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Effect of Local Soil Stratigraphy on Microtremor Measurements

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YNOPSIS: The method of microtremors has been recently applied for the microzonation of the town of alamata, in southern Greece. Results from this study are evaluated in comparison with predictions f seismic ground response obtained by 1-D wave propagation analyses. Predominant periods of micro-remor are considerably lower than estimated fundamental ground periods. It is shown that a small part of the observed differences in due to soil non-linearity in connection with the small strain amplitudes induced by microtremors. The largest part appears to be due to geologic factors, namely he existence of rigid soil layers within the soft soil above the seismic bedrock of the area.These ayers act as a "pseudo" seismic bedrock and may consequently reduce the predominant period of microtremors relative to that of earthquake motions.

NTRODUCTION

One of the earliest methods proposed for microzonation of large areas is that of microtremors. This method may provide estimations of the fundamental ground period for seismically-induced vibrations, based upon recording and subsequent Fourier analysis of small amplitude excitations travelling through the soil.

Systematic development of the method is attributed to K. Kanai and colleagues (e.g. Kanai and Tanaka 1961, Kanai et al. 1965), although its initial application may be traced back to the microzonation of Tokyo and Osaka at the beginning of this century (Omori, 1908). These studies assume that microtremors are seismic noise, caused by the continuous local tectonic activity and filtered through the soft soil. Thus, it is concluded that microtremor characteritics are closely related to the characteristics of the seismic ground response.

Since its initial development, the method of microtremors has found extensive application, as a simple and cost effective means for microzonation studies. In parallel, however,it has become the subject of considerable debate (e.g. Douze 1964, Kubotera and Otsuka 1970, Murphy et al. 1971, Udwadia and Trifunac 1973, Katz 1976). The critics argue that, unlike earthquakes, microtremors are mostly generated on the ground surface by natural or artificial sources, such as wind, traffic and machine vibrations. As a result, they are a mixture of surface waves and refracted body (P- and S-) waves, which have not necessarily penetrated the entire thickness of the loose soil deposits. In addittion, concern is expressed over the extremely small strain levels induced by microtremors, relative to earthquakes, in connection with soil non-linearity.

A number of case studies have been published today to support the views of the critics, as well as, the followers of the method. The present article focuses upon microtremor predictions for non-uniform soils. The results from a recent microtremor study are evaluated in comparison with analytical predictions of seismic ground response at locations with well established soil profiles. Based upon the observed similarities and differences, a reasonable mechanism is proposed to explain microtremor generation and propagation in non-uniform soils.

MICROTREMOR MEASUREMENTS

Leventakis et al. (1986,1987) published the results from a microtremor study at the town of Kalamata in southern Greece, aimed at a preliminary assesment of the local soil effects during the 1986 eathquakes in the area. The study includes measurements at 102 locations, more or less uniformly distributed over the greater area of Kalamata. The distance between the locations varies from 250 to 400 m and allows a reasonably accurate interpolation of the results.

The instruments used for carrying out the measurements of microtremors consist of :

a) Two ranger, velocity type seismometers with a natural period of 1 s.
b) A signal conditioner with four independent amplification channels and low-pass filters. The frequency range of the instrument covers from 0.5 to 30 Hz with frequency response within 0.5 db. Its total gain is 54 db and has a 9 ranges attenuator.
c) A thermal signal recorder with variable sensitivity (1, 10, 100 and 100 mV/mm) and velocity of recording (1, 5, 25 and 50 mm/s).
d) A portable magnetic recorder for the registration of signals from the singal conditioner.

Reported measurements are based on 2 to 3 min recordings of microtremor velocities, obtained on the ground surface, in two horizontal directions (N-S and E-W). Using the "zero crossing" method (Kanai and Tanaka, 1961), period distribution curves were deduced for each location and fundamental ground periods were determined from the highest peak of these curves.

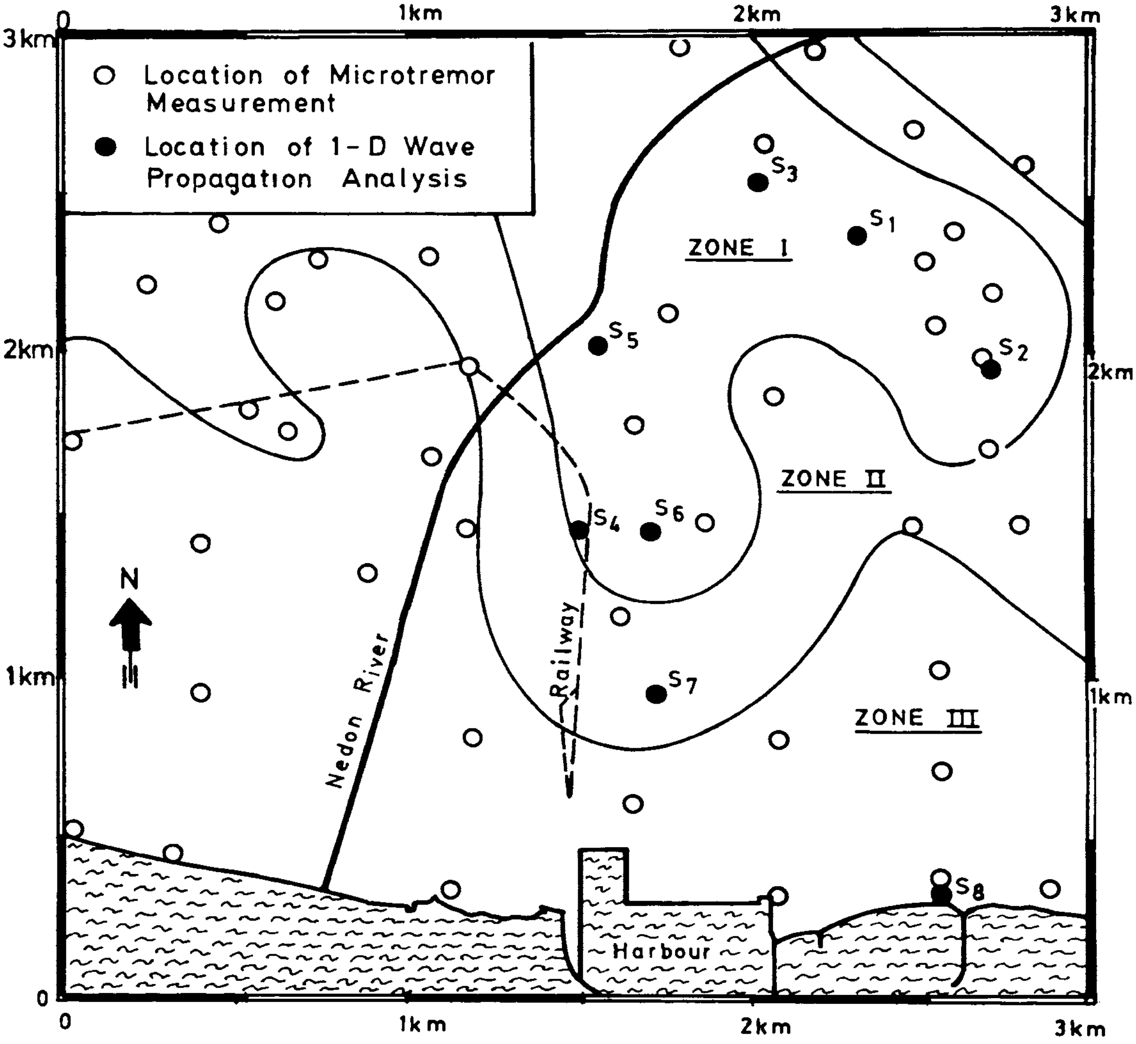

Fig. 1. Map of Kalamata Area showing the Sites of 1-D wave Propagation Analyses.

The results are summarized in the map of Fig. 1 which shows the area of interest divided into three seismic zones, according to the method proposed by Kanai and Tanaka (1961). The most possible range of estimated predominant ground periods (T) in each zone are :

ZONE I $0.09 \text{ s} < T < 0.20 \text{ s}$
ZONE II $0.20 \text{ s} < T < 0.30 \text{ s}$
ZONE III $0.30 \text{ s} < T < 0.50 \text{ s}$

It is noted that the above division does not exclude the possibility that the zones include locations with predominant periods outside the corresponding limits. This possibility, however, is relatively small and is not considered in the present study.

SOIL CONDITIONS

Soil conditions in the area of Kalamata have been thoroughly investigated after the 1986 earthquakes, as part of a microzonation study (Sabatakakis et al. 1987, Athanasopoulos 1987). The site investigation was based in 25 exploratory boreholes, 91 cone penetration tests anc cross-hole measurements of shear wave velocity in 9 locations.

Figure 2 shows a typical geological section across the town of Kalamata, which is indicativ of the complex soil stratigraphy of the area The major soil formations identified during drilling are the following :

a) Silt and sand with variable content of grave and very low plasticity (plasticity index PI 0-8%). The shear wave velocity of this form tion is relatively low, between 150 and 40 m/s, increasing consistently with depth.
b) Clay, stiff to very stiff, with variable san content and relatively low plasticity (PI = 7 20%). The shear wave velocities increases in general with depth, from about 250 m/s close to the ground surface to about 650 m/s at 20-30 m depth.
c) Sand and Gravel with silty sand inclusions (seams and lenses). The density of depositio of this formation varies widely without any consistent pattern, from loose to dense and

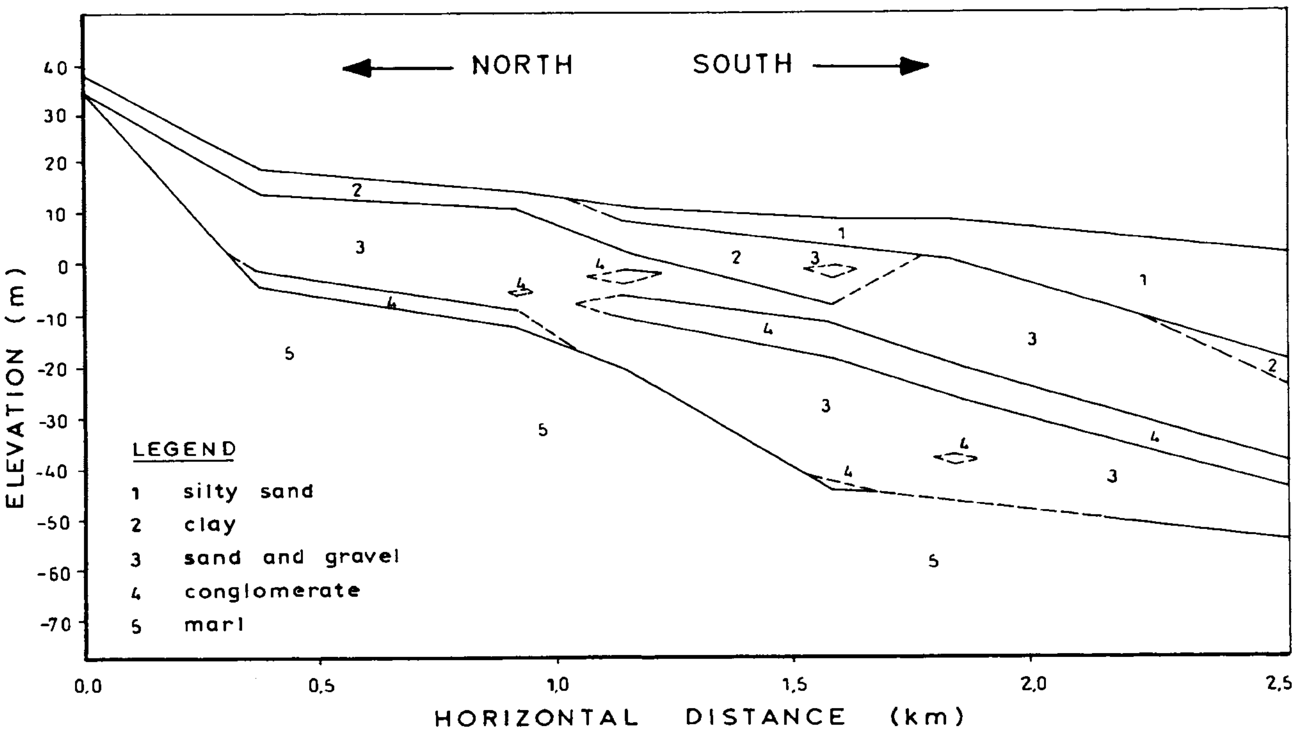

Fig. 2. Representative Geological Section Across the Town of Kalamata.

very dense. Similar is the variation of shear wave velocity measurements, which range between 200 and 650 m/s.

d) Conglomerate, in 2.0 to 0.8 m thick layers, embedded within soil formations (b) and (c) above. Cross-hole measurements of shear wave velocity in these layers are remarkably high, ranging between 800 and 1700 m/s.

e) Marl, which consists the geologic bedrock of the area. This formation is in general very stiff to hard with relatively high shear wave velocity, between 500 and 800 m/s, increasing consistently with depth.

Piezometric measurements in the area, show considerable seasonal variation. During the wet months of Spring 1987, the ground water level was at 15.0 to 20.0 m depth in the northern bounds of the town and at about 2.0 m depth at the Harbour.

ANALYTICAL PREDICTION OF SEISMIC RESPONSE

A common means to predict the seismic response of soil profiles with grossly horizontal deposition, is one-dimensional (1-D) wave propagation analyses. This kind of analyses were performed for 8 sites within the central area of Kalamata (Fig. 1) in order to compare the results with microtremor predictions. The soil conditions at these sites have been thoroughly investigated by borehole drilling and cross-hole measurements of shear wave velocity.

In all cases it was assumed that seismic waves propagate vertically upwards, from the seismic bedrock to the free surface of the ground. To account for soil non-linearity and inhomogeneity solutions were obtained with the finite element (layer) method and time-domain integration of the differential equations of motion. The following paragraphs discuss further some of the basic assumptions and input parameters used to obtain the analytical predictions.

The soil stratigraphy of each site, was determined on the basis of results obtained from conventional geotechnical investigation and cross-hole testing. Figure 3 summarizes the shear wave velocity profiles for all sites analysed and indicates the position of the seismic bedrock (marked as S.B.). In general, it was assumed that the seismic bedrock is located within the geologic bedrock of the area, at a depth below which shear wave velocity consistently exceeds 700 m/s.

The soil response during seismic excitation was assumed non-linear hysteretic, described by a hyperbolic model obeying Masing generalized criteria for dynamic loading (Pyke, 1979). The backbone curve of this model is defined as :

$$\tau = \frac{G_o \gamma}{1 + \frac{G_o}{\tau_m} \gamma} \qquad (1)$$

where τ and γ denote shear stress and shear strain respectively, G_o is the shear modulus of the soil at very small shear strains ($\gamma < 10^{-5}$) and τ_m is the maximum resistance to simple shear loading.

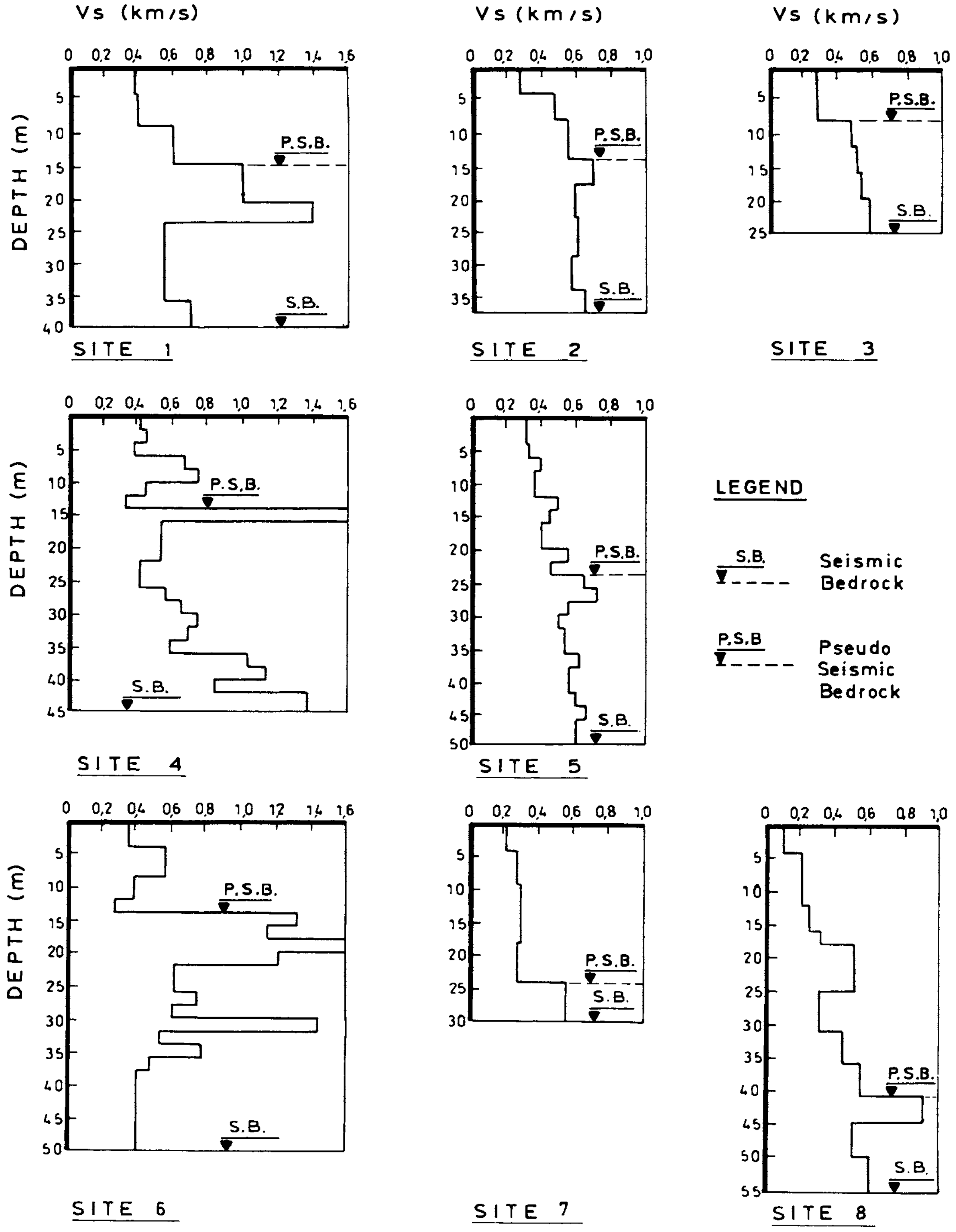

Fig. 3. Shear Wave Velocity Profiles for the Sites of 1-D Wave Propagation Analyses.

Upon reversal of the loading at a point with coordinates (τ_r, γ_r), shear stresses and strains are related with the following expression :

$$\frac{\tau - \tau_r}{2} = G_o \frac{\gamma - \gamma_r}{1 + \frac{G_o}{\tau_m} | \gamma - \gamma_r |} \qquad (2)$$

Stress-strain curves described by the previou equation are not allowed to intersect during th consequtive unloadings and reloadins caused by seismic excitation. Instead, when the curren curve meets that of a previous load cycle the later is followed until a new reversal in the direction of loading occurs.

rom Eqs. 1 and 2 it becomes evident that the asic parameters required to describe the stress-train response of a soil layer are the shear odulus G_o and the maximum shear resistance τ_m. n the present study, G_o was calculated from the hear wave velocity V_s and the mass density of he soil ρ as :

$$G_o = \rho V_s^2 \qquad (3)$$

he maximum shear resistance τ_m is usually estiated from laboratory measurements of shear odulus at different levels of shear strain mplitude. In the absence of similar data for he soils of Kalamata, τ_m was determined by fiting Eq. 1 to the empirical curves for shear modulus degradation proposed by Seed and Idriss (1970). This is certainly an approximation, and introduces some uncertainty with regard to the soil parameters used in the analyses,even though G_o estimates are reasonably accurate.

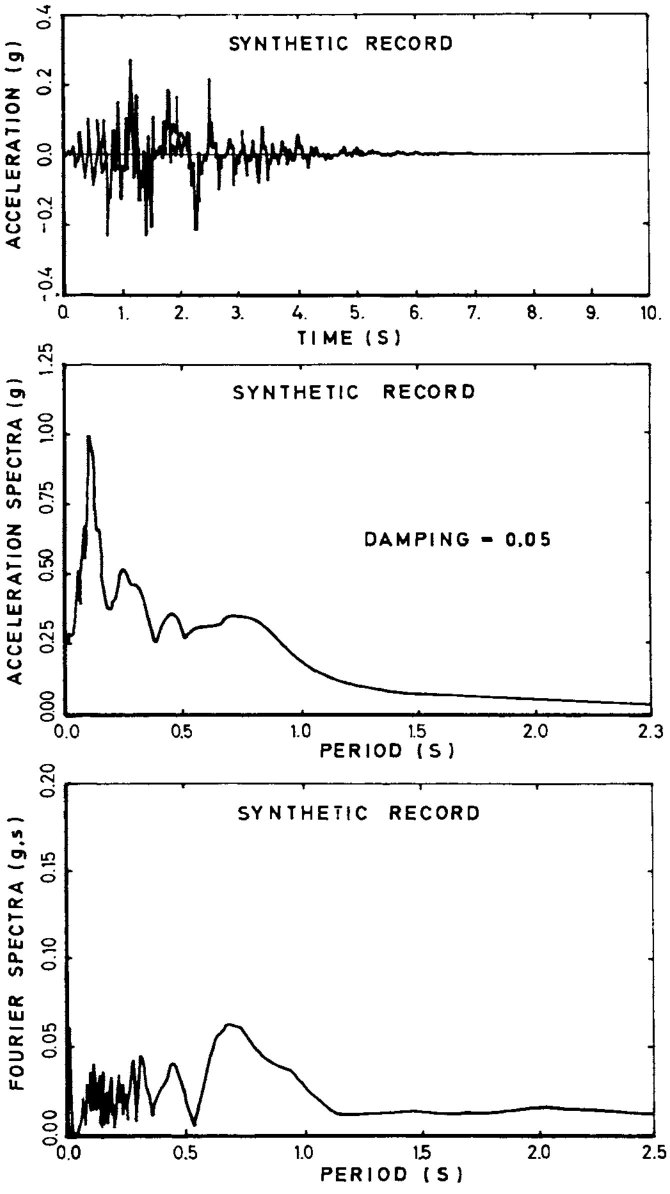

Fig. 4. Input Seismic Motion at Bedrock.

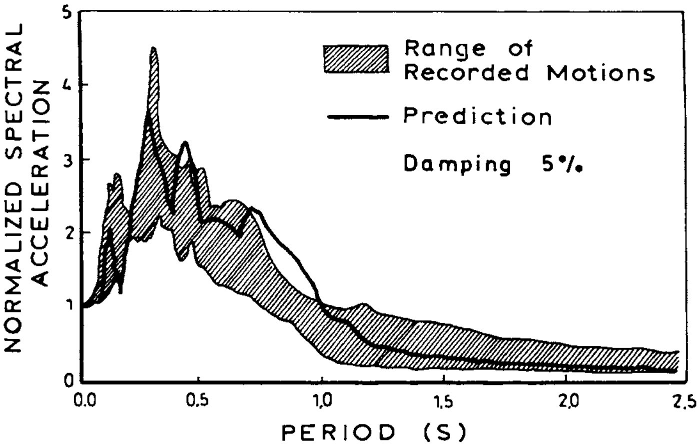

Fig. 5. Comparison of Analytical and Recorded Response for Site S4.

The input seismic motion at bedrock, used for the analyses, is shown in Figure 4. The assumed motion simulates the major earthquake that hit the area in September 1986 and was derived analytically (Gazetas et al. 1990), in the absence of physical recordings on rock outcrop. Use of this particular excitation was decided, so that the overall accuracy of the analysis may be checked against actual recordings of free field motion.

Figure 5 shows a typical comparison between normalized acceleration response spectra, derived from predicted and recorded free field motions at site S4. The spectra are presented in normalized form so that analytical predictions may be compared simultaneously with recordings from two seismic events with different magnitudes ; the main shock (M=6.2) and the strongest aftershock (M=5.4) of the 1986 earthquakes. The agreement observed in this figure indicates that, despite existing uncertainties the results from the analyses are within acceptable accuracy limits.

COMPARISON OF ANALYTICAL PREDICTIONS AND MICROTREMOR MEASUREMENTS

The comparison presented here focuses upon the fundamental period of vibration of a soil column extending from the seismic bedrock to the ground surface. As it was explained earlier, this quantity is one of the main results with practical importance obtained from microtremors.

Figure 6 compares predicted fundamental ground periods with predominant microtremor periods for the 8 sites where dynamic analyses have been performed. Periods deduced from microtremors are shown as a possible range, corresponding to the reported range of fundamental periods for the zone where each site belongs (Fig. 1). Analytically predicted periods were estimated from spectral acceleration amplification curves,

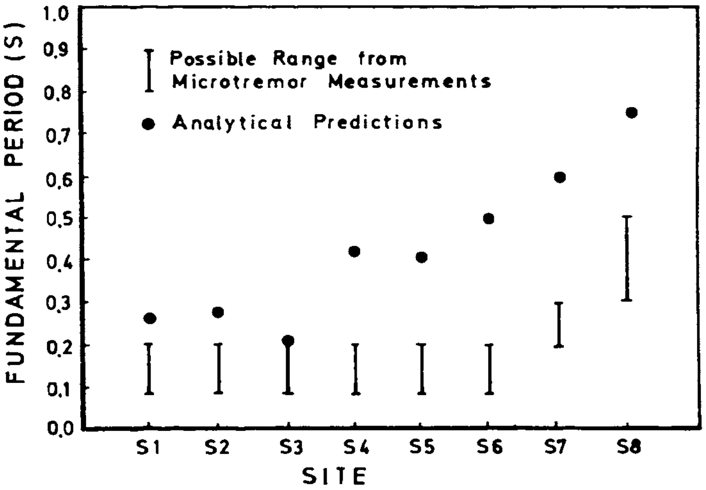

Fig. 6. Comparison of Microtremor and Analytical Predictions.

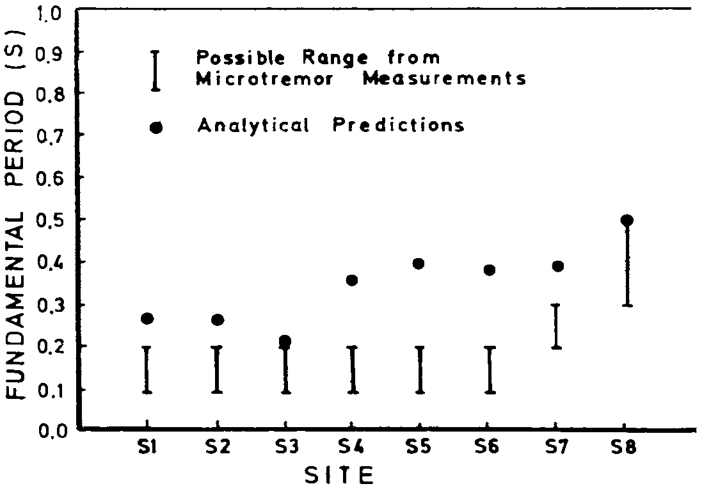

Fig. 7. Comparison of Microtremor and Analytica Predictions - Elastic Soil.

obtained by dividing spectral acceleration at ground surface with spectral accelerations at bedrock. With this procedure, spectral acceleration peaks due to soil amplification are isolated from peaks due to high frequency content in the input ground motion and fundamental ground periods can be determined with certainty.

In Figure 6 it is observed that analytically predicted fundamental ground periods are significantly higher than predominant periods of microtremors for all sites. The differences, with respect to the mean period deduced from microtremors, range from about 40% for site S3 to over than 100% for sites S4, S5, S6 and S7.

INTERPRETATION OF MICROTREMOR MEASUREMENTS

To explain the above differences, the hypothesis is first examined that they are attributed to the extremely small amplitude of microtremors as compared to earthquakes. Thus, 1-D wave propagation analyses were repeated assuming elastic soil response and constant shear modulus corresponding to very small strains ($\gamma < 10^{-5}$).

Figure 7 compares analytically predicted fundamental ground for elastic soil with predominant microtremor periods. Analytical predictions in this case appear somewhat reduced relative to the ones obtained for non-linear soil response, especially for the softer sites S6, S7 and S8. Even for these sites, however, the differences remain large, indicating that the assumption of elastic response cannot fully explain the small ground periods predicted by the method of microtremors.

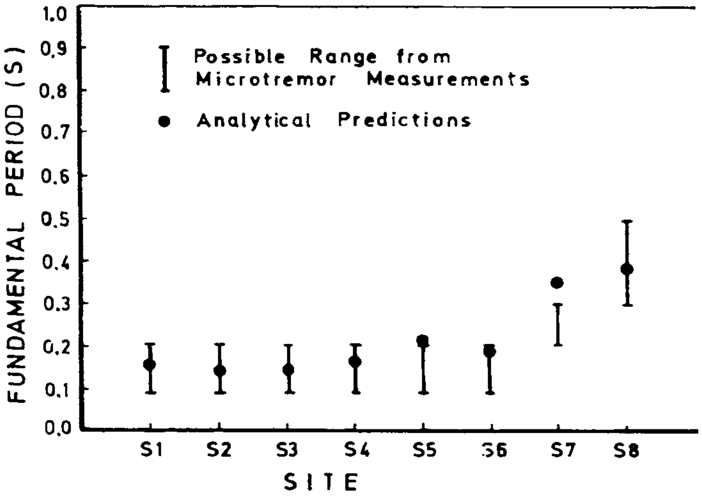

Fig. 8. Comparison of Microtremor and Analytica Predictions - Pseudo Seismic Bedrock.

Examination of the soil conditions at the sites where the difference between microtremor and analytical estimations remain substantial,shows that high shear wave velocity strata (conglomerates) are interbeded within the soft soil above the seismic bedrock. Based on this observation, it was subsequently assumed that microtremors are generated on the ground surface and propagate to the location of measurement by refraction in these strata.

To simulate this mechanism, 1-D wave propagatio analyses were repeated assuming a pseudo-seismi bedrock, indicated by "P.S.B." in the velocity profiles of Figure 3, at the level of the first sharp increase in shear wave velocity. The new estimates of fundamental ground period are compared to predominant periods of microtremors in Figure 8. One may observe that use of a "pseud seismic bedrock, in place of the actual seismic bedrock, yields a much stiffer ground response which is in good agreement with microtremors.

It is interesting to note that Nakajima and Otsuka (1978) also conclude that microtremors emanate from that level below the ground surfac where the shear wave velocity or the Standart enetration test values show an abrupt increase. hey assume, however, that this level coincides ith the seismic bedrock of the area and con-equently come to the conclusion that the fre-uency characteristics of the ground may be btained by proper analysis of microtremors. rom the present study, it becomes evident that his conclusion is valid only in the case where he soil stiffness increases smoothly with depth o that the "pseudo" seismic bedrock coincides ith the seismic bedrock of the area. In all ther cases it is reasonable to expect that the esponse of the ground to microtremors is stif-er than the response during earthquakes.

ONCLUSION

he previous analyses indicate that application f the method of microtremors in the town of alamata underestimated fundamental periods of eismic ground response. A small part of the bserved differences,which in some sites exceeds 100% of microtremor predictions, may be attri-uted to the small shear strains induced by icrotremors in connection with soil non-linearity. The largest part, appears to be related to the source of microtremors and the soil conditions in the area of investigation.

hypothesis which explains the specific measurements reasonably well, is that microtremors result from excitations on the ground surface and arrive at the location of recording after refraction at layers with high shear wave velocity. Based on this hypothesis, microtremors may be visualised as emanating from a "pseudo" seismic bedrock, located above the actual seismic bedrock of the area, at the depth of the first sharp increase in shear wave velocity.

The previous interpretation implies that the response of the ground surface to microtremors is generally stiffer than the response to earthquakes. Good correlation between microtremor and seismic response appears to be possible only in the case of smooth variation of soil stiffness with depth, when the "pseudo" seismic bedrock coincides with the actual seismic bedrock of the area. To this extend, it appears reasonable to suggest that microtremor measurements are followed by a gross at least evaluation of the soil conditions at the sites of measurements so that unrealistic predictions are avoided.

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