Comparative Analysis of Economic and Human Casualty Seismic Risk for South American Andean Capital Cities

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SUMMARY:
This paper presents a quantitative, comparative analysis of the impact of future earthquakes on three South American Andean capital cities: Lima, Perú; Quito, Ecuador; and Santiago, Chile. The goal of this study is twofold: (1) quantify the relative seismic risk of the three capital cities and (2) provide a tool to evaluate the potential reduction of loss (both economic and humanitarian impacts) for structural mitigation and construction alternatives. Development of the different model components for assessment of the seismic risk in the capital cities is discussed. A comparative analysis of the three cities shows that Lima faces the highest seismic risk when comparing normalized building losses and total casualties. Total loss is generally highest in Santiago because of high exposure value and high hazard. A mitigation case study for a section of Lima shows that up to 60% of fatalities could be mitigated in a 1746 M8.3 repeat scenario earthquake.

Keywords: seismic risk, mitigation, self-constructed housing, South America

1. PURPOSE AND SCOPE

The capitals included in this study lie along the seismically active northern and western plate boundaries of South America: Lima, Perú; Quito, Ecuador; and Santiago, Chile. These Andean capital cities have some of the highest seismic risk globally. Collectively these four capital cities are home to more than 14 million people (which represent 19-36% of total populations in their respective countries) and generate between 30-50% of their entire countries' Gross Domestic Product (GDP). The South American Capital Cities (SACC) seismic risk project presented is based both on probabilistic and scenario results, which is in contrast to previous hazard and risk studies funded by governments and other development agencies. Previous studies have common themes of focusing on one city or selected districts within one city, being carried out independently, and using scenario-based results. This paper aims to present a method for developing city-wide estimations of people and buildings at risk, building damage and losses, and humanitarian impacts within a probabilistic risk framework. The framework is applicable across all cities such that results can be compared and used in development of loss reduction projects and/or allocation of funding. A sample case study using this approach is presented later in the paper along with suggestions for future applications.

2. SEISMIC RISK ASSESSMENT FOR CAPITAL CITIES

Catastrophe models are used across the insurance industry to assess and manage property and casualty (P&C) risk. People or structures at risk (exposure) are input to these models, which consist of the three main components of hazard, damage, and financial modeling, to estimate loss. These models are probabilistic in nature, with the ability to consider all possible events, defined in a stochastic event set, which could impact a portfolio at risk. A key output from a model is the exceedance probability (EP) curve, which estimates the probability of exceeding a certain loss threshold. RMS models estimate losses from different perils (e.g., earthquakes, hurricanes) and their related hazards (e.g., tsunami, storm surge). A similar approach is applied and presented in this study. Many of the SACC components were developed within the RMS modeling framework such that the seismic hazard and financial modeling components from the commercial model could be utilized. In the following sections, details of the remaining components (i.e., exposure, building vulnerability, and casualty) are described for SACC.

2.1. Building and Population Exposure Development

There are three specific questions that exposure models should address:
(1) For every unique combination of attributes of buildings, what is the number of buildings per unit of analysis area (e.g., number of two-story, steel, commercial, constructed before 1967 buildings per postal code)?
(2) For every unique combination of attributes, what is the number of people per unit of analysis area (e.g., number of people living in two-story, masonry, single-family dwellings, constructed before 1967 in each postal code)
(3) What is the monetary value of building inventory?

The primary building attributes that affect vulnerability are: (1) construction type (e.g., reinforced concrete, steel), (2) year of construction, (3) building height (i.e., number of stories), and (4) construction quality (e.g., low-income areas tend to have higher structural vulnerability). For example, year of construction is important because it can capture whether there have been improvements in the building stock from building codes, especially those that follow a significant event. It is important to identify which of these attributes are important in a given city and group the building exposure based on those attributes.

Depending on data availability and the purpose of the project, the exposure information can be developed at different levels of resolution. Higher resolution enables the risk model to capture variations in building/casualty vulnerability and hazard within the city and therefore provide a more robust assessment of risk.

2.1.1. Exposure model methodology and development

For the South America Capital Cities (SACC) seismic risk assessment project, five main steps were followed to develop the exposure models.

Step1: Gather data, specify the resolution of exposure model, and determine the most important building attributes for vulnerability modeling

Table 2.1 shows the options that were considered for various attributes. With collaboration of our local consultants and due to lack of data, the construction year is not considered in the attributes of the exposure model. Table 2.2 shows the data sources used for development of exposure in each city. In all cities, collaboration with local experts played a pivotal role in understanding the building characteristics important for vulnerability development, defining inventory regions, and developing replacement cost values. All cities are developed for residential (single- and multi-family dwellings), commercial, and industrial occupancies. The exposure models are developed on 1km by 1km grids from the LandScan^{TM} (2009) dataset.

Table 2.1. SACC primary building attributes used in exposure model development

Construction Class: Light Wood Frame; Adobe; Bahareque; Unreinforced Masonry (URM)-Solid Brick; URM-Hollow Brick; Reinforced Masonry (RM); Confined Masonry (CM); Reinforced Concrete (RC) Moment Resisting Frame (MRF); RC MRF with Shear Walls; RC Shear Wall; RC MRF with Solid Brick URM Infill; RC MRF with Hollow Brick URM Infill; Steel MRF; Steel MRF with URM Infill; Braced Steel Frame; Light Metal Frame with Solid Brick URM Infill; Light Metal Frame with Hollow Brick URM Infill
Occupancy: Residential (Single- and Multi-family Dwellings); Commercial; Industrial
Number of Stories (Building Height Bands): 1-story (very low-rise); 2-3 stories (low-rise); 4-7 stories (mid-rise); 8-14 stories (high-rise); 15+ stories (tall)
Construction Quality: Engineered and Self-Built (Lima, Santiago); Low and High Quality (Quito)

Table 2.2. Data sources used in SACC exposure models

City	Characteristic	Source	Resolution
Lima	Building	Census (2007) Local experts	43 districts aggregated to 10 inventory zones
	Population	Census (2007) LandScan™ (2009)	Census: 43 districts LandScan™: 1-kilometer grids
	Replacement Cost Value	Local experts	Ten inventory zones
Santiago	Building	Census (2002) Local experts	32 comunas
	Population	Census (2007) LandScan™ (2009)	Census: 32 comunas LandScan™: 1-kilometer grids
	Replacement Cost Value	Local experts	32 comunas; varies by construction type and number of stories
Quito	Building	Census (2001) Local Experts	32 urban parishes grouped into 15 inventory zones
	Population	Census (2001) LandScan™ (2009)	Census: 32 parishes LandScan™: 1 kilometer grids
	Replacement Cost Value	Quito Municipality (2004) Local experts	Three socioeconomic levels; varies by construction type and number of stories

Step 2: Identify building inventory regions based on similar characteristics and construction practices
Lima consists of 43 districts. A local consultant grouped these districts into 10 "inventory zones" based on the socioeconomic study conducted by Asociación Peruana de Empresas de Investigación de Mercado APEIM (2007). The information on number of buildings for different occupancies and the type of exterior wall was extracted from census data and was mapped to construction class options in Table 2.1. Sub-regions of informal housing were defined based on the study conducted by United Nations Human Settlements Programme (UN-Habitat, 2003). These regions were assigned "self-built" construction quality, which means higher vulnerability for the same construction class relative to other regions.

The Municipality of Quito divides the city into 32 urban parishes. The 2001 census (INEC, 2001) provides population and building counts for each parish. A local consultant grouped parishes into 15 inventory zones based on construction data available from the "Cámara de la Construcción de Quito" (2009) and socioeconomic statistics obtained directly from city representatives at the office of the Municipality of Quito. Each inventory zone is assigned a specific socioeconomic level based on data from the Quito municipality and local consultants. These levels are later used in refining the assignment of vulnerability levels and replacement costs for different construction types.

The inventory regions for Santiago were developed individually for its 32 comunas. The dwelling counts for single- and multi-family dwellings in each comuna are extracted from the census. Assumptions on number of dwellings per buildings at different height bands were made by our local consultant based on national numbers from the census. Due to lack of data, numbers of buildings for commercial and industrial occupancies are assumed to be relative to multi-family dwelling building count. Inventory assumptions of building distribution for different construction types are also developed based on expert opinion from a local consultant.

Step 3: Spatially distribute regional building counts based on population concentrations and regional inventory distribution factors
Once the total count of buildings is specified in each inventory region, buildings are spatially distributed within the region proportional to local population concentrations. The underlying assumption is that concentrations of buildings and population are directly related. In this project, the LandScan™ (2009) grid is used as the basis of building disaggregation. Therefore, the final resolution of exposure in all three cities is based on the LandScan™ 1-km grid. The final goal in development of building exposure is to quantify the number of buildings per unit area for every unique combination of building attributes. In this project, distribution factors are based on attributes from the inventory

regions. Once numbers of buildings per grid are calculated, regional distribution factors are applied to all grids within that region.

Step 4: Distribute population into buildings based on regional population distribution factors
In order to distribute the population into buildings, assumptions about the number of people per building in each inventory zone are used. Two scenarios are considered to account for the mobility of people. First, the census population data are assumed to be the night-time scenario, as the population is concentrated in residential buildings. Second, LandScan™ data are an estimate of population that is averaged over 24 hours; it is assumed to be an average of day and night conditions. Therefore, portions of the population for this second scenario are placed in commercial and industrial buildings.

Step 5: Assign monetary value to building inventory
The total replacement cost per building is the total floor area multiplied by replacement value per unit of floor area. In Lima, the assumptions on average floor area per occupancy are made based on different socioeconomic levels of each zone and vary by occupancy, height, construction class and whether the building is self-constructed. In Quito, three base replacement costs are assumed for reinforced concrete buildings by local consultants for three socioeconomic levels. Other construction types are defined relative to this base. For Santiago, average area and cost per building are defined based on national-level information extracted from the census. At each comuna, the base is then multiplied by a comuna-specific relativity factor. Due to lack of sufficient data, replacement values for commercial buildings at each comuna are defined relative to multi-family dwellings of that comuna.

2.1.2. Exposure summary of the cities
Table 2.3 summarizes the exposure model in each city

Table 2.3. Summary of exposure models for all cities

City	Occupancy	No. of Stories	Total No. of Buildings	Total Bldg. Val. ($USD Millions)	Total Floor Area (m^2)	Total Pop. (Night)	Total Pop. (24hr Avg.)
Lima	Residential	1-3	1,657,917	68,535	1,271,759	7,499,777	2,721,875
		4-7	12,649	253	1,271,573	75,295	23,796
		8-14	11,060	12,969	26,263,527	740,427	247,856
		15+	590	1,330	2,319,793	75,588	36,879
	COM/IND	1-3	131,588	36,706	89,785,823	0	4,339,297
		4-7	13,841	8,138	19,732,747	0	1,060,714
		8-14	1,466	1,724	4,453,670	0	279,276
		15+	378	834	2,137,212	0	136,157
Santiago	Residential	1-3	945,589	107,050	153,437,392	3,781,960	1,722,636
		4-7	26,509	7,050	8,909,199	198,994	45,425
		8-14	7,060	8,010	5,388,214	109,666	26,413
		15+	6,388	34,000	19,363,584	141,388	34,660
	COM/IND	1-3	106,374	30,500	56,036,975	0	1,431,129
		4-7	22,517	18,900	17,990,602	0	625,584
		8-14	9,992	42,500	32,587,646	0	488,963
		15+	4,387	37,400	22,491,837	0	477,649
Quito	Residential	1-3	194,010	13,319	41,202,849	831,419	505,690
		4-7	26,145	5,599	17,810,674	273,262	171,588
		8-14	10,197	7,884	19,893,978	297,595	207,152
		15+	3,773	9,280	17,789,051	244,543	132,905
	COM/IND	1-3	12,941	2,521	8,751,373	16,948	201,024
		4-7	3,537	2,521	6,900,559	7,091	304,162
		8-14	859	1,934	4,050,038	2,542	213,767
		15+	97	363	788,515	425	61,984

2.2. Seismic Hazard Component

To assess the potential risk to the South American capital cities in this study within a probabilistic framework, the RMS commercial model components for the stochastic event set and ground motion were used. The stochastic event set is a set of simulated earthquakes characterizing the observed or scientifically modeled probabilities of earthquake size, frequency of occurrence, and location. For every stochastic event, the ground motion is calculated at each building site.

2.3. Building Vulnerability

Building vulnerability functions define the relationship between earthquake intensity and building damage. The Modified Mercalli Intensity (MMI) scale is used to quantify the intensity of ground shaking at a site. The Mean Damage Ratio (MDR), which represents the expected value of a building's repair or replacement cost normalized by its total replacement cost, is used to quantify the expected building loss at a given earthquake intensity.

Compared to what is commonly done for vulnerability function development (Aslani, 2005), SACC uses a simplified approach: (1) Start with a "reference vulnerability function" that represents typical building performance for a given set of characteristics in a particular city; (2) Estimate the relative damageability of other building types compared to the reference building and use factors to develop vulnerability functions for all other building types; (3) Test the resulting vulnerability functions with exposure and hazard models; (4) Modify relativity factors until relativity factors, vulnerability functions, and modelled losses are collectively consistent with all available data.

The reference vulnerability function and relativity factors were defined using a consensus-based approach with consultants in each city. Table 2.4 shows the reference vulnerability function, which represents a typical one-story reinforced concrete (RC) building in Lima.

Table 2.4. SACC reference vulnerability function

MMI	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12
Ref. Func.	0	0.15	0.35	0.75	1.5	2.8	4.5	6.7	10	15.5	23	33	45	57	68

Relativity factors of 3.10, 1.50, 1.00, and 0.70 are used to quantify the performance of one-story buildings that are constructed using unreinforced masonry (URM), confined masonry (CM), reinforced concrete (RC), and steel, respectively. In Quito, steel is uncommon and has only been used recently, so steel buildings in Quito use a relativity factor of 0.85 instead of 0.70. To prevent the curves from saturating at 100% quickly, these factors converge towards 1.0 as the MMI increases. In order to determine the vulnerability function for adobe structures, the unreinforced masonry (URM) function is increased by 15%. For wood frame structures, the steel function is increased by 20%. The product of the reference function with these construction type relativities produces the vulnerability functions in Table 2.5 for low-rise buildings in Lima.

Table 2.5. Vulnerability functions for one-story buildings in Lima with good construction quality

MMI	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12
Adobe	0	0.5	1.2	2.6	5.2	9.6	14.9	21.3	30.6	45.5	65.3	90.5	100	100	100
URM	0	0.5	1.1	2.3	4.6	8.3	13.0	18.5	26.6	39.6	56.8	78.7	100	100	100
CM	0	0.2	0.5	1.1	2.2	4.1	6.5	9.5	14.0	21.2	31.1	43.9	59.3	74.7	88.7
RC	0	0.2	0.4	0.8	1.5	2.8	4.5	6.7	10.0	15.5	23.0	33.0	45	57	68
Wood	0	0.1	0.1	0.6	1.3	2.4	4.0	6.0	9.2	14.5	21.8	31.8	43.7	55.7	66.7

Height relativity factors are used to quantify the relative performance of buildings with different heights. They are only used in Lima and Quito as advised by local consultants. For 1-story, 2-3 stories, 4-7 stories, 8-14 stories, and 15 stories and greater, the relativity factors of 1.00, 1.12, 1.07, 0.92, and 0.85 were used, respectively. In Santiago, it was deemed appropriate to implement no variation by height; the height relativity factors are 1.0. These height relativities converge towards 1.0 with increasing earthquake intensity in a similar fashion as the construction type relativities. Applying these height relativity factors to the reference curve produces vulnerability functions in Table 2.6 for confined masonry (CM) and reinforced concrete (RC) buildings in Lima and Quito.

Informal and engineered construction is identified for some areas of the cities where buildings are relatively vulnerable in the exposure model. Table 2.7 shows the relativity factors used to develop the vulnerability functions for these relatively-vulnerable buildings in each city. These factors are used in regions where the construction consists primarily of non-engineered buildings, such as in the “barrios” of capital cities.

Table 2.6. Vulnerability functions for well-constructed confined masonry (CM) and reinforced concrete (RC) buildings in Lima and Quito

MMI	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12
CM (1 ST)	0	0.2	0.5	1.1	2.2	4.1	6.5	9.5	14.0	21.2	31.1	43.9	59.3	74.7	88.7
CM (2-3 ST)	0	0.3	0.6	1.3	2.5	4.6	7.2	10.5	15.3	23.1	33.7	47.4	63.8	80.2	95.2
RC (2-3 ST)	0	0.2	0.4	0.8	1.7	3.1	5.0	7.4	10.9	16.9	24.9	35.6	48.4	61.2	73.0
RC (4-7 ST)	0	0.2	0.4	0.8	1.6	3.0	4.8	7.1	10.6	16.3	24.1	34.5	47.0	59.5	70.9

Table 2.7. Construction quality relativity factors used for relatively-vulnerable construction in all three cities

Construction Type\MDR	0%	5%	10%	50%	100%
Wood	1.60	1.58	1.53	1.48	1.42
Masonry	1.60	1.58	1.53	1.48	1.42
Reinforced Concrete	2.00	1.96	1.88	1.80	1.70
Steel	2.00	1.96	1.88	1.80	1.70

2.4. Casualty Modeling

A casualty vulnerability rate is defined as the ratio of the number of people injured to the number of people exposed for two injury states (fatal and injured) when subjected to a given level of ground motion. The degree and type of damage, specifically the type of collapse, are drivers of casualties. Certain construction classes, such as unreinforced masonry, are much more likely to collapse without survival space, contributing to the large numbers of casualties attributable to these construction classes. The modeled injuries are divided into two states, fatal and (seriously) injured.

Table 2.8. SACC casualty rates (%) for fatalities and serious injuries by construction type (*WD = Wood/Light Metal, URM = Unreinf. Masonry, RM = Reinf. Masonry, RC = Reinf. Concrete, and STL = Steel)

	Fatality Casualty Rates (%)					Serious Injury Casualty Rates (%)				
MDR	WD	URM	RM	RC	STL	WD	URM	RM	RC	STL
0%	0	0	0	0	0	0	0	0	0	0
1%	0.0000	0.0001	0.0000	0.0001	0.0000	0.0001	0.0002	0.0001	0.0008	0.0002
2.5%	0.0000	0.0003	0.0002	0.0005	0.0001	0.0005	0.0008	0.0005	0.0038	0.0012
5%	0.0015	0.0216	0.0180	0.0115	0.0051	0.0268	0.0378	0.0309	0.0480	0.0608
10%	0.0023	0.7509	0.4857	0.3121	0.0073	0.0407	1.3666	0.8622	1.3052	0.0871
15%	0.0036	1.0362	0.6521	0.4185	0.0105	0.0607	1.9885	1.2135	1.7434	0.1228
20%	0.0055	1.4187	0.8708	0.5531	0.0148	0.0891	2.9046	1.7242	2.2886	0.1705
25%	0.0084	1.9263	1.1567	0.7208	0.0209	0.1290	4.2380	2.4681	2.9525	0.2335
30%	0.0127	2.5897	1.5277	0.9264	0.0293	0.1844	6.1274	3.5390	3.7440	0.3157
35%	0.0192	3.4383	2.0032	1.1744	0.0410	0.2603	8.6988	5.0400	4.6677	0.4221
40%	0.0288	4.4937	2.6008	1.4688	0.0573	0.3637	12.019	7.0605	5.7223	0.5589
45%	0.0430	5.7626	3.3326	1.8130	0.0804	0.5032	16.048	9.6428	6.9004	0.7343
50%	0.0636	7.2313	4.2001	2.2094	0.1129	0.6900	20.598	12.745	8.1878	0.9585
55%	0.0931	8.8654	5.1911	2.6594	0.1585	0.9378	25.349	16.219	9.5638	1.2447
60%	0.1346	10.615	6.2796	3.1628	0.2222	1.2632	29.893	19.809	11.0020	1.6094
65%	0.1917	12.428	7.4301	3.7183	0.3098	1.6853	33.845	23.198	12.4720	2.0720
70%	0.2686	14.261	8.6051	4.3230	0.4282	2.2248	36.942	26.077	13.941	2.6546
75%	0.3693	16.086	9.7743	4.9724	0.5845	2.9021	39.125	28.226	15.377	3.3795
80%	0.4977	17.898	10.921	5.6608	0.7855	3.7350	40.540	29.574	16.750	4.2669
85%	0.6566	19.699	12.044	6.3809	1.0362	4.7350	41.476	30.217	18.034	5.3305
90%	0.8469	21.491	13.153	7.1237	1.3387	5.9033	42.263	30.381	19.208	6.5725
95%	1.0670	23.262	14.262	7.8792	1.6905	7.2271	43.164	30.348	20.258	7.9785
100%	1.3122	24.980	15.377	8.6357	2.0833	8.6763	44.313	30.374	21.177	9.5136

The casualty modeling method developed and implemented is used in conjunction with building damage/loss estimates to determine the full impact of seismic risk in the three cities. Casualty rates are compiled using an event tree approach based on a method from Coburn & Spence (1992) to determine injuries and fatalities. The casualty rate curves are MMI-based and developed using a collapse-based methodology. There were five main construction classes for which fatality and total injury rate curves were developed: wood/light metal, reinforced concrete, steel, unreinforced masonry, and reinforced masonry. Table 2.8 shows the casualty rates by construction class and mean damage ratio (MDR).

2.6. Calibration/Validation Discussion

Calibration and validation of the model components developed for this study were based on comparing city relativities in exposure and loss results as mentioned in previous sections. Scenario-based results were also used to calibrate/validate the building and casualty vulnerability components. One extra step was taken to validate the casualty rates for large earthquakes in applying them to a repeat of the 2010 Haiti event to confirm that the fatality estimates are within the range of estimates projected in early February 2010 by RMS (2010).

2.6.1. Scenario-based calibration of model components

To calibrate the SACC building and casualty vulnerabilities, both large and small earthquakes were considered. The smaller earthquakes (i.e., non-loss causing events) were used to constrain the casualty rates for smaller intensities and building mean damage ratios. For larger earthquakes, the casualty rates were calibrated with information from the project's South American consultants and worldwide earthquake data. Building damage and casualty estimates for 1 small and 1 large earthquake are presented in Table 2.9 for the 3 cities. Some of the casualty estimates for the small earthquake are higher than those reported, but the overall casualty rate (number of casualties/population exposed) is very small (Table 2.9).

The larger earthquakes are either scenarios or a historical event that happened too long ago to directly compare reported damage and casualties to model estimates. In this case, the relativities between the cities in the injury and fatality rates for a suite of large earthquakes in each city are examined. For example, the estimated property loss from the large events in Lima and Santiago are similar in building loss ratio (7.1% vs. 6.5%) and casualty rates (0.85% vs. 0.90%), whereas the Quito event is much lower (4.4% and 0.24%). This can be attributed to the characteristics of the event hazard; there are higher ground motions from the larger earthquakes in Lima and Santiago compared to Quito.

Table 2.9. SACC casualty calibration/validation results for Lima, Quito, and Santiago census exposures

City	Event/Scenario	#Serious Injuries	#Fatalities	Building Loss Ratio	Injury Rate	Fatality Rate
Lima	1746 Lima M8.3	46,200	25,100	7.1%	0.55%	0.30%
	2007 Pisco M8.0	<200	<100	1.4%	<0.002%	<0.001%
Quito	M6.5 Quito Fault	2,700	900	4.4%	0.18%	0.06%
	1987 Ecuador	<5	<1	0.3%	<0.001%	<0.001%
Santiago	M6.8 San Ramón Fault	27,300	14,000	6.5%	0.59%	0.31%
	2010 Maule M8.8	<350	<200	1.4%	<0.007%	<0.004%

2.6.2. Casualty rate validation with the 2010 Haiti earthquake

In order to calibrate the casualty rate curves for the South American cities, they were applied to a reconstruction of the 2010 Haiti Earthquake. Following the 2010 disaster, RMS released an FAQ document to discuss the earthquake risk on January 22, 2010 (RMS, 2010). This document included a casualty estimate for the total fatalities anticipated from the earthquake (250,000). The actual death toll from the earthquake is still uncertain; the Haitian government, NGO's, and other studies estimate fatalities range from about 50,000 up to 320,000. The January 2010 casualty estimates were developed using publically available information including population data, ground shaking intensities, and

Haitian construction materials and practices. When applying the casualty rates from the study, the self-built URM curves (closest to the Haitian building stock quality) yielded fatalities of 190,000-200,000 for the Haiti earthquake.

2.7. Probabilistic Risk Assessment

A key output from the SACC model is the exceedance probability (EP) curve, which estimates the annual probability of exceeding various loss thresholds. The reciprocal of this annual probability is what is usually referred to as the return period of loss. Another key output of the model is average annual loss (AAL), which is the area under the EP curve. It is a single loss metric that accounts for both the severity and frequency of all possible events.

Fig 2.1 shows the EP curve for all three cities. Due to relatively low exposure and low hazard in Quito, the exceedance probabilities of loss thresholds in Quito are lower than Santiago and Lima. Table 2.10 shows the losses for different return periods.

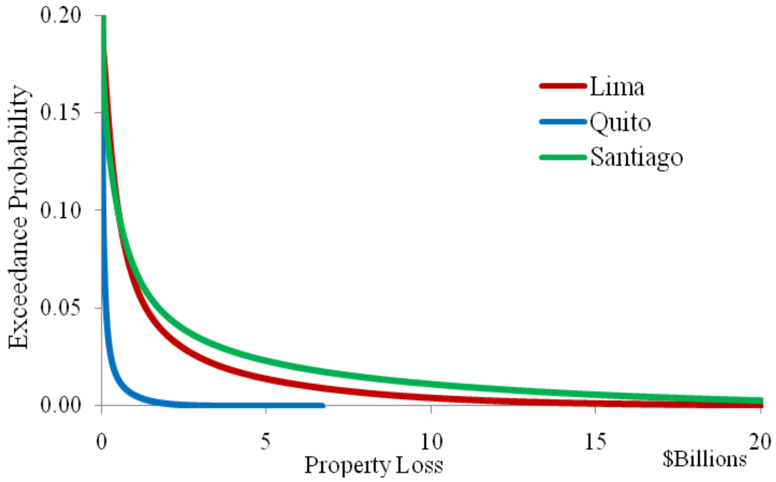

Figure 2.1. Exceedance probability curves for Quito, Lima, and Santiago

Table 2.10. Losses for Quito, Lima, and Santiago

City	AAL (USD)	Total Exposure (USD)	Loss Cost	OEP-50	OEP-100	OEP-500
Quito	27,400,000	41,530,000,000	$0.66	337,500,000	641,300,000	1,660,000,000
Lima	281,700,000	131,200,000,000	$2.15	3,513,000,000	6,165,000,000	12,945,000,000
Santiago	419,200,000	320,400,000,000	$1.31	5,908,000,000	10,934,000,000	22,282,000,000

Another measure of relative risk among the cities is the loss cost, which is defined as the average annual loss per 1,000 unit cost (i.e., $USD) of exposure. Note that although Santiago has the highest average annual loss, its loss cost is lower than Lima (Table 2.10). This is indicative of lower hazard in Santiago relative to Lima and less-vulnerable buildings. The loss costs vary regionally within each city. In Quito, loss costs range from $0.27 to $1.30 whereas in Santiago this range is between $0.97 and $2.87. In Lima, the minimum loss cost is $1.66 (higher than Santiago's city-wide loss cost) but the maximum loss cost is $2.73, which is similar to Santiago's maximum loss cost.

Table 2.11 summarizes casualty results for the cities. Overall, Lima's casualty rates are higher than in Santiago and Quito for all perspectives. Similar to the building loss results in Table 2.10, Lima's higher hazard and more-vulnerable building stock produce higher casualty losses. Night-time scenarios show higher rates of fatality and injury because commercial buildings usually have better construction quality than residential buildings (Table 2.11).

Table 2.11. SACC casualty probabilistic results

Loss Perspective	City	Night		24 Hour Avg.		Night		24 Hour Avg.	
		Total Injuries	Total Fatalities	Total Injuries	Total Fatalities	Injury Rate	Fatality Rate	Injury Rate	Fatality Rate
Average Annual Casualty	Lima	615	334	503	272	0.007%	0.004%	0.006%	0.003%
	Santiago	318	168	176	90	0.007%	0.004%	0.004%	0.002%
	Quito	13	4	14	4	0.001%	0.000%	0.001%	0.000%
1-50 OEP	Lima	4,776	2,648	2,931	1,621	0.057%	0.032%	0.033%	0.018%
	Santiago	1,561	858	744	397	0.034%	0.019%	0.018%	0.010%
	Quito	15	3	17	3	0.001%	0.000%	0.001%	0.000%
1-100 OEP	Lima	24,008	13,158	17,545	9,687	0.287%	0.157%	0.199%	0.110%
	Santiago	13,952	7,551	6,445	3,459	0.303%	0.164%	0.158%	0.085%
	Quito	100	30	114	31	0.007%	0.002%	0.007%	0.002%
1-500 OEP	Lima	62,446	33,217	59,427	30,965	0.746%	0.397%	0.673%	0.350%
	Santiago	34,235	17,768	19,943	10,052	0.744%	0.386%	0.488%	0.246%
	Quito	2,039	695	2,287	696	0.137%	0.047%	0.136%	0.041%

3. COMPARATIVE ANALYSIS FOR EXAMPLE MITIGATION ALTERNATIVE

3.1. Case Study: Improve Informal and Poor Construction in Lima's Inventory Zone #3

Probabilistic loss estimation can also be a tool to evaluate the potential reduction of loss (both economic and humanitarian impacts) for structural mitigation and construction alternatives. For many decisions such as regional mitigation resource allocation, it is important to consider all possible earthquakes because an optimal decision for one earthquake might be ineffective for another. Therefore, compared to a deterministic approach, probabilistic loss estimation provides a better, more comprehensive tool for evaluating mitigation alternatives.

As an illustrative example, the district of San Juan de Lurigancho in Lima (Inventory Zone #3) is considered for a mitigation case study. Self-built and more-vulnerable construction (e.g., URM, Adobe) make up 66% of the buildings and 18% of the total exposure value in this district. While the low value of these buildings may seem as a disincentive for retrofit, it is often true that these buildings have higher concentrations of people and therefore any retrofit action could potentially reduce casualties.

A possible retrofit action can be rebuilding or retrofitting the buildings in Zone #3 such that their seismic performance approximates engineered construction. In addition to replacing self-constructed buildings, we assume that adobe and URM buildings are replaced with confined masonry, which is a less-vulnerable construction type. While this could be an expensive measure to undertake, the results in Table 3.1 illustrate the expected benefits of these measures. Average annual losses for buildings decrease by 9%. The spatial distribution of loss costs in Zone #3 clearly shows that the greatest reduction in loss cost happens where self-built regions are located (Fig. 3.1). The value of applying mitigation measures could also be illustrated by looking at a 1746 scenario for the city and how the number of casualties is impacted. While the mitigation measure reduces the property losses by 10%, serious injuries and fatalities for this earthquake are reduced by 60% and 61%, respectively.

Table 3.1. Improvement in property loss due to mitigation

Return Period	Loss Before Mitigation (USD)	Loss After Mitigation (USD)	Improvement
500 Years	777,444,445	706,651,768	-9%
100 Years	349,669,808	314,067,814	-10%
50 Years	190,502,057	171,473,815	-10%

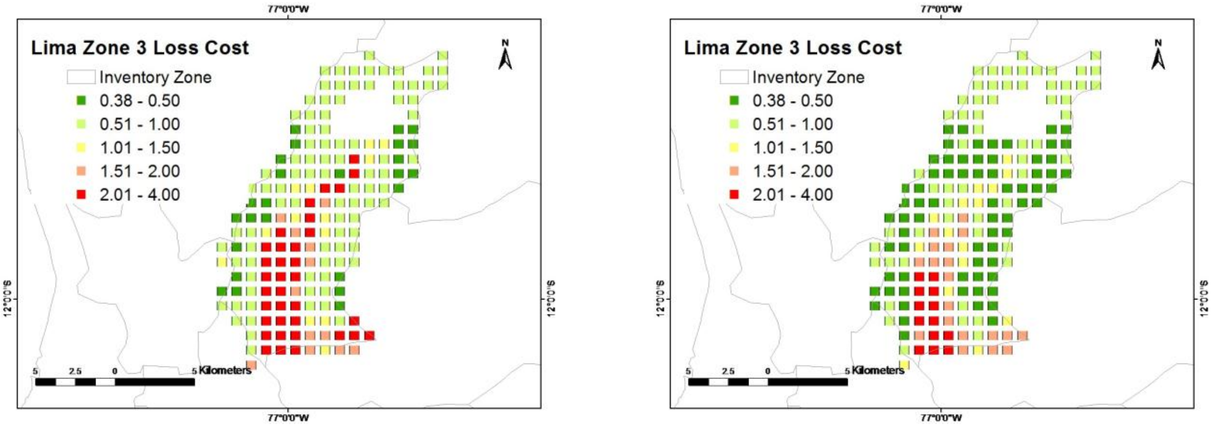

Figure 3.1. The spatial distribution of loss costs before (left) and after (right) mitigation in Lima Zone #3

3.2. Potential Future Applications

Probabilistic loss analysis can provide a platform for comparative risk analysis among different regions with common loss metrics (e.g., exceedance probability curves, loss costs). This can give governments and multi-national organizations a more robust perspective of relative risk in a region. Moreover, because these models simulate all plausible scenarios in a region, they can provide a tool for contingency planners and policy makers to prioritize retrofit actions to the measures and locations that will have the highest expected reduction in risk. Opportunities exist to build on this study both in improving model inputs and including a full cost-benefit analysis for various mitigation measures. Refining the definitions of structural mitigation measures and including budgetary constraints can improve future cost-benefit analyses that leverage the SACC modeling framework.

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