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SYNOPSIS: Presented in this paper are the results of the analyses of dynamic soil-structure interaction effects based on recorded strong motions during Montenegro (Yugoslavia) earthquake of April 15, 1979. Acceleration time histories have been recorded by strong motion instruments installed at foundation level of structures located in the epicentral area, founded in different soil conditions including stiff, medium and soft soils. Applying substructure technique from known motions at foundation level of structures, corresponding free field motions were computed. By comparison of computed free field motions and recorded motions at foundation level, dynamic soil-structure interaction effects, in different soil conditions and levels of earthquake excitation were analysed.

INTRODUCTION

Recorded strong motions during earthquakes could be considered as results of a large natural experiment, the complexity and reality of which cannot be simulated thoroughly either analytically or experimentally. Taking into account the complexity of the dynamic soil-structure interaction phenomena, strong motion records incorporating interaction effects appear to be extremely essential data for clarification of the dynamic soil-structure interaction characteristics and effects.

During the Montenegro earthquake of April 1979, including several foreshocks and many aftershocks, a great number of acceleration time histories have been recorded by strong motion instruments located in the epicentral area. These strong motion instruments were installed at foundation level on many different structures founded in different soil conditions. Out of the great number of records, chosen for analysis were the records of the strongest foreshock, the main shock and the four aftershocks obtained at similar structures founded on rock site, as well as on medium soft/soft soil. Accordingly, the recorded strong motions were used in the analysis of dynamic soil-structure interaction for different soil conditions and levels of seismic excitation.

CHARACTERISTICS OF MONTENEGRO EARTHQUAKE

The Montenegro, Yugoslavia earthquake of April 15, 1979 is one of the strongest which have occurred in this century in the Balkan region. The earthquake magnitude, according to several seismological stations, has been determined to have been M = 7.0/7.2 on the Richter's scale.

The main shock was preceded by several foreshocks which had started at the end of March 1979. The strongest foreshock occurred on April 9 with a magnitude of M = 5.1. After the main shock, many aftershocks occurred. The number of those with $M \geq 4$ was 75. The epicenters of these earthquakes were in the Adriatic Sea, but, very near the coast.

The main shock, the strongest foreshock and several aftershocks activated a great number of

TABLE I. Maximum Recorded Accelerations and Instrument Sites Data

Site No.	Name	Epi-central distance km	Hipo-central distance km	Soil Type	Accelerogram	Maximum Recorded Acceleration (g)			
						(N-S)	(W-E)	(N-S)+(W-E)	Vertical
1	Hotel Albatros Ulcinj	16	23.3	Flysch Rock	E60 Ulcinj-2	0.1714	0.2223	0.2392	0.1629
2	Hotel Olimpic Ulcinj	16	23.3	Medium Soft Soil	E59 Ulcinj-1	0.2848	0.2398	0.2865	0.3619
3	Town Assembly Bar	8	18.8	Soft Soil	E61 Bar	0.3640	0.3592	0.4029	0.2357
4	Hotel Oliva Petrovac	22	27.8	Stiff Soil	E58 Petrovac	0.4356	0.3044	0.4376	0.2016
5	School Herceg Novi	63	65.3	Rock	E62 Herceg Novi	0.2134	0.2305	0.2795	0.1747
6	School Lapad Dubrovnik	110	111.3	Limestone Rock	E64 Dubrovnik	0.0629	0.0754	0.763	0.0232
7	Salt Factory Ston	140	141.0	Soft Soil	E63 Veliki Ston	0.2692	0.1729	0.2829	0.0462

SMA-1 instruments in the epicentral zone and wider on the territory of Yugoslavia. Table I shows the basic instrument sites data for seven sites at distances of 20 to 140 km from the epicenter of the main released energy during the main shock of the earthquake of April 15, 1979. The maximum recorded accelerations are also presented.

PURPOSE AND APPLIED MODELS AND METHODS OF ANALYSIS

Out of the great number of accelerograms obtained at the mentioned sites, chosen for analysis were the horizontal components of the records of the strongest foreshock (April 9, 1979), the main shock (April 15, 1979) and the four aftershocks (April 15 and 16, and May 14 and 24, 1979), obtained at Hotel "Albatros" - Ulcinj, Hotel "Olimpic" - Ulcinj and Town Assembly - Bar sites. The chosen shocks are further in the text referred to with indexes from (1) to (6), respectively. The choice was made based on the following considerations and assumptions:

- The strong motions excited by the chosen shocks are with sufficiently high amplitude level, and the obtained records are of high quality;
- The sites have similar regional characteristics (distance and position in relation to the source, regional geological conditions, etc.);
- The soil properties of the sites are different, affecting the characteristics of strong motions excited at the sites. One of them, Hotel "Albatros" site, is characterized by hard soil/rock conditions, while the remaining two by medium soft/soft soil conditions. Therefore, Hotel "Albatros" site can be used as a reference for comparison with the other two sites, as well as for analysis of the local effects;
- The dynamic characteristics of the buildings at the sites are similar. The relationship between the structural stiffness characteristics and the soil of Hotel "Olimpic" - Ulcinj and Town Assembly - Bar points to existence of soil-structure interaction effects.

The basic data and characteristics of the chosen accelerograms are given in Table II and Fig. 1. Table II presents peak horizontal accelerations in N-S direction, while Fig. 1 depicts absolute acceleration response spectra.

TABLE II. Maximum Accelerations of Recorded Motions (g)

	Earthquake	Recorded Motions on Rock (Albatros)	Recorded Motions at Foundation Level	
			Olimpic	Bar
1	Foreshock (9.04)	0.043	0.075	-
2	Main Shock(15.04)	0.172	0.272	0.363
3	Aftershock(15.04)	-	0.053	0.054
4	Aftershock(16.04)	0.059	0.077	0.051
5	Aftershock(14.05)	0.037	0.083	-
6	Aftershock(24.05)	-	0.035	0.201

The accelerograms are obtained from instruments installed on buildings at foundation level. Since the foundations are shallow, it can be assumed that this level is on the surface of the sites.

The comparison of the peak accelerations in Table II and the spectral amplitudes in Fig. 1 point to existence of significant differences of the values for the three sites. If it was assumed that possible differences of the values of strong motions from the viewpoint of regional effects might be neglected because of the similar regional conditions at the sites (with the

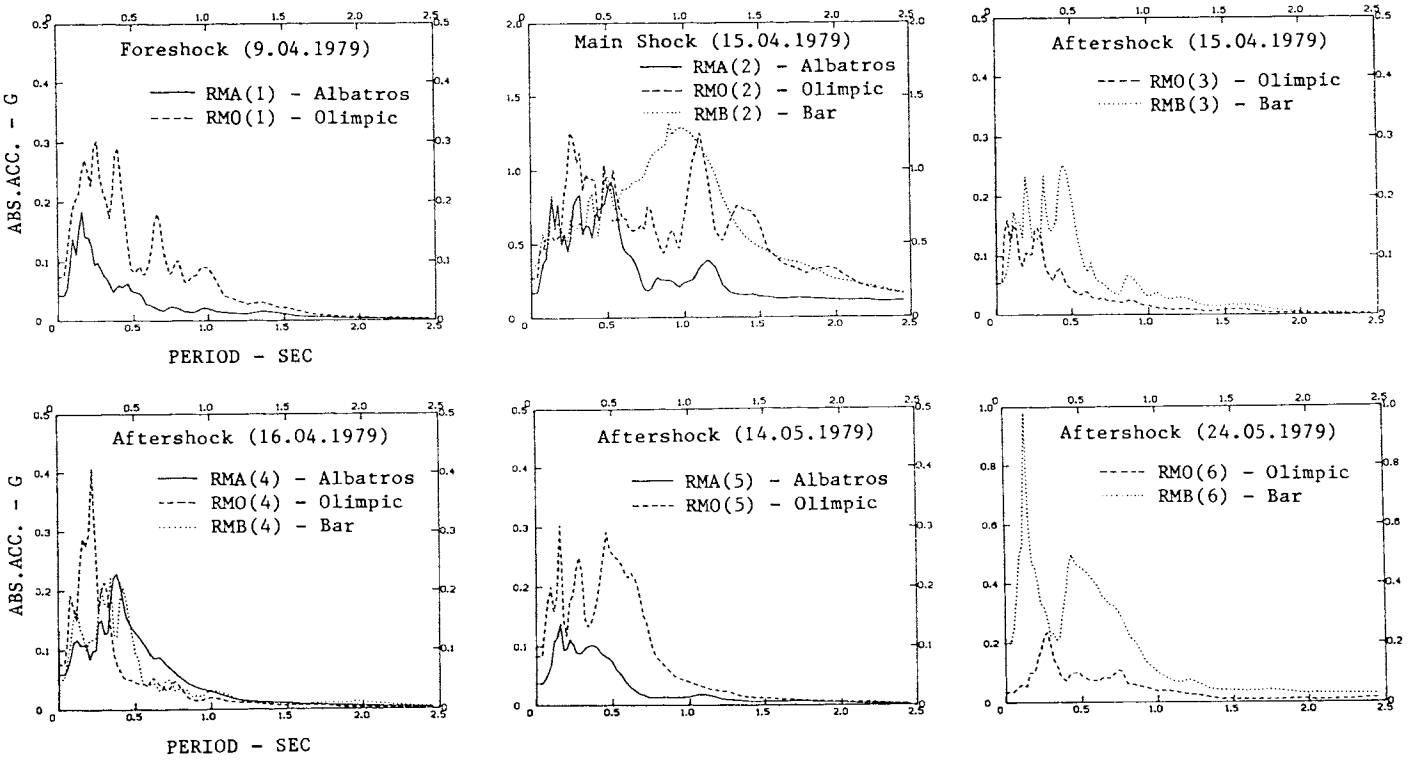

Fig. 1. Absolute Acceleration Response Spectra of Recorded Accelerograms

exception of May 24 aftershock), then the differences between the results in Table II and Fig. 1 would result from the effects of local conditions and building structural systems at the sites.

Analysis of the effects of local soil conditions and dynamic soil-structure interaction incorporated in the records is the main objective of the investigations presented in this paper. The analysis is aimed at dividing the summary effect into the effect of soil conditions and dynamic soil--structure interaction system, and thus assessing their significance. Since the analyses are performed by existing analytical methods for analysis of such problems, the results enable assessment of the applicability of these methods, as well.

For realization of these objectives, it was first necessary to define the soil profiles and the dynamic soil properties and then the building structural characteristics.

The site soil profiles were defined by geophysical measurements of elastic seismic waves velocities and by measurements and analysis of microtremors at the sites. Also used were the available results from geomechanical tests. The soil profiles at the sites are shown in Fig. 2.

The profile at Hotel "Albatros" site indicates that the site is on rock and that the strong motion at the site incorporates no significant local effects of soil conditions. From the other two profiles, the sites can be considered to have medium soft/soft soil conditions, where effects of local soil conditions upon strong motions should be expected.

For definition of the mathematical models of the structures at the sites, in addition to the existing data used were also the results from post-earthquake testing of the buildings by ambient vibration technique. The basic data on the buildings and the results from ambient vibration measurements are given in Table III and Fig. 3.

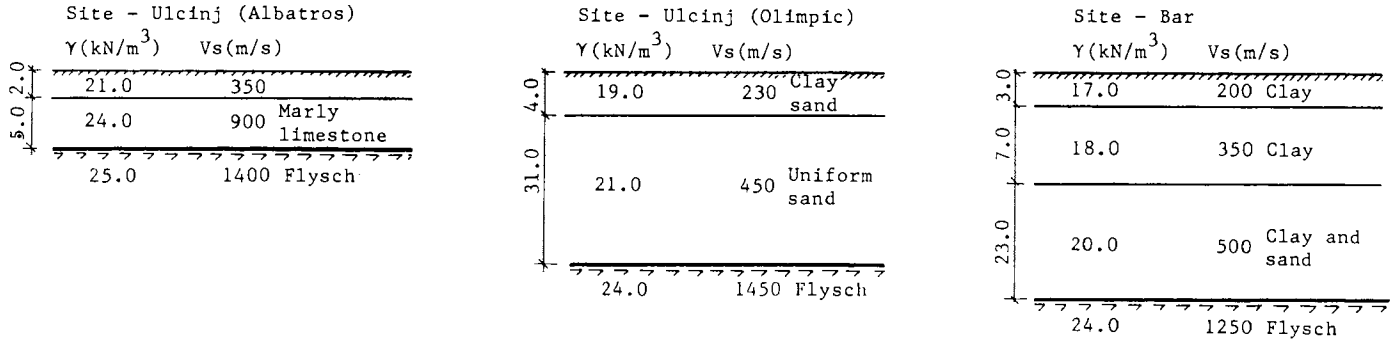

Fig. 2. The Soil Profiles at the Sites

TABLE III. Basic Data on the Buildings and Results from Ambient Vibration Measurements

Building	Structural System	Geometry			Foundation	Fundamental Period	
		Stories	Length N-S (m)	Length E-W (m)		N-S (sec)	E-W (sec)
Hotel "Albatros" - Ulcinj	Skeleton	5	30	14	Shallow	0.313	0.227
Hotel "Olimpic" - Ulcinj	Diaphragm	6	46	10	Shallow	0.327	0.341
Town Assembly - Bar	Skeleton	6	43	13	Shallow	0.327	0.268

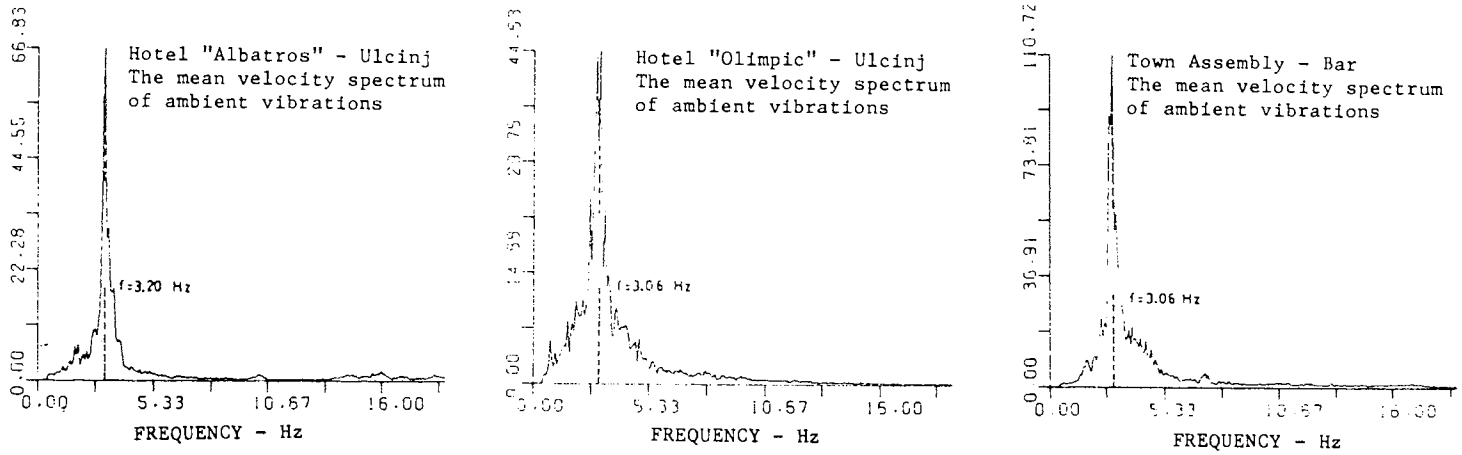

Fig. 3. Fourier Amplitude Spectra Based on Ambient Vibration Measurements

Considering the main dynamic characteristics of the buildings, which indicate that they are relatively rigid structural systems, and the site soil conditions, it may be assumed that the records taken at Hotel "Albatros" site do not incorporate significant interaction effects, while they are present in the records at Hotel "Olimpic" - Ulcinj and Town Asembly - Bar.

Based on the above discussion, the records obtained at Hotel "Albatros" site, not incorporating the effects of local soil conditions and the building, it has been adopted that the recorded strong motions at this site result only from regional effects. Since there are no other records on rock in this region, Hotel "Albatros" site records will be further adopted as characteristics of strong motion on rock outcrop of all three analysed sites.

The analysis of the effects of local soil conditions and dynamic interaction in the records at Hotel "Olimpic" - Ulcinj and Town Assembly - Bar sites has been carried out based on predefined models and by application of dynamic analysis of soil-structure systems at Olimpic and Bar sites applying the standard substructure procedure, as schematically presented in Fig. 4. The analysis was made in the frequency domain. The recorded motions at Olimpic and Bar sites were used as known input motions at foundation level. The analysis was realized in the following steps:

- Using the elastic soil parameters corresponding to the conditions of ambient vibration measurements of the buildings, the initial soil-structure models were defined;
- Deconvolution analyses were carried out for determination of soil strain levels for each of the analysed shocks (1) to (6) and strain compatible soil parameters. So defined soil parameters were used for determination of corresponding frequency dependent impedance functions and definition of soil-structure systems;
- For such soil strain compatible interaction model, defined were the transfer functions (TF) of motion of the foundations in relation to the free field motion;
- Fourier transformations of recorded motions at foundation level at Olimpic and Bar site were divided by the transfer functions obtained in the previous step, thus determining the Fourier transformations of free field motions at the sites. By Inverse Fourier Transformation also defined were the corresponding free field time histories marked as CMOO (Computed Motion at Olimpic from Olimpic Record) and CMBB (Computed Motion at Bar from Bar Record), respectively. It was assumed in the analyses that the effects of kinematic interaction were insignificant. The defined free field parameters represent a basis for comparison with the recorded motions and assessment of the effects of soil condions and soil-structure interaction.

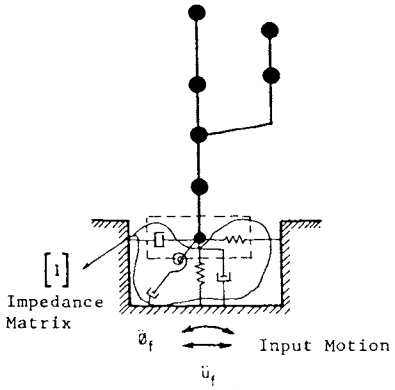

Fig. 4. Applied Mathematical Model in Substructure Approach

RESULTS AND DISCUSSION

The results from performed analyses are presented by maximum accelerations and absolute acceleration response spectra. Because of voluminous number of results, presented are only those related to N-S direction, with the explanation that effects with similar tendencies have also been observed for E-W direction.

Table IV gives the maximum accelerations of computed motions for the six shocks. In order to better clarify the comparative analysis, all recorded motions including Hotel "Albatros" site are presented again.

By comparison of the presented values estimations can be given on the effects of soil-structure interaction and soil conditions upon the values of maximum accelerations.

Soil-structure interaction effects at Hotel "Olimpic" - Ulcinj and Bar sites can be determined by comparison of the values of maximum accelerations from recorded motions (RM) at foundation level with those from computed free field motions (CM). It can be observed that as a result of interaction, the maximum acceleration increase/decrease is in the range up to +30%, i.e., -100%.

The effects of only local soil conditions for the shocks marked with indexes (1), (2), (4) and (5) can be obtained from the comparison of the

TABLE IV. Recorded and Computed Maximum Accelerations

Earthquake		Maximum Accelerations in N-S Direction (g)				
		Albatros	Olimpic		Bar	
		Recorded	Recorded at Foundation	Computed Free Field	Recorded at Foundation	Computed Free Field
No.	Name	RMA	RMO	CMOO	RMB	CMBB
1	Foreshock (9.04)	0.043	0.075	0.059	-	-
2	Main Shock (15.04)	0.172	0.272	0.234	0.363	0.414
3	Aftershock (15.04)	-	0.053	0.111	0.054	0.047
4	Aftershock (16.04)	0.059	0.077	0.086	0.051	0.065
5	Aftershock (14.05)	0.037	0.083	0.082	-	-
6	Aftershock (24.05)	-	0.035	0.027	0.201	0.199

maximum acceleration values from computed free field motions (CM) with recorded motions at Hotel "Albatros" site (RMA). It can be observed that due to local effects there is a significant increase of maximum accelerations. For Hotel "Olimpic" site this increase is in the range up to 120%. For Bar site, for the main shock, it reaches even 140%. This increase, however, probably results from certain regional effects.

The interaction effects, estimated only through maximum accelerations, are perhaps not sufficiently expressed. But, when estimated through absolute acceleration response spectra, they are far more expressed.

The interaction effects for Hotel "Olimpic" site can be seen in Fig. 5, giving a comparative presentation of response spectra of recorded motions

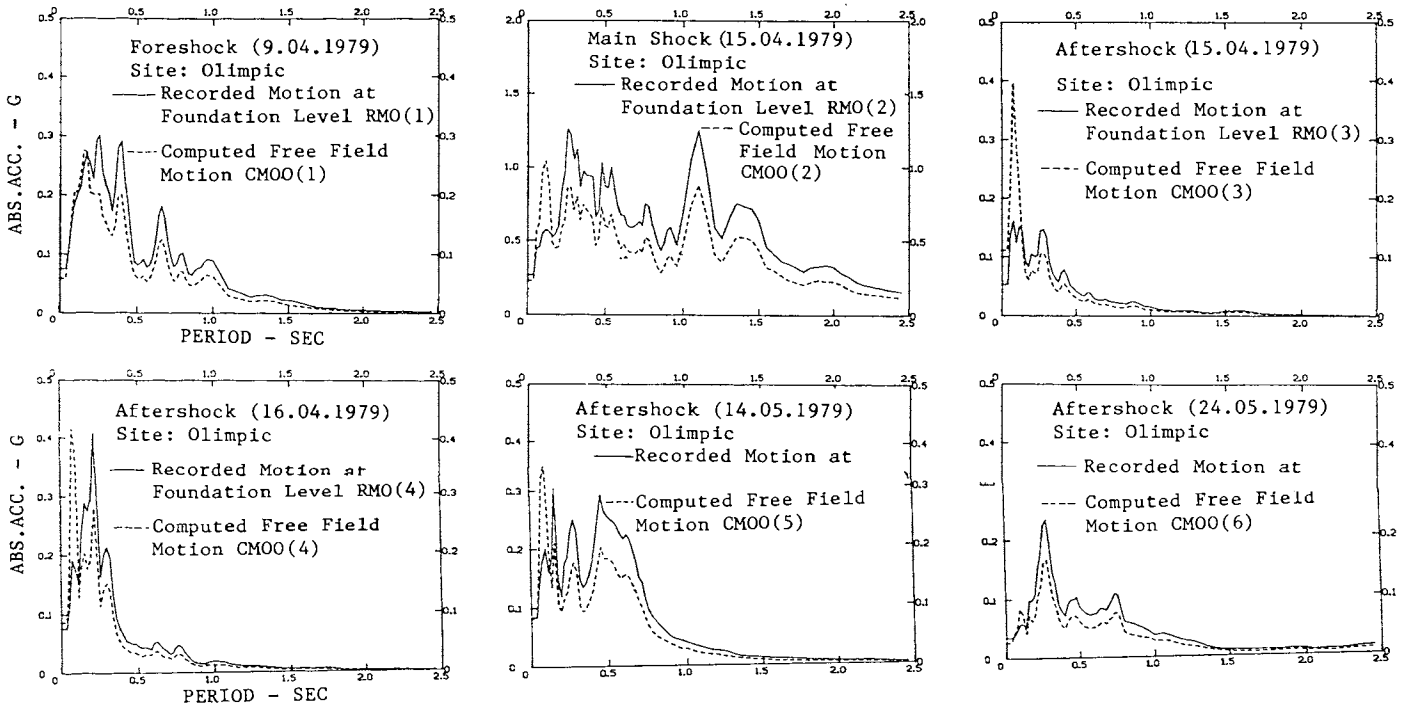

Fig. 5. Response Spectra at Hotel "Olimpic" Site

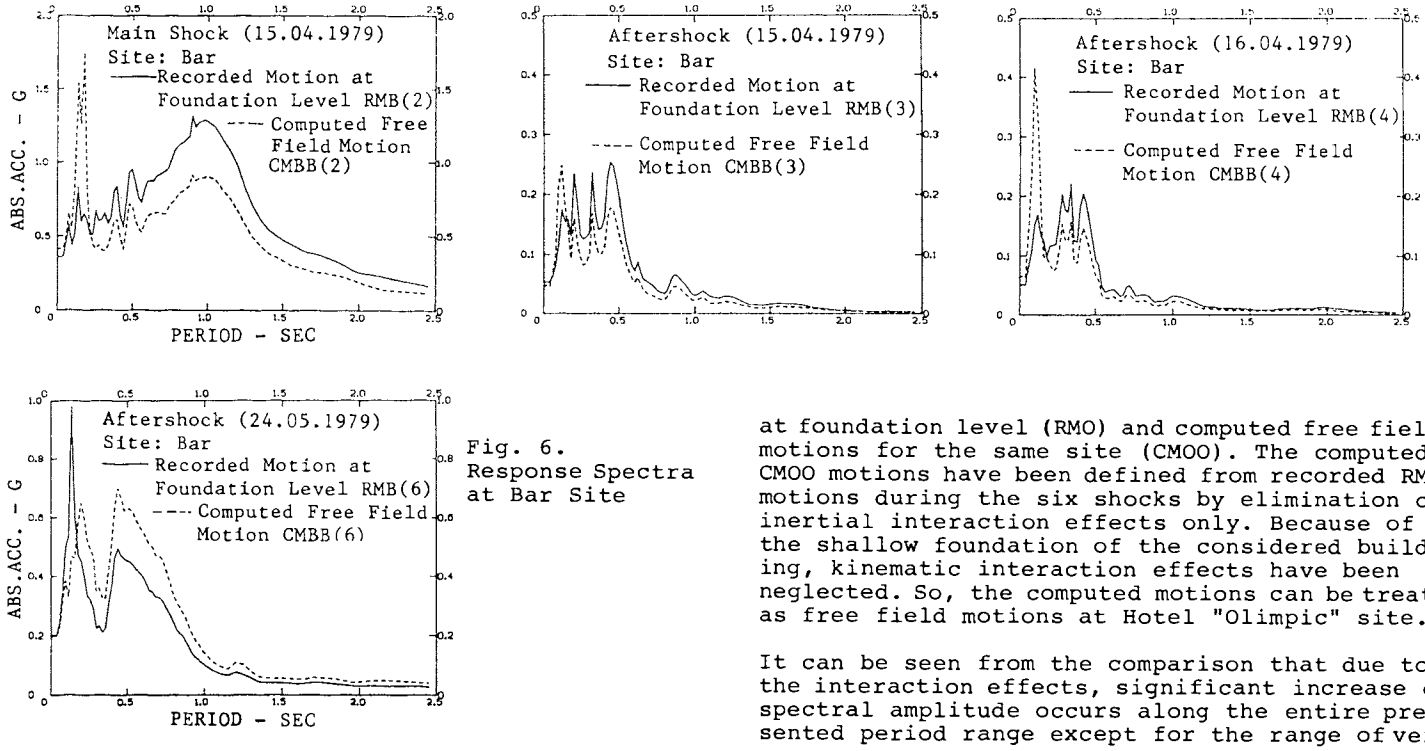

Fig. 6. Response Spectra at Bar Site

at foundation level (RMO) and computed free field motions for the same site (CMOO). The computed CMOO motions have been defined from recorded RMO motions during the six shocks by elimination of inertial interaction effects only. Because of the shallow foundation of the considered building, kinematic interaction effects have been neglected. So, the computed motions can be treated as free field motions at Hotel "Olimpic" site.

It can be seen from the comparison that due to the interaction effects, significant increase of spectral amplitude occurs along the entire presented period range except for the range of very

low periods. This amplitude increase is highest for the main shock.

The interaction effects for the Town Assembly building in Bar can be seen in Fig. 6, giving a comparative presentation of response spectra of recorded motions at foundation level (RMB) and computed free field motions for the same site (CMBB). The computed CMBB motions have been defined from recorded RMB motions during four shocks by elimination of inertial interaction effects only. Again kinematic interaction effects have been neglected because of the shallow foundation of the considered building.

It can be seen from the comparison that also in this case for three of the four analysed earthquakes, as a result of the interaction effects, there is a significant increase of spectral amplitudes along the entire period range except for the range of very low periods. However, for the aftershock of April 24, 1979, due to the interaction effects, there is an opposite case, that is, decrease of spectral amplitudes except for the range of low periods with increasing amplitudes.

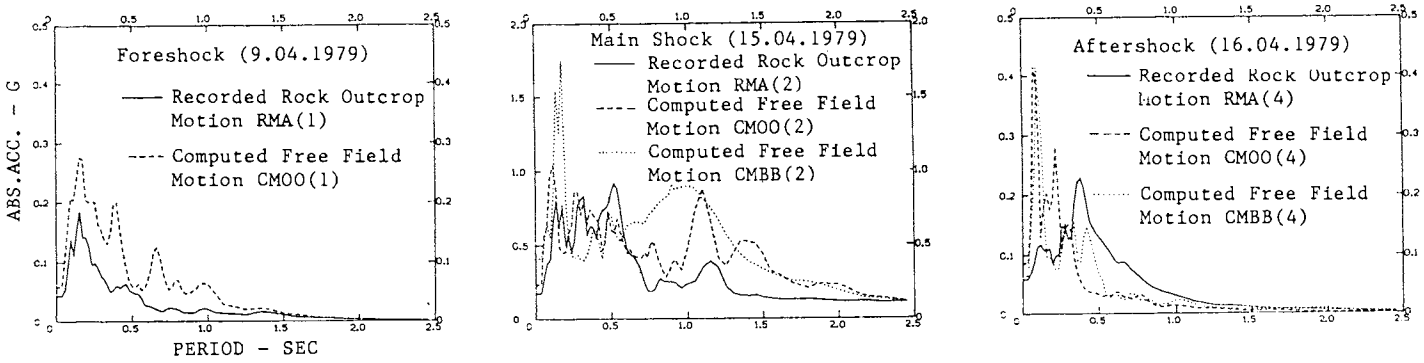

Fig. 7. Response Spectra of Free Field Motions

Fig. 7 shows the corresponding response spectra of recorded motions at Hotel "Albatros" site (RMA) and the computed free field motions at Hotel "Olimpic" (CMOO) and at Bar (CMBB) sites. Based on the assumption for the insignificant effect of the dynamic interaction upon the motion of the structure founded on rock and the neglected effects of the kinematic interaction, RMA, CMOO and CMBB motions are in fact free field motions at the sites. Consequently, the difference between the three response spectra expresses the amplitude-frequency modification of motions as a result of the effects of local soil conditions of Hotel "Olimpic" and Bar sites.

CONCLUSIONS

The presented results from the comparative analysys of the dynamic soil-structure interaction based on records from strong earthquakes support the importance of the effects of the local soil conditions and the interaction effects upon the seismic response of the soil-structure systems. Therefore, in the records of strong earthquakes obtained at foundations, that is, at the level of foundation structures of buildings, existence of such effects should be expected. Taking this into consideration, for accurate interpretation of the strong motion records and for definition of free field motions and input motions for seismic response alysis of soil-structure systems, the need is imposed for previous definition of the interaction effects incorporated in the recorded strong motions.

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