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Seismic microzonation of the city of Popayan, Colombia

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ABSTRACT: After the 1983 Popayan earthquake, it was decided to draw up a seismic microzonation. This first study of its kind in Colombia showed how certain areas of the town have specific seismic responses, explaining some of the damage observed in 1983 and leading to recommendations for town planning and construction work.

1 INTRODUCTION

On 31 March 1983 an earthquake destroyed most of the city of Popayan, killing over 200 persons and causing material damage of about US$ 400 million. As a result, the Colombian authorities recognized the need for a rational urban-planning policy and a suitable building code for this area of high seismic hazard. In view of geological (proximity of major faults) and geotechnical (e.g. presence of weak soils) peculiarities, systematic study of seismic hazard at regional and local scales, leading to seismic microzonation, was recommended.

Close collaboration between Colombian and European teams led to the following methods:

a - Evaluation of regional seismic hazard:
- Evaluation of previous seismicity, providing insight into earlier destructive earthquakes (1566, 1736, 1827, 1885, 1906, 1967) and leading to specific maps at scale 1:500,000.
- Analysis of structural geological setting:
  . at scale 1:500,000, showing major fault systems in a vast area around Popayan;
  . at scale 1:50,000, palaeoseismic analysis of local faults (trenches dug across the Rosas-Julumito fault, locus of the 1983 earthquake), and microtectonic studies.
- Seismotectonic synthesis, defining geometry and probabilistic activity of source areas.
- Probabilistic evaluation of seismic hazard for the new source model.

b - Evaluation of local seismic hazard leading to a seismic microzonation map at 1:10,000 of the city of Popayan covering about 40 km^2: - Detailed geological/geomorphological survey of formations underlying the city (mostly lava, pyroclastics and alluvial deposits).
- Geotechnical survey: 460 m of drilling, 6 km of geophysical profiles, various static and dynamic tests, interpretation of all data.
- Analysis of site effects based on data from the 1983 earthquake, and a one-dimensional numerical analysis based on the SHAKE code.
- Analysis of induced effects (mostly landslides in the Maria Oriente quarter).
- Consideration of the effects of active faults that are found on surface.
- Recommendations based on the above and on application of the Colombian earthquake resistance regulations (Decree 1400/84).

2 EVALUATING THE SEISMIC HAZARD AFFECTING THE CITY OF POPAYAN

The city of Popayan, which is located in the southwestern Cauca province of Colombia, today counts 190,000 inhabitants.

2.1 - The seismotectonic setting

Popayan lies in one of the seismically most active areas of the country. Earthquakes can be caused by crustal movement related to (Fig. 1):
- subduction (Colombia trench) as in 1906; - the intermediate Benioff-Wadati zone;
- the Romeral fault zone as in 1566, 1736 and 1983 (intensity IX at Popayan);
- the frontal fault of the Cordillera as in 1827.

Figure 2 shows probable maximum magnitudes and focal depths.

Regional analysis of historical seismicity has helped to define seismic activity in the standard manner of $\log N = a - bM$ for all homogeneous seismotectonic sources.

At local scale, neotectonic field studies (microtectonics, morphology, palaeoseismicity) led to recognition of three stress regimes:
- E-W tension during the Pliocene,
- NE-SW extension during the Quaternary,
- E-W tension during Recent times.

The Romeral faults that threaten Popayan (Fig. 3) are affected by these stresses, and it is to these faults that probable maximum magnitudes were assigned on the basis of the length of their failure traces.

2.2 Evaluating the seismic hazard at Popayan

On a regional scale, the use of seismotectonic data and a line-source model (Der Kiureghian, 1975) led to a value of 0.24 g for a return period of 475 years (20% more than that planned for in Decree 1400/84 of the Colombian Earthquake Resistant Regulation).

For calculating the response of soil columns four accelerograms were used:

- those of Corralitos (Loma Prieta earthquake) with two maximum accelerations (0.6 g and 0.3 g) for the local context;
- a synthetic one based on the spectrum of Decree 1400: maximum acceleration of 0.24 g and a duration of 40 s;
- that obtained on rock west of Mexico D.F.: maximum acceleration of 0.28 g.

2.3 Geological/geotechnical study of Popayan

Observations were made and plotted on 1:10,000 scale, using data from outcrops, geotechnical tests, drilling and geophysics (Figs. 4 & 5).

Eight homogeneous (thickness and properties of soils) zones were defined from this work (Fig. 6), of which zones 1, 2 and 3 merit special mention.

Zone 1, located northeast of Popayan, comprises:

- 0-10 m: debris flow composed of grey sandy clay, soft to medium hard: N = 4-11, Vs = 300 m/s;
- 10-25 m: gravelly/sandy alluvium, medium hard and compact: Vs # 600 m/s;
- 25-40 m: weathered clayey/sandy ignimbrite of medium hardness: Vs # 300 m/s.

Zone 2, underlying much of Popayan, comprises the following soils:

- 0 to 20 m: debris flow composed of soft sandy soil: N(SPT) = 1-12, Vs = 150/200 m/s;
- 20 to 30 m: debris flow composed of soft and medium clayey-sandy soil (N = 45);
- 30 to 75 m: weathered ignimbrite (medium clay/sand soil: N = 15-50, Vs = 200-330 m/s;
- below 75 m: hard ignimbrite.

Zone 3, located west of Popayan, comprises:

- 0-18 m: debris flow composed of light- yellow soft sandy clay: N = 2-14;
- 18-47 m: weathered ignimbrite, medium-hard to hard: N = 23 and over 50;
- below 47 m: hard ignimbrite.

2.4 Seismic response of the soil

Systematic study was based on:

- use of the one-dimensional SHAKE model, based on linear equivalent behaviour of soils (Schnabel et al., 1972);
- use of the 4 accelerograms, whose response spectra are shown on Fig. 7;
- use of the 11 soil columns that correspond to representative boreholes in the 8 zones;
- final choice of 6 soil columns corresponding to 3 site categories, soft, medium and firm, each with minimum and maximum hypotheses for correlation between N(SPT) and Su (shear strength, obtained from geotechnical tests.

Combination of all data (2 examples on Fig. 8) enabled to propose 3 types of design spectra corresponding to the four areas A, B, C and D (Fig. 9), with transition zones between areas. Fig. 10 shows the design spectrum at rock in Decree 1400/84 of the Colombian code.

3 MICROZONATION OF POPAYAN - CONCLUSIONS

Based on the 1:10,000-scale mapping, micro- zonation takes account of site effects and of:

- prohibition to construct critical facilities or public buildings near active faults (Fig. 3);
- prohibition to construct in the beds and on the banks of the Cauca and Molina rivers (flooding, mudflow and landslide dangers);
- compulsory geotechnical study in Area D, where the slope exceeds 25%.

The above work, completed with a vulnerability study, led to recommendations for necessary development work and building codes. This should lead to better use of available ground, better definition of building types, and, last but not least, better risk management.

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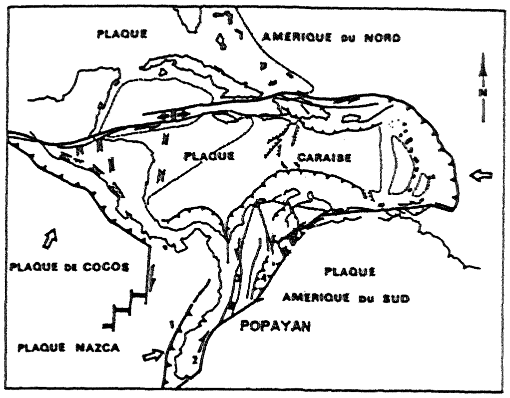

1: Colombia trench
2: Dolores-Guayaquil fault (Ecuador)
3: Romeral fault system (Colombia)
4: Eastern Cordillera of Colombia
5: Pamplona wedge
6: Merida Andes

Figure 1 - Location and geodynamic setting of Popayan (after: Boinet, T., 1985).

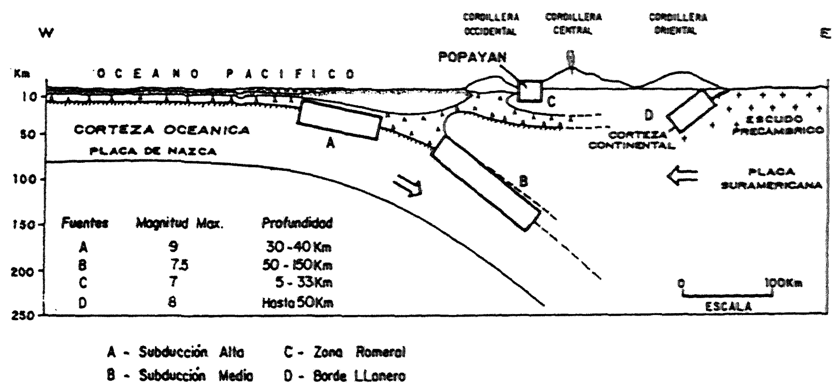

Figure 2 - Schematic cross-section, showing the main seismic zones that can affect Popayan.

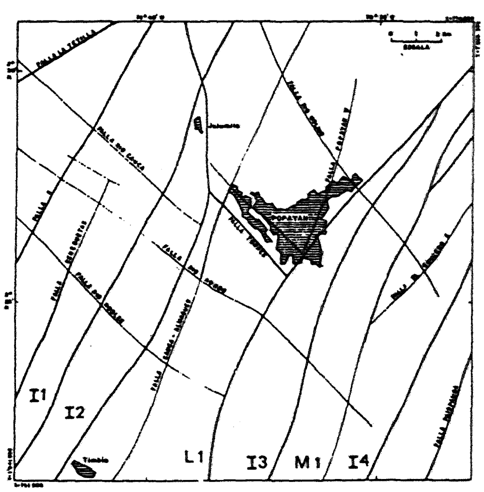

Figure 3 - Map of active and potentially active faults around Popayan

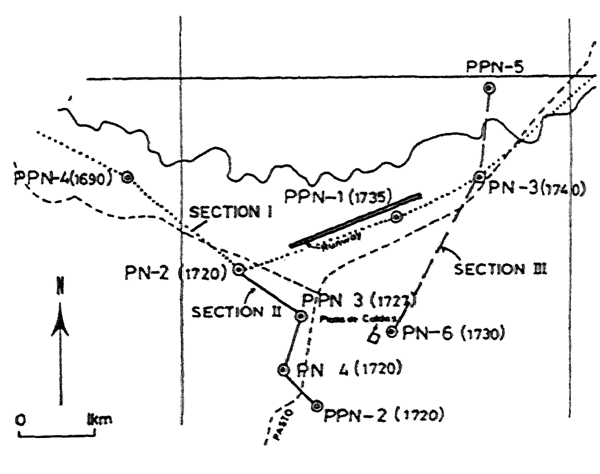

Figure 4 - Borehole sites drilled in 1990 for the microzonation of Popayan.

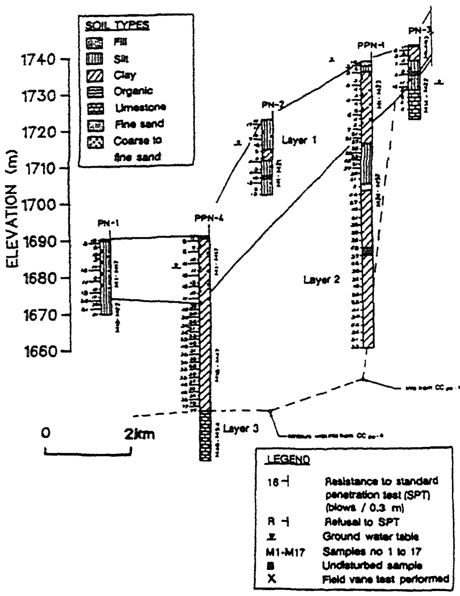

Figure 5 - Popayan: Section 1, showing the three main soil horizons in Zone 2 (see Fig. 6).

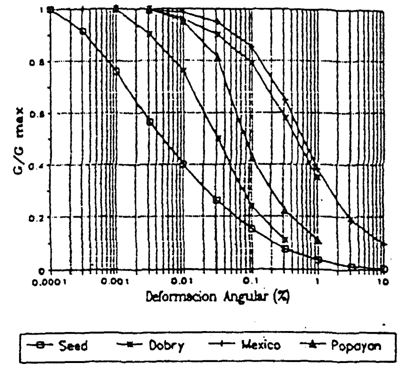

Figure 7 - G/Go = f( ) curves for different soils, including those of Popayan.

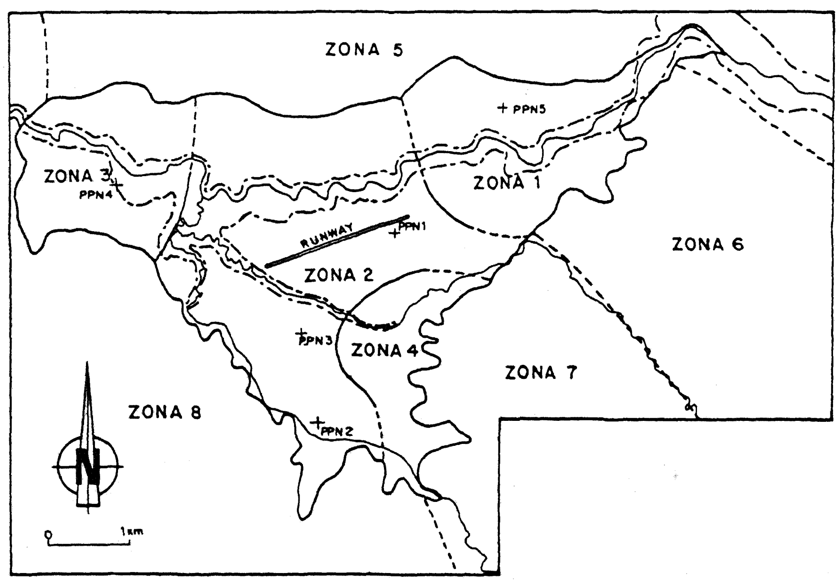

Figure 6 - Popayan: geological and geotechnical zonation.
___... boundary of homogeneous area in terms of soil response
_._._. boundary of slope edges along the Cauca and Molino rivers

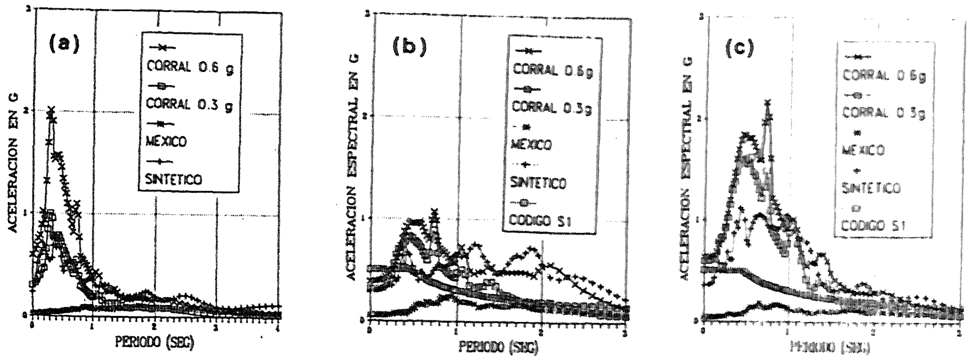

Figure 8 - Example of response spectra (5%):
(a) reference spectra at rock
(b) spectra obtained with SHAKE for a soft soil
(c) spectra obtained with SHAKE for a medium soil
the spactra of the Colombian code are indicated on (b) and (c).

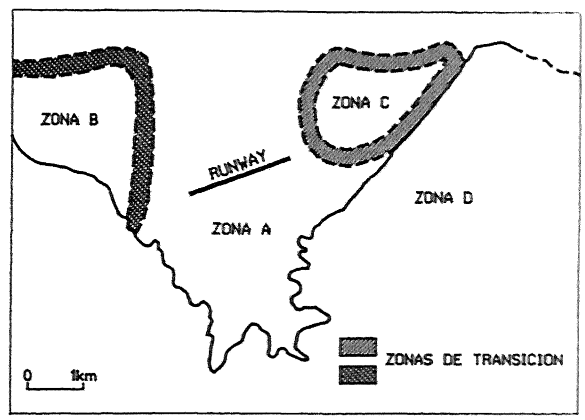

Figure 9 - Popayan: microzonation of site effects - Proposal for the final selection of four zones (A, B, C and D) and transition zones.

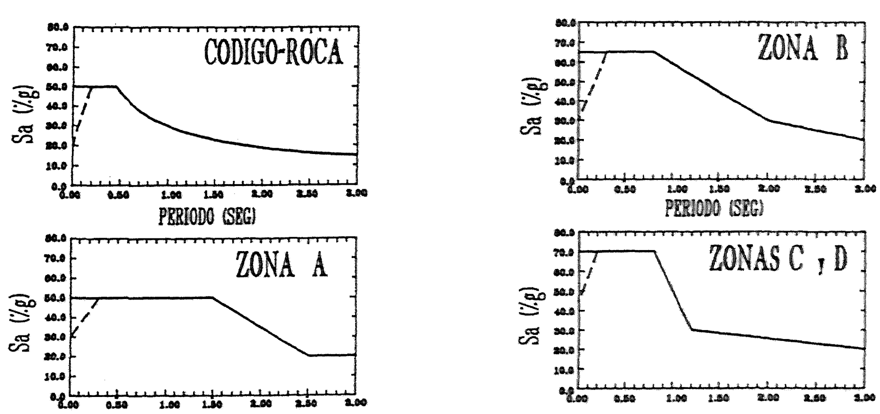

Figure 10 - Popayan: proposed design spectra (5%) for the four zones, and the design spectrum at rock of the Colombian code as used for Popayan.