Regional Seismic Damage, Loss and Risk Scenarios of Venezuelan School Buildings

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SUMMARY:
Regional seismic scenarios for Venezuelan school buildings are presented, based on a simplified methodology that develops fragility curves to characterize the seismic vulnerability, assess damages, losses and risk levels. The basic hypothesis is that buildings were designed and built in compliance with the seismic code in force at the time of the construction. Adopting a bilinear capacity curve five damage states were defined. The proposed methodology was calibrated by means of comparing the predicted damage with the observed damaged in an ensemble of school buildings affected by the 1997 Cariaco earthquake. A computational tool based on GIS to estimate damages and losses associated with a particular seismic event was developed, using modern seismic attenuation relationships. Seismic risk based on seismic hazard maps is also determined, which facilitates the task of prioritization for structural retrofitting decisions. The computational tool was applied to the evaluation of three regional scenarios.

Keywords: damage, loss, seismic risk, school buildings, fragility curves.

1. INTRODUCTION

Past earthquakes have pointed out the high seismic vulnerability of old school buildings, even if they were designed to comply with the seismic standards for the time of construction. Seismic events of the last 10 years as the Molise (Italy) 2002, Boumerdes (Argelia) 2003, Bingöl (Turkey) 2003, Kashmir (Paquistan) 2005, Peru 2007, Sichuan (China) 2008, Haití 2010 y Chile 2010, among others, have caused significant damage to school buildings and significant losses. The 1997 Cariaco earthquake (Mw =6.9) in Venezuela caused 74 deaths and 522 wounded , including 22 children and a teacher who died due to the collapse of four school buildings (Bonilla et al, 2000).

The Cariaco event motivated the initiation of a research project to evaluate and reduce the seismic risk in school buildings in Venezuela, which was developed by the Institute of Materials and Structural Models (IMME) of the Central University of Venezuela (UCV), the Venezuelan Foundation for Seismological Research (FUNVISIS) and the Foundation for Educational Buildings (FEDE) of the Ministry of Education, with funding from the Ministry of Science and Technology (IMME, FUNVISIS and FEDE, 2011, Lopez et al. , 2012). This work is part of this initiative and aims to develop a methodology for estimating damage and loss of school buildings in Venezuela produced by the action of earthquakes, using fragility curves for the purpose of prioritizing structural retrofitting and to provide support for decision making plans for prevention, risk reduction and emergency response.

2. METHODOLOGY

There are 28,878 registered educational institutions in Venezuela, but the number of school buildings is probably far higher. Different strategies for searching and collecting information on the existing school buildings were developed and the data was incorporated in a Geographic Information Systems (GIS).

2.1. Inventory of Schools Buildings

The inventory data of school buildings was focused on the structural characteristics that determine their seismic performance. Between 2007 and 2008 the Ministry of Education conducted a national survey to obtain information regarding geographic location, number of stories, year of construction, construction type and school population, among others. It was possible to obtain information from 16,921 school buildings of 28,878 registered schools. This information has been incorporated into the basic database of 19,792 educational institutions that were located using georeferenced coordinates. Fig. 2.1 shows the location of school sites on the seismic zoning map of the country, where zones 0 and 7 are the lowest and highest seismic hazard zones, respectively.

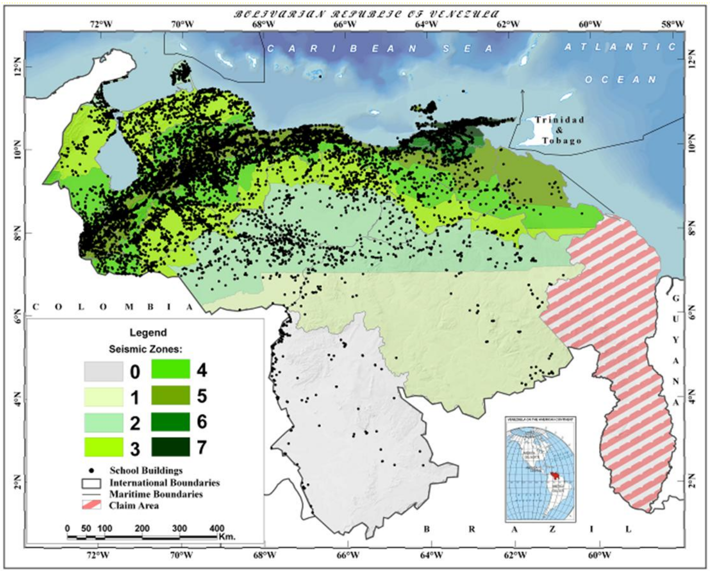

Figure 2.1. Spatial distribution of schools on the seismic zoning map of a sample of 19,792 schools.

About 49.5% of schools are in areas of high seismic hazard (zones 5, 6 and 7 in Fig. 2.1) with peak ground acceleration (*PGA*) values between 0.30 and 0.40g for return periods of 475 years. About 46% of buildings were built before 1982, when earthquake resistant requirements were less demanding than those included in the actual seismic code of 2001. Moreover, about 21% were built before 1967 when there was a significant improvement in the seismic requirements due to the occurrence of the Caracas earthquake that caused the collapse of five modern buildings.

2.2. Capacity Curves and Damage States

The strength and deformation capacity of each school building was estimated assuming that it was designed and constructed in compliance with the seismic code in force at the time of construction.

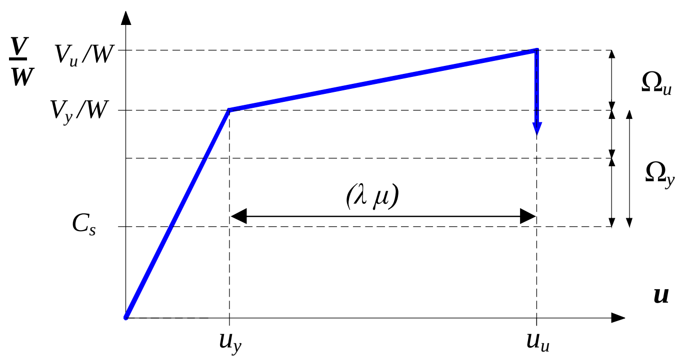

Figure 2.2. Bilinear representation and parameters of the capacity curve.

Under this hypothesis the bilinear capacity curve shown in Fig. 2.2 is obtained as follows:

i) The base shear capacity at yield level (V_y) divided by the weight (W) of the building (Eqn. 2.1), is obtained from the seismic coefficient (C_s) established by the seven Venezuelan code of years 1939, 1947, 1955, 1967, 1982, 1998 and 2001, incorporating a yield overstrength factor (Ω_y):

$$\frac{V_y}{W} = \Omega_y \cdot C_s \cdot f_W \tag{2.1}$$

Where f_w factor corrects for the differences in the determination of seismic weight W in each code and which varies between 0.86 and 1.14. V_u is the ultimate base shear capacity (Fig. 2.2) which incorporates the ultimate overstrength factor (Ω_u):

$$\frac{V_u}{W} = \Omega_u \cdot \frac{V_y}{W} \tag{2.2}$$

The values used in this work for Ω_y and Ω_u are shown in Table 2.1; they were adjusted by comparing predicted and observed damage in the 1997 Cariaco earthquake, which will be presented later. The values of Table 2.1 are within the range suggested by FEMA (2003).

ii) The yield displacement (u_y) is calculated assuming that the dynamic response of the structure is contained in the fundamental vibration mode of effective period (T_e):

$$u_y = \frac{\alpha_1}{\beta_1}\frac{V_y}{W} g \left(\frac{T_e}{2\pi}\right)^2 \tag{2.3}$$

Where α_1 is the participation factor of the fundamental mode in the top floor displacement (u), β_1 is the fraction of the building mass contained in the fundamental mode, V_y/W is the ratio defined above (Eqn. 2.1) and g is the acceleration of gravity.

iii) The ultimate displacement (u_u) is calculated using an ultimate ductility factor given by the product ($\mu.\lambda$):

$$u_u = \mu \, \lambda \, u_y \tag{2.4}$$

The parameter μ is the nominal value of ductility, estimated for old building codes from an expert consultation (Coronel, 2012) and which vary between 1.5 for old codes (Low design) and 4.5 for the actual 2001 code (Special design) . The parameter λ is taken as 3.0 (FEMA-NIBS, 2009).

Table 2.1 shows the values adopted for the parameters α_1, β_1, total building height (H), elastic period (T_a), effective period (T_e) and overstrength factors Ω_y and Ω_u, for reinforced concrete frame buildings with 1, 2, 3 and 4 stories (N). These parameters were adjusted for the particular cases of one-story rural schools which have light roofs and masonry walls.

Table 2.1. Adopted values for N, H, α_1, β_1, T_a, T_e, Ω_y y Ω_u for school buildings at three construction times.

<table>
<tr><td colspan="5"></td><td colspan="3">Before 1967
(Low design)</td><td colspan="3">Between 1967 and
1982 (Medium design)</td><td colspan="3">After 1982
(Special design)</td></tr>
<tr><td>N</td><td>H
(m)</td><td>α_1</td><td>β_1</td><td>T_a
(sec.)</td><td>T_e
(sec.)</td><td>Ω_y</td><td>Ω_u</td><td>T_e
(sec.)</td><td>Ω_y</td><td>Ω_u</td><td>T_e
(sec.)</td><td>Ω_y</td><td>Ω_u</td></tr>
<tr><td>1</td><td>3</td><td>1.00</td><td>1.00</td><td>0.16</td><td>0.34</td><td rowspan="4">1.60</td><td rowspan="4">1.50</td><td>0.34</td><td rowspan="4">1.70</td><td rowspan="4">1.50</td><td>0.27</td><td rowspan="4">1.80</td><td rowspan="4">1.50</td></tr>
<tr><td>2</td><td>6</td><td>1.15</td><td>0.96</td><td>0.27</td><td>0.58</td><td>0.58</td><td>0.45</td></tr>
<tr><td>3</td><td>9</td><td>1.20</td><td>0.93</td><td>0.36</td><td>0.79</td><td>0.79</td><td>0.61</td></tr>
<tr><td>4</td><td>12</td><td>1.25</td><td>0.91</td><td>0.45</td><td>0.99</td><td>0.99</td><td>0.76</td></tr>
</table>

Four damage states were defined: (1) slight, (2) moderate, (3) severe and (4) complete. Each damage state is represented in Fig. 2.3(a) as a function of the yield and ultimate displacement (Barbat et al., 2008).

2.4. Fragility Curves

From the capacity curve of each building the fragility curve is determined for each damage state adopting a lognormal distribution, which is expressed as:

$$P\left[d \geq i \,/ PGA\right] = \Phi\left[\frac{1}{\beta_{Ai}} \ln\left(\frac{PGA}{\bar{A}_i}\right)\right] \tag{2.5}$$

Where Φ [.] is the cumulative standard normal distribution, β_{Ai} is the standard deviation of ln (*PGA*) for damage state (*i*), $\bar{A}_i$ is the mean value of peak ground acceleration (*PGA*) associated with the initiation of damage state (*i*) and $P\ [d \geq i\ /\ PGA]$ is the probability that the damage (*d*) the structure meets or exceeds the discrete damage state (*i*) subject to a *PGA* value. Fig. 2.3(b), shows the four fragility curves for each damage state. Each curve represents the probability of reaching or exceeding the state of damage indicated in the area below the curve. The difference in the ordinate between the curves (ΔP_1, ΔP_2, ΔP_3 and ΔP_4) represents the probability of occurrence of each damage state *PGA*. The mean values of ground acceleration ($\bar{A}_1$, $\bar{A}_2$, $\bar{A}_3$ and $\bar{A}_4$) are associated with the onset of each damage state and are estimated by the coefficients method of (FEMA, 2005) from the displacement (u_1, u_2, u_3 and u_4), respectively.

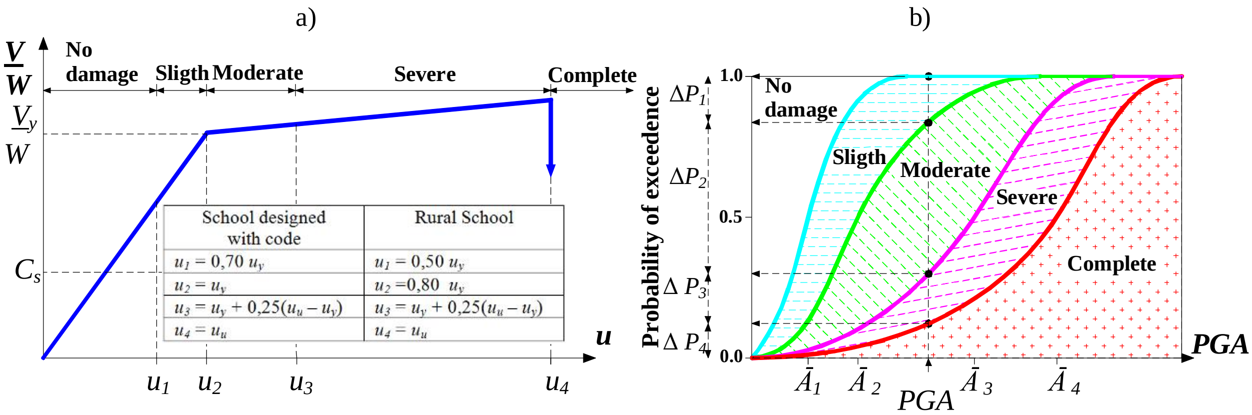

Figure 2.3. (a) Damage states; (b) Fragility curves for each damage state.

The adopted values of the standard deviation β_{Ai}, associated with the $\bar{A}_i$ values for each damage state (*i*) are shown in Table 2.2, which are based on national and international experiences (FEMA-NIBS, 2009; Bonet, 2003; Barbat et al., 2008; Marinilli, 2009 and Safina et al., 2008).

Table 2.2. Adopted values of β_{Ai} for each damage state.

School	1) Slight	2) Moderate	3) Severe	4) Complete
Designed with code	0.40	0.45	0.50	0.60
Rural	0.50	0.55	0.60	0.70

Fig. 2.4 compares the fragility curves for severe and complete damage states for 2-story school buildings with the curves implemented in HAZUS for low-rise (1-3 floors) reinforced concrete frames (CL1) (FEMA-NIBS, 2009). In Fig. 2.4(a) curves for old buildings designed with the 1947 Venezuelan code are compared with HAZUS for low code design. In Fig. 2.4(b) the curves for Venezuelan modern buildings designed with current 2001 code are compared with HAZUS for a high code design.

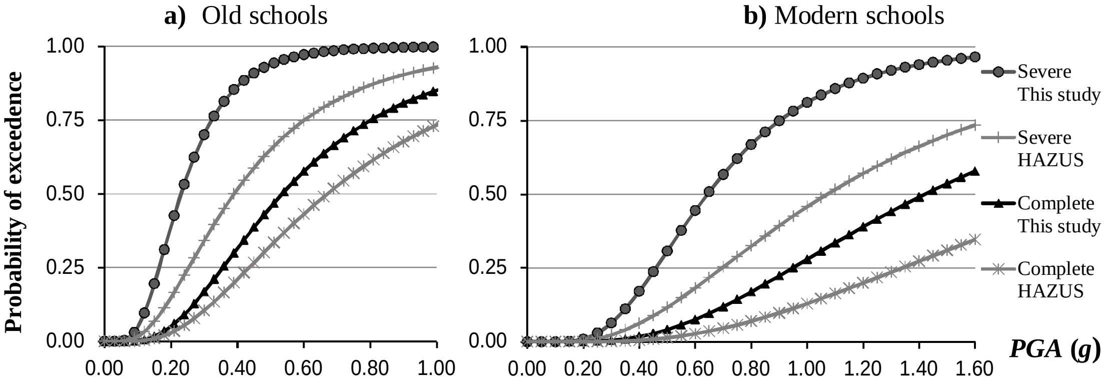

Figure 2.4. Comparison of fragility curves for Severe and Complete Damage: a) 1947 code vs. HAZUS (low code), b) 2001 code vs. HAZUS (high code).

For the state of Severe Damage, the curves of this study indicate a larger vulnerability than that obtained with the HAZUS methodology; the median of the ground acceleration is about 45% larger in HAZUS. The differences between the two methods are reduced for the Complete Damage state in the case of old school, although this study still leads to a slightly increased vulnerability as compared with HAZUS.

2.5. Estimation of Consequences

Given a seismic event characterized by a value of *PGA*, the probability of occurrence (ΔP_i) of a damage state (i) is obtained from the building fragility curve (Fig. 2.3(b)). Each damage state has a loss factor (F_i) that is shown in Table 2.3 (FEMA-NIBS, 2009). The loss index (I_L) of a building is defined by weighting the probabilities (ΔP_i) and loss factors (F_i) for all damage states:

$$I_L = \sum_{i=0}^{4} \Delta P_i \cdot F_i \tag{2.6}$$

The loss index represents the average expected loss and takes values between 0% and 100%. The I_L index allows qualitative and quantitative description of losses for purposes of comparing buildings and making decisions on prevention and reduction of seismic risk. The Weighted Damage is defined by a discrete value between 0 and 4 as shown in Table 2.3, according to the calculated loss index (I_L). This definition allows a single value representing the effect of an earthquake on a building and facilitates the interpretation of results expressed in maps or charts.

For a given earthquake, economic and social losses are estimated from the *PGA* value obtained at each school. Direct economic losses are estimated from I_L given the school construction area that is estimated from the known school population. Social losses (L_{Sj}) associated to the number of human casualties are classified as: j = 1) Minor Injuries; j = 2) Serious Injuries; j = 3) Deaths. These losses are calculated by weighting the probabilities of occurrence for each damage state (ΔP_i) with F_{Sj} that is a social loss factors adopted from ATC-13 (ATC, 1985) as shown in Eqn. 2.7, incorporating the school population (S_P) and an occupancy factor (O_F):

$$L_{Sj} = S_P O_F \cdot \sum_{i=0}^{4} \Delta P_i \cdot F_{Sj} \tag{2.7}$$

Another result of interest towards the prioritization and retrofitting of school buildings is to determine the levels of risk for *PGA* values of equal probability of occurrence. This involves the use of the zoning map of the national code and micro zonation of the city for an event with a given return period. Risk levels are associated with I_L ranges as shown in Table 2.3.

Table 2.3. Definition of Weighted Damage, loss factor and Risk Levels.

Weighted Damage	Description	Loss factor F_i (%)	Range of I_L (%)	Risk Levels
0	No Damage	0	0 – 2.5	Very Low
1	Slight	2	2.5 – 10.5	Low
2	Moderate	10	10.5 – 30.0	Moderate
3	Severe	50	30.0 – 70.0	High
4	Complete	100	> 70.0	Very High

3. PREDICTED VS OBSERVED DAMAGE IN THE 1997 CARIACO EARTHQUAKE

Nineteen schools that were exposed to 1997 Cariaco Earthquake for which inspection reports of damages were available (FEDE, 1997), were selected in the Sucre state in order to assess the degree of validity of the proposed procedure to estimate damage. Information was gathered on their geographic location, structural characteristics, soil profile and observed damage (Fig. 3.1). The seismic event of 1997 had a magnitude Mw = 6.9, a focal depth of 10 km and a surface rupture of about 30 km as shown in Fig. 3.1 (Audemard, 2007). The schools were distributed at distances between 0.47 and 64.9 km from the rupture fault.

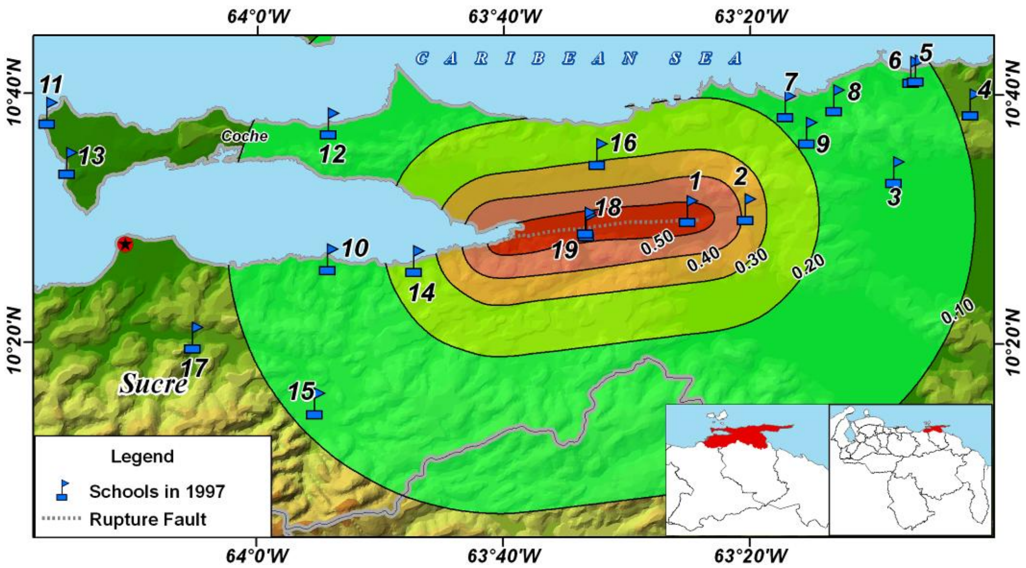

Figure 3.1. Spatial distribution of 19 schools and rupture fault observed in the 1997 Cariaco earthquake.

Table 3.1 shows the *PGA* values of the fragility curves ($\bar{A}_i$), the probability of occurrence of each damage state (ΔP_i), the estimated values of the *PGA* at the site using NGA attenuation models, the loss index (I_L) and the Weighted Damage calculated at each school. Also shown is the observed damage obtained from the interpretation of collected inspection reports at the time of the earthquake. The value of Δd which is defined as the difference between the weighted damage and the observed damage for each school is also shown in the table and plotted in Fig. 3.2.

The Δd values shown in Fig. 3.2 point out that the damage prediction model produces results more or less balanced with the observed damage, with a slight tendency to overestimate. Ten of the nineteen schools have a Weighted Damage that is consistent with the observed damage, which represents 53%, while the model over-estimates the damage in five schools (26%) and sub-estimates it in four schools (21%). In all schools the damage difference (Δd) is less than one. It should be mentioned that these results were obtained after making some adjustments to the values of the yield overstrength and the standard deviations of the model as explained earlier. Notably, schools #18 and #19, the Valentín Valiente and Martinez Centeno schools that collapsed during the 1997 earthquake were found to be underestimated by the model which predicts a severe damage state. However it can be noted in Table

3.1 that there is a probability of occurrence of the complete damage state of 30.5% and 7.9%, for the schools #18 and #19, respectively, pointing out that the probabilistic model to some extent recognized the possibility of collapse.

Table 3.1. Predicted and observed damage for nineteen schools during the 1997 Cariaco earthquake.

#	$\bar{A}_1$ *(g)*	$\bar{A}_2$ *(g)*	$\bar{A}_3$ *(g)*	$\bar{A}_4$ *(g)*	ΔP_0	ΔP_1	ΔP_2	ΔP_3	ΔP_4	*PGA* (g)	I_L	Weighted Damage	Observed Damage	Δd
1	0.09	0.12	0.35	0.93	0.000	0.004	0.386	0.531	0.079	0.40	38.3	3	2	1
2	0.28	0.40	0.63	0.96	0.460	0.249	0.182	0.062	0.047	0.30	10.2	1	1	0
3	0.06	0.09	0.19	0.45	0.084	0.243	0.544	0.120	0.010	0.11	12.9	2	2	0
4	0.10	0.14	0.30	0.70	0.599	0.240	0.154	0.007	0.000	0.09	2.4	0	0	0
5	0.10	0.14	0.31	0.71	0.500	0.282	0.205	0.012	0.001	0.10	3.3	1	0	1
6	0.10	0.14	0.31	0.71	0.264	0.319	0.375	0.040	0.002	0.13	6.6	1	1	0
7	0.09	0.12	0.40	0.89	0.036	0.165	0.745	0.051	0.004	0.18	10.7	2	2	0
8	0.06	0.08	0.17	0.38	0.008	0.073	0.518	0.343	0.058	0.15	28.3	2	1	1
9	0.08	0.12	0.34	0.92	0.030	0.154	0.717	0.095	0.003	0.18	12.6	2	1	1
10	0.11	0.16	0.47	1.28	0.239	0.321	0.429	0.011	0.000	0.15	5.5	1	1	0
11	0.12	0.19	0.27	0.39	0.987	0.010	0.002	0.000	0.000	0.04	0.1	0	1	-1
12	0.12	0.18	0.27	0.38	0.644	0.220	0.084	0.024	0.027	0.10	5.2	1	1	0
13	0.10	0.14	0.40	1.13	0.948	0.039	0.013	0.000	0.000	0.05	0.2	0	0	0
14	0.15	0.22	0.08	1.90	0.221	0.319	0.455	0.005	0.000	0.21	5.4	1	0	1
15	0.11	0.15	0.44	1.22	0.480	0.290	0.227	0.003	0.000	0.11	2.9	1	2	-1
16	0.24	0.36	0.59	0.94	0.452	0.274	0.187	0.053	0.034	0.26	8.4	1	1	0
17	0.09	0.12	0.36	1.01	0.456	0.299	0.242	0.003	0.000	0.09	3.1	1	1	0
18	0.08	0.12	0.25	0.56	0.000	0.003	0.151	0.541	0.305	0.41	59.1	3	4	-1
19	0.09	0.12	0.35	0.93	0.000	0.004	0.386	0.531	0.079	0.40	38.3	3	4	-1

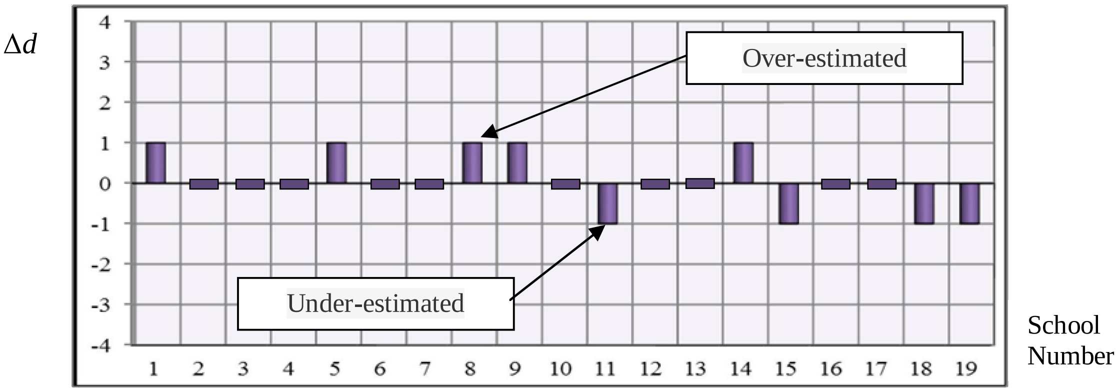

Figure 3.2. Difference (Δd) between Weighted Damage and Observed Damage in a sample of 19 schools during the Cariaco earthquake of 1997.

4. REGIONAL SEISMIC SCENARIOS

The attenuation model used in this simulation is reported by (Abrahamson & Silva, 1997). The first scenario evaluates a sample of 636 schools located in the state of Sucre in a simulation of the 1997 Cariaco earthquake (Mw = 6.9) described earlier in Section 3. Fig. 4.1 shows *PGA* values considering intermediate stiff soil, and the spatial distribution of Weighted Damage at each school predicted by the model; the values of Weighted Damage varies from 0 (No damage) to 4 (Complete damage) according to Table 2.3. The percentages of schools that have each level of Weighted Damage are: 0) 32.5%, 1)

30.3%, 2) 23.4%; 3) 12.4%, and 4) 1.3%. It should be mentioned that the number of observed collapses was 0.6% of the schools existing at the time (1997) of the earthquake (FEDE, 1997), a value of the same order than the predicted 1.3% schools with complete damage in this simulations with the existing schools at this moment (2012). For this scenario it is estimated that economic losses would be approximately $ 45 million and victims would be about 90, 80 and 40, minor injuries, serious injuries, and deaths, respectively. In the case of a 475 years- return period scenario that is associated with *PGA* values of 0.35g and 0.40g for the 6 and 7 seismic zones in this State, respectively, 4.9% of the 636 schools have a Very High risk level (Table 2.3), an alarming 78.1% have a High risk level and finally 17.0% have a Moderate risk level.

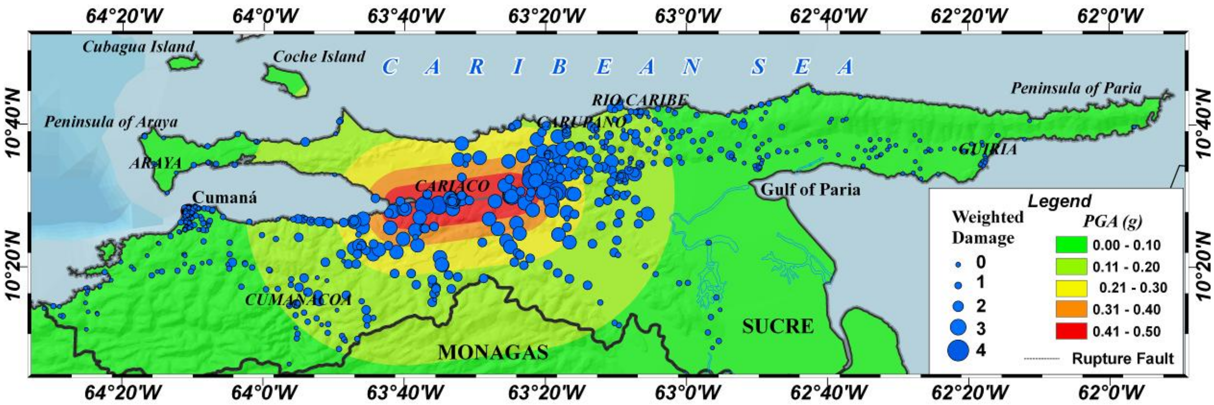

Figure 4.1. Spatial distribution of Weighted Damage for each school in the Sucre State under the 1997 Cariaco Earthquake Scenario.

The second scenario corresponds to the 1929 earthquake (Mw =6.6), whose 30 km rupture fault came about 4 km into the city of Cumaná (Fig. 4.2) (Audemard, 2007). Estimated *PGA* values considering the local soil conditions are shown in Fig. 4.2. Values as high as 0.50g are observed in zones very close to the rupture fault. The Weighted Damage was calculated for a sample of 83 schools in the Cumana city that are reported in the inventory. Fig. 4.2 shows the values of the Weighted Damage (Table 2.3) at each school: only 5 schools (6%) would likely result in complete damage, while most of them represented by 63 schools (75%) would be severely damaged and the rest (19%) would be moderately damage. Economic losses are estimated in about $ 60 million. Victims would be about 1,100 that include about 200 deaths.

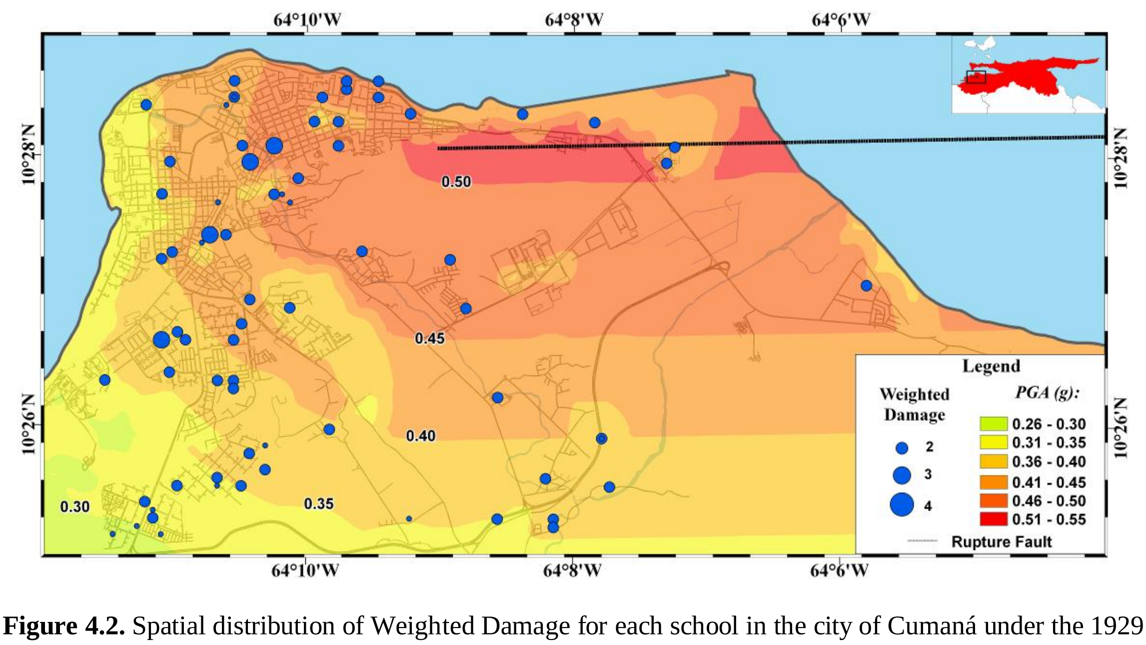

Figure 4.2. Spatial distribution of Weighted Damage for each school in the city of Cumaná under the 1929 Cumana Earthquake Scenario.

The third scenario considers a simulation of the 1967 earthquake affecting a sample of 569 schools in the city of Caracas that are plotted in Fig. 4.3. The Mw = 6.4 event was about 25 km from the city, leading to *PGA* values between 0.07g and 0.12g, depending on the soil condition as shown in Fig. 4.3. As a result of the simulation about 2.3% of the schools could be severely damaged, 23.6% with moderate damage and 36.4% would be slightly damage. Economic losses are estimated in the order of $ 65 million and about 120 people would be injured in the school buildings. In the case of a 475 years-return period scenario that is associated with *PGA* values between 0.265g and 0.30g, depending on the school's location on the Caracas seismic microzonation map, 1% of the schools would have a Very High risk level and 48% a High risk level.

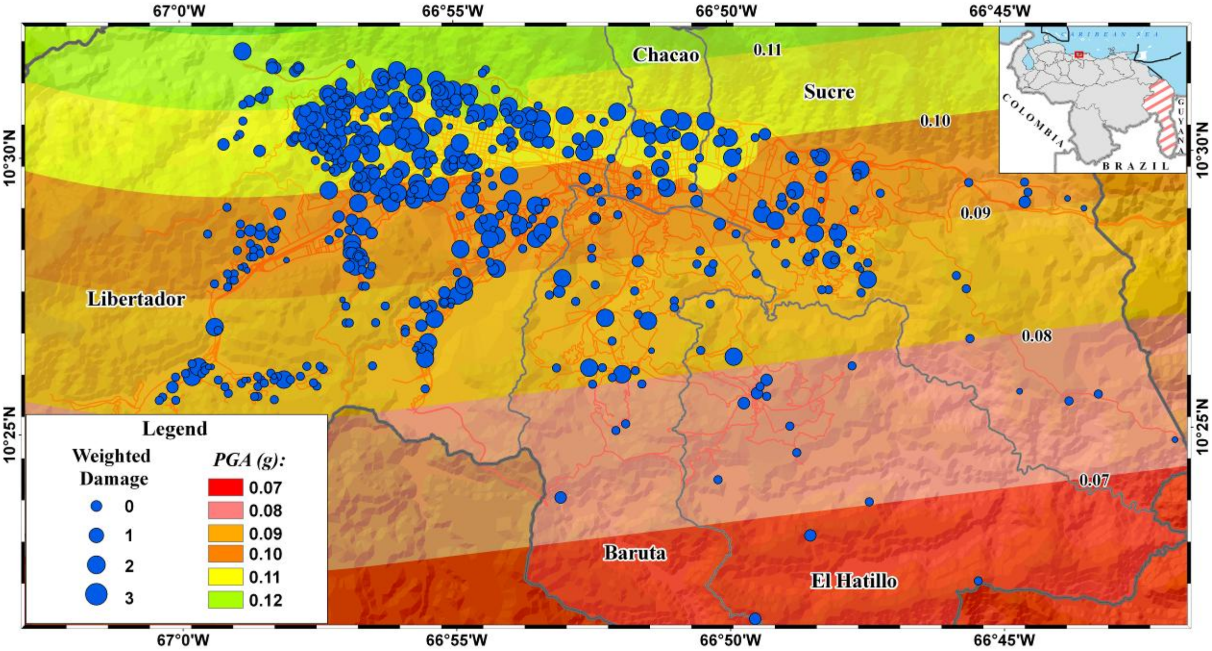

Figure 4.3. Spatial distribution of Weighted Damage for each school in the city of Caracas under the 1967 Caracas Earthquake Scenario.

5. CONCLUSIONS

From a national survey conducted by the Ministry of Education it was possible to obtain information regarding geographic location, number of stories, year of construction, construction type and school population for 16,921 school buildings in the country. When other schools where the seismic information is limited to the geographical location are included in the data base, the total raises to 19.792 schools that were incorporated in a GIS system. About 49.5% are in high seismic hazard zones and 41.1% in intermediate zones. Approximately 46% of buildings were constructed before 1982, with earthquake-resistant standards less demanding than those in modern standards. In addition, about 21% were built before 1967 when there was a significant improvement in the seismic requirements due to the occurrence of the Caracas earthquake that caused the collapse of modern buildings.

A methodology developed to estimate fragility curves for schools buildings in Venezuela was developed assuming that buildings were designed and constructed in compliance with the seismic code in force at the time of construction. The parameters of the fragility curve were calibrated and adjusted based on information from the effects of the 1997 Cariaco earthquake on 19 schools located in the Sucre state in which information regarding observed damage, soil condition and structural type was available. The resulting curves show a somehow larger vulnerability than those obtained using the HAZUS methodology.

A sample of 636 schools located in the Sucre state were subjected to a simulation of the 1997 Cariaco earthquake (Mw = 6.9). Results point out that about 14% would have severe or complete damage leading to human and material losses. For the 475 years-return period event an alarming 80% of the schools would be at a risk level between high and very high. A sample of 83 school buildings in the Cumana city was subjected to the 1929 earthquake (Mw = 6.6) whose surface rupture was in the City; 50% of school buildings would have severe structural damage and heavy losses are expected. A simulation of the 1967 earthquake (Mw = 6.4) was applied to a sample of 569 school buildings in the city of Caracas, pointing out that 2.3% of schools would have severe damage.

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