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USE OF REMOTE DIGITAL SURVEYS TO GENERATE EXPOSURE MODELS OF RESIDENTIAL STRUCTURES IN CHILE

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Abstract

This article describes a methodology used to build detailed exposure models of residential structures in three cities of Chile using remote digital surveys. The models provide the location of the structures classified into 18 different structural typologies. Two tools were used simultaneously to build the models: Google *StreetView*, and GEM's *Inventory Data Capture Tool*. The method is described, a summary of the results of the exposure models is presented, and the detailed results of the local models are compared with a previously developed national exposure model for the whole country. The proposed methodology to develop exposure models proved to be useful, simple, and low cost, and can be replicated elsewhere with proper StreetView coverage. The methodology is accurate to count structures, despite presenting certain difficulties to classify the surveyed buildings into different structural typologies. The developed exposure models represent an important input for risk calculations, thus improving technical capabilities for seismic risk management of the country.

Keywords: exposure model; building stock; digital surveys; remote sensing; seismic vulnerability

1. Introduction

Urban development and population growth, especially in developing countries in seismic active regions, highlight the need for quantitative tools that provide information to better prepare and respond to seismic hazard risk, thus improving overall resilience to natural extreme events. Seismic risk assessment, a composition of the seismic hazard, the exposed physical and social inventories, and their vulnerabilities, is an alternative approach to address this need.

Within the methods used to characterize the physical inventory for seismic risk assessment, remote sensing (RS) has proved to be useful not only to study the exposure, but also to assess the vulnerability of the building stock [1], especially because of its capacity of covering large regions in a systematic manner. Commonly, RS data has been combined with local knowledge and *in situ* acquired data [2, 3, 4] to improve the models. Other strategies have also integrated RS with other methodologies and data sources, such as aerial images, local statistical data, and virtual surveys, to characterize the local building inventory [5]; or have combined the use of different imaging technologies with a Bayesian information integration scheme to characterize exposure and vulnerability [6]. Moreover, RS imagery has been also used to explore and characterize both the spatial and the temporal dimensions of physical exposure [7], and to estimate seismic vulnerability not only at the building level, but also for larger scales such as homogeneous urban structures [8].

Most of the cited work involves sophisticated and costly methodologies, which requires highly qualified personnel to characterize physical exposure. However, these conditions are not always met in developing countries. Due to the importance of exposure characterization for pre-disaster planning and for disaster recovery, the need for a simple methodology to generate exposure models arises. This study describes the use of low-tech, publicly available, easy access remote sensing tools (i.e. remote digital surveys) to develop local exposure models of residential structures in three cities of Chile. The results were compared to a national exposure model of residential structures of Chile developed using only statistical information from publicly accessible databases [9].

The results presented in this paper are an outcome of the Chile Risk Assessment project, within the regional South America integrated Risk Assessment (SARA) project by the Global Earthquake Model (GEM) Foundation. The following section presents the methodology used to develop the local exposure models with remote digital surveys. The results of the models and the comparison with the national exposure model, described in [9], are also summarized in this paper.

2. Remote digital surveys to build the local exposure models

Local exposure models with a structure-level resolution were developed for residential structures in three cities of Chile: (i) Iquique, a coastal city and capital of Tarapacá Region in the north; (ii) Rancagua, the capital of Libertador Bernardo O'Higgins Region, in the central valley of the central zone of the country; and Osorno, an important city in Los Lagos Region, in the south. The cities were chosen as representative of three macro regions of Chile, each with different distribution of residential structural typologies: (i) concrete block masonry in the north; (ii) adobe and clay brick masonry in the central zone of the country; and (iii) timber houses in the south. See details in [9]. Also, those cities have less than 250.00 inhabitants and are easier to survey.

The models were built using digital remote surveys in each city, similar to a residential housing census, to count and later classify the structures into different structural typologies. Two tools were used simultaneously to conduct the surveys: *Google StreetView* [10] to remotely visit the cities at a street level, and GEM's tool for field data collection and management, *Inventory Data Capture Tools* (IDCT) [11], to store the geographic position of each surveyed structure, and the observed structural characteristics.

For each city, the initial step of the methodology was to load a georeferenced image of the city into IDCT. The image of each city was generated as a mosaic of smaller superimposed georeferenced images at a 1:2500 scale, using ESRI ArcGIS 10.2 [12]. Fig.1 shows the mosaic built for Osorno as example. A total of 116, 196, and 168 georeferenced images were used to cover a surface of 18.5, 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.

Fig. 1 – Map of the city of Osorno (left), and the georeferenced mosaic created for remote surveying (right)

After constructing the georeferenced mosaic, the methodology for the remote surveys consisted on two steps. First, a residential structure was identified using Google Maps (marked with a point in Fig.2a) and remotely observed at the street level using Google StreetView to identify its building characteristics (Fig.2b). Then, IDCT was used to record its location (Fig.2c) and to store the observed information in the georeferenced mosaic of the city (Fig.2d). For each surveyed structure, the following data was collected by remotely observing using Google StreetView: (i) geographic coordinates (latitude and longitude), obtained directly from the georeferenced image; (ii) main building material (reinforced concrete (RC), masonry (unreinforced, reinforced, or confined), wood, adobe (earth), or other material); (iii) building occupancy (residential, or mixed use – residential and commercial); (iv) material technology (only for masonry structures: clay hollow bricks, clay solid bricks, or concrete hollow blocks); and (v) general comments on the structure (number of stories, number of dwellings in adjoining houses, and use of mixed materials, such as houses with confined masonry in the first story and timber and/or other light materials in the second story). The collected information was used to classify the surveyed buildings into 18 structural typologies previously defined [9], as described later.

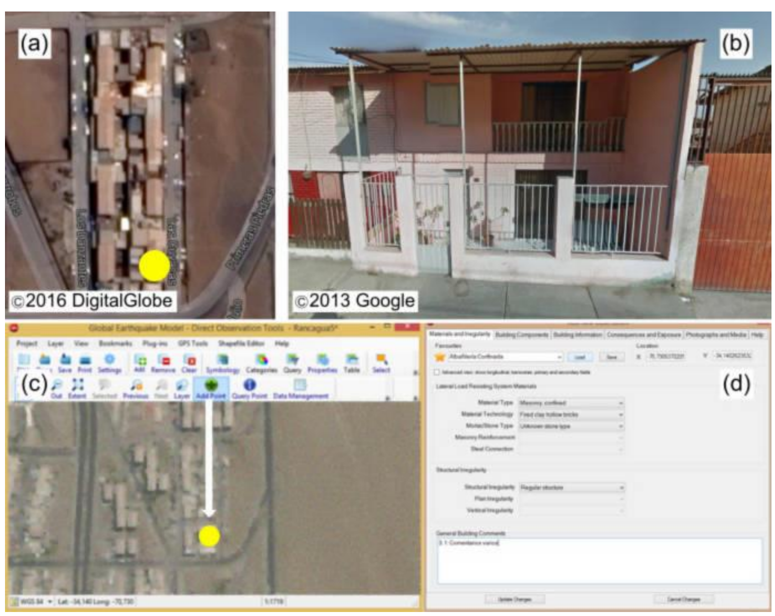

Fig. 2 – Digital surveying process: (a) a residential building is identified using Google Maps; (b) it is remotely observed using Google StreetView; (c) the building is identified in the georeferenced image loaded into IDCT and its geographic position is saved; and (d) the observed information is stored in IDCT for later analysis

Two different data collection schemes were used with IDCT: house-by-house, and grouping. The house-by-house scheme consisted in storing the information of a single structure with one georeferenced point at IDCT. The advantage of this house-by-house scheme is that the exact location of each structure is stored, providing information with high resolution for later risk assessment purposes. However, this method is highly time-consuming, as the information needed to be typed for each identified structure is considerable. The grouping scheme consisted in storing the data of several structures within the same block that could be classified under the same typology with a single point at IDCT. The advantage of this scheme is increasing the speed of the surveys, but the drawback is losing the exact location of each structure. This loss of information may not be significant for risk assessment studies of a large area, where knowing both the quantity of structures within a block, and the geographic coordinates of such block provide acceptable accuracy. The grouping scheme was highly efficient to survey neighborhoods with many similar houses or apartment buildings. Fig.3 shows an example of the points needed to be stored in IDCT with both schemes for the remote survey of a residential complex in the city of Rancagua.

Fig. 3 – Data collection in a remote survey of a residential complex in Rancagua using house-by-house (left) and grouping (right) surveying schemes

Remote surveying was performed in parallel for the three cities during six weeks, five days per week, working approximately 8 hours per day, by three undergraduate third-year civil engineering students. These students had no training in data collection and have passed a course of solid mechanics. A senior structural engineering student supervised the work. During the first week and a half, the students generated the georeferenced maps of the cities. Then, they surveyed the cities and collected data using the described methodology. A fourth student was incorporated during the last three weeks of the survey to improve the performance. For the first week and a half, only house-by-house scheme was used for data collection. For the remaining four weeks and a half, the grouping scheme was introduced.

Finally, the physical inventory was classified into eighteen different residential structural typologies, previously defined in [9]. One typology was used for RC houses (up to 3-story high), and three for RC apartment buildings (low-rise, 3- to 9-story high; mid-rise, 10- to 24-story high; and high-rise, 25-story and taller). Four typologies were used for masonry houses up to 2-story high (unreinforced clay brick, reinforced clay brick, confined clay brick, and reinforced or confined concrete block), and six for masonry apartment buildings (three for 3-story high apartment buildings of reinforced clay brick, confined clay brick, and reinforced or confined concrete block, and three for masonry apartment buildings 4- or 5-story high with the same classification as 3-story buildings). Two typologies were used for timber structures, since there are no timber apartment buildings in Chile: timber houses (up to three stories high), and timber emergency houses. One typology was used for adobe houses, and one final typology was used for informal constructions.

Two main characteristics were considered to classify each structure. First, if the structure corresponded to a house (typically a single-family occupancy dwelling) or to an apartment building (a structure with multiple apartments per story, each apartment a single-family occupancy dwelling). Second, the main wall building material: RC, clay brick or concrete block masonry, timber, or adobe.

3. Local exposure models results

On average, 76% of the surface of the three cities was remotely surveyed during the six weeks of work. Table 1 shows a summary of the results of the surveying process. Fig.4 shows an example of the surveyed area and points collected in IDCT for the city of Rancagua.

Table 1 – Performance of the remote surveying process for the detailed local exposure models of Iquique, Rancagua, and Osorno

City	Surveyed surface (km^2)	Total surface (km^2)	Surveyed surface (%)	Points marked in IDCT (number)	Surveyed structures (number)
Iquique	14.4	18.5	77.6%	8,216	27,025
Rancagua	34.4	46.2	74.4%	5,680	47,220
Osorno	22.0	29.0	75.7%	7,070	29,734

Fig. 4 – The 74.4% of Rancagua was remotely surveyed (highlighted, in the left), where 5,680 data points were collected using IDCT, corresponding to 47,220 structures (right)

The largest density of structures was identified in Iquique (1,877 structures/km^2), while the densities in Rancagua (1,373 structures/km^2) and Osorno (1,352 structures/km^2) were similar. During the remote surveying process, large variability of structural typologies in small areas was observed in the city of Iquique, so the grouping scheme for data collection was not very helpful in this city. This characteristic of Iquique slowed down the identification and classification of the structures, making the remote surveying of Iquique more time-costly than in the other two cities. In Rancagua and Osorno, several residential complexes with similar or identical type of structures were observed, which allowed grouping many structures at one point per complex. Moreover, identification of the building material in houses was simpler in Osorno than for the other cities, allowing faster data collection. This is mainly attributed to the lack of coating in timber houses, which are predominant in Osorno.

The information of points collected in the surveyed areas with StreetView and IDCT was converted into number of structures in the city to obtain the total number of structures in each city. Results are summarized in Fig.5.

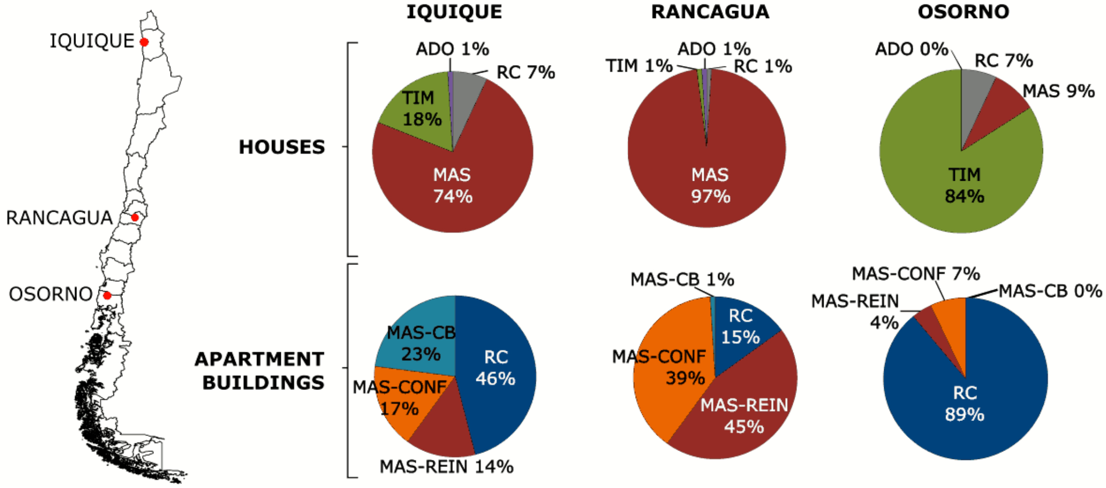

Fig. 5 – Distribution of structural typologies for Iquique, Rancagua, and Osorno. *RC* stands for reinforced concrete, *MAS* for masonry, *TIM* for timber, and *ADO* for adobe. For apartment buildings, *MAS-REIN* stands for reinforced clay brick masonry, *MAS-CONF* for confined clay brick masonry, and *MAS-CB* for reinforced and confined concrete block masonry

From the exposure models, it was obtained that an average of 98% of the residential buildings in the three cities corresponds to houses, with predominance of masonry houses in Iquique (74%) and Rancagua (97%), and of timber houses in Osorno (84%) (see Fig. 5). The larger presence of houses was identified in Osorno representing 99.2% of the structures, while the larger presence of apartment buildings was identified in Iquique with 3.5% of the total structures. The participation of Adobe houses, which are seismically vulnerable, is small (less than 1% in Iquique and Rancagua), disappearing in Osorno because of the rainy weather in the region. Apartment buildings constitute only about 2% of the building stock on average of the three cities, with similar share of RC and masonry in Iquique (46% and 54%, respectively), predominance of masonry over RC in Rancagua (85% against 15%), and predominance of RC (89%) over masonry (11%) in Osorno. Due to the availability of building materials in the different regions of the country, the predominant material is masonry in Iquique (73%) and in Rancagua (97%), and timber in Osorno (84%).

The remote digital surveys are expected to be very accurate to count the total number of structures, considering that it is easy to differentiate houses from apartment buildings. Additionally, they are expected to be very accurate to count the number of stories of apartment buildings using Google StreetView.

The information of the exposure models can be displayed in ArcGIS to study the spatial distribution of the different structural typologies throughout each city. The city of Iquique is shown as an example in Fig.6. Results can also be analyzed at different aggregation levels, such as census block. Such aggregation level may be convenient to relate the obtained data in the exposure model with that obtained from census (e.g. demographics, income, and other socio-economic aspects).

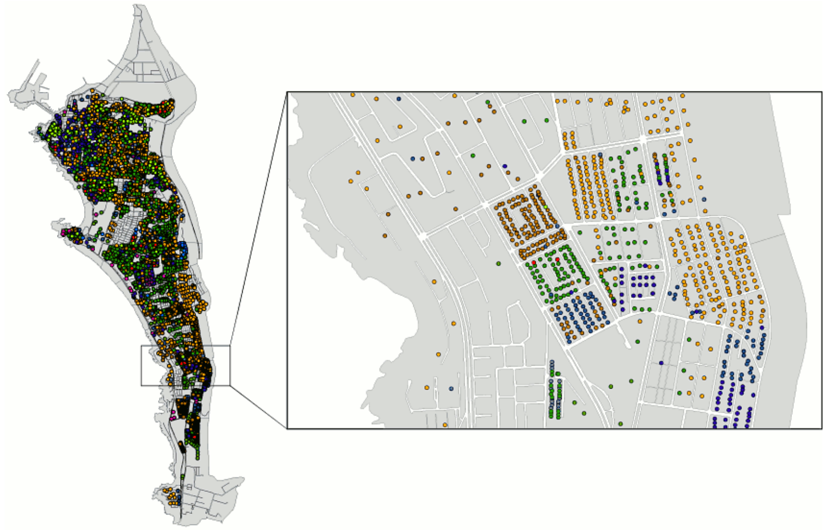

Fig. 6 – Map of Iquique identifying the 18 different typologies throughout the city (left). A zoom shows the distribution of the different structural typologies and its uniformity in a southern region of the city (right)

Despite being appropriate to count structures, the proposed methodology has some difficulties to classify structures into the different structural typologies. This is mainly due to the difficulty of identifying the main building material when low-resolution images were available at StreetView, when the structures were coated with painting or stucco, or when exterior protection (e.g. bars, vegetation) was present. Fig. 7 shows examples of structures that were difficult to classify. In addition, the variability of structural typologies throughout large cities, the lack of coverage of Street View in rural zones of the country –where usually the most vulnerable people live-, and the large amount of time it takes to cover large areas of dense cities, would make this methodology inefficient to generate an exposure model for the whole country. In spite of these limitations, valuable information can be generated with the proposed methodology. The most common misclassification of structures into the structural typologies may have occurred between masonry and RC typologies, because of the difficulty to differentiate them with the presence of any coating. For apartment buildings, this issue was a problem only for structures up to 5-story high, since taller buildings are always built with RC in the country due to Chilean design standards and practice.

Fig. 7 – The identification of features of different structures during the remote surveys was hampered by the lack of better digital images or the presence of coating (Source: (a) https://goo.gl/maps/noJw6FYGkxA2; (b) https://goo.gl/maps/rFSHWTS2PaP2; (c) https://goo.gl/maps/R2JCEejQUkr)

4. Comparison with the national exposure model

The results from the local exposure models obtained for the three cities are compared with those obtained from the national exposure model previously developed by the authors with statistical data [9]. To be able to compare the local and national models, a linear extrapolation of the data from the local exposure models was performed to represent 100% of the surface of the cities instead of the actual 76% of average coverage of the local exposure models (see Table 1). These results are referred to as “extrapolated models”, and are presented in Tables 2 and 3.

The comparison of the results of the models for houses and apartment buildings are summarized in the following sections.

4.1. Comparison for houses

Table 2 presents the comparison of the number of houses obtained for Iquique, Rancagua, and Osorno by the extrapolated and national models.

Table 2 – Number of houses for each typology of the extrapolated and the national exposure models

Typology	**Iquique**		**Rancagua**		**Osorno**	
	Extrap*	National	Extrap*	National	Extrap*	National
Reinforced concrete	2,478	6,244	624	3,849	2,664	1,441
Adobe	232	25	372	2,605	1	11
Masonry	24,821	18,052	60,016	49,993	3,383	3,345
Unreinforced clay brick	*128*	*172*	*6,569*	*3,387*	*4*	*934*
Reinforced clay brick	*8,005*	*3,154*	*48,560*	*43,719*	*3,103*	*1,304*
Confined clay brick	*2,649*	*49*	*4,765*	*1,238*	*95*	*1,070*
Concrete block	*14,039*	*14,677*	*122*	*1,649*	*181*	*37*
Timber	5,938	6,185	909	3,958	32,856	33,415
Emergency	3	103	35	408	63	496
Self-construction	122	110	39	22	3	34
Total number of houses	**33,594**	**30,719**	**61,995**	**60,835**	**38,970**	**38,742**

**Extrap* refers to the extrapolated local exposure models. *National* refers to the national exposure model from [9]

Table 2 shows an overall agreement between the total number of houses in both extrapolated and national exposure models in the three cities. The average difference between the models for the total number of houses is 4%, and the largest difference (less than 10%) is obtained for Iquique. However, large differences are observed when the number of structures classified into each structural typology is compared. For Iquique and Rancagua, the sum of RC and masonry houses in both models is similar (difference around 12%), but large differences are observed when comparing the houses of each structural typology associated with these materials. 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. Due to the low share of emergency and self-construction houses (less than 1% of the total number of structures for each city), no proper comparison can be made for these typologies.

The observed difference in the classification of houses into structural typologies responds to the different methodologies used to develop the exposure models. Remote observation using Google StreetView was used for the local models, and statistical data mainly from census information was used for the national exposure model. Note that for the characteristic typology of each macro region (concrete blocks in the north (Iquique), reinforced clay masonry in the center (Rancagua), timber in the south (Osorno)), best agreement was found between the local and the national models.

4.2. Comparison for apartment buildings

Table 3 presents the comparison of the number of houses obtained for Iquique, Rancagua, and Osorno by the extrapolated and national models. When comparing the total number of apartment buildings, between the extrapolated and the national exposure models, larger differences are obtained than when comparing the total number of houses. The total numbers of apartment buildings predicted by the extrapolated local models are 59%, 198%, and 144% larger than that from the national exposure model for Iquique, Rancagua, and Osorno, respectively. Again, larger differences are observed between the two models when comparing the number of apartment buildings of a particular structural typology. The differences observed can be explained by the different methodologies used to develop the exposure models. For the extrapolated exposure models the apartment buildings were counted one by one using the methodology described in Section 2, whereas for the national exposure model the number of apartment buildings was estimated from the available statistical data [9]. Hence, the total number of buildings is considered a more reliable result in the extrapolated exposure models than in the national exposure model.

Table 3 – Number of apartment buildings for each typology of the extrapolated and the national exposure models

Typology		**Iquique**		**Rancagua**		**Osorno**	
		Extrap	National	Extrap	National	Extrap	National
Reinforced Concrete	3-9 stories	394	62	210	129	262	64
	10-24 stories	130	78	9	20	12	6
	25+ stories	40	44	0	2	0	0
Reinforced clay bricks masonry	3 stories	99	101	448	28	5	0
	4-5 stories	75	0	214	180	7	28
Confined clay bricks masonry	3 stories	35	194	343	54	21	0
	4-5 stories	170	0	234	70	0	28
Concrete blocks masonry	3 stories	119	0	0	0	1	0
	4-5 stories	170	294	16	13	0	0
Total number of apartment buildings		**1,232**	**774**	**1,474**	**495**	**308**	**126**

**Extrap* refers to the extrapolated local exposure models. *National* refers to the national exposure model from [9]

5. Discussion and Conclusions

This paper presents a simple and low-cost methodology to generate local exposure models using remote digital surveys. The methodology was used in three different cities in Chile. A summary of the obtained results for the cities are presented and briefly discussed. The exposure models include information on geographic location of the structures, and their classification into one of the 18 defined structural typologies, and are intended to be used to perform high-resolution (i.e. structure per structure) seismic risk calculations. However, the obtained exposure model may be used for other purposes. The methodology used in this study can be easily applied elsewhere if proper coverage is provided by Google StreetView, constituting a viable alternative for places that lack strong databases or statistical information.

The results of the exposure models obtained for the three cities were compared to those obtained from a national exposure model previously developed by the authors, showing overall agreement in the total number of houses per city (average difference of 4% between the two models). However, large differences were observed for the total number of structures of each structural typology. This is explained by the low quality of the 2002 census data in terms of correctness of classification of the typology of the structures. The census data accounted for 73% of all the structures in the national exposure model. Also, the methodologies used to correlate number of dwellings with the number of structures in both the national and the local exposure models are have limitations. This result stresses the need to integrate different methodologies (e.g. statistical data, remote sensing tools, field work) to obtain more accurate structural classifications while optimizing the trade-off between accuracy and costs. The methodology described in this paper provides a baseline to build infrastructure exposure maps, which can be largely improved with additional information such as databases, field work, and expert judgement.

The results of this study represent an example of how a simple methodology using daily tools can produce important outputs for the quantification of exposed physical infrastructure zones prone to hazard. The obtained output is essential for risk assessments studies.

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