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SEISMIC WAVE AMPLIFICATION BY LOCAL EFFECTS IN SANTA FE DE BOGOTA AND ARMENIA, COLOMBIA

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SUMMARY

Since the past 70s, part of the damages caused by many earthquakes around the world, especially to diverse types of civil engineering works, has been explained by the incidence of local site conditions, expressed as topographic forms and changes in earth materials. Many researchers have developed numeric models that show the generation of amplification of the seismic signals (R, SH and SV waves) due to these local conditions.

This paper includes two examples where the topographic effect in the ground seismic response has been evaluated. In the first case, the existing information from the Santa Fe de Bogota Seismic Microzonation project (INGEOMINAS, Universidad de los Andes, 1997) was used to infer future building behavior in the city. In the second case the incidence of the topographic forms of creeks is studied for the city of Armenia, Quindío, to try to explain great damage concentration in those places resulting from the Quindio Earthquake that occurred on January 25st, 1999.

For this purpose, bidimensional finite element models were analyzed, using the actual geometry of the two sites, dynamic soil tests recently completed and accelerograms registered by the Colombian National Seismological Network (Red Sismológica Nacional de Colombia - RSNC).

INTRODUCTION

The earthquakes that had affected Colombia during the past two decades of this century had caused high losses in human lives and large impacts to the country economy. In several of these events a close relationship has been observed, in diverse cities in the country, between damage and local topographic features. Examples of these are the damages caused by the Calima (1995) and Quindío (1999) earthquakes respectively to the cities of Pereira and Armenia, both located in the Coffee Growing Zone of Colombia.

Research developed previously in Colombia, among others, by Rodríguez and González (1988, 1991), Rodríguez (1994) and Nivia (1998), had focused in the estimation of seismic amplification due to topographic effects that could originate in zones of Santa Fe de Bogota, the capital city of Colombia, in case of the probable occurrence of earthquakes generated in the main active tectonic systems that surround the City. Additionally, in preliminary studies, the Colombian Institute of Research and Information on Geosciences: Mining, Geoenvironmental and Nuclear, INGEOMINAS, has recently identified and evaluated elevated seismic amplifications due to topography in several zones in Armenia, due to the Quindio Earthquake that occurred on January 25st, 1999 and that affected the western central region of Colombia (INGEOMINAS, 1999a, 1999b)

The purpose of this paper is to present numerical results obtained from bidimensional dynamic modelling of two cross-sections: the first one in Santa Fe de Bogota, for hypothetical earthquakes and the second one in Armenia for the Quindio Earthquake.

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SEISMIC TOPOGRAPHIC AMPLIFICATIONS IN SANTAFE DE BOGOTA

The zone studied belongs to a sector located along 127th Street, in the northern part of the city, with general orientation West-East and geomorphological special characteristics: the Eastern Mountains ("Cerros") composed mainly of cretaceous sandstones and the Suba Hills at the West, composed of Tertiary claystones, that enclose, in a syncline, the typical Bogota Sabana quaternary lacustrine soft soil deposits up to 250m thick in this particular site, although its maximum depth can reach 700m in the central western part of the city.

Geometric Subsoil Model

To model the geometry, the soil/rock contact was defined based on the isopach map developed by INGEOMINAS (1997) by means of geophysical studies and direct exploration. The 127th St. model section has 15 km length, surface levels between 2580 and 3050 m.a.s.l., soft soil deposit minimum level estimated at 2330 m.a.s.l. and model minimum level of 2250 m.a.s.l.

Geotechnical Modelling

To model the stratigraphy, an average profile was obtained as result of a weighted characterization both of layer thicknesses and static and dynamic geomechanical parameters. trying always to simplify the large section analyzed, but minimizing accuracy loss. Parameter data was obtained form the borings and tests available in the zone (INGEOMINAS, Universidad de los Andes, 1997) and 7 representative soft soil layers were defined, which formed the average simplified geotechnical profile. In Table 1 assigned index and dynamic parameters for 9 layers and 5 materials (3 lacustrine soils, 1 colluvial deposit and 1 rock) are shown.

Table 1. Average subsoil geotechnical characteristics in Santa Fe de Bogota

Layer	**Material**	**Depth (m)**	**Thickness (m)**	**Wn (%)**	**LL (%)**	**IP (%)**	**γt (ton/m^3)**	**Qu (ton/m^3)**	**Vs (m/sec)**	**General Description**
1	2	0 – 10	10	57	90	60	1,63	0,72	120	Clayey materials
2	1	10 - 20	10	139	168	117	1,39	0,48	200	Clayey materials
3	1	20 - 40	20	122	147	100	1,47	0,62	280	Clayey materials
4	2	40 - 70	30	72	98	66	1,52	0,97	300	Clayey materials, with Peat
5	3	70 - 140	70	48	63	32	1,56	1,44	320	Clayey silty materials, with fine sand
6	3	140- 175	35	59	102	59	1,64	4,15	350	Clayey silty materials, with some fine sand
7	3	175 - 188	13	30	49	22	1,76	5,98	400	Clayey materials, with some fine sand
	4	variable					2,00		500	Colluvium
	5	variable					2,60		2000	Rock

Design Accelerograms

The main seismic sources for the city were taken as those identified and studied in the seismological, neotectonic and seismic hazard studies at national level by AIS (1996) and at local level by INGEOMINAS-Universidad de los Andes (1997). Regional accelerograms in rock supplied by RSNC and historical accelerograms in rock of other parts of the world were used to obtain seismic signals that complied with maximum acceleration, duration and frequency content corresponding to earthquakes coming from four seismic sources: local (near-field), near, intermediate and distant, whose main characteristics are shown in Table 2.

Table 2. Seismic sources

Seismic Source	Earthquake Type	Epicentral Distance (km)	Maximum Acceleration(g)
Sabana de Bogotá Faults	Local	20	0.25
Eastern Cordillera Front Fault	Near	60	0.20
Salinas and Romeral Faults	Intermediate	200	0.10
Subduction Zone	Distant	400	0.04

Seismic Response Model

The seismic response model adopted was the shear wave propagation technique incorporated in the finite element code QUAD4M (Idriss et. al, 1993).

It is difficult to establish beforehand an optimum procedure to choose and configurate the best finite element mesh in dynamic models. The available technique is to systematically vary mesh shape and element size and number, having the constraint of computer capacity.

The seismic response was evaluated mainly with maximum horizontal acceleration values and surface response spectra. Maximum horizontal accelerations for the earthquakes studied are presented in Figure 1. In all cases peak accelerations occur in the transition zone between the flat lacustrine deposits and the mountains (piedmont zone, where also colluvial deposits exist), in relatively short lengths between 1.0 and 1.5 km. This phenomenon is thought to occur due both to topographic effects and material heterogeneity in these sectors.

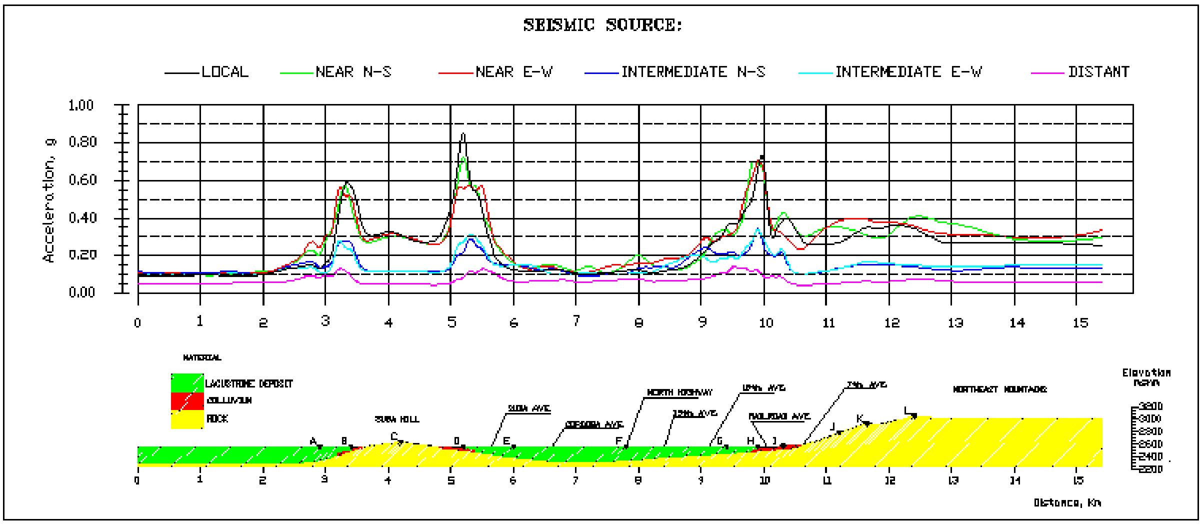

Figure 1 - Maximum surface response accelerations - 127th Street Cross-Section

The earthquakes that affect most this section, in terms of maximum accelerations, are those coming from the local and near sources, as shown in this Figure 1.

In the flat soft zone, local and near earthquakes, of short periods and large accelerations, result in seismic acceleration attenuations, whereas for intermediate and distant earthquakes, with relatively small accelerations and long periods, acceleration amplifications occur of the order of 2. These amplifications are due to the proximity of the fundamental period of the earthquake signal to that of the soil deposit. In the mountains, amplifications up to twice the incident acceleration are observed, especially in sectors of upward positive gradient change (protuberances) and for local and near earthquakes.

In summary, local and near earthquakes affect mainly the mountain and transition zones (amplification factors from 1.24 to 4.05), whereas in the flat soft soil zones far away from the mountains there are always attenuations that vary from 0.48 to 0.80. Intermediate and distant earthquakes affect mainly the flat soft soil and intermediate zones (amplification factors up to 3.75), but there are always amplifications everywhere.

Acceleration surface response spectra of several points in Figure 1 were grouped according with the seismic zones of the city and with each seismic source, as shown in Figure 2. It is observed that higher acceleration spectral values correspond to the mountain and piedmont zones, that surpassed noticingly those obtained with 1D models. In contrast, lower spectral values for lacustrine soils A and B were similar with 1D results.

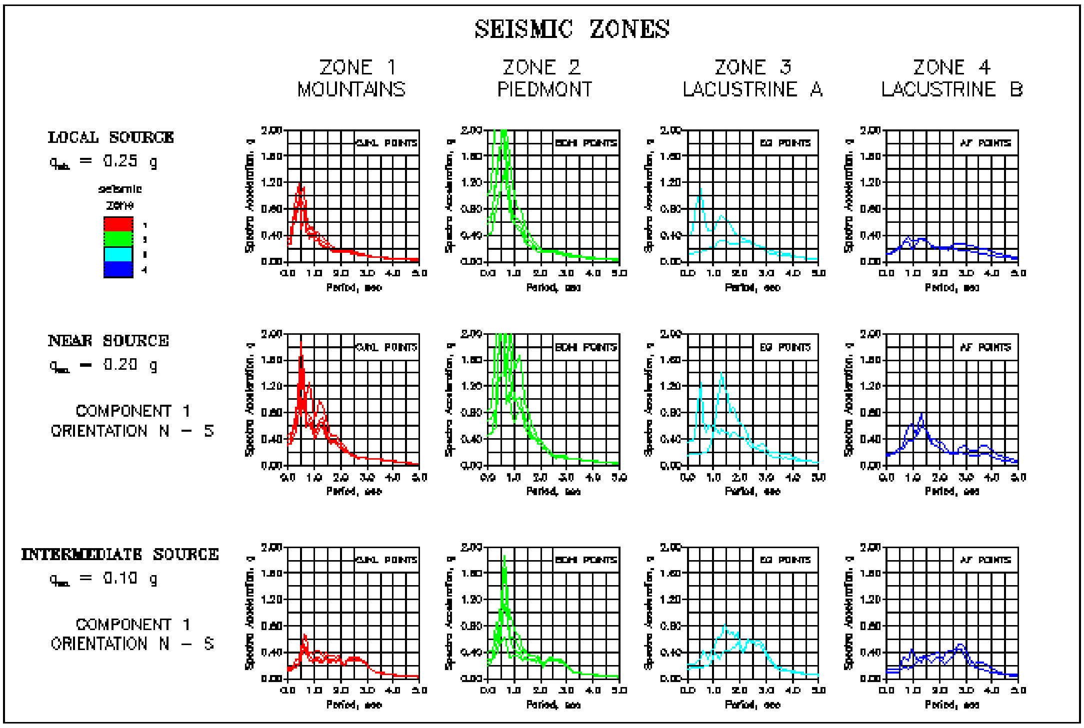

Figure 2 – Acceleration Response Spectra For Different Zones And Earthquakes In Santa Fe De Bogota

SEISMIC AMPLIFICATIONS IN ARMENIA DURING THE QUINDIO EARTHQUAKE

The Quindío Earthquake that occurred in 25th January, 1999 constitutes perhaps the most disastrous seismic event in the 20th century for Colombia. The main shock hit at 13:19 local time (18:19 UT) with Richter magnitude 6.2, hypocenter at 4.41° N Latitude, 75.72° W Longitude and depth less than 20 km. Additionally, of the great number of aftershocks, at 17:40 local time (22:40 UT) of the same day, there was a 5.8 Ms shock, also superficial, that concluded the devastating effect of the main shock.

Of the instruments that recorded the main event, the accelerograph installed by RSNC in the Quindio University Campus in Armenia, 15km northeast from the epicenter, gives the best idea of the severity of the telluric movement. This instrument is in flat terrain, at 1m depth, over 13m of volcanic ashes that overlay 14m of residual soil and saprolite of the underlying old laharic flow consolidated material of great depth and strength.

The three components of the registers (Figure 3) show that the vertical component (Amax = 0.48g) was 91% of the E-W component (Amax = 0.53g) and 83% of the N-S component (0.58g), typical proportions of a near-field effect.

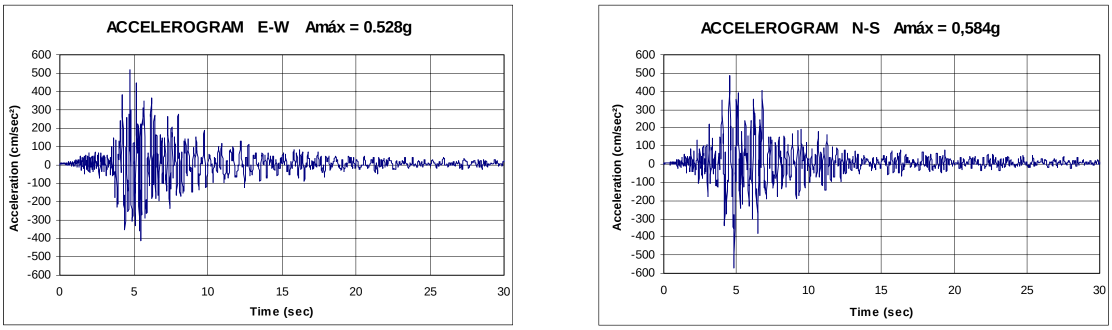

Figure 3 - Surface accelerograms of the Quindio Earthquake at the Quindio University Station

From the first visits and preliminary earthquake effect evaluations clear damage concentrations were noted in zones of the city where houses and buildings were located near or on sites with abrupt topographic changes in E-W parallel creeks and slopes, as shown in Figure 4.

Figure 4 - Typical creek and slope configuration in Nueva Brasilia and Santander Quarters (Barrios)

Geometric Subsoil Modelling

A cross-section in NE-SW direction was chosen so as to cover the zone of the abovementioned "barrios", with 1230m length, and valley depths varying from 15m to 40m. The general stratigraphy was modelled by a sequence, from top to bottom, of 7m to 18m of volcanic ashes, 6m to 9m of residual soil and 5m to 10m of saprolite, all over the old deep laharic hard deposit (Figure 5)

Geotechnical Modelling

For Armenia, the average geotechnical profile and the geomechanical properties, as obtained from borings and field and laboratory tests, both static and dynamic, is presented in Table 3.

Table 3 - Average geotechnical characteristics of the Armenia subsoil

Material Description	Depth (m)	Unit weight (ton/m3)	Vs (m/s)
Volcanic ash	0 – 14	1.45	150
Residual soil	14 – 20	1.5	320
Saprolite	20 – 25	1.75	400
Laharic flow deposit	> 25	2.0	1200

Design Accelerogram

Unfortunately the accelerograph in rock in Calarca, was damaged few days before the time of the shock, and therefore it was neccesary to make the deconvolution of the surface signals at the Quindio University, by means of the SHAKE91 code (Idriss et al., 1992) to obtain signals at the top of the deep laharic hard deposit, which resulted in an accelerogram with Amax=0.28g, which was used as input data for the bidimensional analyses.

Seismic Response Model

Again, the finite element code QUAD4M (Idriss et. al, 1993) was used, with the deconvoluted register of the E-W component to obtain, for the cross-section shown on Figure 5, accelerograms and surface horizontal maximum accelerations at selected points, which are also indicated in this same Figure 5.

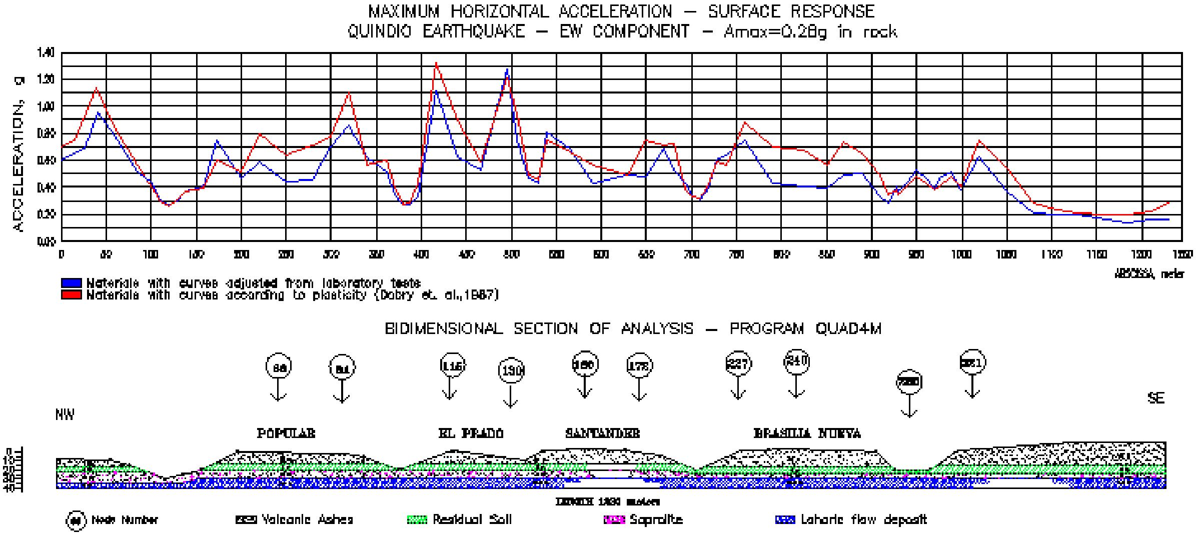

Figure 5 - Cross Section and Maximum Accelerations in Armenia - N. Brasilia and Santander Quarters

Elevated values of surface horizontal accelerations are noted on top of the creek slopes, reaching values from 0.8g to 1.1g, whereas in the flat zones and creek depressions, the accelerations are much lower, from 0.3g to 0.6g, values that are similar to those obtained both at the Quindio University and with SHAKE91 one-dimensional models.

In Figures 6 and 7 are shown 2-D response surface acceleration spectra obtained for several points in the model, grouped into creek zones (Figure 6) and flat zones (Figure 7), with two models of subsoil dynamic parameters (Plasticity Model (Dobry et al.,1987) and Laboratory Tests).

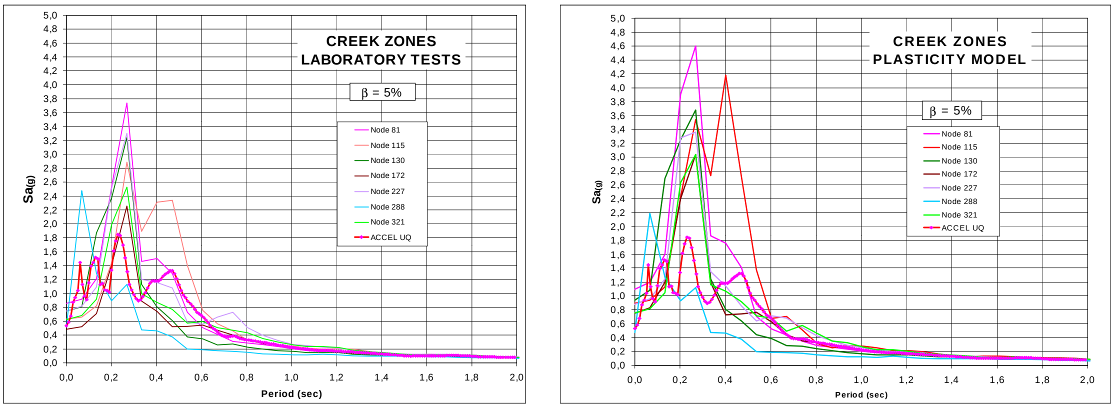

Figure 6 - Response spectra – Bidimensional Model – Creek Zones – Section B-B - Armenia

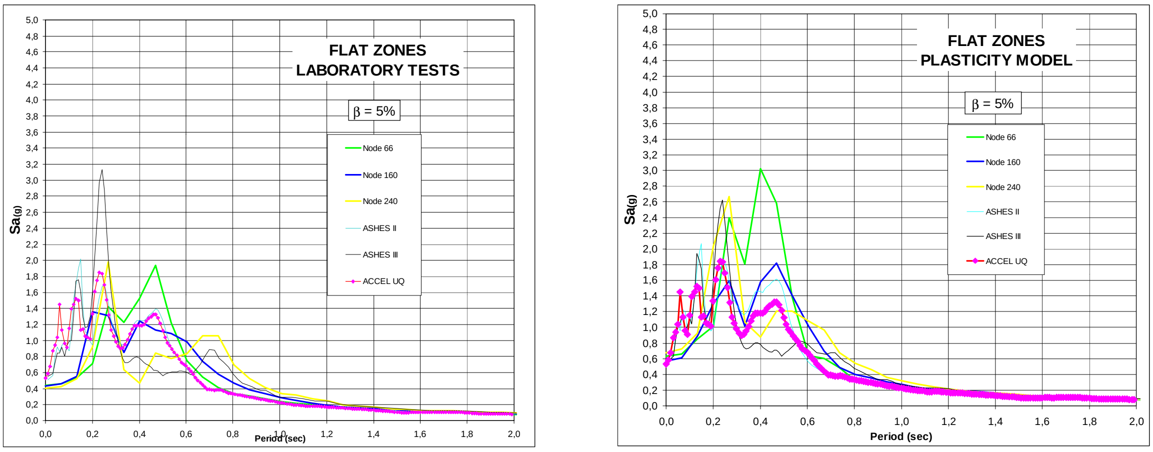

Figure 7 - Response spectra – Bidimensional Model – Flat Zones – Section B-B - Armenia

In these Figures 6 and 7 are also included the spectra obtained with 1-D models and the with the actual record at Universidad del Quindio. The 2-D spectra in the creek zones are much higher than the ones from the 1D models or the actual register, but in the flat zones the differences between the 2-D spectra and the 1-D or the actual ones are not large. Therefore, it is clear the effect of the topographic forms in the dynamic response of the Armenia subsoil and hence on the observed earthquake damage.

CONCLUSIONS

1. The analyses of the effects originated from the subsoil conditions and geometry on the earthquake damage to buildings, requires the understanding of complex relationships between the different types of subsoil materials, their properties and spatial position, the frequency content and intensity of the seismic signals and the structural configuration, strength and ductility of the buildings. Because of this complexity, the careful observation of real earthquake effects and its validation through modelling, is very useful to mitigate future damages. The works presented in this paper are a complementary part to the more ample studies of seismic hazard evaluation and of seismic resistant design of buildings that are currently undertaken both in Santafe de Bogota for regulation purposes and in Armenia to begin the reconstruction of the city in a safer environment.

2. Local conditions, as shown along this article, generate large amplifications and important spatial variations of the incident seismic movements. Surface accelerations in zones of topographic change and material transitions such as the piedmont areas in Santa Fe de Bogota, or in top of natural slopes and in fills in Armenia, vary in more than 100% in the cases analyzed, with reference to the flat natural surfaces.

3. In the case of Santa Fe de Bogota, local and near earthquakes with incident accelerations in rock higher than 0.20g, mainly affect with large amplifications the mountain and piedmont zones, whereas in the far away zones in the lacustrine flat deposits there are acceleration attenuations. Intermediate and distant earthquakes produce amplifications everywhere, being more marked in the flat soft deep lacustrine zone and in the piedmont than in the mountains.

4. In the case of Armenia, larger damage due the Quindio Earthquake of 25th January, 1999, in slope borders and in some fills in relation to other zones, are explained by topographic effects as confirmed by the simplified 2-D model used in this paper.

5. Proper boundary conditions in finite element dynamic models are fundamental to reproduce earthquake phenomena. The use of boundary absorbing base elements in the QUAD4M code avoids spurious overamplification effects due to artificial wave reflection of seismic waves in a rigid base.

6. The observation and analyses of the effects produced by several recent earthquakes, had demonstrated the very important incidence of local subsoil conditions, both of its depth and topography, on seismic damage. The soil depth effects had been taken into account in many seismic regulations in the world, but the topographic influence is still not explicitly taken into account. In a mountainous country such as Colombia, this last effect

may have paramount importance in city planing and building regulations, and therefore it deserves a greater research effort.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to the Colombian Institute and Information on Geosciences: Mining, Geo-environmental and Nuclear, INGEOMINAS and to the National University of Colombia for their valuable contributions during the development of these investigations, as well as for the permission to publish the results.

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