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THE APPLICATION OF A UNIFORM FRAMEWORK OF SEISMIC VULNERABILITY ASSESSMENT TO SOUTH AMERICAN COUNTRIES

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Summary
Seismic loss estimation faces multiple challenges pertaining to the modeling of regional seismicity, ground motion, exposure distribution and vulnerability assessment. A common approach in modelling vulnerability in this context is to group buildings with similar seismic behavior based on construction material, structural system and height. This approach is adequate provided that seismic performance of the buildings does not significantly vary temporally and spatially within the model domain. This is however not the case in South America or in many regions of the world. This paper focuses on presenting the local information necessary for the application of a uniform framework of seismic vulnerability assessment to South American countries based on the stringency of design codes. An application of the vulnerability framework to building age distributions in different regions is also presented.

Keywords: Loss estimation, risk analysis, vulnerability assessment.

Introduction
Economic loss estimates from possible future earthquakes are of key importance to emergency planners and financial institutions in mitigating and managing seismic risk. These parties, as well as government organizations rely on regional risk analysis to make strategic decisions. Catastrophe models have emerged as sophisticated and popular tools in aiding said organizations reach their goals. In the past few decades these models have advanced to take into account many factors affecting earthquake risk. These factors can be categorized into three model components, or modules, within a catastrophe model. The hazard module accounts for the seismic sources and the generated ground motion. The exposure module accounts for the elements (buildings, infrastructure etc) at risk from earthquake damage; and the vulnerability module, which is the focus of this paper. The vulnerability module translates the hazard to expected damage for each building hence enabling a monetary estimate of the damage. Each component is integrated in a probabilistic manner to provide a balanced view of the risk.

In an ideal situation, the vulnerability module would employ detailed, computer intensive, structural analysis of each building. This method however becomes computationally intractable, due to the large number of buildings in the model domain. The AIR Worldwide model applies damage functions derived through Non-Linear Dynamic Time History Analysis of multiple degree of freedom systems representative of building groups. Each group of buildings is approximated by buildings which have similar seismic behavior. Many factors determine the

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damage function applied to a specific group of buildings, such as, the country, the construction material, structural type, height and the age of the construction.

Age of construction, or the year built has an impact on a building's vulnerability due to the design and construction practices used in the place and time of construction. Internationally, the lessons learnt from earthquake damage have led to improved seismic design and construction practices, and have lowered building vulnerability. Each country has a unique seismic design and construction practice development history. A major challenge in regional risk analysis covering several countries has been to systematically represent the spatial and temporal variability in vulnerability across countries due to different seismic design practices. An additional challenge is that local practice might differ from that stated in design codes, with some countries strictly enforcing provisions while others not.

Several frameworks to capture the varying vulnerability due to different design practices exist. HAZUS (FEMA/NIBS, 1999) and EMS-98 (Grünthal et al., 1998) provide criteria to define the vulnerability class of a structure. HAZUS defines its vulnerability classes ("Special-Code", "High-Code", "Low-Code" and "Pre-Code") as the seismic performance obtained in different zones of the UBC 1976.

This study will employ a framework detailed in (Lai et al., 2012). This method, similar to EMS-98 and HAZUS defines vulnerability classes. The method uses five main vulnerability classes ("pre code" (PC), "low code" (LC), "moderate code" (MC), "high code" (HC) and "special code" (SC) defined by a range of base shear coefficients. The base shear coefficient ranges for each class are based on the IBC-2009 code for a 5-story ordinary reinforced concrete frame. The method introduces sublevels to the main vulnerability classes to allow for finer differentiation as shown in Table 1. The vulnerability classes and their sub levels are abbreviated in this study. For example Low Code Sub-Level II is abbreviated as LC2.

Table 1. Vulnerability classes (calculated for a five story RC frame) (Lai et al., 2012).

Vulnerability Class	Sub-Level	Base Shear Coefficient	
		Min (>=)	Max (<)
Pre Code (PC)	I	0.000	0.035
Low Code (LC)	I	0.035	0.055
	II	0.055	0.090
Moderate Code (MC)	I	0.090	0.115
	II	0.115	0.130
	III	0.130	0.150
High Code (HC)	I	0.150	0.175
	II	0.175	0.200
	III	0.200	0.220
Special Code (SC)	I	0.220	0.300
	II	0.300	0.400
	III	0.400	0.500
	IV	0.500	-

This paper focuses on the application of the previously described framework to South American countries. The study conducted on the evolution of seismic design codes for Venezuela, Colombia, Ecuador, Peru and Chile is detailed. Emphasis is placed on information provided by local engineers, which is crucial to form a realistic view of code development and stringency in each country.

Development of Seismic Design Codes in South America

As is common throughout the world, the damage caused by earthquakes leads to the development of seismic design codes. The western Coast of South America has a long history of destructive earthquakes (NOAA, 2013), which have driven seismic code and construction practice development. The following section will detail the codes and their enforcement periods in Venezuela, Colombia, Ecuador, Peru and Chile; as well as any damaging earthquakes that drove code development in the affected country.

Table 2. Venezuelan code development history

Year	Event	Comment
1929	6.9Mw Earthquake	Affected the Cumana Area causing 50 deaths (NOAA, 2013). Steel structures performed well. RC performance varied with quality of concrete mix (Paige, 1930).
1939	First Seismic Code, MOP 1939	The basic provisions of this code were not enforced according to the local engineer consulted for this study.
1947	Code Update, MOP 1947	First zonation map based on known effects of past earthquakes. Seismic design forces did not vary with building height or structural period (MOP, 1947). Based on the static method of analysis from the UBC (Paz, 1994).
1955	Code Update, MOP 1955	Updated zonation map. Seismic design forces are varied with building height (MOP, 1955).
1967	6.6Mw Earthquake	Pockets of high damage in Caracas. In the neighborhoods of Los Palos Grandes and Altamira considerable damages were observed to mid-rise and high-rise RC Buildings (Degenkolb & Hanson, 1969).
1967	Code Update, MOP 1967	Updates zonation map. Dynamic analysis becomes mandatory for high-rise buildings and soil type definitions were updated (MOP, 1967).
1982	Code Update, COVENIN 1756-82	Introduces ductility levels and reduction factors. Influenced by ATC3:1978. This provisional code was considered to be used in practice by the local engineer consulted.
1997	6.9Mw Earthquake	Severe damage in Cariaco. Six low-rise reinforced concrete structures collapsed, two of which were schools (Gonzalez, et al., 2003).
1998	Provisional Code Update, COVENIN 1756-98	Provisional update that as per the information provided by the local engineer consulted was never enforced.
2001	Code Update, COVENIN 1756:2001	Horizontal acceleration coefficients varying by zone and soil type were introduced (COVENIN 1756-1:2001).

Table 3. Ecuadorian code development history

Year	Event	Comment
1949	6.8Mw Earthquake	The earthquake caused 6,000 deaths. The city of Ambato was heavily damaged (Cedeno, 2011).
1951	First Design Code, CEC 1951	This first code was not enforced or used in engineering practice (INEN, 1976).
1976	6.7Mw Earthquake	High damage to engineered and non-engineered constructions in Esmeraldas. Low concrete confinement and other design deficiencies were identified in damaged buildings (Estrada, 1979).
1977	Seismic Code, CEC-77	This code lacked seismic zonation and was published along with a practical seismic design manual to promote its use (INEN, 1976).
1987	7.2Mw Earthquake	Caused 1,000 deaths and damage to buildings in Ecuador’s northeast.

Table 3 (Continued). Ecuadorian code development history

Year	Event	Comment
1998	7.2Mw Earthquake	Caused considerable damage in the province of Manabi. In Bahia de Caraquez, a coastal city, 71% of RC buildings were damaged (CERESIS, 1998).
2001	Code Update, CPE: INEN 5:2001	Introduced a seismic zonation map, reduction factors and updated the design spectrum and sol coefficients (CPE INEN 5:2001, 2001)
2011	Code Update, NEC-11	Updated seismic zonation, incorporated an amplification factor and site conditions were accounted for in more detail (NEC-11, 2011). This code's use became an official requirement in design in 2015 (Registro Oficial, 2015).

Table 4. Colombian code development history

Year	Event	Comment
1970	M6.6 Earthquake	In Puerto Mutis, now known as Bahia Solano, only 16% of structures were undamaged and 39% were destroyed (Ramírez, 1975).
1974	First Seismic Code, SEAOC 1974	The recently formed Association of Earthquake Engineers (AIS) publishes Colombia's first hazard map along with a translation of the 1974 SEAOC Code.
1979	8.1Mw Earthquake	Damage was worst in the cities of Cali, Pasto and Popayan, with MMI intensities of VII to VIII
1979	Code Update, ATC-3-06	The AIS updated the seismic zonation map and translated the ATC-3-06.
1981	Provisional Code, AIS100-81	The first Colombian seismic provisions are provisionally published (Garcia, 1984).
1983	5.6Mw Earthquake	The event, whose epicenter was only 10km away from Popayan, caused 250 deaths and 1500 injuries (Garcia, 1984).
1984	Code Update, CCCSR-84	Updated seismic provisions by the AIS made their way to a formal, seismic design enforced code, the CCCSR-84. This code included non-compliance legal penalties (Paz, 1994).
1994	6.8Mw Earthquake	Damage was reported in the departments of Cauca, Huila and Valle del Cauca. The event caused 566 fatalities (DesInventar, 2011).
1998	Code Update, NSR 98	Lowered displacement limits used in design and simplified the seismic hazard map (Gomez & Farbiarz, 2005).
1999	6.2Mw Earthquake	The Eje Cafetero earthquake affected the coffee growing region of Colombia causing an economic loss of 1,857 million USD (NOAA, 2013).
2010	Code Update, NSR-10	Incorporated new seismic hazard map, updated its design spectrum and refined the coefficients for site amplification (NSR-10, 2010).

Table 5. Peruvian code development history

Year	Event	Comment
1970	7.7Mw Earthquake	The earthquake induced an avalanche which destroyed more than 70,000 homes and around 70,000 fatalities (Kuroiwa, Deza, & Jaen, 1974).
1970	First Seismic Code, RNC 1970	This first code's seismic design was influenced by the 1961 UBC, it did not account for the effects of the soil but included a zonation map (Blanco Blasco, 2010).
1974	8.1Mw Earthquake	Damage in downtown Lima was slight to low. In some areas site amplification led to damage in buildings following the 1970 code (Moran, Ferver, Thiel, Stratta, & Valera, 1975).
1977	Code Update, RNC 1977	Updated the zonation map and accounted for the soil's effect (Blanco Blasco, 2010).
1990	6.5Mw Earthquake	30% of Adobe and Tapial housing in Moyobamba was damaged.
1996	7.7Mw Earthquake	This earthquake most affected the Nazca region, it caused 16 fatalities and destroyed 5,133 homes (Sistema Nacional de Defensa Civil, 1966).
1997	Code Update, E.030 1997	Promoted stiffer designs to prevent damage observed in the 1996 Nazca earthquake (Blanco Blasco, 2010).

Table 5 (Continued). Peruvian code development history

Year	Event	Comment
2001	8.4Mw Earthquake	Caused widespread damage in Arequipa, Tacna and Moquegua (Rodriguez-Marek, et al., 2003). Performance of Post-1997 buildings confirmed the correction of the displacement problem with the introduction of the 1997 code (Blanco Blasco, 2010).
2003	Code Update, E.030 2003	The use of the ultimate state earthquake used in design loads was implemented.
2007	7.9Mw Earthquake	The earthquake destroyed 52,154 homes in the departments of Ica, Lima and Huancavelica and claimed about 600 lives (INEI, 2007).
2014	Code Update under Review	A seismic code update adding a new seismic zone to Peru's zonation was put under public review. The local consulting engineer expects it to become enforced in 2015.

Table 6. Chilean code development history

Year	Event	Comment
1928	7.6Mw Earthquake	Caused 300 fatalities and severe damage to the town of Talca (Escobar, 2011)
1932	First Design Code, DFL 1931	Code offered simple guidelines to calculate a lateral design force, which did not vary with building period. Code was published in 1931, but became enforced in 1932 (Ministerio del Interior, 1931).
1939	8.1Mw Earthquake	Around 1,600 were destroyed in Chillan (Escobar, 2011)
1942	Code Update,	Changes were made to increase lateral load capacity (Sismos24, 2011)
1949	Code Update, Decreto 884	Incorporated the effect of both the soil's and the structure's period on seismic design loads (Decreto 884, 1949).
1960	9.5Mw Earthquake	Largest magnitude recorded earthquake. Caused 2,000 fatalities, damaged 4,500 structures (Housner, 1963).
1972	Code Update, NCh 433 of 1972	Introduces importance factors and adds empirical expression to find the building's period (INN, 1972).
1985	8.5Mw Earthquake	Damaged 142,498 homes and caused 177 fatalities (ONEMI, 2009).
1989	Code Update, INN89	Added new clauses for wood construction, otherwise the seismic load calculation section was unchanged (Paz, 1994).
1993	Code Update, NCh 433 of 93	Major update. Introduced reduction factors and included a seismic zonation map for the first time (IAEE, 1996).
1996	Code Update, NCh 433 of 96	made updates to soil parameters and resolution was added to reduction factors for masonry structures (INN, 1996)
1997	7.1 Mw Earthquake	Caused 5,000 collapses in Punitaqui, a town less than 10km away from the epicenter (Pardo, Comte, & Monfret, 1999).
2009	Code Update, Nch 433 of 96 mod 2009	Refined reduction factors for certain structure types.
2010	8.8Mw Earthquake	Shake and Tsunami waves caused 81,000 collapses and severe damage to 109,000 structures (EERI, 2010).
2011	Code Update, Decree 61	Modifies shear wall reinforcement detailing based on damage observations and makes changes to soil classifications (MINVU, 2011).

Code Based Vulnerability Classes through Time in South America

For each code detailed in Tables 2-6, AIR researchers carried out the calculation of base shear coefficients as per the code's provisions for each seismic zone using the 5 story RC moment resisting frame building. Comparing the calculated base shears with Table 1, appropriate vulnerability class, in terms of code levels, is assigned to each zone.

Figure 1, shows Colombia's vulnerability classes for each age band. An age band is defined as a period of time in which the vulnerability of buildings did not change due to the stringency of seismic codes. Defining age bands therefore involves identifying the milestones in seismic code evolution that led to periods of time with distinct vulnerability characteristics. Usually each age band is defined by the enforcement period of a particular seismic design code, as is the case in Colombia.

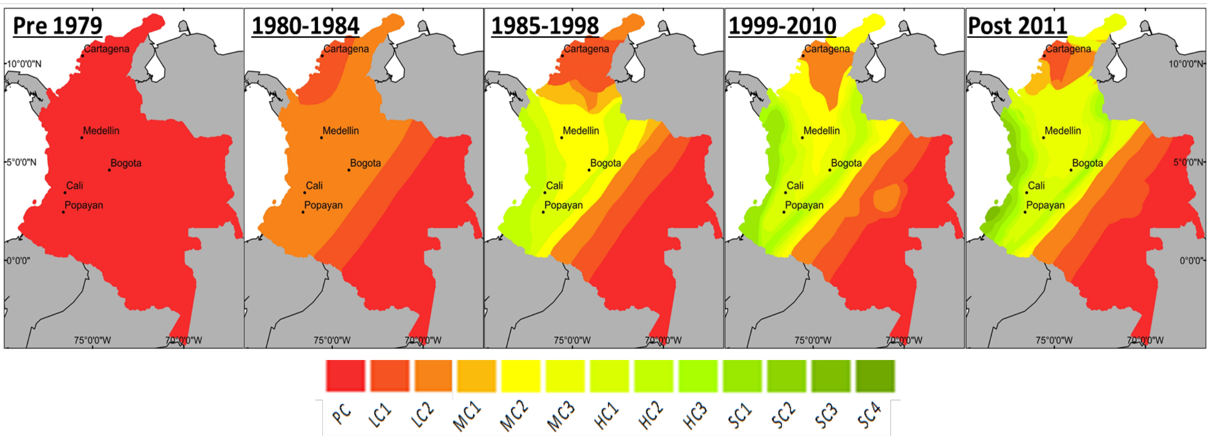

Figure 1. Assigned vulnerability classes through time in Colombia. Warmer colours indicate a higher vulnerability.

Local information is key to forming a clear picture of the code evolution in a country. Detailed local research and consulting the local engineer in Ecuador showed that NEC-11, Ecuador's latest seismic design code, became mandatory until 2015 (Registro Oficial, 2015). In this case 2011, the year NEC-11 was published, does not mark a milestone changing the vulnerability of buildings and therefore does not define an age band. The example of Ecuador's NEC-11 enforcement year, illustrates the importance of careful local research when applying this vulnerability assessment framework.

Please note that in cases where enforcement information was unavailable, a code's enforcement period has been assumed to have begun a year after the publication of the code. This lag is implemented to account for the time it takes for engineers to fully adopt the updates.

Through incorporating the evolution of seismic design codes and assigning vulnerability classes in each country, as discussed previously, one can compare vulnerability classifications across countries in any given year or time period. Figure 2 shows the vulnerability classes of Venezuela, Colombia, Ecuador, Peru and Chile in four different years. The application of the vulnerability assessment framework as shown in Figures 1 and 2, help gain an understanding of the relative stringency of design codes through time and space in the region.

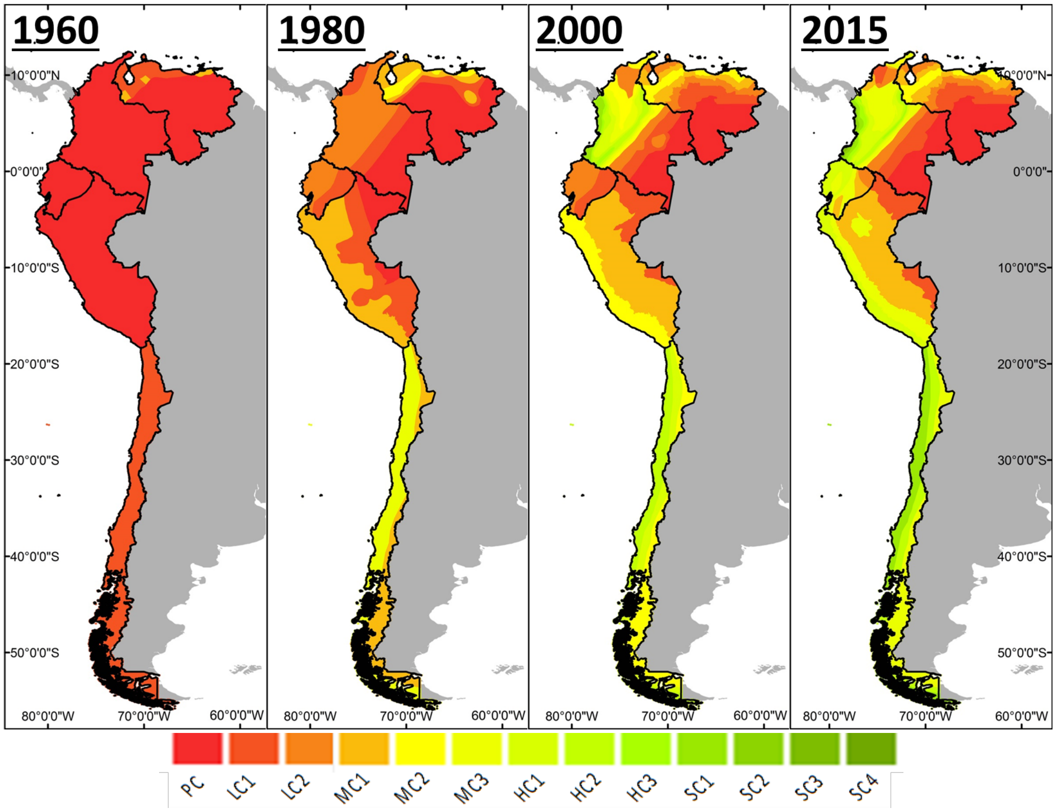

Figure 2. Code Level designations for Venezuela, Colombia, Ecuador, Peru and Chile through time. Warmer colours indicate a higher vulnerability.

Please note that the vulnerability classification maps based on code levels (Figure 1 and 2) do not represent the actual vulnerability of buildings in each country, nor do they represent the seismic risk. The vulnerability classes only represent the spatial and temporal variation due to seismic design provisions and their enforcement.

The vulnerability classification framework presented has many applications. Risk maps that integrate the hazard and vulnerability components for uniform exposures (of varying construction type, age, height, etc.) benefit from vulnerability classification (Lai et al., 2012). Furthermore, blending the information from vulnerability classification with information about the age of the building inventory in a given region provides quick understanding about the vulnerability classes in the region.

Application of Vulnerability class and Age Distributions to Peru

An additional insight into the vulnerability of a region can be gained through integrating the age distribution of the current building stock with vulnerability classifications. In the applied framework, a building's age determines it's age band and vulnerability class. The vulnerability class of a group of buildings can therefore also be determined if their age distribution is known. Figure 3 illustrates said analysis for the departments of Lima, Arequipa and Cusco in Peru.

Statistics of residential buildings with year built information by department in Peru is obtained from (INEI, 2014) and (INEI, 1981). (INEI, 2014) Provided total counts of residential buildings for the census of 1981, 1993 and 2007. In addition (INEI, 1981) provided the number of residential units built every year since 1800 to 1981 broken down by department. Through assuming a constant construction rate per year in between each census, the number of new builds in each year is estimated by linear interpolation. The number of residences built after 2007 was obtained assuming the same rate of construction as in the period of 1993 to 2007. The analysis estimates the number of houses built from 1800 to 2014.

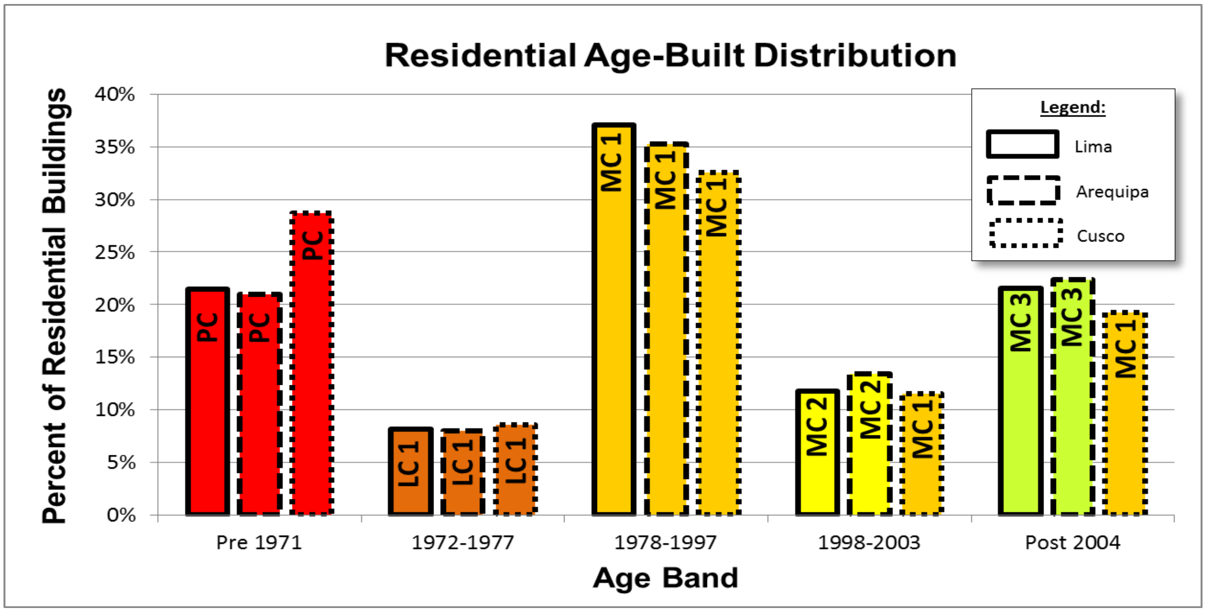

Figure 3. Residential age-built distribution and vulnerability class in the departments of Lima, Arequipa and Cusco in Peru.

Figure 3 shows that the portion of building's built in each age band for Lima and Arequipa is very similar. Cusco has a higher portion of buildings built before 1971. In addition Figure 3 shows the vulnerability classifications for each age band. Again, Lima's and Arequipa's vulnerability classification is the same. This is due to both cities falling in the same seismic zone (highest hazard) in all of Peru's codes. Cusco has a lower vulnerability classification (reflecting higher vulnerability) after 1998. This reflects a lower seismic design stringency in Cusco post 1998 than in Arequipa and Lima. Please note that the 1978-1997 age-band zonation splits the department of Cusco between Low Code 1 (LC1) and Moderate Code 1 (MC1). The vulnerability class shown in Figure 3 for Cusco is of its capital city, since that is the location where most buildings are located within the department.

Conclusion

Regional loss assessments are challenging due to the inherent uncertainties in each model component and in their complex integration. To render confidence in a catastrophe model it is not only essential that it is extensively validated; but also, that the development of each module has been built on local, detailed information as a means to reduce uncertainty. The vulnerability assessment framework employed in this study has the merit of being sensitive to such detailed local information. Its application to the South American region offers insight into the stringency of design codes across the region, and a complete history of each country's code development. This information is useful for parties interested in the seismic vulnerability of the South American region.

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