EXPERIMENTAL INVESTIGATIONS REGARDING SOIL-UNDERGROUND METROTYPE STRUCTURE DYNAMIC INTERACTION

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Synopsis: To carry aut economically and safely underground structures for the urban transport in Bucharest, the Company "METROUL" - Bucharest, initiated and financed a large program of investigations regarding the dynamic interaction effects of the soil and the underground structures of gallery, tunnel or subway station type under seismic actions.

The researches performed at Central Institute for Research, Design and Guidance in Civil Engineering (ICCPDC)-Branch of Iassy, consisted of testing phisical models as well as theoretical researches using various models and computation tehniques.

The tests of the models in the dynamic range were carried aut by using a mechanical generator of armonical vibrations of 1o Kw and some seismic shaking tables of 15o and 14oo KN capacity.

Some aspects of interest for aseismic desing of those types of underground constructions as resulted from performed researches are also presented in this paper.

1. INTRODUCTION

The behaviour of underground structures to earthquake actions presents a complex character due to the interaction phenomenon between the soil - a medium having varied geomechanical and reological characteristics and the "under-

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ground structures" - structural sistems of different forms and complexity levels.

The stress and strain state, the dynamic pressure variation on the closing elements as well as the aseismic design of the underground structures are aspects seldom encountered in the technical literature.

Due to technical difficulty involved by testing and by the necessity of a special testing equipment, the investigations on physical models were studied in a less degree in the world.

In order to construct, in proper economic and safety conditions, the underground structures for the urban traffic in the capital of Socialist Republic of Roumania the "Metro" Company Bucharest initiated and financed a large research program regarding the dynamic interaction effects between soil and underground structures of gallery, tunnel or metro station type in the case of earthquake actions.

The research performed at Central Institute for Research, Design and Guidance in Civil Engineering, Branch of Iassy, included testings on physical models as well as theoretical investigations using different models and computing approaches. These investigations refered to the determination of the plane strain state using three set of gallery and metro-station models having different cross section shapes, specific to the execution methodes adopted.

2. EXPERIMENTAL INVESTIGATIONS

Three set of physical models at length scales of $K_L = 36$, $K_L = 18$ and $K_L = 6$ (Fig.1, 2 and Table 1) were tested in harmonic and seismic range, each set consisting of two soil-models - "MS" (dry sand and satured sand) and several models "MC" for underground structure.

To point out the dynamic interaction effects between the "MS" and "MC" subsystems, the adopted technical approach provided first the testing of individual "MS" models and finaly the coupled „M"=„MS"+„MC" models.

A number of 214 tests in dynamic regime were carried out in this manner using 7o different models from which 35 were of "soil + underground structure" type.

The models were subjected to harmonical actions, shocks and seismic actions (three artificial earthquakes and Romanian earthquake of 1977).

3. MAIN EXPERIMENTAL RESULTS

To harmonical actions

In the case of "MS" models, the accelerations of surface stratum motions, exhibited values of 1.5...2.5 times the acceleration recorded in the stratum located to the base of the models. Dynamic behaviour of "MS" model soil layers is similar to that of a sheared column.

The tests performed in harmonical regime, initially on the individual "MS" and "MC" models and subsequently on coupled "M" models, pointed aut that natural frequencies as well as the damping ratios of the "M" models presented values closed to those recorded on the individual "MS" models, that is practically independent of the mass, forms and dynamic characteristics of the "MC" models (Tabel 2).

The "M" models under variable frequency harmonic actions exhibited accelerations, at the floor level and the foundation raft level for the "MC" models (Fig.3) and relative displacements between the floor plate and foundation raft which were closed to the values recorded in the corresponding "MS" model soil stratum.

Maximum values of the dynamic response for "M" model were recorded near the natural frequency oscillations of the "MS" models, the influence of the "MC" model form and rigidity being unsignificant.

To seismic action

The tests conducted in seismic regime emphasized the model behaviour characteristics, which were similar to those recorded at the tests in harmonical regime.

In the case of "M" models having structures with moulded walls the maximum values of relative displacements between floors and foundation raft were generally greater than the "MS" model relative displacements among soil strata located at the same level, in contrast with the case of "M" models having structures without moulded walls, where relative displacements exhibited smaller values. The raft slidings are restrained by the moulded walls so that a larger amount of energy associated to adjoining soil strata is transformed to the structure, in contrast with simple constructions at which the raft clasical joinings with the soil enable plan-parallel displacement without any implications to structure.

In the case of "M" models, having stations with moulded walls and lateral tunnels (Fig.1) with stiffness nearly equal to that of stations at which the moulded wall cross section is rectangular, smaller relative displacements between upper floor and raft were recorded as compared with the displacements of soil strata within "MS" model.

This result may be due to the fact that a larger soil mass is involved in the motion, so that a reactive couple being generated which tends to reduce the structure relative displacements.

The dynamic pressures recorded on "MC" model walls showed a nonuniform distribution along the height. In the case of models without moulded walls, the dynamic pressure diagram had approximately the same shape for all section types, the maximum values being usually recorded at the upper part of the structure.

In the case of models with moulded walls, the maximum pressures were recorded either to upper floor level, or to raft level depending on the dynamic action characteristics.

The pressure related to the accelerations of harmonical motion exciting the "M" models, exhibited maximum values within low frequency range, where the action was characterized by large displacements.

CONCLUSIONS

- Seismic response of soil strata located at upper part of the site, where the "on the surface" common buildings are generally founded, shows larger values than those corresponding to motion of deep strata. Due to this aspect, the construction located at depth into resistant strata, present a better seismic behaviour as compared to those erected on soft soil strata, near to the earth surface.

- The seismic response of soil strata in which underground structures are to be constructed is not modified in a great extent by the presence of the construction, excepting a zone in its close vicinity.

- Underground structures do not exhibit the resonance phenomena as in the case of common surface structure.

The effects of intercation between soil and underground structure could be predicted in terms of ratio of energy last within the volume of soil dislocated by the construction to that of the construction itself in the view of obtaining some similar equal deformations.

- The main seismic action upon the underground construction is the deformation state change of soil strata in interaction with the structure and not with mass forces due to motion accelerations.

R E F E R E N C E S

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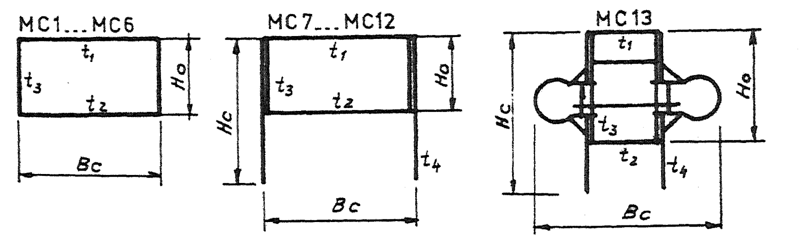
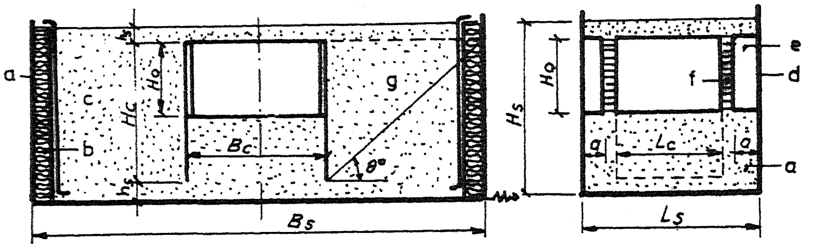


a. MC Models



b.1 Cross section

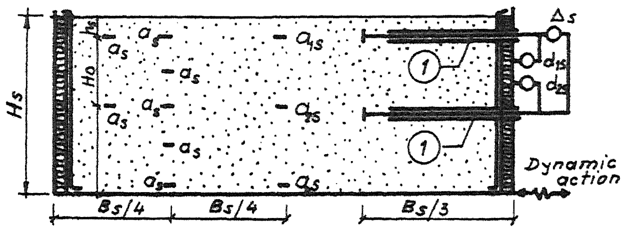
b.2 Longitudinal section

a.- steel box; b - damping cushion from mineral wool panels; c - P.V.C. sheet; d - admitance window into model inner; e - MS-MC stiff coupling flange; f - MS-MC flexible coupling flange; g - uniform sand; U_n = 3,4 ... 3,8; $\gamma(w_o)$ = 18 KN/m³; $\gamma(w_{saturated})$ = 21 KN/m³

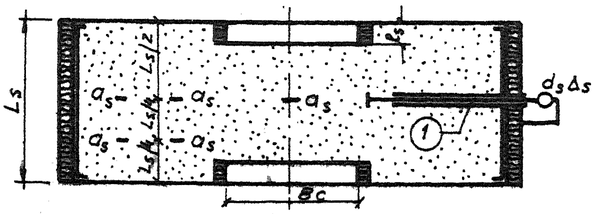
Fig. 1 - Experimental models

Table 1

Model set	Soil model sizes MS (cm) Bs/Ls	Hs/a	hs/h's	θ°	Structural model MC-type	Model sizes of the underground structure MC-(cm) Bc/Lc	Ho/Hc	Wall thickness t_1	t_2	t_3	t_4	Weight Ms (to)	Mc (Kg)	MC weight to dislocated soil volum ratio
M I	130/65	40/9	5/7	32°	MC1 ... 3	27/42	15/–	0,4	0.4	0.2		0.7-0.8	11 ... 25	0.36 .... 0.83
					MC4 ... 6					0.3			12 ... 27	0.40 .... 0.87
					MC7 ... 9	27/42	15/28	0.4	0.4	0.2	0.2		16 ... 31	0.54 .... 1.02
					MC10 ... 12						0.3		18 ... 32	0.58 .... 1.06
M II	200/80	80/12	15/5	41°	MC 1 ... 3	54/50	30/–	0.8	1.0	0.4		2.45-2.80	53 ... 85	0.35 .... 0.56
					MC4 ... 6					0.8			62 ... 94	0.41 ... 0.62
					MC 7 ... 9	54/50	30/60	0.8	1.0	0.4	0.4		66 ... 98	0.45 .... 0.66
					MC 10 ... 12						0.8		80 ... 112	0.50 .... 0.70
			7/5	37°	MC 13	65/50	41/68	0.8	0.8	0.4	0.8		65	0.55
M III	600/200	220/47,5	30/22	37°	MC 4	160/100	90/168	2.5	3.0	2.5		50-57.8	1.100	0.42
					Mc 10						2.5		1.600	0.61

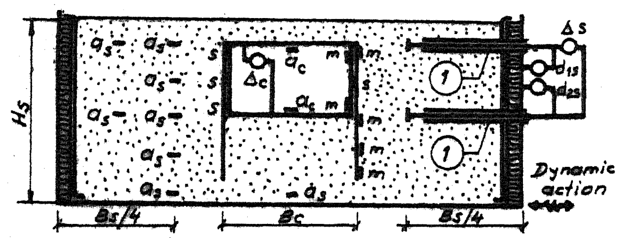


a.1. Cross section



a 2 Horizontal section

MS Models



b. MS+MC models

Fig 2 Strain gage Location

a_s , a_c - piezoelectric accelerometers B & K - mounted in MS or on MC.

d_s - Philips type strain gage to record the displacements of the sand layers relativ to the steel boxwalls.

(1) - steel rods mounted into the PVC tubes provided with plates to be fixed in the sand layer.

Δ_s ; Δ_c - strain gage for recording the relative displacements between the sand layers and between the floor and the foundation plate respectively

m - resistive electric strain gage for measuring the strain of the MC model walls.

p - transducer for measuring dynamic pressure.

Table 2

Dynamic response of the models	Type of action	II set models $K_L = 17{,}5 \ldots 35$				III set models $K_L = 5.83 \ldots 11.67$		
		MII-5	MII-4	MII-10	MII-13	MIII-5	MIII-4	MIII-10
Natural frequency of the oscillation (Hz)	Harmonic	11	11	12	12	6,5	8	8,5
	Seismic	13,8-15,5	13-14,6	11,2-14,5	12,1-15,0	5-8,8	6,5-8,9	5,5-8,8
critical damping percentage.	shock	8-12	7-11,5	6,5-14	8,5-15	10-13,5	9-12,5	7,5-15
Relative displacements $f = \left(\frac{\Delta}{H_o \cdot a_{0s}}\right)$ ‰ (average value)	Harmonic	0.60	0.53	0.74	0.58	0.60	0.63	0.73
	Seismic	0.65	0.57	0.81	0.55	0.55	0.46	0.82

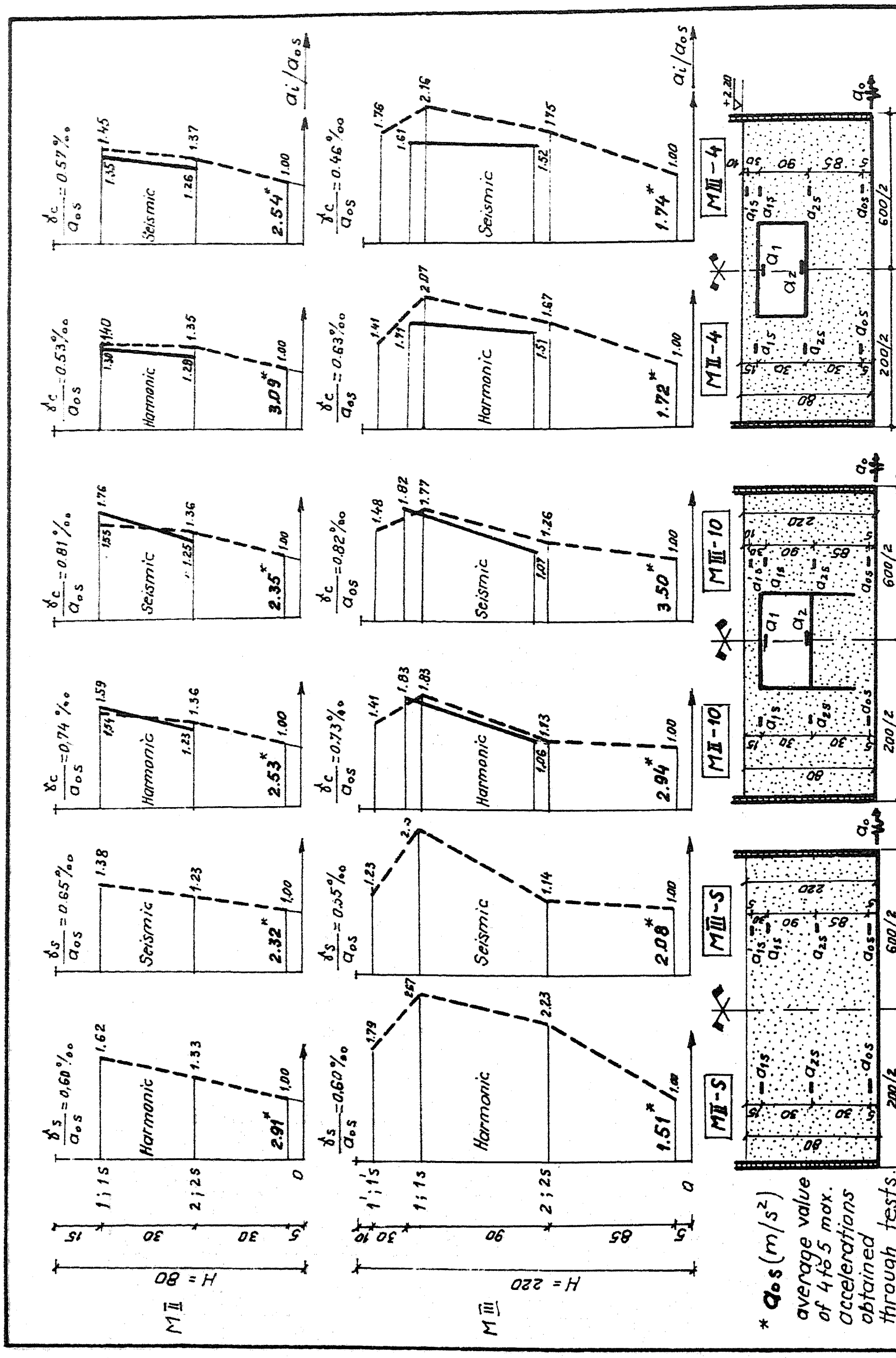


Fig. 3 - Acceleration distribution diagram on the models due to seismic and harmonic actions.