DIFFICULTIES ON PSHA IN COLOMBIA BECAUSE OF DATA SCARCITY

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ABSTRACT

This paper presents a PSHA for Colombia, using data since 1960 until 2010, covering an area from 80° W to 70°W longitude and 1°S to 15° N latitude. Recurrence laws and seismic hazard curves were calculated for 2° by 2° areas. There are areas without enough data to obtain a slightly acceptable recurrence law. After that, hazard curves were calculated using Fukushima and Tanaka (1990) attenuation relationship. Finally a peak ground acceleration map was developed for Colombia. There are zones that, from a probabilistic point of view, it is not possible to assign any value. Assessments have been done mean an algorithm developed by author.

Peak ground accelerations, for 475 years return period, range from 438 gals on Pacific Colombian coast in places such Uraba swarm and Colombia-Ecuador borderline, to 270 gals on Magdalena Medio Zone.

There is not an agreement to assign a seismic hazard level in prone earthquake zones, with well know catastrophic events, but in a scarcity of historical and instrumental data. Recent Haiti earthquake (2010) is an example of zones with significant shaking background but not enough seismological data.

Key words: Seismic hazard, PSHA, Colombia, scarcity, completeness, Uraba

INTRODUCTION

Colombia is located in an earthquake prone zone (Ramirez, 1933, 1953, 1971, 1975, 1980); in a tectonic complex region (Van Hissenhoven, 2009), due to the interaction of four plates: South America, Caribbean, Nazca and Cocos plates, which have developed country landscape. Additionally tectonics has developed approximately one hundred volcanic structures, some of them active volcanoes.

This paper presents a PSHA for Colombia using robust hazard assessment methodology and attenuation relationships, like Hanks and Cornell (1994) and Fukushima and Tanaka (1990). In order to perform the hazard assessment, instrumental data since 1960 to 2010 were used, in an area from 80°W to 70° W longitude and 1°S to 15°N latitude, focal depths less than 100 km, and magnitude MS larger than 3.5.

Following Canas *et al.* (1996) earthquake data are essential information, in order to assess the probability of success. A seismic catalog in "perfect" condition must accomplish the following requirements:

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a) Completeness and extension, in other words, it should include all the earthquakes in the zone in a long period of time.
b) Precise location of epicenters
c) Precise time and date of earthquakes
d) Exhaustive information, which includes: peak ground accelerations, magnitude, dominant frequency, intensity and focal mechanism for each earthquake
e) Relationships in between: precursory events, main shock and aftershocks.
f) Isoseismic curves for each earthquake.

According to Canas *et al.* (1996) and author's experience, the optimal conditions are unrealistic. Seismic catalogs are based on instrumental data from the early twentieth century, so it is not possible to have data such as focal mechanism, the maximum acceleration and dominant frequency of earthquakes before the twentieth century, but such data are even currently difficult to obtain due to insufficient or poor quality of seismic instruments. Even simple seismic parameters as the magnitude or location of hypocenter are scarce or inaccurate in many regions, like Colombia.

Even in the case of having a complete instrumental catalog, there is a problem of temporary extension of earthquake data. Large earthquakes occur at relatively large time intervals, compared to approximately 110 years of instrumental record (Canas *et al.*, 1996). In Colombia, the first station was installed in 1922 at the Colegio Mayor de San Bartolomé (Goberna, 1988); in 1941 the Geophysical Institute of the Colombian Andes was established, which reported to USGS and ISC until 2001, finally, the National Seismic Network was established in 1993.

BACKGROUND

There are several studies about Colombian Seismic Hazard such as Estrada & Ramírez (1977); Earthquake Engineering Colombian Society - AIS (1984); Salcedo (1992, 1993); AIS (1996); Ceresis (1996); Aguiar & Haro (2000); Gallego (2000) and AIS (2009). Of those studies Estrada & Ramirez (1977) and Salcedo (1992, 1993) present Magnitude values while the rest of studies present peak ground accelerations and design spectrums.

AIS (1984, 1996) are based on fault-rupture model, they assigned Seismicity to faults in a strip of land 60 kilometers wide. On AIS (1984) they analyzed three time windows: 1566-1984; 1922-1984 and 1957-1984, recurrence laws were assessed for each seismic fault. Such characterizations presents a problem because data scarcity, as is shown in chart 1.

Chart 1. Faults and Earthquakes according AIS(1984)

Seismic Fault	Number of earthquakes assigned to the fault
Bocono	9
Bolivar	4
Bucaramanga-Santa Marta	23
Cauca	6
Cimitarra	6
Cuiza	4
Espiritu Santo	6
Frontal Cordillera Oriental	22
Nataga	5
Oca	4
Palestina	5
Romeral	9
Salinas	4
Sinu	3

Other important issue is that AIS(1984, 1996) only consider seismic sources in Colombia, not taking into account sources located in Panama, Venezuela, Ecuador and Peru, all of them very active.

Salcedo's research (1992, 1993) has the advantage that includes additional geophysical parameters such as: type of crust (continental, oceanic, transition); type of geological faults (reverse, normal, strike-slip); Bouguer anomalies, and topography.

Salcedo's map (1992, 1993) shows maximum magnitude $M_{max} > 7.5$ on Choco region; $M_{max} > 7.0$ on Nariño and Sierra Nevada de Santa Marta. According to Salcedo the minimum value of magnitude for Colombia is 6.0.

However, Salcedo's map doesn't show the largest magnitudes already occurred on Tumaco and Ecuador borderline, which is an Mw=8.6 earthquake which happened on 1906.

Additionally, there is the South America Probabilistic Hazard Map that has been done by Ceresis (1996), peak ground accelerations are in general larger than AIS (1984, 1996).

Following Stein *et al.* (2011) it is necessary to check and compare forecasting with real events. In Colombian cases there are two main problems: small amount of strong motion instruments, and, maybe a worst one, that is that majority of accelerometers are located in soft soils, without a reference site.

There are only strong ground motions records (pga greater than 100 gals) for two earthquakes (1999/01/25) on Quindio Region and (2008/05/24) on Quetame – Cundinamarca. On 1999/01/25 there are records in soil with pga equal to 518 gals, 13 kilometers far from epicenter in Armenia city, Sugito & Taniguchi (1999) assessed a pga on rock equal to 217 gals.

According with field campaign and aerial photographs it is supposed that peak accelerations were larger than one gravity. In spite of that fact, AIS (2009) assessment doesn't show any change of peak ground acceleration for Armenia city.

On the other hand, on 2008/05/24 earthquake were recorded accelerations of 605 gals on rock 9 kilometers far from epicenter. AIS (1998) assessment shows a 0.30 g, meanwhile AIS (2009) presents a 0.25 g value. In other words AIS (2009) didn't take into account the previous earthquake, and the seismic hazard level went down instead of an increment of pga values.

This study, as it is shown later, presents for this zone a value of 0.35 g, taking into account that Fukushima & Tanaka (9990) standard deviation is 0.21, and additionally including completeness of data catalog, the result is 0.64 g, which means a 3% difference with recorded data. This is one of the reasons to review and update Colombian seismic hazard studies (Correa & Alfaro, 2011; Stein *et al.*, 2011).

METHODOLOGY AND DATA ANALYSIS

In this study, for hazard curves assessment, methodology of Hanks and Cornell (1994) and Takada (2005) was followed. The catalogs of U.S. Geological Survey (USGS, 2010) were used. Utsu studies (Hung, 2002) were used to unify the scales of magnitude to Ms. Focal mechanisms were taken from Centroid Moment Tensor Project results (Ekström, 2010).

Due to the scarcity of data, earthquakes with MS magnitude greater than 3.5 were used. In order to have fewer variables in the analysis all areas were 2 ° by 2 °. It was assumed that the seismicity is a Poisson process in space, this assumption underestimates the level of hazard in the area where the Andes mountain range ends and the Amazon plain begins. The apparent low seismicity in that zone corresponds mainly to the lack of instrumentation, because geological and seismological studies show major seismogenetic sources (Paris *et al.*, 2000; Montes & Sandoval, 2001).

The method of Hanks and Cornell (1994) also assumes that occurrence of earthquakes in a region approaches to a Poisson process with a constant rate of earthquakes in time. In this analysis, a time window from 1960 to 2010 was used. It is important to remark that seismic catalog was not completed. This is because the amount of data is low and the seismicity is heterogeneous. On the other hand, the recurrence laws follow to the classical evaluation by Gutenberg-Richter (1942, 1956).

Chart No. 2 shows the number of data available for each sub-area, with a maximum number of data in the swarm of Urabá (375 data) and Bucaramanga (389 data), nevertheless the largest amount is low in order to characterize seismogenetic source. According to Felzer (2006) more than 2000 good quality earthquakes are required for 98% confidence errors less than 0.05.

It is possible to see that the area of the Caribbean seashore has a scarcity of instrumental data, although there is historical evidence of destructive earthquakes such as 1825/02/26 and 1834/05/22 earthquakes, among others. These events generated large damage in the city of Santa Marta and surroundings (Ramirez, 1975). This is a similar case to Haiti; there were several devastating historical earthquakes, but low instrumental information (Alfaro & Van Hissenhoven, 2010).

To determine the acceleration for each earthquake it is necessary to estimate attenuation of acceleration with distance. Multiple equations have been developed worldwide; Douglas (2001, 2002) collected more than 200 robust equations determined in several earthquake prone zones all over the world. In this study equation of Fukushima and Tanaka (1990) was used, which meets several criteria: be relatively recent, that used a large database, the magnitude was expressed in MS, applies both for crustal and subduction earthquakes and robustness (Equation 1).

$$\mathrm{Log}\ a = 0.41Ms - \log(R + 0.032\mathrm{x}10^{0.41Ms}) - 0.0034R + 1.30 \qquad (1)$$

Where
a = acceleration on gals
σ = 0.21 = standard deviation
R = epicentral distance in kilometers

The results are presented in terms of return time. For structural design is commonly used 475 years. This corresponds to a lifespan of 50 years structure and an excedance probability of 10%.

Figure 1 shows the values of peak ground accelerations for a return period of 475 years. There are areas that, from the standpoint of probability, any value can be assigned, because number of data is too low, less than one event per year.

DISCUSION AND CONCLUSIONS

Since 1970's several seismic hazard assessment maps have been done for Colombia such as Estrada & Ramirez (1977); AIS (1984, 1996, 2009); Salcedo (1992, 1993); Ceresis (1996), Gallego (2000), all of them with strengths and weaknesses.

According with the catastrophic recent events, such as Haiti (2010) and Tohoku-Japan(2011) earthquakes, and taking into account Stein *et al.* (2011) recommendations, it is necessary to perform an objective review of forecasts, in Colombian case it is important to observe that earthquake construction rules don't take into account about historical and recorded evidences.

A probabilistic seismic hazard assessment is limited in Colombia, mainly because of data scarcity, as it is show in this study. 2 ° by 2 ° quadrants were analyzed in the area included between the longitudes 80 ° W and 70 ° W and between latitudes 1 ° S and 15 ° N. The analyzed data were from 1960 to 2010, since they have an approximately Poisson time distribution. The earthquakes have depths less than 100km and magnitudes MS greater than 3.5. The conversion of magnitude scales was done by using Utsu studies (Hung, 2002). The peak ground acceleration assessed, for a return period of 475 years, ranging from 438 gals in the Colombian Pacific coast, both in the swarm of Urabá (borderline with Panama), as in the borderline with Ecuador; to 270 gals in the area of Magdalena Medio.

Due to the scarcity of data, the values in the piedmont plains are assumed unrealistic, because they underestimate the hazard levels. Additionally there is a lack of instrumental information in all departments of the Caribbean Coast, in spite of the fact that there were catastrophic events in XIX Century.

Chart 2. Number of earthquakes in each quadrant. 1960-2010 time window. Depth of less than 100 km. MS magnitude greater than or equal to 3.5. Hazard curves were assessed only for shaded quadrants.

		Longitude										
		-80		**-78**		**-76**		**-74**		**-72**		**-70**
Latitude	**15**											
			0		0		2		4		7	
	13											
			0		0		11		23		36	
	11											
			73		31		21		24		**61**	
	9											
			124		**371**		**91**		**217**		**74**	
	7											
			89		**375**		**83**		**389**		23	
	5											
			161		**168**		**121**		**45**		3	
	3											
			275		**46**		**58**		4		6	
	1											
			95		**42**		1		0		1	
	-1											

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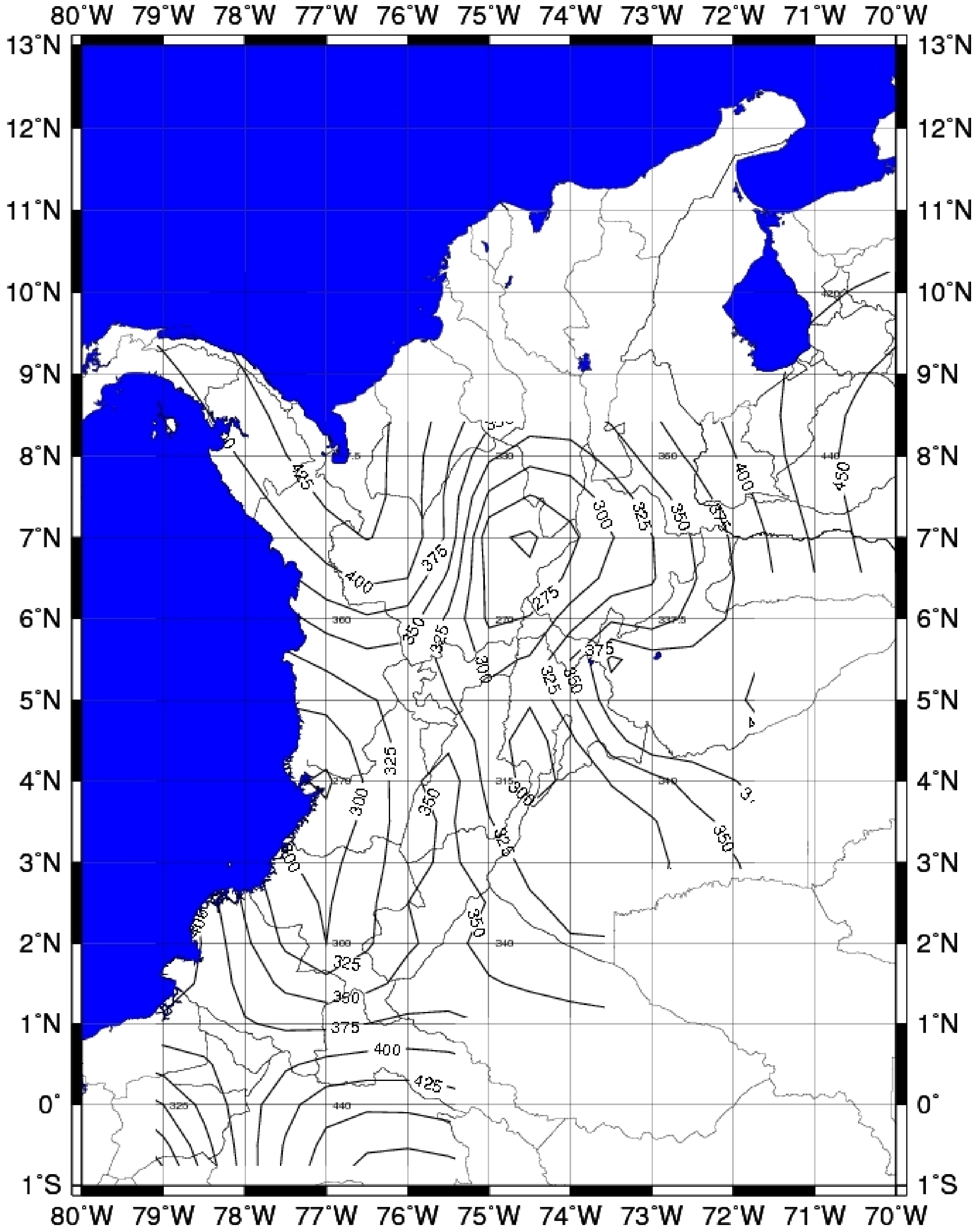

Figure 1. Peak ground accelerations for Colombia. Period time 1960-2010. Depths less than 100 km. MS Magnitude greater than 3.5.

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