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CHARACTERISTICS OF SITE-SPECIFIC AMPLIFIACTION FUNCTIONS MEASURED IN MONTENEGRO

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SUMMARY

The paper describes the period and amplitude variations, and re-occurrence of the local peaks, in the Fourier amplitude spectra of strong ground motion, during different earthquakes, recorded at seven stations along the Adriatic Coast in Montenegro. The data show that some local peaks re-occur during shaking by small local earthquakes (peak ground velocities $v_{\max} < 10 - 20$ cm/s). During large strong-motion amplitudes, $v_{\max} > 20$ cm/s, these peaks are shifted toward longer periods (by non-linear soil response) or disappear.

INTRODUCTION

Before reaching the foundation of the structure, seismic waves traverse a volume that is loosely termed 'local site conditions'. Perusal of literature shows considerable variation and lack of precision in what is meant by 'local site conditions' [1,2,3]. In all cases, what would be desirable attributes of local site conditions is limited by the lack of available data on site properties.

Once the local site properties have been defined, one can select the model and compute its response to incident waves. It is at this stage that the computation of "amplification" of incident waves and 'non-linear' site response, for example, are formulated and evaluated. Agreement between measured and computed site frequencies and amplification, then, represents a basis for accepting or rejecting the assumptions theory, and models adopted for analysis. Such verification is usually performed for one or several recordings, and it is assumed that measured site amplification characteristics do not change. It has been proposed that the site amplification characteristics can also be 'measured' by extrapolating observed amplification of microtremors [4,5] or using recordings of distant earthquakes and aftershocks [6].

For earthquake engineering application it is thus important to verify the repeatability of the computed and 'measured' site amplification. This is a difficult task because for only a small subset of strong motion

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stations are there sufficient digitized data to perform such comparisons [7,8]. Trifunac et. al. [9] presented such results for aftershocks of 1994 Northridge earthquake in California. At the five stations studied, they found that for weak motions (peak ground velocities smaller than 5 – 10 cm/s), local peaks in Fourier amplitude spectra of strong motion reappeared at most 55 percent of time. Occurrence of these peaks could not be associated with any specific direction of wave arrival. They found that for intermediate and strong-motion amplitudes, identified site peaks shifted toward longer periods, indicating non-linear soil response. The largest peak velocities in analyzed data were 50 and 110 cm/s, there was no visible evidence of site liquefaction or lateral spreading, and the identified peaks at all five stations returned to their pre-earthquake frequencies corresponding to low strain, with no indication of permanent deformations.

Trifunac and Ivanovic [10] presented results of a similar study in Montenegro, Yugoslavia for strong-motion aftershock sequence following the $M_s = 6.7$ earthquake of April 15, 1979. The companion paper, Trifunac and Ivanovic [11], presents the data and results of the remaining three active areas in Former Yugoslavia: Friuli, Banja Luka and Kopaonik. It is hoped that with accumulation of such rare case studies and the systematic recording of required strong motion data in different geological settings, a picture may eventually emerge on usefulness and reliability of site specific studies of amplification. This paper presents highlights of analysis and the results for the area of Montenegro, studied by Trifunac and Ivanovic [10].

THE DATA

The data studied were recorded by the strong motion accelerograph network that started to operate in former Yugoslavia in 1973. The data were digitized at University of Southern California in the Department of Civil Engineering, using digitization and software methods described by Trifunac and Lee [12]. For the periods between 1975 and 1983 the data come mainly from four areas of earthquake activity [13]: Friuli, Banja Luka, Kopaonik and Montenegro (Fig.1a). This work analyzes records from Montenegro.

Montenegro Earthquakes

The Montenegro, Yugoslavia, earthquake of April 15, 1979 (Main event 6:19 GMT) had magnitude $M_L = 6.8$, seismic moment $M_0 = 4.6\times 10^{26} dyne\ cm$, and epicenter at $42^o\ 2^{'}\ 24^{''} N$ latitude and $10^o\ 03^{'}\ 00^{''} E$ longitude (Fig. 1b). It occurred on a fault plane with $NW - SE$ strike, dipping steeply, 85^o, to the northeast [14]. It was followed by many aftershocks and a second main shock on May 24, 1979, with magnitude 6.4, at $42^o\ 14^{'}\ 24^{''} N$ latitude and $18^o\ 45^{'}\ 00^{''} E$ longitude, at 17:23 GMT (Fig. 1b).

Between March 31 and July 30, 1979, the European seismic network [15] recorded 229 events with $M \geq 3.5$. During the same period, seven strong motion stations, distributed along the Adriatic coast (Fig. 1b) recorded 79 events with $M \geq 3.2$. Strong motion accelerographs in the Yugoslav network did not have self-contained absolute time, and therefore identification of all recorded accelerograms was not possible.

All accelerograms selected for this study were recorded at seven stations: Ulcinj – Hotel Olimpic, Ulcinj – Hotel Albatros, Bar - Skupstina Opstine, Petrovac – Hotel Oliva, Budva – P.T.T., Kotor – Naselje Rakite, and Herceg Novi - Osnovna Skola Pavicic. All records are listed in Table 1, in Trifunac and Ivanovic [10]. Total number of accelerograms used in that analysis was 222. Number of recorded events per station was as follows: Ulcinj (Hotel Olimpic) - 123, Ulcinj (Hotel Albatros) – 22,

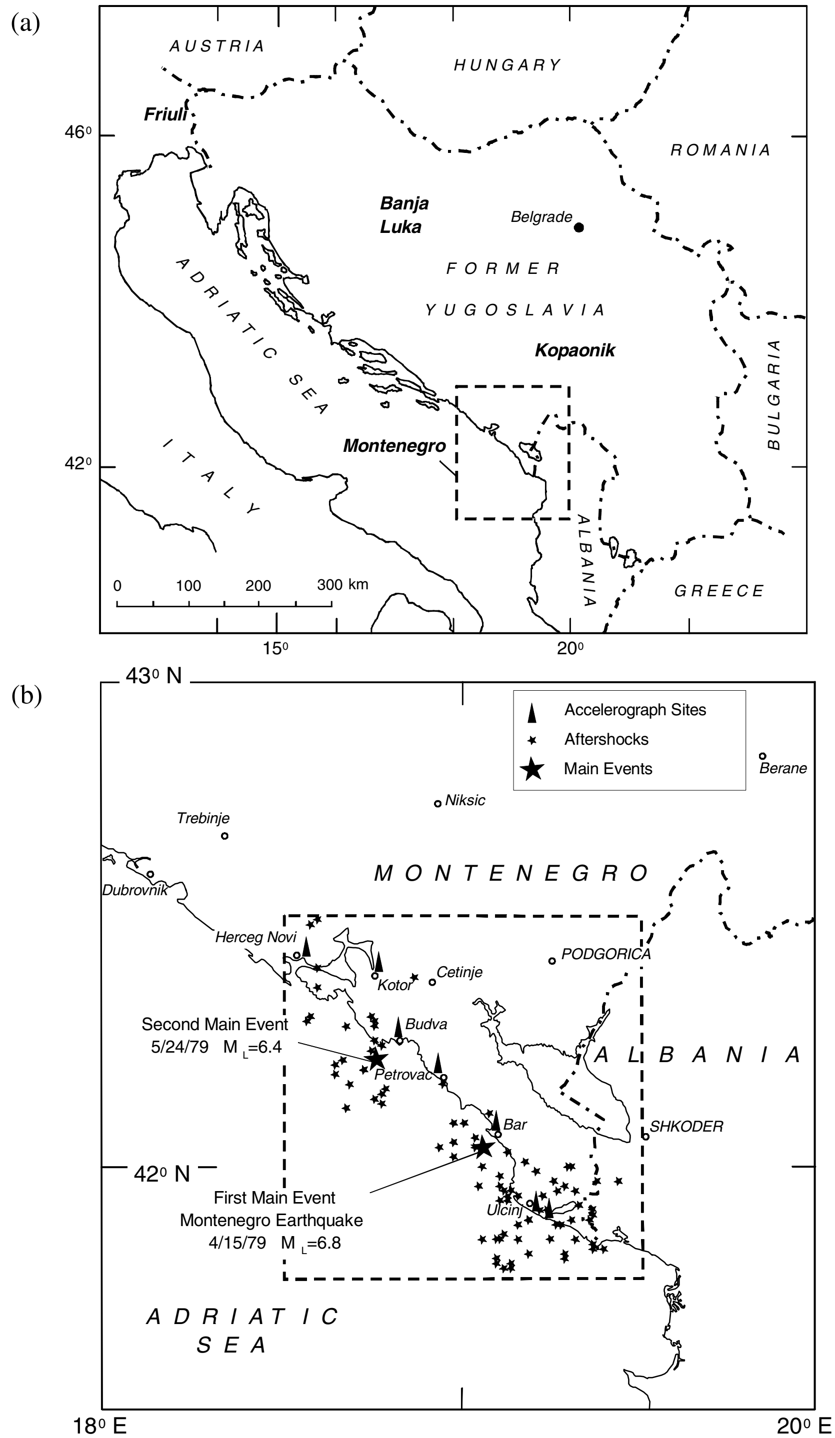


Fig. 1. (a) Map of Former Yugoslavia showing the location of the area studied in this paper – Montenegro. The other active areas with multiple earthquake recordings are Friuli, Banja Luka and Kopaonik. (b) Area of Montenegro showing two main events (April 15, 1979 $M_L = 6.8$ and 5/24/79 with $M_L = 6.4$) and their aftershocks. Seven strong-motion recording stations are shown by solid triangles. Dashed square outlines the area shown in Fig. 3a.

(Hotel Albatros) – 22, Bar (Skupstina Opstine) - 24, Petrovac (Hotel Oliva) - 14, Budva (P.T.T.) – 23, Kotor (Naselje Rakite) – 5, and Herceg Novi (Osnovna Skola Pavicic) - 11.

METHOD OF ANALYSIS

For each of the seven stations, the method of analysis outlined in Trifunac et al. [9] and Trifunac and Ivanovic [10] was used.

1. For each record, Fourier amplitude spectra of acceleration and the pseudo relative velocity spectra (PSV), were plotted for both recorded horizontal components of motion. Using subjective visual analysis of these spectra, peaks for each spectra, that could have been cased by some local amplification were identified. 'Obvious' local peaks, that appear on both spectra (Fourier and PSV) were marked with a solid circle, and the not-so-obvious 'smaller' or 'multiple' (broad) peaks were marked with an open circle, as shown in Fig.2. Other oscillations of Fourier and PSV spectra were treated as a noise and ignored. Finally, periods of identified peaks were read and stored.

2. Part (a) of Fig. 3 shows epicenters of all identified earthquakes recorded at the station shown by solid triangle. All epicenters are identified by the corresponding reference number. Fourier amplitude spectra are plotted for both horizontal components of motion, normalized to unit peak spectral amplitude, as shown on the top of part (b) of Fig. 3. The number of occurrences of the peaks that appear to correspond to some characteristic site response, and histograms of occurrences of these peaks versus period were constructed. Those are shown in the bottom of the part (b) in Fig 3.

3. The records were ordered by the larger of two horizontal PSV spectrum amplitudes. Periods of identified peaks were plotted (using open or full circles) on horizontal axis separately for each record, with these axes shifted vertically and with the largest amplitude record on the top, as it is shown in part (c) of Fig 3. Similarly, peak horizontal PSV amplitudes were plotted for each record. We were looking for a trend of changing periods for a repeated peak with increasing amplitude of motion as an indication of nonlinear response of the local soils. When a group of identified peaks fell closely along a vertical line, those were connected by wide gray lines.

4. As in part (a) in Fig. 3, a map was plotted, containing stations and epicenters of the events that contributed to the records analyzed at that station. Station is shown by a triangle and epicenters by open circles. Map was plotted for each group of identified peaks that were connected by wide gray lines (shown in part (c)). Events that contributed to identified re-occurring peaks were emphasized by solid points. We were looking for an azimuthal trend of epicenters, relative to the recorded station, for the repeatedly recorded peaks with period T. Those maps are shown in part (d) of Fig. 3.

5. Part (e) of Fig. 3 shows Fourier amplitude spectra for the 10 largest horizontal motions in each group. All selected peaks are identified by solid points.

6. For the peaks identified as corresponding to a particular mode of the site response, $1/T$ (from part (c) in Fig. 3, proportional to the square root of the modulus μ) was plotted versus $v_{\max}/V_{s,30}$ (proportional to the near surface strain) in Fig. 4. In these plots, we were looking for the evidence of 'site softening', i.e. decrease of 'site stiffness' with increase of strain in the soil.

RESULTS

In this paper, as an illustration, only results for one station, Bar – Skupstina Opstine, are presented. Results for the remaining six stations, Ulcinj – Hotel Olimpic, Ulcinj – Hotel Albatros, Petrovac – Hotel Oliva, Budva – P.T.T. Kotor – Naselje Rakite, and Herceg Novi - Osnovna Skola Pavicic are presented and discussed in reference [10].

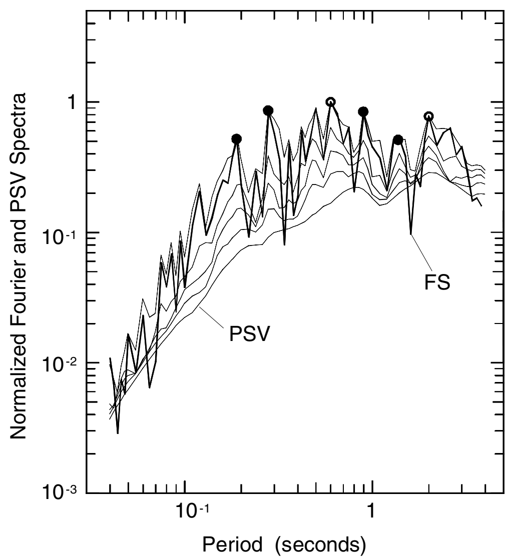


Fig. 2. Typical Fourier (FS) and pseudo relative velocity PSV spectra of recorded aftershocks at a strong-motion station. Solid circles show the ‘peaks’ that may have been caused by some local amplification mechanisms. The open circles show the less ‘obvious’ choices.

Station: Bar – Skupstina Opstine

At this station, the largest horizontal peak velocity, equal to 57.2 cm/s, was recorded during the main event on April 15, 1979. Of the seven identified periods at which peaks tend to re-occur a this site, only three, at (1) 0.8-1.2 s, (2) 0.5-0.8 s, and (3) 0.3-0.5 s showed clear and large changes with respect to the excitation amplitudes. The first shift of the peaks, near 0.3 s, begins for $v_{\max} \sim 1$ cm/s for events ZE332 down to ZE331. For $v_{\max} > 10$ cm/s, three periods (labeled 1, 2 and 3 in Fig. 3c) shift from 0.32, 052 and 0.8 s to 0.55, 0.85 and 1.4 s. Those were interpreted to be the largest possible shifts at this site. It is also possible that those shifts are smaller or insignificant. That is shown by several short ‘branches’ adjacent to and to the left from the gray lines labeled 1, 2 and 3 in Fig. 3c. Fig. 3d shows that there were no preferred directions of wave arrival that could be associated with the re-occurrence of the spectral peaks at this site. The peak (3) at $T \sim 0.3-0.5\ s$ re-occurs 67 percent of time.

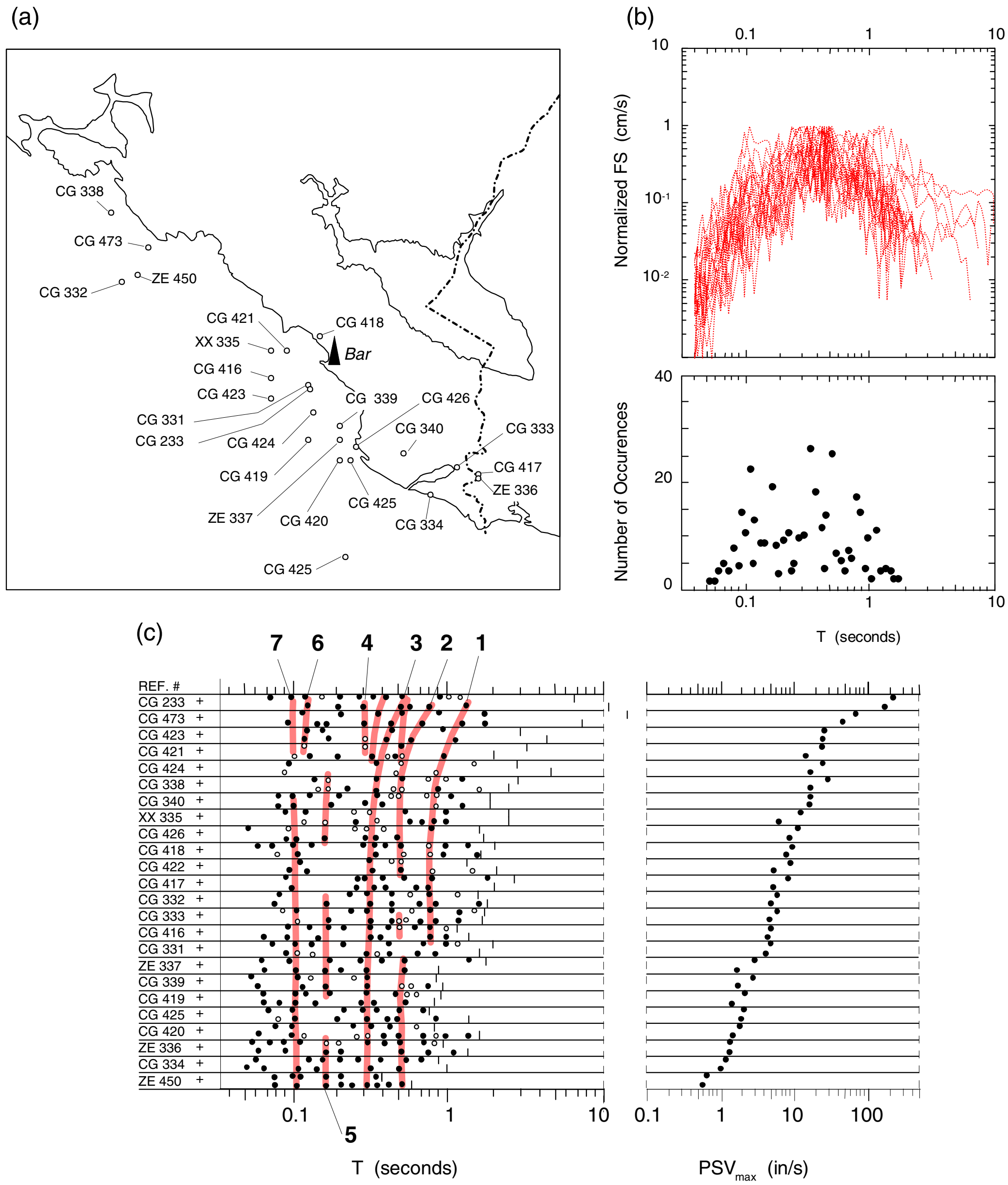
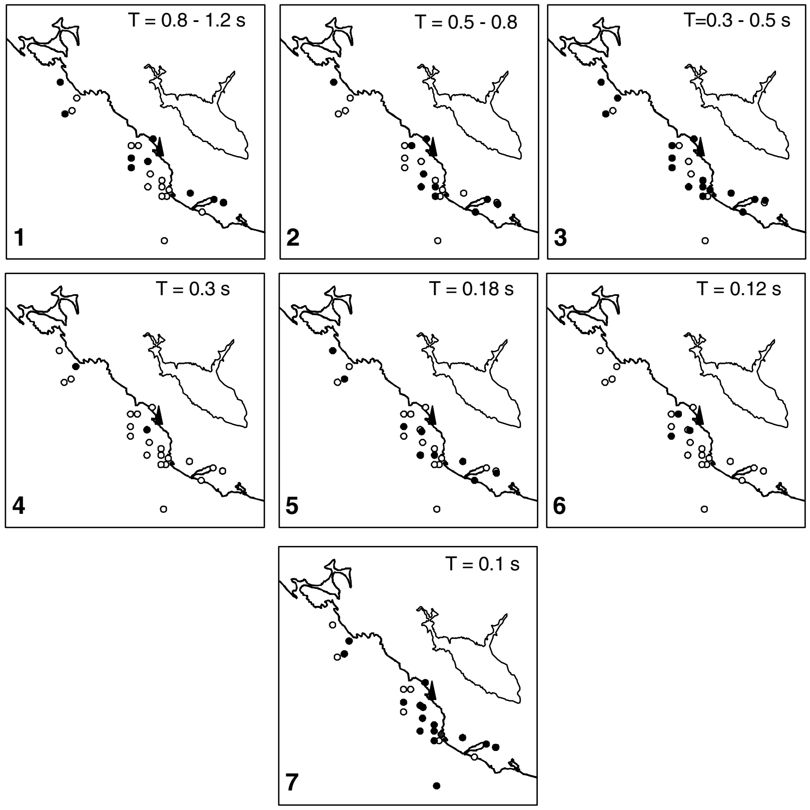


Fig.3. (a) Map of epicenters of identified events that were recorded at Bar – Skupstina Opstine (shown by solid triangle). Events are identified by their record reference numbers [10]. (b) Superposition of normalized Fourier amplitude spectra (top) and a histogram of the number of occurrences of the identified peaks in (c) (bottom), for station Bar - Skupstina Opstine. (c) Periods of 'identified' (solid points) and 'potential' (open circles) peaks of Fourier amplitude spectra (left) and the peak pseudo relative velocity (PSV) spectrum (right) for records of the Montenegro earthquake and its aftershocks (in decreasing order of PSV spectrum amplitudes). The gray lines labeled (1), (2), … show the amplitude dependence of the frequently re-occurring peaks near 0.8-1.2 s, 0.5-0.8 s, … at strong motion station at Bar – Skupstina Opstine. (d) Map of epicenters of all identified events (open circle) at station Bar – Skupstina Opstine. All events for which both horizontal components of recorded motion do have the peak, at the selected period, are emphasized by black points. (e) Fourier amplitude spectra of the 10 largest recorded horizontal motions at station Bar - Skupstina Opstine (the vertical coordinate has been shifted to avoid clutter, but the overall spectral amplitudes decrease from top to bottom).

(d)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2
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T = 0.3 s
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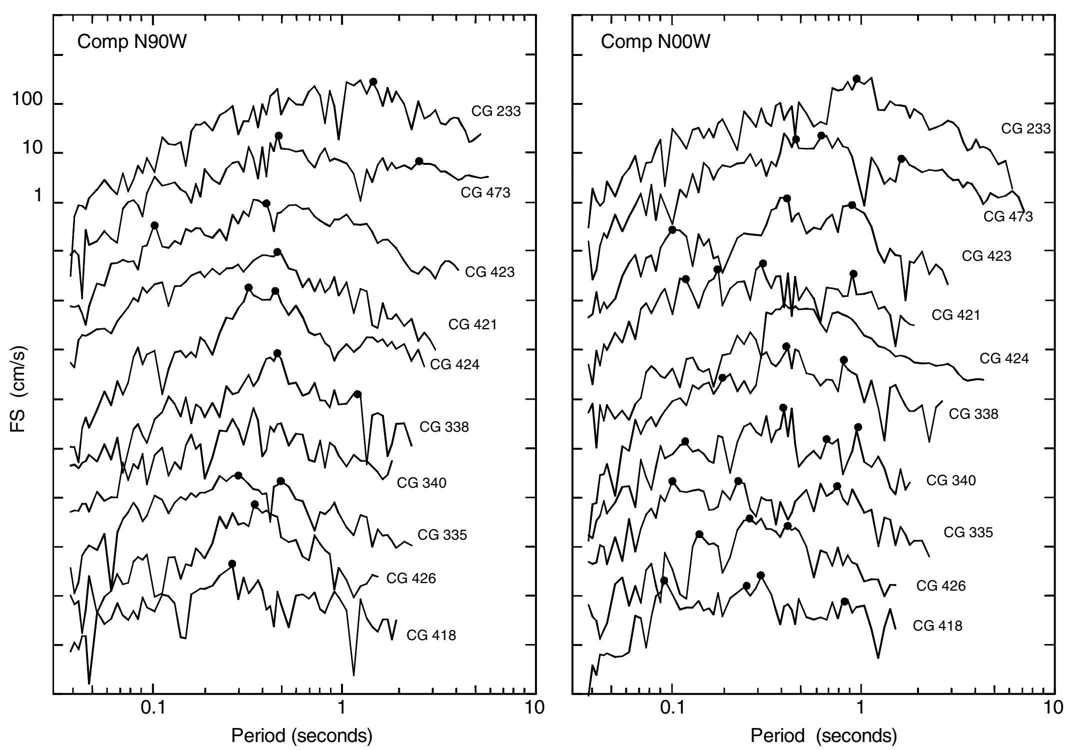
5
T = 0.12 s
6
T = 0.1 s
7

(e)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DISCUSSIONS AND CONCLUSIONS

The analysis shows that there are site periods for which Fourier amplitude spectra of ground motion have re-occurring local peaks. These peaks are not excited by all events. In this study the frequency of re-occurrence is in the range from 1 to 83 percent [10]. It is found that periods of selected peaks depend upon the amplitude of excitation. Examples show that these periods lengthen for increasing strains in the soil. Generally, such trends are consistent with several previous studies [9,16] and with a model with equivalent softening spring representation of the medium. After the shacking, when the large strains are over, the equivalent soil stiffness (for this data set) appears to return to its pre-earthquake values. In general it is also possible that repeated shacking may cause dynamic compaction to such a degree that the effective soil stiffness may increase enough to be noticeable in the period shift of selected peaks of Fourier amplitude spectra, during and after a sequence of earthquakes and/or aftershocks [9].

Recent research has shown that the modulus reduction curves for soils are influenced more by the plasticity index (PI) than by the void ratio and that the linear cyclic shear strain is greater for highly plastic soils than for soils with low plasticity. Fig.4 shows a shaded zone for the over-consolidation ratio (OCR) in the range from 1 to 15, bounded by PI = 0 and PI = 50. Fig. 4 also shows (the gray shaded zone) the dependence of the modulus reduction curves for non-plastic (PI = 0) soils upon mean effective confining pressure $\sigma_m^{'}$ in the range from 1- 200 KN/m [17]. $(\mu(\varepsilon)/\mu_o)^{1/2}$ was plotted instead of the customary $(\mu(\varepsilon)/\mu_o)$, to enable direct comparison with the shifting periods of the peaks in the site response Fourier spectra. A frequency of vibration, of a soil layer $f = 1/T \sim (\mu(\varepsilon)/\rho)^{1/2}$, where $\mu(\varepsilon)$ is the Lamé shear modulus at certain strain amplitude ε and ρ is the material density. Approximating $T(\varepsilon)$ by $T_0 \equiv T(\varepsilon_{\min})$, where $\varepsilon_{\min}$ corresponds to the smallest observed strain factor $\varepsilon = V_{\max}/V_{s,30}$, [9,18] and approximating $\mu(\varepsilon \sim 0)$ by $\mu_0 = \rho/T_0$, it follows that $(\mu(\varepsilon)/\mu_o)^{1/2} \sim T_0/T(\varepsilon)$. Estimates of $(\mu(\varepsilon)/\mu_o)^{1/2}$ were plotted versus $v_{\max}/V_{s,30}$ for all identified periods T. Then, for each station, an 'average' curve through all $T_0/T(\varepsilon)$ versus $v_{\max}/V_{s,30}$ was plotted. Strain factors $v_{\max}/V_{s,30}$ and $V_{s,30}$ (average shear wave velocity in the top 30 m of soil, Fig. 5) are both only rough first- order approximations. Yet, the qualitative trends seen in Fig. 4 suggest that the observed changes of the periods of the selected peaks have realistic trends and reasonable ranges of variation and that they agree with the trends of modulus reduction expected for typical soils.

Trifunac and Todorovska [6] reviewed several site amplification studies following the 1994 Northridge earthquake and argued that he peaks at the periods of site-specific amplification functions determined for small amplitude measurements at the site (e.g. using aftershocks) will cease to re-occur during strong motion that is accompanied by the non-linear soil response. The trends found in references [10, 11] and illustrated here in Fig. 3, confirm that interpretation. Perusal of the largest recorded motion, as in Fig. 3, shows that many identified peaks will not only shift to different periods but will also disappear. For the seven stations studied [10,11], there are three to seven periods (per station) with re-occurring spectral peaks. For larger levels of shaking, many of those peaks disappear. Fig. 6 shows how the percentage of remaining peaks decreases with increasing peak recorded velocity. The shaded zone suggests the overall trend. Of course, the peaks can 'appear' and 'disappear' from spectra of recorded motion for numerous other reasons [9], but at Fig. 6, the trends are interpreted to be driven mainly by the non-linear site response.

It is concluded that the characteristics of site-specific amplification functions can be measured, but the success rate of prediction of prominent peaks during future severe shaking is difficult to quantify. The successful predictions may be possible for small amplitudes of motion only, for example for $v_{max} \le 5 \text{cm/s}$. The destructive strong motion is associated with $v_{max} > 10-20 \text{cm/s}$ and is accompanied by a non-linear response of the soil near the ground surface [19-24]. Site-specific amplification characteristics of such large motion cannot be predicted by the linear transfer functions theory, based on the theory or experimental measurements.

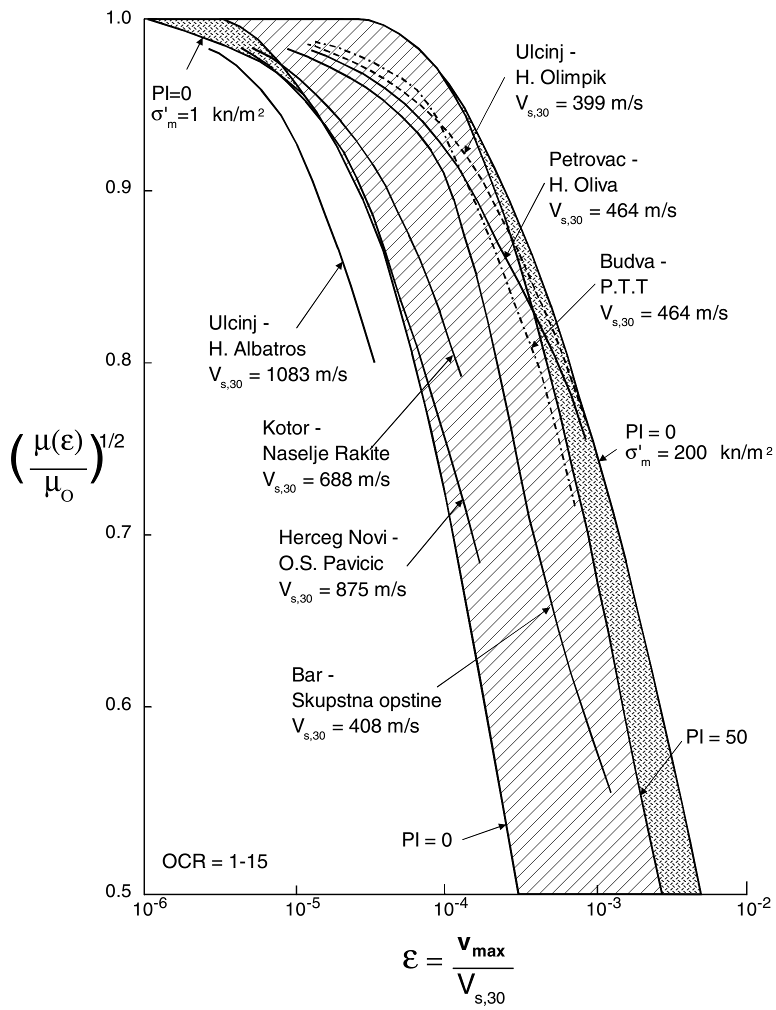

Fig. 4. Estimated modulus reduction curves $(\mu(\varepsilon)/\mu_0)^{1/2}$ for strong-motion recorded at seven stations versus strain factor $\varepsilon = v_{max}/V_{s,30}$. The range of modulus reduction values for soils with over-consolidation ratio OCE = 1-15 and for 0 < PI <50 is shown by shaded zone. The range of modulus reduction values for non-plastic soils (PI = 0) for mean effective confining pressure σ_m' between 1 and 200 KN/m^2 is shown by gray zone.

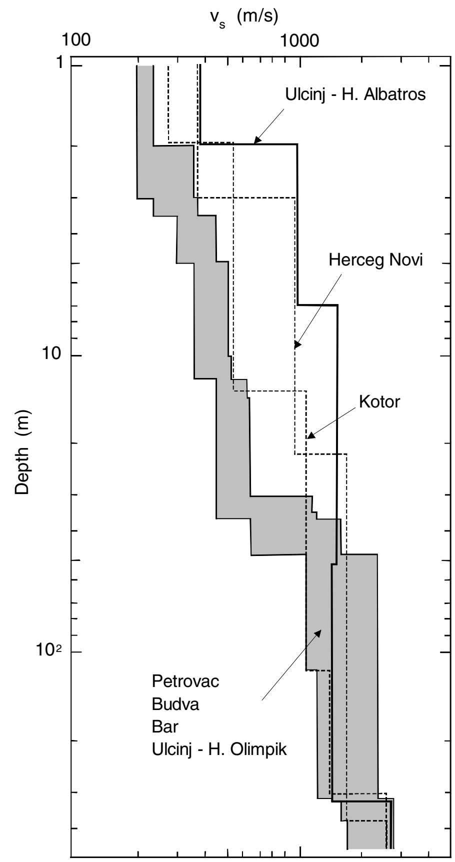

Fig. 5 Shear wave velocity profiles at seven stations studied in reference [10].

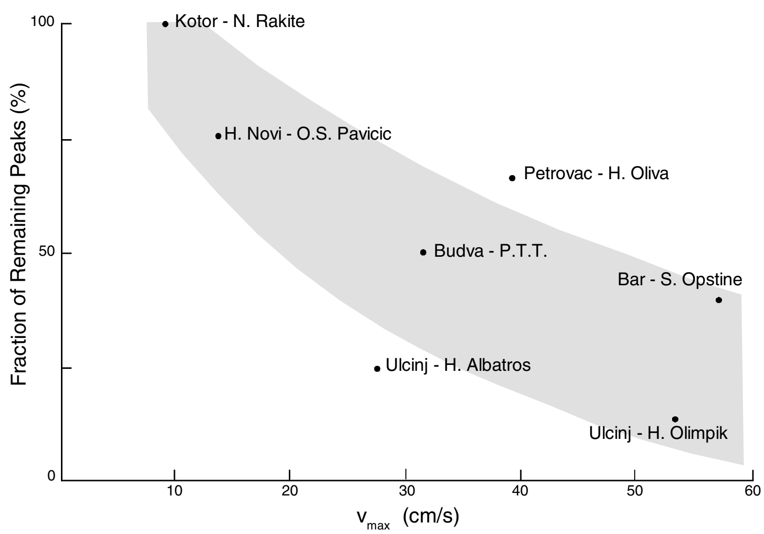

Fig. 6. Fraction of identified site-specific peaks that remain in the data set, studied in reference [10], as ground velocity v_m increases from 10 to 60 cm/s. At 60 cm/s and above, 60-90 percent of all site-specific peaks disappear due to non-linear response of the soil.

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