SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World
9-10 July 2015, Cambridge UK

A REVIEW OF SEISMIC VULNERABILITY ASSESSMENTS IN CENTRAL AMERICA

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Abstract: For effective earthquake risk reduction, an accurate representation of seismic risk is needed. Thus, assessments of seismic vulnerability–an important component of seismic risk–need to be reliable. Central America is a highly seismically active region with a history of large physical and economic losses from earthquake events, however literature concerning the seismic vulnerability of buildings in the region is scarce. To address this gap we have completed an extensive search for and review of documentation reporting seismic vulnerability assessments in the region, collated it into a database, developed and applied a framework for appraising the document quality, and compared the different results. The study concludes that Central American seismic vulnerability assessments are few in number and are not easily available, and that the assessment methodologies used are poorly described, simplistic, and aged and produce vulnerability estimations that vary widely, impacting significantly on loss estimations. Ultimately, this paper highlights the need for an improved understanding of the seismic vulnerability of buildings in Central America.

Background

As aspirations shift from disaster response to resilience (Twigg 2004; Wisner 2004) it is increasingly important that evidence used to inform earthquake risk reduction strategies is competent. However, seismic risk calculations are complex and imperfect (D'Ayala & Meslem 2012) due to uncertainty in the three constituent parts: (1) seismic hazard, (2) the extent of the built environment exposed to the hazard, and (3) the structural vulnerability of exposed buildings. In particular, accurate assessment of structural vulnerability is vital, as variation impacts profoundly on overall loss estimations (Erduran et al. 2010; Rashmin Gunasekera, pers. comm., November 11, 2014).

Numerous seismic vulnerability assessment (SVA) methodologies have been developed over recent years (Calvi et al. 2006; Scawthorn 2008), drawing on empirical, analytical, expert judgement, or hybrid approaches, each with their own advantages and limitations (D'Ayala and Meslem 2012; Kwon and Elnashai 2006; Porter 2003; Rossetto et al. 2013; Rossetto et al. 2014). These methods range in complexity, inputs required, and calculation techniques, and thus they achieve differing levels of accuracy. Generally, methods aim to balance the demand for simple and usable methodologies, with the need for accuracy.

Central America is particularly vulnerable to earthquakes (Coburn and Spence 2002), with low levels of development (Bilham 2012), substantial seismic hazards (Benito et al. 2012), and prolific low- or non-engineered construction (Holliday 2009; Papanikolaou and Taucer 2004; Rodriguez and Blondet 2004; Verbicaro et al. 2009). Despite this, there is little formally published about regional seismic vulnerability: for instance, there are no Central American

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entries in the newly published Global Earthquake Model (GEM) analytical and empirical functions compendia (D'Ayala and Meslem 2012; Rossetto et al. 2013).

This article gives an overview of existing SVAs for the Central American isthmus, which includes Guatemala, Honduras, El Salvador, Costa Rica, Nicaragua, and Panama. Information has been collated from all available sources on the SVA methodologies used, the underlying approaches, and the results achieved. The spread of results for the same PAGER (Prompt Assessment or Global Earthquakes for Response) building typologies is then investigated, followed by a simple examination of the level of impact that different vulnerability information has on loss estimations, using the Central American findings as a case study.

Central American Seismic Vulnerability Assessment Documents

In the absence of published literature on SVAs for Central America, a wide variety of sources were used to gather information, including project reports, government reports, presentation slides, masters and doctoral theses, meeting minutes, conversations, presentation and workshop notes, and email correspondence. In total, around two hundred items were reviewed and thirty-four specifically documented seismic vulnerability assessments. In general, documents were difficult to find (sometimes impossible) and reasons for this may include unavailable, inaccessible, or inefficient mechanisms to publish this type of work; or a lack of incentive or will to share work publically, perhaps due to challenges with intellectual property, political or social motivations; or simply because the work was completed for practical use without thought of dissemination.

The document quality was considered carefully, due to the nature of the sources used. An assessment framework was developed based on Scott's four principles (Bryman 2008; Scott 1990): *representativeness, meaning, authenticity*, and *credibility*. *Representativeness* assesses whether the document is typical in the body of available documents and in this study is considered to be negligible, as the full body of available documents are used and the scope of unobtainable documents is not known. *Meaning* concerns potential sources of influence or distortion (both conscious and sub-conscious) to a document and is difficult to measure without a much deeper contextual understanding and analysis of the body of documents, so for this study we have assumed that any influences are negligible. The *authenticity* of a document can be affected by alterations of documents or information, which may be more commonplace in countries that lack strong governance and respected institutional expectations, or where there are persons who have the motivation and ability to falsify information. Platt (1981) suggests that to check authenticity close scrutiny should be paid to instances such as: lack of coherence or sense; obvious errors; internal inconsistencies in style, formatting or content; or multiple versions of the same document being available. The *authenticity* will be assessed, as will a document's *credibility*, which concerns possible error, distortion, and/or bias in the information.

Thus, a framework to assess the *credibility* and *authenticity*, and hence the document quality has been developed (see Table 1), and in order to reduce subjectivity, clear attributes have been defined for each scoring level. An average is used for the overall quality score. Of those documents assessed, 50% were of 'moderate' credibility and just less than 30% were judged to be of 'moderate' authenticity. The remainder were all scored as 'high'.

All of the information retrieved has been compiled into a database, with details of the source document, the building typologies studied (all typologies have been translated into PAGER typologies (Porter et al. 2008)), the country of the study, results achieved, methodological information, and the ratings of document quality using the framework proposed herein.

From the information gathered, eleven different methodologies were identified, with information on each summarised in **Table 2**. The methodologies range in intended geographical usage, required inputs, underlying approaches, and age, but all have been applied in Central America.

Table 1 - Document quality scoring framework

	Low	Moderate	High
Authenticity	Lack of overall coherence Inconsistencies in formatting and style More than one version of the same document available Document not verified through triangulation Document obtained from an unreliable source	Document obtained from other credible source Secondary information	Overall coherence Consistent formatting and style Only one version of the same document available Document verified through triangulation Document obtained from the publisher directly Primary information
Credibility	Document authored by a lesser expert, e.g. students Lesser reputable publisher, e.g. conference, independent Over 25 years old Errors found during review Inadequate information given about how methodology was applied	Documents authored by government engineer Moderately reputable publisher, e.g. local agency, university Between 5 and 25 years old Minor errors found during review Some information missing about how methodology was applied Not written in the country	Document authored by experts e.g. consultant, academic Unquestionable author or publisher, e.g. government, consultancy, academic journal, international organisation Less than 5 years old Errors not found during review All information given about how methodology was applied Authored from within the country

Comparison studies

Two main comparison studies have been undertaken to investigate (1) the range in results from Central America SVAs, and (2) the effects that this range has on overall seismic loss estimations.

Firstly, comparisons have been made between results for the same building typologies in order to investigate the spread of results available. This required the translation of building classifications into PAGER building classes (see Stone (2014) for more information on the translation) and the transposing of curves to a common intensity measure, which required the assumptions of a common fundamental period (0.2s) and a maximum spectral acceleration/peak ground acceleration ratio (2.5), and the use of MMI-PGA relationships (Linkimer 2007; Sauter and Shah 1978). The results for each PAGER building type were then plotted, and the standard deviation calculated (see Figure 1 for an example).

Table 2 - Information on methods used in Central American SVAs

Method	Inputs	Approach	Applications	Comments
Jerez (2001): based on FEMA (1988a) & FEMA (1988b)	Building typology; observable structural defects; soil type; building height	Expert judgement	Guatemala City (Farfán-Mendoza and Díaz Beteta 2009; Pérez-Pérez 2005; Rivas and Vásquez-Rubio 2008)	More recent version of FEMA (1988a) available with significant updates
European Macro-seismic Scale (EMS-98) (Grunthal et al. 1998)	Building typology	Not clear, but includes some global empirical data	Guatemala (Villagrán De Leon 2008)	Good for data poor contexts; developed for European use
Earthquake Lethality Estimation Method (ELEM) (GeoHazards International 2001)	Building typology; quality of design, construction and materials	The judgement of a global group of experts	San José, Costa Rica (Salas 2003)	Derivation information not obtainable (Brian Tucker, personal communication, July 30, 2014)
Chan et al. (1998)	GDP; population data	Empirical	Each Central American country (Yong et al. 2002)	Aged empirical data, global application
ERN/Miranda (1999)	Structural typology; elevation geometry, lateral deformation type, fundamental period, ductility, age	Analytical	Throughout the region (ERN 2012; ERN 2010; ERN 2009a; ERN 2009c; ERN 2009b)	Explanations of methods methodology not clear and incomplete
RESIS II (Lang et al. 2009a)	Building typology	Analytical (Cattari et al. 2004; FEMA 2010; Geneturk et al. 2007; Kappos and Panagopoulos 2008; Mouroux et al. 2004; Singh et al. 2009)	Honduras & Santa Tecla, El Salvador (Guardiola 2010; Lopez 2011)	Not derived for Central America, different authors, assumptions and associated uncertainties between building typologies
Hazard-US (HAZUS) (FEMA 2010)	Building typology; code level (referring to US codes); number of storeys or building height	Hybrid	El Salvador (Castellanos 2011)	For US buildings typologies
Italian Vulnerability Index Method (IVIM) (Benedetti and Petrini 1984)	Structural system; geometry; materials used; state of conservation; non-structural elements	Empirical	Nicaragua (Reyes et al. 2003; Ugarte et al. 2004).	Masonry only, derived for Italian buildings.
Lang et al. (2009b)	Geometry; structural defects; current state of the structure age; non-structural elements.	Not clear, likely to be expert judgement	Central America (Lang et al. 2009b)	RC and masonry schools and hospitals; outputs not quantitative
Iervolino et al. (2007)	3D lumped-plasticity structural model	Analytical	Single school building in Guatemala (Verbicaro et al. 2009)	More complex and time-consuming, deals well with uncertainty
Sauter and Shah (1978)	Building typology	Empirical (Haresh Shah, personal communication, November 24, 2014)	Turrialba, Costa Rica (Lamadrid 2002)	Aged empirical data, method unclear

Table 3 summarises the maximum standard deviation calculated for each building typology for which more than ten curves were obtained. The highest variation in results is observed for timber structures, followed by reinforced masonry, but large variations are observed over all building types, often at lower-middle range earthquake intensities. It is important to note that the variance has been calculated using all of the results found; any clear outliers have not been excluded and thus may unduly influence the standard deviation.

Some spread in results should be expected due to natural variation within building classes, and between Central American countries, however undoubtedly the differences between SVA methodologies used plays a large part in the range of results achieved. Hence, the second comparison study examines the impact of using different SVA methodologies on loss estimations.

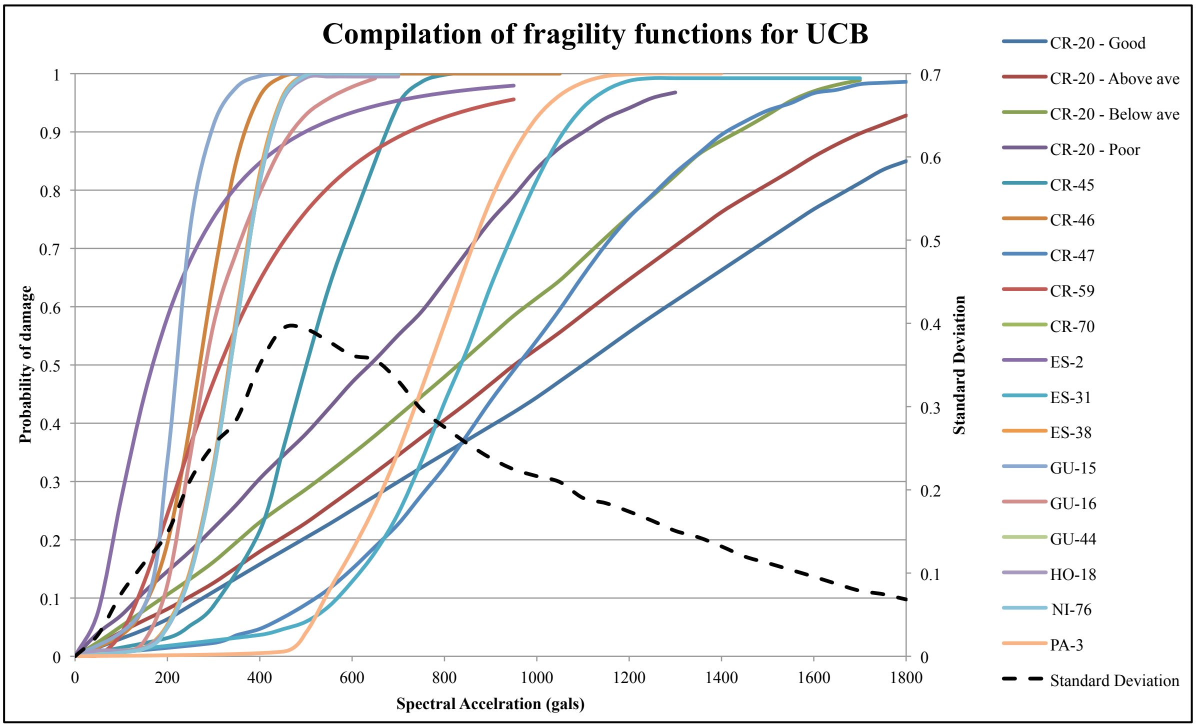

Figure 1 - Compilation of fragility functions for PAGER typology UCB

Table 3 - The variations between Central American SVA results for different PAGER typologies

PAGER typology	Number of curves	Maximum standard deviation of all curves
A	16	0.344 at 350 gals
C1	14	0.312 at 850 gals
RM	18	0.417 at 1100 gals
UCB	18	0.394 at 450 gals
UFB	10	0.382 at 450 gals
W	14	0.421 at 450 gals

Vulnerability results achieved using the eleven different SVA methodologies (see Table 2) were used alongside static exposure (see Table 4) and hazard components (see Table 5), to calculate the seismic losses for three scenario earthquakes. The exposure profile was modelled on simplified building typology data for Panamá: for simplicity the total number of

Table 4 - Exposure details for scenario comparison study

PAGER building class	Proportion of building stock	Total buildings	Average floor size of building (m^2)	Average replacement value (US$/$m^2$)
UCB	69%	1 000 000	75	335.5
C3	7%			
W	20%			
A	4%			

Table 5 - Intensity measures for the three scenario earthquakes in Panamá City. PGA and S_a values from Benito *et al.* (2012), MMI values derived from Linkimer (2007) and Sauter and Shah (1978)

Scenario no.	1	2	3
Return period (years)	500	1000	2500
PGA (g)	0.26	0.32	0.422
PGA (m/s^2)	2.52	3.15	4.14
MMI	VII	VIII	IX
PGA (gals)	252	315	414
Sa (T=0.2s) (gals)	504	637	858

buildings in the study area was assumed to be one million, with the financial values assumed to be consistent between building classes.

A number of interesting observations can be made from the results (see Figure 2), which are normalised to aid comparison. Firstly, methodologies specifically developed for, or applied to, Central American cases (e.g. Jerez (2001), ERN/Miranda (1999), RESIS II) have estimated the highest losses. This may add weight to the common assumption that Central American buildings are, in general, more vulnerable than those found in Europe or the US (for which most of the other methods are devised). Secondly, the variation between results is largest for the smallest scenario earthquake and smallest for the largest earthquake, which suggests more agreement between SVA methodologies at higher earthquake intensities. This would be expected after consideration of Figure 2 and Table 3. Thirdly, as the average loss estimations from each methodology increases, the variation between results for the different scenario earthquakes reduces, as may be expected for SVA results that follow lognormal or other similar distributions. Finally, the differences in loss estimations range up to a factor of 6.8, which is substantial.

In summary, existing SVA results for Central America vary substantially for all building typologies studied and may be caused by natural and methodological variations. Moreover, the selection of vulnerability information has been shown to result in significant impact on the total loss estimations–in the worst case, up to 6.8 times. This scale of uncertainty may put the usefulness and credibility of simplistic loss assessments in jeopardy.

Conclusions

This paper has reported the results of a search for and investigation into Central American SVAs. Some considerable questions on existing SVAs for Central America have been raised. Firstly, assessments for the region are poorly documented, hard to obtain, few in number, and lacked completeness. The quality of the documents obtained has been assessed using a novel framework, and, in this case, all are rated as high or moderate.

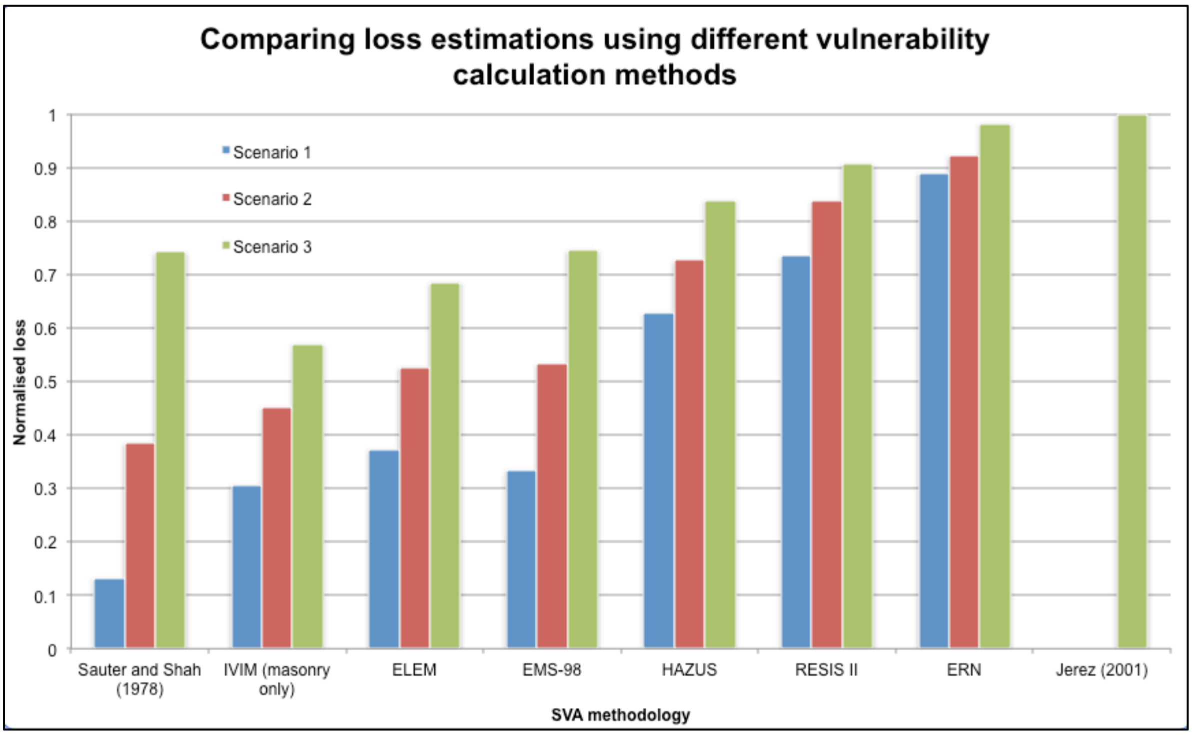

Figure 2 – Normalised loss results for vulnerability calculated using different methodologies

The range in fragility functions used in different Central America risk assessments is large and is likely to be due to natural factors, such as actual variation in building classes, but also due to differences in the SVA methodologies used, which are fairly simplistic and aged, and are often derived for buildings in countries outside of the region. The largest variation in functions was found for timber structures, however all typologies had high variations.

In addition, the variation in fragility results was shown to propagate into large differences (up to 6.8 times) in loss estimations. Central American specific methods or applications of methods exhibited the highest loss results, perhaps indicating that Central American building typologies are more vulnerable than those in regions for which the other methods were derived (Europe and the USA).

Ultimately, this work has shown that seismic vulnerability assessments for Central America are lacking, and that further and more accurate assessments of the region's existing building types are needed to get a better idea of seismic risk, and hence instigate more effective earthquake risk reduction initiatives.

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