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NEAR FAULT EARTHQUAKES OF MEDIUM MAGNITUDE: THE CASE OF THE ATHENS 1999 EVENT

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Abstract: In this paper the moderate earthquake event of 1999, which affected the large urban area of Athens, is presented as a case study for the evaluation of the effects of strong directivity in the near field region for small to moderate events. Ground motion records at a distance from the causative fault are analyzed in order to estimate crucial characteristics associated with the event, as possible directivity pulses and their predominant period. Ground motions recorded at rock sites are scaled up to new generation attenuation models of characteristic spectra, accounting for either mean, near field, acceleration amplification or possible directivity related velocity pulses. These ground motions are used as input at the bedrock of typical soil deposits in order to obtain surface ground motions accounting for different soil profiles at various distances from the causative fault in the near field region. Inelastic spectra are generated and the difference between mean and strong, directivity affected, ground motion is established. For ground motions affected by forward directivity it is concluded that even for medium events seismic coefficients, provided by aseismic codes are inadequate for safe structural design. Seismic zonation coefficients must be re-examined and most likely upgraded in order to account for near field directivity, even in the case of moderate earthquake events.

1. INTRODUCTION

During the last decade a serious effort has been made in order to estimate the expected ground motion and spectral values in the near field region. New generation attenuation relationships have been developed in order to account for different parameters affecting the response of ground motion. Such parameters are associated with characteristics as moment magnitude, distance from the fault, type of fault, soil conditions, etc. These new generation attenuation relationships estimate ground motion values associated with a geometric mean of the horizontal spectral demand, lower than the maximum demand in the near field region affected by forward directivity. As a result, further investigation has been conducted in order to associate the predicted spectral values with this maximum spectral demand (Huang et al, 2008). Up to now this investigation has been undertaken for events with moment magnitude greater than 6.5. In the present paper such an investigation is conducted for events with a moment magnitude in the range of 6.0 presenting a larger frequency of occurrence and consequently more probable events at the vicinity of great urban centers.

As a case study, the Athens earthquake of 1999 is presented and an effort is made to develop the elastic and inelastic spectra associated with such an event of $M_w = 5.9$, for different soil conditions, at a distance of 2 and 5 kilometers from the causative fault. Two cases of spectral values are considered, associated, on the one hand with new generation relationships, predicting mean values at the near field zone, and, on the other, with the maximum spectral demand in the region, associated with directivity effects. In the case of the Athens earthquake the existing data for the earthquake ground motion are records taken at a distance from the most affected region. These records are at soft rock sites mostly, next to subway stations, near the center of the metropolitan area of Athens.

The analysis of these records presents a pulse with a period of around 1.5 to 2.0 seconds on the time history of ground velocity, which appears to be associated with the directivity pulses expected for events of such magnitude, according to existing relationships. Pulses of that period affect the frequency content lower than 1 Hz, an observation conforming with the prediction of Somerville (1998), separating the frequency content in a region higher than 1 Hz that remains unaffected from directivity amplification, and a region lower than 1 Hz, affected by the directivity phenomenon and presenting amplification dependent on the azimuth of the recording site. This directivity amplification is expected to strongly influence the ratio between the maximum spectral demand and the geometric mean spectral values at the near field region.

Up to now, comparison between the maximum and the mean spectral values has been conducted for earthquakes larger than 6.5 and distances from the fault plane less than 15 kilometers. The ratios between maximum and mean spectral demands have been evaluated for different period ranges. According to Huang et al (2008), for most periods the strike normal component of the forward directivity records can be considered to represent the maximum spectral demand. Furthermore, for strong forward directivity and for periods 1.0 and 3.0 seconds, spectral ratios of 1.5 to 2.0 have been estimated.

These results present average values for magnitudes larger than 6.5 and do not account for the effect of magnitude variation on the estimated ratios. As well known from many studies (Alavi and Krawinkler (2000), Rodriguez-Marek (2000), Somerville (2003)), the predominant period of the directivity pulses depends on the moment magnitude of the event and varies exponentially with magnitude. Consequently, the spectral amplification associated with these pulses is magnitude and period dependent. In order to estimate appropriate ratios between maximum and mean spectral demands for moderate events, the case of the Athens earthquake is presented in this study.

2. THE ATHENS 1999 EARTHQUAKE

On September 7 1999, an earthquake event with moment magnitude 5.9 rocked the city of Athens (Psycharis et al, 1999). The strongly affected area was within a radius of 12 km from the epicenter. A number of modern buildings collapsed causing the death of 140 persons. About a hundred thousand people became homeless.

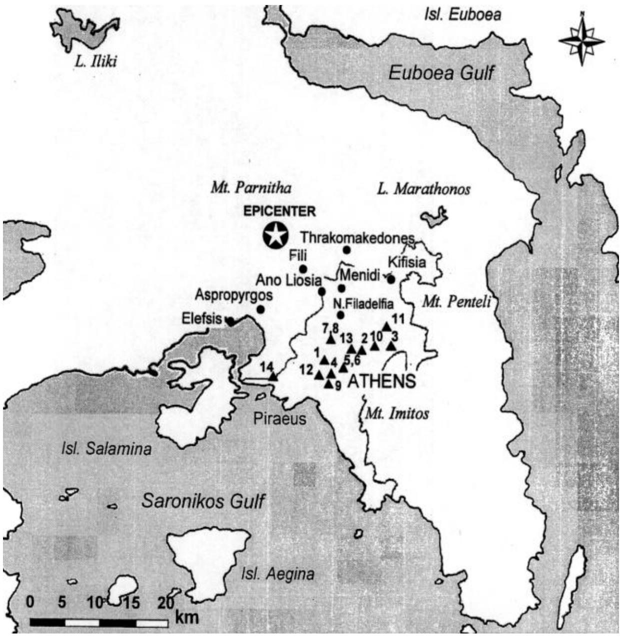

Fig.1. The urban area of Athens affected by the 1999 earthquake. Circles show the mostly affected sites and triangles the sites of recording stations (Psycharis et al, 1999) (see Table 1).

A number of strong ground motion time histories were recorded on soft rock sites at distances of 15 to 20 km from the epicenter (see Fig.1 and Table 1).

Table 1. Characteristics of main records of the Athens 1999 event (Psycharis et al, 1999).

No.	CODE	SITE	GEOLOGY	PLACE	EPICEN. DIST. Km	Max ACCELER., g		
						L	V	T
1	MNSA1	Monastiraki	Schist of bad quality, black soft phylite, archaeological deposits, underground caves	Free field	17	0.223	0.223	0.534
2	ATHA1	Neo Psychiko	Tertiary deposits	Basement, 3-story bldg	18	0.083	0.121	0.104
3	DMK1	Ag. Paraskevi	Limestone	Free field	19	0.052	0.042	0.073
4	FIX1	Syngrou-FIX	Limestone / Sandstone of good quality	Metro station, level –1	19	0.086	0.046	0.122
5	SMGA1	Syntagma	Limestone / schist	Metro station, level –1	18	0.146	0.051	0.239
6	SMGB1	Syntagma	Limestone / schist	Metro station, level –3	18	0.115	0.088	0.092
7	SPLA1	Sepolia	Deposits of Kifissos river	Metro station, level –1	15	0.248	0.093	0.226
8	SPLB1	Sepolia	Deposits of Kifissos river	Basement, 2-story steel bldg	15	0.356	0.204	0.326
9	DFN1	Dafni	Schist	Metro station, level –2	21	0.038	0.041	0.112
10	PNT1	Papagos	Tertiary deposits	Metro station, level –2	19	0.090	0.057	0.080
11	ATHO2	Chalandri	Alluvial deposits	Basement, 2-story bldg	17	0.130	0.190	0.110
12	ATH03	Piraeus str – KEDE	Alluvial deposits	Ground floor, 1-story bldg	16	0.290	0.350	0.190
13	ATH04	Kypseli	Schist	Basement, 4-story bldg	16	0.140	0.120	0.060
14	KERA	Keratsini	Soft rock	Basement, Administr. bldg	15	0.186	0.220	0.157

3. PRESENTATION OF THE ANALYSIS PROCEDURE

The existing records have been used in order to determine the referred ratios between maximum and mean spectral demands according to the following procedure:

- The original accelerograms FIX1 and DFN1 are filtered in order to obtain two frequency components, a component of high frequency, i.e., higher than 1 Hz, and a component with frequencies lower than 1 Hz.
- The two components are scaled in order to represent mean near field ground motion at rock sites, at a distance of 2 and 5 kilometers from the fault plane. Consequently, the high and low frequency components are scaled up to the values given by a representative attenuation relationship for the near field ground motion acceleration spectra, given by Ambraseys and Douglas (2003). The target spectral values are related to the 50% and 84% probability of non-exceedence and the frequency components are combined after scaling. The resulting time histories are considered to represent the mean near field records at rock sites at the referred distances from the fault and probabilities.
- The two components of the original accelerograms are scaled in order to represent maximum near field records, affected by forward directivity, at rock sites located at distances of 2 and 5 kilometers from the fault plane. The high frequency component is scaled, as before, up to the values given by Ambraseys and Douglas (2003). This scaling conforms to the observation presented by Somerville (1998) that the high frequency component of the ground motion remains unaffected from near field directivity. The low frequency component is scaled in order to attain a

maximum velocity, comparable to that predicted by the attenuation relationship proposed by Rodriguez-Marek (2000), for near field ground motions affected by forward directivity. The scaling is performed for 5.9 moment magnitude, rock sites at 2 and 5 km distance from the fault and 50% as well as 84% probabilities of non-exceedance.

- The artificial accelerograms generated by this procedure are used as rock outcrop ground motions in order to estimate the response and the subsequent ground motions at the top of soil deposits corresponding to A, B and C categories of the EC8 regulations. As a result of this procedure, a large sample of artificial time histories, approximating cases of near field ground motions, were generated. These time histories represent ground motion either affected or not by forward directivity, for a moment magnitude 5.9, distance from the fault plane of 2 and 5 kilometers, three different soil conditions and two levels of non-exceedance probability.
- The spectra of these artificial ground motions are used in order to determine the ratios between maximum and mean near field spectral demands.
- The artificial ground motions are used in order to estimate inelastic spectra and especially the design spectral acceleration values in order to attain a ductility level of 2 for representative SDOF systems.
- Finally, the obtained elastic and inelastic spectra are compared with spectra obtained during the San Salvador 1986 earthquake, an event considered to represent the case of near field directivity effects for small to moderate earthquakes (Bommer et al, 2001).

4. SPECTRAL ACCELERATIONS GIVEN BY AMBRASEYS AND DOUGLAS

Ambraseys and Douglas (2003) have studied the horizontal and vertical ground motions for near field and developed attenuation relationships for spectral accelerations. These relationships depend on the surface-wave magnitude, the distance from the horizontal projection of the fault plane and the soil conditions. Forward directivity is not taken into account. Consequently, the corresponding spectra are associated with the mean near field ground motions. The general form of the relationship given by Ambraseys and Douglas is:

$$logy = b_1 + b_2 M_s + b_3 d + b_4 S_A + b_s S_S \qquad (1)$$

with M_S denoting the surface wave magnitude, d is the distance from the horizontal projection of the fault plane, S_A and S_S take the value of 1 for stiff and for soft soil respectively. For rock S_A and S_S are zero. The relationships have been developed with the aid of a worldwide set of 186 strong ground motion records recorded within 15 kilometers from the surface projection of the fault rupture and for event surface magnitudes of 5.8 up to 7.8. Figures 2 and 3 present the target near field spectral accelerations, used for scaling the original records.

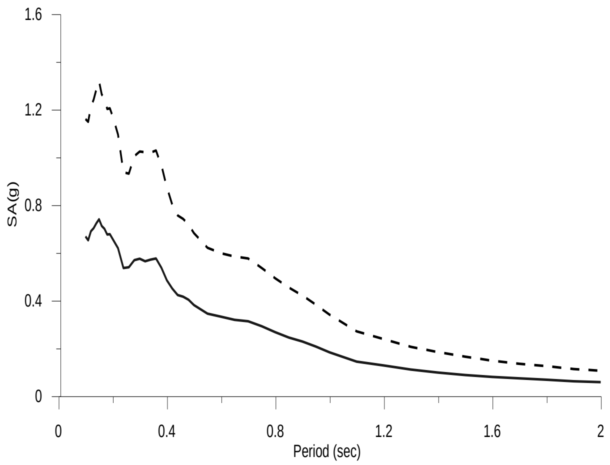

Fig.2 Target acceleration spectra as developed by Ambraseys and Douglas (2003) for surface magnitude 5.9, rock sites at 2 km from the fault and 50%, 84% probabilities in non exceedance.

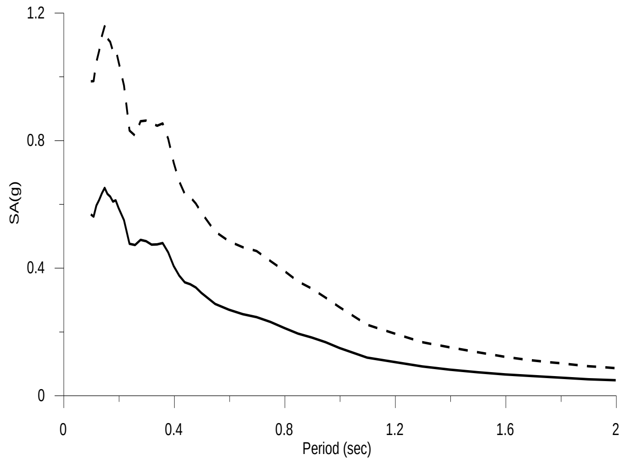

Fig.3 Target acceleration spectra as developed by Ambraseys and Douglas (2003) for surface magnitude 5.9, rock sites at 5 km from the fault and 50%, 84% probabilities in non exceedance.

5. RELATIONSHIPS PROPOSED BY RODRIGUEZ-MAREK TO ESTIMATE DIRECTIVITY PULSE PERIOD AND MAXIMUM GROUND VELOCITY

Rodriguez-Marek in his dissertation (2000) presented relationships to estimate the pulse periods associated with forward directivity, as well as attenuation relationships for the maximum ground velocity associated with directivity velocity pulses. The former relationship is presented in Fig. 4 in order to demonstrate that the pulse period estimated for the Athens records is close to those estimated for 5.9 moment magnitude. The velocity attenuation relationship presented in Fig. 5 was used to scale the low frequency component of the original records in order to simulate near field time histories affected by near field forward directivity.

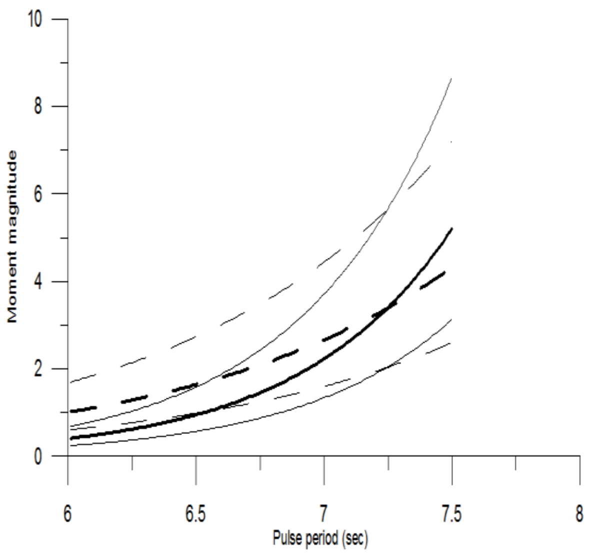

Fig 4. Relationships estimating directivity pulse period for rock sites (continuous line, mean-σ,mean,mean+σ) and soil sites (dashed, mean-σ,mean,mean+σ) (Rodriguez-Marek 2000)

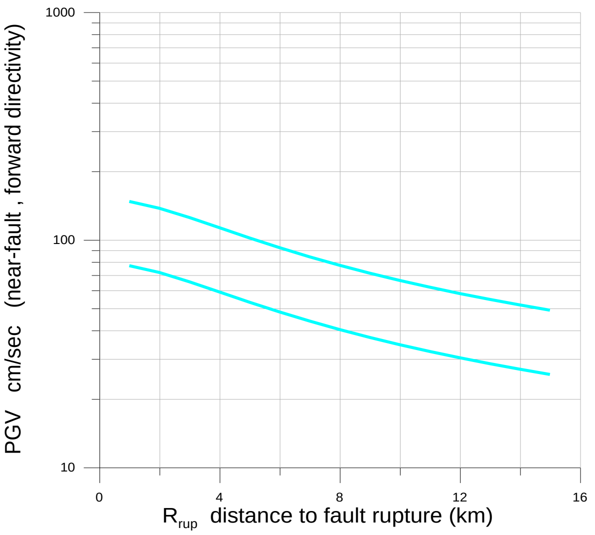

Fig 5. Relationships estimating max ground velocity for 6.1 and 7.4 moment magnitude. (Rodriguez-Marek 2000)

6. ANALYSIS RESULTS

In fig.6 spectra produced from the scaling of the original FIX1 accelerogram are presented. The maximum ground accelerations range from 0.30g for mean near field ground motion and B soil category at a distance of 5 km from the fault plane for a 50% percentile of non exceedance to 0.70g for strong forward directivity and B soil category at a distance of 2 km from the fault plane for a 84% percentile of non exceedance. At the 1 sec period the estimated spectral values are the following, for B soil category:

- At a distance of 5 km from the fault plane, for mean near field ground motion and a 50% probability of non exceedance 0.35g.
- At a distance of 5 km from the fault plane, for mean near field ground motion and a 84% probability of non exceedance 0.6g.
- At a distance of 2 km from the fault plane, for mean near field ground motion and a 50% probability of non exceedance 0.4g.
- At a distance of 2 km from the fault plane, for mean near field ground motion and a 84% probability of non exceedance 0.7g.
- At a distance of 5 km from the fault plane, for near field strong forward directivity and a 50% probability of non exceedance 0.7g.
- At a distance of 5 km from the fault plane, for near field strong forward directivity and a 84% probability of non exceedance 1.2g.
- At a distance of 2 km from the fault plane, for near field strong forward directivity and a 50% probability of non exceedance 0.9g.
- At a distance of 2 km from the fault plane, for near field strong forward directivity and a 84% probability of non exceedance 1.4g.

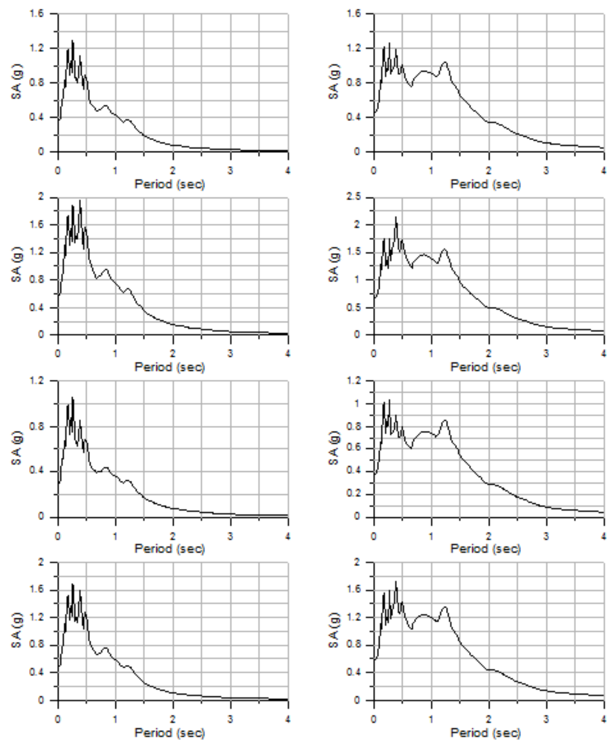

Fig.6 Spectra of artificial accelerograms produced from the FIX1 record. First column presents scaling to the Ambraseys-Douglas spectral values a) mean at 2 km b) mean+σ at 2 km c) mean at 5 km d) mean+σ at 5 km and the second column the same cases but with the low frequency range scaled up to the appropriate max ground velocity as given by Rodriguez-Marek.

In Fig.7 spectra produced from the scaling of the original DFN1 accelerogram are presented. The maximum ground accelerations range from 0.35g for mean near field ground motion and B soil category, at a distance of 5 km from the fault plane for a 50% percentile of non exceedance to 0.60g for strong forward directivity and B soil category at a distance of 2 km from the fault plane for a 50% percentile of non exceedance. At the 1 sec period the estimated spectral values are the following, for B soil category:

- At a distance of 5 km from the fault plane, for mean near field ground motion and a 50% probability of non exceedance 0.25g.
- At a distance of 2 km from the fault plane, for mean near field ground motion and a 50% probability of non exceedance 0.30g.
- At a distance of 5 km from the fault plane, for near field strong forward directivity and a 50% probability of non exceedance 0.6g.
- At a distance of 2 km from the fault plane, for near field strong forward directivity and a 50% probability of non exceedance 0.8g.

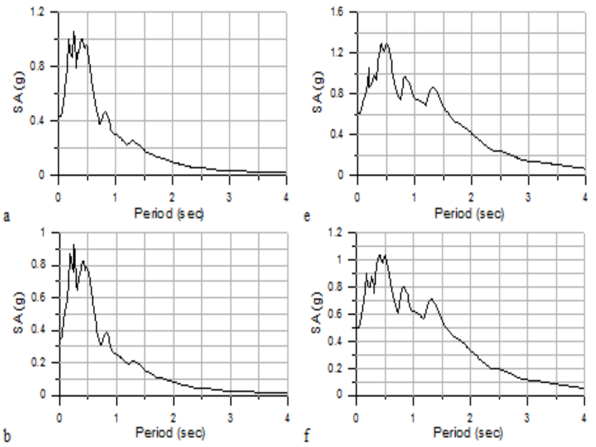

Fig.7 Spectra of artificial accelerograms produced from the DFN1 record. First column presents a) scaling to the Ambraseys-Douglas spectral values mean at 2 km b) at 5km.The second column presents the same with the low frequency range scaled up to the appropriate max ground velocity as given by Rodriguez-Marek.

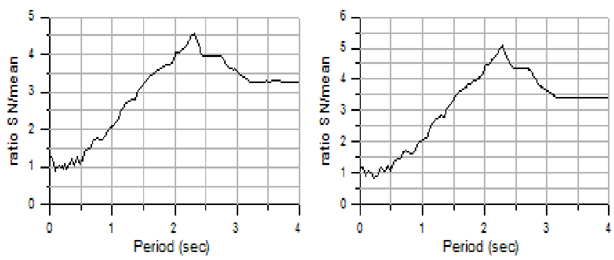

Fig. 8 Ratios between strike-normal (maximum) and mean spectral demand for different artificial accelerograms produced from the FIX1 record.

The values for the latter cases are slightly lower than those for the FIX1 record. For both records, as shown in Figs 6 and 7, a strong amplification in the range of 1 to 2 seconds characterizes the forward directivity records. This amplification is associated with the velocity pulse presenting a period around 1.5 sec.

In what regards the amplification factors between the mean near field and the maximum forward directivity spectra for the artificial accelerograms, these, for all cases, fluctuate between the values of 2 and 4 with a mean value about 3. These amplification values refer to the period range between 1 and 2 sec, where quite a lot of existing structures have their larger natural period. The amplification values given by Huang et al (2008) to estimate forward directivity spectra through new generation attenuation relationships range from 1.5 to 2. This discrepancy could be attributed to the fact that amplification factors for those studies are computed from earthquakes with moment magnitudes larger than 6.5. For such earthquakes the pulse period is expected to be larger than 2 seconds. Consequently, the amplification in the range from 1 to 2 seconds is not associated with the velocity pulses of the directivity effects. In the case presented in our study, earthquake events with magnitude around 6.0 present, as already seen, periods in the referred range of 1 to 2 seconds.

In order to assess the obtained results, a real record obtained at San Salvador in 1986 for a 5.6 earthquake, near the fault plane, at an epicentral distance of 4 km, is compared with the spectra obtained through the presented procedure from the Athens strong motion records. Bommer et al (2001) presented such records as a justification of the assumption that there exist forward directivity effects even for small to moderate earthquake events. Figure 9 shows the acceleration response spectrum of the San Salvador record and the spectrum corresponding to the artifical FIX1 record for a B soil deposit at a distance of 5 klm from the fault plane. The artificial record spectral values correlate very well to those of the real record for the forward directivity effects, which permits the assumption that the Rodriguez-Marek relationships are a good estimator for the maximum ground velocity caused by directivity effects.

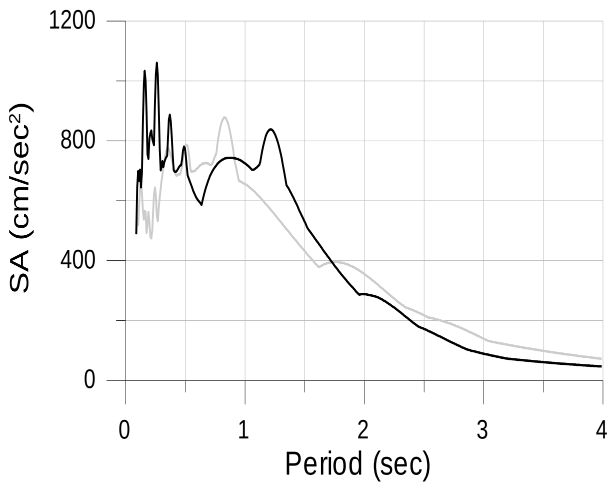

Fig.9 Comparison of spectral acceleration for the artificial ground motion (strong forward directivity, B soil category, at 5 km distance from fault plane, with 50% probability of non-exceedance),(black line), produced from the FIX1 record, with the CIG (San Salvador, 1986),(gray line) record.

Accordingly, these relationships appear to be an appropriate tool to scale accelerograms in the low frequency range, in order to simulate ground motions affected by forward directivity.

Further evaluation of the effects of strong forward directivity on structures with natural periods in the range of 1 to 2 seconds is presented by a series of inelastic spectra, for the artificial FIX1 record, as well as, for the CIG San Salvador record. From the inelastic analyses of SDOF systems the design spectral acceleration for a ductility 2 has been determined.

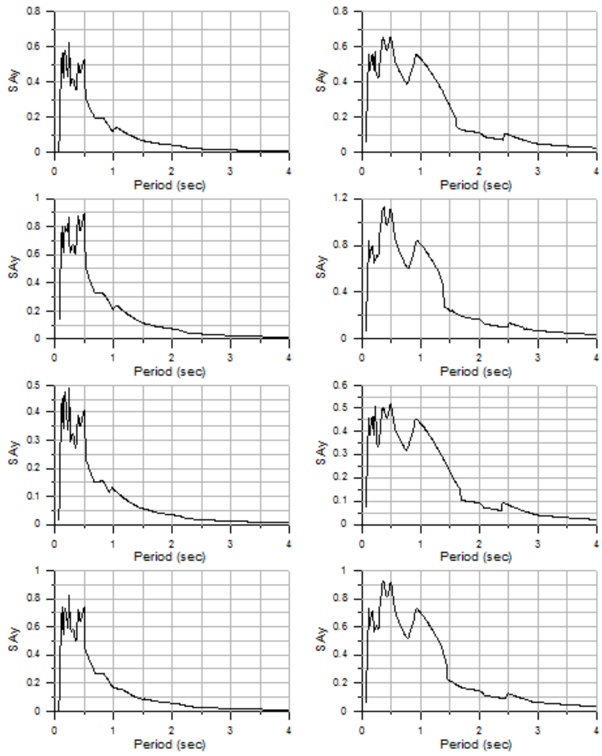

Fig.10 Design spectral acceleration for μ=2 for artificial ground motions produced from the FIX1 record, (first column) scaled to Ambraseys-Douglas for mean and mean+σ at 2 and 5 km and (second column) low frequencies scaled to max ground velocity given by Rodriquez-Marek for the same cases.

As can be seen from Fig.10, at the 1 sec period the estimated design spectral values, for a ductility of 2 and soil category B, are the following:

- At a distance of 5 km from the fault plane, for near field strong forward directivity and a 50% probability of non exceedance, 0.45g.
- At a distance of 5 km from the fault plane, for near field strong forward directivity and a 84% probability of non exceedance, 0.7g.
- At a distance of 2 km from the fault plane, for near field strong forward directivity and a 50% probability of non exceedance, 0.55g.
- At a distance of 2 km from the fault plane, for near field strong forward directivity and a 84% probability of non exceedance, 0.8g.

In Fig. 11 a comparison is made with the design spectral values for ductility 2 for the CIG record. The values are close to those of the FIX1 artificial record at a distance of 5 km from the fault plane, for near field strong forward directivity and a 50% probability of non exceedance.

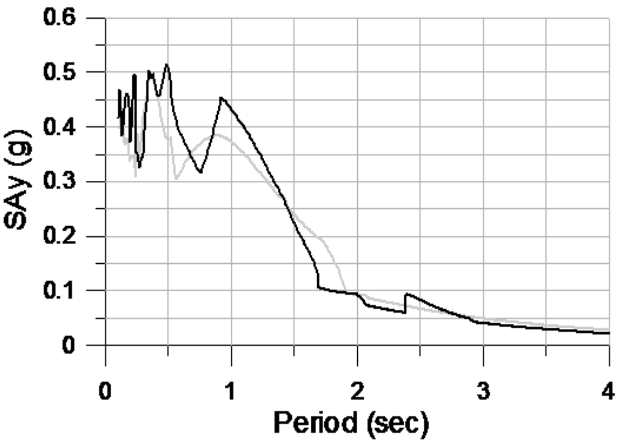

Fig.11 Comparison of design spectral values (μ=2) for the artificial ground motion (strong forward directivity, B soil category, at 5 km distance from fault plane, with 50% probability of non-exceedance),(black line), produced from the FIX1 record, with the CIG (San Salvador, 1986),(gray line) record.

7. CONCLUSIONS

This paper presents a procedure to determine spectral acceleration accounting for strong forward directivity effects of moderate earthquakes, in the period range of 1 to 2 sec. Ground motions recorded at rock sites during the Athens 1999 earthquake are scaled up using new generation attenuation models of characteristic spectra, that account for either mean, near field, acceleration amplification or possible directivity related velocity pulses. Consequently, the ground motions are used as input at the bedrock of typical soil deposits. Surface ground motions, accounting for different soil profiles at various distances from the causative fault, are produced. Elastic and inelastic spectra have been generated and the difference between mean and strong forward directivity ground motion is established. Recent studies estimate the ratio between maximum and mean near field spectral values at about 1.5 to 2. This study, taking explicitly into account the amplification attributed to directivity velocity pulses for moderate events, demonstrates that the ratios may present values of 2 to 4, almost doubling the expected effects. As a result, the spectral values at a period of 1 sec, caused by this strong amplification, may range from 0.7 to 1.4g, according to the distance from the fault plane and the estimated probability of non exceedance. The produced spectral values are compared with those of a characteristic near field record for moderate events. The real spectrum appears to correlate very well to the spectral values of artificial ground motion at a similar distance from the causal fault. Consequently, even for moderate events in the period range of 1 to 2 sec, a larger amplification of spectral values, even for moderate events, in the period range of 1 to 2 sec, appears to be induced by near field directivity effects.

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