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DYNAMIC BEHAVIOR OF BOGOTA'S SUBSOIL PEAT AND IT'S EFFECT IN SEISMIC WAVE PROPAGATION

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SUMMARY

An experimental research which included the static characterization (index properties, un-drained shear strength, compressibility) and dynamic (down-hole tests, cyclic triaxial resonant column test) of some peat deposits located within an extent sedimentary filling that conform the Bogota savannah was conducted. A hyperbolic function was used to represent the nonlinear stress-strain skeletal curve under cyclic loading up to shear strain close to 2%, and the hyperbolic model of Nakagawa [1] to predict the dynamic curves of the different peat's studied. Starting with the results of cyclic triaxial tests under controlled strain, and by using the Matasovic model [2], the cyclic degradation of the peat samples was associated to the generation of pore-water pressure excess after reaching 10 cycles at different strain levels. Finally, the dynamic response of soft soil deposits located in zones with a horizontal topography of Bogota was modeled and the influence of peat layers presence was evaluated.

Due to the low stiffness of the peats (γt =1.1-1.3 t/m³, Vs = 90-130 m/s), the impedance ratio with the lower stratums (0.45 a 0.6) and the difference between the dynamic curves (G/Gmax-γ y β–γ) of this soil compared to the other clayey soils, it was found through the numeric modeling of the dynamic response 1D and 2D (EERA[3], NERA[4] and PLAXIS DYNAMIC [5] soft-wares) of real and typical profiles of soils with peat layers, that the peat layers after being exposed to seismic events comparable to that of a real seismic threat to the city show greater strain by shear and high damping, even greater than those of the other layers of the profile, causing a attenuation of the acceleration on the surface. Therefore, the designed response spectrums obtained with the incidence of the peat deposits end up having a lower level of spectral acceleration than those expected for soft clay profiles obtained in the MSB study [6]. This is just an indication that future MSB actualizations of the city should include the incidence of the peat layers, since they have not been considered appropriately.

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1. INTRODUCTION

The great majority of peat deposits in Bogota are located within the limits of Zone 2 (foothill) and Zone 3 (lake-land A) of the Seismic Microzonation Study of Bogota (MSB) [6] due to the fact that a great part of them were formed in a lacustrine environment. Peat lenses of an average of one meter of thickness located throughout the flat area of Bogota are found at some of the typical depths (11-12m, 22-23m, 30-31m, 58-59m), which evidence the occurrence of certain paleo-climatic or tectonic conditions that favored its formation and accumulation.

Several investigations about the superficial dynamic peat behavior have demonstrated that these exhibit a strong no linearity, low stiffness, great strain, thus, higher damping ratio than the clays when seismic waves go through, being influential in the dynamic response of the subsoil where they are found. Nonetheless, the effect of deep peat layers has not been considered and this response has not been associated with its dynamic behavior and some of its index or constitutive parameters, such as Vucetic [7] did for clays.

2. CHARACTERIZATION OF PEAT DEPOSITS

2.1 Physical Characterization

Thin-walled tubes of 65-75mm diameter and 500mm of length were used to obtain undisturbed samples in 6 peat deposits (t) located at different depths and sectors of the city of Bogota: S1) 11-13m (Calle 210), S2) 58-59m (Calle 170), S3) 0-7m (Qda. Salitrosa), S4) 31-32m (Calle 100), S5) 2-3m (Calle 77), S6) 4-6m (Av. Caracas), (Fig.1). Based on the results of the physical characterization made and compiled, correlations were found between index parameters and compressibility parameters (Fig. 2).

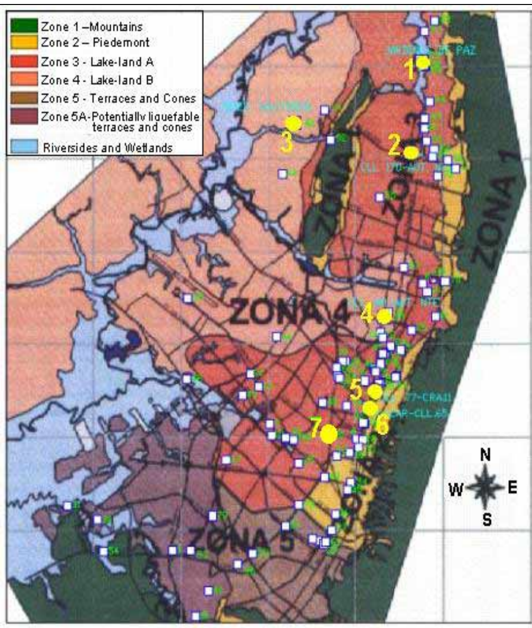


Fig.1. Location of study sites

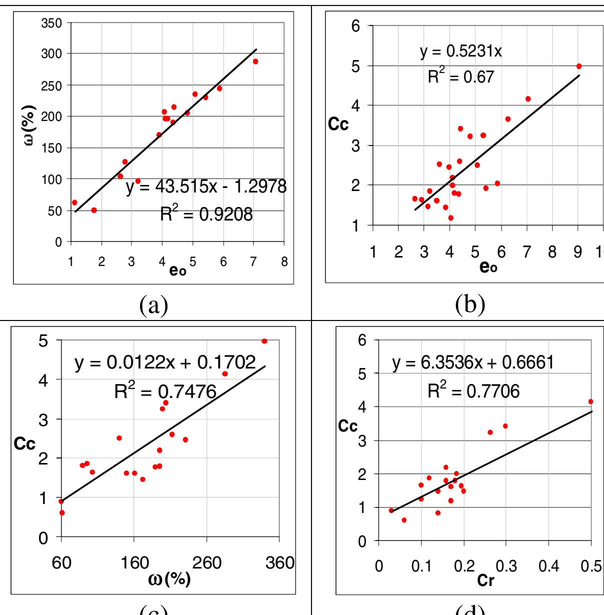


Fig. 2. Correlations for Bogota's peats

2.2 Static Characterization

The undrained shear strength of the peats increased with the reduction of the decomposing degree, from very low for amorphous peats (c´= 0-0.12 kg/cm², y ϕ´=10-15º) up to high for more fibrous peats (c´= 0.15-0.25 kg/cm², ϕ´=15-38º), which was reached at a strain at failure of 4-10% for amorphous peats to semi fibrous, and higher at 12% for fibrous peats (Fig. 3). As of the results of the direct shear and triaxial tests CIU, ratios of stress failure (τ/σ) for amorphous peats between 0.3 and 0.6, and for semi fibrous peats between 0.6 and 1.2, with an average value of 0.6, just like reported by Edil [8] (Fig. 4).

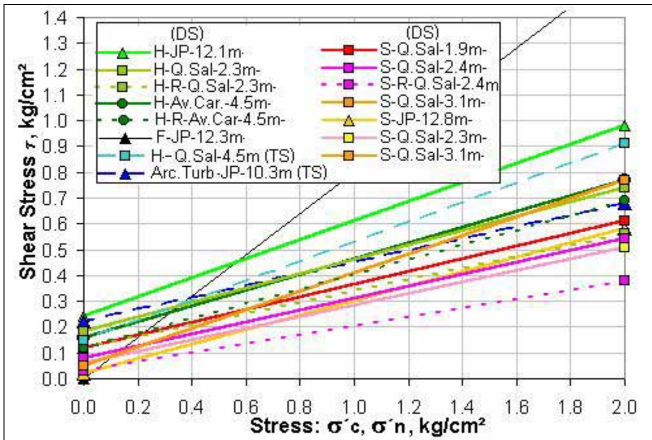


Fig. 3 τ–σ trajectories for superficial peat samples of Bogotá.

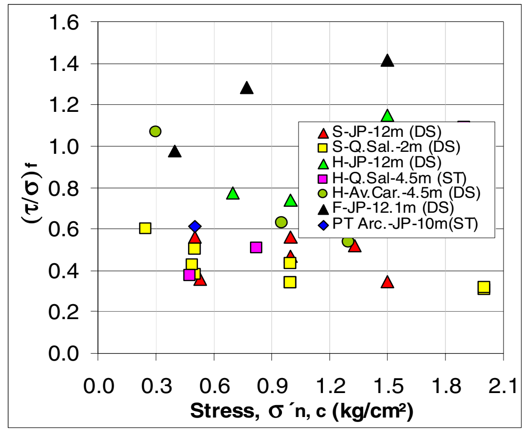


Fig. 4. Stress failure ratios vs. effective confinement pressure for Bogotá's peats.

As of multi-charge oedometric tests performed, it was observed that the compression index (Cc) varies from 1-2 for deep amorphous peats up to values of 4 for the more fibrous peats, and the secondary compression index (Cα) for a normal stress of 1 kg/cm² varies between 0.05 (amorphous peats) to 0.1 (fibrous peats).

2.3 Dynamic Characterization of Peats

Geophysical field tests were performed (down-hole) in the 6 peat deposits studied, and dynamic laboratory tests (resonant column tests, RC, triaxial cyclic tests, TC) on peat: S1, S2 y S4 (Table ---1). In the clay-muddy soils of the first 100m of the profiles of S2 (H=130m) y S4 (H=220m), a down-hole test was conducted (measurement of wave velocity Vs, y Vp every 1 to 2m of deepness) and laboratory tests (RC and TC) to dynamically characterize the soils of the profile every 10 m deep or at every stratum soil change.

Table ---1 Summary of dynamic laboratory tests program and sample characteristics

			Basic Characteristics					Resonant Column		Triaxial Test			
Peat (Pt)	Depth (m)	Eo	Water Content (%) [a]	Ash Content (%) [b]	γ total (t/m²)	PI (%)	σ´vo (t/m²)	Sample No.[d]	σ′3 (kg/cm²)	%[c] Fiber	Sample No.	σ′3 (kg/cm²)	Type [e]
1)	12.1	4.1	205	36	1.21	153	0.61	1b	1.0	22	2	1.18	EC
	12.3	4.3	185		1.23		0.64	1ª	0.5	38	3	0.55	DC
	12.0	4.4	206		1.19		0.60	1c	2.0	51	4	1.40	DC
	12.7	4.6	174	22	1.26		0.67			64	5	0.22	EC
	12.2	4.3	196		1.22	153	0.60	6	0.05				
2)	58	3.6	195	54	1.25	100	1.86	7ª	1.5		7b	1.50	DC
4)	31	3.9	151		1.29	181	0.96	8ª	0.8		8b	0.80	DC

[a] Drying temperature of 60 - 80ºC
[b] ASTM D2794-91
[c] ASTM D 1997-91
[d] Sub-index peat sample (a,b): sample used to perform more than one dynamic test
[e] Strain-controlled cyclic triaxial tests (DC) and Stress-controlled (SC) conducted with an application of a cyclic charge at a frequency of 5Hz

In addition to this, the Ingeominas Accelerographic Station soil profile was used (H=185m, S7). It contains peat layers located at a depth of 29m and 49m with 0.5 to 1 m thick, whose properties were obtained from the MSB study (1997), and their velocity profile was found theoretically through the Kokusho expression (1982) for cohesive soils and the proposed by Seed & Idriss (1970) for sands. See Fig. 5.

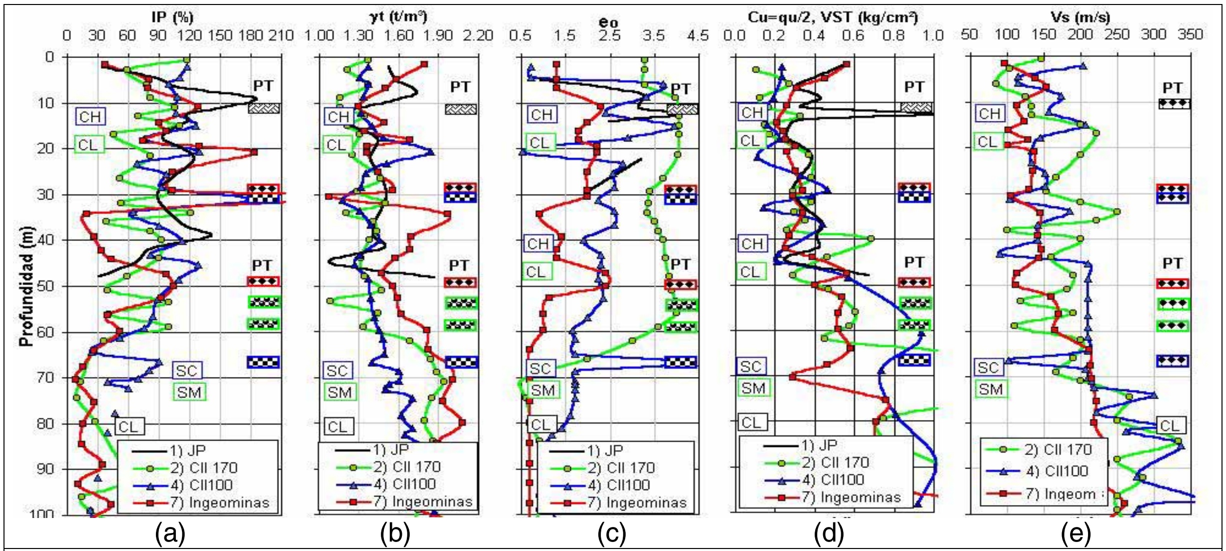


Fig. 5. Variation according to depth of: a) plasticity index (PI), b)Total unit weight (γt), c)void ratio(eo), d)undrained shear strength (Cu) as of vane shear tests and unconfined compression tests, e) shear wave velocity (Vs) of the profile's soils (1,2,4,7) with peat located in lacustrine zone 3 and 4 of MSB.

2.4 Dynamic Response for Profiles with Peats

The influence of the peat layers on the local dynamic response of places located within Zones 3 and 4 of the MSB (1997) was determined through various analyses of sensitivity that take into consideration different variables (thickness and depth of the peat layer, dynamic behavior curves and stiffness of the profile soils, tectonic source of the analysis signals) on the dynamic response of some real soil profiles (S2, S4 y S7) and theoretical (S8, S9, S10) both with peat stratums (See Table -2 and Fig. 7), through which design earthquakes propagate (see
Table -3), according to the Bogotá seismic hazard study, using linear equivalent model (EERA),1D, non linear (NERA)1D, and 2D (PLAXIS DYINAMIC), the analysis profiles were:

Table -2. Models of dynamic response

Model	Description	Depth (m)	PI	Stiffness	Dynamic* Curves	Peat E (m)	Peat Z (m)	Seismic Design
2-R	Calle 170	130	Profile	Profile	CP	1	53, 58	Several
4-R	Calle 100	220	Profile	Profile	CP	1	31,40,66	Several
7-R	Ingeominas	195	Profile	Profile	CP	1	29, 50	Several
8-T	Surface Peat	100-200	4	8, 9	CP, Dobry	1,3,5,10	0-10	Several
9-T	T.:(Zone 4-MSB)	200	4	9	CP	1,3,5	0,10,20,30,50	Several
10-T	T.:Zone 3-MSB)	130	4	10	CP	1	0,10,20,30,50	F. Frontal
11-R**	Calle 170	130	Profile	Profile	PLAXIS	1	53, 58	F. Cercana

* Usage of dynamic curves found on profiles S2 and S4 (CP).
** Bi-dimensional dynamic response model, using PLAXIS DYNAMIC soft-ware.

The theoretical profiles have a stiffness that increases linearly with depth and consider the presence of a layer of superficial over-consolidated soil of 7.5m thickness. The profiles are conformed by 4 types of typical clayey soils whose dynamic behavior curves are also shown with other place's peats in Fig. 6.

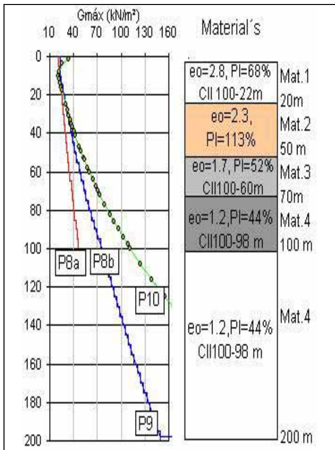


Fig. 6. Material's stiffness variation according to the depth of the profiles S8,S9,S10.

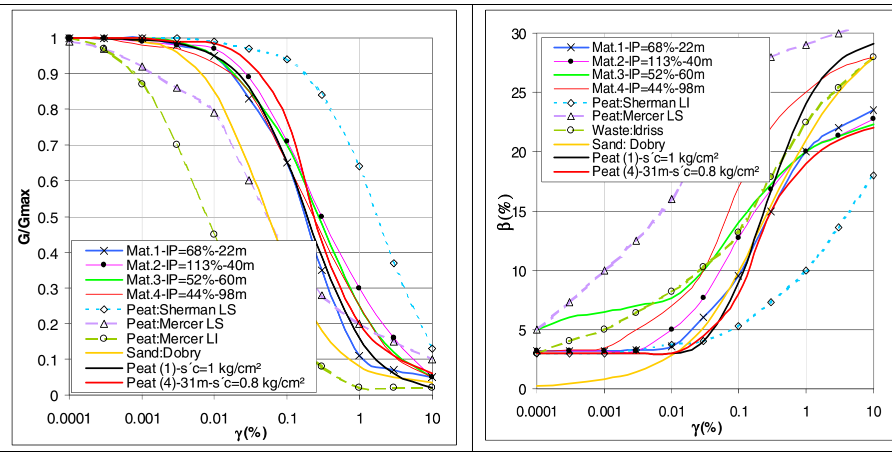


Fig. 7. Dynamic curves of typical clayey soils with other place´s peats: a) G/Gmáx vs. γ, b) β vs. γ.

***Table -3**. Characteristics of some of the seismic design signals used*

Earthquake Scenario	No.	Seismic Design	Ahmáx.(g)	T(seg.)	t (seg)	Ms	Scaling at: Ahmáx.(g)
F. Cercana	1C	Corral(N-S)	0.63	0.29	40	7.1	0.20
	4C	Umbría	0.201	0.11	25	5.9	0.20
F. Frontal	2F	Frontal	0.148	1.06	57		0.20
	3F	Loma Prieta	0.198	0.48	40	7.1	0.20
F. Lejana	1L	México	0.032	0.93	114	8.1	0.038

3. RESULTS

3.1 Dynamic Behavior of Peats

As of the results of cyclic triaxial tests at controlled strain (C) on peat (1), values of t (parameters of degradation) were obtained, intermediate to the ones reported by Dobry [7] for high plasticity clay (PI=50%) and a low plasticity one (PI=15%) for strains between γcy= 0.1%-1.0%. See Tabla -4

The curves τ–γ result of these tests were constructed accordingly to the hyperbolic model of Hardin-Drnevich (H-D), adjusting a function $\tau=f(\gamma)$ to each one of the experimental skeletal curves (Fig. 8) and applying Masing's rules, to approximately describe the charge-discharge-recharge cycles up to cyclic strain levels of an order of 2% (Fig. 9).

Based on the shear modulus G obtained at the lower strain on the resonant column tests, the maximum shear modulus was estimated (Gmax1) at the laboratory (no Bender element tests were performed) through the hyperbolic model of Nakagawa [1] considering that this maximum shear modulus presents a shear strain of γ=0.0001%. The Nakagawa model allows us to estimate Gmax = (Gmax1) based on the equation:

$$\frac{G}{G\max} = \frac{1}{1+\alpha|\gamma|^{\beta}}$$ Equation 1, α y β for Bogota soils, given by:

$$\alpha = 12.9837\ e^{2.8104\ \beta}.$$ Equation 2,

$$\beta = 0.3431(PI)^{0.212}$$ Equation 3

Where: e: void ratio
PI: plasticity index

Tabla -4 Summary of cyclic triaxial testing results

Type	Peat	Sample – (% Fiber)	σ′₃ (kg/cm²)	γ(%)-τ(kg/cm²) (máx.)	τ/σ´c (máx.)	Δu/σ´c (máx.)	γcy (%)	δ=GN/G1 (N=10)	T
DC	1) JP	3)- (38%)	0.55	3.3-0.36	0.65	0.18	0.1-1	0.93- 0.78	0.03-0.1
		4)- (51%)	1.4	2.2-0.7	0.50	0.11	0.1-1	0.97-0.77	0.01-0.1
SC		5)- (64%)	0.22	2.4-0.49	2.22	0.11	0.1	0.94	0.02
		2)- (22%)	1.18	2.0-0.53	0.45	0.10	0.1	0.86	0.06
DC	4)Cll100	8b)	0.8	0.9-0.23	0.29				
DC	2)Cl 170	7b)	1.5	1.6-0.51	0.34	0.03			
SC		7ca)**	2.2	~0.12–σd=0.33	~0.07	0.05			
		7cb)	2.2	~0.14–σd=0.44	~0.1	0.13			
		7cc)	2.2	~0.4–σd=0.88	~0.2	0.15			
DC*	Clay Dobry	IP=15%					0.1-1	0.92- 0.58	0.03-0.24
		IP=50%					0.1-1	0.97-0.87	0.01-0.06

* Taken of Vucetic [7]
** Peat sample 7c) of type (2) peat tested under different cyclic stress ratios (τ/σ)

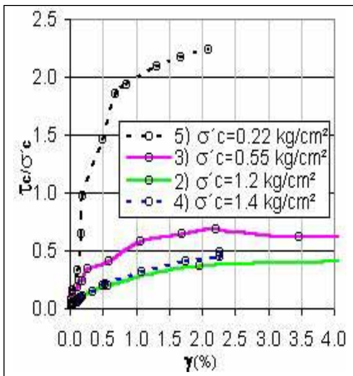
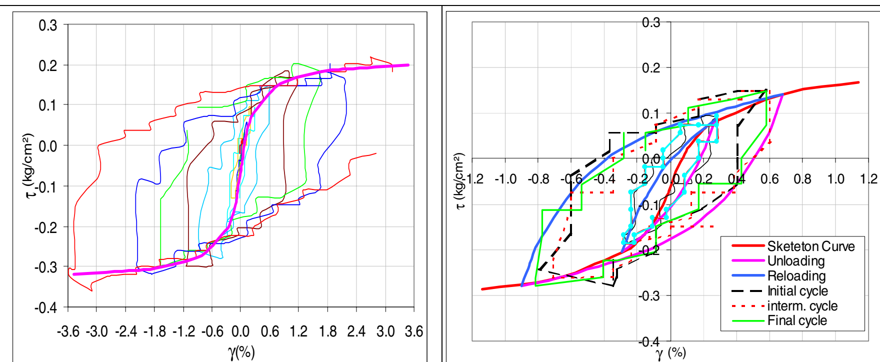


Fig. 8. Skeletal curves normalized byσ´c for the peat (1) samples



(a) (b)

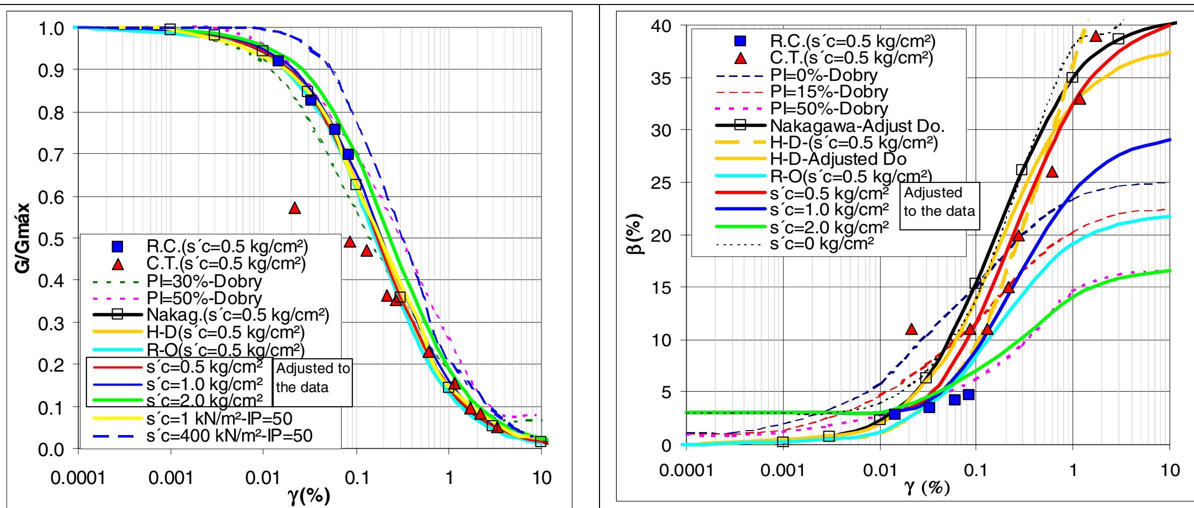
Fig. 9. Cyclic stress-strain behavior modeling for peat 1 tested at controlled strain at σ´c = 0.55 kg/cm²: a) Skeletal curve, b) hysteretic cycles.

Using the model of H-D, the shear modulus degradation curve with strain was estimated analytically, G/Gmax-γ (described by the laboratory results), while the damping one with strain (β–γ) was estimated using the empiric expression proposed by H-D ((Fig. 10)), by means of:

D = Do (1-(G/Gmax) Equation 4

Where Do = maximum damping expected.

The variation curve of G/Gmax with γ of some superficial peats (S1) of the city of Bogota and others, was predicted in an approximate way by means of the hyperbolic model of Nakagawa [1] using the empiric parameters found in the MSB for Bogota's clayey soils, and considering the plasticity and y compressibility of each type of peat in particular (Table --5). The variation curve of β with γ, was predicted by the empirical expression of H-D (see Fig. 11). For the other peats, the isotropic compression index value was assumed λ (Δlne/Δlnp), not reported in any literature, to estimate the void ratio at effective confinement pressures used in the tests on peat to obtain the dynamic curves reported.



(a) (b)

Fig. 10. Adjustment of theoretical models to laboratory dynamic curves of peat sample 3 of type 1 peat tested under σ´c=0.55 kg/cm²: a) G/Gmáx vs. γ b) β vs. γ,

Table --5. Characteristic of the sample of different types of peats

Peat *	Depth. (m)	γ_t (t/m³)	ω (%)	e_o**	OCR	PI (%)	CMO (%)	Vs (m/s)	σ´c (kg/cm²)	λ ***	e_f
1)	11-13	1.2-1.3	180-205	4.1	1.3	153	70-80	120	0.5-1.4 (0.5)	0.15	3.0
2)	58-59	1.33	157	3.6	1.3	(100)-154	46	100-118	1.53	0.19	3.6
4)	31-32	1.29	151	3.86	1.0	181		103	0.8	0.13	3.9
5) M	0-18	1-1.04	500-1500	17	< 1	(200)-600	73-82	12-30	0.12-(0.3)	0.3	10
6) Q	9-10.5		210-285	4.3		200*	35-63	65-79	0.76-3.03 (2.0)	0.25	1.8
7)SH	13-14	1.1-1.2	152-240	4.2	< 1.1	100-200 (150)	44-65	83-90	0.14-1.36 (1.0)	0.25	2.0

* Peat (5) is Mercer-Slough's studied by Kramer[9], peat (6) of Queensboro studied by Stokoe[10], peat (7) of Sherman Island studied by Boulanger[11].
**Initial void ratio of the peat was estimated as of the corresponding natural humidity
***Isotropic compression index was assumed as of average values reported by Yamaguchi [12]on fibrous superficial peats of Saitama, Japan

For the deeper amorphous peats (S2, S4) and the clay-muddy soils of both profiles, the model estimated with great approximation the dynamic curves using the initial void ratio (eo) instead of the void ratio at the end of the consolidation stage (ef). Normalizing the skeletal curves of the different peat samples (1) by its confinement stress, it was observed that the curves group very close to one another (except the most fibrous one, sample 5), which explains the low influence of the confinement pressure observed over the G/Gmax curves with γ of the peat (1), just like happens with high plasticity clayey soils (IP>50%). See Fig. 10.

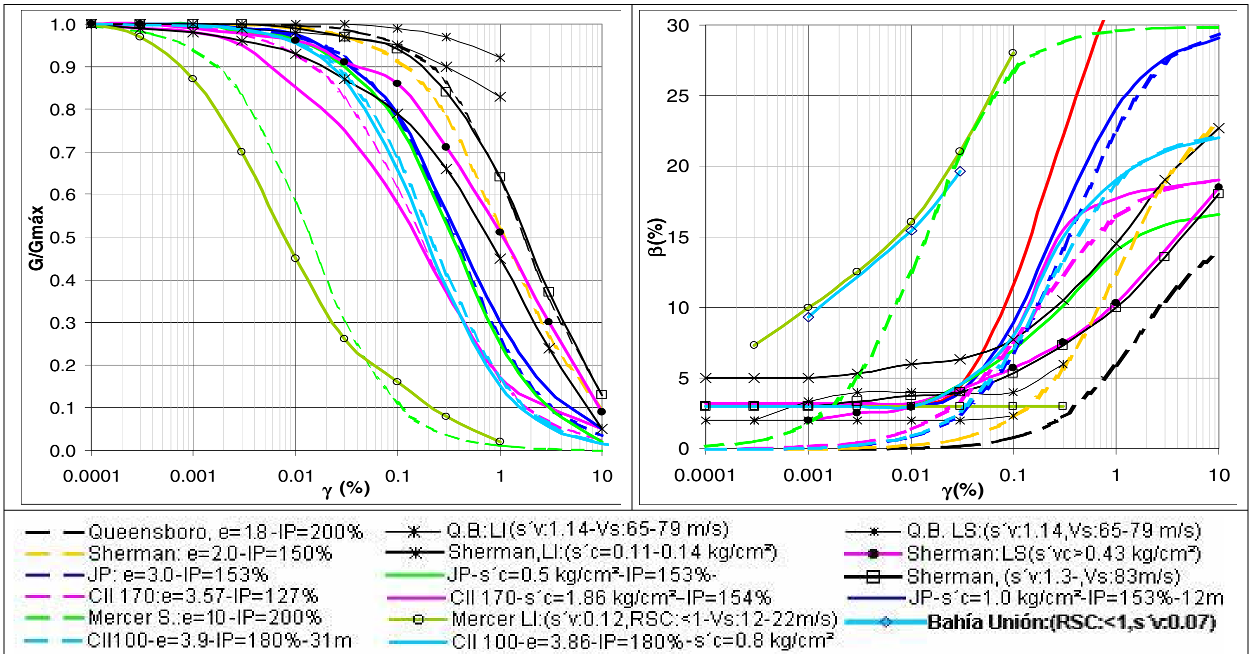


Fig. 11. Prediction of variation curves of: *a) modulus of shear, b) damping ratio with shear strain,* for different types of peat using Nakagawa's model and the empiric expression of Hardin *Drnevich (H-D).*

It was observed that peat samples (1) at different confinement pressures exhibited in a cyclical shear strain range between 0.3% to 1% a growth on the damping ratio, and a shear modulus degradation of 10% at the end of the first 5 cycles of each strain level, and of 20% after10 cycles, due to the gradual destruction of its structure. Applying the methodology proposed by Matasovic [2], based on the controlled strain cyclic triaxial tests on peat (1), a ratio between the degradation index, δ, and the water-pore pressure excess normalized was found ($u^*_N=u_N/\sigma'c$), generated on cycle N=10 at the different strain levels given by the next expression and the coefficients shown in **Table -6**:

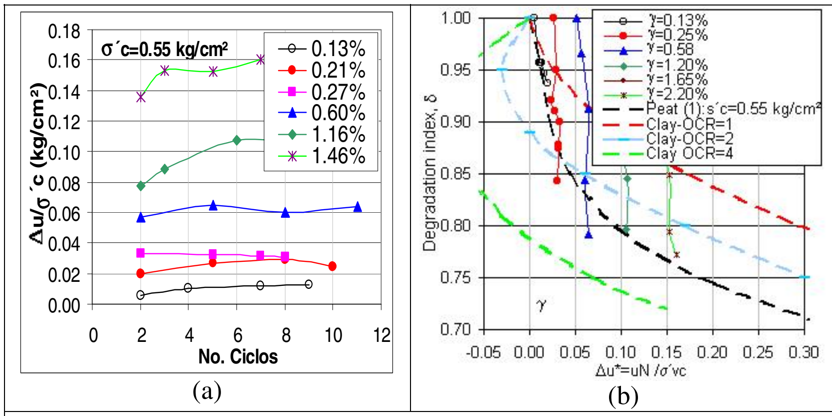
$$u_N^* = AN^{-3*s(\gamma c-\gamma v)^r} + BN^{-2*s(\gamma c-\gamma v)^r} + AN^{-s(\gamma c-\gamma v)^r} + D \quad \textit{Equation 5}$$

Additionally, it was noticed that in peat (1) the excess pore-water pressure generation depends mainly on the strain level reached and on the cyclic degradation produced, and on a small proportion, on the increase on the number of cycles. For strains close to 2%, excess pore-water pressure close to 20% de σ´c is expected. See Fig.12 and 13.

Comparing the variation curves of shear modulus G with the strain of the deep peat layers 2) and 4) with the ones of the other soils of the respective profiles, it was observed that they show a stiffness of about 50% less than the ones of the layers above or below. Still, the peats are the soils of the profile that display a lower degradation of shear modulus (G/Gmax) and less damping ratios at strains lower than 0.1% (due to the micro-structure of amorphous peat layers). The degradation of shear modulus and damping ratios increase rapidly once the 0.1% of shear strain is exceeded by the gradual destruction of its structure. See Fig.14 y 15.

Table -6. Parameters of the cyclic-degradation-pore-pressure generation model for the studied peats

σ´c (kg/cm²)	Sample	S	r	γtv	A	B	C	D
0.55	1	0.093	0.35	0.01	-20.07	56.66	-53.48	16.90
1.40	2	0.08	0.55	0.1	-7.20	20.77	-20.14	6.57



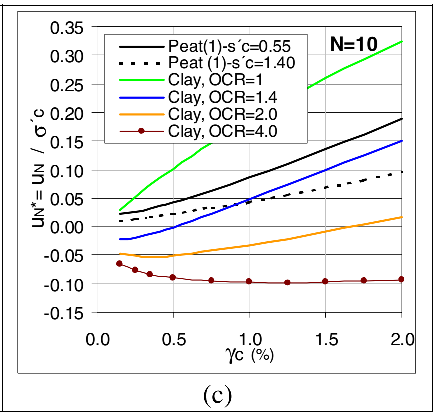
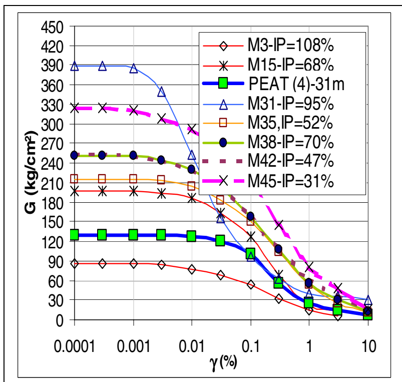


Fig.12. Variation of normalized cyclic pore water pressure excess ($\Delta u/\sigma'c$) respect of the: a) number of cycles, and b) degradation index (δ).

Fig.13. Variación modelada de $\Delta u/\sigma'c$ con γ de a turba (1).



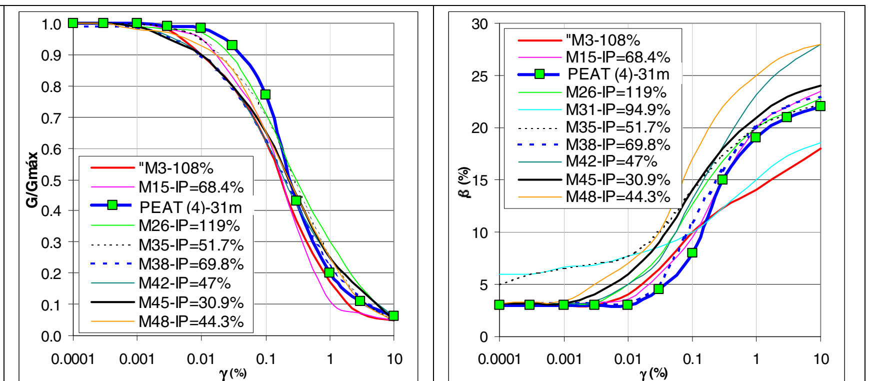


Fig.14. Variation of the shear modulus with shear strain of the soils of the profile 4.

Fig.15. Dynamic curves of soils the profile (4) Cll100: a) G/Gmáx vs. γ, b) β vs. γ.

3.2 Dynamic Response of Profiles with Peat Layers

Superficial peats with a rapid shear modulus degradation and great increase of damping with the strain as in swamp peats (peat 5), generate a strong attenuation of the surface acceleration, which grows with the increase of its thickness. In the meantime, peats with a lower shear modulus degradation and lower increase of damping up to strains of less than 0.1%, are lower than that of soft clayey soils, thus, generating greater effects of local amplification than the clays under influence of seismic events which produce shear strain on the superficial layer lower than 0.1% (seismic source near and afar), while its effects of amplification is reduced for seismic events that generate greater strains at 0.1% (seismic regional source). Due to all this, it was observed that the maximum horizontal acceleration on the surface increases with the thickness of the superficial peat deposit up to a certain thickness limit (given by the fundamental period of the design earthquake and the level of shear strain and damping induced in the peat layer), thus, for earthquakes of near source of shorter periods, the limit thickness for 100m and 200 m thick profile was close to 7m, while for earthquakes of frontal source of a greater fundamental period, this limit thickness increased to a depth of 10m, and is even greater at 20m of thickness for the afar source signal 1L. See Fig.16.

With the increase of the stiff soil thickness (8b) from 100m to 200 m thick (profile 9), the level of maximum acceleration reached on the surface was attenuated close to a 20%. A similar attenuation was produced when the stiffness of the deposit was reduced 2.5 times (8b) to obtain the profile (8a). See Fig.16.

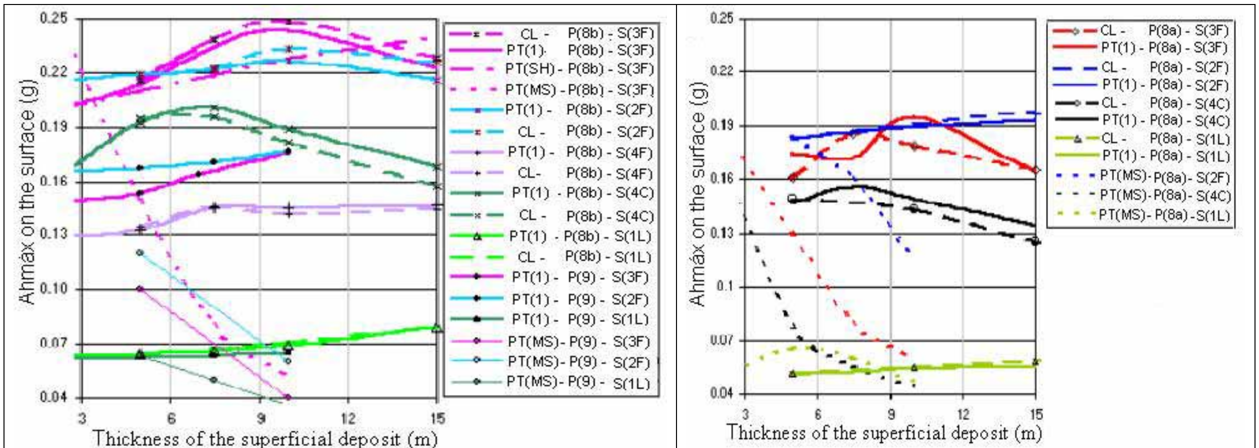


Fig.16. Maximum horizontal acceleration (Ahmáx) variation with the increase of thickness of the soft superficial deposit and stiffness of the profile under propagation of seismic design through the profiles: a) 8b y 9, b) 8a.

Due to the reduction of the impedance ratio between the peat layer and the layer underneath with the deepening of the peat layer, the level of shear strain estimated on the 1m thick peat layer below 10m deepness is greater than 1% (see Fig.17a), overcoming the strain limit mentioned by Ishihara [13] to reach a reasonable solution through the equivalent linear method (Shak91 soft-ware), which is why in this cases the NEERA soft-ware [4] was used (non linear analysis response method). It utilizes the finite difference method to resolve the wave movement propagation equation and the Iwan non linear model [15] to describe the soil's stress-strain during cyclic charges, allowing in cases of low stiffness materials like peat, the development of great strain and damping when approaching the material to failure (when overcoming the material's shear resistance as being the result of the last pair of points on the G/Gmax-γ x Gmax curve found experimentally and introduced in the model).

Assuming the presence of a peat layer (1) at different depths on the profile 8b, with a thickness (E) of 1m and 2m, characterized by Vs=100m/s and γ=1.2 t/m³ value, it was noticed that the influence of the peat layer under the propagation of the earthquake 3F on the profile varied accordingly to the analysis method used. In this way, with the equivalent linear method it was observed that by locating the peat layer within the first 10m an effect of amplification of the horizontal acceleration on the surface close to 10% was generated, while the attenuation of the horizontal acceleration and the spectral acceleration on the surface increase with the deepening and increase in thickness of the peat layer below a depth of 10m (without altering the form of the spectrum). This is due by the reduction of the shear strain transmission to the upper layers by the development of vast strains and damping in the peat layer. While modeling the dynamic response with the nonlinear model the result was a 1m thick peat layer that exercises an attenuation of the horizontal acceleration on the surface with its increasing deepening, which is much lower than the estimated by the first model when considering a peat layer below a depth of 20m (just where the equivalent linear model becomes somewhat untrustworthy given the strain level reached). See Fig.17.

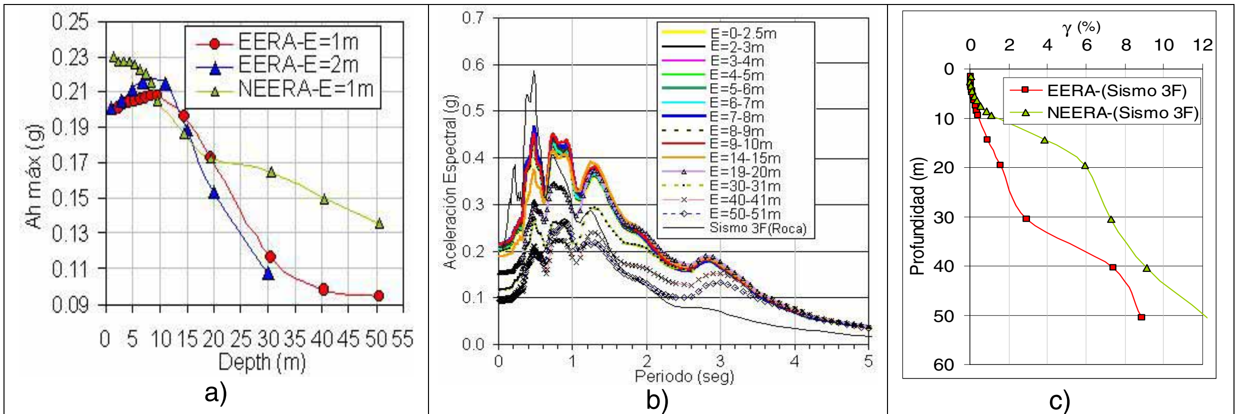


Fig.17. Variation of: a) surface horizontal acceleration, b) surface response spectrum, c) strain level on the peat layer, of profile 8B under seismic design 3F, with the location of the peat layer of 1m thick in the profile. (Note: Depth=(P), thick peat layer =(E)).

It was observed that the deep peat layers' influence in the dynamic response of the theoretical profile (9) and real (7) of zone 4 (MSB) can be ignored as the considerable thickness of the deposits (close to 200m) and the presence of soft clayey soil layers exercise greater influence over the attenuation of the accelerations than the presence of the peat layer (see Figura--18). Meanwhile, for the theoretical profile (10) and real profile (2) of zone 3 (MSB), the influence of the peat layer is important since it is located below a depth of 20m (strain on the peat layer from 1% to 2%), producing an attenuation of the horizontal and spectral accelerations on the surface of an order of 15% between periods of T=0.7-1.3 sec., under the propagation of earthquake of regional and near-by source, and without any influence when propagating the afar earthquake source. See Figura--19 and 20.

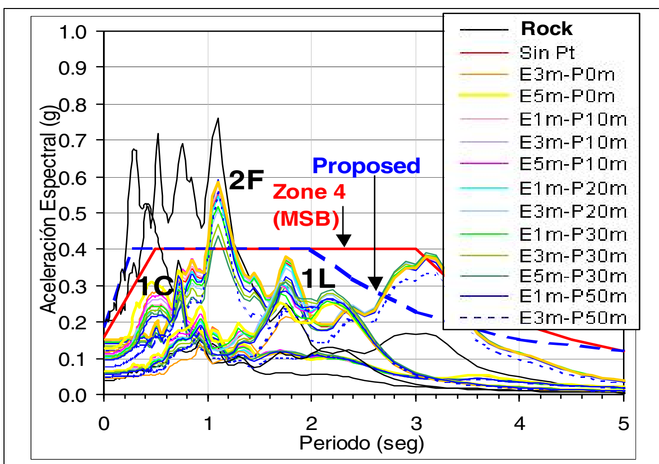


Figura--18. Surface response spectrum variation of model 9 with the location of the peat layer and seismic design (in site dynamic curves).

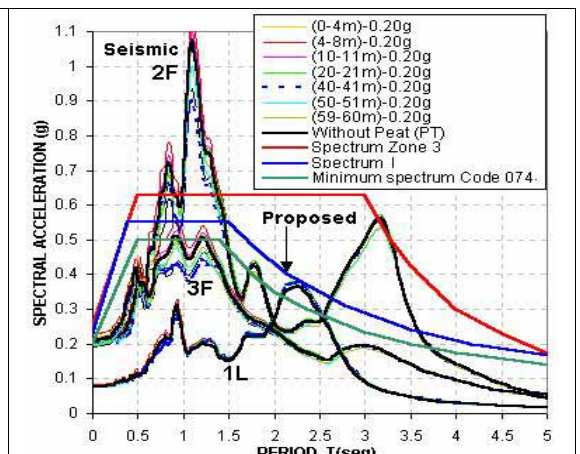


Figura--19. Surface response spectrum variation of model 10 with the location of the peat layer and seismic design.

Through making the analysis model (11) of bi-dimensional dynamic response (triangular elements of 6 nodes, ratio width/thickness=10, H=150m) in terms of effective stress, under flat strain conditions, undrained conditions, whose layers (profile 2R) of clayey with strains lower than 0.3% were characterized with the elastic linear model and the other layers with the Hardening Soil model (using parameters found in other investigations about soft soils in the same area studied), and the different peats studied (1),(2) and (4) using the Soft Soil model (parameters found in this investigation) , the effect of the peat layers on the dynamic response of the profile 2R was evaluated when assuming its existence at different depths on the profile.

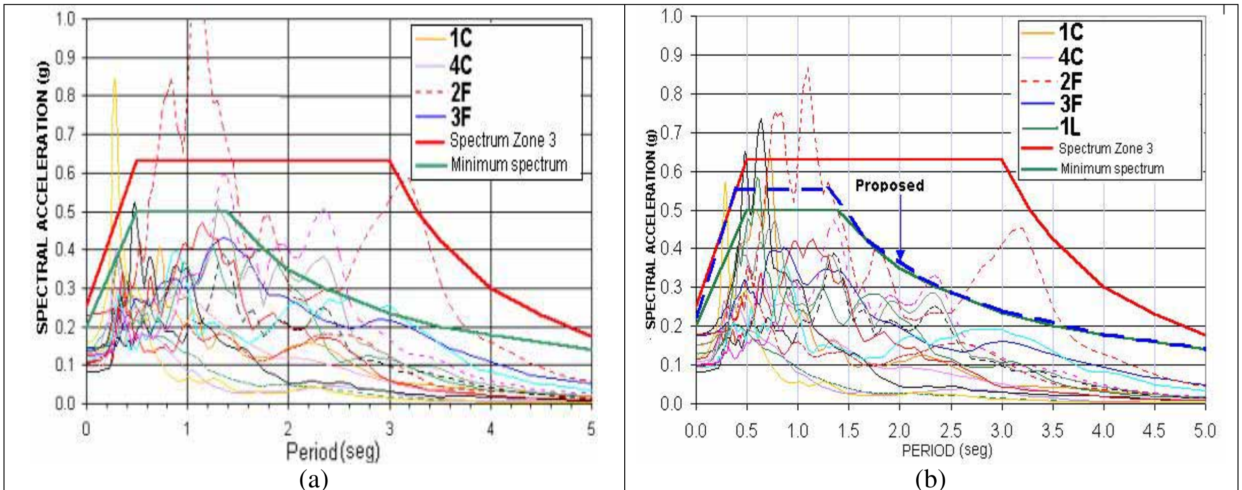


Fig.20. Response spectrum of the profile 2 (calibrated) under different seismic designs using the dynamic curves of the location (CP): a)without peat layers b)with peat layers.

Due to the lower ratio of impedance generated when assuming the peat layer at a depth of 30m with 1m of thickness over 2R profile it was observed that greater shear strain develops (γxy=1.7%), excess pore-water pressure ($\Delta u/\sigma ́c$=0.32, exaggerated by the other layers being elastic), under a cyclic stress ratio $\tau xy/\sigma ́c$ of 0.27 (distant to failure conditions). Also, it was perceived that the behavior models H.S and S.S. used are not appropriate to describe the dynamic stress-strain behavior since as a skeletal curve was used the stress-strain curve obtained under static conditions and a global damping of the whole profile under the influence of seismic charges was used, without distinction between one layer and the other and the effect of the strain level and number of cycles applied. See Fig. 21 and 22.

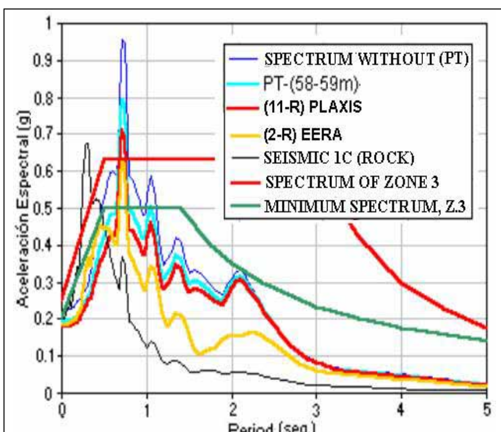


Fig. 21 Calibration of the bi-dimensional model´s (11) dynamic response (unidimensional model 2-R).

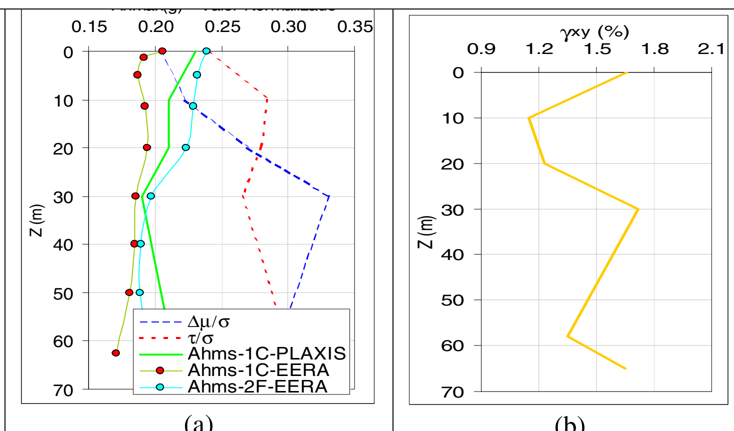


Fig.22. Variation of: a) $\Delta u/\sigma ́c$, $\tau/\sigma ́c$, Ahmáx (on the surface), b) shear strain (in the peat layer), with the location of the peat layer in the model 11, under the propagation of seismic design 1C.

4. DISCUSSION

Additional dynamic one-dimensional models were made to evaluate the impedance effect between deep peat layers (or soft soil) with the underlying layer (sand, stiff clay) over the dynamic response of a profile, starting from which it was observed that the equivalent linear model as an analysis tool is not trustworthy when reaching impedance ratios lower than 0.6 in typical profiles of the city of Bogota (when surpassing the 1% of shear strain in the peat layer) or by being the latter below a depth of 30m. Nevertheless, in profiles with other layers of soft soils of considerable thickness at different depths (zone 4, MSB), the importance of the peat layer can be ignored (without superceding the limit strain on this layer). See Fig. 23.

Only the dynamic response of profile 2 was calibrated using a pair of signals registered at the base and on the surface (earthquake Betulia-Santander on 08/11/99, of ML=6.5) of an accelerographic station located at about 500m from the profile 2 (statigraphic correspondence, but with possible palaeotographic differences or bi-dimensional effects), assuming a damping respect to the critical of a 3%, reaching maximum shear strain in the profile lower than 0.0043% (see Fig. 24). Due to the lack of strong seismic movements being registered, it is impossible to calibrate the models appropriately (to a close strain level induced by the design earthquakes), to establish which analysis model of response and dynamic behavior of the soils used is the one indicated to estimate the dynamic response of the profiles.

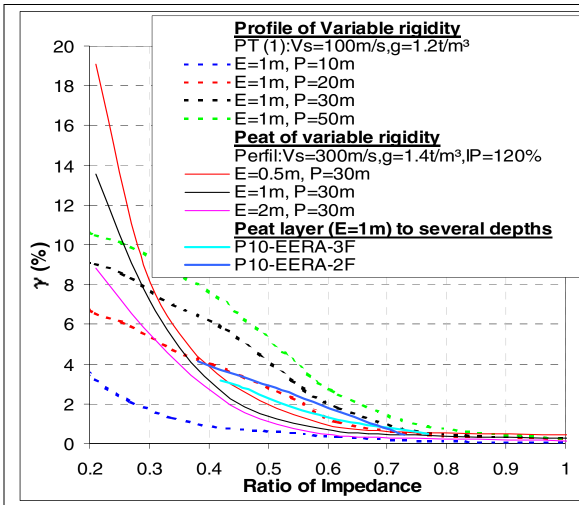


Fig. 23 Variation of shear strain with the impedance ratio between the peat layer and the layer underneath. (Note: Depth=(P), thick peat layer =(E))

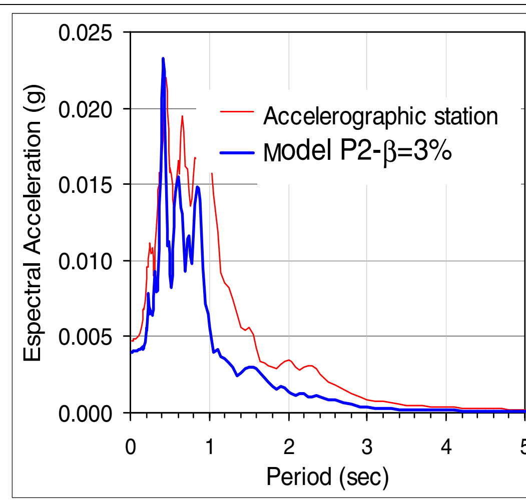


Fig. 24. Surface response spectrum of profile 2 vs. registered response spectrum by the accelerographic station for the earthquake Betulia-Santander.

5. CONCLUSSIONS

It was observed that deep peat layers present a stiffness lower than 50% compared to that of the layers above, and approximately less than 25% of the underlying layers, generating variable impedance ratios between 0.4 and 0.6, therefore it is expected that they suffer greater shear strain than the other layers during the propagation of seismic waves, in spite of exhibiting a lower shear modulus reduction curve up to strain less than 0.1% compared to the other soil layers. Due to its structure, the peat samples exhibited a lower degradation of the shear modulus than most of the clayey materials, and developed lower damping at strain less than 0.1%, after which it is understood that it begins to destroy itself.

It is important to make an appropriate characterization of the peat in terms of its physical properties, intrinsic (fibrous content, organic material content) strength and compressibility with the purpose of identifying correlations between these and their dynamic behavior. It was perceived that the augmentation in fibrous content increases the compressibility of these materials and their shear strength, by the strength to the tension of the fibers which expanded the friction angle and the cohesive intercept.

Through Nakagawa's hyperbolic model [1], it was possible to predict in an approximate manner the dynamic behavior of the peats of Bogota, and some others (assuming its compressibility based on its natural humidity and correlations).

The linear equivalent model alters the profile of accelerations and shear strain in a drastic way to adjust to the frontier conditions after reaching at some point the greater strain profile at 1% and impedances lower than 0.5. Then, in these cases, another trustworthy dynamic response analysis tool must be used.

Layers of peat located in typical profiles of zone 4 of the MSB (1997), do not influence in a noticeable way in its dynamic response due to the presence of other soft soil deposits in the profile. Nonetheless, its influence is noticeable in stiffer deposits, or of less thickness like the ones found in zones 2 and 3 of the MSB (1997), which increases with the deepening and thickening of the peat layer, generating attenuation of the spectral acceleration of 15 to 20% between periods T=0.7-1.3 sec.

The effect of peat as a soft superficial deposit is variable according to the type of peat, attenuated when it is swamp peat (like Mercer Slough's), and amplifying the horizontal and spectral accelerations on the surface in a range of 10% for deposits between 5 to 10m of thickness when the peat presents a shear modulus degradation similar to or less than that of the typical soft superficial clays of the northern part of Bogotá.

It was deducted that the hyperbolic model constitutes a rational alternative to describe the dynamic behavior of peats even at high strains (up to a 2%), without expressing it in terms of constitutive laws. The estimation of the excess pore-water pressure by Matasovic's methodology [2], and the hyperbolic model developed by Li [13] to describe the non linear elastic behavior of reinforced soils with different fiber content are examples of it. A large number of strain-controlled triaxial cyclic tests on different types of peat at different RSC and confinement stress are needed to formulate typical curves of its dynamic stress-strain behavior in function of its intrinsic characteristics and stress state.

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