# PROBABILISTIC ASSESSMENT OF EARTHQUAKE-INDUCED DEBRIS GENERATION USING PBEE METHODOLOGY

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## *Abstract*

Buildings collapse due to the occurrence of seismic events in urban areas could generate a great amount of debris and waste, depending on buildings structural fragility, intensity of the ground motion and materials of structural and non-structural elements. Providing reasonable predictions on the size, type and location of earthquake-induced debris is of critical importance for developing effective disaster risk management plans, that could improve emergency response and recovery phases (i.e., selection of evacuation routes, debris management possibility of recycling practices, etc.).

In this article, we present a methodology to estimate debris produced by the partial and total collapse of buildings after an earthquake scenario at urban scale, using the conceptual framework of Performance-Based Earthquake Engineering, PBEE. The proposed methodology includes three steps: 1) GIS-based exposure modeling, where the residential building stock and its material composition is evaluated, 2) fragility modeling, where fragility curves (expected percentage of debris vs. seismic intensity) for different building typologies are generated within the PBEE framework, and 3) scenario-based seismic risk analysis, developed to estimate the amount of debris and its spatial distribution.

The methodology was applied to a case study to demonstrate its usefulness and capability to support decision-making for seismic risk reduction at a city scale. In a retrospective analysis, a similar scenario to the 7.9 Mw earthquake that hit Pisco city (Peru) in 2007 was simulated in order to estimate debris generation. The proposed methodology estimated a volume of debris of around 1’196,000 m$^3$, which is very close to the official amount reported by local authorities, 1’000,000 m$^3$. Debris estimated with this method were mainly constituted by concrete (34%), clay bricks (27%) and mortar (27%). Moreover, the GIS-based analysis shows that debris distribution across the city was diffuse and debris removal was probably time-consuming with a great demand of truck-trips. In addition, it is most likely that critical infrastructure accessibility (i.e., roads, schools, hospitals) was affected by the debris accumulation. However, these findings also suggest that it could have been a good opportunity to start novel recycling practices of debris (e.g., concrete debris) in the region. Finally, the debris fragility curves developed in this study could be used for earthquake-induced debris assessment in other cities with similar building typologies.

*Keywords: earthquake induced debris, Performance Based Earthquake Engineering, GIS, seismic risk reduction. disaster risk management*

# 1. Introduction

Building collapse due to the occurrence of seismic events in urban areas could generate a great amount of debris and waste, depending on buildings structural fragility, intensity of the ground motion, and materials of structural and non-structural elements. For example, 9.9 million $m^3$ of debris were generated after the 7.9 Mw Pisco earthquake in 2007 [1]; around 23 to 60 million ton of waste were estimated due to the 7.0 Mw Haiti earthquake in 2010 [2], and approximately 28 million ton of debris were produced in the 9.0 Mw Great East Japan earthquake in 2011 [3]. The presence of these debris impacts negatively on the environment and public health, as well as it impedes a quick response to emergency situations in the affected areas. Providing reasonable predictions on the size, type and location of earthquake-induced debris is of critical importance for developing effective disaster risk management plans that could improve emergency response and recovery phases (i.e., selection of evacuation routes, debris management possibility of recycling practices, etc.).

Performance-Based Earthquake Engineering, PBEE, provides a probabilistic framework which allows to evaluate performance measures that serve as decision variables (e.g., monetary losses, casualties, etc.) by considering different sources of uncertainty (e.g., ground motion characteristics, structural properties, damage occurrence). This approach considers systematically the intensity, structural response, damage and losses through conditional functions; therefore, losses can be understood as a measure of the structure performance [4]. Literature review indicates that PBEE methodology has been extensively employed in civil engineering to develop fragility curves for structural vulnerability assessment, where the probability of failure associated with a specific criteria (e.g., maximum inter-story drift of a building exceeding a certain limit) is represented as a function of the ground motion intensity (e.g., peak ground acceleration) [5, 6]. Nevertheless, literature review also suggests that PBEE methodology has not yet been utilized to evaluate material vulnerability (i.e., losses in terms of debris) to earthquake occurrence.

In this article, we present a methodology to estimate debris produced by the partial and total collapse of buildings after an earthquake scenario at urban scale, using the conceptual framework of Performance-Based Earthquake Engineering. The proposed methodology includes three steps: 1) GIS-based exposure modeling, where the residential building stock and its material composition is evaluated, 2) fragility modeling, where fragility curves (in terms of expected percentage of debris vs. seismic intensity) for different building typologies are generated within the PBEE framework, and 3) scenario-based seismic risk analysis, developed to estimate the amount of debris and its spatial distribution. The methodology was applied to a case study to demonstrate its usefulness and capability to support decision-making for seismic risk reduction at a city scale. In a retrospective analysis, a similar scenario to the 7.9 Mw earthquake that hit Pisco city (Peru) in 2007 was simulated.

# 2. Materials and Methods

The proposed methodology includes three main stages: 1) GIS-based exposure modeling, 2) fragility modeling, and 3) scenario-based seismic risk analysis. These stages are explained in the following paragraphs.

## 2.1 GIS-based exposure modeling

An exposure model should contain the spatial distribution and risk-oriented characteristics (e.g., structural characteristics, replacement cost) of the elements that are susceptible to be damaged due to seismic activity. In seismic risk applications, the exposure mainly refers to the building portfolios, although it may also include civil infrastructure (i.e., transportation networks, lifelines). Providing a reliable description of the structural characteristics of buildings related to their seismic vulnerability is complex, due to the variety of construction techniques, materials, geometric configurations, etc. This leads to the utilization of building types/classes in large-scale risk assessments with the aim of describing individual buildings which may exhibit similar seismic performance. In this study, the residential building stock has been classified into various building types using information provided from the national census.

In most studies related to seismic risk assessment, the exposure is commonly characterized in terms of its economic value, thus the results of the analysis are expressed in terms of monetary losses. However, in order to assess the potential earthquake-induced debris, it is necessary to describe the exposure in terms of the construction materials embedded in the buildings. In this research, a “bottom-up” approach was used to characterize the amount, type and location of the material stock in buildings. Two important parameters were used: gross floor area of buildings – GFA ($m^2$) and the ratio of weight of materials per GFA unit, named material intensities – MI (metric ton/$m^2$). By combining both indicators with statistical data on the number of buildings, we estimate the material stock – MS from Eq. (1) and Eq. (2):

$$M_{m,i} = (\sum GFA_i \cdot N_i) \cdot MI_{m,i} \quad (1)$$

$$MS = \sum_{m,i} M_{m,i} \quad (2)$$

Where, $GFA_i$: gross floor area by building type *i* [$m^2$], $N_i$: number of buildings by building type *i*, $MI_{m,i}$: material intensity for material *m* and building type *i* [metric ton/$m^2$], $M_{m,i}$: mass of material *m* built in building type *i* [metric ton], MS: total mass of materials (material stock) in buildings [metric ton]

## 2.2 Fragility modeling

The PBEE framework established by the Pacific Earthquake Engineering Research (PEER) Center decomposes the performance assessment into four steps: seismic hazard analysis, evaluation of structural response, damage analysis and loss/consequence analysis [4]. The outcomes of the individual analysis are then combined using the total probability theorem as described in Eq. (3), which represents the conditional probability of a decision variable exceeding a value *dv* given a value of intensity measure *im*.

$$G(dv|im) = \int_{dm} \int_{edp} G(dv|dm)\, dG(dm|edp)\, dG(edp|im) \quad (3)$$

Where, dv: decision variable (e.g., repair cost), dm: damage measure (e.g., amount of crack in a concrete element), edp: engineering demand parameter (e.g., inter-story drift ratio), im: intensity measure (e.g., peak ground acceleration).

For the purposes of this study, the PBEE framework has been adapted in order to develop fragility functions which relates seismic intensity with debris fraction (i.e., the proportion of the material stock likely to be converted into debris), according to Eq. (4).

$$G(DF_{m,i}|im) \int_{dm} \int_{ds} G(DF|ds)\, dG(ds|dm)\, dG(dm|im) \quad (4)$$

Where, im: intensity measure, dm: damage measure, ds: damage state, $DF_{m,i}$: debris fraction (%) of material *m* built in building type *i*, $G(DF_{m,i}|im)$: conditional probability function of variable $DF_{m,i}$ given an intensity measure *im*. The expected value of debris fraction $E[DF_{m,i}|im]$ for each intensity measure represents the ordinate of the fragility curve.

## 2.3 Scenario-based risk analysis

Scenario-based risk analysis constitutes an effective tool for reducing earthquake-induced losses since it can support decision-making from local governments. For instance, it can be beneficial in order to identify vulnerability level of existing facilities and critical infrastructure, to assess the efficiency of disaster planning measures, to allocate human resources for emergency-response actions, etc. [7].

The general methodology to perform a seismic risk analysis is based on the convolution of three main components: hazard, fragility and exposure. In this study, the seismic risk analysis has been developed according to the ERN-AL framework [8]. The exposure is represented by the building stock classified in various typologies with similar structural characteristics that reflect their seismic performance, and which is characterized in terms of their construction materials. Next, the hazard is defined by a single earthquake scenario in the study area, characterized by the position of the epicenter, hypocenter, and magnitude of the earthquake. The influence of the local site conditions (site effects) on the spatial distribution of the ground motion is also considered. Lastly, fragility is represented by fragility curves which provides the expected debris fraction for a given seismic intensity. Consequently, we estimate the amount of earthquake-induced debris (i.e., losses in the material stock) – LMS from Eq. (5) and Eq. (6):

$$LM_{m,i} = E[DF_{m,i}|im] \cdot M_{m,i} \tag{5}$$

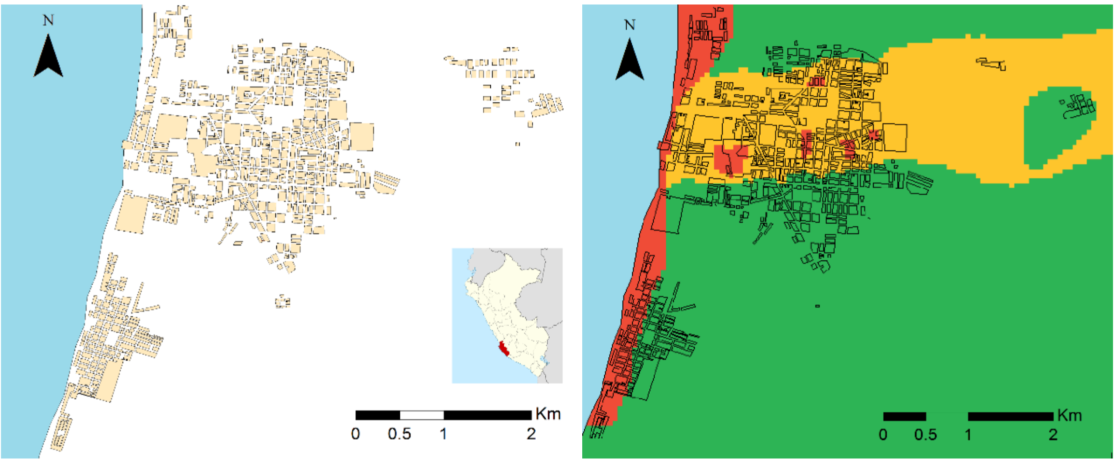
$$LMS = \sum_{m,i} LM_{m,i} \tag{6}$$

Where, $E[DF_{m,i}|im]$: expected debris fraction (%) of material *m* built in building type *i*, $M_{m,i}$: mass of material *m* built in building type *i* [metric ton], $LM_{m,i}$: mass of lost material (debris) *m* built in building type *i* [metric ton], LMS: total mass of lost material (debris) in buildings [metric ton]

## 3. Application to the 7.9 Mw Pisco Earthquake

### 3.1 Area of study

Pisco, capital city of the Ica region, is located in the central coast of Peru, approximately 250 km south of Lima, as shown in Fig. 1.a. Pisco city has an extension of 24.9 km$^2$, with a population of 55,000 inhabitants in 2007. On 15 August 2007, an earthquake of large magnitude (Mw 7.9, IGP; Mw 8.0, USGS) hit Pisco city and surrounding areas, resulted in 519 death, 1,366 injured and more than 650,000 affected people. Also, around 75,000 dwellings presented severe damage, or they collapsed [9].



a)

b)

Fig. 1 – a) Location of Pisco city, b) Site effects map of Pisco city [18]

### 3.2 Development of the exposure model

The main source for the development of the exposure model was the National Housing Census provided by INEI [10]. Two available attributes were used to assign a building type to the dwellings identified in the census: a) predominant material of the exterior walls, and b) type of dwelling. Based on this criterion, the residential building stock was classified in 4 building types: brick masonry houses, adobe houses, reinforced concrete (RC) apartment buildings, and straw houses. A briefly description of the buildings types is presented in Table 1.

In Table 2, we present a summary of the composition of the building stock for Pisco city according to the proposed classification. The information shown in this table corresponds to the year 2007, prior to the occurrence of the 7.9 Mw earthquake.

Table 1 – Description of building types in Pisco city

| **Building type** | **Description** | **Number of stories** |
|---|---|---|
| Brick masonry house | They are composed of clay brick walls, with cement mortar, confined by cast-in-place RC columns and beams which support cast-in-place RC floors (ribbed slabs with hollow roof bricks). Unconfined brick masonry exists in minor proportion. | 1-3 |
| Adobe house | They are composed of unreinforced adobe blocks walls, with mud mortar, which support roofs composed of wooden joists framework covered with crushed cane and mud. | 1 |
| RC apartment building | These dwellings are contained in buildings composed of cast-in-place RC structural frames with columns, beams and shear walls, which support cast-in-place RC floors (ribbed slabs with hollow roof bricks). Infilled walls are typically made of hollow clay bricks. | 1 |
| Straw house | They are built using inadequate materials for construction, such as mats, plastics, and corrugated zinc sheets. | 1 |

Table 2 – Composition of the building stock in Pisco city

| **Building type** | **Number of dwellings** | **%** |
|---|---|---|
| Brick masonry house | 8,484 | 71.0 |
| Adobe house | 830 | 7.0 |
| RC apartment building | 240 | 2.0 |
| Straw houses | 2,394 | 2.0 |
| Total | 11,948 | 100.0 |

In order to estimate the building material stock in Pisco from Eq. (1) and Eq. (2), we used the values of GFA [m$^2$] and MI [metric ton/m$^2$] calculated by Mesta et al. [11] for another Peruvian city with the same building typologies than Pisco. The data sources and techniques used by the authors included cadastral maps and exploration with Google Street View tool to define the values of gross floor area; and technical documentation (i.e., construction blueprints, budgets), on-site investigation and literature review to define the material intensities. Straw houses were not considered because its share to the material stock is negligible.

The gross floor area and material intensities considered for each building type are presented in Table 3 and Table 4, respectively. The values were incorporated in the geodatabase to complete the exposure model.

Table 3 – Gross floor area by building type for Pisco city

| **Building type** | **GFA [m$^2$]** |
|---|---|
| Brick masonry house | 160 |
| Adobe house | 100 |
| RC apartment building | 100 |

Table 4 – Material intensities (metric ton/m$^2$) by building type for Pisco city [11]

| **Building type** | **Building components** | **Concrete** | **Clay brick** | **Cement mortar** | **Steel** | **Adobe brick** | **Mud** | **Wood** |
|---|---|---|---|---|---|---|---|---|
| Brick masonry house | Structural | 0.509 | 0.267 | 0.116 | 0.0266 | - | - | |
| | Non-structural | - | - | 0.140 | - | - | - | |
| Adobe house | Structural | - | - | - | - | 0.688 | 0.313 | 0.03 |
| | Non-structural | - | - | - | - | - | - | |
| RC apartment building | Structural | 0.616 | 0.056 | 0.064 | 0.0311 | - | - | |
| | Non-structural | - | 0.178 | 0.177 | - | - | - | |

### 3.3 Development of the fragility model

Using the PBEE framework, the three components presented in Eq. (4) were analyzed independently. Firstly, the distribution of damage for each intensity measure dG (dm|im) was assumed as a Beta distribution, with the mean and standard deviation from the vulnerability functions (in terms of damage ratio vs. spectral acceleration) for Peruvian buildings developed by CIRNA-PUCP [12]. In that study, the vulnerability functions were constructed following the HAZUS [13] guidelines.

Secondly, some damage scales available in the literature were studied to evaluate the distribution of damage state for each damage measure dG (ds|dm). The damage scales proposed by ATC-13 [14] with some modifications, HAZUS-99 [15], and GEM Foundation [16], were considered to define four damage states according to the probable range of damage, as shown in Table 4.

Table 4 – Values of damage ratio (%) by damage state [14, 15, 16]

| Building type | Slight | Moderate | Extensive | Complete |
|---|---|---|---|---|
| ATC-13 | 0-10 | 10.1-30 | 30.1-80 | 80.1-100 |
| HAZUS-99 | 2 | 10 | 44.7 | 100 |
| GEM Foundation | 5 | 25 | 60 | 100 |
| **THIS STUDY** | **0-10** | **10-30** | **30.1-70** | **70.1-100** |

Finally, to evaluate the distribution of debris fraction for each damage state dG (DF|ds), we used the approach proposed by HAZUS [13], in which two types of debris are estimated according to the building type, damage state, and components (structural or non-structural). The first type of debris refers to small pieces which can be easily removed, such as brick, wood, glass, etc.; and the second type of debris are large pieces which require special treatment to break into smaller pieces before that are removed, such as wrecked steel members or RC elements. The values of debris fraction (%) proposed by HAZUS have been compiled in multiple tables based on damage observations occurred in past earthquakes.

With the aim of adapting the HAZUS approach to our context, the building types of this study were associated to those from HAZUS based on the similarity of its structural characteristics: brick masonry houses with reinforced masonry bearing walls with precast concrete diaphragms (RM2), adobe houses with unreinforced masonry bearing walls (URM), and RC apartment building with concrete shear walls (C2). Additionally, since the tables from HAZUS only provide the mean of the debris fraction, we considered a standard deviation with the form of $\sigma = k\,\mu(1-\mu)$, $k=0.40$, and then assumed a Beta distribution. In Table 5, the mean values of debris fraction DF (%) by building type are presented.

Table 5 – Mean values of debris fraction DF (%) by building type [13]

| | **Brick masonry house** | | | **Adobe house** | **RC apartment building** | |
|---|---|---|---|---|---|---|
| | Structural components | | Non-structur components | Structural components | Structural components | Non-structur components |
| **Damage state** | Small pieces | Large pieces | Small pieces | Small pieces | Small pieces | Large pieces |
| Slight | 5 | 0 | 1 | 5 | 1 | 1 |
| Moderate | 25 | 3 | 7 | 25 | 8 | 7 |
| Extensive | 60 | 30.5 | 35 | 55 | 35 | 35 |
| Complete | 100 | 100 | 100 | 100 | 100 | 100 |

### 3.4 Development of the hazard model

The seismic hazard component for this study is based on the most updated model of probabilistic seismic hazard analysis (PSHA) for Peru, developed by the Geophysical Institute of Peru in cooperation with the World Bank [17]. This model allows to express the seismicity of the country through hazard maps for different return periods as well as to generate stochastic scenarios which are usefulness for estimation of earthquake damage and losses.

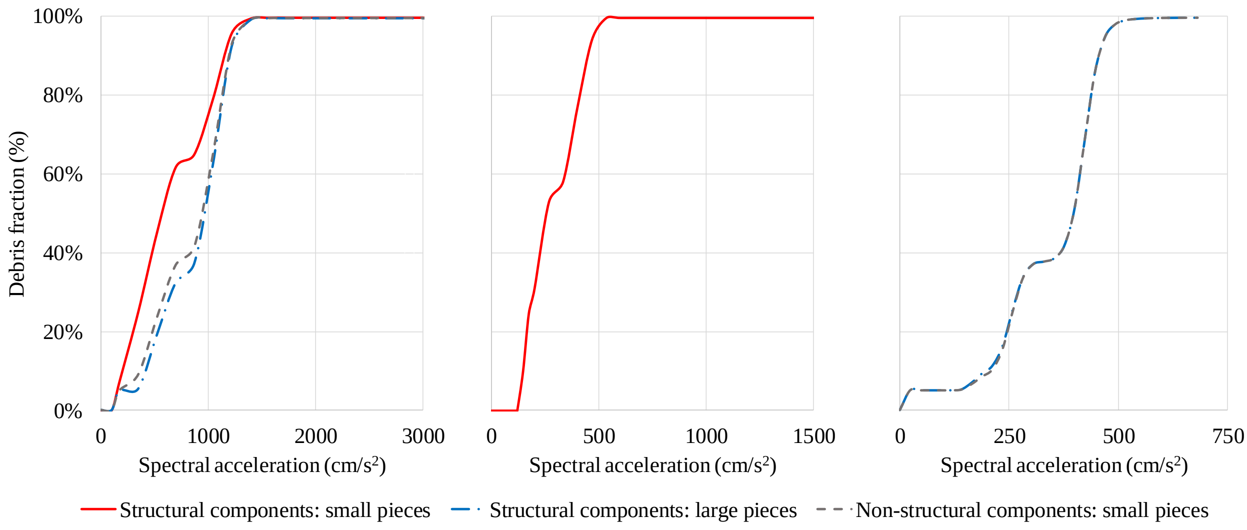
In this study, a seismic scenario was generated in order to simulate the spatial distribution of intensities produced by the 7.9 Mw Pisco earthquake, which registered a peak ground acceleration (PGA) of 334.1 cm/s$^2$. The site effects were included by using amplification factors, which were calculated based on a geotechnical microzonation map of Pisco city [18] and the criteria of the Peruvian seismic code [19]. As shown in Fig. 1.b, the city was divided in three zones: the green one corresponds to rigid soil ($S_1$ profile, S=1.0), the yellow one corresponds to intermediate soil ($S_2$ profile, S=1.2), and the red one corresponds to soft soil ($S_3$ profile, S=1.4). Consequently, the seismic intensity for the simulated scenario was incremented by 20% in the yellow zone and 40% in the red zone. The target PGA of 334.1 cm/s$^2$ was obtained after including the site effects.

## 4. Results

### 4.1 Fragility curves of debris

Five fragility curves were derived for the different building types and were subsequently used for the seismic risk assessment. The fragility curves are shown in Fig. 2, where the seismic intensity is expressed as spectral acceleration (cm/s$^2$), and debris fraction is expressed as percentage (%).

Fragility curves are classified by the size of debris; for example, debris resulting from damaged walls built with clay or adobe brick are considered as small pieces, meanwhile debris from wrecked RC elements are considered as large pieces. Moreover, debris are differentiated depending whether they were generated from a structural or a non-structural building component. For instance, debris resulting from damaged confined walls in the brick masonry houses are classified as structural debris, meanwhile debris resulting from damaged infilled walls in the RC apartment buildings are classified as non-structural debris. With regards to the shape of the curves, we identify some horizontal sections, which occurs because damage states were considered in a discrete manner.



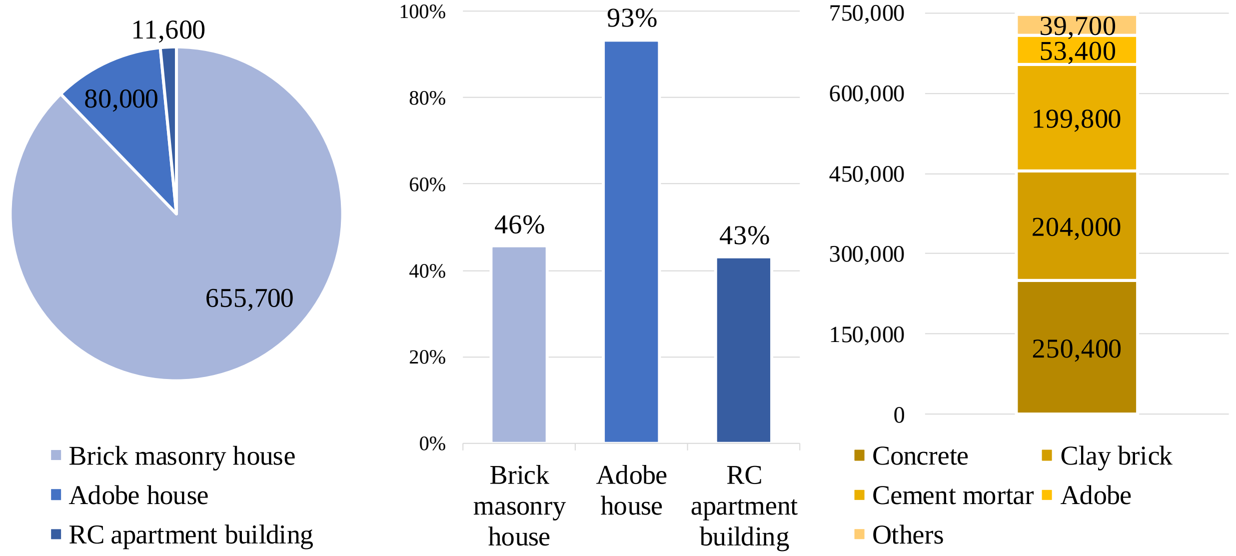
a) b) c)

Fig. 2 – Fragility curves of debris: a) Brick masonry house, b) Adobe house, c) RC apartment building

### 4.2 Generation of debris due to the 7.9 Mw Pisco Earthquake

The total amount of debris estimated with the proposed methodology for the analyzed scenario is 747,000 metric ton, which represents a relative loss of 48% of the material stock in buildings.

Debris are disaggregated by building type and material in Fig. 3, the relative material losses by building type are also shown. We can appreciate that brick masonry houses, which is the most common building type in Pisco, contributes with a predominant share (88%) to the overall amount of debris. Additionally, adobe houses, usually associated with very poor seismic performance, evidence the highest relative losses (93%), meanwhile brick masonry houses and RC apartment buildings present relative losses slightly less than 50%. In terms of construction materials, debris are mainly constituted by concrete (34%); followed by clay brick and cement mortar which present similar figures (27%).



a) b) c)

Fig. 3 – a) Debris by building type, b) Relative material losses by building type, c) Debris by material

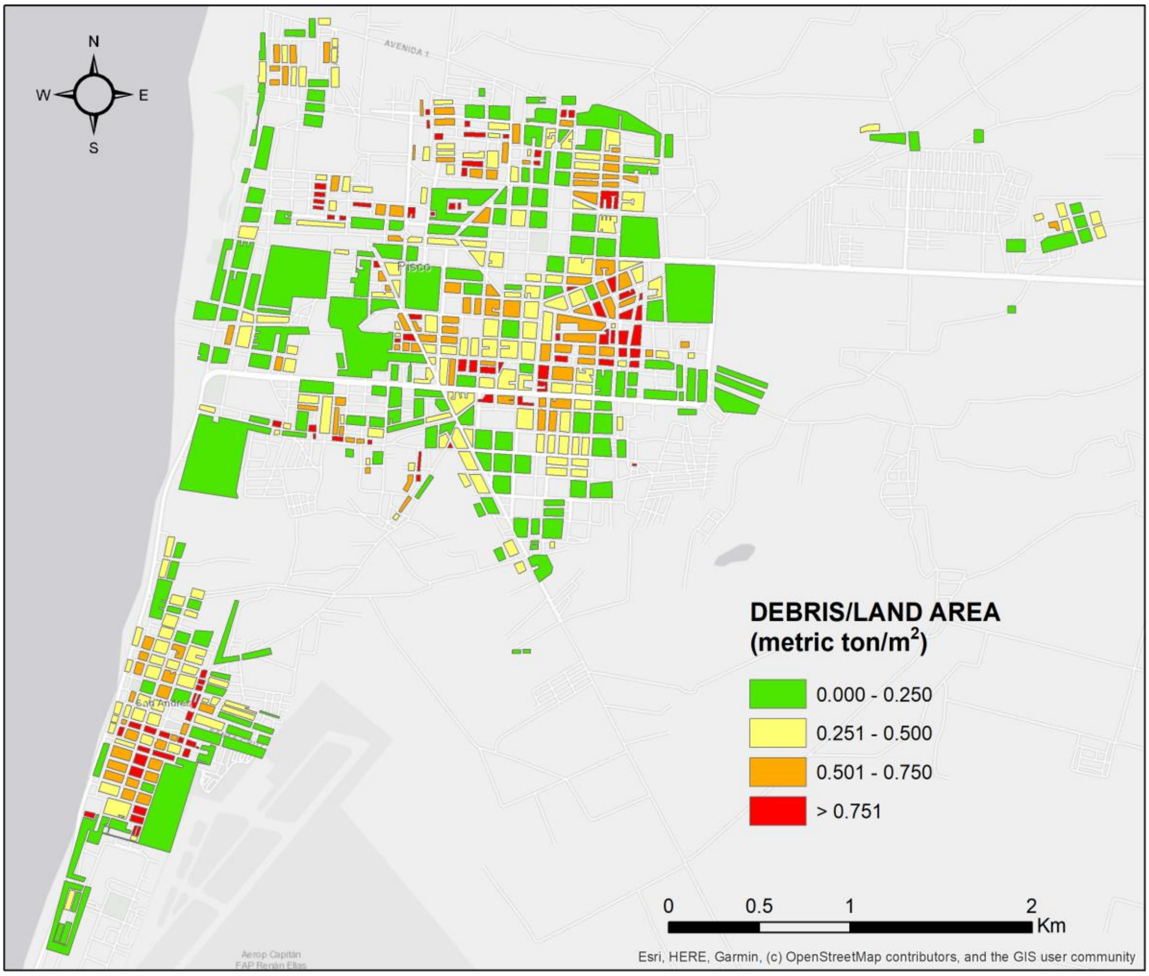
The estimation of debris generation in mass units (metric ton) was translated to volume units (m$^3$), by using a conversion factor of 1.6, which is into the range of conversion values (1.53-3.06) recommended by FEMA [20]. Consequently, the equivalent volume of debris estimated is around 1’196,000 m$^3$. The official amount of debris reported by local authorities after the 7.9 Mw earthquake was 2’120,000 m$^3$ for Pisco province [21]. By considering the proportion of damaged buildings in Pisco city (16,644 houses) in comparison with the affected buildings in the entire province (36,298 houses) [21], the volume of debris for Pisco city should be around 1’000,000 m$^3$. Based on these results, we observe a good correlation between the volume of debris estimated with the proposed methodology and the real data.

In addition, the results of waste generation, in terms of the mass of debris per land area unit (metric ton/m$^2$), are presented in Fig. 4. The map shows that the spatial distribution of debris across the city was diffuse and debris removal was probably time-consuming with a great demand of truck trips. The central core and the southern part of the city seems to be the most critical zones due to the high accumulation of waste. In addition, it is most likely that critical infrastructure accessibility (i.e., roads, schools, hospitals) was affected by the debris accumulation. However, these findings also suggest that it could have been a good opportunity to start novel recycling practices of debris (e.g., concrete debris) in the region, and in this way promote a circular economy.

## 5. Conclusions

In this research, we have presented a methodology to characterize and quantify earthquake-induced debris produced by the partial and total collapse of buildings at a city scale.

Fragility curves which relate seismic intensity with expected debris fraction were obtained for different building typologies and type of debris. The fragility curves were calibrated with a similar scenario to the 7.9 Mw earthquake that hit Pisco city (Peru) in 2007, obtaining an error of 20%. The seismic risk analysis was developed into a georeferenced platform, providing the possibility of visualizing the spatial distribution of debris across the city. This represents a major advantage because it could help to identify the most affected zones, the proximity to critical infrastructure (i.e., roads, schools, hospitals) likely to be affected, or possible evacuation routes. In this way, the methodology constitutes an effective tool to support decision-making from the stakeholders involved in disaster risk management, both in the planning stages and the post-disaster response. Finally, the debris fragility curves developed in this study could be used for future earthquake-induced debris assessment in other cities with similar building typologies, as well as to evaluate the possibility of reusing or recycling debris (e.g., use debris as aggregate in concrete or sub-base layer for roads).



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Fig. 4 – Modelled spatial distribution of debris for Pisco city, 7.9 Mw earthquake

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