PROBABILISTIC AND PSEUDO-DETERMINISTIC SEISMIC HAZARD ASSESSMENT FOR NEIVA – COLOMBIA

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ABSTRACT

Neiva is located in a region with a significant seismic hazard due to the proximity of several active faults that have generated large earthquakes like that of February 9th,1967 the epicenter of which was located just a few kilometers away from the city. Said earthquake caused a significant number of casualties and considerable damage. In this study, earthquakes with magnitude MS greater than 4.0 were analyzed within a 33,400 km^2 area. Earthquakes of this intensity can cause victims and damages in a country such as Colombia. Peak ground acceleration is 272 gals for a 475 years return period. Pseudo-deterministic analysis shows a credible maximum acceleration of 339 gals due to the Dina Fault.

Key words: Neiva, Huila, Colombia, hazard, earthquakes, probabilistic, deterministic, Dina Fault.

INTRODUCTION

Neiva, the capital of Huila province, is located 304 km southwest of Bogota, between the eastern and central mountain ranges of the Andes, in the Magdalena River Valley. This study has examined an area of 33,400 km2 around Neiva which includes three major fault systems (Figure 1): the Romeral Fault System, under the western flank of the Cordillera Central, which extends across Colombia from the Caribbean Sea to Ecuador and has generated significant earthquakes such as those of 1983 near Popayan, 1994 to the west of Huila, and 1999 in Quindio province; in second place, the Magdalena Fault System, which crosses the western edge of the Magdalena River Valley and has suffered intermediate intensity earthquakes as those of 1805, 1816, 1824 and 1942 may be related to this fault system; and finally, the Guaicaramo Fault System, beneath the Eastern Cordillera, which is considered very active and has generated large earthquakes like those of 1827 in Huila, 1834 in Nariño, 1967 in Huila, and the 1995 earthquake in northern Huila (Ramírez 1975; Paris et al. 2000). Because of completeness of seismic catalog and deterministic approach, this paper supplements the Bohórquez (2007) and Bohórquez & Alfaro (2008) studies.

Three earthquakes have caused disasters in the city of Neiva are the earthquake of November 16th, 1827; the earthquake of February 9th, 1967 and the earthquake of June 6th, 1994. Following the earthquake of 1827, the Suaza river was dammed for 55 days due to landslides and rupture of the dam, which caused flooding and devastation in Neiva. The macro-earthquake of Huila on April 9th, 1967 is known as such because "It was felt from Caracas to Iquitos in Peru and from Buenaventura on the Pacific Coast to Mitú on the border with Brazil." It was recorded by more than 500 seismic stations all over the world and it left 15 dead and nearly 100,000 affected in Neiva." (Ramírez 1967).

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The seismic station Bogota BOG recorded more than 350 aftershocks. The focus was located 58 km beneath the Eastern Cordillera with the epicenter at coordinates 9.02 º N and 74.8 º W (Ramírez 1967). According to Blume & Associates (1968) the magnitudes estimated are between 7.3 and 7.5. In Bogota (400 km away from the epicenter) thirty structures were seriously affected. Finally, the 1994 earthquake, which had a magnitude Ms of 7.6, caused an avalanche in the Páez River basin, leaving approximately 1,000 dead and 30,000 homeless.

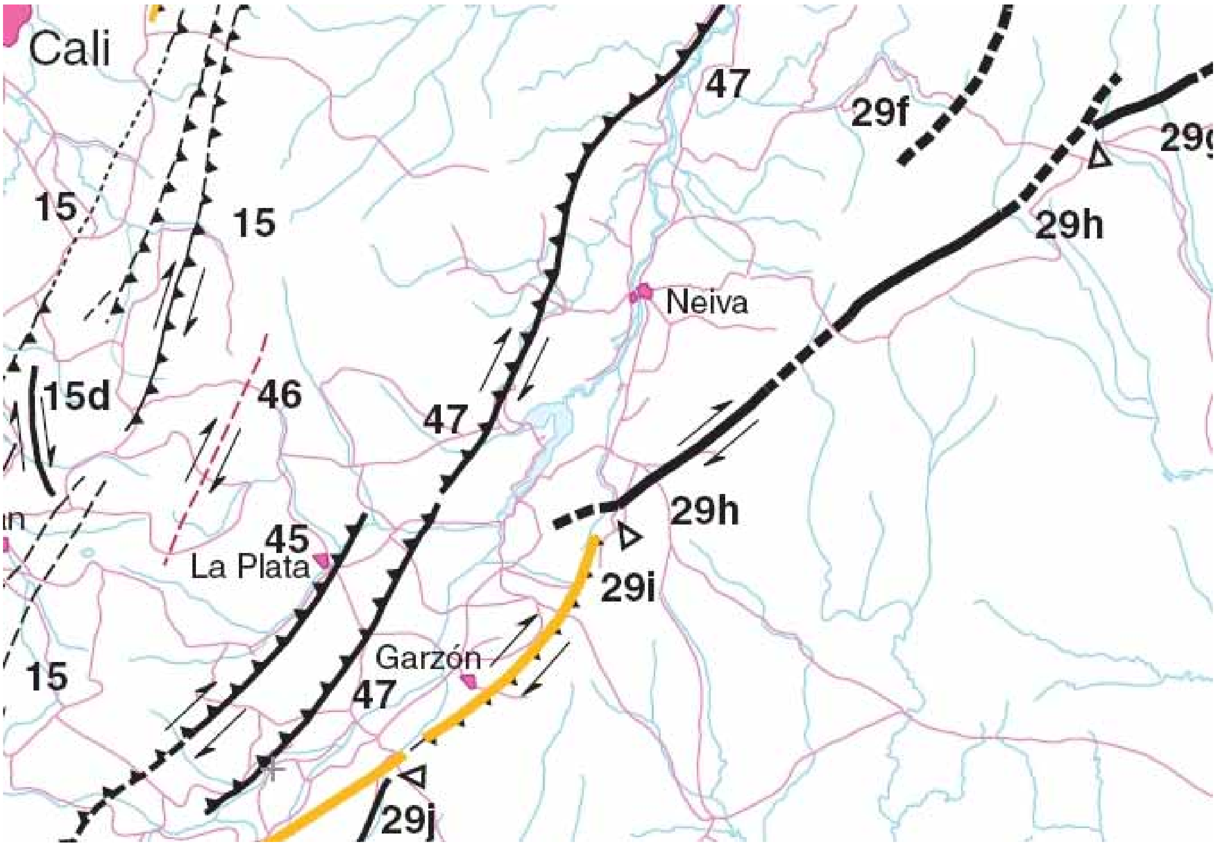

Figure 1. Major Faults in the area studied: 34. Cucuana; 15. Sistema Romeral; 15d. Piendamó; 45. La Plata-Chusma; 46. Irlanda; 47. La Dina; 29f. Servitá-Santa María; 29h. Algeciras; 29j. Suaza; 29i. Garzón-Pitalito (Paris *et al.*, 2000).

PROBABILISTIC SEISMIC HAZARD ANALYSIS

This study has followed the methodologies of Hanks & Cornell (1994) and Takada (2005). The following seismic catalogs were used: Ramírez (1975); the U.S. Geological Survey (USGS 2010), this catalog includes SISRA (Program for Mitigating the Effects of Earthquakes in the Andean Region) data for the period 1766-1981 and data from the PDE (Preliminary Determination of Epicenters) for the period 1973-2010. The ISC International Seismological Center catalog (2010) was also used. Following the Takada (2005) methodology, earthquakes with magnitudes greater than 4.0 were analyzed. This kind of earthquakes can cause casualties and/or damage in the Colombian case (Figure 2).

The method of Hanks and Cornell (1994) assumes that the occurrence of earthquakes in the region approaches a Poisson process, with a constant rate of earthquakes in time and space. Figure 3 shows that it is possible to analyze a relatively homogeneous time distribution from 1944 to 2010. A completeness analysis of earthquake catalog was done using the Stepp (1971, 1972) methodology (Figure 4).

According to Stepp(1972) it has been suggested by Allen et al (1965) that a 29-year sample drawn from small regions of the dimension of interest in earthquake hazard mapping may not give earthquake recurrence estimates that represent long term Seismicity. Therefore it is necessary to use longer samples that give more accurate statistical averages of the large earthquakes of primary engineering interest (Benjamin, 1968).

Following Stepp(1972), the usual method in practice has been to choose the interval of data to be fitted by inspection of a plot of log $N(M_o)$ on M_o. The smallest magnitude is usually selected as the value where log N(mo) clearly departs from a straight line plot, while the largest earthquake sample is usually included. However this procedure cannot be used in whole cases.

According to Stepp(1972) in order to analyze the nature of the incompleteness of the data sample in this detail earthquakes are grouped in magnitude classes and each magnitude class is modeled as a point process in time. Use is made of the property of statistical estimation that the variance of the estimate of a sample mean is inversely proportional to the number of observations in the sample. Thus the variance can be made as small as desired by making the number of observations in the sample large enough, provided that reporting is complete in time and the process is stationary, i.e. , the mean, variance and other moments of each observation stay the same. To obtain an efficient estimate of the variance of the sample mean, it is assumed that the earthquake sequence can be modeled by the Poisson distribution. If $k_1,k_2,k_3,\ldots,k_n$, are the number of quakes per unit time interval, then an unbiased estimate of the mean rate per unit time interval of this sample is

$$\lambda = \frac{1}{\mathbf{n}}\sum_{\mathbf{i}=1}^{\mathbf{n}}\mathbf{k}_{\mathbf{i}} \qquad (1)$$

And its variance is

$$\sigma_\lambda^2 = \lambda/n \qquad (2)$$

Where n is the number of unit time intervals. Taking the unit time interval to be one year gives

$$\sigma_\lambda = \sqrt{\lambda}/\sqrt{T} \qquad (3)$$

As the standard deviation of the estimate of the mean, where T is the sample length.

Thus, assuming stationarity, it is expected that σ_λ behaves as $1/\sqrt{T}$ in the subinterval of the sample in which the mean rate of occurrence in a magnitude is constant. If the mean rate of occurrence is constant it is expected stability to occur only in the subinterval that is long enough to give a good estimate of the mean but short enough that it does not include intervals in which reports are incomplete (Stepp, 1972).

To assess peak ground acceleration it is necessary to estimate the attenuation of acceleration with distance. Multiple equations have been developed worldwide; Douglas (2001, 2002) collected more than 200 robust equations determined in numerous sites all over the world. Currently, no robust attenuation equation is available for Colombia, which implies the use of equations developed in other parts of the world. The Fukushima and Tanaka (1990) equation was used in the present study (Equation 4).

$$\text{Log a} = 0.41\text{Ms} - \log(R + 0.032\text{x}10^{0.41\text{Ms}}) - 0.0034R + 1.30 \qquad (4)$$

In the field of seismic engineering it is common to express results in a return time. A period of 475 years corresponds to a lifespan of 50 years structure and a probability of 10%. In the Neiva case the result for a return period of 475 years is 272 gals.

PSEUDO-DETERMINISTIC SEISMIC HAZARD ANALYSIS

In this study the possible magnitudes generated by geological faults, characterized by Paris et al. (2000), using the empirical equations by Wells and Coppersmith (1994) and Stirling et al. (2002), were assessed (Equations 5 and 6).

$$Mw=5.16 + 1.12 \text{ Log } L \qquad (5)$$

$$Mw=5.45 + 0.95 \text{ Log } L \qquad (6)$$

Each scenario is represented by the occurrence of an earthquake at a source and the epicenter was located to the minimal distance from the site. Table 1 shows the deterministic analysis results and values of peak ground acceleration in rock using the Fukushima and Tanaka (1990) attenuation equation. The maximum peak ground acceleration that might happen in Neiva would be 339 gals and would be caused by an earthquake on the Dina fault.

Table 1. Pseudo-deterministic Seismic Hazard Analysis

Fault Id (Figure 1)	**FAULT**	**Length [km]**	**Strike**	**Sense of movement**	**Type**	**Rupture Length [km]**	**Distance to the site [km]**	**MW (Wells and Coppersmith, 1994)**	**pga gals**	**MW (Stirling et al, 2002)**	**pga gals**
47	La Dina	207	N32.9°E	R - dextral	**R**	25	15	6,6	284	7,0	339
29H	Algeciras	157	N51.6°E	Dextral	**SS**	15	27	6,1	136	6,8	213
29F	Servitá-Santa María	296	N42.3°E	R - dextral	**R**	30	50	6,7	111	7,1	146
29I	Garzón-Pitalito	126	N48.9°E	R - dextral	**R**	15	43	6,2	94	6,8	139
45	La Plata-Chusma	113	N39.0°E	R - dextral	**R**	15	62	6,2	61	6,8	93
46	Irlanda	55	N23.9°E	Dextral	**SS**	15	65	6,1	50	6,8	87
29G	Guayuriba	131	N40.7°E	R - dextral	**R**	15	83	6,2	40	6,8	62
34	Cucuana	141	N67.9°E	Dextral	**SS**	15	94	6,1	28	6,8	51
29J	Suaza	126	N50.9°E	R - dextral	**R**	15	95	6,2	32	6,8	51
15C	Paraíso	35	N12.5°E	R - dextral	**R**	15	97	6,2	31	6,8	49

Fault Id (Figure 1)	FAULT	Length [km]	Strike	Sense of movement	Type	Rupture Length [km]	Distance to the site [km]	MW (Wells and Coppersmith, 1994)	pga gals	MW (Stirling et al, 2002)	pga gals
15D	Piendamó	28	N8.4°W	Dextral	**SS**	15	106	6,1	23	6,8	43
29K	Mocoa	117	N55.1°E	R - dextral	**R**	15	106	6,2	27	6,8	42
30	La Macarena	50	N0.6°E	R	**R**	15	127	6,2	19	6,8	31
SS = Strike Slip Fault R = Reverse Fault											

CONCLUSIONS

The city of Neiva is located in a earthquake-prone zone, with evidence of earthquakes that have caused damage and casualties. The most recent earthquakes happened on February 9th, 1967 and June 6th, 1997. The pseudo-deterministic and probabilistic analyses were made in an area between latitudes 2° to 4° north and between longitudes 74.3° and 76.3° west. The time window used was from 1944 to 2010. A completeness analysis of earthquake catalog using the methodology of Stepp (1971, 1972) was done. Deterministic hazard assessment took into account the following faults: La Dina, Algeciras, Servitá-Santa Maria, Garzon-Pitalito, La Plata- Chusma, Irlanda, Guayuriba, Cucuana, Suaza, Paraiso, Piendamó, Mocoa and La Macarena. The probabilistic analysis showed an acceleration of 272 gals for a return period of 475 years. Pseudo-deterministic analysis shows a peak ground acceleration of 339 gals due to the Dina Fault.

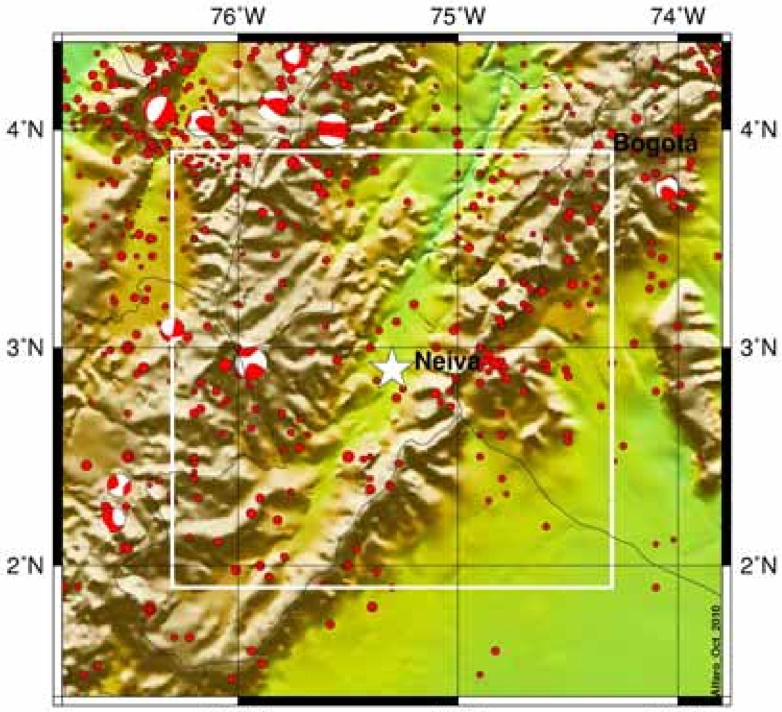

Figure 2. Location of epicenters and focal mechanisms for the studied area.

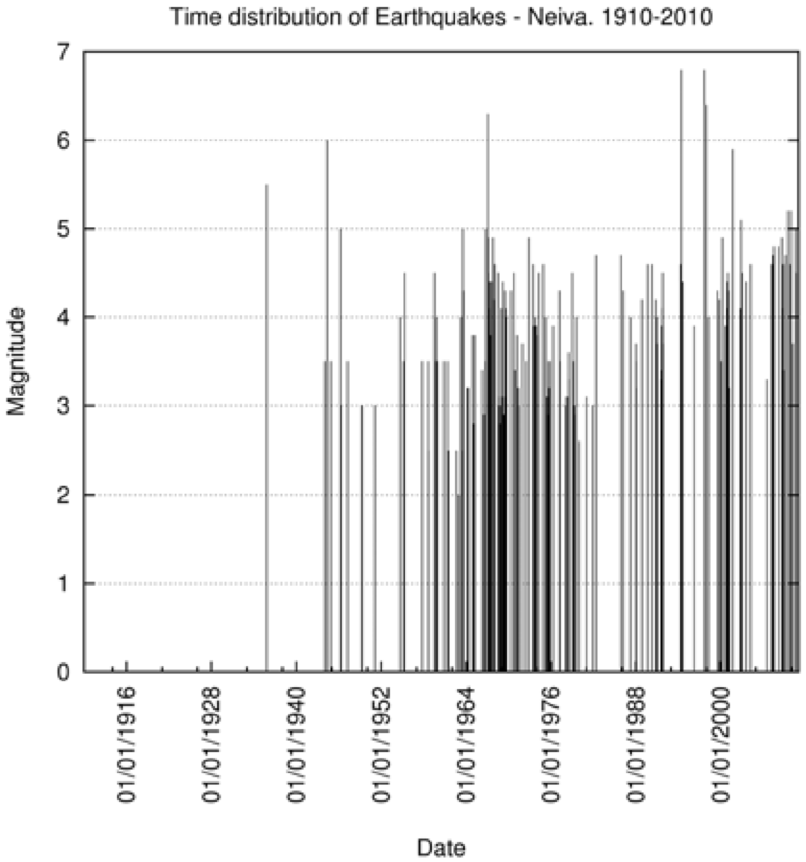

Figure 3. Earthquake time distribution in the area studied from 1910 to 2010.

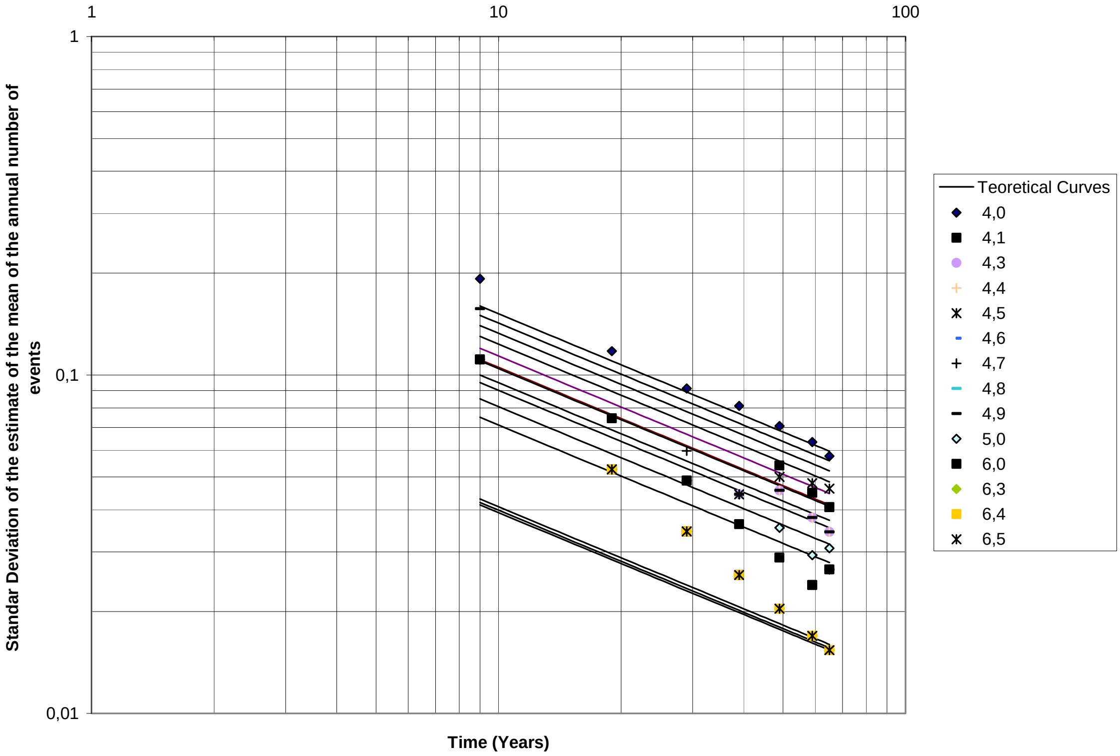

Figure 4. Standard Deviation of the estimate of the mean of the annual number of events as a function of sample length and Magnitude MS class.

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Figure 2 was developed by using GMT (Wessel and Smith, 2004). Figure 3 was developed by using Gnuplot (Williams and Kelley, 2007). We also appreciate the recommendations of the anonymous referee how helped us to improve the original manuscript.

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