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Effects of Local Soil Conditions in the 1986 Kalamata Earthquakes

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YNOPSIS: Seismic ground response analyses and simplified determinations of fundamental periods of soil profiles were onducted for nine sites of the Greek coastal city of Kalamata which was struck by two destructive small epicentral istance earthquakes in September of 1986. The response analyses were performed by using the computer program LUSH hereas the fundamental periods were determined by applying simplified methods suggested in recent literature. The ynamic soil properties needed in all calculations were obtained by in-situ and laboratory testing. The results of all nalyses showed differentiation of response from site to site in terms of both frequency content and intensity of otion. Furthermore, the calculated fundamental periods fell within the period band of strong motion for all nine sites. t is concluded that local soil conditions have affected appreciably the ground surface response and may offer an xplanation for the non-uniform earthquake damage distribution in some portions of the city.

NTRODUCTION

n September 13, 1986, the Greek coastal city of alamata (pop. ≈ 42,000), Fig. 1, was shaken by n earthquake of magnitude M_s = 6.2 and focal istance of 15 km (Anagnostopoulos et al., 987). The main event was followed by a number f aftershocks, the strongest of which occurred wo days later, with a magnitude of M_s = 5.6 and ocal distance of 11 km. The earthquakes esulted in the loss of 20 human lives and heavy lamage (including total collapses) to the uildings of the city.

'wo sets of strong motion records were obtained or the main shock (site 1 and site 2) and three ets for the major aftershock (site 1, site 2 and site 3), Fig. 2. The recordings were ob- ained by strong motion accelerographs (SMA-1) nstalled at the basement of a 7-, 3- and 4- tory reinforced concrete buildings for sites 1, 2 and 3 respectively. Unfortunately, no record is available for the bedrock motion of the area (Anagnostopoulos et al., 1987; Gazetas, 1988). The causitive fault was found to lie underneath the city of Kalamata (Papazachos et al., 1988).

The distribution of damage was not uniform with most of the damage concentrated in the Northeast part of the city. Fig. 2 shows the distribution of damage for both rigid buildings (T ≤ 0.30 sec) and flexible buildings (0.40 ≤ T ≤ 0.70 sec), where T = fundamental period of building, (Gazetas, 1988). The type of construction encountered in Kalamata includes modern reinforced concrete buildings (2 to 6 stories), composite-reinforced concrete/stone (or brick) masonry buildings (1 to 3 stories) and old stone (or brick) masonry buildings (1 to 2 stories), (Anagnostopoulos et al., 1987; Fardis, 1987). According to Fig. 2, rigid buildings suffered very extensive damages in the northern part of the city whereas flexible buildings were vulnerable in the southern part of the city. It is worth mentioning that the damage was insignificant along the waterfront and the western part of the city.

Fig. 1 Map of Greece Showing the Geographic Location of Kalamata

The close proximity of the causitive fault to the city, undoubtedly suggests that source mechanism and directivity of wave propagation have contributed to the non-uniform distribution of earthquake damage in the city (Gazetas 1988). However, the parallel effect of local soil conditions (Seed and Idriss, 1982; Faccioli and Resendiz, 1976; Gazetas, 1987) on the seismic response of ground and on damage distribution of Kalamata still remains a rather controversial issue.

In this paper are presented results of ground response calculations for the nine sites of the city shown in Fig. 2. Dynamic soil properties at these sites are known from cross-hole and re-

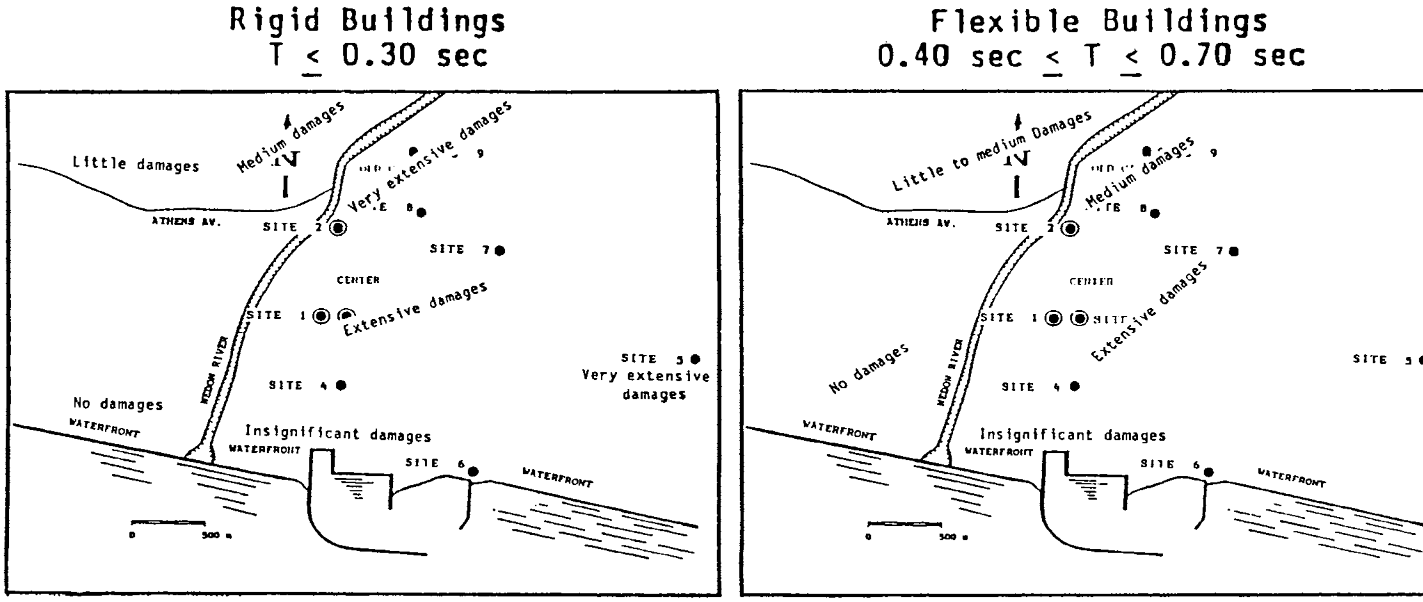

Fig. 2 Distribution of Earthquake Damage in the City of Kalamata

sonant column testing. The results show a definite differentiation of response from site to site and may be related to the changes of corresponding soil profiles. Furthermore, the fundamental periods of the same nine profiles were calculated by applying simplified procedures suggested in recent technical literature. The strong motion period-band of ground response spectra was found to include the calculated values of fundamental periods for all sites. This is taken as an additional indication that local soil conditions have affected the response of ground surface for the portion of the city examined in this paper.

GEOTECHNICAL DATA

An extensive geotechnical investigation of the Kalamata area was undertaken by the Public Works Research Center of Greece, immediately after the destructive earthquakes of Sept. 1986. The investigation consisted of drilling a large number of boreholes, of undisturbed and representitive sampling and of in-situ (SPT and CPT) and laboratory testing (Sabatakakis et al., 1987). According to this investigation the local soils of the city consist of deposits of sand-gravel mixtures interbedded with layers of silty or clayey material and underlain by pleistoncene marine sediments of dense silty marls.

At nine sites of the city, shown in Fig. 2, cross-hole testing was conducted up to depth of 50 m from ground surface (Athanasopoulos, 1987, a, b). These sites included the sites of strong motion records (1, 2 and 3) and sites of total building collapse (4 and 5). Fig. 3 shows the soil profiles at the nine sites of cross-hole testing. These profiles are shown ordered along the N-S and W-E directions to help visualize the change of local soil conditions across the city. Cross-hole testing provided values of shear wave velocity, V_{so}, vs. depth at intervals of 2 m and it was conducted in accordance to the ASTM D 4428/D 4428M-84 standard test method and the suggestions of pertinent literature (Woods an Stokoe, 1985). A limited number of resonan column tests were also conducted on undisturbe samples of marl to determine the dependence o dynamic modulus and damping on confinin pressure, time and cyclic shear strain (Athanasopoulos, 1987a).

SEISMIC RESPONSE ANALYSES

The ground response at the nine sites wa estimated by using the program LUSH. This is 2-D finite element dynamic soil-structure interaction program developed by Prof. Lysmer and co workers at Berkeley (Lysmer et al., 1974). Th program estimates the acceleration respons spectrum for all nodes, the time history o acceleration and displacement at the groun surface and the maximum values of shear strain acceleration and shear stress for all nodes. Th input acceleration time history is applied a the "rigid base" which represents either th actual or the "equivalent" bedrock. Remarkabl features of the program LUSH are: 1) the use o the method of complex response eith complex moduli which assures reliability of results fo the high-frequency components of motion and 2) the use of the equivalent linear method fo taking into account the non-linear behavior o soils under strong cyclic loading. Several investigations (e.g. Tsai et al., 1980) suggest th use of non-linear soil behavior for seismic response calculations, especially for soft cohesive soils. The soils underlying Kalamata, clearly, do not belong to this category and it should be noted that programs using the equivalent linear method have repeatedly beer checked against programs using the non-linear method and close agreement between the calculated soil responses was found for a variety of soil profiles (e.g. Martin and Seed, 1982; National Research Council, 1985, pp. 137-147).

In this study the program LUSH was used in 1-D mode for each site, representing the vertical

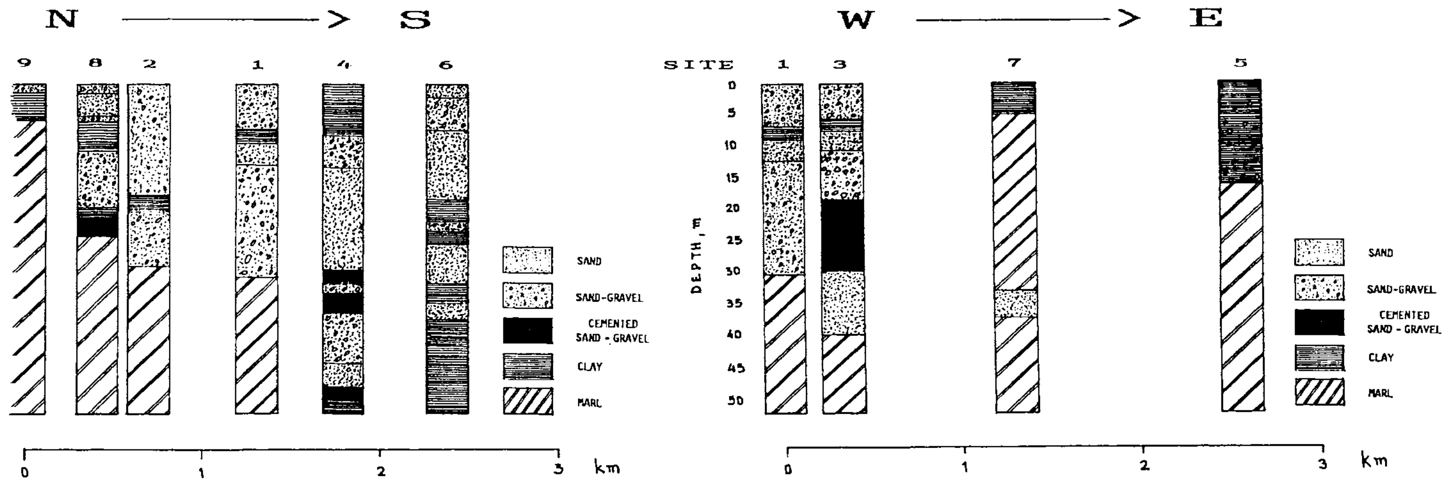

Fig. 3 Soil Profiles at the Investigated Sites

ropagation of seismic waves from a rigid base o the free ground surface. A single column of lements was used at each site between the rigid ase and ground surface with the nodal points orced to move in the horizontal direction only. 'he dynamic soil properties of soil layers eeded for the calculation were based on the re- ults of cross-hole and resonant column testing. .ctual bedrock was not found in Kalamata up to lepths of 80 m. For this reason a depth to 'equivalent" bedrock, H, was assigned to each rofile by using the following criteria: i) for ;ites where the value of V_{so} showed a constant ncreasing trend with depth, soil material with $'_{so} \geq$ 750 m/sec was considered as equivalent edrock (Algermissen, 1983); for some sites of .his type it became necessary to extrapolate the esults of cross-hole measurements (following he average trend) to depths greater than the actual depth of measurement, ii) for sites where .wo or more layers, each with constant value of V_{so}, were found to exist, the depth to the in- terface with the sharpest velocity contrast was taken as depth to equivalent bedrock even when the velocity of underlying layer was less than 750 m/sec.

As rigid base input acceleration, for all sites, was used a synthetic accelerogram of horizontal motion, Fig. 4, derived by Gazetas (1988) for the main sock of 1986 Kalamata earthquakes. This accelerogram denoted as (W3), was actually one of several statistically equivalent accelero- grams derived by probabilistic approach and based on the values of seismic moment, stress drop, cut-off frequency and shear wave veloci- ty of rock materials in the vicinity of the causitive fault (Gazetas, 1988).

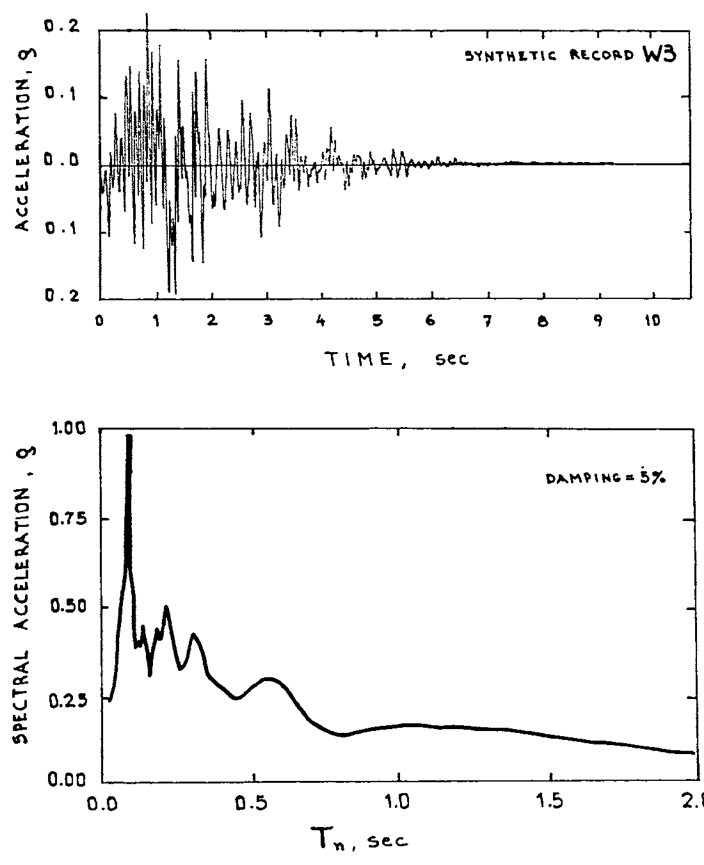

Fig. 4 Time History and Response Spectrum of the Synthetic Based Accelerogram Used in Analysis

FUNDAMENTAL PERIODS OF SOIL PROFILES

Values of fundamental periods, T_s, of soil pro- files at the nine sites were determined by using the solutions reported by Dobry et al., 1976 and Dobry and Gazetas, 1985, for vertical propaga- tion of shear waves. For Site 2 the solution for linear increase of V_s with depth was utilized whereas for the remaining sites the approximate solution for layered soil profiles was applied.

The values of fundamental periods estimated from the above solutions were corrected for high amplitude effects ($\gamma = 10^{-4} \div 10^{-3}$) by taking into consideration degradation curves G/G_0 ob- btained from laboratory resonant column tests on undisturbed samples from the Cross-Hole boreholes (Athanasopoulos, 1987a). The depth to rigid base used in the calculations was the same depth used in the seismic response analyses described in the previous section.

RESULTS AND DISCUSSION

The results of seismic response analyses for SITE 1 and SITE 2 are shown in graphical form in Fig. 5 and Fig. 6, respectively. Each of these figures includes the calcalated acceleration time history at the surface of free field, the calculated and recorded spectral accelerations for 5% of critical damping, and the variation of measured shear wave velocity, V_{so}, and calculated max acceleration, a_{max}, max shear strain, γ_{max}, and max shear stress, τ_{max}, with depth. The maximum value of horizontal surface acceleration recorded during the main shock of Sept. 13, 1986 and the value of calculated fundamental period, T_s of soil profile are also indicated in Fig. 5 and Fig. 6. According to Fig. 5, for SITE 1 the calculated and recorded response are in very close agreement in terms of both intensity and frequency content of motion. The relatively high values of calculated spectral accelerations in the period range of T_n = 0.20 sec to 0.50 sec offer an explanation for the extensive damage of both rigid and flexible buildings in the vicinity of this site, as indicated in Fig. 2. It is worth mentioning that the calculated value of fundamental period for this site almost coincides with the period of peak motion of both recorded and calculated response spectra.

The results shown in Fig. 6 indicate that for SITE 2 the agreement between recorded and calculated spectra - although not as close as the one for SITE 1 - is still good in terms of overall spectral shape and spectral values. The striking difference in spectral shape between sites 1 and 2 is believed to be due to the different soil conditions in these two site The measured values of shear wave velocity v depth in the two sites indicate that SITE 2 "softer" than SITE 1. It is generally accept that rigid profiles produce spectra with sha peaks in contrast to flat spectra produced the soft profiles. The calculated value of fu damental period for SITE 2 (T_s = 0.41 se falls within the strong motion period band defined by both recorded and calculated spectr

The results of calculations for the rest of t sites are included in Table 1 which summariz the results of response analyses and fundament period calculations for the nine sites examin in this study. Table 1 gives the values maximum surface acceleration, a_{max}, of stror motion period band, T_{peak} and of fundamental pe riod, T_s, for each site. The sites are ordere along the N-S and W-E directions and correspor to the soil profiles shown in Fig. 3.

According to Table 1 both surface and spectra accelerations are decreasing in the N-S direc ion whereas the period band of peak response moving toward higher values of period. Further more, the calculated values of fundamenta period fall within the peak response period bar for all sites. It is believed that these differ ences in response can be related to the ir creasing depth to marl deposits in the soil prc files along the N-S direction, Fig. 3, ar are, therefore, manifesting the effects of loca soil conditions. Similar effects can also b detected when examining the variation of grour respnse along the W-E direction, shown i Table 1. Both surface and spectral acceleratior are increasing whereas the period values of pea response and calculated fundamental periods ar decreasing along the W-E direction. This trer can again be related to the decreasing depth t marl deposits along this direction, Fig. 3. I may, therefore, be concluded again that the lc

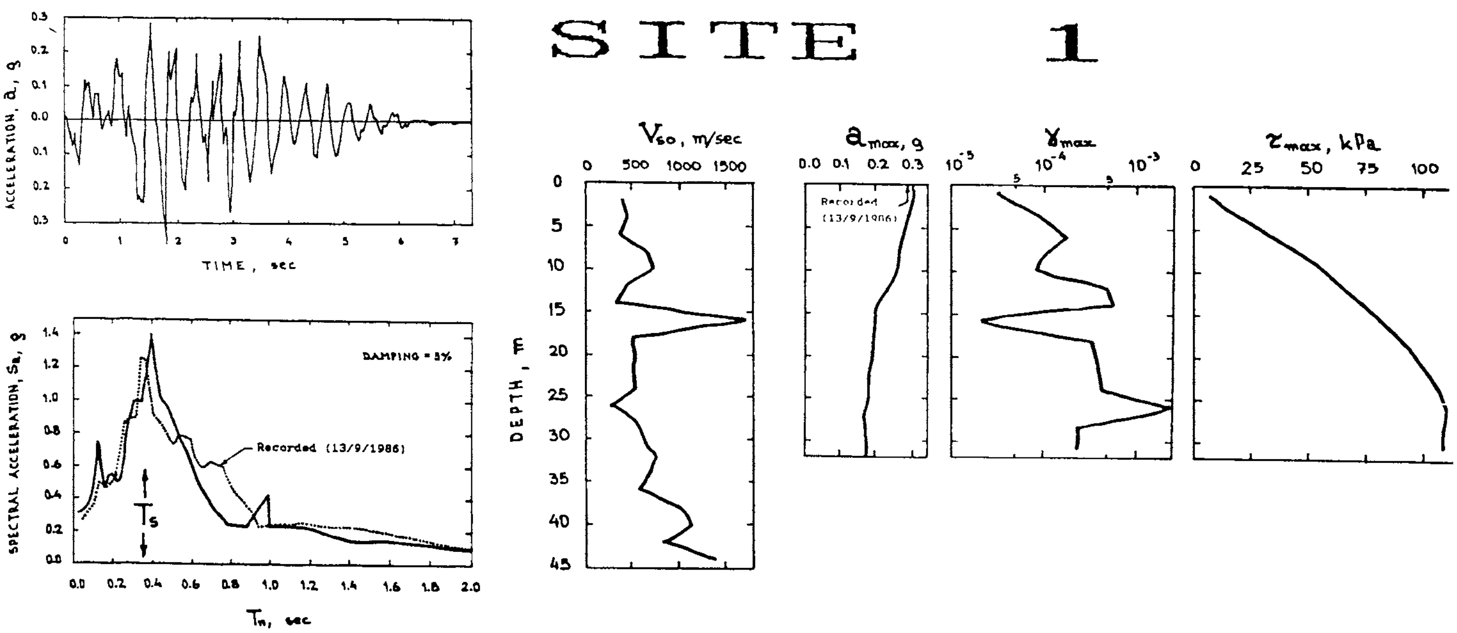

Fig. 5 Results of Seismic Response Analysis for SITE 1

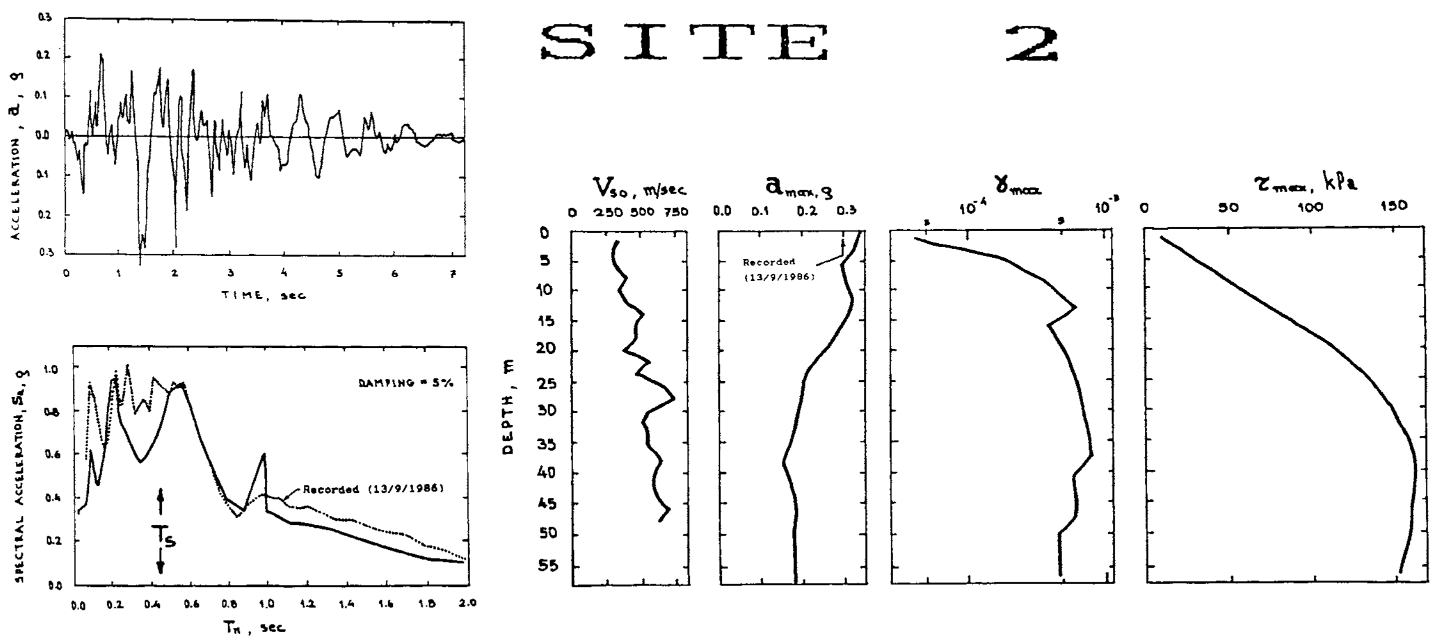

Fig. 6 Results of Seismic Response Analysis for SITE 2

cal soil conditions modified the base motion and affected the response of ground surface in the eastern part of the city.

It should be noted, however, that response analyses were not conducted for the western part of Kalamata, since no cross-hole data are available for this part of the city. As was mentioned in the INTRODUCTION the damage of both rigid and flexible buildings was insignificant in the western part of Kalamata. The very close proximity of the city to the earthquake source suggests that the source mechanism and the directivity of propagation of seismic waves may have produced the differentiation of response and of corresponding earthquake damage between the western and eastern parts of the city (Gazetas, 1988).

CONCLUSIONS

1. At nine sites of the city of Kalamata dynamic properties of soil profiles are known directly from cross-hole measurements up to depths of 50 m from ground surface. At three of the sites, strong motion records are also available for the 1986 earthquakes.
2. Seismic response analyses were performed for the nine sites by using the computer program LUSH in 1-D mode and a published synthetic base accelerogram, calculated for the main shock of Sept. 13, 1986.
3. Good agreement was found between calculated and recorded response at the sites of strong motion recordings. This agreement enhanced the reliability of results for the rest of the sites.
4. The results of analyses show differentiation of response from site to site in terms of both intensity and frequency content of motion. This differentiation can be related satisfactorily with differentiation of soil profiles and suggests the presence of effects of local soil conditions.
5. Values of fundamental periods of soil profiles were calculated for all sites by applying simplified procedures for vertical propagation of shear waves. These values were found to lie within the strong motion period band of response for all sites. This may be taken as an additional indication that the seismic response of ground surface, in the portion of Kalamata studied in this paper, was affected by the local soil conditions.

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TABLE 1. Summary of Ground Response Relults

DIREC-TION	SITE	a_{max} (g)	$S_{a\ max}$ (g)	T_{peak} (sec)	T_s (sec)
N	9	0.40	1.45	0.17 ÷ 0.53	0.32
↓	8	0.30	1.20	0.18 ÷ 0.65	0.39
	2	0.30	0.93	0.22 ÷ 0.58	0.41
	1	0.30	1.40	0.34 ÷ 0.42	0.34
	4	0.35	0.90	0.30 ÷ 0.85	0.69
S	6	0.20	0.90	0.20 ÷ 1.10	1.04
W	1	0.30	1.40	0.34 ÷ 0.42	0.34
↓	3	0.50	2.40	0.20 ÷ 0.40	0.31
	7	0.35	1.35	0.20 ÷ 0.60	0.33
E	5	0.45	2.40	0.13 ÷ 0.30	0.14

Sept. 13, 1986 Kalamata earthquake in digital form and Prof. D. Beskos for making available the program LUSH.

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