Methodology to characterize and quantify debris generation in residential buildings after seismic events

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ABSTRACT

Earthquakes are natural phenomena that can cause severe damage to housing infrastructure and prolonged disruption to society. Depending on their magnitude, epicenter location, local construction characteristics, and many other features, earthquakes may generate large amounts of debris and waste. The large amounts of debris generated after the disaster become one of the main problems for a population facing health issues and the need to reconstruct the city. Proper characterization and quantification of debris, subsequent waste management and reconstruction planning are essential for the restoration of an area affected by an earthquake. This study presents a methodological approach to characterize, quantify and forecast the debris produced as a consequence of earthquakes, as well as the flow of materials required for the reconstruction of the area affected. The proposed methodology includes a residential infrastructure characterization stage, a probabilistic estimation of damage by characterizing the vulnerability functions using CAPRA-GIS tool, and material flow analyses (MFA) for the characterization and quantification of debris associated with the event of an earthquake and for new materials for the reconstruction stage. A case study was developed to test this methodological approach. The residential sector of Tacna, a city with high seismic risk located on the southern coast of Peru, was selected. Moreover, five different construction systems (i.e., reinforced masonry-bearing walls with concrete diaphragms, adobe, wood, concrete shear walls, and straw) used in the residential sector of Tacna were characterized. Also, three possible earthquake scenarios (i.e., 8.6 Mw, 7.5 Mw and 6.2 Mw) were analyzed, each one with three different material end-of-life management situations. Simultaneously, the origin and quantities of new materials needed for the reconstruction of housing infrastructure were determined. The flow of new materials considered productivity rates in the construction and manufacturing sectors. The results show that in the presence of the greatest earthquake (8.6 Mw), adobe and straw homes suffered greatest damage, with damage proportions of 63% and 48%, yielding 27,000 and 1390 tonnes of debris, respectively. Also, 204,000 tonnes of concrete, 7400 tonnes of steel and 461,400 tonnes of clay brick were included as debris generated in this scenario. Furthermore, for all scenarios, the MFA provides an estimate of regional import of materials (e.g., cement, steel, brick and wood) for the reconstruction phase. Finally, the methodology is applicable to developed and undeveloped countries with different housing types, their respective vulnerability functions and constant earthquake recurrence.

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1. Introduction

Natural disasters may pose severe consequences in the social, economic and environmental spheres, including death, injury, diseases, pollution, property damage and related economic burdens (Smith, 2013). Earthquakes, a natural geological hazard, are a peril to society in many parts of the world. Depending on its characteristics (e.g., magnitude, epicenter location), seismic activity may pose different levels of threats to civilization. In particular, impacts from vulnerable residential infrastructure include deaths or injuries, interruption of transportation and communication systems, etc. Moreover, large amounts of debris may be generated after a seismic event and could constitute serious health, environmental and logistic problems, such as disease propagation, pollution or delays in the transfer of aid to the affected area. In many countries affected by earthquakes or other natural disasters, there is continuous work related to the identification and reduction of risk connected to this natural hazard, such as SiRAD’s research (Gamarra et al., 2011).

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Nevertheless, risk prevention and reconstruction planning require the development of methodologies that include the characterization and quantification of debris and its subsequent management after disaster events.

The generation of debris due to earthquakes and other natural disasters has been studied by some authors. For example, Rafiee et al. (2008) analyzed the implementation of strategies in debris management after seismic events in the city of Tehran, Iran. Among their findings, Rafiee and colleagues indicated that the estimation of debris is a highly important strategy when developing waste management plans (Rafiee et al., 2008). Moreover, in the work done by Hirayama et al. (2010) an estimation of debris obtained from natural disasters, in particular earthquakes and floods, was developed. Based on data from past disasters and natural hazard maps, debris were calculated for the Tokyo Metropolitan area (Hirayama et al., 2010). This work emphasized the need for a “disaster debris management system” and cooperative measures. In addition, Tanikawa et al. (2014) used material stock analysis to estimate construction material losses from buildings and roads, generated after a 9.0 Mw earthquake and subsequent tsunami hit Japan in 2011. Their work was highly dependent on geographical information systems, material intensities for roads and buildings, and statistical databases, and estimated around 33.9 million tonnes of material stock losses from buildings and roads (Tanikawa et al., 2014).

While related to debris estimation and management, not natural disasters, the study of construction and demolition (C&D) waste, its estimation, generation and management are presented below due to its relevance to the present research. Shi and Xu (2006) used cement production data and building area data to estimate the amount of concrete debris generated in China. In addition, different methodologies have been established to estimate building demolition waste in certain regions of the world. For example, Cochran’s study (2007) explored a method to quantify and characterize the generation of C&D from residential and non-residential buildings in three main activities: construction, renovation, and demolition or end-of-life. Activity level and waste ratios per activity were used to predict the amount of C&D generated. Using Florida as a case study, this research calculated around 3.8 megatons of C&D generated in the year 2000. In addition, Kleemann and colleagues presented an approach that quantifies and locates in a georeferenced system the stock of materials in urban areas, specifically buildings (Kleemann et al., 2016a). In addition, Kleemann et al. developed a method that traces demolition activities and estimates the amount of material that was removed from the stock of materials of a studied area (Kleemann et al., 2016c,b). The city of Vienna, Austria was selected as the case study to test these methods.

The estimation of material stocks and subsequent estimation of the generation of C&D waste or debris is a growing research area that still has some unresolved factors. Especially important is the need to forecast the generation of debris due to an earthquake before this event takes place. Consequently, this research paper presents an original and comprehensive methodological approach that characterizes and quantifies the generation of debris as a consequence of earthquakes, considering several earthquake scenarios with vulnerability functions per housing type, such as adobe and straw dwellings. The interdisciplinary methodology developed to predict debris generation makes this study unique. In addition, the relevance of the project is due to the need to avoid difficulties in the arrival of aid and allow for better estimations of the amounts of new materials needed for reconstruction.

Peru, specifically the city of Tacna, was selected as a case study to test this methodology. Peru is a country that presents a very high seismic activity. Historically, several earthquakes have impacted the country. According to Giesecke and Silgado (1981), more than 2500 earthquakes struck Peru between the sixteenth and nineteenth centuries and 60,100 were recorded between 1471 and 2008 (INDECI, 2009). Moreover, recorded losses are extensive. In the earthquake that hit Huaraz in 1971, for example, 186,000 homes were destroyed, 69,000 people died, 150,000 were injured and over a million were left homeless (Morales-Soto and Zavala, 2008). Also, the earthquake that hit Pisco in 2007 affected 431,000 people, 1500 people died and 2291 injured (IGP, 2012). In addition, the earthquake generated more than 900,000 t of debris in Pisco alone and also affected neighbor locations (INDECI, 2009; MINSA, 2007; Alatrista and Gutiérrez, 2012).

This paper is divided into five sections. The second section provides a description of the proposed methodological approach, in which tools from the risk assessment and industrial ecology fields have been used to accomplish the objective of this work. Section 3 presents the important characteristics of the selected case study (Tacna) and Section 4 describes the main findings related to the application of the developed methodology. Finally, in Section 5, the main findings of this work are discussed and the conclusions of this work are presented in Section 6.

2. Methodology

The methodological framework proposed in this study, summarized in Fig. 1, utilizes tools from several disciplines (e.g., Risk Assessment and Industrial Ecology) to characterize and quantify prior to a seismic event the debris generated after occurrence of this natural hazard. The initial step of the methodology includes a classification of the residential infrastructure and the quantification of the embedded materials or material stock. Then, physical damage to the infrastructure is estimated by characterizing vulnerability functions using the CAPRA-GIS tool. Finally, Material Flow Analysis (MFA) is used for the characterization and quantification of debris associated with the earthquake event and, subsequently, new materials for the reconstruction stage.

2.1. Material stock

The initial step of this methodology requires the classification of the infrastructure under analysis and quantification of the embedded materials. This step combines in-situ infrastructure recognition, technical recording, Census Data of Population and Housing (INEI, 2007) and the use of Google Street View (Street View, Google Maps, 2014) which makes it possible to obtain approximate dimensions of infrastructure. A second field study is proposed for data validation. The Total Material Stock contained per housing type is estimated by multiplying the total material in one house by the total number of houses per type, as shown in Eq. (1).

\[
TMS_{si} = M_{ki} \times Ni
\]

where \(TMS_{si}\) is the total stock for material \(k\) per housing type \(i\), \(M_{ki}\) is the amount of material \(k\) per housing type \(i\), and \(Ni\) represent the total number of dwellings of housing type \(i\). The quantification of embedded materials is performed assuming average features per housing type, such as number of floors, dimensions of building material or structural system. Also, for low-rise structures, foundation materials per each type of house are not considered due to the insignificant relationship between the substructure and the superstructure. Also, if basements are extremely rare in the studied residential sector, they can be excluded from the analysis. Urban material stocks have been studied in some areas, for example, Beijing, Tianjin and Shanghai (Huang et al., 2016; Hu et al., 2010), Vienna (Kleemann et al., 2016b), and Los Angeles (Reyna and Chester, 2015).
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