

Developing Seismic Risk Maps for Mérida State, Venezuela



A. Bendito

Faculty of Engineering, Universidad de Los Andes, Venezuela.

J. Rozelle & D. Bausch

FEMA, Mitigation Division, Region VIII, USA.

SUMMARY:

Until recently, the focus of FEMA's Hazus earthquake model has been US centric, largely due to a lack of standardized building/infrastructure data formats applicable elsewhere. In a combined effort between FEMA Region 8 and the Universidad de Los Andes, Venezuela, the Hazus earthquake model was adapted to conduct earthquake loss estimations for Venezuela. The required population totals and demographic distributions were developed using Oak Ridge National Labs Landscan 2008 population data and the census 2001 data from the country. The accuracy of the model was further enhanced for Mérida State by the inclusion of geologic data maps and risk assessment data from other investigations. To identify possible scenarios we used a *USGS ShakeMap scenario*, representing the historical earthquake that occurred in Mérida in 1674 with an estimated magnitude $M_s7.5$. Countless minor seismic tremors are continually registered but there is an increasing probability of a damaging earthquake.

Keywords: Risk Management, Hazus, Andean Region, Scenario, Earthquake.

1. INTRODUCTION

Earthquake disasters result in severe devastation and cause deaths of a large number of people every year. Deaths and destruction due to earthquakes can be reduced with the application of basic principles and targeted investments. Managing risk will become a more urgent and demanding task in the coming years, mainly because vulnerabilities are rapidly increasing. Therefore, mechanisms of response to risk need to be more agile and effective at all levels and scales of government, as well as in people's daily lives.

Another catastrophic earthquake is a potential reality in Mérida State at any time; however the day this may occur cannot be predicted. An important objective of this study is to highlight that it will have a more severe impact than the last large earthquake due to the fact that the total population has grown from 4,500 since the last earthquake in 1894 to about 800,000 (as per 2011 Census of Venezuela); now 88.19% of the actual population lives in urban areas, and the city may be ill prepared. In order to be prepared for such a natural hazard, we must be able to estimate and predict the seismic risk associated with the potential losses and thus be in a better position to plan for the long term. The seismic risk maps are and can be used in a number of ways such as increasing general public awareness of earthquake hazard, urban planning, selecting sites for important facilities (e.g. hospitals, schools), providing a basis for whether site-specific hazard evaluations should be performed, aiding emergency preparedness and response, and loss estimation. (Wong 2010). We believe this study is important to engineers, building architects, policymakers at all levels-local, state and federal, insurance companies and business owners.

To identify possible scenarios we considered the ShakeMap provided by United States Geological Survey (USGS), developed for one of the most documented historical earthquakes that occurred in Mérida in 1674. (Laffaille et al. 2010). This study used Hazus to estimate earthquake damage and losses. Hazus is a comprehensive GIS-based technology developed by the Federal Emergency Management Agency (FEMA) in partnership with the National Institute of Building Sciences (NIBS). By including detailed data on the building inventory, demography, soil condition, region's geology, and history of earthquakes in the region we can identify and map the areas of greater vulnerability and structures with the highest risk.

2. THE STATE AND ITS EARTHQUAKE POTENTIAL

Venezuela is a country that contains many geographical features, from deserts to jungle, and from extended plains to steep slope mountain ranges. Mérida is settled over an elongated plateau inside a valley, within the Andean Region in western Venezuela. This plateau is oriented SW-NE surrounded by two mountain chains: the Sierra Nevada (SE) and the Sierra de la Culata (NW). Two rivers flow through the tableland: the Chama and the Albarregas rivers. (Castillo 2006).

In the western region of Venezuela, large earthquakes have occurred. One of the most destructive occurred on March 26, 1812, with an estimate magnitude M_s 7.3; is one of the most controversial seismic events in Venezuela's history because it affected the whole country and also had destructive effects in Saint Vincent and Jamaica. Caracas, a city of 32,000 inhabitants and the capital of Venezuela, was reduced to ruins, and most of the churches were completely destroyed. La Guaira, Maiquetia, Mérida and San Felipe suffered the same fate. (Laffaille et al. 2009). The last ruinous earthquake occurred on April 28, 1894 in the central longitudinal valley between Mérida and Bailadores, with a magnitude M_s 7.1; 345 people were killed.

Mérida has not experienced a damaging local earthquake during the last few hundred years, which has contributed to a false feeling of stability in society. However the city has experienced slight ground shaking numerous times during the recent past due to local low-magnitude earthquakes.

The seismic zone map of the Venezuelan standard for seismic regulations (COVENIN1756:2001) divides the country into seven zones; the hazard in these zones can be described as very high, high, intermediate and low. Design peak ground acceleration varies from 0.40g in the zone 7 to 0.10 g in zone 1 at rock sites, associated to a probability of exceedance of 10% in 50 years. Mérida State is placed in seismic zone 5 as a high seismic zone that is consistent with the global hazard map developed by the Global Seismic Hazard Assessment Program (GSHAP).

Mérida State is located on the western region of Venezuela, with the fault systems of Boconó, Oca-Ancón, Perijá and the Nido of Bucaramanga being the principal tectonic features, which have historically been the cause of important earthquakes. Fig. 1 shows the active quaternary faults of the western Venezuela.

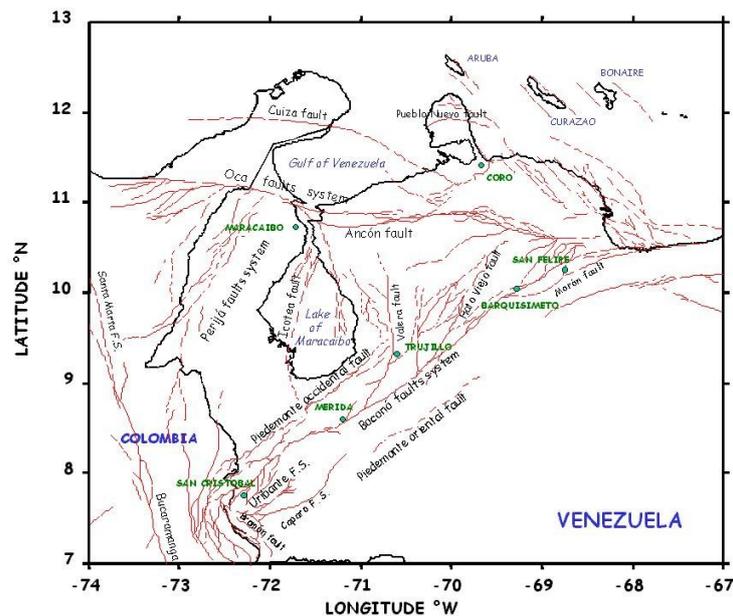


Figure 1. Neotectonic map of western Venezuela, showing active quaternary faults. (Bendito et al. 2001).

3. SELECTION OF SCENARIO EARTHQUAKES

The scenario earthquake in the Hazus earthquake model, may be a deterministic event, a probabilistic analysis of seismic hazard or given by a user-supplied map of ground motion. The user-supplied map, with the ShakeMap, will be used for this study.

3.1 ShakeMap scenario earthquake

A ShakeMap is a representation of ground shaking produced by an earthquake. The information it presents is different from the earthquake magnitude and epicenter that are released after an earthquake because ShakeMap focuses on the ground-shaking produced by the earthquake, rather than the parameters describing the earthquake source. So, although an earthquake has one magnitude and one epicenter, it produces a range of ground shaking levels at sites throughout the region depending on distance from the earthquake, the rock and soil conditions at sites, and variations in the propagation of seismic waves from the earthquake due to complexities in the structure of the Earth's crust. ShakeMap generates separate maps of the spatial distribution of peak ground-motions (acceleration, velocity, and spectral response) as well as a map of instrumentally derived seismic intensities. These maps provide a rapid portrayal of the extent of potentially damaging shaking following an earthquake and can be used for emergency response, loss estimation, and for public information through the media. For potentially damaging earthquakes, ShakeMap produces response spectral acceleration values at three periods (0.3, 1.0, and 3 s) for use not only in loss estimation, but also for earthquake engineering analyses. Response spectra for a given location are useful for portraying the potential effects of shaking on particular types of buildings and structures. Following a damaging earthquake, ShakeMaps of spectral response will be key for prioritizing and focusing post-earthquake occupancy and damage inspection by civil engineers. For the Hazus program, the ShakeMap system produces a hazus.zip file containing the GIS layers that Hazus requires, including PGA, PGV and spectral accelerations at 0.3 and 1.0 seconds. In addition, ShakeMap modeling incorporates available strong ground motions with recorded on strong motion instrumentation or through the Did You Feel It? internet intensity information <http://pubs.usgs.gov/tm/2005/12A01/>.

We used a *USGS ShakeMap scenario*, representing the historical earthquake that occurred in Mérida in 1674 with an estimated magnitude M_s 7.5. We used Chiou & Youngs 2008 (an NGA relations) for the peak ground and spectral values, Trevor Allen's (TA09) intensity prediction equation and Wald et al. 1999 equations to relate ground motion to intensity (GMICE).

4. METHODOLOGY

This study used Hazus to estimate earthquake damage and losses. Hazus is a GIS-based desktop application used for comprehensive seismic risk assessment modeling. This tool allows an engineering approach to modeling of infrastructure and helps in quantifying consequences to interdependent systems and sectors. The technology was developed by the Federal Emergency Management Agency (FEMA) in partnership with the National Institute of Building Sciences (NIBS). The first version of Hazus was made only for earthquake loss estimation. The recent version Hazus (2.0 was used) is extended to multi hazard loss estimation and also includes, hurricane and flood loss estimation. Government agencies and researchers use Hazus for mitigation, emergency preparedness, and disaster response. The software was adopted successfully in several states in the USA (e.g. Kircher et al. 2006; Tantala et al. 2008) and recently it was even tested and adopted in several countries overseas. Istanbul (Turkey), Newcastle (Australia), Taiwan, Bhuj (India), Israel (Levi et al. 2010) and Bangkok (Thailand).

A conceptual view of how Hazus methodology works is shown in Fig. 2. The advantage of this modular methodology is that it enables users to limit their studies to selected losses. For this study, for example, we concentrated our efforts on the direct physical damage to building stock estimate direct losses.

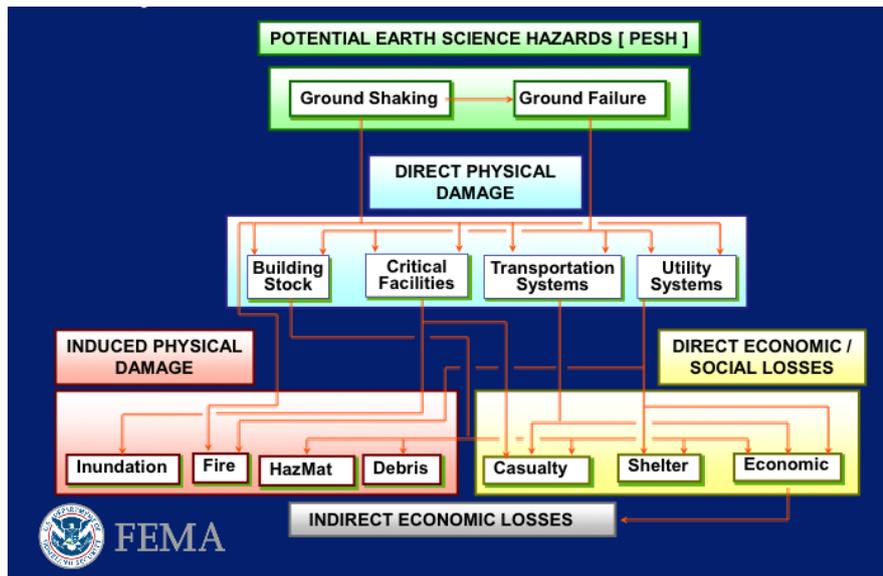


Figure 2. Modules of HAZUS methodology.

The building stock is classified both in terms of their use, or occupancy class, and in terms of their structural system, or model building type. Twenty-eight occupancy classes define residential, commercial, industrial, or other building occupancies and 36 model-building types define structural systems of wood, steel, concrete, masonry materials, and mobile homes.

The building damage functions distinguish among buildings that are designed to different seismic standards, or are otherwise expected to perform differently during an earthquake. Damage functions are provided for three “code” seismic designs levels, categorized as High-Code (H), Moderate-Code (M), and Low-Code (L), and an additional design category for Pre-Code buildings. The Pre-Code design category includes buildings built before seismic codes were required for building design. (Kircher et al. 2006). The Hazus building damage functions have two basic components: capacity curves and fragility curves. The capacity curves are based on engineering parameters of structural strength that characterize the non-linear pushover structural behavior of the 36 types of model buildings. The fragility curves, describe the probability of reaching or exceeding discrete states of damage for the structure and nonstructural systems. The states of the damage are: None (N), Slight (S), Moderate (M), Extensive (E) and Complete Damage (C). Descriptions of these damage states are found in the Hazus Technical Manual (NIBS 2012).

The methodology for determining injuries and casualties is based on the strong correlation between building damage (both structural and non-structural) and the number and severity of casualties.

5. DATA COLLECTION AND PREPARATION

To generate more accurate estimates, this study collected and incorporated region and specific inventories including soil maps, liquefaction susceptibility, landslide susceptibility, demographic data, building inventory.

5.1 Soil condition

The Venezuelan Code, COVENIN1756:2001, divides the soil into three classes S1 (hard and dense soil) to S3 (soft and loose soil). Hazus divides the soil into five classes, from hard rock (A) to soft rock (E). In the Table 1 we can see the equivalence done between the soil types using Hazus format and Venezuelan code.

Table 1. Equivalence between soil types for Hazus format and Venezuelan code

	Soil types Hazus format		Soil types Venezuelan code	
	Shear Wave Velocity (m/s)		Shear Wave Velocity (m/s)	
Type	Minimum	Maximum	Minimum	Maximum
A	1500			
B	760	1500	500	
C	360	760	250/400	500
D	180	360	170	250/400
E		180		170

5.2 Other induced effects

Other induced local effects, such as liquefaction and landslide were aggregated into Hazus, using the information and results maps provided by Castillo (2006).

5.3 Demographic data

The required population totals and demographic distributions were derived using Oak Ridge National Labs Landscan 2008 population data and census data obtained from the website pages referenced in the references below, and assigned to each census tract by following the procedure suggested by Hansen et al. 2010.

Our study provides estimated impacts for both a daytime and nighttime scenario.

The geographical size of the detailed Mérida study region is 5,711 square miles and contains 2,448 census tracts. For the urban area the census tracts have one square kilometer and for the rural area ten square kilometer.

5.4 Building inventory

Past earthquakes have shown that economic and social losses are primarily a function of damage to buildings. This is true for two very basic reasons: (1) buildings are the predominant kind of facility in the built environment; and (2) buildings are vulnerable to earthquake damage. Buildings provide shelter for people, whether at home or at work, house commercial and industrial operations, and serve as essential facilities, such as schools and hospitals. Accurate prediction of building damage and loss is at the heart of the reliable estimates of earthquake impacts. (Kircher et al. 2006).

The building inventory data for Mérida State are based on census data, field data from different studies conducted at the Universidad de Los Andes, personal knowledge and experience from expert professionals. The building inventory includes residential, commercial, industrial, agricultural, religious, government, and educational buildings.

The building stock in the region used in this work consists of about 172,900 buildings. The stock was classified according to the following types of occupancy: residential, 81% of the total number of buildings; commercial and industrial (18%); religious, governmental and educational (1%).

The buildings were further aggregated into Hazus by the year built, estimated floor area, the number of stories and the seismic design level. We also collected detailed information for some buildings for example the University hospital (Hospital type IV), key government buildings, theaters, and airports were aggregated and included into Hazus.

The damage state probability of the general building stock is computed at the centroid of the census tract.

Since there are no specific damage functions available for Mérida State, the present study used the default functions provided by Hazus that best fit the Mérida building types and design levels. The 36 model building types were reduced to six groups (Table 2) that best fit the Mérida building types.

Table 2. The main building types for Mérida State. (For more details see Table 3.1 in the technical manual of Hazus)

Label	Merida building types
C2 (L,M)	Concrete Shear Walls
C1 (L,M)	Concrete Moment Frame
C3 (L,M,H)	Concrete Frame with Unreinforced Masonry Infill Walls
PC2 (L)	Precast Concrete Frames with Concrete Shear Walls
S5 (L)	Steel Frame with Unreinforced Masonry Infill Walls
URM (L)	Unreinforced Masonry Bearing Walls

6. RESULTS AND DISCUSSION

Obviously an accurate performance of a particular edification depends on many variables, these include, the presence or absence of irregularities in height, the level of structural redundancy, differences in the height between adjacent buildings, the disposition of non-structural elements, the accuracy of the structural calculus, the relative fulfillment of structural detail, the level of inspection and the control of construction and even the degree of existing maintenance. But we believe that with the variables that we are using, we can present the major aspects of seismic risk for Mérida State.

6.1 Building damage

Hazus estimates that about 144,951 buildings will be at least moderately damaged (damage is expressed as the probability that a given building will develop at least moderate damage). This corresponds to over 48% of the buildings in the region. There are an estimated 67,148 buildings that will be damaged beyond repair. Table 3 below summarizes the expected building damage by general occupancy and by general building type in Mérida State.

Table 3. Expected Building Damage by Occupancy and by Building Type for some of the states of damage

	Slight	Moderate	Complete
Building Occupancy	Percentage		
Agriculture	0.14	0.17	0.18
Commercial	12.55	19.68	10.93
Education	0.29	0.52	0.26
Government	0.17	0.21	0.05
Industrial	1.65	2.34	2.22
Religion	0.42	0.50	0.54
Residential	84.77	76.58	85.82
Building Type	Percentage		
Steel	3.72	5.38	4.96
Concrete	32.82	41.70	31.96
Precast	0.90	2.17	0.69
URM	62.56	50.75	62.37

The majority of damage will occur in residential structures, which are predominately unreinforced masonry. In this sense, it is appropriate to start a mitigation plan for the residential housing in order to reduce their vulnerability.

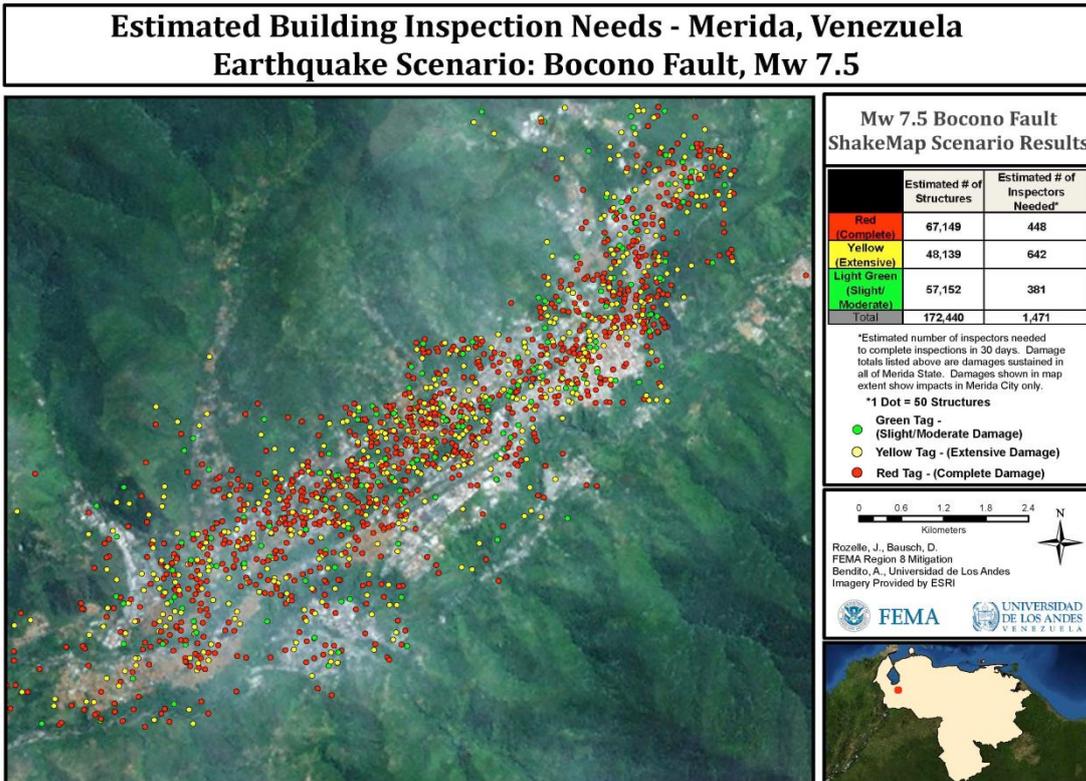


Figure 3. Estimated Building Inspection Needs

This map depicts building damages and estimated building inspection needs. Buildings marked as yellow or “extensive” require greater inspection time. Slight/moderate damaged buildings can be indentified for re-entry much faster due to their level of damage, and completely damaged buildings are quickly identified for no reentry. Extensively damaged buildings need further inspection to verify their safety.

6.2 Casualties

The casualties (people that will be injured or killed by the earthquake) are broken down into four (4) severity levels that describe the extent of the injuries. The levels are described as follows:

Severity Level 1: Injuries will require medical attention but hospitalization is not needed.

Severity Level 2: Injuries will require hospitalization but are not considered life threatening.

Severity Level 3: Injuries will require hospitalization and can become life threatening if not promptly treated.

Severity Level 4: Victims are killed by the earthquake.

Table 4 below provides a summary of the casualties for each scenario at different times of the day; 2 am (when people are asleep and at home) and 2 pm (when people are at work).

Table 4. Casualty Estimates

2:00 AM	Level 1	Level 2	Level 3	Level 4
	28,084	8,856	1,484	2,936
2:00 PM	Level 1	Level 2	Level 3	Level 4
	11,901	3,859	680	1,328

By far, this event at 2 am would result in more injuries and deaths. This time represents when the residential occupancy load is at maximum. Therefore we need to start mitigation plans especially focused on residential housing in order to reduce its vulnerability to future earthquake events.

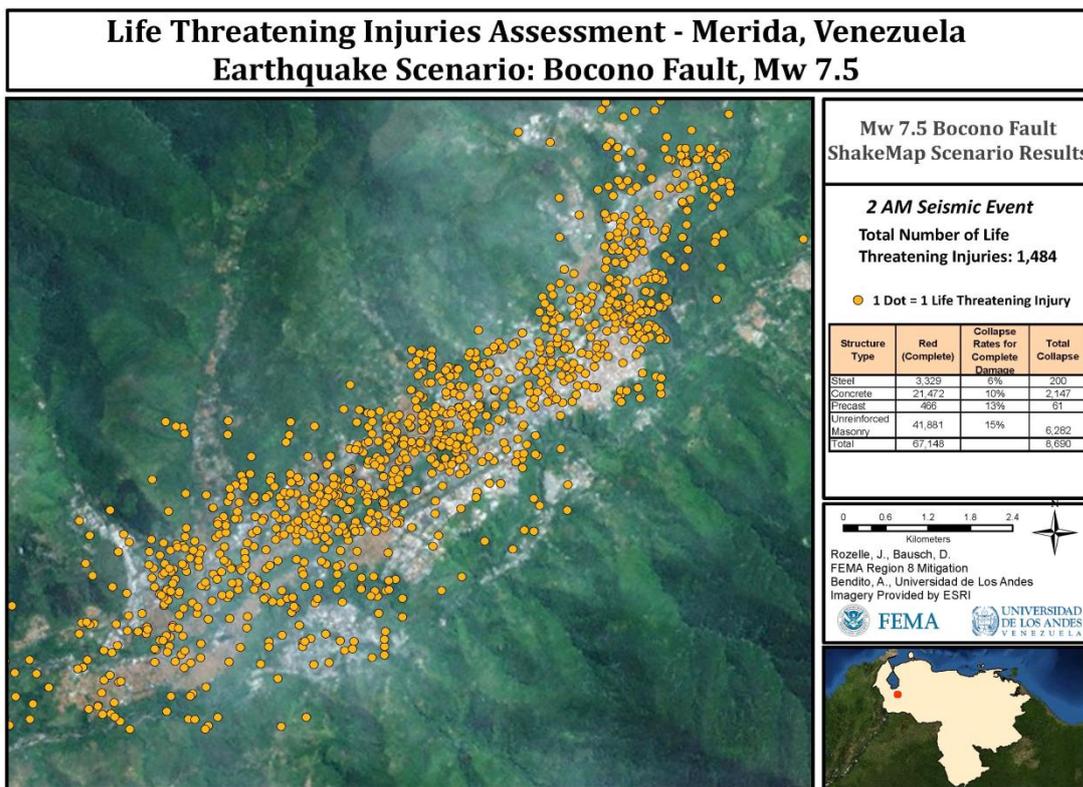


Figure 4. *Life Threatening Injuries Assessment*

This map depicts life threatening injuries (Hazard level 3 injuries) for this event. Total numbers of collapsed buildings were also calculated based on number of completely damaged buildings for each structure type, and the collapse rates for completely damaged structures by type. This total can greatly assist in identifying the number of USAR (Urban Search and Rescue) teams required for live saving efforts

7. CONCLUSIONS

While we have shown that Hazus is a useful loss estimation methodology there are several necessary steps required to improve the existing Hazus database (e.g. developing capacity and fragility curves for the Mérida State, in accordance with the Hazus platform demands).

In this paper we have implemented a GIS tool to obtain seismic risk scenarios in urban and rural areas and we have analyzed the case of Mérida State (Venezuela). This has been possible because of the great amount of information available about the seismic hazard of the city and the typology, age and other characteristics of almost the complete stock of buildings of the city. This project can be improved by collecting and inputting the data of the essential facilities such as hospitals, schools, electric power stations, pumping stations, water, gas, electricity, communications, data of hazard-material facilities, etc.

These methods should be extended to a multi-hazard assessment, including floods, liquefaction, and land sliding.

Mérida currently has high seismic risk because of its tremendous assets, concentration of buildings, and the fragility of their structures. The residential buildings would be the most severely affected.

Without doubt, Venezuela has seismic design code, but the damage clearly demonstrated that improvement is needed in pre- earthquake mitigation.

People need to be given sufficient information to enable them to make their own, sensible, personal safety risk assessments. In the medium and longer terms, more education for the general public about seismic risk, what happens during an earthquake and the simple rules for construction that can help mitigate the risk of building collapse will go a long way. Once people understand the hazard better they will be in a stronger position to make better decisions. We believe these results will enable the State and City Governments to prepare and thus reduce the potential impact of a future seismic disaster.

ACKNOWLEDGEMENT

To the mayor of Mérida city, Dr. Lester Rodriguez, for recognizing Mérida city seismic vulnerability and supporting this university-local government collaborative effort. We thank the professors: Jaime Laffaille, Arnaldo Guitierrez and Angel Rangel for many discussions and their valuable comments to help with this project. We also thank USGS specially Dr. David Wald for generating the ShakeMap scenario earthquake. The authors greatly appreciate information provided by Instituto de Protección Civil y Administración de Desastres del estado Mérida (INPRADEM) and Fundación Venezolana de Investigaciones Sismológicas (FUNVISIS).

REFERENCES

- Bendito, A., Rivero, P. and Lobo-Quintero, W. (2001). Curvas de Isoaceleración para Estados de Desempeño Estructural en el Occidente de Venezuela. *Boletín Técnico del Instituto de Materiales y Modelos Estructurales (IMME), Venezuela*. **39**: 2,1-18.
- Castillo, A. (2006). Seismic risk scenarios for buildings in Mérida, Venezuela. Detailed vulnerability assessment for non-engineered housing. *Doctoral Dissertation, Technical University of Catalonia, Barcelona*.
- Hansen, R., Bausch, D., Rozelle, J. and McNabb, S. (2010). An Updated GIS-Based Methodology for Exporting the Hazus Earthquake Model for Global Applications: HAZ EM (Extended Mediterranean) Loss Estimation. Available via www.unesco.org/science/doc/earthquake/RELEMR2010_Short_Description_Agenda.pdf.
- Kircher, C.A., Whitman, R.V., and Holmes, W.T. (2006). HAZUS Earthquake Loss Estimation Methods. *Natural Hazards Rev.* **7**: 2, 45-59.
- Laffaille, J., Ferrer, C. and Laffaille, K. (2009) Venezuela: The Construction of Vulnerability and Its Relation to the High Seismic Risk. *Developments in Earth Surface Processes*. **13(C)**, 99-114.
- Laffaille, J., Audemard, F., Alvarado, M. (2010). San Antonio de Mucúño, Mérida Andes, Venezuela: Relocation of a doctrine town following the 1674 earthquake. *The Geological Society of America Special Paper* 471.
- Levi, T., Tavron, B., Katz, O., Amit, R., Segal, D., Hamiel, Y., Bar-Lavi, Y., Romach, S., Salamon, A. (2010). Earthquake loss estimation in Israel using the new HAZUS-MH software: preliminary implementation. *Geological Survey of Israel, Report GSI /11*
- National Institute of Building Science NIBS. (2012). HAZUS^{MH} technical manual, developed by the Federal Emergency Management Agency, FEMA, Washington, DC. <http://www.fema.gov/plan/prevent/hazus/>.
- Tantala, M., Nordenson, G., Deodatis, G and Jacob, K. (2008). Earthquake loss estimation for the New York City Metropolitan Region. *Soil Dynamics and Earthquake Engineering*, **28**, 812–835.
- Wald, D.J., Quitoriano, V., Heaton, T.H., and Kanamori, H. (1999). Relationship between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California. *Earthquake Spectra*. **15,3**, 557-564.
- Wong, Ivan (2010). Development of Urban Earthquake Hazard Maps in the United States. *China/USA Symposium for the Advancement of Earthquake Sciences and Hazard Mitigation Practices*.
- Web pages:
Censo 2001, de las Proyecciones de Poblacion 1950-2050, y de los Anuarios Estadísticos anuales: <http://www.ine.gov.ve/>
<http://www.google.co.ve/>
- Fuentes: Prof. Dinorah Castro "Estudio sobre heterogenidad genética y dirección del flujo genético en la población venezolana". Laboratorio de Genética Humana, IVIC/ www.simonbolivar.org. *Revista Interciencia*, enero 2001, vol.26, no. 001.