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Development of an exposure model of residential structures for Chile

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ABSTRACT: Seismic risk assessment requires the composition of three different components: the seismic hazard, the exposed inventory, and the vulnerability of the inventory. This article describes the methodology used to obtain an exposure model for residential structures in Chile, and summarizes its results. The exposure model consists in a database with the number of residential structures of each structural typology, and their spatial distribution throughout the country. Three data sources were used: the 2002 and the 2012 Census, and the 2002-2014 Unique Edification Statistic Form. Eighteen structural typologies were defined: ten for masonry, four for reinforced concrete (RC), two for timber, one for adobe, and one for informal constructions. The model showed that 86% of the dwellings are in urban areas and 14% are in rural areas, and that 81% of the dwellings are houses and 19% are located in apartment buildings. The most used materials are masonry (47%), timber (27%), and RC (22%). The model was compared to the PAGER database for Chile, finding agreement on the definition of the main typologies and some differences on dwelling distributions. The model represents an important input for risk calculations, improving the technical capabilities for seismic risk management in Chile.

1 INTRODUCTION

Seismic risk assessment requires the composition of three different components: the characterization of seismic hazard, the description of the physical stock and the social environment exposed to the seismic hazard represented in an exposure model, and the characterization of the vulnerability of the physical and social stock through vulnerability and fragility curves. Considerable research has been conducted to characterize the seismic hazard in Chile and South America, but not much attention has been given to generate exposure models. The generation of exposure models is not an easy task and it is highly dependent on local cultures and idiosyncrasies, especially because of the manner each country collects, records, and stores data related to the built environment.

Several methodologies have been used to obtain seismic exposure models worldwide, ranging from field work performing building-per-building surveys, to the use of remote sensing to cover large regions in a systematic manner. The capabilities of remote sensing to assess earthquake risk have been developed in both hazard- and vulnerability-driven research, with a long research tradition for the first, and an increasing tendency in the recent years for the later (Geiss and Taubenböck 2013). For the development of refined exposure models, mixed techniques seem to be leading the way. Examples of this are the use of *in situ* acquired data combined with remote sensing data (Borfecchia et al. 2009), the joint use of remote sensing and volunteered geographical information (Schauss 2015), and the use of aerial images together with locally produced data (e.g. census data, local reports) and virtual surveys (i.e. *Google StreetView*) to characterize the local building inventory (Osorio et al. 2015). Current trends have also incorporated the generation of exposure models that include the characterization of the vulnerability of the building stock using remote sensing and *in situ* data (Matsuka et al. 2012), and the combination of scarce in situ observations, remote sensing data, and machine learning techniques for structural typology classification (Geiss et al. 2015).

This paper describes the development of an exposure model for residential structures for Chile. The model is a database with a resolution at a census block level, containing the information of the number of buildings for each one of the structural typologies defined to classify the physical residential stock and their spatial distribution throughout the country. The model is a result of the South America Risk Assessment (SARA) project, in collaboration with the Global Earthquake Model Foundation (GEM), in an effort to improve the capabilities to conduct risk assessment in the region.

In the next section, the methodology to build the exposure model is summarized. Then, a summary of the results of the model is presented to give an overview of the residential building stock in Chile. Finally, a comparison between this model and the PAGER database for Chile is presented.

2 METHODOLOGY

This section summarizes the methodology used to obtain the exposure model for residential structures for Chile. First, the data sources are identified, and the information available on each of them is described. Then, the structural typologies used in the model are identified. Finally, the assumptions and steps to build the model with the available information are discussed.

2.1 Data sources

Dwelling and building inventory data in Chile is highly disaggregated. There is a lack of a central statistical database that reunites the information needed to build an exposure model for the country. It is common that some of the relevant information is stored at municipalities (communal level) and/or at the Ministry of Housing and Urbanism, MINVU (central/country level). The *Servicio de Impuestos Internos* (Internal Revenue Service) also stores relevant information, but it is difficult to access to it due to privacy policies. Hence, different sources at different resolution levels had to be used to obtain the information needed to characterize the building stock.

Three data sources were used to build the exposure model: the 2002 Census, the 2012 Census, and the 2002-2014 Unique Edification Statistic Form (UESF). These sources do not intend to characterize the built environment in Chile. They are collected with other purposes, and partially provide valuable technical information. Hence, data needs to be manipulated, and some assumptions are required for the construction of the exposure model.

The 2002 Census accounted for about 73% of the model, considering all the structures built before 2002 in Chile. The UESF was used to complement the information of the 2002 Census with structures built from 2002 until 2014. It also provided information to convert the Census data from a dwelling basis to actual structures. Finally, the 2012 Census was used to obtain the updated number of emergency houses and informal constructions in the country. A description of the three data sources used for the model is given next.

2.1.1 *The 2002 Census of population and housing*

Census information is available at request at the National Institute of Statistics (INE). Data from 2002 is available with a census block level resolution, which corresponds to the smallest and most basic information unit defined by the Census in populated centres, and is determined by natural or anthropic limits. The 2002 Census consisted on a nationwide dwelling-per-dwelling survey, including informal settlements and informal constructions. Its omission rate was low, and has been widely used in Chile in the last decade.

Census data is registered after the response of the dwelling owner or an adult responsible of answering the survey. Therefore, technical information of the Census (e.g. exterior wall material of the dwelling) is provided by non-experts, and may be highly inaccurate, as the non-experts may classify the wall material based on its cover material instead of its structural material. This information is highly relevant for structural classification and later risk assessment.

Since Census data is collected per dwelling, it is easy to use when it is referred to houses (usually, one house corresponds to one dwelling), but poses a major difficulty when it corresponds to apartments (i.e. dwellings in an apartment building). Neither the number of storeys nor the number of apartments per storey are registered when surveying apartment buildings in the Census. Hence, assumptions are required to relate dwellings with structures in this case.

The data used from the 2002 Census to build the exposure model was the following: (i) location of the dwelling as per the location of its census block, with a classification as urban or rural; (ii) type of dwelling, classified between house, apartment, emergency house, informal house, or other (part of an old house, ranch, collective, etc.); and (iii) exterior wall material, between reinforced concrete (RC) or stone, brick masonry, structural panels or blocks, timber, adobe, recycled materials, or other (e.g. gypsum board).

The main drawback of 2002 Census is that it is outdated: it does not account for administrative changes in the country at the municipality and regional levels, and it does not represent the country's population growth in the last decade, which has been of approximately 1% annually (INE 2014).

2.1.2 *Unique edification statistics form (UESF)*

The UESF is a database that contains all construction permits granted by Chilean municipalities between January 2002 and September 2014 for both houses and apartment buildings. It is aggregated at the municipality level, and it is publicly available upon request at INE. The technical quality of this database is better than the Census, because the construction permit is signed by the real state owner and by the architect or engineer in charge of the project, and is reviewed and approved by the Director of Municipal Works of the correspondent municipality or by an inspector from MINVU. In Chile, there is a good correlation between issued construction permits and actually built structures, so it is considered as a good approximation of the structure actually built between 2002 and 2014.

The data used from the UESF to build the exposure model was the following: (i) location of the dwelling as per its municipality; (ii) number of structures and dwellings (apartments or houses) per construction permit; (iii) type of structure, between *house* (detached, semi-adjoining, or adjoining), or *apartment building* (indicating the number of apartment buildings within a project, and total number of apartments per permit); (iii) number of storeys per structure (one datum per permit); (iv) exterior wall material, between RC, hollow clay brick, handmade clay brick, concrete block, timber, adobe, or others; and (v) percentage of main exterior wall material in all exterior walls.

Three major drawbacks are identified for the use of the UESF data: (i) it contains information of construction permits and not of constructed structures; (ii) there is no information of construction permits issued before 2002; and (iii) it does not include information on emergency and informal constructions and settlements, which are usually built without construction permits.

2.1.3 *The 2012 Census of population and housing*

The 2012 Census was performed by INE, and its results are no longer available after experts and politicians heavily criticized the methodology used for the Census, which lead to mistakes in data collection and a high national omission rate (9.6%). Hence, the results of the 2012 Census were declared as non-valid by the government, and its information should not be used for official estimations.

Only preliminary results of the 2012 Census were officially released, which were aggregated at the municipality level, and not at the census block level as desired for constructing the exposure model in this study. Given the lack of accuracy of this database, it was used only to estimate the number of emergency houses and informal constructions.

2.2 **Structural typologies**

Eighteen different structural typologies were defined for the exposure model. More typologies could have been defined, but that number was considered reasonable for developing different fragility functions in the future to assess seismic risk. Additionally, the lack of information from the data sources is a drawback to classify structures into more typologies.

The first level of classification of the structures is based on its predominant construction material (masonry, RC, timber, or adobe). Then, structures are classified between *houses* and *apartment buildings*. Each *house* typically corresponds to a single family occupancy dwelling. An *apartment building* is a structure with multiple apartments per storey, each apartment corresponding to a single family occupancy dwelling. Finally, structures are classified according to its height, in number of storeys.

Ten typologies were defined for masonry structures. Four of them corresponded to houses up to 2-

storey high, divided into unreinforced clay brick, reinforced clay brick, confined clay brick, and reinforced or confined concrete block. The remaining six masonry typologies were for apartment buildings. Three corresponded to 3-storey high apartment buildings of reinforced clay brick, confined clay brick, and reinforced or confined concrete block. The final three were for masonry apartment buildings 4- to 5-storey high, similar to the 3-storey high masonry apartment buildings. Despite there is no explicit height limitation in the Chilean masonry design standards, it is not practical to build masonry structures taller than 5 storeys due to high shear stresses imposed by the corresponding design codes (INN 2003, INN 2009). Hence, tallest masonry buildings in the model are 5 storeys high.

RC structures were classified into four different typologies. One type was defined for RC houses (up to 3-storey high), and three for apartment buildings depending on their height: low-rise (3 to 9 storeys), mid-rise (10 to 24 storeys), and high-rise apartment buildings (25 storeys and taller).

For timber structures, two typologies were defined. One for timber houses up to 3-storey high, and one for timber emergency houses, which consist on prefabricated wood panels mounted on timber piles (to provide isolation from the ground) with a light roofing system of zinc plates.

One typology was defined for adobe houses, commonly 1- or 2-storey high. There are no adobe apartment buildings in Chile, although it is possible to find some 3-storey houses. Finally, one typology for self and informal construction with no design of any kind was defined.

2.3 Construction of the exposure model

The model was built in three steps. First, the 2002 Census data was used to obtain the residential stock built up to 2002, which accounted for 72.9% of the structures in the model. Then, the 2002-2014 UESF data was used to determine the stock built after 2002 (25.5%). Finally, the 2012 Census was used to account for the informal constructions (1.6%). This methodology was applied in both urban and rural zones separately.

The key issue in the methodology is to relate the dwelling information from the 2002 Census data to the 18 proposed structural typologies. Considering that each house corresponds to one dwelling, the typology of a house was assigned based on the exterior wall material based on Census information. For masonry houses, information on the construction technology (i.e. unreinforced, reinforced, or confined masonry) was only available in the UESF, but not in the Census. Hence, to classify the structures built before 2002 into the 4 masonry houses typologies, the average proportions of each construction technology in each municipality from the UESF were used.

The biggest challenge was to relate dwellings information from the Census to the number of structures of each different apartment building typology. To do this, similarly as what was done with masonry houses, the information from the UESF was used to obtain average distributions at the municipality level, which were used to estimate the number of apartment buildings of each typology built before 2002 in each census block. Two parameters were obtained from the UESF for each municipality: (i) the number of storeys and the number of apartments per apartment building for both RC and masonry; and (ii) the construction technology type of each masonry unit for masonry structures. Because the average height of the new apartment buildings has increased in time, it is important to notice that the apartment building distributions obtained between 2002 and 2014 may overestimate the number of high-rise apartment buildings in structures prior to 2002.

When there was no information available on certain typology for certain municipality in the UESF (i.e. no construction permits have been issued for certain typology in that municipality between 2002 and 2014), the average distribution at the regional level was considered to classify the existing dwellings prior to 2002 for that particular municipality. If there was no information available at the regional level in the UESF, then the national average was considered.

When UESF data showed that only one type of structure represented all the structures in a municipality for a certain wall material, the regional distribution was used to classify the structures from the 2002 Census in that municipality to avoid classifying all the structures into a single type of structure. For example, if the UESF had only one permit of a 3-storey RC apartment building in a municipality from 2002 to 2014, without the previous consideration, the model would have calculated that all the existing RC apartment buildings in that municipality were 3-storey high. Instead, the model used the regional distribution, accounting for a larger variability of typologies in the built stock within a municipality.

After processing the data up to 2002, the inventory was complemented using the UESF data to estimate the number of structures for each of the 18 typologies. The UESF data is available aggregated at the municipality level, with a classification of urban or rural. Hence, the number of structures per typology in each municipality after 2002 was uniformly distributed in all the census blocks within the municipality.

Finally, the 2012 Census was used to estimate the number of emergency and informal houses, which are typically built without construction permits. Since the 2012 Census data was aggregated at the municipality level, the total number of emergency and informal houses was uniformly distributed in all the census blocks of each municipality.

3 EXPOSURE MODEL RESULTS

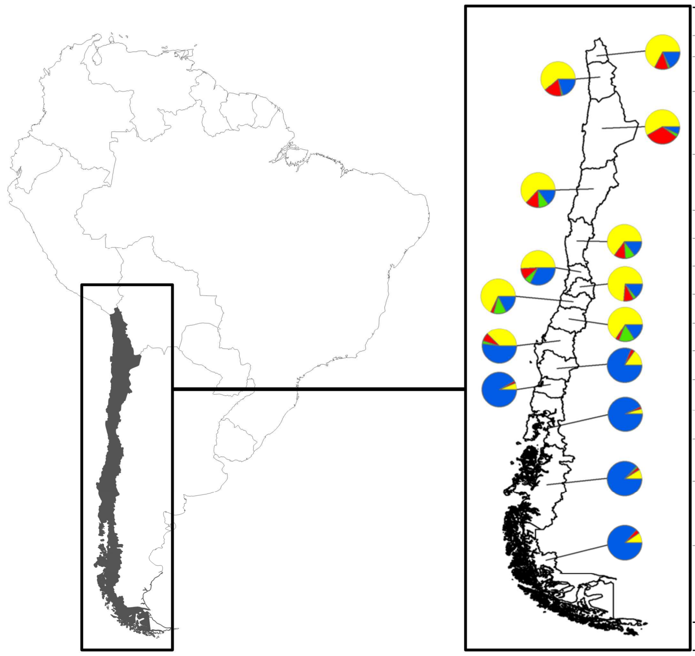
This section presents a summary of the results of the exposure model to give a quick overview of the composition of the residential stock in Chile. The complete database will be made available through GEM's SARA Wiki webpage by the end of 2015 to everyone interested on using it for risk assessment or other purposes.

A total of 4,259,190 residential structures were identified in the exposure model. The distribution of this inventory throughout the country, aggregated at a regional level, is presented in Figure 1 for the four main construction materials in Chile. The third column, "Timber", considers both timber and emergency houses. A fifth column, "Informal", was included to aggregate informal construction and self-constructed dwellings. The Metropolitan Region (MR) concentrates 40% of the population and a 33% of the residential stock, while the XI Region only has 0.6% of the population and less than 1% of the residential stock. As expected, masonry, RC, and adobe are predominant in the north (from XV to IV regions) and central regions of Chile (V to VII, including MR), while timber is predominant in the south (from VIII to XII).

The model shows that 82% of the structures are located in urban areas. The most predominant typologies in urban areas are reinforced clay brick masonry houses (24% of the total number of structures), timber houses (23%), and confined clay brick masonry houses (12%). Rural areas only concentrate 18% of the structures of the country, where the main typologies present 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%).

From the model, it is also obtained that the 99.5% of the total number of structures (4,236,637 structures) corresponds to houses, while only the remaining 0.5%, (22,553 structures), corresponds to RC and masonry apartment buildings. For houses, timber and reinforced clay brick masonry typologies are predominant in Chile, representing 32% and 26% of the total number of houses, respectively. Informal construction represents 0.1% of the total houses, and emergency houses 1.5%. The highly seismic vulnerable typology of adobe houses represents 4.6% of the total number of houses in Chile. For apartment buildings, RC is the most common material with 55% of the total of apartment buildings (12,459). Of this share, 37% are low-rise, 16% are mid-rise, and 2% are high-rise apartment buildings. Masonry apartment buildings represent 45% of the total of apartment buildings, of which 14% are 3-storey high, 25% are 4-storey high, and 6% are 5-storey high.

The total number of apartment buildings obtained in the exposure model might be underestimated. This could happen because the parameters to go from dwellings (from the Census) to structures (in the model) were obtained from the UESF, which contains information of the last decade, when an increase in the apartment building height and on the number of apartments per storey has been observed throughout the country. Thus, when dividing the total number of dwellings (apartments) in a census block by the average number of apartments per storey in an apartment building, the result may be lower than the real number. The same would occur when estimating the height of the apartment buildings.



Region	RC	Masonry	Timber	Adobe	Informal	Total
XV	6,233	32,062	8,523	764	247	47,829
I	8,416	30,903	10,288	670	301	50,579
II	41,425	75,134	8,976	3,726	186	129,447
III	9,306	46,400	11,065	6,872	88	73,731
IV	21,914	131,432	30,504	18,055	81	201,987
V	43,193	211,030	135,041	26,278	251	415,795
XIII	132,205	1,046,146	203,847	37,723	390	1,420,316
VI	7,743	178,942	45,788	31,440	110	264,023
VII	10,603	226,782	55,392	50,972	107	343,856
VIII	46,495	228,919	315,409	16,751	224	607,798
IX	9,731	44,040	231,843	1,163	94	286,872
XIV	2,232	6,386	97,681	33	41	106,372
X	4,779	13,166	219,298	249	119	237,611
XI	834	2,547	25,558	430	19	29,389
XII	1,571	4,158	37,853	4	6	43,592
Total	**346,682**	**2,278,049**	**1,437,066**	**195,130**	**2,264**	**4,259,190**

Figure 1: Distribution of structures per construction material at the regional level as a result of the model.

The largest inaccuracy in the model is the classification as masonry or RC houses and apartment buildings. This comes from the data collection mechanism as aforementioned: the main wall material is reported by the person answering the Census, and as a non-expert, masonry and RC may be confused when stucco, painting, or other common coating is used. While this confusion is common when dealing with houses, it only occurs in apartment buildings up to 5-storeys high; taller buildings are always built with RC, and its classification is immediate.

The average area and the replacement costs per typology in the exposure model are currently being estimated by the authors, and will be published in the near future. In the following section, the proposed model is compared with the PAGER database for Chile as a reference for validation of the results.

4 COMPARISON WITH PAGER DATABASE

The WHE-PAGER project is a collaborative initiative to improve the understanding and classification of building inventory and collapse vulnerability of non-US construction types worldwide. The methodology to develop the PAGER database has been thoroughly described elsewhere (Jaiswal and Wald 2008; Porter et al. 2008). The source of the data for Chile in the PAGER database is the Phase I WHE-Survey, from 2007 (Jaiswal and Wald 2014). The database contains the dwelling fraction for urban and rural areas, and for residential and non-residential occupancy. The distribution for residential dwellings is showed in Table 1, and compared to the residential dwellings proportions in the proposed exposure model. The main difference between the PAGER Model (Table 1) and the proposed model is that the first one shows dwelling fraction instead of structures fraction. Therefore, no difference is made between houses and apartment buildings.

Table 1: Dwelling fraction in urban and rural areas as calculated by the proposed exposure model (left), and in the PAGER database for Chile (right)

Model Typology	Urban (%)	Rural (%)	PAGER Typology	Urban (%)	Rural (%)
Timber and emergency houses	22	57	Wood (*W*)	11	18
RC houses and apartment buildings	25	2	RC shear walls (*C2*)	25	1
Clay-brick and concrete-blocks unreinforced, reinforced and confined	50	31	Reinforced masonry (*RM*), Reinforced masonry bearing walls with concrete diaphragms low-rise (*RM2L*), Concrete block unreinforced masonry with lime or cement mortar (*UCB*)	60	64
Adobe houses	3	10	Adobe blocks (unbaked sundried mud block) walls (*A*)	1	2
Self and informal constructions	0.03	0.09	Rubble stone (field stone) masonry (*RS*), Not specified (unknown/default) (*UNK*)	2	15
-	-	-	Steel braced frame (*S2*)	1	0
Total	100	100	Total	100	100

PAGER uses 9 different typologies to describe the Chilean building stock. Steel structures were not considered in the proposed model because neither the Census nor the UESF have steel as an option for wall material. Besides, the small share of steel structures in Chile is for commercial or industrial use, and not for residential purposes. In both models, the predominant typologies are clay-bricks and concrete-blocks masonry, timber, and RC. The absence of confined masonry as a typology in PAGER database is of importance, because it corresponds to 13% of the total structures according to the proposed model. It is important to note that the dwelling proportions in the PAGER database for Chile date back to 2007, while the model is updated to 2014. As expected, more vulnerable typologies (A, RS, UNK) are more predominant in rural areas. The largest differences between urban and rural areas are observed for RC.

For urban areas, the RC proportion is the same in both models (25% of the number dwellings). The proposed model shows larger proportions for timber (22% against 11%) and adobe (3% against 1%). A difference of 10% is observed in masonry dwellings. Part of this difference can be explained by the limitations in the classification process into different masonry typologies. For rural areas, differences between the proposed model and PAGER are large. The model shows larger proportions of timber (57% against 18%) and adobe houses (10% against 2%). For masonry, the model shows lower participation (31% against 64%).

5 DISCUSSION AND CONCLUSIONS

This paper presents the methodology used to obtain an exposure model for residential structures in Chile and a summary of its results. As expected, the lack of reliable data at national and local levels to correctly classify the building stock was the major hurdle faced in this study. Census data is not the most reliable source of information, since technical information is not accurately collected. The additional information obtained from UESF constitutes an important complement to Census data because of its technical accuracy, and because it allows obtaining distribution of heights of apartment buildings, number of dwellings per storey and construction material techniques. The model was compared with the PAGER database for Chile, showing overall agreement in the typologies used to describe the physical stock, and some differences in observed dwelling proportions.

This study is a new effort to characterize the seismic vulnerability of the residential Chilean building stock. Despite a long history of research and development on seismic engineering, risk assessment is a fairly new concept in the country. Therefore, the presented model represents an important input for risk calculations for Chile. The complete exposure model, at both census block level and at municipality level, will be available at GEM's SARA Wiki webpage by the end of 2015. Further work to improve the model will be performed to obtain the average surface, and the reposition costs associated to each typology, which are required to construct vulnerability curves. This result constitutes an important contribution to the seismic risk assessment community.

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