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Assessment of earthquake damage considering the characteristics of past events in South America

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ABSTRACT

The evaluation of earthquake damage considering past events can be a useful tool to verify or calibrate damage and risk models, as well as to assess the possible consequences that future events may cause in a region. This study describes a process to estimate earthquake damage considering past events, and using the OpenQuake-engine, the open-source software for seismic hazard and risk analysis of the Global Earthquake Model Foundation. Exposure and fragility models from the recently completed South America Risk Assessment (SARA) project were combined with conditioned ground motion fields from past events to calculate structural damage in the affected region. These results can facilitate the creation of risk reduction measures, such as retrofitting campaigns, development of insurance mechanisms and enhancement of building codes. The challenges in assessing damage and losses from past events are thoroughly discussed, and several recommendations are proposed.

1. Introduction

The estimation of the impact from specific earthquakes (historical or hypothetical) can support decision makers in the development of risk reduction strategies. In the case of historical events, they are not only useful to calibrate risk models (e.g. fragility or vulnerability functions), but they also contribute to the understanding of the consequences that an earthquake with similar characteristics may cause in the future. This becomes essential in areas of high seismic risk, such as South America, and in particular in the Andean countries. In this region, the moderate to high seismic hazard combined with the high vulnerability of structures and heavily populated urban areas has led to tragic economic and human losses in the past. Hence, it is imperative to understand the potential impact of earthquakes in this part of the world, and develop efficient risk reduction strategies.

Several South American cities have been the target of seismic risk analyses, which provided important information for the study presented herein. Vaziri et al. [41] performed a probabilistic risk assessment for three capital cities: Quito (Ecuador), Lima (Peru) and Santiago (Chile). For each of these cities, exposure and vulnerability models were derived and two seismic scenarios were explored. The results were calibrated based on several past events. The results demonstrated that Santiago has the highest average annual loss (419 million USD); but Lima presents a greater seismic hazard and vulnerable buildings. Hence, a case study was performed to analyse the impact that an improvement in the structural capacity of adobe and unreinforced masonry buildings would have in a district in Lima. On average, a reduction of 10% in the average annual losses was observed. Cardona and Yamín [6] evaluated the seismic risk in Bogotá (Colombia) based on three hypothetical earthquake scenarios, corresponding to different return periods and sources. In order to obtain vulnerability functions representative of the local building classes, the damage matrix forms provided by the ATC-13 [1] were adjusted, based on local expertise and experience from previous earthquakes. The seismic risk was estimated from the convolution of hazard and the vulnerability of the exposed elements. For the considered events, it was estimated that between 4% and 11% of the constructed area of the city could suffer structural collapse. Finally, the Peruvian Centre of Disaster Studies and Prevention [8] studied the consequences that a Mw 8.0 earthquake, 33 km deep, would have on the Metropolitan Lima and Callao region. For each area, a vulnerability class was assigned to the structures, based on their predominant wall material, construction typology, condition of the dwellings and height. A regression was performed in order to relate the repair costs with the interstorey drift of each structure, allowing the allocation of a damage level to each building. For this scenario, 51,000 fatalities were estimated, along with 200,000 collapsed houses.

In the study presented herein, three input models were defined for each earthquake scenario: a ground shaking model, an exposure dataset

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and a set of fragility functions. Regarding the first component, two approaches can be followed to estimate the spatial distribution of the ground shaking in the region. The first option consists in the definition of a seismic rupture (i.e. magnitude, hypocentre, rake, strike and dip) and the use of one or more ground motion prediction equations (GMPEs) to generate sets of ground motion fields. This approach allows considering any seismic rupture (granted that reliable data concerning local fault geometry is available) and to propagate the aleatory uncertainty in the GMPEs (e.g. [33]). In the second approach, locally recorded strong motion data (e.g. ShakeMap system from the United States Geological Survey (USGS) – [44]) can be employed to generate spatially cross-correlated ground motion fields conditioned on observations [34]. Both of these options are explored in this study, considering six past events (Armenia 1999, Arequipa 2001, Pisco 2007, Maule 2010, Salta 2015 and Muisne 2016).

Besides the ground shaking model, it is necessary to define an exposure dataset describing the spatial distribution and characteristics of the assets exposed to the seismic hazard. This study uses the exposure model for the residential building stock developed by Yepes-Estrada et al., [45]. Finally, the fragility functions establish the probability of physical damage conditional on a set of ground shaking level, as described in Villar-Vega et al., [42] for common building classes in South America. These models were developed within the South America Risk Assessment (SARA) project, led by the Global Earthquake Model (GEM) and supported by the SwissRe Foundation. This project involved several local experts and resulted in a probabilistic seismic hazard and risk model for the region. The earthquake scenarios were performed using the OpenQuake-engine [30], the open-source software for seismic hazard and risk assessment of the GEM Foundation.

The estimation of damage or losses considering the characteristics of past events also offers the opportunity to compare the estimated impact with what was observed. Such exercise is frequently carried out by catastrophe modeling companies or civil protection agencies, as it allows evaluating directly the performance of the earthquake model. However, there are numerous reasons for the possible discrepancies between the observed and estimated damage values. These include possible limitations and bias in the different components of the earthquake model, as well as factors associated with the inherent variability of the event. The results from this study are used to discuss these challenges.

2. Selection of past events

In this study, six historical events were selected to develop the earthquake scenarios. Since the existing exposure dataset was developed using recent building data (see Section 3.1), a decision was made to select events that happened relatively recently (within the last two decades), and for which ground shaking and damage data were available. This section describes the main characteristics and consequences of the six selected events. Moreover, a summary of the damage and casualties is described in Table 1, and the median ground shaking (in term of peak ground acceleration) for each event is illustrated in Fig. 4.

2.1. Armenia, Colombia 1999

The city of Armenia (Colombia) experienced a M_w 6.2 earthquake on January 25, 1999. This event occurred at 1:19 p.m. local time on the Romeral Fault System. The combination of a shallow hypocentre (10 km, according to [28]), proximity to a populated area, presence of soft soils and poor construction practices caused extensive destruction. It was estimated that over 60% of the structures in Armenia suffered damage [2]. The economic loss was estimated to be approximately USD 1.9 billion [28]. According to Macdonald et al. [25], high levels of damage were observed in non-engineered low-rise buildings. Wattle-and-daub (*bajareque*), unreinforced masonry and reinforced concrete structures exhibited a poor performance, mainly due to low quality of materials and construction techniques (e.g. lack of seismic detailing). On the other hand, *guadua* (modern bamboo constructions) and most engineered structures showed a satisfactory seismic performance [28]. Some multi-storey reinforced concrete frame buildings presented beam plastic hinging. The Economic Commission for Latin America and the Caribbean [11] reported 18421 inhabitable houses, 17551 houses with total loss and 43471 partially affected houses.

2.2. Arequipa, Peru 2001

The Mw 8.4 Arequipa earthquake struck the southern region of Peru on June 23, 2001 at 8:33 p.m. local time. It had a focal depth of 38 km [37], and it was generated due to the subduction of the Nazca plate under the South American plate. According to Comte et al. [10], the mainshock presented a strong directivity towards the south. As a consequence of the earthquake, a tsunami was produced on the southern coast of Peru, increasing both the casualties and the economic losses. According to the National Institute of Civil Defence [20], the estimated losses due to this event rose to more than USD 311 million, out of which USD 27 million correspond to housing losses. Severe damages were observed in historical buildings in Arequipa. In addition, collapses and major damages also occurred on old adobe and *quincha* structures (bamboo or cane framework covered with mud or gypsum) in Arequipa, Moquegua and Tacna [37]. In Camaná, some reinforced concrete frames with masonry infills exhibited structural deficiencies such as soft-storeys or short-column effects [12,13].

2.3. Pisco, Peru 2007

On August 15, 2007, a Mw 8.0 earthquake occurred in Pisco (Peru) at 6:40 p.m. local time. The hypocentre was located at a depth of 39 km [14]. This event was also produced by the subduction process of the Nazca plate under the South American plate. According to official statistics [21], the earthquake affected five regions (first administrative level), namely Ica, Lima, Junín, Huancavelica and Ayacucho. The total economic loss reached USD 2 billion [35]. According to Taucer et al. [36], approximately 80% of the non-engineered adobe houses collapsed in the Ica region. Earthquake-resistant earth structures (i.e. houses that had been seismically designed or retrofitted) performed satisfactorily. Non-engineered masonry structures exhibited medium to light damage,

Table 1
Summary of the housing damages and casualties for each seismic event.

Event	Housing (buildings)		People			Source
	Damaged	Collapsed	Injured	Missing	Fatalities	
Armenia, 1999	61895	17551	8523	731	1187	Adapted from CEPAL [11].
Arequipa, 2001	37576	22052	2812	66	83	Adapted from INDECI [20].
Pisco, 2007	124877	48173	1286	–	596	Adapted from INDECI [21].
Maule, 2010	288607	81444	10334	56	521	Adapted from Gobierno de Chile [19] and www.emdat.be
Salta, 2015	NA	15	30	–	2	USGS [41]
Muisne, 2016	35264	6998	4859	12	663	NGDC/WDS [27]