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# FRAMEWORK OF THE ESTIMATION OF THE HEALTH STATUS OF THE POPULATION DURING AN EARTHQUAKE EMERGENCY

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Abstract

Hospitals play a paramount role during an earthquake emergency response. Large earthquakes have caused a large number of casualties in many communities in the past to the extent that the hospitals were overcrowded. Therefore, an important information for policy makers and leaders of the emergency response is the estimation of numbers of casualties that can result from critical earthquake scenarios. This paper assesses the demand of medical resources during an earthquake emergency response for a case study in the Carabayllo District, located in Lima, Peru, subjected to the 1974 Lima earthquake scenario occurring in the subduction zone off the coast of Lima. In order to evaluate this demand, this paper focuses on the injuries resulting from the earthquake. The analysis of this demand is based on the framework elaborated proposed by Ceferino et al. [1], which is also briefly described, to estimate the probability distribution of the number of injuries resulting from the earthquake and associated to different injury severities. The results verify the applicability and validity of this framework. Additionally, they indicate that the correlation of injury occurrence within buildings is very important to model the probability distribution of the number of casualties, particularly, for injuries that are very severe or for deaths.

*Keywords: casualty; earthquake scenario; emergency response; resilience*

## 1. Introduction

According to recent frameworks for assessing resilience, as a consequence of a disaster, resilient communities should avoid disruption of their societal dynamics, or if there is a disruption, they should recover fairly quickly [3]–[5]. The recovery of a city can be divided into three phases: a short-term phase that is expected to last days and usually focuses on rescuing and stabilizing people and preparing the community for the next phases, a medium-term phase that extends for weeks or months and focuses on restoring neighborhoods, workforce, and caring for the vulnerable population, and a long-term phase that may last for years and is associated with restoring the community's economy, social institutions and physical infrastructure [3], [6]. Hospital plays a tremendous role in the first phase of the of the recovery. In this sense, not only the assessment of the functionality of hospitals is key to understand the resilience of a community [6], but also the assessment of demands on the medical system are extremely important to evaluate the sufficiency of medical supplies in case of an earthquake. This paper deals with estimations of demands of medical treatment after an earthquake.

Previous earthquakes have caused a large number of casualties in cities and made hospitals easily prone to overcrowding. Some examples are the 1995 Kobe earthquake [7]–[9], the 1999 Turkey earthquake [8], [9] and the 2015 Nepal earthquake [10]. The evidence relates large structural damage and collapse to fatalities and/or injuries of the building's occupants [11]–[15]. Nevertheless, other data shows that a significant number of injuries also occurred in buildings with slight structural damage. For example, in the 2004 Mid-Niigata Earthquake, the larger levels of structural damage of wooden buildings did not relate to the larger levels of injury rates (ratio between the number of injured and the total number of occupants) in buildings. Rather these rates relate to the occupants behavior (vehemently exiting the house) or falling objects [16]. Similarly, the 1985 Chile Earthquake caused several injuries in buildings without apparent structural damage [17]. Injuries due to earthquakes also can be very different. After the 1994 Northridge Earthquake, approximately 60% of the patients at four emergency rooms had soft-tissue or orthopedic injuries and nearly 15% had cardiovascular injuries [18]. Whereas in the Northridge Earthquake most injuries were minor [19], in Kocaeli Earthquake, in Turkey, 47% were minor, 45% moderate and 8% serious. In the latter, 86% of the injured and deaths were in buildings damaged beyond repair, and a high proportion of moderate injuries were in less damaged buildings. More than 50% of the injuries were caused by falling objects, and 11% were caused by a cutting and a piercing object- [15]. The hour at which the earthquake occurs can greatly affect the number of injuries in the region since this number is dependent on the occupancy of buildings, and this occupancy changes during the day.

Decision makers and leaders of the disaster management can prepare better emergency response plans if they could obtain reliable projections of the number of injured people and the severity of these injuries. The projections can be particularly helpful for decisions on strengthening existing hospital facilities and on the need for constructing additional facilities. Moreover, hospitals can develop response plans targeting specific scenarios arising from various damage conditions occurring from different earthquakes that can affect the region. With current knowledge, modeling and information it is not possible to obtain exact numbers of injuries for specified earthquake magnitude in a city. Nevertheless, reasonable projections of the number of injuries can be made using a probabilistic framework. This paper presents a framework for estimating the number of injuries in a city given an earthquake scenario. This paper focuses on modeling the demand on a hospital by estimating the probability distribution of the number of injured individuals within an earthquake affected region.

There have been investigations on this realm. The National Oceanographic and Atmospheric Administration (NOAA) pioneered these studies and estimated the of injuries and fatalities expected after earthquakes in San Francisco [20]. According to a building classification, NOAA estimated the number of deaths and serious injuries—defined as requiring hospitalization—based on expert opinion and, data from previous earthquakes according to the different ground shaking severity using isoseismals. Three different scenarios were explored: (i) at 2:30 A.M. when most people are at home, (ii) at 2:00 P.M. when many people are at work, schools, or out on the streets, and (iii) at 4:30 P.M. when many people are using the transportation systems. The Applied Technological Council (ATC) also proposed a framework to estimate injuries and deaths in its study [21]. They estimated minor injuries, serious injuries, and casualties. First, this study performs a damage assessment of buildings. Afterward, ATC related the damage state to percentages of injuries and casualties in the building. This relationship is also based on expert opinion. Severely damaged buildings were assigned higher rates than slightly damaged buildings. The Federal Emergency Management Administration (FEMA) developed the HAZUS® software that also includes the assessment of injuries within its methodology [22]. It estimates four levels injury severity—the worst severity being death. HAZUS® software first performs a damage assessment for buildings, and then, it estimates the number of injuries in buildings according to the buildings' damage state and the structural type. For example, it is deemed that low-rise concrete buildings on average cause more injuries than low-rise steel buildings. HAZUS® software also uses different building occupancy rates according to the hour at which the earthquake occurs.The rates of injuries per damage state for each structural system were based on a combination of expert opinion and the ATC's study. Recently, more robust analytical methodologies have been proposed to estimate injuries and/or fatalities according to the damage condition of the building [23]–[25]. For instance, Liel used a methodology based on an event tree of structural collapse mechanisms and the buildings' collapse volume to estimate injuries in non-ductile reinforced concrete frame buildings [26]. The event tree allowed her to evaluate different collapse mechanisms that lead to different numbers of injuries and fatalities in buildings. For example, if the global collapse of the building triggers a pancake collapse, more injuries would be expected than if the global collapse only occurs due to large damage in a few stories. The collapse volume was found to be a good predictor of fatalities [27], [28], and Liel estimated it using the Incremental Dynamic Analysis (IDA).

These previous works on the estimation of the number of casualties due to an earthquake have looked at both the single building and the regional scale. Still, in both scales, they have focused on estimating an expected number of people injured or death rather than a probabilistic distribution of this number. This paper elaborates a framework for estimating the probability distribution of the number of injuries according to their severity for a specified earthquake scenario. This framework takes into consideration the earthquake ground shaking spatial distribution, the performance of structures and the correspondence to injury and death occurrence.

The framework is applied to the Carabayllo district in Lima for the $M_W$ 8.0 earthquake scenario that occurred in 1974 off the coast of Lima. Carabayllo is located in the periphery of Lima and it is characterized by housing buildings that are constructed without engineering supervision or proper seismic design. More than 250,000 people live in this district [29], and there are more than 50,000 housing buildings [30]. In this application, the focus is on the scenario resulting from an earthquake occurring at nighttime since it is considered that this is the worst case scenario for the Carabayllo district since most of people are at their houses, considered vulnerable, Whereas the industrial, school, university and other buildings, where people spend their time at the daytime, are considered to comply with seismic code.

## 2. Framework

This framework enables us to estimate the probabilistic distribution of the number of injured people in a geographic region due to an earthquake. Details about this framework can be found in Ceferino et al. [1]. In order to briefly describe this methodology, consider the Fig. 1a. This figure shows a hypothetical geographic region occupied by $N$ people that is subjected to an earthquake of magnitude $M_W$ with epicenter at $(x_{EQ}, y_{EQ})$. The area within the dashed curve represents the region of interest, and the black points represent a people in the region. Fig. 2b shows a small area within the geographic area of interest—dashed rectangle. This graph shows different geometric shapes, e.g. the square, the triangle and the circle, that represent different bulging typologies, and the black points within them indicate the buildings' occupants during the earthquake occurrence. The building typologies are defined by their structural type (masonry buildings, steel moment frames and so on—different construction qualities can also be included, e.g. informal buildings without proper engineering design), and their number of stories.

The location of the $j$-th building of the $k$-th structural typology is defined as at $\left(x_{jk}, y_{jk}\right)$. $n_{jk}$ are the number of occupants at this building at the time of the earthquake. The total number of buildings that belongs to the $k$-th structural typology is defined as $\tau_k$ whereas the number of structural typologies in the region is defined as $T$ (Fig. 2).

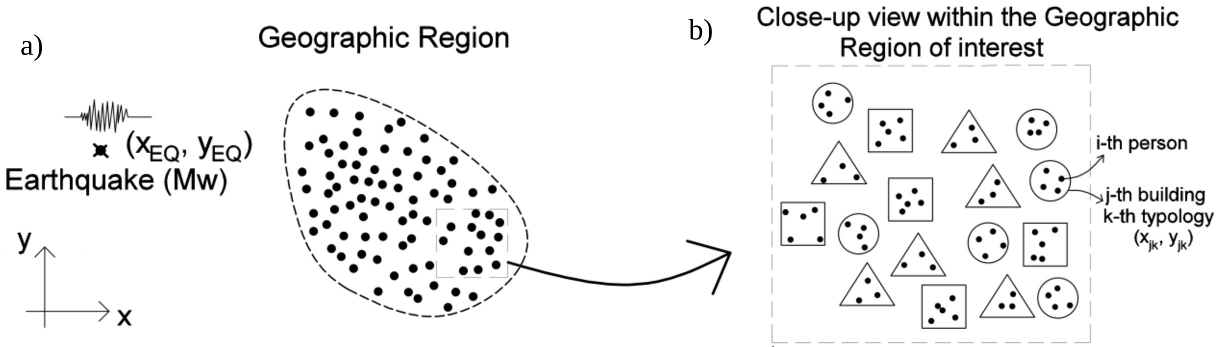

Fig. 1 – a) A geographic region affected by an earthquake and b) close-up view of the buildings and their occupants.

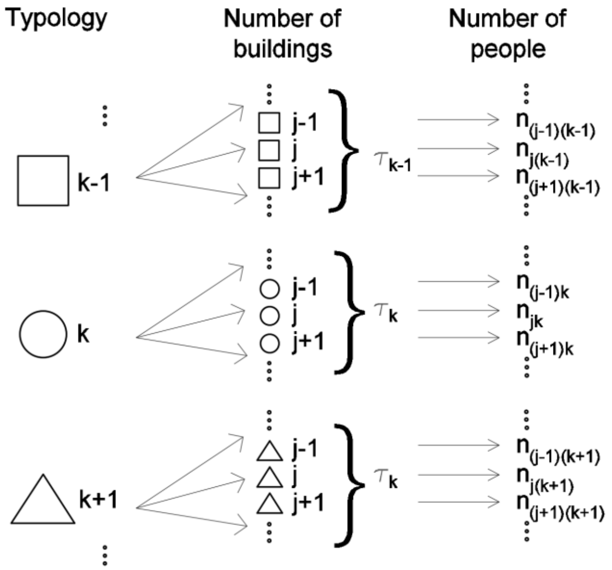

Fig. 2 –Structural typology, the number of buildings for typology and occupants per building in the region of interest.

The ground motion field in the in all the points $(x_{jk}, y_{jk})$, where the buildings are located, is collected in a vector $\overline{IM}$ composed of all these intensity values $IM_{jk}$ associated to the earthquake scenario—with magnitude $M_W$ and location $(x_{EQ}, y_{EQ})$. This $\overline{IM}$ values can be simulated using a unique intensity type—e.g. peak ground acceleration (PGA)—with which the damage states of all the buildings will be calculated, as it will be seen later. Additionally, $\overline{IM}$ can represent different intensity type so that the damage assessment of different structural typologies can be calculated using fragility curves based on different intensity types—e.g. Spectral acceleration (Sa) at the period of the respective structural typology. Methods for simulations are already developed in the literature [31]–[33].

The health status of the $i$-th person occupying the $j$-th building of the $k$-th structural typology is defined as $H_{ijk}$. $H_{ijk}$ takes categorical values according to the health status classification—or injury severity—of the specific person, then:

$$H_{ijk} \in \{1,2,3,\dots,Q\} \tag{1}$$

where $Q$ is the total number of injury severities or health statuses considered in the analysis. For instance, Status 1 may represent minor injuries, e.g. small scratches or bruises, Status 2 may represent more severe injuries for which hospitalization is required, and so on. The most severe status, Status $Q$, may represent the individuals' death. Consequently, $1\{H_{ijk} = q\}$ will equal 1 if the $i$-th occupant of the $j$-th building with the $k$-th structural typology has an injury of Status $q$, or will equal 0 otherwise. Hence, the total number of casualties of Status $q$ conditioned on $\overline{IM}$ is given in Eq. (2). In the triple sum, the number of casualty is counted as follows: firstly, within specific buildings; secondly, in all the buildings with the same structural typology; and thirdly, in the entire region.

$$I_q|\overline{IM} = \sum_{k=1}^{T}\sum_{j=1}^{\tau_k}\sum_{i=1}^{n_{jk}} 1\{H_{ijk} = q|\overline{IM}\} \tag{2}$$

This framework assesses the injury occurrence as a conditional probability on the structural damage state $DS_{jk}$ of the building at location $(x_{jk}, y_{jk})$. Similarly, it assesses damage state $DS_{jk}$ of the corresponding building as conditional on the intensity $IM_{jk}$ at the corresponding location. This framework assumes that the probability of being injured conditioned on $IM_{jk}$—or also on $\overline{IM}$ since injuries are only dependent on the intensity at $(x_{jk}, y_{jk})$—with health status $q$ is defined as $p_{jkq}$ and given in Eq. (3). This framework considers that all occupants within a building are equally likely to be injured [1].

$$p_{jkq} = \sum_{DS_{jk}} P\left[H_{ijk} = q|DS_{jk} = ds_m\right]P\left[DS_{jk} = ds_m|\overline{IM}\right]= P\left[H_{ijk} = q|\overline{IM}\right] \tag{3}$$

Then, Ceferino et al. demonstrate that under two circumstances the number of casualties with health status $q$ given a vector $\overline{IM}$ converges to well known probability distributions [1].

The first case assumes that the injury occurrence conditioned on $\overline{IM}$ is mutually independent in the whole region. This implies that the source of spatial correlation comes from the spatial correlation on the intensities at different locations. Under this supposition, it is demonstrated that the number of casualties with health status $q$ in the region converges to a Poisson distribution when the number of people in the region is large (Eq. (4)). The mean of this Poisson distribution is given in Eq. (5).

$$I_q|\overline{IM} \sim Poisson(\lambda_q) \tag{4}$$

$$\lambda_q = \sum_{k=1}^{T}\sum_{j=1}^{\tau_k} n_{jk}p_{jkq} \tag{5}$$

The second case considers that there is a correlation between the casualty occurrence conditioned on $\overline{IM}$ and associated to the health status $q$ of the people occupaying the same buildings. Additioanlly, it considers that the injury occurrance is mutually independendent conditioned on $\overline{IM}$ for people that are not occupying the same building. A general correlation parameter $\rho$ was introduced to model this correlation for all health statuses. This parameter represents the general correlation between the injury occurrance associated with an specific health status of people occupying the same building conditioned on $\overline{IM}$. According to this description, the correlation is assumed to be present within an associated health status of the occupants of a building. For example, the minor injury occurrences of two occupants—which might be classified as Status 1—are correlated, but the minor injury occurrence of one occupant—Status 1—is considered independent with the occurrence of a major injury occurrence of another occupant—which might be classified as Status 2. Additionally, it is considered that the injury occurrence correlation among the occupants of one building is independent of the damage state of the building. Even though the impact of taking into account these considerations is unknown, the lack of reliable data to quantify different correlation parameters, makes the idea of using one general correlation parameter practical and reasonable. Under these consideration, it is demonstrated that the number of casualties with health statuses $q$ in the entire region converges to a normal distribution according to Eq. (6). The mean and the standard deviation are given in Eq. (7) and (8), respectively.

$$I_q|\overline{IM} \sim N(\mu_{I_q|\overline{IM}}, \sigma_{I_q|\overline{IM}}) \tag{6}$$

$$\mu_{I_q|\overline{IM}} = \sum_{k=1}^{T}\sum_{j=1}^{\tau_k} n_{jk} p_{jkq} \tag{7}$$

$$\sigma_{I_q|\overline{IM}} = \sqrt{\sum_{k=1}^{T}\sum_{j=1}^{\tau_k}\left(p_{jkq}(1-p_{jkq})\right)\left(\left(\left(n_{jk}\right)^2 - n_{jk}\right)\rho + n_{jk}\right)} \tag{8}$$

## 3. Case Study

In this section, the described framework is applied to estimate the probabilistic distribution of the number of injuries in the Carabayllo district in Lima, Peru, for a ground motion associated with the Mw 8.0 1974 Lima earthquake. In this application, a sensitivity analysis of the correlation parameter $\rho$ is also performed to understand its influence on the resulting number of casualties.

Carabayllo has an extension of nearly 350 km$^2$ and has a population of nearly 250,000 people [29]. Fig. 3a shows the distribution of people per km$^2$ in the city of Lima, obtained from LandScan [29] and the boundaries of Carabayllo. This district has been experiencing a fast urban densification; it has nearly doubled its population from 100,000 people to more than 200,000 from 1993 to 2007 [30], [34]. This densification has been accompanied by the construction of new houses and the expansion of existing houses without proper engineering design and construction quality control [35], [36]. Though Carabayllo has undergone this heavy densification, it is one of the least dense districts in Lima, and therefore, it is expected to keep growing in population and infrastructure. Consequently, given its early stage of urban development, it is very flexible to implement disaster mitigation measures according to information provided by the application. Lallemant showed that the risk of damaged houses due to earthquakes grows exponentially in fast-growing urban environments characterized by non-engineered construction [37]. Therefore, this framework has the potential to inform policymakers to establish seismic mitigation measures before the current trends of vulnerability keep its fast increase due to the non-engineered construction practices.

The 1974 Lima earthquake occurred at latitude -12.39°, longitude -77.66 ° and at a depth of 17.5 km. The strike was 340°, the dip 17°, and the rake 90° [38]. Though the analysis can accommodate any spatial distribution of $IM$, for demonstrative purposes, here the distribution of the number of injuries will be calculated for the occurrence of median values of the earthquake intensities in the region. Fig. 3b, c and d show the distributions of the median values of PGA, Sa(0.3s) and Sa(1.0s) respectively due to the earthquake of interest. These computations were calculated using Openquake software [39] and the GMPE proposed by Atkinson and Boore [40]. The Vs30 was taken as 760 m/s, which is consistent with the study of the soils in Carabayllo by Aguilar et al. [41].

The structural typology was classified in four classes (Table 1). This classification does not intend to represent the whole variety of structural typologies in Carabayllo, but it can be considered representative of most of the buildings in the district. Table 1 also shows the code of these typologies and the relative contribution to the total housing portfolio in the district. These percentages are according to the surveys previously performed in the zone [36] and in neighboring communities [42]. Fig. 4 shows four buildings that are representative of each structural typology in Carabayllo.

Table 1– Main structural typologies in Carabayllo District and their distribution

| Typology | Code | Distribution |
|---|---|---|
| 1-story light wood | LW01 | 15 % |
| 1-story non-ductile confined masonry | ND-CM01 | 49 % |
| 2-story non-ductile confined masonry | ND-CM02 | 24 % |
| 3-story non-ductile confined masonry | ND-CM03 | 12 % |

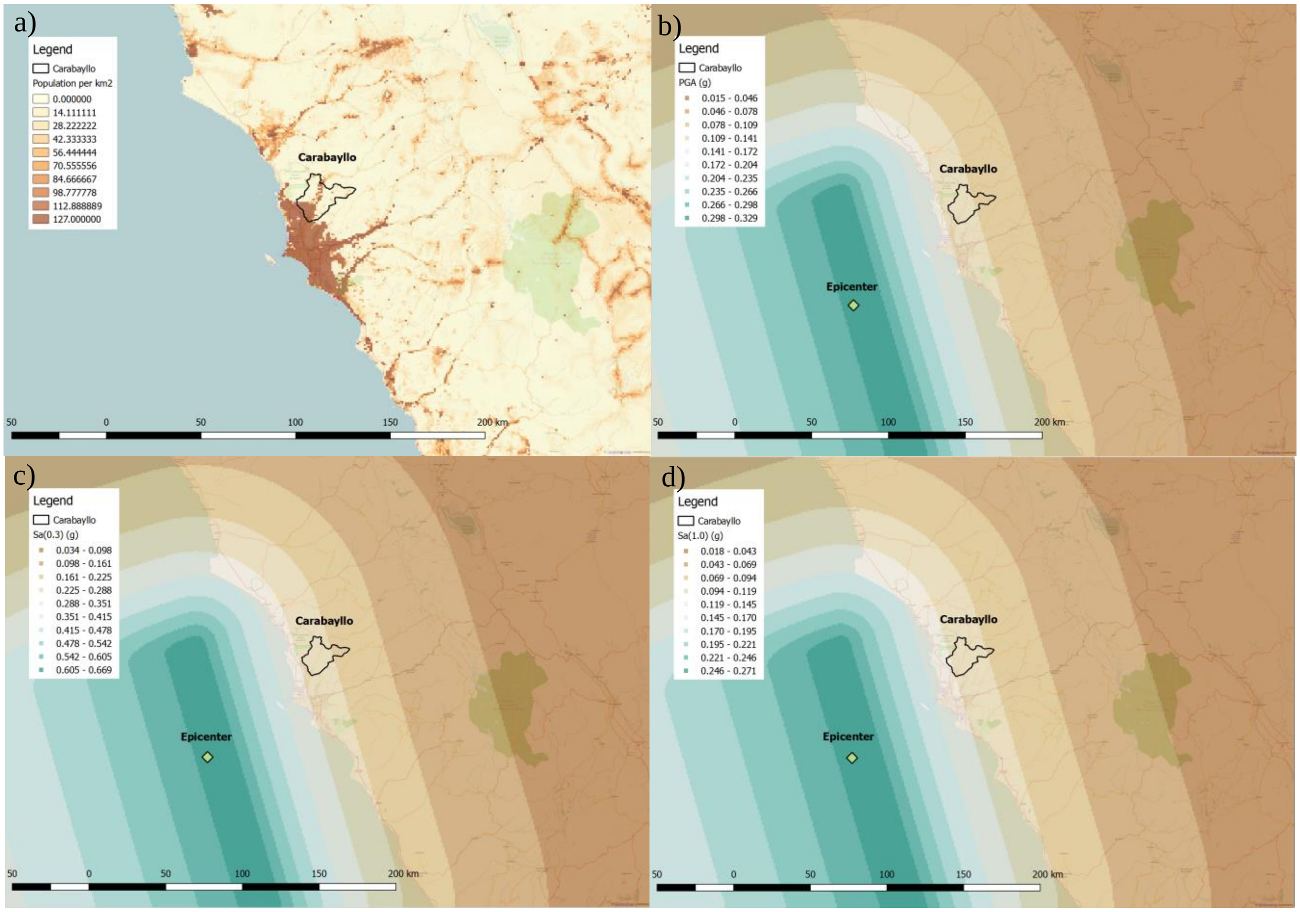

Fig. 3– a) Distribution of number of population per km$^2$ in 2012, b-d) Median PGA (g), Sa(0.3s) (g) and Sa(1.0s) (g) map due to the 1974 Lima earthquake, respectively.

There were around 4.00 people per housing building conforming to the 2007 census in Carabayllo, and 4.70 conforming to the 1993 census. By extrapolating these numbers to 2015, a ratio of 3.60 was used to estimate the total number of buildings in this district from the distribution of people per square kilometer given by LandScan. Additionally, we considered that the average number of people on each different typology is given according to Table 2. These values were set up such that the rate number of people to the number of buildings were 3.60. In this application, the assessment was done by analyzing each area element of the LandScan grid (1 km x 1 km) according to the population size and then assembling the contribution of each area element. Eq. (4) and (5) were used for the case in which mutually independence is assumed among the injury occurrences in the region conditioned on $\overline{IM}$, whereas Eq. (6), (7) and (8) were used for the case in which correlation ($\rho$) exists among injury occurrence of people within a building conditioned on $\overline{IM}$.

Table 2– Average number of people living on each structural typology

| Code | Average people living |
|---|---|
| LW01 | 3 |
| ND-CM01 | 3 |
| ND-CM02 | 4 |
| ND-CM03 | 7 |

Fig. 4– Typologies in El Carabayllo District. a) LW01, b) ND-CM01, c) ND-CM02 and d) ND-CM03.

Structural damage states were classified as Slight, Moderate, Extensive, and Collapse. This study will use the fragility curves proposed by Villar et al. [43] for the four structural typologies in order to relate structural damage to the earthquake intensity measure at the building's location. The logarithm means and logarithmic standard deviations that define these fragility curves for all the damage states are given in Table 3.

Table 3– Fragility curve parameters for the different structural typologies

| **Code** | **IM** | **Damage State** | $\mu_{lnIM}$ | $\sigma_{lnIM}$ | **Damage State** | $\mu_{lnIM}$ | $\sigma_{lnIM}$ |
|---|---|---|---|---|---|---|---|
| LW01 | Sa(0.3) | Slight | -2.521 | 0.496 | Extensive | -1.146 | -0.514 |
| | | Moderate | -1.654 | 0.567 | Collapse | 0.615 | 0.646 |
| ND-CM01 | Sa(0.1) | Slight | -1.211 | 0.353 | Extensive | -0.168 | 0.302 |
| | | Moderate | -0.391 | 0.333 | Collapse | 0.109 | 0.361 |
| ND-CM02 | Sa(0.1) | Slight | -2.52 | 0.535 | Extensive | -1.284 | 0.748 |
| | | Moderate | -1.707 | 0.644 | Collapse | -0.472 | 0.805 |
| ND-CM03 | Sa(0.3) | Slight | -2.521 | 0.496 | Extensive | -1.146 | 0.615 |
| | | Moderate | -1.654 | 0.567 | Collapse | -0.514 | 0.646 |

In this paper, we used four injury severity states according to the classification used in HAZUS® software [22]. The description of each severity state is given in Table 4. The rate of an injury severity occurrence given a damage state is given in Table 5. Here, we used the rates proposed by HAZUS® software for indoor injury occurrence. For the confined masonry injury rates in this paper, we used the injury rates of unreinforced masonry provided by HAZUS® software (Case I), and in the case of injuries occurring in wooden houses, we used the values of wood with a light frame and area lesser than 5,000 square ft. provided by HAZUS® software (Case II).

Table 4– Injury severity classification

| **Injury classification** | **Description** |
|---|---|
| Severity 1 | Requires basic medical attention and no hospitalization |
| Severity 2 | Requires hospitalization, but is not expected to be life-threatening |
| Severity 3 | Requires hospitalization and are life threatening |
| Severity 4 | Immediately killed or mortally injured |

Table 5– Injury severity rates (%) according to damage state

| **Injury Severity** | **Case I (%)** | | | | **Case II (%)** | | | |
|---|---|---|---|---|---|---|---|---|
| | Slight | Moderate | Extensive | Collapse | Slight | Moderate | Extensive | Collapse |
| 1 | 0.05 | 0.35 | 12 | 40 | 0.05 | 0.25 | 6 | 40 |
| 2 | 0 | 0.40 | 2.2 | 20 | 0 | 0.30 | 1.1 | 20 |
| 3 | 0 | 0.001 | 0.022 | 5 | 0 | 0 | 0.011 | 3 |
| 4 | 0 | 0.001 | 0.022 | 10 | 0 | 0 | 0.011 | 5 |

In this paper, we assessed the case on which the housing buildings were fully occupied at the moment of the seismic disaster. This roughly corresponds to the case in which the earthquake occurs late at night e.g. ~2 A.M. [20], [44]. This hour might correspond to the most critical case compared to other hours of earthquake occurrences. At commuting hours, we expect that the damage to roads does not threaten the people health at the extent of the damage of informal houses. At daytime, when people is mostly working at an industry plant or an office, at school, university or in other infrastructure, we expect that they are more ready to evacuate buildings if possible than at night, and that the buildings other than houses are mostly built with formal standards (according to seismic code provisions), so that they are less vulnerable than the informal housing in Carabayllo.

Finally, the results are given in Fig. 5a-d. These distributions represent the probability density function of the number of injuries (in percentage) for each of the four considered health statuses. These distributions are conditioned on the occurrence of median values of the ground motion intensity produced by the earthquake scenario. Plots for different correlation values $\rho$ were generated. Here it is verified that the independent case and the uncorrelated case ($\rho = 0$) converge to the same distribution. In this framework, uncorrelatedness implies independence [1]. Then, these results verify the consistency and validity of the framework.

Table 6 reports the means and standard deviations of the number of injured people associated to the different health statuses for the cases shown in Fig. 5a-d. From this graph and the table, it is interesting to show that for all the cases the mean values are the same. In the case of the standard deviation, the stronger correlations of the injuries occurrences (larger $\rho$ values) have the larger standard deviations. When $\rho = 0.3$ the standard deviation increments in nearly 50% with respect to the independent—uncorrelated—case, whereas when $\rho = 0.7$ the standard deviation increments in nearly 100% with respect to the independent case. The ratio between standard deviation and the mean value (coefficient of variation) is larger for Status 3 and 4— when $\rho$ goes from 0 to 0.7, in Status 3, the standard deviation goes from 29% to 53%, and in Status 4, it goes from 20% to 38%. This suggest that the correlation ratio $\rho$ is very important when modeling the number of casualties with severe severities due to an earthquake. Additionally, it can be observed that the mean number of casualties is smaller for the more severe health statuses. This might be expected for earthquakes that do not cause collapse on most of the buildings since the collapse is associated to higher rates of severe injury occurrence. However, the results show one exception, the mean number of injuries with health status 3—severe injuries requiring urgent hospitalization—is smaller than the number of casualties with health status 4—death. This interesting result was expected from Table 5. In this table, the rate of casualty occurrence of health status 3 was always smaller (for collapse) or equal (for slight, moderate and extensive) to the rate of casualty occurrence of health status 4. Therefore, the results are dependent on this input data. The reason why we might expect to have smaller injuries for health status 3 than for health status 4 in collapse is that occupants who could not evacuate the house before it collapses have a low survival likeliness. Considering that in collapsed buildings, people are at risk of being hit by falling heavy walls, ceilings, slabs, and so on, this consideration is reasonable.

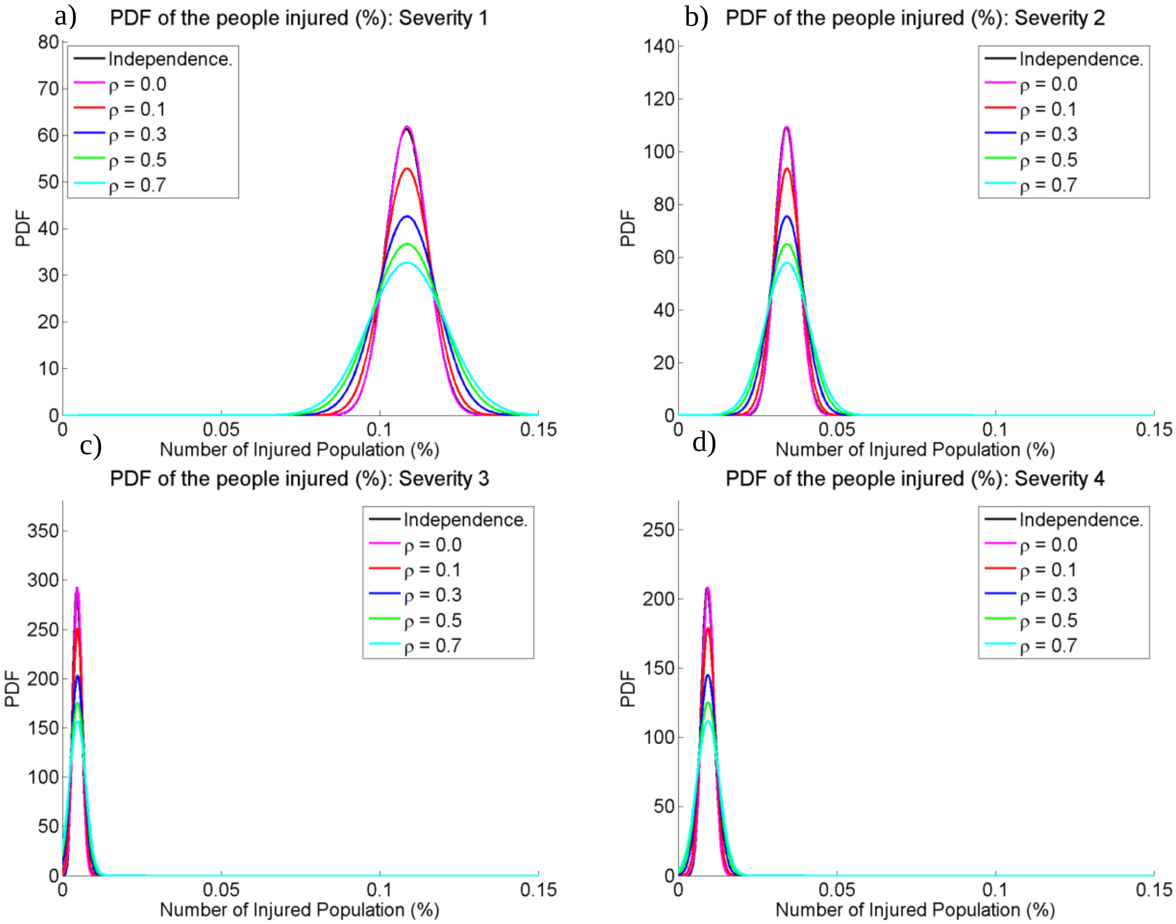

Fig. 5– Distribution of the number of injuries in Carabayllo District. a) Severity 1, b) Severity 2, c) Severity 3 and d) Severity 4.

Table 6– Mean and standard deviation of the number of injuries for each severity

| Injury Severity ($j$) | $\mu_{I_j\mid\overline{IM}}$ | $\sigma_{I_j\mid\overline{IM}}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | Independence | $\rho = 0.0$ | $\rho = 0.1$ | $\rho = 0.3$ | $\rho = 0.5$ | $\rho = 0.7$ |
| 1 | 279 | 16.7 | 16.6 | 19.4 | 24.0 | 27.9 | 31.3 |
| 2 | 88 | 9.4 | 9.4 | 11.0 | 13.6 | 15.8 | 17.7 |
| 3 | 12 | 3.5 | 3.5 | 4.1 | 5.0 | 5.8 | 6.5 |
| 4 | 24 | 4.9 | 4.9 | 5.7 | 7.1 | 8.2 | 9.2 |

In Carabayllo, where nearly 250,000 people live, mean values of the number of injuries with severity 3 and 4 (death) might be considered small. Nevertheless, if we extrapolate the percentage of injured people to the whole city of Lima, where the population is reaching the 10 million people, these numbers increase significantly. We have to consider also that the soil type of Carabayllo is not as critical as in other districts of Lima [41] so that we can expect larger earthquake intensities on other areas. Additionally, though the 1974 earthquake might be considered large, there other large, but less documented earthquakes that might affect the city to a larger extent.

For example, evidence indicated that the 1746 earthquake, that occurred in the subduction zone off the coast of Lima, had a $Mw$ of 8.6~8.8—or even more [45], [46]. Similarly, the 1940 earthquake of $Mw$ 8.0 occurred in the same subduction zone at a closer distance than the 1974 earthquake, and then it might induce larger earthquake intensities to Lima. Though these events are not as well documented as the 1746 earthquake, further studies will have to evaluate the distribution of injuries due to these events to understand the worst case scenarios that Carabayllo and Lima city can face.

## 4. Conclusions

The framework, proposed by Ceferino et al. [1], for calculation of probability distribution of the number of casualties according different health status classifications has been presented and applied in this paper. The case study was the Carabayllo District subjected to the 1974 Lima earthquake ($Mw$ 8.0). The analysis was performed for the median values of the ground motion intensities associated to this earthquake. The worst case scenario was considered by assessing the earthquake occurrence at night when most people are at home since it is deemed that the housing infrastructure is particularly vulnerable. Additionally, a sensitivity analysis was performed to analyze the importance of the correlation of injury occurrence (correlation parameter $\rho$) within buildings.

For the results, it can be noticed that the mean values of the number of casualties for all the health statuses do no vary with the correlation parameter $\rho$. Yet, the standard deviation is highly impacted by $\rho$. Bigger $\rho$ values produce bigger standard deviations. Since the coefficient of variation is larger for the most severe injuries, the results suggest that using the correlation parameter is key to determine the probabilistic distribution of number deaths and severe injuries requiring urgent hospitalization. Therefore, since there is no estimation of the value of $\rho$ in the literature, engineers need to start quantifying this value from casualty data of previous earthquakes.

Additionally, the results show that it is more expected to have slight injuries than severe injuries in this earthquake scenario. For example, the mean number of casualties with severity 1 is 25 times larger than the mean number of casualties with severity 3. Yet, they also show that the number of the people needing urgent hospitalization—or otherwise with a high risk of dying—is expected to be lower than the number of death people after the earthquake. Though this might be counterintuitive, these results are very dependent on the occurrence rate of the injury severities conditioned on the damage state used as one of the inputs in the analysis. In our analysis, the input data was consistent with the results. This would imply that if house collapses and the occupants do not evacuate, there is a small probability of survival.

Finally, the mean number of injuries in the Carabayllo District due to the 1974 Lima earthquake might seem small. Nevertheless, if we consider that the percentage of the injured population can be extrapolated to the whole Lima city, where nearly 10 million people live, then, the scale of the number of injured people becomes very large. Additionally, other districts in Lima have worse soil condition than Carabayllo so that the percentage of thes injured population in other districts might be larger. Moreover, closer and large seismic events have occurred in the subduction zone off the coast of Lima (1940 and 1976 earthquakes, respectively). Though less documented than the 1974 Lima Earthquake, they also need to be assessed in further studies to understand the worst case scenario that Lima city can have.

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## 6. Copyrights

## 7. References

[1] L. Ceferino, A. S. Kiremidjian, and G. G. Deierlein, "Framework for the Estimation of the Health Status of the Population during and Earthquake Emergency," *Prep.*, 2016.
[2] J. Moehle and G. G. Deierlein, "A framework methodology for performance-based earthquake engineering," *Proc. 13 th World Conf. Earthq. Eng.*, no. 679, pp. 3812–3814, 2004.
[3] National Insitute of Standards and Technology (NIST), "NIST Special Publication 1190: Community Resilience Planning Guide for Buildings and Infrastructure Systems Volume I," 2015.
[4] National Insitute of Standards and Technology (NIST), "NIST Special Publication 1190: Community Resilience Planning Guide for Buildings and Infrastructure Systems Volume II," 2015.
[5] National Insitute of Standards and Technology (NIST), "Grand Challenges for Disaster Reduction," 2005.
[6] San Francisco Planning + Urban Research Association (SPUR), "The resilient city: defining what San Francisco needs from its seimsic mitigation policies," San Francisco, CA, 2009.
[7] Department of Health an Environment (DOHE), "Actual Result of the Investigation on the Disaster Medicine." Hanshin-Awaji Great Earthquake Restoration Headquarters, Kobe, Japan, 1995.
[8] R. C. Myrtle, S. F. Masri, R. L. Nigbor, and J. P. Caffrey, "Classification and prioritization of essential systems in hospitals under extreme events," *Earthq. Spectra*, vol. 21, no. 3, pp. 779–802, 2005.
[9] USGS, "Earthquakes with 1,000 or More Deaths 1900-2014," 2015. [Online]. Available: http://earthquake.usgs.gov/earthquakes/world/world_deaths.php. [Accessed: 27-Nov-2015].
[10] Nepal Disaster Risk Reduction Portal, "Incident Report of Earthquake 2015," 2015. [Online]. Available: https://web.archive.org/web/20150629024928/http://drrportal.gov.np/incidentreport. [Accessed: 27-Nov-2015].
[11] M. E. Durkin, C. C. Thiel, J. E. Schneider, and T. De Vriend, "Injuries and emergency medical response in the Loma Prieta earthquake," *Bull. Seismol. Soc. Am.*, vol. 81, no. 5, pp. 2143–2166, 1991.
[12] D. Alexander, "The health effects of earthquakes in the mid-1990s," *Disasters*, vol. 20, no. 3, pp. 231–247, 1996.
[13] K. Shoaf, H. Seligson, M. Kano, and R. M., "Fatality Model for Non-Ductile Concrete Frame Structures Developed From Golcuk Population Survey Data," in *Van Nuys Hotel Building Test Bed Report: Exercising Seismic Performance Assessment*, H. Krawinkler, Ed. Pacific Earthquake Engineering Research Center, 2005.
[14] M. A. Ferreira, O. C.S., and F. Mota de Sá, "Estimating Casualties for the Southern California Shakeout," in *Human Casualties in Earthquakes: Progress in Modelling and Mitigation*, Springer, 2011, pp. 255–266.
[15] M. Petal, "Earthquake Casualties Research and Public Education," in *Human Casualties in Earthquakes: Progress in Modelling and Mitigation*, Springer, 2011, pp. 25–50.
[16] M. Koyama, S. Okada, and Y. Otha, "Major Factors Controlling Earthquake Casualties as Revealed via a Diversified Questionnaire Survey in Ojiya City for the 2004 Mid-Niigata Earthquake," in *Human Casualties in Earthquakes: Progress in Modelling and Mitigation*, Springer, 2011, pp. 199–217.
[17] S. Aroni and M. E. Durkin, "Injuries and occupant behavior in earthquakes," *Joint US-Romanian Seminar on Earthquakes and Energy, Bucharest, Romania*. Architectural Research Centers Consortium, Washington, DC, pp. 3–40, 1985.
[18] M. E. Durkin, "Fatalities, nonfatal injuries and medical aspects of the Northridge earthquake, Northridge, California earthquake of 17 January 1994," 1995.
[19] K. I. Shoaf, H. R. Sareen, L. H. Nguyen, and L. B. Bourque, "Injuries as a result of California earthquakes in the past decade.," *Disasters*, vol. 22, no. 3, pp. 218–35, 1998.
[20] NOAA, *A Study of Earthquake Losses in San Francisco Bay Area: Data and Analysis*. Boulder, CO, 1972.
[21] Applied Technology Council (ATC), "ATC-13, Earthquake damage evaluation data for California," *Applied Technology Council*. 1985.
[22] Federal Emergency Management Agency, "Hazus–MH 2.1: Technical Manual," Washington, D.C., 2015.
[23] G. L. Yeo and C. A. Cornell, "Building-specific seismic fatality estimation methodology," *The Fourth U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*. Pacific Earthquake Engineering Research Center, University of California, Berkeley, Toba, Japan, 2002.
[24] A. B. Liel, C. B. Haselton, G. G. Deierlein, and J. W. Baker, "Incorporating modeling uncertainties in the assessment of seismic collapse risk of buildings," *Struct. Saf.*, vol. 31, no. 2, pp. 197–211, Mar. 2009.
[25] D. J. Wald, K. Jaiswal, K. D. Marano, P. S. Earle, and T. I. Allen, "Advancements in Casualty Modelling facilitated

by the USGS Prompt Assessment of global earthquakes for response (PAGER) system," in *Second International Workshop on Disaster Casualties*, 2009, no. June, pp. 221–230.

[26] A. Liel, "Assessing the collapse risk of California's existing reinforced concrete frame structures: Metrics for seismic safety decisions," *PhD Thesis*, p. 314, 2008.

[27] A. W. Coburn, R. J. S. Spence, and A. Pomonis, "Factors determining human casualty levels in earthquakes: Mortality prediction in building collapse," in *Earthquake Engineering, Tenth World Conference*, 1992, pp. 5989–5994.

[28] N. Tabata, N. Takai, and S. Okada, "13 th World Conference on Earthquake Engineering CASUALTY ESTIMATION MODEL BASED ON THE MECHANISM OF HUMAN INJURY IN DAMAGED BUILDINGS," *Earthquake*, no. 729, 2004.

[29] Oak Ridge National Laboratory and I. East View Cartographic, "East View LandScan global 2012." Oak Ridge, Tennessee, 2013.

[30] Instituto Nacional de Estadísticas e Informática (INEI), "Censos Nacionales 2007: XI de Población y VI de Vivienda." Lima, Peru, 2007.

[31] J. Park, P. Bazzurro, and J. W. Baker, "Modeling spatial correlation of ground motion Intensity Measures for regional seismic hazard and portfolio loss estimation," *Civ. Eng.*, pp. 1–8, 2007.

[32] K. Goda and G. M. Atkinson, "Probabilistic characterization of spatially correlated response spectra for earthquakes in Japan," *Bull. Seismol. Soc. Am.*, vol. 99, no. 5, pp. 3003–3020, 2009.

[33] C. Loth and J. W. Baker, "A spatial cross-correlation model of spectral accelerations at multiple periods," *Earthq. Eng. Struct. Dyn.*, vol. 42, no. 3, pp. 397–417, 2013.

[34] Instituto Nacional de Estadísticas e Informática (INEI), "Censos Nacionales 1993: IX de Población y IV de Vivienda." Lima, Peru, 1993.

[35] C. Zavala, M. Estrada, F. Lazares, S. Alarcón, J. Taira, and J. Morales, "Quick Risk Evaluation of Earthquake Losses on Housing," in *15th World Conference on Earthquake Engineering, Lisbon Portugal*, 2012.

[36] Soluciones Prácticas, "Survey of buiding typology in El Progreso Community." Unpublished work, 2015.

[37] D. Lallemant, H. Burton, L. Ceferino, Z. Bullock, and A. S. Kiremidjian, "A Framework and Case Study for Earthquake Vulnerability Assessment of Incrementally Expanding Buildings," *Earthq. Spectra*, vol. Under Revi, 2016.

[38] C. J. Langer and W. Spence, "The 1974 Peru Earthquake Series," *Bull. Seismol. Soc. Am.*, vol. 85, no. 3, pp. 665–687, 1995.

[39] GEM, "The OpenQuake-engine User Manual." p. 189, 2016.

[40] G. M. Atkinson and D. M. Boore, "Empirical ground-motion relations for subduction-zone earthquakes and their application to Cascadia and other regions," *Bull. Seismol. Soc. Am.*, vol. 93, no. 4, pp. 1703–1729, 2003.

[41] Z. Aguilar, F. Lazares, S. Alarcón, S. Quispe, R. Uriarte, and D. Calderón, "Actualización de la Microzonificación Sísmica de la cuidad de Lima," in *The International Symposium for CISMID 25th Anniversary*, 2013, no. 1, pp. 1–5.

[42] C. Zavala, M. Estrada, J. Morales, and J. Taira, "LOSS ESTIMATION ON LIMA CITY USING A RETROFITTING COST ESTIMATION TOOL," in *9th International Conference on Urban Earthquake Engineering/4th Asia Conference on Earthquake Engineering*, 2008, pp. 1667–1670.

[43] M. Villar-Vega, V. Silva, H. Crowley, C. Yepes, N. Tarque, A. B. Acevedo, and M. Hube, "Development of a Fragility Model for the Residential Building Stock in South America."

[44] Department of Homeland Security and Federal Emergency Managment Agengy, "Hazus –MH 2.1. User Manual," 2015. [Online]. Available: http://www.fema.gov/media-library/assets/documents/24609. [Accessed: 22-Dec-2015].

[45] S. L. Beck and S. P. Nishenko, "Variations in the mode of great earthquake rupture along the Central Peru Subduction Zone," *Geophys. Res. Lett.*, vol. 17, no. 11, pp. 1969–1972, 1990.

[46] L. Dorbath, A. Cisternas, and C. Dorbath, "Assessment of the size of large and great historical earthquakes in Peru," *Bull. Seismol. Soc. Am.*, vol. 80, no. 3, pp. 551–576, 1990.