Exposure and vulnerability for seismic risk evaluations

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I, Harriette Stone, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed: Date:

Abstract

To make effective decisions for earthquake risk reduction, accurate seismic risk evaluations are required. Substantial data, methods, and tools from the field of structural engineering are used in the seismic risk assessment process, including the collection and interpretation of building data and the estimation of seismic vulnerability, for which there are numerous sources of inefficiency and inaccuracy.

Compiling building exposure datasets in an effective manner for use in seismic vulnerability and risk assessments requires methods that collect applicable or useful data whilst balancing accuracy and cost. This thesis investigates this three-way balance. First, a systematic review of the literature is completed to ascertain the most useful building data for estimating seismic vulnerability. Useful building characteristics are determined by: (1) investigating the frequency of building characteristics used in published seismic vulnerability assessment methods, and (2) reviewing studies that explore the sensitivity of inputs to vulnerability assessments; the more sensitive the input, the more useful the data.

Second, a range of building data collection methods are tested in the urban centre of Guatemala City. A series of desk-based studies are used to collate published and available information, such as housing censuses, existing studies, the history of urban development, and construction practices and trends. Field-based methods are then employed including established methods such as street-level rapid visual surveys and detailed internal surveys, and newer methods such as virtual surveys using omnidirectional imagery and three-dimensional models derived from unmanned aerial vehicle imagery.

The resources required by each method are calculated from the actual costs encountered in the desk study, fieldwork, and post-trip analysis. The accuracy of collected data is determined by justifying assumptions of accurate data and comparing results for individual buildings across the methods using inter-rater agreement statistical methods. The balance of data usefulness, cost and accuracy is examined in detail to highlight the effectiveness of the tested data collection methods. It is found that the building data collection methods that employ newer technology have great potential in this field, although some struggle to collect all of the necessary data to classify building typologies and assess seismic vulnerability, so are most effective when combined with other datasets.

Using the collected data, the seismic vulnerability and risk of the study area are estimated, and a preliminary study starts to investigate the impacts of uncertainties in building data when propagated through to loss ratios. Further work is required, but the preliminary result indicate that range the in losses is significant, highlighting the need for accurate building data collection to feed into seismic exposure and vulnerability assessments and, in turn, seismic risk evaluations.

This thesis is dedicated to

Ann Trumble

1932 - 2018

I have you to thank for so many of the best things in my life. Dementia may have taken first your memory then your life, but I will never forget how lucky I am to be your granddaughter.

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To all colleagues over the years, thank you for challenging and inspiring me, all whilst making me laugh constantly.

Thank you to my family and friends who have held me up, encouraged me, prayed for me, cooked for me, hugged me, distracted me, and believed in me.

And to my rock (or more accurately my Stone). We did it! Jonathan, I can't thank you or sing your praises enough. This year has been our worst and best, but even with the ups and downs, I'm glad I am doing it with you.

And finally, to my Father. You are before all things, and in You all things hold together (*Colossians 1-17*).

> *'You counted the buildings…and tore down houses to strengthen the wall. …but you did not look to the One who made it, or have regard for the One who planned it long ago.'* from Isaiah 22: 10-11

List of Acronyms

AAL	*Average annual loss*
ASCE	*Association of Structural and Civil Engineers, USA*
ATC	*Applied Technology Council, USA*
CEN	*Comité Européen de Normalisation* (European Committee for Standardisation)
DRR	*Disaster risk reduction*
EMS	*European Macroseismic Scale*
ERD	*Earthquake resistant design*
FaMIVE	*Failure mechanisms identifications and vulnerability evaluation*
FE	*Foreign expert*
FEMA	*Federal Emergency Management Agency*
GAR	*Global Assessment Method*
GED4GEM	*Global Exposure Database for Global Earthquake Modell*
GEM	*Global Earthquake Model*
GIS	*Geographical Information System*
GNDT	*Gruppo Nazionale per la Difesa dai Terremoti* (National Group for Protection against Earthquakes)
HAZUS	*Hazard US*
LE	*Local expert*
LLRS	*Lateral Load Resisting System*
NLTHA	*Non-Linear Time History Analysis*
OD	*Omnidirectional*
PAGER	*Prompt Assessment of Global Earthquakes for Response*
PML	*Probable maximum loss*
PSHA	*Probabilistic seismic hazard assessment*
RC	*Reinforced Concrete*
RVS	*Rapid visual survey*
SDOF	*Single Degree of Freedom*
STU	*Student*
SVA	*Seismic Vulnerability assessment*
UAV	*Unmanned Aerial Vehicle (used interchangeably with 'drone')*
UNISDR	*United National International Strategy for Disaster Reduction*
URM	*Unreinforced Masonry*
WHE	*World Housing Encyclopaedia*

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Chapter 1

Introduction

1. Introduction

> *'Priority 1: Understanding disaster risk*
>
> *Policies and practices for disaster risk management should be based on an **understanding** of disaster **risk** in all its dimensions of vulnerability, capacity, **exposure** of persons and **assets**, hazard characteristics and the environment.'*
>
> *Sendai Framework for Disaster Risk Reduction*
> *2015 – 2030 (UNISDR, 2015b)*

Understanding earthquakes and the risks they pose is a challenge that has stretched scientists for centuries (Musson, 2013). The natural phenomenon causes shaking of the ground for short periods of time which impact on natural and built structures, affecting the lives of those nearby. In light of recent devastating seismic events that impact across scales, from individuals to nations, and alter long-term regional economic development (Daniell, 2014), recent drives have focussed on understanding, and hence, reducing the risks faced, as depicted in the above quote (UNISDR, 2015b). There remains much about earthquake risk that is unknown: from the stresses in the earth's crust; through how structures respond to seismic waves; to the impacts on socio-economic development and individual lives. As urban populations exposed to earthquakes grow (UNISDR, 2015a), it becomes increasingly important to estimate the potential impacts of future seismic events using the latest knowledge in the sciences, engineering, economics, social sciences, etc., so that effective decisions can be made to drive reduce the devastating effects of earthquakes.

1.1. Uncertainty in seismic risk assessment

Seismological research has been developed into relative maturity since the work of John Milne and Robert Mallet in the 19th century (Musson, 2013). More recently, since in the second half of the 20th century, research has advanced from seismic hazard studies into methodologies for the assessment of seismic vulnerability of the built environment, which have developed rapidly (Calvi et al., 2006; Scawthorn, 2008). For the evaluation of risk, these two components are important, alongside an understanding of the built environment that is exposed to the earthquake hazards. This is denoted throughout the literature by the following relationship:

$$Risk = f(hazard, exposure, vulnerability)$$

Clearly on a city scale there is a vast amount of data available, thus the effective collection of building data is key. A balance of gathering accurate data, without overspending or taking too long is important, and relies, in part, on collecting only the data that are required for estimating the vulnerability of structures.

Worryingly, there are few studies exploring the impact of uncertainties in built environment data on the estimations of risk, whereas both epistemic and aleatory uncertainties have been studied in depth for both the seismic hazard (e.g. Crowley et al. (2005); Gaspar-Escribano et al. (2015); Ioannou et al. (2015); Kotha et al. (2017)) and vulnerability (e.g. Crowley et al. (2005); Celik and Ellingwood, (2010); Chacón et al. (2017); Sousa et al. (2017)). What if buildings are assumed to be constructed with timber where they are actually of masonry? What if buildings are recorded as three storeys tall when they are actually taller? How does the seismic risk estimated, change with different data on the buildings in a city? How can building data be collected effectively, balancing the cost of collecting key data accuracy for the assessment of seismic vulnerability? These questions highlight the gap in knowledge that is investigated in this study.

1.2. Goals of the study

This study defends the thesis that significant ranges in seismic loss assessments arise from the use of different building data collection methods, and will be reduced through the use of emerging technology or other data collection methods depending on requirements on budgets and/or precision.

This requires the collection of building data using different methods, comparing results, estimating the effectiveness of the data collection methods, and propagating the differences between methods into the differences in expected losses due to earthquakes.

In order to defend this thesis, the following specific objectives will be addressed:

1. To understand the current practice in seismic vulnerability assessment and explore the building characteristic inputs required.
2. To devise a method for measuring the usefulness of building characteristics for the assessment of building vulnerability, and use this to explore in detail the most important or useful inputs.
3. To understand the range of accuracy and costs associated with the collection of building data using current building data collection practices and new methods using recent technologies.
4. To compare the effectiveness of new technology in the practice of building data collection with existing methods including both desk- and field-based approaches.
5. To take a first step in examining the potential range in expected seismic losses given the uncertainty in building data associated with the range of building data obtained from the range of data collection methods.

The aims of this study have been developed with the work of the industrial sponsor, the World Bank Group, in mind. The Central American region is of particular interest in terms of seismic risks, thus this study selects the main case study from this region. In addition, potential improvements to the risk evaluations that are completed by the World Bank Group helped in the formulation of the main thesis.

1.3. Organisation of the study

A review of the broader literature on seismic risk, vulnerability and exposure is compiled and discussed in **Chapter 2**. The key concepts around the thesis are introduced, including published uses of the new technology trialled in this study. **Chapter 3** presents the research methodology for the study. **Chapter 4** contains the analysis and results for the assessment of the usefulness of different inputs to seismic vulnerability assessments, providing a comprehensive list of more or less useful building data for the assessment of seismic vulnerability. **Chapter 5** introduces the case study area and explains the building data collection methodologies tested before presenting the headline results from both desk- and field-based work. These results are analysed further in **Chapter 6** using the framework of usefulness, cost, and accuracy. The results for each method tested are compared and the balance of these metrics is discussed. These results are used to classify buildings, select existing vulnerability relationships for building classes, and to estimate loss ratios in **Chapter 7**. The range between loss ratios investigated for different building data collection method tested is highlighted and discussed in terms of uncertainty for decision makers. The thesis defence is concluded in **Chapter 8**.

The organisation of the study is shown diagrammatically in Figure 1-1.

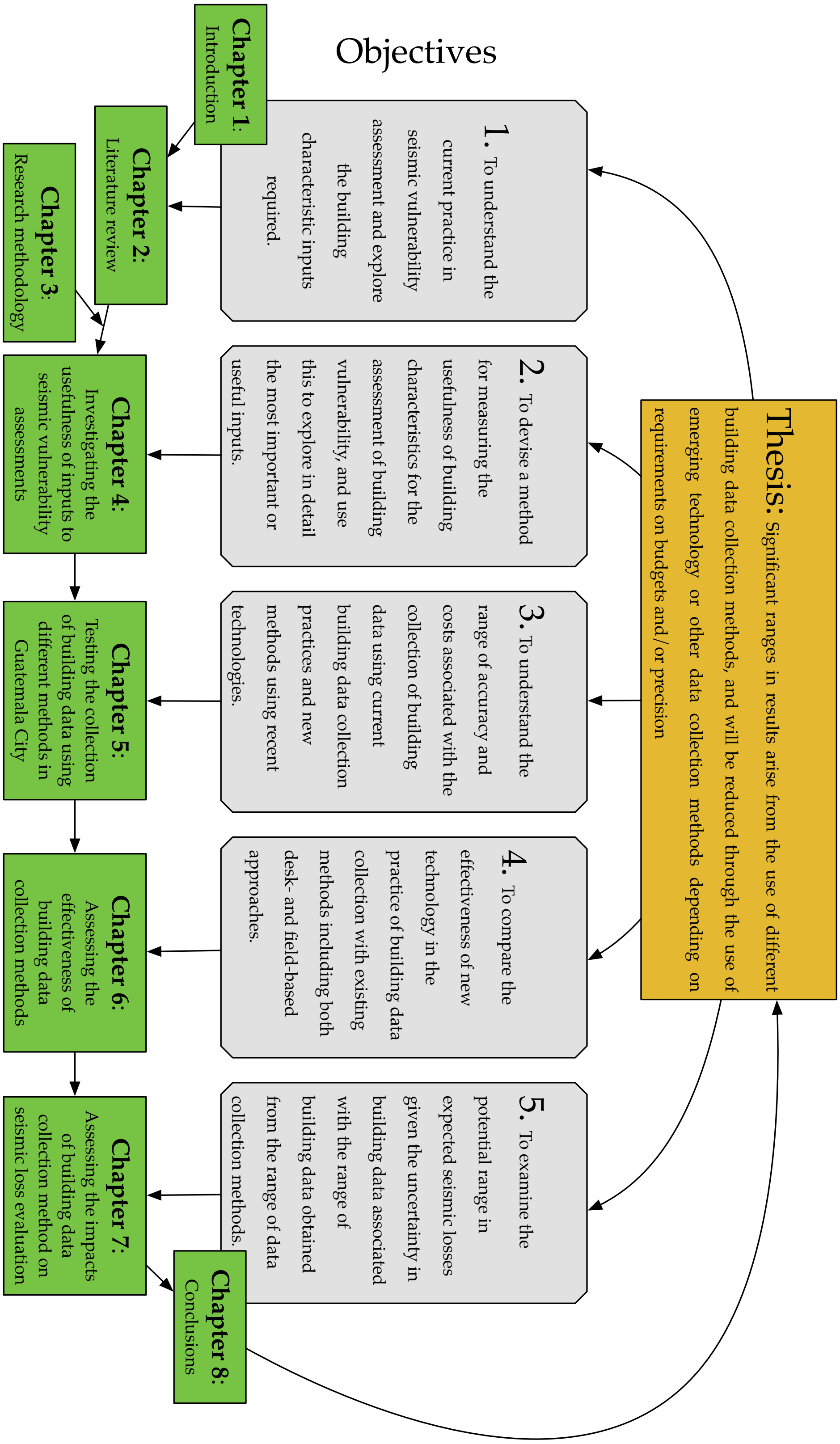


Figure 1-1 Organisation of the study

Chapter 2

Literature review

2. Literature review

2.1. Why assess seismic risk?

As the world's population booms, urbanisation increases, and megacities grow, the economic impacts of natural disasters continue to rise (UNISDR, 2015a). The accumulation of disaster risk is of global concern: in 2015, world leaders in disaster management met in Sendai, Japan, to establish the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015b), which sets out a global strategy for the substantial reduction of disaster risk before 2030. Despite the rising costs of disasters, funding of disaster risk reduction (DRR) initiatives prior to an event remains low (Tanner and Rentschaler, 2015). Earthquake events contribute a significant proportion to the escalating economic impacts (Daniell et al., 2016), damage to cultural and social environments, numbers of fatalities, injuries, and destruction of shelter and livelihoods (UNISDR, 2015a). Increasingly, middle-income countries, particularly those with rapidly growing cities, are more susceptible to devastating earthquakes, due to considerable levels of building vulnerability (Rahman, 2017).

Seismic risk evaluation at urban, regional, and national levels aim to measure the size of the potential impacts of future earthquakes, so that policy makers and society may act to better protect themselves (Newman et al., 2017). The assessment of risk is a very complex challenge due in part to the dynamic nexus between a city's built environment, inhabitants, and the various networks that exist (Bosher and Dainty, 2011; Miles et al., 2011).

Practically, the reduction of risk to earthquakes may be manifested as increased public knowledge of the risks, the enforcement of new or improved policy on land-use or construction regulations, the improvement of disaster response plans, strengthening of infrastructure (e.g. retrofitting), or the development of financial protection through insurance or household saving (Wilkinson and

Brenes, 2014). Nevertheless, the political imperatives for action often overshadow any technical advice or warnings (Stone, 2001) in the melange of pressures that surround policy making (Brower, 2017). This is not helped by the presence of technical, institutional, and operational obstacles between technical experts (in the case of earthquake DRR, scientists or engineers) and decision makers, including difficulties in interpreting results, low salience, low technical capacity, and short political timescales (Wilkinson and Brenes, 2014). There are arguments to improve the political perspectives of investing in disaster resilience such as the yielding of a 'triple dividend', where co-benefits to reducing disaster losses are highlighted, including improvements to general economic, social, and environmental development (Tanner and Rentschaler, 2015; Burton et al., 2017).

Decisions on how to wisely and effectively invest limited resources on the most beneficial or cost-effective strategies for seismic risk reduction (Liel and Deierlein, 2013; Shreve and Kelman, 2014) rely on accurate risk assessments (Mulargia et al., 2017; UNISDR, 2015b) and a full understanding of the scale of uncertainties associated. As with all modelling, seismic risk assessments have both epistemic (Rougier and Baven, 2013) and aleatory uncertainties (Riga et al., 2017) accumulated from the data used as modelling inputs (Celarec et al., 2012), and from the modelling approach (Rohmer et al., 2014): communicating the scale of these methodological limitations and the impact on results is vital to ensure effective DRR decisions (Hill et al., 2013; Newman et al., 2017). There is a wide body of literature on decision-making under uncertainty which deals with how uncertainty is conceptualised, how individuals cope with the lack of certainty (Lipshitz and Strauss, 1997), and how our personal biases and heuristics can impact on our ability to decide rationally in uncertain situations (Tversky and Kahneman, 1974). Diverse attitudes to uncertainty and risk exist between DDR decisions makers, but when the financial benefits are apparent these balance out significantly (Goda, 2007).

Seismic risk can be measured using any category of potential loss, such as economic, social, ecological, or environmental. Evaluating the economic losses to a set of buildings requires information on (1) the properties of the ground shaking (hazard), (2) the inventory of buildings exposed to the ground shaking (exposure), and (3) the vulnerability of the buildings exposed for the expected ground shaking (UNISDR, 2009). This process is inherently convoluted, but in its most basic form is presented in Figure 2-1 (Grossi, 2000): a substantial amount of data is needed for each box and collecting this is cumbersome and fraught with uncertainties, particularly when the study area is large and complex, as all cities are.

The literature is well developed on the assessment of seismic hazard (Box 1 Figure 2-1), particularly on PSHA (probabilistic seismic hazard assessment) techniques (Douglas, 2003; McGuire, 2008; Stirling, 2014) despite arguements that they can or should not be used to calculate reliable seismic risk estimates (Castaños and Lomnitz, 2002; Mulargia et al., 2017). This debate is ongoing, but this study is interested primarily in the collection of inventory characteristics (Box 2: Figure 2-1) and how that can provide inputs to the assessment of damage and loss (Box 3 and 4: Figure 2-1).

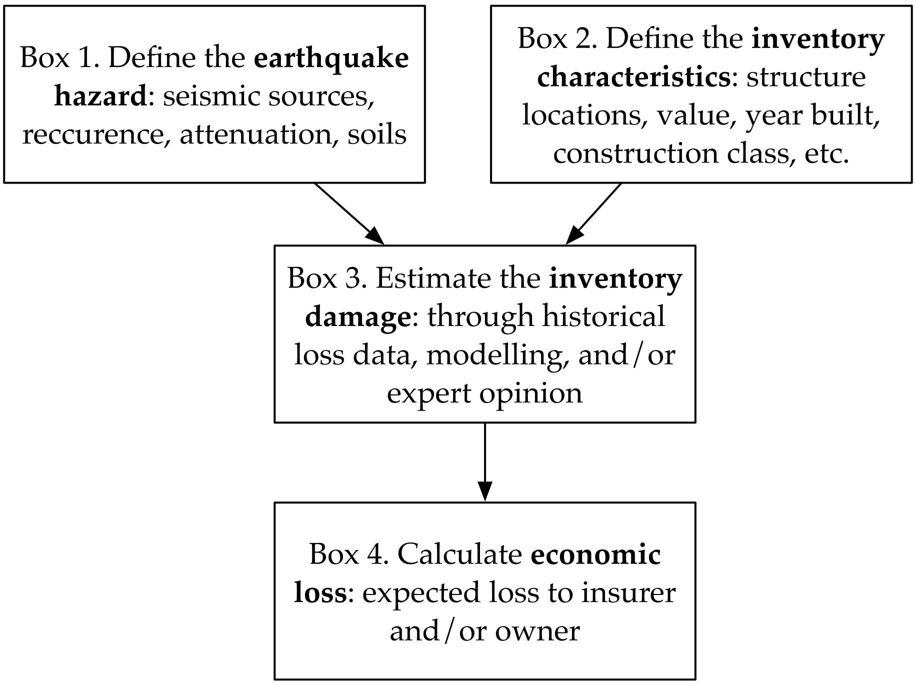


Figure 2-1 The process of seismic risk assessment, adapted from Grossi (2000)

Uncertainty exists in all forms of modelling, and is rife in seismic risk assessment (Nilsen and Aven, 2003; Aven et al., 2014) as it includes many imperfect inputs and employs imperfect modelling procedures. The uncertainty in the assessments accumulate from the primary components (seismic hazard, exposure and vulnerability, e.g. Figure 2-1)(Erduran et al., 2010), and are exacerbated by their combination.

Despite widespread uncertainty, results rarely report or estimate it (Rossetto et al., 2014a) despite recent advances in its quantification, particularly in the assessment of hazard (Tyagunov et al., 2014; Gaspar-Escribano et al., 2015; Kotha et al., 2017; Riga et al., 2017) and, increasingly, vulnerability (Celarec et al., 2012; Borgonovo et al., 2013; Rota et al., 2013; Meslem et al., 2014; Tyagunov et al., 2014; Riga et al., 2017; Sousa et al., 2017b;). Studies on the uncertainty caused by the exposure component are lacking (Erduran et al., 2010; Del Gaudio et al 2013; Ricci et al, 2014), so this thesis aims to address part of this lacuna by investigating the uncertainty that results from a lack of complete or accurate knowledge of the built environment when assessing seismic vulnerability and risk.

Epistemic uncertainty can often be reduced if more resources are employed, yet despite the benefits of reducing uncertainty, throwing money at the problem may not the best approach; achieving effective reduction in uncertainty is likely to involve finding a balance between accuracy and cost. This study explores this balance by measuring the cost and accuracy of different exposure data collection methods, leading to improvements in the design of risk assessments.

Seismic risk is concentrated and intensifying in large sprawling urban centres, which are home to large and increasing populations, numerous assets, and complex interacting networks (UNISDR, 2015a). These epicentres of risk require substantial, but scarcely available, funding for risk reduction, therefore the effective spending of resources that are available is particularly vital, hence urban areas will be used as the context in this study. Gathering accurate building data at this scale is a difficult, costly, and time-consuming task, therefore the use of less sophisticated inspection methods is usually advised (Vicente, 2011). Additionally, cities are ever changing. They grow and sprawl quickly, with continuous construction activities. Population increases, natural features (e.g. mountains or rivers), infrastructure, past disasters (Miles et al., 2011), historical events (e.g. colonization and wars (Miles et al., 2011)), enacted legislation, construction trends (e.g. the advent of reinforced concrete (RC)), and increasingly, climate change (De Sherbinin et al., 2016; Garschagen and Romero-Lankao, 2013) all impact on the scale, shape, and composition of urban development. Not only is there growth, but there will be the replacement or extension of existing buildings (Lallemant et al., 2017): a city surveyed one year, will be a different city five years later, hence, a seismic risk assessment becomes less relevant and reliable as time passes. Future developments in exposure modelling need to focus on methodologies that capture these temporal changes (Saito, 2014; Newman et al., 2017).

A number of important challenges are to be explored in-depth in this chapter, beginning with the general challenges of assessing seismic vulnerability, including building classification, key building characteristics, and the vast array of assessment procedures. The lack of SVA (seismic vulnerability assessment) methodologies specifically applicable to urban contexts (as a whole system) is highlighted and attributed to the relatively narrow focus and wide-ranging approaches of the current literature. A number of potential methods for building data collection are then introduced including commonly used methods and those from the wider literature that employ emerging imaging technologies such as unmanned aerial vehicles and omnidirectional cameras. The key benefits and challenges are discussed in relation to their application and comments are provided on their potential for use in collecting building data for assessing seismic risk.

2.2. How is seismic vulnerability assessed?

Seismic vulnerability assessments aim to estimate the vulnerability of buildings to earthquake shaking. The first step is to classify buildings into groups with similar seismic responses to reduce the number of calculations required (if classification were not used, an assessment would be required for each individual building). A method of assessing seismic vulnerability is then employed for each building class, resulting in a seismic vulnerability functions which relate a measure of the vulnerability (such as loss ratio) to the intensity of earthquake. In recent years, the literature has developed a number of systems for the classification of building types (Brzev et al., 2013), and a plethora of methodologies for assessing seismic vulnerability (Calvi et al., 2006): both will be introduced and discussed below.

2.2.1. Classifying building typologies for seismic vulnerability assessments

The classification of buildings aims to group structures with similar attributes (and assumed comparable seismic responses) in order to assess them en masse. The crux of the challenge of building classification is in the definition of buildings as similar. Which characteristics of buildings should be used to group them? The literature handles building classification in various ways (Brzev et al., 2013), from which a number of classification systems or taxonomies have developed; the most prevalent are introduced below, with a focus on the characteristics they use to inform classification. As the taxonomies involve a large number of building classes with descriptions, the full descriptions can be found in Appendix A.

The European Macroseismic Scale (EMS-98) (Grünthal et al., 1998) was developed for the classification of common European building types and defines building classes based on primary structural material, and for some additional categories for design level, lateral load resisting system (LLRS), reinforcement level, and/or floor material. The fifteen building classes are given in Appendix A. There is currently an initiative aiming to expand EMS-98 to be applicable internationally (Lang et al., 2017)

The Hazard-US (HAZUS) project (ATC, 2010) divides the building stock by considering the basic structural system, building height, and seismic design criteria. Developed for the US building stock, sixteen building types are identified, which expands to thirty-six when the number of storeys are considered: these are considered in three groups, low-rise for buildings with up to three storeys, mid-rise from four to seven storeys, and high-rise above seven storeys up to twenty storeys above which the use of classification is not advised in favour of more individual specific assessment. The taxonomy further expands to one hundred and thirty-two separate typologies with the inclusion of the consideration of engineering design level, either pre-code, low-code, moderate-code, or high-code. The HAZUS typologies are given in Appendix A. Despite HAZUS being developed specifically for the US, it has been widely used globally with and without local adaptations (e.g. in India (Gulati, 2006), Venezuela (Bendito et al., 2014), and Canada (Ulmi et al., 2014)), and for validation of results of other SVAs globally (Miura et al., 2008; Hancilar et al., 2014). One large adaptation to a global risk assessment study can be found in the 2013 UNISDR (United Nations International Strategy for Disaster Reduction) Global Assessment Report on Disaster Risk Reduction (GAR-13) (UN, 2013), for which the authors used the HAZUS building classification system, adding classes where considered necessary in order to capture global building types (Yamin et al., 2014). This results in twenty-one structural types; five more than in the original HAZUS taxonomy, a required to extend the taxonomy to international application. The groupings are then further categorised by height and design level, as with HAZUS, but with some subtle differences in the heights and code levels considered. These are detailed in full in Appendix A.

The PAGER (Prompt Assessment of Global Earthquakes for Response) system (Porter et al., 2008) classifies global building typologies using sixteen main construction types defined by primary structural material and LLRS, which expand to eighty-seven sub-types when more specific descriptions of buildings are available, including information on diaphragms type, construction techniques, specific material types, the level of ductility, and height. The PAGER classes table is relatively extensive and is included in Appendix A.

The Global Earthquake Model (GEM) building taxonomy (Brzev et al., 2012) is another system designed to encompass global building typologies. When being developed, GEM focused on forming a classification system that is collapsible (i.e. applies to all levels of detail of building data), detailed, distinguishes between different levels of seismic performance, extendable, applicable globally applicability, and user-friendly (Brzev et al., 2012). With this in mind, a system was devised that uses different levels of detail for eleven characteristics: position, plan shape, structural irregularity, exterior walls, foundation, floor type, roof type, occupancy, date of construction, height, lateral load-resisting system, material of the LLRS, and direction, see Appendix A. The GEM system uses three levels to classify datasets of differing detail. Level 1 data types denote the most key building characteristics for classification, as determined by GEM. Level 1 data include the following: material type, type of LLRS, height, age, general occupancy, building position, regular or irregular building, roof shape, floor material, and foundation system. The GEM approach to classifying buildings is similar to that for the European-focussed Syner-G project (Hancilar and Taucer, 2013), and so this will not be considered directly in this chapter.

The RESIS-II building classification scheme was developed specifically for use in Central America (Lang et al., 2009a). The system (as with GAR-13) started with HAZUS structural types, but with a reduced number of typologies that consider differences in height. The design level is not considered for any structural typology, consistent with the extent of building regulation in the region. Additional structural types are also included to cover further building typologies common to Central America but not present in the US. The twenty-four resulting classes are presented in Appendix A.

In summary, a number of existing classification systems are presented ranging in scope, detail, and methods of grouping. The EMS-98 system is fairly simplistic, and its European focus leads to greater attention given to masonry and RC building types, with a number of more detailed options given for each. All steel and all timber structures are grouped together with no differentiation for any characteristics other than the primary structural material. In contrast, the American HAZUS system has many building classes, however it does struggle to capture building typologies outside of the US. The GAR-13 and RESIS II systems both adapted HAZUS building typologies in order to serve global and local building classifications respectively. It is interesting to note that HAZUS deems code level relatively important, and this is clearly appropriate for a country that has had defined and enforced codes over several decades. This delineation is less important in a country where building codes are relatively new or unenforced, and this is reflected in the Central American focused RESIS II system. In addition, HAZUS, as well as GEM, consider height (or number of storeys) to be paramount to the classification of building types, however this is only case with PAGER and RESIS II for certain building materials, and is not considered at all by EMS-98. The PAGER building classification system primarily employs the construction material and structural system, and has the great advantage of including a level of more aggregated groupings for datasets that do not contain enough detail. Vernacular typologies common in distinct regions in the world are also included, enabling global coverage. The GEM building taxonomy scheme extends the flexibility of the PAGER system and allows a large number of levels of additional information to be included to group buildings. The GEM system uses a large number of attributes that describe buildings well, reducing the chance of losing detail, as is the case with the PAGER system. The optimum level of detail used by a classification system depends on the contents of exposure datasets, as well as the method of vulnerability assessment proposed: different approaches demand different levels of data.

Out of the systems, GEM is the most extensive and has the capability to effectively classify all types, shapes, and qualities of building inventory datasets. Using this system, however, is likely to result in a large number of different building classes, and some judgement is needed to aggregate groups into an appropriate number for seismic vulnerability assessment, so as to not lose too much detail, but also not require extensive vulnerability calculations.

Overall, a range of systems exist, each with different strengths and limitations. Some are developed with a region in mind and hence the classes may not capture all typologies adequately outside of the region. Others attempt to capture typologies on a global scale (even though individual typologies may not be found globally); however, the number of classes is large leaving the need for extensive vulnerability assessment calculations. This balance, between detail and resource, is one that is highlighted throughout this study.

2.2.2. Methods for the estimation of the seismic vulnerability of buildings

The next step of assessing the seismic vulnerability is applying an approach or methodology found in the literature. SVA methods are based on one of the following underlying approaches: empirical, analytical, expert judgement, or using a hybrid of the three (Porter, 2003; Rossetto et al., 2014a). Each approach has advantages and limitations (Kwon and Elnashai, 2006) and selecting which to use often depends on the quality type of data obtained, the analyst's expertise, the available resources, and the scale of the assessment.

Empirical approaches use data from past earthquakes to infer relationships between a decision variable, such as damage or economic loss, and earthquake intensity relying on the assumption that history will repeat itself. A key advantage is that aleatory uncertainties – such as natural variations in ground shaking or building response – are inherently considered (Rossetto et al., 2014a), however lack of data for (1) larger, rarer earthquakes, (2) similar engineering contexts, and (3) comparable seismological and shallow geological contexts, can affect the wider applicability of results (Rossetto et al., 2013). Furthermore, available databases capturing earthquake damage data may be incomplete, of poor quality, or collated using coarse or ambiguously defined damage states and building classes, making the combination of a number of databases difficult (Rossetto et al., 2013). Empirical approaches also lack the ability to reflect differences in engineering and tectonic environments, and are unable to account for specific structural details and the strengthening of buildings (Kwon and Elnashai, 2006).

Analytical approaches use modelling techniques to analyse the response of a structure subjected to earthquake loading (Calvi et al., 2006; D'Ayala et al., 2013). Structural models can be idealised to a greater or lesser extent but will always involve assumptions that can cause significant discrepancies in results (Kwon and Elnashai, 2006). Analytical modelling can vary in many ways, including the use of different modelling techniques, input data, and ways to assign characteristics to the model. Generally, simpler models are quicker to build and solve but rely on more assumptions; more complex models require more substantial computational effort and a deeper engineering expertise but provide more accurate results (D'Ayala et al., 2013). Analytical approaches may be grouped into the following methods: mechanics-based (e.g. D’Ayala and Speranza (2003)), capacity spectrum (adaptive or not) (e.g. HAZUS (ATC, 2010)), coefficient displacement (e.g. Miranda (1999)), N2 (e.g. Fajfar (1999)), and more simplified methods (e.g. Silva et al. (2013), Borzi et al. (2008)), amongst others (Calvi et al., 2006; Silva et al., 2013; Cardone and Flora, 2017)).

Structured expert judgement approaches may be used to elicit, weight and pool the knowledge of experts (Cooke, 1991), and have been shown to provide an acceptable estimation of vulnerability (ATC, 1985; Jaiswal et al., 2012). There are different methods available to collect the opinions of a group (Cooke, 1991) with the aim being to reduce participant bias (Tversky and Kahneman, 1974). The reliability of results depends on the experience of each expert involved, particularly with regard to specific local building typologies, construction practice, detailing and materials (Kwon and Elnashai, 2006).

Hybrid approaches use a combination of analytical, empirical, and expert opinion methods (Calvi et al., 2006). They are often employed due to a lack of comprehensive data to employ one approach in isolation (Kwon and Elnashai, 2006). Results using this approach may be subjective, but can also benefit from validation with results from different approaches (Rossetto et al., 2014a).

The fastest way to obtain vulnerability functions is to select them from existing studies and either apply them directly or adjust them to fit the scenario. This method is likely to yield more inaccurate results due to the lack of specificity to the new location or building type, however it provides an option when resource is limited. This method could also be used for a first pass to get a ball-park figure of the estimated risk or losses, prior to more accurate vulnerability assessments. This practice is commonplace in the private and public sectors (e.g. Lang et al. (2009a)) where expertise, data, and/or time are limited, and it is also practiced in some evaluations of risk for academic purposes (e.g. Makhoul et al. (2016)). This, and a growing body of literature publishing derived functions, led to the GEM developing a database of existing fragility and vulnerability functions within the OpenQuake platform (Silva et al., 2012) from where functions can be downloaded for reuse (Yepes et al., 2016; Stone et al., 2017b). The GEM also developed a framework for the evaluation and selection of existing functions for new studies (Rossetto et al., 2014a) which guides an analyst to consider the overall quality of the existing function as well as its relevance to the new study, with the aim of reducing inaccuracies by improving the selections made. The selection of existing functions is very subjective and the GEM framework requires a depth of knowledge about any function that is evaluated. This requires a well reported document detailing the process of its derivation (Stone et al., 2017b) which is uncommon in developing countries.

Index-based methods are a simplified approach, using key characteristics about a building type to obtain a score which is related to seismic vulnerability using relationships derived through empirical, analytical, expert judgement, or hybrid approaches. These methods are common in the SVA literature (Calvi et al., 2006) with different building types studied, for different geographical locations, and different opinions of the key defining building characteristics.

The first widely-used index-based method was developed in Japan for low-rise RC buildings (Shiga et al., 1968), using damage data from the 1968 Tokachioki earthquake to calculate a relationship between easily available structural information (wall or column areas) and observed damage. Later, a similar empirical approach was used to derive relationships for Italian unreinforced masonry where eleven parameters are scored and combined with specified weightings according to their relative importance. Given the overall score, a damage factor relating to peak ground acceleration is assigned from a library of functions (Benedetti and Petrini, 1984). Others have employed, adapted, or improved this empirical methodology using different damage datasets (Angeletti et al., 1988; Yépes et al., 1995) and for different locations (e.g. Barcelona, Spain (Barbat et al., 1996), Turkey (Özhendekci and Özhendekci, 2012), and Haiti (O'Brien et al., 2011)).

A different approach calculates column and wall indices which are used to prioritise RC frame buildings for further investigation (Hassan and Sozen, 1997). Despite positive validation of results with empirical damage datasets from Turkey and Haiti (O'Brien et al., 2011), it is not possible to develop seismic vulnerability functions using this method; instead these types of methods are known as prioritisation schemes, used as the first level screening to highlight the most vulnerable structures (Grant et al., 2007). This initial index scoring approach is used widely in practice and the academic literature, with the aim of prioritising the more vulnerable structures for detailed seismic vulnerability assessments (ATC, 2002; Lourenço and Roque, 2006; Tezcan et al., 2011; Nanda and Majhi, 2014a; Al-Nimry et al., 2015), hence these methods are very common for critical buildings such as public buildings (Sucuoğlu et al., 2015), hospitals (Lang et al., 2009b; Perrone et al., 2015), and schools (Grant et al., 2007). These basic methods, however, do not directly generate vulnerability functions able to be used in a seismic risk assessment but aim to highlight relative risk between structures. Other methods do not aim to generate vulnerability functions, but instead use a series of indices to estimate seismic risk directly (McCormack and Rad, 1997; Sucuoğlu et al., 2007; Tesfamariam and Saatcioglu, 2008).

The European Macroseismic Scale (EMS-98) (Grunthal et al., 1998) was originally developed for use with European buildings, however it has been applied throughout the world (Foulser-Piggott and Spence, 2013; Seismic Vulnerability Assessment Project Group, 2013; Stone et al., 2015). It primarily acts to describe the intensity of an earthquake using observable information, (used as the damage intensity scale by some index methods (Guéguen et al., 2007)) however it also contains assumptions about the vulnerability of building classes. The EMS-98 system is used as a foundation for the development of a methodology to derive fragility functions for masonry and RC buildings (Giovinazzi and Lagomarsino, 2004). Results of a comparison between an EMS-98-based vulnerability index method developed by GNDT (*Gruppo Nazionale per la Difesa dai Terremoti*, National Group for Protection against Earthquakes) with those from an analytical modelling method, are promising highlighting the potential of the EMS-98 system (Lantada et al., 2008). This comparison, however, is specific to Spain as the scoring relies on the age of the structure compared to past Spanish building codes. It would therefore require some work to adjust the scoring method to enable application to other countries.

A vulnerability index method has been developed for an Algerian context (Belheouane and Bensaibi, 2013) which, when combined with damage probability matrices, enables fragility curves to be derived for RC framed structures using inputs which closely echo those first proposed by Benedetti and Petrini (1984). Others have adapted the original masonry index method (Benedetti and Petrini, 1984) for different applications, such as for confined masonry (Gent Franch et al., 2008), slender masonry (Shakya et al., 2014) and Portuguese contexts (Vicente et al., 2014).

More recently Rodriguez (2015) derived a globally-applicable index method for estimating damage based on the fundamental period of an equivalent single degree of freedom (SDOF) system and the dissipated hysteretic energy. Many assumptions are made in this procedure, alongside some variables that are defined using data from twelve global earthquakes (Rodriguez, 2015). Similarly, a method applied in Croatia developed a damage index from the results of analytical analyses using SDOF models, which results in a score relating to a specified damage grade (Hadzima-Nyarko et al., 2017).

Each index method employs data that is thought to represent the seismic damageability of the structure concerned. Methods reviewed here employ analytical and empirical data and have been applied throughout the world in seismically active regions. As with other simplified methods, inputs and approaches are reduced for simplicity, and hence inputs to index methods are prioritised. Thus, the input data used in index methods are an indication of the authors assumption of the importance of different building characteristics for assessing vulnerability. A systematic review of the inputs used in index methods is presented in Chapter 4 as part of the methodology for determining more useful building characteristics for SVAs.

Other simplified methods for assessing seismic vulnerability focus on developing a measure of elastic and plastic response or capacity curves, without the need for complex structural modelling and analysis. Following on from the index methods introduced above, Matamoros et al. (2003) develops an indices scoring method to estimate the maximum drift of RC buildings, validating results through comparison with other analytical methods. Sanchez-Silva et al. (1993) developed a simple relationship for estimating the yield and ultimate displacements for masonry and RC buildings using a simple coefficient and the number of storeys. The method validated well with observed damage from the Caracas 1967 earthquake. This method has the great benefit of being very quick and easy to complete, but the accuracy of results in other contexts (both spatially and temporally) needs to be examined further.

Miranda (1999) uses a series of coefficients to estimate the inelastic behaviour of framed multi-storey buildings, with the ability to apply different lateral load patterns, soils types, number of floors, total height, and the modal shape of the fundamental period. In a similar way, Calvi (1999) uses assumptions about the characteristics of RC and masonry structures to derive a range of displacements for defined damage states. Energy dissipation is also considered. This method has been extensively used by ERN in Central America (e.g. ERN (2010)) and globally (Yamin et al., 2014).

The FaMIVE (Failure Mechanisms Identifications and Vulnerability Evaluation) procedure (D'Ayala and Speranza, 2002; 2003) builds on previous work (D’Ayala et al., 1997) and focuses on the likelihood of different potential in- and out-of-plane failure mechanisms for masonry structures. The procedures provides a data collection form (D'Ayala and Speranza, 2002) to gather the specific information needed to calculate collapse multipliers for each possible mechanism using derived formulae. The lowest collapse multiplier value identifies the first activated failure mechanism and the base shear capacity of the structure. The procedure has been used successfully in historical urban centres worldwide to derive vulnerability curves (D’Ayala, 2005; Bernardini et al., 2008; Novelli et al., 2014).

Other methods use hybrid approaches (analytical and empirical) to develop a relationship to estimate the capacity curve of unreinforced masonry (URM) buildings (Penelis et al., 2003) and RC wall structures using some more detailed structural characteristics (such as an assumed cracked stiffness and the capacity of the wall in shear as the first yield point) whilst accounting for any potential coupling effect of walls, spandrels, and floors (Lang and Bachmann, 2004). The ultimate displacement is estimated using an empirical relationship which uses coefficients and the normal stress, and has been shown to give good results (Lang and Bachmann, 2004). Displacement-based methodologies are proposed for RC frames which estimate the displacement capacities at different limits states using material and geometrical parameters (Crowley et al., 2004). This fundamental approach is also extended to unreinforced masonry (Oropeza et al., 2004; Borzi et al., 2008).

Although fraught with assumptions, these methods provide simplistic procedures for estimating elastic and post-elastic behaviours of buildings under seismic loading. Assessments of seismic vulnerability can use these derived capacity curves to estimate fragility and vulnerability functions using a number of analytically-based methods (D'Ayala et al., 2013).

In addition to more simplified methods, many complex methods exist in the literature. They require an in-depth knowledge about the buildings, including geometry and material property data. Empirical approaches increase in complexity with the techniques and statistics used to combine and analyse the damage datasets (Rossetto et al., 2014b), whereas more complex analytical assessments use increasingly complex and detailed structural modelling and analysis (D'Ayala et al., 2013). Linear static and linear dynamic analyses are procedures that apply seismic loading to an elastic structural model used to estimate some response properties of a structure, such as the yield point of a capacity curve. Estimations of inelastic behaviour can be made using these methods by assuming a reduction in the strength of, or even omitting, individual elements that have reached capacity. These linear procedures are common with design methods, however are only permitted for seismic assessment in certain circumstances (CEN, 2005).

The simplest approach that directly models the nonlinear behaviour of structures is a nonlinear static, analysis, also known as a pushover analysis, where an equivalent static seismic load is employed to model the seismic demand. Alternatively, accelerograms (or earthquake time histories) can be used to represent the seismic demand applied to a structural model, and hence the analysis is named nonlinear dynamic or nonlinear time history analysis. Both of these analysis techniques require more computing time than simplified methods, as nonlinear structural modelling in a capable software is required. Simple pushover analyses often use a modal lateral loading pattern, and this can be challenging as the effects of higher modes of vibration are not considered, which can be significant for taller buildings. Additionally, as the structure starts to behave nonlinearly the fundamental period changes and hence so do the modal characteristics, but the lateral loading pattern is not updated. This can cause significant errors in the inelastic behaviour results (Antoniou and Pinho, 2004; Abbasnia et al., 2014). To deal with the effects of the higher modes, multiple capacity curves can be derived for a number of modes and then combined (Chopra, 2004). A mass proportional pushover procedure removes the need for modal analyses and multiple pushover runs by using the distribution of seismic mass to adapt the seismic loading pattern (Kim and Kurama, 2008). When compared to standard modal pushover analyses the results were improved and closer to those arrived at using a nonlinear dynamic analysis.

To deal with the issue of changes in modal behaviour post-yield, adaptive pushover analysis procedures can be used, which employ a progressive change in seismic demand patterns post-yield (Antoniou and Pinho, 2004). The results of a comparative study with a standard pushover analysis, an adaptive pushover analysis, and a dynamic analysis showed that the adaptive method better matched the results from dynamic analyses without having to employ any extra computing power, and when compared to basic static loading regimes (such as triangular or uniform distributions) the adaptive procedure offered the best results (Antoniou and Pinho, 2004). Additional positive results have been achieved for populations of RC structures (Rossetto and Elnashai, 2005) when comparing adaptive pushover analysis results to observed damage data. This method extends the process even further by accounting specifically for uncertainty in the capacity (by assigning random variables for the material properties) and the ground motion (by utilising accelerograms to derive a range of acceleration and displacement spectra to represent the seismic demand).

Nonlinear dynamic analyses (also known as nonlinear time history analyses (NLTHA)) build on pushover analyses by incorporating dynamic seismic demands through the use of accelerograms or earthquake time histories. These can be real, if appropriate records are available, or artificial (Humbert et al., 2014). It is widely suggested that a range of time histories should be used to assessing the dynamic response of a structural model in order to capture the record-to-record variability; eleven pairs of ground motions, one in each orthogonal direction, are recommended as a minimum (D'Ayala et al., 2013). The chosen accelerograms are incrementally scaled in order to understand how the building behaves in bigger (and smaller) earthquakes. Key advantages of NLTHA methods include the innate ability to report uncertainty well in both capacity and demand (Dymiotis et al., 2001; Möller et al., 2010; Park et al., 2009; Rota et al., 2010) as well as the ability to directly account for hysteretic behaviour of the structure, which is particularly important for masonry structures (Magenes, 2000).

Nonlinear methods are written about extensively in seismic evaluation and retrofitting guidelines for the United States, following their initial introduction in detail in ATC-40 (ATC, 1996) which includes modelling rules and step-by-step methods for both the capacity spectrum method and the displacement coefficient methods of estimating structural performance in earthquakes. ATC-40 has been followed by a succession of guidance documents, updating recommendations according to the latest knowledge (FEMA, 1992; ASCE, 1997; ATC, 1998; ASCE 2000; ASCE 2003; ASCE 2006; ASCE 2014) including a document specifically highlighting improvements to nonlinear static procedures (ATC, 2005). Similar documents in Europe (CEN, 2005) and New Zealand (New Zealand Society for Earthquake Engineering, 2006) are available. These guidelines tend to focus on individual building assessment only, not the study of populations of structures that make up large urban areas. They are also, on the most part, focused on force-based processes (Magenes, 2000), which have been proven to be less able to model seismic behaviour than displacement-based methods (Abbasnia et al., 2014).

In summary, the wide-range of methods, options, techniques, complexity, and approaches found in the SVA method literature are highlighted. The input data requirements differ considerably depending on the SVA method employed, from simplified methods that prioritise the use of data that most impacts on seismic vulnerability, to more complex methods that use a very detailed level of data on the building characteristics. When considering the assessment of vulnerability of a large city, it can be challenging to obtain the level of detail required for more complex assessment methods, and thus more simplified methods are generally applied. Many methods, however, are narrowly-focused on specific buildings or building classes or locations which limits their wider-application. This challenge will be discussed further in section 2.3.

2.2.3. Applicability of the current SVA research to urban situations

A pattern of assessment and methodologies has emerged from the review of the academic literature thus far: the published studies are fairly narrow in scope, thus, selecting methods for use in an urban context is challenging, particularly when cost and time are key considerations. The academic literature lacks accurate, widely-tested and validated, global SVA methodology, compatible to and applicable in the assessment of whole urban areas, despite this being one of the largest challenges facing governments and exposed populations. Many existing studies are focused on a single type of building in a specific town or city. Although this is potentially of use to that specific site, it is not widely applicable for understanding risk in a wide range of urban settings.

Many studies are geographically focused (e.g. Lisbon (Sousa et al., 2017b), Southern Europe (Pantò et al., 2017), Lorca (Spain) (Tomás et al., 2017), to name but a few) and even if new methods are developed, they are often only tested in a single location, so their application in different contexts is not validated. Similarly, many studies are focused on single building typologies (e.g. RC masonry infilled frames (Pantò et al., 2017), RC (Tomás et al., 2017), adobe (Varum et al., 2014) to name but a few). Some even focus on specific building types in specific places (e.g. wood-frame in south-western British Columbia (Goda et al. 2011), adobe in Cusco, Peru (Tarque et al. 2010), masonry in Chile (Moroni et al., 2004), to name but a few). Fewer studies apply vulnerability or risk assessments to an entire city's building portfolio (e.g. Algiers, Algeria

(Novelli et al., 2014a); Wadi Musa, Jordon (Novelli et al., 2014b); Thessaloniki, Greece, (Riga et al. 2017)), therefore, relatively, the difficulties in the overall process are not well understood, such as deciding the number of surveys requires and locations of survey, methods for effective data collection,

More specific challenges arise from this issue in the published literature. Although methods are likely available for most existing building typologies found globally, it is not prudent to apply different approaches to derive vulnerability functions for use in a single seismic risk assessment. First, the input data required for the different methods will differ, making the data collection process challenging. Second, it would be very difficult to keep track of the level of uncertainty in the final results as different methods will consider and account different types of uncertainty in different ways, and third, different methods may not be compatible or comparable, for example the underlying assumptions in the approach may not align or the units of loss or the intensity measure used may differ. Additionally, different methods are validated (if at all) using datasets from specific geographical locations causing difficulties in comparing the validity of results for different building types.

There are a handful of studies that are less narrowly framed, that attempt to address some of the issues of assessing the vulnerability of large urban areas. D’Ayala (2013) investigates the differences between masonry types, highlighting that different masonry behaves very differently and should be considered separately in a city risk assessment.

Investigating a homogenous methodology for assessing the vulnerability of buildings that make up a large urban area is a key need in future research and developing a standardised way to collect the required building data to use as inputs would be an important aspect. However, there is little agreement in the literature on how to gather data on a large scale for SVAs, as will be explored in section 2.3.

2.2.4. Synthesis of seismic vulnerability assessment review

The process of assessing seismic vulnerability is examined, highlighting the range of classification systems available for assigning individual structures into larger groups with similar seismic responses, to reduce calculation intensity. These classification systems range in geographical applicability, from regional to global. They differ in the characteristics used to classify buildings, with all using the primary structural material, and some employing information about the structural system, height, code level, and more. Similarly, the review of SVA methods highlights the wide range of inputs, techniques, and approaches used to understand seismic behaviour, as well as the gap in knowledge of best practice for connecting larger complex contexts with suitable and rigourous SVA methods.

These differences exhibit the disagreement that exists in the literature around the key indicators of seismic behaviour. This, hereby, poses the question of: what are the most important building characteristics for classification and assessment of seismic vulnerability? Often, building classification systems are not specifically designed to work in tandem with SVAs; there is often a mismatch between the building data required to classify buildings and those required to assess the seismic vulnerability. This results in ineffective data collection and data processing, but also defies common-sense as the data that enables the best estimation of seismic vulnerability would also identify similar seismic responses.

Most often, commonly available data (e.g. those observable externally) are used to classify buildings, relying on the assumption that buildings with the same basic characteristics will behave similarly. As is often observed in earthquakes, buildings that appear very similar in shape, size, and material behave very differently in earthquakes (e.g. Wilkinson et al. (2011); Goda et al. (2017)) for a number of wide varying reasons. The result is that classes contain buildings with a wide range of seismic responses, that are likely to overlap with other building classes.

Investigating the importance of different building characteristics for accurate assessments of seismic vulnerability would help to solve this challenge and this is conducted in Chapter 4 where the relevant literature is systematically reviewed to draw out the common themes of important data types for SVAs and hence those that should also be used for building classification systems.

2.3. Effective collection of building data for seismic vulnerability assessment

The collection of building data is a vital part of any seismic risk assessment, and is likely to be the most time-consuming and expensive part of a seismic risk assessment (Dunbar et al., 2003). A number of the most common building data collection methods, each with the ability to collect different building characteristics with varying levels of accuracy and using different amounts of time and costs, are introduced and discussed below. Alongside the well-known desk- and field-based methods, a series of technological advances have more recently allowed different types of data to be collected at scale, with the potential for improvements in accuracy: the potential for unmanned aerial vehicles and omnidirectional imagery to collect building data for SVAs is discussed in section 2.3.2.

2.3.1. Existing methods of data collection

The simplest way to gather building information is to obtain existing information. A number of building inventory databases are available following large research projects, for example the PAGER project compiled a global building database from a range of sources, and used a defined procedure to fill any gaps in data (Porter et al., 2008). The 2013 UN's Global Assessment Report (GAR-13) developed a global exposure model in order to assess the economic risk from natural hazards at the global scale (De Bono and Mora, 2014). GAR-13 used a combination of data from censuses, the World Housing Encyclopaedia (WHE), PAGER, United Nations reports, HAZUS (Hazard-US), and other research (Wyss et al., 2013). This was updated in 2015 (UNISDR, 2015a). The GEM project developed the GED4GEM (Global Exposure Database for the Global Earthquake Model) by incorporating existing sources of physical, socio-economic, demographic, geological, and geographical information over a number of different scales from global to individual buildings, as data availability allowed (Huyuk et al., 2010; Chen et al., 2011; Gamba et al., 2012;).

The WHE offers detailed information on buildings throughout the world based on standardised reports from individual experts, however the information, although very useful when available, is scarce, geographically sporadic, and does not cover all building types prevalent in each country (D'Ayala, 2009). These large datasets typically contain incomplete, vague, old, and/or non-specific data. It can also be difficult to assess the accuracy of the data provided. Additionally, information is often highly aggregated (e.g. national level) in order to manage the large amounts of information, but this causes a loss of detail important to risk assessments at urban level. Some governments and national institutions may have more detailed information about buildings which could be useful if they are able and willing to share it.

Housing census reports are another source of existing information which gives data on building types or prevalent construction materials, as well as socio-economic statistics (Armaş et al., 2016). Population and housing censuses are completed every decade in many countries, and they often include information on wall and roof material, which gives a sense of the types and proportions of buildings at the spatial scales for which the data are available (Mansouri et al., 2014). The accuracy of the census data collection methods used, and the skill level of the surveyors is often not reported, so the quality of the data is unknown. There are international standards for censuses (UN, 2015a; UN 2015b) however the reality of the surveys on the ground may not reflect these requirements. Challenges can be envisioned, such as the potential for the cladding material to be captured as wall types (this may even be the aim of the surveyor), and hence information about the structural type is uncertain. Additionally, building census data are often aggregated to parish or neighbourhood level, so data aggregation or disaggregation is required if the scale of the data does not match that of the study region.

Investigating the history of a city also offers some information about the buildings stock, particularly the ages of developments, the construction trends and practices at the time of development, the political history driving development of buildings, the timeline of design and construction codes used throughout time, and the impacts and rebuilding of past destructive events. A historical timeline can also show the population growth and movements through time, which indicate potential pressure points on urban areas. In relation to the growth of the urban extents and all of the other drivers, some data may be obtained to help make good judgements and assumptions about the building inventory in a city. There are, of course, shortcomings with the use of historical documentation, which is prone to bias, error, misreporting, lack of detail, and incompleteness.

The final source of existing information considered here is data collected through interviews or workshops from local experts. These data can be collected in a variety of ways (e.g. Bryman (2008)), including expert elicitation exercises (Cooke, 1991). These processes are able to gather any type of building data, but are limited by the opinions, biases, and experience levels of the participants.

The benefits of using existing data are that very low levels of resource are required in order to obtain data on buildings present in an urban area. Many sources of data are free and do not require the expense of travelling to the study area significantly reducing costs. This notwithstanding, many cities in earthquake prone regions are not likely to have good building stock data, and any information that does exist may be outdated, of poor quality, or aggregated (Geiß et al., 2015), in which case, new datasets need to be collected. Although this approach may overcome many of the challenges with existing data, it does come at significantly greater expense.

The analysis of satellite imagery is becoming more prevalent as the availability and capability of satellites increases (Ramly et al., 2014). This type of aerial imagery has been used in many disciplines to map, monitor, and assess objects visible from space (e.g. glacier monitoring (Bhardwaj et al., 2016), crop mapping (Grace et al., 2012), and even to assess the impacts of disasters on economic development (Klomp, 2016)).

Satellite imagery can be used both prior to an earthquake to extract building data that helps assess the vulnerability of large urban areas (Geiß and Taubenböck, 2012), and after to assess damage (Saito et al., 2004; Eguchi et al., 2010; Corbane et al., 2011; Erdik et al., 2011; Voigt et al., 2011), although not always with success due to the limitations of a top-down perspective (Voigt et al., 2011). Satellite imagery can be used to assess vulnerability by identifying characteristics about the exposed buildings directly from the images or by association due to the type of structures known to be prevalent in that location (Mueller et al., 2006). GIS (geographical information system) analysis techniques can be used to identify land cover usage (specifically the extents of built up areas) (Hayashi et al., 2002; Wieland, Pittore et al., 2012a), building footprints (Hayashi et al., 2002; Pittore and Wieland, 2012), and building-by-building characteristics such as size, occupancy (Aubrecht and León Torres, 2015; Aubrecht and León Torres, 2016), position in block, height, plan irregularities, spatial context, age, and roof type (Hayashi et al., 2002; Mueller et al., 2006; Sarabandi and Kiremidjian, 2007; Pittore and Wieland, 2012; Wieland et al., 2012a; Geiß et al., 2015; Mesgar and Jalilvand, 2017) for use in seismic vulnerability assessments (Hancilar et al., 2013; Geiß et al., 2014). Elements of satellite data collection and analysis processes can be automated, reducing both time and cost.

Satellite imagery can be even more powerful for creating building inventories when they are combined with additional data, such as housing censuses (Sarabandi and Kiremidjian, 2007; Jaiswal et al., 2010; Gamba et al., 2012; Wieland, Pittore et al. 2012a; De Bono and Mora, 2014; Karimzadeh et al., 2014; Mansouri et al., 2014; Gunasekera et al., 2015; Mesgar and Jalilvand, 2017; Yepes-Estrada et al., 2017) and other data collected from the ground (Jaiswal et al., 2010; Pittore and Wieland, 2012; Wieland et al. 2012a; De Bono and Mora, 2014; Geiß et al., 2014; Porter et al., 2014; Gunasekera et al., 2015; Mesgar and Jalilvand, 2017). Despite success stories of satellite imagery being applied in practice (Gunasekera et al., 2015), there a number of key issues with this data collection method. The poor ability to identify structural building characteristics, when used in isolation, means that remotely-sensed data is only be able to identify very aggregated building typologies (e.g. EMS-98 (Grünthal et al. 1998)) (Geiß and Taubenböck, 2012). Obtaining more detailed images in order to try and gather more building characteristics is extremely costly, particularly for large areas such as cities (Bhardwaj et al., 2016). Additionally, data cannot be acquired on demand for specific times and specific dates (Bhardwaj et al., 2016). Similarly, obtaining a full cloud-free dataset is challenging (Bhardwaj et al., 2016). Therefore, combining different data sources is often required to achieve a more substantial and reliable building inventory.

Rapid visual surveys offer an excellent, flexible way to gather building data, however the process of street surveying is slow, resource intensive, and limited as only the façade and the building's surroundings are observed. RVS methods, or walking street surveys, are fairly prevalent in the literature, and are used as a way to quickly gather information about buildings in an area. Often statistical sampling is used to reduce resource intensity (Porter et al., 2014) and to gather a dataset able to be extrapolated to a wider area. The most prominent RVS method is FEMA 154, which was first published in 1988 (ATC, 1988) and updated in 2002 (ATC, 2002). It describes a procedure for collecting building inventory information using a provided form. This technique has been adapted and further developed for different areas around the world (Institute for Research in Construction, 1993; Jerez, 2001; Sucuoğlu et al., 2007; Wang and Goettel, 2007; Jain et al., 2010; Tischer, 2012; Nanda and Majhi, 2014b; Albayrak et al., 2015). Each method differs in the specific information that it collects (this flexibility is a benefit of this method), but all information is obtainable from the street. RVS methods can be particularly resource intensive if a high level of detail is required, however they can be used to gain an accurate and relatively rapid appreciation of the building stock in a study area. It is generally much faster than structural surveys and gives better structural information than satellite images or existing datasets, but detailed structural information for use in more complex analytical models cannot be gathered using this method alone (without substantial assumptions).

An interesting prospect to reduce costs using RVS techniques is to use volunteer citizens, engineering students, or building owners to gather building inventory information, as volunteers have been shown to add valuable scientific data in other communities exposed to natural hazards (Stone et al., 2014). In fact, citizen and engineering student surveyors have been used on previous occasions (NORSAR, 2009; NORSAR 2010; Lopez, 2011), however the accuracy of building data gathered by these groups has not been fully explored or tested. The uncertainty in the use of rapid visual surveying methods overall also needs further consideration as simply surveying the façade only allows certain information to be gathered and may lead to the incorrect classification of buildings.

The most resource intensive method of gathering building data is a structural survey. The data collected are better able to serve the needs of more complex SVA methodologies where specific structural data are needed. The additional resource required by this method results in information that cannot be gleaned from RVS methods or using imagery, and should thus result in more accurate building inventory data. There is some available guidance in the literature on detailed internal structural surveys (ASCE, 2000; ASCE 2014; ATC, 1998). Beyond collecting geometrical and dimensional data, destructive and non-destructive material testing are advised, as well as a review of available design documentation, in order to gather knowledge about material properties. In more developed countries design information will be available, especially for newer buildings, however it is much more unlikely in developing contexts where building codes may not exist or are not strictly enforced.

There are a number of challenges with collating a building inventory database using structural surveys, beyond the substantial resources required to gather a big enough sample. Firstly, access to buildings may be restricted as building owners may not be willing or able to allow entry. Additionally, buildings tend to have cladding, ceilings, decorations, or flooring that hides structural elements, making it hard to gather information without removing or disturbing non-structural finishes. Similarly, foundations are rarely visible, and the detailing of reinforcement in concrete is difficult to ascertain once constructed, but is key to seismic performance.

In addition to the existing data collection methods that are tested in this study, advances in technology may have inadvertently developed useful tools to collect building data effectively.

2.3.2. New approaches to collecting building data using emerging technology

Technology continues to advance rapidly, and recent inventions or new applications of existing technology have proven their potential in wider academia. In particular, aerial imagery captured by UAV, and street imagery obtained from omnidirectional cameras, have been used to gather data for a number of disciplines and studies, and both exhibit the qualities of promising application to collection building data for seismic risk assessments. Both technologies can collect large amounts of imagery rapidly required for the study of larger urban areas. Additionally, costs may reduce through virtual surveying (i.e. the remote analysis of data) reducing the need for extensive time in the field. Thus, these tools have the potential for effective building data collection for SVA however are yet to be tested and compared to existing methods. This thesis will address this lacuna in knowledge by testing these methods, alongside the existing ones, in the case study area.

Although these technologies have not been used to collect building data for seismic vulnerability assessments, they have been used in other applications (as previously mentioned). These are discussed below, with the key benefits and challenges identified. One of the most recent 'innovation shocks' to have occurred is the advent of unmanned aerial vehicles, otherwise known as drones (Giones and Brem, 2017). The UAV industry is projected to grow from US$ 2 billion in 2016 to US$ 127 billion in 2020 (Giones and Brem, 2017). The use of UAVs has rapidly expanded in research practice in recent years (Turner et al., 2016), and despite some arguing that further development is needed to develop the technology from a toy to a professional tool (Giones and Brem, 2017), easy to use, off the shelf, quality hardware and software are readily available to researchers wanting to view subjects from above (Turner et al., 2016).

Since 1950 UAVs were used in military reconnaissance missions for activities that were too risky for humans (Giones and Brem, 2017), but more recently UAVs have been used for scientific applications such as mapping, sensing, detecting, monitoring, surveying, and modelling.

Geographers have successfully modelled geological formations in 3D using UAV imagery, mapped water quality (Su, 2017), surveyed rivers (Rusnák et al., 2018), and monitored glaciers (Bhardwaj et al., 2016). Archaeologists have built highly accurate models of heritage sites (Stek, 2016; Nikolakopoulos et al., 2017), recording the site in 3D for many different applications. UAVs have also been helpful in developing 3D models of earthworks (Siebert and Teizer, 2014) and existing buildings, both internally and externally (Dupont et al., 2017), as well as capturing the thermography of a building (Entrop and Vasenev, 2017). Conservationists have used them to detect animals in the African Savanna (Rey et al., 2017), and people have been studied to measure levels of park-based exercise (Park and Ewing, 2017). Researchers in biological science have extensively used UAVs for research, including the monitoring of invasive alien plants (Mafanya et al., 2017) and the spread of disease (Dash et al., 2017), mapping vegetation (Senthilnath et al., 2017; Tian et al., 2017)

The first record of the use of UAVs in an earthquake response was in L'Aquila, Italy in 2009. They have since been deployed in Haiti in 2010, Christchurch in 2011, Fukushima Daiichi in 2011, Cyprus naval base explosion in 2011, Great Thailand Floods in 2011, and the Emilia Italy Earthquake in 2012, and their deployments in disasters are increasing (Murphy, 2014b). Further research and examples from practice show UAVs as being suitable for, tested, and used in disaster response contexts for tasks such as search and rescue (Murphy, 2014a; American Red Cross, 2015; Erdelj, Karaca et al., 2017; Natalizio et al., 2017; Yanmaz et al., 2017), real-time aerial monitoring of an ongoing situation

(American Red Cross, 2015) with the useful ability to have images relayed live to a control centre sited at a safe distance (Yanmaz et al., 2017), and initial reconnaissance (Erdelj et al., 2017). Guidelines have been produced to ensure the safe and effective use of this technology in disaster response (American Red Cross, 2015; Murphy, 2014a). After a disaster, UAVs can also be deployed to transport supplies to remote or cut-off disaster affected areas (American Red Cross, 2015), or from storage areas to a distribution centre (Murphy, 2014a), although they more costly than trucks, but did not rely on road networks (Chowdhury et al., 2017), They have also been tested in the inspection or surveying of damage caused by a disaster, such as for insurance surveys (American Red Cross, 2015), structural integrity surveys on specific buildings (Murphy, 2014a; American Red Cross, 2015), and statistical engineering damage surveying on reconnaissance missions (Stone et al., 2017a). They have also successfully estimated the volume of debris to allow effective waste removal (Murphy, 2014a). UAVs have also been proven to be useful prior to a disaster with capabilities in a number of disaster management, preparedness, and assessment applications such as monitoring water levels of rising floods (Erdelj et al., 2017).

Researchers using drones have reported numerous benefits of the use of UAVs. First, the cost of acquiring high-resolution imagery is much less than the equivalent data obtained from satellites (Siebert and Teizer, 2014; Bhardwaj et al., 2016; Turner et al., 2016; Park and Ewing, 2017; Rey et al., 2017; Rusnák et al., 2018). UAVs are also reported to offer less time-consuming data collection (Murphy, 2014a; Siebert and Teizer, 2014; Stek, 2016; Karaca et al., 2017; Park and Ewing, 2017; Rey et al., 2017; Rusnák et al., 2017;), by covering larger area in little time compared to traditional ground surveying techniques as reported in a number of context (e.g. archaeological (Stek, 2016), search and rescue (Karaca et al., 2017), disaster situation monitoring (Yanmaz et al., 2017), mapping (Rey et al., 2017) and object monitoring (Park and Ewing, 2017)). Not only this, but they provide access to areas otherwise inaccessible for safety, weather, time, space, or practical reasons (Murphy, 2014a; Bhardwaj et al., 2016;

Stek, 2016; Turner et al., 2016; Stone et al., 2017a). In fact, the safety benefits of using a remotely piloted camera to observe things whilst researchers or practitioners remained in safety was widely reported as a major advantage of this technology (Murphy, 2014a; Siebert and Teizer, 2014; Stek, 2016; Giones and Brem, 2017; Stone et al., 2017a; Yanmaz et al., 2017).

In relation to the proposed application in this study, UAVs are reported to collect accurate 3D geometry, even when complex (Bhardwaj et al., 2016; Nikolakopoulos et al., 2017; Turner et al., 2016) as well as automatic geolocation of data with accurate GPS (Bhardwaj et al., 2016). The ability to rapidly deploy UAVs in time-sensitive applications is highlighted as highly beneficial (Murphy, 2014a; Turner et al., 2016) in addition to the usability and manoeuvrability of the vehicles (Siebert and Teizer, 2014; Stek, 2016).

Clearly, the use of different brands and models (and hence cost), of both UAVs and the post-processing software, will determine the specific benefits. Bhardwaj et al. (2016) praises the ability to be flexible with the camera type used (and hence the data acquired), and there are also benefits in the post-processing phase with algorithms employed to filter data for subsequent human verification, hence reducing the demands on the user (Rey et al., 2017). UAVs can also be used for collecting datasets over time to monitor changes; some examples where this has been tested are during construction works (Siebert and Teizer, 2014) and monitoring glacial change (Bhardwaj et al., 2016).

The literature also reports a number of challenges encountered when using UAVs. The issue of flight regulations and restrictions is something that has been reported more recently in the media, and is also a potential issue for flight abroad (Turner et al., 2016; Stone et al., 2017a). The benefits of using UAVs in areas difficult to access brings with it the challenge of having accurate and reliable ground control points to accurately place any images in a spatial coordinates system (Bhardwaj et al., 2016). In addition, obstructions, such as trees in urban areas, can interfere with data collection (Siebert and Teizer, 2014). Weather restrictions were also cited often as a major disadvantage of using this technology, as wind, precipitation, and extreme temperatures can all lead to failed data collection (Bhardwaj et al., 2016; KPark and Ewing, 2017). Similarly, at high elevations, air density conditions might not be compatible with flight (Bhardwaj et al., 2016). The restrictions of the payload are cited in relation to the use of more advanced (and heavy) imaging equipment (Yanmaz et al., 2017) and the distribution of supplies (Chowdhury et al., 2017). Other hardware restrictions mentioned in the literature are the restrictions in flight time due to battery life (Siebert and Teizer, 2014); as technology advances this will undoubtedly improve. Finally, the physical failures of UAVs have been reviewed (Pappot and de Boer, 2015) and the causes attributed to either (1) an external factor in the environment, (2) breakage or malfunction of the technology, or (3) human error. The risk of failure mid-flight has the safety implications for those on the ground, and needs to be considered carefully before use.

In addition to the UAV, the recent advent of cheap and small omnidirectional cameras (e.g. Ricoh Theta S model) and the development of online platforms to host images (e.g. Google Street View and Mapillary) has caused an increase in the application of this type of data collection in the wider published research. A selection of recent applications of the technology will be introduced here, in particular those that focus on a similar application to that investigated by this study. The benefits and challenges associated with the technology will then be discussed.

OD imagery has been used to conduct surveys for various purposes. Examples include classifying land use types along roads, by using algorithms to capture and recognise urban signage (Zhang et al., 2017). Surveys have also gathered environmental indicators such as the presence of recreational facilities, food infrastructure, and general land use to audit neighbourhoods (Clarke et al., 2010). The presence of indicators of cycling and walking functionality, safety, and aesthetics have also been collected using OD images (Badland et al., 2010; Yin et al., 2015). Other environmental and neighbourhood surveys conducted using this technology include investigating the extent of trees (Berland and

Lange, 2017), of tree shade provision (Li et al., 2017), car and pedestrian traffic conditions and safety (Hanson et al., 2013; Yin et al., 2015), the provision of parking facilities (Guo, 2013) and other positive and negative features of a neighbourhood impacting on the health of children (Odgers et al., 2012). Surveys of indicators of crime in neighbourhoods have also been conducted, collecting data on potential indicators of high crime, such as graffiti, litter, and damage to property (Rundle et al., 2011; Mooney et al., 2014; He et al., 2017).

Engineers have used OD imagery to collect damage data on post-earthquake reconnaissance missions, finding that surveying using a virtual environment achieved very similar results to engineers in the field (Stone et al., 2017a). There is currently a single example of OD imagery being used post disaster to assess the recovery of a neighbourhood in New Orleans following Hurricane Katrina, with attributes such as abandoned plots used to identify spatial patterns of recovery speeds (Curtis et al., 2010). There is one study that uses OD imagery to assess the seismic vulnerability of buildings by developing an algorithm that accurately estimates building heights automatically from images collected on fieldwork (Pittore and Wieland, 2012).

An interesting study used OD imagery to collecting building data to assess flooding vulnerability in Athens, Greece (Diakakis et al., 2017). Surveyors collected external building data such as the position and orientation of openings, the presence of garage ramps, column positions, presence of basement door, position of yard, presence of light well, position of building relative to neighbours (Diakakis et al., 2017).

There are a number of key benefits highlighted in the literature related to the use of OD imagery in collected data about buildings or neighbourhoods more in general. The literature agree that the cost involved in street surveys are significantly more than those employing freely available OD images on the Google Street View or Mapillary platforms to conduct virtual (or online) surveys (Badland et al., 2010; Clarke et al., 2010; Rundle et al., 2011; Odgers et al., 2012; Less et al., 2015; Berland and Lange, 2017; He et al., 2017). Authors also agreed that the time and cost of surveying virtually were similar, (Rundle et al., 2011), excluding any resources required for collecting the imagery (Badland et al., 2010; Berland and Lange, 2017; He et al., 2017). The impressive availability of existing data provided by the online, open-access platforms was hailed as a major benefit of these data collection methods (Badland et al., 2010), with the potential for international replicability of systematic methodologies (He et al., 2017) and the wide comparability of results is cited as a key benefit (Badland et al., 2010). Another central benefit that has led to this approach being used for a relatively large number of crime studies, is the remoteness of the surveyor, away from potentially unsafe situations (Rundle et al., 2011; Berland and Lange, 2017; He et al., 2017) and surveying from a much less intrusive perspective (Rundle et al., 2011), where despite the inherent remoteness of the approach, the accuracy in comparison to street surveys collecting the same data is generally accepted to be good (Yin et al., 2015; Berland and Lange, 2017; Stone et al., 2017a;) due to the broad field of vision captured by these types of camera (Jacquey et al., 2008; Curtis et al., 2010;). The remoteness of the survey also removes the impact of poor weather conditions (Berland and Lange, 2017), although this would not be the case if the images were being collected by the researchers.

Some issues were highlighted in the literature, including the issue of the lack of detail available in the OD imagery (Badland et al., 2010; Clarke et al., 2010; Curtis et al., 2010) which meant that the identification or assessment of smaller details, such as litter or signage, was not consistently possible (Rundle et al., 2011; Guo, 2013; Mooney et al., 2014; Vanwolleghem et al., 2014). Similarly gaps in the imagery were cited as restricting some data collection (Rundle et al., 2011; Diakakis et al., 2017), and the presence of automated blurring effects programmed to hide personal identities or advertising also meant that all data was not available to survey (Rundle et al., 2011). A common issue reported was the age of the OD images available in the online platforms meaning that current reality was not represented exactly by the virtual environment (Badland et al., 2010). This causes issues when surveying data that are unstable over short periods of time (e.g. pedestrian and car traffic) (Rundle et al., 2011). Similarly, the impact of the time of day, week, or year had an impact on some of the applications for which OD imagery was used, for example the tree coverage surveys would depend on season Rundle et al., 2011; Mooney et al., 2014; Li et al., 2017). Further challenges were highlighted around surveyor bias (Mooney et al., 2014), although this is a common challenge with all survey data and a robust research design should aim to eliminate much of this. In addition, the lack of general spatial awareness (of nearby rivers, highways and other features) caused by the narrow view of the street only (Mooney et al., 2014) could easily be rectified through the simultaneous use of a free online map platform such as Google Maps, or Bing Maps.

2.3.3. Synthesis of building data collection methods

A number of building data collection methods have been introduced, from the collection and analysis of existing data or knowledge, to methods for collecting new datasets using street-level rapid visual surveys or internal surveys. Increasingly, technological advances in satellite imaging have been adopted and used alongside ever-improving computing power to analyse larger urban areas, despite the restrictions on the top-down perspective, and costs of imagery.

Possible new approaches to building data collection have been reviewed, highlighting the challenges and benefits they might bring. Advantages such as covering large areas, being cost-effective, time-efficient, able to accurately capture complex 3D geometry, and being able to avoid unsafe areas are all complementary to the task of collecting building data in large urban areas, despite a lack of examples of large scale mapping of urban areas for the purpose of assessing buildings or infrastructure in the literature. The challenges reported by users may be overcome by checking restrictions in the research location, the use of multiple batteries, pilot training, good maintenance of the UAV, and including float in the fieldwork timetable to account for possible bad weather. Both high resolution aerial imagery and the development of 3D models from captured imagery could benefit the building data collection process by allowing data to be extracted for less cost, however the data collection abilities are not yet known, as well as the accuracy of virtual surveying methods for this context. This study fills this gap in knowledge by testing the ability of UAV imagery to capture building data and comparing the resulting dataset to datasets collected for the same buildings.

The use of omnidirectional imagery, such as those hosted on Google Street View and Mapillary, or captured using an omnidirectional camera, is an interesting and evolving prospect for the collection of building information (Torii et al., 2009), particularly as the technology becomes more affordable and user-friendly. The use of this imagery could remove the need for skilled groups to conduct street surveying in-situ, by instead doing this remotely with just the images (Pittore and Wieland, 2012; Wieland et al., 2012b). The main benefit of using this type of imagery is to reduce time on the ground (encompassing both cost and time savings and hence improving the effectiveness of this method) in the study location (which may be unsafe or unsuitable for surveying), as well as the ability to share methodologies between researchers and achieve comparable results. There are issues reported in the literature around lack of detail, the age of the images, or other challenges with surveying an image as opposed to being in-situ. Some of these potential downfalls can be overcome by combining omnidirectional imagery with other sources of information (Wieland et al., 2012b). For this study, OD imagery will be collected in the field, therefore there are no timing issues, however the extent of the impacts of the lack of detail in identifying structural characteristics will be uncovered. Using the images collection, the virtual surveying approach will be tested for the first time in application to the assessment of seismic vulnerability: if found to be effective, it would provide global opportunities for accurate and cost-efficient collection of building data for SVAs.

To date in the published literature, there are no studies that directly compare different building data collection methods, despite building data forming a fundamental part of the seismic risk assessment process on which decisions are made on how to spend large sums of money for risk reduction or management. There are benefits and challenges with each method, therefore it is important to ascertain the cost, accuracy, and data collection capabilities of different methods to draw out preferences. Any comparison should also test whether the data collection methods obtain building data that are more important to the SVA process (the concept of useful building data is investigated in Chapter 4). The process of assessing seismic vulnerability, including the collection of input data, could more effective if some this gap in knowledge were filled, therefore this thesis aims to investigate this topic. In Chapter 5 a range of building data collection methods are employed in a case study area and Chapter 6 critically compares the costs, accuracy, and usefulness of datasets collected by each.

In summary, a wide range of existing and new building collection methods have been reviewed in this section, with the focus on the methodology of this study. Individual testing of these methods to compare the cost of collecting the data and with the accuracy of the resulting datasets as well as assessing the ability of each method to collect the important or ‘more useful’ building data, will determine the most effective methods of data collection. The inclusion of new technologies in the tested methodologies add an additional novel aspect to this study.

2.4. Summary

This chapter has identified some of the gaps in current knowledge in the field of seismic risk assessments, particularly around the relationship between exposure and vulnerability. These findings highlight the following lacunas that this study aims to explore.

- The relationship between exposure and vulnerability is not well studied.

There is an imbalance in the academic literature, which more focusses on assessing seismic hazard and vulnerability, whilst seismic exposure and the relationship it has with the assessment of seismic vulnerability, receives very little attention. In particular, the key building data for an accurate seismic vulnerability assessment is not well-defined and is, thus, investigated herein.

- The effectiveness of a range of building data collection methods is not known.

There is no 'best practice' methods for collecting building data for the assessment of seismic vulnerability. A range of methods are presented in the literature, with different benefits and challenges, but there exist no direct comparisons to highlight the more effective, complete, accurate, or cost-efficient method. This series of tests is studied herein, inclusive of methods that utilise emerging technology, including UAVs or omnidirectional cameras and virtual surveys, which have a number of advantages and shortcomings.

- The scale of the impact that differences in building data have on results of seismic risk assessments is not known.

Uncertainty in seismic risk assessments is widespread, accumulating from ever input and modelling technique employed. The scale of uncertainty caused by the seismic hazard components is fairly well studied, and is increasing for the seismic vulnerability component. Uncertainty caused by seismic exposure components, however, has little attention. This study aims to highlight the potential range of risk results given building datasets collected using a range of methods to highlight the potential impact that poor building data could have.

Based on these findings, the next chapter lays out the research methodology. The processes employed aim to tackle the gaps in knowledge highlighted in this chapter.

Chapter 3

Research methodology

3. Research methodology

In the previous chapter a number of gaps were highlighted in the academic literature. This chapter explains the methodology used in the rest of this study to address these gaps.

3.1. Investigating the usefulness of inputs to seismic vulnerability assessments (Chapter 4)

Three separate literature analyses are used to determine which building characteristics are more useful for inputting to seismic vulnerability assessment methods. The three different approaches are used in order to corroborate results. As analytical methods use structural information to build structural models, only these approaches are considered in this analysis. All construction types are considered in this analysis together. Depending on agreement between the separate literature reviews, building characteristics are labelled as high, moderate, or low in usefulness. The individual methods and assumptions are explained below:

1. Index-based methods simplify the assessment of seismic vulnerability by – amongst other things – reducing the number of inputs required, hence only the most important characteristics relating to the seismic response of a building are used. The frequency that different inputs are used in published index methods is used as a measure for usefulness: the more frequently used, the more useful an input is assumed.

   All index methods found in a wide search of the literature are included in this review. Search terms such as ‘index method’, ‘seismic vulnerability’, and ‘rapid screening procedure’ were used to find studies.

The search primarily focussed on methods in journal papers, but if reputable institutional authors had published a method (e.g. FEMA, NORSAR, or a government institution) then this was also included. The methods are reviewed and the required inputs extracted. Inputs are thematically coded (Bryman, 2008) into groups of similar characteristics. Arbitrarily, if less than 20% of the studies required an input it was designated as 'low usefulness, between 20% and 40% of studies employed the input it was labelled as being of 'moderate usefulness', and above 40% it was denoted as being of 'high usefulness'. This analysis results in a list of inputs with corresponding levels of usefulness.

This methodology extends one study that compares inputs used by six index-based methods (Tezcan et al., 2011), by including a larger number of studies and analysing the frequency of parameter usage. The collation of literature, review and coding process would benefit from multiple independent reviewers to ensure robustness in the results (e.g. Mountain (2017)), however this is beyond the scope and resources of this study.

2. Sensitivity analyses of SVA methods highlight the importance of different data inputs. A systematic review is used to extract the more sensitive inputs, and a meta-analysis (e.g. Bryman (2008)) checks for agreement between different studies to corroborate which data should be considered of high, moderate, or low usefulness.

   An extensive literature search is completed for publications reporting either results from sensitivity analyses, or recommendations about input building data priorities. These studies are all concerned with analytical SVA methods. A large range of structural typologies, building characteristics, and analysis methods are covered by the studies found.

   The meta-analysis focusses on the conclusions of these studies; whether a characteristic is of high, moderate, or low importance in terms of sensitivity. For validation of the results across the different sensitivity analysis studies, a number of conditions are required to be met:

a. Two or more studies must agree on the level of importance of a characteristic.

b. More than half of the studies that investigate a certain characteristic must report the same levels of importance.

The level of importance of the building characteristics studied is deemed correct if the results can be validated.

3. The GEM conducted extensive work on the classification of building type and, hence, developed a taxonomy system that uses the characteristics required to best understand seismic behaviour, and employs levels (1-5) to highlight the key building characteristics (Brzev et al., 2013). The attributes and the corresponding levels (1-5) were derived using the collective judgement of the GEM community. The level 1 data types are the most fundamental building characteristics; the data thought by the GEM community to be of paramount importance to defining a building typology in terms of seismic risk. Employing the assumption that the level 1 attributes are more useful, herein they are designated to be of high usefulness.

Results from these three steps are compared and results presented. The scale of the data types tested by the different methods mean that often there is a mismatch when comparing, for example, one study may assess the sensitivity of a beam's strength in a frame, whereas others may study a data type that influences the beam strength, such as beam cross-sectional area, beam material properties, etc. These differences are coped with by retaining all scales of data, despite the resulting overlaps.

Building characteristics which are consistently considered to be of a certain level of importance (across the methods which study it) are given that level of usefulness. If results disagree about the level of usefulness but have at least one score of high importance, the characteristic is assumed to be of moderate usefulness. All the other attributes are considered to be of low importance.

There are inherent challenges associated with using these proxies to define 'usefulness', namely that index-based SVA methods may be set up with data that are widely-available or easy to collect in mind. However, given that empirical relationships, analytical validation, or expert judgement are used to inform the published index methods, the extensive research of the GEM, and the validation required in the sensitivity analysis review, challenges are not considered prohibitive. This review, by combining the opinions of the body of literature, is a form of expert judgement (Cooke, 1991) where biases and heuristics in individual results are reduced through the adoption of systematic processes that pool judgements together to achieve general consensus.

3.2. Testing the collection of building data using different methods in Guatemala City and assessing the effectiveness of building data collection methods (Chapter 5 and 6)

Another challenge highlighted in the literature review is the lack of investigation on the most effective methods for collecting building data for at-risk urban areas; particularly focusing on collecting the useful inputs for seismic vulnerability assessments (as derived in Chapter 4). To address this, a range of data collection methods are employed in a case study area and results compared to evaluate effectiveness.

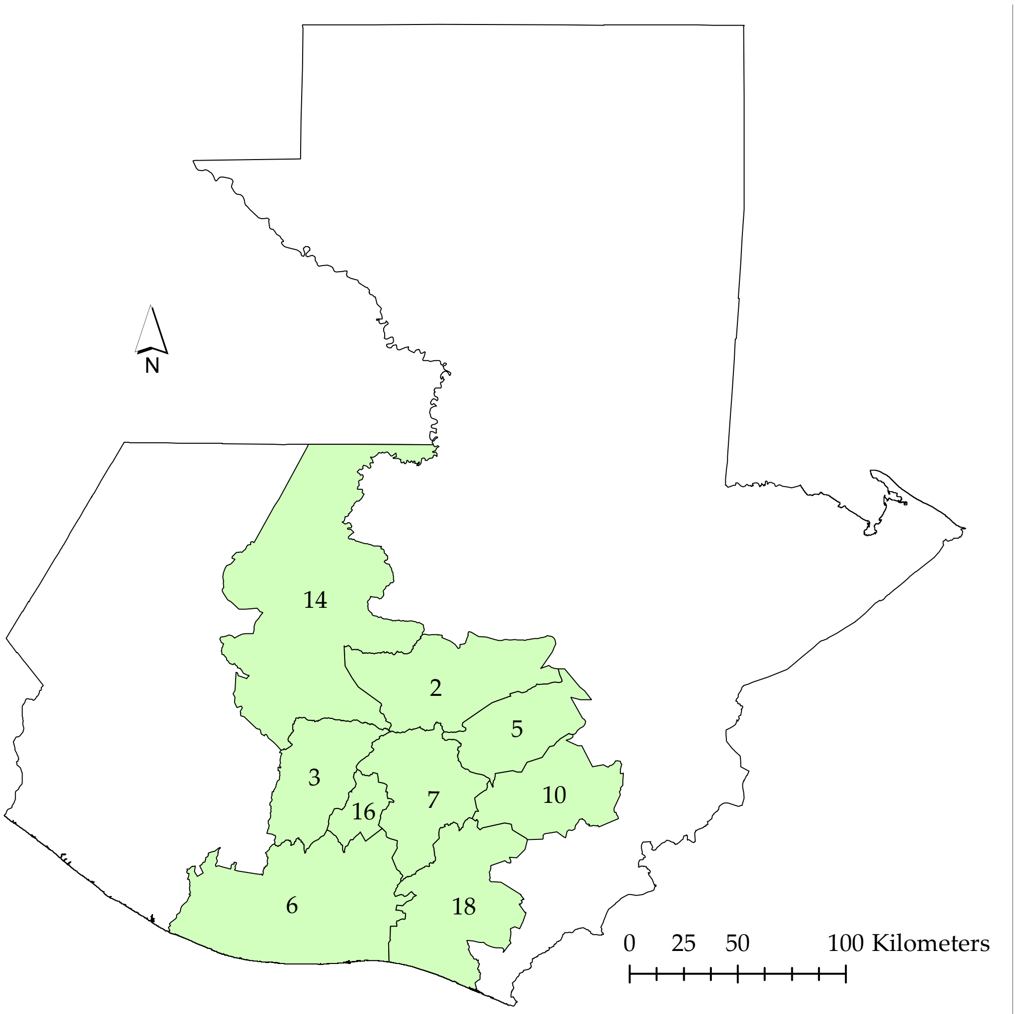
3.2.1. Selecting the case study area

A case study area in the region of Central America was sought, as this region is very little understood in the seismic risk literature (Stone, 2015; Yepes et al., 2016), despite being subjected to large earthquakes, including devastating events in Managua (1972), Guatemala City (1976), and San Salvador (1986). Selecting a case study area in the Central American isthmus provides a relatively clean slate with which to investigate the thesis, a fairly rare opportunity to provide results that break ground, simply due to location, and the opportunity to collect data that the industrial partner of this project (the World Bank Group) could use directly to help achieve their poverty reduction mandate.

An urban context is selected as a case study due to the spatial concentration of risk and the resources available in this study. Guatemala City is chosen as the case study city as it is a typical Central American city, with colonial roots, and a history of deadly civil war, poverty, poor construction standards, and periodic earthquakes. It is an excellent case of rapid urban sprawl observed in all of Central America’s largest cities which breads potentially seismically vulnerable building stock. Although there are likely to be characteristics unique to different cities in the region, there are likely to be many commonalities which will add an element of transferability of the findings herein.

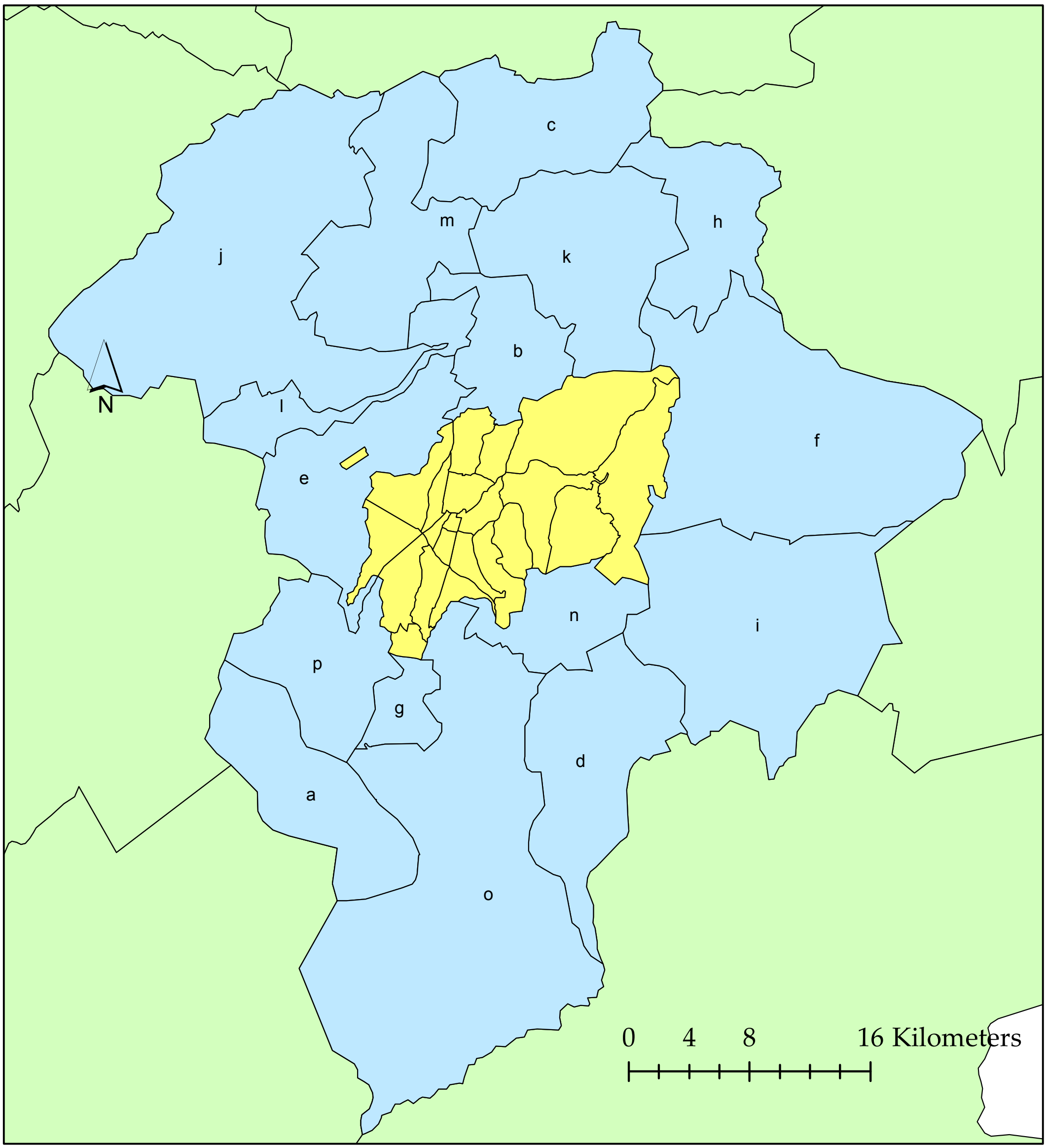
Guatemala City is the largest city in the Republic of Guatemala, and is the largest in terms of population in all of Central America, see Figure 3-1. It was designated as the capital in 1775 after a large earthquake destroyed much of the previous capital, Antigua. The city is located within the *Municipalidad de la Ciudad de Guatemala* (Guatemala City Municipality) which is part of the *Departamento de Guatemala* (Department of Guatemala): Figure 3-2 and Figure 3-3 show the situation of these locations. The metropolitan area of the current city is divided in twenty-two zones, number from one to twenty-five (zones twenty, twenty-two, and twenty-three do not exist), and the most densely urbanised zones (for example see Figure 3-5) are selected as the study area and denoted using a red boundary line in Figure 3-4.

Figure 3-1 Aerial photo looking south towards Volcán Agua (left) and Volcán Fuego (right) over Guatemala City in November 2007. © Ing. Omar Flores Beltetón



Reference	Department name
2	Baja Verapaz
3	Chimaltenango
5	El Progreso
6	Escuintla
7	Guatemala
10	Jalapa
14	Quiché
16	Sacatepéquez
18	Santa Rosa

Figure 3-2 Neighbouring departments to Guatemala department (number 7)



Reference	Municipality name
a	Amatitlán
b	Chinautla
c	Churrancho
d	Fraijanes
e	Mixco
f	Palencia
g	San Miguel Petapa
h	San José del Golfo
i	San José Pinula
j	San Juan Sacatepéquez
k	San Pedro Ayampuc
l	San Pedro Sacatepéquez
m	San Raymundo
n	Santa Catarina Pinula
o	Villa Canales
p	Villa Nueva

Figure 3-3 Municipalities within the Department of Guatemala. Yellow denotes the Guatemala City municipality (see Figure 3-4).

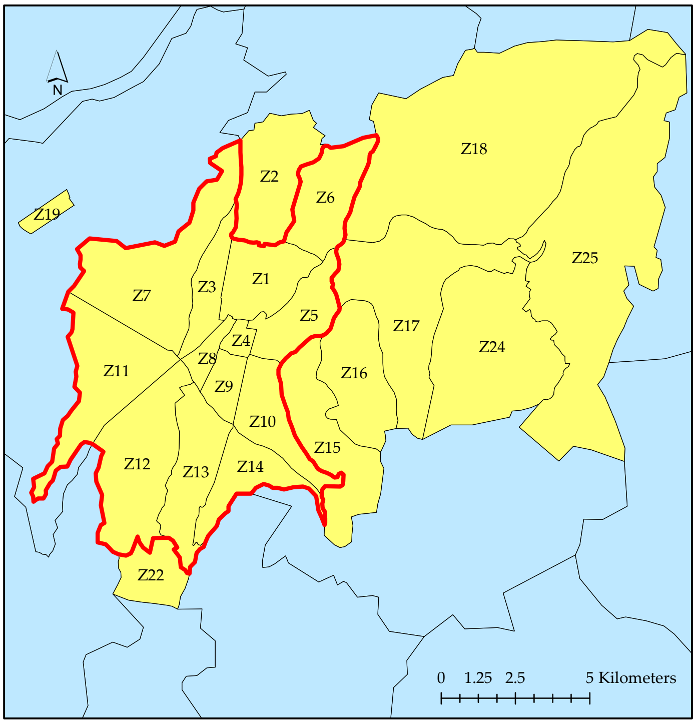


Figure 3-4 Map of the Guatemala City municipality with the zone numbers (Z#). The red boundary highlights the densely urbanised area, as in Figure 3-5.

The city often perceives minor earthquake tremors, and suffered two devastating earthquakes, in 1912-3, and 1976. The city is a miscellany of poorer informal areas, poorer semi-formal areas combining low-end residential buildings with large industrial operations, and richer formal areas combining white-collar businesses and high-end residential buildings. The transportation networks are all road based (car and buses) (an old railroad system now disused), thus congestion and traffic jams are rife. Crime is also widespread.

The department of Guatemala has an estimated population of just over 3.5 million, (INE, 2015), and the number of buildings is likely to be in the order of a hundred thousand. Sampling is therefore vital to collecting building data in the city. Three phases of systematic sampling were used to determine seven locations for surveys in the study area. Assuming the city follows Tobler's law of spatial autocorrelation (Tobler, 1970) (i.e. that neighbouring buildings share similar characteristics related to seismic vulnerability, e.g. age, construction materials, occupation (Pittore and Wieland, 2012)), the aim of the sampling was to survey areas spread out throughout the city in enough detail to understand the characteristics of that neighbourhood. By examining different areas and extrapolating results locally (e.g. by zone), a satisfactory balance was struck between a manageable survey program, and investigations of the range of different urban neighbourhoods that make up the city.

The first phase of sampling ensured that surveys would take place in different municipal zones, see Figure 3-4. The second sampling phase used a 2km square grid drawn on top of the study area, see Figure 3-5, and survey locations were spread between grid squares that were fully contained within the study area (in Figure 3-5 these are shaded in green). The third phase of systematic sampling involved the use of dartboard segments which is appropriate for use in cities which tend to radiate out from a central area, see Figure 3-6. In fact, Guatemala City has grown disproportionately towards the south due to topographical constraints towards the north, however the dartboard sampling was still considered to be a worthwhile phase in the selection of survey locations. The location of a substantial existing survey dataset from the RESIS II project (Lang et al., 2009a) was omitted from this sampling phase as the area (in zone 11) has already been surveyed extensively.

The multi-phase sampling process highlighted potential areas for surveying. It was proposed that the final survey locations would be located randomly within these potential survey areas, however safety concerns were a priority, so instead they were selected with the expertise of locals, who advised on safe and unsafe areas to access within the selected areas. The final street survey routes were in the centre of the safe parts of the selected areas. Avoiding the unsafe areas may have resulted in a biased dataset; one that excluded a set of different building typologies common in these areas, however methods that avoid the need to enter a survey area directly (e.g. using UAVs) or that allow imagery to be taken from a vehicle and virtually surveyed (e.g. omnidirectional imagery) are tested in this work, so although the safety was not compromised in this project, in the future these methods may enable surveyors to collect less biased datasets in dangerous study areas.

The survey routes are presented in detail in Appendix F. The field-based data collection methods were tested in these sampled survey areas. The methodologies applied are explained in more detail in subsequent sections.

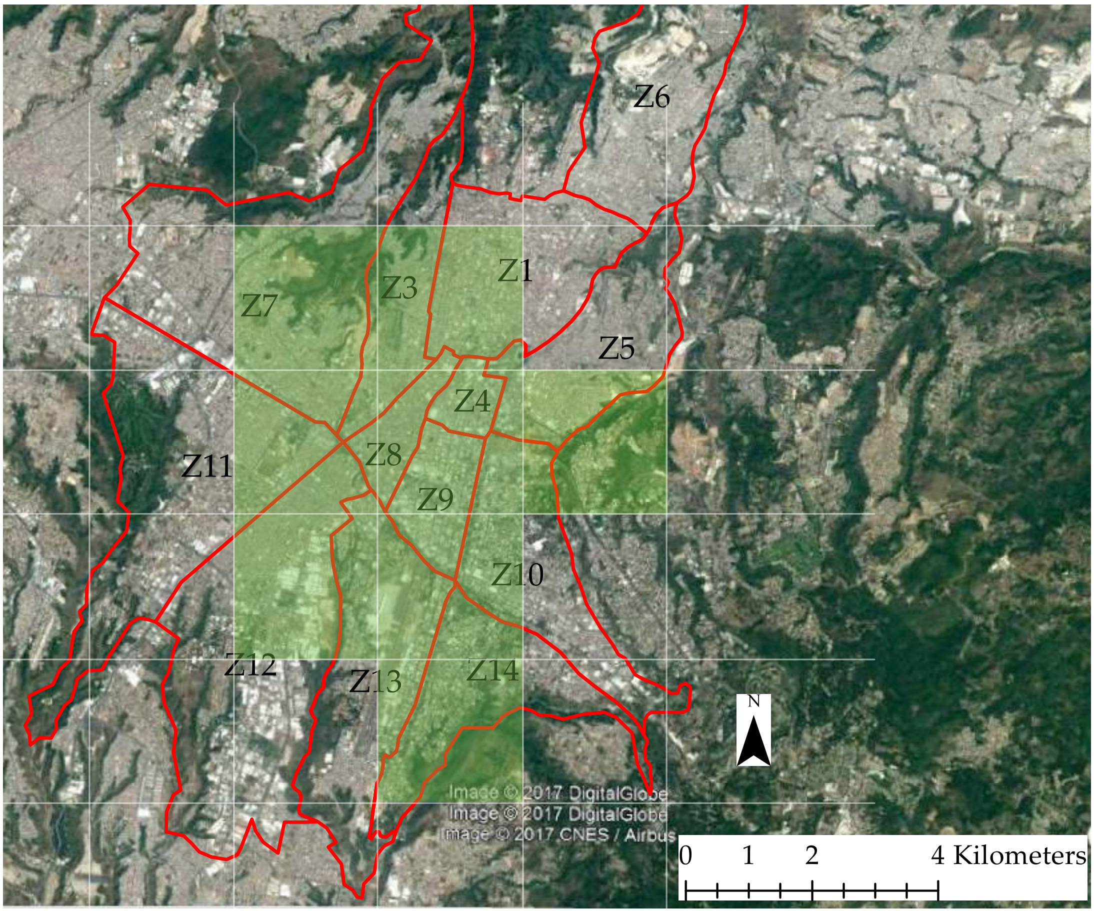


Figure 3-5 Sampling grid over the study area boundary in red

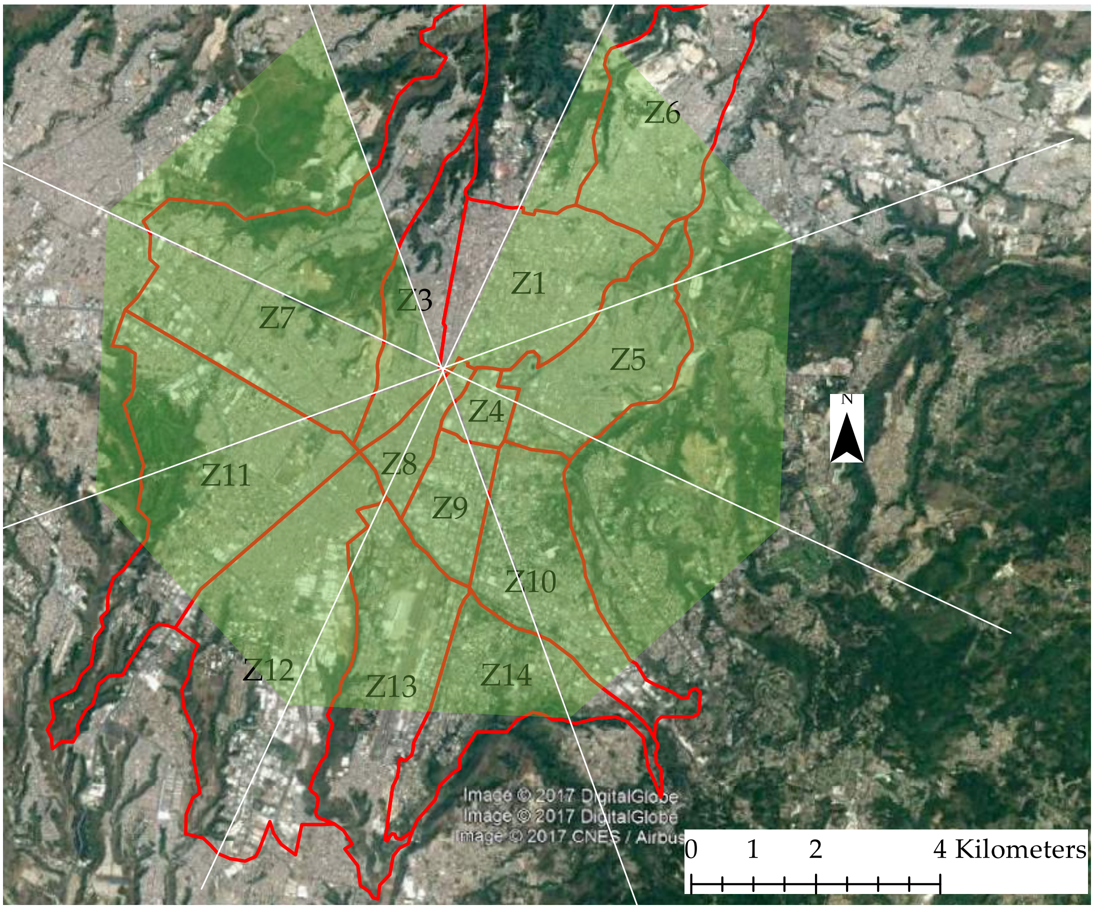


Figure 3-6 Sampling dartboard over the study area boundary in red

3.2.2. The data collection methods tested

Building data is both important to seismic vulnerability and risk assessments and very challenging to collect. The process is costly; fraught with errors, biases, heuristics; time consuming; and, in some circumstances, dangerous. The amount of data that could be collected is vast, so effective choices and statistical techniques are required to arrive at an acceptable procedure for collecting and modelling exposure. Heretofore, methods such as rapid visual surveys (e.g. ATC (2002)), analysis of the housing census data (e.g. Sousa et al. (2017a)), and recent advances in imaging technology (Pittore and Wieland, 2012), have been used to collect building data with varying associated costs, timings, quality of results, and amount of more useful data captured, however, as highlighted in Chapter 2, there is little critical analysis of the most effective methods for obtaining these data. Hence, this chapter tests the ability of different data collection methods to collate building data using both desk- and field-based methods. Desk-based methods tend to collect more qualitative data, whilst field-based methods collect quantitative data building-by-building. The qualitative data collected is used to inform a historical timeline and building information repository whilst quantitative data allows the direct formation of building inventory datasets. Building inventory datasets can also be developed using assumptions and judgement given qualitative data. Some of the methods tested combine field- and desk-based methods by collecting imagery in the field, and analysing it after the field-work in a process referred to herein as 'virtual surveying'.

The methods tested are listed in Table 3-1 and explained below, and their application is explained in detail in Chapter 5. The desk-based methods tested include analysis of historical texts and maps showing how the city grew and any significant changes in construction practices over time, allowing the age of regions in the city and the predominant construction materials for those periods to be understood. Large events such as earthquakes or other disasters can lead to a partial renewal of the building stock so focussing of the types of buildings that were damaged and demolished, and the implementation of regulations can identify step changes in the quality of construction on a wide scale. Reviewing existing literature, in particular, documents containing previous risk assessments, can provide indications as to the type of buildings that may be found in the study area. Analysis of the housing census data can also be completed remotely, giving an aggregated overview of building materials. Desk-based data collection methods depend on the data available and are generally much less resource intensive than field-based methods, but despite not collecting building-by-building details, they can provide valuable insight into the study area. These seven desk-based building data collection methods were tested between 2014 and 2017.

Field-based data collection methods usually collect building-by-building information using different external viewpoints or by entering a building.

Rapid visual surveys are tested in the field area using a form to collect data from street level. Comparisons are drawn between results from three groups with different engineering experience and different levels of knowledge about the study area. With the advent of omnidirectional cameras, the collection of virtual street imagery enables street surveys to be conducted in a virtual environment: if imagery already exists in the public domain, for example on platforms such as Google Street View or Mapillary, then virtual surveys could be considered a desk-based data collection method. OD imagery was collected for the study area. UAVs continue to rapidly advance in capability, and can provide an aerial viewpoint that was previously difficult or prohibitively expensive to obtain. This viewpoint gives the ability to collect accurate data about the roof and plan shape. UAV imagery can also be used to construct 3D models of survey areas, which gives a virtual surveyor many useful external viewpoints of a building and therefore more opportunities for collecting good quality data. Internal surveys are much more detailed as there is much more to be learnt about a building from the inside. These surveys take much longer than any other method tested in the study area, but do ensure that a full understanding of a building is gained. Finally, interviews with local experts are also a valuable source of information about design and construction regulations and building practices in recent history: although they are usually conducted in the field, the data collected tend to enrich findings from desk-based methods.

These field-based methods were all tested, alongside colleagues from the *Universidad de San Carlos* (University of San Carlos) the country's oldest university (founded in 1676, one hundred and fifty years before University College London), between July and September 2016 using the buildings in the metropolitan area of Guatemala City as the laboratory. Post-processing, virtual surveying, and analysis continued into 2017.

Method description	Code name	Desk- or field-based	Type of data collected
Review and analysis of historical maps and remotely-sensed imagery	HM	Desk-based	Qualitative
Review of construction regulations and guidelines	Regs	Desk-based	Qualitative
Review of damage and recovery from past significant earthquakes	EQ	Desk-based	Qualitative and quantitative
Analysis of national housing census data (1994 and 2002)	Census	Desk-based	Quantitative
Review of municipality city maps	MM	Desk-based	Quantitative
Review of relevant existing literature	ES	Desk-based	Qualitative and quantitative
Review of existing building imagery	BI	Desk-based	Qualitative
Rapid visual surveys (RVS) completed by a local engineer (LE), a foreign engineer (FE), and local students (STU)	RVS LE RVS FE RVS STU	Field-based	Quantitative
Omnidirectional imagery collection with subsequent virtual surveys completed by an engineer in the UK	OD	Field-based & desk-based	Quantitative
UAV collection of high-resolution top-down aerial imagery with subsequent post-processing and virtual surveys completed by an engineer in the UK	AS (aerial survey)	Field-based & desk-based	Quantitative
UAV collection of high-resolution aerial imagery, post-processing to derive a 3D surface model, used for virtual surveys completed by an engineer in the UK	3D	Field-based & desk-based	Quantitative
Detailed internal surveys	DIS	Field-based	Quantitative

Table 3-1 The data collection methodologies tested on Guatemala City

Chapter 6 further analyses theses data collected to draw conclusions in terms of data usefulness, data cost, and data accuracy, all of which are important when assessing the effectiveness of different methods.

3.2.3. The data types to be collected

The desk-based methods sought any data that could be added to a historical timeline that tells the story of the development of Guatemala City over time, or a repository of structural information collect from various sources. Data includes general socio-economic statistics in addition to key events in history that may have impacted on the types, directions, methods, or ages of development. These data are, in generally, qualitative (see Table 3-1) and are therefore used in a very different way to the mostly quantitative data collected using field-based methods.

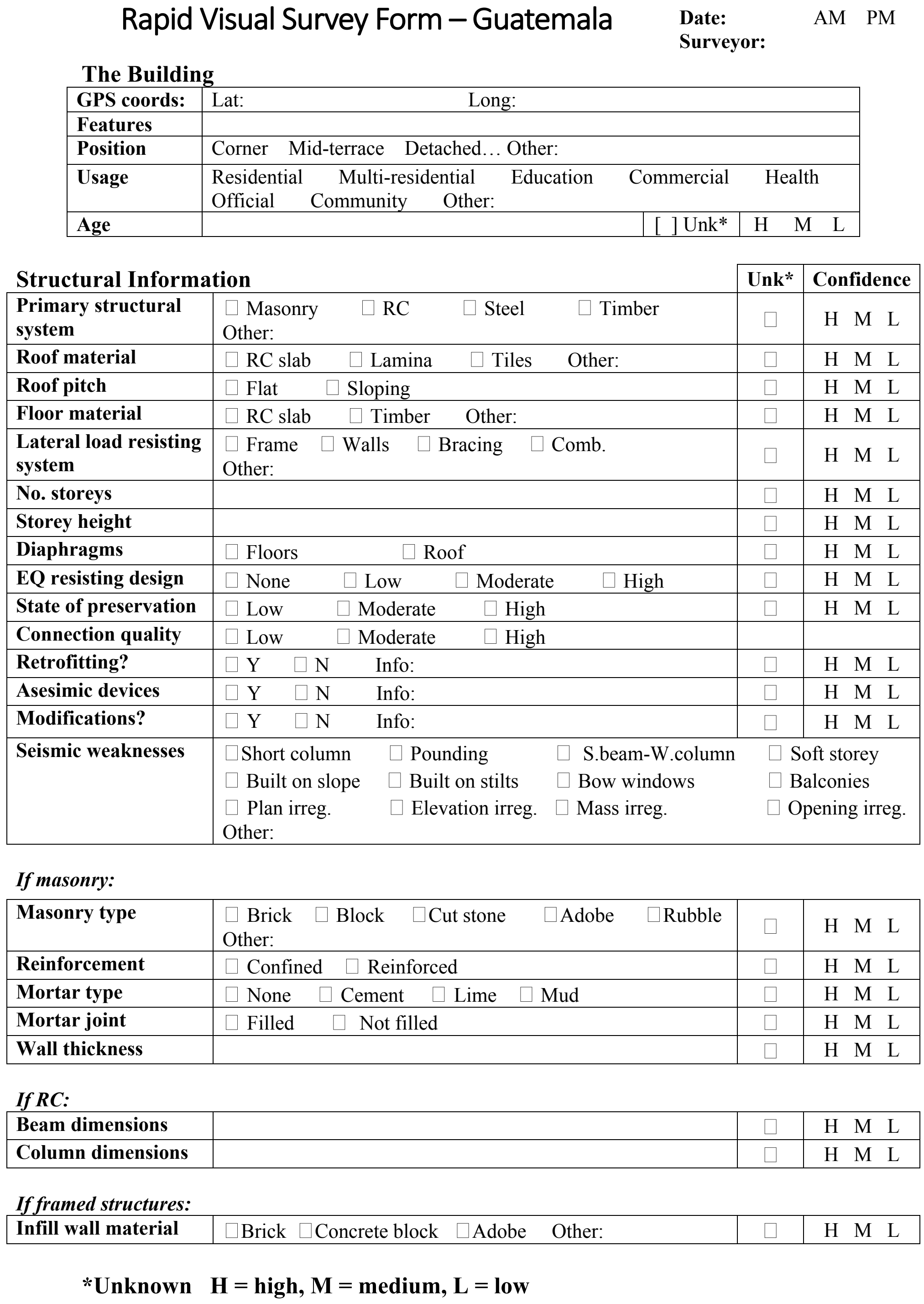
Using the literature reviewed in Chapter 4, thirty-five building characteristics were sought by the field-based methods. These characteristics are explained in detail, along with the recording options, in Table 3-2. The survey form developed to allow the collection of this data through the RVS methods is given in Figure 3-7. These characteristics are given in Table 3-3 alongside an indication of which data are collected using the different field-based methods. These indications show what data were collected and do not represent the extents of potential for data collection. Clearly, the aerial survey, and 3D model survey do not collect enough data to determine individual exposure profiles as the primary structural material and LLRS are both not collected. Although the methods will be deployed and tested on their own, the resulting datasets will be combined with the OD datasets for the further analysis and development of exposure profiles completed later in this study. This allows the comparison of the newer technology with the traditional street survey methods.

Building characteristic	Description	Options
Position	The position of a building in a block.	Corner, Mid-terrace, Detached, Other
Usage	The use of the building.	Residential, Multi-residential, Education, Commercial, Health, Official, Community, Other
Age	The age of the building.	Modern, Mid-age, Old, Unknown
Age [years]	The age, in years, of the building.	Numerical
Primary structural material	The primary structural material of the building, used to form the vertical and lateral load resisting systems.	Masonry, RC, Steel, Timber, Other, Unknown
Roof material	The material used as the roof finish of the building.	RC slab, Sheet metal, Tiles, Combination, Other, Unknown
Roof pitch	The pitch of the roof on the building.	Flat, Sloping, Unknown
Floor material	The material used as the floor structure in the building.	RC slab, Timber, Unknown
LLRS	The lateral load resisting system type on the building.	Frames, Walls, Bracing, Combination, Other, Unknown
No. storeys	The maximum number of storeys of the building.	Numerical
Storey height	The height of each storey in the building.	Numerical
Diaphragms	The locations of rigid diaphragms in the building.	Roof, Floors, Roof & floors, None, Unknown
EQ resisting design	The level of earthquake resisting design in the building.	None, Low, Moderate, High, Unknown
State of preservation	The state of preservation in the building.	Low, Moderate, High, Unknown
Connection quality	The quality of the connections between structural elements in the building.	Y, N, Unknown
Retrofitting	The presence of any seismic retrofitting in the building.	Y, N, Unknown
Aseismic devices	The presence of any aseismic devices in the building.	Y, N, Unknown
Modifications	The presence of any modifications to the original structure of the building.	Y, N, Unknown
Short column	The presence of short column weaknesses (also known as captive columns) in the building.	Y, N, Unknown
Pounding	The potential for seismic pounding to occur between the building and any neighbouring structures.	Y, N, Unknown
SBWC	The presence of strong-beam weak-column weaknesses in the building.	Y, N, Unknown
Soft storey	The presence of a soft storey in the building, defined as a single storey that lacks the lateral strength or stiffness of the others.	Y, N, Unknown
Built on slope	The situation of the building is on sloped ground.	Y, N, Unknown
Built on stilts	The building is raised above ground level on stilts.	Y, N, Unknown
Bow windows	The building has bow windows that cantilever out from the façade.	Y, N, Unknown
Balconies	The building has balconies that extend beyond the main façade.	Y, N, Unknown
Plan irregularities	The building in plan is irregular in shape.	Y, N, Unknown
Elevation irregularities	The building has irregularities in elevation (in stiffness or shape).	Y, N, Unknown
Mass irregularities	The building has irregularities in mass over its height.	Y, N, Unknown
Opening irregularities	The openings in the building's façade do not line up vertically or horizontally.	Y, N, Unknown
Masonry type	If the primary structural material is masonry, the type of masonry with which the building is constructed?	Brick, Block, Cut stone, Adobe, Rubble, Other, Unknown
Reinforcement type	If the primary structural material is masonry, is the masonry confined, reinforced (using any method), or unreinforced?	Confined, Reinforced, None, Unknown
Mortar type	If the primary structural material is masonry, what is the mortar type used to construct the buildings masonry structure?	None, Cement, Lime, Mud, Unknown
Mortar joints	If the primary structural material is masonry, how filled are the mortar joints in the buildings masonry structure?	Filled, Not filled, Unknown
Wall thickness	If the primary structural material is masonry, how thick are the structural masonry walls of the building?	Numerical

Table 3-2 Building characteristics sought by the data collection methods

Building characteristic	Field-based data collection method						
	DIS	RVS LE	RVS FE	RVS STU	OD	AS	3D
Position	•	•	•	•	•	•	•
Usage	•	•	•	•	•		
Age	•	•	•	•	•		
Age [years]	•	•	•	•			
Primary structural material	•	•	•	•	•		
Roof material	•	•	•	•	•	•	•
Roof pitch	•	•	•	•	•		•
Floor material	•	•	•	•	•		
LLRS	•	•	•	•	•		
No. storeys	•	•	•	•	•		•
Storey height	•	•	•	•			
Diaphragms	•	•	•	•		•	
EQ resisting design	•	•	•	•	•		
State of preservation	•	•	•	•	•		
Connection quality	•	•	•	•			
Retrofitting	•	•	•	•	•		
Aseismic devices	•	•	•	•	•		
Modifications	•	•	•	•	•	•	•
Short column	•	•	•	•	•		
Pounding	•	•	•	•	•	•	•
SBWC	•	•	•	•	•		
Soft storey	•	•	•	•	•		•
Built on slope	•	•	•	•	•		•
Built on stilts	•	•	•	•	•		•
Bow windows	•	•	•	•	•	•	•
Balconies	•	•	•	•	•	•	•
Plan irregularities	•	•	•	•	•	•	•
Elevation irregularities	•	•	•	•	•		•
Mass irregularities	•	•	•	•	•		•
Opening irregularities	•	•	•	•	•		•
Masonry type	•	•	•	•	•		
Reinforcement type	•	•	•	•			
Mortar type	•	•	•	•			
Mortar joints	•	•	•	•			
Wall thickness	•	•	•	•			

Table 3-3 Building characteristics for collection by test methods



Rapid Visual Survey Form – Guatemala

Date: AM PM
Surveyor:

The Building

GPS coords:	Lat: Long:		
Features			
Position	Corner Mid-terrace Detached… Other:		
Usage	Residential Multi-residential Education Commercial Health Official Community Other:		
Age		[ ] Unk*	H M L

Structural Information		**Unk***	**Confidence**
Primary structural system	☐ Masonry ☐ RC ☐ Steel ☐ Timber Other:	☐	H M L
Roof material	☐ RC slab ☐ Lamina ☐ Tiles Other:	☐	H M L
Roof pitch	☐ Flat ☐ Sloping	☐	H M L
Floor material	☐ RC slab ☐ Timber Other:	☐	H M L
Lateral load resisting system	☐ Frame ☐ Walls ☐ Bracing ☐ Comb. Other:	☐	H M L
No. storeys		☐	H M L
Storey height		☐	H M L
Diaphragms	☐ Floors ☐ Roof	☐	H M L
EQ resisting design	☐ None ☐ Low ☐ Moderate ☐ High	☐	H M L
State of preservation	☐ Low ☐ Moderate ☐ High	☐	H M L
Connection quality	☐ Low ☐ Moderate ☐ High		
Retrofitting?	☐ Y ☐ N Info:	☐	H M L
Asesimic devices	☐ Y ☐ N Info:	☐	H M L
Modifications?	☐ Y ☐ N Info:	☐	H M L
Seismic weaknesses	☐Short column ☐ Pounding ☐ S.beam-W.column ☐ Soft storey ☐ Built on slope ☐ Built on stilts ☐ Bow windows ☐ Balconies ☐ Plan irreg. ☐ Elevation irreg. ☐ Mass irreg. ☐ Opening irreg. Other:		

If masonry:

Masonry type	☐ Brick ☐ Block ☐Cut stone ☐Adobe ☐Rubble Other:	☐	H M L
Reinforcement	☐ Confined ☐ Reinforced	☐	H M L
Mortar type	☐ None ☐ Cement ☐ Lime ☐ Mud	☐	H M L
Mortar joint	☐ Filled ☐ Not filled	☐	H M L
Wall thickness		☐	H M L

If RC:

Beam dimensions		☐	H M L
Column dimensions		☐	H M L

If framed structures:

Infill wall material	☐Brick ☐Concrete block ☐Adobe Other:	☐	H M L

***Unknown H = high, M = medium, L = low**

Figure 3-7 Survey form in English. A translated form in Spanish is given in Appendix G.

Using the data collected in Chapter 5, three aspects are investigated in Chapter 6 to assess the effectiveness of different building data collection methods. An effective method is defined as one that provides useful (as defined in Chapter 4), accurate data, at a low cost. These three attributes are interlinked and in tension with each other, however this analysis will highlight any methods that perform well across the board.

Measuring the usefulness of data is challenging, and is tackled in Chapter 4 which explores the importance of different data types, using a series of results from literature reviews on the sensitivity of input data to SVAs, the frequency of use of the input data across a number of SVAs, and the level 1 GEM taxonomy characteristics to conclude which data are highly, moderately, or less useful. The cost of the data collected is calculated from the actual costs of the work completed in Chapter 5. Pay rates are assumed at a reasonable rate and can be altered to suit different applications, as can the fixed costs. The accuracy of the results from each data collection methodology is determined using a series of inter-rater agreement assessments, based on the level of consensus when comparing different survey results for the same building against an assumed reasonable truth.

3.2.4. Assessing the effectiveness of data collection methods

In this study, the effectiveness of data collection methods is defined as follows:

$effectiveness = f(cost, accuracy, usefulness)$, where:

$$cost = \frac{cost\ of\ data\ collection\ method\ (per\ building)}{number\ of\ characteristics\ collected\ (per\ building)}$$

$$accuracy = \frac{number\ of\ correct\ characteristics\ collected}{total\ number\ of\ characteristics\ collected}$$

$$usefulness = \frac{\sum(usefulness\ score\ of\ characteristics\ collected\ by\ method)}{total\ number\ of\ characteristics\ collected}$$

As such, the effectiveness is only evaluated for the field-based methods, as the accuracy can be assessed for the data on a building-by-building basis. The methodologies of estimating the components of effectiveness are explained in detail in Chapter 6.

3.3. Assessing the impacts of building data collection methods on seismic risk evaluation (Chapter 7)

This chapter aims to run a simple risk assessment to highlight potential future research directions. The first step of this assessment is the classification of buildings in each data collection method's dataset, resulting in proportions of building typologies: for this, the PAGER taxonomy (Porter et al., 2008) is employed in this study. Once the proportions of building types have been determined, the seismic vulnerability is assessed.

The simplest way of obtaining seismic vulnerability functions is to select and use functions that already exist in the literature. A method for selecting functions with a more standardised approach is used to select functions for the PAGER building classes.

These functions are used to calculate loss ratios for the building class proportions derived from each data collection method dataset. The magnitude of the range of loss ratios offers preliminary views on the range in seismic loss assessments caused by the differences in exposure profiles caused by different building data collection methods and other uncertainty sources from the seismic risk assessment process.

3.4. Summary

This chapter introduces a number of techniques that are used to argue the thesis, and these are summarised in Figure 3-8.

The review and analysis of the existing body of literature is used to meet objectives 1 and 2. This is limited in the sense that the literature is incomplete, however gathering and analysis of a collection of published findings is similar to collating a group of experts and eliciting their judgements. Agreement between methods is sought to corroborate results.

A period of fieldwork in Guatemala City allowed for the testing of different building data collection methods and the subsequent costing and evaluation of accuracy. Desk- and field-based methods are employed including widely used methods such as rapid visual surveys (RVSs), and those employing new technology (unmanned aerial vehicles (UAVs) and omnidirectional (OD) cameras). Results from this are likely to differ between each available case study in the world, with different buildings, layouts, histories, existing datasets, geographical features, legislation, social development, etc.; all variables of influence to the results. The resources of this study only allowed the study of one city therefore a single viewpoint is provided, however there remains important value in the novelty of the study.

Once building data is collected from the case study location, buildings are classified into groups of similar seismic response using systems published in the literature. Fragility functions representing the probability of damage with earthquake intensity are selected from a database of existing functions using a novel framework, devised in an attempt to improve this commonplace practice. Although the selection of these relationships will impact on the final loss ratios, it is the difference between loss ratios (i.e. the range in results that arises between different data collection methods) that are of primary interest is this study.

Additionally, the impacts on risk are not considered in a financial sense (i.e. in dollars) but instead the analysis (for pragmatic reasons) focuses on the expected mean damage ratios defined as the mean ratio of replacement costs to total value of assets. This approach means that results are relatable to those developed for other locations in the future.

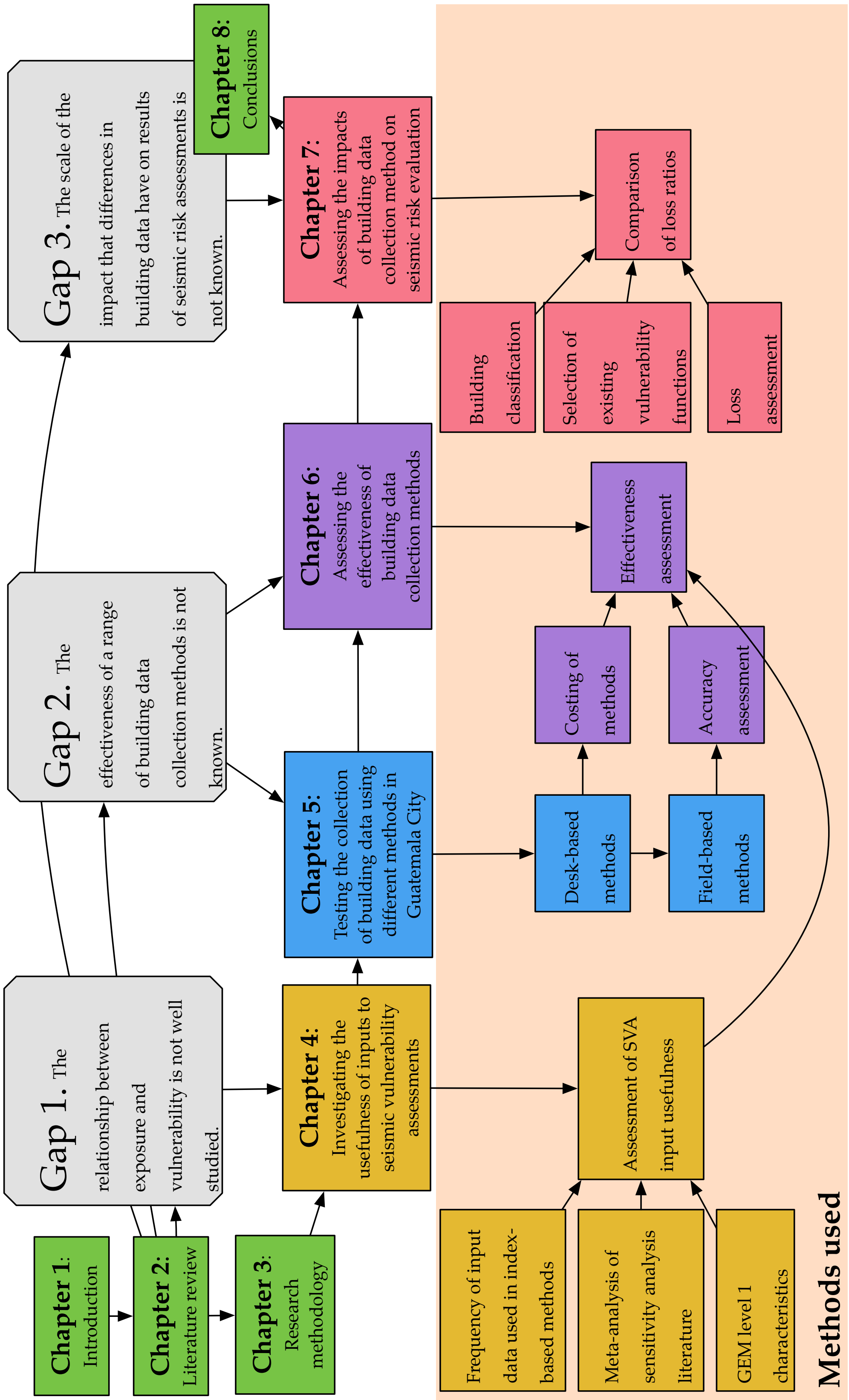


Figure 3-8 The research methodology

Chapter 4

Investigating the usefulness of inputs to seismic vulnerability assessments

4. Investigating the usefulness of inputs to seismic vulnerability assessments

As discussed in Chapter 2, there are many methods available in the literature for the assessment of the seismic vulnerability of buildings. Each of these methods rely on different approaches (see section 2.2.2) and use a specific set of input data. Whilst there are a large number of characteristics that could be collected about a building, prioritisation is needed for effectiveness, focussing on those key to accurate seismic vulnerability assessments, i.e. they play a significant part in informing a building's seismic response. This chapter employs the concept of building data 'usefulness' in the context of seismic vulnerability assessments, and uses a series of analyses to ascertain how important different building data are. These analyses use the available published literature to test the level of usefulness of different inputs to analytical SVA methods. If an input is deemed important, it is denoted as of 'high usefulness'. Lesser important data are labelled as of 'moderate usefulness', or further still of 'low usefulness'. This scale is arbitrary, and is defined clearly in each analysis. The results from each analysis are then combined to establish an overall view of the data inputs that are of high, moderate, or low usefulness.

The methodology used for each of these analyses is explained in Chapter 3. Here, reviews of the relevant literature are presented prior to establishing the level of data usefulness.

4.1. The frequency of input data used in index-based seismic vulnerability assessment methods

4.1.1. The index method literature

Index methods are one of the oldest methods for assessing seismic vulnerability. In 1968, Shiga et al. (1968) studied a pattern observed in the damaged RC buildings after the 1968 Tokachioki, Japan earthquake; that the most damaged buildings had relatively few walls. Relationships were derived between the cross-sectional area of vertical structure (whether column or walls) and the size of the building (represented by weight) using the observed damage data, informing the assessment of RC buildings. Although this index method seems crude, ignoring many building characteristics that influence a structure's seismic response, this reductionist approach employs few variables thereby enabling the simple and rapid assessment of this type of Japanese structure.

Aoyama (1981) extends the first method (Shiga et al., 1968) by developing a three-tiered method for calculating a seismic index for existing Japanese RC buildings up to six storeys. The index incorporates: a geological index which considers the local ground conditions; a structural design index (which considers unbalanced stiffness distribution in plan and elevation) derived using the 1968 Tokachioki, Japan earthquake damage data (the same as used by Shiga et al. (1968)), and a time index which considers the degradation of material properties caused by age.

The use of wall and column cross-sectional areas to represent seismic capacity (and hence damage as its complement) has also been used in the derivations of an index-based method by Hassan and Sozen (1997), which showed strong correlations with damage data collected from the 1992 Erzincan, Turkey earthquake. Later, Ozcebe et al. (2003) analysed damage data from the 1999 Düzce, Turkey earthquakes for a correlation between building characteristics and damage level. Column or wall dimensions (i.e. the lateral strength and stiffness of a building) were found to be key variables, alongside the number of storeys, the presence of overhangs or soft storeys, and the level of redundancy (i.e. number of frame lines) in the lateral load resisting system. Following this, Yakut (2004) published a more detailed method of estimating the vulnerability of Turkish RC buildings by estimating concrete shear capacity based on material properties and wall or column geometry and using a relationship to extend this to base shear capacity of the whole building, using the number of storeys. Lourenço et al. (2013) followed a similar analytical approach to developing an index method for heritage masonry buildings in Italy, Portugal and Spain and validating the method using 2011 Canterbury, New Zealand earthquake damage data.

The use of wall and column dimensions as a proxy or indicator of seismic capacity has developed over time as more variables have been added to improve the prediction of structural behaviour under earthquake loading. Earlier methods failed to capture important basic structural information such as the distance between walls, irregularities, or the capacity of wall or frame elements in the pursuit of simplicity but this improved over time. However, these reductionist approaches, whilst trying to simplify the analysis process, do not account for the time-consuming collection of wall and column dimension data which requires either obtaining an accurate floor plan, or conducting a detailed internal survey to produce one. If there is information available about buildings, this is often just architectural drawings, from which structural elements and dimensions may not be clear. For older buildings, it is likely that original drawings will not be available, hence, it can be very costly and time-consuming to obtain the data required for these types of index-based methods. Validation against empirical damage datasets ensure that any other affects not considered directly by the inputs or calculation process are considered indirectly, but do then restrict the appropriate application of the methodology both spatially and temporally. Examples of such methods include those developed for Italy (Benedetti and Petrini, 1984; Gavarini and

Angeletti, 1984; Benedetti et al., 1988; Angeletti et al., 1988; Zuccaro and Cacace, 2015), Turkey (Hassan and Sozen, 1997; Özcebe et al., 2003; Sucuoğlu et al., 2007; Özhendekci and Özhendekci, 2012), India (Jain et al., 2010), and Algeria (Belheouane and Bensaibi, 2013). Despite these restrictions, a wide range of studies employ wall and column dimensions in their methods, and the frequency of the use of these data will be reflected in the results.

Other methods are based on expert judgement (e.g. Perrone et al. (2015) and Lang et al. (2009b)), hence require validation, which Perrone et al. (2015) achieve comparing results with both analytical (pushover analysis of two buildings) and empirical data (damage data from L'Aquila 2009 and Emilia 2012 earthquakes). Although these validations are only completed with a very small number of buildings, if validated correctly, this better than no validation at all (Lang et al., 2009b): such index-based method should be used with caution. These methods, despite their shortcomings, are also included in this analysis.

Some methods, particularly those from national organisations do not give details about the development of the published index method, for example those from the USA (ATC, 1988; Rainer et al., 1993; ATC, 1998; ATC, 2002). Despite this, these methods forms the basis of other methodologies that have employed or adapted them to fit other geographical contexts for building types, for example the method published by the Italian authorities (GNDT,1993) forms the basis of methods for: Portugal (Vicente et al., 2011; Vicente et al., 2014), Europe (Guéguen et al., 2007), Chile (Gent Franch et al., 2008), slender masonry (Shakya et al., 2014), and confined masonry (Gent Franch et al., 2008). All of these methods, or their underlying principles, are widely-used and thus are included in this analysis.

Other studies use the EMS-98 (Grunthal et al., 1998) vulnerability scale (which is also developed through a methodology that is somewhat unclear) to derive an index-based SVA method. Giovinazzi and Lagomarsino (2004) use fuzzy set theory to derive damage probability matrices and functions relating damage to seismic intensity (given EMS-98), resulting in a vulnerability index applicable to European buildings. The index uses a building typology index which is estimated using the probability of damage (previously defined in relation to EMS-98 classes) and a set of behaviour modifiers. The building modifiers, derived for both RC and masonry structures, include: state of preservation; level of earthquake resistant design; number of storeys; structural system (including masonry wall dimensions); presence of plan, elevation, and mass irregularities; information of floor, roof, and foundation elements; connection adequacy; position of building in a block, and; further general seismic weaknesses, including the presence of short columns, bow windows, and pounding. This method relies heavily on the accuracy of the EMS-98 vulnerability classes (Grunthal et al., 1998), for which the derivation process is not well documents but includes both expert opinion and empirical data from global earthquakes (despite an European remit, although this has not stopped authors from using it further afield (Sinha and Goyal, 2004; Lantada et al., 2008)

Finally, some index methods are developed based on analytical approaches. Simplistic structural relationships are used to model and estimate seismic behaviour. Relatively complex analytical principles were used to develop the P25 method (Bal et al., 2008; Gulay et al., 2011; Tezcan et al., 2011), which employs a combination of seven indices: an estimate of rigidity using wall and column dimensions (corrected for height) and soil properties (liquefaction potential and bearing capacity failure), as well as scores for the presence of short columns, soft storeys, frame discontinuities, and pounding potential. An accurate prediction of vulnerability to collapse can be calculated using this method, as demonstrated when tested on buildings affected by recent Turkish earthquakes (Tezcan et al., 2011). Again in the literature there are examples of analytical methods both with appropriate validation (Tesfamariam and Saatcioglu, 2008) and without (Lourenço and Roque, 2006; Sucuoğlu et al., 2015). As before, any methods with validation need to be used with care, but in the case of this analysis, all of these methods will be considered.

4.1.2. Results

Table 4-1 and Table 4-2 give a summary of the review of the index-based literature (see section 4.1.1), with the geographical restrictions, material types considered, and inputs required by each method, as well as the approach taken and details of any validation process. Figure 4-1 shows the frequency that each input is required. Thirty-two index methods were reviewed in total published between 1968 and 2015. Fifteen methods were for reinforced concrete, eight were for masonry, four were for both RC and masonry, and five considered all construction types. Methods have been developed for many different countries in Europe, Asia, Northern Africa, and the Americas. The group of studies show the progress of thinking in index-based methods through time, although this does not necessarily mean the newer methods are more accurate; this depends primarily on the quality of the validation process and the index scoring derivation method used.

Reference	Location developed for	Structural type	Approach used	Validation approach	Material type	LLRS	Elevation regularity	State of preservation	Plan regularity	Number of storeys	Element dimensions	Soil type	Soft storey	Short column	Diaphragms	Pounding	Occupancy	Torsion irregularity	Topography	Roof type	Structural capacity	Connections	Non-structural hazard	Building weight	Detailing	Age
Shiga et al. 1968	Japan	C	E	E	●						●													●		
Aoyama et al. 1981	Japan	C	A	E	●			●		●	●	●		●										●		●
Benedetti et al. 1984	Italy	M	E		●		●	●	●			●			●					●	●	●			●	
Gavarini et al. 1984	Italy	C	E	E	●	●		●			●			●							●	●				
Bennedetti et al. 1988	Italy	M	E	E	●	●	●	●	●			●			●					●	●	●			●	
ATC 1988	USA	C			●		●			●		●	●	●	●	●		●								
Angeletti 1988	Italy	M	U		●	●	●	●	●						●					●	●		●			
GNDT 1993	Italy	C			●	●	●	●	●						●	●		●	●	●		●	●			
Rainer et al. 1993	Canada	A			●	●	●			●	●	●	●	●		●	●	●	●				●	●		
Hassan and Sozen 1997	Turkey	CM	E	E	●					●	●		●	●	●	●	●	●	●							
ATC 1998	USA	A			●	●		●		●	●	●	●	●		●	●	●			●	●			●	
ATC 2002	USA	A			●	●	●		●	●		●					●						●			●
Ozcebe 2003	Turkey	C	E	E	●	●	●			●	●		●													
Giovinazzi & Lagomarsino 2004	Europe	CM			●	●	●	●	●	●	●			●						●		●				
Yakut et al. 2004	Turkey	C	A	E	●	●				●	●		●													
Lourenço et al. 2006	Portugal	M	A		●	●					●						●							●		●
Sucuolglu et al. 2007	Turkey	C	E	E	●		●	●		●			●													
Gueguen et al. 2007	Europe	A	U	A	●	●	●		●			●							●							●
Lantada et al. 2008	Spain	A	U	A	●	●	●	●	●	●	●															
Gent French et al. 2008	Chile	M	U	E	●	●	●	●	●						●	●		●	●	●	●		●			
Tesfamariam et al. 2008	USA	C	A	E	●	●	●	●	●			●					●									●
Lang et al. 2009		CM	EJ		●	●	●	●	●				●	●		●		●								
Jain et al. 2010	India	C	E	E	●	●		●	●	●			●	●	●											
Vincente et al. 2011	Portugal	M	U	A	●	●	●	●	●	●		●			●				●	●	●		●			
Tezcan et al. 2011	Turkey	C	A	E	●	●	●	●		●	●	●	●	●	●	●	●	●	●			●		●	●	
Ozhendekci et al. 2012	Turkey	C	E	E	●	●	●			●			●	●		●	●									
Belheouane et al. 2013	Algeria	C	E	E	●	●	●	●	●			●		●	●	●					●	●			●	
Lourenço et al. 2013	Europe	M	A	E	●	●					●													●		
Shakya et al. 2014	Italy	M	U	A	●	●	●	●	●		●	●							●	●	●		●			
Sucuolglu et al. 2015	Turkey	C	A		●	●	●		●	●	●	●	●				●							●	●	
Zuccaro et al. 2015	Italy	CM	E	E	●	●	●	●	●	●									●	●			●			●
Perrone et al. 2015	Italy	C	EJ	AE	●	●	●	●	●				●	●			●	●				●	●		●	●

Table 4-1 Frequency of inputs review results. Definitions of characteristics and abbreviations are given in Table 4-3. Table continues in Table 4-2.

Reference	LLRS quality	Foundations	Building footprint	Height	LLRS quantity	Max. horizontal span	Mass irregularity	Position in block	Lateral load path	Retrofitting	Material quality	Heavy façade	SBWC	Infill wall info	Fundamental period	Vertical load path	Openings regularity	Floor material	Mezzanines	Roof shape	Balconies	Aseismic devices	Bow windows	Safe elevators/stairs	Modifications	Code level
Shiga et al. 1968																										
Aoyama et al. 1981																										
Benedetti et al. 1984																										
Gavarini et al. 1984											●															
Bennedetti et al. 1988																										
ATC 1988												●														
Angeletti 1988	●	●				●																				
GNDT 1993	●	●	●		●										●											
Rainer et al. 1993												●		●												
Hassan and Sozen 1997											●		●													
ATC 1998		●		●	●	●	●		●							●			●							
ATC 2002																										●
Ozcebe 2003			●		●																					
Giovinazzi & Lagomarsino 2004		●					●	●		●				●								●	●			
Yakut et al. 2004																										
Lourenço et al. 2006			●	●																						
Sucuolglu et al. 2007																										
Gueguen et al. 2007																				●						
Lantada et al. 2008																										
Gent French et al. 2008	●		●		●										●											
Tesfamariam et al. 2008																										
Lang et al. 2009			●						●	●			●							●						
Jain et al. 2010																					●					
Vincente et al. 2011	●					●		●									●									
Tezcan et al. 2011		●	●	●			●		●		●	●	●	●		●			●							
Ozhendekci et al. 2012						●																				
Belheouane et al. 2013	●																								●	
Lourenço et al. 2013			●	●																						
Shakya et al. 2014	●							●									●	●								
Sucuolglu et al. 2015																										
Zuccaro et al. 2015				●				●		●								●								
Perrone et al. 2015		●					●		●	●											●			●		

Table 4-2 Frequency of inputs review results. Definitions of characteristics and abbreviations are given in Table 4-3. Table follows from Table 4-1.

Characteristics	Definition
Location developed for	The geographical location for which the method is developed
Structural type	The general structural type or types that the method is developed for. Abbreviations are defined as follows: (A)ll, reinforced (C)oncrete, (M)asonry
Approach used	The approach used the develop the methodology. Abbreviations are defined as follows: (U)pdate (which refers to a method that updates an pre-existing method), (E)mpirical (developed using relationships inferred from damage data), (A)nalytical (developed using results from analytical modelling techniques), Expert Judgement (EJ) (developed using inputs or judgements from a group of experts).
Validation approach	The approach used the validate the methodology. Abbreviations are defined as follows: (E)mpirical (validated using relationships inferred from damage data), (A)nalytical (validated using results from analytical modelling techniques), or Expert Judgement (EJ) (validated using inputs or judgements from experts).
Material type	The primary structural material used,
LLRS	The presence of a complete lateral load resisting system.
Elevation regularity	The regularity of the structure in elevation.
State of preservation	The state of preservations of the structure.
Plan regularity	The regularity of the structure in plan
Number of storeys	The maximum number of storeys of a structure.
Element dimensions	The dimensions of the main structural elements (e.g. beams, slab, columns)
Soil type	The type of soil where the structure is located.
Soft storey	The presence of a soft storey level in the structure. A soft storey is a storey where the stiffness changes significantly.
Short column	The presence of short columns in the structure. A short column is formed when a structural column is short in length, usually caused by stiff walls built not to the full height of a column. Also called a captive column.
Diaphragms	The presence of stiff diaphragms in plan between lateral load resisting system elements.
Pounding	The presence of pounding potential between the structure and neighbouring structures. Pounding is caused by structures with different periods of oscillation swaying out of sync in an earthquake and hitting into each other causing damage.
Occupancy	The occupancy or usage of the building.
Torsion irregularity	The presence of irregularities in the structural system that causes torsion under earthquake loading.
Topography	The topography of the ground at the structure's location.
Roof type	The type of roof material used on the structure.
Structural capacity	The capacity of the structure to withstand earthquake loading.
Connections	The capacity of the connections between structural elements.
Non-structural hazard	The presence of hazards in or around the building that are non-structural, such as cladding panels, chimneys, etc.
Building weight	The weight of the building.
Detailing	The level of detailing present in the structural elements and connections.
Age	The age of the structure.
LLRS quality	The quality of the lateral load resisting system.
Foundations	The type of foundations to the structure.
Building footprint	The shape and size of the footprint of the building on plan.
Height	The maximum height of the structure.
LLRS quantity	The quantity of lateral load resisting frames or elements.
Max. horizontal span	The maximum horizontal span between vertical load resisting elements.
Mass irregularity	The presence of irregularities of mass in the structural system.
Position in block	The position of the structure in relation to neighbouring structures.
Lateral load path	The simplicity of the lateral load resisting path.
Retrofitting	The presence of retrofitting to the structural system.
Material quality	The quality of the material used in the structural system.
Heavy façade	The presence of a heavy façade system.
SBWC	The presence of strong beam, weak column (SBWC) weaknesses in the structural system. SBWC is present when structural beams have more capacity than the structural columns that support them.
Infill wall info	The presence of infill walls and information about the quantity, direction, the material, and proximity to the LLRS or floor or roof diaphragms
Fundamental period	The fundamental period of the building.
Vertical load path	The presence of a direct vertical load path.
Opening regularity	The presence of irregularities in elevation openings (e.g. for windows and doors).
Floor material	The material used for the floor plates in the building.
Mezzanines	The presence of mezzanine floors between structural floor levels.
Roof shape	The shape of the roof structure, whether flat or sloped.
Balconies	The presence of overhanging balconies cantilevering from the structure.

Aseismic devices	The presence of aseismic devices, installed to reduce the effects of seismic loading.
Bow windows	The presence of bow windows that overhang the building footprint.
Safe elevators/stairs	The presence of safe vertical escape routes.
Modifications	The presence of any modifications to the original structure.
Code level	The level of structural building code that the structure was originally designed for.

Table 4-3 Definitions of building parameters used by index-based vulnerability methods

From the thirty-two methods reviewed, forty-nine different variables are identified, see Table 4-1, Table 4-2, and Figure 4-1. The most frequently needed parameters are material type and the LLRS, highlighting them as two key inputs for assessing the seismic vulnerability of a building. The presence of common seismic weaknesses, such as irregularities in elevation, plan, and torsion; soft storeys; pounding potential; and short columns are also frequently required by methods. In addition, factors that affect the capacity of the structure, such as state of preservation of the structure, the number of storeys, dimensions of structural elements, and information about the horizontal diaphragm, are also commonly employed. Although soil type could be considered to be a characteristic of the seismic demand (i.e. the seismic hazard), these simplified methods tend to modify the vulnerability scores according to the local soil, as simplified seismic design approaches do. Lesser used attributes include the presence of balconies, mezzanines, aseismic devices, and irregular frame-infill panels.

There are, of course, overlaps or irregularities in the defined variables, which could be interpreted in a number of ways. Keeping 'structural capacity' as a separate measure is odd as many of the analytical methods aim to use other characteristics to calculate this, but methods explicitly state this as an input without a thorough prescription of how to estimate it (e.g. methods based on Benedetti and Petrini (1984)), leaving it open to interpretation and thus it remains separated in this analysis. These overlaps need to be considered when combining these results with those of the review of sensitivity analysis literature (see section 4.2) and the GEM results (see section 4.3) when ultimately defining which data are considered more useful (see section 4.4).

Deciding the level of usefulness from the frequency analysis is arbitrary. For this analysis, it was decided that if more than 40% of studies require a characteristic then it is considered to be of high usefulness; between 20% and 40%, moderate usefulness; and fewer than 20%, low usefulness. This is reflected in Figure 4-1

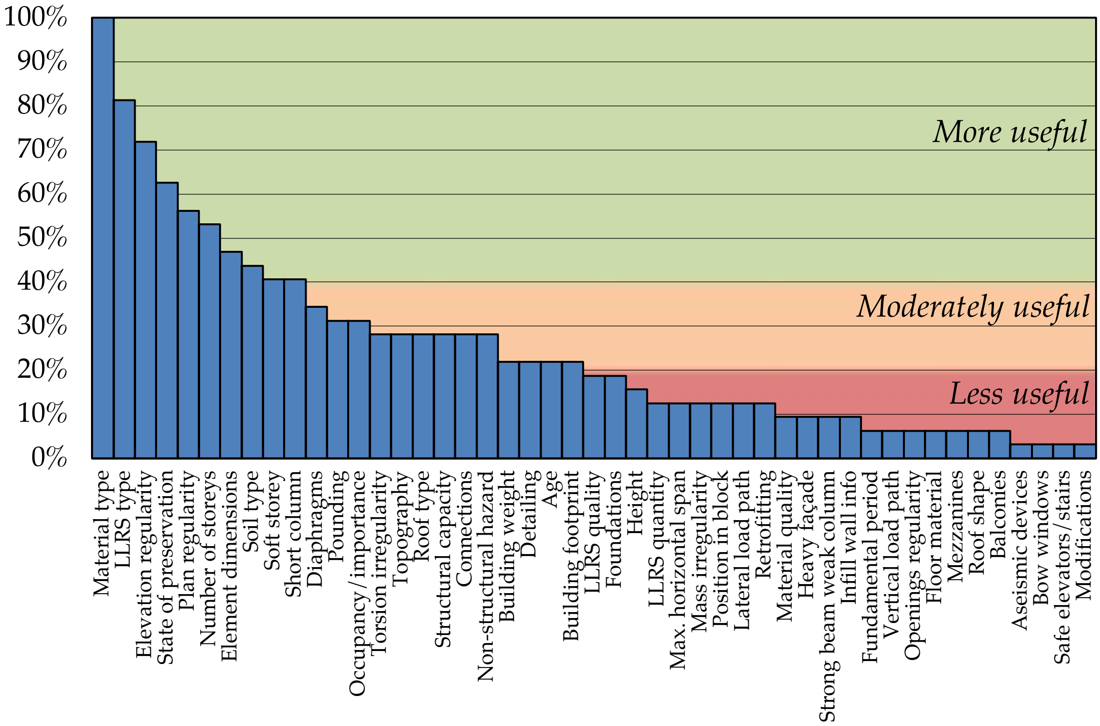


Figure 4-1 Proportion of the index methods in literature that prioritise different building parameters (which are defined in Table 4-3)

4.2. Meta-analysis of sensitivity analysis literature

Sensitivity analyses investigate the variation in the output caused by variation in the input, and have been used widely, leading to a large number of methods and applications (Pianosi and Wagener, 2015; Leonelli et al., 2017). Seismic risk assessments are shown to be highly influenced by seismic fragility and vulnerability by a number of authors (Restrepo-Vélez and Magenes, 2004; Riga et al., 2017). The sensitivity of building data (the input) to the results from seismic vulnerability assessments (the outputs) highlights the most important data to the assessment, and hence what should be prioritised during data collection (Spence et al., 2003).

A number of studies exist that conduct sensitivity analyses for SVAs. These papers have been reviewed and the results collated and reviewed for patterns or agreement between studies about the importance of different building characteristics. The building characteristic that are consistently reported to be of high importance will be classified as 'more useful'. The results from the review will be effected to some extent by objectivity, however they aim to represent directly findings published in the academic literature.

4.2.1. Sensitivity analysis literature

Porter et al. (2002) explored the effect that varying input parameters had on results, concluding that parameters associated with structural capacity cause the most variation in results, hence the determination of structural capacity and response using building characteristics is a key part of SVAs. Different building characteristics have been investigated by different authors and are reviewed below.

Bird et al. (2004) suggested that losses from ground failure, including landslides, fault rupture and liquefaction, should be included in seismic loss estimation processes to avoid underestimation of vulnerability. Authors disagree on the importance of the soil type, with some finding it of high (Pianigiani and Mariani, 2017), others of moderate (Esteva and Ruiz, 1989; Spence et al., 2003), and yet others of low influence on results (Rohmer et al., 2014). On the contrary, after studying the effects of site conditions on the damage caused by the Northridge earthquake in 1994, Olshansky (1997) concluded that buildings built on 'moderate to very highly liquefiable' ground were between 1.5 and 2 times more likely to be damaged, hence, inferring that if site conditions are not properly considered in a vulnerability analysis, damage predictions could be significantly inaccurate.

The modelling of sub-structural elements was also considered important by Restrépo-Velez and Magenes (2004), who concluded, following an extensive literature review, that an ideal seismic vulnerability assessment methodology would consider foundations. This is in agreement with findings that found that good modelling of the soil-structure interaction is important to achieving accurate results (Chacón et al., 2017).

Many SVA methods in the literature require information about structural condition, but studies testing the value of such information are scarce. D'Ayala and Meslem (D'Ayala and Meslem, 2013) concluded that strengthening modifications and previous damage incurred were both non-essential (albeit useful) inputs and thus are deemed to have a diminished influence on results, a conclusion corroborated by others (Pianigiani and Mariani, 2017). Elsewhere, the construction quality of timber buildings was found to be a highly sensitive input (Pei and van de Lindt, 2010).

Elevation geometry, including the total height, interstorey height and number of storeys of a building is reported to be either highly influential (Ibarra and Krawinkler, 2005; D'Ayala and Meslem, 2013) or only moderately important (Esteva and Ruiz, 1989; Masi, 2003). In contrast, Crowley et al. (2005) concluded that defining a range of building heights (such as 1 to 9 storeys) within a building class did not significantly impact on the uncertainty of results, provided that the median storey number was selected to represent the range.

Masi (2003) reports that variability in plan geometry did not affect results significantly but results from Meslem and D'Ayala (2012) disagree, indicating the number of bays is an essential input, and span length as desirable. Esteva and Ruiz (1989) report that element geometry is of low influence but Crowley et al. (2005) disagree, finding that one of the most significant parameters in determining seismic capacity were the geometrical properties of the elements. The sensitivity of RC slab geometry has also been investigated but is found to be of moderate to low importance (Celarec et al., 2012; Celarec and Dolšek, 2013).

Rossetto et al. (2014a) highlight the preference of using representative geometrical characteristics of buildings, instead of assumed or default values.

There are many studies concerned with the sensitivity of material properties, with a range of results achieved. Kwon and Elnahsai (2006) found that, in general, variation in material properties contribute significantly to uncertainty in structural behaviour, especially at high ground shaking levels; others found that RC material properties were moderately sensitive to results (Pianigiani and Mariani, 2017).

Generally, the sensitivity of concrete strength is disputed: some studies report it as a lesser influence (Esteva and Ruiz 1989); some as moderately important (Spence et al. 2003; Celarec et al. 2012; Celarec and Dolšek 2013) and others deemed it to be of high importance (Meslem and D'Ayala, 2012; D'Ayala and Meslem, 2013; Pianigiani and Mariani, 2017). The ultimate and tensile concrete strength and Young's modulus are generally found to be highly important, whereas shear strength and Poisson's ratio does not notably influence results (Kwon and Elnashai 2006; Meslem and D'Ayala 2012).

The strength of steel reinforcement is considered important by some (Meslem and D'Ayala 2012) and negligible by others (Esteva and Ruiz 1989; Celarec et al. 2012; Celarec and Dolšek 2013), whereas it is agreed that variability in transverse reinforcement is not highly influential (Inel and Ozmen, 2006; Meslem and D'Ayala, 2012).

RC frame hinge properties are, for the most part, found to be important (Crowley et al. 2005; Inel and Ozmen 2006; Meslem and D'Ayala 2012; Celarec et al. 2012; Celarec and Dolšek 2013). Inel and Ozmen (2006) highlight that the use of default or assumed plastic hinge properties is not good practice, particularly with buildings that lack good seismic detailing.

Properties of masonry infill walls have been investigated, finding that typically, the important properties of the infill masonry are compressive strength, cracking strength, stiffness, Young's modulus and shear modulus (Meslem and D'Ayala 2012; Celarec et al. 2012; D'Ayala and Meslem 2013).

Respectively, for masonry and timber structures, Spence et al. (2003) and Goda et al. (2011) found that the ultimate capacity was only moderately influential on the vulnerability results. Furthermore, the strength and stiffness of timber (Pei and Van der Lindt 2010) and steel (Ellingwood and Kinali, 2009)were found to be of negligible influence to results.

Some studies have examined the effects of frame element properties in general, but varied results have been achieved (Masi 2003; Meslem and D'Ayala 2012; Celarec et al. 2012). The properties of diaphragms at both floor and roof levels was found to be moderately and highly important to results by different authors (Meslem and D'Ayala, 2012; Clementi et al., 2016; Chacón et al., 2017).

Finally, the overall ductility of structures in response to seismic loading was found to be important by Ibarra and Krawinkler (2005) but only moderately important by Esteva and Ruiz (1989).

The number of degrees of freedom of a structure is an important parameter with the fundamental period of lesser importance (Esteva and Ruiz (1989). Conversely, Crowley and Pinho (2004) found that the fundamental period could have a significant effect on results and in particular argued that a properly derived fundamental period provides more accurate results. Conversely, Chacón et al. (2017) found the fundamental period to be of a moderate influence on results.

Hysteretic damping properties of both RC and masonry structures were found by Spence et al. (2003) and Riga et al. (2017) to be of low influence, while Porter et al. (2002) reported that damping properties were moderately important.

Restrépo-Velez and Magenes (2002) stated that the ideal assessment method would consider non-structural elements but Meslem and D'Ayala (2012) suggested that modelling non-structural cladding elements is non-essential.

4.2.2. Agreement analysis

The results of this analysis are presented in Table 4-4, excluding the building characteristics for which there was no agreement. Results include all types of data for a range of building typologies. Full results, including those for which agreement was not found, are given in Appendix C.

Building characteristics	Total H scores	Total M scores	Total L scores	Majority score
RC material properties	28	13	10	H
Infill wall properties	7	3	1	H
Hinge/rotation properties	7	2	1	H
Concrete properties	5	3	2	H
Ground effects and sub-structure	5	2	1	H
Consideration of infill walls	5	1	0	H
Concrete strength	4	3	1	H
Number of storeys	2	1	1	H
Storey height	2	0	0	H
Compressive strength of infill walls	2	0	0	H
Young's modulus of infill walls	2	0	0	H
Frame element properties	1	2	1	M
Fundamental period	1	2	0	M
Longitudinal reinforcement properties	3	1	5	L
Element geometry	1	2	4	L
Reinforcement steel strength	2	0	4	L
Structural condition	1	0	3	L
Damping	0	1	3	L
Timber material properties	0	1	2	L
Element breadth	0	1	2	L
Yield strength of steel reinforcement	1	0	2	L
Structural steel material properties	0	0	2	L

Table 4-4 Results of the meta-analysis of the sensitivity analysis

Eleven properties are determined as of high usefulness in this analysis, including various material property parameters, ground information, and number of storeys/height data. Interestingly, material properties are designated as of low usefulness. Most parameters in Table 4-4 are required for more complex SVA methods than simplified index-based methods would consider, so due care must be made when the results are combined in section 4.4.

4.3. Global Earthquake Model taxonomy levels

The most basic requirements required for the Global Earthquake Model's taxonomy are designated as level 1. These characteristics are therefore assumed to be of high usefulness in the estimation of seismic response of buildings. The level 1 characteristics are:

- Material type
- Type of LLRS

- Height
- Age
- General occupancy
- Building position
- Regular or irregular building
- Roof shape
- Floor material
- Foundation system

Age and occupancy data are not directly applicable to analytical SVA modelling, however may be used to inform structural characteristics. All of these level 1 data types are combined with results from the two systematic literature reviews (see sections 4.1 and 4.2) below.

4.4. Determining 'more useful' data for the assessment of seismic vulnerability

The results for the input frequency review, the sensitivity analysis systematic review, and the GEM taxonomy level 1, are combined below to give a combined result on building data usefulness from the three method's perspectives. Not all parameters matched across methods, so a mapping exercise was required. The process of matching building characteristics is completed by the author only, and therefore may be subjective, however many of the matches were for obvious characteristics. Some detail was lost, however, such as each specific material properties were all combined into a single 'material properties' attribute. The mapping process of the different characteristics is shown in the first four columns of Table 4-5.

The results are given in columns five to eight of Table 4-5, which shows the combined usefulness scores for different building characteristics reported by each of the three methods used in this chapter. The combined scores are given as high, moderate, or low usefulness if methods agreed. Where there was disagreement, a moderate usefulness score was given.

Although there are various subjectivities in the results, as well as the difficulties of comparing the results of the different methods and combining them, there remains a number of useful and usable outputs. The inclusion of future studies would further enhance the results, as would independent completion of the methods which could act as validation or of a refinement of the results.

There are also various challenges with ranking or scoring the usefulness of data of different levels or interdependence. For example, the parameter 'age' is inextricably linked to code level, state of preservation, material type and most other parameters in the table. However, from the perspective of prioritizing the gathering of building data for a seismic vulnerability assessment, the level of the data (whether overarching or specific and detailed) becomes less relevant and the overall usefulness score is important.

These findings are not only novel in stating the usefulness of different building parameters to seismic vulnerability assessments, but they are also paramount to the development of effective, SVA-focused building data collection methods. The most effective methods will collect highly useful data consistently, leading to improved assessments of seismic vulnerability. These findings are used in Chapter 6 which explores the overall effectiveness of different data collection methods.

Names of building characteristics found in the literature in each study			**Mapped characteristic name**	**Combined usefulness scores**			**Overall usefulness score**
Study 1: The frequency of input data used by index-based seismic vulnerability assessment methods	**Study 2: Meta-analysis of sensitivity analysis literature**	**Study 3: GEM taxonomy level 1**		**High usefulness**	**Moderate usefulness**	**Low usefulness**	
Number of storeys	Number of storeys	Height	Number of storeys	3			H
Material type		Material type	Material type	2			H
LLRS type		Type of LLRS	LLRS type	2			H
Elevation regularity		Regularities	Elevation regularity	2			H
Plan regularity		Regularities	Plan irregularity	2			H
Soil type	Ground effects and sub-structure		Soil type	2			H
Soft storey		Regularities	Soft storey	2			H
Short column			Short column	1			H
Occupancy/importance		General occupancy	Usage	1	1		M
Torsion irregularity		Regularities	Torsional irregularity	1	1		M
Roof type		Roof shape	Roof type	1	1		M
Connections	Hinge/rotation properties		Connections	1	1		M
Age		Age	Age	1	1		M
Foundations	Ground effects and sub-structure	Foundation system	Foundations	2		1	M
Height	Storey height	Height	Height	2		1	M
State of preservation	Structural condition		State of preservation	1		1	M
	Concrete properties		Material properties	1		1	M
	Concrete strength			1		1	M
	RC material properties			1		1	M
	Reinforcement steel strength			1		1	M
	Yield strength of steel reinforcement			1		1	M
	Longitudinal reinforcement properties			1		1	M
	Timber material properties			1		1	M
	Structural steel material properties			1		1	M
	Damping			1		1	M

Names of building characteristics found in the literature in each study			Mapped characteristic name	Combined usefulness scores			Overall usefulness score
Study 1: The frequency of input data used by index-based seismic vulnerability assessment methods	**Study 2: Meta-analysis of sensitivity analysis literature**	**Study 3: GEM taxonomy level 1**		**High usefulness**	**Moderate usefulness**	**Low usefulness**	
Element dimensions	Element geometry		Element dimensions	1		1	M
Mass irregularity		Regularities	Mass irregularity	1		1	M
Position in block		Position	Position in block	1		1	M
Infill wall info	Hinge/rotation properties		Infill wall details	1		1	M
	Consideration of infill walls			1		1	M
	Infill wall properties			1		1	M
	Young's modulus of infill walls			1		1	M
	Compressive strength of infill walls			1		1	M
	Infill wall properties			1		1	M
Openings regularity		Regularities	Openings irregularity	1		1	M
Floor material		Floor material	Floor material	1		1	M
Roof shape		Roof shape	Roof shape	1		1	M
Diaphragms			Diaphragms		1		M
Pounding			Pounding		1		M
Topography			Topography		1		M
Structural capacity			Structural capacity		1		M
Non-structural hazard			Non-structural hazard		1		M
Building weight			Building weight		1		M
Detailing			Detailing		1		M
LLRS quality	Frame element properties		LLRS quality		1	1	M
Fundamental period	Fundamental period		Fundamental period		1	1	M
Building footprint			Building footprint			1	L
LLRS quantity			LLRS quantity			1	L
Max. horizontal span			Max. horizontal span			1	L
Lateral load path			Lateral load path complete			1	L
Retrofitting			Retrofitting			1	L
Material quality			Material quality			1	L

Names of building characteristics found in the literature in each study			**Mapped characteristic name**	**Combined usefulness scores**			**Overall usefulness score**
Study 1: The frequency of input data used by index-based seismic vulnerability assessment methods	**Study 2: Meta-analysis of sensitivity analysis literature**	**Study 3: GEM taxonomy level 1**		**High usefulness**	**Moderate usefulness**	**Low usefulness**	
Heavy façade			Heavy façade			1	L
Strong beam weak column			Strong beam weak column			1	L
Vertical load path			Vertical load path complete			1	L
Mezzanines			Mezzanines			1	L
Balconies			Balconies			1	L
Aseismic devices			Aseismic devices			1	L
Bow windows			Bow windows			1	L
Safe elevators/stairs			Safe stairs/lifts			1	L
Modifications			Incremental construction			1	L
Code level			Level of design			1	L

Table 4-5 Results of usefulness assessment of building characteristics

4.5. Conclusions

This chapter presents a thorough systematic review of two groups of literature. First, index methods for seismic vulnerability assessment are reviewed and the input data required are compiled. The frequency of inputs required by the collection of methods is considered to be a proxy for importance in representing the seismic response of structures. The most frequently used parameters are material type, the type of LLRS, the soil type, the presence of common seismic weaknesses. Characteristics that affect the capacity of the structure, such as state of preservation of the structure, the number of storeys, dimensions of structural elements, and information about the horizontal diaphragm, are also commonly employed. Limitations may exist with these conclusions due to biases or heuristics of a sole reviewer.

Second, the body of literature that investigates the sensitivity of inputs to seismic vulnerability assessments is reviewed, drawing out the level of importance of different SVA inputs. Agreement between studies on the importance of different building characteristics is sought to positively identify data types as either of high, moderate, or low usefulness. A set of characteristics are considered highly important to SVAs, including material properties, ground information and number of storeys or height. A different set of detailed material characteristics are found to be of low usefulness, including the geometry of elements, structural condition, reinforcement steel strength. These findings consider characteristics that are much more detailed compared to those in the index-based review.

Finally, the GEM taxonomy level 1 building characteristics, including material type, type of LLRS, height, age, occupancy, building position, presence of irregularities, roof shape, floor material, and foundation system, are considered to be ‘more useful’, All findings are then compiled to reveal the agreed level of usefulness. This chapter identifies the highly useful building characteristics as: number of storeys, material type, LLRS type, elevation regularity, plan irregularity, soil type, soft storey, and short column.

Building data collection methods that obtain these more useful data will be scored well for usefulness, but effectiveness also depends on the cost or accuracy of the methods. In order to determine these additional scores, a number of data collection methods, both desk- and field-based, are tested in a case study area. The costs are recorded and the accuracy is estimated using interrater agreement statistics. The next chapter presents the catalogue of building data collection methods tested, and the initial results from each method.

Chapter 5

Testing the collection of building data using different methods in Guatemala City

5. Testing the collection of building data using different methods in Guatemala City

The built environment is vast, and encompasses a widely diverse collection of buildings, unique in age, location, height, geometry, usage, structural characteristics, etc. It is, therefore, onerous to accurately gather information on buildings over a large area, but reliable building data is key to accurately estimating losses due to an earthquake (Bal et al., 2010; Rohmer et al., 2014). To simplify this challenge, exposure is often estimated by extrapolating from a surveyed sample, as well as grouping buildings with similar seismic behaviours together for analysis; the literature on classification has been introduced in Chapter 2. Additionally, methods collecting 'big data' are used, such as national housing censuses, or satellite imagery, and although they avoid the need to extrapolate from a small sample, they only capture a small number of building characteristics. Accurate and reliable vulnerability functions are challenging to derive even with extensive data, but if little is known about the building stock, the accuracy and reliability of risk assessments will suffer leading to unreliable risk estimations.

A wide range of data collection methods exist, and this number is ever-increasing with the advent of new technologies. A selection of these methods is tested for the case study area defined in Chapter 3 in order to evaluate the effectiveness of different building data collection approaches. This chapter begins by explaining the methodologies tested in detail for both the desk and field studies. The results obtained from the methodologies are then presented.

5.1. Methodology for testing the collection of building data

The case study area in Guatemala City has been used to test both desk- and field-based study. The desk-based study was conducted between January 2014 and August 2017 and consisted of the following:

i review and analysis of historical maps and remotely-sensed imagery,

ii review of construction regulations and guidelines,

iii review of damage and recovery from past significant earthquakes,

iv analysis of national housing census data (1994 and 2002),

v review of municipality city maps,

vi review of relevant existing literature

vii review of existing building imagery

Fieldwork was conducted in July, August, and September of 2016 in Guatemala City, and the following field-based methods were tested:

i rapid visual surveys completed by a local engineer (LE), a foreign engineer (FE), and local students (STU),

ii omnidirectional imagery collection with subsequent virtual surveys completed by an engineer in the UK,

iii UAV collection of high-resolution top-down aerial imagery with subsequent post-processing and virtual surveys completed by an engineer in the UK,

iv UAV collection of high-resolution aerial imagery, post-processing to derive a 3D surface model, used for virtual surveys completed by an engineer in the UK, v detailed internal surveys (DIS), and

vi interviews with local engineering experts.

These approaches to building data collection are selected as they cover commonly used methods as well as testing new methods all within the scope and resources of this study. The technology was available to be tested in the field, including the omnidirectional camera and the UAV. Other methods, such as a full analysis of high-resolution remotely sensed images were too expensive for this project and have been well tested in the literature (see section 2.3.2).

The application of the desk-based methods will be explained first, followed by descriptions of the field-based methods.

5.1.1. Desk-based methods

Desk-based methods use information from the past to better understand the current situation. Information from an array of sources was collated into a historical timeline, rich with relevant data on the development of Guatemala City. In addition, literature that contains useful information on the types buildings present or specific details about construction practices over the years were collected together into a building typology repository. Each individual application is explained below.

5.1.1.1. Review of historical maps and remotely-sensed imagery

A number of historical maps and freely available satellite imagery capture the development of the conurbation of Guatemala City throughout time. These changes indicate the age of buildings in different city regions. Historical maps dating back to the foundation of the present-day capital city have been found for a number of dates, see Table 5-1. Copies of the maps are given in Appendix D. The more recent maps from 1945 (Niederheitmann and de Leòn C, 1945), 1955 (US Army Corps of Engineers, 1955), 1965 (Instituto Geografico Nacional, 1965), and 1973 (Instituto Geografico Nacional, 1973) were digitised using the photo mosaic tool in Adobe Illustrator, and imported into a GIS (geographical information system) in order to analyse the changes in built-up areas over time. These more recent maps are analysed as they are most likely to be relevant to the present-day building stock, although reference is made in the timeline to the development of the city in its early years, determined using visual comparisons of the older maps.

Year	Reference
1776	Gulicia Díaz (1968)
1791	Gellert and Pinto Soria (1990)
1800	Gellert and Pinto Soria (1990)
1800	Gulicia Díaz (1968)
1821	Gulicia Díaz (1968)
1842	Lara F (1977)
1850	Lara F (1977)
1868	Lara F (1977)
1882	Lara F (1977)
1889	Lara F (1977)
1925	Gellert and Pinto Soria (1990)
1936	Gellert and Pinto Soria (1990)
1945	Niederheitmann and de León C (1945)
1955	US Army Corps of Engineers (1955)
1965	Instituto Geografico Nacional (1965)
1973	Instituto Geografico Nacional (1973)

Table 5-1 List of map collated for the historical map analysis of Guatemala City

The digitised historical maps were georeferenced using the ArcGIS Georeferencing tool with a minimum of forty control points, to ensure accurate placement in the geospatial environment. The ArcGIS image classification tool was used to analyse the maps; training samples were used to teach the program which map colour related to built-up areas. As each historical map uses different colour schemes and designs, individual sets of training samples were used for each map. Urban and non-urban areas were categorised on each map, and the changes from rural to urban land uses were identified between consecutive maps in time, revealing how the urban area of the city changed.

Landsat satellite imagery is available for free on the Google Earth platform for 1970, and then annually from 1984, and these were used to analyse more recent changes to the urban area, again using the image classification tools in ArcGIS.

The satellite images were georeferenced using the same method as the historical maps. The ArcGIS ISO Cluster Unsupervised Classification tool was used to analyse the urban extent in the satellite imagery. Two classes were extracted from the image, one to represent the built-up area, and the second to cover all other land uses. The changes in built-up area over time were analysed to highlight the changes in land usage from 'other' to 'urban'. Initially, the analyses were completed for each year, however key changes were difficult to identify, so instead changes over a period of ten years are analysed, clearly identifying hotspots of urban development. The decades investigated were from 1984 to 1994, 1994 to 2004, and 2004 to 2014.

The conclusions from the analysis are used to form the basis of the historical timeline, with notes detailing the zones which underwent urban development in different periods of time in the city's history.

5.1.1.2. Review of construction regulations and guidelines

Documents pertaining to past and present construction processes, materials, and legislation were reviewed to examine the influence on the current building stock. The types of documents reviewed included construction guidelines, research projects, planning guidelines, and engineering design guidelines.

A thorough review of these documents was completed enriching the historical timeline with key events or dates that influenced the composition of the buildings in Guatemala City today. These data can be used alongside the historical map and imagery analysis to link the characteristics of buildings built at different times throughout Guatemala City's recent history. In addition, any mention of construction trends was added to the building typology repository.

5.1.1.3. Review of damage and recovery from past significant event

Reports of past damaging events, such as earthquakes, offer a direct view into how the city's building stock behaved under seismic loading. Clearly, event reports offer information about how the buildings at that time reacted to that specific event, however some information can be understood from the response of buildings to the shock, and similarly the decisions in recovery and rebuilding after the event are likely to have influenced the shape and type of city found today.

Large damaging events often form a pivot point for the improvement of legislation or construction practices in a country (GFDRR, 2016). If damage to buildings was widespread, that signifies a widespread renewal of the built environment, hence the scale of damage, strategies for rebuilding, and subsequent changes in regulations were collated from literature and added to the historical timeline and the building typology repository.

5.1.1.4. Analysis of national housing census (1994 and 2002)

Housing censuses are vital for understanding the building stock at national and at more disaggregated levels. The UN suggests completing censuses every ten years (UN, 2015a) however there are often prohibitive legal, financial, administrative, or circumstantial reasons that this is not achieved, particularly in developing countries (UN, 2015a). Housing censuses collect information on residences, including occupancy type, ownership status, occupant employment status, connections to utilities, age, and wall and roof construction materials.

Guatemalan census data is collected and published by INE (*Instituto National de Estadística;* National Statistics Office). The housing censuses are completed in accordance with the UN principles and recommendations, which gives guidance on topics including sampling, data collection techniques, data processing, dissemination of results (UN, 2015a). Data are reported on a departmental or municipal scale, and with distinctions between urban and rural data. Guatemala has completed six housing censuses in its history; held rather sporadically in 1950, 1964, 1973, 1981, 1994 and 2002. The next census is planned for 2017-8 (INE, 2017).

Housing census data may be used to estimate proportions of residential building types by implying structural characteristics from data reported on the prevalence of wall and roof material usage. In addition, data from the previous censuses are usually reported so that fluctuations in quantity of buildings and changes in the use of construction materials can be observed.

The first step in this method is to transcribe the relevant data from the census reports published by INE. With these data, conditional probability matrices are produced relating roof and wall types. A simple conditional probability matrix can be estimated by multiplying the total proportion of buildings required in each row (i.e. roof material) by the total proportion of buildings required in each column (i.e. wall type) however this results in some unlikely buildings, for example with *bahareque* walls and concrete roofs. Hence, the conditional probability of the unlikely combinations is set as zero and the rest of the values are calculated in order that they match the reported number of buildings for each row and column.

This methodology is used to estimate a conditional probability matrix relating wall and roofs types for the 2002 census dataset, for the municipality of Guatemala. As can be seen in Figure 3-4 this does not match exactly the study area selected, however it is the closest data set available and no reliable statistics are available to convert between municipality-level results and those for the study area. Hence, the data is kept as it is and is assumed to satisfactorily represent the proportions of building types in the study area. One of the main anticipated impacts of this assumption is that a higher proportion of predominantly rural building typologies will be present in the census results, as the municipality extends beyond the main metropolitan area (the study area) into more rural or sparsely populated areas.

Changes in material types used for construction is investigated by comparing the proportions wall and roof materials in national level statistics over the most recent three censuses. Although this may not represent the changes in the study area exactly, the national construction trends will be evident, and as most of the new construction takes place in urban areas, national trends are likely to reflect those in Guatemala City well. Significant trends were incorporated in the timeline. Information on the use of construction materials and building typologies is added to the list of buildings information, where relevant.

This analysis of the housing census enriches the historical map and satellite imagery analysis (section 5.1.1.1), by providing information on the likely wall and roof materials for areas of new urban development in different time periods.

5.1.1.5. Review of municipality city maps

The GIS section at the Guatemala City Municipality have some good data about the city, including routings of the main utilities, communication networks, land values, ages of buildings, and the regularity of plots. The methodology used to collate and analyse these data was not shared.

Only limited data was shared by the municipality, relating to the age and plot regularity data on printed maps for zones 1, 7, 11, 12, and 14. These maps were used simply to verify the ages of buildings that were surveyed in the field. The maps can be found in Appendix D.

5.1.1.6. Review of relevant existing studies and other literature

A thorough review of existing studies with exposure and seismic vulnerability data for Guatemala City was completed. Most of these data are unpublished and therefore obtained directly from local contacts. These studies were examined to explore the differences between results obtained by different authors.

There were several issues noted when directly comparing the data so any conclusions are sensitive to this: first, there are discrepancies in the classification of building types, some studies consider broad building classes, for instance concrete and masonry, whereas others include more detailed descriptions of building typologies including height and lateral load resisting system; second, the scope of the different studies ranges vastly, from national level to a sample of streets in Guatemala City; and third, the age of the studies differs.

The data are presented in tabular format and the comparisons are discussed. The results were also incorporated in the list of building types.

5.1.1.7. Review of online building imagery

Images of buildings in Guatemala City are widely available online through both formal and informal sources. These images offer limited but potentially useful and free information about the buildings in the city.

Imagery can be viewed on numerous platforms and in different forms. Official omnidirectional imagery is available for part of the city from Google Street View (Google Inc, 2017) (collected in 2016), alongside crowd-sourced omnidirectional images uploaded to platforms such as Google Street View and Mapillary (www.mapillary.com). Photographs are widely available online, published primarily by tourists on websites such as Instagram (www.instagram.com), Flikr (www.flikr.com), Google Maps (www.google.com/maps), and many others. It is possible on some platforms to see the location, which helps to derive spatial patterns of different types of buildings. Most often, images are spatially biased, with more photographs in touristy areas, near hotels, restaurants, and shops. Less photographs are available in unsafe or normal residential areas. The accuracy of the data can also be difficult to judge as the age of the photograph is often unknown and other meta-data is often lost, incomplete, or even incorrect.

5.1.2. Field-based methods

Field-based data collection methods collect information during one (or a series of) time period(s). It involves travel to the study area and the direct employment of data collection methods. In field-based methods are usually considered buildings individually, therefore in a city, sampling techniques are required so that the proposed data collection methods can be completed within the time available.

5.1.2.1. Rapid visual surveys

Rapid visual surveys have been used widely as a methodology for collecting building data as it balances the accuracy of assessing a building in person with rapidity over a detailed internal survey (ATC, 2002; Wang and Goettel, 2007; Jain et al., 2010). Information about each building is collected on a form which may be bespoke or standardised. The form for this study was specifically derived to collect information required for vulnerability assessments, as explained below. The results collected by the RVS were used to define the proportions of building types or construction materials in the city, and compared with results from other methods to understand the relative usefulness, the cost, and the accuracy of the data collected.

The survey form was devised particularly for this study. It was designed to include all inputs from Chapter 4 that are collectable from the street as well as some influence from other RVS survey forms and SVA input requirements (ATC 2002; D'Ayala and Speranza, 2002; Jerez 2010). Clearly, it is not possible to collect all the information required, particularly for more complex methodologies where geometrical information or material properties. The characteristics used on the RVS forms are mapped from Table 4-5 in Table 5-2.

Extensive details were requested on the form, with the option of 'unknown' offered in order to collate as much information as possible. The first iteration of the survey form was tested by surveying for one morning (around two hours) by the author and a local expert, and the feedback was used to improve it for further applications. Changes were applied, particularly in the reporting of confidence and the order of the questions. The final survey form was translated into Spanish and checked by a native speaker.

The form is set up to survey one building per page. As can be seen in Figure 3-7, the form is divided into sections to collect data on the building (including location, a description, position of the building, occupancy, and the age), general structural information (such as materials, structural system, design levels, seismic weaknesses) and some supplementary structural information using multiple choice, where appropriate, in addition to the confidence level (low, moderate, or high) that the surveyor has in their answer.

Books of the forms were printed in English and Spanish to allow for ease of use in the street. The books were collected each day after surveying and results entered into the database. After the first couple of days, or as issues arose, feedback was given to surveyors including clearer explanations of the questions or answers, and encouragements to complete all the relevant questions.

Characteristics from Table 4-5: Mapped characteristic name	RVS form characteristics	Usefulness
Number of storeys	No. storeys	H
Material type	Primary structural material	H
Sub-question	Masonry type	H
Sub-question	Reinforcement	H
Sub-question	Mortar type	H
Sub-question	Mortar joints	H
LLRS type	LLRS	H
Elevation regularity	Elevation irregularity	H
Plan irregularity	Plan irregularity	H
Soil type	Not collectable	-
Soft storey	Soft storey	H
Sub-question	Built on stilts	H
Short column	Short column	H
Usage	Usage	M
Torsional irregularity	Not collectable	-
Roof type	Roof material	M
Connections	Connection quality	M
Age	Age	M
Sub-question	Age [years]	M
Foundations	Not collectable	-
Height	Storey height	M
State of preservation	State of preservation	M
Material properties	Not collectable	-
Element dimensions	Wall thickness	M
Mass irregularity	Mass irregularity	M
Position in block	Position	M
Infill wall details	Not collectable	-
Openings irregularity	Opening irregularity	M
Floor material	Floor material	M
Roof shape	Roof pitch	M
Diaphragms	Diaphragms	M
Pounding	Pounding	M
Topography	Built on slope	M
Structural capacity	Not collectable	-
Non-structural hazard	Not collectable	-
Building weight	Not collectable	-
Detailing	Not collectable	-
LLRS quality	Not collectable	-
Fundamental period	Not collectable	-
Building footprint	Not collectable	-
LLRS quantity	Not collectable	-
Max. horizontal span	Not collectable	-
Lateral load path complete	Not collectable	-
Retrofitting	Retrofitting	L
Material quality	Not collectable	-
Heavy façade	Not collectable	-
Strong beam weak column	SBWC	L
Vertical load path complete	Not collectable	-
Mezzanines	Not collectable	-
Balconies	Balconies	L
Aseismic devices	Aseismic devices	L
Bow windows	Bow windows	L
Safe stairs/lifts	Not collectable§	-
Incremental construction	Modifications	L
Level of design	EQ design	L

Table 5-2 Development of the survey data requirements from the usefulness of data study in Table 4-5

Three groups of surveyors completed the RVSs: a local engineer, Ing. Omar Flores Beltetón; a group of undergraduate engineering students recruited from the *Universidad de San Carlos* (USAC) (see Appendix H) and; a foreign engineer, the author. These three groups bring different levels of experience of engineering and working knowledge of buildings in Guatemala City. The local expert, a Professor of Engineering at the Universidad de San Carlos in Guatemala City, has lived in the city for over 50 years and has substantial engineering knowledge, particularly on structures in Guatemala City, having seen construction practices change over time and having lived through the large 1976 earthquake. He was a founding member of AGIES (*Asociacion Guatemalteca de Ingenieria Estructural y Sismica*; Guatemalan Association of Structural and Seismic Engineering). The students were recruited through one of the courses that Ing. Flores gives at USAC. The opportunity to volunteer on this research was presented in a lecture and a sign-up sheet set up at the administrative office. No incentives were offered, except gaining experience of surveying and a certificate stating that they had volunteered. This group were judged to have lower levels of engineering capability and of construction practices in Guatemala City, as they have lived in the city for less time and had completed just three years of engineering study at the time of the surveying. The foreign engineer, the author, has nine years' experience as a structural engineer in the UK, and three years' experience of research in earthquake engineering and seismic risk assessment in Central America and the Caribbean. This trip was the author's first trip to Guatemala. The foreign expert has less engineering experience than the local expert, but has a similar level of specific earthquake engineering and seismic vulnerability assessment knowledge and experience than the local expert. Knowledge and experience of Guatemala construction was low however with no previous trips to Guatemala. It is worth noting that there is potentially a relationship between the local expert and the engineering students, who learn much of their related engineering knowledge from him. This may present itself as a bias in the results. Figure 5-1 indicates the levels of knowledge expected by each surveyor group.

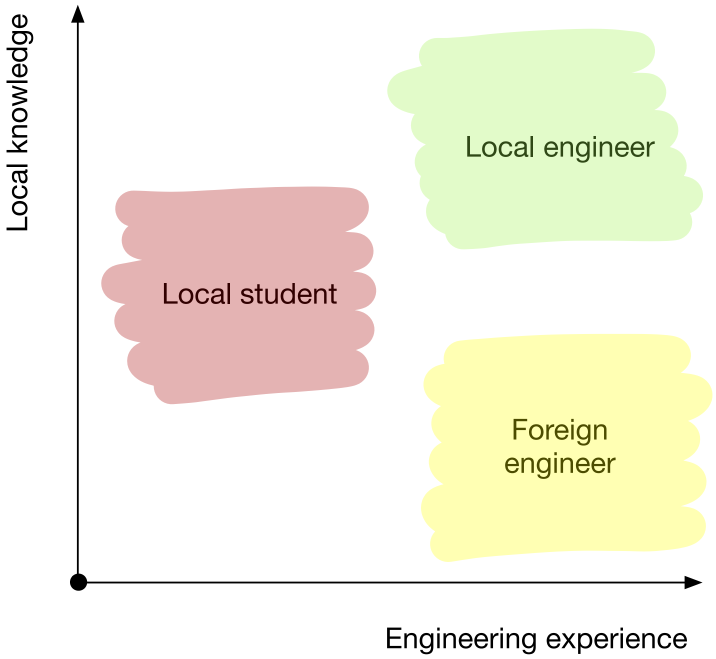


Figure 5-1 Local and engineering experience of the survey groups

A presentation written by the author was given by Ing. Flores to the volunteers, focussing on seismic vulnerability of buildings, the surveying process, and a detailed look at the survey form, with photographic examples of buildings demonstrating different answers. A copy of the presentation slides can be found in Appendix I.

Rapid visual surveys took place in Zones 1, 4, 5, 7, 10 (including a small part of 9), 12, and 14. Routes were selected to satisfy the sampling methods explained in Chapter 3. Each building was surveyed by one or more of the groups, balancing the quantity of buildings surveyed with the interest in comparing directly the results obtained by the three groups.

5.1.2.2. Omnidirectional imagery collection and virtual surveys

Omnidirectional imagery has been collected in all the survey areas using a GPS-enabled Ricoh Theta S camera attached to a vehicle (see Figure 5-2) or on foot.

The aim was to take images every 10 - 12m (a balance between image number and speed of survey, and ability to capture each building along a route), but due to traffic conditions or obstacles the actual distance may have been shorter or longer. In some cases, when the distances between images were significantly longer, a second pass of the area was conducted to collect another set of images from the routes. The images are hosted online on Google Street View (www.google.com/maps) and Mapillary platforms (www.mapillary.com). A total of 2103 photos were taken and uploaded and have, to-date (September 2017), accrued a total of 1.25 million views since they were uploaded (in July and August 2016). The Google Street View iOS smart phone application was used to take photos on a timer in the survey area, see Figure 5-3 for a single example: the complete set of survey routes are shown in Appendix F.

Figure 5-2 The omnidirectional camera attached to the surveying vehicle

254 ready to publish

No one else sees these until you publish

Figure 5-3 A screenshot of the Google Street View iOS application, showing the locations of omnidirectional images taken in Zone 14

The omnidirectional imagery, although collected on the ground (assuming the data doesn’t already exist), was used and analysed alongside the desk-based methods. Virtual surveys were completed using the imagery and the same form and routes as the field RVS method (see section 5.1.2.1), however due to time and budget constraints, it was only completed for Zone 1, selected because of its diversity of building types (in terms of construction material and height).

The data collected through the virtual survey methodology were used to compare with results from other data collection methods, in terms of data usefulness, cost, and accuracy (see Chapter 6).

5.1.2.3. UAV imagery collection and virtual surveys

Continuous advances in technology offer the potential for improved accuracy or extent of building data collection. Notably, unmanned aerial vehicles or drones, are increasingly used for a range of research and recreational purposes. Of interest to seismic risk assessments is the collection of aerial imagery which can not only be combined to form a high-resolution aerial image, but they can also be used to construct three-dimensional point cloud models, offering additional data that cannot be collected from street level. A software package called PhotoScan Pro was used to post-process the images and output the high-resolution aerial mosaic of the surveyed area, and the 3D model.

An iOS application called Pix4D was used to program the UAV to self-fly a route designed to image the specified the study area (see Appendix J) for details on survey locations. The UAV was launched from roofs of taller buildings, with the owner's permission, as can be seen in Figure 5-4 and Figure 5-5.

One major benefit of using drones is that the pilot need not be in the area being imaged. Street survey areas were restricted due to safety concerns, however using this method, building data can be collected without having to enter the area. Conversely, drone flight regulations and restrictions can hinder data collection. Zone 14 is located next to the airport in Guatemala City it would have been unsafe to operate a UAV in this survey area.

Figure 5-4 The UAV ready to fly from a rooftop in Zone 4

Figure 5-5 The author working alongside a local engineer to gather UAV data in Zone 5

The aerial images are stitched together to form a mosaic in PhotoScan Pro software package. These larger images were automatically georeferenced during the mosaic building process and were imported directly into a GIS. Desk-based surveying was completed along the RVS routes using the street RVS forms but only collecting building characteristics that could be observed from above.

These 3D models derived from the UAV images were developed for each survey area, except for Zone 14 due to its proximity to the airport. Views of the models are presented in Appendix K and an example is given in Figure 5-6 showing a view along *Calle* 13 in Zone 1. The RVS survey form was used to collect building data observable from the 3D models for the same buildings covered by the street RVSs.

Figure 5-6 Looking west along Calle 13, Zone 1, Guatemala City: an example of a 3D tiled point cloud model constructed from UAV imagery

5.1.2.4. Detailed internal surveys

Detailed internal surveys are the best way to gather the most in-depth and accurate information about a building, although they are time consuming and require the cooperation of the occupants. To enable access to properties, letters were drafted introducing the project, and were delivered in Zones 1, 5, and 12 with the support of the local mayor's office (*la alcaldia auxiliar* in Spanish). In zone 12, the mayor's office supported the work, but the mayor judged that it was too dangerous for her staff to even enter the survey area, so attempts to complete detailed internal surveys in this area were abandoned. Despite these measures taken to reassure owners or tenants, detailed internal surveys were completed in just nine buildings, six in zone 1 and three in zone 5. The aim had been to survey at least ten buildings in all three zones, however, finding willing owners or occupiers was very difficult due to safety concerns despite the presence of the local authorities. Building-by-building solicitations were done in the zones asking for permission to survey the buildings: only nine occupants agreed to give us access.

Detailed surveys collected observational information only as it would not have been possible to use any kind of material testing, destructive or not. Data collected by the street RVS form was collected, supplemented by floorplans, plan and elevation dimensions, construction materials, roof types, extensions, state of the structure, primary usage, and other structural characteristics. Detailed internal survey forms were used for each building to prompt the surveyor to collect the required data.

5.1.2.5. Interviews with local experts

All of the fieldwork was conducted with the support of Ing. Omar Flores Beltetón, the founder and current vice president of AGIES (*Asociacion Guatemalteca de Ingenieria Estructural y Sismica*; Guatemalan Association of Structural and Seismic Engineering). The knowledge gained throughout the field season from Ing. Flores was invaluable and is evident throughout this thesis, although he was not formally interviewed.

A semi-structured interview (Bryman, 2008) was held with the current AGIES President Dr. Hector Monzón Despang on 17th August 2016 (see Figure 5-7). Dr

Monzón runs a successful engineering consultancy firm in Guatemala City and has authored a number of design and construction guidelines and reports on buildings in Guatemala.

The interview was guided by a list of key areas which prompted the interviewer towards collecting the required information. The questions were flexible and could be expanded or followed up with supplementary questions. The key areas were formulated to gain knowledge around exposure and seismic vulnerability in Guatemala City, conscious of the experience of the interviewee which was primarily in design of new structures. The key areas were as follows:

- Historical construction practices in the city
- Current and past design and construction regulations, guidelines or codes
- Training of engineers in Guatemala
- View on proportion of building types in the city today
- Opinion on the performance of the city's assets to a large earthquake
- Memories from the 1976 Guatemala City earthquake

Data collected from the interview was added to the timeline and building typology list.

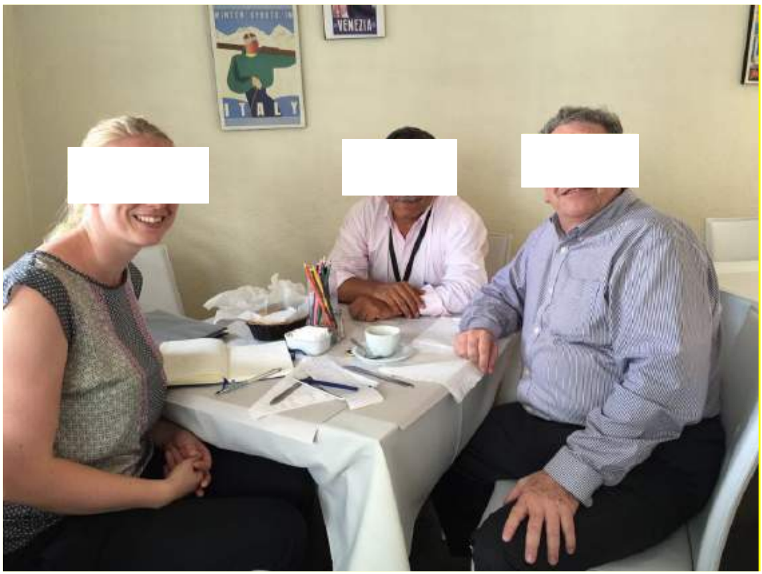


Figure 5-7 Interview with Dr. Hector Monzón Despang (right) and Ing. Omar Flores Beltetón (centre).

5.2. Data collection results

In this section, the results of the desk studies are presented individually for each methodology. The accumulated knowledge from these studies is collected in the form of a historical timeline and a compendium of building typology information.

Data collected using desk-based methods is mostly general information about building types and urban development over time. Field-based methods collect building-by-building data, but clearly not all field methods tested would be able to collect all of the thirty-eight items of building data sought, with different methods reporting different levels of completeness. The data collected consistently by different methods is given in Table 5-3. Although certain data are collected, the accuracy of it may be fairly low; this is investigated further in Chapter 6. Table 5-3 reflects the anticipated collection of data by different methodologies in Table 3-3 well and the issues of using the AS and 3D results individually still apply.

Data name	DIS	RVS LE	RVS FE	RVS STU	OD	AS	3D
Position	●	●	●	●	●	●	●
Usage	●	●	●	●	●		
Age	●	●	●	●	●		
Age [years]	●						
Primary structural material	●	●	●	●	●		
Roof material	●	●	●	●	●	●	●
Roof pitch	●	●	●	●			●
Floor material	●	●	●	●	●		
LLRS	●	●	●	●	●		
No. storeys	●	●	●	●	●		●
Storey height	●						
Diaphragms	●		●			●	
EQ resisting design	●	●	●	●	●		
State of preservation	●	●	●	●	●		
Connection quality	●	●	●	●			
Retrofitting	●	●	●	●	●		
Aseismic devices	●	●	●	●	●		
Modifications	●	●	●	●		●	●
Short column	●	●	●	●	●		
Pounding	●	●	●	●	●	●	●
SBWC	●	●	●	●	●		
Soft storey	●	●	●	●	●		
Built on slope	●	●	●	●	●		●
Built on stilts	●	●	●	●	●		●
Bow windows	●	●	●	●	●	●	●
Balconies	●	●	●	●	●	●	●
Plan irregularities	●	●	●	●	●	●	●
Elevation irregularities	●	●	●	●	●		●
Mass irregularities	●	●	●	●	●		●
Opening irregularities	●	●	●	●	●		●
Masonry type	●	●	●	●	●		
Reinforcement type	●	●	●	●			
Mortar type	●	●	●	●			
Mortar joints	●	●	●	●			
Wall thickness	●		●				
Position	●						
Usage	●						
Age	●						

Table 5-3 Data collected by different methodologies

5.2.1. Desk-based data collection results

5.2.1.1. Historical maps and remotely-sensed imagery review results

Guatemala City was founded following the destruction of present-day Antigua in a large earthquake in 1773. A new capital city was proposed in the supposedly safer *valle de Ermita* (the Ermita Valley) just forty-five kilometres to the north-east of Antigua, despite much protestation (Gillert, 1995). The new plans started with a zonal pattern radiating from the centre of the valley, which to this day still roughly informs the numbering of the zones in the city (see Figure 5-8).

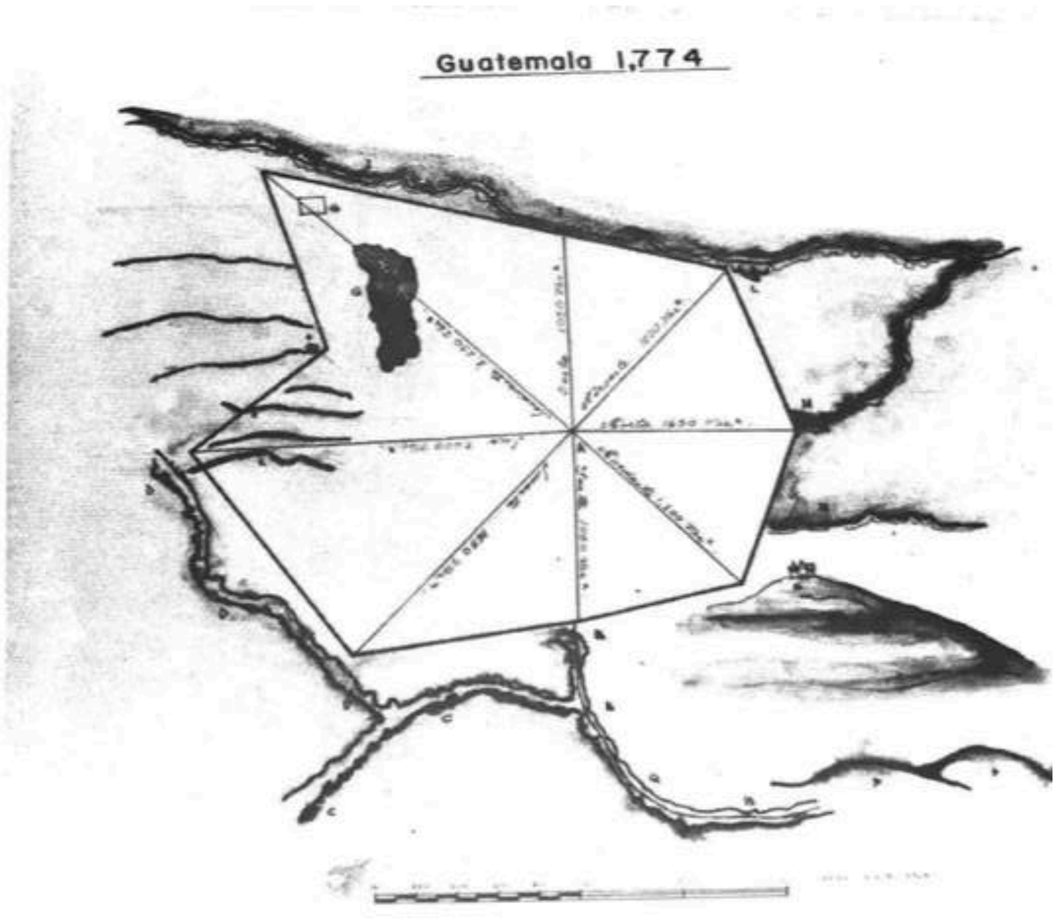


Figure 5-8 Photo of early (1774) zonal plans for the new city, from Gulicia Díaz (1968)

The first construction was influenced heavily by Spanish cities, with a central open square reserved for markets and ceremonial events (Gillert, 1995) surrounded by streets in a uniform grid, mirroring the previous capital Antigua (see Figure 5-9). By 1791 the grid formation that is the present-day zone 1 had been constructed (see Figure 5-10), with the existing town of Ermita just to the north-east.

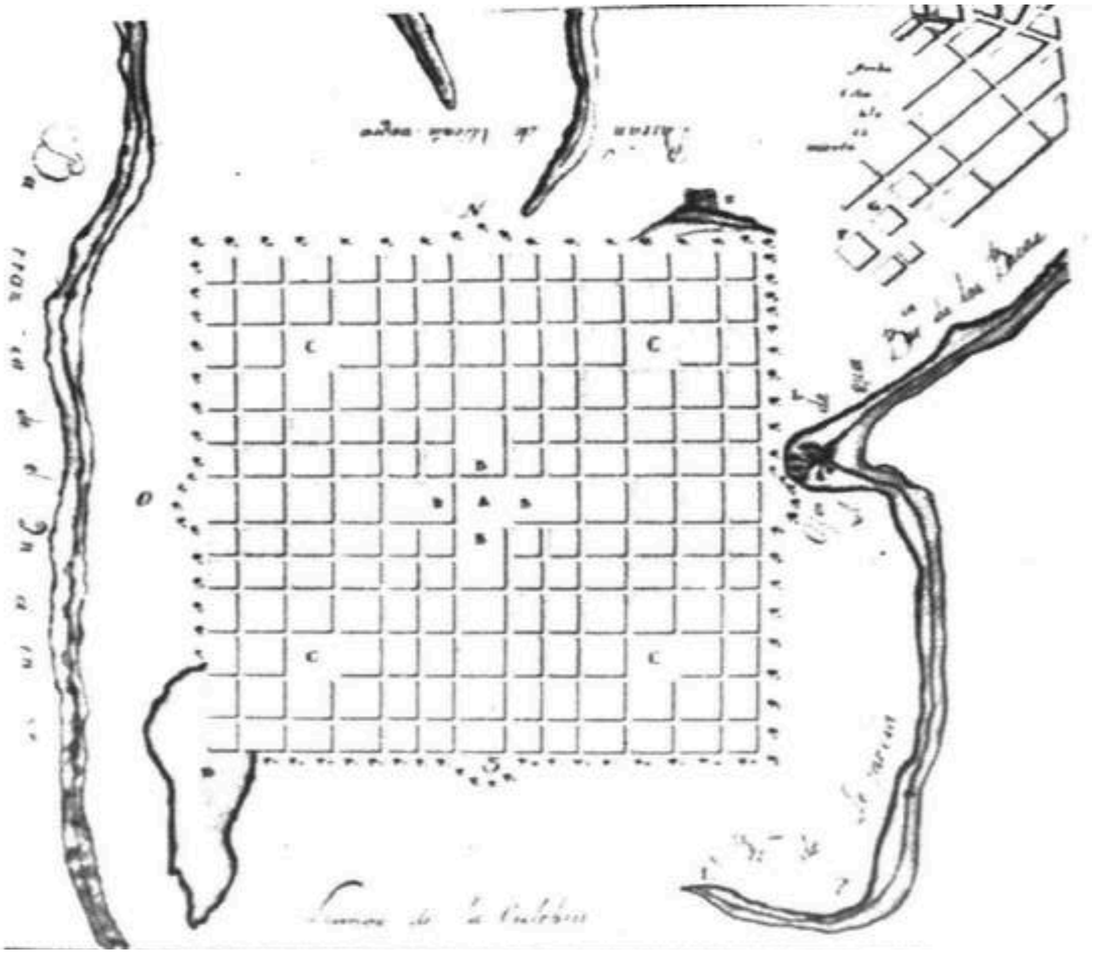


Figure 5-9 Photo ofa map of the early established capital city in 1776, from Gulicia Díaz (1968)

Figure 5-10 Photo of a map of development of Ciudad de Guatemala in 1791, from Gellert and Pinto Soria (1990)

By 1800 neighbouring towns had been built for the indigenous workforce who were required to construct the new city (such as Ciudad Vieja, Villa De Guadaloupe, Sainta Isabel, San Gaspar, and Jocotenango in (Figure 5-11 and Figure 5-12). The 1821 map of Guatemala City (Figure 5-13) shows a small amount of additional development to the south-east but the built areas looks much the same as it did in 1791 (Figure 5-10). By 1842 the city was still a very similar size (Figure 5-14) however by 1850 there are potentially some observable developments (Figure 5-15), particularly towards the south, thereby avoiding the unfavourable relief towards the north. Very little observable growth is achieved between 1850 and 1882 (Figure 5-15, Figure 5-16, and Figure 5-17), however by 1889, the city has grown substantially towards the south, with construction into the present-day zones 3, 5, and 8 (Figure 5-18). By 1925 the city had expanded significantly towards the south into zones 4, 9, 10, 13 and further into zones 3 and 5 (Figure 5-19), with increased urbanisation of all developed areas and small expansions into zone 7, 11, and 12 observed in 1936 (Figure 5-20).

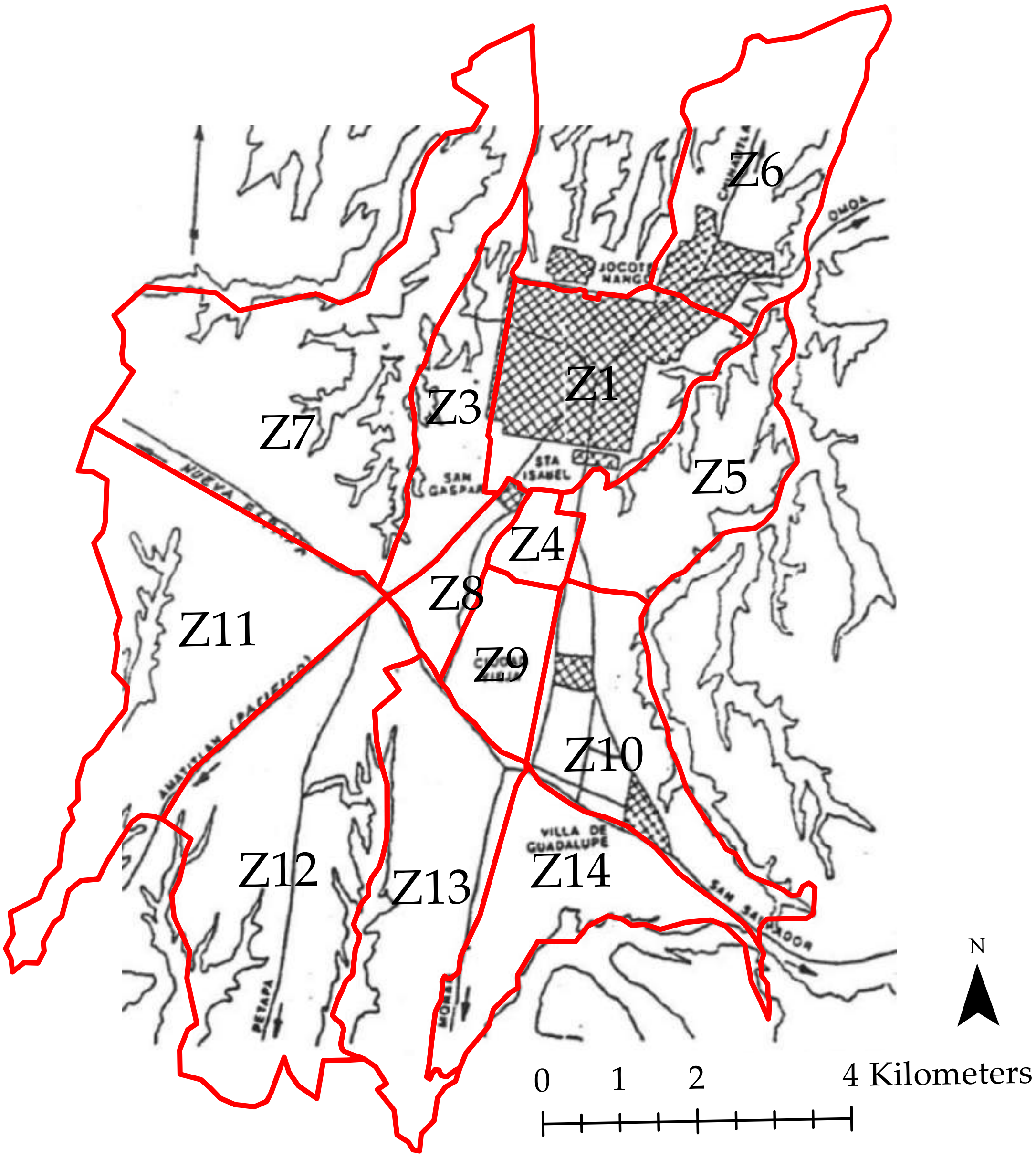


Figure 5-11 The site of the new capital city in 1800 with the surrounding communication routes and villages, from Gellert and Pinto Soria (1990). The present-day city zones are imposed roughly over the top in red.

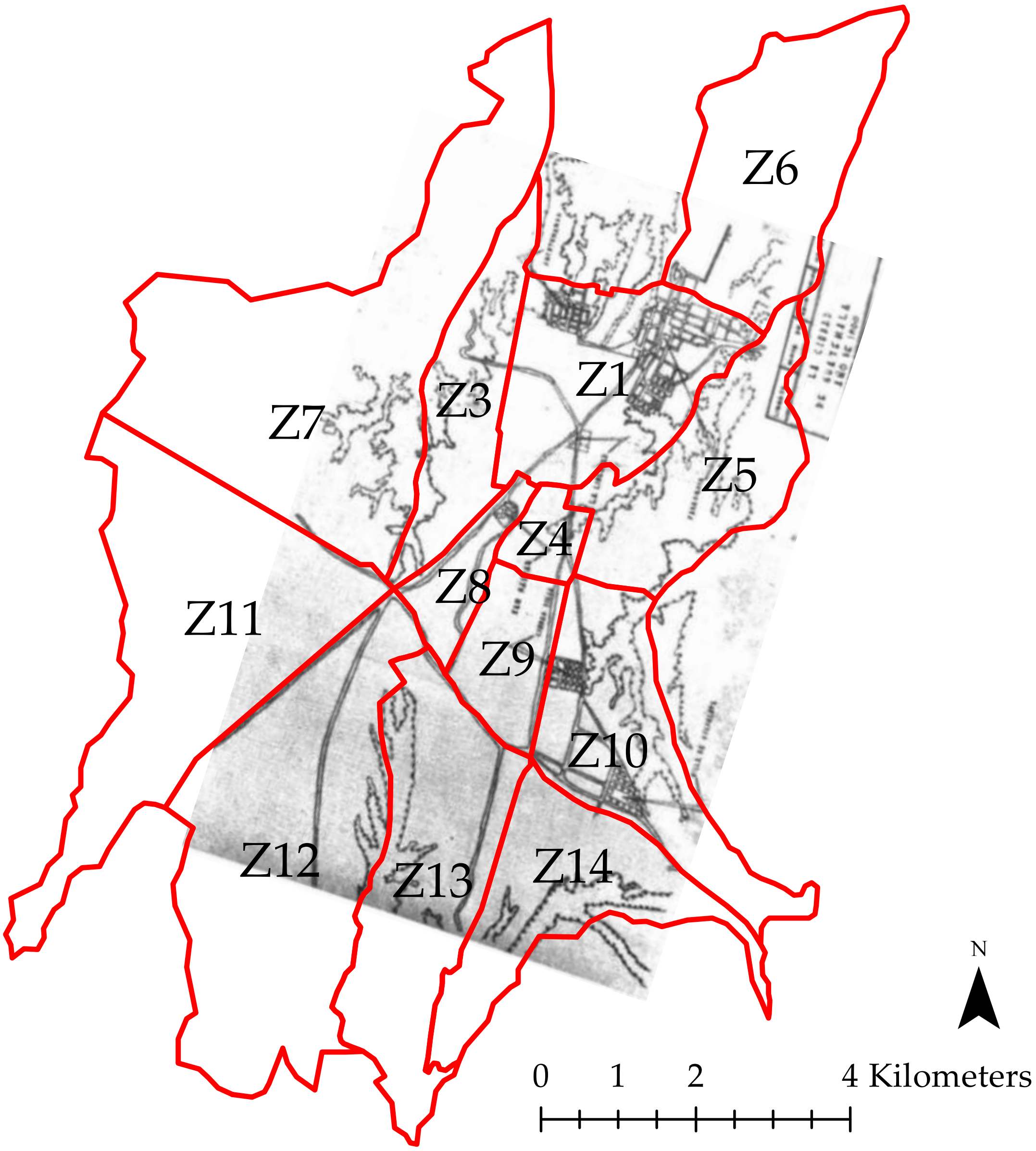


Figure 5-12 The urban areas of 1800 Guatemala City, from Gulicia Díaz (1968). The present-day city zones are imposed roughly over the top in red.

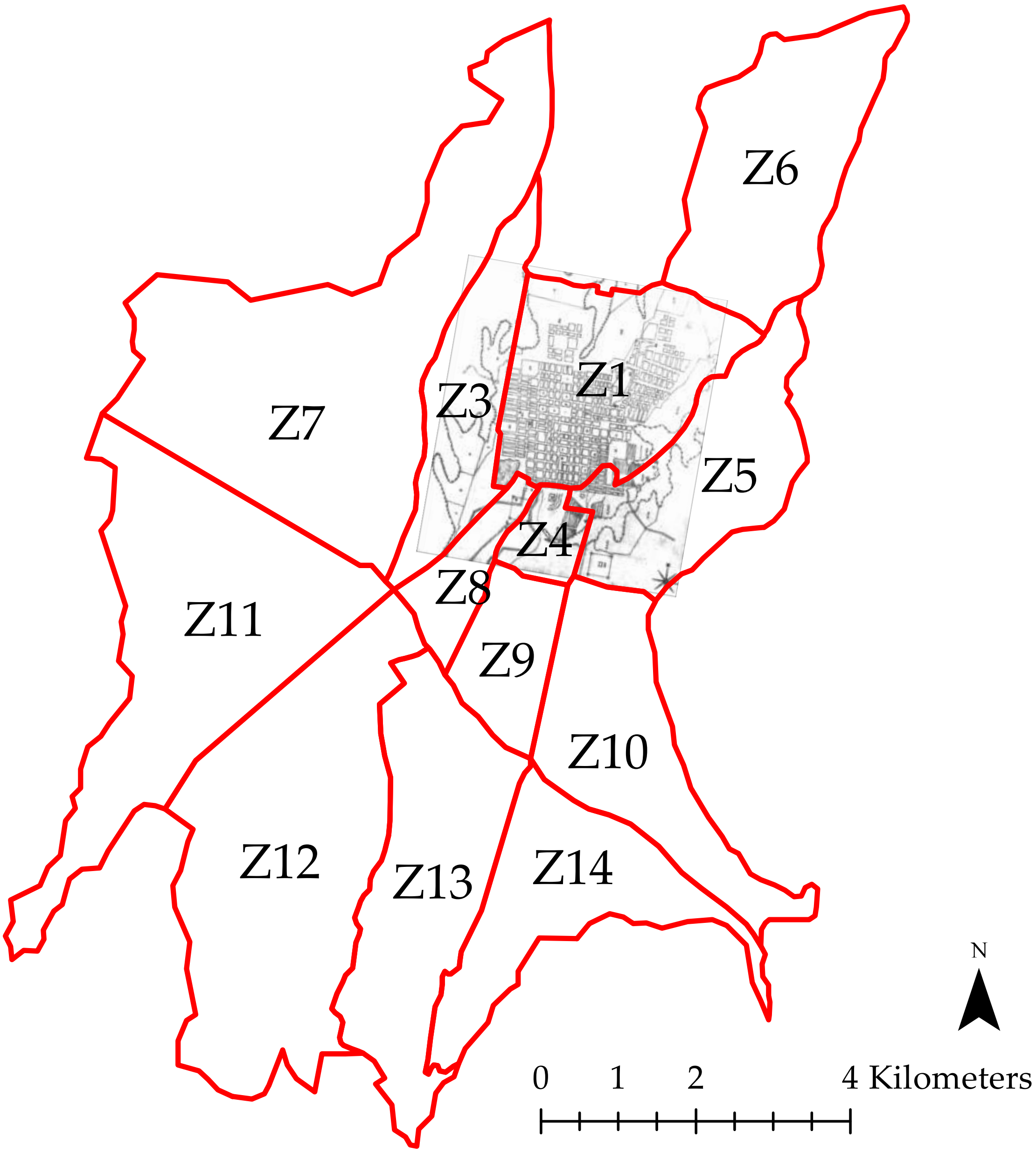


Figure 5-13 Map of Guatemala City in 1821, from Gulicia Díaz (1968). The present-day city zones are imposed roughly over the top in red.

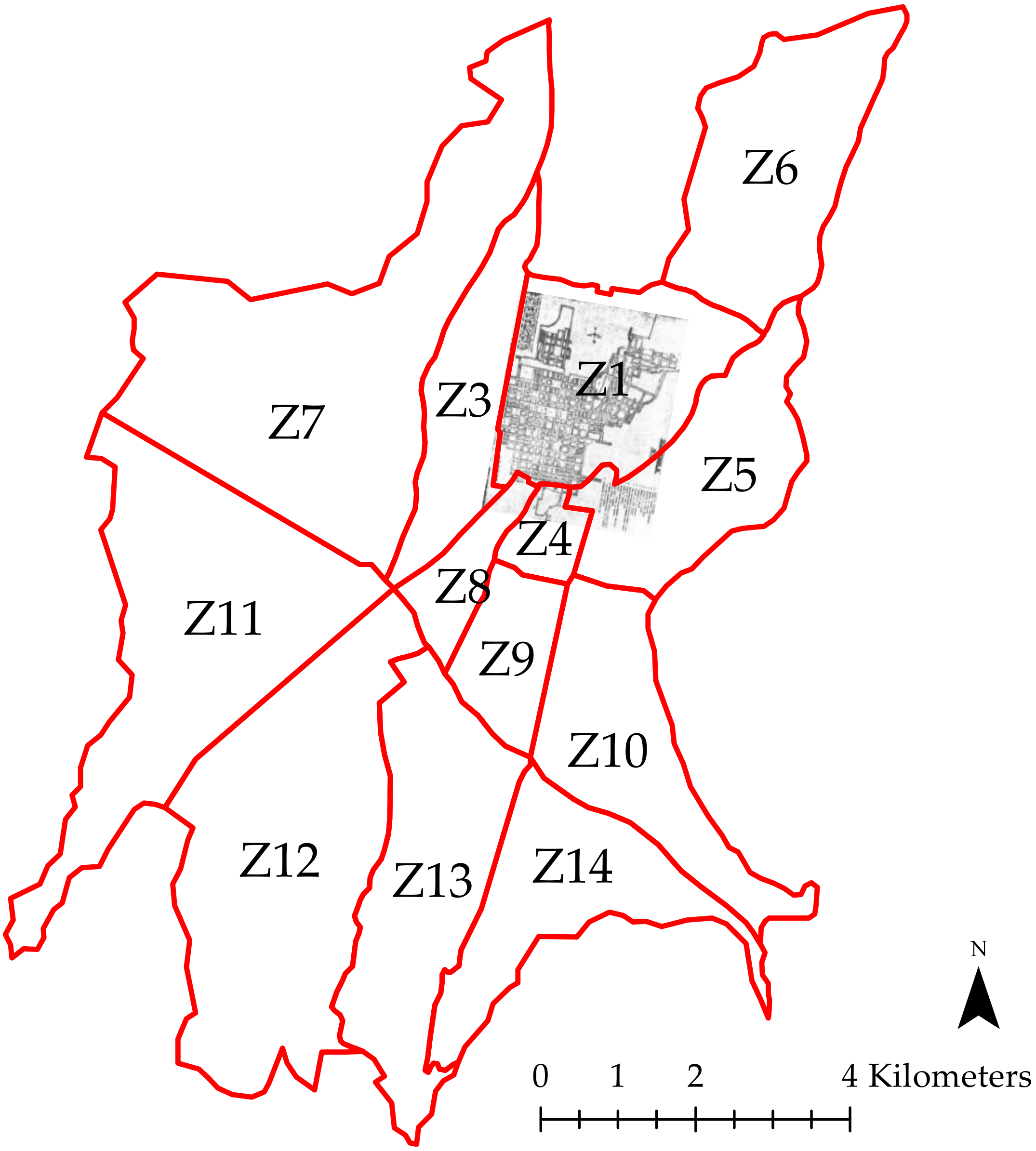


Figure 5-14 Map of Guatemala City in 1842, from Lara F (1977). The present-day city zones are imposed roughly over the top in red.

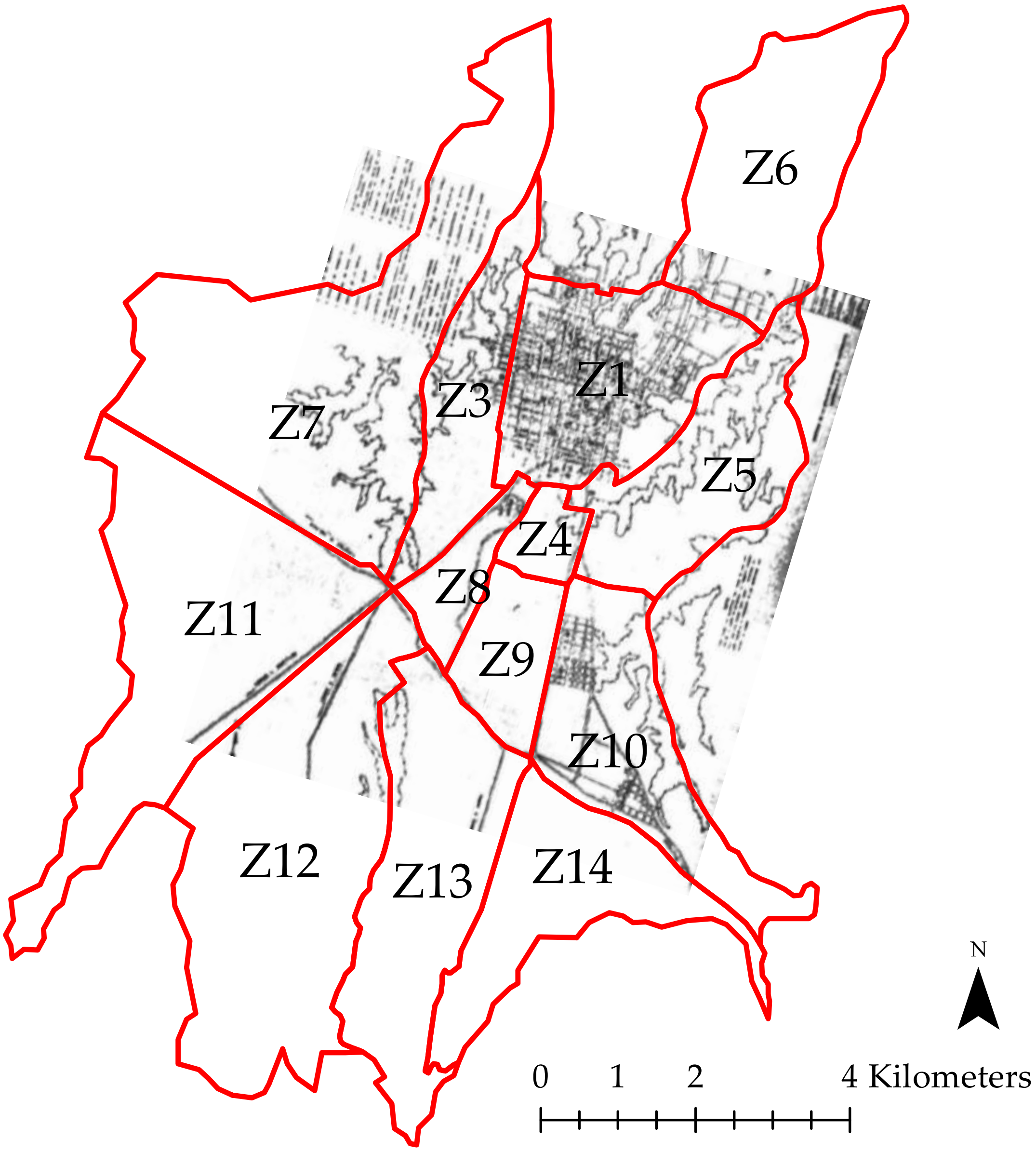


Figure 5-15 Built-up areas of Guatemala City and surrounding villages in 1850, from Lara F (1977). The present-day city zones are imposed roughly over the top in red.

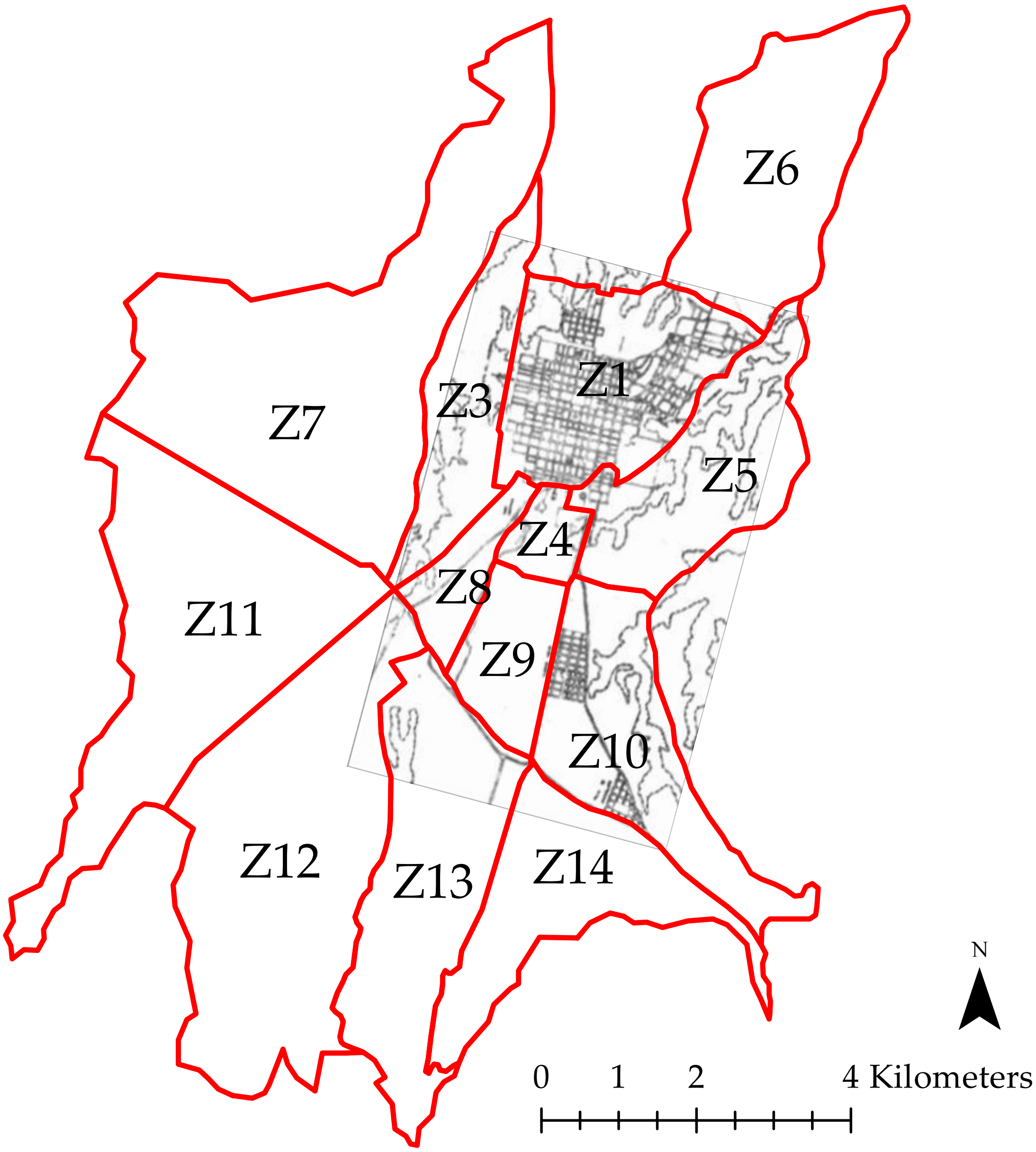


Figure 5-16 1868 Guatemala City, with nearby villages, from Lara F (1977). The present-day city zones are imposed roughly over the top in red.

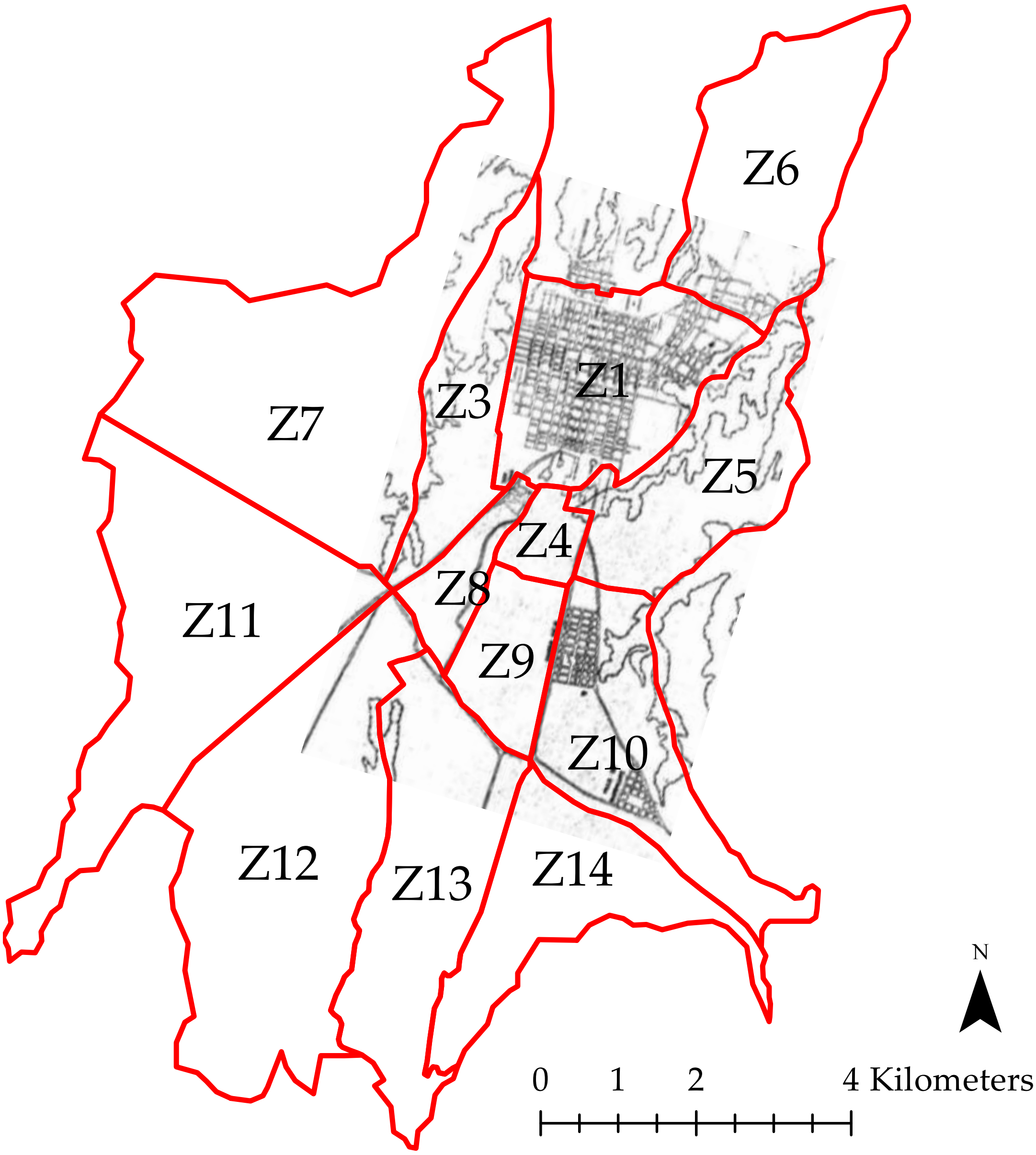


Figure 5-17 The extent of Guatemala City in 1882, from Lara F (1977). The present-day city zones are imposed roughly over the top in red.

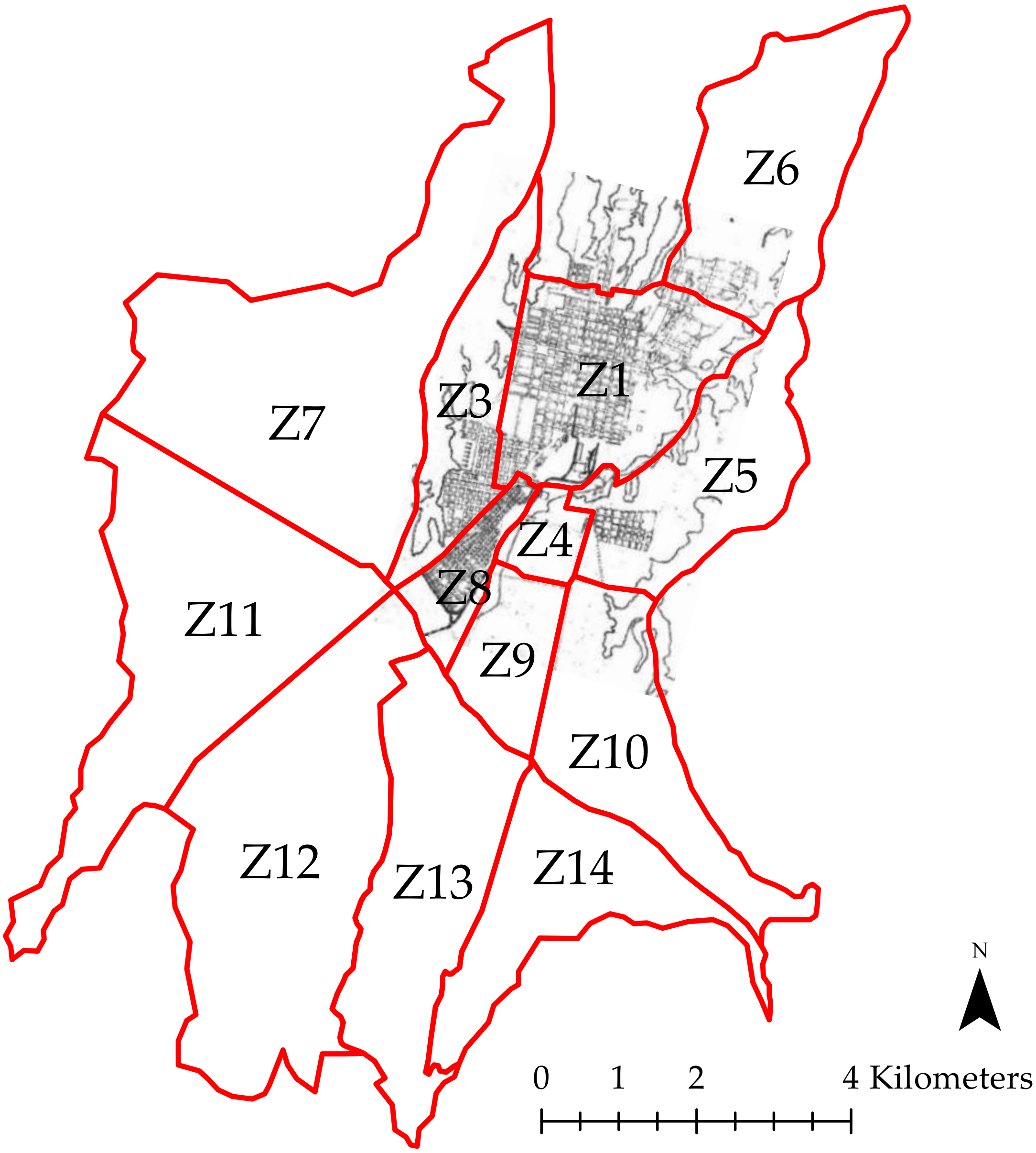


Figure 5-18 Extensive growth of Guatemala City is observed in 1889, from Lara F (1977). The present-day city zones are imposed roughly over the top in red.

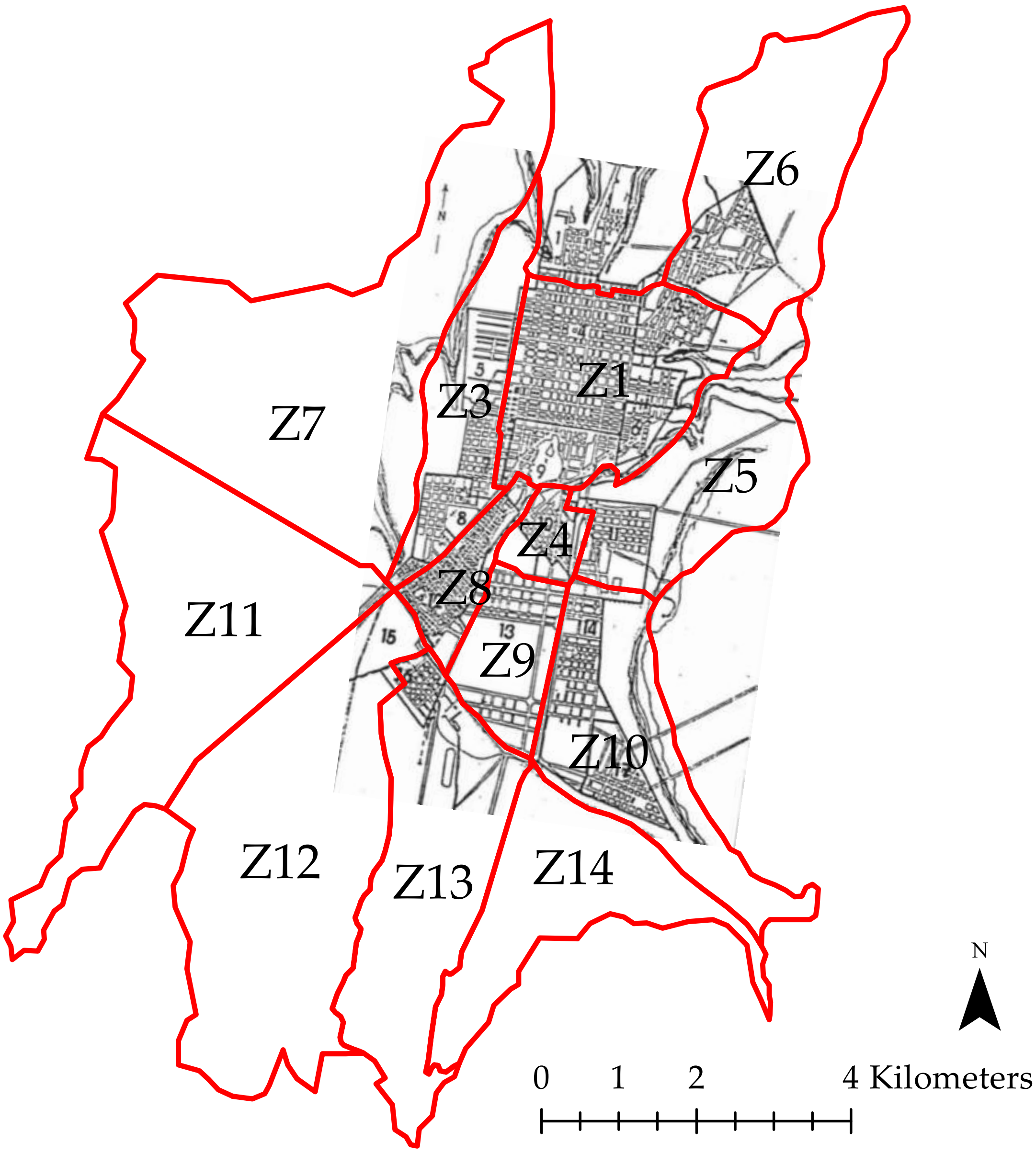


Figure 5-19 The spread of urban development is clear in this 1925 map of Guatemala City, from Gellert and Pinto Soria (1990). The present-day city zones are imposed roughly over the top in red.

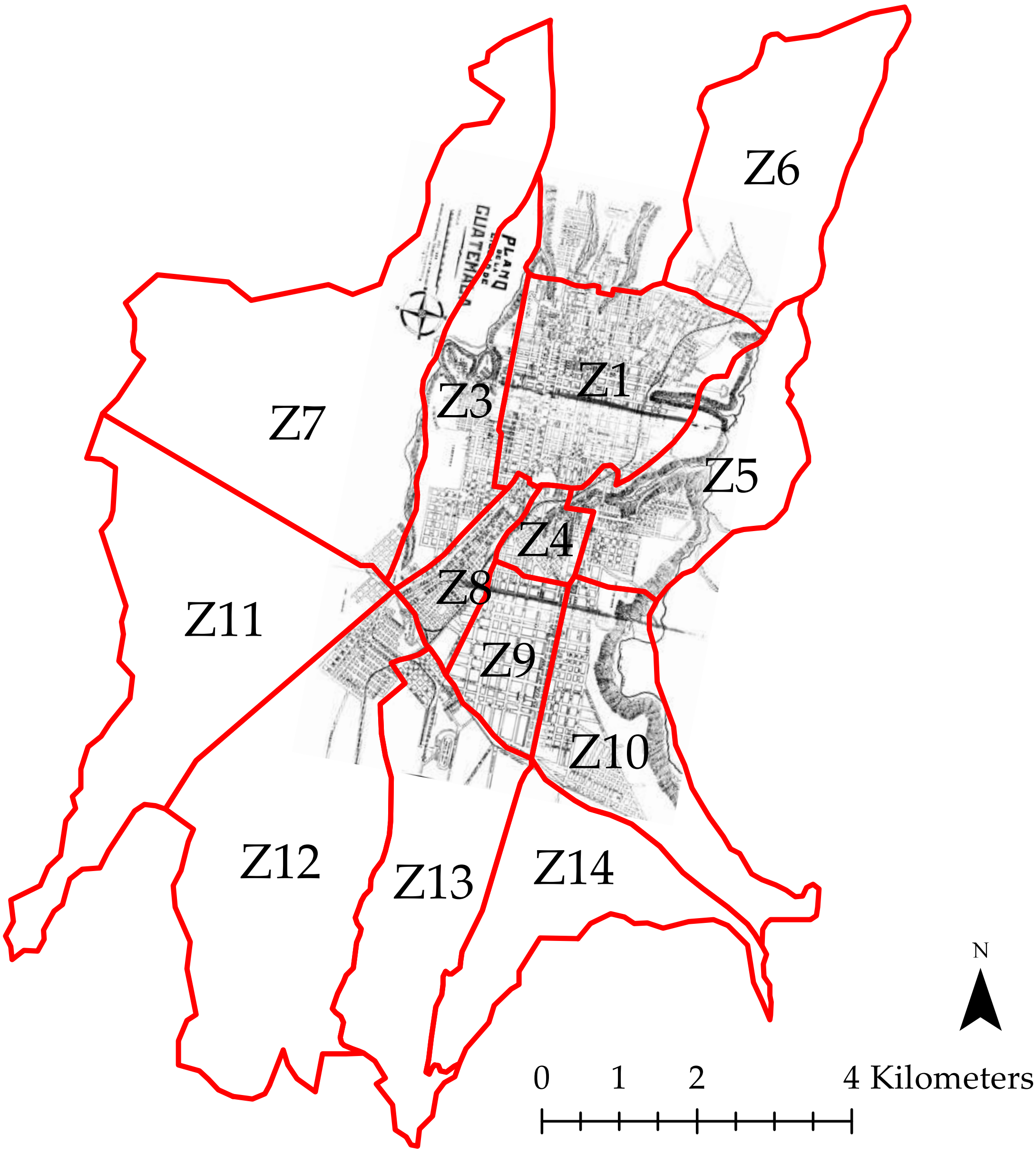


Figure 5-20 Further growth is observed in this 1936 map of Guatemala City, from Gellert and Pinto Soria (1990). The present-day city zones are imposed roughly over the top in red.

Urban development between 1945 and 1973 is highlighted through the results of the historical map image classification analysis, shown in Figure 5-21. The analysis is confined to the study area, and shows indications of urban development during the time periods investigated, despite a significant amount of noise, particularly for the period beginning in 1955. To avoid the misclassification of noise, larger areas of new development are the focus. Once identified, the original maps can be used to validate the result.

For the decade between 1945 and 1955 (yellow) there are a few regions that appear to have been developed, see Figure 5-21, particularly in zone 11. Zones 3, 5, 7, 11, and 14 grow significantly between 1955 and 1965 (orange) with further substantially additions to Zone 5, 7, and 14 between 1965 and 1973 (red).

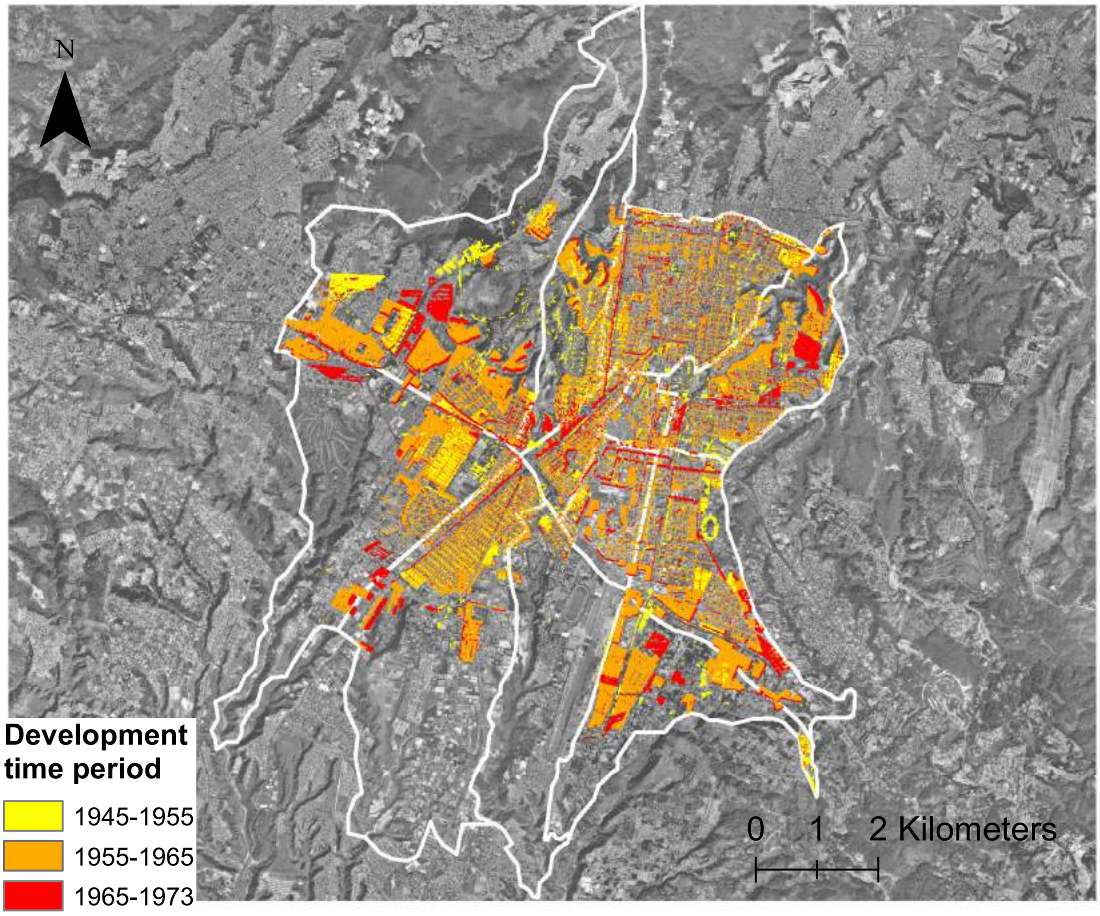


Figure 5-21 Urban development of Guatemala City between 1945 and 1973. The white line shows the study area boundary.

The analysis of the satellite imagery is more precise as it is not dealing with scans of old maps, but instead a real image of the city, more able to capture different land uses. These results for urban development between 1984 and 2014, found in Figure 5-22, show that Zone 7 continues to expand between 1984 and 1994 (yellow), with a densification of buildings, particularly in zones 10 and 12. Between 1994 and 2004 (orange) significant new areas of zones 3, 7, and 11 and further densification of zones 10 and 14, and the southern parts of zone 12. The decade ending in 2014 (red) saw areas of zones 3, 7, and 12 developed further as well as further development throughout zone 10, 11, and 14. These findings are also added to the timeline.

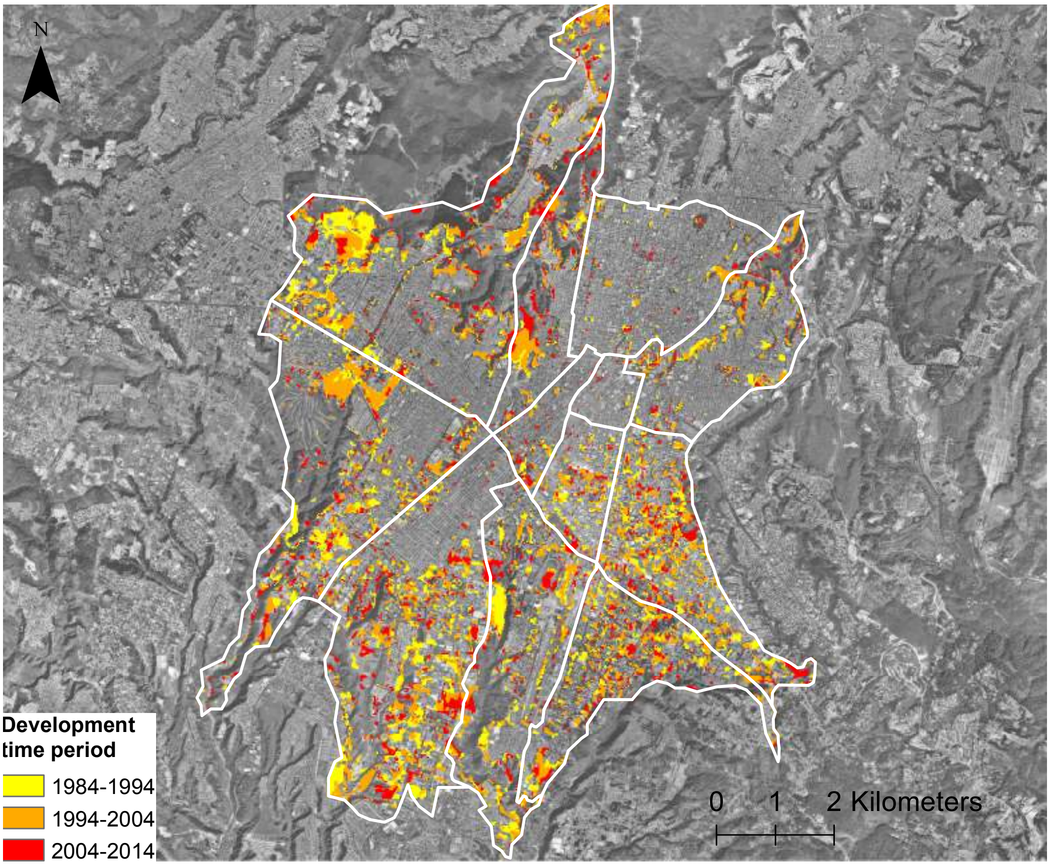


Figure 5-22 Urban development of Guatemala City between 1984 to 2014

The older maps are simple sketches or hand drawn impressions of the growing city and, as with all historical documents, are prone to errors (deliberate or not), biases, or misreporting. More recent maps and satellite imagery are considered more accurate, and were deemed suitable for analysis with ArcGIS. This analysis is not without its challenges, and there are likely to be errors in the results, particularly around the misclassification of land uses, but as it is used simply to identify general areas of development and growth, not the development of specific locations in detail, the results can be verified visually.

In addition, two studies are available for validating results, see Figure 5-23 and Figure 5-24. If we test the findings that the city grows mostly southwards from zone 1 in the north, and that significant development started after 1900, then all studies agree. The temporal and spatial similarities between data validate this analyses results, although this was expected as is it likely that all studies used the same historical maps. This work has extended the work completed in the literature by furthering analysis up to 2014 and by using satellite imagery, but it is restricted in that only the selected study area has been analysed.

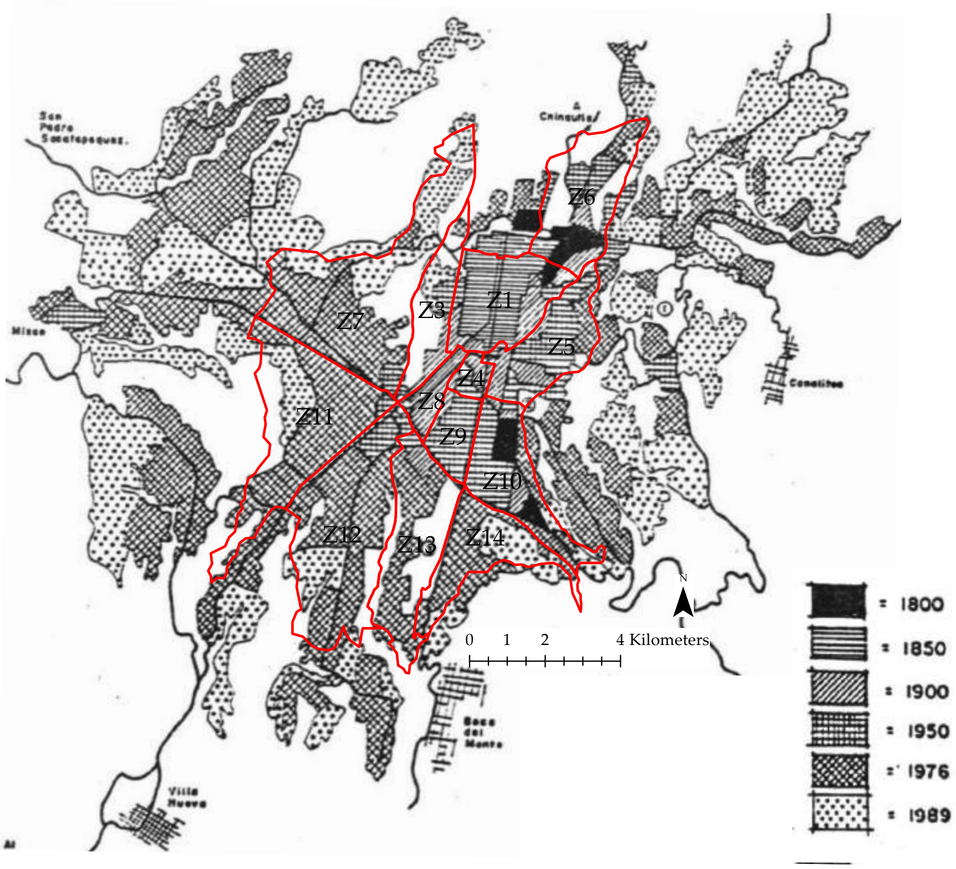


Figure 5-23 The urban development of Guatemala City between 1800 and 1989, from (Gellert and Pinto Soria, 1990). The present-day city zones are imposed roughly over the top in red.

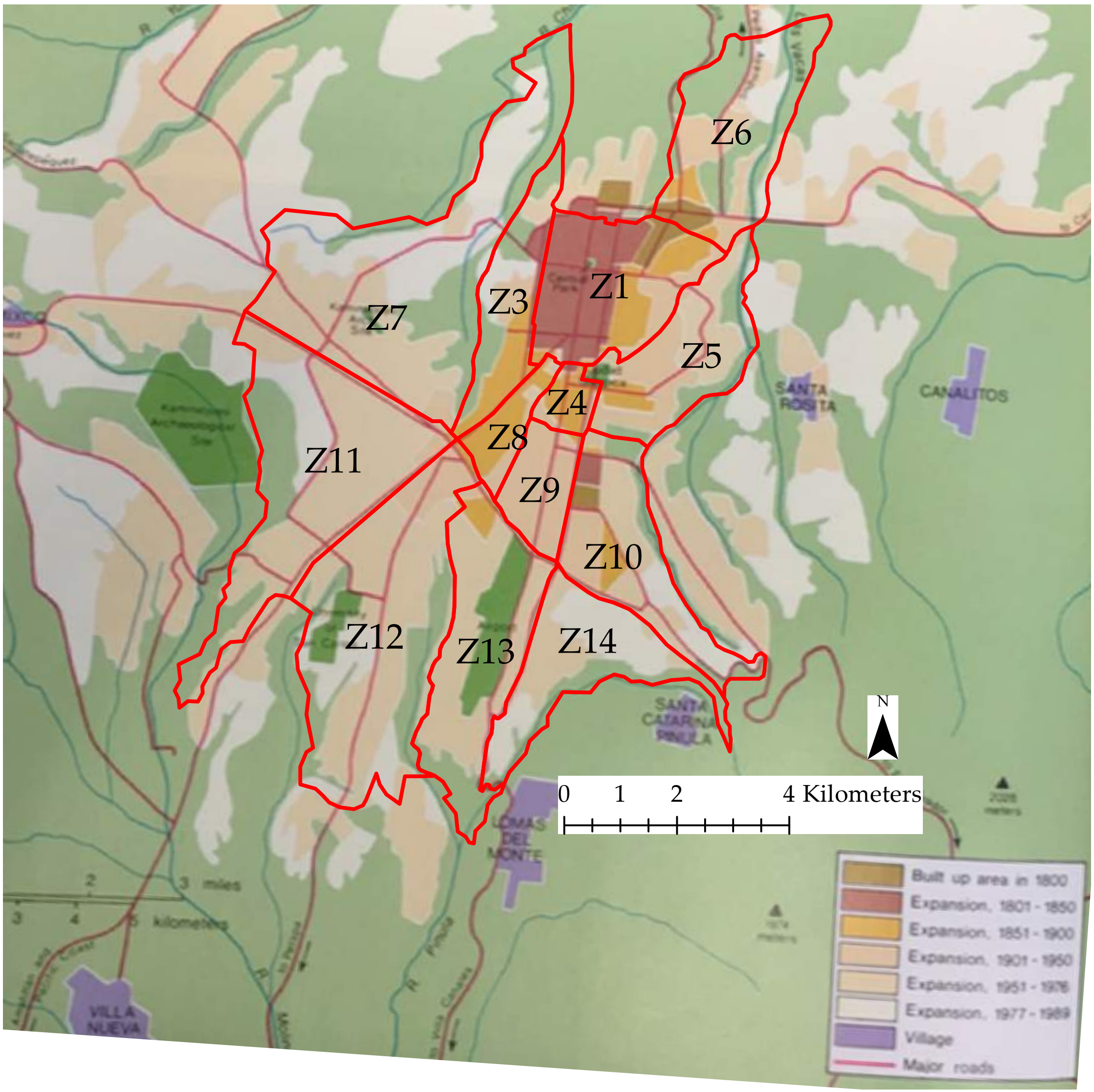


Figure 5-24 Growth of Guatemala City between 1800 and 1989, from (Hall and Pérez Brignoli, 2003). The present-day city zones are imposed roughly over the top in blue.

5.2.1.2. Findings from the review of construction regulations and guidelines

The level of regulation in the construction industry over the history of the city is important for understanding the vulnerability of existing buildings to earthquakes, as the level of design and quality of construction is fundamental to a building's performance during seismic shaking. Information was gathered from literature and is presented here and included in the timeline.

Despite a number of efforts to establish regulations for design and construction in Guatemala (Arce Valenzuela, 1992), there is still no official national building, design, or construction codes (Preece, 1976; Monzón-Despang, 1996). There are some reports by visiting engineers of a building code after the 1976 earthquake (Preece, 1976; Smith, 1976), although well-respected local engineer Dr Monzón Despang reported in 2003 that no code exists, and confirmed that was still the case in 2016 (Monzón-Despang, 2016). A procedure for seismic resistant design in Guatemala was published in 1978, but not legally adopted (Shah and Zsutty, 1978).

Despite no official building design or construction code, there have been a number of regulations over the years. In 1973, the first was published by the FHA (*Fomento de Hipotecas Aseguradas* or Promotion of Mortgage Protection) called the *Normas de Planificacion y Construccion* (or Planning and Construction Standards) (FHA, 1973). These standards present the requirements of building to be eligible for a mortgage.

For structural engineers, FHA (1973) offers basic guidance on the design of confined masonry, unreinforced masonry, reinforced concrete, and steel buildings, and it requires the use of US design codes for buildings over three storeys which may be constructed with either reinforced concrete or structural steel. For structures of one and two storeys, the design parameters are reasonably well defined. The FHA standards were updated in 2011 (FHA, 2011) with minor developments to the original document. This level of design requirements for obtaining a loan has, no doubt, sparked improvements in design and construction practices, however it does not apply to all new construction or the large number of existing buildings in the city.

Furthermore, every building site requires a construction licence or permit, which carries the signature of an engineer. An engineer is officially defined as anyone who has an engineering degree; no further professional development or accreditation is required as in the UK or US. There are concerns as to the level of rigour of this process, which is at risk of voluntary or involuntary poor practice (Monzón-Despang, 1996).

AGIES, who continue to advocate for improvements in design and construction of infrastructure, have published a number of standards and guidelines for the construction sector, which are broadly based on the US code design principles, with relevance for application in Guatemala (AGIES, 2002; AGIES 2010; Monzón Despang, 2014). There are also documents relevant for *maestros de obra* (a term widely used in Latin America for builders without formal training) (AGIES, 2015), who can follow some more simplified building techniques and guidelines, in an attempt to improve the informal construction sector. In 2010, a suite of standards was published by AGIES with the support of CONRED (*Coordinadora Nactional para la Reducción de Desastres*, or National Coordinator for Disaster Reduction in English) which covered both design and construction of buildings and infrastructure (Monzón Despang et al., 2013), but these documents remain without official legal standing. The legal implementation of building codes is, however, not correlated with safer buildings, particularly in the developing world, due to lack of understanding of the hazard or how to adhere to regulations, the financial means to comply, corruption, or of sufficient regulations (Bilham, 2013; Arendt et al., 2017).

This information demonstrates the progress of building regulations in Guatemala City, and offers some insight on the likely level of design of buildings built during certain time periods. The key findings were added to the timeline.

5.2.1.3. Findings from the review of damage and recovery from significant past events

Guatemala City has been repeatedly affected by earthquakes in its history (Collier et al., 1985), moving location twice to avoid natural disasters. Information about the performance of building structures in past earthquakes gives an idea of the make-up of the city in the past, offering clues about the current city. The two most recent events are likely to be most relevant to the present building stock and are, thus, considered in more detail. Any information will be added to the timeline or building typology repository.

A series of large earthquakes in December 1917 and January 1918 'practically destroyed' (Saville, 1918) Guatemala City which was comprised of structures '…built on shallow foundations, with weak walls of red brick or sun-dried mud, and heavy tile roofs, whose unsightliness was hidden by exceedingly heavy over roof walls and cornices' (Saville, 1918). Reports give a bleak picture of the aftermath:

> *'With a single exception (the exception noted is a house of reinforced concrete which was in the process of construction and was absolutely undamaged) every house not only in the city but for a radius of perhaps twenty miles was damaged. In the city itself, perhaps twenty houses may be repaired.'* (Saville, 1918)

The reconstruction process of the city after the events is unclear, although despite warnings not to '…rebuild the city with brick and adobe…' (Saville, 1918), it is likely that similar buildings replaced those that were lost or damaged beyond repair due to the expense of other materials (Saville, 1918; González, 2014).

There is a collection of imagery of the damage incurred (Saville, 1918; Taracena Flores, 1970) and it is clear that most of the damage was to masonry walls and parapets (e.g. Figure 5-26). The recovery was slow, eventually leading to the overthrow of Manuel Estrada Cabera's long presidency in 1920 (Saville, 1918). Evidence of reconstruction is still present today, see Figure 5-25, Figure 5-26, and Figure 5-27 which show a progression of images of the same building. Following damage caused by the 1912-13 earthquake sequence, the building was reduced to a single storey.

On February 4, 1976, the Motagua Fault ruptured to the north-east of Guatemala City, causing a large earthquake with an estimated surface-wave magnitude of 7.5. The event caused around 24,000 fatalities (Plafker, 1976; Espinosa, 1977; White, 1985) and destroyed thousands of houses in the Department of Guatemala. Approximately 60 000 non-engineered low rise (one to three stories) houses of adobe, brick, or *bahareque* construction with either tile or sheet metal roofs were damaged beyond repair (Sozen and Roësset, 1976). Mid-rise structures (four to nine stories) performed well except for some disastrous examples, likely of non-engineered RC frame construction with short columns (Sozen and Roësset, 1976). High-rise buildings (10 – 25-stories) performed well with RC frame and shear wall structures sustaining some light to significant structural damage (Sozen and Roësset, 1976). Revilla (1976) reported that 45% of the capital city's buildings were damaged. Visible damage was estimated spatially by EERI (1976), see Figure 5-28: it is unclear whether the zones without reported damage were unvisited or undamaged.

Figure 5-25 The electrical company building before the 1912-3 earthquake sequence, from Taracena Flores (1970)

Figure 5-26 Damage to the electrical company building during the 1912-3 earthquake sequence, from Taracena Flores (1970)

Figure 5-27 The electrical company building in September 2016. The building was reduced to a single storey structure after the earthquake.

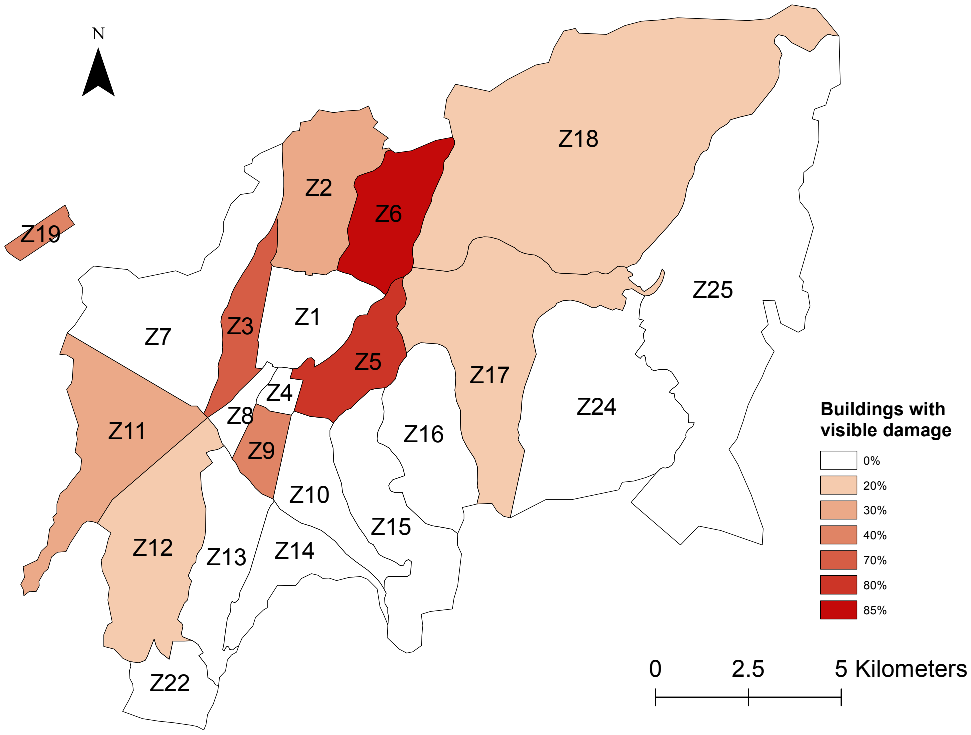


Figure 5-28 Estimated percentages of visible damage to buildings from the 1976 earthquake (EERI, 1976)

Following the earthquake, the government sold inexpensive lots on hillsides (such as in zone 3) for disaster victims to build new homes which has led to large neighbourhoods of informal housing. Elsewhere, construction with concrete block masonry and clay brick masonry increased (Quiñóez de la Cruz, 1996; González, 2014).

The data collected for each earthquake was included in the timeline, especially the spatial damage reports, which informs the main areas of building renewal in the late 1970s, and the changes to the predominant building materials for reconstruction.

5.2.1.4. Results from the 2002 housing census analysis

The 2002 housing census is a national dataset indicating the prevalence of construction materials used for walls and roofs. Changes in materials over time (analysed using past census results) also indicate the trends in building practices and may infer the age of various construction typologies.

The raw data from the census in 2002 for the municipality of Guatemala indicates the prevalence of materials used for exterior walls (vertically) and roof (horizontally) materials. A matrix comparing likely wall-roof combinations is derived for building numbers and percentages in Table 5-4, showing that the most prevalent building type has block masonry exterior walls and a concrete roof (39.96%), followed by block masonry exterior walls with a sheet metal roof (22.7%).

Data for the floor types was available for the 2002 census, however is not considered here as a lot of construction in single storey, and the relationship between floor material and roof and wall materials is not straight-forward and would be prone to inaccuracies.

The national level proportions of construction materials from 1973 (1981 for roof material)) to 2002 are given in Table 5-5 and Table 5-6, with green indicating higher proportions. Clay brick, block masonry or concrete are combined into a single category in the 1973 housing census, therefore remain aggregated in the later data, despite it potentially encompassing a large and wide range of buildings. It becomes immediately clear that clay brick, block masonry or concrete is the fastest growing external wall type, in 1994 becoming the most prevalent and extending its dominance significantly in 2002. Meanwhile the proportion of adobe walls has decreased, however between 1981 and 2002 there were new adobe buildings built, rising in number from 384,582 to 625,905. This increase is likely to be observed more in rural areas more than urban, where there is access to better construction materials and where the deadly consequences of adobe building failures in the 1976 earthquake are a recent memory.

		Roof material							
		Concrete	**Sheet metal**	**Asbestos cement**	**Tiles**	**Thatch, palms or similar**	**Other**	**Totals**	
Wall material	**Clay brick masonry**	16,706 7.0%	11,933 5.0%	942 0.4%	0	0	0	**29,581**	**12.4%**
	Concrete block masonry	95,366 40.0%	54,198 22.7%	4,678 2.0%	0	0	0	**154,242**	**64.6%**
	Concrete	9,546 4.0%	6,208 2.6%	2,157 0.9%	1,599 0.7%	0	0	**19,510**	**8.2%**
	Adobe	0	13,486 5.7%	0	0	0	21 0.01%	**13,507**	**5.7%**
	Wood	0	8,624 3.6%	0	0	20 0.01%	0	**8,644**	**3.6%**
	Metal sheeting	0	10,963 4.6%	0	0	0	0	**10,963**	**4.6%**
	Bahareque	0	351 0.1%	0	0	20 0.01%	20 0.01%	**391**	**0.2%**
	Waste wood or cane	0	468 0.2%	0	0	28 0.01%	20 0.01%	**516**	**0.2%**
	Other	0	0	0	0	0	1,297 0.5%	**1,297**	**0.5%**
	Totals	**121,618** **51.0%**	**106,231** **44.5%**	**7,777** **3.3%**	**1,599** **0.7%**	**6** **0.03%**	**1,358** **0.6%**	**238,651**	**100%**

Table 5-4 Derived wall-roof material matrix for Guatemala municipality from the 2002 census

Decreases in actual numbers of buildings is found for *bahareque* and waste wood or cane wall types indicating few, if any, new constructions using this material, and the replacement or upgrading of existing buildings of these types of materials with buildings using newer construction materials.

Less dramatic changes are observed in the proportions of roof materials, with sheet metal dominating all three censuses, increasing its proportion from 50% to 67% between 1981 and 2002. Concrete roofs also increase in proportion, whilst there are decreases in less formal construction materials; tiles and thatch, palms or similar. Note that concrete roofs are found in much higher proportions in Guatemala City (51% in 2002), than in the rest of Guatemala (11% in 2002), confirming that this is predominantly an urban building typology rather than a rural one.

Predominant material in the exterior wall (%age)	**1973**	**1981**	**1994**	**2002**
Clay brick masonry, block masonry, or concrete	9%	19%	35%	50%
Adobe	39%	31%	30%	24%
Wood	17%	21%	16%	17%
Sheet metal	0%	1%	2%	2%
Bajareque	11%	8%	5%	3%
Waste wood or cane	22%	17%	11%	3%
Other	2%	3%	2%	0%
Total no. buildings	1,013,817	1,256,156	1,805,732	2,578,265

Table 5-5 Proportion of exterior wall materials in the four most recent censuses at national scale

Predominant material in the roof (%age)	**1981**	**1994**	**2002**
Concrete	5%	9%	15%
Sheet metal	50%	58%	67%
Asbestos cement	3%	2%	2%
Tiles	21%	18%	12%
Thatch, palms, or similar	19%	12%	4%
Other	2%	1%	1%
Total no. buildings	1,256,156	1,805,732	2,578,265

Table 5-6 Proportion of roof material in the three most recent censuses at national scale

5.2.1.5. Findings from the review of government-held city maps

The government-held city maps are used only to check the age of specific buildings in the field-based surveys. If more maps had been shared then an analysis of the ages in each zone could have fully complemented the results in section 5.2.1.1, however these were not available. The ages of buildings in Zone 1, 7, and 12 taken from these maps are presented in Figure 5-29, Figure 5-30, and Figure 5-31.

Figure 5-29 Age of surveyed buildings in Zone 1

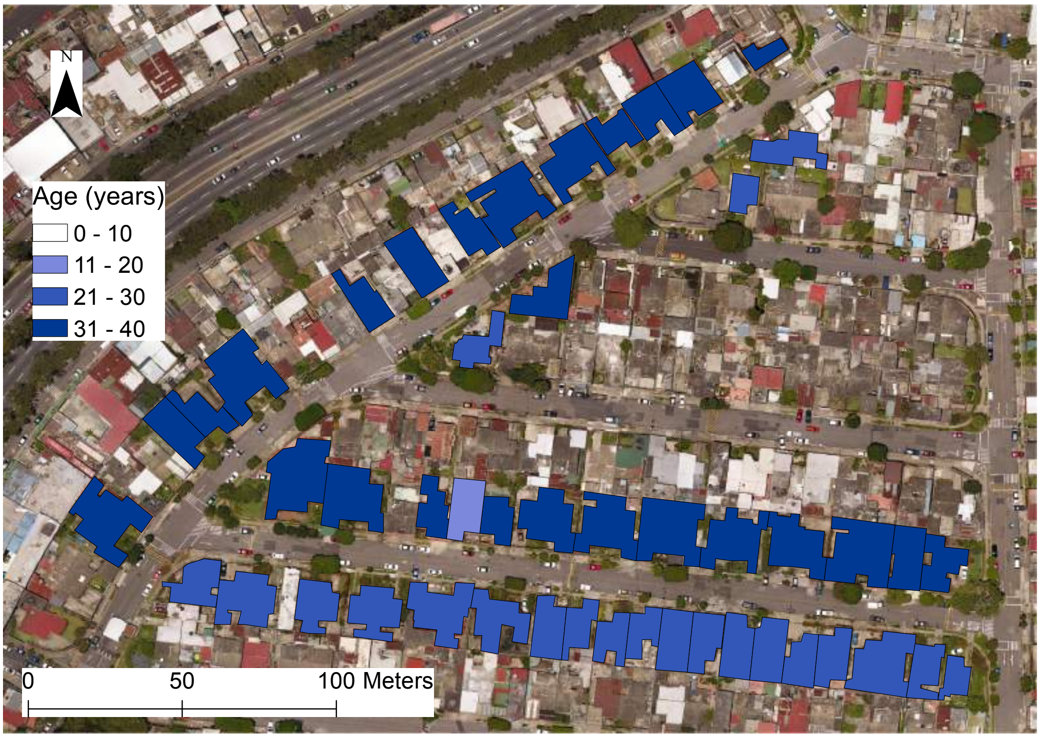


Figure 5-30 Age of surveyed buildings in Zone 7

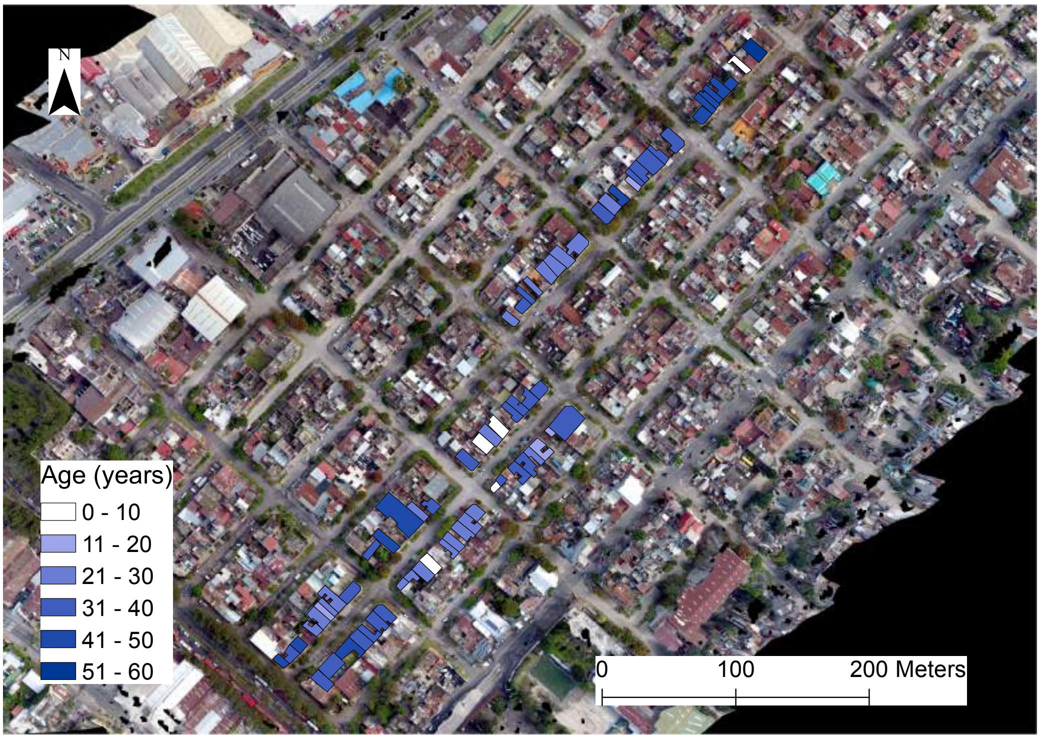


Figure 5-31 Age of surveyed buildings in Zone 12

5.2.1.6. Results from the review of existing works

A number of different sources of existing survey data have been identified for Guatemala City from past academic research projects, university-level projects, and analysis of housing census data. Additionally, data for Guatemala from global datasets were collected and are presented.

The existing data relate to different spatial scales, from neighbourhood to national level. In addition, the studies cover different building usages or occupancies and use different methods of building data collection. Table 5-7 give the key information on the available building data from past studies, and Table 5-8 gives the proportions of building types reported by each study. The discrepancies are large, so further comparisons are made to understand them further.

To explore the agreement between data from different existing sources, the data were compared by the principal structural material, see Figure 5-32. To compare between studies, buildings are collated into broad groups of masonry, steel, concrete, and other. As masonry is such a significant proportion of the building stock, this is further divided into brick, block, earth, and other.

Author	Area covered	Building use covered	Information source
ERN (2010)	Guatemala	Education	Coarse grain data and expert opinions
Farfán and Díaz (2009)	Zone 12, Guatemala City	All (but occupancies not linked to typologies)	Street surveys
Flores (2014)	Zone 3, Guatemala City	All (no information on occupancy types)	Street survey
Lang et al. (2009a)	Part of Zone 11, Guatemala City	All (occupancy type linked to broad building class)	Street surveys
PAGER (2008)	Guatemala	All (residential/non-residential occupancy information available)	UN-HABITAT
Pérez (2005)	San Antonio neighbourhood in Zone 6, Guatemala City	All (but occupancies not linked to typologies)	Street surveys
Pita (2014)	Guatemala Department	All (occupancy information available)	Building census
Rivas and Vásquez (2008)	Zone 7, Guatemala City	All (but occupancies not linked to typologies)	Street surveys
Villagrán de Leon (2008)	Guatemala Department	Residential	Building census

Table 5-7 Data on existing building data sources relevant to Guatemala City

All studies agree that the proportion of masonry structures is high and that the other building types consist of a range of smaller groups of concrete, timber, and other constructions. When the composition of masonry types is compared (where more information is available), it becomes harder to see any clear similarities between information from different sources as they all show different types of masonry buildings in different quantities, see Figure 5-33 . It is key to note that different types of masonry have very different seismic vulnerability (D'Ayala, 2013), thus these differences highlight large discrepancies between studies. Additionally, when the non-masonry buildings types are considered more closely (Figure 5-34), again, there are no clear similarities.

Source	**Source building description**	**Prevalence**
ERN (2010)	Unreinforced masonry	49%
	Reinforced masonry	31%
	Concrete moment frames	10%
	Wood	6%
	Adobe	4%
Farfán and Díaz (2009)	Masonry	67%
	Adobe	26%
	Wood	2.5%
Flores (2014)	Medium reinforced masonry	54%
	Unreinforced masonry	39%
	RC moment frames	3%
	Wood	3%
	Light steel	1%
Lang 2009	Confined baked brick masonry with reinforced concrete frames	20%
	Unreinforced concrete block masonry incl.	20%
	Reinforced concrete block masonry	20%
	Confined concrete block masonry with RC frames	20%
	Adobe and *Tapial*	4%
	Minifalda, light timber frames	4%
	Unreinforced baked brick masonry	4%
	Steel bar reinforced baked brick masonry	4%
	Block panel system	4%
PAGER	Unreinforced concrete block masonry	65%
	Mud walls	18%
	Wood	13%
	Unreinforced fired brick masonry	2%
	Informal constructions	2%
Pérez (2005)	Medium reinforced masonry	75.3%
	Unreinforced masonry	17.1%
	Wood	6.8%
	Superior reinforced masonry	0.4%
	RC moment frames	0.3%
	Light steel	0.1%
Pita (2014)	Block – Concrete (wall – roof)	37.3%
	Block - Metal Sheet (wall – roof)	40.3%
	Timber - Metal Sheet (wall – roof)	4.5%
	Metal - Metal Sheet (wall – roof)	7.8%
Rivas and Vásquez (2008)	Masonry	69%
	Adobe	28%
	Wood	1.6%
	Concrete	0.9%
	Steel	0.6%
Villagrán de Leon (2008)	Clay, block - cement	83%
	Adobe	5.8%
	Wood	4.7%
	Metal sheet	5.4%
	Bajareque	0.3%
	Wood waste and cane	0.7%

Table 5-8 Proportions of buildings derived by each existing building data source

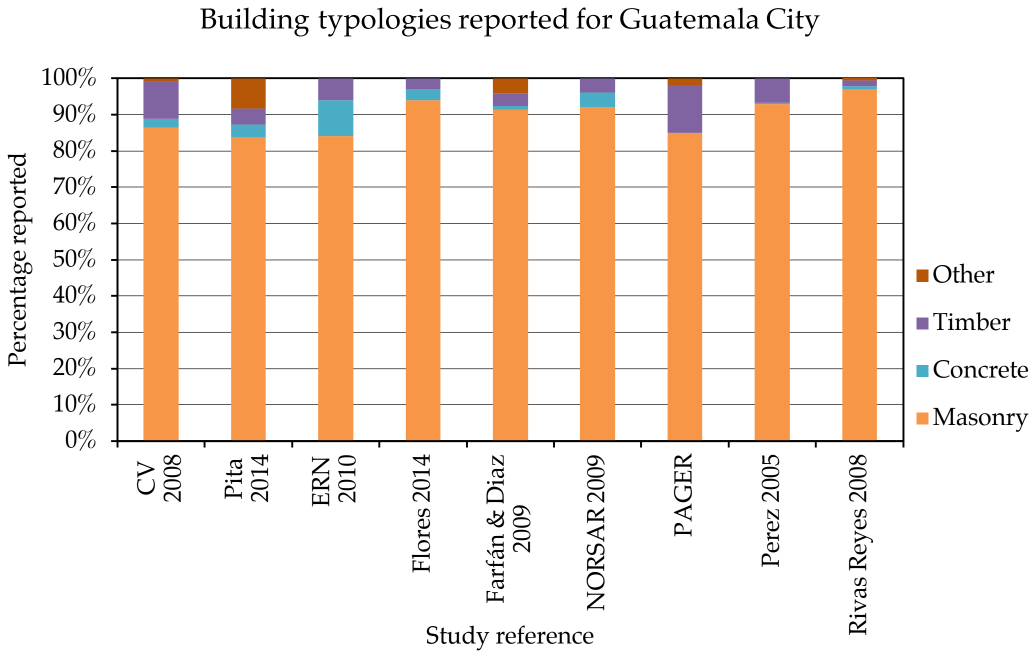


Figure 5-32 Aggregated building type information

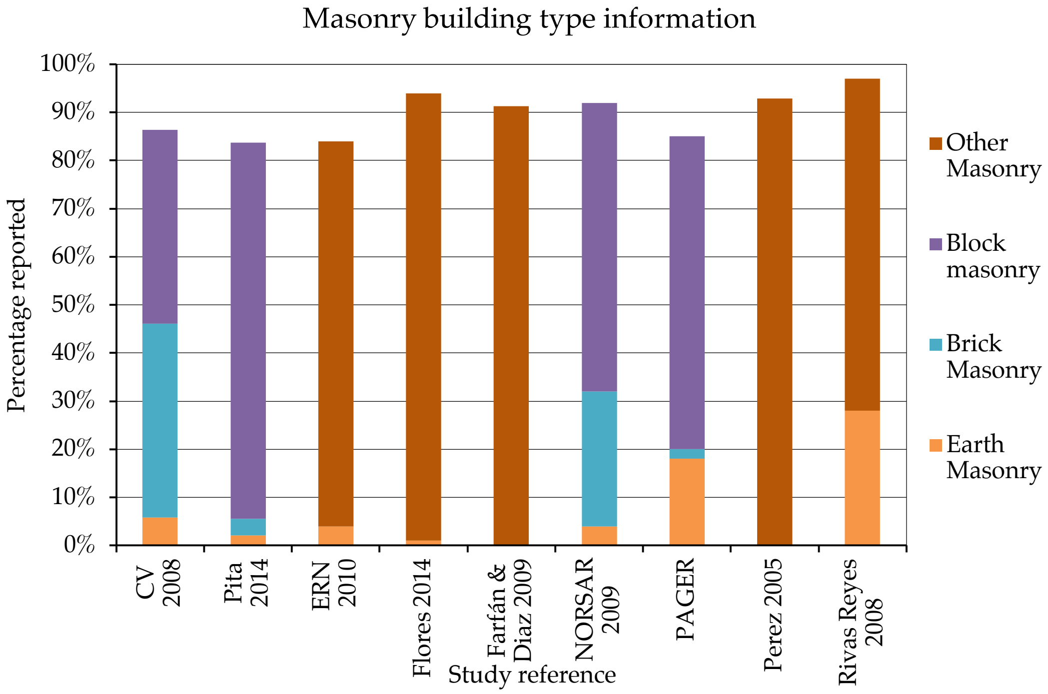


Figure 5-33 Disaggregated masonry building type information

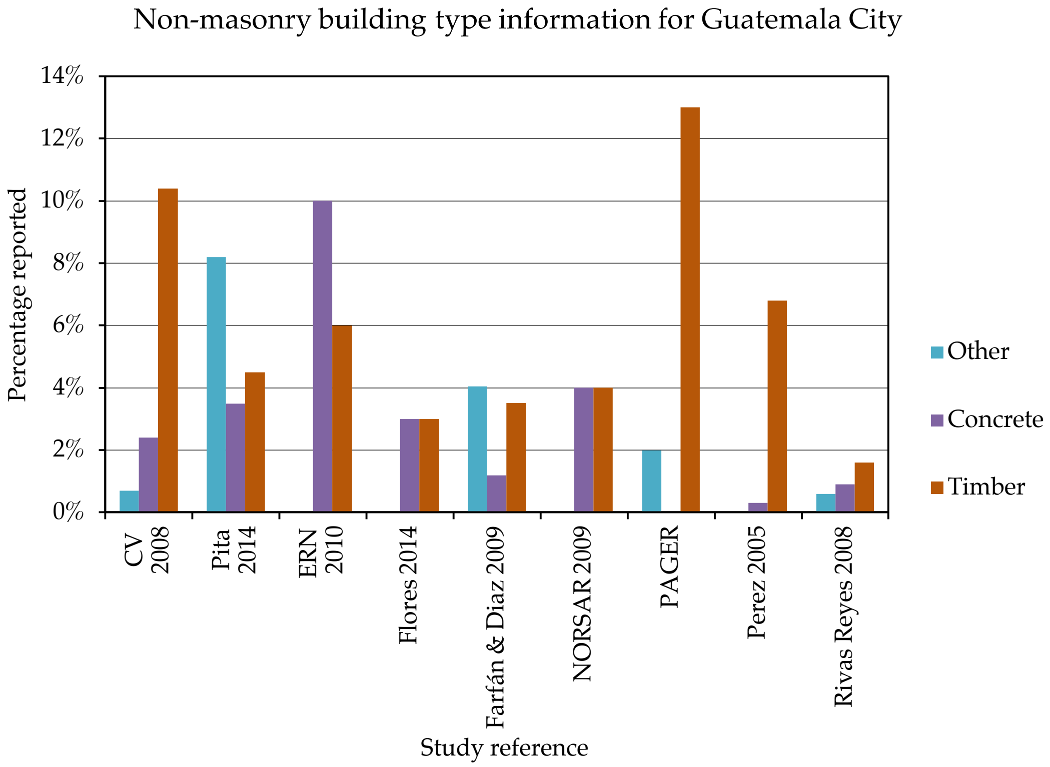


Figure 5-34 Focus on non-masonry building types

When these differences in building type between different sources are propagated through to loss assessments, it has been observed that the differences between results is large, and hence that there is a large sensitivity in exposure inputs, meaning that it is important to obtain accurate building data (see Appendix M).

5.2.1.7. Findings from the review of public imagery

A plethora of images of the urban landscape of Guatemala City are publically available. Popular with tourists, images appear on travel blogs and social media websites, as well as on Google Maps, and Google Earth. The clear majority of photos are of significant historical buildings, hotel buildings, and outdoor spaces.

Conclusions from the review of available images are:

- Generally, buildings are low rise with clusters of high-rise in certain neighbourhoods.
- There are heritage masonry facades to low rise buildings, and modern facades (e.g. glass) to high-rise hotels and apartment blocks.
- Buildings tend to be built in close proximity (often touching), without architectural or structural similarities to neighbouring buildings, hence risk of pounding is potentially high.
- Incremental construction is present.

These conclusions will be incorporated into the analysis in the next chapter, allowing the potential validation of results. It must be noted that these conclusions come from biased data, usually taken in the more touristy areas.

5.2.1.8. Collation of desk-based study findings

Instead of collecting information on individual buildings, some of the data collection methods report more general information about construction practices, historical events, and the spatial development of the city. These data have been organised into a historical timeline, cataloguing historical events that may have had an effect of the make-up, size, and shape of the city, as well as a generic list of building typologies found in the city.

A systematic look at the development of Guatemala City over time offers clues as to the current exposure and vulnerability of the buildings. The data collected was separated into political events, building practice progress, or spatial changes in urban development. Additionally, the changing population of Guatemala City was also collected, as well as the dates of major earthquakes and housing censuses. These data have been incorporated into a timeline, given in Figure 5-35.

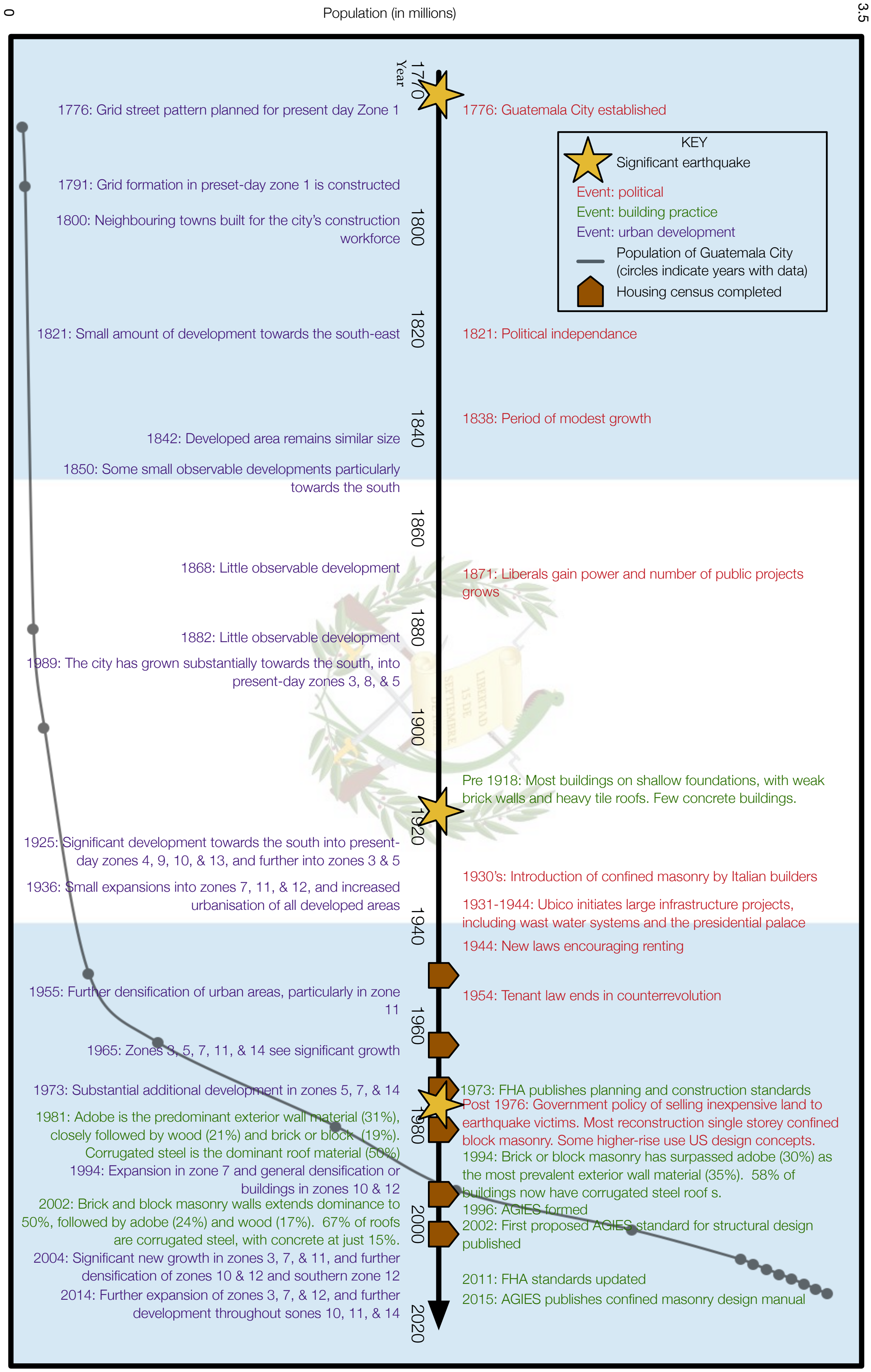


Figure 5-35 Historical timeline of Guatemala City

The most obvious finding is that the development of Guatemala City has been rapidly expanding since the mid-20th century. Political decisions have influenced the seismic risk of the city by allowing and even encouraging urban development in vulnerable area (e.g. the hillsides of zone 3), and the lack of action in regulating construction. The city has expanded primarily southwards, from the original settlement in zone 1, particularly since the mid-20th century. Construction has transferred from vernacular materials such as adobe and *bahareque*, towards confined masonry, accelerated by the partial renewal of building stock required after two widely devastating earthquakes in the last hundred years. The timeline of Guatemala City is used for further analysis and discussion in subsequent chapters.

Any information about the types of construction or buildings found in Guatemala City was collated in a single repository, as it is very useful when examining the seismic exposure and vulnerability. The largest source of data was collected by collecting existing works (see Table 5-8). All the studies defined the building stock according to the prevalent construction which highlights the types of construction present. From this, the following can be concluded:

- The main structural materials found in the city include RC, masonry, mud (including *tapial*), lightweight steel, timber, and cane (including *bahareque*).
- Masonry types include adobe, concrete block, and clay brick.
- Masonry can be unreinforced, reinforced, or confined.
- Cement mortar is found in some masonry.
- RC buildings can have a LLRS of moment frames, shear walls, or a combination of either.

Other literature enriches these conclusions by adding the following information:

- Brick masonry is present (Saville, 1918), and bricks can be either solid (2"x4"x8"), hollow, or double celled (3"x6"x9") (Preece, 1976)
- Brick masonry can be reinforced or filled (Preece, 1976).
- Block masonry compression strengths should range from 70kg/cm^2 (class a, grade 1), to 50 kg/cm^2 (class A, grade 2) (Quiñóez de la Cruz, 1996). For non-load bearing walls, blocks have a strength of 40 kg/cm^2 (Quiñóez de la Cruz, 1996). A study in 1989 found that blocks used in construction in Guatemala City all had a low compressive strength, below 25 kg/cm^2 at 28 days (Quiñóez de la Cruz, 1996).
- Adobe-walled buildings are present, usually of one storey with heavy tiled roofs (Earthquake Engineering Research Institute, 1976)
- Many masonry buildings built after 1976 would have been confined (Monzón-Despang, 2016).
- Mortar quality varies widely (Preece, 1976).
- Shallow foundations are common (Saville, 1918; Rice, 1976; Monzón-Despang, 2016).
- Around thirty high-rise RC and steel buildings (over four storeys) are present in the city in 1976 (Griffith, 1973; Preece, 1976). It is estimated that one-third are moment-frame buildings and around two-thirds have an LLRS of both moment frames and shear walls (Monzón-Despang, 2016).

- High-rise concrete buildings built in the 60s and 70s are non-ductile moment frames (Monzón-Despang, 1996).

- Masonry infill walls in high-rise buildings are tied to slabs using drilled anchors, with internal walls usually formed of gypsum panels (Monzón-Despang, 2016).

- In 1976, the vast majority of steel reinforcement bars for RC buildings were sourced from Mexico (Preece, 1976).

- Concrete used for RC construction was (in 1976) quality tested and had good strengths (between 13.8 and 34.5 MPa) (Preece, 1976).

- In 1996, the strengths of concrete used in block masonry construction were tested (Quiñóez de la Cruz, 1996). The results, shown in Table 5-9, highlight the poor quality of concrete masonry blocks used in construction in Guatemala.

Compressive strength at 28 days (MPa)	**%age of tests**
0 – 4.9	24
5 – 9.8	47
9.9 – 14.7	17
14.8 +	12

Table 5-9 Compressive strengths of concrete block masonry (Quiñóez de la Cruz, 1996)

- Ground conditions throughout the Guatemala City valley are formed of partially-weathered volcanic tephra from 0 to 5m deep, and compacted volcanic ash-flow deposits below 5m.

- In 2016, it was estimated that around 60% of construction was carried out by builders without formal training, and the others are either self-builds or designed by university-educated engineers or architects.

- Confined masonry buildings are still vulnerable as they are commonly built too high, built with poor quality materials, and have poor distribution of internal walls (González, 2014).

This information is helpful for checking results of building typologies found using other methods, as well as developing a deep knowledge about the city that allows expert judgement to be employed more accurately, when required. The data found will also improve models for assessing seismic vulnerability.

The coverage of data compiled in the building repository not only determines the ability of it to help with seismic vulnerability assessments, but it is also important for identifying information that could subsequently be collected by other methods.

Using the GEM taxonomy, five levels of data are prescribed in order of importance (Brzev et al., 2013). These are summarised in Table 5-10. The green shading shows that some information regarding this characteristic is present in the data collected from the desk-based methods, whereas the red shading shows that no information is present. The desk-based methods responsible for the collection of data are referenced. Although this is not directly applicable to an assessment of seismic vulnerability, this table shows the gaps in data, and how buildings could be classified based the data available. Generally, the characteristics that are collected are able to be used to define index buildings for seismic vulnerability assessments, after some assumptions or judgements are made to fill in the structural data gaps or transform qualitative data into quantitative data. Proportions of different building types may be estimated using the housing census data which provide an indication of the prevalence of construction materials in the study area.

Attribute	Level	Characteristic	Source
Direction	1	Direction of the building	
Material of the LLRS	1	Material type	• Review of damage and recovery from significant past events • Housing census • Existing works
	2	Material technology	• Review of damage and recovery from significant past events • Existing works
	3	Material properties	• Review of construction regulations and guidelines • Review of damage and recovery from significant past events
LLRS	1	Type of LLRS	• Review of construction regulations and guidelines • Review of damage and recovery from significant past events • Existing works
	2	System ductility	• Review of construction regulations and guidelines • Review of damage and recovery from significant past events • Existing works
Height	1	Height	• Review of damage and recovery from significant past events • Public imagery
Date of construction or retrofit	1	Construction completed (year)	• Historical maps and remotely-sensed imagery review • Review of damage and recovery from significant past events • Housing census • Government-held city maps • Public imagery
Occupancy	1	Building occupancy class - general	
	2	Building occupancy class - detail	
Position	1	Building position within block	
Plan shape	1	Plan shape (footprint)	
Structural irregularity	1	Regular or irregular	
	2	Plan irregularity or vertical irregularity	
	3	Type of irregularity	
Exterior walls	1	Exterior walls	• Review of damage and recovery from significant past events • Housing census • Existing works • Public imagery
Roof	1	Roof shape	•
	2	Roof covering material	• Review of damage and recovery from significant past events • Housing census • Existing works • Public imagery
	3	Roof system material	• Review of construction regulations and guidelines • Review of damage and recovery from significant past events • Existing works
	4	Roof system type	
	5	Roof connections	
Floor	1	Floor system material	
	2	Floor system type	
	3	Floor connections	
Foundation system	1	Foundation system	• Review of construction regulations and guidelines

Table 5-10 GEM taxonomy data levels (Brzev et al. 2013) collected by desk-based methods

5.2.2. Results from the field-based study

Surveys were completed in several zones in the city in an attempt to obtain an unbiased representation of the building stock throughout the study area, however, only a small sample of the city was surveyed, and this may have an impact of the results obtained. The number of surveys completed by each method in each zone in the survey area are given in Table 5-11. A total of 1,635 surveys were completed but, as can be seen, the total surveys (in zones visited) is consistently higher than the number of unique buildings surveyed, due to the overlapping methodologies. In total 569 unique buildings are surveyed, each by a number of different data collection methods from the seven tested. The overlaps are summarised in Table 5-12, which shows that in total, four unique buildings in zone 1 were surveyed by all seven methods, thirty buildings in zone 1 were surveyed by six of the seven methods, and forty-six buildings in zone 1 were covered by five methods. Less than five survey methods covered the rest of the buildings in the other survey zones. The most number of unique buildings were surveyed in zone 12 (one-hundred-and-thirty-three), followed by zone 1 (ninety-two).

The total number of buildings in Guatemala City or the study area is not known exactly. It was reported that the Guatemala municipality had 238,651 buildings in the 2002 housing census, but this is well-outdated and covers the entire municipality, not just the study area. Instead, to estimate the coverage of the surveys, the number of plots shown on the government city maps (see Appendix E) for zone's 1, 7, 11, and 12 are estimated. These values are shown in Table 5-11. The area of each zone is calculated using ArcGIS to calculate the area of the zone's polygons. The average density of buildings per square kilometre from zone 1, 7, 11, and 12 is assumed as the density of the other zones surveyed to estimate the number of buildings. This allows the estimation of the number of buildings in each zone (see Table 5-11) as well as estimating that the total buildings in the study area is approximately 81,500: with 569 unique buildings surveyed, this gives an overall coverage of 0.7%.

This is a small sample of the survey area, however, as mentioned before, this study does not aim to collect a credible exposure model for Guatemala City. Analysis or tests run on such a small sample size may skew or bias any results, so validation by a larger study, or a parallel study elsewhere would give credibility to the conclusions made herein. In particular, the detailed internal surveying of nine buildings is a very small sample, and if a validation study was completed, strategies to allow a larger sample of DIS would be vital.

It is important to note that some biases may have been introduced by a surveyor seeing the same building whilst using different methods for surveying: the virtual surveyor will have surveyed the same buildings using aerial, 3D, and OD methods. However, with the numbers of buildings considered, and with training on bias awareness, it is deemed unlikely that this would have a significant effect on the results.

Data collection method	Zone in study area													Total
	Z1	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	
DIS	6	0	0	3	0	0	0	0	0	0	0	0	0	9
RVS LE	59	0	30	40	0	21	0	0	0	0	45	0	61	256
RVS FE	87	0	46	49	0	49	0	0	31	0	119	0	62	443
RVS STU	62	0	0	0	0	0	0	0	4	0	130	0	78	273
OD	90	0	0	3	0	0	0	0	0	0	0	0	0	93
AS	80	0	75	89	0	56	0	0	20	0	133	0	0	453
3D	92	0	0	3	0	0	0	0	0	0	0	0	0	95
Total surveys	476	0	151	187	0	126	0	0	55	0	427	0	201	1623
Unique buildings surveyed	92	0	75	89	0	56	0	0	35	0	133	0	83	563
Estimated total buildings	7600	3925	990	5464	6872	12300	1527	2302	5780	15740	6100	7528	5331	81459
Area (km^2)	5.54	3.50	0.88	4.87	6.12	12.93	1.36	2.05	5.15	9.79	10.92	6.71	4.75	74.57
Estimated density (buildings/km^2)	1372	1122	1122	1122	1122	951	1122	1122	1122	1607	558	1122	1122	
Estimated coverage of surveys to total buildings	1.21%	0.00%	7.57%	1.63%	0.00%	0.46%	0.00%	0.00%	0.61%	0.00%	2.18%	0.00%	1.56%	0.69%

Table 5-11 Field-based survey totals, and estimation of coverage

The individual zone coverage (of those visited) ranges from 0.46% to 7.57%, varying due to the speed of surveying and the time available in the field (logistics and weather permitting) on different days. It is suggested that 10% of buildings should be surveyed in order to extrapolate results accurately (Novelli et al., 2014a) over an urban area and clearly, the surveying undertaken in this study falls short significantly, however this study does not aim to provide actual exposure data for the study area, but instead, test different methods of collecting building data.

Survey location	**Number of surveys for each building**							
	7	**6**	**5**	**4**	**3**	**2**	**1**	**Total**
Z1	4	30	46	6	2	**4**	0	92
Z4	0	0	0	0	1	74	0	75
Z5	0	0	0	3	0	86	0	89
Z7	0	0	0	0	14	42	0	56
Z10	0	0	0	0	0	20	15	35
Z12	0	0	0	40	81	12	0	133
Z14	0	0	0	0	41	36	6	83
Total	4	30	49	46	139	274	21	563

Table 5-12 Summary of survey completed for each building

The headline survey results from the individual methods are presented below.

5.2.2.1. Rapid visual surveys results

The rapid visual survey collected more information about buildings than the census, however only for a limited sample of buildings. Three different types of surveyor completed the surveys, a local engineering expert (LE), a foreign engineering expert (FE), and local engineering students (STU). The number of rapid visual surveys completed in each zone by each surveyor group is given in Figure 5-36. The numbers of surveys by the different surveyor groups are shown in Figure 5-37.

The RVSs completed by different surveyor groups are not directly compared in detail or commented on. This is for a number of reasons. Firstly, the correct values are not known, so direct comparisons will not be helpful: the focus is on the differences in costs and accuracy between the groups, which are studied in detail in Chapter 6. No further comments or conclusion will be made about the differences between the RVS groups, except about the general accuracy and costs, in Chapter 6. Additionally, the different surveyor groups could have been tested in a virtual surveying context, however this was beyond the scope and resources of this study.

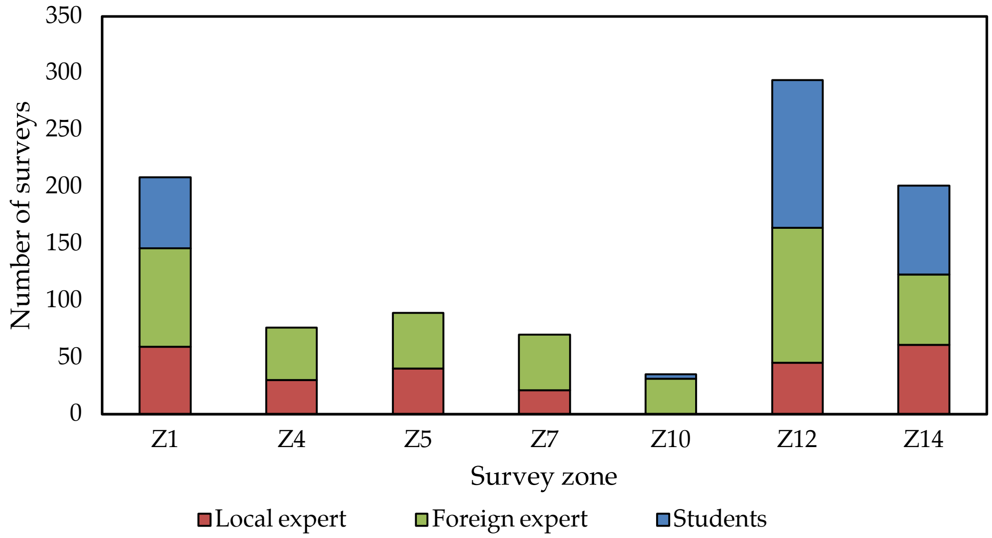


Figure 5-36 Number of surveys completed by each group of surveyors

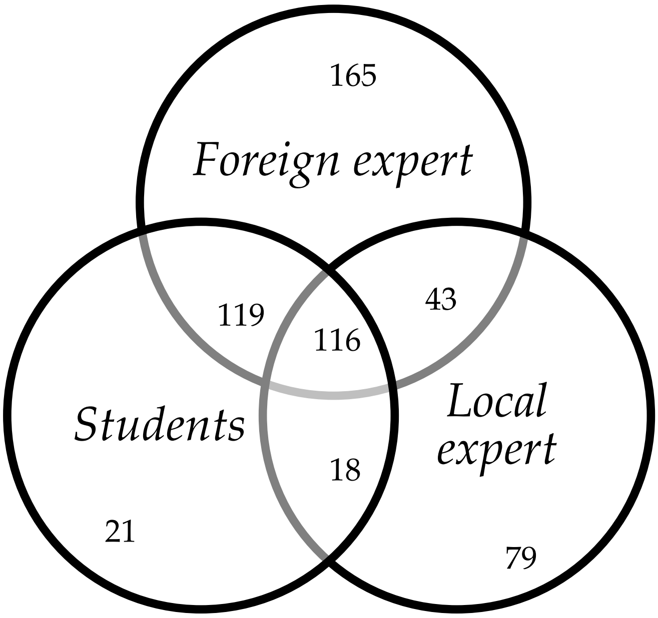


Figure 5-37 Venn diagram of the number of unique buildings surveyed by different surveyors using the RVS method

The proportion of primary construction material noted by the survey groups and with all results combined are found in Table 5-13. There is a clear consensus that masonry is the dominant material with proportions of between 78 and 89% recorded.

Surveyor	Masonry	RC	Steel	Timber	Other	Unknown
LE	89%	8%	1%	0%	1%	0%
FE	78%	12%	2%	1%	1%	6%
STU	88%	7%	1%	2%	2%	0%
Overall	84%	9%	2%	1%	1%	3%

Table 5-13 Primary structural material results from RVS

The results for the type of masonry (see Table 5-14) is predominantly brick or block, with some adobe, although consensus between survey groups is not very strong as they surveyed different zones in the city (see Figure 5-36).

Surveyor	Brick	Block	Cut stone	Adobe	Rubble	Other	Unknown
LE	35%	46%	0%	7%	0%	12%	0%
FE	34%	24%	0%	11%	0%	4%	27%
STU	16%	63%	0%	17%	0%	4%	0%
Overall	28%	43%	0%	12%	0%	6%	11%

Table 5-14 Masonry type results from RVS

The reported reinforcement of the predominant material, masonry, is given in Table 5-15. Confined masonry is clearly prevalent along the survey routes.

Reinforcement	Confined	Reinforced	None	Unknown
LE	48%	0%	23%	29%
FE	99%	0%	1%	0%
STU	86%	3%	0%	12%
Overall	74%	1%	10%	15%

Table 5-15 Masonry reinforcement results from RVS

The majority of roof material is consistently reported to be reinforced concrete slab, followed by sheet metal, see Table 5-16.

Surveyor	RC slab	Sheet metal	Tiles	Other	Unknown
LE	85%	12%	2%	0%	2%
FE	71%	22%	5%	1%	1%
STU	84%	9%	1%	3%	3%
Overall	79%	15%	3%	1%	2%

Table 5-16 Roof material results from RVS

The reported lateral load resisting system of structures, see Table 5-17, is predominantly walls. In total, forty-four surveys failed to identify the LLRS.

Surveyor	Frames	Walls	Bracing	Combination	Other	Unknown
LE	13%	79%	0%	1%	0%	6%
FE	7%	91%	0%	1%	0%	0%
STU	28%	66%	0%	1%	0%	5%
Overall	16%	79%	0%	1%	0%	4%

Table 5-17 LLRS results from RVS

The number of storeys results are shown in Table 5-18, highlighting that the vast majority of buildings are either of one or two storeys. 10% of buildings are reported to be three storeys high, and 4% of buildings are over three storeys.

Surveyor	1	2	3	4	5	6	7	8	9	10	11	12
LE	43%	43%	10%	1%	0%	0%	0%	0%	0%	1%	1%	0%
FE	44%	42%	9%	2%	0%	0%	0%	0%	0%	1%	0%	0%
STU	46%	41%	10%	1%	0%	1%	0%	0%	0%	0%	0%	0%
Overall	44%	42%	10%	1%	0%	0%	0%	0%	0%	0%	0%	0%

Table 5-18 Number of storeys results from RVS

In terms of seismic weaknesses, the proportions reported for different weaknesses are given in Figure 5-38 for the different surveyors. There is relatively good agreement on the proportions of some weaknesses, such as short columns, strong beam-weak column (SBWC), and the presence of balconies, a slope, or bow windows. Large discrepancies are notes for all of the irregularities, soft storeys, and pounding. This may have been down to the understanding of the surveyor group, the local knowledge of what may be hidden behind a façade, or different judgement on the significance of the irregularity, or a change in stiffness between storeys.

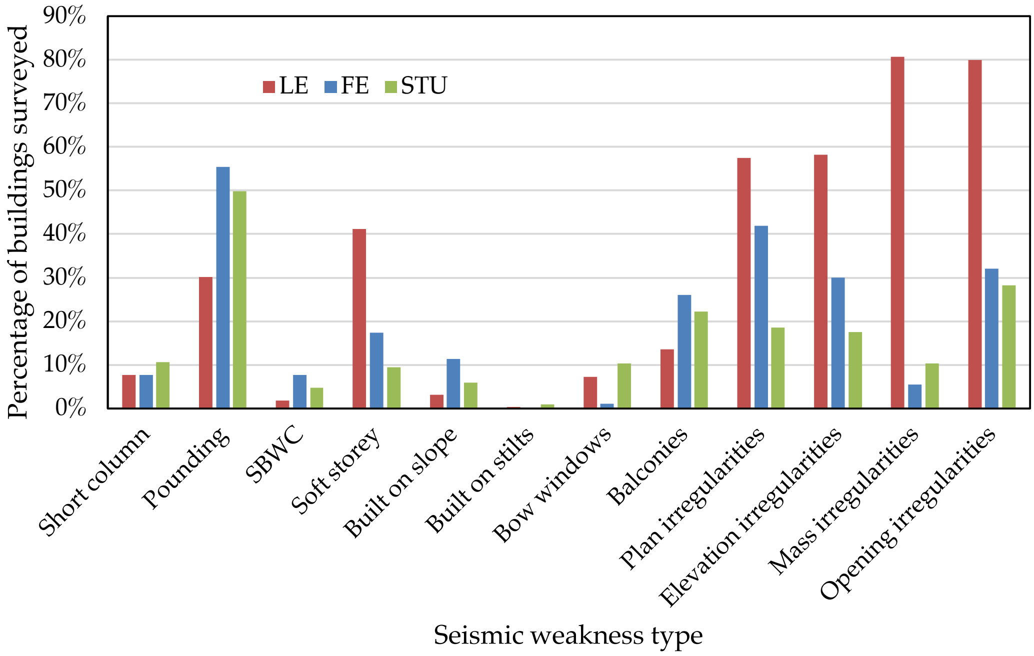


Figure 5-38 Proportion of seismic weaknesses as a percentage of rapid visual survey completed (N.B. there is no normalisation between surveyed zones)

5.2.2.2. Virtual rapid visual survey using OD imagery

Omnidirectional images were captured in the survey areas in Guatemala City and uploaded to both Google Street View and Mapillary platforms. An example of the collected imagery hosted on Google Street View is given in Figure 5-39. The streets imaged and the virtual surveys carried out followed exactly the same streets as the RVS routes, helping to increase the overlapping statistics.

Figure 5-39 An example of omnidirectional imagery collected by the author in Zone 1

The virtual street survey using the omnidirectional imagery was carried out along the zone 1 survey route. In total, ninety-four buildings were surveyed; Figure 5-40 shows the surveyed buildings in ArcMap.

Figure 5-41 and Figure 5-42 show the proportion of primary building materials with RC and masonry found in similar numbers, and highlights the inability of the surveyor to identify a primary material and masonry types. Often adobe buildings have thicker walls or have gaps in older plaster so are visible; this may be why more adobe structures have been positively identified. Similarly, concrete block masonry buildings are generally the newer constructions so the plaster covering or the façade is likely to be in a better condition, thus concealing the masonry type. In contrast to the street RVS, the omnidirectional imagery offers much less detail concealing clues as to the masonry type (e.g. gaps in plastering), and a good view of the building including the façade and the gable walls was not always available due to the gaps in the OD images. In addition, obstructions such as vehicles, vegetation, or people, were more often able to be overcome on the ground, whereas if the view of a building was restricted on an OD image it was often not possible to get a good alternative perspective.

Figure 5-40 The buildings surveyed in Zone 1

The number of storeys of a structure can often be judged from street level and the results from the virtual survey are given in Figure 5-43, showing most structures having one or two storeys. Figure 5-44 gives reported results for the LLRS, again with a large proportion of unknowns as this can be very difficult to judge through external finishes.

These results are just the basic results achieved by this data collection method; results will be investigated and compared to results from other field-based methods in much more detail in the next chapter.

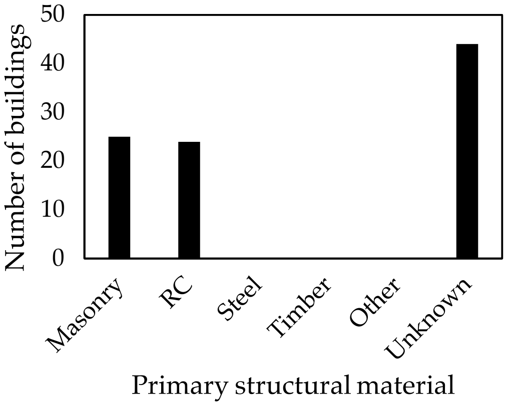


Figure 5-41 Virtual RVS primary structural material results

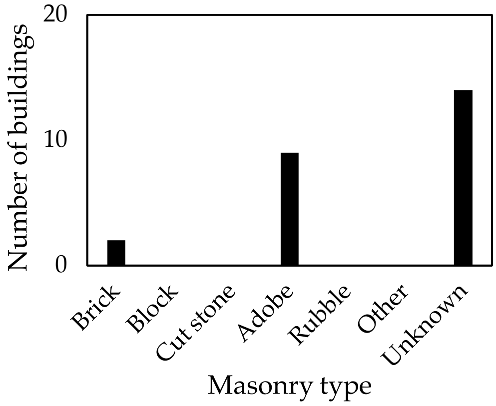


Figure 5-42 Virtual RVS masonry type results

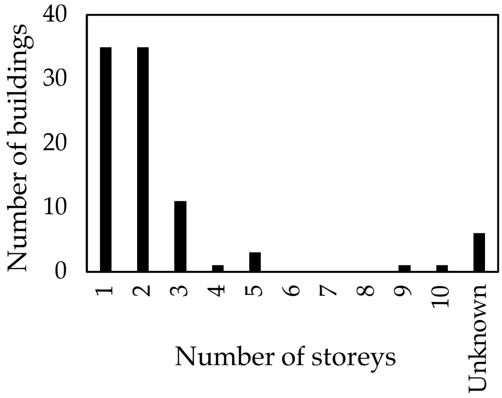


Figure 5-43 Virtual RVS number of storey results

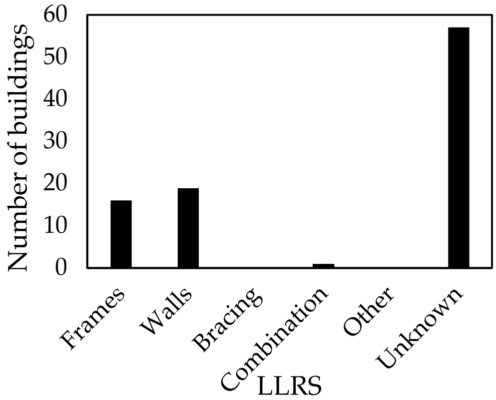


Figure 5-44 Virtual RVS LLRS results

5.2.2.3. UAV derived aerial imagery virtual survey results

The UAV collected aerial imagery covering buildings along the survey routes in each zone, except zone 14 which was too close to the airport for the UAV to safely operate. Some example images from each zone can be viewed in Appendix N.

For each zone (except zone 14) the same buildings surveyed in the street RVS were surveyed using the aerial imagery. Information collected is restricted to that available from above, such as position in block, roof material, presence of modifications, and the presence of some seismic weaknesses.

Figure 5-45 presents building position results from the aerial survey (AS). Zone 7 and 10 have a significantly larger proportion of detached buildings, and the other zones have larger proportions of both mid-terrace and corner buildings.

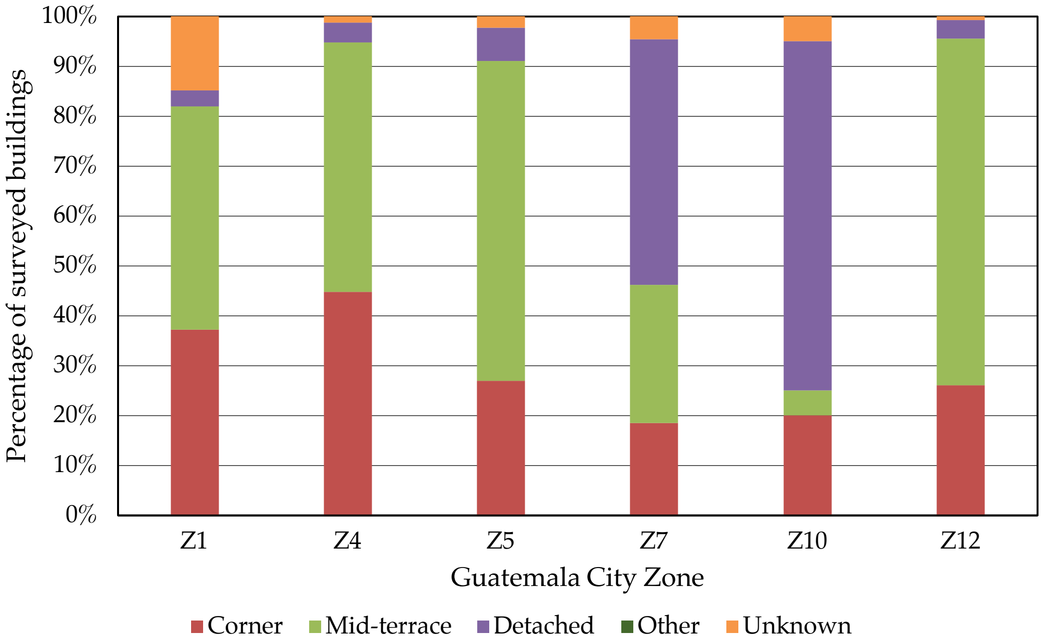


Figure 5-45 Aerial survey building position results

The roof material results (see Figure 5-46) highlight the dominance of RC slab and sheet metal roofs. A combination of material types, usually sheet metal and RC slab is common when modifications to the building have taken place since its original construction, which increases its vulnerability (Lallemant, 2016; Lallemant et al., 2017). The presence of such modifications has been judged, where possible, and the results for each zone are presented in Figure 5-47. The majority of buildings in the areas surveyed, had some level of modification visible from above, identified by changes in colour of the roof material (denoting a different age of roof), or in some cases different roof materials.

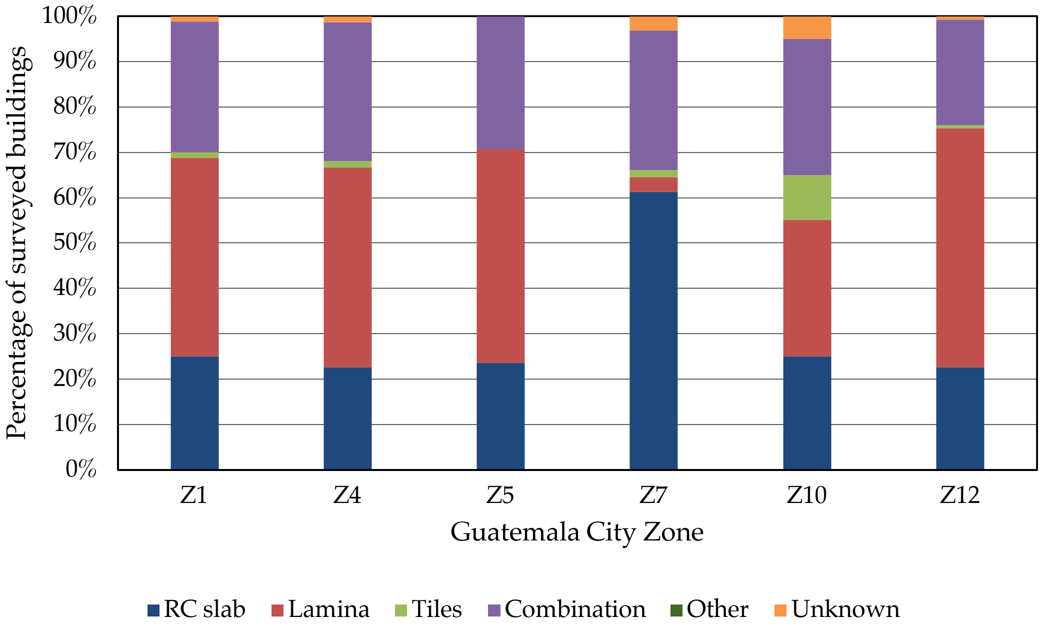


Figure 5-46 Aerial survey roof material results

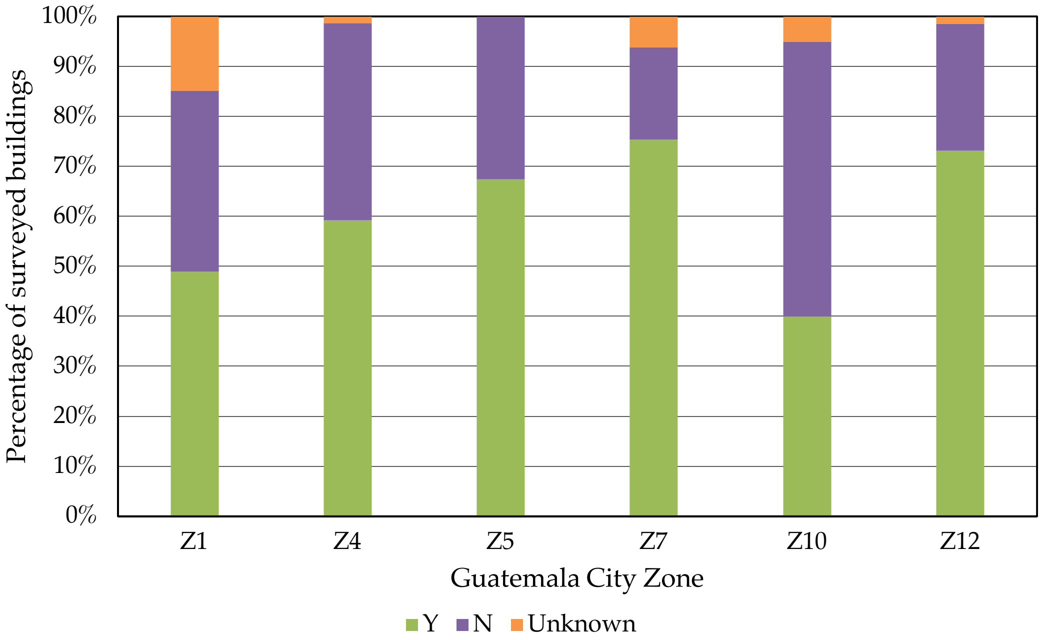


Figure 5-47 Aerial survey presence of modifications results

Some seismic weaknesses can be judged with aerial imagery. The proportions of different weaknesses observed in each zone are presented in Figure 5-48. The vast majority of buildings surveyed were judged to have plan irregularities and the potential for pounding damage with adjacent structures. No bow windows could be identified and a small number of overhanging balconies were observed, particularly in the high-rise structures of Zone 10.

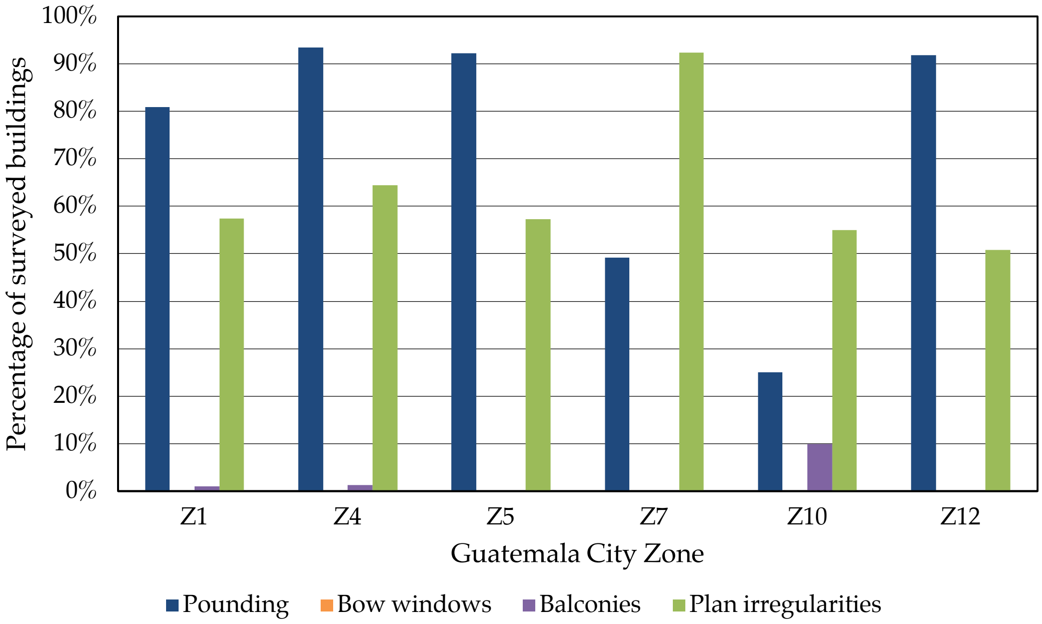


Figure 5-48 Aerial survey presence of seismic weaknesses results

These results offer a brief insight into the data collected from a remote aerial survey. Limited data were collected because of the top-down vantage point, however, some data are best collected from above, such as roof material, and therefore the accuracy of the dataset, although limited in type of data collected, is likely to be high.

5.2.2.4. UAV derived 3D model virtual survey results

The 3D model derived from the UAV aerial imagery offers a number of perspectives, enabling buildings to be surveyed from all angles. Furthering the capabilities of the aerial surveys, additional data can be collected, including the number of storeys, the roof pitch, and more seismic weakness types. This method was employed in Zone 1 only, where the same buildings along the street rapid visual survey routes were surveyed.

A selection of the data collected for Zone 1 are presented in Figure 5-49 to Figure 5-53. The results show a majority of corner and mid-terrace buildings with few detached structures (see Figure 5-49). Roof materials are predominantly sheet metal or RC slab, or a combination of both, although there are a small number of tiled roofs and combinations including tiles (see Figure 5-50).

Zone 1 is a fairly low-rise area, with the majority of structures standing at one or two storeys high, however there are a handful of higher-rise structures (see Figure 5-51). The 3D model survey (also denoted as 3D) method identified that modifications are popular in this zone, with around two-thirds of buildings identified as having some modifications since initial construction (see Figure 5-52). Another observation from these results is that there are no unknown results, which highlights the consistent capability of this method to provide building data.

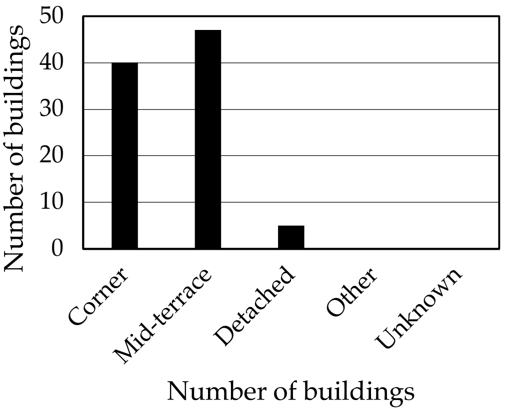


Figure 5-49 3D model survey building position results

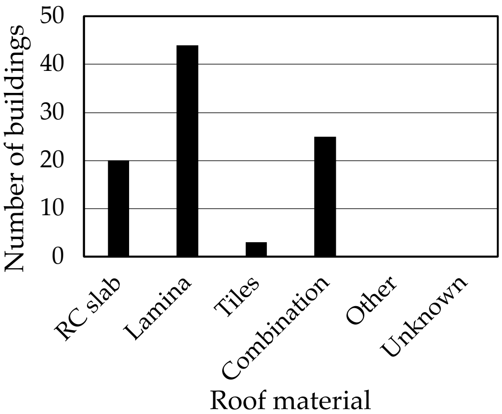


Figure 5-50 3D model survey roof material results

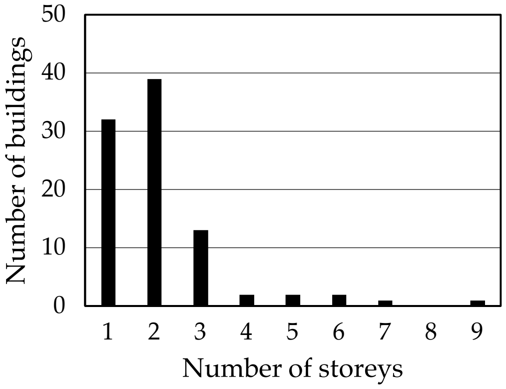


Figure 5-51 3D model survey number of storey results

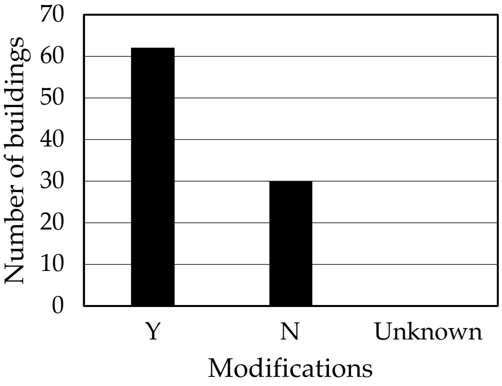


Figure 5-52 3D model survey presence of modifications results

Figure 5-53 highlights some of the seismic weaknesses able to be identified using the 3D model survey. There are notable proportions of buildings with pounding potential, and plan, elevation, and opening irregularities. Other seismic weaknesses were not identified in the 3D model surveying.

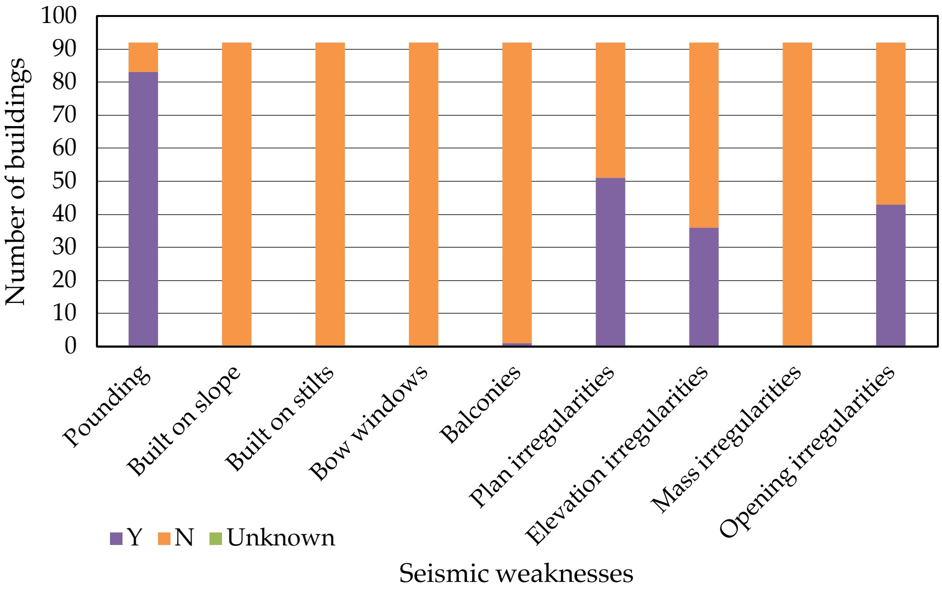


Figure 5-53 3D model survey seismic weakness results

5.2.2.5. Internal detailed survey results

In total, nine detailed internal surveys (DIS) were completed, six in zone 1 and three in zone 5. Surveys were completed in buildings where access could be agreed with the building owner. Extensive data was collected for each building. The locations of the surveyed buildings are given in Figure 5-54 and Figure 5-55 and addresses, locations, images, and more details are given in Appendix L.

Figure 5-54 Locations of detailed surveys in zone 1. Buildings shown in yellow and RVS survey routes in red.

Figure 5-55 Locations of detailed surveys in zone 5. Buildings shown in yellow and RVS survey routes in red.

The detailed survey results are presented in Table 5-19. The results show the range of information obtained using this survey technique, including dimensions of wall thicknesses and building heights. In addition, floorplans of the buildings were either sketched or obtained from the building owner. It is evident from this small number of surveys that fitting individually buildings into categories is not always possible: often multiple options are applicable. These results will be important when determining the accuracy of the other survey methods. This will be developed further in Chapter 6.

Building reference	Z5_19Avenida_27Calle_E_09	Z5_19Avenida_27Calle_E_17	Z5_19Avenida_27Calle_E_22	Z1_Calle13_Avenida2A_N_04	Z1_Calle13_Avenida2A_N_06	Z1_Calle13_Avenida2A_N_10	Z1_Calle13_Avenida2A_N_11	Z1_Calle13_Avenida2A_S_01	Z1_Calle13_Avenida2A_S_02
Position	Corner	Corner	Mid-terrace	Mid-terrace	Mid-terrace	Mid-terrace	Mid-terrace	Corner	Mid-terrace
Usage	Residential, commercial	Residential	Residential	Education and commercial	Commercial	Education	Education	Education	Education
Age	Old	Old	Mid-age	Old	Old	Mid-age	Old	Old	Old
Years				90	100		70	100	100
Primary structural material	Masonry	Masonry	Masonry	Masonry	Masonry	Masonry	Masonry	Masonry	Masonry
Roof material	Lamina	Lamina	Sheet, RC slab, tiles	Lamina	Lamina	Lamina and RC slab	Lamina, plastic sheeting	RC slab, Lamina	RC slab
Roof pitch	Sloping	Sloping	Sloping and flat	Sloping	Sloping	Sloping and flat	Sloping	Sloping and flat	Flat
Floor material	Timber		RC slab	RC slab		RC slab		RC slab	RC slab
LLRS	Walls	Walls	Walls	Walls	Walls	Walls	Walls	Walls	Walls
No. of storeys	2	1	2	2	1	2	1	2	3
Storey height [m]	3.85	3.85	2.74	5.28	3.15	4.84	4.2	4.2	
Diaphragms	None	None	Floor	None	None	None	None	None	Roof and floors
EQ design	None	None	None	None	None	None	None	None	None
State of preservation	Low	Low	High	Low - moderate	Low	Moderate	Moderate	Moderate	High
Connection quality	Low	Low	Moderate	Moderate	Low	Moderate	Moderate	Moderate	Moderate
Retrofitting	N	N	N	N	N	N	N	N	N
Aseismic devices	N	N	N	N	N	N	N	N	N
Modifications	Y	Y	Y	Y	Y	Y	Y	Y	Y
Short column	N	N	N	N	N	N	N	N	N
Pounding	Y	Y	Y	Y	Y	Y	Y	Y	Y
SBWC	N	N	N	N	N	N	N	N	N
Soft storey	N	N	N	N	N	N	N	N	N
Built on slope	N	N	N	N	N	N	N	N	N
Built on stilts	N	N	N	N	N	N	N	N	N
Bow windows	N	N	N	N	N	N	N	N	N
Balconies	N	N	N	N	N	N	N	N	Y
Plan irregularities	Y	Y	Y	Y	Y	Y	Y	Y	Y
Elevation irregularities	Y	Y	Y	Y	N	Y	N	Y	Y
Mass irregularities	N	N	N	N	N	Y	N	N	N
Opening irregularities	N	N	Y	N	N	N	N	N	Y
Masonry type	Adobe, block	Adobe	Block	Adobe, block	Adobe, block	Adobe, brick, and block	Brick	Brick	Block, brick
Reinforcement	None	None	Confined	None, confined	None	None	None	None	Confined
Mortar type	Mud, cement	Mud	Cement	Lime, cement	Lime, cement	Cement	Lime	Cement	Cement
Mortar joints	Not filled	Not filled	Filled	Filled	Filled	Not filled	Filled	Filled	Filled
Wall thickness [mm]	400	400	140	140 - 400	140 - 440	140 - 250	400	100	200

Table 5-19 Detailed internal survey results for zone 1 and 5

5.2.2.6. Findings from the interviews with local experts

One interview was conducted with local engineer Dr Hector Monzón Despang, president of AGIES, and owner of one of the premier engineering consultancies in Guatemala. Notes from the interview are presented in Appendix O; the key findings from the interview are as follows:

1. Historically the city was formed of adobe and brick (for more affluent families). In the 1930's Italian builders introduced confined masonry. Since the 1976 earthquake, the city has built most low-rise structures as confined masonry, most often with concrete block masonry.
2. Buildings in Guatemala are constructed by (1) self-builders as a once in a lifetime project, where adobe is most often used however more recently this practice has decreased significantly, (2) by 'maestros de obra' (around 60% of construction now) who are builders without formal qualifications and mostly building confined block buildings, and (3) by university-educated engineers and/or architects.
3. The vast majority of higher-rise buildings are of RC frame (~1/3) or frame and wall combination (~2/3). Infill masonry is tied into the slabs using drilled anchors. Internal walls are now more commonly gypsum. Column sizes are approximately 600-900 mm square, reducing with height.
4. Ground conditions throughout Guatemala City are generally 0-5m partially weathered tephra (~US soil type D), and below 5m, ash flow deposits (~US soil type C). Foundations are most commonly rafts or pads (for high-rise) or simple dug strip foundations supporting external walls in residential buildings.

5. The most prevalent building type in Guatemala City was estimated to be confined masonry, following by RC frame and then adobe (primarily in zone 1 where it may be around 10%).

These findings have been added to the timeline and the building typology repository.

5.3. Conclusions

This chapter has presented the methodology and initial results for the collection of building data in Guatemala City using different methodologies, both desk-based and field-based. Desk-based methodologies resulted in the development of a timeline of the history of Guatemala City, including events and moments in time that impacted on the exposure and buildings types found in the study area. Additionally, a list of descriptions about building types has been collated from any source of information found during the desk-based study phase. This list is useful for making assumptions about building types found in the city which is required for seismic risk assessments.

The field-based methods were deployed on the ground and collected more focused data on individual buildings. Street survey techniques were used, and data was collected suing omnidirectional cameras and UAVs allowing virtual surveying (post-fieldwork) to be completed. Additionally, a key interview whilst in the field enriched the timeline and building typology list. The initial results for each method are presented.

In the next chapter the results presented herein are analysed further to examine the usefulness, accuracy, and cost of the data obtained using desk- and field-based methods. This is followed by a longer discussion about the benefits and challenges of the different methodologies for application in seismic risk assessments.

Chapter 6

Assessing the effectiveness of building data collection methods

6. Assessing the effectiveness of building data collection methods

There are numerous challenges and difficulties when obtaining information about buildings on a large scale for seismic risk assessments. First, ensuring that the most useful data are collected. Second, the cost of collecting building data can be high, and thus influence the methodology used. Third, the accuracy of the data collected is important for ensuring that the results of the analysis are fit for purpose, such as risk reduction strategies, or improvements to building regulations.

The chapter concludes by bringing together the resulting usefulness, cost, and accuracy of data collected by different methods, and comparing the effectiveness of each methodology. These comparisons result in the most effective data collection methods being highlighted.

This chapter aims to:

- determine methods for the measurement of building data usefulness, cost, and accuracy, and;
- apply these three methods to the Guatemala City dataset in order to determine effective data collection methods.

6.1. Usefulness of building data

The usefulness of building data has been explored in detail in Chapter 4, highlighting the building characteristics that are frequently required by seismic vulnerability assessment methods, as well as the most sensitive inputs drawn from a systematic review of the published literature, and those considered most important by the GEM taxonomy.

In conclusion, the most useful building characteristics are:

- Number of storeys
- Primary structural material type
- Lateral load resisting system type
- Presence of elevation irregularities
- Presence of plan irregularities
- Soil type
- Presence of soft stories (for RC frame buildings)
- Presence of short columns (for RC frame buildings)

From the data collected by the field-based methods, the following designations of more or less usefulness are defined in Table 6-1.

All other properties may still be useful for individual SVA methods, and more data would always be beneficial, but Chapter 4 highlights the most useful building characteristics that are useful above others, and without which, SVA results would be significantly impacted. These findings will be used further in section 6.4 to investigate the balance of collected building data that are useful, not costly, and accurate.

Building characteristic	Usefulness
No. storeys	H
Primary structural material	H
Masonry type	H
Reinforcement	H
Mortar type	H
Mortar joints	H
LLRS	H
Elevation irregularity	H
Built on stilts	H
Plan irregularity	H
Soft storey	H
Short column	H
Usage	M
Roof material	M
Connection quality	M
Age	M
Age [years]	M
Storey height	M
Wall thickness	M
State of preservation	M
Mass irregularity	M
Position	M
Opening irregularity	M
Floor material	M
Roof pitch	M
Diaphragms	M
Pounding	M
Built on slope	M
Retrofitting	L
SBWC	L
Balconies	L
Aseismic devices	L
Bow windows	L
Modifications	L
EQ design	L

Table 6-1 Usefulness of data collected using field-based methods, from Table 5-2

In addition to the data of high usefulness, it is imperative that a method collects a complete set of data, so that assumptions are not required for important data. Methods should be judged less effective if they are only capable of collecting partial datasets, particularly if substantial numbers of 'more useful' data are not collected. As previously predicted and observed, the AS and 3D methods do not collect enough of the highly useful data types to develop exposure profiles from them individually. This is reflected in the completeness of the datasets, given in Table 6-2, where from the thirty-five data points sought, the percentage completeness is given, alongside the ratio of collecting data of high, moderate, or low usefulness.

All methods deliver good datasets in terms of completeness, except the AS and 3D surveys, which fail to capture the majority of 'more useful' data points, obtaining just 13% and 38% respectively. This poor performance of the UAV-derived methods in this category excludes their meaningful inclusion in further effectiveness scoring and comparison. As UAV technologies and post processing software improve, this barrier may be able to be overcome.

Method	All data collected	H level data collected	M level data collected	L level data collected
DIS	100%	100%	100%	100%
RVS LE	82%	100%	70%	100%
RVS FE	87%	100%	78%	100%
RVS STU	82%	100%	70%	100%
OD	66%	100%	48%	86%
AS	21%	13%	17%	43%
3D	37%	38%	35%	43%

Table 6-2 Completeness of building characteristic datasets collected by the tested building data collection methods

Instead of considering the AS and 3D survey datasets individually, it is proposed that the datasets are combined with the OD survey dataset to form three combined ‘emerging technologies’ dataset. The following combinations will be formed: (1) OD and 3D, (2) AS and OD, and (3) OD, AS, and 3D. The most accurate data in each combination will be used, and the costs will be calculated to include the data collection and analysis expenses for each method included in the dataset (see section 6.2).

6.2. Cost of building data

The different methods for building data collection tested in Chapter 5 deliver information of different aspects of the building, with ranging levels of accuracy, and for different levels of resource (in terms of finance and time). As discussed in section 6.1 the UAV methods are combined with the OD survey dataset due to a lack of completeness.

The cost of the data collected in Guatemala City has been estimated in Table 6-3. Where the number of buildings is not important, an arbitrary number of buildings is used (in this case 1000) and the rates (in buildings/hour) are designated following the experience in the field and the post-field analysis. This results in a very high total value for the detailed internal survey, however the rate per building is the more important value to consider. The assumptions used to calculate other values are as follows:

- International travel and equipment costs are estimated individually for each methodology. If multiple survey methods, or the same equipment was used, costs are saved.
- Foreign subsistence is estimated as £60/day and includes food, drink, accommodation, insurance, etc.
- Local subsistence is estimated at £15 which covers food and drink.
- One day is assumed to be comprised of eight working hours.
- Experienced engineers are assumed to have a payment rate of £30 per hour, whereas inexperienced surveyors (i.e. the students) were assumed to have a payment rate of £20 per hour.
- Experienced engineers conduct all of the post-processing and virtual surveying.

- Field collection, post-processing, and virtual surveying rates are estimated according to time taken to collect the data in the field.
- Equipment costs are based on prices in June 2016 and the technology taken to Guatemala. These costs are likely to change rapidly as technology evolves.
- It is assumed that printing of one thousand survey forms costs £20. This may, of course, advance towards a digital form, reducing printing costs and post-processing costs (i.e. data input), but would likely increase equipment costs.
- The car cost is estimated at £60/day which includes fuel and all fees associated with the rental.
- Any bulk buying considerations are ignored, which skews the one off costs somewhat, but this consideration is consistent across the methods.

These assumptions and the costs in Table 6-3 are for survey methods that for a number of areas consider neighbouring buildings. The costs and assumptions would differ if individual buildings were spatially sampled across the city. This would be very time consuming and costly from a street surveying perspective, but if there was OD, aerial and 3D imagery available for the city then this method would be feasible and beneficial in terms of improving the sampling strategy used, and hence the results. Costs would also be reduced if some or all of the post-processing was automated.

These results are used in the discussion about the usefulness, cost, and accuracy of data in section 6.4.

	Data collection method	**Desk-based methods**		**Field-based methods**				**Field-based data collection and virtual surveying**			**Combinations of field-based data collection and virtual surveying**		
		Census	**Existing survey data**	**RVS STU**	**RVS LE**	**RVS FE**	**DIS**	**OD**	**AS**	**3D**	**OD+3D**	**OD+AS**	**OD+3D +AS**
	No. buildings	238,651	10,326	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Working rates	**Data collection rate (buildings/hour)**	-	-	6	8	8	0.3	200	500	500	-	-	-
	Post-processing rate (buildings/hour)	-	-	10	10	10	10	1000	500	50	-	-	-
	Virtual survey rate (buildings/hour)	-	-	-	-	-	-	12	20	12	-	-	-
Data collection	**International travel**	£0	£0	£0	£0	£1,000	£1,000	£600	£600	£600	£1,000	£1,000	£1,000
	Equipment	£0	£0	£20	£20	£20	£20	£300	£1,000	£1,000	£1,300	£1,300	£1,300
	Data collection time (days)	0.5	3	21	16	16	417	0.6	0.3	0.3	0.9	0.9	1.1
	Data collection fees (total)	£120	£720	£3,333	£3,750	£3,750	£100,000	£150	£60	£60	£210	£210	£270
	Field time (days)	0	0	21	16	16	417	0.6	0.3	0.3	0.9	0.9	1.1
	In-field subsistence	£0	£0	£313	£234	£938	£25,000	£38	£15	£15	£53	£53	£53
	Car	£0	£0	£1,250	£938	£938	£25,000	£38	£15	£15	£53	£53	£53
	Specialist software	£0	£0	£0	£0	£0	£0	£0	£250	£250	£250	£250	£250
Post-processing	**Post-processing time (days)**	1	2	13	13	13	13	0.1	0.3	2.5	2.6	0.4	2.9
	Post-processing fees (total)	£240	£480	£3,000	£3,000	£3,000	£3,000	£30	£60	£600	£630	£90	£690
Virtual survey	**Virtual survey time (days)**	-	-	-	-	-	-	10	6	10	21	17	27
	Virtual survey fees (total)	-	-	-	-	-	-	£2,500	£1,500	£2,500	£5,000	£4,000	£6,500
	Total time (days)	2	5	33	28	28	429	11	7	11	22	18	28
	Total cost	£360	£1,200	£7,916	£7,942	£9,645	£154,020	£3,655	£3,500	£5,040	£8,495	£6,955	£10,115
	Cost/building	£0.002	£0.116	£7.92	£7.94	£9.65	£154.02	£3.66	£3.50	£5.04	£8.50	£6.96	£10.12
	Data points collected			31	31	33	38	25	8	14	27	27	27
	Cost/data point			£0.26	£0.26	£0.29	£4.05	£0.15	£0.44	£0.36	£0.31	£0.26	£0.37

Table 6-3 The cost of collecting building data in Guatemala City using different methods

6.3. Accuracy of building data

The accuracy of the building data collected is important for assessing the capability of the method to collect quality data, and when considered alongside the usefulness of the data collected and the cost of collecting it.

Assessing the accuracy of data collected is difficult when the correct answer is not known: to overcome this, a correct answer is assumed and results compared against that. This assumed correct answer is hereby referred to as the reasonable truth and is defined as the most accurate reasonably obtainable result. Understanding all of the characteristics of a building is not feasible – hypothetically, data would need to be gathered during construction, as well as having a complete understanding of any building modifications and the impacts of the environment over time –, instead the concept of reasonable truth is more palatable.

There are different ways to assume the reasonable truth for different data types collected in Chapter 5. Initially, the reasonable truth is assumed to be the results of the detailed internal survey, where the building is observed throughout and the data of the highest quality is collected. For the nine buildings that this method was applied to, the results reported are compared to those collected by the other methods. Agreement indicates accuracy, and disagreement indicates inaccuracy. When results are numerical, for example storey height, a range of 20% either side of the correct answer is arbitrarily deemed acceptable. Additionally, when there is a combination of results that are true, for example a roof type that consists of both RC slab and sheet metal, if a dataset only reports one, it is deemed partially correct. A comparison between the results for the nine buildings covered by the detailed internal survey and each other survey method covering those nine buildings is carried out for each data type collected to obtain an initial accuracy assessment, but as the sample size is so small due the limited DIS results, subsequent accuracy assessments are completed.

The first of these methods is applied when there is a good accuracy score in the initial assessment for a data type and a method; for example, assume that the roof material data is initially assessed to be 100% accurate in the aerial survey dataset (i.e. it matches the DIS results perfectly). This data type and method will henceforth be assumed to be the reasonable truth, and the accuracy assessment is extended to a larger group of buildings as the aerial survey is more extensive. This inferred reasonable truth is used wherever there are data types and methods that score highly in the initial assessment.

For the data types and methods that don't score as highly in the initial assessment, a different method is used to improve the results beyond the initial assessment results. Instead of using an inferred reasonable truth comparison approach, results for each data type and each data collection method are compared, building-by-building. When there is agreement on the result between the methods, it is assumed that the result is accurate. Arbitrarily, accuracy is assumed when there is a majority in agreement (i.e. more than 50% of results). For example, say data type A is collected for building i by six field-based collection methods, *1* to *6*. For building i, five of the methods report A as x, one reports A as y. It is thereby assumed that the five methods that agree are correct (i.e. $A = x$), and the one that does not agree is incorrect (i.e. $A \neq y$). This is repeated for all buildings and data types that are surveyed by more than two methods (see Table 5-12). The percentage of correct results for data type A collected by method *1* across all buildings for which data was collected is given as the accuracy rate.

The underlying approach of all of these methods is the assumed correctness when the same results from different methods is observed. This principle is defined as the 'joint probability of agreement' and is used widely in the medical literature to test the agreement between the diagnostic decision made by different professionals (Gisev et al, 2013; Slaug et al, 2017). This statistical technique for measuring accuracy is criticised as ignoring the chance of raters (in this case data collection methods) erroneously agreeing (Uebersax, 1987): this chance increases significantly as the number of possible answers for the raters decreases (Brenner and Kliebsch, 1996) (see Table 3-2 for the numbers of available answers for the data collected in this study). To tackle this, a number of statistical techniques have been developed to calculate coefficients that consider this chance, including Cohen's kappa (Cohen, 1960; Cohen 1968) (for comparing two raters) and Fleiss's kappa (Fleiss, 1971; Shrout and Fliess, 1979) (for comparing between multiple raters). These methods have been criticised in the literature for a number of reasons {Zwick:1988ue}{Saal:1980wy}, such as the method not always being applicable or robust (Feinstein and Cicchetti, 1990); and results not being meaningful as they do not measure – or allow arbitrary categorisation of – validity (Thompson and Walter, 1988). The kappa statistics have also been criticised in the past for not being comparable across studies (Thompson and Walter, 1988; Feinstein and Cicchetti, 1990). In this study, the surveyors were always given the option to mark the data to be collected as unknown (see Table 3-2), thus reducing any lack of knowledge leading to guesswork and erroneous agreement, therefore these coefficient-based methods are not adopted herein, instead favouring the use of 'the joint probability of agreement'.

6.3.1. Initial assessment of accuracy of data collection method

In terms of surveying buildings for seismic exposure and vulnerability assessment data, it is initially suggested that the most reasonable truth can be arrived at through detailed internal surveying, where a building's characteristics are observed by a surveyor. If detailed internal surveying is taken as the most reasonable truth about a building, the Guatemala City dataset has nine buildings for which the reasonable truth is known. As an initial assessment of data collection method accuracy, data collected for these nine buildings using all survey methodologies can be compared with the detailed internal survey results.

From the desk study (see Chapter 5), it was concluded that five types of masonry – (1) unreinforced block; (2) unreinforced brick; (3) unreinforced adobe; (4) confined block; and (5) confined brick – are prevalent throughout Guatemala City, forming the vast majority of the building population. These nine buildings are all of different masonry constructions, so despite a small sample number, they are representative of the study area.

The proportions of correct, partially correct, incorrect, and not collected data for each sought characteristic for each data collection methodology are given in Figure 6-1 to Figure 6-6. These results show that despite the surveyor, the RVS method consistently collects accurate data on primary structural material, LLRS, design level, and the presence of some seismic weaknesses. Despite the RVS being assumed to be a good method to collect the number of storeys, this is not the case in Guatemala City due to additional storeys being constructed at the back of long slender plots, and relatively narrow streets reducing the ability for the additional construction to be observed. The foreign expert has a significantly higher proportion of uncollected data, whilst the local expert tended to complete more of the survey, even if responses were incorrect. It is the same pattern for the data collected by the students, however less errors were made. The student-teacher relationship between the students and the local expert is likely to have driven the results towards the similarity that is present. Additionally, despite an option for passing on collecting data that is not obvious the local participants prioritised reporting any result, rather than stating an inability to report the data accurately.

The aerial survey method only collects limited data, but what it collects is observed to be fairly accurate. The 3D model survey method collects more data than the aerial survey, and is also likely to collect high quality data. The omnidirectional image survey method attempts to collect more data about each building, but is only able to collect some information accurately, and complete datasets are not common as significant amounts data remain uncollected.

This comparison is based on nine or less comparisons of building data collected using different methods (see Table 6-4), which is a small comparative dataset, therefore further analysis on accuracy with the larger datasets is presented below.

Building number	Data collection method						
	DIS	RVS LE	RVS FE	RVS STU	AS	3D	OD
1	•	•	•	•	•	•	•
2	•	•	•	•	•	•	•
3	•	•	•	•	•	•	•
4	•		•	•	•	•	•
5	•	•	•		•	•	•
6	•	•	•	•	•	•	•
7	•		•		•	•	•
8	•		•		•	•	•
9	•		•		•	•	•

Table 6-4 The detailed internal survey data collected by different methodologies

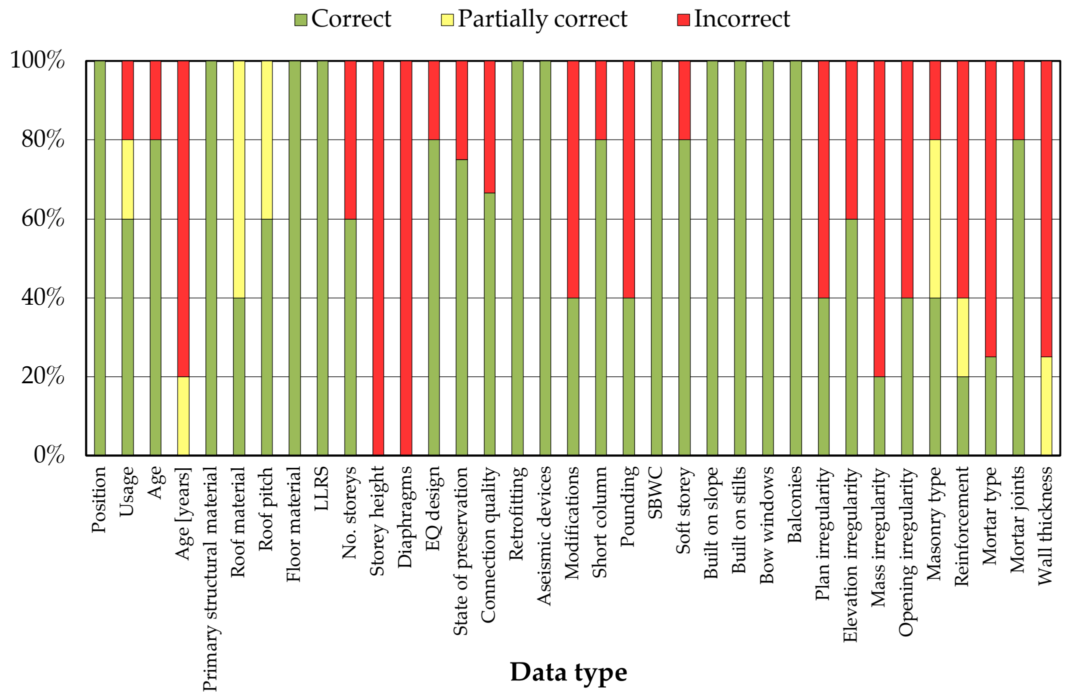


Figure 6-1 Accuracy of RVS data collection method by local expert after the initial assessment

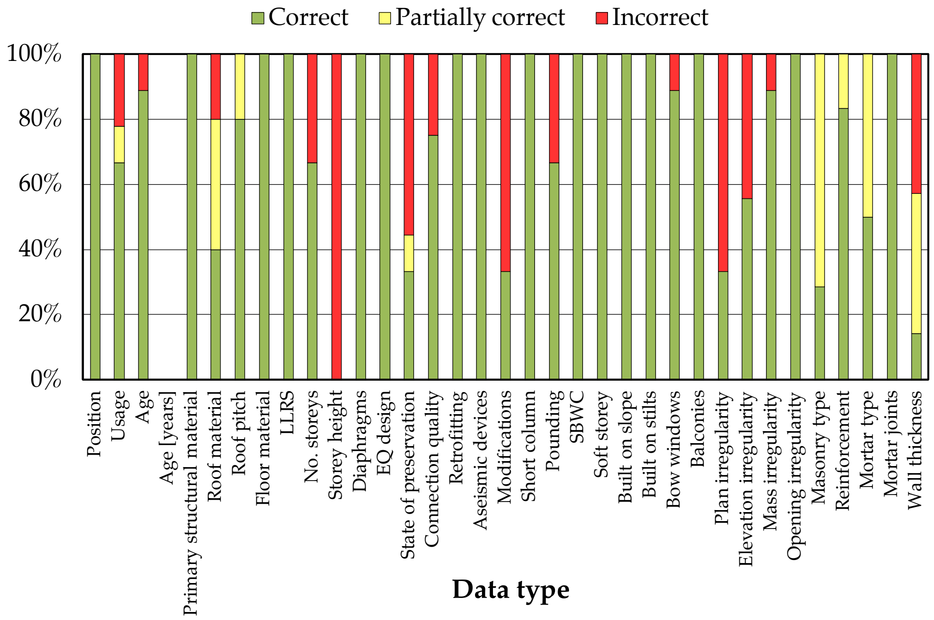


Figure 6-2 Accuracy of RVS data collection method by foreign expert after the initial assessment

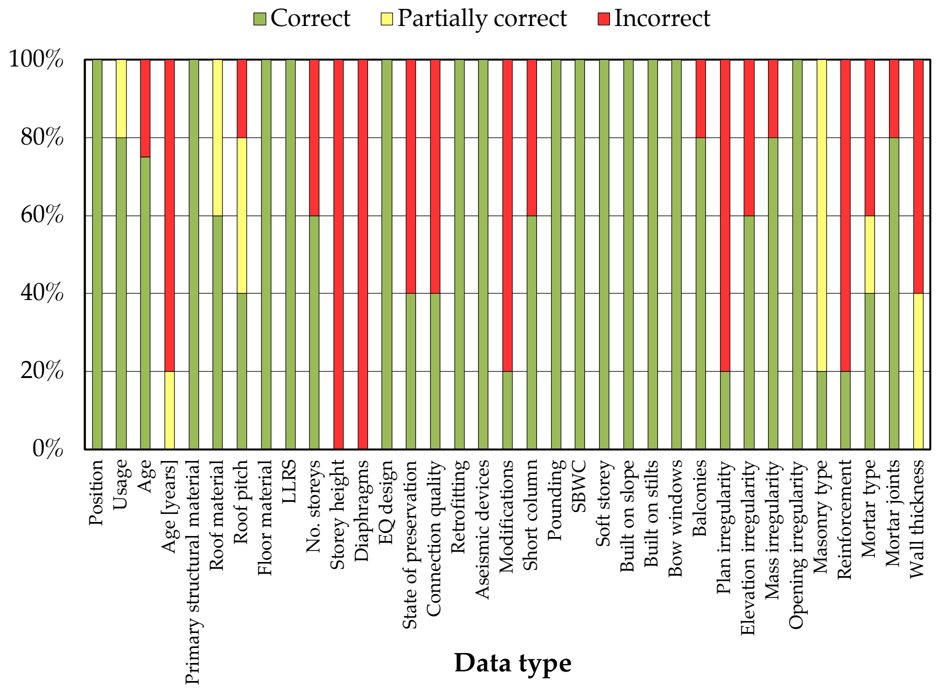


Figure 6-3 Accuracy of RVS data collection method by local student after the initial asssessment

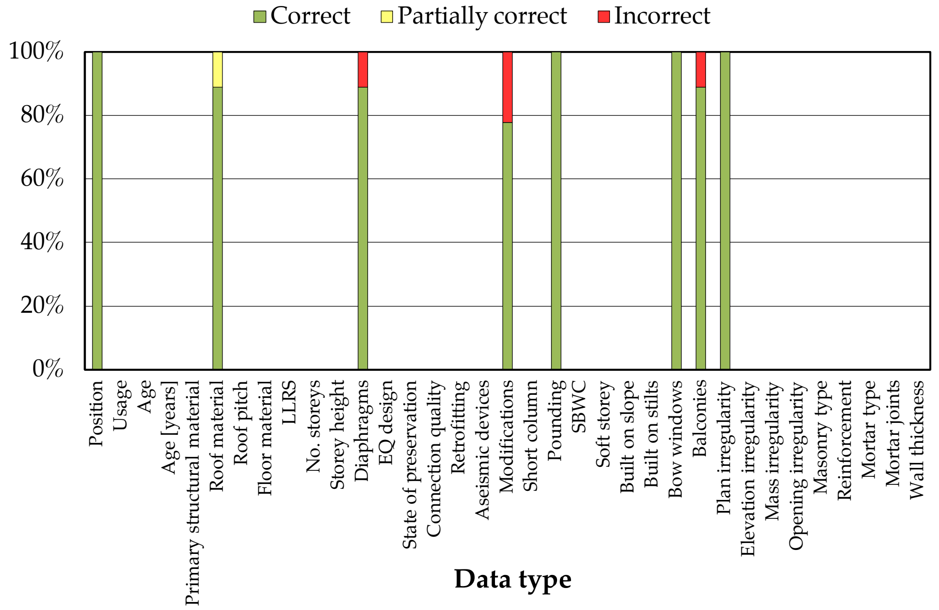


Figure 6-4 Accuracy of aerial survey data collection method after the initial asssessment

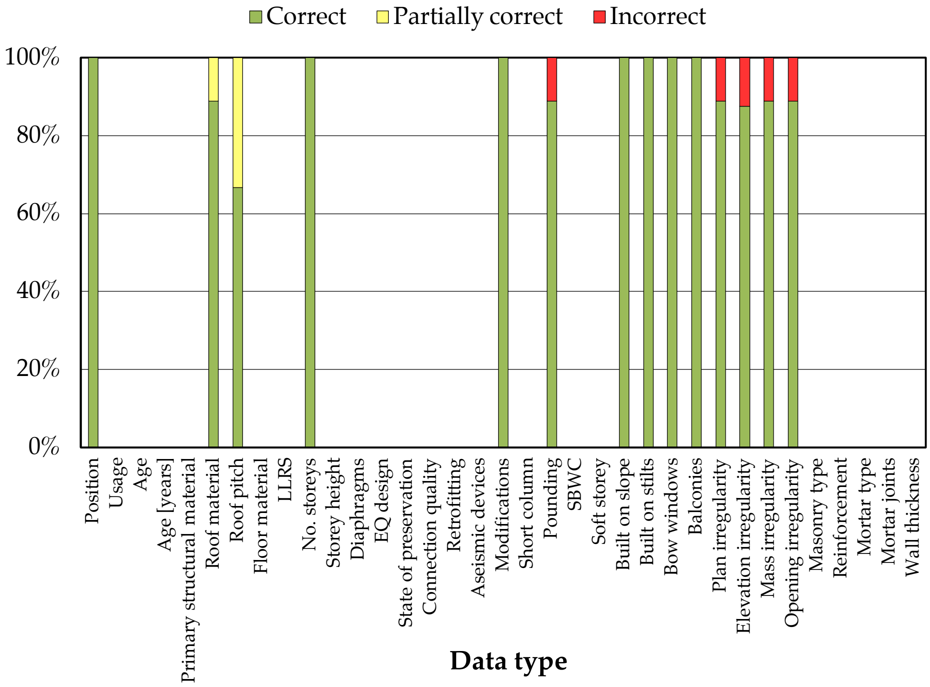


Figure 6-5 Accuracy of 3D model survey data collection method after the initial asssessment

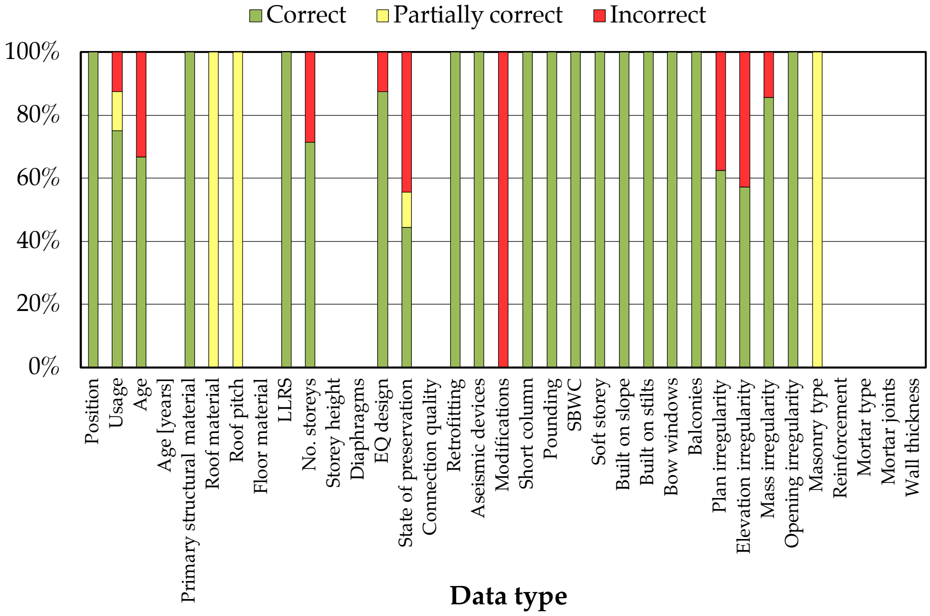


Figure 6-6 Accuracy of omnidirectional survey data collection method after the initial asssessment

The levels of accuracy recorded within this initial assessment decide the method used for the subsequent accuracy analysis for each data type. The selection procedure is in Figure 6-7, showing the progression through the decisions on which procedure (the inferred reasonable truth analysis or the comparative analysis) is more appropriate. The results from the selection process are given in Table 6-5, with methods proposed according the procedure presented in Figure 6-7. These further accuracy analyses are completed below.

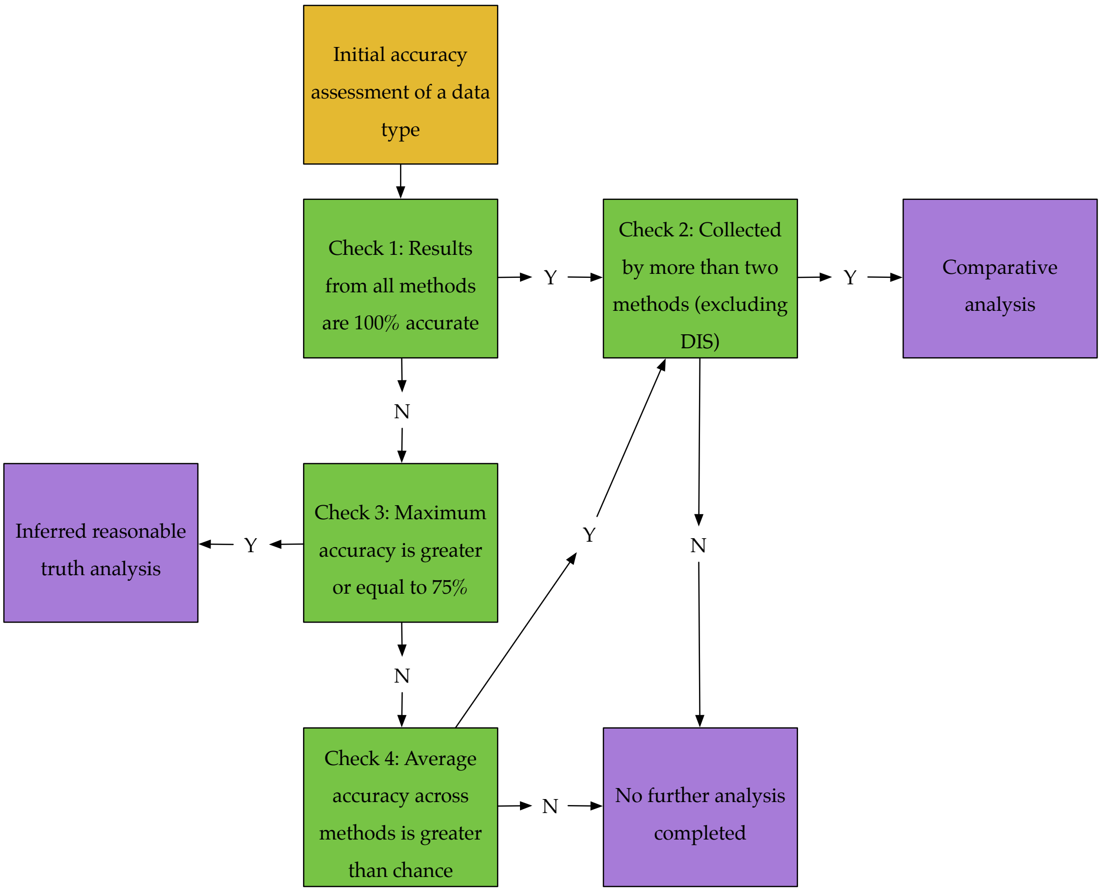


Figure 6-7 Post-initial accuracy analysis method selection procedure

Building characteristics	Accuracy of data collection method – results from the initial assessment							Checks (refer to Figure 6-7)				Method proposed
	DIS	RVS LE	RVS FE	RVS STU	AS	3D	OD	Check 1	Check 2	Check 3	Check 4	
Position	100%	100%	100%	100%	100%	100%	100%	Y	Y	Y	Y	Comparative analysis
Usage	100%	60%	67%	80%			75%	N	Y	Y	Y	Inferred reasonable truth analysis
Age	100%	80%	89%	75%			67%	N	Y	Y	Y	Inferred reasonable truth analysis
Age [years]	100%	0%		0%				N	N	N	N/A	None
Primary structural material	100%	100%	100%	100%			100%	Y	Y	Y	Y	Comparative analysis
Roof material	100%	40%	40%	60%	89%	89%	0%	N	Y	Y	Y	Inferred reasonable truth analysis
Roof pitch	100%	60%	80%	40%		67%	0%	N	Y	Y	N	Inferred reasonable truth analysis
Floor material	100%	100%	100%	100%				Y	Y	Y	Y	Comparative analysis
LLRS	100%	100%	100%	100%			100%	Y	Y	Y	Y	Comparative analysis
No. storeys	100%	60%	67%	60%		100%	71%	N	Y	Y	Y	Inferred reasonable truth analysis
Storey height	100%	0%	0%	0%				N	Y	N	N/A	None
Diaphragms	100%	0%	100%	0%	89%			N	Y	Y	Y	Inferred reasonable truth analysis
EQ design	100%	80%	100%	100%			88%	N	Y	Y	Y	Inferred reasonable truth analysis
State of preservation	100%	75%	33%	40%			44%	N	Y	Y	Y	Inferred reasonable truth analysis
Connection quality	100%	67%	75%	40%				N	Y	Y	Y	Inferred reasonable truth analysis
Retrofitting	100%	100%	100%	100%				Y	Y	Y	Y	Comparative analysis
Aseismic devices	100%	100%	100%	100%				Y	Y	Y	Y	Comparative analysis
Modifications	100%	40%	33%	20%	78%	100%	0%	N	Y	Y	N	Inferred reasonable truth analysis
Short column	100%	80%	100%	60%			100%	N	Y	Y	Y	Inferred reasonable truth analysis
Pounding	100%	40%	67%	100%	100%	89%	100%	N	Y	Y	Y	Inferred reasonable truth analysis
SBWC	100%	100%	100%	100%			100%	Y	Y	Y	Y	Comparative analysis
Soft storey	100%	80%	100%	100%			100%	N	Y	Y	Y	Inferred reasonable truth analysis
Built on slope	100%	100%	100%	100%		100%	100%	Y	Y	Y	Y	Comparative analysis
Built on stilts	100%	100%	100%	100%		100%	100%	Y	Y	Y	Y	Comparative analysis
Bow windows	100%	100%	89%	100%	100%	100%	100%	N	Y	Y	Y	Inferred reasonable truth analysis
Balconies	100%	100%	100%	80%	89%	100%	100%	N	Y	Y	Y	Inferred reasonable truth analysis
Plan irregularity	100%	40%	33%	20%	100%	89%	63%	N	Y	Y	Y	Inferred reasonable truth analysis
Elevation irregularity	100%	60%	56%	60%		88%	57%	N	Y	Y	Y	Inferred reasonable truth analysis
Mass irregularity	100%	20%	89%	80%		89%	86%	N	Y	Y	Y	Inferred reasonable truth analysis
Opening irregularity	100%	40%	100%	100%		89%	100%	N	Y	Y	Y	Inferred reasonable truth analysis
Masonry type	100%	40%	29%	20%			0%	N	Y	N	Y	Comparative analysis
Reinforcement	100%	20%	83%	20%				N	Y	Y	Y	Inferred reasonable truth analysis
Mortar type	100%	25%	50%	40%				N	Y	N	Y	Comparative analysis
Mortar joints	100%	80%	100%	80%				N	Y	Y	Y	Inferred reasonable truth analysis
Wall thickness	100%	0%	14%	0%				N	Y	N	N/A	None

Table 6-5 Selection of further accuracy analysis for key building data (the highest accuracy is given as green, the lowest as red, with shadings or orange between)

6.3.2. Inferred reasonable truth analysis

As determined in Table 6-5, the inferred reasonable truth analysis is used for twenty-one data types to further assess the accuracy of data collected by each method. The method with the most accurate results following the initial assessment is assumed as the reasonable truth. When there are a number of methods with the same maximum accuracy score, the method with the larger sample size is used. The survey method used as the reasonable truth for each data type tested are given in in Table 6-6.

Data type	Data collection methodology					
	RVS LE	RVS FE	RVS STU	AS	3D	OD
Usage	c	c	I	c	c	c
Age	c	I	c			c
Roof material	c	c	c	I	c	c
Roof pitch	c	I	c		c	c
No. storeys	c	c	c		I	c
Diaphragms	c	I	c	c		
EQ design	c	I	c			c
State of preservation	I		c			c
Connection quality	c	I	c			
Modifications	c	c	c	c	I	c
Short column	c	c	c			I
Pounding	c	c	c	I	c	c
Soft storey	c	I	c			c
Bow windows	c	c	c	I	c	c
Balconies	c	I	c	c	c	c
Plan irregularity	c	c	c	I	c	c
Elevation irregularity	c	c	c		I	c
Mass irregularity	c	I	c		c	c
Opening irregularity	c	I	c		c	c
Reinforcement	c	I	c			
Mortar joints	c	I	c			

Table 6-6 The inferred reasonable analysis setup showing the data type used as the (I)inferred reasonable truth (also shown in green) and the data types (c)ompared (shown in blue)

This analysis considers only the correct and incorrect values; any uncollected data or partially correct data are disregarded, thus the proportion of correct to incorrect data is calculated. Each assessment is completed individually. The sample size available for analysis differs depending on how many times each survey method collected each building characteristics: this and the updated accuracy of results are reported in Table 6-7. These results are used to update the accuracy values reported initially (in Figure 6-1, Figure 6-2, Figure 6-3, Figure 6-4, Figure 6-5, and Figure 6-6).

Building characteristic	Survey method											
	RVS LE		RVS FE		RVS STU		OD		AS		3D	
	Test sample size	Updated accuracy	*Test sample size*	Updated accuracy	*Test sample size*	Updated accuracy	*Test sample size*	Updated accuracy	*Test sample size*	Updated accuracy	*Test sample size*	Updated accuracy
Usage	*126*	*73%*	*227*	*67%*	*263*	*80%*	*33*	*58%*				
Age	*146*	*65%*	*434*	*89%*	*178*	*57%*	*86*	*88%*				
Roof material	*190*	*54%*	*362*	*35%*	*184*	*48%*	*30*	*43%*	*452*	*89%*	*83*	*78%*
Roof pitch	*157*	*66%*	*440*	*80%*	*233*	*58%*	*30*	*70%*			*89*	*42%*
No. storeys	*58*	*84%*	*90*	*77%*	*62*	*82%*	*90*	*74%*			*95*	*100%*
Diaphragms	*154*	*14%*	*440*	*100%*	*231*	*16%*			*360*	*8%*		
EQ design	*153*	*35%*	*441*	*100%*	*231*	*47%*	*56*	*77%*				
State of preservation	*256*	*75%*	*412*	*3%*	*246*	*2%*	*59*	*31%*				
Connection quality	*148*	*36%*	*438*	*75%*	*225*	*45%*						
Modifications	*58*	*43%*	*90*	*44%*	*61*	*52%*	*56*	*54%*	*83*	*71%*	*95*	*100%*
Short column	*42*	*81%*	*73*	*89%*	*43*	*88%*	*76*	*100%*				
Pounding	*190*	*48%*	*356*	*70%*	*185*	*62%*	*80*	*95%*	*453*	*100%*	*83*	*93%*
Soft storey	*154*	*65%*	*418*	*100%*	*215*	*82%*	*71*	*79%*				
Bow windows	*190*	*91%*	*356*	*99%*	*185*	*90%*	*81*	*98%*	*453*	*100%*	*83*	*99%*
Balconies	*154*	*82%*	*421*	*100%*	*218*	*75%*	*74*	*74%*	*356*	*76%*	*90*	*70%*
Plan irregularity	*190*	*57%*	*356*	*54%*	*185*	*43%*	*76*	*42%*	*453*	*100%*	*83*	*63%*
Elevation irregularity	*59*	*61%*	*90*	*67%*	*62*	*69%*	*89*	*61%*			*95*	*88%*
Mass irregularity	*154*	*24%*	*419*	*89%*	*216*	*85%*	*71*	*96%*			*90*	*96%*
Opening irregularity	*153*	*44%*	*420*	*100%*	*217*	*65%*	*78*	*83%*			*90*	*74%*
Reinforcement	*109*	*44%*	*350*	*83%*	*173*	*38%*						
Mortar joints	*109*	*23%*	*350*	*100%*	*171*	*17%*						

Table 6-7 Results from the inferred reasonable truth analysis. Green shading denotes the inferred truth data. The grey shading denotes uncollected data

In Table 6-6 it can be seen that eleven data types rely on one single method to assess the reasonable truth following the results of the initial accuracy assessment. This is due to the generally good data collected by the foreign expert for the initial nine buildings (see Table 6-5), as well as the larger coverage of this dataset (see Table 5-11) which results in it being preferred for certain data types over other survey methods. The average accuracy of the inferred reasonable truth across all data types tested is 93%, significantly higher than the lowest allowed by the methodology, 75%, and this, in conjunction with the average sample size of 346 used to infer reasonable accuracy, signifies that good results are likely from this second assessment of accuracy.

The sample sizes used for comparison with the inferred accuracy range from 30 to 412, with an average of 145. These sample sizes are significantly larger than those available for the initial accuracy assessment, where a maximum of nine was available, thus further signifying good results from this analysis. With these numbers available for comparison it is also most likely that a large range of building typologies and characteristics common to the study area are compared, increasing the likelihood that these results are relevant more widely.

The changes in accuracy from the initial results, to the those reported in Table 6-7 show a slight overall reduction from an overall average of 71% down to 68%. The change in each method is highlighted in Figure 6-8. The AS and 3D methods collect building characteristics relatively accurately, but they collect relatively few data points.

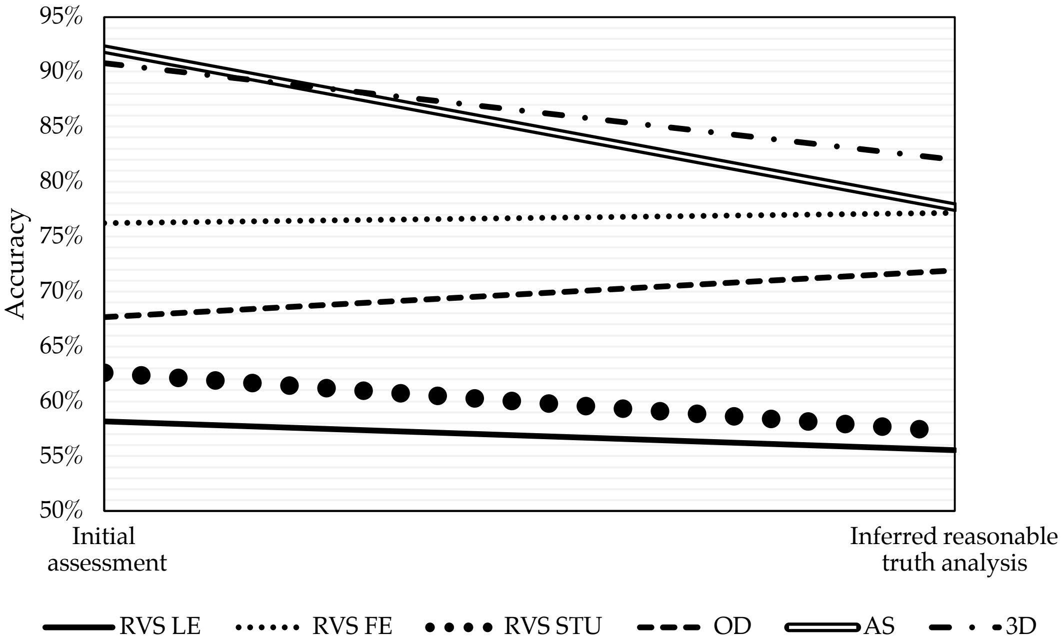


Figure 6-8 The change observed in average accuracy scores for each field-based method from the initial assessment, and after updating certain accuracy scores using the inferred reasonable truth analysis

This analysis provides a much more robust assessment of the accuracy of different survey methods collect building characteristics than the initial assessment provided. Despite the assumptions of reasonable truths, the sample over which the accuracy is tested is much larger, a representation of the buildings in the study area.

6.3.3. Comparative analysis

As determined in Table 6-5 the certain types of building data will be assessed further using the comparative analysis method. This employs the comparison of results across a number of methods and if consensus is found then accuracy is assumed. Table 6-8 shows the data that are to be investigated using this method; the green shading shows the data available from the different survey methods for comparison.

Building characteristics	RVS LE	RVS FE	RVS STU	OD	AS	3D
Position	●	●	●	●	●	●
Primary structural material	●	●	●	●		
Floor material	●	●	●			
LLRS	●	●	●	●		
Retrofitting	●	●	●	●		
Aseismic devices	●	●	●	●		
SBWC	●	●	●	●		
Built on slope	●	●	●	●		●
Built on stilts	●	●	●	●		●
Masonry type	●	●	●			
Mortar type	●	●	●	●		

Table 6-8 Data available for comparative analysis

Building characteristic	Survey method											
	RVS LE		RVS FE		RVS STU		OD		AS		3D	
	Test sample size	Updated accuracy	*Test sample size*	Updated accuracy	*Test sample size*	Updated accuracy	*Test sample size*	Updated accuracy	*Test sample size*	Updated accuracy	*Test sample size*	Updated accuracy
Position	*218*	41%	*424*	43%	*246*	60%	*89*	88%	*452*	37%	*95*	92%
Primary structural material	*252*	37%	*411*	23%	*266*	33%	*51*	57%				
Floor material	*150*	37%	*189*	31%	*156*	34%	*21*	90%				
LLRS	*253*	30%	*411*	19%	*255*	29%	*38*	61%				
Retrofitting	*255*	27%	*417*	17%	*249*	28%						
Aseismic devices	*255*	38%	*418*	23%	*260*	38%						
SBWC	*256*	43%	*418*	31%	*273*	43%	*67*	76%				
Built on slope	*256*	52%	*419*	37%	*273*	49%	*91*	96%			*95*	95%
Built on stilts	*256*	53%	*419*	40%	*273*	49%	*91*	98%			*95*	96%
Masonry type	*206*	9%	*238*	8%	*236*	8%	*13*	23%				
Mortar type	*220*	7%	*170*	9%	*241*	7%						

Table 6-9 Results from the comparative analysis

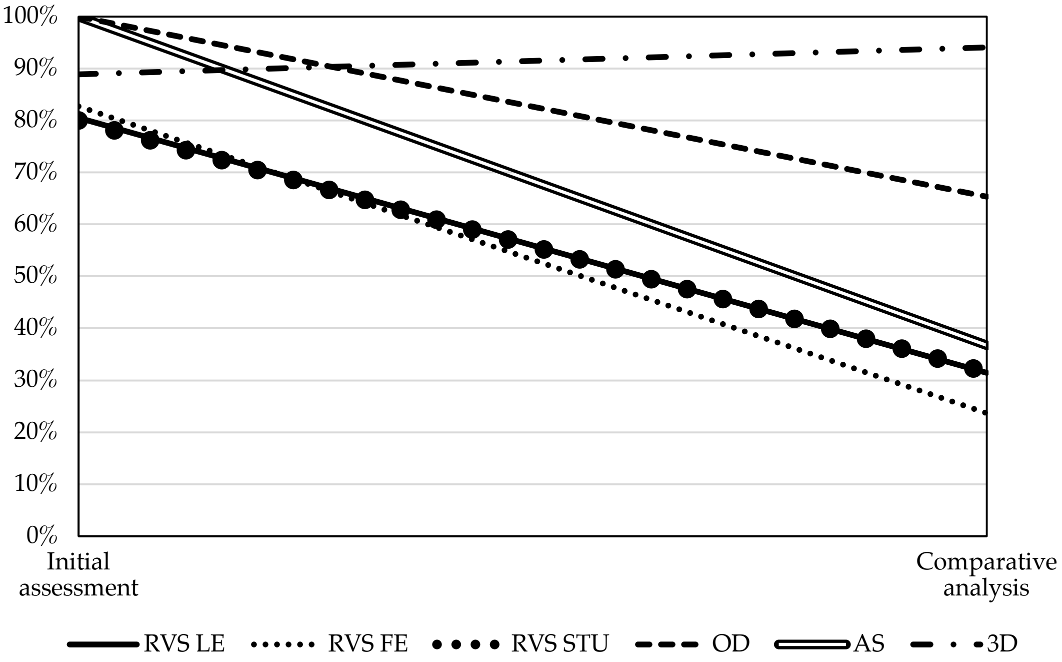


Figure 6-9 The change observed in accuracy scores for each field-based method from the initial assessment, and after the inferred reasonable truth analysis

6.3.4. Final results of accuracy analyses

Following the initial assessment, and the subsequent inferred reasonable truth and comparative analysis (see sections 6.3.2 and 6.3.3 respectively), the estimated final accuracy of collecting building data using the different field-based methods is found in Table 6-10. This is a collection of the results obtained in Table 6-5, Table 6-7, and Table 6-9, according to the assessment procedure methods selected in Table 6-5.

The detailed internal survey is clearly estimated to be the most accurate, based on the assumption that it is the most accurate (in a reasonable world) method for building data collection. According to the results, each method has a wide-ranging ability to collect accurate building data, from 0% accuracy to 100%. On average, the 3D survey method is the most consistently accurate method (85%), followed by the AS (73%), and the OD (72%), however, these methods (particularly the AS and 3D) only collect a limited number of building characteristics in their surveys. What they do collect, they collect relatively accurately.

The RVS methods trail at some distance with an average accuracy of 44% (RVS LE), 56% (RVS FE), and 45% (RVS STU). These methods aim to collect more building data, even when it is challenging and relies on assumptions or experience-based guesses. This will lead to biases and errors (Tversky and Khaneman, 1974), and ultimately inaccuracy, as seen in Table 6-10.

Some building data is proven to be more accurately obtained, regardless of the survey method. The presence of bow windows is captured well across the board, as are the number of storeys, the presence of short columns, and pounding potential for the methods that capture them. The data collected with the lowest accuracy across the methods include in numerically scaled data types (e.g. the age in years, storey height, and wall thickness), and well as more difficult to see attributes such as masonry and mortar type.

These results will be used in the next section to compare accuracy of results with the cost of collecting the data and the importance or usefulness of an input to a SVA. When the survey datasets are combined, the most accurate data point is used.

Building characteristic	**Accuracy of data collection method – final results**							**Method of accuracy analysis**
	DIS	**RVS LE**	**RVS FE**	**RVS STU**	**OD**	**AS**	**3D**	
Position	100%	41%	43%	60%	88%	37%	92%	C***
Usage	100%	73%	67%	80%	58%			I**
Age	100%	65%	89%	57%	88%			I**
Age [years]	100%	0%		0%				In*
Primary structural material	100%	37%	23%	33%	57%			C***
Roof material	100%	54%	35%	48%	43%	89%	78%	I**
Roof pitch	100%	66%	80%	58%	70%		42%	I**
Floor material	100%	37%	31%	34%	90%			C***
LLRS	100%	30%	19%	29%	61%			C***
No. storeys	100%	84%	77%	82%	74%		100%	I**
Storey height	100%	0%	0%	0%				In*
Diaphragms	100%	14%	100%	16%		8%		I**
EQ design	100%	35%	100%	47%	77%			I**
State of preservation	100%	75%	3%	2%	31%			I**
Connection quality	100%	36%	75%	45%				I**
Retrofitting	100%	27%	17%	28%				C***
Aseismic devices	100%	38%	23%	38%				C***
Modifications	100%	43%	44%	52%	54%	71%	100%	I**
Short column	100%	81%	89%	88%	100%			I**
Pounding	100%	48%	70%	62%	95%	100%	93%	I**
SBWC	100%	43%	31%	43%	76%			C***
Soft storey	100%	65%	100%	82%	79%			I**
Built on slope	100%	52%	37%	49%	96%		95%	C***
Built on stilts	100%	53%	40%	49%	98%		96%	C***
Bow windows	100%	91%	99%	90%	98%	100%	99%	I**
Balconies	100%	82%	100%	75%	74%	76%	70%	I**
Plan irregularity	100%	57%	54%	43%	42%	100%	63%	I**
Elevation irregularity	100%	61%	67%	69%	61%		88%	I**
Mass irregularity	100%	24%	89%	85%	96%		96%	I**
Opening irregularity	100%	44%	100%	65%	83%		74%	I**
Masonry type	100%	9%	8%	8%	23%			C***
Reinforcement	100%	44%	83%	38%				I**
Mortar type	100%	7%	9%	7%				C***
Mortar joints	100%	23%	100%	17%				I**
Wall thickness	100%	0%	14%	0%				In*

*Initial assessment method (section 6.3.1)
**Inferred reasonable truth analysis (section 6.3.2)
***Comparative analysis (section 6.3.4)

Table 6-10 Final estimated accuracy of different data collection methodologies for different building characteristics. Blank squares indicate no data collected. The colour scale runs from green (highest accuracy) through yellow (average accuracy) to red (lowest accuracy).

6.4. Effective building data collection

The focus of this chapter is assessing the effectiveness of the field-based building data collection methods tested in Chapter 5. Effectiveness, defined as the balance of cost, accuracy, and usefulness, can be viewed in two ways: (1) the effectiveness of a method in collecting a set of building data, or (2) the data types which can be more effectively collected by any method. Both will be explored herein.

In order to identify the more effective data types and collection methods, a scoring system is required. An arbitrary system is defined here which combines individual scores for cost (C), accuracy (A), and usefulness (U) for method i, and data type x. The scoring system is defined as follows:

$$C(x,i) = \frac{minimum\ cost\ of\ collecting\ x\ using\ any\ method}{cost\ of\ collecting\ x\ using\ method\ i} \qquad (see \text{ Table 6-3 })$$

$$A(x,i) = \frac{accuracy\ percentage\ for\ x\ collected\ using\ i}{100} \qquad (see \text{ Table 6-10})$$

	high usefulness (see Table 4-5):	$U(x,i) = 1$
If x is of:	moderate usefulness (see Table 4-5):	$U(x,i) = 0.75$
	low usefulness (see Table 4-5):	$U(x,i) = 0.5$

These scores are then combined by simple addition to arrive at an effectiveness score, E. Depending on the priorities of the seismic risk assessment, different weighting scores (w) may be used to prioritise any of the elements, as follows:

$$E(x,i) = w_C \cdot C(x,i) + w_A \cdot A(x,i) + w_U \cdot U(x,i)$$

where $w_C + w_A + w_U = 1$

Although these scores are not evenly distributed, the weighting process can balance that out if different results are sought. All scales run from 0 to 1 except the usefulness scale, as the low usefulness data types are not of zero worth to a SVA, instead they are still worth something. This is arbitrarily decided to be half of the high usefulness data types. The findings and data are all presented herein so these scoring regimes can be easily adjusted.

Using these relationships and scoring methods, the effectiveness of data types, and data collection methods can be determined. Effectiveness scores are given in Table 6-11 for equally weighted cost, accuracy, and usefulness. There is a subtle trend of more effectiveness for data collection methods on the right of the table, including the combination of methods that employ emerging technology, deliver effective results, whereas the traditional rapid visual survey methods lag behind in effectiveness, particularly the expensive detailed internal survey method, despite its assumed perfect accuracy. The OD survey method is clearly the most effective method.

The average scores in the last column show that, overall, the most effective data types to collect are the presence of short columns, number of storeys, and the presence of soft storeys or stilted structures. The least effective data types to collect are the presence of retrofitting, aseismic devices, storey height, wall thickness, and age in years: all data that is difficult to collect during a brief external survey, instead require more detail investigation.

The average scores in the last row highlight the most effective data collection methods for the equally weighted scores. When the scores are weighted (in this case by three times) to prioritise different components of effectiveness, different methods are highlighted as more or less effective, see Figure 6-10. As previously deduced, the OD survey method is the most effective method, and this is consistent regardless of the priority. The combination of the OD dataset with either the AS or 3D datasets are also deemed to be generally highly effective. Overall, the methods that employ the new technology outperform the traditional street-based surveys. The more expensive street surveys range slightly in accuracy, cost, and usefulness, and some of these nuances become apparent in the results in Figure 6-10. The relatively low accuracy by all survey groups is highlighted when accuracy is prioritised and they fall to fill the lowest ranks. The DIS method ranks highly when accuracy is important despite the high cost that renders it a relatively ineffective method for all other priorities, particularly cost.

There are many limitations with the sets of results presented in Table 6-11 and Figure 6-10. For instance, combining the scoring of cost, accuracy, and usefulness has a number of issues discussed previously, which can be dealt with by redoing the calculations presented here. These results represent an example of the kind of results that may be achieved depending on the priorities for the collection of building data. In addition, there is no concept of time taken into account here, except for direct costs of surveying time. If there is a programme of works for surveying buildings, no direct indication is given in this study as to the fastest or slowest survey methods. This is something that could be further studied or estimates deduced directly from the cost analysis in section 6.2.

It is worth reiterating that different data collection methods will be more of less effective if different sampling techniques were applied over an urban area. In particular, the virtual surveying methods would handle a sampling techniques that identified single buildings spread throughout the city much more effectively (from a cost perspective) than street surveying techniques.

The overwhelming pattern is that the methods that use emerging technology and virtual surveys perform consistently better than the traditional field-based methods. The shortcomings of these methods include their inability to collect comprehensive building datasets, but this is overcome effectively by combining datasets which, despite additional costs, still perform well in comparison to traditional methods.

Data type	Data collection method										
	DIS	RVS LE	RVS FE	RVS STU	OD	AS	3D	OD+3D	OD+AS	OD+AS +3D	Ave $E(x)$
Position	0.60	0.58	0.56	0.64	0.88	0.48	0.69	0.71	0.73	0.69	0.66
Usage	0.60	0.68	0.64	0.71	0.78			0.60		0.57	0.65
Age	0.60	0.66	0.71	0.63	0.88			0.70	0.73	0.67	0.70
Age [years]	0.60	0.44		0.44							0.49
Primary structural material	0.68	0.65	0.58	0.63	0.86			0.68	0.71	0.65	0.68
Roof material	0.60	0.62	0.53	0.60	0.73	0.66	0.65	0.67	0.74	0.68	0.65
Roof pitch	0.60	0.66	0.68	0.63	0.82		0.52	0.64	0.67	0.61	0.65
Floor material	0.60	0.56	0.52	0.55	0.88			0.71	0.74	0.68	0.66
LLRS	0.68	0.62	0.56	0.62	0.87			0.69	0.72	0.67	0.68
No. storeys	0.68	0.81	0.76	0.80	0.91		0.80	0.82	0.77	0.80	0.79
Storey height	0.60	0.44	0.42	0.44							0.47
Diaphragms	0.60	0.49	0.75	0.49		0.39			0.46	0.41	0.51
EQ design	0.51	0.47	0.67	0.51	0.76			0.58	0.61	0.55	0.58
State of preservation	0.60	0.69	0.43	0.45	0.69			0.51	0.54	0.48	0.55
Connection quality	0.60	0.56	0.67	0.59							0.60
Retrofitting	0.51	0.45	0.39	0.45							0.45
Aseismic devices	0.51	0.48	0.41	0.48							0.47
Modifications	0.51	0.50	0.48	0.53	0.68	0.52	0.64	0.65	0.59	0.63	0.57
Short column	0.68	0.79	0.80	0.82	1.00			0.82	0.86	0.80	0.82
Pounding	0.60	0.60	0.65	0.65	0.90	0.69	0.69	0.72	0.77	0.71	0.70
SBWC	0.51	0.50	0.44	0.50	0.75			0.58	0.61	0.55	0.55
Soft storey	0.68	0.74	0.83	0.80	0.93			0.75	0.79	0.73	0.78
Built on slope	0.60	0.61	0.54	0.60	0.90		0.70	0.72	0.76	0.70	0.68
Built on stilts	0.68	0.70	0.63	0.69	0.99		0.79	0.81	0.85	0.79	0.77
Bow windows	0.51	0.66	0.66	0.66	0.83	0.61	0.63	0.65	0.69	0.63	0.65
Balconies	0.51	0.63	0.67	0.61	0.75	0.53	0.54	0.57	0.61	0.55	0.60
Plan irregularity	0.68	0.71	0.68	0.67	0.81	0.78	0.68	0.70	0.86	0.80	0.74
Elevation irregularity	0.68	0.73	0.72	0.76	0.87		0.76	0.78	0.72	0.76	0.75
Mass irregularity	0.60	0.52	0.71	0.72	0.90		0.70	0.72	0.76	0.70	0.70
Opening irregularity	0.60	0.59	0.75	0.66	0.86		0.63	0.68	0.72	0.66	0.68
Masonry type	0.68	0.55	0.53	0.55	0.74			0.57	0.60	0.54	0.59
Reinforcement	0.68	0.67	0.78	0.65							0.69
Mortar type	0.68	0.55	0.53	0.55							0.58
Mortar joints	0.68	0.60	0.83	0.58							0.67
Wall thickness	0.60	0.44	0.46	0.44							0.49
Ave $E(i)$	0.61	0.60	0.62	0.60	0.84	0.58	0.67	0.68	0.70	0.65	

Table 6-11 Effectiveness scores for equally (although note the different scoring regimes discussed in section 6.4) weighted cost, accuracy, and usefulness. Green denotes high effectiveness, red denotes low effectiveness, with shades in between.

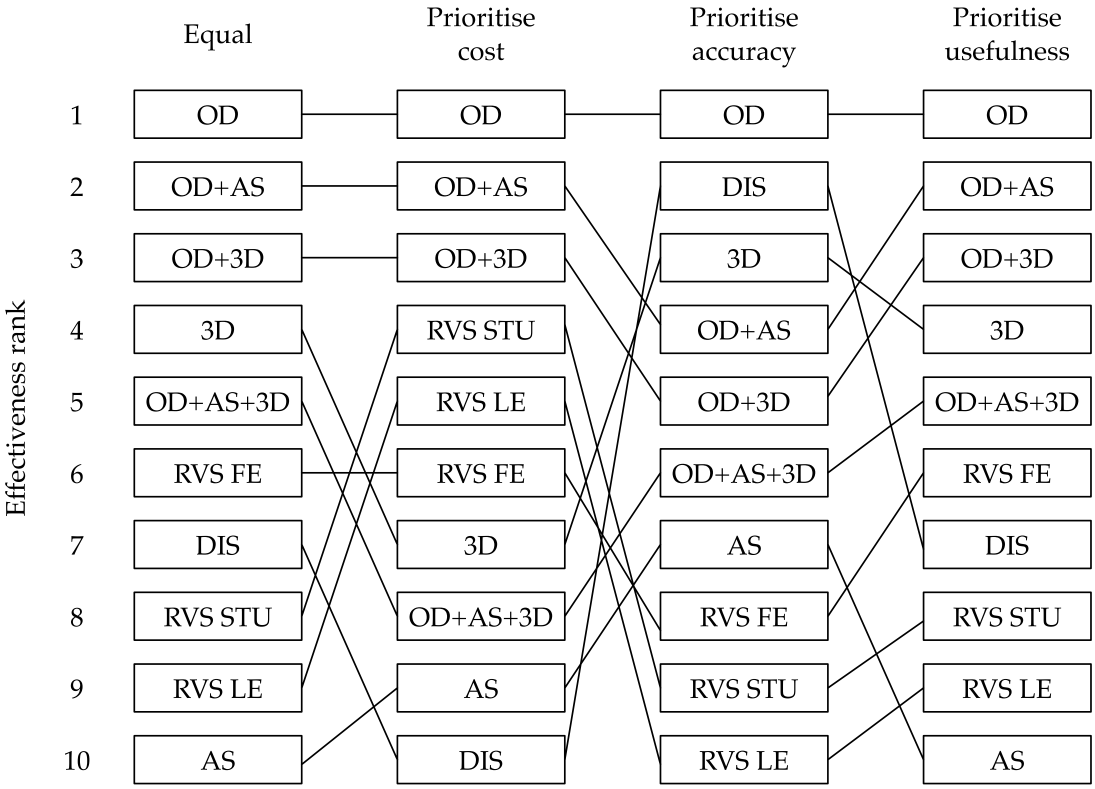


Figure 6-10 Effectiveness rank of building survey methods given different priorities. Priority is given by making the weighting 3 times more importance than the other two.

6.5. Conclusions

The objective of this chapter is to investigate the different data collection methods tested in the case study area in more depth, particularly through the lens of effectiveness.

The results from Chapter 4 were drawn on to score the usefulness of the different types of data collected by the methods of data collection tested. The completeness of datasets collected using individual methods is assessed and the UAV-derived results are deemed incapable of providing a complete enough dataset, so they are combined with the OD survey results and each other to form a more expensive, yet more complete set of data. The costs associated with each method were calculated using the rates of field surveying, post-processing, or virtual surveying and some pay-rate assumptions. Equipment, travelling, car hire, and subsistence costs are based on the prices incurred during the field season. The accuracy of the data collected is estimated using a three-tiered joint probability of agreement approach, between the result and an assumed reasonable truth.

The findings show us that the omnidirectional imagery collection and virtual surveying methodology offer the best balance of collecting more useful data whilst balancing cost and accuracy. This is followed by the combined datasets selecting the most accurate results from the OD survey results and either the AS or 3D surveys. The DIS is so costly, that the effectiveness suffers significantly, despite assumed perfect accuracy and the best possible usefulness score.

These results enhance the body of literature on seismic vulnerability and risk assessment, adding novel findings on the collection of building data for gathering accurate seismic risk assessment. These results will lead to improved design of risk assessments, including the potential increases in use of omnidirectional imagery for procuring seismic exposure data. There are issues with the UAVs and OD cameras (as discussed in Chapter 5) and even though they were rarely encountered during the field season in Guatemala City, they might impact on these results if the methodologies were applied elsewhere. Furthermore, the use of existing OD imagery (curated by Google Street View or other platforms) would lead to a much cheaper method for collecting building data, improving the effectiveness of the OD surveys significantly. This is an exciting prospect for cities at risk to earthquakes that already have recent OD imagery published on free online platforms. Further investigation is needed to test the process of virtual surveying using non-user collected OD (or UAV) imagery. Issues that are highlighted in section 2.3.2 are possible, including having to work with limited datasets that only capture parts of a city (as is the current case in Guatemala City with Google Street View, see Figure 8-1).

Cities are dynamic systems that continue to expand and evolve, therefore to ensure that risk assessment results remain relevant, updating of building data is required. Using the emerging technologies, this could take place in the most effective way. If the online platforms, such as Google Street View, or other organisations, continue to extend the coverage and work to update imagery regularly this would enable effective updating of building data using virtual surveying techniques. Nevertheless, the findings in this chapter will enable decision-makers to procure effective building data collection for seismic risk assessments, offering financial savings without a reduction in accuracy.

The accuracy of building data is assumed to be important in the overall seismic risk assessment process, however the scale of the impact is not known. It is important to understand the impact that ranging data accuracy has on the seismic risk results, as then the correct decisions can be made on spending more to improve accuracy. The next chapter investigates this further, by using the range of results collected in Guatemala City to assess seismic risk, with the scale of the range in results due to different levels of accuracy and effectiveness helping to identify the scale of the potential impacts of different quality building data on seismic risk.

Chapter 7

Assessing the impacts of building data collection method on seismic risk evaluations

7. First steps to assessing the impacts of building data collection method on uncertainty in seismic risk evaluations

As observed in Chapters 4 and 5, collecting building data for the assessment of seismic risk is a challenging task with the potential for significant ineffectiveness. The impact of this ineffectiveness on the seismic risk evaluation process is key to the design of seismic risk assessments, particularly in the proportioning of time and resources. The scale of the impact of building data with different accuracy levels is investigated in this chapter.

Inaccuracies in the data collection process lead to differences between building typology datasets. These differences will propagate uncertainty into seismic vulnerability and, ultimately, risk evaluations: the scale of the impact is important to understanding the scales and sources of uncertainty. An initial calculation of risk is completed a designated area utilising the datasets in turn, and results are compared. Recommendations and discussion points for future research are highlighted.

This chapter aims to:

- Classify buildings using data from Chapter 4 according to different classification systems, and select a system for the subsequent estimations.

- Develop and employ a novel procedure for the selection of existing seismic vulnerability functions for the building classes, using them to estimate risk using the building class proportions derived from each dataset.

- Highlight the potential implications of the range of risk estimates obtained for datasets collected using different methods, and suggest future directions of research to further this investigation.

7.1. Determining the proportions of building classes for collected data

The first step of any SVA, after the collection of building data (see Chapter 4), is the definition of building typologies. Chapter 5 presents the collection of a number of datasets comprised of building data collected using a number of desk- and field-based methods for Guatemala City. The following datasets are used here to estimate proportions of building typologies for zone 1:

- RVS LE data
- RVS FE data
- RVS STU data
- OD survey data
- OD and AS combined data
- OD and 3D survey combined data
- OD, AS, and 3D survey combined data
- Desk study data, including housing census statistics
- Data from existing studies

Instead of assessing the seismic vulnerability of every building in each dataset, buildings with similar seismic responses are grouped together into building classes. Existing classification systems found in the literature use different building characteristics to assume the seismic response of buildings. The PAGER classification system (Porter et al., 2008) is used to classify the datasets listed above, as it covers a broad range of building types, including those surveyed in Guatemala City. The process for translating the building databases into PAGER typologies is given in Appendix P.

Results for the PAGER classification of the Guatemala City datasets are given in Table 7-1. In general, the predominant building typologies are confined masonry (RM3 or CM), low-rise (1-3 storeys) non-ductile RC frames without masonry infill (C4L), and general reinforced concrete structures (C). Depending on the level of detail collected on each survey, some buildings are designated to the aggregated classes such as such as A and C: this is common for the emerging technology datasets.

PAGER Code*	**Field-based survey datasets**						
	RVS LE	**RVS FE**	**RVS STU**	**OD**	**OD+3D**	**OD+AS**	**OD+AS+3D**
W	0%	0%	1%	0%	0%	0%	0%
A	3%	14%	7%	28%	28%	28%	28%
A5	0%	0%	1%	0%	0%	0%	0%
UCB	0%	2%	0%	0%	0%	0%	0%
UFB	0%	7%	0%	6%	6%	6%	6%
UFB3	2%	5%	0%	0%	0%	0%	0%
UFB4	0%	16%	0%	0%	0%	0%	0%
RM3 or CM	81%	25%	73%	0%	0%	0%	0%
C	2%	0%	0%	25%	25%	25%	25%
C1L	7%	0%	1%	0%	0%	0%	0%
C1M	0%	0%	4%	0%	0%	0%	0%
C1H	2%	2%	1%	3%	3%	3%	3%
C2L	2%	0%	1%	0%	0%	0%	0%
C2M	2%	0%	0%	0%	0%	0%	0%
C3L	0%	5%	0%	6%	0%	0%	2%
C4L	0%	16%	6%	25%	33%	31%	30%
C4M	0%	7%	0%	6%	3%	6%	5%
C4H	0%	2%	0%	0%	0%	0%	0%
C6L	0%	0%	1%	3%	0%	3%	2%
C6M	0%	0%	0%	0%	3%	0%	1%
Total	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*

* For the building class descriptions associated with the PAGER codes, see Appendix A

Table 7-1 The proportions of PAGER building classes for the Guatemala City building datasets

Additional information on buildings was collected in the desk study, including details about the history of buildings, housing census statistics, and information about prevalent building types (see section 5.2). This information is used to estimate the proportions of building types in the study area. The 2002 housing census data gives a good base of proportions of different materials and lacks enough detail to classify buildings on its own without assumptions. The building types designated as 'other' in the census are proportionally distributed between the other building classes. As the level of reinforcement of the masonry is not captured in housing census data but is known to be a common feature (see section 5.2), the following assumptions are made (based on the desk study findings): (1) in 1994 (the year of the housing census preceding the most recent) 50% of block and brick masonry is assumed to be confined, (2) of the additional block and brick structures reported in the 2002 housing census, 90% is assumed to be confined and 10% unreinforced. These assumptions result in the building class proportions in Table 7-2.

PAGER code*	Proportion
W	9%
A	6%
UCB	13%
UFB	3%
RM3	61%
C	8%

* For the building class descriptions associated with the PAGER codes, see Appendix A

Table 7-2 Desk study building class proportion dataset

There are also building datasets collected by past studies. The results of translating these to PAGER classes are found in Table 7-3. The main difference here is the lack of any study picking up on the confined masonry class, instead grouping masonry buildings, regardless of reinforcement level. In general, low

PAGER code*	Existing study PAGER class proportions								Average
	Pita (2014)	**ERN (2010)**	**Flores (2014)**	**Farfán and Diaz (2009)**	**NORSAR (2009)**	**PAGER**	**Perez (2005)**	**Rivas and Vásquez (2008)**	
W	5.0%	6.0%	3.0%	3.7%	4.0%	13.3%	6.8%	0%	*5.2%*
A	2.3%	4.0%	1.0%	0%	4.0%	18.4%	0.1%	2.1%	*4.0%*
UCB	85.2%	40.0%	46.5%	47.5%	60.0%	66.3%	46.4%	48.5%	*55.1%*
UFB	3.7%	40.0%	46.5%	47.5%	28.0%	2.0%	46.4%	48.5%	*32.8%*
C	3.8%	10.0%	3.0%	1.2%	4.0%	0.0%	0.3%	0.9%	*2.9%*

* For the building class descriptions associated with the PAGER codes, see Appendix A

Table 7-3 Building class proportions for existing studies

These datasets are included in the following analysis which investigates the impact of using different sources of building data (collected using different methods) on seismic loss calculations.

7.1.1. Comparison of PAGER typology results

The results achieved at the end of the classification stage are presented in Figure 7-1 (specific values are presented in Table 7-1, Table 7-2 and Table 7-3). Overall, patterns of agreement exist that there are low levels of adobe and unreinforced brick masonry, and higher amounts of reinforced concrete and confined masonry buildings present.

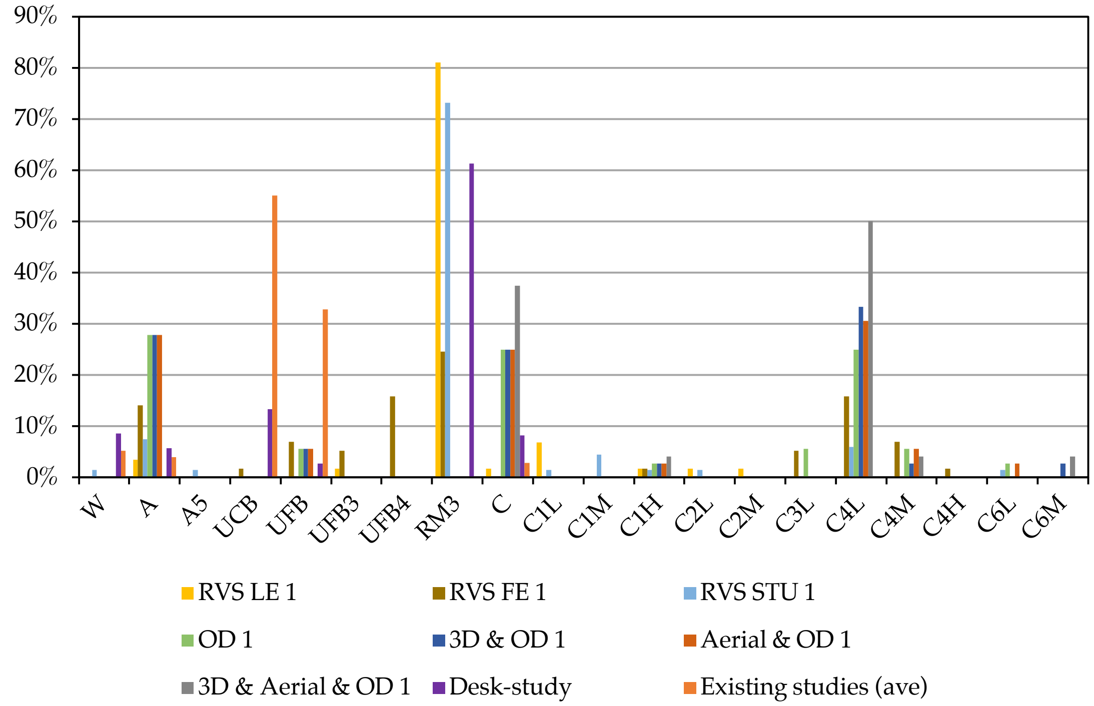


Figure 7-1 Comparison of PAGER classification proportions for different building datasets

There are, however, a wide range of proportions of building classes determined from the different building datasets. this is demonstrated for all datasets in Figure 7-2.

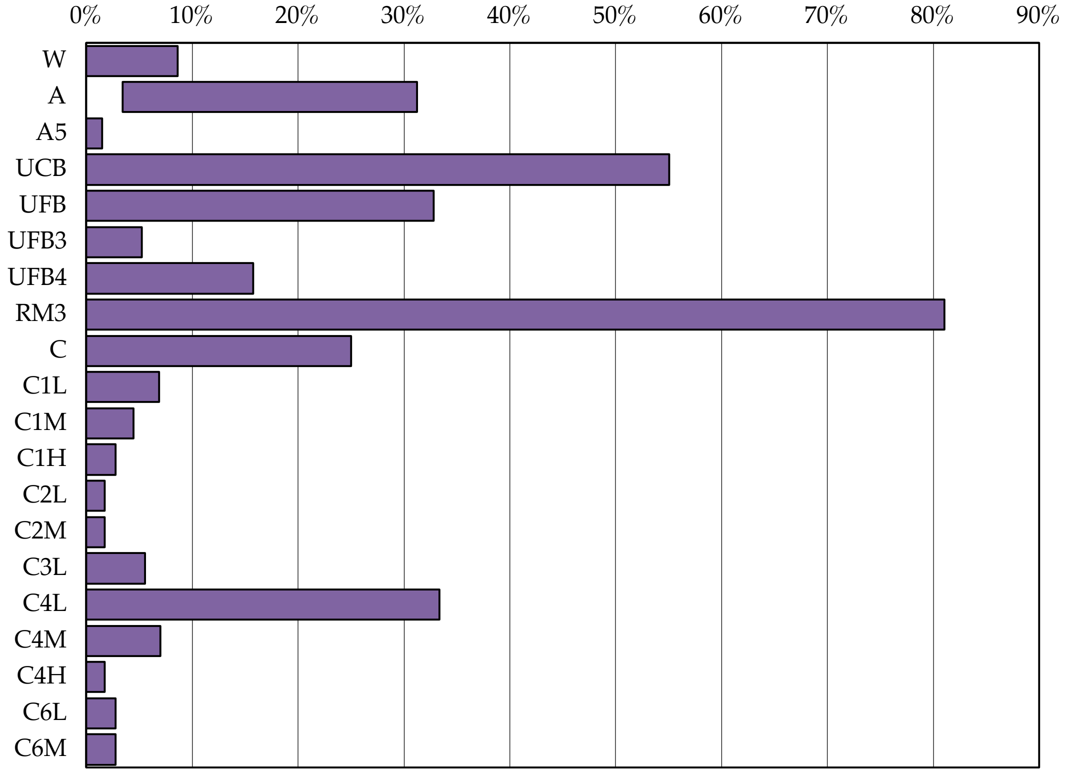


Figure 7-2 The maximum range of resulting proportions of PAGER building typologies across all datasets

The largest ranges of values are for confined masonry (RM3) and unreinforced concrete block masonry (UCB) followed by C4L (low-rise non-ductile RC frame without masonry infill walls low-rise), UFB (unreinforced fired clay brick), C (reinforced concrete) and A (adobe block walls).

RM3 is, on average, the largest building class (by proportion), followed by UFB, highlighting the dominance of masonry construction in the study area. However, different masonry behaves differently, depending on the masonry type, mortar type, amount of mortar in the joints, and how it is reinforced (D'Ayala 2013). These distinguishing characteristics are hard to collect for most buildings and remains one of the main shortcomings of rapid building survey methods.

In order to investigate the impact of the significant ranges in proportions of building classes observed in Figure 7-2, seismic vulnerability functions are derived for each building class and applied to the building class proportions derived for each dataset. The range of risk will highlight the potential scale of the impacts of the quality and completeness of building data.

7.1.2. Future options for research on building classification

There are a number of additional items of work to be completed in the field of translating building data into building typologies, including:

- Investigation around the impacts, behaviours and effectiveness of different building classification systems;
- Investigation into the relationships between data used to assign building typologies, and the building data needed to effectively assess building vulnerability (see Chapter 4);
- The most effective way to group buildings considering the cost and accuracy of building data collection and assessment of seismic vulnerability, and;
- The uncertainty introduced into the seismic risk assessment for different structures, scales, types, methods of grouping building datasets into building typologies.

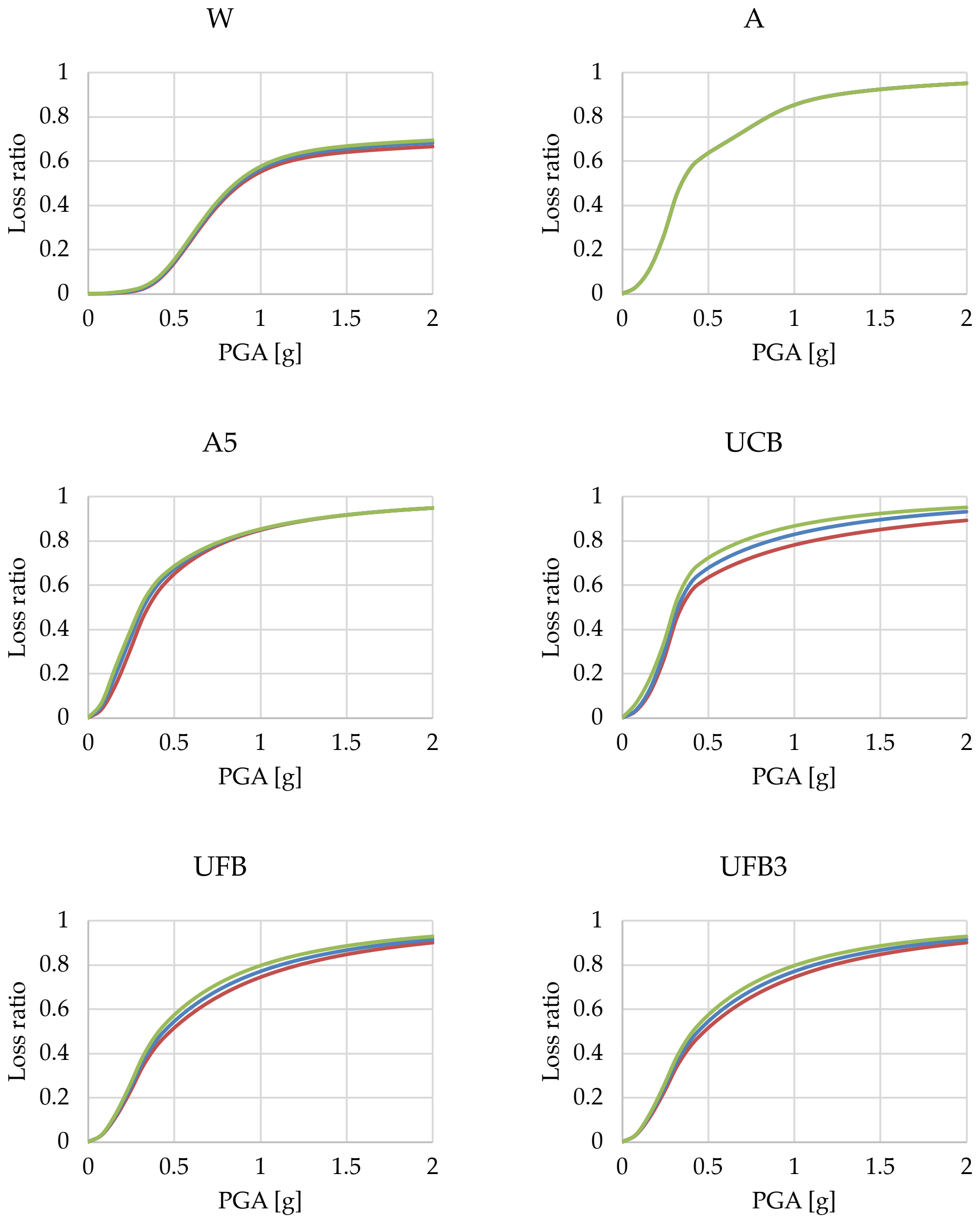
7.2. Assessment of seismic vulnerability

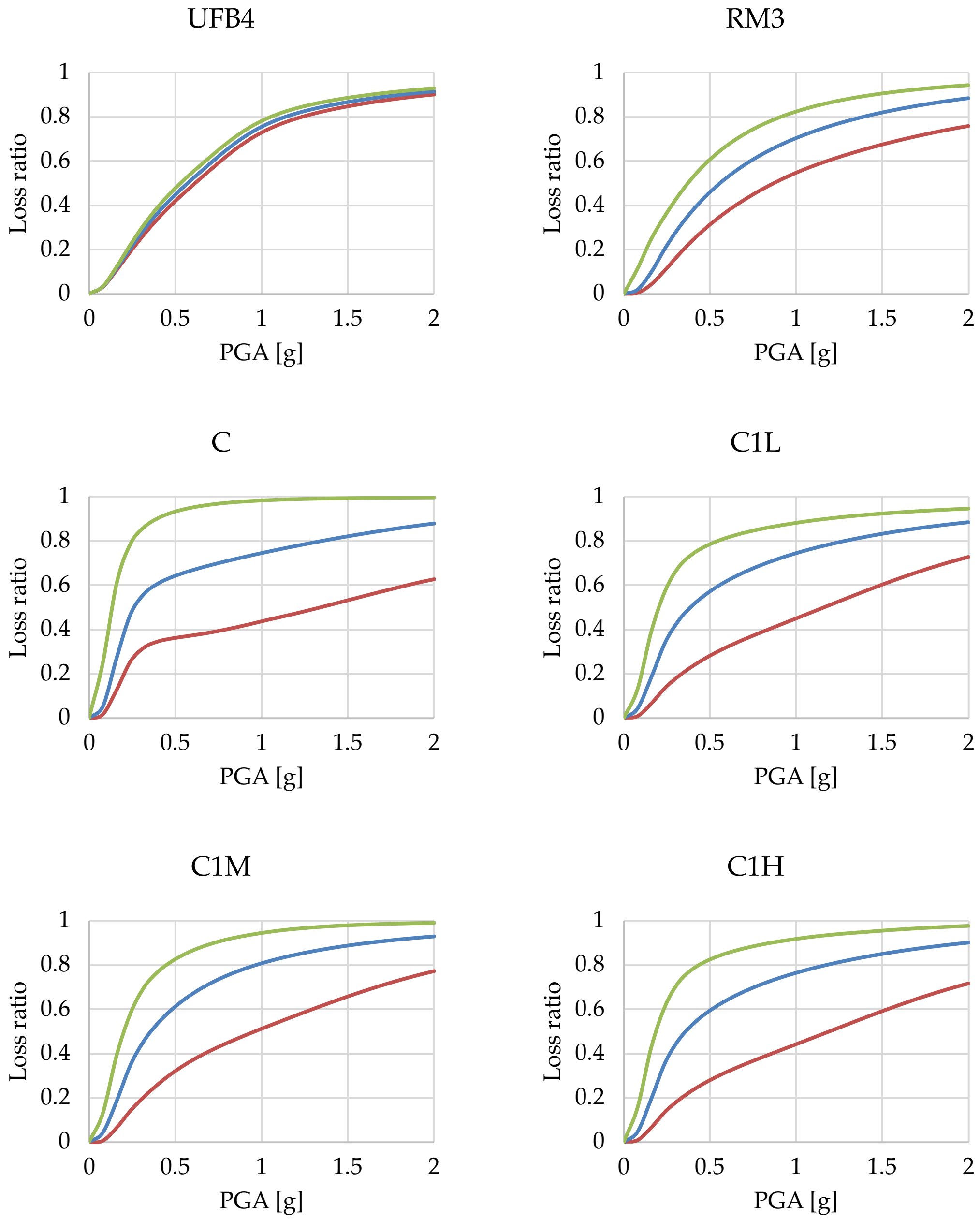
As has been extensively mentioned herein, numerous methods for the assessment of seismic vulnerability exist in the literature, covering different building types, and different geographical locations and scales (Calvi et al., 2006; Rossetto et al., 2014a, and see section 2.2). The result of a seismic vulnerability assessment is a vulnerability function, which relates a seismic intensity measure (e.g. peak ground acceleration (PGA)) with the probability of loss (in terms of replacement cost) of a certain building type.

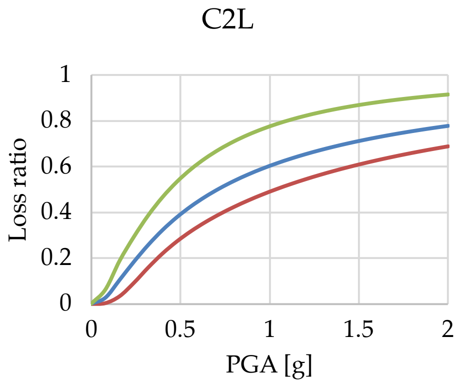
For the purposes of this chapter, existing functions will be selected from the literature to represent the vulnerability of the PAGER building classes defined above. The process of selecting existing vulnerability functions, although widely used, is challenging, subjective, and likely to lead to inaccuracies in risk assessments. The methodology used to select functions is the once presented by the author at the 16th World Conference of Earthquake Engineering (Stone et al., 2017b).

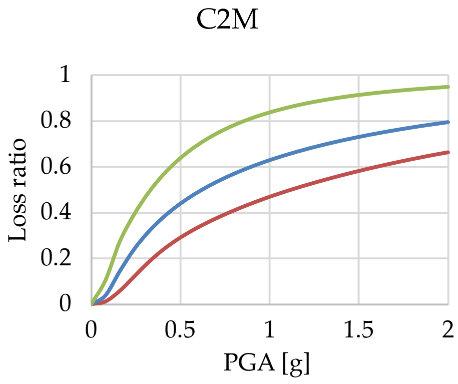
7.2.1. Applying the framework to this study

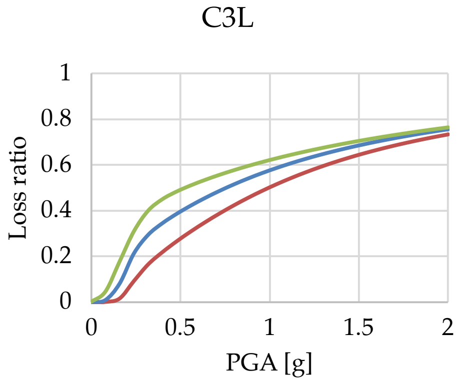
The Stone et al. (2017b) method has selected and drawn out the most highly-scored functions from the published literature; the most relevant and quality functions for the PAGER building typologies identified in Guatemala City. They are given in in Figure 7-2. The results for the minimum, average, and maximum vulnerability functions are given in Figure 7-3.

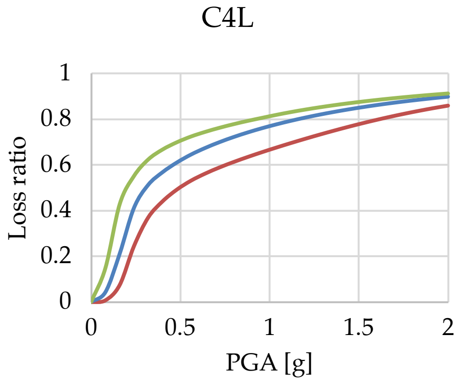

W
A
A5
UCB
UFB
UFB3
Loss ratio
PGA [g]
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2

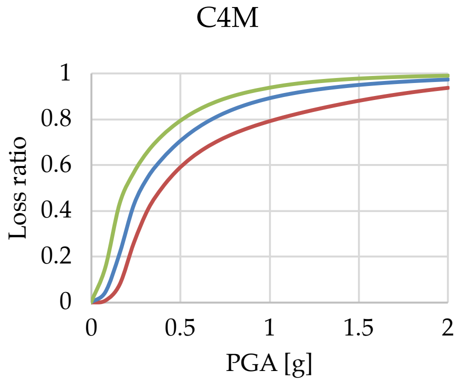

UFB4
RM3
C
C1L
C1M
C1H
Loss ratio
PGA [g]
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2

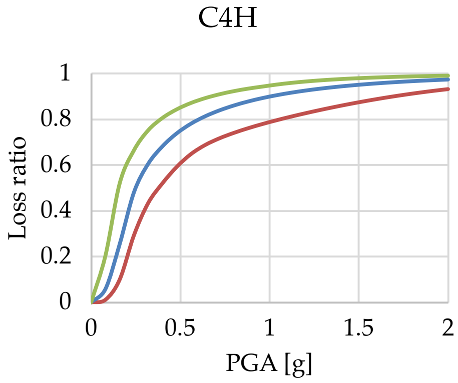

C2L
Loss ratio
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
PGA [g]


C2M
Loss ratio
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
PGA [g]


C3L
Loss ratio
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
PGA [g]


C4L
Loss ratio
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
PGA [g]


C4M
Loss ratio
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
PGA [g]


C4H
Loss ratio
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
PGA [g]

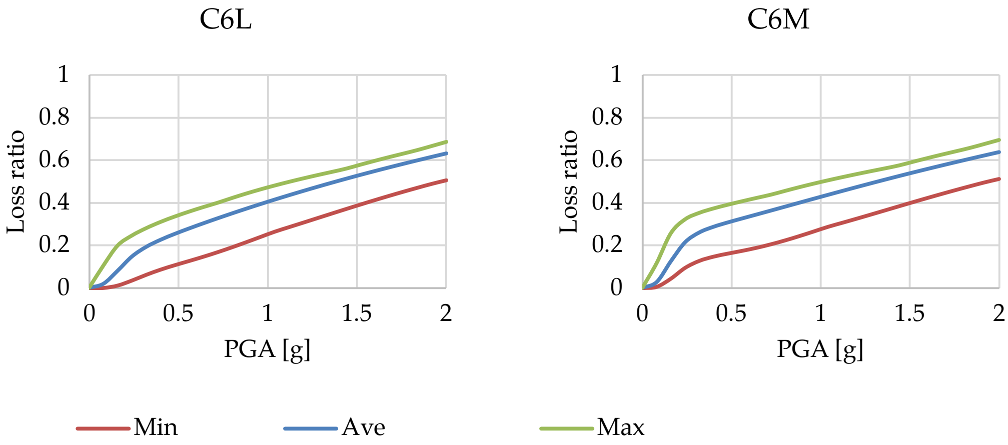


Figure 7-3 Minimum, average, and maximum vulnerability functions selected using the existing functions framework

The resulting functions for the wood and adobe building types only range slightly between the minimum and maximum. This is due to the general lack of functions in the database (and published literature) that concern these building types. The database does contain many concrete functions as these are the focus of much of the published literature, and the range of these functions is shown in the aggregated C functions which exhibit a large range between the minimum and maximum potential functions. This level of spread reduces as the building class is more defined by LLRS and height, for functions from C1L to C6M. This highlights the benefits of more detailed definitions of building classes.

The variability in vulnerability observed is also due to the uncertainty in capturing the attributes of the building most correlated with fragility and vulnerability, and also other aleatory variability representing the range of performance within a homogeneous group.

7.2.2. Future options for research on determining seismic vulnerability

There are a number of additional items of work to be completed in the field of seismic vulnerability assessment of buildings, including:

- Investigating the best ways to develop functions for use in seismic risk models;
- Investigations of the difference in results between different approaches and methodologies;
- Investigation of the balance of time and accuracy of different seismic vulnerability assessment methods, and;
- The quantification and attribution of uncertainties added to the seismic risk assessment process from the seismic vulnerability inputs.

7.3. Assessment of seismic risk assessments

Using the seismic vulnerability functions selected (see Figure 7-3) and each building dataset individually (see Table 7-1, Table 7-2, and Table 7-3) the combined loss ratios (for the whole exposure portfolio) have been calculated using an arbitrary damage-to-loss ratio (see Table 7-4). The results are given for each data collection methodology to allow comparison. The numerical results themselves are not the focus; it is the range of results that is of interest. The range in the three sets of results (using the minimum, average, and maximum vulnerability functions from Figure 7-3 for each building type) are presented in Figure 7-4, Figure 7-5, and Figure 7-6. The dotted lines are for the methodologies for which effectiveness was not investigated.

Damage state	Loss ratio
1	0.01
2	0.1
3	0.6
4	1.0

Table 7-4 Damage-to-loss ratio

The maximum range between minimum and maximum risk peaks between a PGA of 0.32g and 0.4g where the range is around 43%.

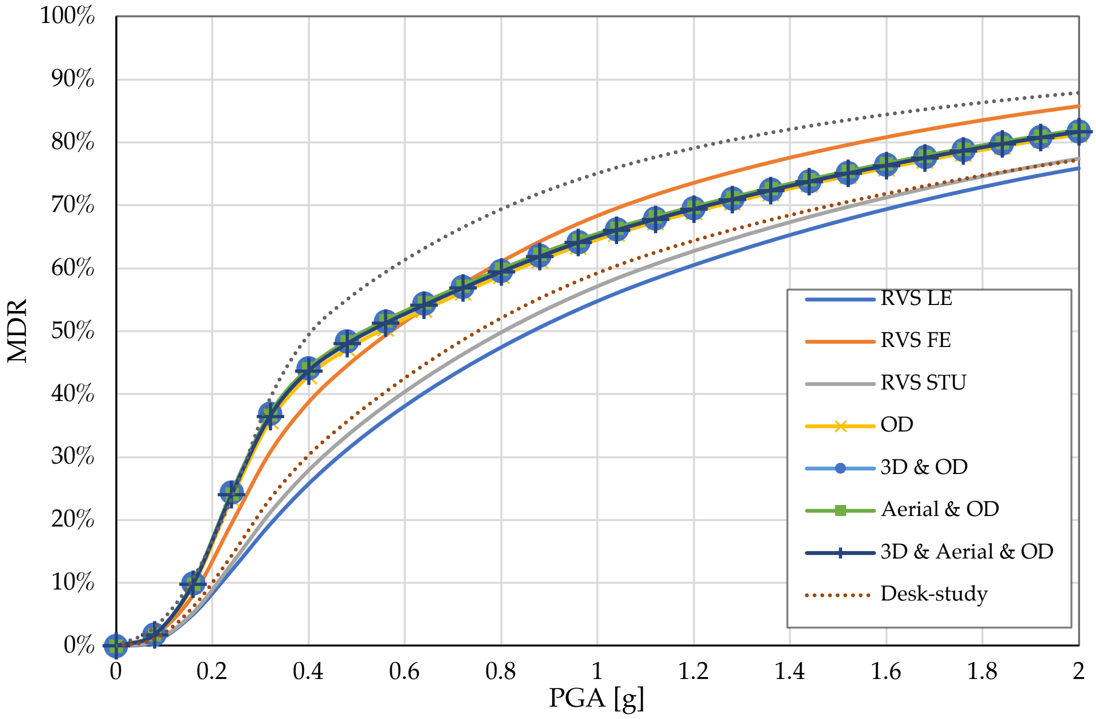


Figure 7-4 Vulnerability functions for all building data collection methods using the minimum selected fragility functions

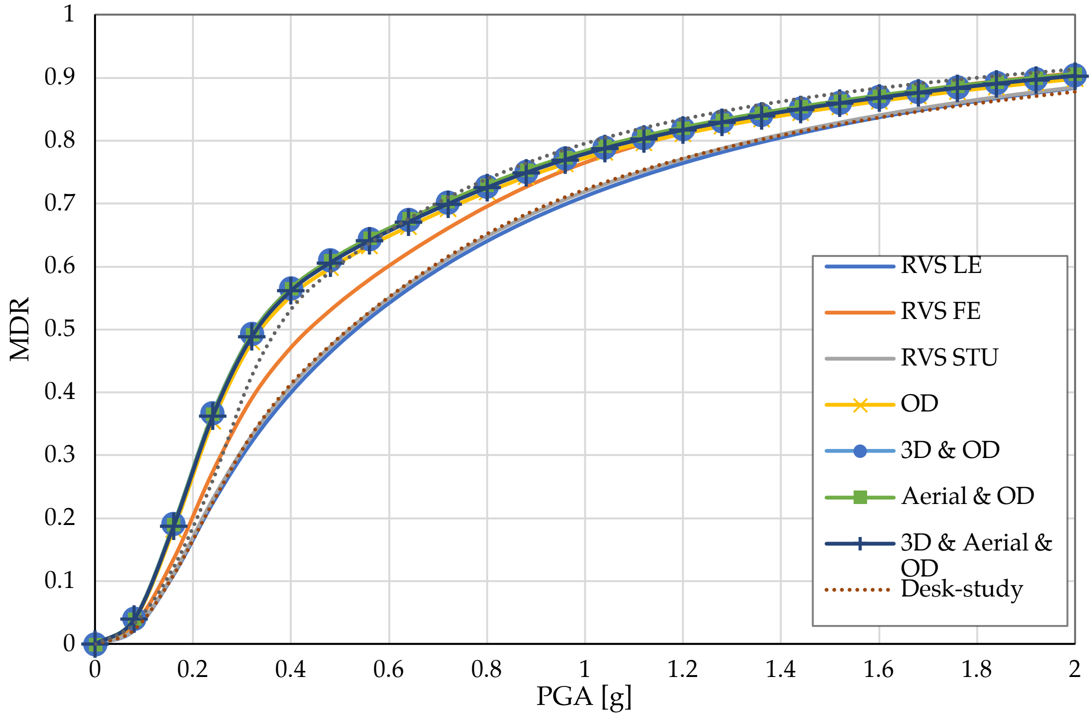


Figure 7-5 Vulnerability functions for all building data collection methods using the average selected fragility functions

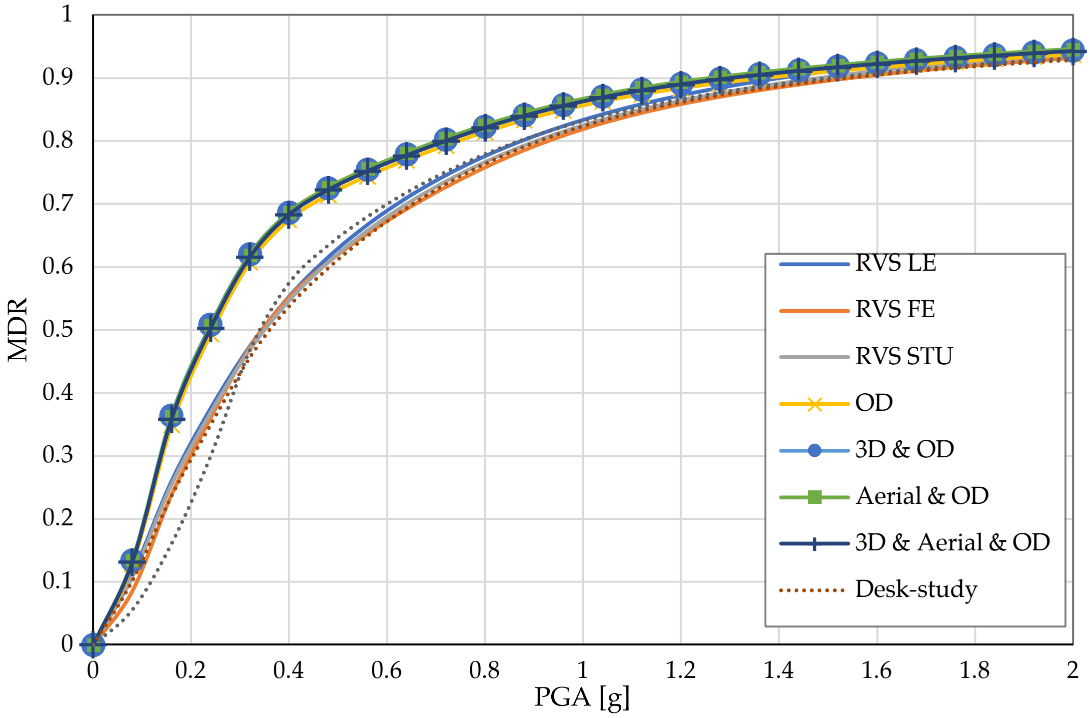


Figure 7-6 Vulnerability functions for all building data collection methods using the maximum selected fragility functions

7.3.1. Further options for research on seismic risk assessments

There are a number of additional items of work to be completed in the field of seismic vulnerability assessment of buildings, including:

- The impacts of damage-to-loss ratios or relationships on seismic risk results.

Uncertainty is accumulated from numerous sources through the steps taken in this chapter towards a seismic risk assessment. In order to make effective decisions for disaster risk reduction, management and financing, a good understanding of the uncertainty of results is vital. There is still much to be understood in the literature on this, and further research work could include:

- Deeper investigations into the sources of uncertainty added at different steps of the seismic risk assessment process, and work to attribute the scale and impact of different sources.

- Investigations on the most effective ways to reduce uncertainty through additional time or finances;

- Investigations around levels of uncertainty that decision-makers are comfortable with;

- Studies to understand the balance between levels of uncertainty and the appetite to pay more and wait longer to achieve more certainty with which to make key decisions;

7.4. Discussion and conclusions

This chapter aimed to introduce future options for testing of different sources of building data on seismic risk assessments. The datasets collected in Chapter 5 are classified using the PAGER taxonomy, and proportions of building types for each data collection method are compared, highlighting some significant differences but an overall consensus that masonry is the predominant construction material

A simplified method was employed and used to select existing fragility functions from the literature. The combined mean damage ratios across a range of earthquake intensities are calculated. As the vulnerability functions have minimum, average, and maximum values, each is used to estimate losses to ensure that the worst-case range of results is discovered.

The maximum range in loss ratios is found to be 43%. This range in losses is significant and could have huge implications on disaster risk reduction, management, or financing initiatives, depending on the context. This uncertainty in potential losses would have a significant impact on the ability of a decision maker to develop policy for reducing or managing the risk to a future earthquake.

Future directions of research investigating are highlighted at each step to guide future options for further work towards improving effective decision-making in this field.

Chapter 8

Conclusions

8. Conclusions

8.1. Research contribution:

This study defends the following thesis:

'significant ranges in seismic loss assessments arise from the use of different building data collection methods, and these can be effectively managed through the use of emerging technology or other methods depending on budget or precision requirements.'

To test this thesis, this study sought to fulfil the following five objectives:

1. To understand the current practice in seismic vulnerability assessment and explore the building characteristic inputs required.
2. To devise a method for measuring the usefulness of building characteristics for the assessment of building vulnerability, and use this to explore in detail the most important or useful inputs.
3. To understand the range of accuracy and costs associated with the collection of building data using current building data collection practices and new methods using new technologies.
4. To compare the effectiveness of new technology in the practice of building data collection with existing methods including both desk- and field-based approaches.
5. To examine the potential range in expected seismic losses given the uncertainty in building data associated with the range of exposure profiles obtained from the range of data collection methods.

The main contributions to research, achieved whilst meeting these objectives, are summarised below.

- Definition of importance levels for SVAs inputs (objectives 1 and 2)

The importance of building data inputs to SVAs is explored in detail using three separate methods. The results highlight that the building data that of high usefulness to SVAs are as follows: number of storeys; primary structural material; LLRS type; and the presence of plan or elevation irregularities, soft storeys, and short columns.

- Assessment of the effectiveness of different building data collection methods (objective 3 and 4)

The effectiveness of a range of field-based data collection methods is evaluated by combining the scores of accuracy, cost, and usefulness of the data collected. The most effective method investigated is found to be collecting omnidirectional imagery in the field and virtually surveying buildings remotely. This method combines the ability to collect a good range of useful data, with accuracy, and the cost savings associated with a shorter field trip. Furthermore, the datasets that combine both the OD survey results with the UAV derived results record good levels of effectiveness in comparison with traditional rapid visual survey techniques, which are inhibited due to costs even when less costly survey groups (e.g. students) are used. Future advances in omnidirectional imagery and UAV technology are likely to increase the effectiveness of these survey methods.

- Estimation of the range of risk results from the use of different data collection methods (objective 5)

Losses are calculated to demonstrate potential future research options. Using the exposure profiles derived from the individual method's building datasets show a fairly large range in possible results due to differences in the exposure profiles and numerous other sources of uncertainty from the seismic risk assessment process. Key future research options are highlighted to continue work towards improving the effectiveness of decisions made using seismic risk results.

8.2. Summary of findings

The study began by reviewing the process of seismic vulnerability assessments, as presented in the published literature (see Chapter 2). The lacuna in knowledge on the relationships between building characteristics and seismic vulnerability assessment was highlighted as a key area to investigate, especially as it impacts directly on the outcomes of seismic vulnerability and loss assessments, but it also forms a significant proportion of the resources spent. If these resources could be more effectively spent, there would be more resources to use for risk reduction strategies, whilst decision makers had a good level of accuracy to base decisions on. The role of existing and potential building data collection methods is also reviewed.

In order to understand the most important (referred to herein as useful) building characteristics on the assessment of seismic vulnerability, and hence the data that should be a priority during the data collection phase, a three-part systematic review of relevant groups of literature is conducted and presented in Chapter 4. The first analysis involves the collation of inputs required for simplified index-based SVA methods, which have used analytical, empirical or expert-judgement to reduce the inputs required to only those of most importance. Thus, the frequency of inputs used in these types of method is used as a proxy for data importance. Next, the literature that investigates the sensitivity of inputs to SVA methods was reviewed, and agreement between sources of the influence of different input types is collated. Finally, the building characteristics used in the level 1 GEM taxonomy (Brzev et al., 2013) are also assumed to be crucial building characteristics for SVAs.

A compilation of these three streams results in eight characteristics that are universally defined as of high usefulness. These are:

- Number of storeys
- Material type

- LLRS type
- Elevation irregularity
- Plan irregularity
- Soil type
- Changes in vertical strength and/or stiffness (e.g. soft storeys)
- Short column (applicable to RC frame structures only)

This conclusion is an important addition to the literature

These characteristics, and others, are then collected in Chapter 5 for the case study area of metropolitan Guatemala City. A wide range of desk- and field-based methods are employed, overlapping where possible to allow direct comparisons. The methodologies, both those existing and already widely used (e.g. RVS) and new techniques using new technology (e.g. UAVs and OD cameras), are introduced, followed by the basic results. A timeline of significant historical events affecting the vulnerability of buildings is collated, along with a building information repository with any specific information on buildings found during the review. Additionally, proportions of building characteristics observed by different methods are presented, with the clear findings that much of the city is built with different types of masonry construction, historically with unreinforced brick and adobe blocks, and more recently with confined concrete block masonry.

The cost of collecting the data in Chapter 5 for the methods that reported building characteristics is calculated in Chapter 6. In addition, agreement between different methods reporting a wide range of building characteristics was used as a proxy for the accuracy of the data collected. The detailed internal surveys were assumed to be the reasonable truth and all data was compared to get initial estimates of accuracy. Methods that performed well reporting the more useful data were then assumed to be the reasonable truth benchmark against which all of the other methods were compared and considered accurate if agreement was found. Further analysis consisted on assuming accuracy where a significant proportion of methods agreed on the result.

Effectiveness is assessed by scoring the accuracy, usefulness (see Chapter 4), and cost of data collected using each method. Overall, the OD survey method is deemed the most effective method, followed closely by the combination of the OD and UAV methods (the virtual 3D survey and the virtual aerial survey). The detailed internal survey is more effective when accuracy is a priority, however its cost renders it fairly ineffective overall. Relatively, RVS methods do not perform well when compared to the methods using emerging technology, due to the cost-inefficiencies of long periods spent in the field.

The datasets collected by different methods are then used to assess seismic vulnerability in Chapter 7, starting with the classification of the data using the PAGER taxonomy. The proportion of buildings associated with each PAGER typology is determined, with significant differences identified between survey datasets, highlighting the potential discrepancies of building inventory datasets depending on the data collection method used.

In order to collate seismic vulnerability functions for the PAGER typologies identified, a published methodology for selecting existing functions from the literature is used to select fragility functions. These are converted to vulnerability functions using a damage-to-loss ratio, for the identified PAGER typologies. The vulnerability functions are used with the proportions of building typologies from each method's dataset to calculate the seismic loss ratios expected over a range of seismic intensities. The range of losses estimated highlights the uncertainty in results depending on the type of data collection method used and numerous other sources of uncertainty from the seismic risk assessment process. Key future research options are highlighted to continue work towards improving the effectiveness of decisions made using seismic risk results.

8.3. Further work

Chapter 7 includes a number of future research options, specific to the work of this study. Further areas of future work that would complement the conclusions herein and those found in the wider published literature; these are suggested below.

- Test in other cities – are the findings consistent?

This study considered one case study city. Although this conurbation is typical of others in Central America, further research and testing in other regions would highlight whether the findings herein are applicable beyond the region.

- Further testing of emerging technology

The emerging technology tested in this study holds much potential in this field. Further testing of these technologies would be beneficial, including the use of more powerful cameras to take aerial images, or the use of OD cameras at height, allowing aerial viewpoints in addition to the streetscape, and the improvement of 3D model building software. Additional technology may also be of use, including the use of crowd-sourcing data, or 'citizen engineers' to gather data using a tool developed for this purpose. The use of existing OD imagery from Google or others must also be explored, especially considering the findings of this study. All of these avenues for gathering building data need to be explored as understanding the world's cities more accurately, more thoroughly, and for less resource is paramount to reducing the risk to future earthquakes.

Google have also recently mapped parts of Guatemala City with a higher quality camera and more frequent images (see Figure 8-1), which extends and enhances the data collected for this work. The official images collected by Google are linked to the omnidirectional images taken for this project so as you virtually 'walk-through' a street, the image changes between the authors and Google's.

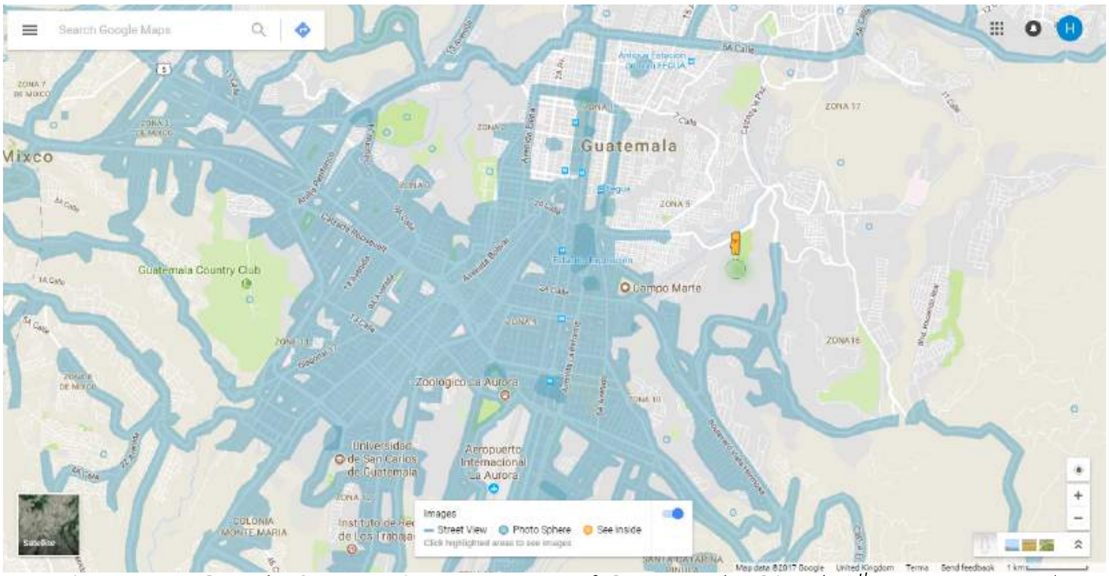


Figure 8-1 Google Street View coverage of Guatemala City (30th August 2017) (available images are denoted by the blue colour)

- Further explore the practical challenges of virtual surveying

The concept of virtual surveying is new, and does require thorough research to test the challenges faced by a virtual surveyor over a street surveyor. Exploring the various biases and heuristics in both forms of surveying is important to ensuring that virtual surveys are accurate going forward.

- Explore automation in the collection of building characteristics from OD and UAV imagery

As computing power and software's capabilities increase, the possibility of automating the collection of building data on a large scale become increasingly possible. It is envisioned that OD and UAV imagery could be reviewed by a well-developed machine learning algorithm to build an exposure dataset with good quality data for an unprecedented quantity of buildings. Despite extensive testing and training, an algorithm may only be able to accurately collect certain building characteristics, but could still add much value to future seismic risk assessments.

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Appendix A: Classification systems for buildings

A.1. EMS-98

Primary material	Material details
Masonry	Rubble stone, field stone
	Adobe (earth brick)
	Simple stone
	Massive stone
	Unreinforced masonry, with manufactured stone units
	Unreinforced, with RC floors
	Reinforced or confined masonry
Reinforced concrete	RC frame without earthquake-resistant design (ERD)
	RC frame with moderate level of ERD
	RC frame with high level of ERD
	RC walls without ERD
	RC walls with moderate level of ERD
	RC walls with high level of ERD
Steel	Steel structures
Wood	Timber structures

Table A-1 EMS-98 building classification system

A.2. HAZUS

The HAZUS typologies are given in Table .

Structure	Height *	Design level **
Wood, light frame (<5000 sq. ft)	OG	PC, LC, MC, HC
Wood, commercial and industrial (> 5000 sq. ft)	OG	PC, LC, MC, HC
Steel moment frame	LR, MR, HR	PC, LC, MC, HC
Steel braced frame	LR, MR, HR	PC, LC, MC, HC
Steel light frame	OG	PC, LC, MC, HC
Steel frame with cast-in-place concrete shear walls	LR, MR, HR	PC, LC, MC, HC
Steel frame with unreinforced masonry infill walls	LR, MR, HR	PC, LC
Concrete moment frame	LR, MR, HR	PC, LC, MC, HC
Concrete shear walls	LR, MR, HR	PC, LC, MC, HC
Concrete frame with unreinforced masonry infill walls	LR, MR, HR	PC, LC
Precast concrete tilt-up walls	OG	PC, LC, MC, HC
Precast concrete frames with concrete shear walls	LR, MR, HR	PC, LC, MC, HC
Reinforced masonry bearing walls with wood or metal deck diaphragms	LR, MR, HR	PC, LC, MC, HC
Reinforced masonry bearing walls with precast concrete diaphragms	LR, MR, HR	PC, LC, MC, HC
Unreinforced masonry bearing walls	LR, MR	PC, LC
Mobile homes	OG	PC, LC, MC, HC

* OG: one group, LR: low-rise, MR: medium-rise, HR: high-rise
**PC: pre-code, LC: low-code, MC: moderate-code, HC: high-code

Table A-2 HAZUS building classification system

A.3. GAR 2013

Description	Height*	Design level**
Wood, light frame (<450m2)	OG	P, L, M, H
Wood, commercial and industrial (>450m2)	OG	P, L, M, H
Steel moment frame	LR, MR, HR	P, L, M, H
Steel braced frame	LR, MR, HR	P, L, M, H
Steel light frame	On group	P, L, M, H
Steel frame with cast-in place concrete shear walls	LR, MR, HR	P, L, M, H
Steel frame with unreinforced masonry walls	LR, MR, HR	P, L, M, H
Concrete moment frames	LR, MR, HR	P, L, M, H
Concrete shear walls	LR, MR, HR	P, L, M, H
Concrete frame with unreinforced masonry infill walls	LR, MR, HR	P, L, M, H
Reinforce concrete frames and concrete shear walls	LR, MR, HR	P, L, M, H
Flat slab structure	LR, MR, HR	P, L, M, H
Precast concrete tilt-up walls	LR, MR, HR	P, L, M, H
Precast concrete frames with concrete shear walls	LR, MR, HR	P, L, M, H
Reinforced concrete frames and steel truss girder (warehouse)	OG	P, L, M, H
Reinforce masonry bearing walls with wood or metal deck diaphragms	LR, MR	P, L, M, H
Reinforced masonry bearing walls with precast concrete diaphragms	LR, MR, HR	P, L, M, H
Unreinforced masonry bearing walls	LR, MR	P, L, M
Confined masonry walls	OG	P, L, M
Adobe	OG	P, L, M
Tapia	OG	P, L, M

* OG: one group, LR: low-rise, MR: medium-rise, HR: high-rise
**P: poor, L: low, M: medium, H: high

Table A-3 GAR 2013 building classification system.

A.4. PAGER

Description	Height*
Wood	OG
Wood stud-wall frame with plywood/gypsum board sheathing.	OG
Wood frame, heavy members (with area > 5000 sq. ft.)	OG
Light post and beam wood frame.	OG
Wooden panel or log construction.	OG
Walls with bamboo/light timber log/reed mesh and post (Wattle and Daub).	OG
Unbraced heavy post and beam wood frame with mud or other infill material.	OG
Braced wood frame with load-bearing infill wall system.	OG
Mud walls	OG
Mud walls without horizontal wood elements	OG
Mud walls with horizontal wood elements	OG
Adobe blocks (unbaked sundried mud block) walls	OG
Adobe block, mud mortar, wood roof and floors	OG
Adobe block, mud mortar, bamboo, straw, and thatch roof	OG
Adobe block, straw, and thatch roof cement- sand mortar	OG
Adobe block, mud mortar, reinforced concrete bond beam, cane and mud roof	OG
Adobe block, mud mortar, with bamboo or rope reinforcement	OG
Rammed Earth/Pneumatically impacted stabilized earth	OG
Rubble stone (field stone) masonry	OG
Local field stones dry stacked (no mortar) with timber floors, earth, or metal roof.	OG
Local field stones with mud mortar.	OG
Local field stones with lime mortar.	OG
Local field stones with cement mortar, vaulted brick roof and floors	OG
Local field stones with cement mortar and reinforced concrete bond beam.	OG
Rectangular cut-stone masonry block	OG
Rectangular cut stone masonry block with mud mortar, timber roof and floors	OG
Rectangular cut stone masonry block with lime mortar	OG
Rectangular cut stone masonry block with cement mortar	OG
Rectangular cut stone masonry block with reinforced concrete floors and roof	OG
Massive stone masonry in lime or cement mortar	OG

Unreinforced concrete block masonry with lime or cement mortar	OG
Unreinforced fired brick masonry	OG
Unreinforced brick masonry in mud mortar without timber posts	OG
Unreinforced brick masonry in mud mortar with timber posts	OG
Unreinforced brick masonry in lime mortar	OG
Unreinforced fired brick masonry, cement mortar.	OG
Unreinforced fired brick masonry, cement mortar, with RC floor and roof slabs	OG
Reinforced masonry	OG
Reinforced masonry bearing walls with wood or metal deck diaphragms	OG, LR, MR
Reinforced masonry bearing walls with concrete diaphragms	OG, LR, MR, HR
Confined masonry	OG
Reinforced concrete	OG
Ductile reinforced concrete moment frame with or without infill	OG, LR, MR, HR
Reinforced concrete shear walls	OG, LR, MR, HR
Nonductile reinforced concrete frame with masonry infill walls	OG, LR, MR, HR
Nonductile reinforced concrete frame without masonry infill walls	OG, LR, MR, HR
Steel reinforced concrete (Steel members encased in reinforced concrete)	OG, LR, MR, HR
Concrete moment resisting frame with shear wall - dual system	OG, LR, MR, HR
Flat slab structure	OG
Precast concrete tilt-up walls	OG
Precast concrete frames with concrete shear walls	OG, LR, MR, HR
Precast reinforced concrete moment resisting frame with masonry infill walls	OG, LR, MR, HR
Precast panels (wall panel structure)	OG
Steel	OG
Steel moment frame	OG, LR, MR, HR
Steel braced frame	OG, LR, MR, HR
Steel light frame	OG, LR, MR, HR
Steel frame with cast-in-place concrete shear walls	OG, LR, MR, HR
Steel frame with unreinforced masonry infill walls	OG, LR, MR, HR
Mobile homes	OG
Informal constructions	OG
No specified (unknown/default)	OG

* OG: one group, LR: low-rise, MR: medium-rise, HR: high-rise

Table A-4 PAGER building classification system

A.5. GEM

Attribute	**Attribute sub-levels**
Direction	None
Material of the lateral load-resisting system	1: Material type 2: Material technology 3: Material properties
Lateral load-resisting system	1: Type of lateral load-resisting system 2: Ductility
Height	1: Number of storeys
Date of construction	1: Construction or retrofit year
Occupancy	1: Building occupancy class – top level 2: building occupancy class – detail
Building position	None
Plan shape	None
Structural irregularity	1: Plan and vertical irregularity 2: Primary and secondary
Exterior walls	None
Floor	1: Floor system material 2: Floor system type 3: Floor connections
Roof	1: Roof shape 2: Roof covering material 3: Roof system material 4: Roof system type 5: Roof connections
Foundation	None

Table A-5 - GEM Building Taxonomy attributes and levels of detail

A.6. RESIS II

Description	**Height***
Minifalda, light timber frames	OG
Adobe and Tapial	OG
Bahareque and Taquezal	OG
Calycanto (quarry stone masonry)	OG
Unreinforced baked brick masonry	OG
Steel bar reinforced baked brick masonry	OG
Confined baked brick masonry with reinforced concrete frames	OG
Unreinforced concrete block masonry including quarry stone masonry	OG
Reinforced concrete block masonry	OG
Confined concrete block masonry with reinforced concrete frames	OG
Block panel system (guides available)	OG
Light steel frames, including Laminada and Troquelada	OG
Steel frames with unreinforced masonry walls	LR, MR, HR
Reinforced concrete portal frames	LR, MR, HR
RC shear walls	LR, MR, HR
Concrete frames with unreinforced masonry infill walls	LR, MR, HR

* OG: one group, LR: low-rise, MR: medium-rise, HR: high-rise

Table A-6 - RESIS II building classes for Central America

Appendix B: Extended tables from index method frequency analysis

Reference	Index-based SVA method meta-data								
	Structural type	Location developed for	Approach used	Validation data used	Validation location	Validation year	Updated from:	Publication year	Examples of application
Shiga et al. 1968	RC	Japan	Empirical	1968 Tokachioki	Japan	1968		1968	
Aoyama et al. 1981	RC	Japan	Analytical	1968 Tokachioki, 1978 Izu Oshima Kinkai, 1978 Miyagiken-oki	Japan			1981	
Benedetti et al. 1984	Masonry	Italy	Empirical		Italy			1984	
Gavarini et al. 1984	RC	Italy	Empirical	Friuli 1976, Irpinia 1980	Italy	1976, 1980		1984	
Bennedetti et al. 1988	Masonry	Italy	Empirical	1983 Parma, 1984 Abruzzo	Italy	1983, 1984		1988	
ATC 1988	RC	USA			N/A	N/A		1988	
Angeletti 1988	Masonry	Italy	Updating				Benedetti 1984, Gavarini 1984	1988	
GNDT 1993	RC	Italy						1993	
Rainer et al. 1993	All	Canada					ATC-21	1993	
Hassan and Sozen 1997	RC, masonry	Turkey	Empirical	Erzincan 1992	Turkey			1997	
ATC 1998	All	USA	Unknown					1998	
ATC 2002	All	USA	Unknown					2002	
Ozcebe 2003	RC	Turkey	Empirical	Dücze 1999, Afyon 2002	Turkey	1999, 2002		2003	
Giovinazzi and Lagomarsino 2004	RC, masonry	Europe	EMS-98					2004	
Yakut et al. 2004	RC	Turkey	Analytical	Erzincan 1992, Afyon 2002, Bingöl 2003				2004	
Lourenço et al. 2006	Masonry	Portugal churches	Analytical	None	None	None		2006	58 Portuguese churches
Sucuolglu et al. 2007	RC	Turkey	Empirical	Düzce 1999	Turkey	1999		2007	
Gueguen et al. 2007	All	Europe	Updating	Analytically against GNDT 1993 (Risk-EU) results			GNDT 1993	2007	Grenoble, France
Lantada et al. 2008	All	Spain	Updating	Analytically against CSM			Govinazzi 2004	2008	
Gent French et al. 2008	Confined masonry	Chile	Updating for confined masonry	1985 Central Chile			GNDT 1993	2008	
Tesfamariam et al. 2008	RC	USA	Analytical	Northridge 1994	California	1994		2008	
Lang et al. 2009	Masonry and RC	CA and India	Expert judgement					2009	Central America and

Reference	Index-based SVA method meta-data								
	Structural type	**Location developed for**	**Approach used**	**Validation data used**	**Validation location**	**Validation year**	**Updated from:**	**Publication year**	**Examples of application**
									Northern India
Jain et al. 2010	RC	India	Empirical	2001 Bhuj	India	2001		2010	
Vincente et al. 2011	Masonry	Portugal	Updating	Analytical			GNDT II 1994	2011	Portugal
Tezcan et al. 2011	RC	Turkey	Analytical	Bingöl 2003, Kocaeli 1999	Turkey	1999, 2003		2011	
Ozhendekci et al. 2012	RC	Turkey	Empirical	Bingöl 2003, Düzce 1999	Turkey	1999, 2003		2012	
Belheouane et al. 2013	RC	Algeria	Empirical	Ain Temouchent 1999, Boumerdes 2003		1999, 2003		2013	
Lourenço et al. 2013	Masonry	Italy, Portugal, Spain	Analytical	Cantebury, NZ 2010-11	New Zealand	2011		2013	
Shakya et al. 2014	Masonry	Italy	Updating	Analytical FE modelling			GNDT II 1994	2014	
Sucuolglu et al. 2015	RC	Turkey	Analytical	None				2015	
Zuccaro et al. 2015	RC, masonry	Italy	Empirical	Irpinia 1980, Abruzzo 1984, Sicilia 1990, Parma 1983, Umbria-Marche 1997, Etna 2002, S Guiliano di Puglia 2002, Pollino 1998				2015	
Perrone et al. 2015	RC	Italy	Expert judgement	Analytical, 2009 L'Aquila, 2012 Emilia	Italy			2015	

Table B-1 Extended tables from index method frequency analysis (table 1 of 7)

Reference	Index-based SVA method meta-data	Index-based SVA method inputs required							
	Other important conclusions	**Elevation regularity**	**State of preservation**	**Plan regularity**	**No. storeys**	**Element dimensions**	**Soft storey**	**Soil type**	**Horizontal diaphragms**
Shiga et al. 1968						Wall and column area			
Aoyama et al. 1981	Method may not be applicable to other places		Time index		No storeys	Wall and column area		Geological index	
Benedetti et al. 1984		Elevation regularity	General maintenance conditions	Plan regularity				Soil condition	Horizontal diaphragms
Gavarini et al. 1984			Construction quality			Type of connections and critical elements/connection and critical elements strength and ductility			
Bennedetti et al. 1988	Various in Italy	Elevation regularity	General maintenance conditions	Plan regularity				Soil condition	Horizontal diaphragms
ATC 1988		Discontinued wall/column			No storeys		Soft storeys	Soil type	Floor openings
Angeletti 1988		Elevation	Damages and decay	Plan					Diaphragms
GNDT 1993	Portugal Vincente 2014	Elevation configuration	State of preservation	Plan configuration					Horizontal floor diaphragms
Rainer et al. 1993		Discontinued wall/column			No storeys	Area of wall or columns	Soft storeys	Soil type	
Hassan and Sozen 1997					No storeys	Vertical structure geometry	Soft storey		Floor openings
ATC 1998			Maintenances		No storeys	Beam, column, wall dimensions	Soft storey	Soil class	
ATC 2002	Sinha 2004 - India, Nanda 2014								
Ozcebe 2003		Overhang			No storeys	Wall and column areas	Soft story		
Giovinazzi and Lagomarsina 2004		Vertical irregularity	State of preservation	Plan irregularity	No storeys	Wall area			
Yakut et al. 2004					No storeys	Column or wall areas	Soft storeys		

Reference	Index-based SVA method meta-data	Index-based SVA method inputs required							
	Other important conclusions	Elevation regularity	State of preservation	Plan regularity	No. storeys	Element dimensions	Soft storey	Soil type	Horizontal diaphragms
Lourenço et al. 2006						Wall area			
Sucuolglu et al. 2007		Heavy overhangs	Apparent building quality		No storeys		Soft storey		
Gueguen et al. 2007		Elevation regularity		Plan regularity				Soil type	
Lantada et al. 2008		Vertical irregularity	Preservation state	Horizontal irregularity (compactness ratio)	No storeys	Length of façade			
Gent French et al. 2008		Elevation configuration	State of preservation	Plan configuration					Horizontal floor diaphragms
Tesfamariam et al. 2008		Vertical irregularity	Construction quality	Plan irregularity				Side condition	
Lang et al. 2009		Elevation irregularities, overhangs	Existing damage	Plan irregularities			Soft storey		
Jain et al. 2010			Maintenance	Re entrant corners	No storeys		Soft storey		Staircase asymmetry wrt plan
Vincente et al. 2011		Regularity in height	Fragilities and conservation state	Plan configuration	No storeys			Soil condition	Horizontal diaphragms
Tezcan et al. 2011		Overhangs	Corrosion		Storey heights and total height	Column, shear wall, infill walls dimensions	Soft storey	Soil type, liquefaction	Floor openings
Ozhendekci et al. 2012		Overhangs					Soft storey		
Belheouane et al. 2013		Elevation irregularity	Maintenance conditions	Plan irregularity				Type of soil, ground conditions	Horizontal diaphragms
Lourenço et al. 2013						Area of the earthquake resistant walls			
Shakya et al. 2014		Irregularity in elevation	Fragilities and conservation state	Irregularity in plan		Slenderness ratio		Soil conditions	
Sucuolglu et al. 2015		Vertical irregularities		Plan irregularities	No storeys	Column structural capacities	Soft storey	Soil conditions	
Zuccaro et al. 2015		Elevation irregularities	Pre-existing damage	Plan irregularities	No storeys/Height				
Perrone et al. 2015		Elevation regularity	Existing damage, State of preservation	Plan irregularity			Soft storeys		

Table B-2 Extended tables from index method frequency analysis (table 2 of 7)

	Index-based SVA method inputs required								
Reference	**Short column**	**Torsion irregularity**	**Pounding**	**Topographical location**	**Roof type**	**LLRS type**	**Structural capacity**	**Structural connections**	**Nonstructural elements**
Shiga et al. 1968									
Aoyama et al. 1981	Structural design index								
Benedetti et al. 1984					Roof		Total shear resistance of walls	Connection of wall	
Gavarini et al. 1984	Low ductility elements					Main seismic resisting system	Type of connections and critical elements/connection and critical elements strength and ductility	Type of connections and critical elements/connection and critical elements strength and ductility	
Bennedetti et al. 1988					Roof		Total shear resistance of walls	Connection of wall	
ATC 1988	Short column	Torsional rigidity	Pounding						
Angeletti 1988					Roof	Type of resisting system	Conventional safety factor		Non-structural elements
GNDT 1993		Torsional Stiffness and torsional eccentricity	Distance between buildings	Building location	Type of roof			Critical elements connection	Non-structural elements
Rainer et al. 1993	Short column	Torsional irregularity	Pounding	Topographic location					Non-structural hazards
Hassan and Sozen 1997	Short column	Torsional irregularity	Pounding	Topographic location					
ATC 1998	Short columns	Torsion	Pounding				Horizontal load	Connection quality	
ATC 2002									
Ozcebe 2003									
Giovinazzi and Lagomarsina 2004	Short columns				Roof type			Wall connections, connection quality	
Yakut et al. 2004									
Lourenço et al. 2006									
Sucuolglu et al. 2007									
Gueguen et al. 2007				Building location					
Lantada et al. 2008									
Gent French et al. 2008		Torsional Stiffness and torsional eccentricity	Distance between buildings	Building location	Type of roof		Conventional strength capacity		Non-structural elements

Tesfamariam et al. 2008						LLRS			
Lang et al. 2009	Short columns	Regular column distribution, eccentric cores	Pounding			Shear walls present			
Jain et al. 2010	Short columns								
Vincente et al. 2011				Location	Roofing system	Type of ER system	Conventional strength		Non-structural elements
Tezcan et al. 2011	Short column	Torsional irregularity	Pounding	Topographic location				Strong tie criterion	
Ozhendekci et al. 2012	Short columns		Pounding			LLRS			
Belheouane et al. 2013	Short column		Pounding			Frame system	Seismic capacity	Quality of the nodes	
Lourenço et al. 2013									
Shakya et al. 2014				Location	Flooring and roofing system	LLRS	Conventional strength		Non structural elements
Sucuolglu et al. 2015									
Zuccaro et al. 2015				Site topography	Roof type				Isolated columns in masonry
Perrone et al. 2015	Short columns	Regularly distributed columns, Rigid eccentric cores				Shear walls		Connection quality	Non-structural impacts on structural elements

Table B-3 Extended tables from index method frequency analysis (table 3 of 7)

Reference	Index-based SVA method inputs required								
	Building weight	LLRS quality	Foundations	Engineering detailing	Building importance	Material type	Building footprint aspect ratio	LLRS quantity	Maximum horizontal span
Shiga et al. 1968	Building weight								
Aoyama et al. 1981	Building weight, axial load								
Benedetti et al. 1984				Details		Type of walls			
Gavarini et al. 1984									
Bennedetti et al. 1988				Details		Type of walls			
ATC 1988									
Angeletti 1988		Quality of resisting system	Foundations						Max walls centre line distance
GNDT 1993		Earthquake resisting system quality	Foundations				Building aspect ratio	Number of earthquake resisting lines	
Rainer et al. 1993	Live load factor				Importance factor				
Hassan and Sozen 1997					Importance factor				
ATC 1998			Foundation	RC detailing	Importance			Redundancy in LLRS, no. of lines	Length of frame
ATC 2002									
Ozcebe 2003								No frame lines	
Giovinazzi and Lagomarsina 2004			Foundation						
Yakut et al. 2004									
Lourenço et al. 2006	Weight of building					Friction angle of masonry			
Sucuolglu et al. 2007									
Gueguen et al. 2007						Material type			
Lantada et al. 2008									
Gent French et al. 2008		ERS quality					Building aspect ratio	Number of ER lines	
Tesfamariam et al. 2008					Occupancy				
Lang et al. 2009							Plan shape not elongated		
Jain et al. 2010									
Vincente et al. 2011		Quality of ERS							Maximum disatance between walls

Reference	Index-based SVA method inputs required								
	Building weight	**LLRS quality**	**Foundations**	**Engineering detailing**	**Building importance**	**Material type**	**Building footprint aspect ratio**	**LLRS quantity**	**Maximum horizontal span**
Tezcan et al. 2011	Live load factor		Foundation type and depth	Lateral tie spacing	Importance factor		Outer plan dimensions of ground floor		
Ozhendekci et al. 2012					Priority				Maximum span
Belheouane et al. 2013		Quality of the frame		Details					
Lourenço et al. 2013	Total weight of construction					Masonry properties	Total plan area		
Shakya et al. 2014		Quality of LLRS							
Sucuolglu et al. 2015	Building weight			Detailing	Importance factor	Material properties			
Zuccaro et al. 2015									
Perrone et al. 2015			Foundation stiffness	Detailing					

Table B-4 Extended tables from index method frequency analysis (table 4 of 7)

Reference	Index-based SVA method inputs required								
	Mass irregularity	Material quality	Height	Building class	Position in block	Lateral load path	Retrofitting	Age	Fundamental period
Shiga et al. 1968									
Aoyama et al. 1981								Time index	
Benedetti et al. 1984									
Gavarini et al. 1984		Construction quality							
Bennedetti et al. 1988									
ATC 1988									
Angeletti 1988									
GNDT 1993									Building period
Rainer et al. 1993									
Hassan and Sozen 1997		Concrete quality							
ATC 1998	Mass irregularities		Height	Building class		Load path			
ATC 2002				Building class					
Ozcebe 2003									
Giovinazzi and Lagomarsina 2004	Mass irregularity			Building class	Position		Retrofitting		
Yakut et al. 2004									
Lourenço et al. 2006			Height						
Sucuolglu et al. 2007									
Gueguen et al. 2007								Age	
Lantada et al. 2008									
Gent French et al. 2008									Building period
Tesfamariam et al. 2008								Year of construction	
Lang et al. 2009						Adequate lateral load paths	Retrofitting		
Jain et al. 2010									
Vincente et al. 2011					Aggregate position and interaction				
Tezcan et al. 2011	Mass irregularity	Concrete quality	Storey heights and total height			Unequal floor levels			

Reference	Index-based SVA method inputs required								
	Mass irregularity	Material quality	Height	Building class	Position in block	Lateral load path	Retrofitting	Age	Fundamental period
Ozhendekci et al. 2012									
Belheouane et al. 2013									
Lourenço et al. 2013			Building height						
Shakya et al. 2014					Position and interaction				
Sucuolglu et al. 2015									
Zuccaro et al. 2015			No storeys/Height	EMS-98 class	Building location in block		Tie rods	Age	
Perrone et al. 2015	Mass irregularities					LLRS is both directions	Retrofitted		

Table B-5 Extended tables from index method frequency analysis (table 5 of 7)

Reference	Index-based SVA method inputs required								
	Heavy façade	**Vertical load path**	**Strong column weak beam**	**Infill wall characteristics**	**Building footprint area**	**Openings regularity**	**Floor material**	**Mezzanines**	**Roof shape**
Shiga et al. 1968									
Aoyama et al. 1981									
Benedetti et al. 1984									
Gavarini et al. 1984									
Bennedetti et al. 1988									
ATC 1988	Heavy facade panel								
Angeletti 1988									
GNDT 1993									
Rainer et al. 1993	Heavy façade panel			Infill wall areas					
Hassan and Sozen 1997			Strong column criterion						
ATC 1998		Vertical discontinuities						Mezzanines	
ATC 2002									
Ozcebe 2003					Plan area				
Giovinazzi and Lagomarsina 2004				Infill wall areas					
Yakut et al. 2004									
Lourenço et al. 2006					Plan area				
Sucuolglu et al. 2007									
Gueguen et al. 2007									Roof shape
Lantada et al. 2008									
Gent French et al. 2008									
Tesfamariam et al. 2008									
Lang et al. 2009			Strong column weak beam						Age
Jain et al. 2010									
Vincente et al. 2011						Wall façade openings and alignments			

Reference	Index-based SVA method inputs required								
	Heavy façade	**Vertical load path**	**Strong column weak beam**	**Infill wall characteristics**	**Building footprint area**	**Openings regularity**	**Floor material**	**Mezzanines**	**Roof shape**
Tezcan et al. 2011	Heavy façade panels	Discontinued wall/column	Strong column criterion	Infill wall rigidity				Mezzanine floor	
Ozhendekci et al. 2012									
Belheouane et al. 2013									
Lourenço et al. 2013									
Shakya et al. 2014						Number, size, and location of wall openings	Flooring and roofing system		
Sucuolglu et al. 2015									
Zuccaro et al. 2015							Horizontal typology, Floor structure		
Perrone et al. 2015									

Table B-6 Extended tables from index method frequency analysis (table 6 of 7)

Reference	Index-based SVA method inputs required						
	Balconies	Aseismic devices	Bow windows	Infill panel irregularities	Past earthquake	Safe elevators and stairs	Modifications
Shiga et al. 1968							
Aoyama et al. 1981							
Benedetti et al. 1984							
Gavarini et al. 1984							
Bennedetti et al. 1988							
ATC 1988							
Angeletti 1988							
GNDT 1993							
Rainer et al. 1993							
Hassan and Sozen 1997							
ATC 1998							
ATC 2002							
Ozcebe 2003							
Giovinazzi and Lagomarsina 2004		Aseismic devices	Bow windows				
Yakut et al. 2004							
Lourenço et al. 2006							
Sucuolglu et al. 2007							
Gueguen et al. 2007							
Lantada et al. 2008							
Gent French et al. 2008							
Tesfamariam et al. 2008							
Lang et al. 2009							
Jain et al. 2010	Basement						
Vincente et al. 2011							
Tezcan et al. 2011							
Ozhendekci et al. 2012							
Belheouane et al. 2013							Modifications
Lourenço et al. 2013							
Shakya et al. 2014							
Sucuolglu et al. 2015							
Zuccaro et al. 2015				Infill panel irregularities			
Perrone et al. 2015	Balconies				Past earthquake	Elevators and stairs safe	

Table B-7 Extended tables from index method frequency analysis (table 7 of 7)

Appendix C: Full results from sensitivity analysis

Category	**Sub cat A**	**Sub cat B**	**Sub cat C**	**Sub cat D**	**Sub cat E**
Structural capacity					
Structural capacity	Ground effects & sub-structure				
Structural capacity	Ground effects & sub-structure	Ground failure			
Structural capacity	Ground effects & sub-structure	Soil type			
Structural capacity	Ground effects & sub-structure	Considers foundations			
Structural capacity	Structural condition				
Structural capacity	Structural condition	Strengthening modifications			
Structural capacity	Structural condition	Construction quality (timber)			
Structural capacity	Structural condition	Previous damage incurred			
Structural capacity	Structural properties				
Structural capacity	Structural properties	Frame element properties			
Structural capacity	Structural properties	Frame element properties	Beam stiffness		
Structural capacity	Structural properties	Frame element properties	Column stiffness		
Structural capacity	Structural properties	Diaphragm element properties			
Structural capacity	Structural properties	Diaphragm element properties	Roof structure		
Structural capacity	Structural properties	Ductility			
Structural capacity	Structural properties	Geometrical properties			
Structural capacity	Structural properties	Geometrical properties	Use of representative geometrical characteristics		
Structural capacity	Structural properties	Geometrical properties	Overall geometry		
Structural capacity	Structural properties	Geometrical properties	Overall geometry	Elevation	
Structural capacity	Structural properties	Geometrical properties	Overall geometry	Elevation	Number of storeys
Structural capacity	Structural properties	Geometrical properties	Overall geometry	Elevation	Storey height
Structural capacity	Structural properties	Geometrical properties	Overall geometry	Plan	
Structural capacity	Structural properties	Geometrical properties	Overall geometry	Plan	Plan dimensions
Structural capacity	Structural properties	Geometrical properties	Overall geometry	Plan	No. of bays
Structural capacity	Structural properties	Geometrical properties	Element geometry		

Category	**Sub cat A**	**Sub cat B**	**Sub cat C**	**Sub cat D**	**Sub cat E**
Structural capacity	Structural properties	Geometrical properties	Element geometry	Element depth	
Structural capacity	Structural properties	Geometrical properties	Element geometry	Element breadth	
Structural capacity	Structural properties	Geometrical properties	Element geometry	Element breadth	Effective slab width
Structural capacity	Structural properties	RC material properties			
Structural capacity	Structural properties	RC material properties	Ultimate RC capacity		
Structural capacity	Structural properties	RC material properties	Concrete properties		
Structural capacity	Structural properties	RC material properties	Concrete properties	Concrete strength	
Structural capacity	Structural properties	RC material properties	Concrete properties	Concrete strength	Ultimate concrete strength
Structural capacity	Structural properties	RC material properties	Concrete properties	Concrete strength	Concrete tensile strength
Structural capacity	Structural properties	RC material properties	Concrete properties	Concrete strength	Concrete shear strength
Structural capacity	Structural properties	RC material properties	Concrete properties	Other properties	
Structural capacity	Structural properties	RC material properties	Concrete properties	Other properties	Concrete Young's modulus
Structural capacity	Structural properties	RC material properties	Concrete properties	Other properties	Concrete Poisson's ratio
Structural capacity	Structural properties	RC material properties	Transverse reinforcement		
Structural capacity	Structural properties	RC material properties	Longitudinal reinforcement properties		
Structural capacity	Structural properties	RC material properties	Longitudinal reinforcement properties	Reinforcement steel strength	
Structural capacity	Structural properties	RC material properties	Longitudinal reinforcement properties	Reinforcement steel strength	Yield strength of steel reinforcement
Structural capacity	Structural properties	RC material properties	Longitudinal reinforcement properties	Reinforcement steel strength	Ultimate strength of steel reinforcement
Structural capacity	Structural properties	RC material properties	Longitudinal reinforcement properties	Other reinforcement properties	
Structural capacity	Structural properties	RC material properties	Longitudinal reinforcement properties	Other reinforcement properties	Cover to reinforcement
Structural capacity	Structural properties	RC material properties	Longitudinal reinforcement properties	Other reinforcement properties	Reinforcing steel Young's modulus
Structural capacity	Structural properties	RC material properties	Hinge/rotation properties		
Structural capacity	Structural properties	RC material properties	Hinge/rotation properties	Use of calculated plastic hinge properties	
Structural capacity	Structural properties	RC material properties	Hinge/rotation properties	Specific hinge properties	
Structural capacity	Structural properties	RC material properties	Hinge/rotation properties	Specific hinge properties	Plastic hinge length
Structural capacity	Structural properties	RC material properties	Hinge/rotation properties	Rotation capacities	
Structural capacity	Structural properties	RC material properties	Hinge/rotation properties	Rotation capacities	Ultimate rotation of RC columns
Structural capacity	Structural properties	RC material properties	Hinge/rotation properties	Rotation capacities	Ultimate rotation of RC beams

Category	Sub cat A	Sub cat B	Sub cat C	Sub cat D	Sub cat E
Structural capacity	Structural properties	RC material properties	Hinge/rotation properties	Rotation capacities	Yield rotation of RC columns
Structural capacity	Structural properties	RC material properties	Hinge/rotation properties	Rotation capacities	Yield rotation of RC beams
Structural capacity	Structural properties	RC material properties	Infill walls		
Structural capacity	Structural properties	RC material properties	Infill walls	Consideration of infill walls	
Structural capacity	Structural properties	RC material properties	Infill walls	Infill wall properties	
Structural capacity	Structural properties	RC material properties	Infill walls	Infill wall properties	Compressive strength of infill walls
Structural capacity	Structural properties	RC material properties	Infill walls	Infill wall properties	Thickness of infill walls
Structural capacity	Structural properties	RC material properties	Infill walls	Infill wall properties	Cracking strength of infill walls
Structural capacity	Structural properties	RC material properties	Infill walls	Infill wall properties	Stiffness of infill walls
Structural capacity	Structural properties	RC material properties	Infill walls	Infill wall properties	Specific weight of infill walls
Structural capacity	Structural properties	RC material properties	Infill walls	Infill wall properties	Young's modulus of infill walls
Structural capacity	Structural properties	RC material properties	Infill walls	Infill wall properties	Shear strength of infill walls
Structural capacity	Structural properties	RC material properties	Infill walls	Infill wall properties	Shear modulus of infill walls
Structural capacity	Structural properties	RC material properties	Infill walls	Infill wall properties	Poisson's ratio of infill walls
Structural capacity	Structural properties	Masonry material properties			
Structural capacity	Structural properties	Masonry material properties	Ultimate capacity of masonry		
Structural capacity	Structural properties	Timber material properties			
Structural capacity	Structural properties	Timber material properties	Ultimate seismic capacity of timber		
Structural capacity	Structural properties	Timber material properties	Timber strength		
Structural capacity	Structural properties	Timber material properties	Timber stiffness		
Structural capacity	Structural properties	Structural steel material properties			
Structural capacity	Structural properties	Structural steel material properties	Structural steel strength		
Structural capacity	Structural properties	Structural steel material properties	Structural steel stiffness		
Structural capacity	Dynamic characteristics				
Structural capacity	Dynamic characteristics	Modes of vibration			
Structural capacity	Dynamic characteristics	Modes of vibration	Number of degrees of freedom		
Structural capacity	Dynamic characteristics	Modes of vibration	Fundamental period		
Structural capacity	Dynamic characteristics	Modes of vibration	Fundamental period	Use of calculated fundamental period	

Category	Sub cat A	Sub cat B	Sub cat C	Sub cat D	Sub cat E
Structural capacity	Dynamic characteristics	Damping			
Structural capacity	Dynamic characteristics	Damping	Hysteretic damping coefficient for RC		
Structural capacity	Dynamic characteristics	Damping	Hysteretic damping coefficient for masonry		
Structural capacity	Dynamic characteristics	Mass			
Structural capacity	Consideration of uncertainty in structural capacity				
Structural capacity	Consider non-structural components				
Structural capacity	Consider non-structural components	Consideration of cladding			

Table C-1 Characteristics investigated in sensitivity analyses

	Esteva & Ruiz 1989	Olshansky 1997	Porter et al 2002	Restrepo-Velez &	Spence et al 2003	Masi 2003	Bird et al 2004	Crowley & Pinho 2004	Ibarra and Krawinkler	Crowley et al 2005	Inel & Ozmen 2006	Kwon & Elnashai 2006	Liel et al 2009	Ellingwood & Kinali	Erduran et al 2010	Sattar & Liel 2010	Pei & Van der Lindt 2010	Goda et al 2011	Meslem & D'Ayala 2012	D'Ayala & Meslem 2013	Celarec et al 2012	Celarec & Dolšek 2013	Rohmer et al 2014	Rossetto et al 2014	Clementi et al 2016	Chacón et al 2017	Pianigianai and Mariani	Riga et al 2017
Structural capacity			H							H					H													
Ground effects and sub-structure																										H		
Ground failure							H																					
Soil type	M	H			M																		L				H	
Considers foundations				H																								
Structural condition																											L	
Strengthening modifications																			L									
Construction quality (timber)																	H											
Previous damage incurred																			L									
Structural properties												M																
Frame element properties																			H									
Beam stiffness						L															M							
Column stiffness																					M							
Diaphragm element properties																			H						H	M		
Roof structure																			M									
Ductility	M								H																			
Geometrical properties																												
Use of representative geometrical characteristics																								H				
Overall geometry																												
Elevation																												
Number of storeys	M								H	L									H									
Storey height																			H	H								
Plan																												
Plan dimensions						L													M									
No. of bays																			H									
Element geometry	L									H									M									
Element depth	L																											
Element breadth	L																											
Effective slab width																					L	M						
RC material properties																											M	
Ultimate RC capacity					M																							
Concrete properties																												
Concrete strength	L																		H	H	M	M						
Ultimate concrete strength												H																
Concrete tensile strength																			H									
Concrete shear strength																			M									
Other properties																												
Concrete Young's modulus																			H									
Concrete Poisson's ratio																			L									
Transverse reinforcement											H								M	L								
Longitudinal reinforcement properties																			M									
Reinforcement steel strength																				L		L						
Yield strength of steel reinforcement	L																		H		L							
Ultimate strength of steel reinforcement																			H									
Other reinforcement properties																												
Cover to reinforcement	L																											
Reinforcing steel Young's modulus																			H									
Hinge/rotation properties																												
Use of calculated plastic hinge properties											H								H									
Specific hinge properties																												
Plastic hinge length										H	H																	

	Esteva & Ruiz 1989	Olshansky 1997	Porter et al 2002	Restrepo-Velez &	Spence et al 2003	Masi 2003	Bird et al 2004	Crowley & Pinho 2004	Ibarra and Krawinkler	Crowley et al 2005	Inel & Ozmen 2006	Kwon & Elnashai 2006	Liel et al 2009	Ellingwood & Kinali	Erduran et al 2010	Sattar & Liel 2010	Pei & Van der Lindt 2010	Goda et al 2011	Meslem & D'Ayala 2012	D'Ayala & Meslem 2013	Celarec et al 2012	Celarec & Dolšek 2013	Rohmer et al 2014	Rossetto et al 2014	Clementi et al 2016	Chacón et al 2017	Pianigianai and Mariani	Riga et al 2017
Rotation capacities																												
Ultimate rotation of RC columns																					H	H						
Ultimate rotation of RC beams																					M	H						
Yield rotation of RC columns																						M						
Yield rotation of RC beams																						L						
Infill walls																												
Consideration of infill walls					H	H										H			M	H				H				
Infill wall properties																												
Compressive strength of infill walls																			H	H								
Thickness of infill walls																				M								
Cracking strength of infill walls																					H							
Stiffness of infill walls																					H							
Specific weight of infill walls																			M									
Young's modulus of infill walls																			H		H							
Shear strength of infill walls																			M									
Shear modulus of infill walls																					H							
Poisson's ratio of infill walls																			L									
Masonry material properties																												
Ultimate capacity of masonry					M																							
Timber material properties																												
Ultimate seismic capacity of timber																		M										
Timber strength																	L											
Timber stiffness																	L											
Structural steel material properties																												
Structural steel strength														L														
Structural steel stiffness														L														
Dynamic characteristics																												
Modes of vibration																												
Number of degrees of freedom	H																											
Fundamental period	M																									M		
Use of calculated fundamental period								H																				
Damping			M																									L
Hysteretic damping coefficient for RC					L																							
Hysteretic damping coefficient for masonry					L																							
Mass			L																			M						
Consideration of uncertainty in structural capacity				H									H											H				
Consider non-structural components				H																								
Consideration of cladding																			L									

Table C-2 Importance level concluded from sensitivity literature

Building characteristic	Total H scores	Total M scores	Total L scores	Total studies	%age H	%age M	%age L	Majority score	Agreement	Large enough sample size	Check for split opinion	Conclusion
Structural capacity	54	31	30	115	47.0%	27.0%	26.1%	H	N	Y	Y	N
Ground effects and sub-structure	5	2	1	8	62.5%	25.0%	12.5%	H	Y	Y	Y	Y
Ground failure	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Soil type	2	2	1	5	40.0%	40.0%	20.0%	H	N	Y	Y	N
Considers foundations	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Structural condition	1	0	3	4	25.0%	0.0%	75.0%	L	Y	Y	Y	Y
Strengthening modifications	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Construction quality (timber)	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Previous damage incurred	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Structural properties	39	25	21	85	45.9%	29.4%	24.7%	H	N	Y	Y	N
Frame element properties	1	2	1	4	25.0%	50.0%	25.0%	M	Y	Y	Y	Y
Beam stiffness	0	1	1	2	0.0%	50.0%	50.0%	M	Y	Y	N	N
Column stiffness	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Diaphragm element properties	2	2	0	4	50.0%	50.0%	0.0%	H	Y	Y	N	N
Roof structure	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Ductility	1	1	0	2	50.0%	50.0%	0.0%	H	Y	Y	N	N
Geometrical properties	7	4	6	17	41.2%	23.5%	35.3%	H	N	Y	Y	N
Use of representative geometrical characteristics	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Overall geometry	5	4	6	15	33.3%	26.7%	40.0%	L	N	Y	Y	N
Elevation	4	1	1	6	66.7%	16.7%	16.7%	H	Y	Y	Y	Y
Number of storeys	2	1	1	4	50.0%	25.0%	25.0%	H	Y	Y	Y	Y
Storey height	2	0	0	2	100.0%	0.0%	0.0%	H	Y	Y	Y	Y
Plan	1	1	1	3	33.3%	33.3%	33.3%	H	N	Y	Y	N
Plan dimensions	0	1	1	2	0.0%	50.0%	50.0%	M	Y	Y	N	N
No. of bays	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Element geometry	1	2	4	7	14.3%	28.6%	57.1%	L	Y	Y	Y	Y
Element depth	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Element breadth	0	1	2	3	0.0%	33.3%	66.7%	L	Y	Y	Y	Y
Effective slab width	0	1	1	2	0.0%	50.0%	50.0%	M	Y	Y	N	N
RC material properties	28	13	10	51	54.9%	25.5%	19.6%	H	Y	Y	Y	Y
Ultimate RC capacity	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Concrete properties	5	3	2	10	50.0%	30.0%	20.0%	H	Y	Y	Y	Y
Concrete strength	4	3	1	8	50.0%	37.5%	12.5%	H	Y	Y	Y	Y
Ultimate concrete strength	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Concrete tensile strength	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Concrete shear strength	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Other properties	1	0	1	2	50.0%	0.0%	50.0%	H	Y	Y	N	N
Concrete Young's modulus	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Concrete Poisson's ratio	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Transverse reinforcement	1	1	1	3	33.3%	33.3%	33.3%	H	N	Y	Y	N
Longitudinal reinforcement properties	3	1	5	9	33.3%	11.1%	55.6%	L	Y	Y	Y	Y
Reinforcement steel strength	2	0	4	6	33.3%	0.0%	66.7%	L	Y	Y	Y	Y
Yield strength of steel reinforcement	1	0	2	3	33.3%	0.0%	66.7%	L	Y	Y	Y	Y
Ultimate strength of steel reinforcement	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Other reinforcement properties	1	0	1	2	50.0%	0.0%	50.0%	H	Y	Y	N	N
Cover to reinforcement	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Reinforcing steel Young's modulus	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Hinge/rotation properties	7	2	1	10	70.0%	20.0%	10.0%	H	Y	Y	Y	Y
Use of calculated plastic hinge properties	2	0	0	2	100.0%	0.0%	0.0%	H	Y	Y	Y	Y
Specific hinge properties	2	0	0	2	100.0%	0.0%	0.0%	H	Y	Y	Y	Y
Plastic hinge length	2	0	0	2	100.0%	0.0%	0.0%	H	Y	Y	Y	Y
Rotation capacities	3	2	1	6	50.0%	33.3%	16.7%	H	Y	Y	Y	Y
Ultimate rotation of RC columns	2	0	0	2	100.0%	0.0%	0.0%	H	Y	Y	Y	Y
Ultimate rotation of RC beams	1	1	0	2	50.0%	50.0%	0.0%	H	Y	Y	N	N
Yield rotation of RC columns	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Yield rotation of RC beams	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N

Building characteristic	Total H scores	Total M scores	Total L scores	Total studies	%age H	%age M	%age L	Majority score	Agreement	Large enough sample size	Check for split opinion	Conclusion
Infill walls	12	4	1	17	70.6%	23.5%	5.9%	H	Y	Y	Y	Y
Consideration of infill walls	5	1	0	6	83.3%	16.7%	0.0%	H	Y	Y	Y	Y
Infill wall properties	7	3	1	11	63.6%	27.3%	9.1%	H	Y	Y	Y	Y
Compressive strength of infill walls	2	0	0	2	100.0%	0.0%	0.0%	H	Y	Y	Y	Y
Thickness of infill walls	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Cracking strength of infill walls	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Stiffness of infill walls	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Specific weight of infill walls	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Young's modulus of infill walls	2	0	0	2	100.0%	0.0%	0.0%	H	Y	Y	Y	Y
Shear strength of infill walls	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Shear modulus of infill walls	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Poisson's ratio of infill walls	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Masonry material properties	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Ultimate capacity of masonry	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Timber material properties	0	1	2	3	0.0%	33.3%	66.7%	L	Y	Y	Y	Y
Ultimate seismic capacity of timber	0	1	0	1	0.0%	100.0%	0.0%	M	Y	N	Y	N
Timber strength	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Timber stiffness	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Structural steel material properties	0	0	2	2	0.0%	0.0%	100.0%	L	Y	Y	Y	Y
Structural steel strength	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Structural steel stiffness	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Dynamic characteristics	2	4	4	10	20.0%	40.0%	40.0%	M	N	Y	Y	N
Modes of vibration	2	2	0	4	50.0%	50.0%	0.0%	H	Y	Y	N	N
Number of degrees of freedom	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Fundamental period	1	2	0	3	33.3%	66.7%	0.0%	M	Y	Y	Y	Y
Use of calculated fundamental period	1	0	0	1	100.0%	0.0%	0.0%	H	Y	N	Y	N
Damping	0	1	3	4	0.0%	25.0%	75.0%	L	Y	Y	Y	Y
Hysteretic damping coefficient for RC	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Hysteretic damping coefficient for masonry	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N
Mass	0	1	1	2	0.0%	50.0%	50.0%	M	Y	Y	N	N
Consideration of uncertainty in structural capacity	3	0	0	3	100.0%	0.0%	0.0%	H	Y	Y	Y	Y
Consider non-structural components	1	0	1	2	50.0%	0.0%	50.0%	H	Y	Y	N	N
Consideration of cladding	0	0	1	1	0.0%	0.0%	100.0%	L	Y	N	Y	N

Table C-3 Sensitivity analysis scoring procedure

Appendix D: Historical maps, Guatemala City

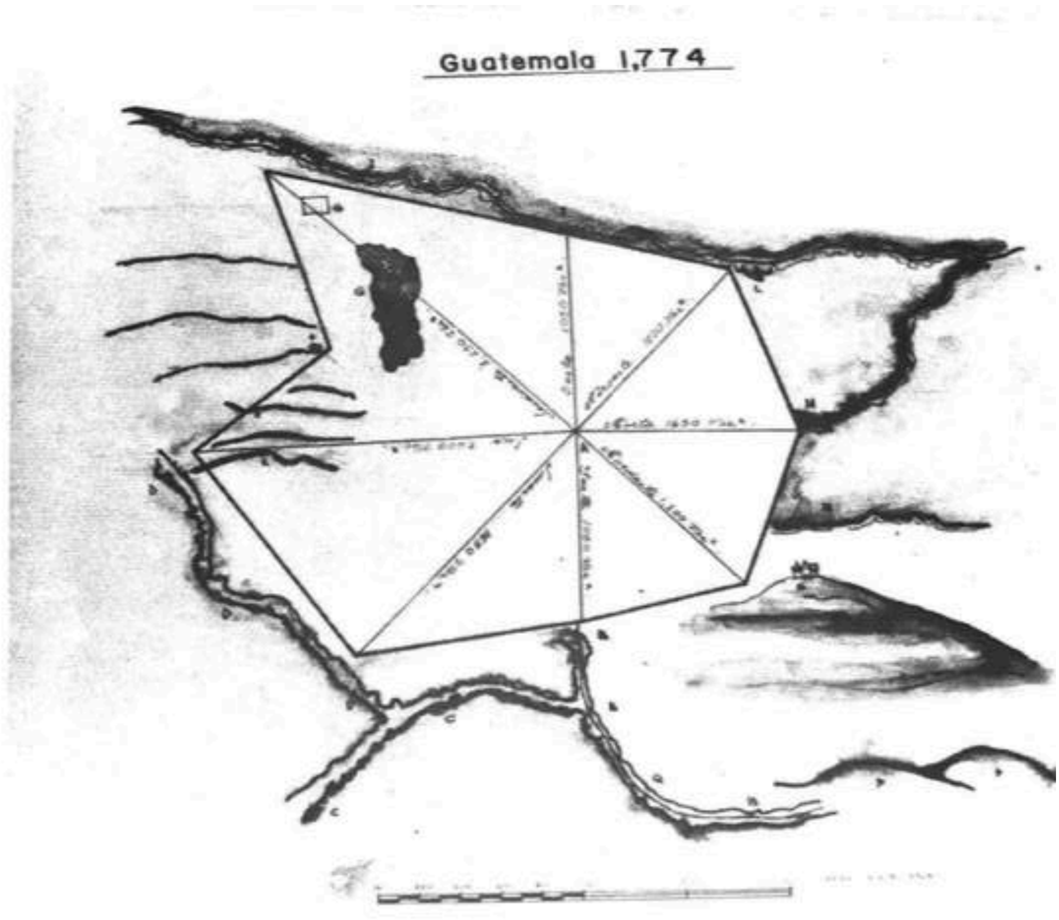


Figure D-1 Early (1774) zonal plans for the new city, from Gulicia Díaz (1968)

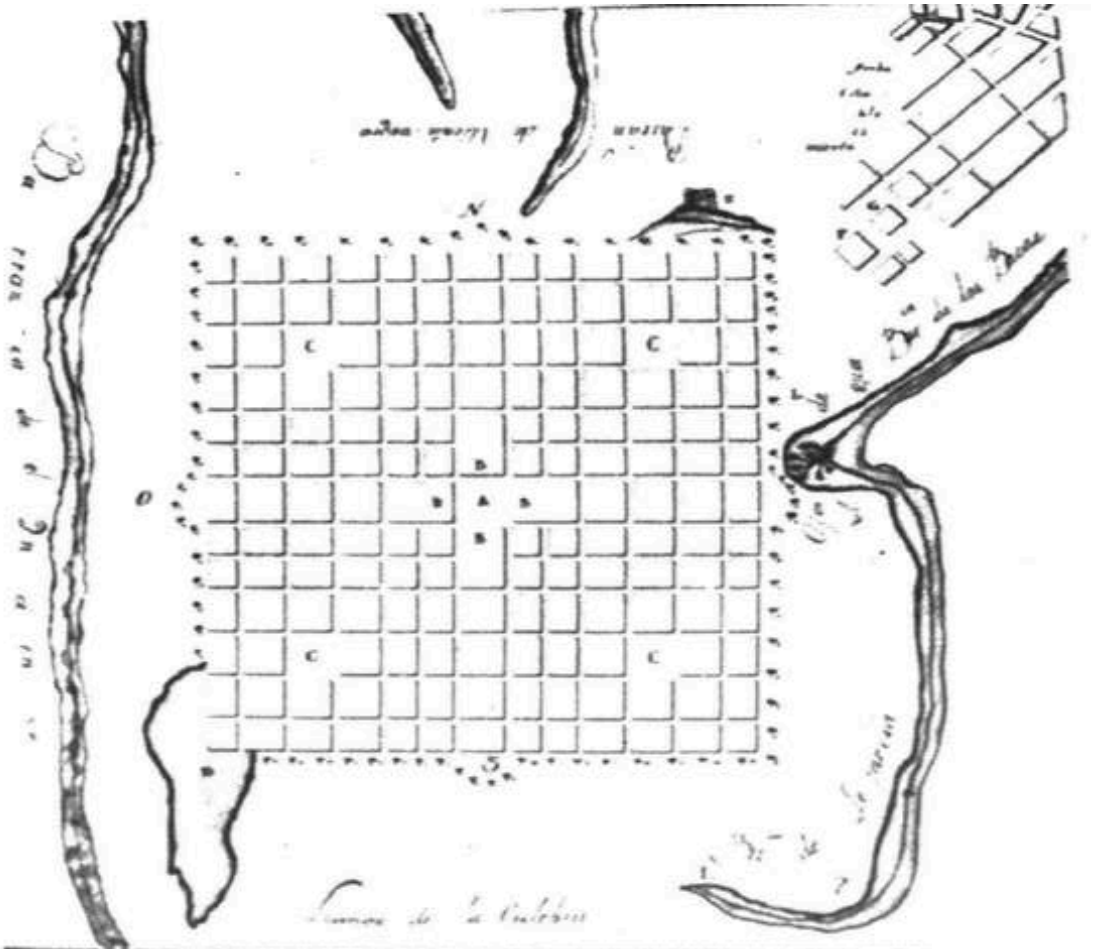


Figure D-2 The early established capital city in 1776, from Gulicia Díaz (1968)

Figure D-3 Map of development of Ciudad de Guatemala in 1791, from Gellert and Pinto Soria (1990)

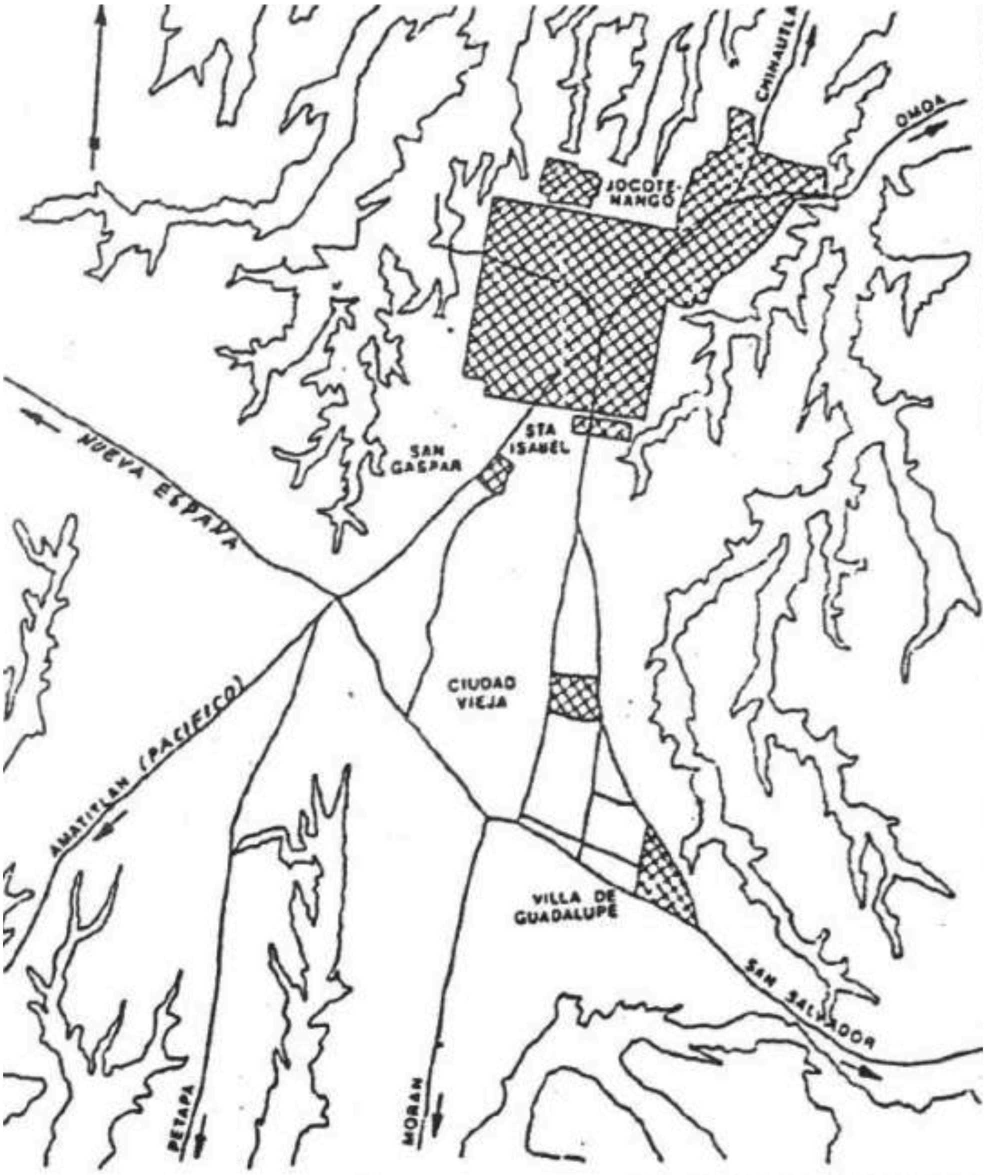


Figure D-4 The site of the new capital city in 1800 with the surrounding communication routes and villages, from Gellert and Pinto Soria (1990)

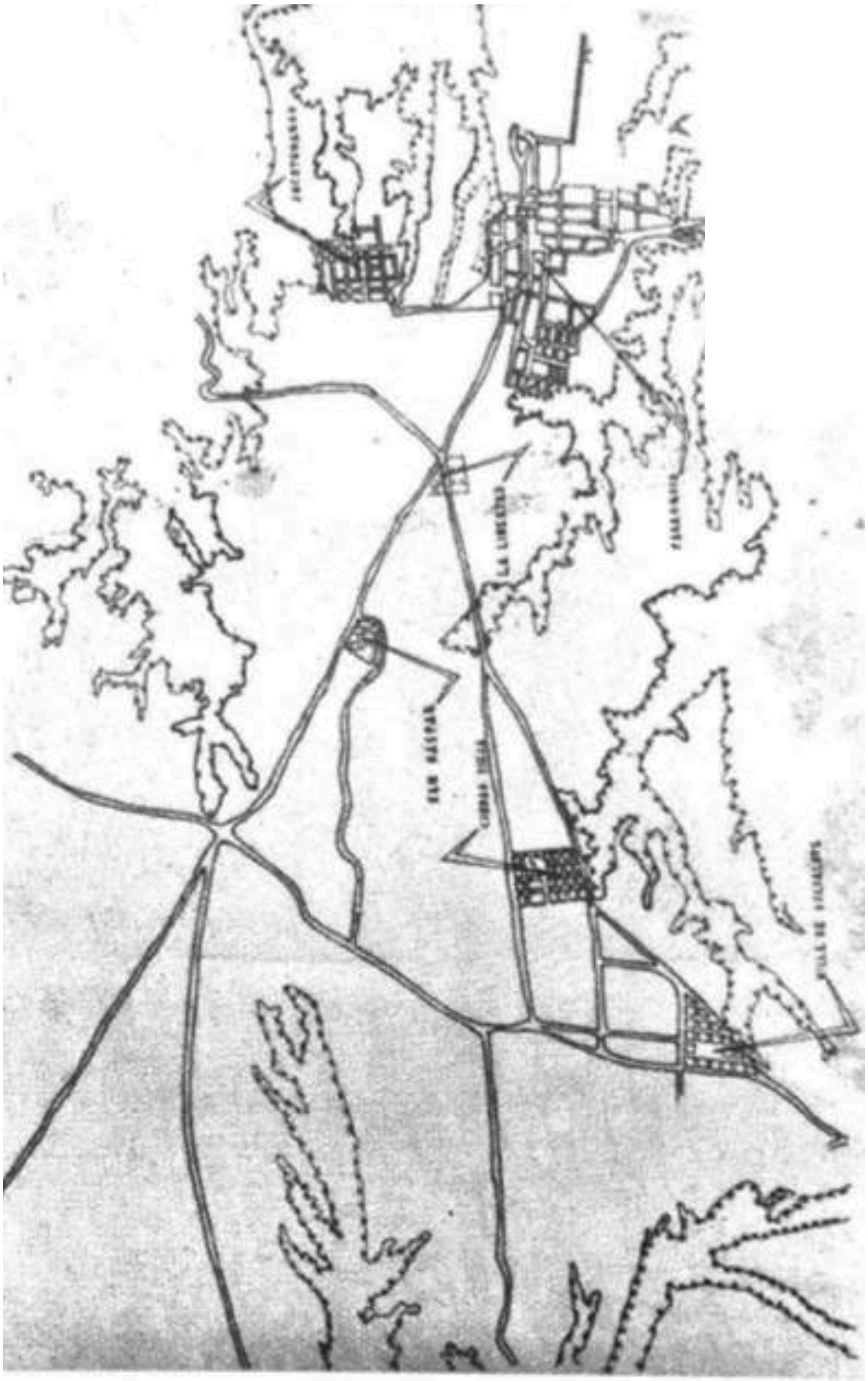


Figure D-5 The urban areas of 1800 Guatemala City, from Gulicia Díaz (1968)

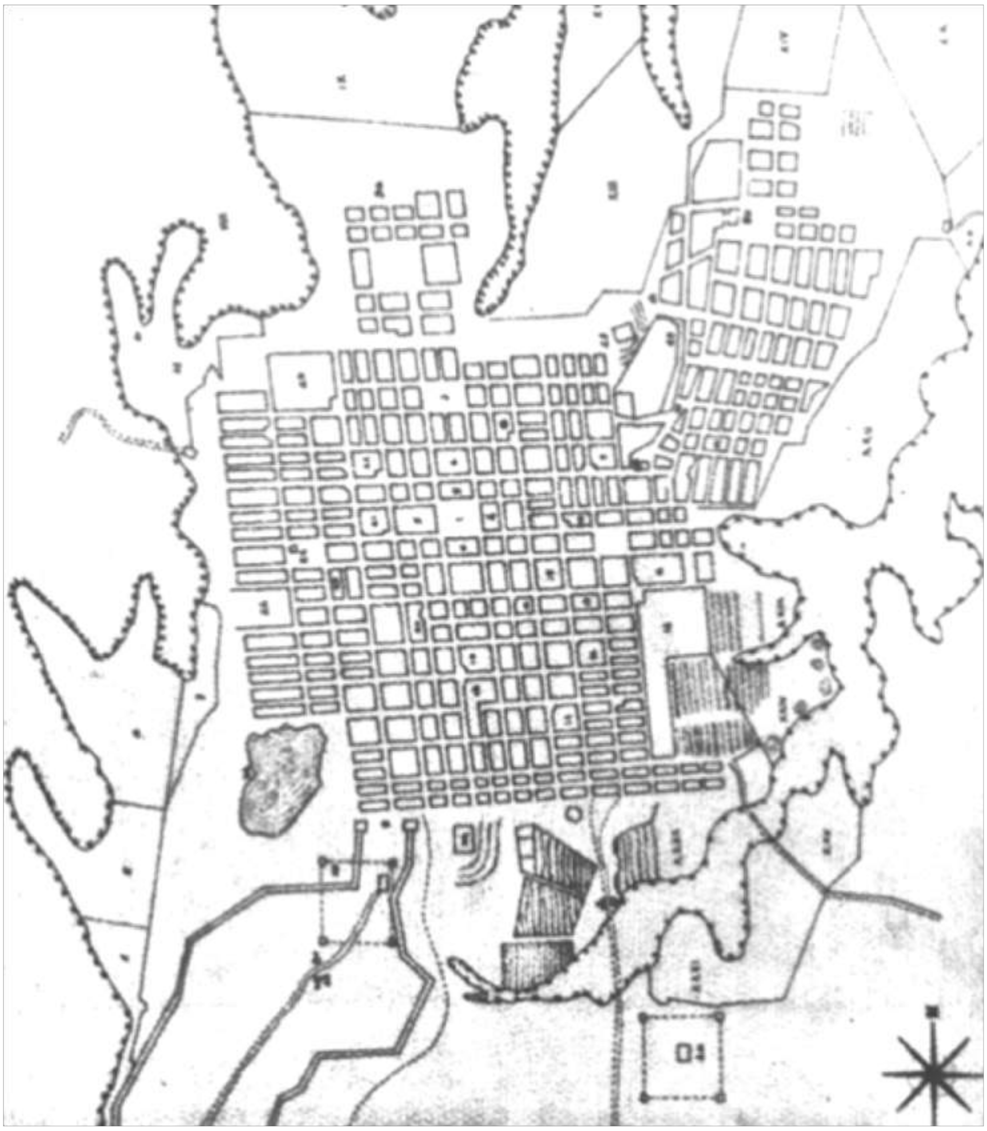


Figure D-6 Map of Guatemala City in 1821, from Gulicia Díaz (1968)

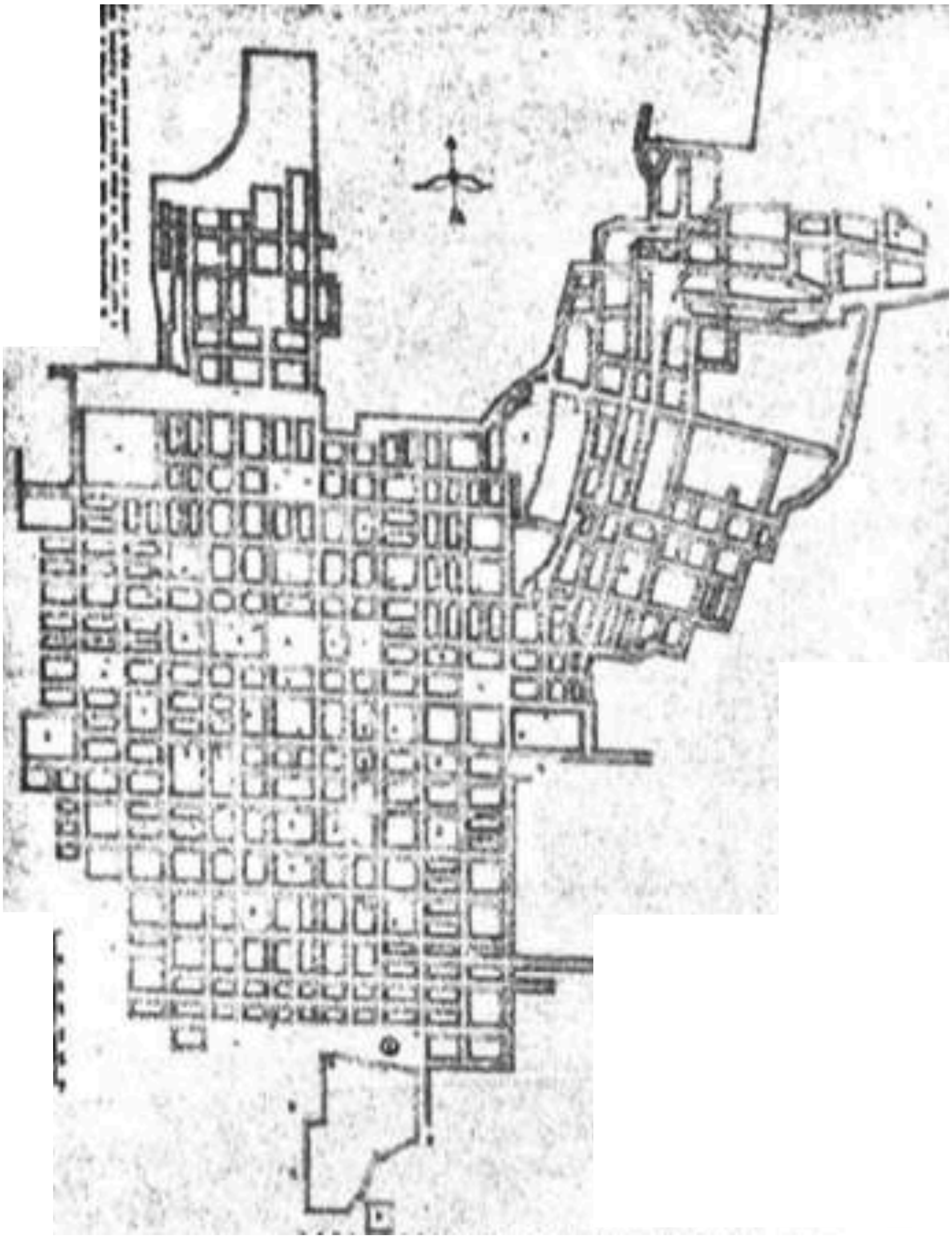


Figure D-7 Map of Guatemala City in 1842, from Lara F (1977)

Figure D-8 Built-up areas of Guatemala City and surrounding villages in 1850, from Lara F (1977)

Figure D-9 1868 Guatemala City, with nearby villages, from Lara F (1977)

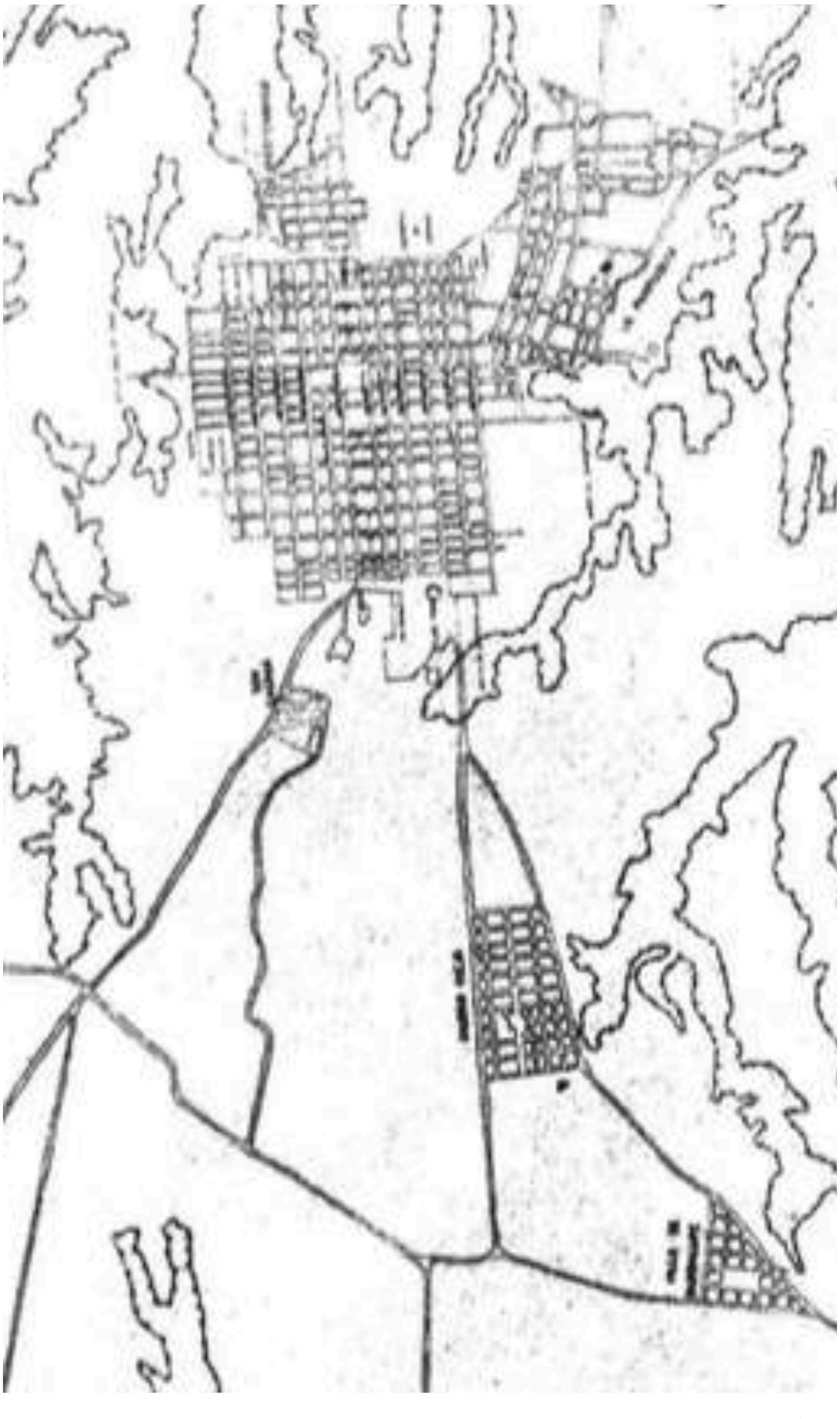


Figure D-10 The extent of Guatemala City in 1882, from Lara F (1977)

Figure D-11 Extensive growth of Guatemala City is observed in 1889, from Lara F (1977)

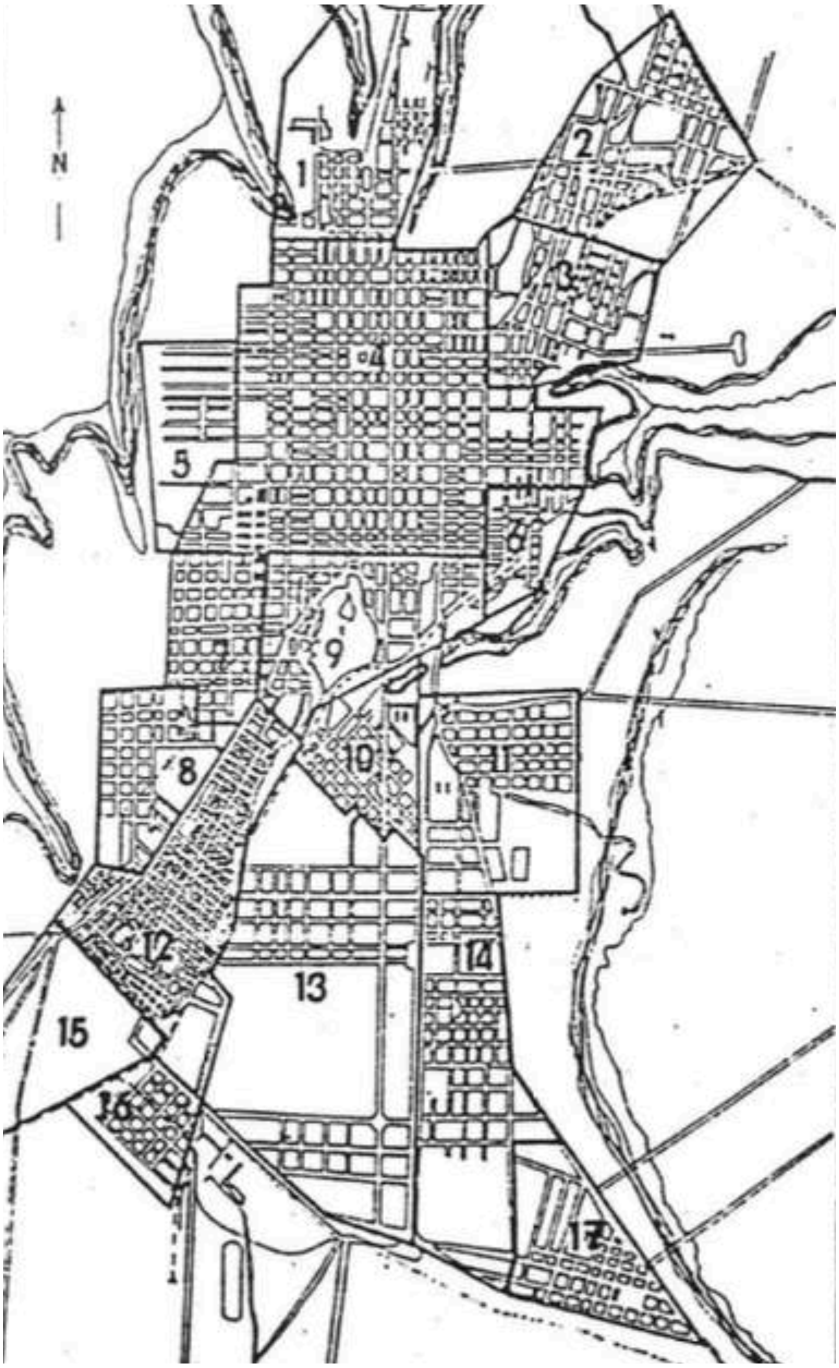


Figure D-12 The spread of urban development is clear in this 1925 map of Guatemala City, from Gellert and Pinto Soria (1990)

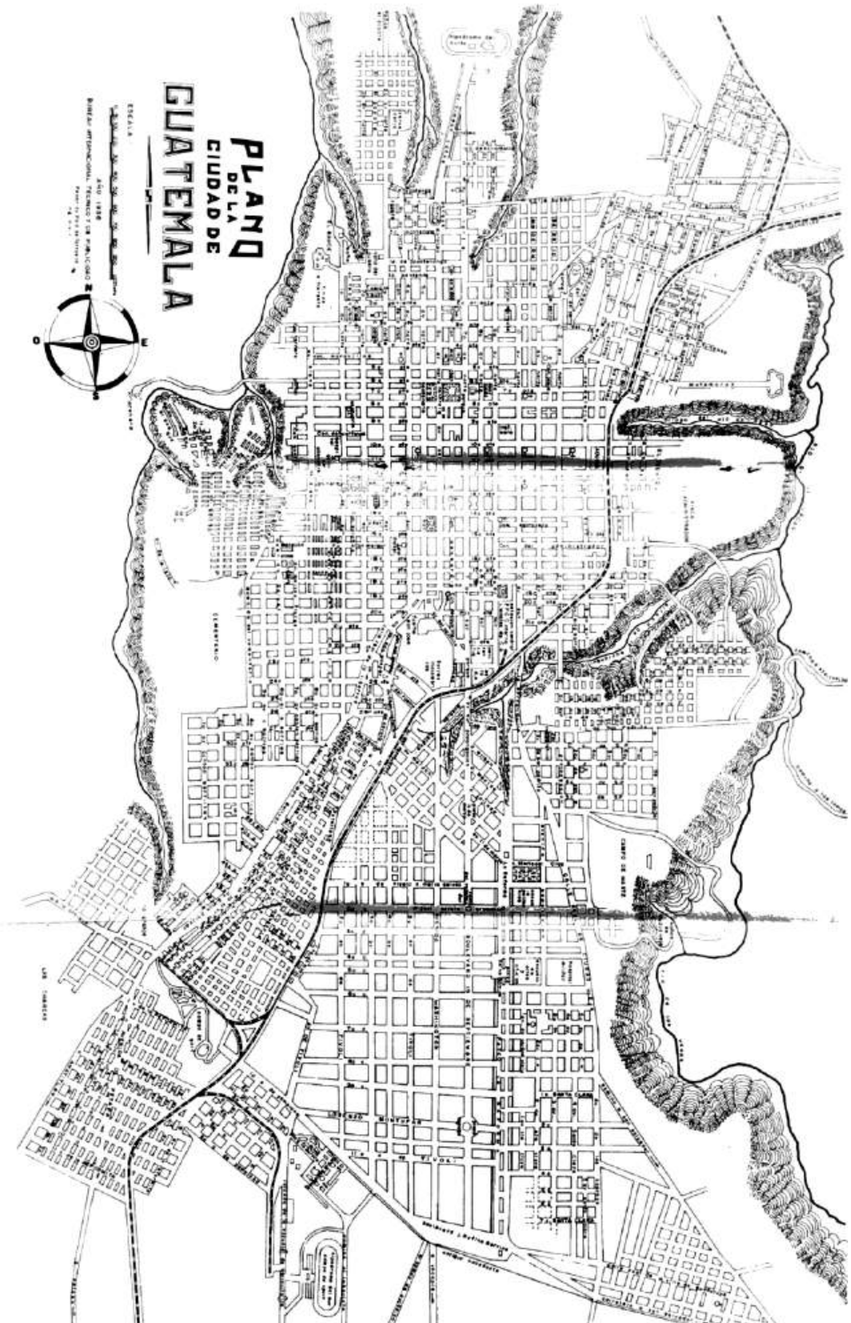


Figure D-13 Further growth is observed in this 1936 map of Guatemala City, from Gellert and Pinto Soria (1990)

Appendix E: Government city maps

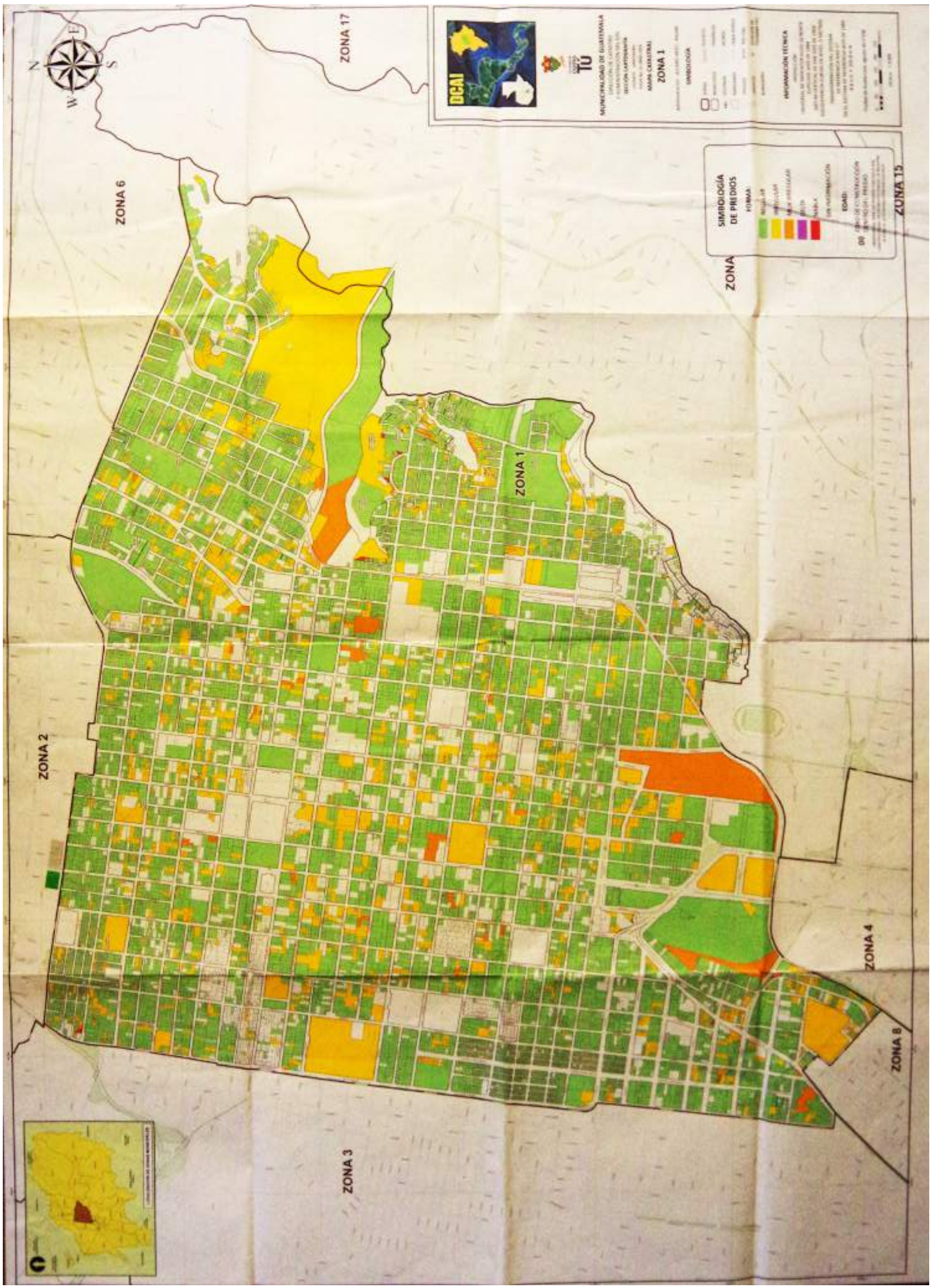


Figure E-1 Government city map for Zone 1

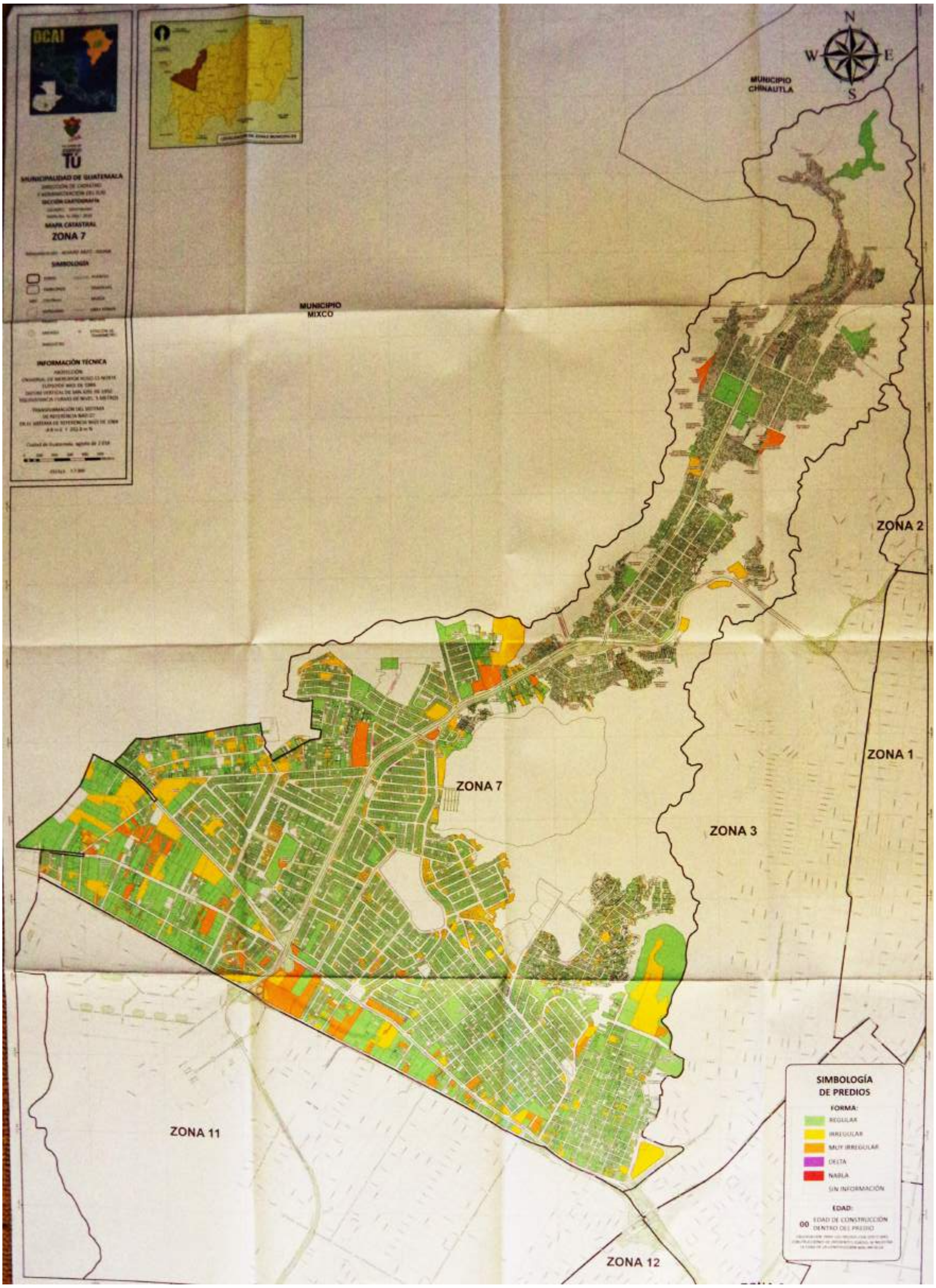


Figure E-2 Government city map for Zone 7

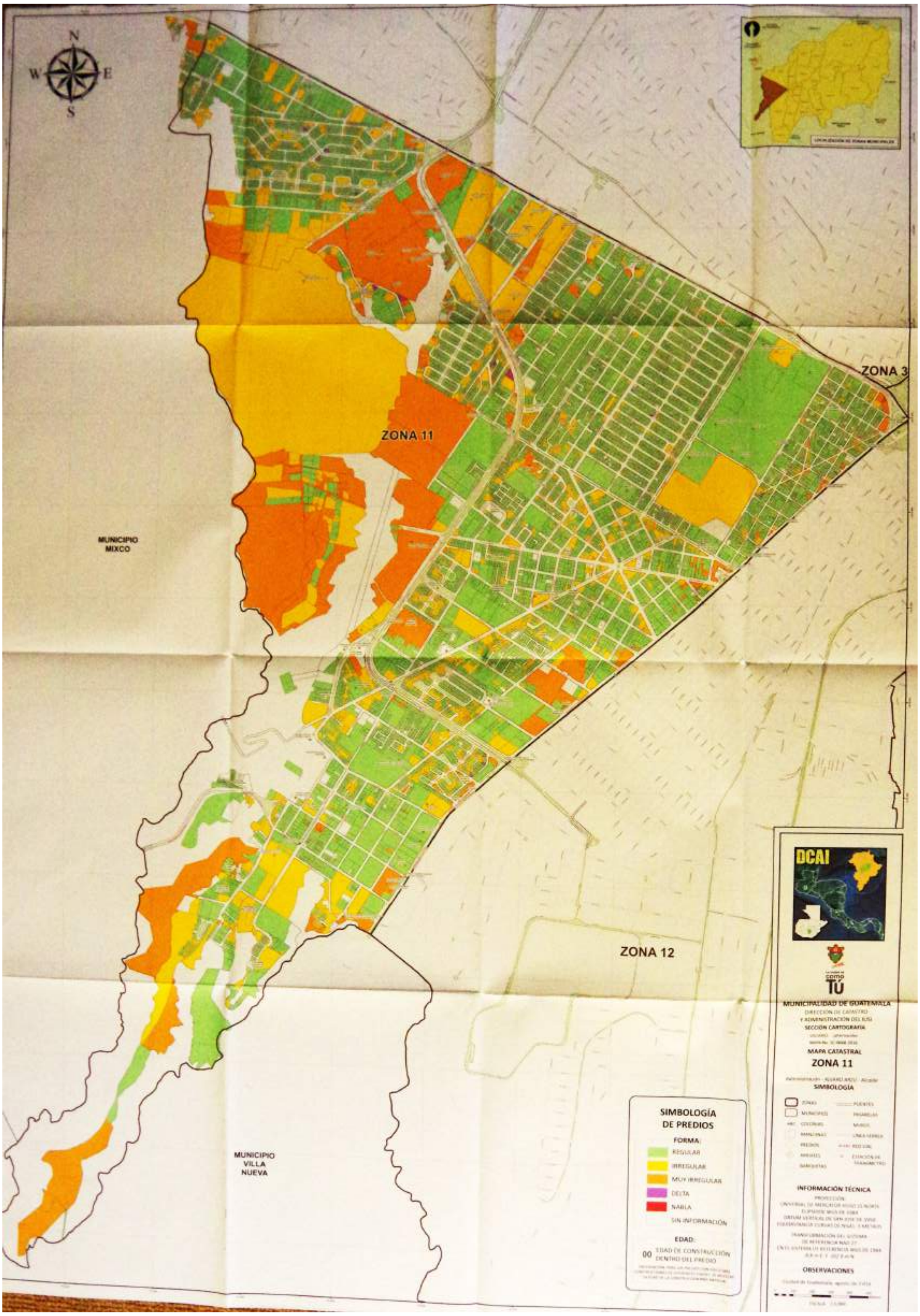


Figure E-3 Government city map for Zone 11

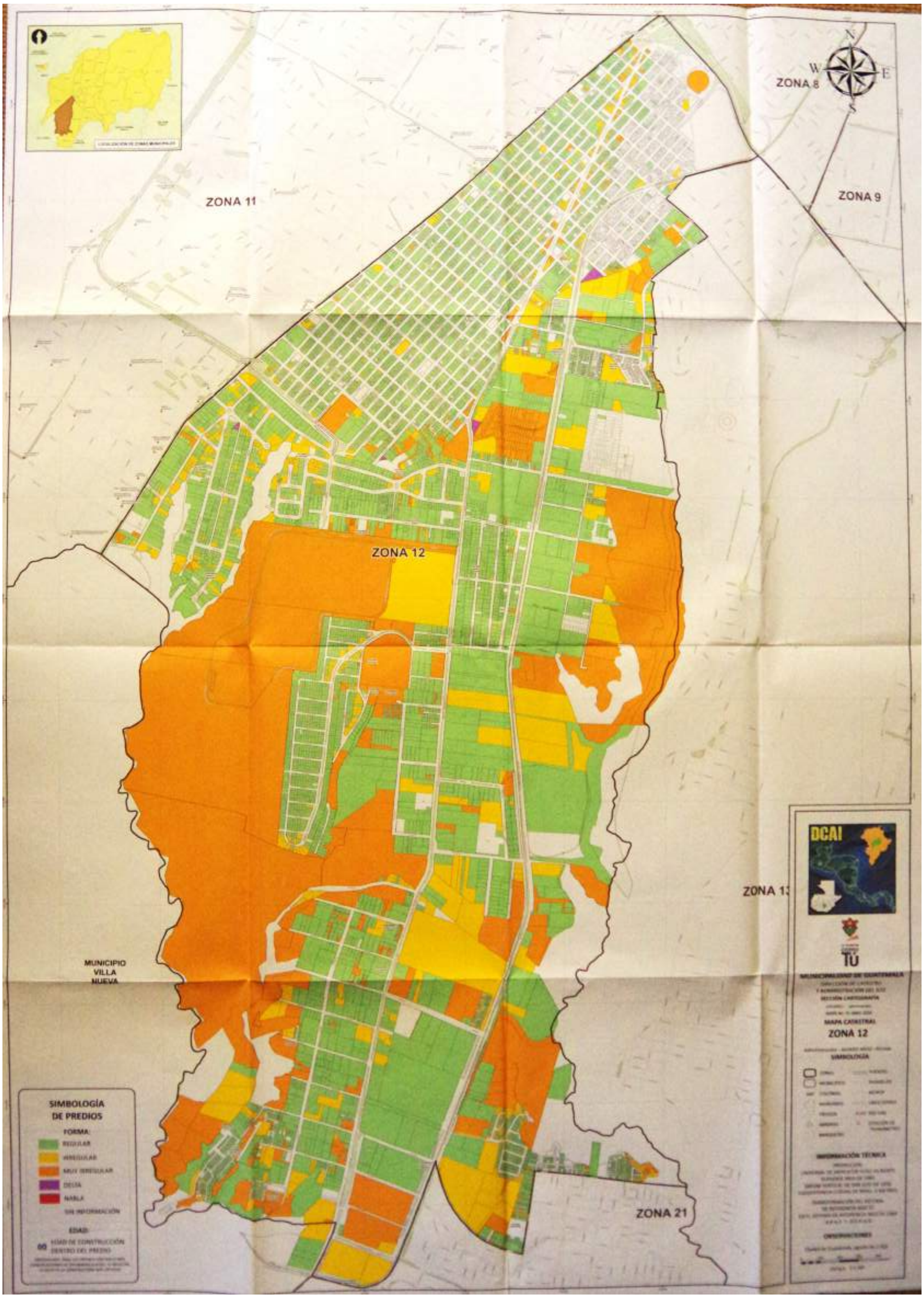


Figure E-4 Government city map for Zone 12

Appendix F: Field survey areas

The survey routes are shown by the orange line in the figures below.

Zone	Surveyors	Date of survey	Map reference
1	Local engineer Students Foreign engineer	10/08/16 11/08/16 25/08/16	Figure F-1
4	Local engineer Foreign engineer	15/08/16	Figure F-2
5	Local engineer Foreign engineer	19/08/16	Figure F-3
7	Local engineer Foreign engineer	17/08/16	Figure F-4
9/10	Foreign engineer Students	16/08/16	Figure F-5
12	Local engineer Students Foreign engineer	08/08/16 09/08/16 25/08/16	Figure F-6
14	Local engineer Students Foreign engineer	12/08/16 26/08/16	Figure F-7

Table F-1 – Rapid visual survey route information

Figure F-1 – RVS routes in Zone 1, Guatemala City (map credit: Google Earth)

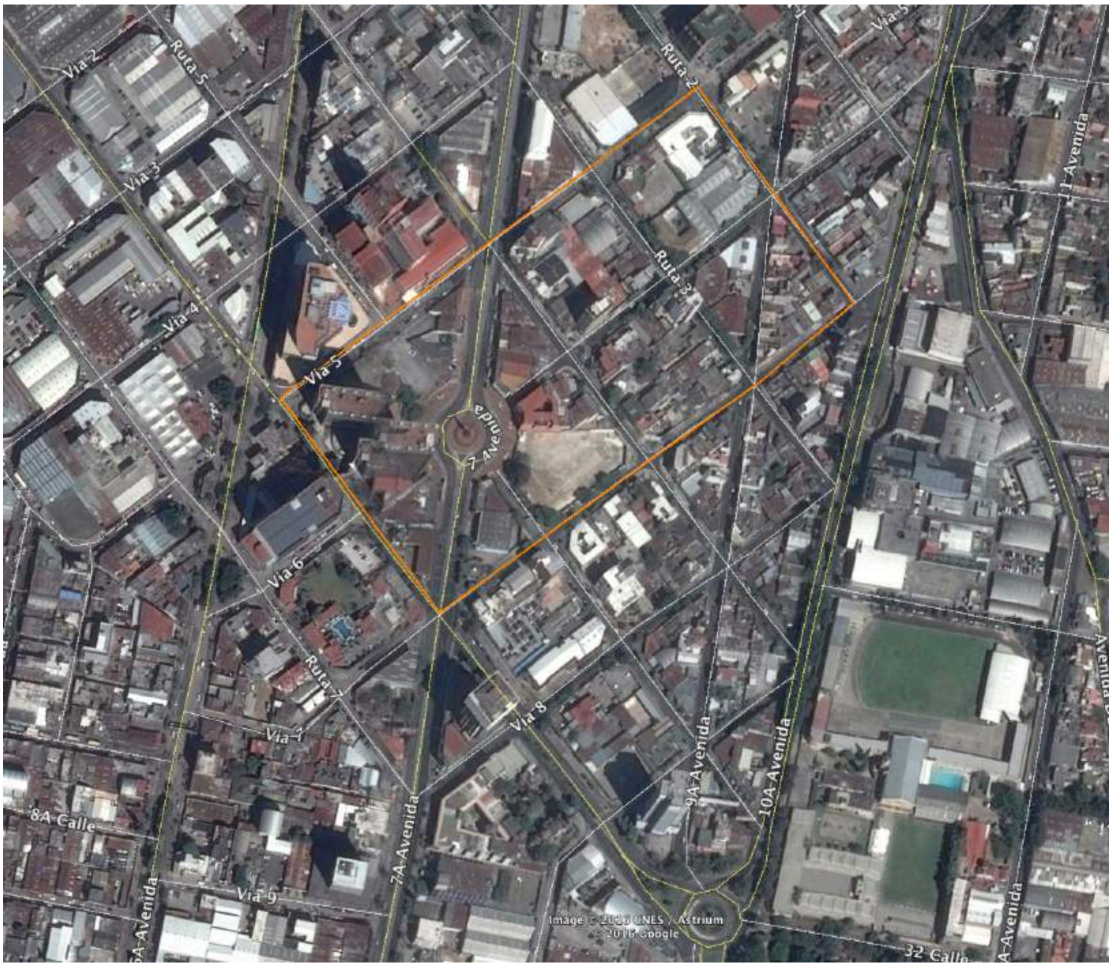


Figure F-2 - RVS routes in Zone 4, Guatemala City (map credit: Google Earth)

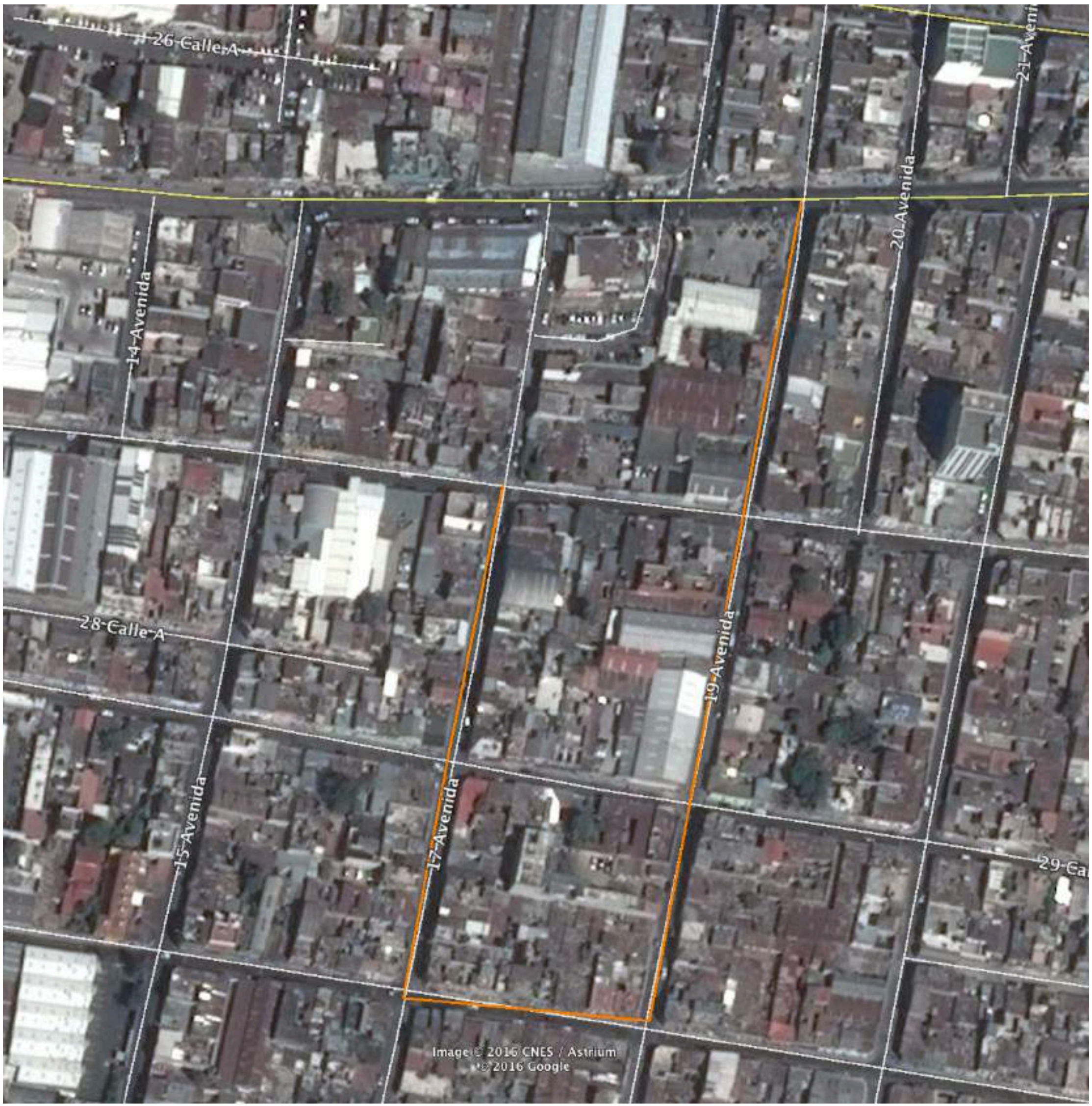


Figure F-3 - RVS routes in Zone 5, Guatemala City (map credit: Google Earth)

Figure F-4 - RVS routes in Zone 7, Guatemala City (map credit: Google Earth)

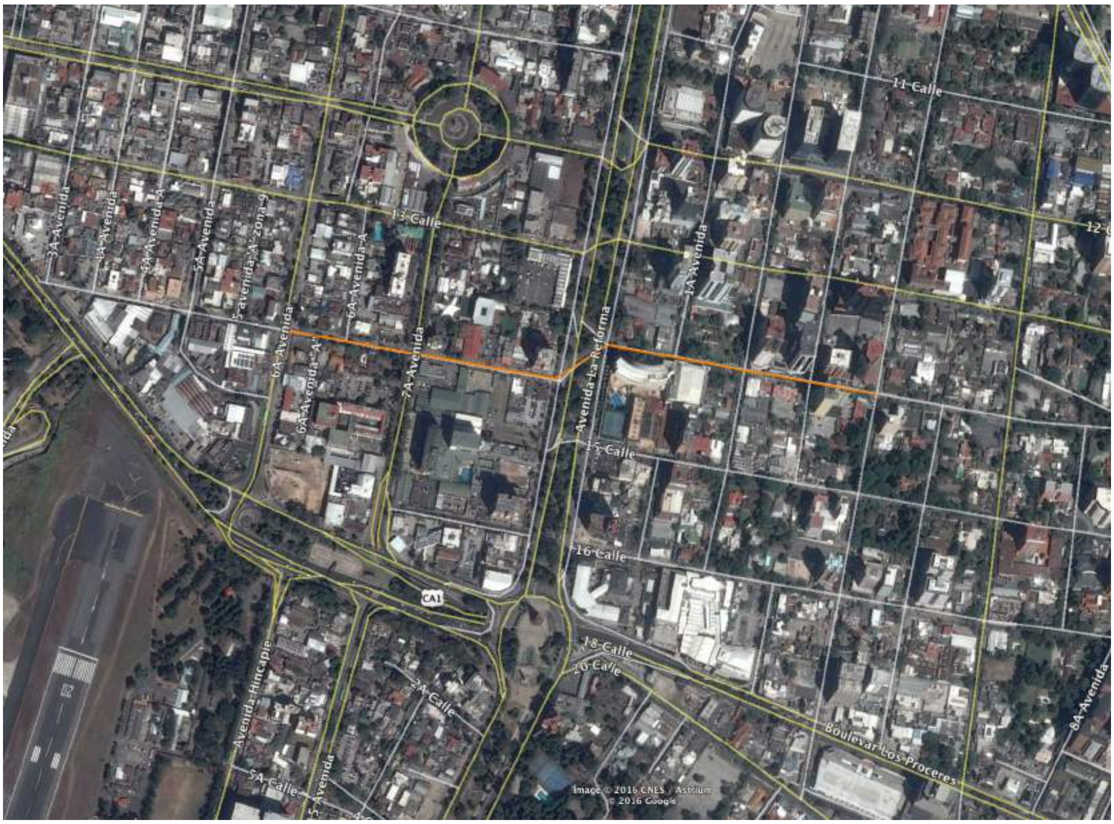


Figure F-5 - RVS routes in Zones 9 and 10, Guatemala City (map credit: Google Earth)

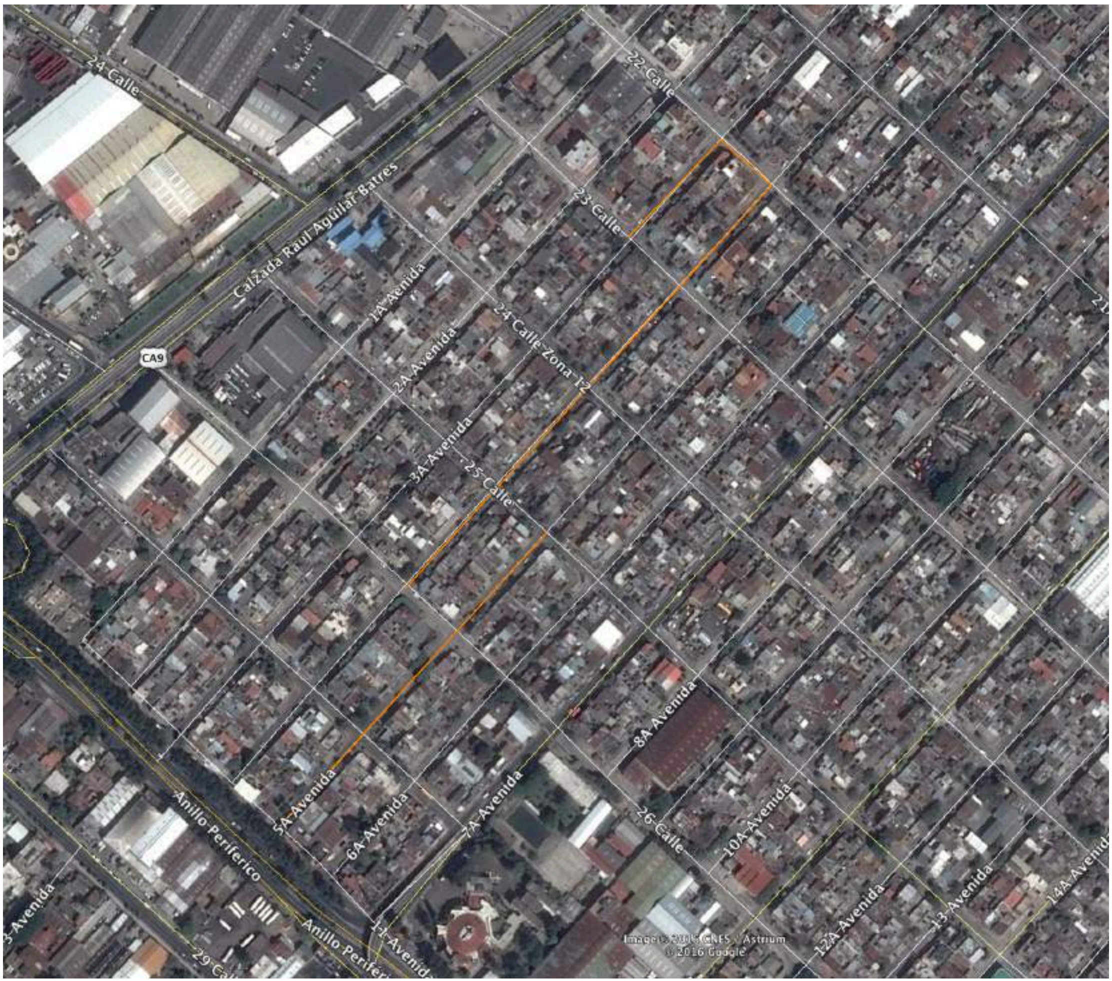


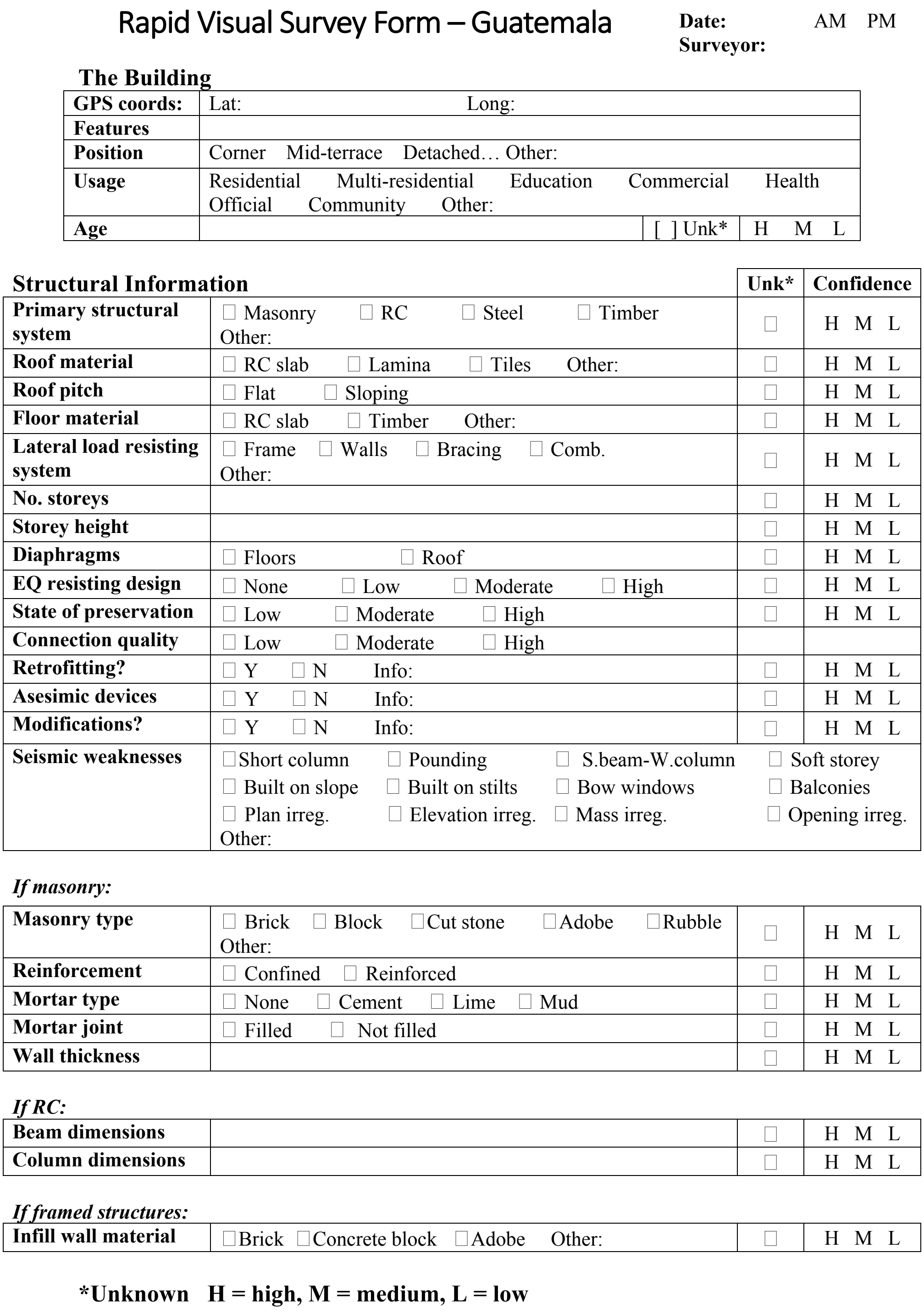
Figure F-6 - RVS routes in Zone 12, Guatemala City (map credit: Google Earth)

Figure F-7 - RVS routes in Zone 14, Guatemala City (map credit: Google Earth)

Zone	RVS LE	RVS FE	RVS STU	UAV	OD	DIS
1	•	•	•	•	•	•
4	•	•		•	•	
5	•	•		•	•	•
7	•	•		•	•	
10		•		•	•	
12	•	•	•	•	•	
14	•	•	•		•	

Table F-2 Locations of method testing

Appendix G: RVS survey form



Rapid Visual Survey Form – Guatemala

Date: AM PM
Surveyor:

The Building

GPS coords:	Lat: Long:		
Features			
Position	Corner Mid-terrace Detached… Other:		
Usage	Residential Multi-residential Education Commercial Health Official Community Other:		
Age		[ ] Unk*	H M L

Structural Information		**Unk***	**Confidence**
Primary structural system	☐ Masonry ☐ RC ☐ Steel ☐ Timber Other:	☐	H M L
Roof material	☐ RC slab ☐ Lamina ☐ Tiles Other:	☐	H M L
Roof pitch	☐ Flat ☐ Sloping	☐	H M L
Floor material	☐ RC slab ☐ Timber Other:	☐	H M L
Lateral load resisting system	☐ Frame ☐ Walls ☐ Bracing ☐ Comb. Other:	☐	H M L
No. storeys		☐	H M L
Storey height		☐	H M L
Diaphragms	☐ Floors ☐ Roof	☐	H M L
EQ resisting design	☐ None ☐ Low ☐ Moderate ☐ High	☐	H M L
State of preservation	☐ Low ☐ Moderate ☐ High	☐	H M L
Connection quality	☐ Low ☐ Moderate ☐ High		
Retrofitting?	☐ Y ☐ N Info:	☐	H M L
Asesimic devices	☐ Y ☐ N Info:	☐	H M L
Modifications?	☐ Y ☐ N Info:	☐	H M L
Seismic weaknesses	☐Short column ☐ Pounding ☐ S.beam-W.column ☐ Soft storey ☐ Built on slope ☐ Built on stilts ☐ Bow windows ☐ Balconies ☐ Plan irreg. ☐ Elevation irreg. ☐ Mass irreg. ☐ Opening irreg. Other:		

If masonry:

Masonry type	☐ Brick ☐ Block ☐Cut stone ☐Adobe ☐Rubble Other:	☐	H M L
Reinforcement	☐ Confined ☐ Reinforced	☐	H M L
Mortar type	☐ None ☐ Cement ☐ Lime ☐ Mud	☐	H M L
Mortar joint	☐ Filled ☐ Not filled	☐	H M L
Wall thickness		☐	H M L

If RC:

Beam dimensions		☐	H M L
Column dimensions		☐	H M L

If framed structures:

Infill wall material	☐Brick ☐Concrete block ☐Adobe Other:	☐	H M L

***Unknown H = high, M = medium, L = low**

Figure G-1 Survey form in English

Formulario Inspección Visual Rápida – Guatemala

Fecha: AM PM
Inspector:

El Edificio

GPS coords:	Lat: Long:		
Caracteristicas			
Posición	☐ Esquina ☐ 2 o más continuas ☐ Seperado… Otro:		
Uso	☐ Residencial ☐ Multi-residencial ☐ Educativo ☐ Comercial ☐ Salud ☐ Oficial ☐ Communidad Otro:		
Edad	años ☐ Moderno ☐ Medio ☐ Antiguo	[ ] Des*	A M B

Información estructurales		**Des***	**Confianza**
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B
Angluo del techo	☐ Plano ☐ En pendiente	☐	A M B
Material de piso	☐ Concreto de losa ☐ Madera Otro:	☐	A M B
Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B
Numero de pisos		☐	A M B
Altura de las pisas		☐	A M B
Diafragmas	☐ Pisos ☐ Techo	☐	A M B
Diseňo sismo-resisente	☐ Ninguno ☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Estado de conservación	☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Construido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		

Si mampostería:

Tipo de mampostería	☐ Ladrillo ☐ Block ☐Piedra cortada ☐Adobe ☐Escombros desechos Other:	☐	A M B
Reforzadas	☐ Confinada ☐ Reinforzada	☐	A M B
Tipe de mortero	☐ Ninguno ☐ Cemento ☐ Cal ☐ Barro/lodo	☐	A M B
Juntas de mortero	☐ Llenas ☐ No llenas	☐	A M B
Espesor de paredes		☐	A M B

Si concreto reforzada:

Dimenciones de vigas		☐	A M B
Dimenciones de columnas		☐	A M B

Si estructuras de marcos:

Material de paredes	☐ Ladrillo ☐ Block ☐Adobe Otro:	☐	A M B

***deconocidos A = alto, M = medio, B = bajo**

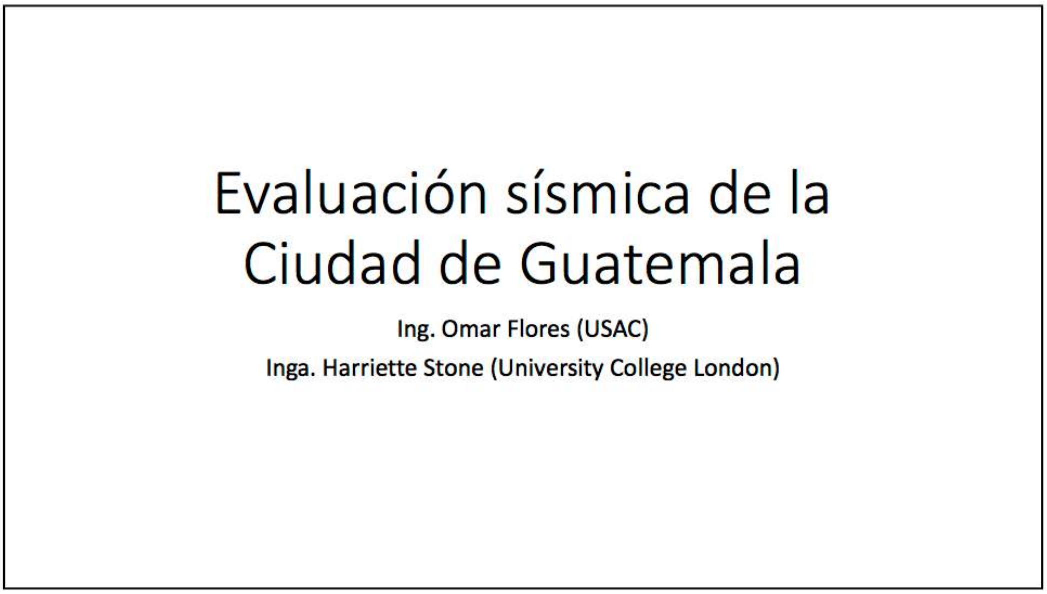
Figure G-2 Survey form in Spanish

Appendix H: Student surveyor info

Date	**8th August 2016**	**9th August 2016**	**10th August 2016**	**11th August 2016**	**12th August 2016**
Zones	12	12	1	1	14
Student volunteers	JS AC CP EG VS	JS AC BS JR ACh BE LC RL EG VS	JS AC LC AM	JS BE	RL LC CP

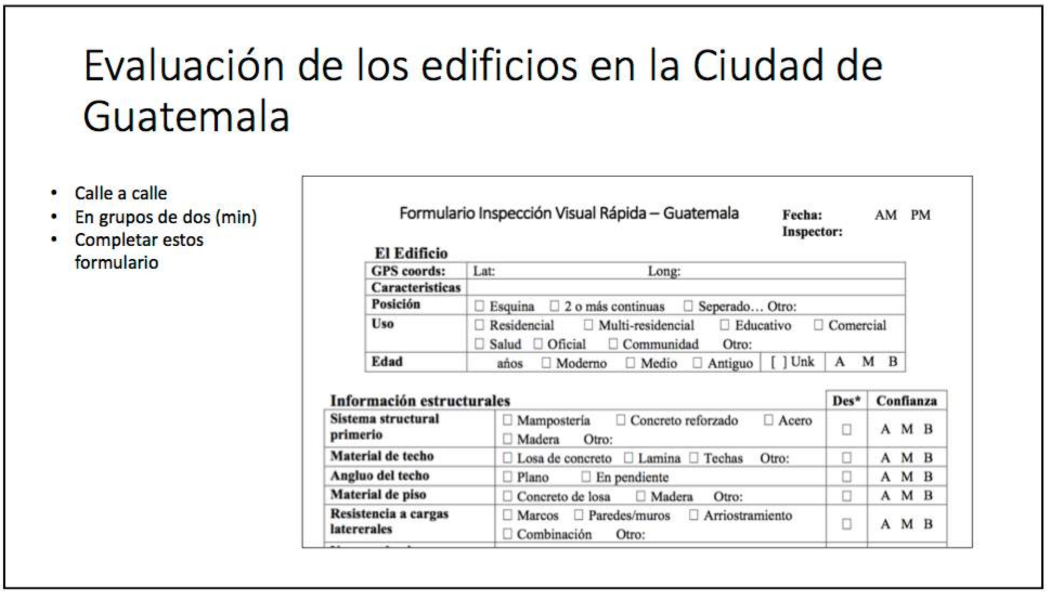
Table H-1 Student volunteer numbers. Only initials are used.

Appendix I: Presentation slides for the RVS briefing



Evaluación sísmica de la Ciudad de Guatemala

Ing. Omar Flores (USAC)
Inga. Harriette Stone (University College London)



Evaluación de los edificios en la Ciudad de Guatemala

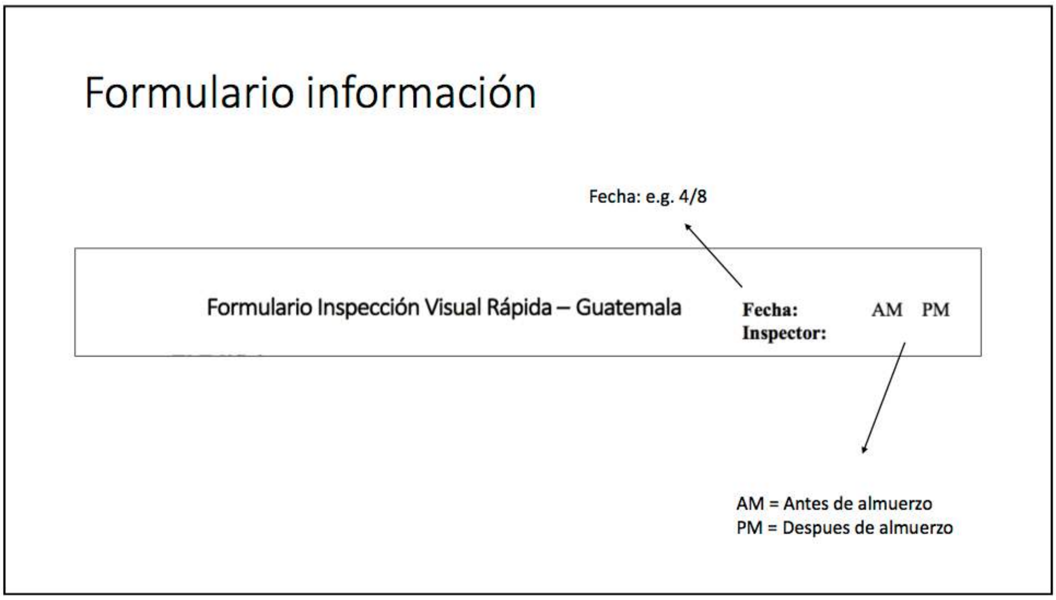
- Calle a calle
- En grupos de dos (min)
- Completar estos formulario

Formulario Inspección Visual Rápida – Guatemala **Fecha:** AM PM
Inspector:

El Edificio

GPS coords:	Lat: Long:		
Caracteristicas			
Posición	☐ Esquina ☐ 2 o más continuas ☐ Seperado… Otro:		
Uso	☐ Residencial ☐ Multi-residencial ☐ Educativo ☐ Comercial ☐ Salud ☐ Oficial ☐ Communidad Otro:		
Edad	años ☐ Moderno ☐ Medio ☐ Antiguo	[ ] Unk	A M B

Información estructurales		**Des***	**Confianza**
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B
Angluo del techo	☐ Plano ☐ En pendiente	☐	A M B
Material de piso	☐ Concreto de losa ☐ Madera Otro:	☐	A M B
Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B



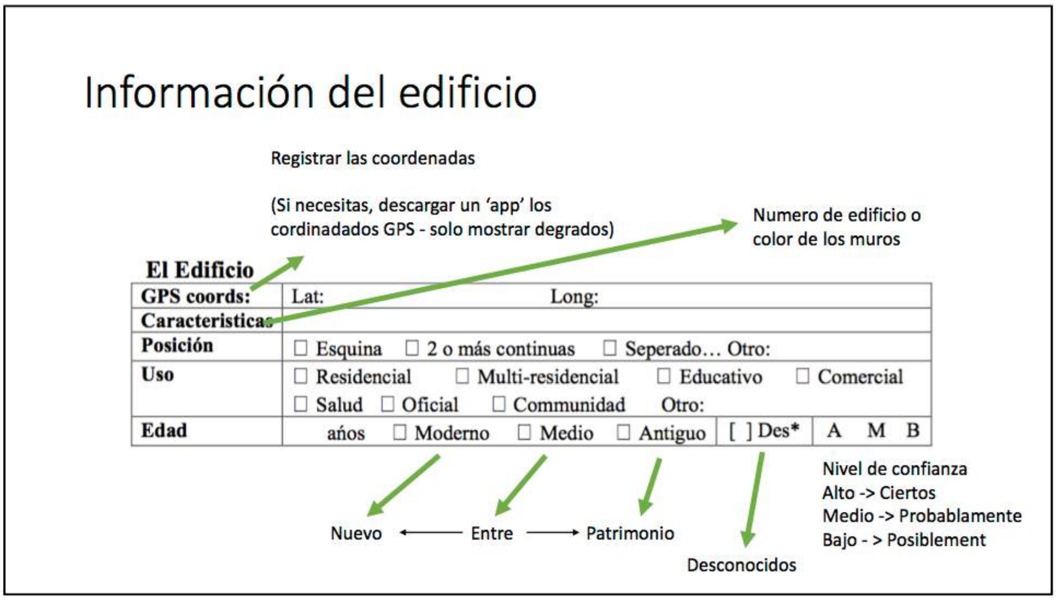
Formulario información

Fecha: e.g. 4/8

Formulario Inspección Visual Rápida – Guatemala

Fecha: AM PM
Inspector:

AM = Antes de almuerzo
PM = Despues de almuerzo



Información del edificio

Registrar las coordenadas

(Si necesitas, descargar un 'app' los cordinadados GPS - solo mostrar degrados)

Numero de edificio o color de los muros

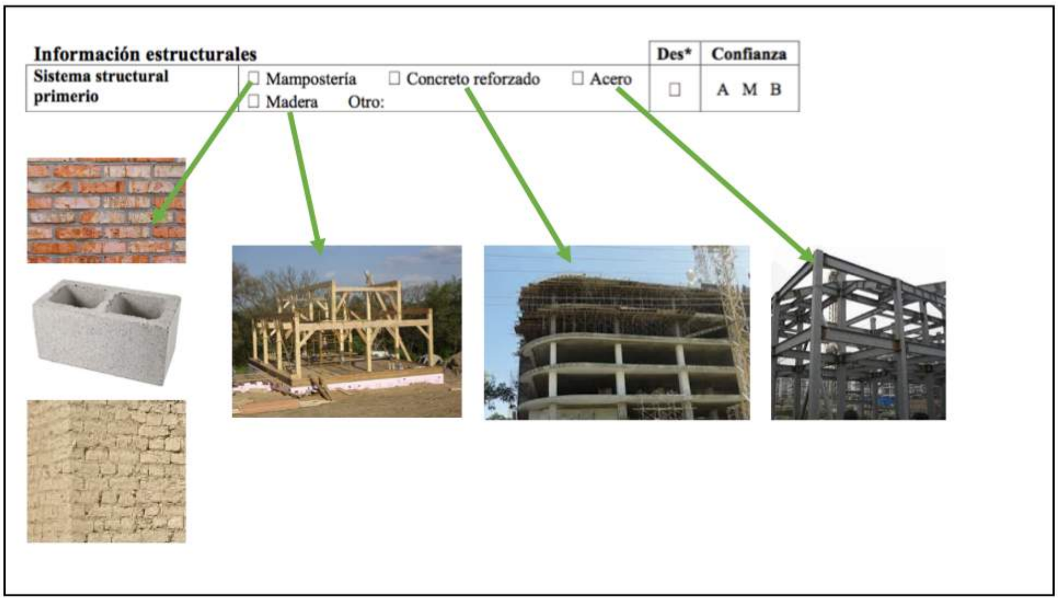
El Edificio

GPS coords:	Lat: Long:
Caracteristicas	
Posición	☐ Esquina ☐ 2 o más continuas ☐ Seperado… Otro:
Uso	☐ Residencial ☐ Multi-residencial ☐ Educativo ☐ Comercial ☐ Salud ☐ Oficial ☐ Communidad Otro:
Edad	años ☐ Moderno ☐ Medio ☐ Antiguo | [ ] Des* | A M B

Nuevo ← Entre → Patrimonio

Desconocidos

Nivel de confianza
Alto -> Ciertos
Medio -> Probablamente
Bajo - > Posiblement



Información estructurales

		Des*	Confianza
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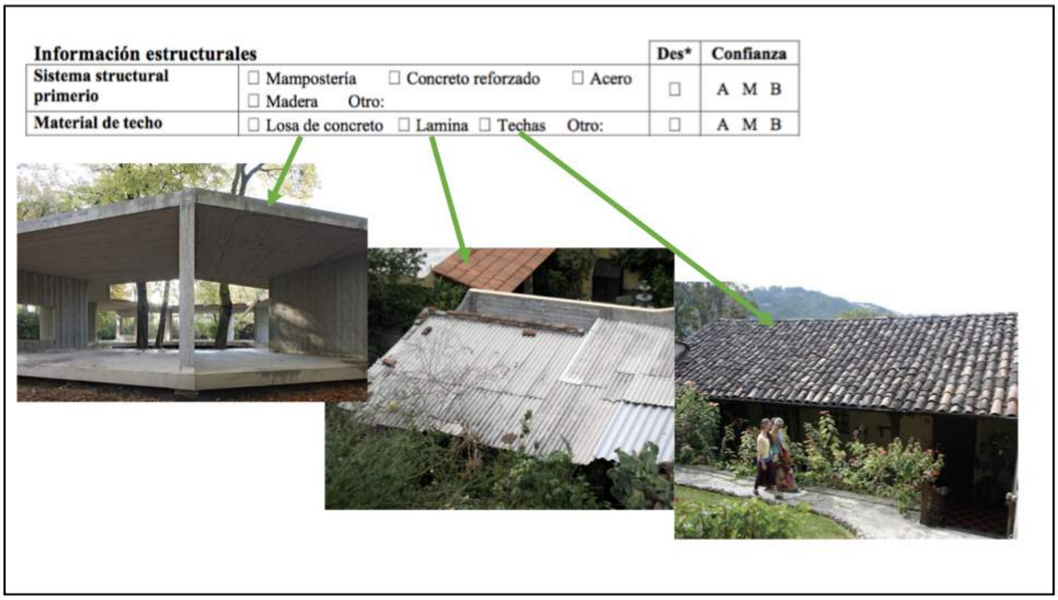
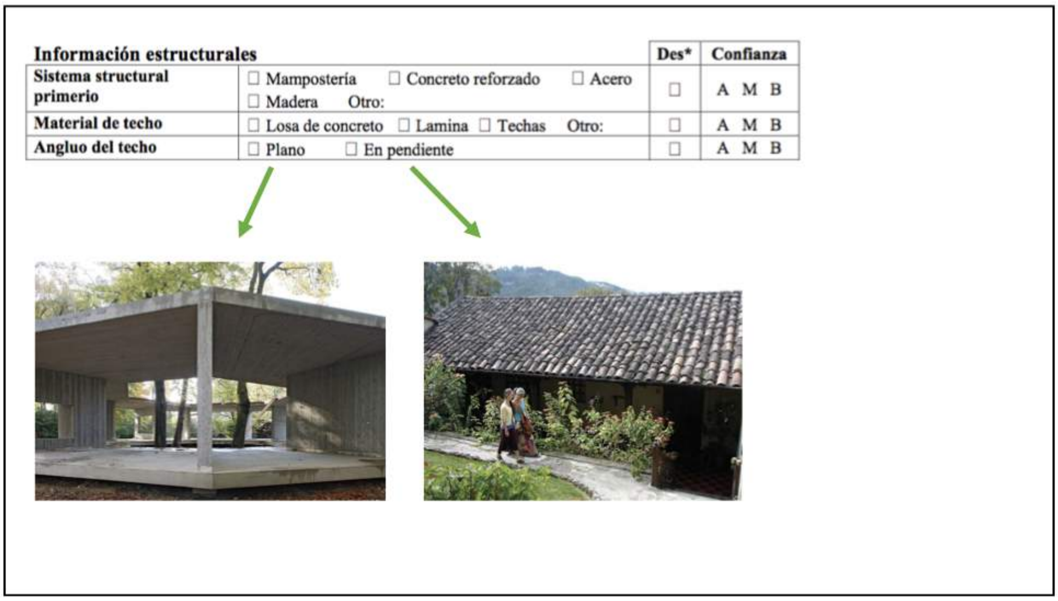
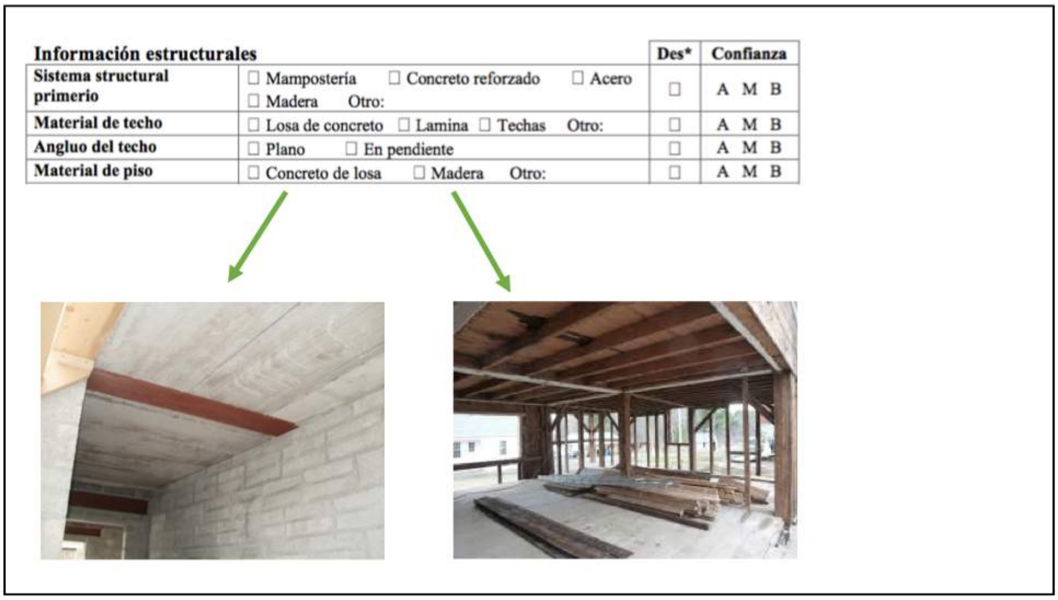


Información estructurales

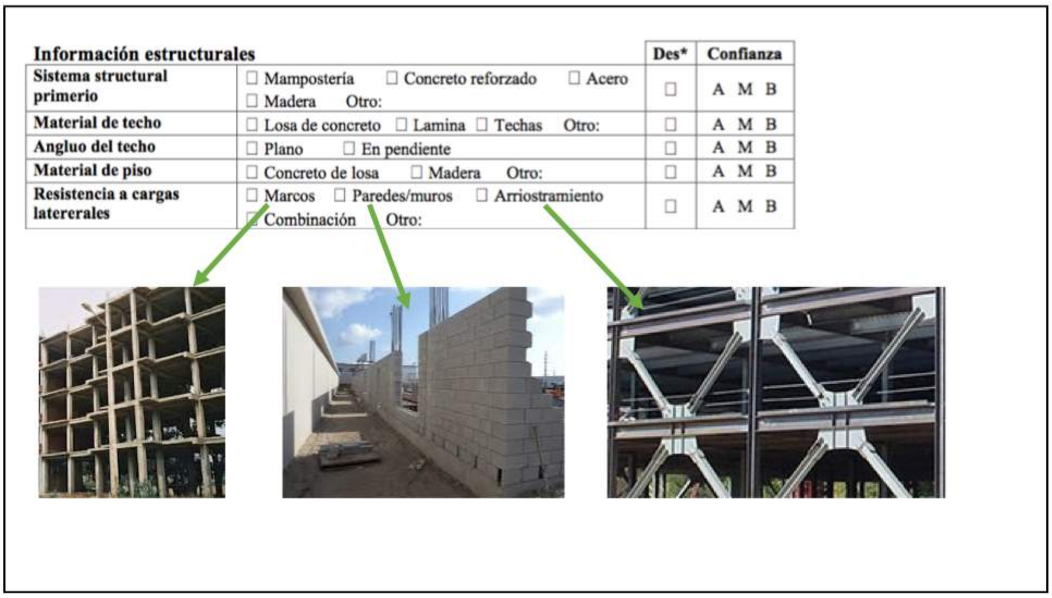
		Des*	Confianza
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B



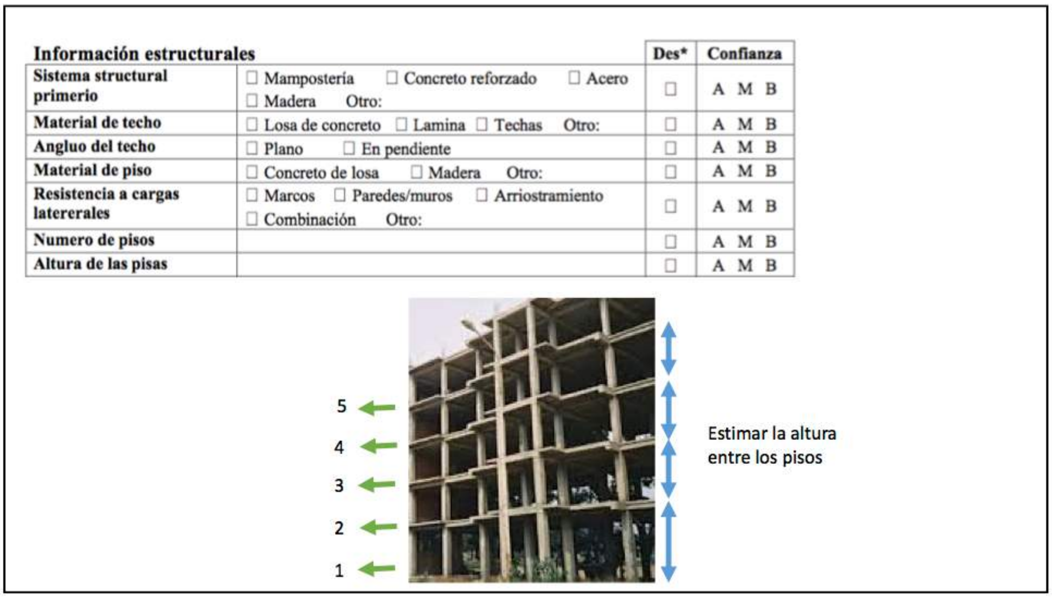
Información estructurales		**Des***	**Confianza**
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B
Angluo del techo	☐ Plano ☐ En pendiente	☐	A M B



Información estructurales		**Des***	**Confianza**
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B
Angluo del techo	☐ Plano ☐ En pendiente	☐	A M B
Material de piso	☐ Concreto de losa ☐ Madera Otro:	☐	A M B

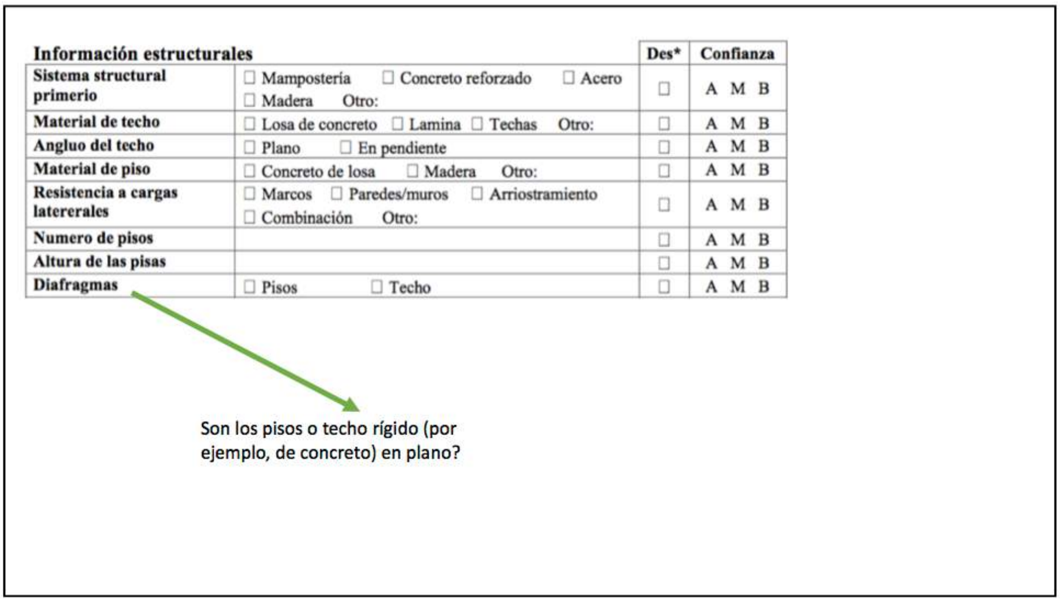


Información estructurales		Des*	Confianza
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B
Angluo del techo	☐ Plano ☐ En pendiente	☐	A M B
Material de piso	☐ Concreto de losa ☐ Madera Otro:	☐	A M B
Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B



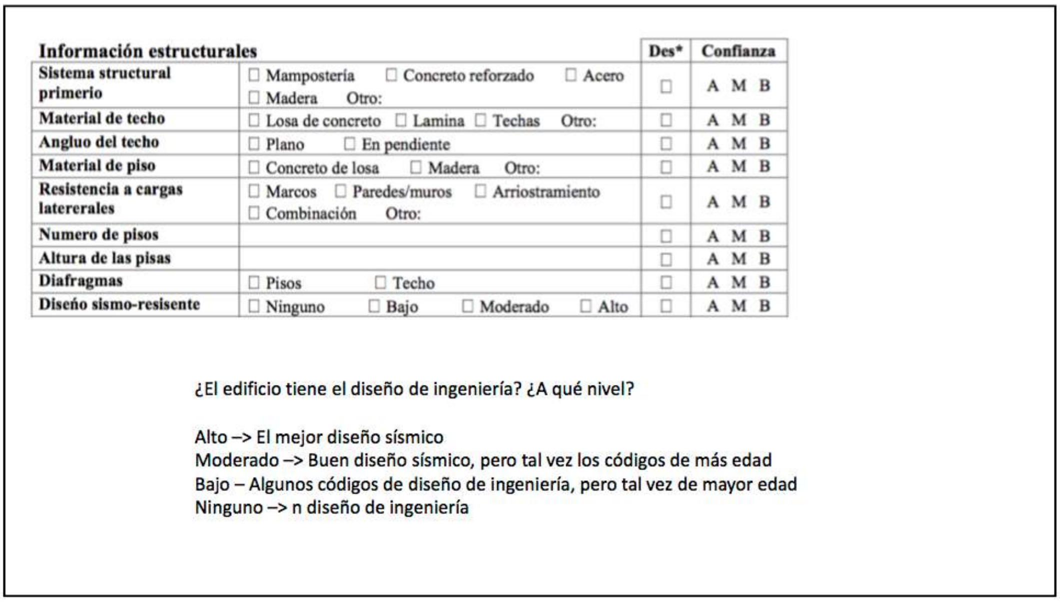
Información estructurales		Des*	Confianza
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B
Angluo del techo	☐ Plano ☐ En pendiente	☐	A M B
Material de piso	☐ Concreto de losa ☐ Madera Otro:	☐	A M B
Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B
Numero de pisos		☐	A M B
Altura de las pisas		☐	A M B

Estimar la altura entre los pisos



Información estructurales		**Des***	**Confianza**
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B
Angluo del techo	☐ Plano ☐ En pendiente	☐	A M B
Material de piso	☐ Concreto de losa ☐ Madera Otro:	☐	A M B
Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B
Numero de pisos		☐	A M B
Altura de las pisas		☐	A M B
Diafragmas	☐ Pisos ☐ Techo	☐	A M B

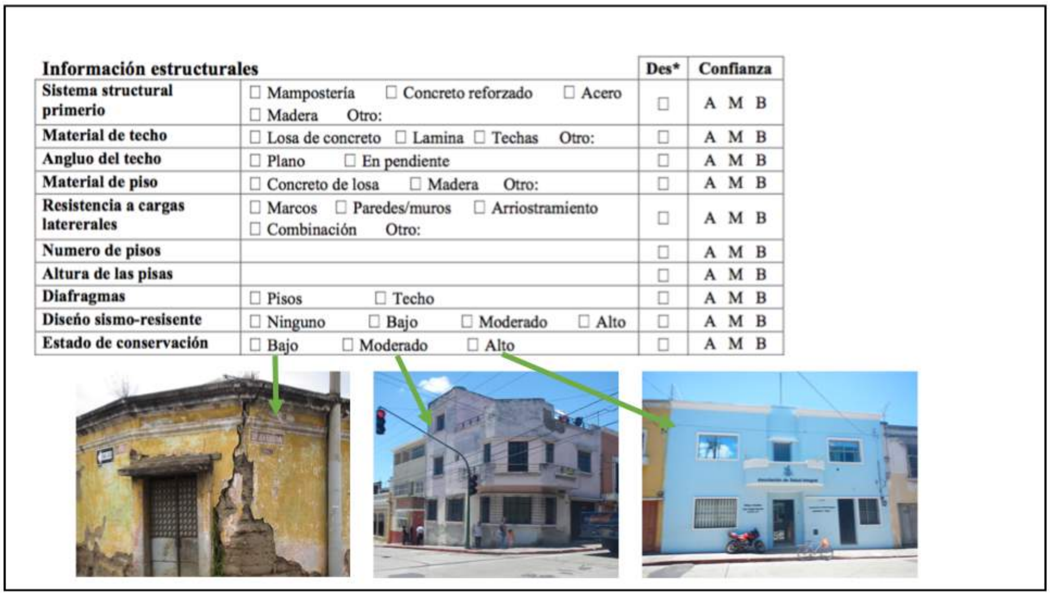
Son los pisos o techo rígido (por ejemplo, de concreto) en plano?



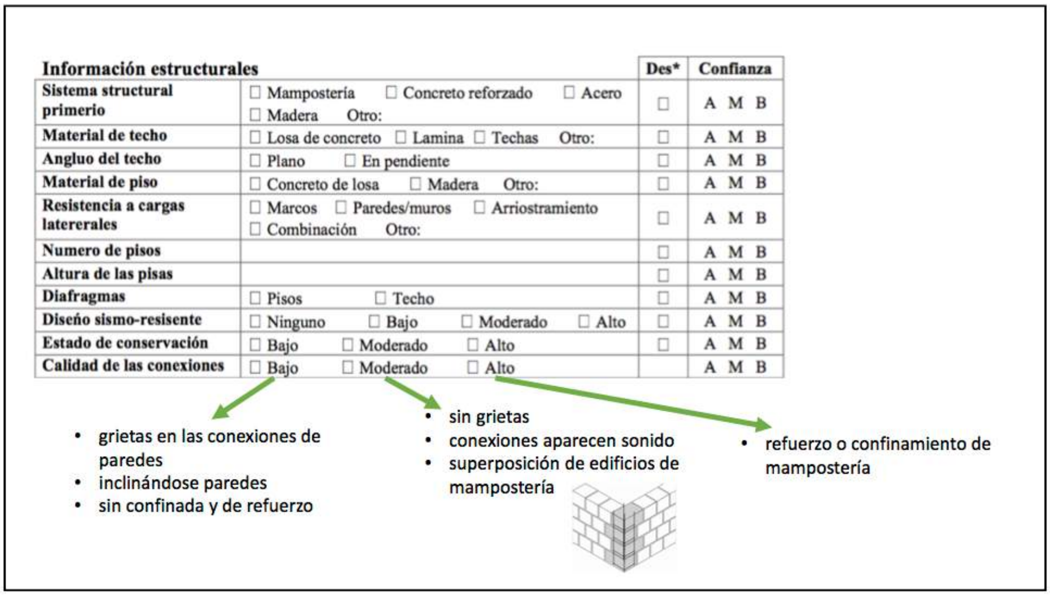
Información estructurales		**Des***	**Confianza**
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B
Angluo del techo	☐ Plano ☐ En pendiente	☐	A M B
Material de piso	☐ Concreto de losa ☐ Madera Otro:	☐	A M B
Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B
Numero de pisos		☐	A M B
Altura de las pisas		☐	A M B
Diafragmas	☐ Pisos ☐ Techo	☐	A M B
Diseño sismo-resisente	☐ Ninguno ☐ Bajo ☐ Moderado ☐ Alto	☐	A M B

¿El edificio tiene el diseño de ingeniería? ¿A qué nivel?

Alto –> El mejor diseño sísmico
Moderado –> Buen diseño sísmico, pero tal vez los códigos de más edad
Bajo – Algunos códigos de diseño de ingeniería, pero tal vez de mayor edad
Ninguno –> n diseño de ingeniería



Información estructurales		Des*	Confianza
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B
Angluo del techo	☐ Plano ☐ En pendiente	☐	A M B
Material de piso	☐ Concreto de losa ☐ Madera Otro:	☐	A M B
Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B
Numero de pisos		☐	A M B
Altura de las pisas		☐	A M B
Diafragmas	☐ Pisos ☐ Techo	☐	A M B
Diseño sismo-resisente	☐ Ninguno ☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Estado de conservación	☐ Bajo ☐ Moderado ☐ Alto	☐	A M B

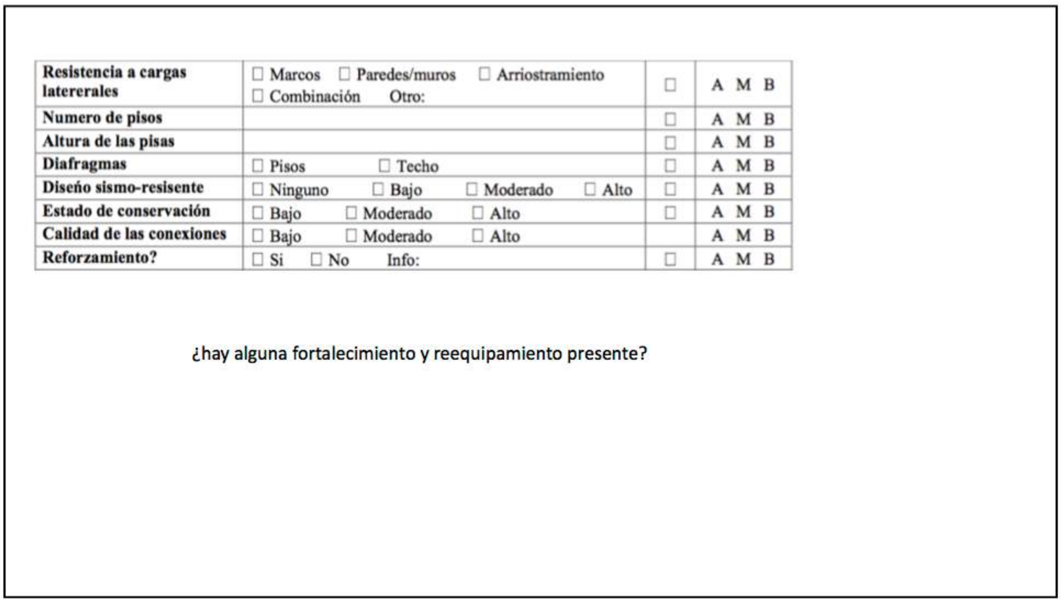


Información estructurales		Des*	Confianza
Sistema structural primerio	☐ Mampostería ☐ Concreto reforzado ☐ Acero ☐ Madera Otro:	☐	A M B
Material de techo	☐ Losa de concreto ☐ Lamina ☐ Techas Otro:	☐	A M B
Angluo del techo	☐ Plano ☐ En pendiente	☐	A M B
Material de piso	☐ Concreto de losa ☐ Madera Otro:	☐	A M B
Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B
Numero de pisos		☐	A M B
Altura de las pisas		☐	A M B
Diafragmas	☐ Pisos ☐ Techo	☐	A M B
Diseño sismo-resisente	☐ Ninguno ☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Estado de conservación	☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B

- grietas en las conexiones de paredes
- inclinándose paredes
- sin confinada y de refuerzo

- sin grietas
- conexiones aparecen sonido
- superposición de edificios de mampostería

- refuerzo o confinamiento de mampostería

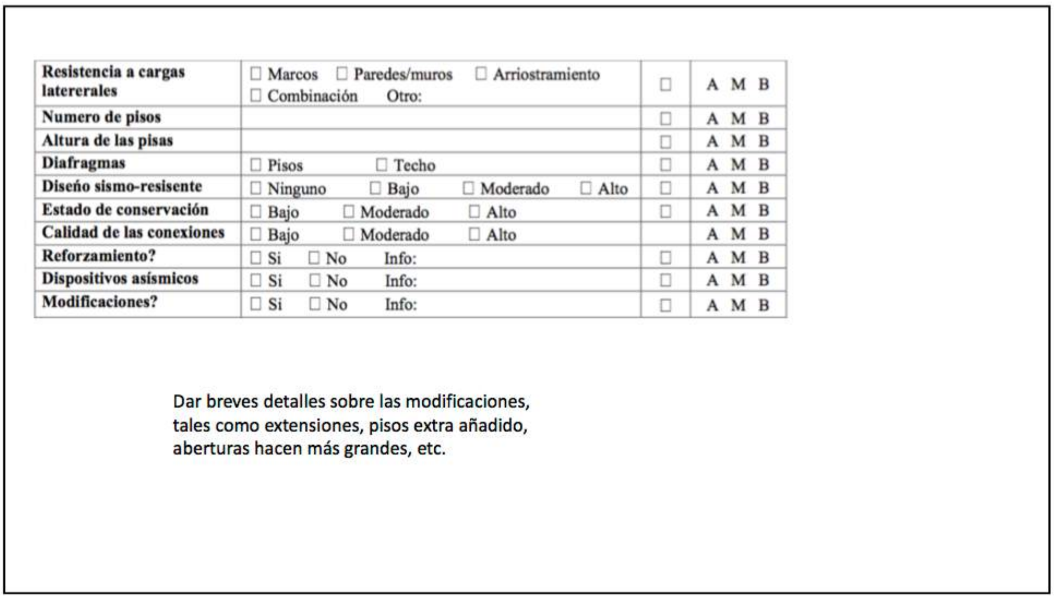


Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B
Numero de pisos		☐	A M B
Altura de las pisas		☐	A M B
Diafragmas	☐ Pisos ☐ Techo	☐	A M B
Diseño sismo-resisente	☐ Ninguno ☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Estado de conservación	☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B

¿hay alguna fortalecimiento y reequipamiento presente?

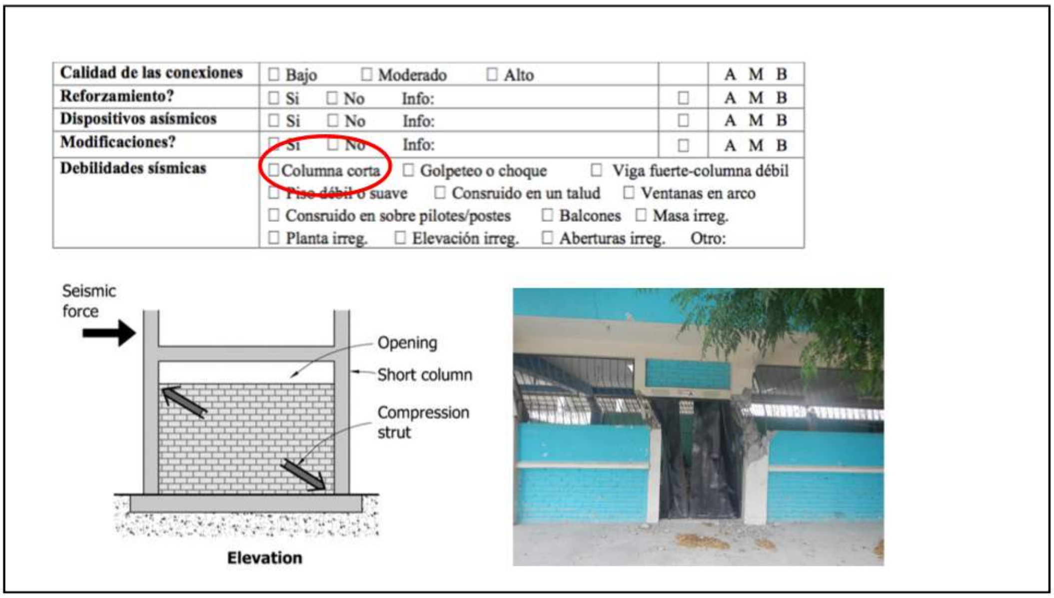
Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B
Numero de pisos		☐	A M B
Altura de las pisas		☐	A M B
Diafragmas	☐ Pisos ☐ Techo	☐	A M B
Diseño sismo-resisente	☐ Ninguno ☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Estado de conservación	☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B

Tecnología normalmente sólo se
utiliza en edificios de gran altura
de alto valor

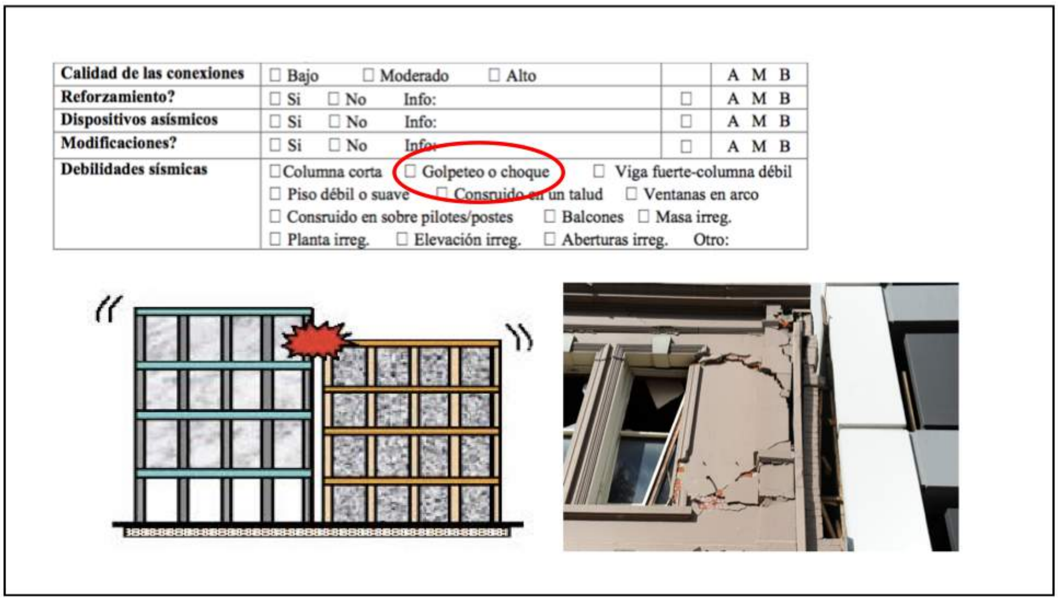


Resistencia a cargas latererales	☐ Marcos ☐ Paredes/muros ☐ Arriostramiento ☐ Combinación Otro:	☐	A M B
Numero de pisos		☐	A M B
Altura de las pisas		☐	A M B
Diafragmas	☐ Pisos ☐ Techo	☐	A M B
Diseño sismo-resisente	☐ Ninguno ☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Estado de conservación	☐ Bajo ☐ Moderado ☐ Alto	☐	A M B
Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B

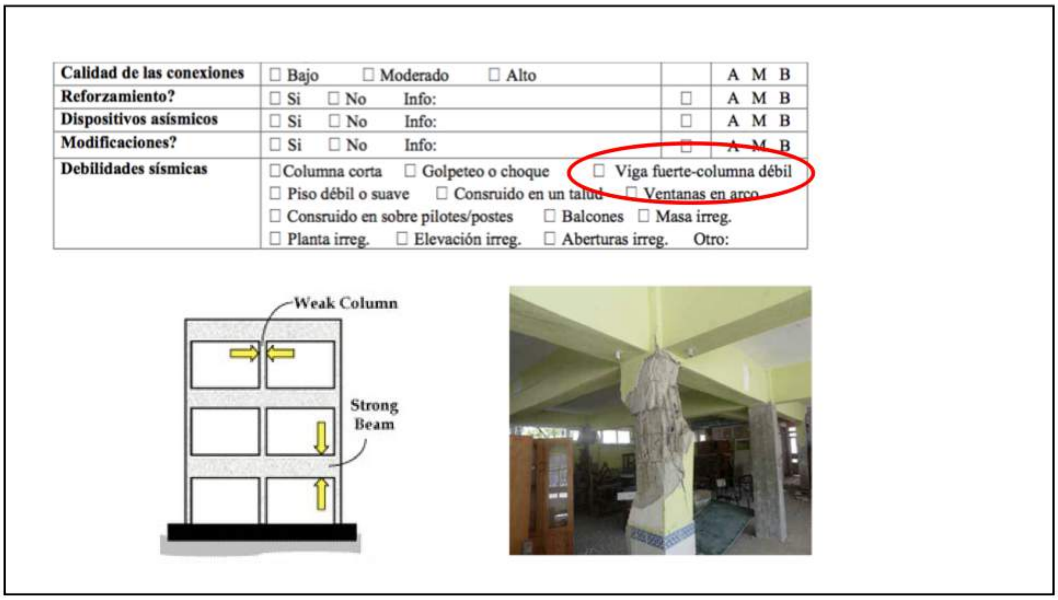
Dar breves detalles sobre las modificaciones, tales como extensiones, pisos extra añadido, aberturas hacen más grandes, etc.



Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		

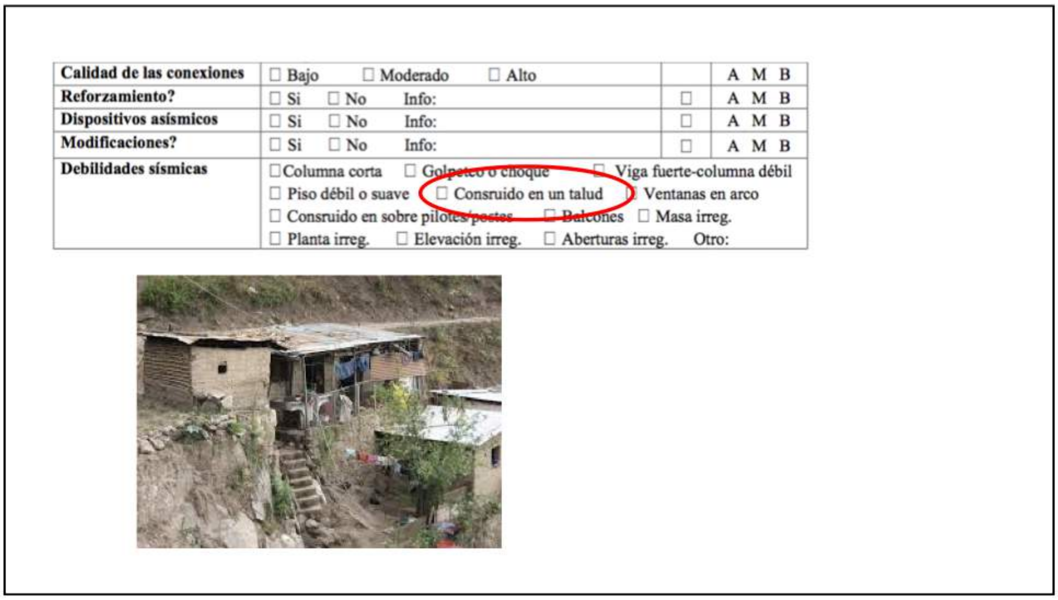


Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		

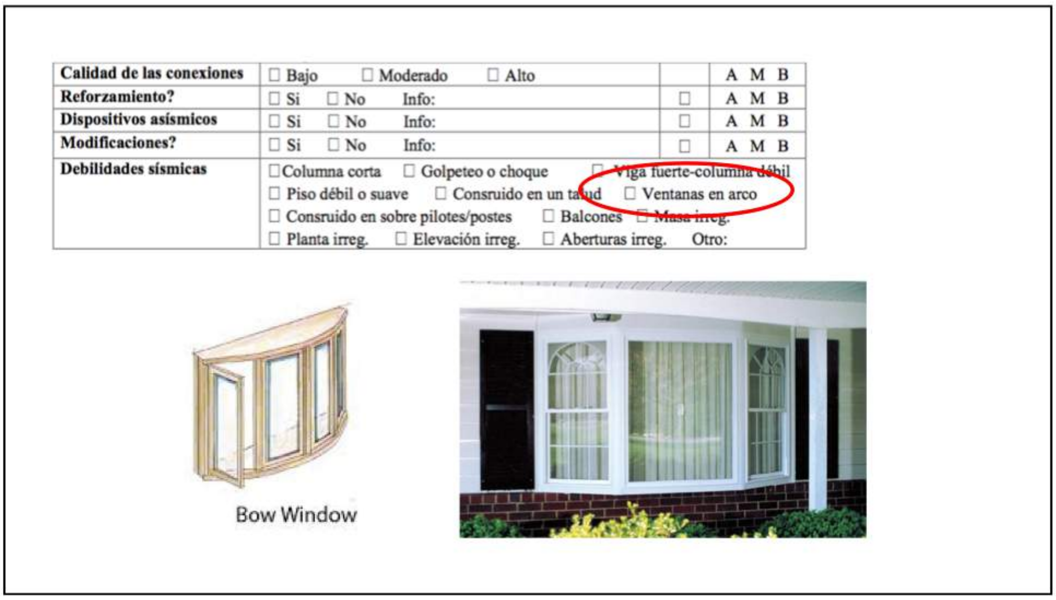


Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		

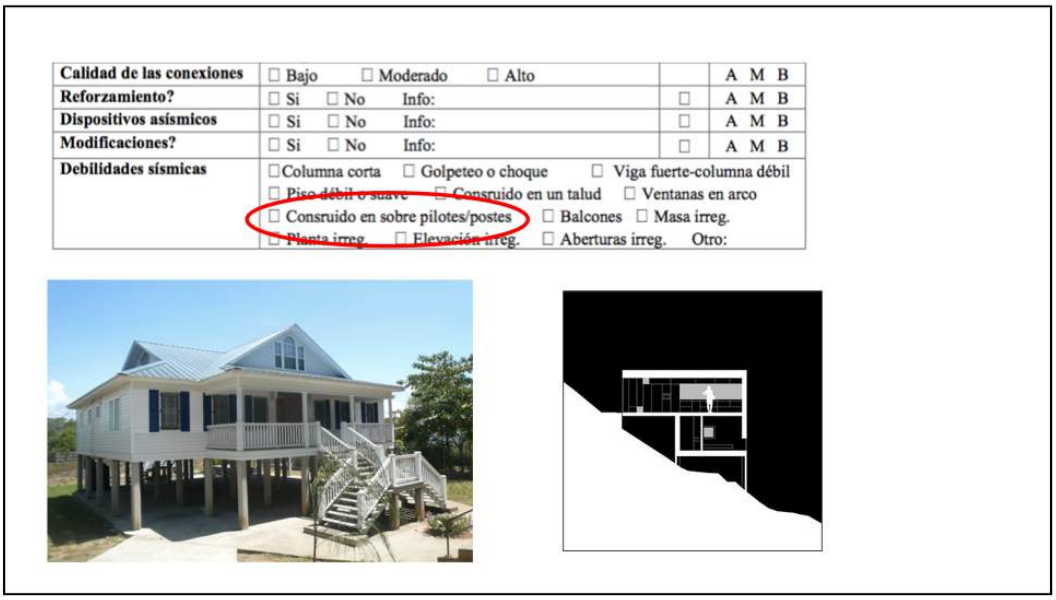
Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐ Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		



Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐ Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		

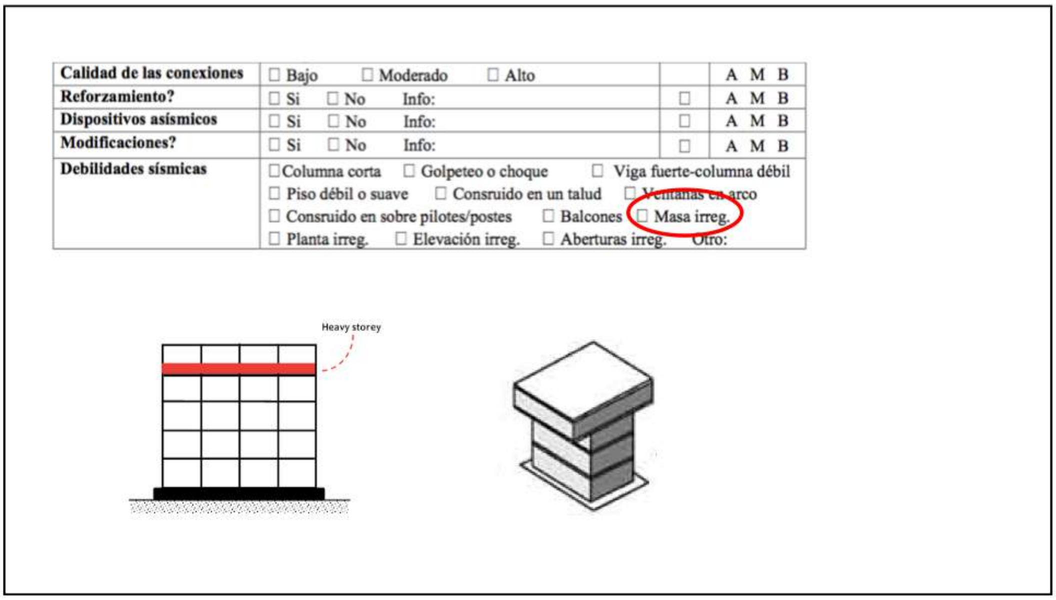


Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		

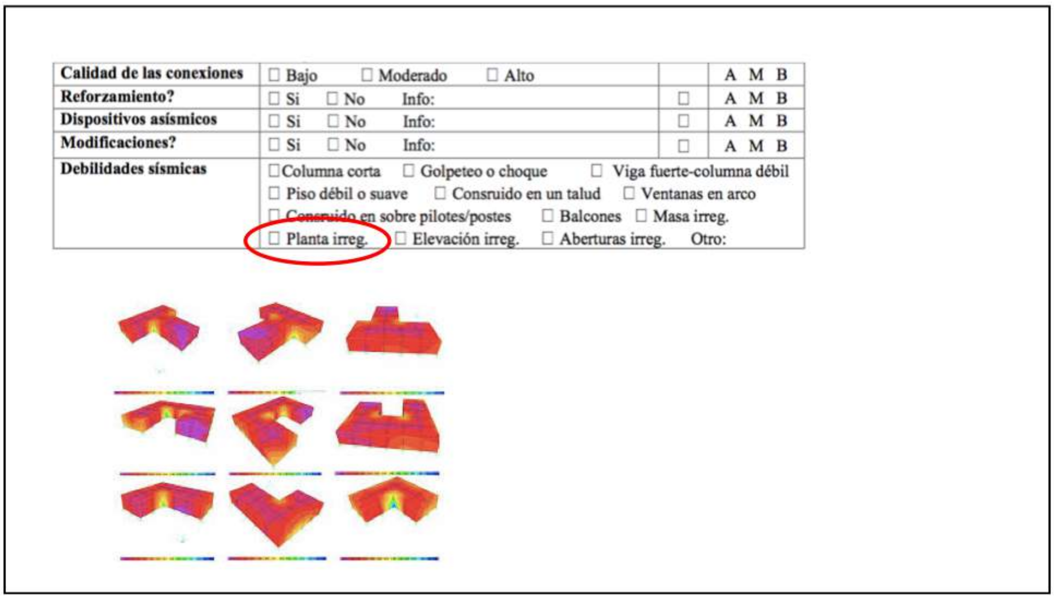


Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		

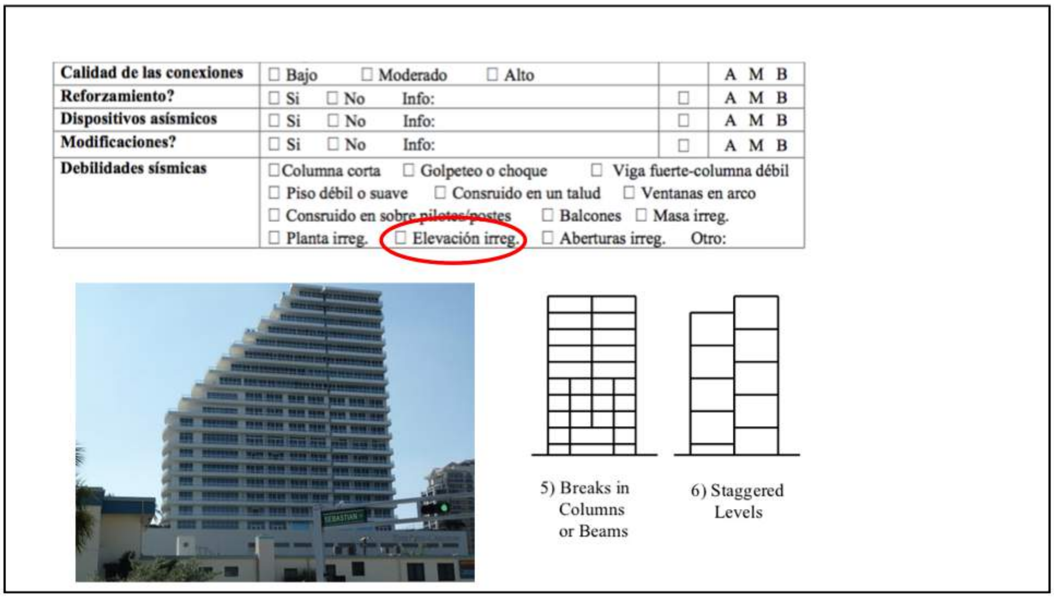
Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		



Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		



Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		

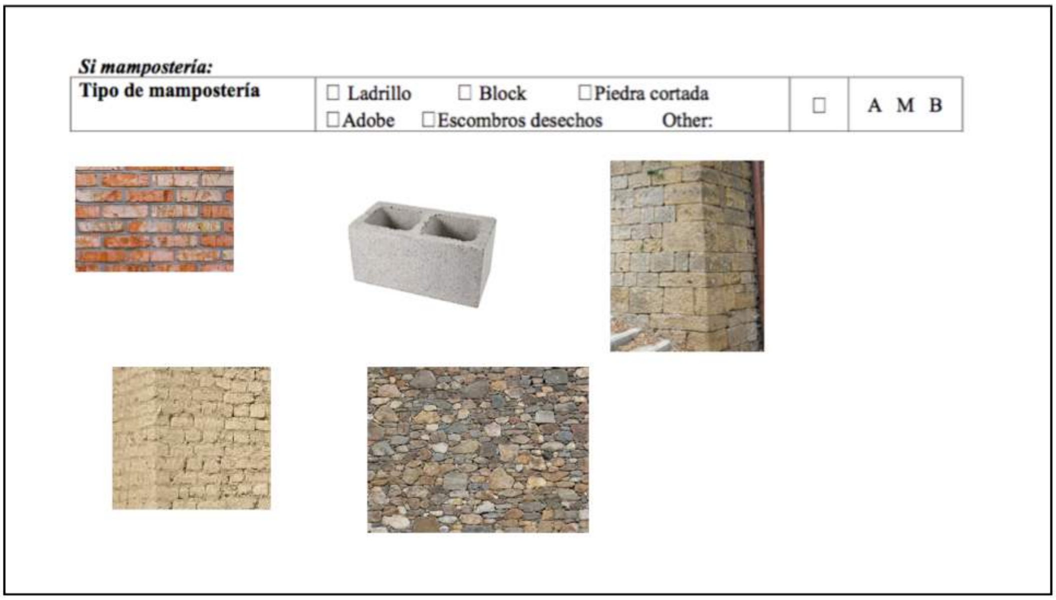


Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		

5) Breaks in Columns or Beams

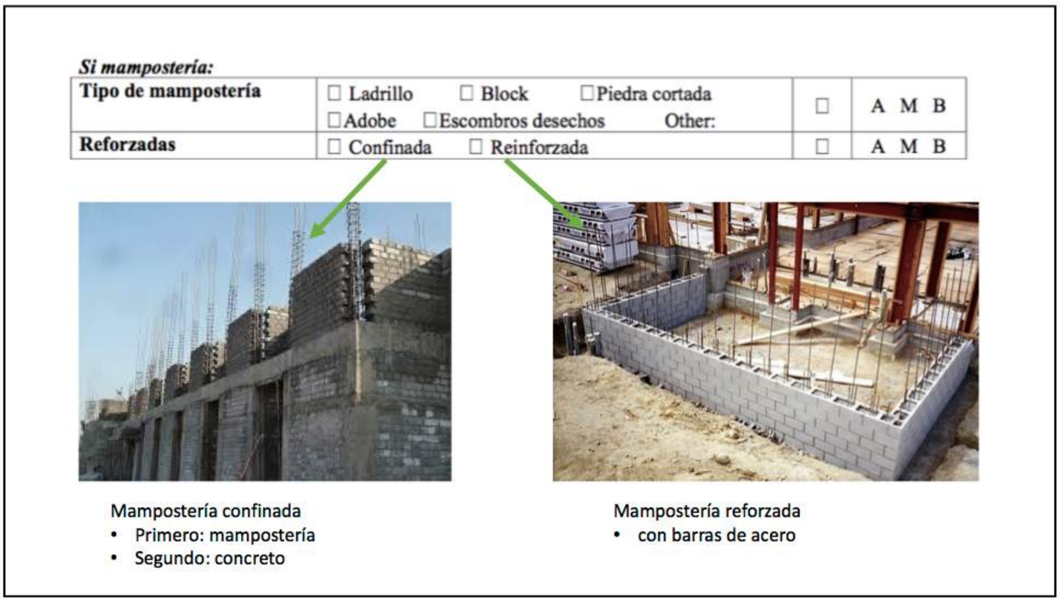
6) Staggered Levels

Calidad de las conexiones	☐ Bajo ☐ Moderado ☐ Alto		A M B
Reforzamiento?	☐ Si ☐ No Info:	☐	A M B
Dispositivos asísmicos	☐ Si ☐ No Info:	☐	A M B
Modificaciones?	☐ Si ☐ No Info:	☐	A M B
Debilidades sísmicas	☐Columna corta ☐ Golpeteo o choque ☐ Viga fuerte-columna débil ☐ Piso débil o suave ☐ Consruido en un talud ☐ Ventanas en arco ☐ Consruido en sobre pilotes/postes ☐ Balcones ☐ Masa irreg. ☐ Planta irreg. ☐ Elevación irreg. ☐ Aberturas irreg. Otro:		



Si mampostería:

Tipo de mampostería	☐ Ladrillo ☐ Block ☐Piedra cortada ☐Adobe ☐Escombros desechos Other:	☐	A M B

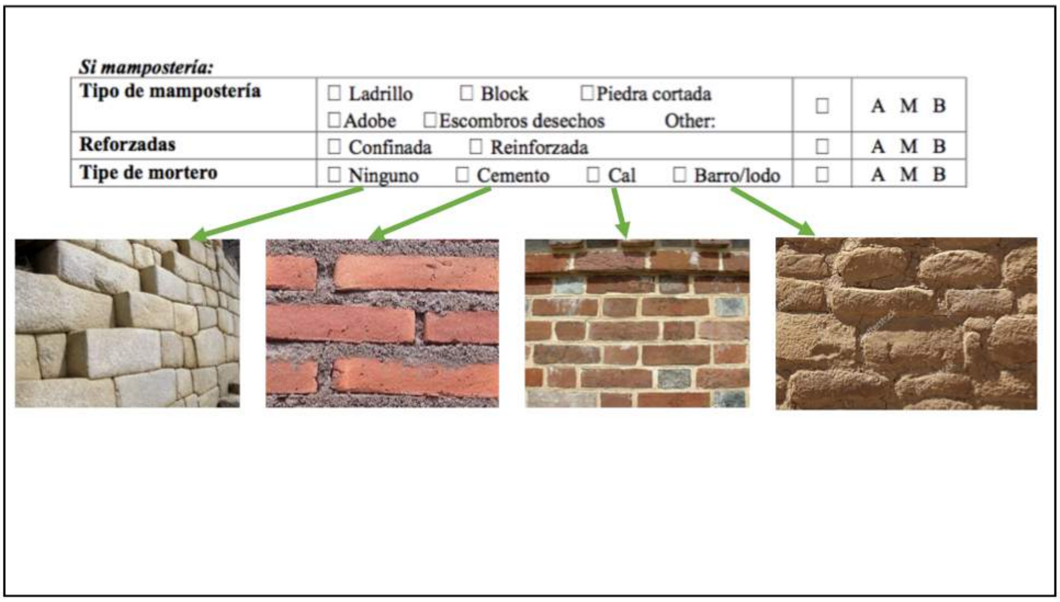


Si mampostería:

Tipo de mampostería	☐ Ladrillo ☐ Block ☐Piedra cortada ☐Adobe ☐Escombros desechos Other:	☐	A M B
Reforzadas	☐ Confinada ☐ Reinforzada	☐	A M B

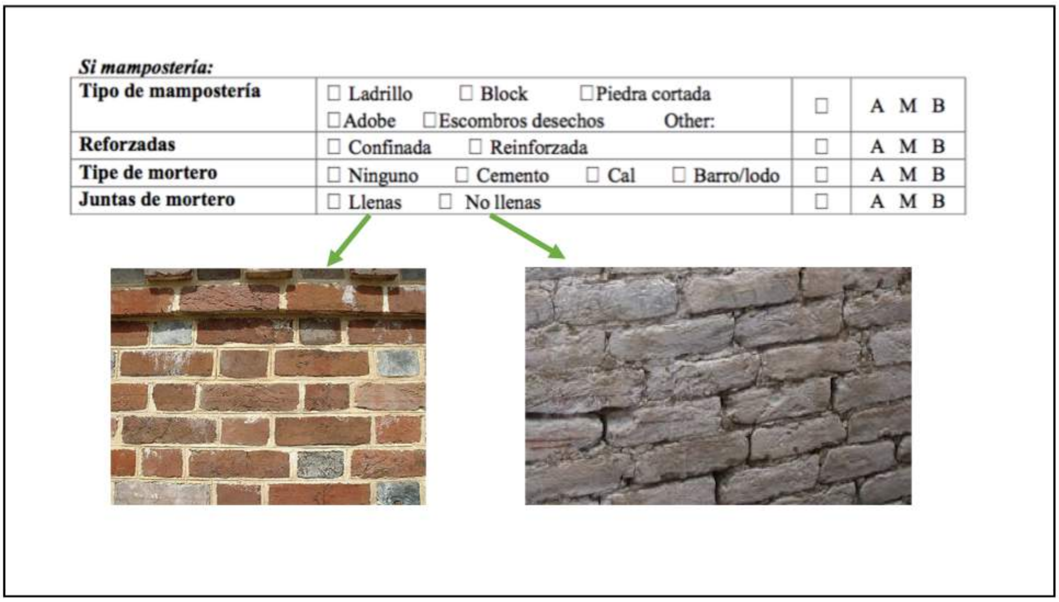
Mampostería confinada
- Primero: mampostería
- Segundo: concreto

Mampostería reforzada
- con barras de acero



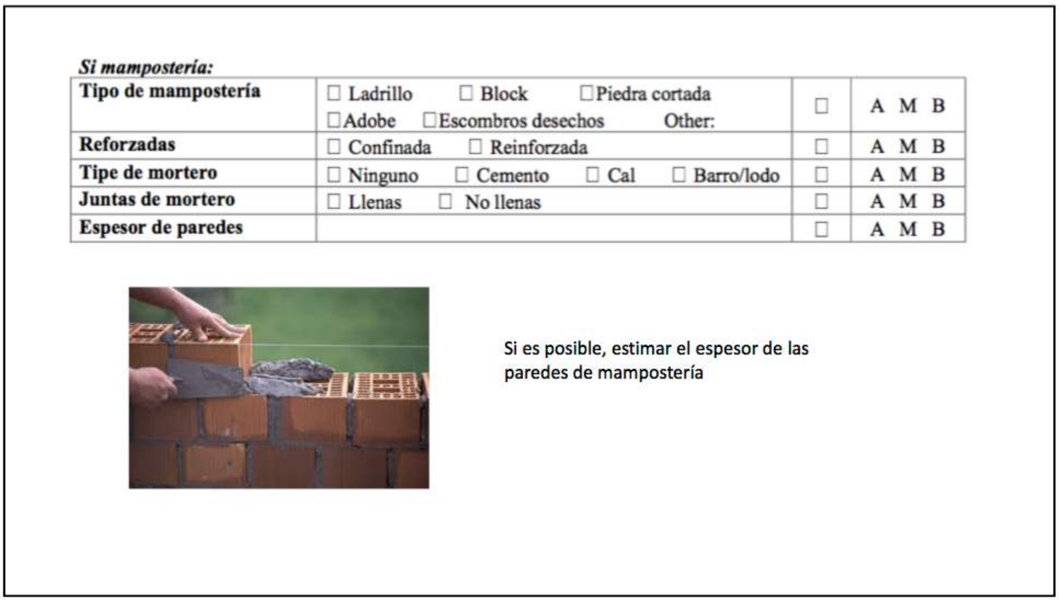
Si mampostería:

Tipo de mampostería	☐ Ladrillo ☐ Block ☐Piedra cortada ☐Adobe ☐Escombros desechos Other:	☐	A M B
Reforzadas	☐ Confinada ☐ Reinforzada	☐	A M B
Tipe de mortero	☐ Ninguno ☐ Cemento ☐ Cal ☐ Barro/lodo	☐	A M B



Si mampostería:

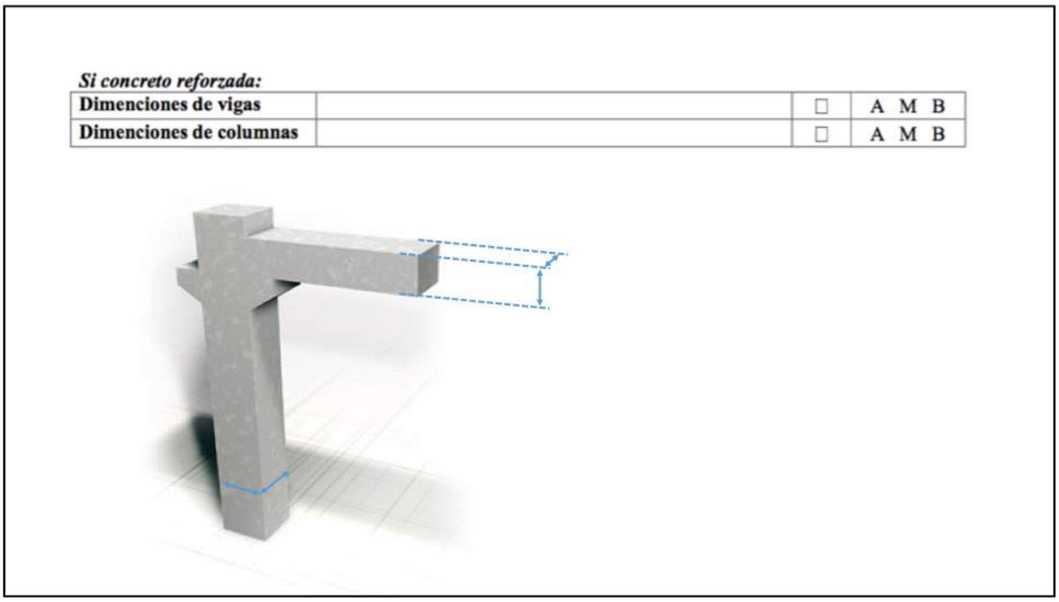
Tipo de mampostería	☐ Ladrillo ☐ Block ☐Piedra cortada ☐Adobe ☐Escombros desechos Other:	☐	A M B
Reforzadas	☐ Confinada ☐ Reinforzada	☐	A M B
Tipe de mortero	☐ Ninguno ☐ Cemento ☐ Cal ☐ Barro/lodo	☐	A M B
Juntas de mortero	☐ Llenas ☐ No llenas	☐	A M B



Si mampostería:

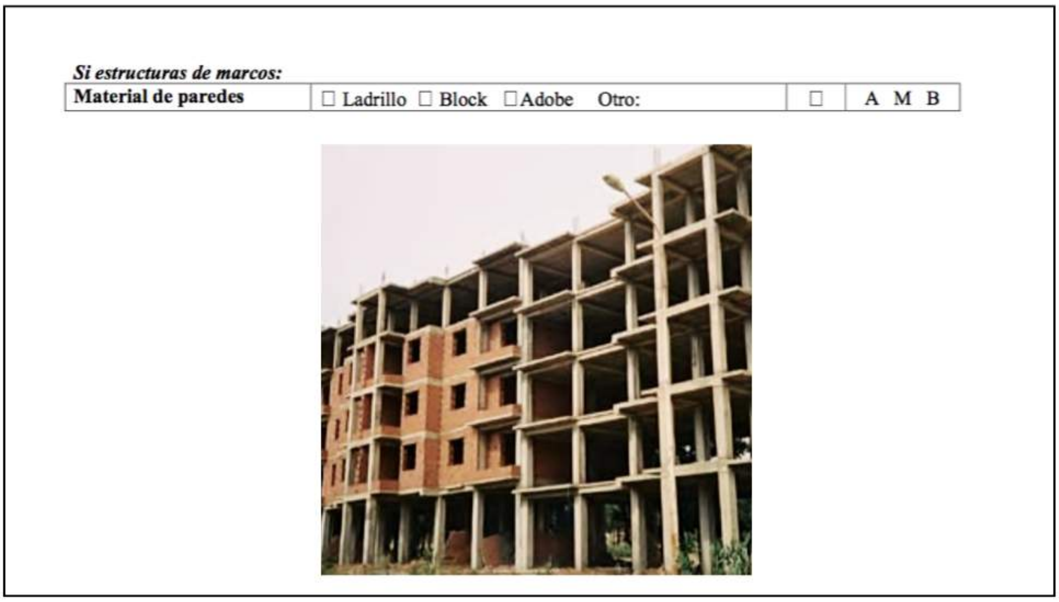
Tipo de mampostería	☐ Ladrillo ☐ Block ☐Piedra cortada ☐Adobe ☐Escombros desechos Other:	☐	A M B
Reforzadas	☐ Confinada ☐ Reinforzada	☐	A M B
Tipe de mortero	☐ Ninguno ☐ Cemento ☐ Cal ☐ Barro/lodo	☐	A M B
Juntas de mortero	☐ Llenas ☐ No llenas	☐	A M B
Espesor de paredes		☐	A M B

Si es posible, estimar el espesor de las paredes de mampostería



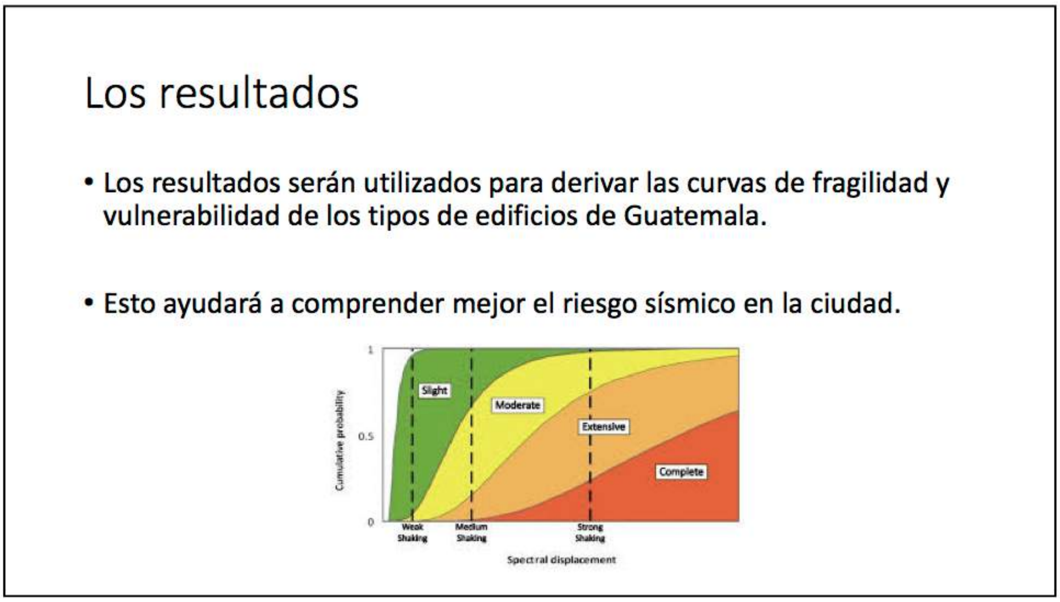
Si concreto reforzada:

Dimenciones de vigas		☐	A M B
Dimenciones de columnas		☐	A M B



Si estructuras de marcos:

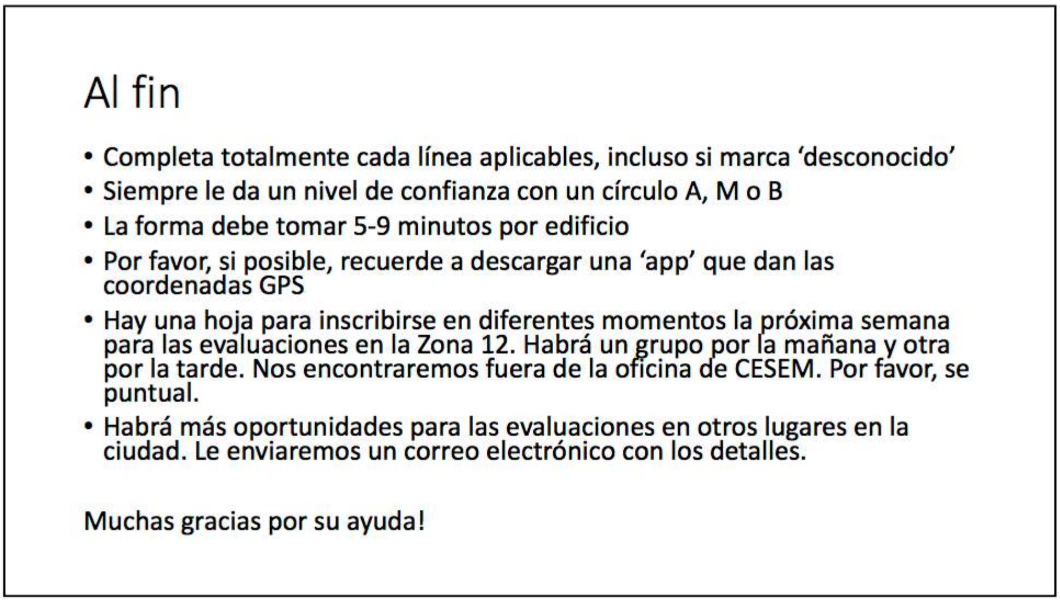
Material de paredes	☐ Ladrillo ☐ Block ☐Adobe Otro:	☐	A M B



Los resultados

- Los resultados serán utilizados para derivar las curvas de fragilidad y vulnerabilidad de los tipos de edificios de Guatemala.

- Esto ayudará a comprender mejor el riesgo sísmico en la ciudad.



Al fin

- Completa totalmente cada línea aplicables, incluso si marca 'desconocido'
- Siempre le da un nivel de confianza con un círculo A, M o B
- La forma debe tomar 5-9 minutos por edificio
- Por favor, si posible, recuerde a descargar una 'app' que dan las coordenadas GPS
- Hay una hoja para inscribirse en diferentes momentos la próxima semana para las evaluaciones en la Zona 12. Habrá un grupo por la mañana y otra por la tarde. Nos encontraremos fuera de la oficina de CESEM. Por favor, se puntual.
- Habrá más oportunidades para las evaluaciones en otros lugares en la ciudad. Le enviaremos un correo electrónico con los detalles.

Muchas gracias por su ayuda!

Appendix J: UAV flight locations

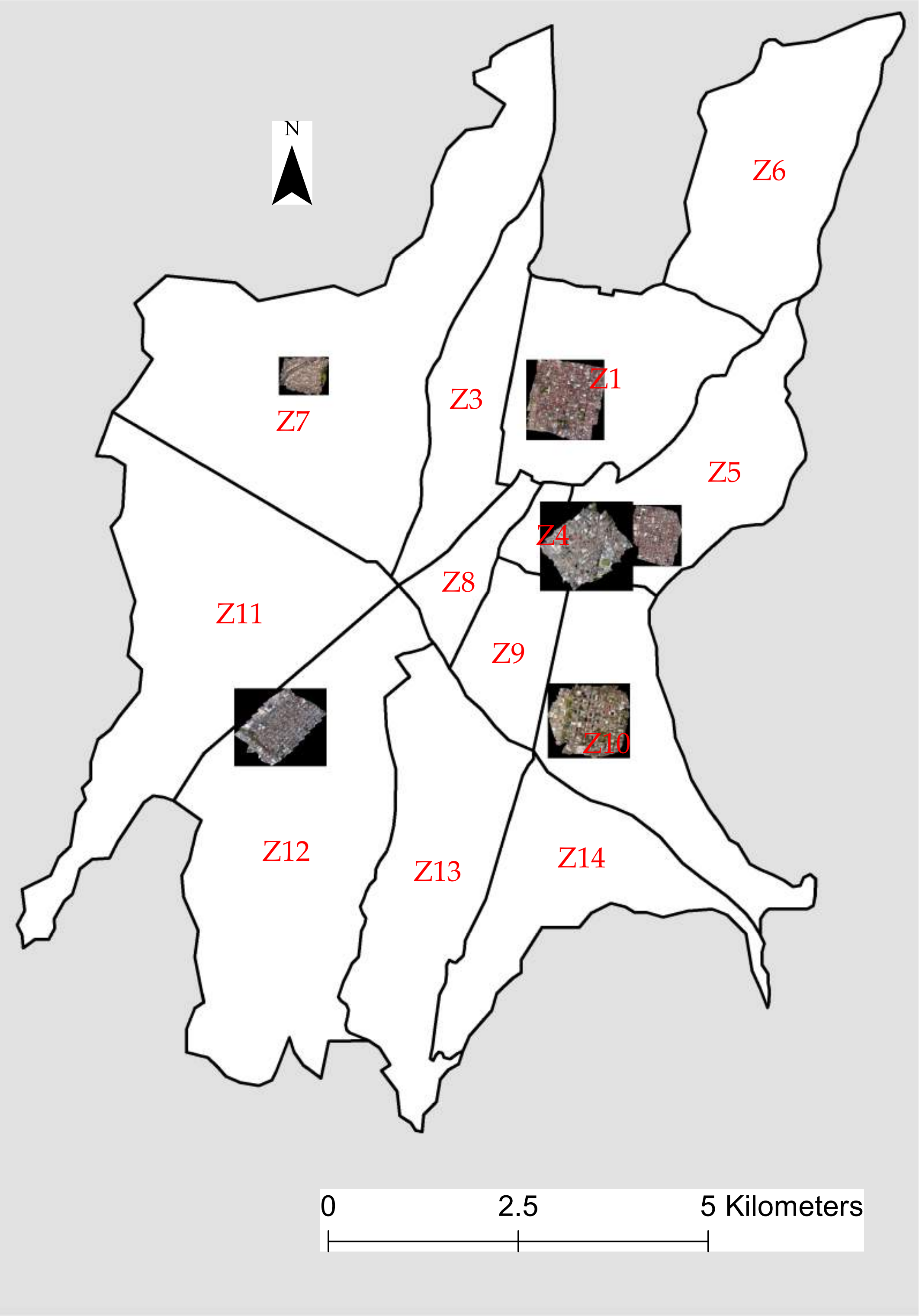


Figure J-1 Study area map with the locations of the UAV surveys

Appendix K: Views from the 3D models

Figure K-1 Zone 1 3D model

Figure K-2 Zone 4 3D model

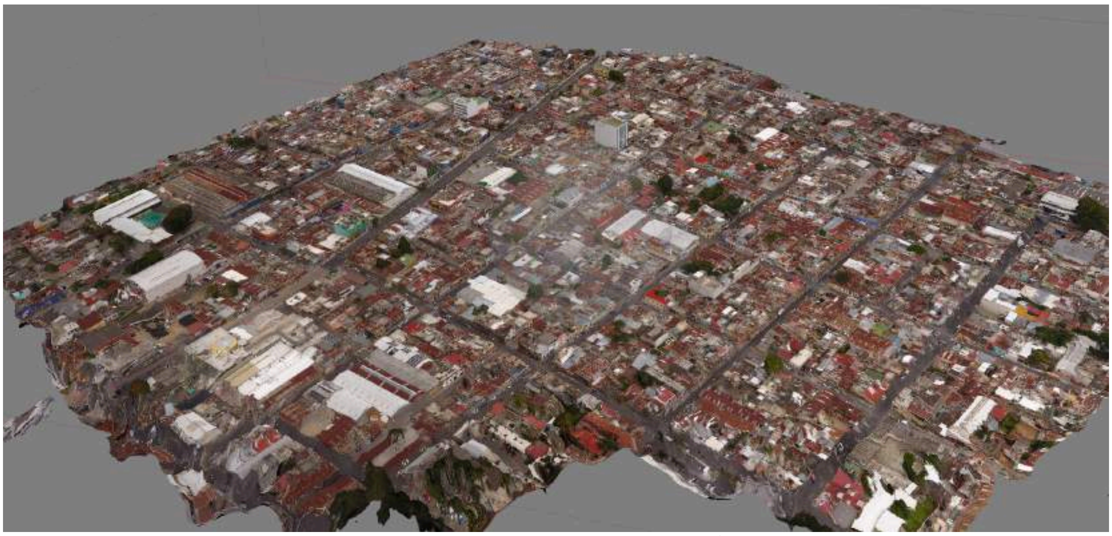


Figure K-3 Zone 5 3D model

Figure K-4 Zone 7 3D model

Figure K-5 Zone 10 3D model

Figure K-6 Zone 12 3D model

Appendix L: Detailed internal survey buildings

L.1. Building 1: 3-13 Calle 13, Zone 1, Guatemala City

- Identifying code: Z1_Calle13_Avenida2A_N_10
- Description: Colegio Mixto Santa Sofia
- Usage: Education
- Location: 14.636635 N, 90.517512 W

Figure L-1 Building 1: Street level photo of Colegio Mixto Santa Sofia

Figure L-2 Building 1: Omni-directional image - view 1

Figure L-3 Building 1: Drone 3D model - the neighbourhood around the Colegio Mixto Santa Sofia

Figure L-4 Building 1: Drone 3D model - Colegio Mixto Santa Sofia from the south west

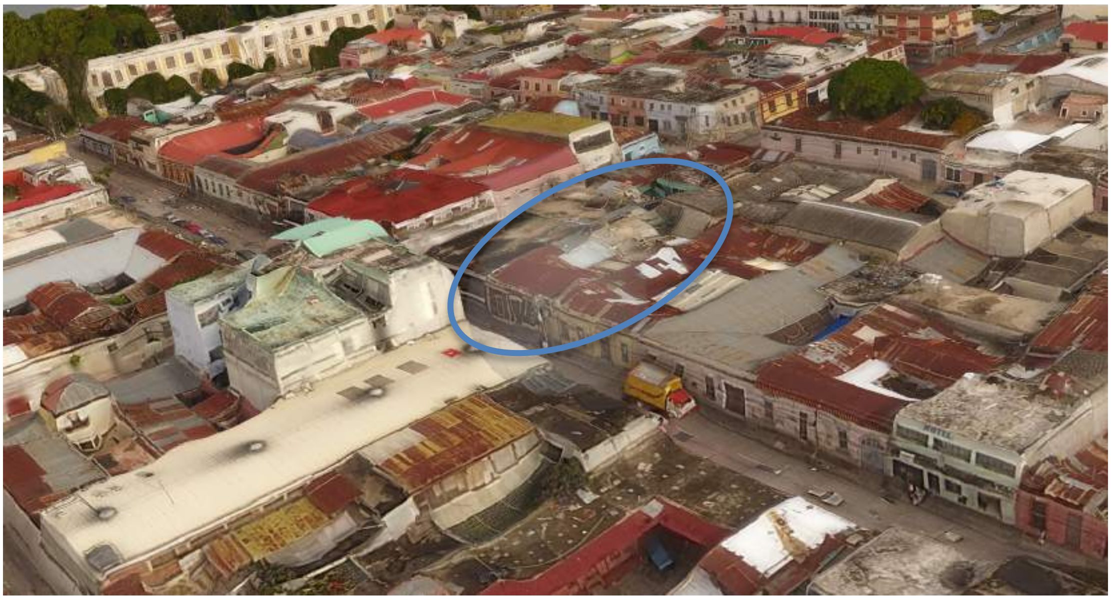


Figure L-5 Building 1: Drone 3D model - Colegio Mixto Santa Sofia from the south east

L.2. Building 2: 2-20 & 2-14 Calle 13, Zone 1, Guatemala City

- Identifying code: Z1_Calle13_Avenida2A_S_02
- Description: Instituto de estudios comparado ciencias penales de Guatemala
- Usage: Education
- Location: 14.6366637 N, 90.518759 W

Figure L-7 Building 2: Street level photo of Instituto de estudios comparado ciencias penales de Guatemala

Figure L-8 Building 2: Omni-directional imagery – view 1

Figure L-9 Building 2: Drone 3D model - The neighbourhood around the Instituto de estudios comparado ciencias penales de Guatemala

Figure P-10 Building 2: Drone 3D model - Instituto de estudios comparado ciencias penales de Guatemala from the north east

Figure P-11 Building 2: Drone 3D model - The Instituto de estudios comparado ciencias penales de Guatemala from the north west

Figure P-12 Building 2: Municipality-held data on building 2

L.3. Building 3: 2-08 Calle 13, Zone 1, Guatemala City

- Identifying code: Z1_Calle13_Avenida2A_S_01
- Description: Light yellow and blue walled building
- Usage: Education
- Location: 14.636673 N, 90.518937 W

Figure P-13 Building 3: Street level view of building 3

Figure P-14 Building 3: Omni-directional image, view 1

Figure P-15 Building 3: Omnidirectional image, view 2

Figure P-16 Building 3: Omni-directional image, view 3

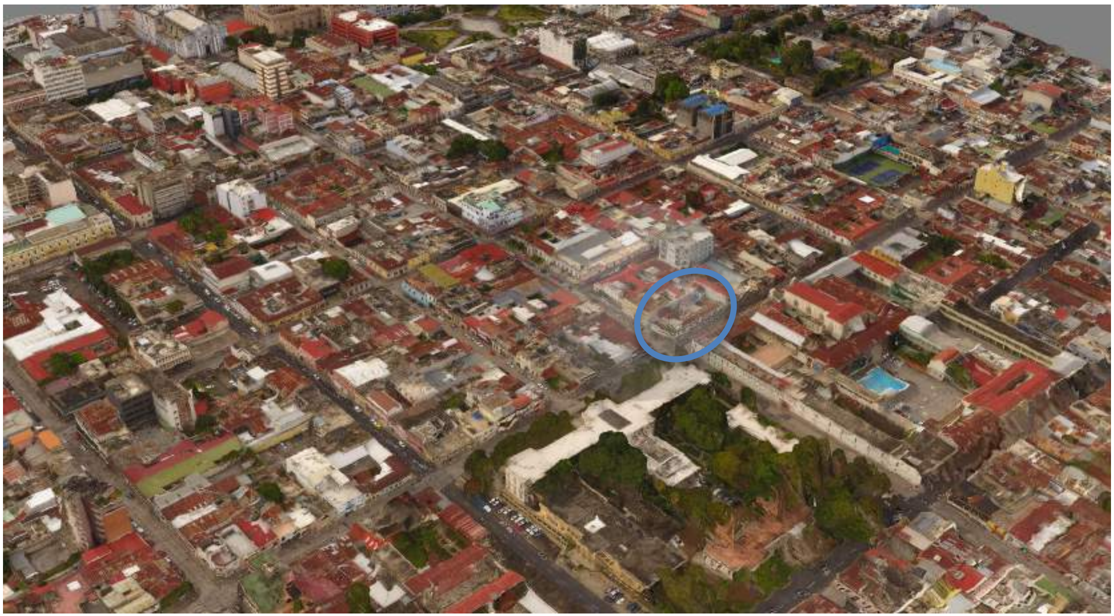


Figure P-17 Building 3: Drone 3D model – the neighbourhood around building 3

Figure P-18 Building 3: Drone 3D model – building 3 from the north west

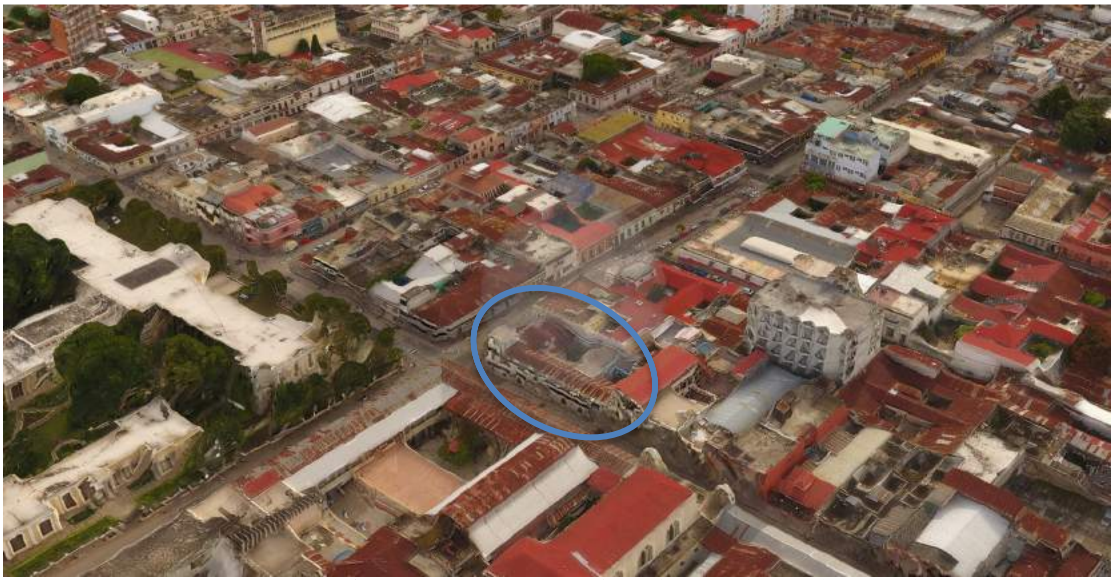


Figure P-19 Building 3: 3D model – building 3 from the south west

Figure P-20 Building 3: Municipality-held data on building 3

L.4. Building 4: 2-63, Calle 13, Zone 1, Guatemala City

- Identifying code: Z1_Calle13_Avenida2A_N_06
- Description: Funerales
- Usage: Commercial
- Location: 14.636751 N, 90.518151 W

Figure P-21 Building 4: Street level view of building 4

Figure P-22 Building 4: Omni-directional imagery of building 4

Figure P-23 Building 4: 3D model – the neighbourhood around building 4

Figure P-24 Building 4: 3D model – building 4 from the south west

Figure P-25 Building 4: 3D model –building 4 from the south east

Figure P-26 Building 4: Municipality-held data on building 4

L.5. Building 5: 2-41, Calle 13, Zone 1, Guatemala City

- Identifying code: Z1_Calle13_Avenida2A_N_04
- Description: Comedor, orange walls
- Usage: Education & education
- Location: 14.636801 N, 90.518445 W

Figure P-27 Building 5: Street level view of building 5

Figure P-28 Building 5: 3D model – the neighbourhood around building 5

Figure P-29 Building 5: 3D model – view of building 5 from the south west

Figure P-30 Building 5: 3D model - view of building 5 from the south east

Figure P-31 Building 5: Municipality-held data on building 5

L.6. Building 6: 3-21/25, Calle 13, Zone 1, Guatemala City

- Identifying code: Z1_Calle13_Avenida2A_N_11
- Description: Colegio de innovacion technologia educative
- Usage: Education
- Location: 14.636632 N, 90.517388 W

Figure P-32 Building 6: Street level view of building 6

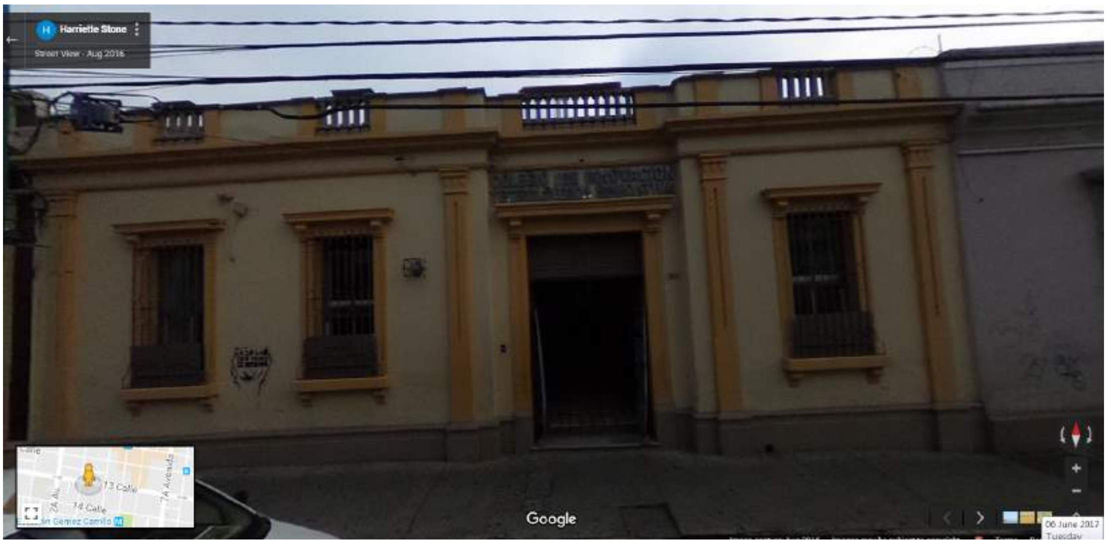


Figure P-33 Building 6: Omni-directional imagery of building 6

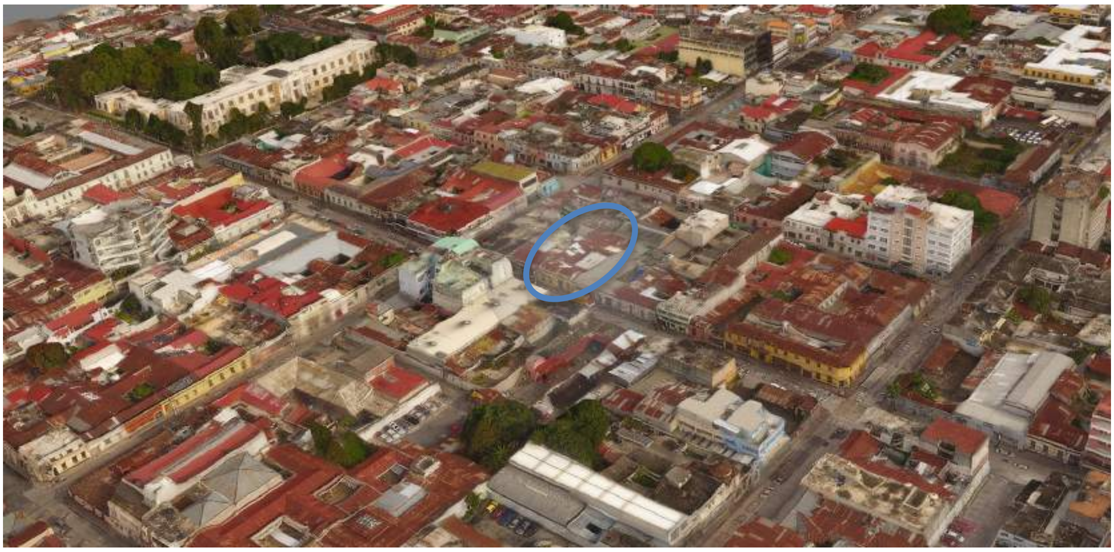


Figure P-34 Building 6: 3D model – the neighbourhood around building 6

Figure P-35 Building 6: 3D model – view of building 6 from the south west

Figure P-36 Building 6: 3D model - view of building 6 from the south east

L.7. Building 7: 27-65 19 Avenida, Zone 5, Guatemala City

- Identifying code: Z5_19Avenida_27Calle_E_09
- Description: Corner, adobe
- Usage: Residential & commercial
- Location: 14.620615 N, 90.506103 W

Figure P-37 Building 7: Street level view of building 7

Figure P-38 Building 7: Omnidirectional imagery of building 7 – view 1

Figure P-39 Building 7: Omnidirectional imagery of building 7 – view 2

Figure P-40 Building 7: 3D model - the neighbourhood around building 7

Figure P-41 Building 7: 3D model – view of building 7 from the south west

L.8. Building 8: No number, Avenida 19, Zone 5, Guatemala City

- Identifying code: Z5_19Avenida_27Calle_E_17
- Description: Mint, corner
- Usage: Residential
- Location: 14.619606 N, 90.506277 W

Figure P-42 Building 8: Street level view of building 8

Figure P-43 Building 8: Omnidirectional image – view 1

Figure P-44 Building 8: Omnidirectional image – view 2

Figure P-45 Building 8: Omnidirectional image – view 3

Figure P-46 Building 8: Omnidirectional image – view 4

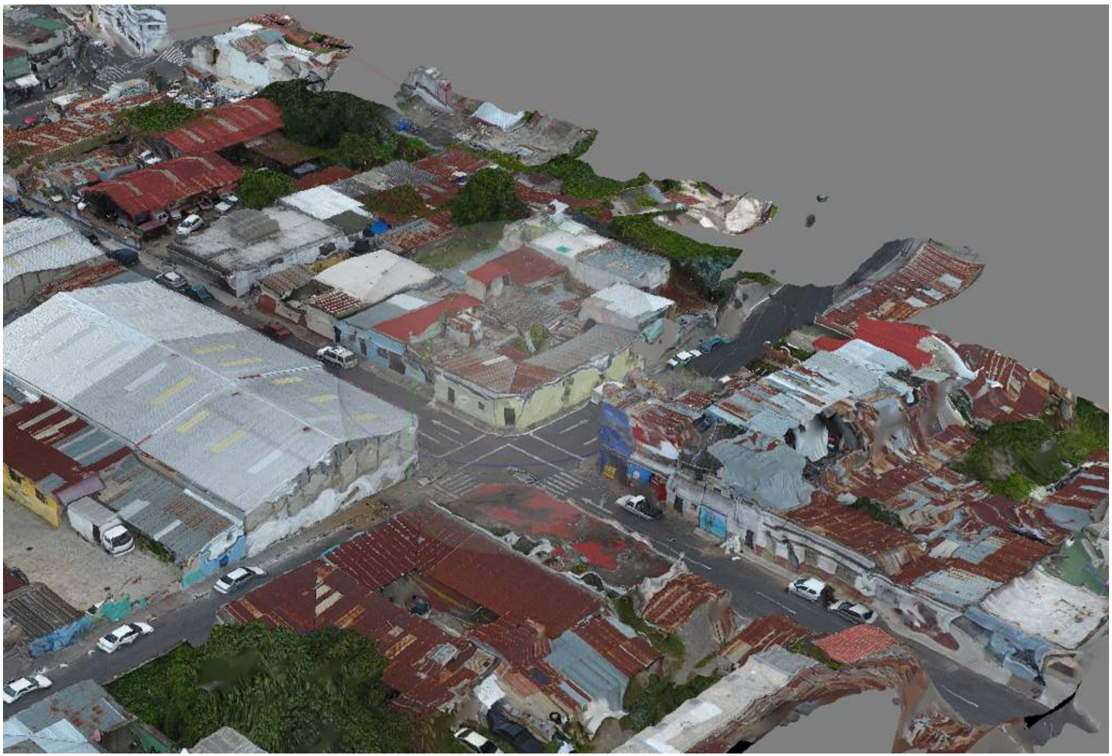


Figure P-47 Building 8: 3D model – neighbourhood around building 8

Figure P-48 Building 8: 3D model – view of building 8 from the south west

L.9. Building 9: 29-51, Avenida 19, Zone 5, Guatemala City

- Identifying code: Z5_19Avenida_27Calle_E_22
- Description: Yellow façade, black garage door
- Usage: Residential
- Location: 14.619037 N, 90.506428 W

19.08.2015 11:43

Figure P-49 Building 9: Street level view of building 9

Figure P-50 Building 9: Omni-directional image – view 1

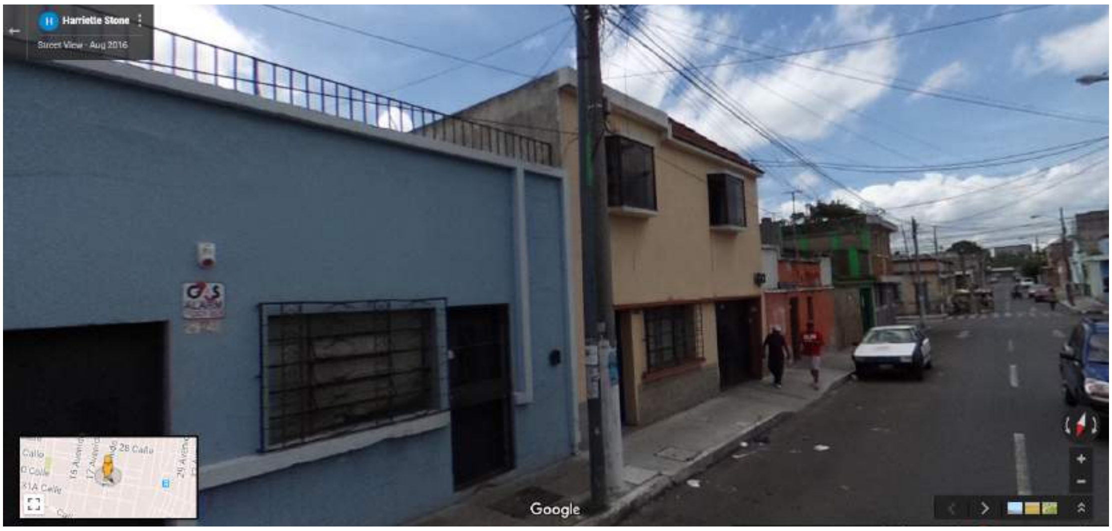
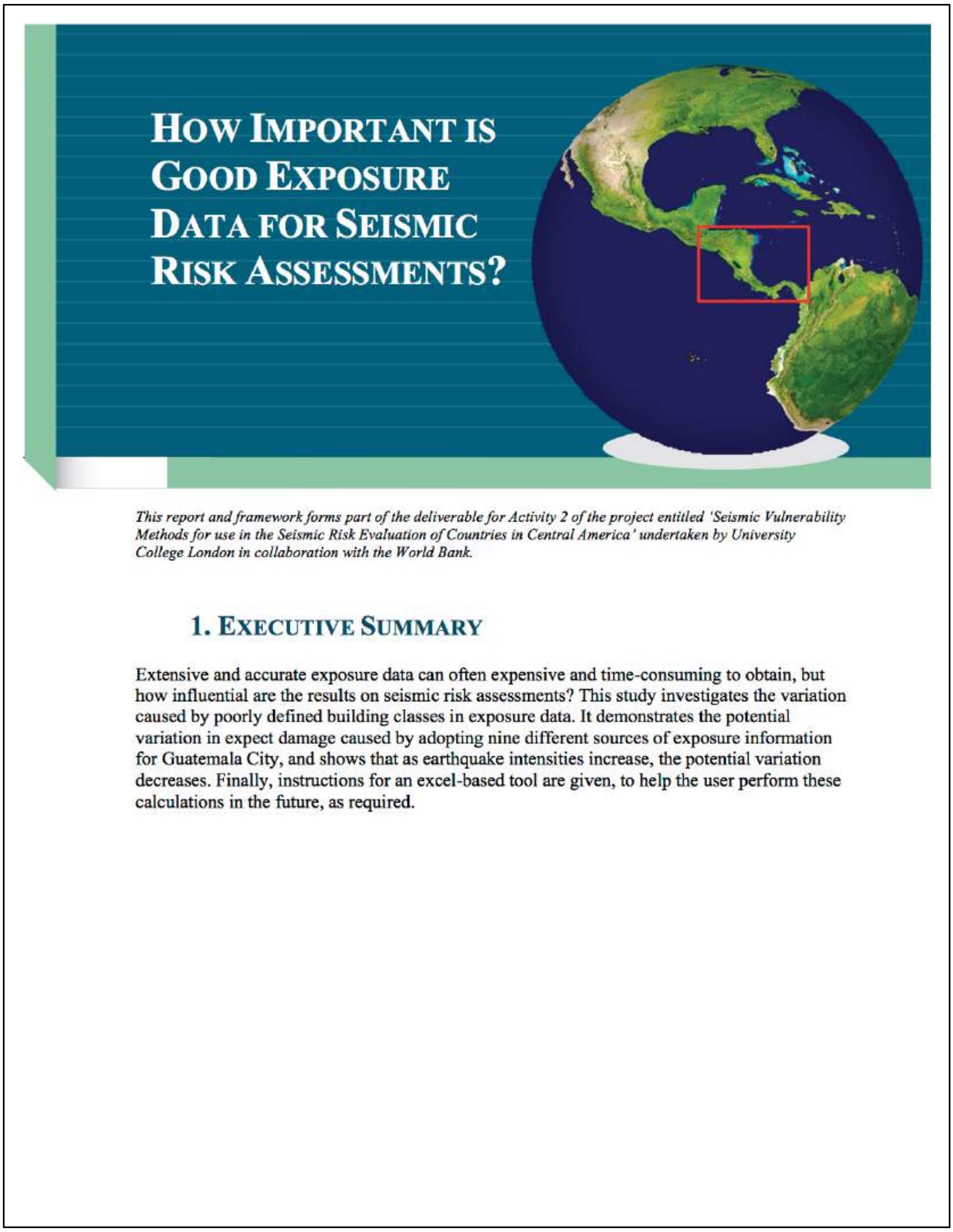


Figure P-51 Building 9: Omni-directional image – view 2

Figure P-52 Building 9: Omni-directional image – view 3

Appendix M: Report: How important is good exposure data for seismic risk assessment?

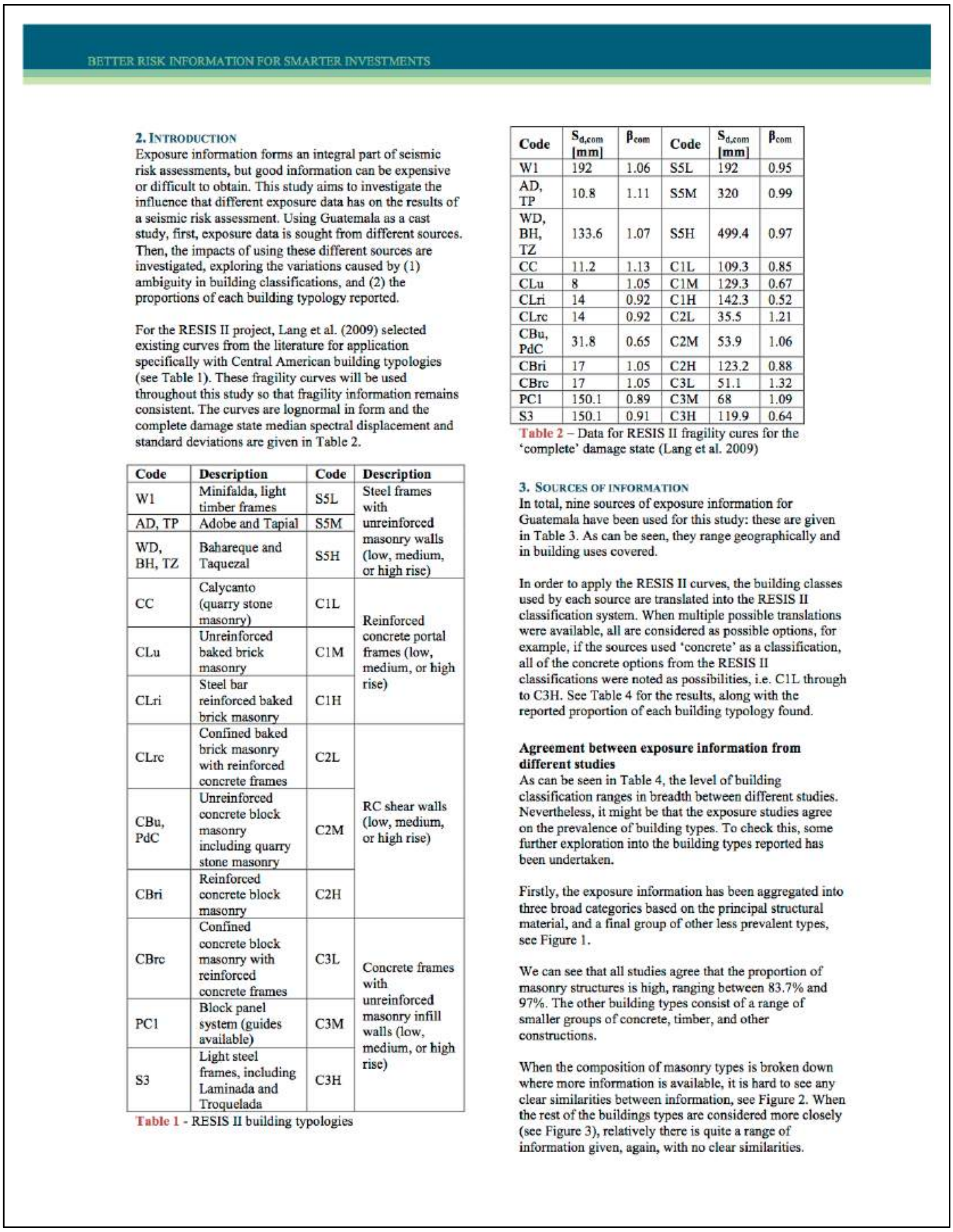


HOW IMPORTANT IS GOOD EXPOSURE DATA FOR SEISMIC RISK ASSESSMENTS?

This report and framework forms part of the deliverable for Activity 2 of the project entitled 'Seismic Vulnerability Methods for use in the Seismic Risk Evaluation of Countries in Central America' undertaken by University College London in collaboration with the World Bank.

1. EXECUTIVE SUMMARY

Extensive and accurate exposure data can often expensive and time-consuming to obtain, but how influential are the results on seismic risk assessments? This study investigates the variation caused by poorly defined building classes in exposure data. It demonstrates the potential variation in expect damage caused by adopting nine different sources of exposure information for Guatemala City, and shows that as earthquake intensities increase, the potential variation decreases. Finally, instructions for an excel-based tool are given, to help the user perform these calculations in the future, as required.



2. INTRODUCTION

Exposure information forms an integral part of seismic risk assessments, but good information can be expensive or difficult to obtain. This study aims to investigate the influence that different exposure data has on the results of a seismic risk assessment. Using Guatemala as a cast study, first, exposure data is sought from different sources. Then, the impacts of using these different sources are investigated, exploring the variations caused by (1) ambiguity in building classifications, and (2) the proportions of each building typology reported.

For the RESIS II project, Lang et al. (2009) selected existing curves from the literature for application specifically with Central American building typologies (see Table 1). These fragility curves will be used throughout this study so that fragility information remains consistent. The curves are lognormal in form and the complete damage state median spectral displacement and standard deviations are given in Table 2.

Code	**Description**	**Code**	**Description**
W1	Minifalda, light timber frames	S5L	Steel frames with unreinforced masonry walls (low, medium, or high rise)
AD, TP	Adobe and Tapial	S5M	
WD, BH, TZ	Bahareque and Taquezal	S5H	
CC	Calycanto (quarry stone masonry)	C1L	Reinforced concrete portal frames (low, medium, or high rise)
CLu	Unreinforced baked brick masonry	C1M	
CLri	Steel bar reinforced baked brick masonry	C1H	
CLrc	Confined baked brick masonry with reinforced concrete frames	C2L	RC shear walls (low, medium, or high rise)
CBu, PdC	Unreinforced concrete block masonry including quarry stone masonry	C2M	
CBri	Reinforced concrete block masonry	C2H	
CBrc	Confined concrete block masonry with reinforced concrete frames	C3L	Concrete frames with unreinforced masonry infill walls (low, medium, or high rise)
PC1	Block panel system (guides available)	C3M	
S3	Light steel frames, including Laminada and Troquelada	C3H	

Table 1 - RESIS II building typologies

Code	$S_{d,com}$ [mm]	β_{com}	**Code**	$S_{d,com}$ [mm]	β_{com}
W1	192	1.06	S5L	192	0.95
AD, TP	10.8	1.11	S5M	320	0.99
WD, BH, TZ	133.6	1.07	S5H	499.4	0.97
CC	11.2	1.13	C1L	109.3	0.85
CLu	8	1.05	C1M	129.3	0.67
CLri	14	0.92	C1H	142.3	0.52
CLrc	14	0.92	C2L	35.5	1.21
CBu, PdC	31.8	0.65	C2M	53.9	1.06
CBri	17	1.05	C2H	123.2	0.88
CBrc	17	1.05	C3L	51.1	1.32
PC1	150.1	0.89	C3M	68	1.09
S3	150.1	0.91	C3H	119.9	0.64

Table 2 – Data for RESIS II fragility cures for the 'complete' damage state (Lang et al. 2009)

3. SOURCES OF INFORMATION

In total, nine sources of exposure information for Guatemala have been used for this study: these are given in Table 3. As can be seen, they range geographically and in building uses covered.

In order to apply the RESIS II curves, the building classes used by each source are translated into the RESIS II classification system. When multiple possible translations were available, all are considered as possible options, for example, if the sources used 'concrete' as a classification, all of the concrete options from the RESIS II classifications were noted as possibilities, i.e. C1L through to C3H. See Table 4 for the results, along with the reported proportion of each building typology found.

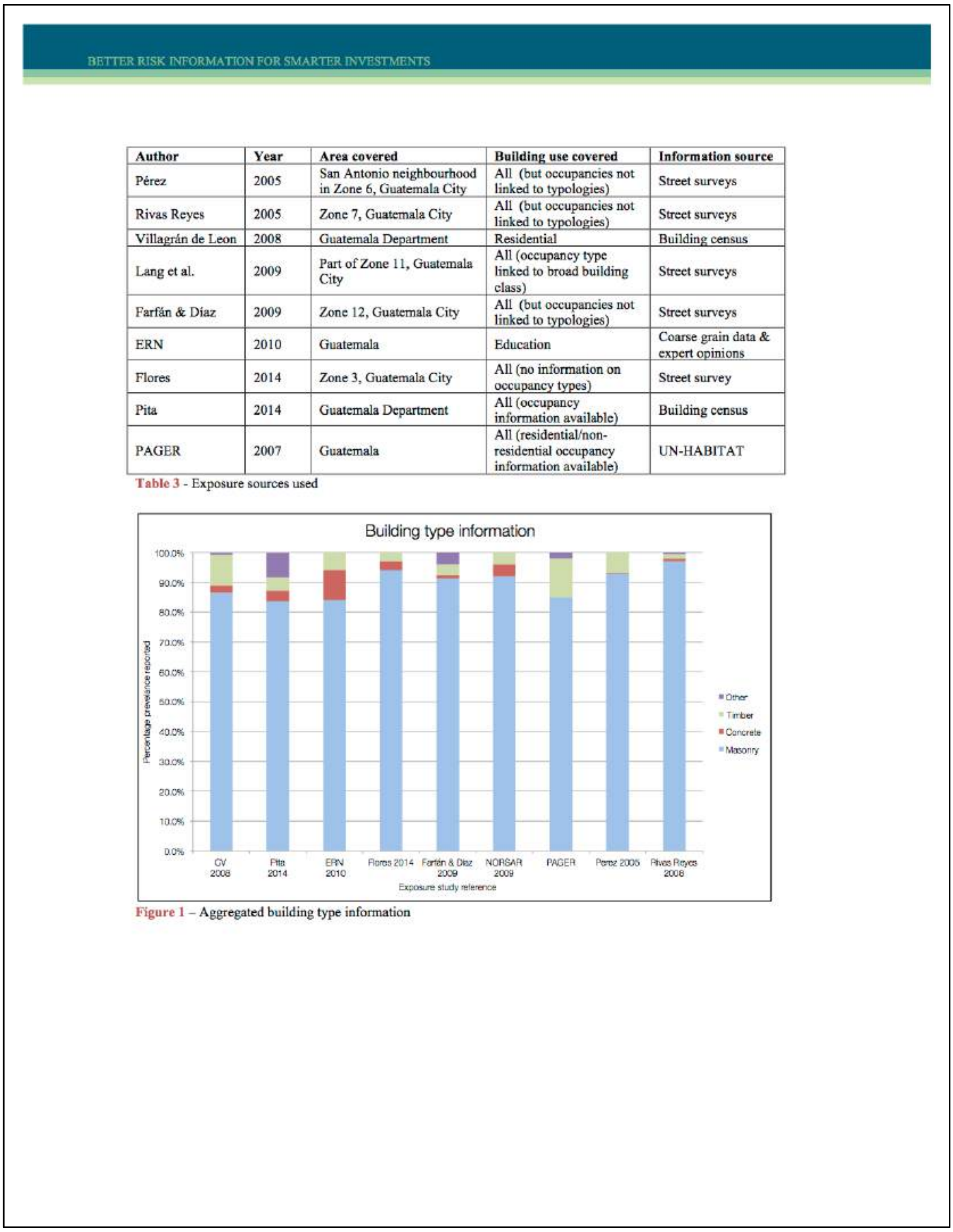
Agreement between exposure information from different studies

As can be seen in Table 4, the level of building classification ranges in breadth between different studies. Nevertheless, it might be that the exposure studies agree on the prevalence of building types. To check this, some further exploration into the building types reported has been undertaken.

Firstly, the exposure information has been aggregated into three broad categories based on the principal structural material, and a final group of other less prevalent types, see Figure 1.

We can see that all studies agree that the proportion of masonry structures is high, ranging between 83.7% and 97%. The other building types consist of a range of smaller groups of concrete, timber, and other constructions.

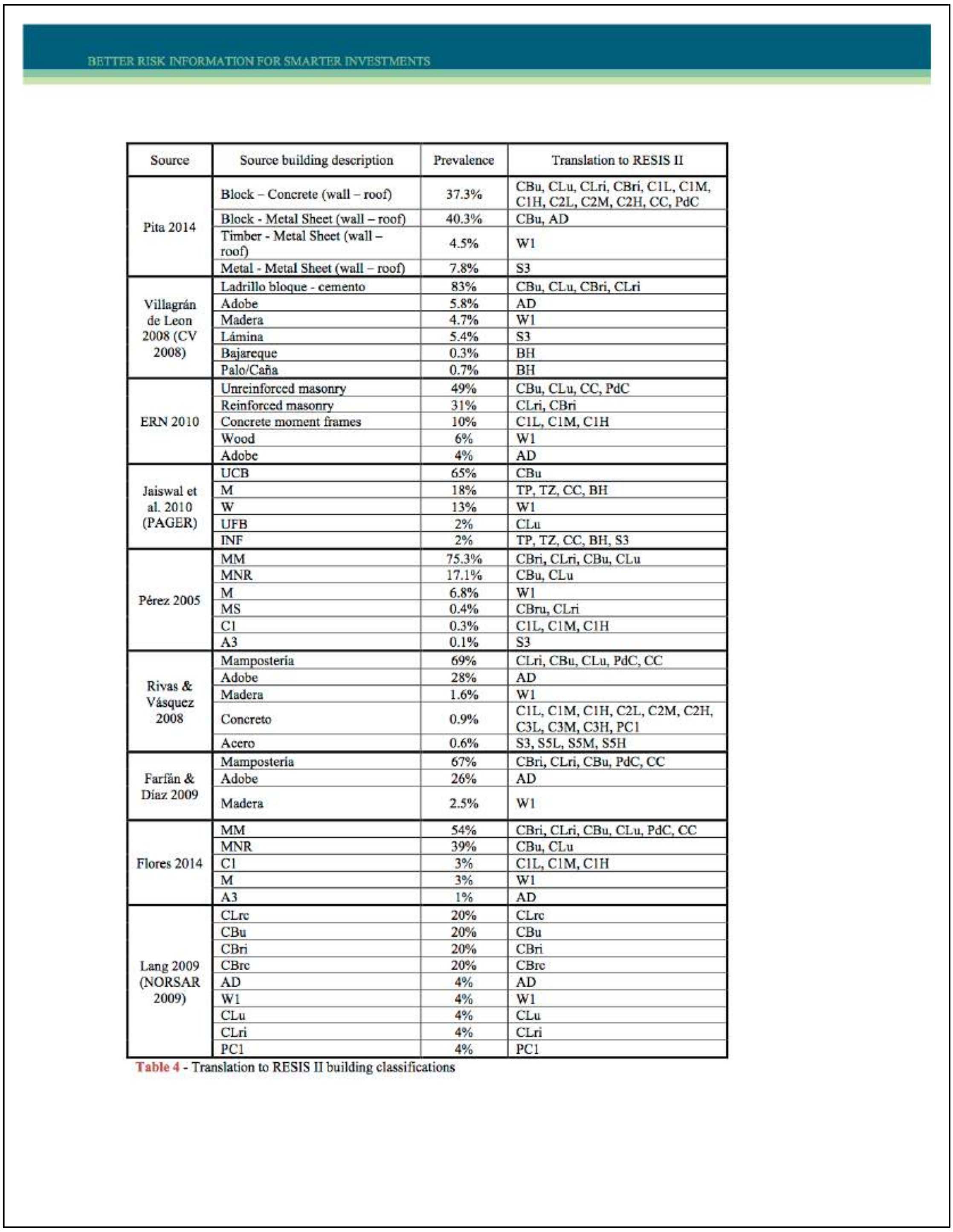
When the composition of masonry types is broken down where more information is available, it is hard to see any clear similarities between information, see Figure 2. When the rest of the buildings types are considered more closely (see Figure 3), relatively there is quite a range of information given, again, with no clear similarities.



Author	Year	Area covered	Building use covered	Information source
Pérez	2005	San Antonio neighbourhood in Zone 6, Guatemala City	All (but occupancies not linked to typologies)	Street surveys
Rivas Reyes	2005	Zone 7, Guatemala City	All (but occupancies not linked to typologies)	Street surveys
Villagrán de Leon	2008	Guatemala Department	Residential	Building census
Lang et al.	2009	Part of Zone 11, Guatemala City	All (occupancy type linked to broad building class)	Street surveys
Farfán & Díaz	2009	Zone 12, Guatemala City	All (but occupancies not linked to typologies)	Street surveys
ERN	2010	Guatemala	Education	Coarse grain data & expert opinions
Flores	2014	Zone 3, Guatemala City	All (no information on occupancy types)	Street survey
Pita	2014	Guatemala Department	All (occupancy information available)	Building census
PAGER	2007	Guatemala	All (residential/non-residential occupancy information available)	UN-HABITAT

Table 3 - Exposure sources used

Figure 1 – Aggregated building type information



Source	Source building description	Prevalence	Translation to RESIS II
Pita 2014	Block – Concrete (wall – roof)	37.3%	CBu, CLu, CLri, CBri, C1L, C1M, C1H, C2L, C2M, C2H, CC, PdC
	Block - Metal Sheet (wall – roof)	40.3%	CBu, AD
	Timber - Metal Sheet (wall – roof)	4.5%	W1
	Metal - Metal Sheet (wall – roof)	7.8%	S3
Villagrán de Leon 2008 (CV 2008)	Ladrillo bloque - cemento	83%	CBu, CLu, CBri, CLri
	Adobe	5.8%	AD
	Madera	4.7%	W1
	Lámina	5.4%	S3
	Bajareque	0.3%	BH
	Palo/Caña	0.7%	BH
ERN 2010	Unreinforced masonry	49%	CBu, CLu, CC, PdC
	Reinforced masonry	31%	CLri, CBri
	Concrete moment frames	10%	C1L, C1M, C1H
	Wood	6%	W1
	Adobe	4%	AD
Jaiswal et al. 2010 (PAGER)	UCB	65%	CBu
	M	18%	TP, TZ, CC, BH
	W	13%	W1
	UFB	2%	CLu
	INF	2%	TP, TZ, CC, BH, S3
Pérez 2005	MM	75.3%	CBri, CLri, CBu, CLu
	MNR	17.1%	CBu, CLu
	M	6.8%	W1
	MS	0.4%	CBru, CLri
	C1	0.3%	C1L, C1M, C1H
	A3	0.1%	S3
Rivas & Vásquez 2008	Mampostería	69%	CLri, CBu, CLu, PdC, CC
	Adobe	28%	AD
	Madera	1.6%	W1
	Concreto	0.9%	C1L, C1M, C1H, C2L, C2M, C2H, C3L, C3M, C3H, PC1
	Acero	0.6%	S3, S5L, S5M, S5H
Farfán & Díaz 2009	Mampostería	67%	CBri, CLri, CBu, PdC, CC
	Adobe	26%	AD
	Madera	2.5%	W1
Flores 2014	MM	54%	CBri, CLri, CBu, CLu, PdC, CC
	MNR	39%	CBu, CLu
	C1	3%	C1L, C1M, C1H
	M	3%	W1
	A3	1%	AD
Lang 2009 (NORSAR 2009)	CLrc	20%	CLrc
	CBu	20%	CBu
	CBri	20%	CBri
	CBrc	20%	CBrc
	AD	4%	AD
	W1	4%	W1
	CLu	4%	CLu
	CLri	4%	CLri
	PC1	4%	PC1

Table 4 - Translation to RESIS II building classifications

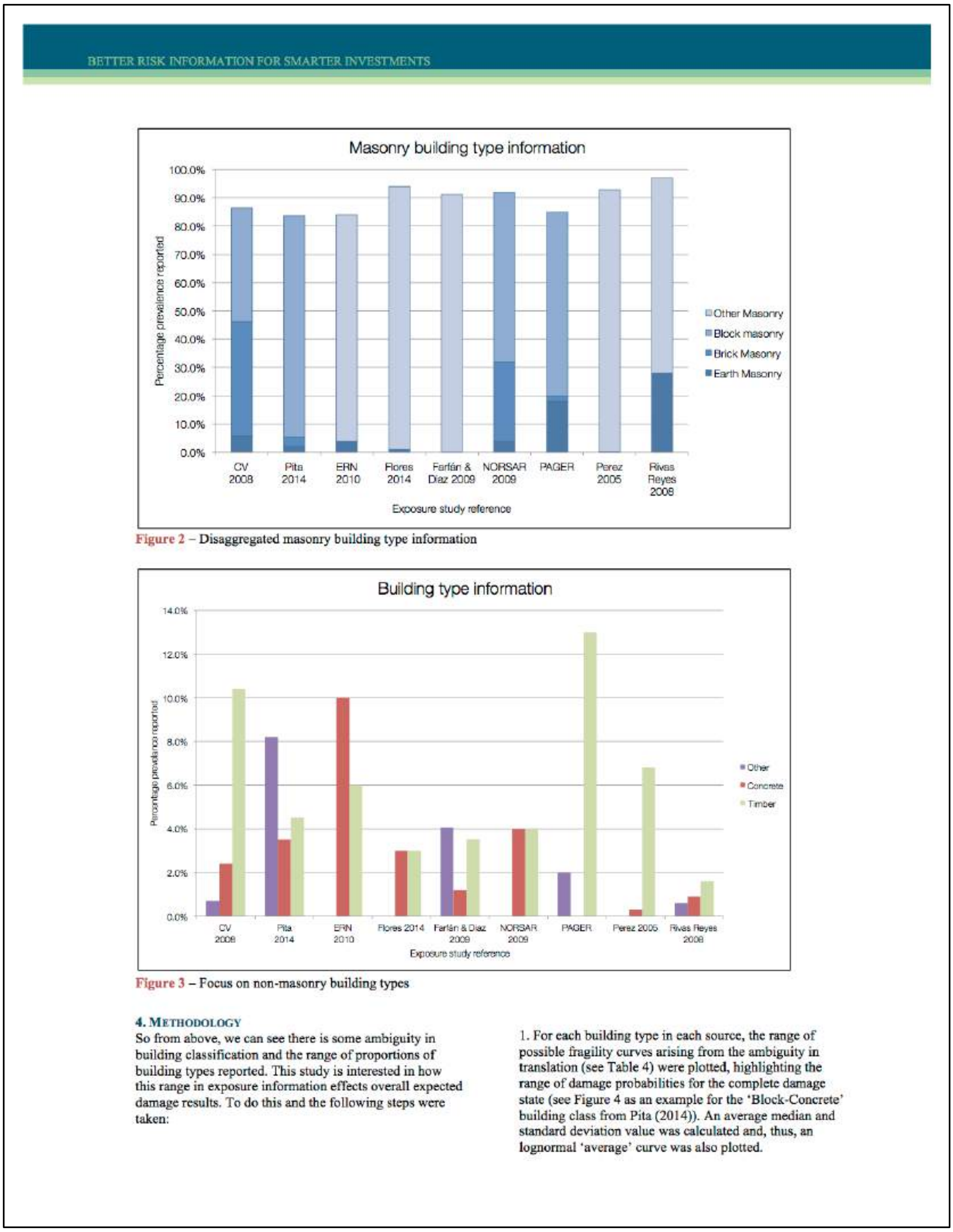


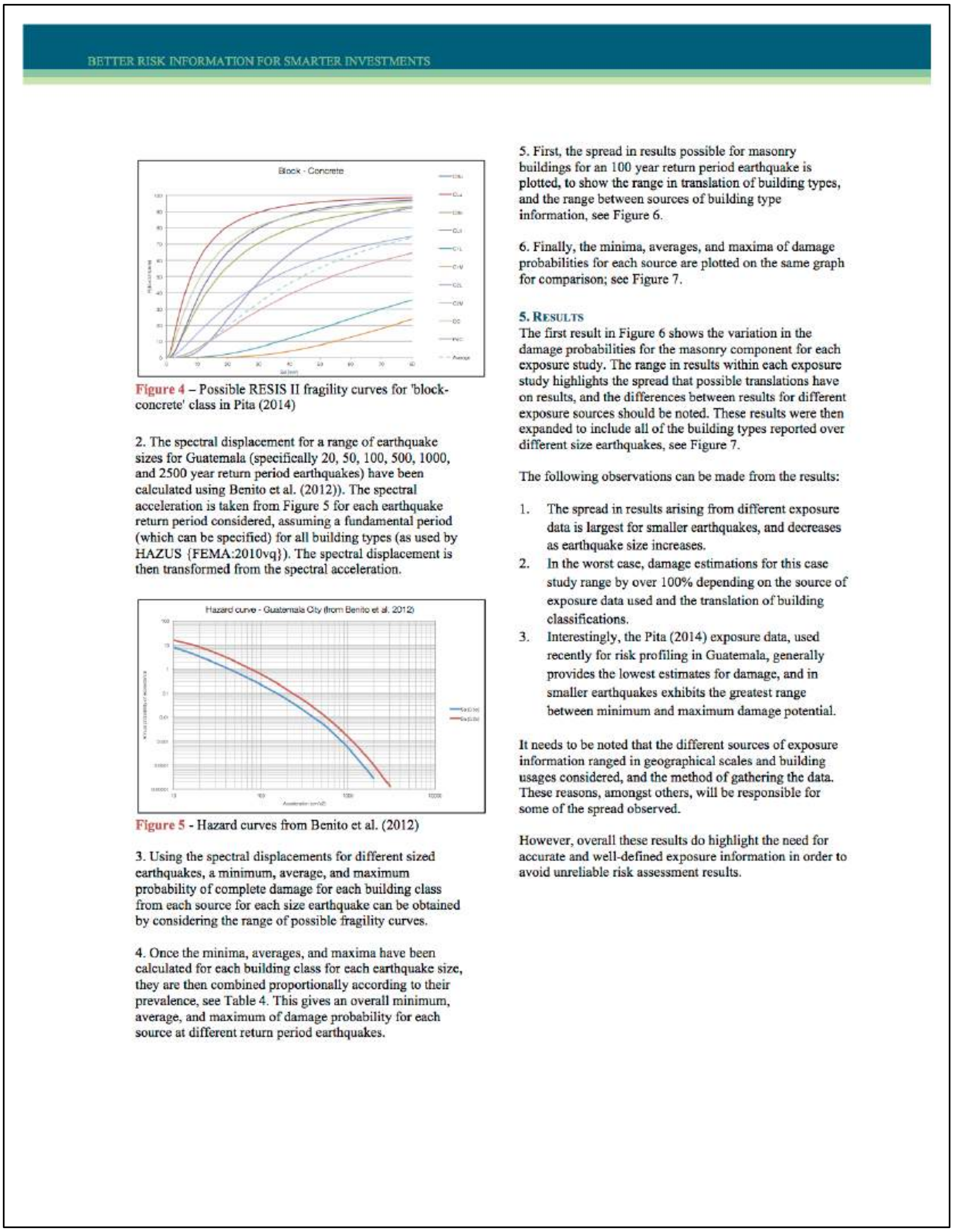
Figure 2 – Disaggregated masonry building type information

Figure 3 – Focus on non-masonry building types

4. METHODOLOGY

So from above, we can see there is some ambiguity in building classification and the range of proportions of building types reported. This study is interested in how this range in exposure information effects overall expected damage results. To do this and the following steps were taken:

1. For each building type in each source, the range of possible fragility curves arising from the ambiguity in translation (see Table 4) were plotted, highlighting the range of damage probabilities for the complete damage state (see Figure 4 as an example for the 'Block-Concrete' building class from Pita (2014)). An average median and standard deviation value was calculated and, thus, an lognormal 'average' curve was also plotted.



BETTER RISK INFORMATION FOR SMARTER INVESTMENTS

Figure 4 – Possible RESIS II fragility curves for 'block-concrete' class in Pita (2014)

2. The spectral displacement for a range of earthquake sizes for Guatemala (specifically 20, 50, 100, 500, 1000, and 2500 year return period earthquakes) have been calculated using Benito et al. (2012)). The spectral acceleration is taken from Figure 5 for each earthquake return period considered, assuming a fundamental period (which can be specified) for all building types (as used by HAZUS {FEMA:2010vq}). The spectral displacement is then transformed from the spectral acceleration.

Figure 5 - Hazard curves from Benito et al. (2012)

3. Using the spectral displacements for different sized earthquakes, a minimum, average, and maximum probability of complete damage for each building class from each source for each size earthquake can be obtained by considering the range of possible fragility curves.

4. Once the minima, averages, and maxima have been calculated for each building class for each earthquake size, they are then combined proportionally according to their prevalence, see Table 4. This gives an overall minimum, average, and maximum of damage probability for each source at different return period earthquakes.

5. First, the spread in results possible for masonry buildings for an 100 year return period earthquake is plotted, to show the range in translation of building types, and the range between sources of building type information, see Figure 6.

6. Finally, the minima, averages, and maxima of damage probabilities for each source are plotted on the same graph for comparison; see Figure 7.

5. RESULTS

The first result in Figure 6 shows the variation in the damage probabilities for the masonry component for each exposure study. The range in results within each exposure study highlights the spread that possible translations have on results, and the differences between results for different exposure sources should be noted. These results were then expanded to include all of the building types reported over different size earthquakes, see Figure 7.

The following observations can be made from the results:

1. The spread in results arising from different exposure data is largest for smaller earthquakes, and decreases as earthquake size increases.
2. In the worst case, damage estimations for this case study range by over 100% depending on the source of exposure data used and the translation of building classifications.
3. Interestingly, the Pita (2014) exposure data, used recently for risk profiling in Guatemala, generally provides the lowest estimates for damage, and in smaller earthquakes exhibits the greatest range between minimum and maximum damage potential.

It needs to be noted that the different sources of exposure information ranged in geographical scales and building usages considered, and the method of gathering the data. These reasons, amongst others, will be responsible for some of the spread observed.

However, overall these results do highlight the need for accurate and well-defined exposure information in order to avoid unreliable risk assessment results.

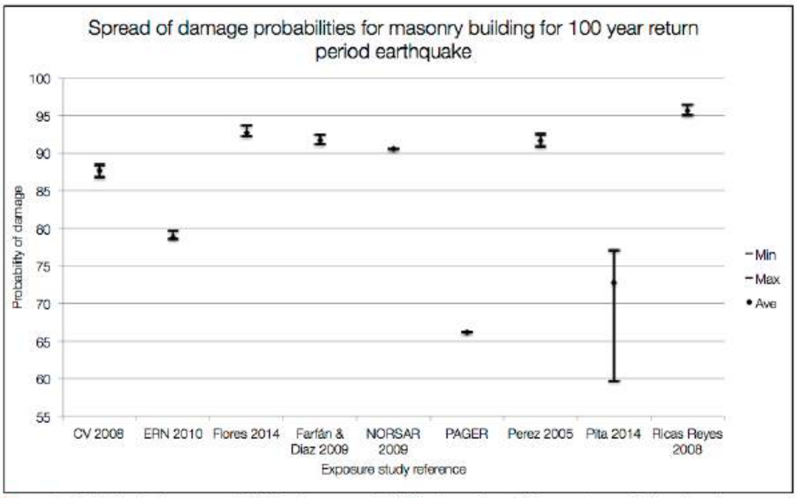


Figure 6 - Variation in damage probabilities for masonry building types for a 100 year return period earthquake

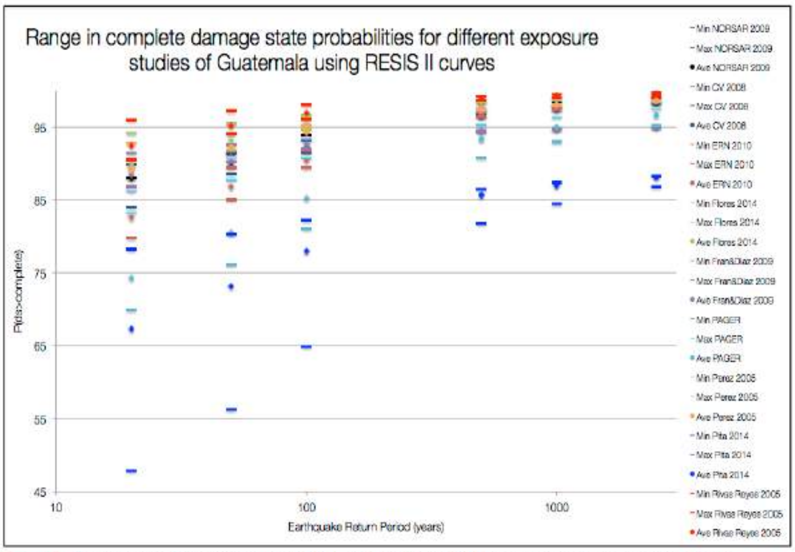


Figure 7 - Range in complete damage state results over different earthquake sizes or different exposure sources

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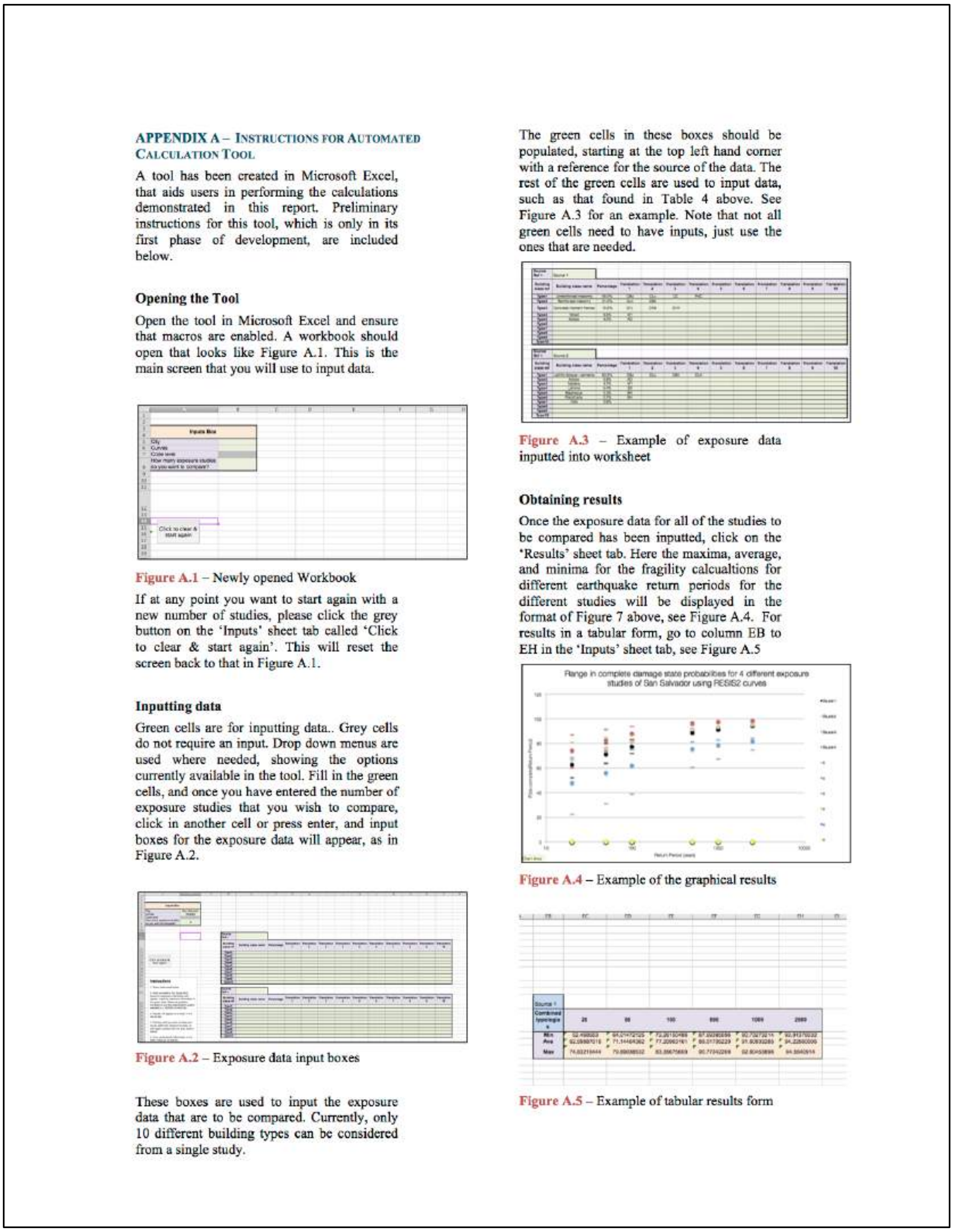
Dr. Oscar Ishizawa, Disaster Risk Management Specialist, World Bank (oishizawa@worldbank.org)



APPENDIX A – INSTRUCTIONS FOR AUTOMATED CALCULATION TOOL

A tool has been created in Microsoft Excel, that aids users in performing the calculations demonstrated in this report. Preliminary instructions for this tool, which is only in its first phase of development, are included below.

Opening the Tool

Open the tool in Microsoft Excel and ensure that macros are enabled. A workbook should open that looks like Figure A.1. This is the main screen that you will use to input data.

Figure A.1 – Newly opened Workbook

If at any point you want to start again with a new number of studies, please click the grey button on the 'Inputs' sheet tab called 'Click to clear & start again'. This will reset the screen back to that in Figure A.1.

Inputting data

Green cells are for inputting data.. Grey cells do not require an input. Drop down menus are used where needed, showing the options currently available in the tool. Fill in the green cells, and once you have entered the number of exposure studies that you wish to compare, click in another cell or press enter, and input boxes for the exposure data will appear, as in Figure A.2.

Figure A.2 – Exposure data input boxes

These boxes are used to input the exposure data that are to be compared. Currently, only 10 different building types can be considered from a single study.

The green cells in these boxes should be populated, starting at the top left hand corner with a reference for the source of the data. The rest of the green cells are used to input data, such as that found in Table 4 above. See Figure A.3 for an example. Note that not all green cells need to have inputs, just use the ones that are needed.

Figure A.3 – Example of exposure data inputted into worksheet

Obtaining results

Once the exposure data for all of the studies to be compared has been inputted, click on the 'Results' sheet tab. Here the maxima, average, and minima for the fragility calcualtions for different earthquake return periods for the different studies will be displayed in the format of Figure 7 above, see Figure A.4. For results in a tabular form, go to column EB to EH in the 'Inputs' sheet tab, see Figure A.5

Figure A.4 – Example of the graphical results

Figure A.5 – Example of tabular results form

Appendix N: Example aerial images

Figure N-1 Zone 1 UAV aerial image, example 1

Figure N-2 Zone 1 UAV aerial image, example 2

Figure N-3 Zone 4 UAV aerial image, example 1

Figure N-4 Zone 4 UAV aerial image, example 2

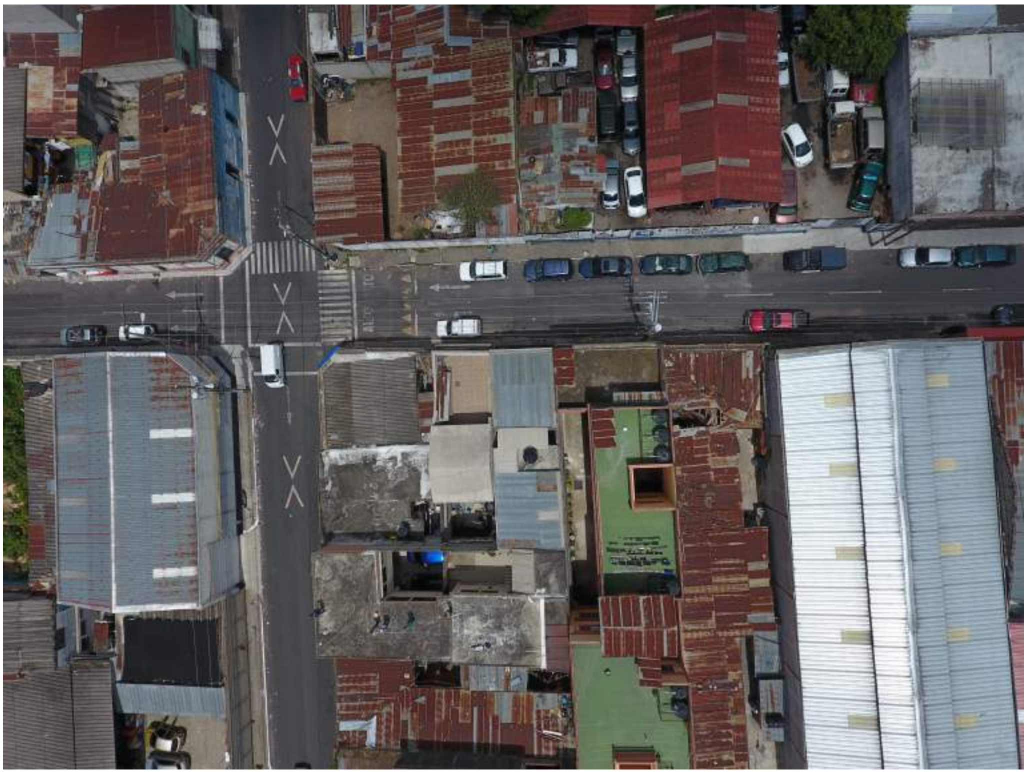


Figure N-5 Zone 5 UAV aerial image, example 1

Figure N-6 Zone 5 UAV aerial image, example 2

Figure N-7 Zone 7 UAV aerial image, example 1

Figure N-8 Zone 7 UAV aerial image, example 2

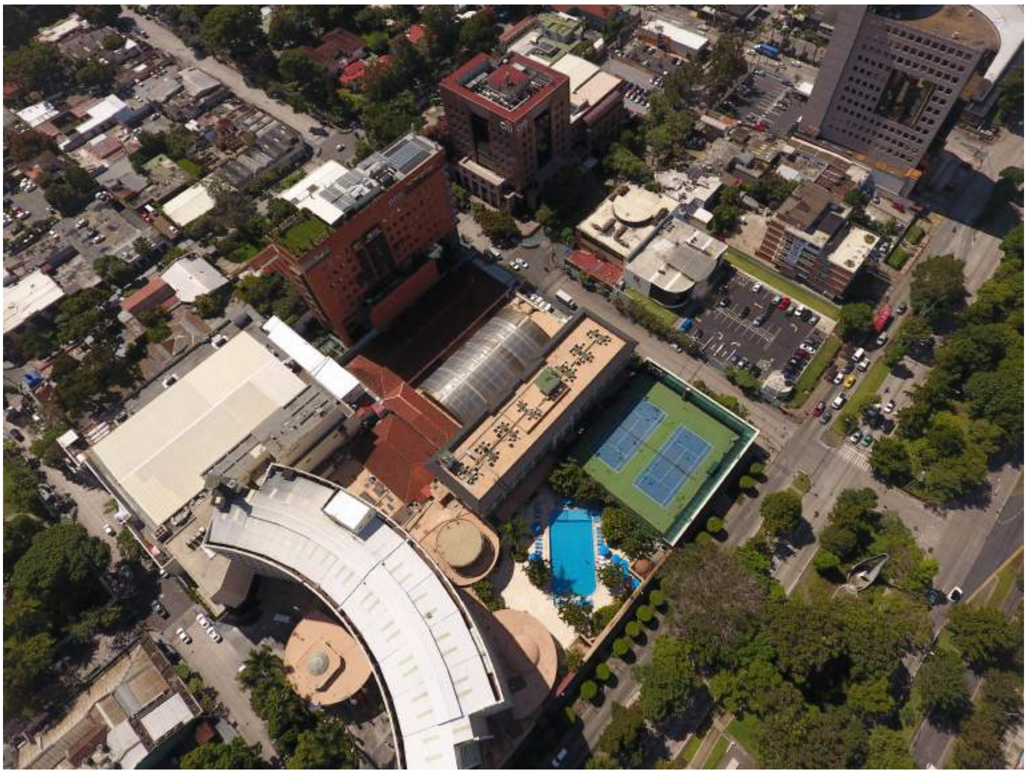


Figure N-9 Zone 10 UAV aerial image, example 1

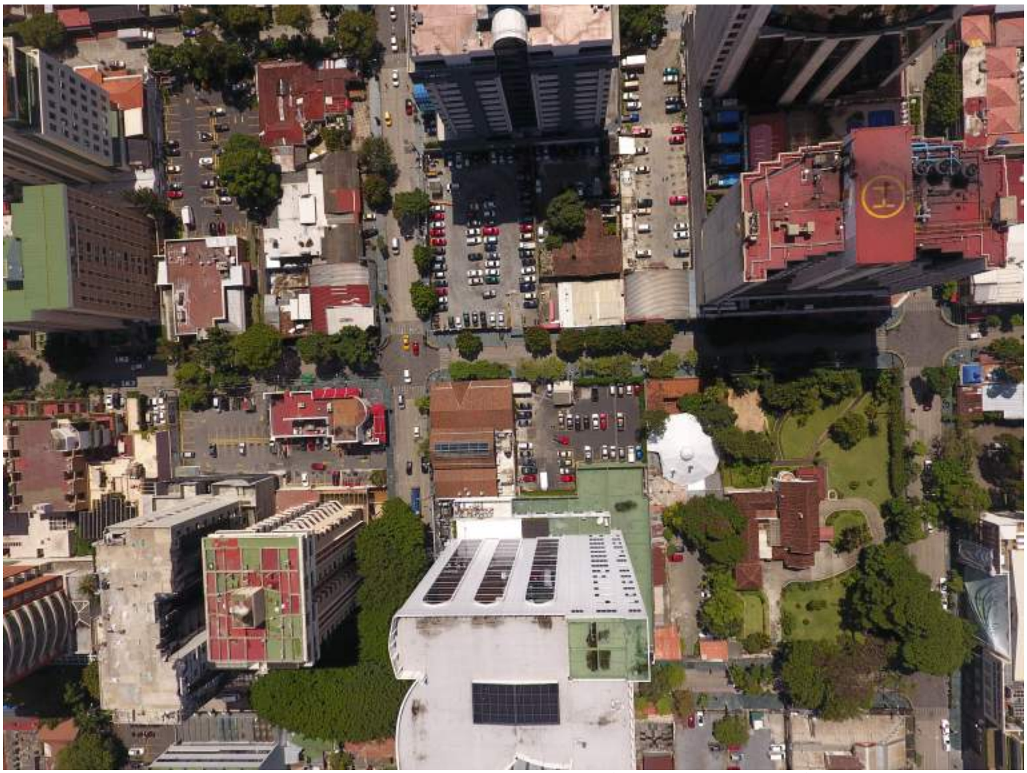


Figure N-10 Zone 10 UAV aerial image, example 2

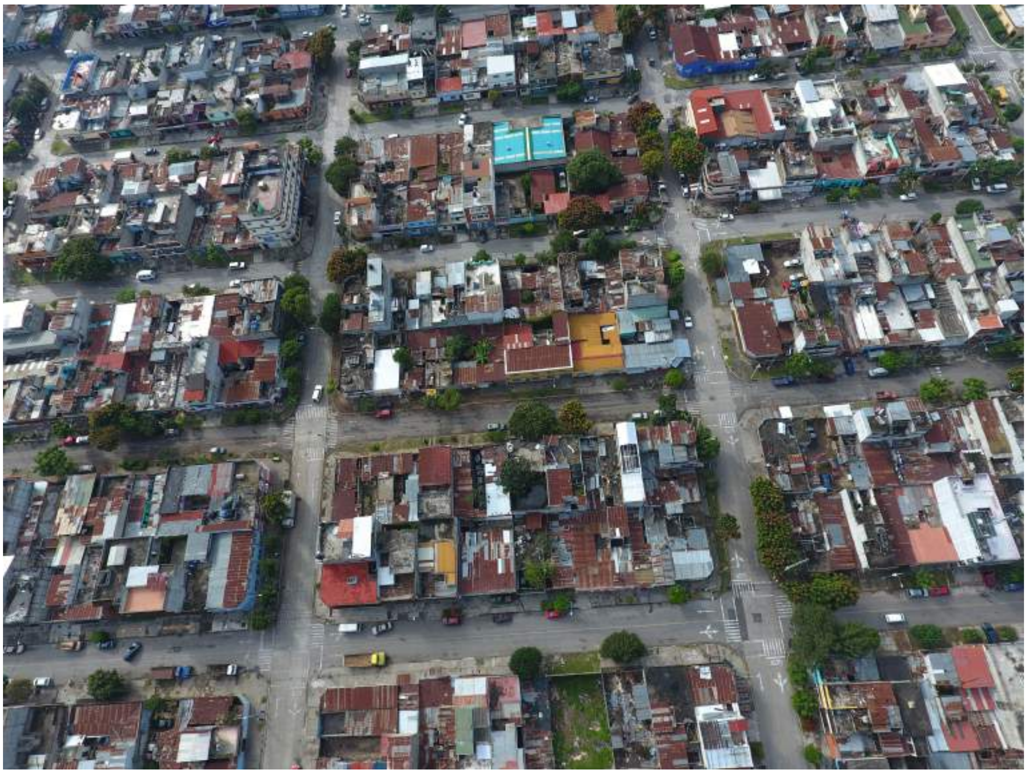


Figure N-11 Zone 12 UAV aerial image, example 1

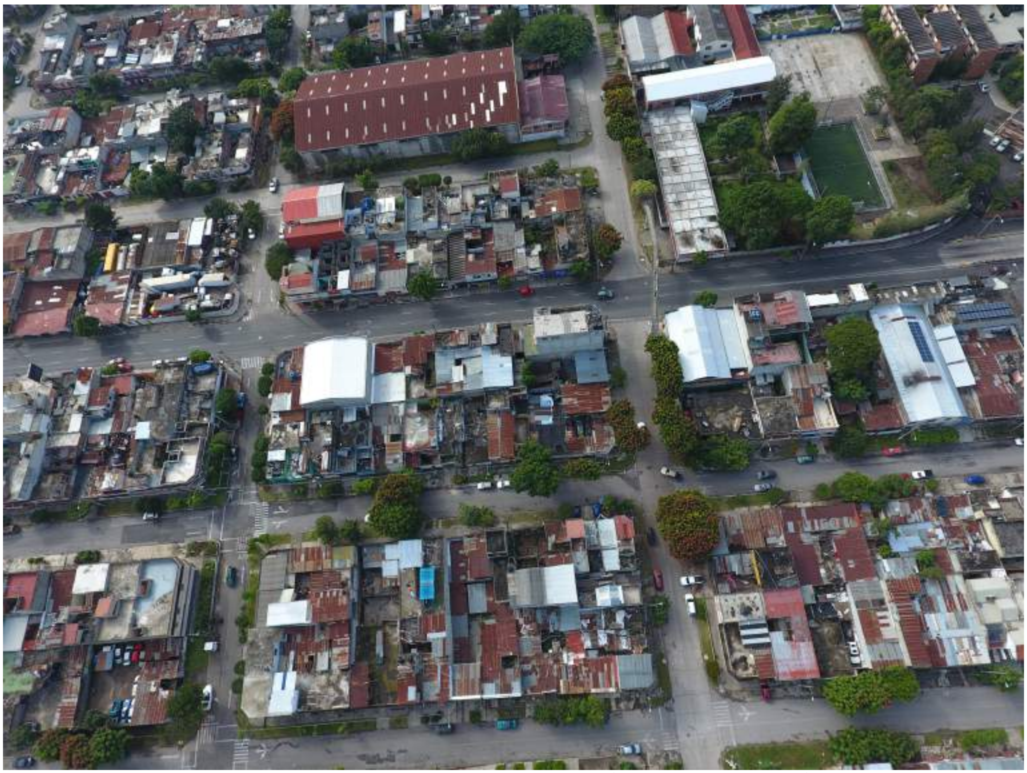


Figure N-12 Zone 12 UAV aerial image, example 2

Appendix O: Interview notes

- Three levels of builders
    - Self construction – done once in a lifetime
        - Not much in Guatemala City anymore
        - Mostly completed in Adobe
        - Similar for all Central America with the exception of Costa Rica
    - Maestros constructing around 60% (increased)
    - University educated (engineering and architects)
- Masonry is now mostly block
- Confined masonry from Italian builders in 1930s. Prior to that, Adobe and Brick (for the richer people). After 1976, immediate stop and now confined masonry as it was seen to have reduced cracking.
- FHA began in 1960s when home owning lending started, with some basic rules. Assumption of 0.25g in Guatemala City. In 1980s and 90s small towns turned to block construction.
- General lack of understanding that the strength of confined masonry is in the blocks, not the RC.
- Buying blocks from quality factories is needed.
- Retrofit older brick or adobe?

- Adjustments with larger openings (garage frontage).
- Manual on confined masonry written as a training guide of maestros.
- Higher-rise buildings >10 storeys usually RC, of frames or wall and frame – masonry is tied into the slab and drilled anchors used to tie.
- Now more gypsum internal walls.
- Column sizes 60-90 cm – reducing with height.
- Proportions of high-rise: 1/3 walls, 2/3 reasonable frames (the older frames are less ductile).
- In towns outside Guatemala City, there are 6-7 storeys max in RC frame. Engineers often involved, there has been column damage with several buildings in the past.
- Maestros mostly build confined masonry
- American codes used
- Ground conditions– ash flow from 2/3 eruptions for 4-5m and deeper (soil C), covered by partially weathered tephra to the surface (soil D).
- Rafts or pads are used for houses. See foundation cross section detail. Often cost cutting reduces the depth or width of the foundations constructed.
- Steel 5-6 storeys, poor definition of joints.
- Universal Building Code – where smaller communities act, without mandate risky for designer.
- There is no PI insurance.

- Design spectra in ASCE 10 Zone 5, values from RESIS II adopted.
- Norma A13 – UBC – ASCE 7 (2010)
- CONRED –
    - 2010 legal forced municipality
    - owners responsible for evaluating
- Next step is an exam for engineers – it's a natural step. And retrofit, e.g. 14 American schools 1956, 1 storey.
- Camino Real Hotel building structured to stiffen, added shear walls from the first floor.
- Estimated proportion of buildings
    - CM (most)
    - RC frames (few)
    - Adobe (10% in Z1)
- 1950s-1970s – mid-rise 4 storeys, one collapsed in 1976. There was a change in architectural trends post-war. Lot's of brickwork integrated with the frames in public buildings. Walls have a thickness of around 350 mm, RC cast afterwards. Brittle. Effective length is around 5m c/c
- Lifts (like in Santiago, Chile) in 2/3rds of buildings.

Appendix P: PAGER translation tables

Code	**Material type**	**Masonry type**	**Occupancy**	**LLRS**	**Infill wall material**	**Mortar**	**Roof type**	**Floor type**	**Reinforcement**	**EQ design**	**Diaphragms**	**Number of storeys**
W	Timber											
W1 & W3	Timber		Residential	Frames								
W2	Timber		Non residential	Frames								
W4	Timber			Walls								
W5												
W6	Timber			Frames	Other							
W7	Timber			Braced	{"Block","Brick"}							
M												
M1												
M2												
A	Masonry	Adobe										
A1	Masonry	Adobe				Mud	Lamina	Timber				
A2	Masonry	Adobe				Mud	Other					
A3	Masonry	Adobe				Cement	Other					
A4	Masonry	Adobe				Mud	Other		Confined			
A5	Masonry	Adobe				Mud			Reinforced			
RE												
RS	Masonry	Rubble										
RS1	Masonry	Rubble				None						
RS2	Masonry	Rubble				Mud						
RS3	Masonry	Rubble				Lime						
RS4	Masonry	Rubble				Cement	Brick	Brick				
RS5	Masonry	Rubble				Cement			Confined			
DS	Masonry	Cut stone										
DS1	Masonry	Cut stone				Mud	Timber	Timber				
DS2	Masonry	Cut stone				Lime						
DS3	Masonry	Cut stone				Cement						
DS4	Masonry	Cut stone					RC slab	RC slab				
MS												
UCB	Masonry	Block							None			
UFB	Masonry	Brick							None			

Code	Material type	Masonry type	Occupancy	LLRS	Infill wall material	Mortar	Roof type	Floor type	Reinforcement	EQ design	Diaphragms	Number of storeys
UFB1 &UFB2	Masonry	Brick				Mud			None			
UFB3	Masonry	Brick				Lime			None			
UFB4	Masonry	Brick				Cement			None			
UFB5	Masonry	Brick				Cement	RC slab	RC slab	None			
RM	Masonry								Reinforced			
RM1	Masonry								Reinforced		None	
RM1L	Masonry								Reinforced		None	{1,2,3}
RM1M	Masonry								Reinforced		None	{4,5,6,7}
RM2	Masonry								Reinforced		{"Roof", "Roof & floors"}	
RM2L	Masonry								Reinforced		{"Roof"; "Roof & floors"}	{1,2,3}
RM2M	Masonry								Reinforced		{"Roof"; "Roof & floors"}	{4,5,6,7}
RM2H	Masonry								Reinforced		{"Roof"; "Roof & floors"}	">7"
RM3	Masonry								Confined			
C	RC											
C1	RC			Frames						{"Moderate", "High"}		
C1L	RC			Frames						{"Moderate"; "High"}		{1,2,3}
C1M	RC			Frames						{"Moderate"; "High"}		{4,5,6,7}
C1H	RC			Frames						{"Moderate"; "High"}		">7"
C2	RC			Walls								
C2L	RC			Walls								{1,2,3}
C2M	RC			Walls								{4,5,6,7}
C2H	RC			Walls								">7"
C3	RC			Frames	{"Brick"; "Block", "Adobe"}					{"None";"Low"}		
C3L	RC			Frames	{"Brick"; "Block", "Adobe"}					{"None";"Low"}		{1,2,3}
C3M	RC			Frames	{"Brick"; "Block", "Adobe"}					{"None";"Low"}		{4,5,6,7}
C3H	RC			Frames	{"Brick"; "Block", "Adobe"}					{"None";"Low"}		">7"
C4	RC			Frames	None					{"None";"Low"}		
C4L	RC			Frames	None					{"None";"Low"}		{1,2,3}
C4M	RC			Frames	None					{"None";"Low"}		{4,5,6,7}
C4H	RC			Frames	None					{"None";"Low"}		">7"
C5												
C5L												
C5M												
C5H												
C6	RC			Combination								

Code	Material type	Masonry type	Occupancy	LLRS	Infill wall material	Mortar	Roof type	Floor type	Reinforcement	EQ design	Diaphragms	Number of storeys
C6L	RC			Combination								{1,2,3}
C6M	RC			Combination								{4,5,6,7}
C6H	RC			Combination								">7"
C7												
PC1												
PC2												
PC2L												
PC2M												
PC2H												
PC3												
PC3L												
PC3M												
PC3H												
PC4												
S	Steel											
S1 & S3	Steel			Frames								
S1L	Steel			Frames								{1,2,3}
S1M	Steel			Frames								{4,5,6,7}
S1H	Steel			Frames								">7"
S2	Steel			Braced								
S2L	Steel			Braced								{1,2,3}
S2M	Steel			Braced								{4,5,6,7}
S2H	Steel			Braced								">7"
S4	Steel			Combination								
S4L	Steel			Combination								{1,2,3}
S4M	Steel			Combination								{4,5,6,7}
S4H	Steel			Combination								">7"
S5	Steel			Frames	{"Brick", "Block", "Adobe"}							
S5L	Steel			Frames	{"Brick", "Block", "Adobe"}							{1,2,3}
S5M	Steel			Frames	{"Brick", "Block", "Adobe"}							{4,5,6,7}
S5H	Steel			Frames	{"Brick", "Block", "Adobe"}							">7"
MH												
INF					Other							
UNK	Unknown											