PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ
ESCUELA DE POSGRADO

DEVELOPMENT OF A METHODOLOGY TO CHARACTERIZE AND QUANTIFY DEBRIS GENERATION AFTER A SEISMIC EVENT: A CASE STUDY OF TACNA, PERÚ

Tesis para optar el Grado de **Magister en Ingeniería Civil**, que presenta la Ingeniera:

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Lima, Febrero del 2016

SUMMARY

Earthquakes are natural phenomena that can cause severe damage to civilian infrastructure and prolonged disruption to society. Depending on their magnitude, epicenter location, infrastructure 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 a health issue and rapid reconstruction of the city. A proper characterization and quantification of debris and subsequent waste management and reconstruction plan is essential for the restoration of an area affected by an earthquake. This study presents a methodological approach to characterize and quantify 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 an infrastructure characterization stage, a probabilistic estimation of damage by characterizing the vulnerability functions using CAPRA-GIS tool, and material flow analysis (MFA) for the characterization and quantification of debris associated with the event of an earthquake and 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) presented 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 end-of-life management situations. Simultaneously, the origin and quantities of new materials needed for the reconstruction of civil 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 greater earthquake (8.6 Mw.), adobe and straw homes suffered greater damage, with damage percentages of 63 and 48, yielding 27000 tonnes and 1390 tonnes of debris, respectively. Also, 204,000 tonnes of concrete, 7,400 tonnes of steel and 461,400 tonnes of clay brick were included as debris generated in this scenario. Furthermore, for all scenarios, the MFA estimates a regional import of materials (e.g. cement, steel, brick and wood) for the reconstruction phase. The following methodology is applicable to developed and undeveloped countries with different housing types, their respective vulnerability functions and constant earthquake recurrence.

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CHAPTER 1. INTRODUCTION

All over the world, the generation of large amounts of debris after a seismic event constitutes a serious problem due to the consequences it may have for the effective arrival of aid to the affected area during the reconstruction stage. Peru is one of the countries that presents the highest seismic activity in the Latin American region. Associated with the subduction process of the Nazca Plate beneath the South American Plate, earthquakes have constantly impacted the country throughout its long history. Between the sixteenth and nineteenth centuries more than 2,500 earthquakes struck the country (Giesecke and Silgado, 1981) and, based on the Geophysical Institute of Peru (IGP), 60,100 earthquakes were recorded between 1471 and 2008 (IGP 2012). One of the most memorable earthquakes in Peru hit Huaraz on May 31 st, 1970 and, with a 7.9 degree magnitude on the Richter scale, left 186,000 homes destroyed, 69,000 dead, 150,000 injured and over a million homeless (Morales-Soto and Zavala, 2008). In addition, an earthquake hit Pisco in 2007 causing 1,500 deaths, 2,291 injured and 431, 000 people affected (IGP, 2012). In addition, the earthquake caused damage in around 192,500 dwellings in different provinces located near Pisco: Huancavelica, Ica and Lima, which corresponded to 78% of the existing dwellings at the time (Alatrista and Gutiérrez, 2012). Approximately 27% of the damaged dwellings were considered destroyed due to the collapse of walls and roofs. The remaining 73% had damage ranging from small cracks to serious damage in most of their structural elements and some were considered uninhabitable (INEI,2008). The earthquake generated more than 900,000 tonnes of debris in Pisco alone, 90% of the total in three provinces of Ica (INDECI, 2009; MINSA, 2007).

According to the characteristics of the earthquake (e. magnitude, epicenter location) and the vulnerability of the civilian infrastructure, seismic activity may pose a severe threat to society which includes human casualties, severe damage to infrastructure, and large amounts of debris waste, creating an important disruption to the affected area. Infrastructure in Peru has a high level of seismic vulnerability caused by several factors including the poor quality of construction materials and the lack of supervision on informal buildings. The vast majority of the population lives in old, self-built homes, causing more risk in highly seismic zones (INEI, 2014). Although the National Civil Defense Institute continuously works on objectives related to the identification and reduction of risk, such as SIRAD´s research (Gamarra, L. et al. 2011), their prevention and reconstruction plans show an insufficiency in the ability to establish methodologies for specific solutions such as quantification of debris and their subsequent management after disaster events (INDECI,2010.)

Different scholars have studied the generation of debris and their management. A group of them dealt with end-of-life construction wastes, while other researchers worked on disaster waste management. The work performed by Shi, J. et al. (2006) calculated the amount of concrete debris with the use of annual concrete production data and the annual house demolition rate. In addition, different methodologies were established to estimate debris amounts from buildings infrastructure demolition in certain regions of the United States. For example, in Cochran´s study (2007) a methodology for the accounting, generation, and composition of building-related construction and demolition (C&D) was explored. Six categories of housing were analyzed: residential construction, non-residential construction, residential demolition, nonresidential demolition, residential renovation and non-residential renovation. Amounts of debris produced from each activity were calculated as the product of the total area of activity and the waste generated per unit area of activity. The composition was estimated as the product of the total area of activity and the amount of each waste component generated per unit area. Since it accommodates regional construction styles and available data, this proposed model differs from others.

Rafee et. al (2008) analyzed the implementation of strategies in debris management after seismic events in the city of Theran. Moreover, in the work done by N. Hirayama et al. (2010) an estimation procedure was established to assess the amount of debris resulting from earthquake and flood disasters. The amount of disaster debris from earthquake and catastrophic flood disasters for the Tokyo Metropolitan area case study, was estimated according to hazard maps. It concludes that disaster debris management systems, including wide-ranging cooperative measures should be stablished. In addition, Tanikawa et al. (2014) used material stock analysis (MSA) to examine the losses of infrastructure materials after the magnitude 9.0 earthquake and tsunami that struck eastern Japan in 2011. The analysis is based on the use of geographical information systems (GIS), databases and statistics. The objective was to describe the construction materials lost and to estimate the amount of infrastructure material needed to rehabilitate affected areas. The study methodology comprises two components: the calculation of the lost Material Stock (MS) of buildings in five prefectures and the lost MS of roads in Iwate, Miyagi, and Fukushima prefectures. All building types in Japan are taken into consideration, and roads, highways and all other types of roadways are categorized by respective width. Three data sources were used to estimate affected materials: Zmap-TOWN II database, which includes digital maps of all buildings in Japan; road GIS data , which considers vector data for the Japanese road network representation; and two tsunami damage maps.

Studies that quantify the amount of debris caused by demolition or natural disasters have been carried out. However, this study presents an original and comprehensive methodological approach to characterize and quantify the debris generated as a consequence of earthquakes, considering earthquake scenarios with vulnerability functions per housing type such as adobe or straw dwellings.

The relevance of the project lies in the need to estimate new materials for the reconstruction phase, which allows an analysis as to whether the city has sufficient capacity for domestic materials supply. From debris quantitative and risk maps results, risk areas with the most damaged dwellings for urgent reconstruction stage would be prioritize. Furthermore, it is possible to designate areas for landfills as well as possible debris treatment plan, and recycling or materials reuse in the end-of-life stage. Moreover, the amount of debris generated per block allows to establish effective arrival routes for new materials.

CHAPTER 2. METHODOLOGY

The methodological framework proposed in this study and summerized in Figure 2.1 utilizes tools from several discplines, such as Risk Assessment and Industrial Ecology, to characterize and quantify the debris generated after a seismic event. The initial step of the methodology includes a classification of the civilian infrastructure and the quantification of the emmbedded materials. The damage to the infrastructure is estimated by characterizing vulnerability functions using the CAPRA-GIS tool. Material Flow Analysis (MFA) is then used for the characterization and quantification of debris associated with the earthquake event and, subsequently, new materials for the reconstruction stage.

Debris Quantification Methodology

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

$$TMS_{ki} = MC_{ki} \times Ni \tag{1}$$

In this case, TMS_{ki} is the total material construction k stock per housing type i, $MCki$ is the amount of material construction k per housing type i, and Ni represent the total number of dwellings of housing type i. The qualification of embedded materials is performed including average features per housing type: an average number of floors, antique, building material and structural system. As the analyzed dwellings are low rise structures , foundation materials per each type of house were not considered due to the insignificant relationship between the substructure and the superstructure .

Then, CAPRA-GIS software, a probabilistic risk calculation tool based on Geographic Information System (GIS), is proposed to calculate the percentage of physical damage of the infrastructure being analized. This tool performs risk calculations based on hazard data, exposure and physical vulnerability (ERN-AL, 2011). For establishing physical damage percentages per damage state: Light, Moderate, Extensive and Collapse, and for the amounts of debris generated after an earthquake, the use of Hazus data is proposed. Hazus is a nationally applicable standardized methodology elaborated by the Federal Emergency Agency that contains models for estimating potential losses from earthquakes, floods and hurricanes (MRI, H. M. ,2003). Hazus uses Geographic Information Systems (GIS) technology to estimate the physical, economic and social impacts of disasters. It is used for mitigation and recovery, as well as preparedness and response and it can be used in the assessment step in the mitigation planning process (Schneider, 2006). In addition, some modifications were needed for it to be used in the Peruvian setting. HAZUS housing inventory, damage states description and debris percentage by weight per housing and material type were used as reference. Conversely, material weight per housing type has been obtained from the Peruvian residential sector carachterization. The methodology for debris estimation is an empirical approach. That is, given the damage states for structural and nonstructural components, debris estimates are based on observations of damage that has occurred in past earthquakes and employs estimates of the weights of structural and nonstructural elements.

The proposed methodology establishes first the estimation of the building physical damage percentage according to the damage level state in order to obtain the relationship between the building physical damage and the weight of debris percentages. Based on the damage levels developed by HAZUS, the percentage of physical damage is obtained by structural element, for each housing type (MRI, H. M. ,2003). Thus, to estimate the percentage of damage associated with the damage level state of the total structure, a weighted average is performed by the sum of each structural element damage percentage multiplied by their participation percentage in the total weight of materials contained in the infrastructure. After obtaining the infrastructure´s physical damage percentage for each damage level, the debris percentage per material for each housing type is obtained using Hazus (MRI, H. M. ,2003). Finally, through the established relationship and an interpolation with the values obtained from CAPRA-GIS, the amounts of debris per material are obtained for the selected earthquake scenarios.

Material Flow Analysis

The flow of debris generated after the seismic event and new materials needed for the reconstruction stage is proposed to be modelled using the material flow analysis (MFA) methodology. MFA is an established methodology used to characterize the flows of materials in a defined system (Graedel and Allenby, 2009; Ayres and Ayres, 2002). MFA requires the establishment of study limits including geographical and natural factors, which set the territory limits and the geographical area to assess (Browne, D. O'Regan, B. , & Moles, R., 2011). Based on the law of conservation of mass, regional and national economies, different techno-social systems, materials, products and substances flows have been described using MFA (Chancerel and Rotter, 2010; Liu et al.,2004; Matthews et al., 2000; Yoshida et al., 2009; Kahhat and Williams, 2012; Kelly,1998). In addition, MFA has been used to estimate the construction and demolition debris generated within a country (Cochran, K. M. et al., 2010; Yost and Halstead, 1996; Wang et al., 2004).

The analysis allows the visualization of the material supply chain before and after the earthquake for the reconstruction phase. It emphasizes the primary materials and the location of possible shortcomings in the materials supply chain for the affected area. The MFA considers the pre and post-earthquake stages and two sub-stages for debris end-of-life: Debris Treatment and Landfill. A debris end-of-life scenario is suggested: 30% Treatment-70%Landfill,based in the amounts of construction material, such as reinforced concrete that can be recycled .

STAN 2.5 software is proposed as a MFA tool. This software follows the Austrian standard ÖNorm S 2096 and by creating a model, develops the behavior of each material in different scenarios graphically, leading to a better understanding of the material supply chain (Cencic, O., & Rechberger, H, 2008).

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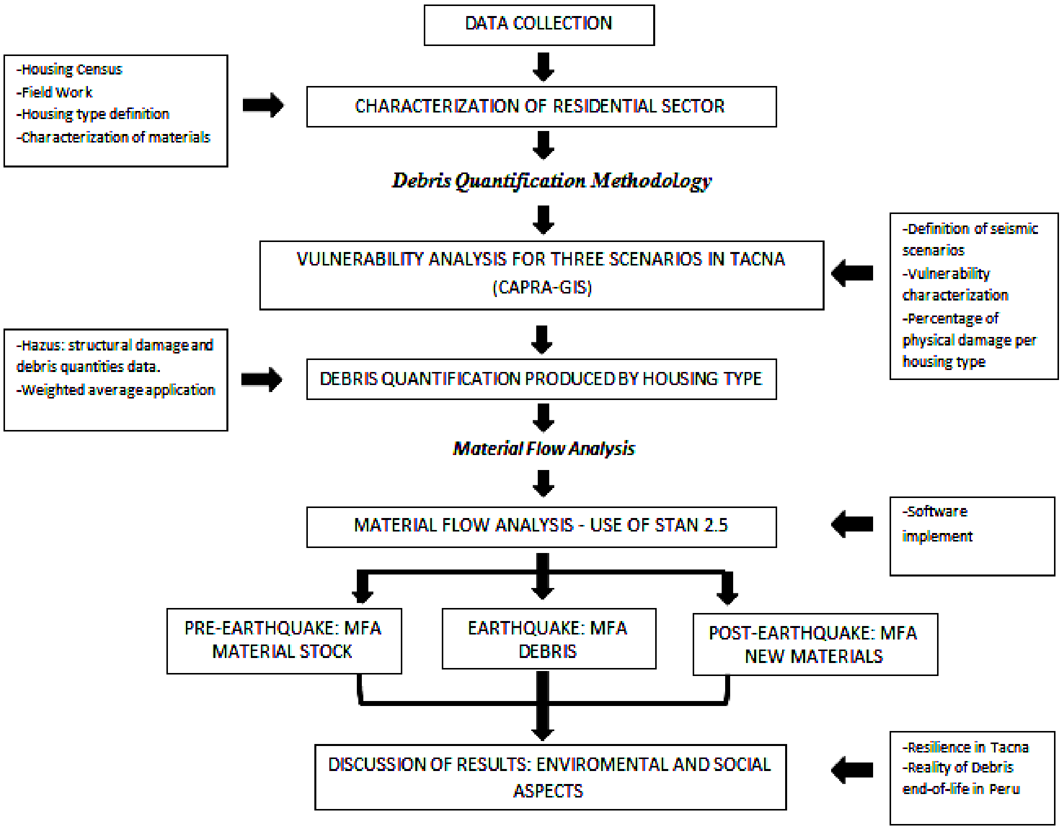

Figure 2.1: Methodological Framework

CHAPTER 3. CASE STUDY

The proposed methodology was applied to Tacna city, located in the extreme south of Peru with a population of 338,000 people (INEI, 2014). This area was chosen as a case study due to its location on the Peruvian coast, high seismic risk level, seismic silence and available information.

The analysis considers as a first step Tacna's housing database obtained from the Peruvian Seismic Risk Profile Study developed by the MEF (Ministry of Economy and Finance, 2014). The database contains information about homes, which have a resolution by block and contain geographic location information fields (city and coordinates), zones, number of houses per block and physical monetary value for different housing type. Five housing types were identified in the residential sector of the city: Reinforced Masonry Bearing Walls with Concrete Diaphragms, Wood, Adobe, Concrete shear walls and Straw.

Table 3.1 Tacna residential sector

DESIGNATION	HOUSING TYPE	NUMBER OF HOUSES
I	Reinforced Masonry Bearing Walls with Concrete Diaphragms	47990
II	Wood	216
III	Adobe	2059
IV	Concrete Shear Walls	2572
V	Straw	5491

In addition, each dwelling type or building system had a corresponding vulnerability function as shown in Figure 3.1, which was developed by the Pontificia Universidad Catolica del Peru (MEF, 2014) following the methodology established by Miranda (1999). Vulnerability functions are represented by two factors: intensity parameters (pseudo acceleration cm² / s) and the percentage of physical damage as a result of certain intensity earthquakes. The Seismic Hazards IGP information database contains seismic sources data, recurrence and attenuation laws. This information was used for the election and modeling of three seismic scenarios in the research (i.e. High magnitude Scenario: 8.6 Mw., Medium Magnitude Scenario: 7.5 Mw. and Low Magnitude Scenario: 6.2 Mw.) (MEF, 2014). The scenarios were chosen in order to obtain high levels of damage, considering the proximity of the earthquake epicenter to the area being analyzed.

Soil characteristics are an important factor that can cause the amplification of seismic intensities. Figure 3.2 shows Tacna city microzoning map that was developed based on INDECI (2004) research work in which two areas with high and medium seismic risk were observed.

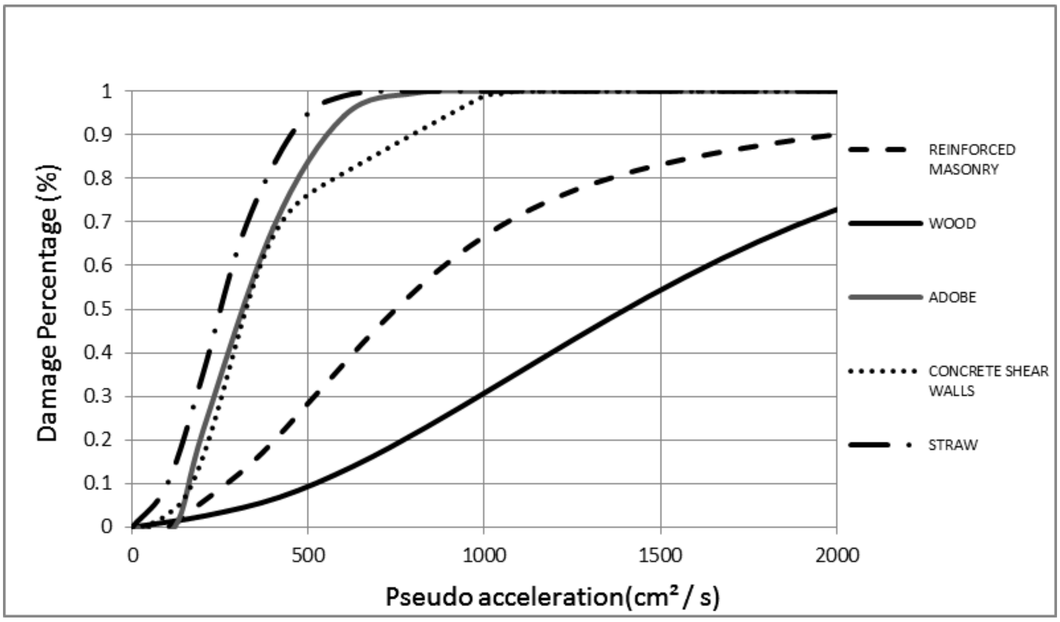

Figure 3.1: Vulnerability Functions for the Residential Sector (MEF, 2014).

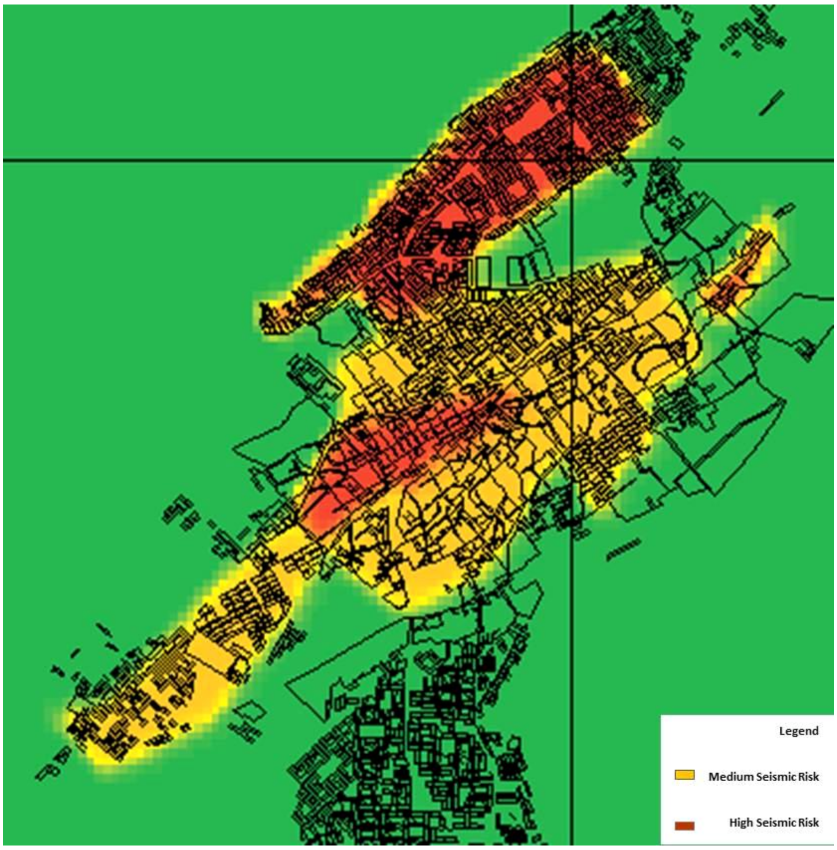

Figure 3.2: Tacna microzoning map

The expected physical damage percentage was elaborated using the previous data and CAPRA-GIS software for three scenarios with different magnitudes. The percentage damage values were estimated for block and housing type for each earthquake scenario. The average damage value of all presented blocks was the value considered for the analysis. After establishing the structural elements description with their physical damage percentage according to HAZUS and the structural element participation in the total building material weight, it was possible to obtain the physical damage percentage.

Moreover, the relationship between the physical damage percentage and the percentage of debris weight produced by housing type obtained from HAZUS (MRL, HM, 2003) was developed (Table 3.2). HAZUS shows debris values for each damage state, however they do not show the variation of these values. Therefore, as debris values are calculated from the damage value, it is assumed that the standard deviation of debris function will be the same as the vulnerability function one.

Table 3.2 Relationship between the physical damage percentage and the percentage of debris weight per material produced by housing type.

	MASONRY (TYPE I)			WOOD (TYPE II)		ADOBE (TYPE III)		CONCRETE SHEAR WALLS (TYPE IV)							STRAW (TYPE V)	
	% Physical Damage	%Debris		% Physical Damage	%Debris	% Physical Damage	%Debris	% Physical Damage	%Debris						% Physical Damage	%Debris
		Structural Elements			Structural Elements		Structural Elements		Structural Elements			Non-Structural Elements				Structural Elements
		Steel	Concrete		Wood		Adobe		Brick	Steel	Concrete	Brick	Steel	Concrete		Straw
SLIGHT	5.4	0 ±1	0 ±1	5.9	0 ±1	5	5±1	9.9	5±3	1±3	1±3	1±1	0.1±1	0.1±1	5.3	0±1
MODERATE	28.4	3 ±1	3±1	33.6	5±1	28.2	25±3	36.8	25±4	8±4	8±4	7±4	10±4	10±4	31.9	5±3
EXTENSIVE	70.1	30.5 ±6	30.5 ±6	61.4	34±6	69.1	60±9	82.9	60±3	35±3	35±3	35±3	30±3	30±3	59.2	33±9
COMPLETE	100	100 ± 0	100 ± 0	100.0	100 ± 0	100	100 ± 0	100	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100	100 ± 0

CHAPTER 4. RESULTS

There is a major presence of Reinforced Masonry and Concrete Shear Walls dwellings in the north and center of Tacna city due to an increase of the population in urban areas since 1961 (INEI, 2007). Thus, materials such as steel, concrete and clay have a relevant presence in this area. Otherwise, the higest adobe and straw material stock is on the periphery, where wood, adobe and straw housing type are located. The percentage of debris generated in each earthquake scenario is shown in Table 4.1 and the results of quantity of debris by material for earthquake scenarios are shown in Figure 4.1. Results presented in Figure 4.1 follow an exponential behavior, which reflects a larger amount of debris as a consequence of a greater earthquake magnitude. Two main factors influence the results obtained in this case study. First, the number of dwellings per housing type in the area being studied. Second, the weight of materials per housing type contained in the residential sector. Results presented in Figure 4.1 show a large amount of clay brick debris generated in, comparison with other materials, presenting around 462,000 tonnes, 72,000 tonnes, and 2,300 tonnes on the 8.6 Mw, 7.5 Mw. and 6.2 Mw scenarios, respectively. These results are mainly due to the large amount of masonry involved in Tacna´s residential sector and the large number of Type I and IV dwellings in the area. Additionally, concrete debris shows 204,000 tonnes in the high magnitude earthquake scenario. Its incidence remains relevant because of the amount of concrete in Type IV and the number of homes within this classification. In the case of adobe dwellings, although they present a high vulnerability, they represent a small number of homes in the area. Hence, a smaller amount of debris was obtained if compared to other materials. In the case of steel, which is present in a large number of houses, the amount of debris produced in the three scenarios is minor due to the percentage of debris obtained from the methodology for this material, which is 3.0% for Type I and 5.9% for Type IV dwellings for the greater magnitude earthquake. Finally, an insignificant amount of wood and straw debris was observed due to the low number of wood dwellings and the low weight of staw material contained per dwelling.

Table 4.1 Percentage of debris generated by selected scenarios of CAPRA-GIS.

		MASONRY (TYPE I)		WOOD (TYPE II)		ADOBE (TYPE III)		CONCRETE SHEAR WALLS (TYPE IV)			STRAW (TYPE V)	
SCENARIO	MATERIAL	% CAPRA-GIS DAMAGE	%DEBRIS GENERATION (STRUCTURAL ELEMENTS)	% CAPRA-GIS DAMAGE	%DEBRIS GENERATION (STRUCTURAL ELEMENTS)	% CAPRA-GIS DAMAGE	%DEBRIS GENERATION (STRUCTURAL ELEMENTS)	% CAPRA-GIS DAMAGE	%DEBRIS GENERATION (STRUCTURAL ELEMENTS)	%DEBRIS GENERATION (NON-STRUCTURAL ELEMENTS)	% CAPRA-GIS DAMAGE	%DEBRIS GENERATION (STRUCTURAL ELEMENTS)
8.6 Mw.	**BRICK**	**28.1**	24.7 ± 1	**12.4**		**72.1**		**27.0**	18.3 ± 5	5.1 ± 5	**86.7**	
	STEEL		3.0 ± 1						5.9 ± 5	7.3 ± 5		
	CONCRETE		3.0 ± 1						5.9 ± 5	7.3 ± 5		
	WOOD				1.8 ± 1							
	ADOBE						62.6 ± 9					
	STRAW											48.3 ± 6
7.5 Mw.	**BRICK**	**4.8**	4.4 ± 1	**2.6**		**11.4**		**3.2**	1.6 ± 1	0.3 ± 1	**27.2**	
	STEEL		0.0 ± 1						0.3 ± 1	0.0 ± 1		
	CONCRETE		0.0 ± 1						0.3 ± 1	0.0 ± 1		
	WOOD				0.0 ± 1							
	ADOBE						10.1 ± 3					
	STRAW											4.3 ± 4
6.2 Mw.	**BRICK**	**0.2**	0.1 ±1	**0.4**		**0.8**		**0.2**	0.1 ± 1	0.0 ± 1	**4.8**	
	STEEL		0.0 ±1						0.0 ± 1	0.0 ± 1		
	CONCRETE		0.0 ±1						0.0 ± 1	0.0 ± 1		
	WOOD				0.0 ± 1							
	ADOBE						0.8 ± 1					
	STRAW											0.0 ± 2

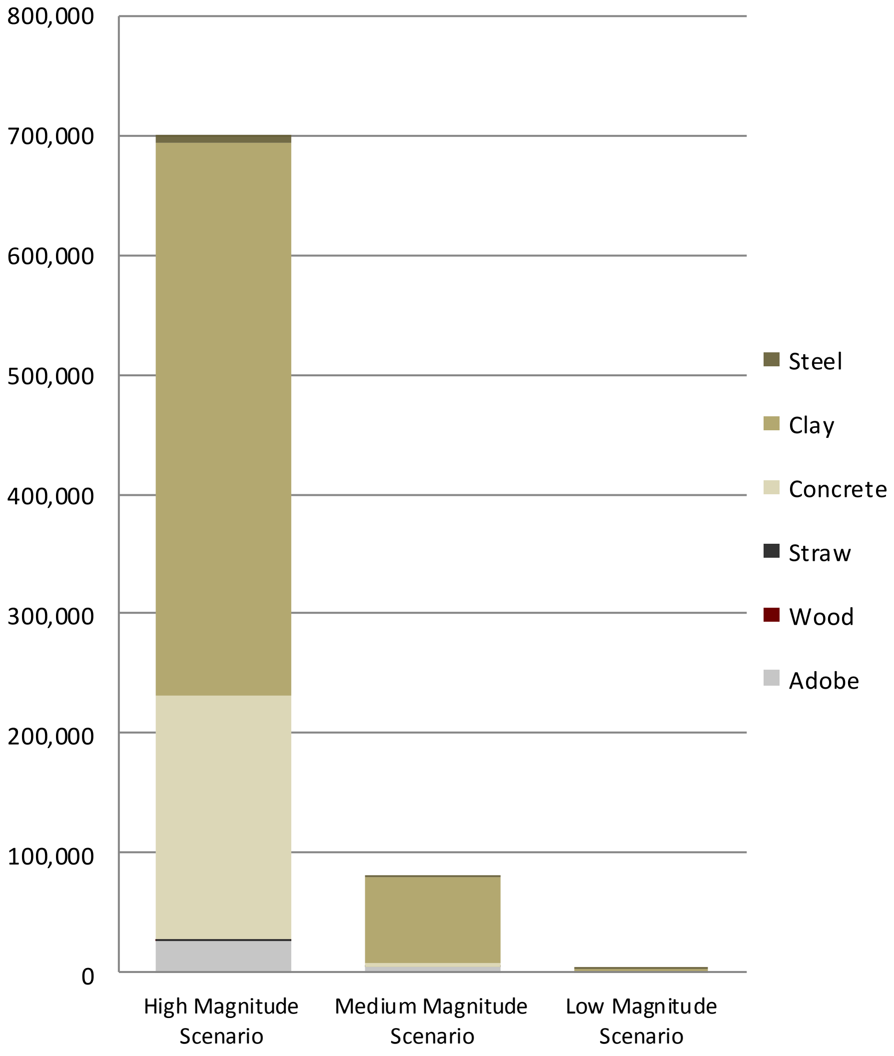

Figure 4.1 Quantity of debris (tonnes) by material for three earthquake scenarios.

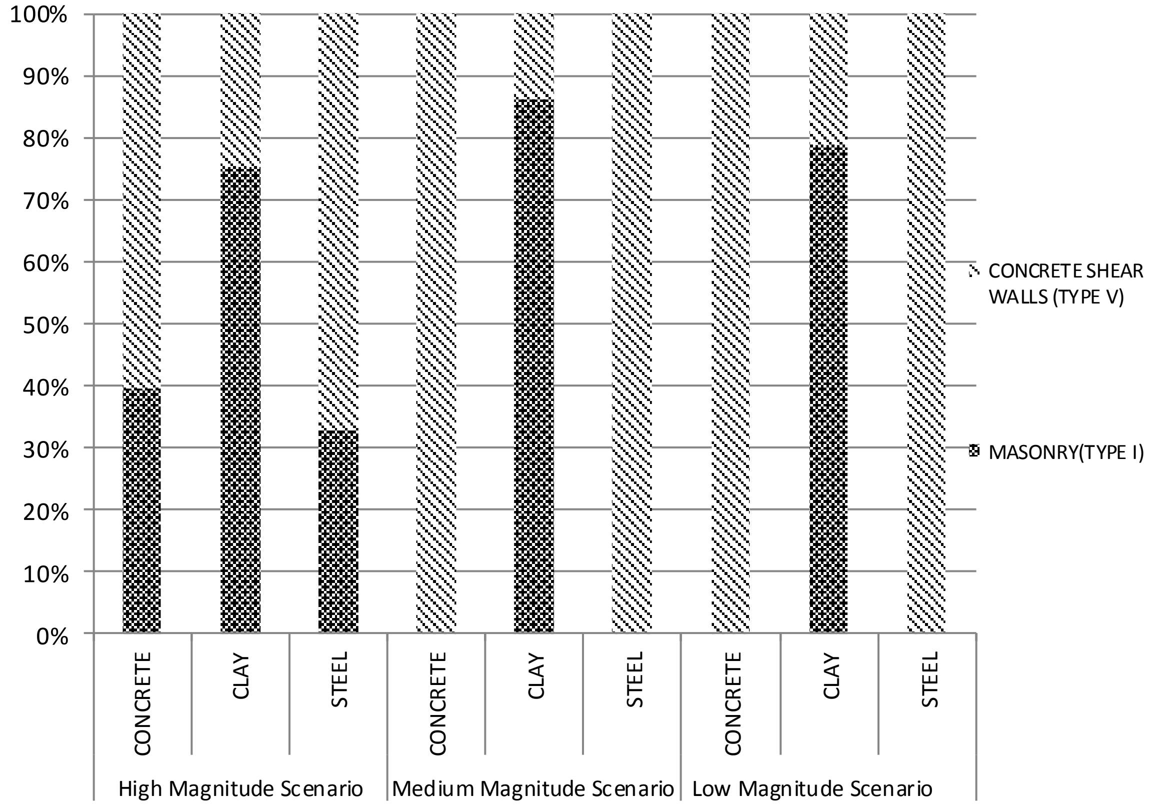

Figura 4.2 Contribution of housing type I and IV in the generation of debris for the three seismic scenarios.

The share of concrete, clay bricks and steel debris generated by housing types (Type I and IV) is presented in Figure 4.2. As shown in Medium and Low magnitude Scenarios, concrete and steel debris comes from Type IV dwellings. Furthermore, in the case of clay brick, there is a greater amount of debris that comes from Type I homes.

The MFA allows the visualization of the material supply chain before the earthquake occurrence and after the same (reconstruction) for the five most important building materials within five housing types analyzed in the case of Tacna: brick, steel, concrete, wood and adobe. The analysis considers the pre and post-earthquake stages, where the first amount of input material corresponds to the material quantities in the residential sector. The initial material amounts in tonnes is obtained from the weight average amount of the total of material involved in the construction of a house, quantities obtained from the characterization process multiplied by the total home number for each type. After the disaster, the percentage for debris amount generated is multiplied by the initial amount of materials in the residential sector and all debris quantities are transferred to the global stage “debris generated”. Debris quantities are aimed at two end-of-life scenarios: Debris Treatment and Landfills. For the reconstruction phase, new construction materials are required depending on the amount of debris generated, and a regional or domestic import is considered. Finally, new material flow is assigned according to housing type reconstruction requirements.

Furthermore, Figure 4.3 presents the MFA for concrete, based on the high earthquake scenario. Concrete is one of the most important materials used in the Peruvian construction sector. Tacna residential sector has an inflow of 4609,680 tonnes of this material and two outflows: one of 2719,700 to housing type I and an outflow of 1890,000 to housing type IV. After the High Magnitude Scenario, the total quantity of concrete debris generated is 204,000 tonnes, with an outflow of 0 tonnes to new materials for reconstruction. The quantity of new concrete material indicates a total amount of 908,400 tonnes for the housing reconstruction stage, a greater amount than the quantity of debris generated after the earthquake due to the need for a completely adobe and straw dwelling reconstruction. The amount of new material needed for the reconstruction phase is considered as a domestic import. For partial reconstruction, the quantities of new materials required are equal to the amount of debris generated and in the case of full reconstruction for scenarios of higher magnitude, a greater amount of material is required due to new Type I and Type IV dwelling construction to replace adobe and straw houses. Considering the Peruvian cultural context and the results obtained, the study analyses whether. Tacna´s current supply chain of materials is sufficient to supply the required new material amounts for the reconstruction stage. The annual domestic production in the case of Yura Cements, which is the main cement provider for Tacna, is 3.2x 10^9 kg (Cementos Yura, 2014). The worst case scenario for Tacna (i.e. 8.6 Mw) requires 132,400 tonnes of cement, approximately, indicating that in a hypothetical reconstruction stage that prioritizes the city being studied, the current supply chain of cement will be sufficient. A similar situation arises in the case of steel. In the case of brick, it is typically a domestically made material in Tacna with an annual production of 19,300 tonnes, so for maximum magnitude scenarios, due to the inability to manufacture clay brick in the affected area, a material importation from other Peruvian regions is required. MFA for clay brick and steel materials are shown in the supporting information section.

Figure 4.4 a) shows the total percentage of debris generated after the high magitude scenario event per area location. In the city center, where most masonry and shear wall concrete dwellings are located, the total of debris reaches 25%. On the other hand, the maximum values of debris generation are presented in Tacna peripheral homes, an economic and socially vulnerable area , financially disadvantaged and with low-cost dwellings. Figure 4.4 b) concrete debris generated after the high magnitude scenario, considering only houses with concrete participation. In this case, quantities of debris reach a maximum of 5% located in the central and north central area.

Excessive amounts of clay, steel and concrete generated within the debris amounts, show the relevance of such materials in the Peruvian housing construction sector. Conversely, building material production in Peru represents the generation of high environmental impacts from the pre-use phase, such as the cement production case. The over-exploitation of natural resources for construction materials causes unsustainable development.

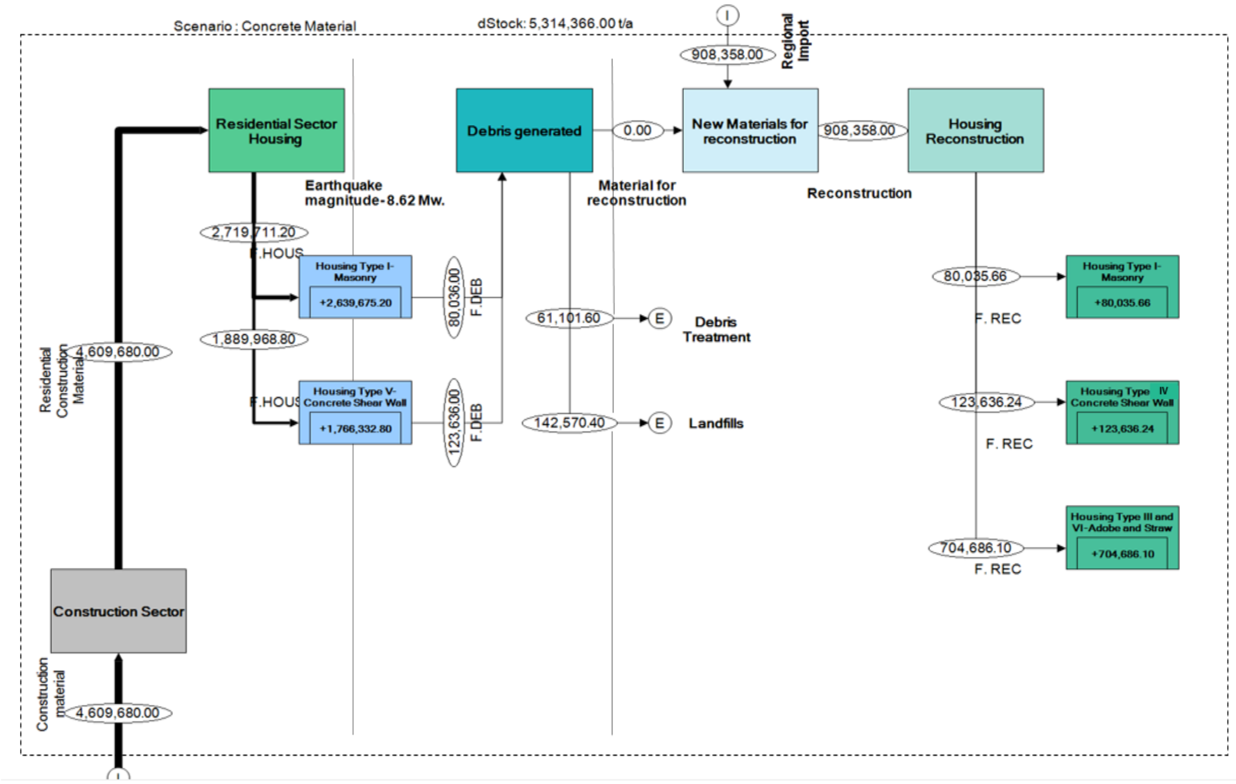

Figure 4.3 Material flow analysis for concrete (tonnes). (Based on a 8.6 Mw. Scenario)

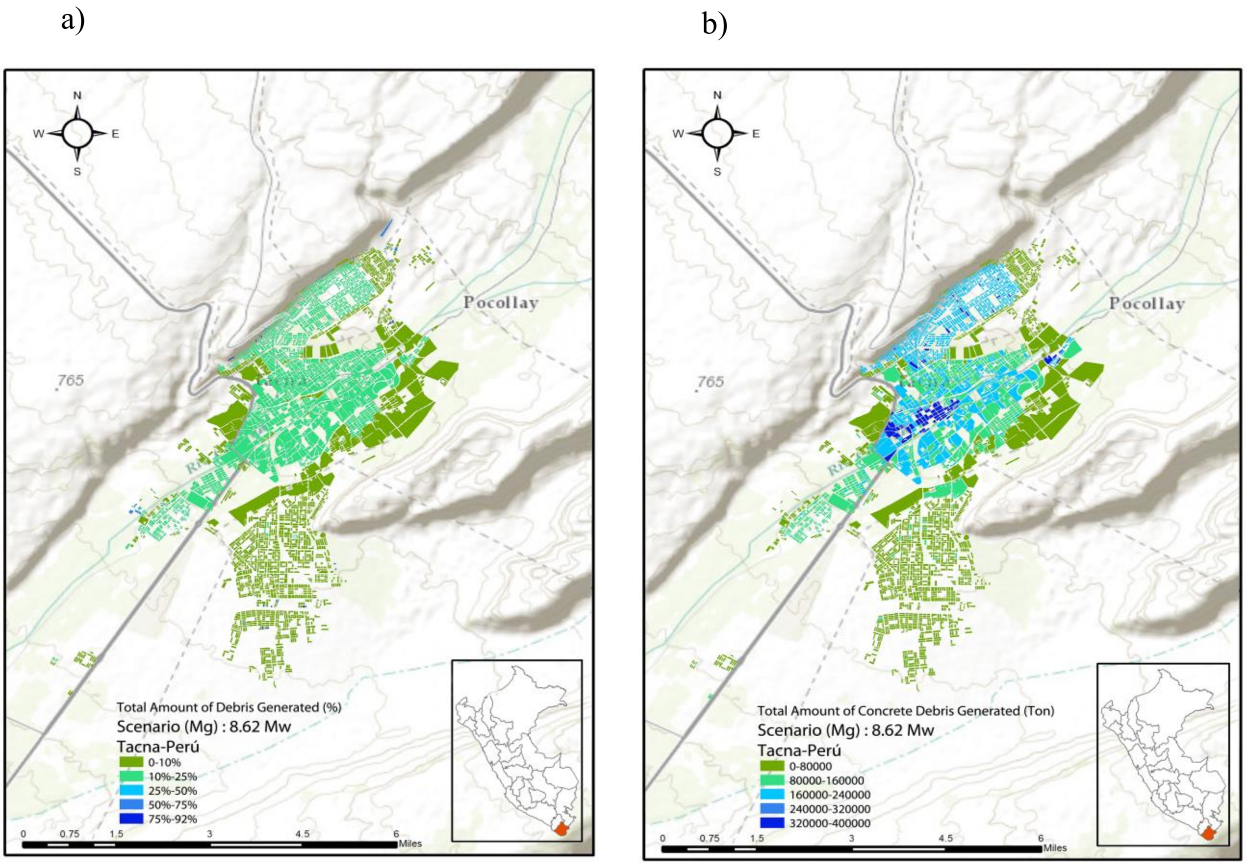

Figure 4.4 a) Total percentage of debris generated after an earthquake event of 8.6 Mw. for all housing types. b) Tonnes of concrete debris generated after an earthquake event of 8.6 Mw.

CHAPTER 5. DISCUSSION

The seismic vulnerability of Tacna´s infrastructure is influenced by a number of factors, including inadequate construction practices, some of which are related to self-construction (Dueñas et al, 2001), type of materials used in the foundations and soil characteristics (JICA, 2013). A reinforcement plan is required to prevent building collapse during the seismic event. Moreover, vulnerable dwellings affected by seismic activities will generate greater amounts of debris. For example, adobe houses are very vulnerable due to deficiencies in their construction, low resistance and brittle behavior (Blondet, et al. 2011). As adobe dwellings are low-cost systems commonly used in areas that are not necessarily foreign to seismic risk, adobe research work in Peru has been presented. The influential factors for an improvement on seismic behavior in adobe houses, are adobe composition units, quality of construction, robust distribution and construction technologies with seismic reinforcement (Blondet, et al. 2004). Providing an adobe house seismic resistance plan preserves the life of those who dwell in adobe houses before the total collapse of the same (Zegarra Ciquero, Luis et al. 2001).

In addition, Tacna and those areas with high vulnerability characteristics must be analyzed with the aim of providing solutions focused on economic and social resilience. After the occurrence of a natural disaster, the population begins what is known as the adaptation process, due to the dramatic changes in their lives. The reconctruction phase should be carried out in the shortest time possible by raising the ability of reaction to a crisis event or resilience (Aguirre 2004, Vargas 2004). There are difficulties to solve problems in an optimal way, so it is necessary to consider systems based on social and economic resilience principles. Resilience is the system ability of keeping functions after being affected by changes (Allenby, 2005). Applying the concept of resilience in the case of Tacna, means setting strategies according to the reality they have to face after an earthquake. Hence, it is relevant to implement strategies to reduce and mitigate threats. Otherwise, in the formulation of management plans for complex systems, it is possible to find a balance between social, economic and environmental aspects along with the ability to rebuild Tacna optimally. Based on global past experience there are two important variables for managing areas affected by a natural disaster: citizen participation in planning processes and the role of the government in management tasks (Comerio, 2013). If the government role is limited, there will be unequal recovery equilibrium whereas if the government is deeply involved, management planning will be promoted by domestic or regional institutions. The combination of regional and national government leadership with the maximum community participation is crucial.

Tacna, a small city in the coastal area of the country, has high chances of making a swift recovery from a severe earthquake event, taking a relatively short time to reach an optimal quality of infrastructure. However, there are external factors such as monetary investment and active governmental participation that can delay this recovery. Focusing on primary functional activities for resilience development in the disaster area, as well as considering the main services part of the basic requirements for a resilient community are considered relevant factors at the commencement of the recovery stage.

Moreover, end-of-life options, such as reuse/recycling technologies and landfills, need to be developed to ensure proper handling of debris. Landfills or dumps are illegal areas that store different types of waste, becoming a health risk to the population and representing a highly negative impact. There is a lack of well managed landfills in Tacna, including those dedicated to construction and demolition waste (Oefa, 2014). Furthermore, reuse and recycling practices for construction waste are not widespread. Hence, the promotion of reuse and recycling practices for construction waste is a priority and the amounts of concrete debris by block location contributes greatly to this end, considering its reuse in road pavement. However, there is a great deal of mistrust regarding the use of recycled material for the residential sector and only few projects such as recycled concrete which can be used as dry aggregate for road prior to the asphalt or concrete pouring (Poon et.al, 2006) have been developed. The advantages of debris treatment offer the possibility of decreasing the levels of raw material extraction from nature reserves and eventually reducing the quantities stored by landfills, generating a longer lifespan (Vanderley et. al, 2001).

CHAPTER 6. CONCLUSIONS

Natural disasters present consequences in social, economic and environmental aspects. In the aftermath of a natural disaster daily difficulties emerge that must be faced by the families affected. From a purely environmental standpoint, natural disasters have high levels of impacts in the industrial and health sectors, according to studies elaborated by Thummarukudy (2010). Furthermore, losses in different ecosystems are irreversible issues to consider in the affected area (Wang et al, 2012). Debris management is presented as the main problem in the affected area reconstruction phase, so it is necessary to estimate new materials for the reconstruction phase, evaluate domestic materials supply and designate landfills areas or debris treatment plan in the end-of-life stage. The proposed methodology to characterize and quantify debris generated after a seismic event is a major tool for debris management in the affected area.

The methodology presented is applicable to countries with frequent seismic events and different types of housing. A proper debris quantification allows reforms in the application of new construction technologies in order to mitigate damage levels and set up appropriate waste management and reconstruction plans after a natural disaster. Reassessment of infrastructure design protocols with the aim of improving resistance as a prevention method is as important as infrastructures monitoring after the construction stage. A proper risk management requires construction standards fulfillment, performing drastic sanctions in cases of non-compliance.

A solid plan of timely debris management will reduce the health risk to the population and accelerate the reconstruction stage. Peru has a deficit of well-managed landfills for municipal waste, construction, and demolition waste or debris. Current waste management practices include an important informal sector that uses illegal dumps. In addition, there are no incentives related to recycling or reuse of construction and demolition waste. Hence, an aggressive waste management improvement plan that includes programs to promote the recycling and reuse of construction materials will play a significant role in the recovery of an affected area. It is possible to find different types of reusable materials in debris, material that can be recovered as clay bricks or tiles which are mostly employed throughout the affected area. Debris treatment brings benefits not only in air quality and consumption of resources, but in the life span of landfills.

Changes in the political aspect and a proper motivation are indispensable factors in order to overcome various obstacles during the reconstruction stage, promoting resilience and sustainability of demographic problems (Tobin, 1999). Governmental , non-governmental and private organizations should keep updated seismic risk, vulnerability and disaster resources knowledge, which are directly related to community networks. Finally, it is relevant to mention that natural disasters should not be seen as obstacles that slow cities´ growth. On the contrary, they should be seen as the reason for generating changes in reconstructive processes based on technologies that can bring benefits in social, environmental and economic aspects.

ACKNOWLEDGEMENTS

This project was partially funded by CONCYTEC within the framework of the 012-2013-FONDECYT Agreement and the Common Funds 2014 of the PUCP Academic Directorate of Social Responsibility.

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