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Development of national and local exposure models of residential structures in Chile

Hernán Santa María[1,2] · Matías A. Hube[1,2] ·
Felipe Rivera[1] · Catalina Yepes-Estrada[3] · Jairo A. Valcárcel[3]

Abstract Large-scale impacts from natural disasters suffered by society encourage researchers and public agencies to develop methods to evaluate, mitigate, respond, and recover from these events. A key aspect for the calculation of the potential earthquake losses is to properly describe the characteristics and value of assets exposed to seismic hazard. This article describes a methodology to develop an exposure model at a census-block resolution for residential structures in Chile using statistical data. The methodology is based on three steps: (1) obtaining dwelling count, construction material and location from census data, (2) defining classification rules for dwellings associated with houses and apartment buildings, and (3) assigning structural typologies and replacement cost. The resulting exposure model consists of a database with the number of residential structures classified into 18 structural typologies at each census block and the associated replacement cost. A total of 4,259,804 residential structures were identified in the national exposure model. Overall, clay brick and concrete block masonry account for 53.5 % of the structures of the country followed by timber (33.7 %), reinforced concrete (8.1 %), and adobe (4.6 %). Also, a methodology using remote digital survey techniques is proposed and used to obtain local exposure models for the cities of Iquique, Rancagua, and Osorno. The results of the national exposure model are compared with the local exposure models. An important feature of the proposed methodologies is that the building stock is classified into structural typologies, which is a key aspect for conducting seismic risk assessment. The methodologies used to construct the national and local exposure models may be extrapolated to other countries by adjusting the classification rules. The exposure models that were constructed represent an important input for risk

✉ Hernán Santa María
   hsm@ing.puc.cl

[1] National Research Center for Integrated Natural Disaster Management CONICYT/FONDAP/ 15110017, Vicuña Mackenna 4860, Santiago, Chile

[2] Department of Structural and Geotechnical Engineering, Pontificia Universidad Católica de Chile, Vicuña Mackenna 4860, Santiago, Chile

[3] GEM Foundation, Via Ferrata 1, 27100 Pavia, Italy

calculations, by improving the technical capabilities for seismic risk management of the country.

1 Introduction

With more than half of the world's population living in urban zones, the rapid urban growth has raised difficulties for sustainable planning and urban governance, particularly for localities not properly prepared to absorb that growth (UN 2014). In 2011, approximately 890 million people (i.e., 60 % of the population living in urban zones larger than one million inhabitants) lived in high-risk zones exposed to at least one type of natural hazards (e.g., floods, droughts, cyclones, earthquakes). While less than 40 % of the large cities with more than one million inhabitants in Africa and Europe are located in high-risk zones, between half and two thirds of the large cities in Latin America and the Caribbean, North America, and Asia are located in high-risk zones (UN 2014). These facts highlight the importance of assessing the exposed physical and social inventory to properly prepare the population and the cities for natural and anthropogenic disasters worldwide.

Chile is one of the countries most affected by natural disasters and stands as the 11th most exposed country in the World Risk Index 2014 (UNU-EHS and ADW 2014). More than 90 natural disasters have been registered in the country between 1950 and 2015, only considering hydrogeological, geophysical, climatological, and meteorological phenomena (Guha-Sapir et al. 2015). These disasters include the largest instrumentally recorded earthquake in the world (M_w 9.5 1960, Valdivia earthquake), and three earthquakes with magnitudes larger than 8.0 in the last five years (M_w 8.8 Maule earthquake in 2010, M_w 8.2 Pisagua earthquake in 2014, and M_w 8.3 Illapel earthquake in 2015) (USGS 2015). Of the G20 plus other selected countries, Chile has the largest losses associated with natural disasters as a percentage of the GDP between 1980 and 2011 (OECD 2012). The high human and economic losses associated with natural disasters in Chile highlight the importance of defining a strategy to improve preparedness, response, and building resilience to these natural disasters. Risk assessment provides a quantitative alternative to evaluate the preparedness and response.

Seismic risk assessment involves the combination of three aspects: the seismic hazard, the exposed physical and social inventories, and the seismic vulnerability of these inventories. Exposure maps are an essential input for risk calculations, as they identify the population and physical assets subjected to different levels of certain hazard (e.g., residential structures, healthcare network, lifelines, and utilities), thus scoping the efforts for preparedness and mitigation actions (Jaiswal et al. 2015). Despite the importance of exposure models, not much attention has been given to their generation in Chile and South America, especially when compared to the considerable efforts conducted to characterize the seismic hazard.

Worldwide, great efforts have been conducted to characterize the exposed physical and social inventories subjected to seismic events. A summary of the most recognized examples of them is provided in Pittore et al. (2016), highlighting the PAGER initiative from the U.S. Geological Survey (Jaiswal et al. 2010), the GED4GEM initiative from the

Global Earthquake Model (GEM) (Dell'Acqua et al. 2013), and the GEG-13 initiative from the Global Assessment Report 13 (GAR 13) (De Bono and Mora 2014) to describe the global physical exposure, and LandScan (Bhaduri et al. 2007) and WorldPop (WorldPop 2015) for the global human exposure. At the local level (i.e., country or city level), statistical data from census may provide important input to build exposure models. For example, the SARA project from GEM foundation has been using census data using a mapping scheme procedure to construct exposure models for countries in South America.

Remote sensing techniques covering larger regions in a systematic manner have also been proposed to construct exposure models. The use of remote sensing to assess earthquake risk has a long tradition as part of hazard research, and there is a growing tendency in recent years to use it to characterize vulnerability (Geiss and Taubenböck 2013). However, the methodologies reviewed by Calvi et al. (2006) show that remote sensing is not able to provide information on the actual vulnerability of structures. The combination of remote sensing with other techniques has provided means to improve the exposure models, adapting also to local capabilities and availability of technical resources; this is being currently reinforced for further research (Wieland et al. 2015; Gamba 2014). Examples of these combinations are the use of in situ acquired data combined with remote sensing data (Borfecchia et al. 2010; Matsuka et al. 2012; Geiss et al. 2014, 2015), the joint use of remote sensing with ground-based in situ omnidirectional imaging (Wieland et al. 2012; Pittore and Wieland 2013) or with volunteered geographical information (Schauss 2015), and the use of aerial images with locally produced data (e.g., census data, local reports) and virtual surveys (e.g., using Google *StreetView*) to characterize the local building inventory (Osorio et al. 2015). Remote sensing techniques have also been extended to collect vulnerability-related characteristics of the built environment (Mueller et al. 2006), which could be later related to its seismic vulnerability.

Despite a long history of research and development on seismic engineering in Chile, risk assessment is a fairly new concept. Thus, local research concerning exposure models and risk assessment is limited as compared to that conducted internationally. In 1999, the IDNDR Secretariat of the United Nations funded and supervised the RADIUS initiative in the city of Antofagasta, in the north of Chile (Villacis and Cardona 1999). An exhaustive risk assessment study was conducted in the city, considering not only damage assessment for different physical systems, but also the implementation of strategies for risk prevention and emergency management. The methodology from RADIUS was later extended to calculate seismic risk in two other cities in the north of Chile: Arica and Copiapó (Tapia et al. 2002). Indirli et al. (2011) conducted a risk assessment in the city of Valparaíso in central Chile within the MAR VASTO project (MAR VASTO 2015) which focused on the vulnerability of three churches and a portion of the city's historical center. Finally, the potential damage due to intraplate and interplate subduction earthquakes was assessed for different structural typologies of apartment buildings for Santiago city by Pina and González (2014), classifying buildings based on several estimated structural parameters.

This article describes a methodology to develop an exposure model at a census-block level for residential structures in Chile using statistical data. The methodology is based on three steps: (1) obtaining dwelling count, construction material and location from census data, (2) defining classification rules for dwellings associated with houses and apartment buildings, and (3) assigning structural typologies and replacement cost. The resulting exposure model consists of a database with the number of residential structures classified into 18 structural typologies at each census block and the associated replacement cost. The structural typologies are defined in this paper where nine typologies correspond to houses and nine to apartment buildings. Additionally, a methodology to construct local exposure

models is proposed. This methodology is applied for the cities of Iquique, Rancagua, and Osorno, and the results are compared to those of the national exposure model. An important feature of the proposed methodologies is that the building stock is classified in structural typologies, which is a key aspect for conducting seismic risk assessment. This study is a result of the Chile Risk Assessment project, which is the local initiative of the regional South America integrated Risk Assessment (SARA) project by the GEM Foundation. The obtained exposure models aim to improve available information to conduct risk assessment studies and thus decrease the impacts of earthquakes in the region. The following section describes the methodology used to build the national exposure model, and a summary of its results to give an overview of the composition of the residential building stock throughout the country. Section 3 presents the methodology of the local exposure model and the results for the selected cities. The national and local models are compared in Sect. 4. Finally, a summary and conclusions are presented in Sect. 5.

2 Construction of a national exposure model using statistical data

This section presents the methodology proposed to obtain a national exposure model of residential structures in Chile. The methodology uses statistical data and classifies dwellings into structural typology. The resulting exposure model contains the number of structures per building typology at the census-block level. Additionally, the average replacement cost of the structures is estimated. The data sources for constructing the model are also described, and a summary of the model provides an overview of the characteristics of the residential building stock in Chile.

2.1 Data sources

Different institutions collect data of residential structures in Chile independently, and a unified database with complete information of the residential physical stock of the country is non-existent. Some relevant information is stored at municipalities and/or at the Ministry of Housing and Urbanism (MINVU). Additionally, the *Servicio de Impuestos Internos* (SII, equivalent to the Internal Revenue Service in the USA) also stores relevant information, but it is difficult to access and requires additional local information for its proper use, which is not always available at every municipality. Hence, three different sources at different resolution levels were used to build the national exposure model: the 2002 and 2012 population and housing census, and the 2002–2014 *Formulario Único de Estadísticas de Edificación* (Unique Edification Statistic Form, UESF). The data obtained from these sources are not intended to characterize the residential structures in Chile and are collected for other purposes. Therefore, they provide partial technical information to build the exposure model.

Data from the 2002 census with a census-block resolution are available upon request from the National Institute of Statistics (INE, http://www.ine.cl/). Census blocks are the smallest subdivisions of a municipality for census purposes. The census is a nationwide dwelling-per-dwelling survey, and the information is obtained from the response of a dwelling owner or an adult responsible for answering the survey. Therefore, information regarding construction materials may be inaccurate, since non-experts may classify the exterior walls material of the dwelling based on the cover material (e.g., cement-based stucco, clay bricks) instead of the structural material. Since census data are collected per dwelling, it is easy to relate it to a structure when the dwelling is a house (usually, one

house corresponds to one dwelling), but poses a major difficulty to relate dwellings in apartment buildings to a structure. Neither the number of stories per building nor the number of apartments per story is registered in the census. Hence, assumptions are required to relate dwellings to structures. Data from the 2002 census used to build the exposure model include: (1) location of the dwelling (census-block location with urban or rural classification); (2) type of dwelling (house, apartment dwelling in an apartment building, emergency house, informal house, or other); and (3) exterior wall material (reinforced concrete or stone, brick masonry, structural panels or blocks, timber, adobe, recycled materials, or other). According to INE, an urban area is defined as a settlement with more than 2000 inhabitants. The main drawback of the 2002 census is that it is outdated, and therefore, it does not represent the current state of the building stock in the country.

The UESF is a database that contains all construction permits issued by Chilean municipalities between January 2002 and September 2014 for both new houses and apartment buildings and modifications of existing buildings. In most cases, the modifications of existing structures do not change the structural typology, and therefore this information was not considered in the proposed methodology. The UESF information is aggregated at the municipality level, and it is publicly available upon request at INE. The technical quality of this database, to classify the structure into a structural typology, is better than that of the census, since the construction permit is signed by the real estate owner and the architect or engineer in charge of the construction project. This permit is reviewed and approved by the municipality or by an inspector from MINVU. In Chile, the correlation between issued construction permits and actually built structures is relatively good, so the construction permits are considered to be a good approximation of structures actually built between 2002 and 2014. Data from the UESF used to build the exposure model include: (1) location of the dwelling (municipality); (2) number of structures (houses or apartment buildings) and number of dwellings per construction permit; (3) type of structure (house or apartment building); (4) number of stories of each structure; (5) exterior wall material (reinforced concrete, hollow clay brick, handmade clay brick, concrete block, timber, adobe, or others); and (6) percentage of main exterior walls material in all exterior walls. The two drawbacks of the UESF data to construct the national exposure model are: (1) The database does not have information about construction permits issued before 2002, which could have been used to relate number of dwellings from the 2002 census to apartment buildings and (2) it does not include information on emergency and informal constructions and settlements, which are usually built without construction permits, and are related to vulnerable inhabitants.

In 2012, a new census was performed by INE. After its preliminary results—aggregated at municipality level—were published, politicians and experts heavily criticized the methodology used for the census. An external expert review showed that the methodology led to mistakes in data collection, with a high national omission rate of responses of at least 9.3 % (Bravo et al. 2013). As a result, the 2012 census was declared as non-valid by the government, and the detailed data at a census-block resolution were not published. Given the lack of accuracy of this database, it was only used to update the number of timber emergency houses and informal houses from the 2002 census at the municipality level.

2.2 Structural typologies

Eighteen different structural typologies were defined by the authors to classify the residential building stock of the country. Different structural typologies are necessary in seismic risk assessment to estimate the seismic performance of each typology by means of

fragility functions. Therefore, the number of structural typologies has to be large enough to represent different seismic behaviors of the exposed structures, but small enough to require a limited number of fragility functions to evaluate seismic risk. The eighteen structural typologies were defined based on common construction materials and techniques, the observed behavior in recent earthquakes, and expert judgement. Different typologies were defined for houses and for apartment buildings, where a house typically corresponds to a single-family occupancy dwelling, while an apartment building corresponds to a structure with multiple apartments per story. Each of these apartments corresponds to a single-family occupancy dwelling. According to the 2002 census, the main construction materials used in Chile for residential structures, which were considered to define the structural typologies are: reinforced concrete (RC), clay brick or concrete block masonry, timber, and adobe. Due to design standards and construction practice in Chile, timber and adobe are used mainly for houses, while reinforced concrete and masonry are used for both houses and apartment buildings. Additionally, the number of stories was considered to define structural typologies. The year of construction is an important feature that is related to the seismic design standards used for designing the structure. However, the year of construction was not used in the definition of the structural typologies since that information is not available in the census database.

RC structures were classified into four different typologies: RC houses (up to 3-stories high), low-rise RC apartment buildings (3–9-stories high), mid-rise RC apartment buildings (10–24-stories high), and high-rise RC apartment buildings (taller than 24-stories). The definition of the height ranges is based on the evidence that buildings 9–24-stories high were the most damaged group of RC apartment buildings after the 2010 Maule earthquake in Chile (Jünemann et al. 2015). Ten typologies were defined for masonry structures. Four typologies correspond to houses up to 2-stories high, separated into unreinforced clay brick (UCB), reinforced clay brick (RCB), confined clay brick (CCB), and reinforced or confined concrete block (CB). The remaining six typologies for masonry structures correspond to apartment buildings. Three of them correspond to 3-story-high apartment buildings of reinforced clay brick, confined clay brick, and reinforced or confined concrete block. The other three typologies correspond to masonry apartment buildings 4- or 5-stories high, with the same materials differentiation as those for 3-stories masonry buildings. Despite there is no explicit height limitation in the Chilean design code for masonry structures, it is not practical to build masonry structures taller than five stories due to high shear stresses imposed by the corresponding design codes (INN 2003, 2009a, b). Hence, tallest masonry buildings in the model are 5-story high. For timber structures, two structural typologies were defined: one for timber houses (up to 3-stories high) and one for timber emergency houses. These emergency houses consist of prefabricated wood panels mounted on timber piles for floor isolation, with a light roofing system typically with zinc sheets. One structural typology was defined for adobe houses, commonly 1- or 2-stories high, although 3-story-high adobe houses can be found on rare occasions. Finally, one structural typology was defined for self- and informal constructions. A table with the 18 typologies is shown in Sect. 2.5.

2.3 Construction of a national exposure model

The methodology proposed to obtain a national exposure model at a census-block level has three steps and is summarized in Fig. 1 for houses and apartment buildings. The key issue of the methodology is to relate the dwelling information from the 2002 census data to the 18 proposed structural typologies. The methodology is applied in both urban and rural
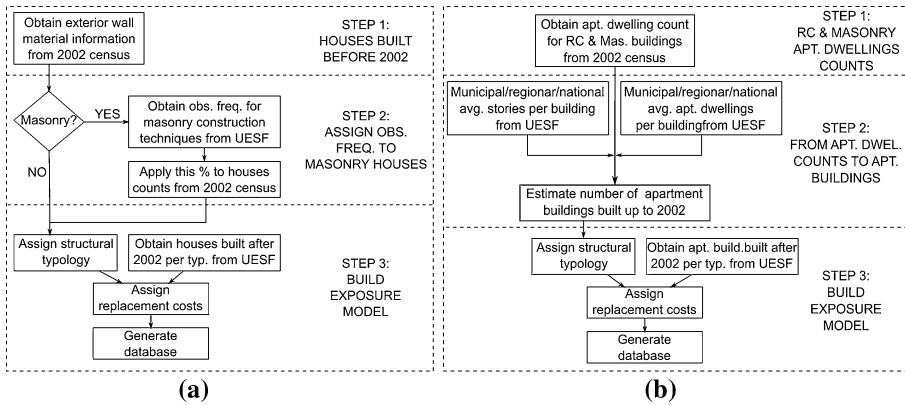
Fig. 1 Flow charts of the methodology to construct a national exposure models using census data: **a** houses and **b** apartment buildings

zones separately. First, the 2002 census data are used to obtain the residential stock built up to 2002 (73 % of the model in terms of number of structures). Then, the 2002–2014 UESF data are used to determine the stock built from 2002 to 2014 (25.5 %). Finally, the 2012 census data are used to account for the informal constructions (1.6 %).

The three steps followed to construct the national exposure model for houses are shown in Fig. 1a. First, the houses from the 2002 census are classified according to the information on the exterior wall material: masonry, reinforced concrete, adobe, or wood house. Since the information on the construction technology (i.e., unreinforced, reinforced, or confined masonry) for masonry houses is not available in the census, it takes a second step to classify masonry houses built before 2002. To classify these houses into the four masonry house typologies defined, the observed frequency of each construction technology is calculated for each municipality using information from the UESF database (for construction permits from 2002 to 2014). Then, those frequencies are applied to the counts of masonry houses built before 2002. The third step consists in assigning to each house built before 2002 one out of the nine structural typologies proposed for houses, and to obtain from the UESF the number of houses built since 2002. Since the UESF data are aggregated at the municipality level, the number of structures per typology in each municipality after 2002 was uniformly distributed in all census blocks within each municipality.

The three steps followed to construct the national exposure model for apartment buildings are shown in Fig. 1b. First, the numbers of RC and masonry apartment dwellings are obtained from the 2002 census. The second step consists in converting the apartment dwelling counts obtained from the 2002 census into number of apartment buildings. For this purpose, the average number of stories per building and the average number of apartments per story are obtained from the UESF database for each municipality. These average values are calculated for every structural typology and then used to estimate for each census block the number of apartment buildings of each typology built before 2002. It is important to notice that the distributions of apartment buildings obtained from the UESF database (buildings built between 2002 and 2014) may overestimate the number of mid- and high-rise buildings in structures built prior to 2002, mainly due to the increase of the average height of RC buildings in recent years. In the third step, the estimated numbers of apartment buildings build before 2002 are completed with the number of buildings built since 2002, information taken from the UESF.

In some cases, no construction permit is available in a municipality between 2002 and 2014 (i.e., no information was available in the UESF) for masonry houses, masonry apartment buildings, or RC apartment buildings. Then, it is not possible to relate 2002 census data for that structural typology in that municipality. In those cases, the frequency of a structural typology calculated at the regional level was used. Moreover, if there was no information for a certain structural typology at the regional level in the UESF, the national average was considered. Additionally, when UESF data contained only one structural typology for a certain municipality, the regional distribution, which considers several structural typologies, was used to classify structures from the 2002 census for that municipality. Using this latter procedure, classifying all structures of a certain municipality into a single typology was avoided. For example, if only one permit of RC apartment buildings is obtained from UESF from 2002 to 2014 in a certain municipality, without the previous consideration the model would estimate that only this type of buildings exists in this municipality. With the proposed methodology, the regional distribution is used, accounting for a larger variability of structural typologies in the built stock within that municipality.

To complete the national exposure model, the 2012 census is used to estimate the number of emergency and informal houses, which are typically built without construction permits. Since the 2012 census data were aggregated at the municipality level, the total number of emergency and informal houses was also uniformly distributed in all census blocks within each municipality.

2.4 Replacement cost

The replacement cost for each of the 18 defined structural typologies is estimated using information from both MINVU and SII. First, unit costs published by MINVU in a yearly basis (MINVU 2015) are used to estimate the unit replacement cost in US dollars per square meter for the different building materials (i.e., RC, masonry, timber, and adobe). MINVU defines four different unit prices for residential structures per construction material, depending on the quality of construction: *superior*, *semi-superior*, *regular*, and *semi-inferior*. The quality of a structure is assigned based on a score calculated according to the design features of the structure (e.g., story height, total height, floor plan area, presence and number of basements and elevators), the installations (e.g., presence of air-conditioning system, optic fiber availability, motion detector sensors), and the finishing works (e.g., interior and exterior coating, pavements, type of doors and windows). In this classification, each construction material of the exposure model can be rated within a certain range of categories. For example, an adobe house will never have *superior* quality since it will never present elevators or basements; instead, it will always have *semi-inferior* quality, independent of its design features. Similarly, the quality of RC houses and apartment buildings ranges from *regular* to *superior*, the quality of timber houses ranges from *semi-inferior* to *superior*, and the quality of masonry houses and apartment buildings ranges from *semi-inferior* to *semi-superior*. Table 1 shows the replacement cost per unit area of the highest and lowest quality category for each type of structure.

It is difficult to estimate a quality score for each structure in the exposure model only from census or UESF data. Therefore, a quality was assigned to each municipality with a simple procedure based on SII information. The SII defines a *location factor* for each municipality in Chile to estimate the appraisal value of residential structures (SII 2013). The location factor ranges from 0.4 to 1.0 and was used to assign a quality score to each municipality. For example, the municipality of Providencia in the Metropolitan Region has

Table 1 Replacement cost per unit floor area for the highest and lowest quality of each residential type of structures in Chile, in USD/m^2. Unit costs associated with each category, taken from MINVU (2015)

Structure type	Highest quality category		Lowest quality category	
	Quality category	$USD/m^2	Quality category	$USD/m^2
RC houses	Superior	544.6	Regular	298.4
RC apartment buildings	Superior	544.6	Regular	298.4
Masonry houses	Semi-superior	354.4	Semi-inferior	186.5
Masonry apartment buildings	Semi-superior	354.4	Semi-inferior	186.5
Timber houses	Superior	339.4	Semi-inferior	134.2
Adobe houses	Semi-inferior	93.2	–	–

a SII location factor of 1.0; therefore, the unit costs assigned for all structures in Providencia correspond to that of the highest possible quality of each material (i.e., *superior* for RC and timber, *semi-superior* for masonry, and *semi-inferior* for adobe). The municipality of Quinta Normal, also located in the Metropolitan Region, has a SII location factor of 0.4; therefore, the unit costs assigned for all structures in Quinta Normal correspond to that of the lowest possible quality of each material (i.e., *regular* for RC, and *semi-inferior* for timber, masonry, and adobe). For municipalities with SII location factors between 0.4 and 1.0, the quality for the replacement costs was calculated by interpolating between the costs of the highest and lowest quality of each material. For example, the municipality of Rancagua has a location factor equal to 0.6; then, the replacement cost of RC structures located in Rancagua is interpolated between the best quality—*superior*, with a replacement cost of 544.6 $USD/m^2, and the worst quality—*regular*, with a replacement cost of 298.4 $USD/m^2 (see Table 1). Thus, the resulting replacement cost for RC structures in Rancagua is 380.5 $USD/m^2.

Finally, the average floor areas for the different structural typologies were estimated. Since this information is not provided in the census, data from the UESF were used to estimate the average floor area per municipality for structures built before 2002. If no construction permits were available for a certain structural typology in a municipality, the regional or the national average floor area was used. This methodology is used to estimate the floor area for 16 out of 18 defined structural typologies, excluding timber emergency houses and informal houses. For these two structural typologies, the replacement cost is estimated directly since MINVU does not define unit costs for them. It is assumed that the replacement cost for timber emergency houses and informal houses is equivalent to the construction cost of a new timber emergency house: an average of $798,000 CLP or $1140 USD (TECHO 2014). The replacement cost of informal houses is also considered equivalent to the construction cost of a timber emergency house because informal houses are not built with a particular material, and it is assumed that after an earthquake, they will be replaced with timber emergency houses by the authorities or humanitarian aid institutions.

2.5 National exposure model results

This section presents a summary of the results of the national exposure model to provide an overview of the residential building stock in Chile. The complete database is available

through GEM's SARA Wiki webpage (https://sara.openquake.org) to everyone interested on using it for risk assessment or other purposes.

A total of 4,259,814 residential structures and 5,297,621 dwellings were identified in the exposure model, for a total of 17,819,054 inhabitants in 2014 (inhabitants obtained from INE 2014), as summarized in Table 2. This results in 3.4 inhabitants per dwelling. Overall, masonry, including both clay bricks and concrete blocks, is the most predominant material in the country, with 47.2 % of the dwellings. It is followed by timber, including both timber and emergency houses, with 27.1 %, RC with 21.9 %, adobe with 3.7 %, and finally informal and self-construction with 0.04 % of the dwellings of the country (see Table 2). The total number of structures of each structural typology for the regions located in the north zone, central zone, and south zone of Chile is detailed in Tables 3, 4 and 5, respectively. The tables also contains the urban ratio (UR), defined as the ratio of number of urban structures to the number of total structures (urban and rural). The distribution of structures according to the main construction materials and the location of each region of the country are shown in Fig. 2. Additionally, the map shows the seismic regions 1, 2, and 3 defined by the seismic design code (INN 2009a, b), which are related to peak ground accelerations of 0.2, 0.3, and 0.4 g, respectively.

The centralization of the country is evident from Fig. 2. The center macro-region accounts for 62 % of the inhabitants and 57 % of the structures in only 10 % of the total surface of the country. The concentration is even larger considering only the Metropolitan Region, where the capital Santiago is located: With 2 % of the surface of the country, this region concentrates 41 % of the inhabitants, 33 % of the structures, and 39 % of the dwellings. The average density of inhabitants in the central region (140 inhabitants/km^2) is 19 times larger that of the north region (7.5 inhabitants/km^2) and 11 times larger that of the south region of the country (12 inhabitants/km^2). Similar numbers are observed when comparing the average density of structures and dwellings between the macro-regions: 31 structures/km^2 (42 dwellings/km^2) in the center region, against less than 2 structures/km^2 (2 dwellings/km^2) in the north region, and about 3.5 structures/km^2 (4 dwellings/km^2) in the south region. These average densities increase around large urban centers such as the regional capitals of the country (e.g., Arica and Iquique in the north, Santiago and Rancagua in the center, and Valdivia and Puerto Montt in the south).

The national exposure model also shows that 82 % of the structures (86 % of dwellings) are located in urban areas and only 18 % (14 % of dwellings) in rural areas. For the urban areas of the three macro-regions, masonry and RC are the predominant construction materials for the north region (65 and 19 % of the structures, respectively), with a smaller participation of timber structures (11 %). Masonry (71 %) and timber (16 %, including

Table 2 Summary of number of structures and dwellings of the different residential structures in Chile

Structure type	Structures	%	Dwellings	%
RC houses	334,220	7.8	334,220	6.3
RC apartment buildings	12,269	0.3	826,474	15.6
Masonry houses	2,267,907	53.2	2,267,907	42.8
Masonry apartment buildings	10,997	0.3	234,600	4.4
Timber houses	1,372,451	32.2	1,372,451	25.9
Adobe houses	195,129	4.6	195,129	3.7
Emergency houses	64,577	1,5	64,577	1,2
Self-construction	2,264	0.05	2,264	0.04
Total	4,259,814	100	5,297,622	100

Table 3 Total number of structures (in thousands) and urban ratio (UR) for each structural typology, regions of the north zone

Typology	XV		I		II		III		IV	
	N°	UR	N°	UR	N°	UR	N°	UR	N°	UR
RC houses	5.8	0.98	8.2	0.96	40.8	0.96	9.2	0.96	21.5	0.89
RC apt. 4-9	0.4	1.00	0.1	1.00	0.4	1.00	0.1	1.00	0.4	0.96
RC apt. 10-24	0.0	1.00	0.1	0.98	0.2	0.99	0.0	1.00	0.1	1.00
RC apt. > 24	0.0	-	0.0	1.00	0.0	1.00	0.0	-	0.0	1.00
M houses UCB	1.1	0.94	0.4	0.99	9.5	1.00	5.3	0.91	5.6	0.88
M houses RCB	25.6	0.94	3.7	0.98	20.4	0.99	21.9	0.95	99.9	0.80
M houses CCB	0.2	0.96	0.3	0.99	0.6	0.97	5.0	0.99	15.0	0.88
M houses CB	5.1	0.96	25.8	0.93	44.5	0.98	14.1	0.88	11.0	0.78
M apt. RCB 3	0.0	-	0.1	1.00	0.0	1.00	0.0	-	0.0	-
M apt. CCB 3	0.0	-	0.2	1.00	0.1	1.00	0.0	-	0.0	-
M apt. CB 3	0.0	-	0.0	-	0.0	1.00	0.0	-	0.0	-
M apt. RCB 4-5	0.2	1.00	0.0	-	0.1	1.00	0.1	1.00	0.0	1.00
M apt. CCB 4-5	0.0	-	0.0	-	0.0	1.00	0.0	1.00	0.0	1.00
M apt. CB 4-5	0.0	-	0.3	1.00	0.0	1.00	0.0	-	0.0	-
Timber houses	6.9	0.91	9.4	0.93	8.2	0.96	1070	0.8	28.7	0.53
Adobe houses	0.8	0.52	0.7	0.36	3.7	0.90	6.9	0.82	18.1	0.49
Emer. houses	1.6	0.12	0.9	0.71	0.8	0.78	0.4	0.58	1.8	0.20
Self-const.	0.2	0.70	0.3	0.85	0.2	0.68	0.1	0.35	0.1	0.46
Total	47.9	0.91	50.6	0.93	129.5	0.97	73.7	0.91	202.0	0.75

emergency houses) increase their share in the center of the country, while RC loses participation (9 %). The three macro-regions have characteristic distributions of structural typologies. In the south region (Table 5), timber is by far the most predominant construction material (65 %), over masonry (27 %), while RC only corresponds to a small share (6 %). Adobe's presence in urban areas in the north and center regions is similar (4 % of the structures) and tends to disappear in the south (less than 1 %) because of the rainy weather of this macro-region. In rural areas, adobe increases its participation to 17 % in both north and center regions and to 3 % in the south. In the north region (Table 3), masonry is also the most predominant construction material in rural areas (47 %), while timber (29 %) replaces RC (7 %) as the second most important construction material. Masonry (49 %) and timber (33 %) are also the most used materials in rural areas in the center; timber is predominant in rural areas the south (86 %), followed by masonry (10 %). These trends were expected by the authors due to the availability of the different construction materials throughout the country. Overall, the most predominant typologies in urban areas are reinforced clay brick masonry houses (29 % of the total number of structures), timber houses (28 %), confined clay brick masonry houses (14 %), and unreinforced clay brick masonry houses (9 %). For rural areas, the main typologies are timber houses (9 % of the total number of structures), reinforced clay brick masonry houses (2 %), unreinforced clay brick masonry houses (2 %), and adobe houses (2 %).

Table 4 Total number of structures (in thousands) and urban ratio (UR) for each structural typology, regions of the central zone

Typology	V		XIII		VI		VII	
	N°	UR	N°	UR	N°	UR	N°	UR
RC houses	41.2	0.96	125.8	0.98	7.6	0.90	10.4	0.80
RC apt. 4-9	1.5	0.99	3.5	0.99	0.1	0.97	0.2	0.99
RC apt. 10-24	0.5	1.00	2.4	1.00	0.0	1.00	0.0	1.00
RC apt. > 24	0.1	1.00	0.3	1.00	0.0	1.00	0.0	-
M houses UCB	21.9	0.88	190.4	0.96	56.4	0.44	50.6	0.46
M houses RCB	131.5	0.93	555.7	0.98	85.2	0.91	87.4	0.68
M houses CCB	46.1	0.95	219.2	0.98	23.1	0.84	79.0	0.74
M houses CB	10.0	0.93	74.9	0.99	13.9	0.88	9.6	0.82
M apt. RCB 3	0.4	1.00	0.3	1.00	0.0	1.00	0.0	1.00
M apt. CCB 3	0.3	1.00	1.1	1.00	0.1	1.00	0.0	1.00
M apt. CB 3	0.0	-	0.1	1.00	0.0	-	0.0	-
M apt. RCB 4-5	0.6	1.00	3.5	1.00	0.2	1.00	0.1	0.93
M apt. CCB 4-5	0.4	1.00	1.3	1.00	0.1	1.00	0.0	0.00
M apt. CB 4-5	0.0	1.00	0.1	1.00	0.0	1.00	0.1	1.00
Timber houses	129.5	0.81	187.2	0.85	38.8	0.54	46.3	0.51
Adobe houses	26.3	0.84	37.7	0.91	31.4	0.46	51.0	0.39
Emer. houses	5.5	0.84	16.6	0.85	6.9	0.38	0.1	0.27
Self-const.	0.3	0.85	0.4	0.85	0.1	0.58	0.1	0.46
Total	416.1	0.89	1420.6	0.96	264.0	0.68	349.3	0.59

From the total inventory of structures, 4.23 million structures are houses (99.5 % of structures, which represents 80 % of the dwellings), while only 23,267 structures are apartment buildings (only 0.5 % of structures, but 20 % of dwellings, Table 2). Timber houses (34 % of the total number of houses) and RCB houses (26 %) are the predominant typologies for houses. Adobe houses, which are highly vulnerable to earthquakes, represent 4.6 % of the total number of houses in Chile. Informal construction represents 0.1 % of the total number of houses and emergency houses 1.5 %. RC is the most common construction material of apartment buildings, with 53 % (12,459) of the total number of apartment buildings, which corresponds to 78 % of the individual apartments. Of these apartment buildings, 35 % are low-rise (3–9-stories high), 16 % are mid-rise (10–24-stories high), and 2 % are high-rise apartment buildings (more than 24 stories tall). Masonry apartment buildings represent 47 % of the total number of apartment buildings. From this share, 14 % are 3-stories high, 27 % are 4-stories high, and 6 % are 5-stories high.

The total replacement cost aggregated in seven structural types for the three macro-regions of Chile is summarized in Table 6. For each macro-region, the percentage of the cost of each structural type relative to the total replacement cost of the country is shown. The total replacement cost of the residential structures of the country ($107.9 billion USD) represents 42 % of the Chilean GDP of 2014, which is $ 258 billion USD (The World Bank 2014). Note that almost 70 % of the replacement cost of the country comes from the central region, in agreement with population distribution. The provided replacement costs

Table 5 Total number of structures (in thousands) and urban ratio (UR) for each structural typology, regions of the south zone

| Typology	VIII		IX		XIV		X		XI		XII	
	N°	UR	N°	UR	N°	UR	N°	UR	N°	UR	N°	UR
RC houses	45.4	0.95	9.4	0.90	2.1	0.93	4.6	0.94	0.8	0.87	1.5	0.94
RC apt. 4-9	0.9	1.00	0.2	0.93	0.1	0.99	0.1	0.99	0.0	0.87	0.0	0.93
RC apt. 10-24	0.2	1.00	0.1	1.00	0.0	0.00	0.0	1.00	0.0	-	0.0	1.00
RC apt. > 24	0.0	1.00	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-
M houses UCB	40.6	0.69	4.0	0.76	1.3	0.82	1.6	0.91	0.3	0.93	2.3	0.99
M houses RCB	62.2	0.93	14.2	0.73	2.2	0.89	3.4	0.92	0.5	0.84	1.1	0.97
M houses CCB	119.0	0.96	21.6	0.90	2.6	0.88	7.2	0.95	0.9	0.93	0.6	0.96
M houses CB	6.6	0.85	3.9	0.41	0.2	0.91	0.8	0.84	0.8	0.60	0.2	1.00
M apt. RCB 3	0.0	-	0.0	-	0.0	1.00	0.0	-	0.0	1.00	0.0	-
M apt. CCB 3	0.2	0.99	0.1	1.00	0.0	1.00	0.0	-	0.0	1.00	0.0	-
M apt. CB 3	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-
M apt. RCB 4-5	0.2	1.00	0.1	1.00	0.0	1.00	0.1	1.00	0.0	1.00	0.0	1.00
M apt. CCB 4-5	0.0	1.00	0.1	1.00	0.0	0.99	0.1	1.00	0.0	1.00	0.0	-
M apt. CB 4-5	0.0	-	0.0	-	0.0	-	0.0	-	0.0	1.00	0.0	-
Timber houses	300.5	0.72	229.5	0.61	96.2	0.64	217.5	0.67	25.3	0.78	37.8	0.93
Adobe houses	16.8	0.36	1.2	0.74	0.0	0.79	0.2	0.93	0.4	0.52	0.0	0.75
Emer. houses	15.0	0.62	2.4	0.40	1.4	0.54	1.8	0.71	0.30	0.69	0.1	0.87
Self-const.	0.2	0.58	0.1	0.41	0.0	0.49	0.1	0.62	0.0	0.95	0.0	0.67
Total	607.8	0.79	286.9	0.65	106.4	0.66	237.6	0.69	29.4	0.78	43.6	0.94
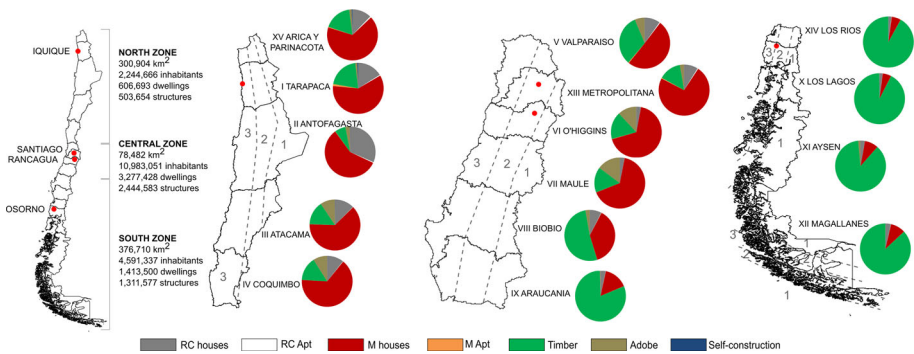
Fig. 2 Distribution of structures and population within three macro-regions (north, center, and south zones), and distribution of structures according to the type of structure and main construction materials

only consider residential structures, and the percentages would likely change when considering also commercial and industrial infrastructure (e.g., the north of Chile concentrates large asset value due to the large mining industry that may change the percentages obtained for residential structures).

Table 6 Total replacement cost of the residential assets for different structural types for the north, center, and south macro-regions of Chile

Structure type	North		Center		South		Total	
	MM$ USD	%	MM$ USD	%	MM$ USD	%	MM$ USD	%
RC houses	2,919	2.7	10,332	9.6	2,689	2.5	15,932	14.8
RC apartment buildings	3,135	2.9	23,293	21.6	2,637	2.4	29,034	26.9
Masonry houses	4,918	4.6	30,100	27.9	5,418	5.0	40,411	37.4
Masonry apt. buildings	233	0.2	3,540	3.3	269	0.2	4,041	3.7
Timber houses	1,262	1.2	5,783	5.4	8,967	8.3	16,000	14.8
Adobe houses	335	0.3	1,939	1.8	174	0.2	2,446	2.3
Emergency houses and self-construction	8	0.0	50.0	0.0	27	0.0	85	0.1
Total	12,811	11.9	75,038	69.5	20,181	18.7	107,949	100

Note that RC structures (houses and apartment buildings) correspond to only 8 % of the total number of structures in the country (Table 2), but account for almost 42 % of the total replacement cost of the residential inventory of the country. This is reasonable because RC structures account for 22 % of the dwellings of the country and because of the higher replacement cost of RC compared to other materials (Table 1). Moreover, RC apartment buildings themselves represent only 0.3 % of the structures, but they represent 27 % of the total replacement cost, as these structures accounts for 15.6 % of the dwellings of the country. On the other hand, masonry structures represent more than 53 % of the structures of the country and 41 % of the replacement cost; timber structures represent 34 % of the total structures and less than 15 % of the replacement cost of the country.

3 Local exposure models using remote digital surveys

Local exposure models are constructed for three cities representative of three macro zones of the country: Iquique, Rancagua, and Osorno. A methodology using remote digital survey techniques is used to obtain these local models. In the following section, the methodology followed to obtain the local exposure models is described, and a summary of the results is presented.

3.1 Remote digital surveys description

Remote digital surveys techniques are used to build local detailed exposure models of Iquique, Rancagua, and Osorno. Google Maps, Google StreetView (Google Inc. 2015), and GEM's Tool for Field Data Collection and Management, Inventory Data Capture Tools (IDCT) (Jordan et al. 2014) were used simultaneously in the proposed methodology. Google StreetView was used to remotely observe the cities at a street level, and IDCT was used to store the geographical position (latitude and longitude) and the observed characteristics of each surveyed structure. Figure 3 presents a flowchart of the steps followed to
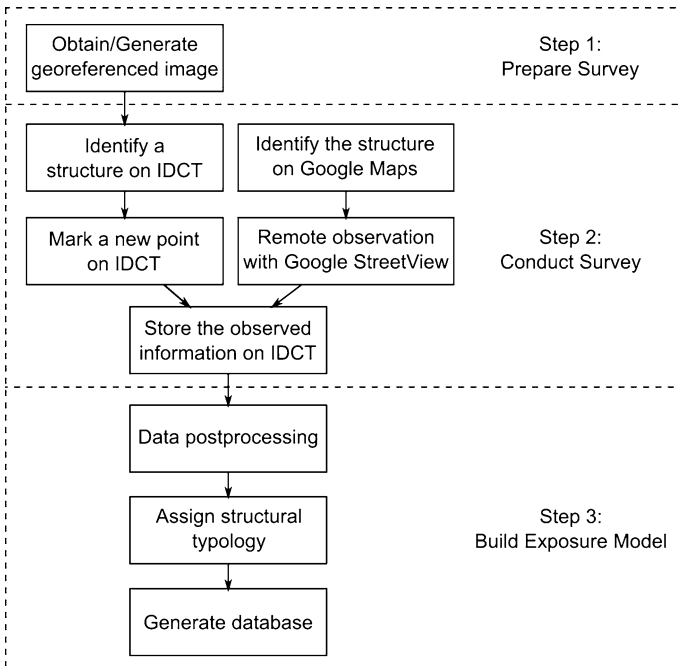
Fig. 3 Three main steps followed to build the local exposure models. The main tools used for this purpose are Google StreetView and GEM's Inventory Data Capture Tools (IDCT)

build the local exposure models. Three main steps are defined: Prepare the remote surveys, conduct the remote surveys, and process the data to build the exposure models.

In the first step, a georeferenced image of each city is obtained to correctly locate the surveyed data. In this project, a mosaic of superimposed georeferenced images of each city was generated using ESRI ArcGIS 10.2 (ESRI 2011) and loaded into IDCT. To allow for proper identification and differentiation of the structures, a 1:2500 scale was used for the georeferenced images. Figure 4 shows the mosaic generated for Rancagua as an example. A total of 116, 196, and 168 georeferenced images were used to cover a surface of 18.5,

Fig. 4 **a** Map of the city of Rancagua; **b** georeferenced mosaic created for the remote surveys

46.2, and 29.0 km^2 for the cities of Iquique, Rancagua, and Osorno, respectively. On average, each image covered 0.20 km^2.

The surveys are performed in the second step of the methodology. Each structure was identified using Google Maps and remotely observed with Google StreetView at the street level to identify its characteristics. Then, the structure is identified in the georeferenced image in IDCT, and the observed structural features are stored in IDCT. An example of the remote survey process is shown in Fig. 5 for a 3-story confined masonry building. Note that images on Fig. 5a, c are different: Fig. 5a comes from Google Maps, while Fig. 5c comes from the georeferenced image generated on ArcGIS. The images contain different information because they were taken on different dates. This difference is not a significant problem for the surveying process; the georeferenced image must be sufficiently updated to allow the surveyor to mark the survey point (i.e., the surveyed structure) on the image, thus saving its location on IDCT. On the other hand, it is important that the most updated image is used for the detailed observation of the building, performed using Google StreetView.

For each surveyed structure, the following information was collected on IDCT after observation with Google StreetView: (1) latitude and longitude, obtained automatically from the georeferenced image after marking a point in IDCT; (2) main construction material (RC, unreinforced masonry, reinforced masonry, confined masonry, earth with
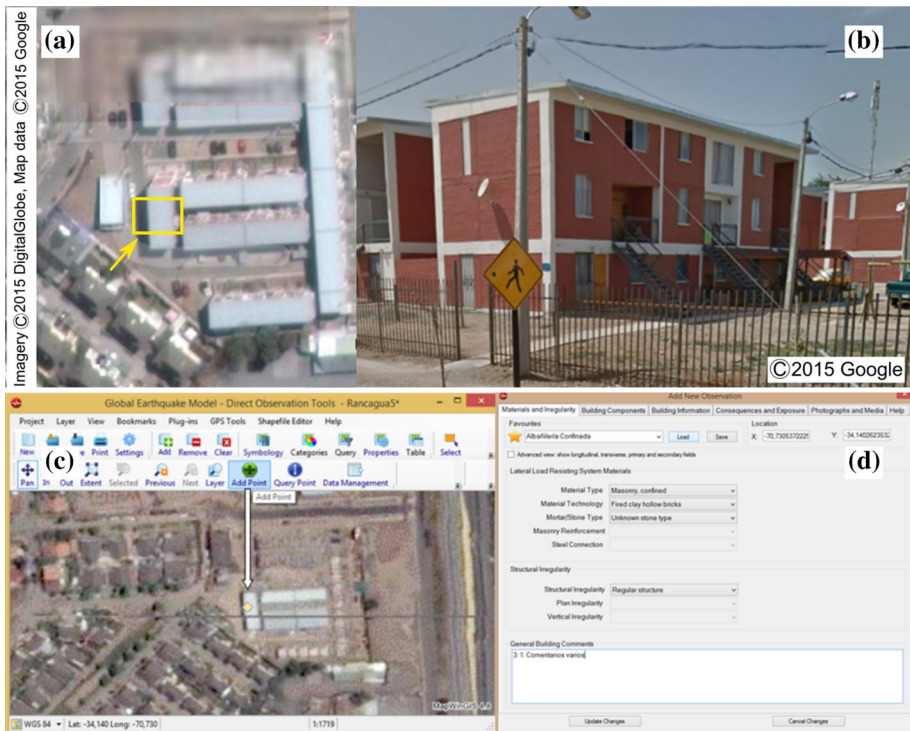

Fig. 5 Example of a remote digital survey to build a detailed exposure model: **a** A building is selected using Google Maps—the *yellow box* identifies the surveyed building, and the *arrow* shows the observation point for the survey; **b** the building is observed using Google StreetView; **c** the building is identified on the georeferenced image in IDCT; **d** the information of the observed structural features of the structure are saved on IDCT

unknown reinforcement, wood with unknown reinforcement, or other material); (3) building occupancy (residential, or mixed use—residential and commercial); (4) material technology of masonry structures (clay hollow bricks, clay solid bricks, or concrete hollow blocks); and (5) general comments on the structure (number of stories; number of dwellings of adjoining houses; and information about the use of mixed materials, e.g., a house with the first level built with confined masonry and the second level with timber and/ or other light materials).

After conducting all the surveys, data stored on IDCT are processed to assign one of the eighteen structural typologies to each surveyed structure. Finally, the local exposure models database is generated by integrating the geographical position of each structure with its structural typology.

3.2 Models' results

Local exposure models of residential structures were constructed for three cities representative of the cities in the three macro-regions shown in Fig. 2: Iquique in the north, Rancagua in the central, and Osorno in the south zone of the country. Iquique is a coastal city, capital of the Tarapacá Region in northern Chile. Iquique has a population of approximately 180,000 (more than 80 % of the Region's population) and was the most affected large city after the 2014 Pisagua earthquake (EERI 2014). Rancagua, with a population of around 236,000, is the main city and capital of the Libertador Bernardo O'Higgins Region. Rancagua suffered severe damage after the 2010 Maule earthquake, especially on masonry and adobe structures (Astroza et al. 2012). Osorno, located in the southern zone of the country, is the second most important city in the Los Lagos Region with a population of approximately 150,000 and is representative of typical southern Chile cities.

The resolution of the local exposure models is at a structure level. It is important to clarify that the municipalities are the smallest administrative level in Chile, and that a city corresponds to an urban portion of the corresponding municipality. The city of Iquique covers 0.8 % of the surface of the Municipality of Iquique, whereas the cities of Rancagua and Osorno correspond to 17.8 and 3.1 % of the surface of their respective municipalities, as calculated with the 2012 census cartography.

An average of 76 % of the surfaces of the cities was surveyed. The surveyed areas and the performance of the remote surveying process are shown in Table 7. Undergraduate second-year civil engineering students conducted the surveys and a senior student with structural engineering background oversaw their work.

Remote surveying is a time-costly process, as can be noted from Table 7, due to the resolution scale being used (structure per structure). The differences observed in the

Table 7 Surveying performance for the detailed local exposure models of Iquique, Rancagua, and Osorno

City	Total surface (km^2)	Surveyed surface (km^2)	Surveyed surface (%)	Number of structures surveyed	Density of structures (per km^2)	Working Hours (WH)	Structures surveyed per WH
Iquique	18.5	14.4	77.6	27,025	1877	360	75.1
Rancagua	46.2	34.4	74.4	47,220	1373	376	125.6
Osorno	29.0	22.0	75.7	29,734	1352	176	168.9

number of structures surveyed per working hour of the three cities are mainly explained by:
(1) In Iquique, great variability of structural typologies was identified (different con-
struction materials and number of stories), which slowed down the data collection process;
(2) in Rancagua, many similar structures were identified in several blocks, which were
grouped in one surveyed point to increase data collection speed; and (3) in Osorno,
identification of the building material in houses was simpler than for the other two cities
because the lack of coating materials in timber houses, allowing for faster data collection.
Figure 6 shows an example of the surveyed area and points collected in IDCT for the city
of Osorno.

The data of surveyed points in IDCT were converted into number of structures to create
the detailed exposure models for the three cities. The city with largest number of structures
is Rancagua, while the numbers of structures in Iquique and Osorno are very similar.
Results of the models within the surveyed surfaces shown in Table 7 are summarized in
Table 8.

Similarly to the national model, the local models show that the residential physical stock
is composed mainly by houses (97.8 % in average for the three cities), with a maximum of
99.2 % of houses in Osorno. Apartment buildings have a small participation (2.2 % in
average), with a maximum of 3.5 % of the total number of structures in Iquique. Masonry
is the predominant construction technology in Iquique (73.2 %) and Rancagua (96.5 %),
and clay is the preferred material for the masonry units (32.0 % in Iquique and 96.3 % in
Rancagua). In Osorno, timber is the most used material overall and corresponds to 83.6 %
of the total number of structures in the city. These results were expected by the authors and
are similar to the results of the national exposure model.

The methodology used to build the local exposure models is very accurate to count the
total number of structures. It is relatively easy to differentiate a house from an apartment
building and to count the number of stories by visual inspection with the available Google
StreetView images. However, a difficulty arises when classifying each structure into the
structural typologies. Identifying the structure construction material is difficult when it is
hidden by exterior walls, protection bars (see Fig. 7a), or large vegetation, when the
images had a low resolution (Fig. 7d), or when the facades of houses or apartment
buildings were painted or coated with stucco or a similar material (Fig. 7b, c). For these
cases, the typology of the surrounding structures is assigned to the inspected structure. For
heterogeneous built environments, the most common typology was assigned.

Given that the methodology used to construct the detailed local exposure models is
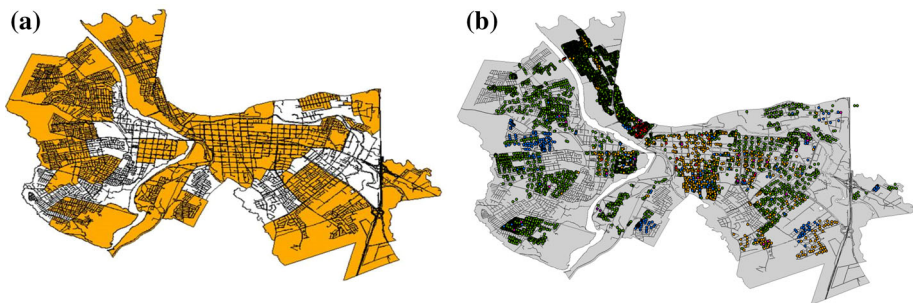time-consuming (see Table 7), generating a detailed exposure model for the whole country

Fig. 6 City of Osorno: **a** *highlighted* area of the city which was remotely surveyed; **b** 7070 data points
collected using IDCT, corresponding to 29,734 structures

Table 8 Summary of the detailed exposure models for Iquique, Rancagua, and Osorno for the surveyed surface

Typology	Iquique		Rancagua		Osorno	
RC houses	1,923	7.1 %	464	1.0 %	2,017	6.8 %
RC apt. 4-9	306	1.1 %	156	0.3 %	198	0.7 %
RC apt. 10-24	101	0.4 %	7	0.0 %	9	0.0 %
RC apt. > 24	31	0.1 %	0	0.0 %	0	0.0 %
M houses UCB	99	0.4 %	4,887	10.3 %	3	0.0 %
M houses RCB	6,212	23.0 %	36,129	76,5 %	2,349	7.9 %
M houses CCB	2,056	7.6 %	3,545	7.5 %	72	0.2 %
M houses CB	10,894	40.3 %	91	0.2 %	137	0.5 %
M apt. RCB 3	77	0.3 %	333	0.7 %	4	0.0 %
M apt. CCB 3	27	0.1 %	255	0.5 %	16	0.1 %
M apt. CB 3	92	0.3 %	0	0.0 %	1	0.0 %
M apt. RCB 4-5	58	0.3 %	159	0.3 %	5	0.0 %
M apt. CCB 4-5	132	0.5 %	174	0.4 %	0	0.0 %
M apt. CB 4-5	132	0.5 %	12	0.0 %	0	0.0 %
Timber houses	4,608	17.1 %	676	1.4 %	24,872	83.6 %
Adobe houses	180	0.7 %	277	0.6 %	1	0.0 %
Emergency houses	2	0.0 %	26	0.1 %	48	0.2 %
Self-construction houses	95	0.4 %	29	0.1 %	2	0.0 %
Total	27,025	100 %	47,220	100 %	29,734	100 %

Number of structures and percentage of structures in each typology

would require plenty of time and would have the limitations discussed above. Moreover, the large variability of the distribution of the residential structures in the country and even within a city limits the extrapolation of the generated information from this study to other similar cities. This extrapolation would lead to an exposure model with unreliable accuracy. The lack of coverage by Google StreetView can be overcome by using a dedicated mobile mapping system, as suggested by Pittore and Wieland (2013), and Wieland et al. (2015).

Despite the described difficulties to construct detailed local exposure models, it is important to recognize that data collected with digital remote surveying are at least as reliable as the census data. In both cases, surveyors are non-experts and have limited information to assess the structural material of a house or an apartment building. However, the undergraduate engineering students that conducted the survey of the detailed exposure models focused on estimating the structural material accurately, which is probably not the case of the surveyor that collected the census data, which may have been focused on other type of information while conducting the survey. The most reliable data to classify a structure are the one obtained from the UESF, as stated in Sect. 2.1.
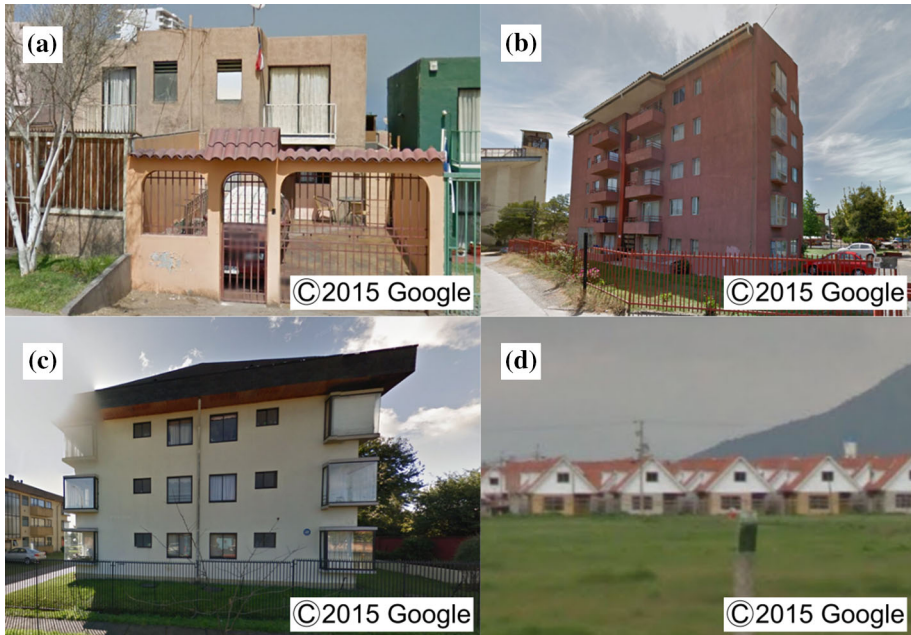
Fig. 7 Difficulties to classify structures when remotely surveying them: **a** interference due to the presence of exterior walls (https://goo.gl/maps/kYZ2nyLT3Ju); **b**, **c** walls painted or coated with stucco (https://goo.gl/maps/6NBkVw19xjw and https://goo.gl/maps/Gz1pKT7ezU42); **d** images with low resolution (https://goo.gl/maps/AAk8saV2qsr)

4 Comparison between the national and local models

A detailed comparison for Iquique, Rancagua, and Osorno is performed between the results of the national exposure model and the local exposure models. To account for the lack of surveyed surface in the cities of the local exposure models (76 % coverage on average, see Table 7), a linear extrapolation was used to obtain the number of structures that would represent 100 % of the surface of each city. These results will be referred to as the *extrapolated exposure models* hereafter, and the results are presented in Table 9. The values of the extrapolated exposure models were obtained by dividing the number of structures per typology by the ratio of the surface effectively covered in the detailed exposure models. For example, the number of RC houses in the detailed exposure model of Iquique is 1923 (Table 8), and the covered area was 77.6 % (Table 7). Thus, in the extrapolated exposure model of Iquique, the number of RC houses is $1923/0.776 \approx 2478$ (see Table 9). Table 9 also shows the results of the national exposure model for structures located in the urban zone of each of the three municipalities, corresponding to the census blocks that match the region considered as the city in the local models.

Table 9 shows that the total number of structures obtained from the national exposure model and the extrapolated exposure models are similar for the three cities. The average difference between the total numbers of structures of these two models is 5 %, where the largest difference of about 11 % is obtained for Iquique.

Table 9 Comparison of national and detailed local extrapolated exposure models

Typology	Iquique		Rancagua		Osorno	
	National	Extrap.	National	Extrap.	National	Extrap.
RC houses	6,244	2,478	3,849	624	1,441	2,664
RC apt. 4-9	62	394	129	210	64	262
RC apt. 10-24	78	130	20	9	6	12
RC apt. > 24	44	40	2	0	0	0
M houses UCB	172	128	3,387	6,569	934	4
M houses RCB	3,154	8,005	43,719	48,560	1,304	3,103
M houses CCB	49	2,649	1,238	4,765	1,070	95
M houses CB	14,677	14,039	1,649	122	37	181
M apt. RCB 3	101	99	28	448	0	5
M apt. CCB 3	194	35	54	343	0	21
M apt. CB 3	0	119	0	0	0	1
M apt. RCB 4-5	0	75	180	214	28	7
M apt. CCB 4-5	0	170	70	234	28	0
M apt. CB 4-5	294	170	13	16	0	0
Timber houses	6,185	5,938	3,958	909	33,415	32,856
Adobe houses	25	232	2,605	372	11	1
Emergency houses	103	3	408	35	496	63
Self-construction houses	110	122	22	39	34	3
Total number of houses	30,719	33,594	60,835	61,995	38,743	38,970
Total number of apartment buildings	774	1,232	495	1,474	126	308
Total	31,493	38,826	61,330	63,469	38,869	39,278

Number of structures for each typology

*National stands for National exposure model; *Extrap.* stands for Extrapolated exposure model

4.1 Houses

The number of houses obtained with the national exposure model and the extrapolated exposure models is similar, the differences in the total number of houses are smaller than 10, 2, and 1 % for Iquique, Rancagua, and Osorno, respectively. However, differences are observed when comparing the number of houses obtained for each structural typology. Even though for Iquique and Rancagua the difference between the sum of RC and masonry houses in both models is less than 12 % (24,296 houses in the national exposure model and 27,299 houses in the extrapolated exposure model for Iquique, and 53,842 and 60,640 houses for Rancagua), larger differences are observed when comparing the number of houses of each structural typology associated with these materials. The large proportion of RC houses in the national exposure model in Iquique was unexpected by the authors and may be explained because of misidentification of the wall material of these houses during

the census, or because the UESF data used for extrapolating 2002 census data are not that reliable. On the other hand, the surveyors of the local models could have misidentified some structures on the remote surveys. To overcome these difficulties, on-site direct inspection of a small number of structures could be used to improve the quality of the local exposure models. Then, the results from local exposure models could be used to improve the quality of the national exposure model.

The number of timber houses in the three cities is similar in both models, which can be explained by the fact that timber houses are easy to identify and classify when not coated with stucco or other material. It is also possible that some emergency houses were classified as timber houses in the extrapolated exposure model, explaining part of the difference observed between the numbers of emergency houses in both models.

Emergency and self-construction houses represent less than 1 % of the total number of structures for each city. Therefore, no proper comparison can be made for those typologies. Similar results are obtained for adobe houses in Iquique and Osorno (north and south regions). On the other hand, due to historical issues, it was expected that the number of adobe houses would be proportionally larger for Rancagua than for the other two cities, as shown in both national and detailed exposure models.

The largest deviations between the national exposure model and local models come from the incorrect classification of masonry or RC houses. Since in the census, a non-expert person reported the main exterior walls material, masonry, and RC can be confused when stucco, painting, or other common coating is used.

It is interesting to notice that, for the characteristic typology of houses of each macro-region (concrete blocks in Iquique, the north region; reinforced clay masonry in Rancagua, center region; and timber in Osorno, south region), best agreement was found between the national and the local models.

4.2 Apartment buildings

Larger differences between the national and extrapolated exposure models are obtained for the total number of apartment buildings than for the total number of houses (Table 6). The total numbers of apartment buildings in the extrapolated exposure models are 59, 197, and 144 % larger than those in the national exposure model for Iquique, Rancagua, and Osorno, respectively. The numbers of apartment buildings of the extrapolated exposure models are more reliable than those from the national exposure model, since several assumptions were made in the latter to obtain the number of buildings from the number of dwellings. Census data—at a dwelling level—was combined with UESF data—at a municipality level—using parameters such as municipal and regional averages of number of stories per building and number of apartments per story per building. The percentage of apartment buildings with different story heights and the average number of apartments per story were calculated from UESF data and then used to estimate the number of buildings from the 2002 census. Given that the height and the number of apartments per story have increased over time, the number of buildings existing before 2002 is underestimated in the national exposure model. On the other hand, the number of apartment buildings in the detailed local exposure models was obtained by counting each of them in the remote surveys, resulting in a more reliable number than the counts obtained in the national exposure model.

Some misclassification of apartment buildings up to 5-stories high into structural typologies may occur in both the national exposure model and the local exposure models because of the difficulty to differentiate masonry and RC, as mentioned earlier. However,

apartment buildings taller than five stories are always classified as RC because there are no masonry buildings taller than 5-stories high, hence lower differences are identified between the models. The proportion of apartment buildings in the extrapolated models represents 3.5, 2.3, and 0.8 % of the total number of structures in Iquique, Rancagua, and Osorno, respectively.

5 Summary and conclusions

This paper presents a methodology used to obtain a national exposure model at a census-block level of residential structures in Chile using statistical information and a summary of its results. The national exposure model contains the number of structures of each of the 18 defined structural typologies and the replacement cost of each one of them. The model is available in the GEM SARA Wiki webpage with both census-block and municipality resolution, and it is intended to be used to perform seismic risk analysis. The methodology used to construct the exposure model can be applied elsewhere following three steps: (1) obtain dwelling count, construction material, and location from census data, (2) define classification rules for dwellings associated with houses and apartment buildings, and (3) assign structural typologies and replacement costs.

A total of 4,259,804 residential structures and 5,297,621 dwellings were identified in the national exposure model, for a total of 17,819,054 inhabitants. From the total inventory of structures, 99.5 % are houses and only 0.5 % are apartment buildings. Timber houses and reinforced clay brick masonry houses are the predominant typologies for houses. Adobe houses, which are highly vulnerable to earthquakes, represent 4.6 % of the total number of structures in Chile. RC is the most common construction material of apartment buildings, with 53 % of the total number of apartment buildings. The estimated total replacement cost of the residential structures in Chile is $108 billion USD. RC structures (houses and apartment buildings) correspond to only 8 % of the total number of structures in the country, but account for almost 42 % of the total replacement cost of the residential inventory.

Local exposure models were constructed using remote digital surveys in three cities— Iquique, Rancagua, and Osorno. Comparing the results of the national and local residential exposure models, overall agreement is found on the total number of houses per city, with an average difference of 4 % between the two models. However, larger differences are found when classifying the structures into the defined structural typologies. This is explained by the low technical quality of the 2002 census data, which accounted for 73 % of all the structures in the national exposure model, and by the limitations of the methodologies to correlate dwellings with structures in both the national and the local exposure models. The results of this comparison highlight the need to continue doing research for developing exposure models.

An integrated approach merging statistical data together with detailed local surveys (in situ or remote) could help to optimize the trade-off between accuracy and costs of developing an updated national exposure model of the physical infrastructure. Local surveys can help by collecting valuable information to classify structures, thus complementing the previous data sources for the analysis. For such integrated approach the country could be divided according to construction practices, and local exposure models may be used for validation. For example, Chile could be separated into north, central, and south macro-regions, which have different distributions of structural typologies. The local exposure

models can be improved by using quality control procedures for gathering information during the surveys and by on-site visits to a small number of structures.

This study contributes to the characterization of the seismic vulnerability of the residential building stock in Chile, representing an important input for risk calculations and for quantification of exposed inventory in hazardous regions. This can help to scope and prioritize preparedness and mitigation strategies for the country. Further work includes the construction of vulnerability curves for the defined structural typologies and the estimation of seismic risk using these results. It is important to mention that the exposure model is open, is transparent, and can be replicated or improved in case users want to use it in local studies.

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