EVALUATION OF THE DYNAMIC SUBSOIL RESPONSE OF THE VOLCANIC DEPOSITS AND MAN-MADE FILLS AND IMPLICATIONS FOR SITE STUDIES AND DESIGN

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SUMMARY

The presence of superficial soils of volcanic origin (known as volcanic ashes) which are supported by more competent soils made up by conglomerates, residual soils or deposits from rivers and lakes is a general characteristic of the Colombian Coffee Growing Region. Besides, cities located in this area like Pereira, Armenia and Manizales, have large man made fills of varying materials within their city limits. These soil deposits have large variability in their mechanical properties and dynamic parameters and induce high dynamic amplifications under seismic excitation. One of the main features that affect the degree of amplification is the degree of cementation of the particles of the volcanic soil. This paper presents results from laboratory tests performed on unaltered samples of volcanic ash soil, the typical ranges of dynamic properties observed and the variation of shear modulus and associated damping with level of strain.

For purposes of seismic microzonation, the expected dynamic response of representative deposits in the area is evaluated and the results of sensibility analyses to relevant variables are presented. The analytic dynamic response is compared with one of the available accelerographic records in the area for the January 25th earthquake. Design spectra are proposed for areas with different characteristics. Due to the fact that most of the variation of the damage observed during the January 25th, 1999 earthquake is associated with amplification and geometric effects in the dynamic response, their approximate evaluation is presented. Based on this information, amplification factors for design spectra are proposed in order to account for geometric and topographic effects.

SEISMIC MICROZONATION STUDIES

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 develop prevention and emergency management plans. Due to the poor instrumental information available, the following general methodology has been used to carry on the above mentioned microzonation studies :

a. Conduction of basic studies, including the following: regional and local geology, neotechtonics, historical and instrumental seismicity, accelerographic local network set up, geophysical characterization (gravimetry, seismic refraction, and microtremors), geotechnical characterization by compiling previous studies, geomorphology, topography, and cartography.
b. Assessment of local seismic hazard and definition of design earthquakes, based on existing studies at national level (references 1, 4, 8 y 9) and the existing instrumental and historical seismic information.

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c. Detailed geotechnical investigation by means of borings in the several different characteristic zones of the city, field tests to measure wave velocities and laboratory tests for soil dynamic behavior characterization.
d. Assessment of dynamic response of the different characteristic deposits by using unidimensional analytical models.
e. Evaluation of dynamic response related to geometric effects, such as fill zones, slope and hill zones, by using two-dimensional analytical models.
f. Definition of earthquake-resistant design spectra for each one of the zones identified with similar seismic behavior.

Even though such studies are not yet finished, with the exception of Pereira, important information has been gathered as a basis to set forth the seismic design requirements for the entire Coffee Growing Region of Colombia.

SUBSOIL PROFILE CHARACTERIZATION OF THE COLOMBIAN COFFEE GROWING REGION

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 Coffee Growing Region 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 complexes.

Figure 1 shows a typical section taken from reference 3, corresponding to a south-northwards cross-section in Pereira downtown. Surface ash deposits are evidenced almost in the whole zone as well as the conglomerates at higher depths and with varied characteristics as for granulometry and matrix properties. Also man-made fills are shown in old river beds or in old creeks. Finally, in the steepest zones, surrounding the rivers, ash thickness reduces, disappearing in abrupt steeps and in river beds.

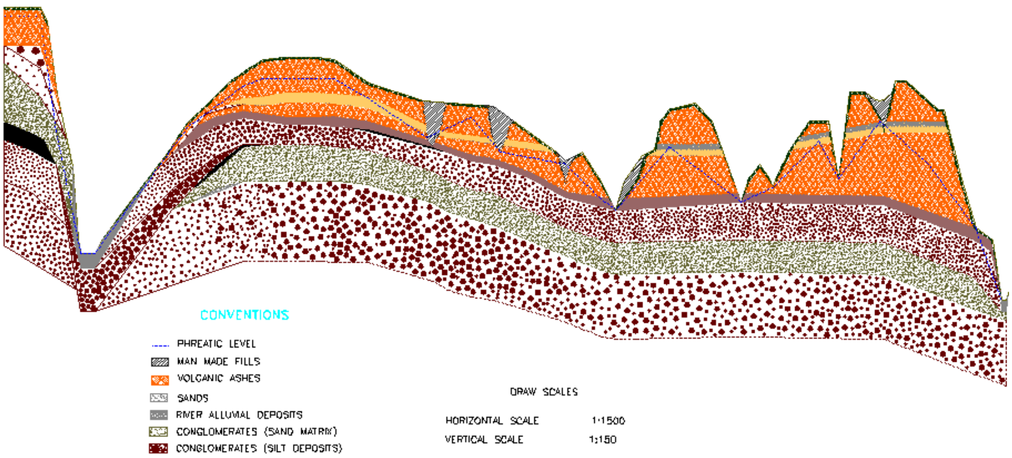

Figure 1: Typical section in Downtown Pereira

SUBSOIL GEOTECHNICAL CHARACTERIZATION FOR DYNAMIC RESPONSE

The subsoil for zones of greater thickness of ash (between 30 to 35 m) can be characterized as shown in Figure 2. A typical ash profile deposited on conglomerates is presented. For the ashes there are plasticity indexes ranging between 0 and 110 %, with natural water content between 10 and 200 %. Total unit weight ranges between 1.2 and 2.0 Ton/m^3. Shear wave velocity ranges between 80 and 250 m/s and shear strength based on unconfined compression strength ranges between 0.1 and 3 Kg/cm^2.

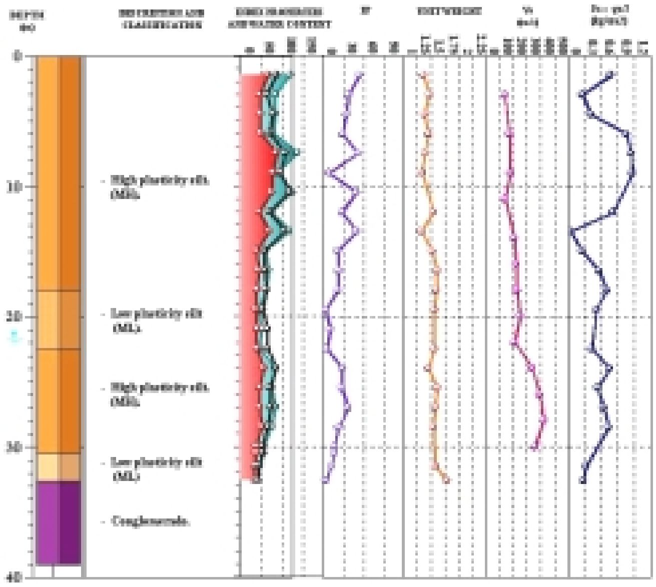

Figure 2: Typical subsoil profile

Volcanic ashes, according to the Unified Soil Classification, classify as silts and clays of high compresibility (MH and CH). Such soils show a noticeable cementation. As a matter of fact, in spite that settling mechanism is eolian, soils show over-consolidation ratios on the order of 3.0 and 7.0, and additionally they show high void ratios ranging between 1.0 and 4.5 %. Given the high void ratios, volcanic ashes can undergo collapse when subject to cyclic shear stresses.

The high variability of ash properties is evidenced in Figure 3, where the results of more than 735 geotechnical studies conducted in the zone (reference 2) have been grouped, in connection with ash basic geotechnical properties, such as liquid limit, plastic limit, plasticity indexes, natural water contents, unconfined shear strength and total unit weight results are shown changing with depth.

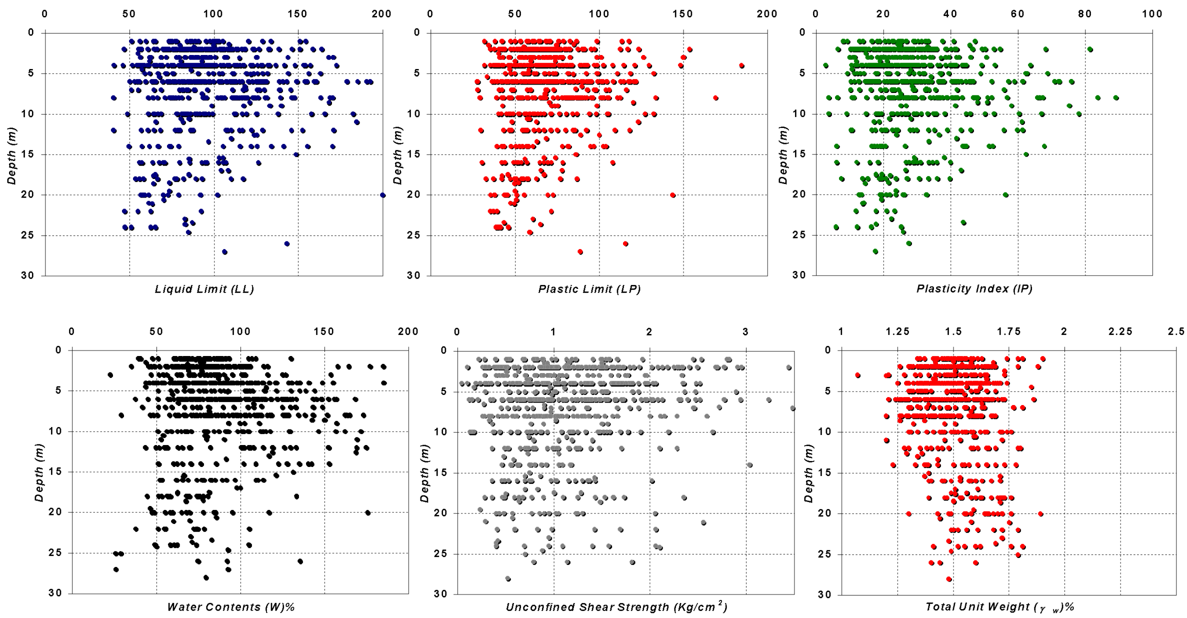

Figure 3: High variability of ash properties

Ash dynamic behavior characterization is studied by means of laboratory 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. Findings from the tests conducted show again a high variability of ash dynamic behavior. Figure 4 shows typical range behavior related to shear stiffness degradation and damping as function of shear strain.

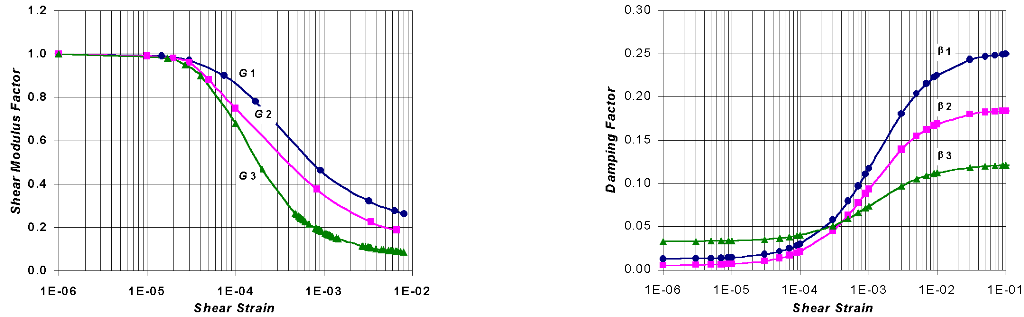

Figure 4: Dynamic parameters for volcanic ash soils

Maximum shear stiffness modulus is estimated based on field measurements of shear wave velocity in Cross Hole tests (standard ASTM D4428M-91). Figure 5 summarizes typical values obtained. Shear wave velocities for such deposits range between 80 and 250 m/s. Figure 6 shows the correlations between maximum shear modulus and depth. Two correlations were determined, corresponding to the mean value plus or minus a standard deviation. Some point shear wave velocities were also measured in the deepest conglomerates, finding shear wave velocities between 800 and 900 m/s.

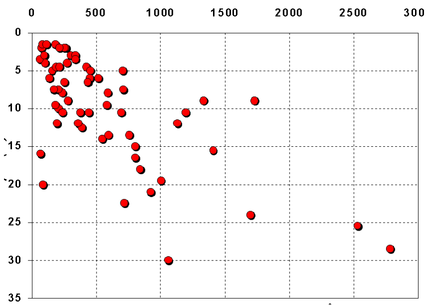

Figure 5: Maximum shear modulus vs Depth

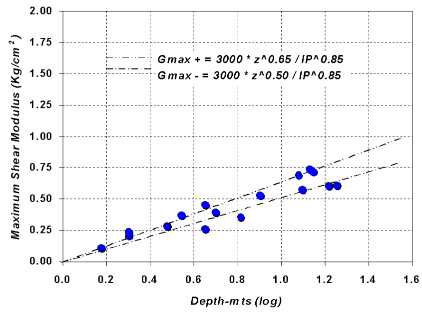

Figure 6: Maximum shear modulus vs Depth

Finally, some cyclic simple shear tests have been made. Figure 7 shows one of the typical results found.

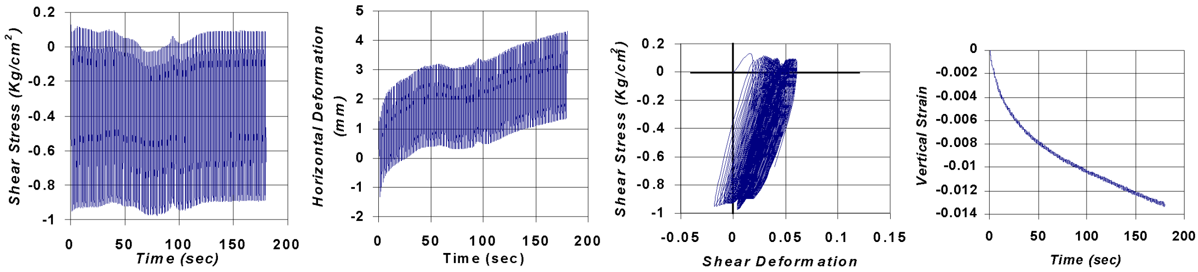

Figure 7: Cyclic simple shear tests

Cyclic simple shear test show that under high cyclic loads, collapse may produce unit vertical strains up to the order of 1%. Considering that, for the collapse to occur, the strength given by cementation should be overcome, it is observed that for a given ratio between cyclic shear stress and vertical stress and for a given number of load cycles, axial strain values increase as the ratio between shear stress and preconsolidation stress increases.

SEISMIC RESPONSE CHARACTERIZATION

Typical ash deposits seismic response is evaluated analytically by using non-linear equivalent unidimensional models. For such purposes, SHAKE-91 computer program (reference 7) is used.

Due to the high variability of soil properties and parameters, the sensitivity of the seismic response is studied with the expected variations of the several different parameters.

To analyze seismic response, a 30 m depth typical profile is chosen, with an average deposit unit weight of 15 KN/m^3, shear modulus given by the Gmax equation in Fig. 6, and stiffness degradation and damping curves corresponding to G2 and β2 curves in Figure 4. The conglomerate is defined with a unit weigth of 17 KN/m^3 and

1000 m/s shear wave velocity. Reference input signal at conglomerate level corresponds to a synthetic earthquake with focus in the Benioff zone, at 100 Km depth and 20 Km horizontal distance. Seismic maximum acceleration at conglomerate level of 0.25g has 10% excedance probability in 50 years corresponding to 475 years mean return period.

Results of the sensitivity analyses for several variables are shown. For such purposes, the reference parameters are kept, and only one select parameter is changed. Firstly, variation for the different input signals corresponding to earthquakes originated from different seismogenic sources is studied. Two alternative synthetic earthquakes are defined corresponding to a nearby surface source with maximum acceleration of the order of 0.35g (based on the registers of the earthquake of January 25, 1999, (see reference 5) and another one corresponding to a far-off source (subduction or similar zone) with 0.10 g maximum acceleration. Figure 8 shows the three hypothetical signals and the response spectra corresponding to a damping of 5% of critical. Comparison of response spectra for firm soils for the three signals are shown in Figure 9.

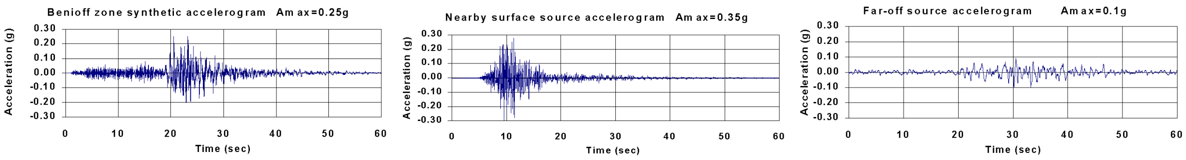

Figure 8: Hypothetical accelerograms

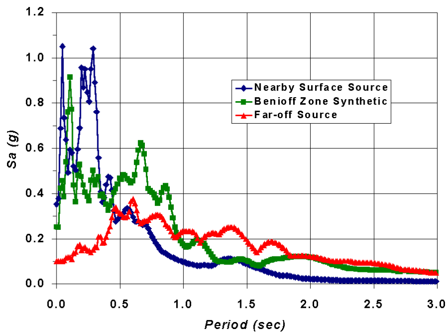

Figure 9: Response spectra for hypothetical accelerograms

Sensitivity to shear velocity of the conglomerate is shown in Figure 10. The effects of shape of the stiffness degradation and damping curves, is shown in Figure 11. Incidence of shear stiffness modulus in the response is shown in Figure 12. Finally, Figure 13 shows the variation obtained in the results for several different depths of ash deposits overlying the conglomerates.

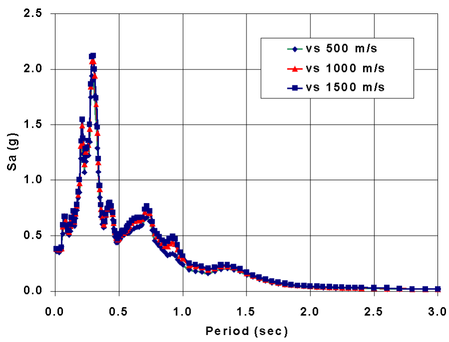

Figure 10: Response spectra for different Shear wave velocity of conglomerates

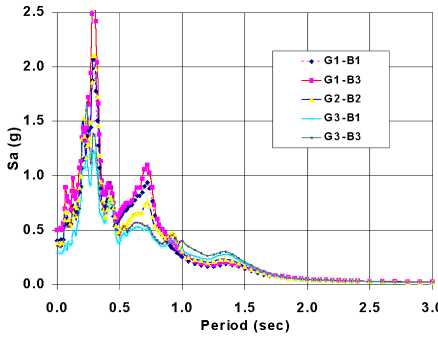

Figure 11: Response spectra for different dynamic soil degradation parameters

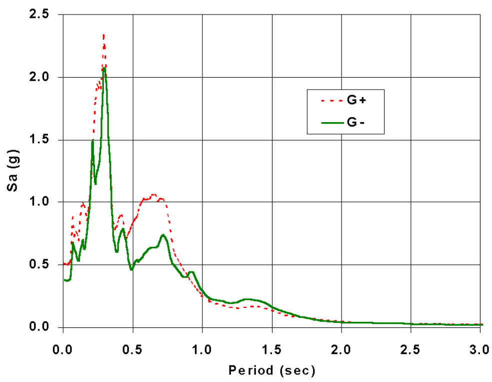

Figure 12: Response spectra for different Gmax curves

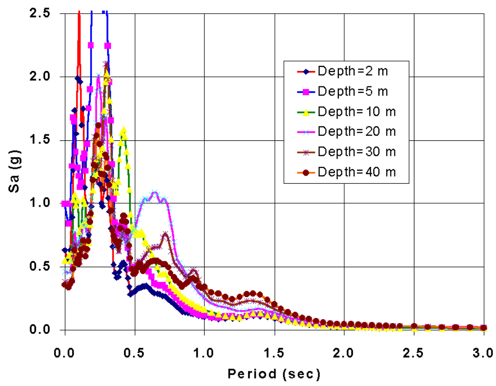

Figure 13: Response spectra for different thickness of soft soils

On the other hand, by using accelerographic records obtained during the earthquake of January 25, 1999, the unidimensional model was developed for Castañares station located on a man-mad fill at Pereira. As an input entrance the register at Bocatoma Nuevo Libaré-Pereira was used with a maximum 0.087 g's acceleration. Figure 14 shows the comparison between the analytical and instrumental responses by means of the response spectra.

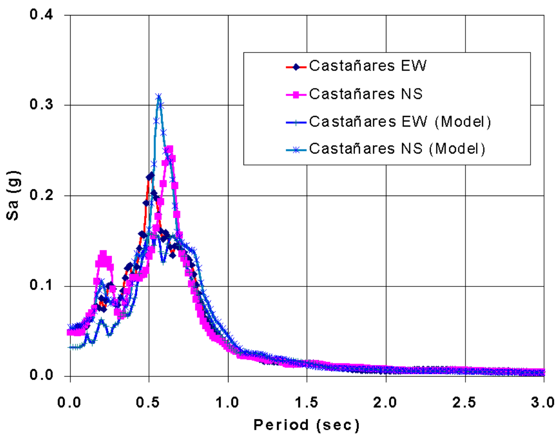

Figure 14: Comparison of response spectra for Castañares station

5. RECOMMENDED DESIGN SPECTRA

The seismic microzonation for the region is carried on by characterizing those variables which influence more the surface dynamic response. In the first place the depth of the deposits is considered as the major geometric variable. Ash deposit thickness defines zones with different seismic behavior.

In other aspect, the high variability of soil dynamic parameters and mechanical properties, both from one to another site of the city, and in each spot under analysis, and even within the same stratum, does not allow to determine a single characterization of a deposit in any given site. It should be taken into account that characterization by laboratory tests is punctual, and for such reason, dynamic parameters variability cannot be determined easily. In contrast, results of field tests do allow the evaluation of the variability within a given soil deposit.

Therefore, it is recommended the use of a design spectrum that involves, up to some extent, all the variability in soil static and dynamic parameters, although basically depending on deposit depth in the zone. Figure 15 recommended shows design spectra for zones with different ash deposit thickness (5 m, 10 m, 20 m, 25 m, 35 m).

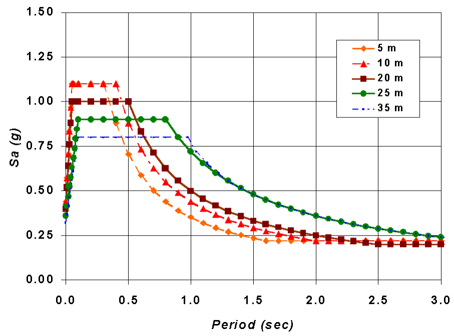

Figure 15: Recommended design spectra for different ash deposit thickness

On the other hand, the effects of fill zones (see Figure 1) in the surface dynamic response are studied. A two-dimensional model is resolved by using QUAD-4M computer program (reference 6). Figure 16 shows the scheme of the model developed and Figure 17 shows some results obtained. Amplification factors are evidenced for the period range under analysis in relation with the response in the center of the fill. The analysis is made in several different points along the fill.

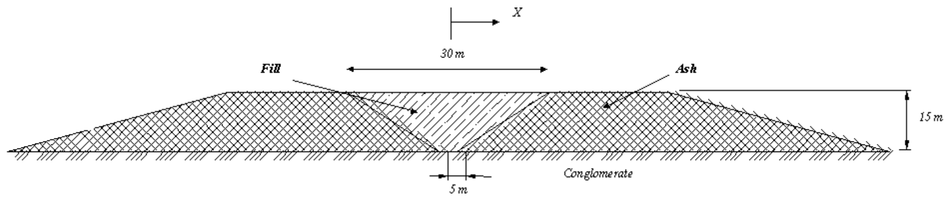

Figure 16: Two dimensional model to study fill effects

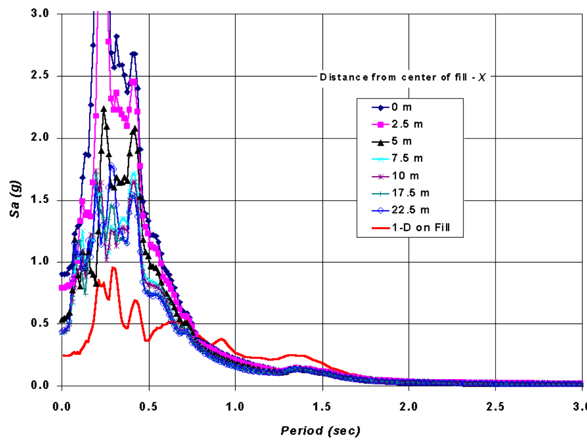

Figure 17: Response spectra for different locations on fills

CONCLUSIONS

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

a. Variables that influence more the characteristic ash deposit dynamic response of the zone under analysis are: the frequency content of the input earthquake in the rock and the depth of the ash deposit over the conglomerate.

b. Considering the high variability of ash dynamic and mechanical properties, the remaining parameters, such as unit weight, shear wave velocities of ash and conglomerate and shape of stiffness degradation and damping curves cannot be characterized in a univocal forme, and its variability should be taken into account in the model in order to interpret the findings.

c. In addition to the high variability in mechanical properties and dynamic parameters, ash is prone to undergo collapse under cyclic strains imposed, for instance, in the case of an strong earthquake.

d. For purposes of microzonation studies of the several different towns within the area under analysis, the thickness of ash deposits in each zone is considered as one of the fundamental variables. Therefore, design spectra as function of ash deposits thickness in each zone are recommended. Should subsoil stratigraphy in some specific site changes relative to the typical model considered, then, for such cases, specific analysis should be made for such site.

e. Man-made fills distributed in different places of towns will result in seismic response amplifications with respect to spectra determined failing to consider geometric effects. For fill zones, it is recommended to use a constant amplification factor of 1.5 in the structural period range between 0 and 1.0 sec. For greater periods no important amplifications are evidenced.

For buildings located on the top of highly steeped hills, it is advised, for structural design, to apply a 1.5 amplification factor for 0 to 1.0 sec period range on the design spectrum proposed.

REFERENCES

AIS (1996), Estudio General de Amenaza Sísmica de Colombia. Santa Fe de Bogotá, Colombia. October, 254pp.

CARDER (1999), Exploración geotécnica, Investigación de laboratorio y Microzonificación sísmica de las areas urbanas y suburbanas de las cuidades de Pereira, Dosquebradas y Santa Rosa de Cabal. Pereira, Colombia. April, 147 pp.

CARDER (1996), Proyecto para la mitigación del riesgo sismico de Pereira, Dosquebradas y Santa Rosa de Cabal, Plan de acción ambiental. Pereira, Colombia. August, 84 pp.

CARDER (1999), Exploración geotécnica, Investigación de laboratorio y Microzonificación sísmica de las areas urbanas y suburbanas de las cuidades de Pereira, Dosquebradas y Santa Rosa de Cabal. Pereira, Colombia. April, pp30-37.

CARDER (1999), Red local de acelerógrafos de la ciudad de Pereira. Pereira. January.

Hudson, M., Idriss, I. and Beikae, M. (1994), QUAD-4M: A computer program evaluate the seismic response of soil structures using finite element procedures and incorporating a compliant base. Davis: University of California. May, 68pp.

Idriss, I., and Sun, J. (1992), SHAKE-91: A computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits. Davis: University of California. November, 35pp.

OMPAD (1998), Estudios de amenaza sísmica y evaluación sismogeotécnica preliminar para la zonificación sísmica de Manizales. Manizales, Colombia. March, pp39-65.

OPES (1996), Proyecto Microzonificación Sísmica de Santa Fe de Bogotá. Santa Fe de Bogotá, Colombia. November, pp57-63.