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RECENT ADVANCES IN SEISMIC MICROZONATION STUDIES IN COLOMBIA: THE MANIZALES CITY CASE

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SUMMARY

The article presents the recent advances on the seismic microzonation studies that have been carried out for some Colombian cities, making emphasis in the microzonation study for the city of Manizales, which is located on volcanic ash soils. An analysis of the Colombian territory's seismological variables was carried out and the attenuation laws for different types of seismological sources were defined based on regional recent strong motion records. The non-linear dynamic properties of the city's characteristic soils were studied using in situ and laboratory dynamic tests. A non-linear transfer function evaluation model for the volcanic ash deposits was developed in order to obtain Fourier Amplitude Spectra (FAS) at ground surface level. Using the FAS at surface level, uniform hazard spectra were constructed at different locations according to the classic hazard theory. Simultaneously, sensibility analyses for the different variables involved were carried out as well as Montecarlo simulations of non -stationary processes. Bidimensional analyses were also performed in order to evaluate the amplification effects generated by abrupt topographic characteristics of the ground on which the city has been built. Artificial earthquakes were generated for the time response analysis of the soil deposits and representative structures using the seismological theory of the Omega Squared model following a Green empirical function procedure. Recommendations for the installation of a seismic instrumentation network were made in order to improve the proposed models. The spectra establish the basis for the city's seismic design code and city's earthquake loss scenarios for emergency response planning. Finally, taking into account disaster risk management and insurance public policies, a seismic risk evaluation was performed on a representative group of government's building infrastructure in order to establish the optimum seismic risk transfer and retention strategies for the city.

INTRODUCTION

The three major cities in the Colombian Coffee Growing Region are, in their order, Pereira (380.000 inhabitants), Manizales (370.000 inhabitants) and Armenia (270.000 inhabitants). Considering the high seismic activity characteristic of the zone, these three cities are undertaking, from some years ago, seismic microzonation studies aimed to estimate the expected seismic response of the several distinctive zones for purposes of structural design and rehabilitation, to estimate damage and loss future scenarios and to

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develop prevention and emergency management plans. The following general methodology has been used to carry on the above mentioned microzonation studies:

- Conduction of basic studies, including the following: regional and local geology, neotechtonics, historical and instrumental seismicity, accelerographic local network set up, geophysical characterization (seismic refraction and microtremors), geotechnical characterization by compiling previous studies, geomorphology, topography, and cartography.
- Assessment of local seismic hazard and definition of design earthquakes, based on existing studies at national level [1, 2, 3, 4, 5] and the existing instrumental and historical seismic information.
- Detailed geotechnical investigation by means of borings in the several different characteristic zones of the city, field tests to measure wave velocities and laboratory and in situ tests for soil dynamic behavior characterization.
- Assessment of dynamic response of the different characteristic deposits by using unidimensional analytical models.
- Evaluation of dynamic response related to geometric effects such as fills, slopes and hill zones, by using two-dimensional analytical models.
- Definition of earthquake-resistant uniform hazard design spectra.
- Instrumentation (using accelerographic networks) in order to calibrate the analytical results.
- Seismic risk evaluation
- Seismic risk management strategies

SEISMIC HAZARD ANALYSIS

An analysis of the Colombian territory's seismological variables was carried out. Figure 1 presents the analytical model developed to evaluate the seismic hazard for Colombia. The most important seismic sources are shown. Each one of them is characterized using the seismic information available from the national accelerographic network.

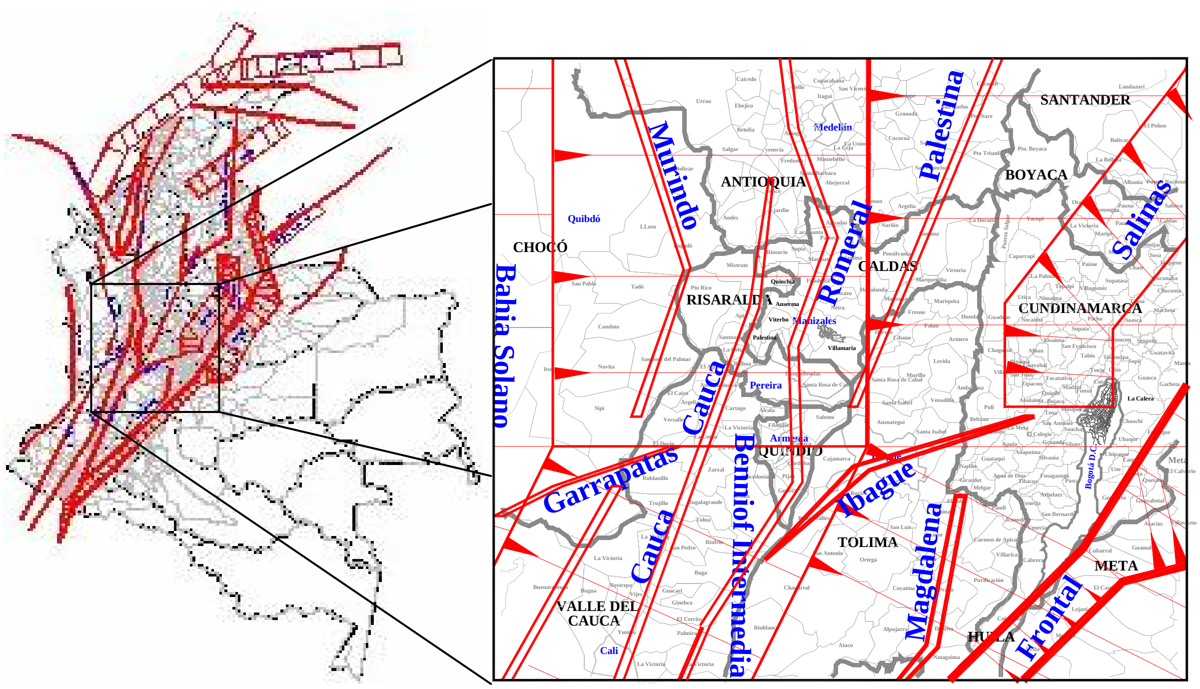

Figure 1: Analytical model for seismic hazard analysis

Attenuation laws for different types of seismological sources were defined based on regional recent strong motion records. Using a probabilistic integration scheme, exceedence rates for firm soil deposits are estimated for the city. Figure 2 illustrates the different acceleration exceedence rates for firm soil for each one of the seismic sources of the zone. In addition, the maximum acceleration exceedance rates considering the integrated effects of all relevant seismic sources is presented as well as the relative participation factor for each one of them in the global hazard curve for the city.

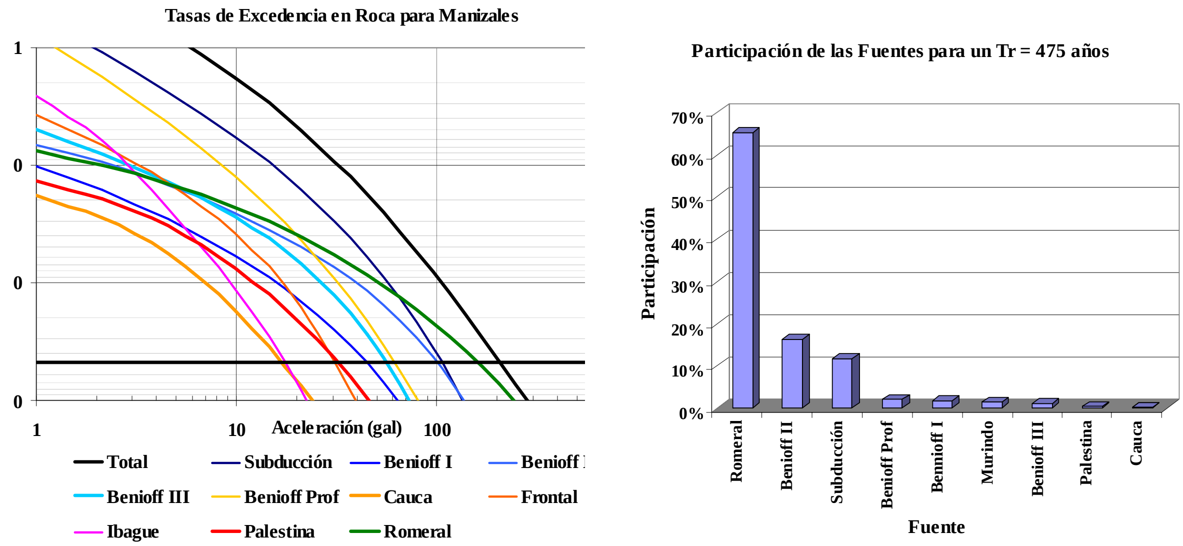

Figure 2: Exceedance rates for relevant seismic sources and relative participation factors

Following the general random vibration theory, different seismic intensity maps such us acceleration, velocity, displacement or any other related parameter, are plotted for different return periods. Figure 3 presents the maximum probable acceleration in firm soil for a 475 year return period, corresponding to the design return period established by local structural design codes. Simultaneously, uniform hazard spectra are presented for the city, for different periods of analysis return.

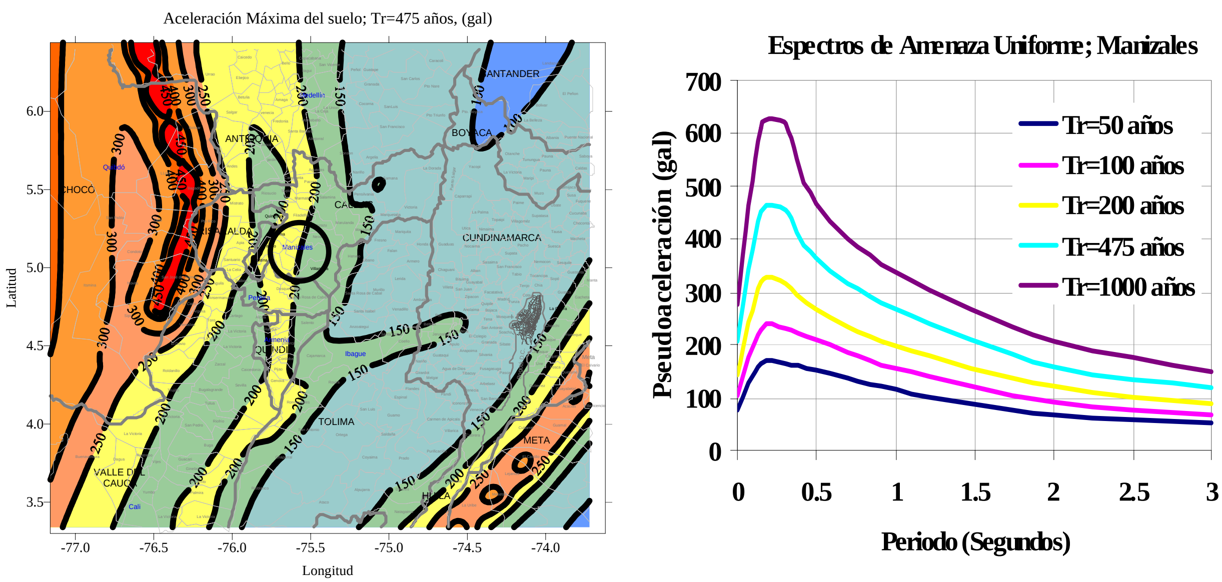

Figure 3: Maximum probable acceleration for firm soil in the area of Manizales and uniform hazard spectra for different return periods

Based on the hazard information available, artificial earthquakes were generated for the time response analysis of the soil deposits and representative structures using the seismological theory of the Omega Squared model following a Green empirical function procedure. Some representative records are presented in Figure 4. Figure 5 presents the response spectra of the artificial earthquakes generated as compared to the design spectrum defined by the local code.

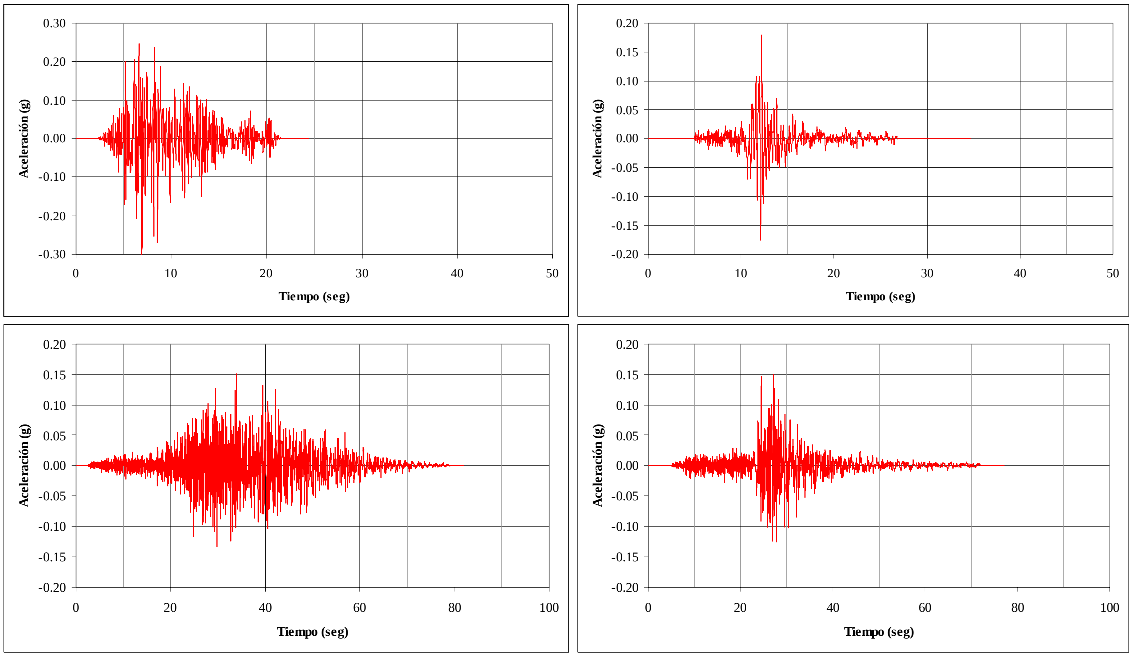

Figure 4: Representative artificial records

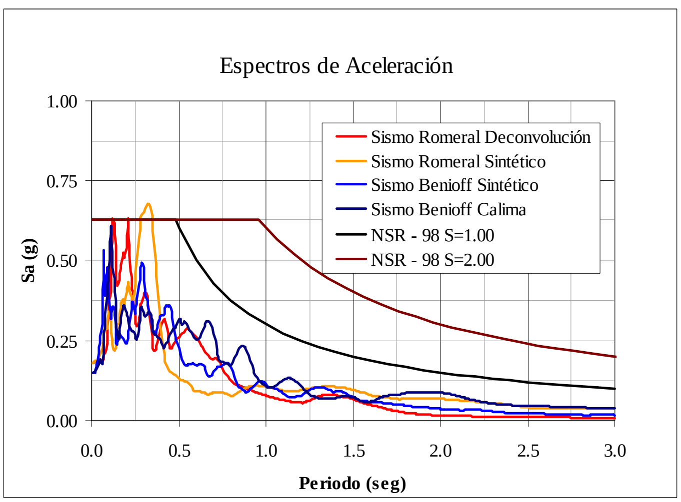

Figure 5: Acceleration response spectra for artificial earthquakes

DYNAMIC SOIL RESPONSE

From the stand point of dynamic response analysis, it is necessary to characterize surface deposits which due to its dynamic behavior features (wave velocity, stiffness or density) show a contrasting condition with deeper deposits. The City of Manizales is located at the western flank of the Colombian Central mountain range, wherein there are found more than 23 of the identified active volcanoes of the country, with high activity in the past. For such reason, surface deposits of the entire zone are characterized by the presence of volcanic ashes or pyroclastic fall deposits of variable thickness, ranging from 3 m to 35 m. These materials were deposited over Tertiary and Cretaceous units or over more recent deposits made up by debris flows, alluvial or colluvial deposits. Also plenty of hydraulic, mechanical, or sanitary fills are found at surface level with variety of geometry and high heterogeneous distribution. The fills were used to form flat zones in initially wavy topography with the purpose of developing housing construction activities. In order to study the dynamic properties of these soils, a comprehensive boring plan was carried out as appears illustrated in Figure 6. A total of 24 boreholes were carried out at different depths which were supplemented with more than 200 previous boreholes.

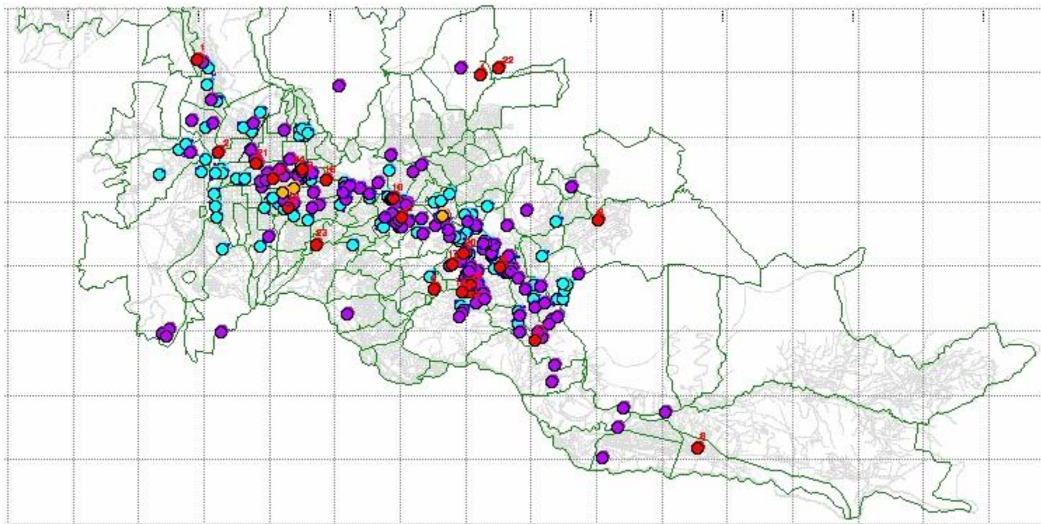

Figure 6: Distribution of boreholes

Geotechnical information as well as microtemors measurements carried out in different locations of the city allowed to develop a thickness map of superficial volcanic ash soils deposits.

Based on the information obtained, recommendations for the installation of a seismic instrumentation network were made in order to improve the proposed models. The location of the accelerographs should match the representative explored locations of the city selected from the points indicated in Figure 6. The installation of at least fifteen (15) strong motion accelerographs at surface level and at least two (2) at base rock level was recommended in order to determine the characteristics of typical earthquake records and the empiric transfer functions for each one of the points of analysis within the study area.

The non-linear dynamic properties of these characteristic soils deposits were studied using in situ and laboratory cyclic tests on unaltered samples. Cyclic triaxial tests (standard ASTM D5311-92), resonant column tests (standard ASTM D4015-92), and wave velocity tests on unaltered samples confined in triaxial chamber ("Bender Element", standard ASTM D2845-95) were made. In addition, seismic cone in situ test, cyclic in situ presionmeter test and down hole shear wave velocity tests were performed. Findings from the tests conducted show in general a high variability of ash dynamic behavior.

Typical results from in situ cyclic presiometer test as well as correlation between different tests is presented in Figure 7.

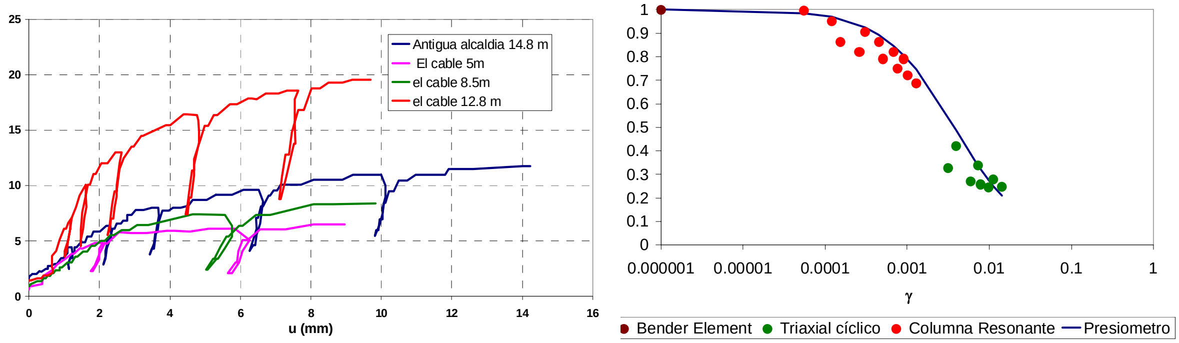

Figure 7: Typical results from in situ cyclic presiometer test and correlation between different tests

UNIFORM HAZARD SPECTRA

A non-linear transfer function evaluation model for the volcanic ash deposits was developed in order to obtain Fourier Amplitude Spectra (FAS) at ground surface level. Using the FAS at surface level, uniform hazard spectra were constructed at different locations according to the classic hazard theory. Simultaneously, sensibility analyses for the different variables involved were carried out as well as Montecarlo simulations of non-stationary processes. The spectra establish the basis for the city's seismic design code. Figure 8 illustrates uniform hazard spectra at different locations of the city as compared with deterministic analysis using classical non-linear equivalent one-dimensional response analysis with four different accelerographic artificial records.

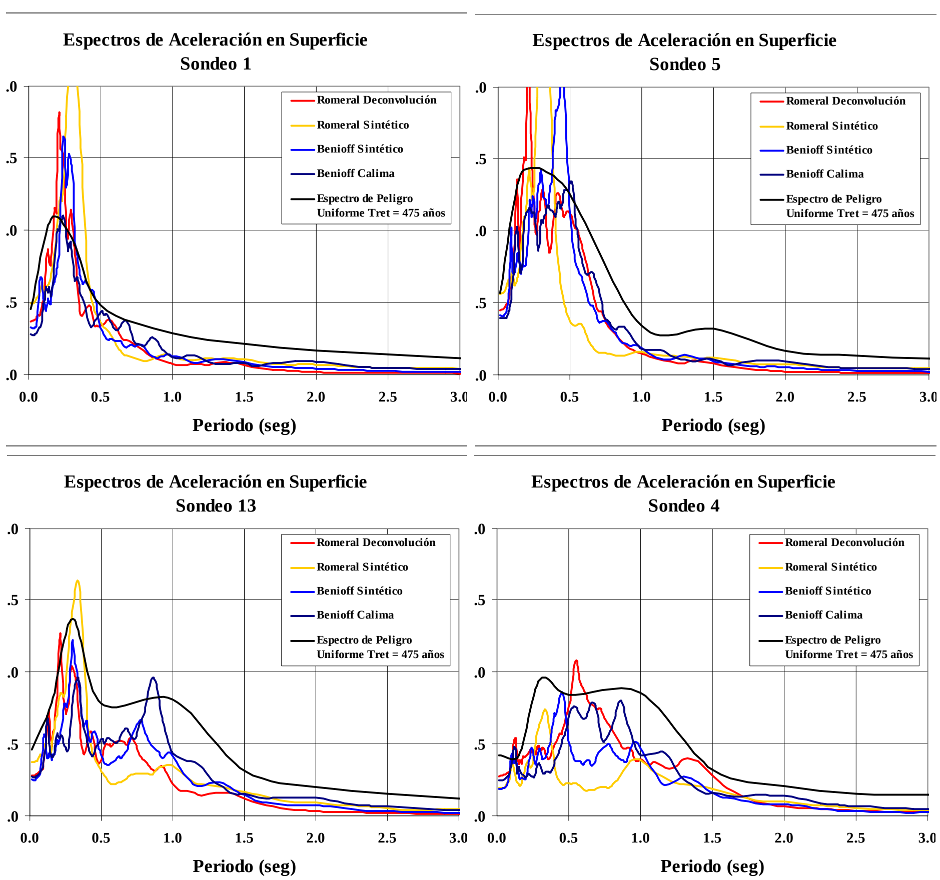

Figure 8: Uniform hazard and deterministic spectra for different locations

TOPOGRAPHIC EFFECTS

The effects of the highly abrupt superficial topography of the city in the surface dynamic response, is studied. A two-dimensional model is resolved by using QUAD-4M computer program [6, 7]. Figure 9 shows the scheme of the model developed and results regarding maximum superficial acceleration for different locations in the modeled slope shown. Figure 10 presents acceleration response spectra and amplification factors for different locations. Amplification factors are evidenced for the period range under analysis in relation with the equivalent one-dimensional response. The analysis is made for several different points along the slope.

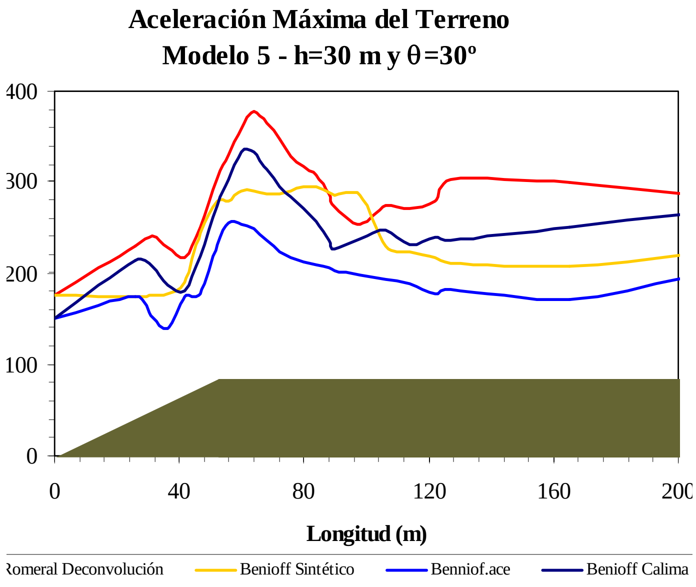

Figure 9: Two- dimensional model and maximum acceleration at different locations

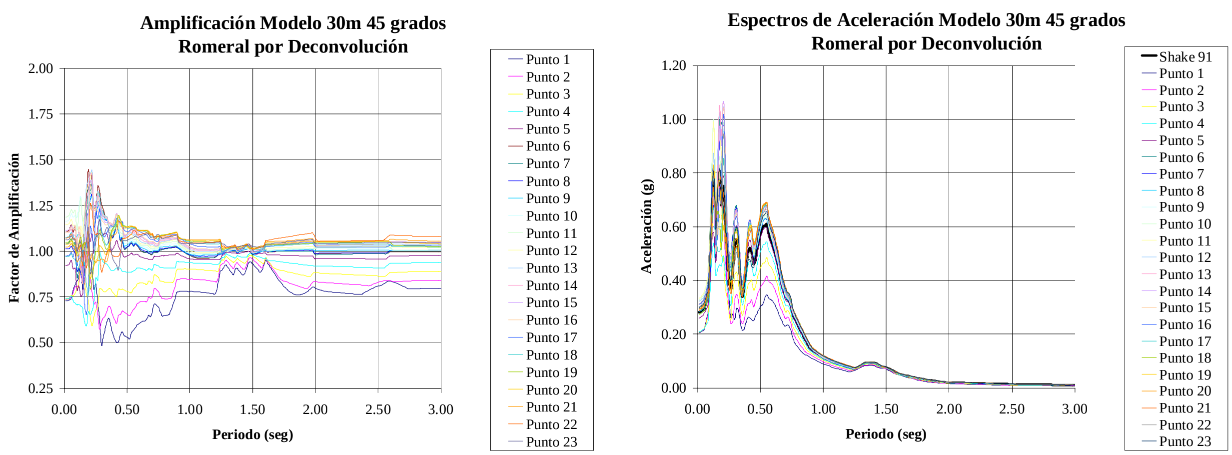

Figure 10: Acceleration response spectra and amplification factors at different locations

SEISMIC MICROZONATION GIS

Considering the high variability of soils deposits, both from the geometric and physical, mechanical and dynamic properties point of view, the results of seismic microzonation are presented using a geographical information system. The system allows the management of all the city's geographical information including general cartography, rivers, roads, places of interest, location of essential and special buildings, geology, geotechnical and in general all the related information available. The system allows visualizing the different seismic intensity parameters (acceleration, velocity or displacement) for any return period and for any structural period of analysis. Simultaneously, for each specific location the system calculates, by means of interpolation, the acceleration spectrum for different return periods and for the damping coefficient selected.

One of the main advantages of the system is that it specifies the design spectra for each location, eliminating the use of traditional seismic microzones which generally bear a considerable overdesign due to the need of specifying enveloping spectra for the specified uniform microzones. Figure 11 presents the main window of the Geographical Information System to calculate seismic hazard for the city and the typical results given by the system for a particular location.

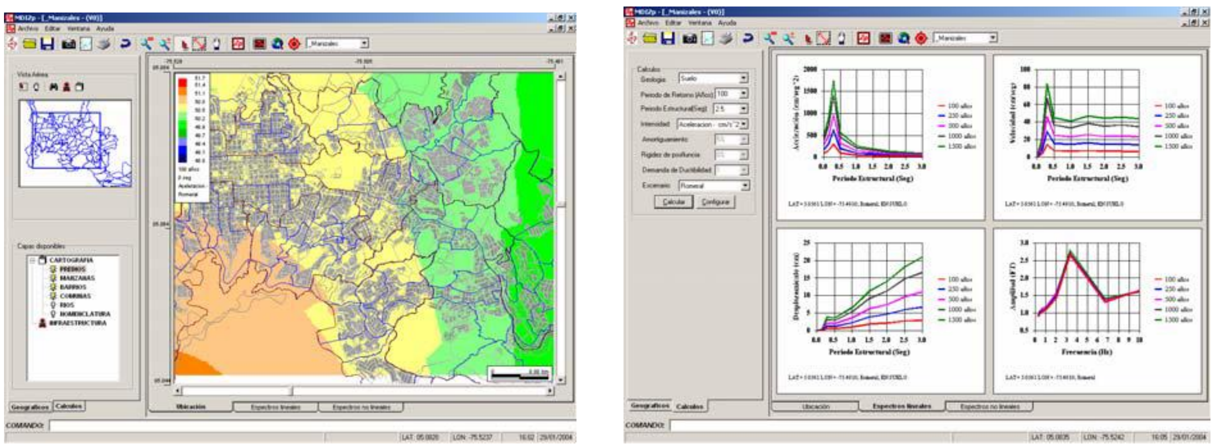

Figure 11: System main window and typical results

SEISMIC RISK EVALUATION

A seismic risk evaluation was performed on a representative group of government's constructions in order to establish the basis for more detailed analyses related to general seismic risk management for the city.

To carry out seismic risk assessment and to evaluate expected losses caused by earthquakes, a modified version of the RN-COL v 2.1 system developed by Evaluación de Riesgos Naturales, ERN – Colombia, was used. This system includes the most comprehensive information available on the country's seismic conditions. The system was integrated to the geographical information system for hazard evaluation in the city, including subsoil amplification effects. Additionally, the system includes the information that characterizes building typologies more often used in the city. The geographical location of the 40 main city buildings analyzed, corresponding to the municipality's public buildings is presented in Figure 12.

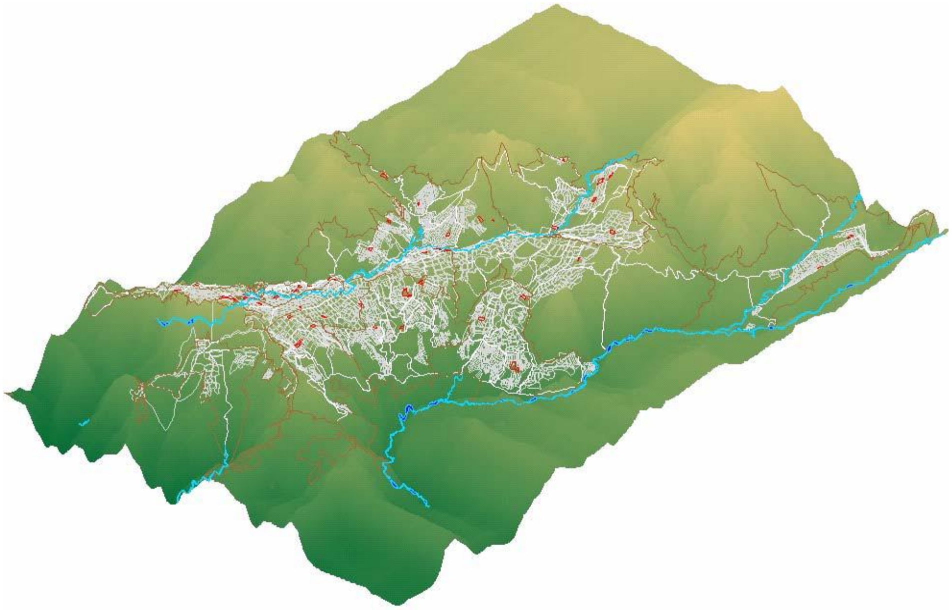

Figure 12: Geographical location of analyzed public risks

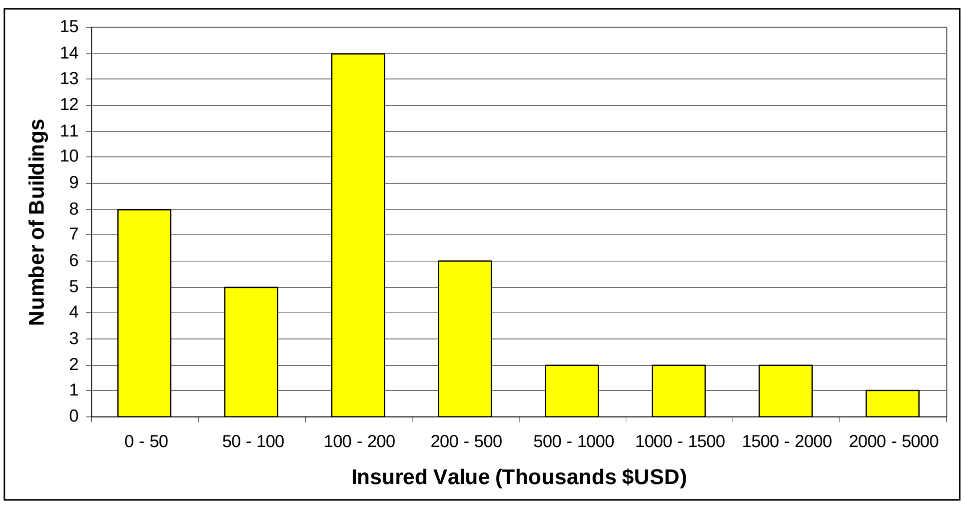

Figure 13: presents a frequency curve of insurable values of the different buildings analyzed.

The results of the analysis are presented in Figures 14 to 16. Figure 14 shows a histogram of expected losses for the buildings analyzed. These results indicate that expected values of the individual loss of the buildings present a great variability with values ranging from 8% to 96% with respect to insurable values. Figure 15 presents a concentration curve of the group of buildings. This curve indicates that about 5% of the most critical buildings concentrate nearly 85% of risk for the city administration. On the other hand, Figure 16 depicts probable maximum loss variation, PML, for the group of buildings as a function of the return period of analysis. It is concluded that the city's public buildings PML varies between 31% and 41% for a range of return periods between 500 and 1500 years. These results set the basis for a risk transfer and retention strategy for the city administration.

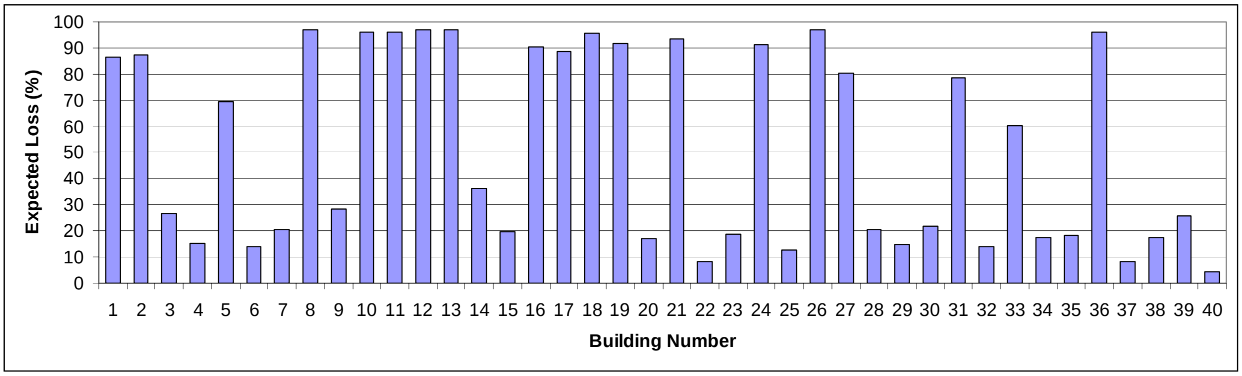

Figure 14: Expected losses for the buildings analyzed

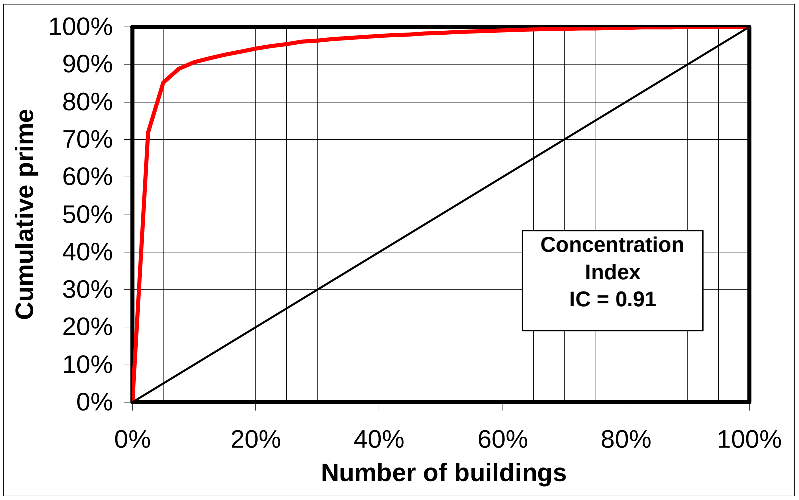

Figure 15: Concentration curve of the group of buildings

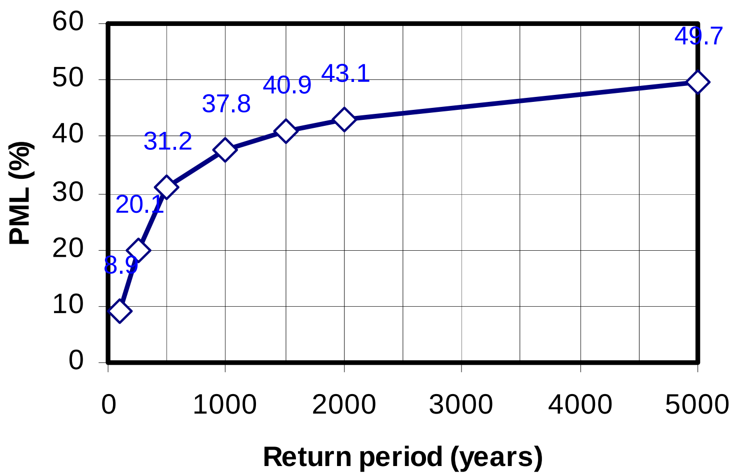

Figure 16: Probable Maximum Loss variation

CONCLUSIONS

Based on the previous findings, the following conclusions can be drawn:

- Uniform hazard spectra resulting from an analysis using the random vibrations theory together with a non-linear transfer function evaluation model developed in order to obtain Fourier Amplitude Spectra (FAS) at ground surface level, indicates very similar results as compared with acceleration spectra resulting from the classical non-linear equivalent one-dimensional response analysis with a group of accelerographic artificial records.
- The characterization of soils dynamic properties for volcanic ash deposits requires different laboratory and field tests in order to adequately characterize their behavior for the entire range of deformations.
- The results given by different laboratory tests such as wave velocity, cyclic triaxial and resonant column present an acceptable agreement with equivalent results obtained from field tests such as down-hole, cyclic presiometer and seismic cone test.
- Abrupt topography can generate geometric amplification effects that can be in the order of 1.2 to 1.3 in the range of structural periods between 0.2 and 0.5 seg (rigid buildings) depending on the relative location of the building within the topographical profile.
- The results of hazard analyses in microzonation studies are interpreted in a more convenient way by using a geographical information system (GIS) which can evaluate the design spectra at each exact location by means of continuous interpolation, thus eliminating traditional seismic microzones which generally bear a considerable over design.
- The results of seismic risk evaluation for public buildings of the city of Manizales indicate that expected values of the individual loss of the buildings present a great variability with values ranging from 8% to 96% with respect to insurable values.
- City's public buildings PML varies between 31% and 41% for a range of return periods between 500 and 1500 years. These results set the basis for a risk management strategy for the city.

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