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DYNAMIC BEHAVIOUR OF TROPICAL SOILS FROM MEDELLÍN, COLOMBIA

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ABSTRACT

Medellin City has a population of about 2.000.000 people and its area is lower than 110 km². This city is located in the northwest of Colombia, that is in the northwest corner of South America, which is a zone with a complex tectonic environment associated to the interaction of the Nazca, Suramerica and Caribe plates. The result of these conditions implies that Medellin has an intermediate seismic hazard.

This city was developed on the valley of Medellin River and his slopes, has a complex geology, which is composed by alluviums, colluviums of different ages, residual soils from igneous and metamorphic rocks.

The Medellin Seismic Microzonation project carried out a detailed geotechnical exploration and laboratory tests to measure the dynamic properties of the different soils of the city. This paper shows the results of this studies focused to evaluate the dynamic properties of Medellin soils and determine the influence of geological origin, weathered level and index properties in its dynamic behavior. Special emphasis is given to the shear wave velocity, and to the variation of shear modulus and damping ratio with cyclic shear strain amplitude.

INTRODUCTION

Medellin city is located on the Central Mountain Range in the northwest of Colombia, that is in the northwest corner of South America, which is a zone with a complex tectonic environment associated to the interaction of the Nazca, Suramerica and Caribe plates. The result of these conditions implies that Medellin has an intermediate seismic hazard. The recent city has been affected by moderated earthquakes in 1938, 1979 and 1992 (Murindo Earthquake). The last event had a Magnitud 7.2 Ms, reported a peak acceleration of 5 gales and produced a loss about ten Millions dollars.

At the beginning, this city was developed on the valley of Medellin River, that it ran from south to north, but then it was extended to the slopes of the valley. These slopes are composing by different soils, since residual soils from igneous and metamorphic rocks until transported soils like alluviums, and colluviums of different ages and composition. It has altitudes from 1400 to 1800 m above the sea level. The temperature in Medellin varies from 22°C to 28°C and its average precipitation is about 2000 mm/year. These environmental conditions made possible the descomposition of different kind of materials and allowed the formation of thick layers 1of residual soils, which are related with special geotechnical characteristics of Medellin.

The geological, geomorphologic, and environmental characteristics of the city increase the seismic risk and it was necessary to do the Medellin Seismic Microzonation and instrumentation project, basic tool to reduce the seismic risk of the city. Project financed by the Disaster Prevention and Attention System, SIMPAD (Reference 1).

The Medellin Seismic Microzonation project carried out a detailed geotechnical exploration, which was composed of approximate 1000 m deep drillings and sampling, field tests (seismic down-hole tests) and laboratory tests (piezoelectric bender element test, cyclic triaxial test and cyclic torsional shear test). The main objective of this geotechnical exploration was to measure the dynamic properties of the different soils of the city.

This paper shows the results of the studies focused to evaluate the dynamic properties of Medellin soils and determine the influence of geological origin, weathered level and index properties in its dynamic behavior. A special emphasis is given to the shear wave velocity, and to the variation of shear modulus and damping ratio with cyclic shear strain amplitude of Medellin soils.

The results of these analyses are compared with the properties of foundation soils of embankments constructed in Colombia and considering recommendations given by Dobry and Vucetic.

GEOLOGY OF THE URBAN AREA DE MEDELLIN

City it was developed along the valley of the Medellin River that runs through a wide valley framed by hillsides that end in raised slopes, which are characterized by the presence of very diverse lithologic and geomorphologic units. Over these hillsides many creeks run down towards the Medellin River. The 45% of the area of the city were covered by residual soils, product by weathering of metamorphic rocks of the Paleozoic and Cretaceous, and igneous rocks of the Cretaceous. The remaining area, (55 %) was covered by not consolidated deposits of possibly Quaternary age and they present different weathering degrees.

The principal existent materials are:

- Residual soils of Metamorphic rocks.

These soils come mainly from two rock types. First, the Iguana Gneiss soils conformed by sandy silts, superficial levels (IA and IB, agree with Deere and Patton, Reference 2) and silty sands with rock fragments, the level IC. They present maximum thickness of 18 m.

Secondly, amphibolite origin residual soils of medium thickness, among 20 to 25 m. The superficial levels, IA and IB, are conformed by soils of medium plasticity to low plasticity, and the IC level is thin.

- Residual soils of Igneous rocks.

There are basically four soil types. The soils from the Altavista Stock compound especially for granodiorite that produces soils of variable thickness, between 28 and 45 m, and low plasticity. Residual soils from San Diego Gabbro, are deeper than 40 m, compound especially by clays and silts of low plasticity.
Soils of Medellín Dunite have thickness from 10 up to 35 m. Superficial levels (IA, IB) are compound for red clays of medium plasticity to high plasticity with an important content of iron minerals (Lateritas).

Residual soils from Las Estancias Stock composed by quatrzdiorite. These soils are sandy silts (SM) and they can reach thickness as 40 m.

- Alluvial deposits.

Soils of variable composition, are distinguished two great groups. First, the deposits transported by the important currents as the Medellin River and the Santa Helena Creek. These old deposits have high density, coarse particles, and great thickness, superior to 200 m in some sectors. Secondly, the recent deposits that are covering the previous ones partially. Silts and sandy clay, locally with high plasticity, compose recent deposits, and they are shallow, thickness lesser than 15 m.

- Diluvial Deposits

Deposits constituted by blocks of rock of great size in a scarce matrix, they are located near the beds of the creeks that lower toward theMedellin River.

- Gravity Deposits

There are mudflows and debris flows, composed by amphibolite blocks or dunite blocks in a matrix of silty clay whit high plasticity to medium plasticity and high water content. If the matrix predominates they are mudflows and if the blocks predominate are called debris flow. They can be classified as recent or mature deposits, if their blocks present an advanced weathering. Agree whit their origin, the gravity deposits are compound by amphibolite or dunite blocks. They can reach thickness up to 20 m.

SUBSOIL EXPLORATION.

The Medellin Seismic Microzonation project carried out 32 boreholes with depths average of 35 m, the first 22 boreholes were located in the places where settled the accelerometers of the Accelerografic Net of Medellin, implemented as part of the project. The localization of the perforations was selected to know the typical profiles of the main geotechnical formations of the city. The boreholes were carried out in diameter H (10cm), they were useful to take altered samples and undisturbed in Shelby sampler. On undisturbed samples were carried out static and dynamic tests. In each one of the holes was made Dow- hole test to determine the variation of the shear wave velocity with the depth.

As part of the geotechnical exploration were carried out in the Andes University Laboratories in Bogotá, 42 dynamic triaxial tests of controlled deformation and numerous tests type Bender Element, to measure the maximum shear wave velocity in the laboratory. They were also carried out in the laboratories of SOLINGRAL, torsion test with the machine developed by the Dr. Zeevaerth. All tests allowed knowing the variation of the shear modulus and the damping ratio with the deformation for the soils from Medellín. Table 11 presents the types of soils and their index properties used in the dynamic trixial test. They are an important number of tests on tropical soil samples.

SHEAR WAVE VELOCITIES

In order to evaluate the shear wave velocities in the different soils of Medellín city, it was conducted a geophysical prospecting program using the DOWN-HOLE exploration technique. The records of velocity of propagation of shear waves with depth, showed that the characteristic soils of Medellín present a wide range variation that mainly depends on the origin of the soil, the weathering state and water content. Those values varied from 100 m/s, in the case of a soft fined alluvial soil, to 500 m/s for weathered horizon IC (Deere and Patton) from igneous and metamorphic rock soils, rigid colluvial and thick alluvial deposits in relatively moderate depths.

Residual soils showed shear wave velocities changing in surface from 100 m/s to 250 m/s. In case of soils from metamorphic rocks from 15 m depth and below, the velocity drastically increases reaching values near 500 m/s, because the weathered profile is thicker than igneous rocks soils. In case of residual soils from igneous rocks the increase in velocity is gradual with depth, and below 15 m they showed values between 200 m/s to 300 m/s. An exception is clearly identified on those soils from dunite located in high slope areas, where it is seen incomplete weathering profile and they register higher values of velocity. The characteristic shear wave velocity in the residual soil - rock transition, in the subsoil of Medellín varies from 400 m/s to 600 m/s.

Samples	Deep	G_{max} Down - Hole	G_{max} bender	W	LL	IP	SOIL TYPE	MATERIAL	LEVEL
	(m)	(Kg/cm²)	(Kg/cm²)	(%)	(%)	(%)			(Deere y Patton)
P-1 M-3	3.30	2200	388	34	52	18	Residual soil	Granodiorite	IB
P-1 M-9	7.75	925	512	34	37	13	Residual soil	Granodiorite	IB-IC
P-1 M-17	13.95	1103	280	48	49	17	Residual soil	Granodiorite	IB-IC
P-1 M-19	15.60	847	241	48	49	17	Residual soil	Granodiorite	IB-IC
P-1 M-21	17.15	958	230	31	54	20	Residual soil	Granodiorite	IB-IC
P-2 M-6	6.45	1168	280	33	50	33	Residual soil	Granodiorite	IB
P-2 M-11	12.45	755	319	38	38	13	Residual soil	Granodiorite	IC
P-5 M-11	9.35	490	220	46	34	9	Residual soil	Gabbro	IC
P-5 M-7	6.40	928	150	28	0	0	Residual soil	Gabbro	IC
P-6 M-9	8.50	775	82	37	37	6	Wheatered flow	T. Amphibolite	
P-6 M-12	12.30	1020	472	60	48	10	Wheatered flow	T. Amphibolite	
P-7 M-5	4.70	1264	718	37	43	12	Coluvial deposit	Dunite	IB
P-7 M-29	25.75	1881	400	43	50	6	Residual soil	Dunite	IC
P-8 M-1	1.80	595	325	28	47	20	Residual soil	Gneiss	IB
P-9 M-1	1.50	722	305	72	49	9	Coluvial deposit	T. Dunite	
P-10 M-2	3.70	2545	167	76	98	71	Coluvial deposit	T. dunite	
P-12 M-3	4.85	1339	280	55	55	24	Residual soil	Dunite	IC
P-14 M-9	8.78	404	404	39	64	36	Fine Alluvial		
P-16 M-13	9.83	1327	369	29	48	24	Wheatered flow	T. Amphibolite	
P-17 M-1	1.70	2241	501	46	69	41	Wheatered flow	T. dunite	
P-18 M-9	8.55	519	180	44	38	8	Wheatered flow	T. Granodiorite	
P-18 M-12	11.60	727	196	44	57	27	Wheatered flow	T. Granodiorite	
P-21 M-3	3.50	1059	269	55	72	20	Wheatered flow	T. Amphibolite	
P-21 M-7	6.70	1090	256	71	51	11	Wheatered flow	T. Amphibolite	
P-22 M-3	3.25	704	160	23	0	0	Fine Alluvial		
P-23 M-1	1.25	840	147	40	71	30	Residual soil	Gneiss	IB
P-23 M-7	9.25	1320	219	43	63	19	Residual soil	Gneiss	IC
P-25 M-8	11.00	775	280	61	83	37	Residual soil	Dunite	IB
P-25 M-16	18.25	1534	400	46	69	38	Residual soil	Dunite	IC
P-26 M-2	1.95	297	90	34	56	34	Coluvial deposit	T. dunite	
P-26 M-10	7.75	286	220	54	65	30	Fine Alluvial		
P-27 M-1	1.75	575	240	30	52	29	Fine Alluvial		
P-28 M-3	3.38	431	133	63	77	38	Residual soil	Amphibolite	IB
P-28 M-9	7.65	938	179	28	35	13	Residual soil	Amphibolite	IC
P-29 M-1	1.68	864	180	55	61	33	Residual soil	Dunite	IC
P-29 M-3	3.35	1250	200	48	55	23	Residual soil	Dunite	IC
P-30 M-7	4.60	267	80	72	78	35	Mud flow	T. dunite	
P-31 M-11	9.30	790	200	86	74	22	Residual soil	Dunite	IC
P-32 M-10	9.30		224	82	84	45	Wheatered flow	T. Amphibolite	

Table 1. Index Properties of samples used in Dynamic Triaxial test.

Velocities in mature colluvial and flows deposits are very variable in the city, due to their composition and humidity. These flows located in the southeast and southwest of Medellín, present maximum shear wave velocities around 500 m/s, meanwhile the deposits in the north area of the city reach velocities up to 1000m/s.

Mud and recent debris flows revealed surface velocities near 200 m/s, which increased to 550 m/s at 30 m depth. In alluvial deposits, low values of velocities are detected (100 m/s) which indicate the presence of soft and fine soils, that show an average thickness of 10 m in the Southwest and Southeast areas of the city. In Central, Northwest and Southeast city areas these softer deposits have velocities in the order of 300 m/s. These soft layers rest on a very competent stratum with velocities up to 700 m/s.

It can be seen that shear wave velocities through the different geotechnical formations in the city subsoil increase rapidly, in such a way that near 15 m in depth, velocities up to 250 m/s are detected. This behavior is directly related to the Standard Penetration number in different soil materials, because in soft layers with low shear wave velocity, SPT values are close to 15 blows per 0,30 m.

Based on field and laboratory testing results carried out on 32 boreholes executed as part of the project exploration program, a multiple regression method was used (Reference 3) to find acceptable correlation which allow to get shear wave velocities from common static parameters. Index properties such as natural water content, SPT Number, material finer than 200 sieve, Atterberg limits, and the effective vertical stress.

In Table 2 these correlation are shown, classified according to their dispersion degree and representatively of sampled data. Notice that they are marked as "Recommended" when they constitute a good representation of the data model and have low dispersion and "Acceptable" if the correlation even represents the data model but it has a high dispersion.

Soil Type	Equation	Range of validity	Notes
Residual soil - Igneous Rock	Vs (m/s)=-201.373+1044.422*W(%)^-0.224	15<=Wn(%)<=100	Accepted
	Vs (m/s)=98.495+44.868* Ln(Nspt)	5<=Nspt<=80	Accepted
Granodiorite	Vs (m/s)=-32.062+13645.519*W(%)^-1.099	15<=Wn<=50	Recommended
	Vs(m/s)=-79.488+1971.071*IP(%)^-0.653	5<=IP<=35	Recommended
	Vs (m/s)=-56.111+5535.045*%F^-0.658	30<=%F<=100	Accepted
	Vs (m/s)=846.161-15.565* W(%)	15<=Wn(%)<=40	Recommended
			Recommended
Gabbro	Vs (m/s)=-11.374+8171.186*W(%)^-	20<=Wn(%)<=50	Recommended
	Vs (m/s)=-14.972+158.841*1.010^Nspt	10<=Nspt<=80	Recommended
	Vs (m/s)=-34.312+5552.276*%F^-0.712	50<=%F=100	Accepted
	Vs (m/s)=-9.023+9096.220*W(%)^-1.010	20<=Wn(%)<=50	Recommended
	Vs (m/s)=-17.478+154.992*1.011^Nspt	10<=Nspt<=80	Recommended
	Vs(m/s)=221.218+ 6744.200 * LL(%)^-0.770+0.582*IP(%)^1.888-123.753* Ln(W(%))	20<=Wn(%)<=50; 20<=LL(%)<=60;5<=IP(%)<=22	Recommended
Dunite	Vs (m/s)=47.395+67.036* Ln(Nspt)	5<=Nspt<=60	Accepted
	Vs (m/s)=-12.196+201.034*1.012^Nspt	5<=Nspt<=60	Accepted
Residual soil - Metamorphics Rock	Vs (m/s)=4.103+49.319*Nspt^0.523	5<=Nspt<=65	Recommended
	Vs(m/s)=1.304+1360.718*IP(%)^-0.562	5<=IP(%)<=40	Recommended
	Vs(m/s)=0.044+267.537*Σv(kg/cm²)^0.34	0.3<=Sv(kg/cm²)<=4.1	Recommended
			Recommended
Anphibolite	Vs (m/s)=-5.511+44.846*Nspt^0.564	5<=Nspt<=65	Recommended
			Recommended
Gneiss	Vs (m/s)=-29.933+2870.566*W(%)^-	15<=Wn(%)<=45	Recommended
	Vs(m/s)=-189.139+2843.074*IP(%)^-0.694+0.121*W(%)^1.850	15<=Wn(%)<=45;8<=IP(%)<=30	Recommended
	Vs(m/s)=186.391+73.226* Sv(kg/cm²)	0.4<=Sv(kg/cm²)<=2.8	Recommended
			Recommended
Coarse Alluvial	Vs (m/s)=1124.379-215.087* Ln(%F)	15%<=%F<=90	Recommended
	Vs(m/s)=-66,148+158,441*1,465^Sv(kg/cm²)	0,4<=Sv(kg/cm²)<=2,5	Accepted
Fine Alluvial	Vs(m/s)=-14.658+61.724* Ln(Nspt)	5<=Nspt<=30	No Recommen.
Weathered deposits	Vs (m/s)=-42.365+1988.155*W(%)^-	15%<=Wn<=70%	Accepted
	Vs (m/s)=8.575+2868.502*W(%)^-0.641	15<=Wn(%)<=50	Accepted
	Vs(m/s)=-614.462+160386.546*LL(%)^-1.343+0.284*1.207^IP(%)	10<=IP(%)<=40;40<=LL(%)<=60	Recommended
	Vs(m/s)=-44.964+186.229*1.635^Sv(kg/cm²)	0.3<=Sv(kg/cm²)<=2.1	Recommended
	Vs (m/s)=-18.990+3915.619*W(%)^-	20<=Wn(%)<=50	Accepted
	)	0,4<=Sv(kg/cm²)<=2,0	Recommended
Mud flows	Vs(m/s)=288.955+426.948*1.005^IP(%)-126.037* Ln(W(%))	30<=Wn(%)<=75;5<=IP(%)<=70	Recommended
			Recommended
Coluvial Deposits	Vs(m/s)=9.987+554.624*Nspt^-0.233+0.000*Sv(kg/cm²)^-18.521	5<=Nspt<=50; 0,4<=Sv(kg/cm²)<=1,5	Recommended
			Recommended
Recent Flows	Vs(m/s)=732.933-526.334*1.002^Nspt+87.111* Sv(kg/cm²)	15<=Nspt<=65;0,4<=Sv(kg/cm²)<=2,0	Recommended
			Recommended
Mud Flow Deposits	Vs (m/s)=143.257+64.366* Ln(Nspt)	15<=Nspt<=75	Recommended
	Vs(m/s)=285.243+29.359* Ln(Nspt)-0.001*Sv(kg/cm²)^-15.539	15<=Nspt<=75; 0,4<=Sv(kg/cm²)<=1,5	Recommended

Where:
Sv = Vertical Effective stress
Nspt = Standar Penetration Test
W = Water Content
IP = Plasticity Index

Table 2. Correlation for the shear wave velocity

SHEAR MODULUS AND DAMPING RATIO

Based on results from field and laboratory testing, the shear modulus and damping ratio variation with the strain level was analyzed. In order to define these figures, it was taken into account the maximum Shear Modulus (Gmax) obtained from the Bender-element test. For each soil, it was estimated a series of values in the G/Gmax and damping ratios (β) for different strain levels. A minimum square distribution was done following the Hyperbolic Model used byVillarraga (Reference 4).

There were carried out different distributions classifying samples according to their soil type, origin, weathered profile and degree of weathering (Reference 5). Keeping in mind soil characteristics, there were defined two groups of materials: residual soils and transported soils.

In first place, residual soils were analyzed and classified in conformity with their origin: igneous or metamorphic rocks. In Figures 1 to 4 are shown G/Gmax and Damping ratio relationships. It can be seen that soils from igneous rocks present a lower lost in strength than those soils from metamorphic rocks. For the damping ratio, metamorphic soils showed a higher dispersion and a higher damping. Each residual soil was analyzed apart accordingly to its weathering level, and big differences were not found among them. Therefore, for each soil type only one distribution can be used.

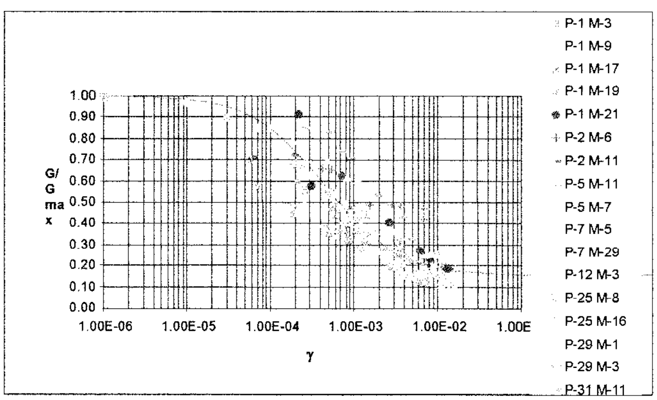

Fig. 1 *Residual soils - Igneous rocks G/Gmax vs. Shear strain*

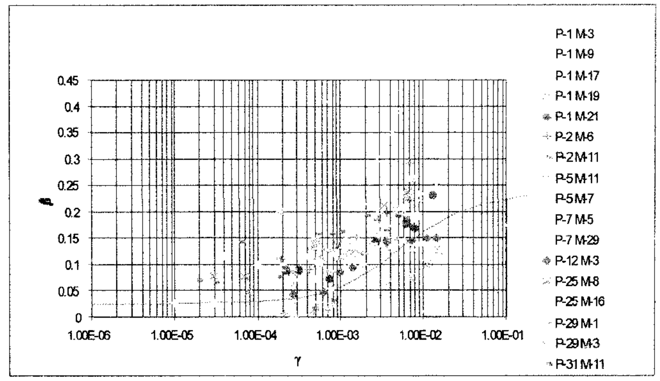

Fig. 2 *Residual soils - Igneous rocks Damping ratio vs. Shear strain*

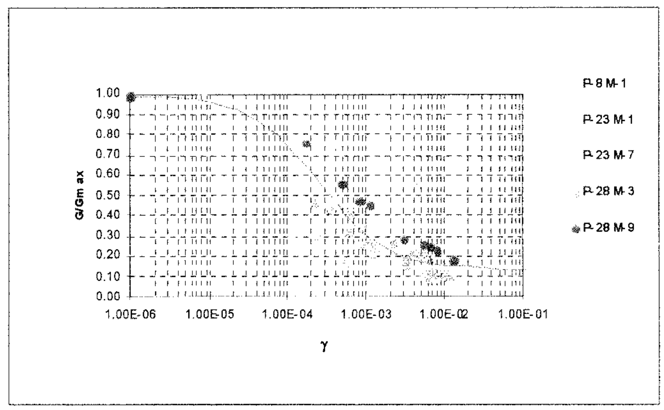

Fig. 3 *Residual soils - Metamorphic rocks G/Gmax vs. Shear strain*

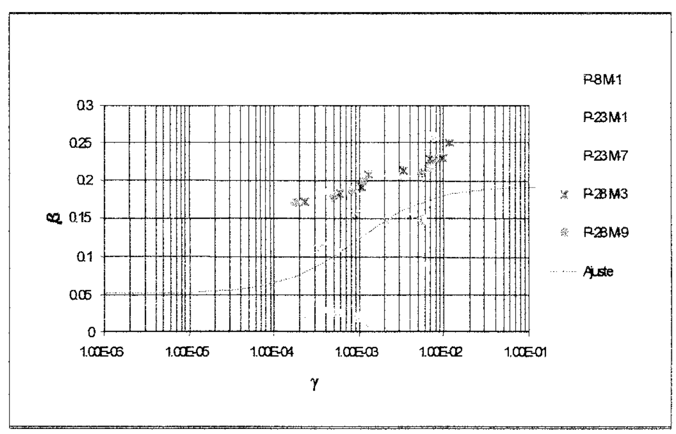

Fig. 4 *Residual soils - Metamorphic rocks Damping ratio vs. Shear strain*

Transported soils samples were grouped considering their transport mechanism and their origin.

In Figures 5 to 8 are shown the curves obtained for the soils of Medellín from Dobry and Vucetic (Reference 6) proposals, in function of their index of plasticity. The range of lost of rigidity with the strain level is generally very narrow related to the variation of the plasticity index. These curves are located downward the inferior part of those proposed by Dobry and Vuccetic for plasticity indexes between 0% and 30%. It is observed that the residual soils are more fragile and show a little higher degradation than soils used by those authors.

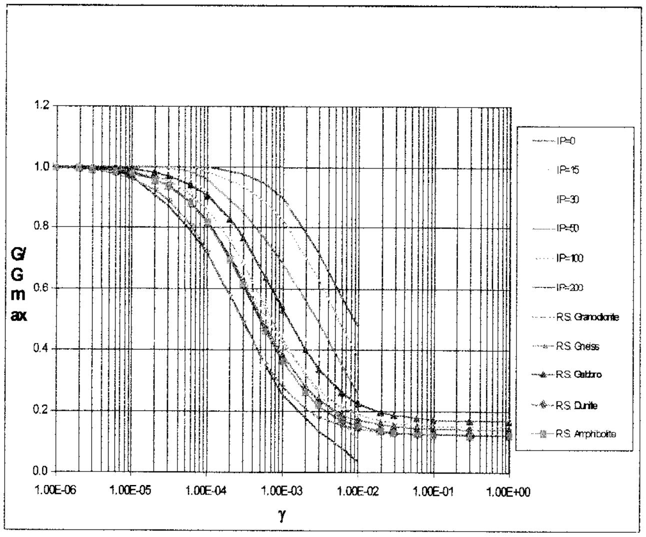

Fig. 5 *Residual soils from Medellín G/Gmax vs. Shear strain*

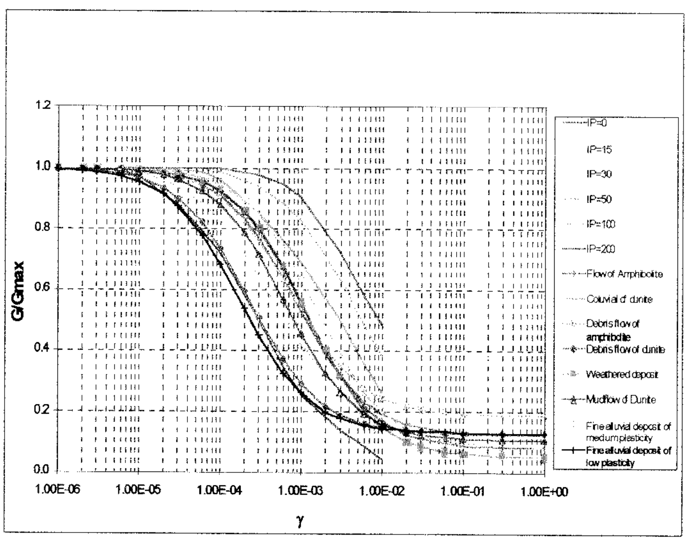

Fig. 6 *Transported soils from Medellín G/Gmax vs. Shear strain*

Residual soils show a tendency to group depending on rock type. In general, soils from igneous rock display a degradation lower than the module of rigidity at the same strain level than residual soils from metamorphic rocks. This can be explained because the presence of foliation and schistosity in metamorphic rocks, characteristics that are copied by soils. This condition makes them a little more fragile than those soils from igneous rocks. In a similar manner, these low values of fragility were observed as the composition of basic minerals increases in the parental rocks. Therefore, residual soils from Dune rocks exhibit a lost of rigidity lower than those soils from granodiorite, quarztdiorite and gabbro rocks, in spite of both having igneous origin.

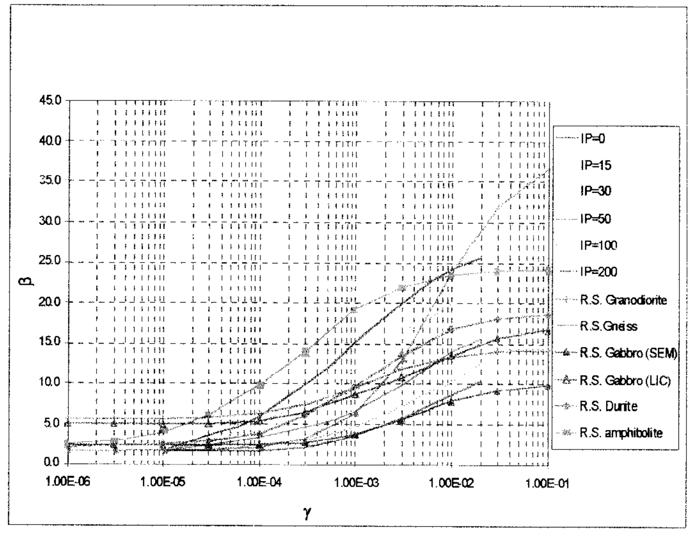

Fig. 7 *Residual soils from Medellín Damping ratio vs. Shear strain*

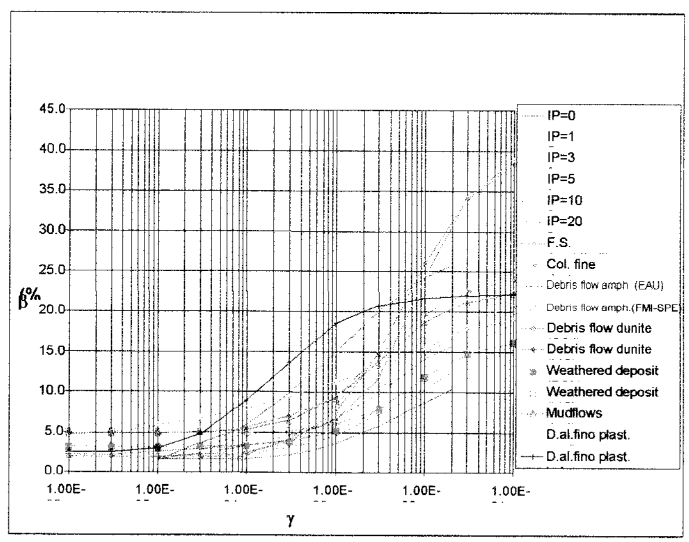

Fig. 8 *Transported soils from Medellín Damping ratio vs. Shear strain*

In case of high weathered colluvial soils and flows, It can be noticed that they show behaviors very close to residual soils.

According to the tendency observed for fine alluvial soils, it was possible to differentiate those of high and low plasticity, with a behavior that coincides with the proposal from Dobry and Vucetic.

CONCLUSIONS

- The origin of soils is a fundamental aspect to be considered in the analysis of the behavior of residual soils of Medellín. Therefore, during geotechnical prospecting it is very important to do a good characterization of soils from their origin and composition. Residual igneous soils exhibit degradation of their rigidity in terms of G/Gmax and damping ratio, lower than metamorphic soils. Therefore, it is expected that they would have a higher amplification during an earthquake.
- Base on the origin and the index properties of the soils, the engineer could get orientation about their dynamic behavior. It is important to notice that it is a first simple approach and has to be adjusted later with more studies.
- The curves proposed by Dobry and Vucetic in their study on the effect of the plasticity in the dynamic properties of the soils, are verified in this work for sedimentary soils, as can be seen in the figures for alluvial soils with those curves from that study. In general, residual soils satisfy this correlation for G/Gmax versus strain level, and tend to take a low degradation for high plasticity indexes. However, they do not necessarily coincide with the curves from Dobry and Vucetic, because of the origin of the soils has a high influence on the dynamic behavior.
- Characterization of residual soils based on theories that have been used until now may have some limitations due to the great soil variety found inMedellín.
- The quality of results in soil dynamic studies directly depends on the quality of laboratory testing. Although these tests are not generalized in a our country yet, the new codes make them more and more necessary and the information that they provide is very useful for dynamic behavior studies.

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