THEORETICAL INVESTIGATIONS UPON ANALYTICAL MODELS REGARDING DYNAMIC INTERCATION BETWEEN SOIL AND METRO-TYPE STRUCTURES

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SUMMARY

Some theoretical investigations regarding the dynamic and seismic interecation between soil and underground structures by using different computation models and techniques are presented. The investigations referred both to reduced scale models tested on seismic tables and to full scale model structures. This study is part of a complex research program undertaken in the ICCPDC-Building Research Center of Iassy, with the purpose of elaborating adequate provisions for aseismic design of metro-structure in Bucharest.

1. INTRODUCTION

There are still little knowledge about the actual seismic behaviour of underground structures and this is why the design provision are scarce in this field [1].

In order to construct economical and safe structures and to draw up adeqaute seismic provisions for the metro in Bucharest the Earthquake Engineering Research Center of Iassy carried out a complex program of investigations on physical and analytical models [2], during 1977 - 1978.

2. THEORETICAL ANALYSIS OF EXPERIMENTAL MODELS

The physical models, consisted of a volume of sand bounded by walls and by bottom part of a rigid steel box (M-S), different underground structure models (M-C) 3 being introduced in the sand mass. The models were analysed in the linear range regarding the plane strain state for the static loads as well as for some dynamic loading sequences realized experimentally.

Two of the computation techniques used as well as some results and general remarks are presented herein.

In the Technique A idealized models with discrete masses and springs (Fig.1) were used under static loads equivalent to the inertial forces determined by the seismic coefficient method.

The variation of natural periods (T), the relative displacements (Δ) between the floor and the foundation raft as well as the maximum soil pressure variations (P) on the structure walls were determined depending both on the sizes of the soil zone (Bs) into dynamic interaction with the structure and the elastic soil coefficients (K).

In Fig.2 some results obtained from the analysis of the experimental model M II-10 are presented. Among various aspects resulted from this analysis, the following are emphasized:

- A large variation of the studied parameters in the range of values of the elastic coefficients;
- The size of the soil volume interacting dynamically with the structure is to be determined depending upon the ratio of "soil rigidity" and structural rigidity;
- The seismic coefficient method, applied on models of similar type, does not comply with the requirements of a rational desing, because the actual dynamic intercation between soil and underground structure is not properly taken into accound.

The Technique B used finite element discrete models.

The incremental accelerations of experimentally recorded motions into the soil model bottom stratum, were applied to nodal points located on the model base and on model vertical sides. Thi step by step analyses was performed automatically by using the ASBAR computing program [4] which is realized on the structure of the EAD program [5].

The responses of models tested on the shaking tables to different seismic and harmonic actions recorded experimentally were calculated. In order to verify the deformation modulus of soil model established by plate testing method, the displacement and pressure responses of the underground structure models to the action of a static horizontal load applied to floor level were also calculated. The computations were performed for several shear modulus values.

In Table 1 some theoretical and experimental respons results regarding the relative displacements (Δ) are presented.

Among the principal results of this analysis the following are pointed below:

- A good reliability with the qualitative experimental results regarding the general soil-underground structure interaction phenomenon [3].
- A satisfactory agreement with the quantitative results regarding the strain state in the condition of using into computation a soil shear modulus of 40-50 % of the value of modulus determined experimentally through shear wave velocity measurements in shock test.

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3. INVESTIGATION ON ANALYTICAL MODEIS CORRESPONDING TO FULL SCALE UNDERGROUND STRUCTURES

Having in view the supplementary distorsions involved by actual soil stata simplist modeling (imposed by the performance limits of experimental facility), the theoretical investigations were also extended to some models of full scale constructuons, using the analysis Technique B.

For the analytical models presented in Fig.3 and Table 3, using as action a sequence of 3.6 sec. from the 4 March, 1977, Romanian earthquake accelerogram, recorded in Bucharest (Fig.10), dynamic and seismic responses, R, were analysed for three different values of the following parameters:

- Soil shear modulus, G;
- damping ratio,v ;
- the length, L, and height, H, of the modeled soil deposit.

The influence of underground structure presence upon dynamic and seismic responses of virgin soil deposit, R(G-S), was also analysed.

In Tables 3 through 8 and Figs.4 through 8 some results of those analyses are presented. The following aspects are emphasized:

- The soil shear modulus presents a significant influence upon the dynamic and seismic responses. A 10 % variation of the G modulus rèlatively to the actual value implies about 20 % variation of the strain state response (Table 4 and Fig. 4).
- A 50 % variation of the damping ratio around the average value of 0.15, which corresponds to the sand soils, is reflected by a seismic response modification of about 10 % (Table 5 and Fig.5).
- Horizontal extension of the soil model size leads to an increase of the seismic response (Table 6 and Fig.6). The length of soil model is to be established in accordance with the geodynamic properties of the in situ layers and predominant seismic motion parameters.
- For the soil deposits having surface strata of small "rigidities", an increase of the soil model hight beyond certain limits, leads to a drop in seismic deformation response of the upper strata (Table 7 and Fig.7). In the case of deposits for which the base rock is located at relatively large depths, the soil model height may be considered up to the level of that stratum which has a shear modulus from 3 to 3,5 times greater than the modulus corresponding to surface stratum.
- The presence of underground structure does not change significantly the seismic response of virgin soil deposit (Table 8 and Fig.8.a and 8.b)

4. COMPUTATION TECHNIJUES FOR USUAL DESING

4.1. The effects by introducing extension of the soil model may be simulated by introducing two marginal zones (with geodynamic characteristics differing from the actual ones), into the soil model having a relatively small length (Fig.3.d). By modifying either the modulus G or the density δ, in the sense of decreasing the propagation velocity of waves through those zones (Table 2), an atenuation of border effects on the seismic response at central zone of soil model is obtained. Some results obtained by this procedure are presented in Table 9 and Fig.9.)

This approach allows a reduction in the volume of computation as a result of reducing the number of the system degree of freedom. It becomes clear that for desing purposes, it is necessary to use as base imput the accelerogram determined by convolution technique of the actual seismic motion.

4.2. The main seismic action upon the underground structure consist of the soil strain state modifications. The coupled soil-structure system exhibits both the amplification and seismic damping effects corresponding to the virgin soil deposits.

Due to the two mentioned aspects, the structure stress state may be evaluated in the regime of static actions, on the basis of imposed deformation method. The structure may be modeled under the form of frame or bar systems, depending on the plane in which the analysis is performed being coupled with the surrounding medium. The strain states resulted from the analysis of the soil model which correspond to the time instants in which maximum stresses appear into the finite elements of the construction location is imposed to thet medium.

5. CONCLUSION

- The underground structure desing based upon the seismic coefficient method is generaly unadequate, because the main action consists in the modification of the soil strain state and not in the change of the motion acceleration.
- The seismic analysis of the soil model supplies sufficient data for the usual desing of underground structure based on imposed deformation method.
- The use of some computation practices into analytical method based on finite element, gives the possibility of using middle capacity computer leading to reduction in the costs of desing.

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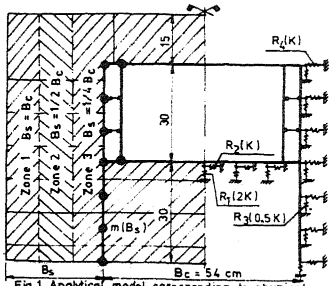


Fig.1 Analytical model coresponding to phyzical model M II-10

Table 1

Model type	E daN/cm²	Frequencies (Hz) Analyt	Frequencies (Hz) Exp.	Δmax (mm) Static Analyt.	Δmax (mm) Static Exp.	Δmax (mm) Harmonic Analyt.	Δmax (mm) Harmonic Exp	Δmax (mm) Seismic Analyt.	Δmax (mm) Seismic Exp.
M II-S	70	17.22	11...	–		0.18	0.26	0.17	0.21
	140	21.82	..15.5	–		0.13		0.09	
M II-4	70	16.15	11...	0.120	0.096	0.16	0.21	0.14	0.18
	140	20.77	..14.6	0.114		0.11		0.08	
M II-10	70	18.25	11...	0.152	0.082	0.20	0.30	0.22	0.28
	140	22.52	..14.5	0.112		0.14		0.17	
M III-S	140	8.89	5...	–	–	1.15	1.30	1.09	1.15
	210	10.12	...8.8	–		0.92		0.80	
M III-4	140	6.79	6..	0.323	0.26	0.96	1.13	1.01	0.90
	210	9.50	8.8	0.311		0.81		0.79	
M III-10	140	6.24	5.5...	0.243	0.22	1.83	2.02	1.64	1.91
	210	7.63	.. 8.0	0.217		1.51		1.26	

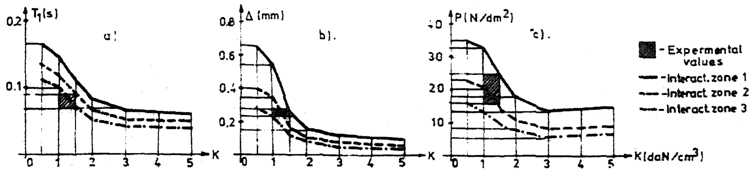
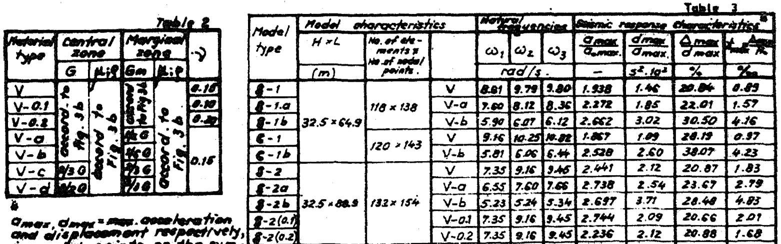


Fig 2 Response variation of model vith discrete sprrngs and masses versus stiffness and width of interaction zones-M II-10



a).Model dimensions

b) Dynamic characteristics of soil layers

FIG.3-FINITE ELEMENT ANALYTICAL MODELS

Table 2

Material type	Central zone G	Central zone μ;ρ	Marginal zone Gm	Marginal zone μ;ρ	ν
V	accord. to fig. 3b	accord. to Fig. 3b	accord. to Fig. 3b	accord. to Fig. 3b	0.16
V-0.1					0.10
V-0.2					0.20
V-a			1/6 G		0.15
V-b			1/6 G		
V-c	1/3 G		1/36 G		
V-d	1/2 G		1/18 G		

a

a_{max}, d_{max} = max. acceleration and displacement respectively, in nodal points on the symmetry axis of the model

Δ_{max} = max. relative displacement between nodal points located at the floor and raft level on the symmetry axis of the model.

$a_{0max.} = 1.95$ m/s²

Table 3

Model type	Model characteristics H × L (m)	Model characteristics No. of elements × No. of nodal points.	Model characteristics	Natural frequencies ω_1 rad/s.	Natural frequencies ω_2 rad/s.	Natural frequencies ω_3 rad/s.	Seismic response characteristics[a] $\frac{a_{max}}{a_{0max.}}$ –	$\frac{d_{max}}{a_{max.}}$ s².10²	$\frac{\Delta_{max}}{d_{max}}$ %	[illegible] ‰
B-1	32.5 × 64.9	118 × 138	V	8.81	9.79	9.80	1.938	1.46	20.84	0.89
B-1.a			V-a	7.60	8.12	8.36	2.272	1.85	22.01	1.57
B-1b			V-b	5.90	6.07	6.12	2.662	3.02	30.50	4.16
C-1		120 × 143	V	9.16	10.25	10.82	1.867	1.09	28.19	0.97
C-1b			V-b	5.81	6.06	6.44	2.528	2.60	38.07	4.23
B-2	32.5 × 88.9	132 × 154	V	7.35	9.16	9.45	2.441	2.12	20.87	1.83
B-2a			V-a	6.55	7.60	7.66	2.738	2.54	23.67	2.79
B-2b			V-b	5.23	5.24	5.34	2.697	3.71	28.48	4.83
B-2(0.1)			V-0.1	7.35	9.16	9.45	2.744	2.09	20.66	2.01
B-2(0.2)			V-0.2	7.35	9.16	9.45	2.236	2.12	20.88	1.68
B-3	32.5 × 120.9	146 × 170	V	6.29	8.13	8.46	3.005	2.78	23.31	3.30
B-4	39.5 × 88.9	182 × 154		6.71	7.85	8.22	2.687	2.37	14.60	1.57
B-5	51.5 × 88.9	148 × 171		6.44	6.78	6.98	2.743	2.39	8.12	0.90
C-5		144 × 172		6.49	6.94	7.51	2.503	2.06	9.87	0.86
C_0-5				6.47	6.90	7.50	2.487	2.06	8.55	0.74
C-5c			V-c	5.31	5.68	6.15	2.990	2.90	12.49	1.83
C-5d			V-d	7.95	8.51	9.21	1.959	1.46	8.17	0.48

TABLE 4

MODEL TYPE	$\frac{G}{G_{max}}$	$R_{max}(G)$ d cm	a m/s^2	Δ cm
C-5c	0.44	16.90	5.83	2.11
C-5	0.66	10.03	4.88	0.99
C-5d	1.00	5.66	3.82	0.47

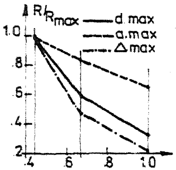


Fig. 4 a

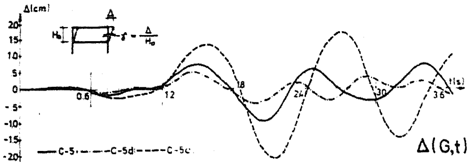


Fig. 4 b

TABLE 5

MODEL TYPE	$\frac{\nu}{\nu_{max}}$	$R_{max}(\nu)$ d cm	a m/s^2	Δ cm
S-2(0.1)	0.50	11.20	5.35	2.31
S-2	0.75	10.10	4.76	2.11
S-2(0.2)	1.00	9.25	4.36	1.92

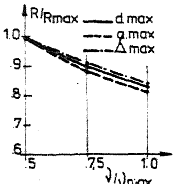


Fig. 5.a

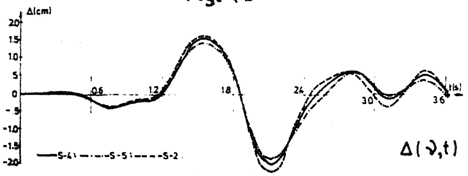


Fig. 5b

TABLE 6

MODEL TYPE	$\frac{L}{L_{max}}$	$R_{max}(L)$ d cm	a cm	Δ cm
S-1	0.45	5.51	3.78	1.02
S-2	0.74	10.10	4.76	2.11
S-3	1.00	16.30	5.86	3.80

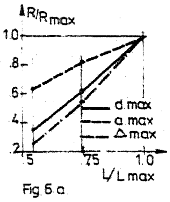


Fig. 6 a

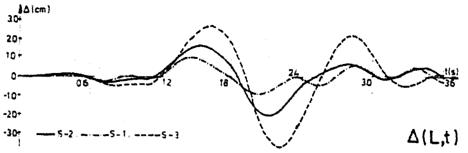


Fig. 6 b

TABLE 7

MODEL TYPE	$\frac{H}{H_{max}}$	tv* s	$R_{max}(H)$ d cm	a m/s^2	Δ cm
S-2	0.63	0.339	10.10	4.76	2.11
S-4	0.77	0.394	12.40	5.24	1.18
S-5	1.00	0.483	12.80	5.35	1.04

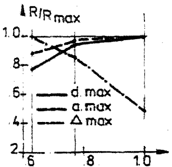


Fig. 7a.

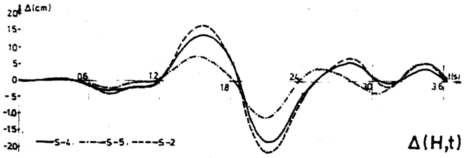


Fig. 7 b

TABLE 8

MODEL TYPE	$R_{max}(S-C)$ d cm	a m/s^2	Δ cm
S-1	5.51	3.78	1.02
C-1	3.97	3.64	-1.12
S-5	12.80	5.35	1.04
C-5	10.03	4.88	0.99
C0-5	9.99	4.85	0.86
S-1b	15.67	5.19	4.78
C-1b	12.80	4.93	4.87

TABLE 9

MODEL TYPE	t_h* s	$R_{max}(L')$ d cm	a m/s^2	Δ cm
S-1	0.67	5.51	3.78	1.02
S-1a	0.75	8.20	4.43	1.81
S-1b	0.92	15.67	5.19	4.78
S-2	0.92	10.10	4.76	2.11
S-2a	1.02	13.56	5.34	3.21
S-2b	1.25	19.63	5.28	5.75
S-3	1.25	16.30	5.86	3.80

* tv, th - average time necessary for shear wave to propagate along the model height H or the length L, respectyvely.

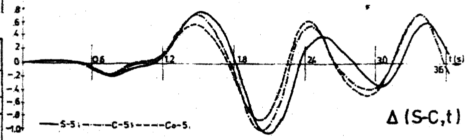


Fig. 8a

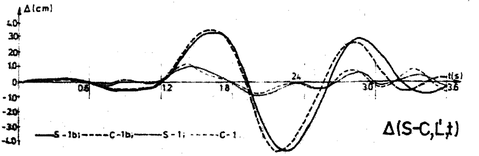


Fig. 8b

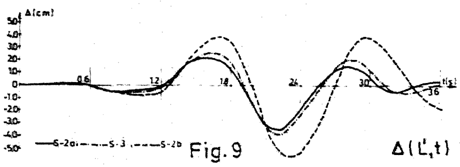


Fig. 9

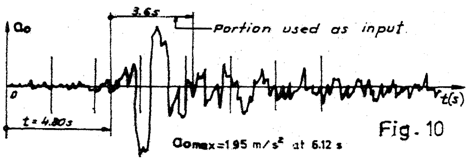


Fig. 10

N-S Component of the Accelerogram Recorded in Bucharest Durig Romania Earthquake of March 4, 1977.