29 Mar 2001, 7:30 pm - 9:30 pm

Influence of Soil Properties in Ground Seismic Response and the Definition of Site Coeffients for Design Provisions

Gloria Estrada
Integral S.A., Consultant Company, Colombia

INFLUENCE OF SOIL PROPERTIES IN GROUND SEISMIC RESPONSE AND THE DEFINITION OF SITE COEFFIENTS FOR DESIGN PROVISIONS

Gloria Estrada
Integral S.A., Consultant Company
Medellin, Antioquia-COLOMBIA

ABSTRACT

Recent earthquakes have showed the important influence of local site conditions on the characteristics of ground surface motions in the city of Medellin (Colombia). The network of accelerographs installed in this city confirmed this hypothesis, providing information about seismic response of different types of soil profiles, and showed the important role of the impedance ratio rock-soil, due to the high bedrock stiffness. The values and trends of Medellin site coefficients, defined in Provisions of Medellin Seismic Microzonation, are described and compared to those of the 1994 NEHRP, and of the 1997 Uniform Building Code Provisions. These comparisons took into account the influence of soil and rock properties over and under 100 ft (30 m), because it was found that the criterion of the average shear wave velocity of the top 100 ft (30 m) of soil to characterize the site is not appropriate to represent seismic response of Medellin soils. Finally, it was proposed some considerations related to seismic coefficients for the specific case of effective peak acceleration Aa lower than 0.05, considering amplifications registered in Medellin for these rock acceleration levels and the criteria suggested for this condition in 1994 NEHRP Provisions.

INTRODUCTION

Local site conditions have a marked influence in the distribution of damage associated to earthquake, and Building Codes play a fundamental role in human and property protection. For these reasons, analysis carried out in base to seismic instrumentation constitutes a good alternative to make out characteristics of potential seismic response of different soil profiles, and identify the main factors that control amplification effects. In this way, site categories and site coefficients of Seismic Building Codes can be adjusted and improved with new knowledge for specific regions.

Effects of site amplification have caused important damage in Medellin, still as a consequence of low rock accelerations, about 3,0% g. The cost of the damage generated by 1992 Murindo earthquake was about eleven million dollars, which was a so high cost for an earthquake with a rock acceleration of only 1,5% g. For these reasons, this paper presents some considerations related to seismic coefficients for the specific case of effective peak acceleration Aa lower than 0.05, and using this information, analyzes the criteria suggested for this condition in 1994 NEHRP Recommended Provisions for Seismic Regulations for New Buildings.

The Provisions of Medellin Seismic Microzonation for different level of rock acceleration were a result of evaluating information of a local network of accelerographs, that have allowed to understand certain characteristics of different soil profiles and stand out the importance of low rock acceleration motions, due to high amplification effects associated to them.

GEOTECHNICAL CHARACTERISTICS AND GROUND SEISMIC RESPONSE OF MEDELLIN SOILS

Medellin is one of the main cities of Colombia, it has an area of just 100 km² and a great topographical, geological and geotechnical diversity, which is very important in its seismic response. The typical soils in Medellin are residual soils of granitic and metamorphic rocks, alluviums and coluviums of different compositions, ages and weathering levels (Figure 1). The geotechnical exploration carried out in Medellin was fundamental to define the different soil layers of typical soil profiles until reaching the rock level.

The seismic instrumentation of Medellin is composed of 23 accelerographs located considering topographical and geotechnical characteristics, so they are distributed in representative soils of the city. In addition, another instrument was installed on bedrock, so that it was possible to define the influence of the different kind of soils wich lie above the bedrock in the ground response motion. The location of accelerographs in Medellin is provided in Figure 1.

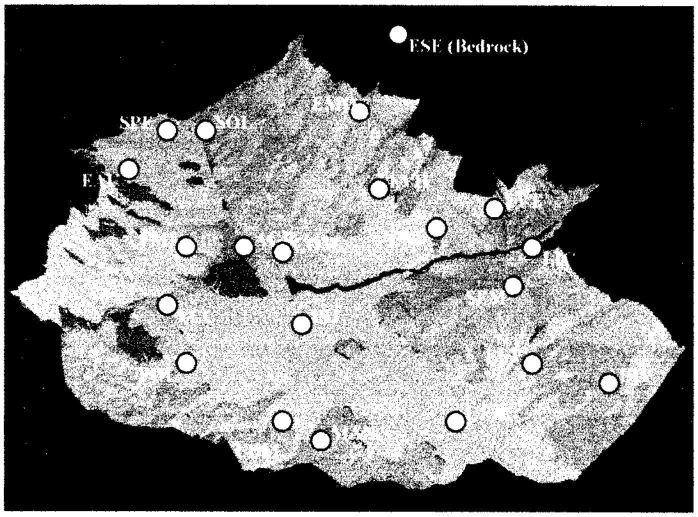
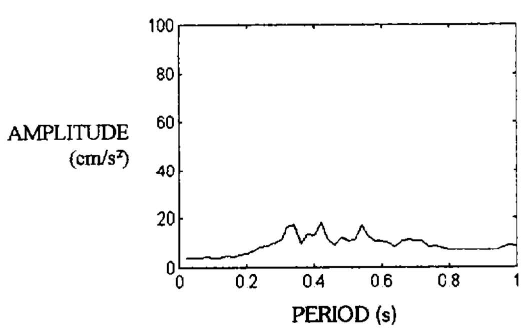


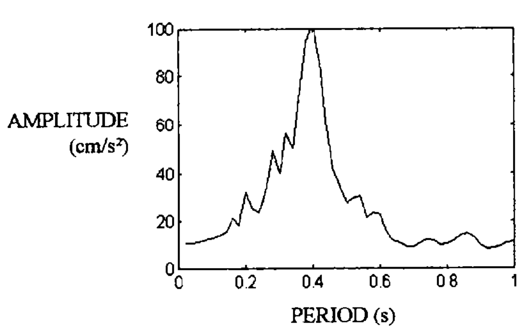
Fig. 1. Geotechnical 3d- model of Medellin and location of accelerograph network.

Recorded earthquakes by accelerograph network showed deep differences in seismic response among several zones of the city. These differences were reflected in the strong effects on peak acceleration amplitudes, and the amplitudes and shapes of response spectra. Plots such as Figure 2 provide response spectra of 3 different accelerograph stations in this Medellin, all of them corresponding to 1999 Armenia earthquake (Armenia is a city located 200 km from Medellin – Armenia earthquake had a magnitude of 6.0 in Richter scale, and its rock acceleration at Medellin was 0.003 g).

UEA ACCELEROGRAPH



MAN ACCELEROGRAPH



EET ACCELEROGRAPH

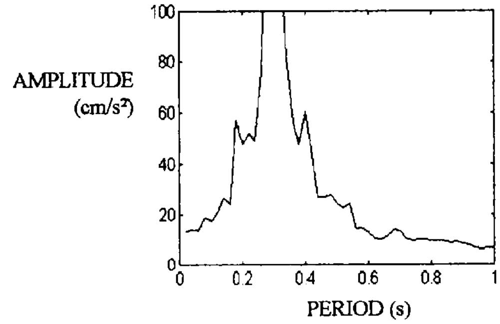


Fig. 2. Recorded response spectra at different soil sites of Medellin, 1999, Armenia (Colombia) earthquake.

Table 1 supplies information about soil horizons and thickness of sites where are located the instruments of Medellin accelerograph network.

Table 1. Geotechnical information of sites where are located accelerographs in Medellin.

Accelerograph Station	Soil Profile Thickness (m)	Soil Horizons (that lie above the bedrock)
MAN	45,0	Residual soil of granodiorite (igneous rock)
UDM	27,5	Residual soil of granodiorite (igneous rock)
AGR	28,0	Hard and coarse alluvial deposit
SPE	80,0	Old and coarse gravitational deposit
SEM	45,0	Residual soil of gabbro (igneous rock)
EET	45,0	Old gravitational deposit and residual soil of anfibolite (metamorphic rock)
COM	75,0	Residual soil of dunite (igneous rock)
ECC	17,0	Residual soil of gneiss (ingeous rock)
EMO	34,0	Recent and coarse gravitational deposit
SOL	26,0	Recent and coarse gravitational and alluvial deposits
EVH	90,0	Old and coarse gravitational deposit
EVT	56,0	Residual soil of dunite (igneous rock)
LIC	35,0	Old and coarse gravitational deposit
ISJ	60,0	Coarse alluvial deposit underlying soft alluvial deposit
EAU	15,0	Old gravitational deposit
FMI	61,0	Coarse and hard alluvial deposit underlying old and coarse gravitational deposit
CSJ	40,0	Old and coarse gravitational deposit
POL	33,0	Old and fine-grained gravitational deposit
UEA	12,0	Hard and coarse alluvial deposit
ISA	32,0	Old gravitational deposit

The characterization of dynamic behavior of different soil profiles was so important to discern the main variables that control the great differences of seismic response. The measurement of dynamic soil properties was carried out by field and laboratory tests, which allowed to analyze variation of shear wave velocity with depth, relationships of modulus reduction and damping ratio of soils with cyclic shear strain for Medellin soils.

In general, variation of shear wave velocity with depth showed a wide range, which depends on soil origin, weathering levels, and moisture conditions, so that the shear wave velocity for Medellin soils presents values ranging from 100 m/s in soft alluviums, to more than 500 m/s in hard gravitational deposits and coarse alluvial deposits. Residual soils showed in their superficial layers shear wave velocities between 150 m/s and 250 m/s, but this property presented marked increments with depth, reaching values higher than 300 m/s from a depth of 15 m. Table 2 provides information related to average shear wave velocity and soil classification according to 1994 NEHRP and 1997 UBC Provisions, both for the sites of accelerograph stations of Medellin.

Table 2. Average shear wave velocity and soil classification for sites of accelerograph stations of Medellin.

Accelerograph Station	1994 NERPH and 1997 UBC Soil Profile Type	Average Shear Wave Velocity (m/s)
MAN	C	322
UDM	D	272
AGR	C	398
SPE	C	473
SEM	D	262
EET	D	292
COM	D	331
ECC	D	282
EMO	D	337
SOL	C	368
EVH	C	563
EVT	C	465
LIC	D	337
ISJ	E	362
EAU	E	245
FMI	C	477
CSJ	C	493
POL	D	280
UEA	D	350
ISA	D	330

Figure 3 shows a comparison between the curves of G/Gmax versus cyclic strain γ_c, and of damping ratio versus γ_c for Medellin soils and Mexico City clays. This comparison shows that Medellin soils present a more nonlinear behavior and dissipates more energy than Mexico City clays.

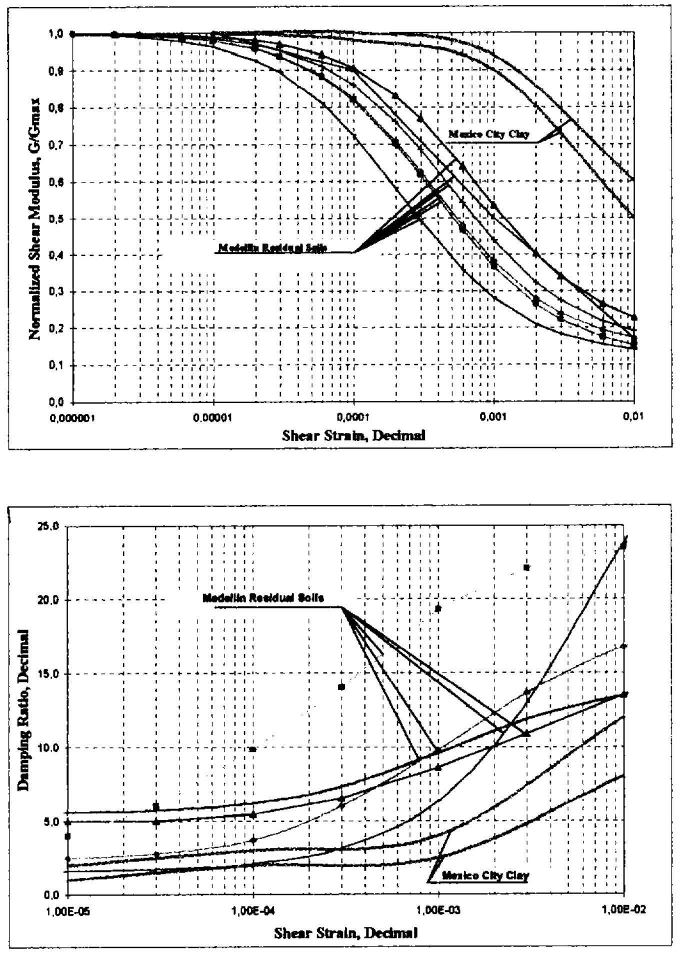


Fig. 3. Comparisons of Shear modulus (G/Gmax) and damping ratio versus cyclic strain for Medellin residual soils and Mexico City Clay.

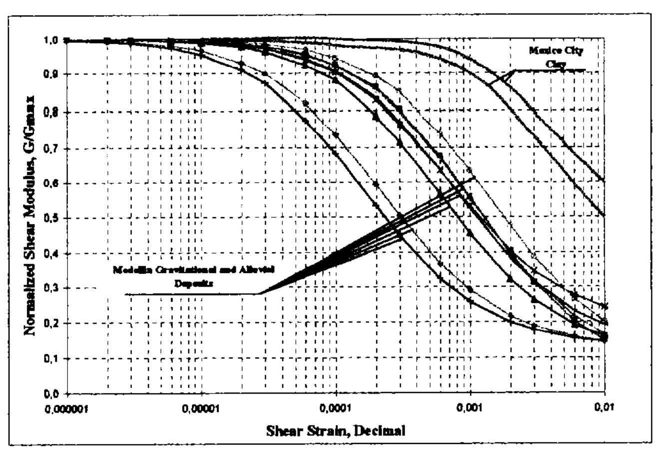


Fig. 4. Comparisons of Shear modulus (G/Gmax) and damping ratio versus cyclic strain for Medellin transported soils and Mexico City Clay.

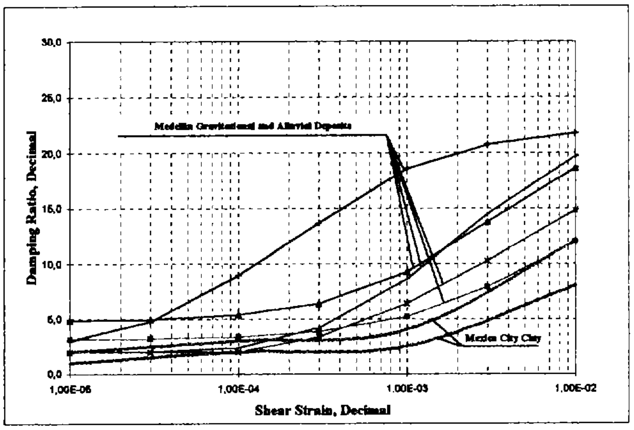


Fig. 4 (Cont.).Comparisons of Shear modulus (G/Gmax) and damping ratio versus cyclic strain for Medellin transported soils and Mexico City Clay.

CONSIDERATIONS ABOUT INFLUENCE OF SOIL-ROCK PROPERTIES IN GROUND SEISMIC RESPONSE

Even though, soft clays manifest low influence of nonlinearly for low rock accelerations, it is very important to stand out that earthquakes with very low rock accelerations (between 0,001g and 0,009 g) recorded by Medellin accelerograph network have showed reduction in amplification levels as rock acceleration increases. This condition can be explained considering variations of G/G_{max} and damping ratio with cyclic strain of Medellin soils (Figures 3 and 4), so that Medellin soils can dissipate more energy than Mexico City clays by higher contribution of damping ratio. Figure 5 shows the influence of nonlinearly effects in Medellin soils for very low rock acceleration earthquakes.

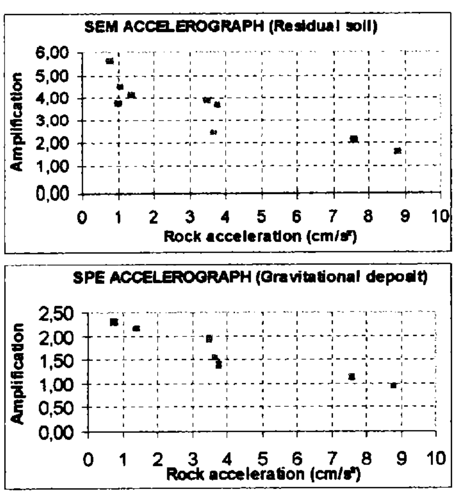


Fig. 5. Influence of rock acceleration on amplification site. Recorded earthquakes at a residual soil site and at a transported soil site in Medellin.

In addition, amplification effects represented in Figure 5 indicate deep differences in seismic response of residual soils and hard transported soils. These differences in amplification levels are associated to differences in shear wave velocity of soil profile. Figure 6 provides information about variation of average amplification with average shear wave velocity of residual soils and, hard and coarse transported soils in Medellin. Figure 6 shows a clear tendency to decrease amplification as shear wave velocity increases, due to the fact that the amplification has a strong dependency of impedance ratio (Dobry, 1992 and 1999).

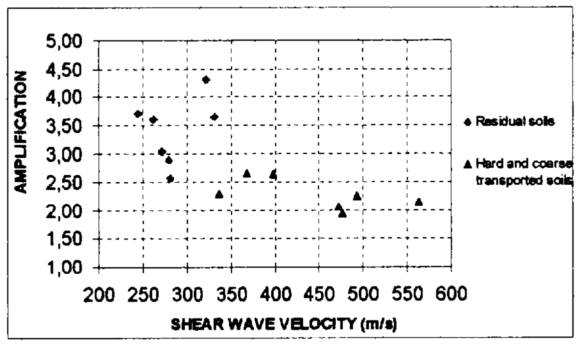


Fig. 6. Influence of shear wave velocity on amplification. Recorded earthquakes at a residual soils and at a hard and coarse transported soils in Medellin.

Therefore, in spite of soil profiles of Medellin are stiff, they have presented relatively high amplification, and the main factor responsible of this phenomenon is the impedance ratio rock-soil, which depends on:

- Total unit weight of rock and soil (ρ_r, ρ_s)
- Shear wave velocities of rock and soil (V_r, V_s)

The impedance ratio (I) is given by the expression (Dobry, 1992):

$$I = (\rho r/\rho r)\ (Vr/Vs) \qquad (1)$$

Equation (2), proposed by Dobry (1992) to evaluate maximum amplification at sites containing a clear rock interface and subjected to low rock acceleration, was used to verify its application to Medellin soils. This analysis showed that this model is not only applicable to soft sites, like Mexico City clays or San Francisco Bay mud, but also to relatively hard soil profiles like those found in Medellin, because the rock underlying the Medellin soil profiles is much stiffer than the rock in Mexico City and San Francisco. The equation (2) confirms that impedance ratio and internal soil damping ratio play an important role on amplification effects.

$$A \approx 1/(1+(\pi/2)\beta I) \qquad (2)$$

Equation (2) is represented in Figure 7, where there are located several points that represent recorded maximum amplification (small rock accelerations between 0,001 g to 0,009 g) and impedance ratio of some accelerograph stations of Medellin. This graphic representation confirms the importance of nonlinearly behavior and of impedance ratio in Medellin amplification phenomenon, and stands out the key factors that control it. Furthermore, it is interesting to illustrate the wide interval of impedance ratio found in different soil-rock profiles of Medellin, ranging from about 3 to 17.

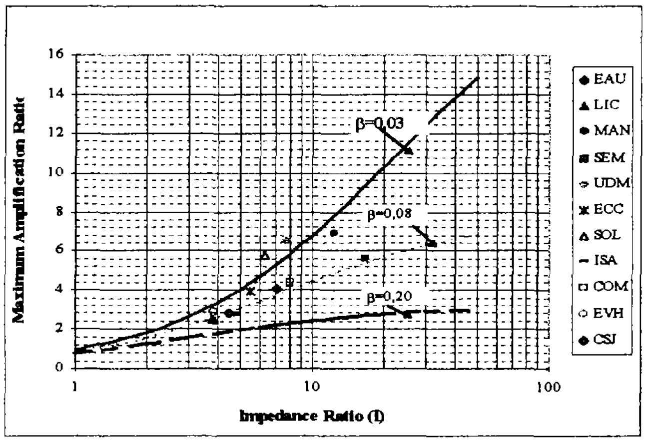


Fig. 7. Relationship between maximum amplification and impedance ratio for Medellin soils.

The values and trends of Medellin site coefficients for provisions of Medellin Seismic Microzonation were defined by using Transfer Functions and Ratio of Response Spectra (RRS) of the sites, according to recommendations of Dobry (1998). Transfer Functions were estimated by dividing Fourier Spectra of recorded horizontal accelerations on nearby soil and rock sites. Ratio of Response Spectra were estimated by dividing response spectra on soil and rock sites. These analyses allowed to evaluate all of the recorded earthquakes by Medellin accelerograph network during 2 years of operation, and estimate the own seismic response of every accelerograph station. These analyses were separated in ranges of rock acceleration, in order to carry out comparisons of soil nonlinearly effects. This methodology permitted to calibrate theorical models of analyses, and it was concluded the importance of knowing in a detailed way the complete soil profile above the bedrock to discern its seismic response. The Figure 8 illustrates plots of real average RRS (for recorded earthquakes with rock accelerations ranging from 0.003 g to 0.004 g) of the accelerographs COM and EVT, located on residual soil of dunite (igneous rock). Even though both accelerographs represent the seismic response of the same soil profile, there are big differences in soil thickness in each site, which has associated marked differences in ground response motion.

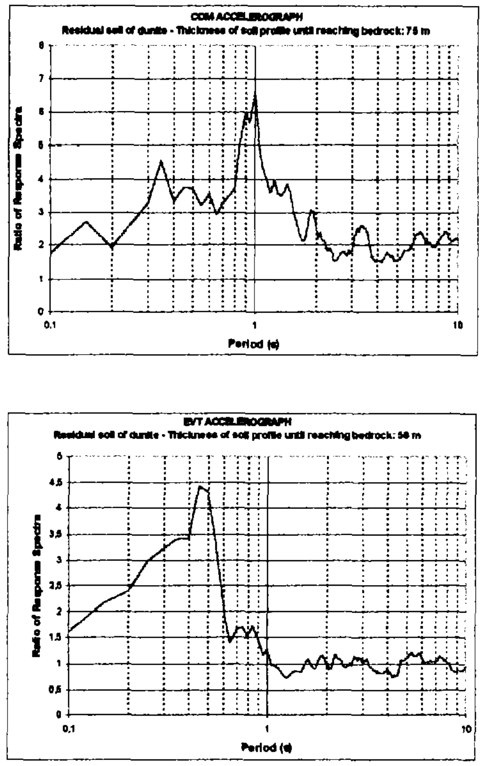


Fig. 8. Real average ratio of response spectra for COM and EVT accelerographs.

On the other hand, the analyses of transfer function estimated for every accelerograph station of Medellin network showed that modifications suffered by the ground shaking when it passes through the soil depend only on site characteristics. Figure 9 illustrates the transfer functions obtained for several recorded earthquakes at MAN accelerograph station, all of them generated by different sources; the shape of those curves are very stable for every station, and it does not depend on seismic source. However, the value of amplification will always depend strongly on rock acceleration level and on internal damping ratio of the soil.

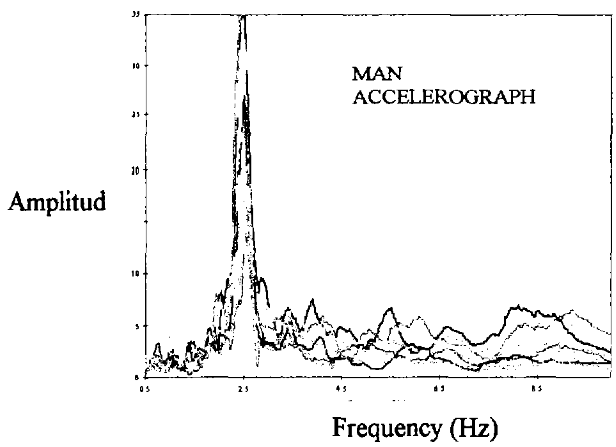


Fig. 9. Transfer funtions of recorded earthquakes at MAN accelerograph.

COMPARISONS OF SITE COEFFICIENTS RESULTED OF MEDELLIN SEISMIC MICROZONATION AND THOSE RECOMMENDED BY 1994 NEHRP AND 1997 UBC

The 1994 NEHRP Provisions recommend seismic coefficients for rock motion (Aa) higher than 0.05 g and assume that values of Aa lesser than 0.05 do not cause amplification phenomena. In addition, the 1997 Uniform Building Code suggest site coefficients for rock acceleration higher than 0.075 g.

Despite rock motions lesser than 0.05 g are relatively low, this kind of earthquakes have caused appreciable damage in Medellin, due to high amplification levels. This behavior is still more important in soft sites which lie on stiffer rocks like New York, due to linear effect of this kind of soils for low rock motions. The recorded earthquakes by Medellin accelerographic network allowed to carry out studies focused to define site coefficients for earthquakes with return period for both 10 years (rock acceleration of 0.03 g) and 500 years (rock acceleration of 0.15 g).

The representative soil profiles of Medellin were classified taking into account recommendations of 1994 NEHRP and 1997 UBC, in order to make comparative analyses. However, in this classification was considered the complete soil profiles until reaching the bedrock. Table 2 shows that Medellin soil profiles present classification of C, D and E according to these Provisions.

CONCLUSIONS

1. The operation of Medellin accelerograph network allowed to analyze the main geotechnical properties which influence the ground seismic response, and showed that the use of a single response spectrum to represent all site conditions of Medellin was not appropriate.

2. The high amplification levels are not only a phenomenon of soft clays but also of stiff soils that lie above of a much stiffer rock. This effect depends on impedance ratio.

3. It is important to consider site coefficients still for low rock acceleration, specialty in sites where high amplification can cause appreciable damage.

4. Site conditions like Medellin soils showed the importance of knowing the soil profile until reaching the bedrock to evaluate ground seismic response. It was found that the criterion of the average shear wave velocity of the top 100 ft of soil to characterize the site is not appropriate to represent seismic response of Medellin soils.

Comparisons of site coefficients for short (Fa) and long (Fv) periods defined in provisions of Medellin Seismic Microzonation respect to those recommended in 1994 NEHRP and 1997 Uniform Building Code permitted to conclude the following:

- Site coefficients for short periods (Fa) considering rock accelerations of 0.03 g ranged between 1,90 to 3,30.

- Site coefficients for long periods (Fv) and rock accelerations of 0.03 g varied from 1.90 to 5.40.

- Site coefficients obtained for short periods (Fa) and taking into account rock accelerations of 0.15 g are very similar to those recommended by 1997 NEHRP and 1997 UBC. The estimated values of Fa in Medellin Seismic Provisions range between 1.30 to 2.10. The site coefficients for long periods (Fv) are also similar to those suggested by 1994 NEHRP and 1997 UBC.

- In calibration process of theorical analysis model of seismic response of Medellin soils it was found that the criterium of the average shear velocity of the top 100 ft (30 m) of soil profile to characterize the site is not appropiate to represent seismic response of Medellin soils.

REFERENCES

Dobry, R. [1992]. Soil properties and earthquake ground response.@, Rensselaer Polytechnic Institute, Troy, New York.

Dobry, R. Et al. [1998]. New site coefficients and site classifications system for structures contained in 1994 and 1997 NEHRP and in 1997 UBC.@, Rensselaer Polytechnic Institute, Troy, New York.

Dobry, R. Et al. [1998]. Site factors and site categories in seismic codes: A perspective.@, Rensselaer Polytechnic Institute, Troy, New York.

BUILDING SEISMIC SAFETY COUNCIL. [1994] NEHRP. Recommended provisions for seismic regulations for new buildings, Washington, D.C.

STRUCTURAL ENGINEERING DESIGN PROVISIONS [1997] Uniform Building Code.

GRUPO DE SISMOLOGÍA DE MEDELLÍN. [1999] Instrumentación y microzonificación sísmica del área urbana de Medellín.@, Municipio de Medellín, Medellín, ANTIOQUIA.

Kramer, S. [1996]. Geotechnical earthquake engineering.@, Prentice – Hall, New Jersey.