of earthquakes justify the costs of implementing risk mitigating measures. In addition, the risk profiles can inform the development of disaster risk financing and insurance solutions and ex ante budget planning options to increase the financial resilience of the countries against earthquakes while maintaining their fiscal balance. The earthquake hazard estimates, which are an intermediate step of the risk assessment procedure, also provide critical information for building codes in terms of country-specific accelerations that buildings should be designed for to ensure adequate shelter to the population. The risk information can also help identify existing vulnerable areas and communities located in or adjacent to these areas. This information can assist in supporting more targeted intervention in community-based disaster risk management. In the occurrence of a natural disaster, the exposure database provides extremely useful baseline data and information for conducting timely and effective post-disaster damage assessments.

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