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Nonlinear Site Response During the 7 September 1999 Athens, Greece, Earthquake (M_W 5.6)

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NONLINEAR SITE RESPONSE DURING THE 7 SEPTEMBER 1999 ATHENS, GREECE, EARTHQUAKE (M_W 5.9)

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ABSTRACT

The largest available strong-motion recording (PGA=0.35g), least affected by topography, structural response and/or soil-structure interaction, is investigated for possible nonlinear site response during the M_w 5.9 Athens earthquake of 7 September 1999. Smoothed horizontal-to-vertical spectral ratios (HVSR) are calculated in subsequent overlapping 3.5-s windows, thus covering a wide range of excitation levels. Mean HVSR curves are computed for a so-called "weak-" and "strong-" motion range (mean horizontal ground acceleration in window, MGA<=10.2 cm/s/s and >=20.5 cm/s/s). The two curves have similar shape, with the "strong" curve visibly shifted toward lower frequencies relative to the "weak" one; the dominant site resonance occurs at 4.0 Hz (0.25 s) and 4.7 Hz (0.21 s), respectively. Linear correlation analysis shows that the resonance frequency, f_0, and MGA are significantly correlated (r=-0.661). We attribute this behaviour to the degradation of the sediment shear modulus (nonlinearity). Our results, combined with indications that sediment sites in the near-fault area were exposed to ground shaking well above PGA=0.35 g during the earthquake of 7 September 1999, imply that these sites exhibited considerable nonlinear response.

INTRODUCTION

On 7 September 1999, at 14:56 local time (11:56 GMT), a strong earthquake with magnitude M_w 5.9 occurred in the vicinity of the capital of Greece Athens. The current best estimate of the hypocentre location is 38.06°N, 23.57°E, with a focal depth of 15 km. The fault-plane solution by Harvard University indicates a WNW-ESE trending, almost south-dipping normal fault. The earthquake caused the collapse of 65 buildings, all but a few residential, killing 143 and injuring about 7,000 persons. The death toll would have been considerably higher had the earthquake occurred slightly earlier or late in the evening or during the night. More than 70,000 families became homeless. The most extensive and severe damage occurred in the north-western suburbs of Athens (~1,000,000 inhabitants), located Northeast of the epicentre, apparently in the direction of the fault rupture. Strong-motion recordings of the main shock are available from fourteen sites in the wider Athens area at epicentral distances approximately between 10 km and 20 km; none of these recordings comes from the meisoseismal area (area of maximum-observed intensity). There has been some controversy regarding the maximum-recorded PGA. Thus the highest value (0.53 g), recorded near the city centre (Monastiraki), is believed to be the result of the complicated foundation conditions and the response of a heavy steel structure covering an archaeological excavation nearby the accelerograph. The strongest among the few recordings that can be considered practically "free-field" are the ones from Sepolia (basement of a 2-story steel building) and Piraeus street (ground floor, KEDE 1-story building); their respective (horizontal) PGAs are 0.36 g and 0.35 g.

METHOD

In search for possible nonlinear site response during the M_w 5.9 Athens earthquake of 7 September 1999, we applied a variation of the procedure proposed by Dimitriu *et al.* (1999) to the largest available strong-motion recording (KEDE) least affected by topographic, structural and/or soil-structure interaction effects. The difference of approach is that here, in order to study site response at different excitation levels, one recording – that of the mainshock – is spanned with (overlapping) windows, as opposed to the use of recordings from various events. The original 3-component analogue accelerogram, rotated so that the L-component had an NS orientation, was processed following a standard procedure: it was first automatically digitised and then instrument and baseline corrected. The high-pass and low-pass filters were set at 0.1–0.4 Hz and 25–27 Hz, respectively. As a result, digitised acceleration, velocity and displacement data were obtained. Horizontal-to-vertical spectral ratios (HVSR) of acceleration were calculated for subsequent overlapping 3.5-s windows and were subsequently smoothed by a 0.5-Hz triangular window. For each horizontal component, the mean horizontal ground acceleration, MGA (a measure of level of excitation), was calculated in each window. In this way, a wide range of excitation levels was spanned (MGA from 4 to 63 cm/s/s).

RESULTS

The obtained smoothed HVSRs were grouped according to MGA: MGA<=10.2 cm/s/s ("weak" motion) and MGA>=20.5 cm/s/s ("strong" motion). For the two ranges of MGA, mean HVSR curves were computed (Fig. 1). The two curves are visibly distinct, with the "strong-motion" curve shifted toward lower frequencies relative to the "weak-motion" one. There are several resonances on the two curves, the dominant one occurring at 4.0 Hz (0.25 s) and 4.7 Hz (0.21 s), respectively. Application of the formula $f_0=V_S/4H$ suggests that these resonances can be attributed to a 20-m thick layer with $V_S^w=320$ m/s and $V_S^s=376$ m/s for the "strong-" and "weak-" motion cases, respectively. These are realistic values for the type of soil beneath the recording site, KEDE (very stiff to hard silty to sandy marly clay and clayey marl).

Another way to show that f_0 depends on MGA (an indication of nonlinearity) is to plot the two sets of data for all time windows. Indeed, the plot reveals that the two quantities are negatively correlated with remarkable statistical significance (r=0.661, $r_{5\%}$=0.285; Fig. 2a). Even consideration of all resonance peaks present in Fig. 1 demonstrates a strong correlation between f_{res} and MGA (Fig. 2b).

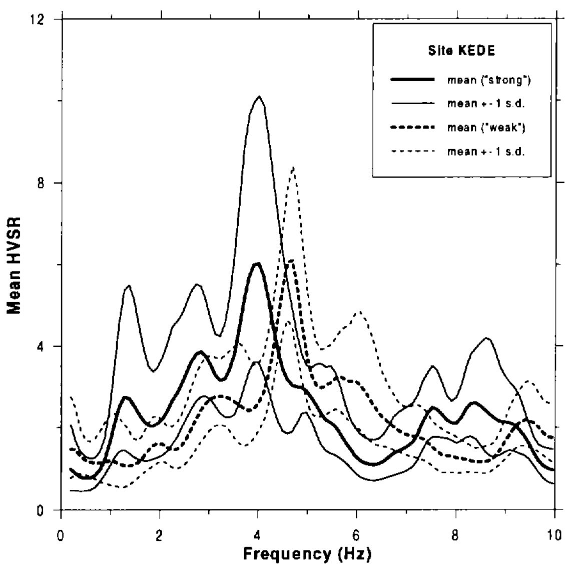

Fig. 1. Mean HVSR curves for the "weak-" and "strong-" motion cases (MGA<=10.2 cm/s/s and >=20.5 cm/s/s).

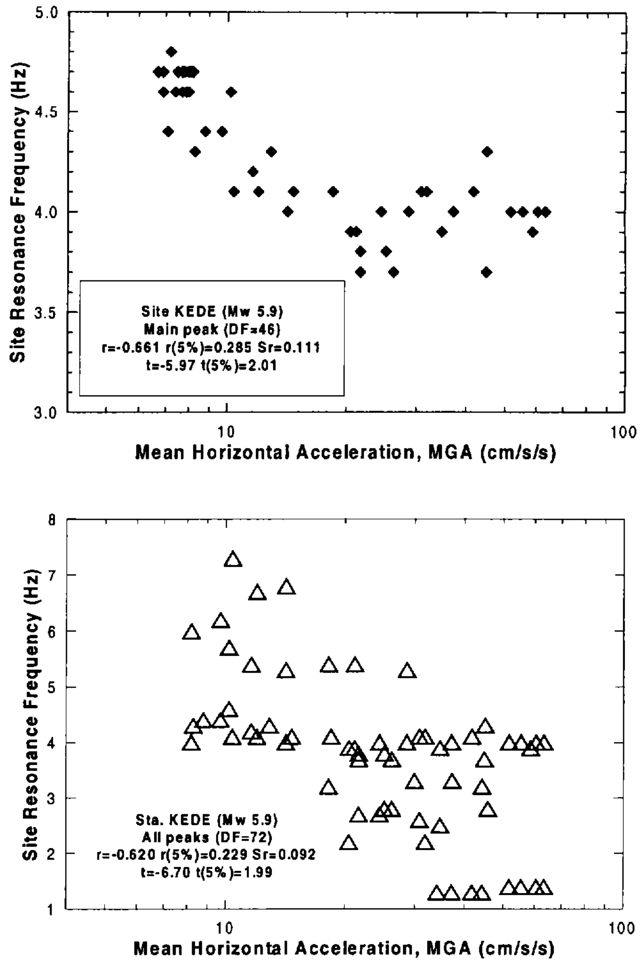

Fig 2. Linear correlation between site-resonance frequencies and mean horizontal ground acceleration in 3.5-s window: (a) dominant resonance peak; (b) all resonance peaks (see Fig. 1). Notations: r – correlation coefficient, S_r – its standard error; t – Student's t-test statistic; r(5%), t(5%) – values at 5% confidence level.

DISCUSSION AND CONCLUSION

Our analysis of the KEDE accelerogram of the Athens earthquake of 7 September 1999, believed to represent fairly well free-field conditions and performed by using a moving window to span a wide range of excitation levels, revealed a statistically significant dependence between the site resonance frequencies and the window mean horizontal ground acceleration. Similar behaviour was observed by Dimitriu *et al.* (1999) in a study of accelerograms from various earthquakes recorded at two nearby sediment sites in the town of Lefkas, western Greece, and was attributed to the reduction (degradation) of the sediment shear modulus with increasing level of shaking (nonlinearity). Indeed, simple computations yield a realistic value for the relative reduction in shear modulus from "weak-" to "strong-" motion, G^s/G^w. From the formulae $f_0=V_S/4H$ and $V_S=(G/\rho)^{1/2}$ it is possible to express G^s/G^w as a function of the change in dominant-resonance frequency, namely $G^s/G^w=(f_0^s/f_0^w)^2$. Substitution of the values f_0^s=4.0 Hz and f_0^w=4.7 Hz yields G^s/G^w=0.72. To verify whether this is a realistic value for the aforementioned sediments, we calculated the "effective" shear strain developed during the "strong" motions (the "effective" strain – 65% of the peak strain – is thought to be representative of the nonlinear response of sediments; e.g., Schnabel *et al.*, 1972). An estimate of the peak shear strain is given by PGV/V_S^s (PGV – peak horizontal ground velocity). Substitutions give an "effective" shear strain of about 3 X 10^{-4}. This strain level justifies the above estimate of modulus degradation (=0.72) as it agrees with $G/G_0 - \gamma$ data for low-plasticity normally- and over-consolidated soils (e.g., Vucetic and Dobry, 1991).

Our results, combined with indications that the earthquake of 7 September 1999 subjected sediment sites in the near-fault area to ground shaking well in excess of PGA=0.35 g, imply that these sites exhibited considerable nonlinear response.

ACKNOWLEDGEMENT

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