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QUANTIFICATION OF LOST MATERIAL STOCK OF BUILDINGS AFTER AN EARTHQUAKE. A CASE STUDY OF CHICLAYO, PERU

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Abstract

The occurrence of seismic events that affect urban areas is associated with the generation of large amounts of debris and waste. The presence of debris and waste induces environmental pollution, affects the public health, and impedes the emergency response in the devastated areas. For these reasons, its proper characterization, quantification and subsequent management are of vital importance. This research describes a material stock analysis (MSA) approach used to characterize and quantify the material losses of buildings produced as a consequence of earthquakes. The methodological approach includes the following stages: estimation of building material stock (MS), seismic risk assessment of the studied infrastructure, and estimation of the material losses. In particular, the residential sector of Chiclayo, the fourth most populous city of Peru, was analyzed by combining geographical information systems (GIS) data and statistical data. The analysis concludes that the total MS of buildings in Chiclayo is 24.5 million metric tons (t), equivalent to 49 t per capita. This mass is primarily composed by mineral materials (96.1%), mainly represented by concrete (57.7%), whereas organic materials (wood) and metals (steel) constitute a minor share (3.9%) of the MS. Sanitary and electrical installations, and domestic furniture are excluded from these calculations. Moreover, the expected MS losses of buildings are 2.9, 4.0 and 6.9 million t for the Mw 6.6, Mw 6.9 and Mw 7.4 scenarios, respectively, where adobe represents the largest losses (54.4%, 52.7% and 45.2%). This study demonstrates the significant contribution of MSA in disaster management, providing appropriate information to decision makers during post-disaster response. Also, the resulting MS losses could help to estimate the amount of construction materials needed in the process of reconstruction, as well as the spatial distribution of lost stock could help in prioritize areas of recovery. The results may be especially important on waste management, emergency response and disaster recovery planning.

Keywords: urban risk, loss estimation, material stock, seismic risk assessment, waste management

1. Introduction

The occurrence of seismic events that affect urban areas is associated with the generation of large amounts of debris and waste. The presence of debris and waste induces environmental pollution, affects the public health, and impedes the emergency response in the devastated areas.

Peru is located in an area of very high seismic activity [1]. In particular, cities along the coast has been devastated multiple times by earthquakes in its history, e.g. Huaraz 1970 (Mw 7.6), Lima 1974 (Mw 8.0), Arequipa 2001 (Mw 8.2) and Pisco 2007 (Mw 7.9) [2, 3]. This led us to believe that coastal cities are highly exposed to seismic risk, thus the vulnerability of the buildings should be studied.

During the last years, several studies have demonstrate an increasing interest in building stock as a research object [4], as well as geographical information systems (GIS) continue to gain a strong importance in disaster management research [5]. Various authors, e.g. Tanikawa and Hashimoto [6], Marcellus-Zamora et al. [7], Kleemann et al. [8] and Tanikawa et al. [9], have applied GIS data in the determination of the building stock in cities and countries. Also the building stock has been explored from different perspectives, e.g. energy, building waste, material flows and disaster planning [4, 10]. Moreover, in a regional approach, Garcia-Torres et al. [10] proposed a methodology to predict the quantity of debris generated after a seismic event in Tacna, Peru.

This article presents an enhanced methodological approach, based on Garcia-Torres and colleagues, to characterize and quantify the material stock of buildings and material losses produced as a consequence of possible earthquakes. The main enhancements include a more detailed analysis of the structure and material composition of the buildings. Material stock analysis (MSA) is developed using GIS data and statistical data. This study aims to evaluate the spatial distribution of material losses of buildings in Chiclayo city, and estimate the amount of construction materials needed in the process of reconstruction. The results can be useful to organize an efficient post-earthquake debris management and recovery of disaster-stricken areas.

2. Material and Methods

This research includes four main stages: i) Generation of the building inventory, ii) Estimation of building material stock, iii) Seismic risk assessment of buildings, and iv) Estimation of building material losses. These stages are explained in the following paragraphs.

2.1 Generation of the building inventory

Based on the construction techniques, local and regional traditions, climate conditions, available materials, and others, buildings can vary widely from one country to another. Thus, building types have been classified in this study based on two available attributes: type of dwelling and predominant construction material on exterior walls. The building inventory data is constructed according to national census information [11].

2.2 Estimation of building material stock

This study considers different strategies to analyze two important parameters: gross floor area of buildings – GFA (m^2) and material intensities – MI (kg/m^2). By combining both, we estimated the total material stock – MS from Eq. (1) and Eq. (2).

$$M_{m,i} = \left(\sum_j GFA_{i,j} \cdot N_{i,j} \right) \cdot MI_{m,i} \tag{1}$$

$$MS = \sum_{m,i} M_{m,i} \tag{2}$$

Where,

$GFA_{i,j}$ = gross floor area by building type *i* and district *j* [m^2]

$N_{i,j}$ = number of buildings by building type *i* and district *j*

$MI_{m,i}$ = material intensity for material *m* and building type *i* [kg/m^2]

$M_{m,i}$ = mass of material *m* built in building type *i* [kg]

MS = total material stock of buildings [metric ton]

The strategy used to obtain information about gross floor area considers a sample of buildings. For these buildings, GFA was calculated using i) cadastral maps obtained from the municipal authorities that provides information about the area of the lots, and ii) exploration of the city using Google Street View tool that provides a panoramic views of the streets and that helped to obtain the number of storeys of the buildings. Then, GFA is calculated by multiplying the area of the lots by the number of storeys by a floor area ratio.

In addition, the material intensity was calculated based on a sample of buildings from which material composition was analyzed according to i) on-site investigation, through measurements of visible components (walls and floors), and ii) detailed construction blueprints, through measurements of all structural and nonstructural components. The material composition is calculated not only for the superstructure of the buildings, but also for their foundations.

Lastly, the total mass is calculated by multiplying the volume, area or unit of the particular materials by its specific density or weight, obtained from literature and design codes.

2.3 Seismic risk assessment of buildings

Seismic risk assessment involves a complex interaction of three main components: exposure, seismic hazard and vulnerability [12]. The evaluation, performed in CAPRA software platform, allows combining these components in order to obtain the structural damage of buildings [13].

Exposure is represented by the building inventory, which is classified into different typologies with structural characteristics that reflect their performance under seismic actions. Next, seismic hazard is defined by possible seismic scenarios in the study area. Each scenario, associated to a specific return period, is characterized by the position of the epicenter, hypocenter, and magnitude of the earthquake. The influence of local soil conditions (site effects) on the spatial distribution of ground motion is also taken into consideration. Lastly, vulnerability assessment is conducted using vulnerability functions, which provides the expected damage value for a given seismic intensity. Damage is expressed in terms of the mean damage ratio (MDR), which is the ratio between the repair cost of the building and the cost of rebuilding it [14].

The resulting damage ratios are classified into damage states, which are indicator ranges of the severity of the global damage. These were adopted as proposed in HAZUS [15].

2.4 Estimation of building material losses

The loss estimation is based on an empirical approach proposed by HAZUS [15], where some tables have been compiled to estimate generated debris from different structural damage states for different building types. We estimated the material stock losses – LMS from Eq. (3) and Eq. (4).

$$LM_{m,i} = \sum_{k} DF_{m,i,k} \cdot M_{m,i,k} \tag{3}$$

$$LMS = \sum_{m,i} LM_{m,i} \tag{4}$$

Where,

$DF_{m,i,k}$ = debris fraction of material *m* built in the building type *i* due to structural damage state *k* [%]

$M_{m,i,k}$ = mass of material *m* built in building type *i* in structural damage state *k* [kg]

$LM_{m,i}$ = mass of lost material *m* built in the building type *i* [kg]

LMS = material stock losses of buildings [metric ton]

3. Case study

3.1 Study region

Chiclayo, capital city of the Lambayeque region, in northern Peru, was selected as a case study. With a population of 600,440 inhabitants in 2015, it is the fourth most populous city in Peru [16], and due its important commercial and industrial activity, it has become one of the most important cities of northern Peru [17]. Chiclayo (central core) comprises 3 contiguous urban districts: Chiclayo, José Leonardo Ortiz and La Victoria, with a total extension of 50.23 km^2 [18]. The location of the city is shown in Fig. 1.

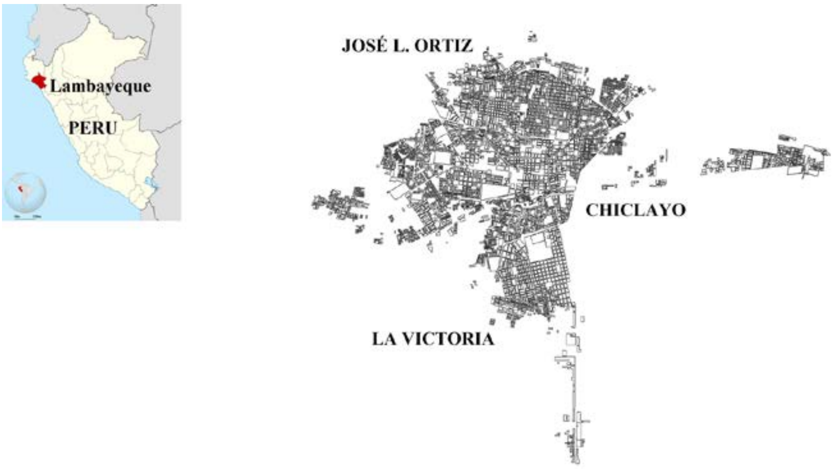

Fig. 1 – Location of Chiclayo city

3.2 Building inventory

The building inventory is classified in four building types. These are brick masonry houses, adobe houses, reinforced concrete (RC) apartment buildings, and straw houses. Brick masonry houses, are composed of clay brick walls confined by reinforced concrete columns and beams which support floors, formed by a series of reinforced concrete ribs separated by hollow roof bricks [19]. Adobe houses are composed of adobe blocks walls, which support roofs composed of wooden joists framework covered with crushed cane and mud [20]. Moreover, RC apartment buildings are composed of structural frames with columns, beams and shear walls, which support similar floors as the ones described in the brick masonry houses. Typically, the interior walls are made of hollow clay bricks [21]. Finally, straw houses are improvised constructions built using inadequate materials, e.g. mats, plastics, and corrugated zinc sheets.

Fig. 2 presents a summary of the building inventory. The data used for this article was obtained in 2007 by the Peruvian national Census.

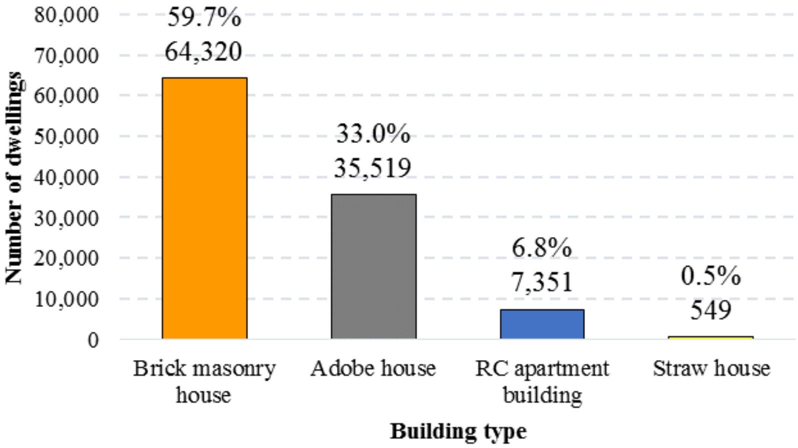

Fig. 2 – Distribution of the building inventory in Chiclayo city

3.3 Estimation of building material stock

Different data sources (i.e. cadastral maps, construction blueprints, on-site investigation, and Google Street View tool) are used to derive information related to gross floor area and material intensities, which is subsequently combined with the GIS data.

For the gross floor area, a total of 8,900 houses were sampled to calculate average values of the number of storeys and gross floor area. The sample size per district is proportional to its total number of buildings; as a result, 1,500, 2,900, and 4,500 buildings were analyzed in La Victoria, José Leonardo Ortiz, and Chiclayo, respectively. Moreover, to calculate the material composition, 30 brick masonry houses and 30 adobe houses were examined on-site, whereas 30 brick masonry houses and 30 RC apartment buildings were analyzed using construction blueprints. Straw houses were not considered in the MSA because its share to the MS is negligible.

3.4 Seismic risk assessment of buildings

The selection of seismic scenarios is based on a Peru's seismic hazard model, developed by IGP [22] using CRISIS 2007, the hazard module of CAPRA. In that study, data from 33 seismic sources and ground motion prediction equations were combined to calculate the seismic intensity for multiple scenarios, in terms of peak ground acceleration (PGA) and maximum spectral acceleration. Three of those multiple scenarios that would affect Chiclayo city were used for this study.

Table 1 presents a summary of the selected scenarios, with epicenter off the coast of Lambayeque, to 80 km depth. Also, the spatial distribution of PGA, worked on CAPRA-GIS, is shown in Fig. 3. The scenarios were selected based on the following criteria: probability of occurrence and risk potential. Although an extreme scenario could result in major losses, other medium scenarios, such as the ones selected, could lead to higher accumulated losses in the medium/long-term.

Table 1 – Seismic scenarios in Chiclayo city

Seismic scenario	**Magnitude (Mw)**	**Peak ground acceleration (cm/s^2)**	**Return period (years)**
1	6.6	152	50
2	6.9	185	85
3	7.4	272	275

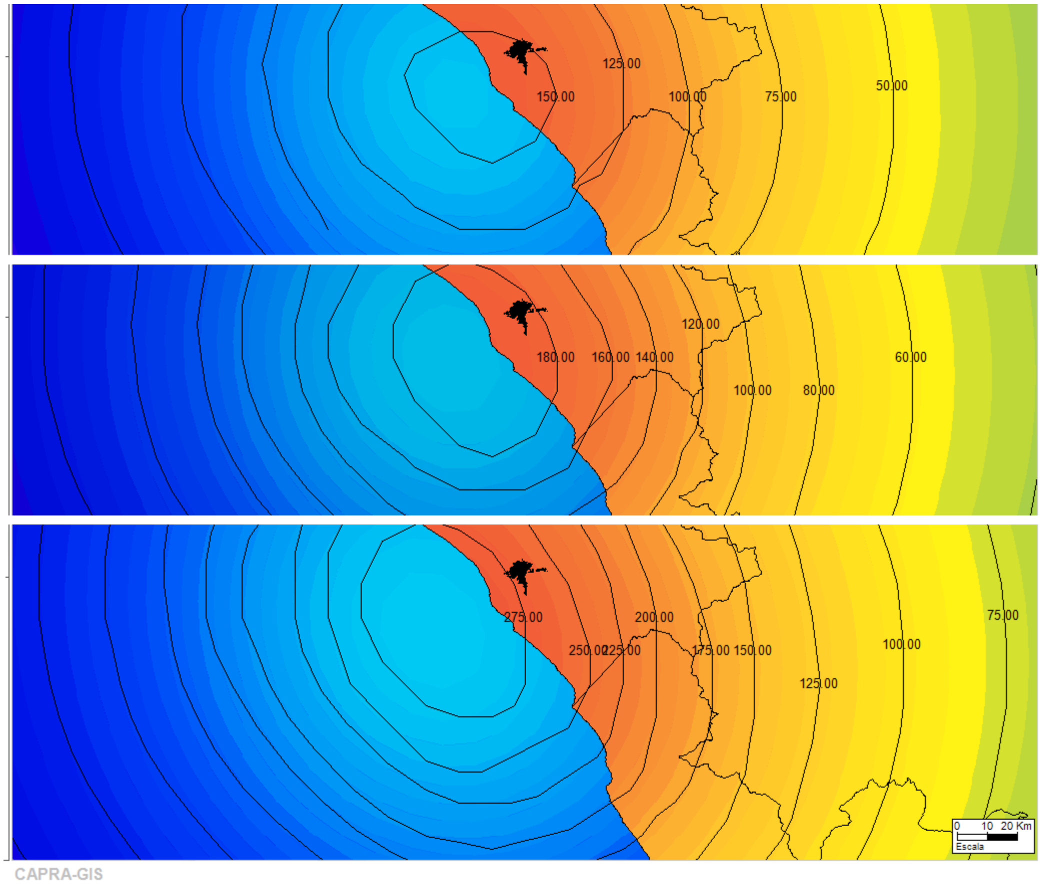

Fig. 3 – Spatial distribution of PGA (cm/s^2) for the seismic scenarios

In addition, the site effects are included using amplification factors. Based on a geotechnical map developed by INDECI [23] and the criteria of the Peruvian seismic code [24], Chiclayo is divided in two zones. Both zones are illustrated in Fig. 4, the green one corresponds with soil type S2 (intermediate soils, S=1.20) and the red one corresponds with soil type S3 (soft soil, S=1.40). This way, the seismic intensity of each scenario is increased by 20% and 40% respectively.

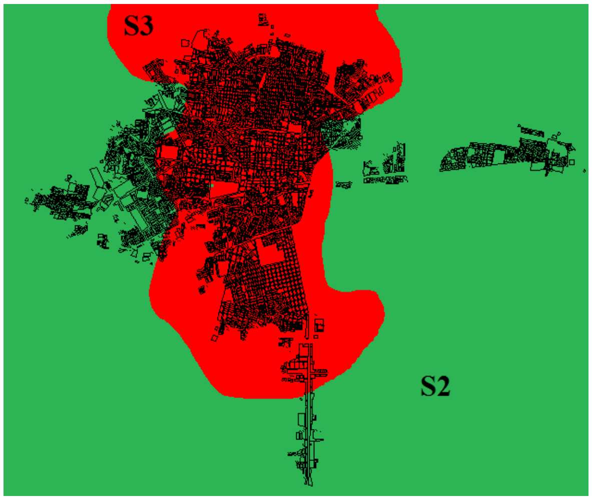

Fig. 4 – Soil types in Chiclayo city (adapted from INDECI)

Moreover, the vulnerability functions used in this study were developed by CIRNA-PUCP Consortium [25] for Peruvian building types, following the guidelines established by HAZUS. The functions allow to associate seismic intensity, expressed as spectral acceleration, with expected damage value, expressed as damage ratio. Subsequently, the buildings are classified into one of the HAZUS damage states, according to the range of possible loss ratios: Slight (0%-5%), Moderate (5%-25%), Extensive (25%-65%), Complete (65%-100%).

3.5 Estimation of building material losses

In order to apply the approach proposed by HAZUS for the estimation of debris, the Peruvian building types need to be associated with the HAZUS model building types, based on the similarity of its structural characteristics. For example, brick masonry house is associated with reinforced masonry bearing walls with precast concrete diaphragms (RM2), adobe house is associated with unreinforced masonry bearing walls (URM), and RC apartment building is associated with concrete shear walls (C2).

Table 2 presents the expected percentage of debris generated due to structural and nonstructural damage for building type, adapted from HAZUS-MH MR5.

Table 2 – Expected percentage of debris generated for building type (adapted from HAZUS-MH MR5)

	Brick masonry house		**Adobe house**	**RC apartment building**	
	Structural elements		Structural elements	Structural elements	Nonstructural elements
Damage state	Clay brick, mortar	Reinforced concrete, steel	Adobe brick, others	Reinforced concrete, steel	Clay brick, mortar
Slight	5.0 %	0.0 %	5.0 %	1.0 %	1.0 %
Moderate	25.0 %	3.0 %	25.0 %	8.0 %	7.0 %
Extensive	60.0 %	30.5 %	55.0 %	35.0 %	35.0 %
Complete	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %

4. Results

4.1 Average values of gross floor area and material intensities

The analysis of the data collected resulted in average values of number of storeys and gross floor area for different building types and districts, which are shown in Table 3. For brick masonry dwellings, the average number of floor and gross floor area, ranged from 1.7 to 1.9 and 153 to 179 m^2, respectively. The gross floor area for adobe dwellings and RC apartment buildings was lower: 97 to 122 m^2.

Moreover, the analysis of the data collected resulted in specific material intensities, classified by construction materials, for different building types, which are shown in Table 4.

Table 3 – Average values of number of storeys and gross floor area (m^2) for different building types and districts

	Chiclayo		**José Leonardo Ortiz**		**La Victoria**	
Building type	**Number of storeys**	**Gross floor area**	**Number of storeys**	**Gross floor area**	**Number of storeys**	**Gross floor area**
Brick masonry house	1.9	179	1.9	153	1.7	165
Adobe house	1.2	105	1.2	96	1.1	122
RC apartment building	1.0	100	1.0	96	1.0	97

Table 4 – Material intensities (kg/m^2) for different building types

Building type	**Building components**	**Concrete**	**Clay brick**	**Mortar**	**Steel**	**Adobe brick**	**Others (wood, mud)**
Brick masonry house	Super-structure	509	267	256	26.6	-	-
	Foundation	549	-	-	8.2	-	-
Adobe house	Super-structure	-	-	-	-	911	150
	Foundation	539	-	-	-	-	-
RC apartment building	Super-structure	616	234	241	31.1	-	-
	Foundation	317	-	-	6.4	-	-

4.2 Material stock

By combining information about the GFA and specific material intensities, the total MS of buildings in Chiclayo in the year 2007 is estimated at 24.5 million t. The mass is primarily composed by mineral materials (96.1%), whereas organic materials and metals constitute a minor share (3.9%) of the MS. Concrete is the predominant material (14.2 million t) of the MS, followed by adobe brick (3.4 million t) and clay brick (3.1 million t). The MS per capita is about 49 t/cap. Fig. 5 illustrates the material composition of the total MS.

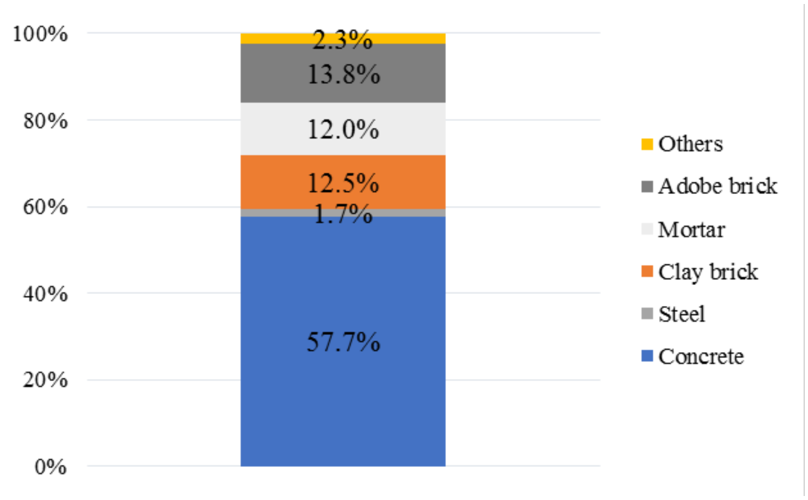

Fig. 5 – Material composition of the total MS of buildings

4.3 Damage ratios

The seismic risk assessment resulted in values of damage ratio by building type and seismic scenario. Although damage ratio varies spatially, in order to get an overview of the vulnerability of the buildings, average values are shown, in Fig. 6.

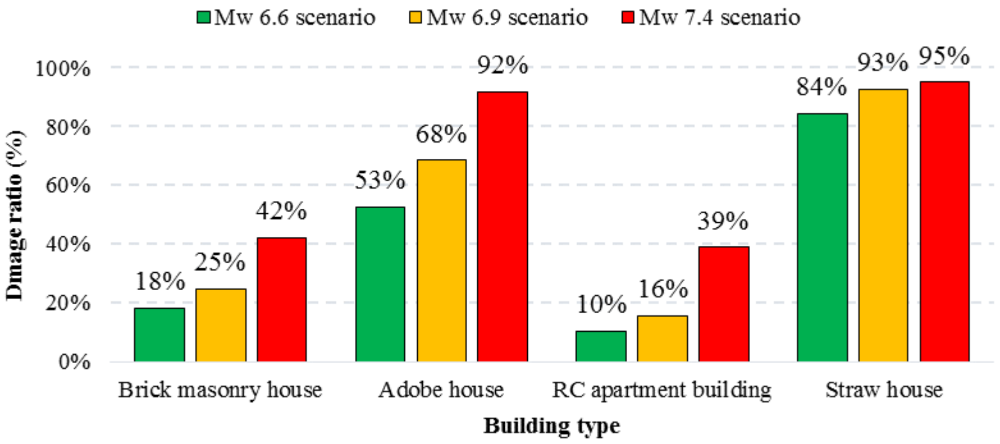

Fig. 6 – Average values of damage ratio by building type and seismic scenario

4.4 Building material losses

By combining information about the total MS and the damage ratios, the expected MS losses of buildings are calculated at 2.9 million t, 4.0 million t, and 6.9 million t for the Mw 6.6, Mw 6.9 and Mw 7.4 scenarios, respectively. These losses represent the 11.9%, 16.3% and 28.0% of the total MS. Moreover, adobe is the material which represents the largest losses (45.2%, 52.7% and 54.4%).

Fig. 7 presents the MS losses in terms of construction materials, per seismic scenario. Also, Fig. 8 illustrates the spatial distribution of MS losses in the city for the Mw 7.4 scenario. The district of La Victoria, where a large number of adobe dwellings exist, would be the most affected area by the concentration of debris. Other critical points dispersed through the city can be easily identified on the map.

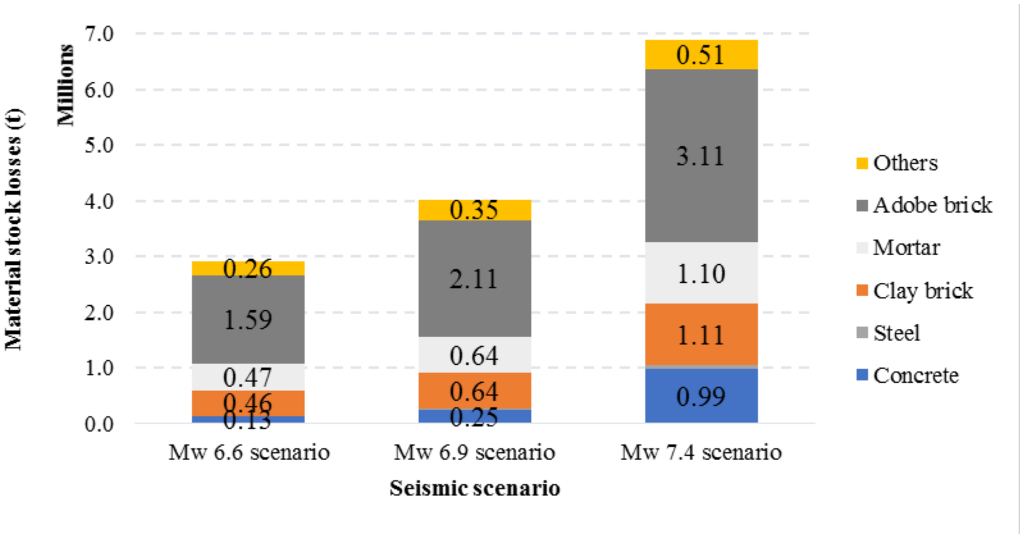

Fig. 7 – MS losses by building type and seismic scenario

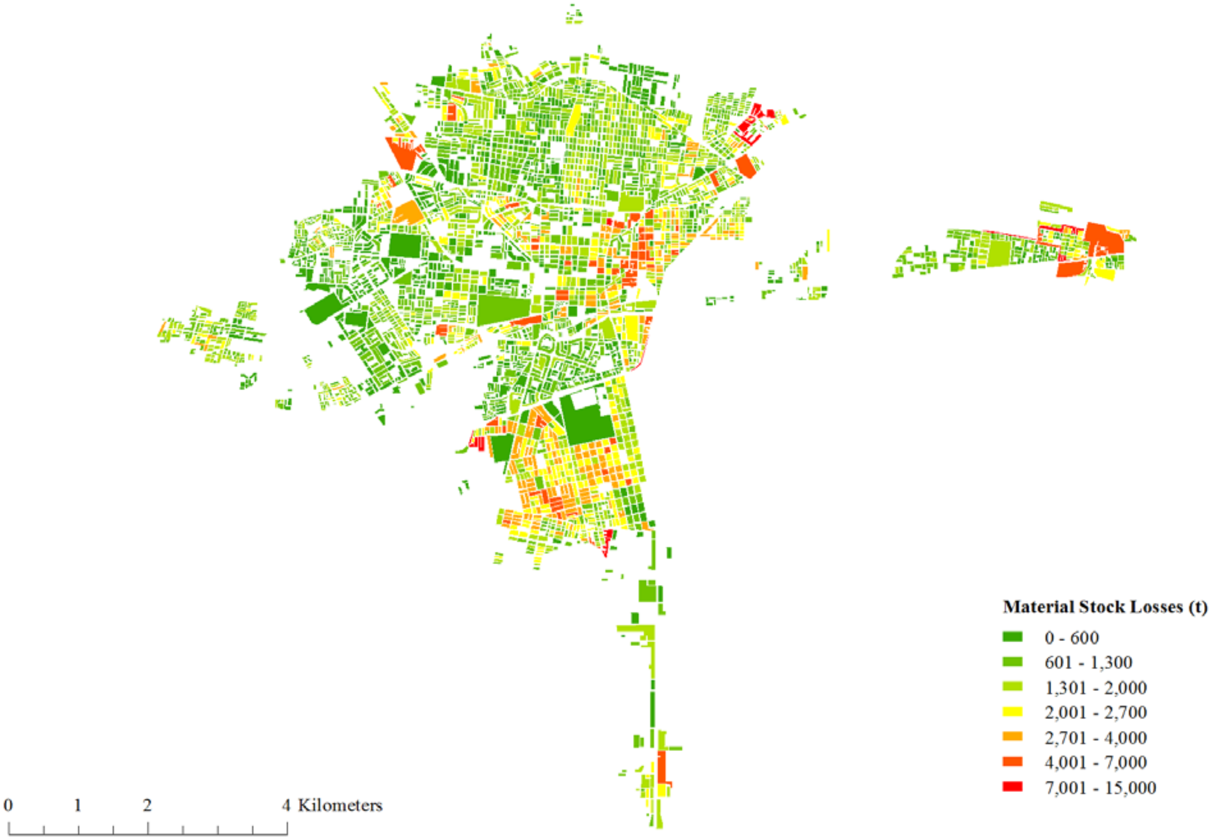

Fig. 8 – Spatial distribution of MS losses for Mw 7.4 scenario

5. Conclusions

This article has presented an approach to characterize and quantify the MS of buildings and material losses produced as a consequence of possible earthquakes and its application on a case study. Findings on MS losses predict the generation of important volumes of debris (i.e. 2.9, 4.0 and 6.9 million t for the Mw 6.6, Mw 6.9 and Mw 7.4 scenarios, respectively) and the need of an appropriate waste management strategy that promotes reuse and recycling practices in the country, such as the case of the use of recycled concrete as a substitute for aggregates. Moreover, the study highlights the importance of the supply chain of construction materials in a possible reconstruction phase.

Additionally, this study reaffirms the need of reinforcement management plans, especially for highly vulnerable structures. For example, adobe dwellings present a high value of damage associated with a moderate earthquake. This corresponds with damage reported in past events, as in the case of Pisco in 2007 (Mw 7.9) [3] where more than 80% of adobe dwellings collapsed or sustained heavy damage [20]. Hence, in order to reduce the seismic vulnerability of this housing type, reinforcement techniques that include wall reinforcement using welded wire mesh [26], geogrid and plastic mesh [27], and nylon rope mesh [28], among others, should be promoted. Moreover, technology-transfer initiatives to increase acceptance of these practices among dwellers should be accompanied [29].

Furthermore, another advantage of this methodology is the use of GIS to visualize the most affected zones trough the city. Thus, the spatial distribution of MS losses (see Figure 8) could help prioritize areas of recovery as well as aid routes.

Finally, this study demonstrates the significant contribution of MSA in disaster management, providing appropriate information to decision makers during post-disaster response. The results could be especially important on waste management, emergency response and infrastructure recovery planning.

6. Acknowledgements

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