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STRONG MOTION SIMULATION OF LARGE INTERMEDIATE DEPTH EARTHQUAKES IN SE EUROPE

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ABSTRACT
Large intermediate depth subduction zone earthquakes occurred in southern Aegean (Hellenic arc) in the past, causing extended damage not only to neighbouring countries but also to northern Africa and Middle East. The biggest known one occurred in October 12, 1856 (M≈7.8) close to Crete Island whereas another one with slightly smaller magnitude occurred in June 26, 1926 close to Rhodes Island. There are no strong motion recordings from such large events in southern Aegean due to the fact that only during the last 20 years a few accelerographs have been installed mainly in SW Peloponnese and in the islands of Crete and Rhodes. However, strong motion recordings from a moderate magnitude intermediate depth earthquake (M≈6.0), have been obtained allowing for strong motion simulation of large events using the empirical Green's function technique (EGF). In this paper the EGF technique is used and forward modelling results are compared with observed macroseismic data. Simulated strong ground motion is compared with elastic design spectra of the Greek seismic code as well as with strong motion values from empirical predictive models.

Keywords: Intermediate depth earthquakes; Strong motion; Empirical Greens' function (EGF)

INTRODUCTION
During the last 20 years many research efforts have been made in strong motion simulation of large events. For this purpose, theoretical and empirical methods were developed. Among the most promising methods is that of the empirical Green's function(EGF) originally proposed by Hartzell (1978). Due to its very clear idea of using recordings of small events - that incorporate propagation path and site effect properties – in order to simulate larger ones using certain source scaling laws, development of the EGF method was fast during the last two decades(Irikura , 1983, 1986, Irikura and Kamae 1994, Kamae et al. 1998). In Greece some efforts were made using the EGF method for simulation of crustal events "*a posteriori*" (Theodulidis and Bard 1994, Diagourtas et al.1994, Roumelioti et al. 2000, Pavic et al 2000, Zahradnik and Tselentis 2000). However, no effort has been attempted for simulation of large (M≥7.5) intermediate depth subduction zone earthquakes that occur in southern Aegean area and caused in the past very large destruction in a widely spread area of the southeastern Mediterranean (Fig. 1a) (Sieberg 1932, Papazachos and Papazachou 1997). In

this paper, using as empirical Green's function an accelerogram recorded at the city of Iraklio, Crete island (Greece), from a moderate magnitude event (M6.1) of an intermediate depth subduction zone fault, forward modeling is attempted. Such a simulation may exhibit gross characteristics of strong motion in the near field of an expected large intermediate depth event. Simulated strong motion is compared and discussed with macroseismic observations of the largest known historical event from the same seismic source as well as with results from empirical predictive models and code provisions in force.

METHOD AND DATA USED

Empirical Green's Function(EGF) Method

In order to simulate the observed strong ground motions from a target event the methodology proposed by Irikura (1983, 1986) was used. Irikura (1983) combined EGF technique with similarity laws of earthquakes and dislocation model of Haskell (1964). Under the similarity assumption, when two events with different magnitude occur within the region of the same seismic source, the following similarity relations was derived,

$$\frac{L}{L_e} = \frac{W}{W_e} = \frac{D}{CD_e} = \frac{\tau}{\tau_e} = \left(\frac{M_0}{CM_{0e}}\right)^{\frac{1}{3}} = N \qquad (1)$$

where L is the length and W the width of the rectangular seismic source, respectively, D is the final offset of the dislocation, τ is the rise time and M_0 is the seismic moment. The parameters without subscript are for the target event and those with subscript, *e*, are for the element event that is going to be used as an EGF. N is the scaling parameter (equal to the closest integer), necessary for the discretization of the target fault and C is the ratio of the stress drop of the target event to the stress drop of the element event. Kamae *et al.* (1998) underlined the importance of the parameter C in the correct estimation of the simulated spectrum level.

Taking into account the aforementioned relations, the seismogram A(t) of the target event is calculated from the relation:

$$A(t) = \sum_{i=1}^{N^2} \frac{r}{r_i} F(t - t_i) * Ca(t) \qquad (2)$$

where,

$$F(t) = \delta(t) + \frac{1}{n'} \sum_{j=1}^{(N-1)n'} \delta\left[t - \frac{(j-1)T}{(N-1)n'}\right] \text{ and } t_i = \frac{r_i}{V_c} + \frac{\xi_i}{V_r} + e_i \qquad (3)$$

In the above relations a(t) is the seismogram of the element event, r is the hypocentral distance of the element event, r_i is the distance of the observation point to the center of the subfault i, ξ_i is the distance of the rupture initiation point to the center of the ith subfault, V_r is rupture velocity, V_c is the velocity of the seismic waves studied, T is the rise time of the target event and n′ an integer to eliminate spurious periodicity (Irikura, 1983). The function F(t) is introduced to account for a difference in the slip time function of the target event and that of the element event. The first term of the right hand part of equation (3) represents a delta function, $\delta(t)$, and the second term represents a square pulse of duration T. e_i is a random number used to give a random character to the rupture propagation process. Due to the slope of the fault of the target event with an angle of about 30°(Fig. 1b), a slight modification of the EGF code input parameters was introduced as "geometric" correction.

Data Used

Source parameters used as input data (seismic moment, M_0, fault area, S and fault width, W) are estimated from the following empirical scaling relations with moment magnitude, M, proposed for Greece and the surrounding area (Papazachos and Papazachou 1997),

$$\log S = 0.70M \quad -1.98 \tag{4}$$
$$\log W = 0.19M \quad -0.13 \tag{5}$$
$$\log M_0 = 1.5M \quad +16.01 \tag{6}$$

It was assumed that these relations proposed for shallow crustal events in the Aegean and the surrounding area also hold for intermediate depth subduction zone earthquakes.

Taking into account the maximum observed magnitude for this part of the Hellenic arc, M≈7.8, (Papazachos, personal communication) a fault area of about $3X10^3$ km^2 is calculated based on relation (4). In addition, the largest fault length of the maximum credible event - following the geometry of the subducted slab (Papazachos et al. 2000) - could be around 110km, starting from a depth of about 40km down to 90km (Fig. 1b). Such a length and area of a fault may result to a fault width, W, of about 27km, following the relation (5). Using the relation (6) between moment Mo and moment magnitude M, the target event corresponds to a moment of Mo=$5.13X10^{27}$ dyn.cm while the element event of $Mo_e=1.45X10^{25}$ dyn.cm. The rise time, τ, may be estimated from the empirical relation (Geller, 1976),

$$\tau = \frac{16S^{1/2}}{(7\pi^{3/2}vs)} \tag{7}$$

where S (L×W) is the fault area and Vs is the shear-wave velocity, with Vs=3.5km/sec. For the target event relation (7) gives rise time equal to τ=6.4sec. Rise time, τ, is also estimated from the total rupture duration Vr=0.8Vs. Heaton (1990) suggested that rise time of large events is very short, about 15%, compared to the overall duration of the earthquake. Thus, for the target event with unilateral rupture τ=5.9sec, while with bilateral rupture τ=2.95sec. Unilateral rupture process gives comparable rise time with that estimated from relation (7). In this study, the values τ=5.9sec and τ=2.95sec for unilateral and bilateral rupture, respectively, were adopted.

Only a few strong motion recordings were acquired during the last 20 years – operation time of ITSAK's strong motion network – from intermediate depth subduction events in southern Aegean. The most important of them come from the May 23, 1994 earthquake (M6.1) and was recorded at the city of Iraklio and Chania both on Crete island. Source parameters of this earthquake, used as element event, have been published by various seismological centers (Table 1).

As the most reliable hypocentral location was considered that of ISC because its solution was based on the largest number of stations (>700). For depth determination the ISC used also the pP phase.

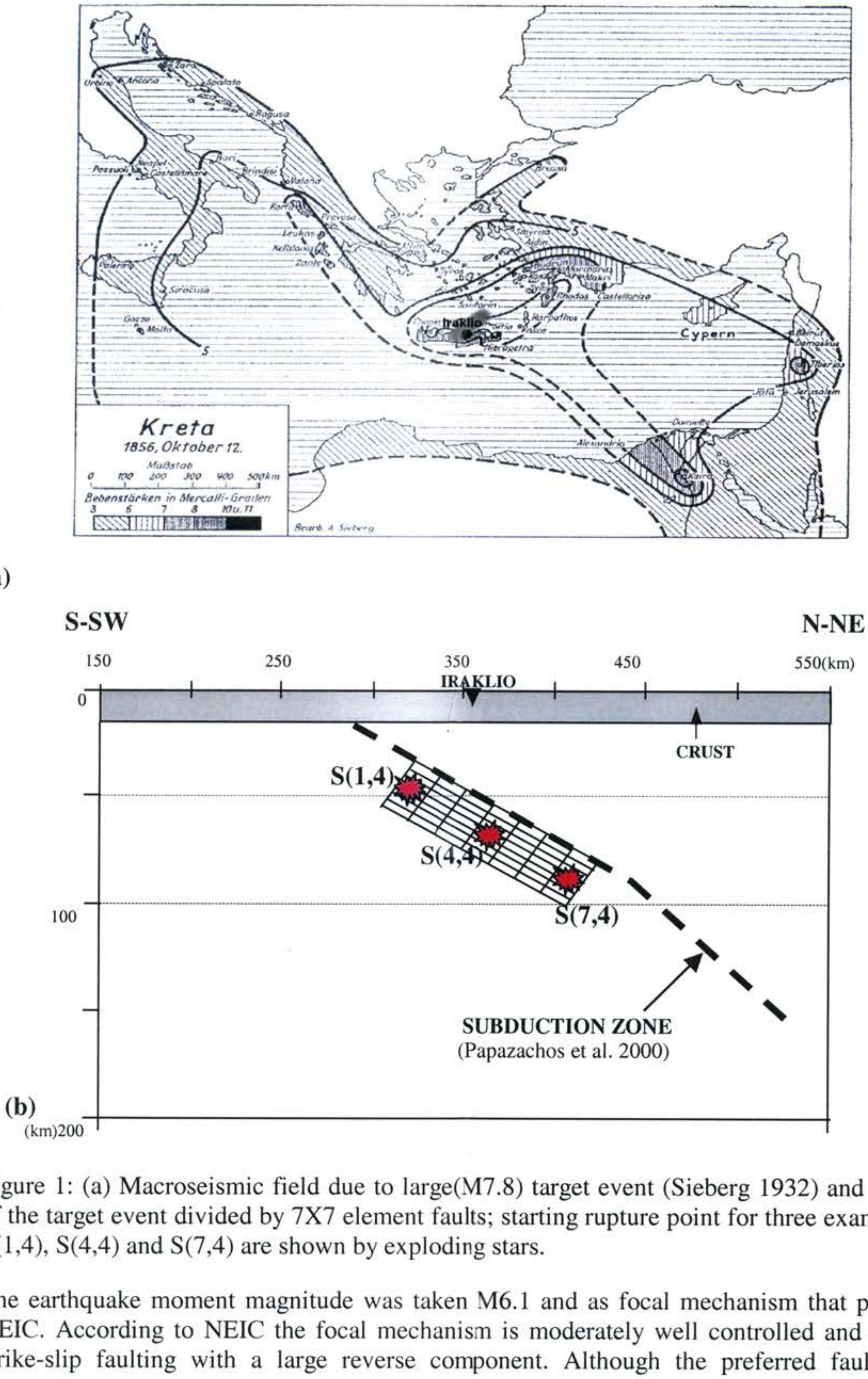

Figure 1: (a) Macroseismic field due to large(M7.8) target event (Sieberg 1932) and (b) Fault plane of the target event divided by 7X7 element faults; starting rupture point for three examined scenarios S(1,4), S(4,4) and S(7,4) are shown by exploding stars.

The earthquake moment magnitude was taken M6.1 and as focal mechanism that proposed by the NEIC. According to NEIC the focal mechanism is moderately well controlled and corresponds to strike-slip faulting with a large reverse component. Although the preferred fault plane is not determined, the one with strike=70°,dip=70°, rake=137° was considered as the most probable since it is in good agreement with the typical fault plane solution of the examined area (Papazachos, 1996).

TABLE 1.
SOURCE PARAMETERS OF THE ELEMENT (SMALL) EVENT

Origin time	Coordinates		Magnitude	Moment (dyn.cm)	Depth (km)	Focal Mechanism			Ref.
	Lat.	Long.				strike	dip	rake	
1994/05/23 06:46:15.16	35.54	24.70	5.9(m_b)		73.5	-	-	-	(1)
1994/05/23 06:46:16.29	35.57	24.74	5.8(Mw)		79	-	-	-	(2)
1994/05/23 06:46:16.30	35.40	24.73	6.1(Mw)		81	-	-	-	(3)
1994/05/23 06:46:16.10	35.56	24.73	6.1(Mw)		76	70	70	137	(4)
1994/05/23 06:46:19.90	35.02	24.89	6.1(Mw)	$1.49X10^{25}$	81	76	70	151	(5)

(1) ISC (International Seismological Center), (2) GLAB (Geophysical Laboratory University of Thessaloniki), (3) GEIN(Geodynamic Institute National Observatory Athens), (4) NEIC (National Earthq. Information Center) (5) HRVD (Harvard University)

TABLE 2
INPUT PARAMETERS FOR THE EGF METHOD APPLICATION

Source Parameters	Target Event	Element Event
M_w	7.8	6.1
M_0 (dyn·cm)	5.13×10^{27}	1.45×10^{25}
Epicenter (φ°N - λ°E)	35.40 24.75 [S(1,4)] 35.70 25.10 [S(4,4)] 35.90 25.40 [S(7,4)]	35.54 24.70
Strike (°)	48	70
Dip (°)	51	70
Rake (°)	150	137
Hypocentral Depth (Km)	45 or 70 or 90	73.5
Fault Length (Km)	110	15.7
Fault Width (Km)	27	3.9
Rise Time (sec)	5.6 or 2.95	0.8

There are no information for stress drop of large intermediate depth events in southern Agean. Assuming that the stress drop of the element event is equal to that of the target event and taking into account relation (1) the factor N is calculated to be of about 7. Consequently, fault plane of the target event may be divided to 7X7 subfaults that have dimensions 15.7km in length and 3.9km in width. Typical focal mechanism of the target event is taken to be strike=48°, dip=51°, rake=150° (Papazachos 1996). Using relation (6) and the moment published by Harvard, moment magnitude, M, is equal to 6.1 as it was published by the majority of seismological centers. A summary of all modelling parameters used for the two simulations is listed in Table 2.Three rupture scenarios were examined and in all of them radial rupture was considered. Namely, two unilateral rupture scenarios with the starting point at the two ends of the fault (S[7,4], S[1,4]) and one bilateral at the center of the fault (S[4,4]) were examined (see Figure 1b and Table 2).

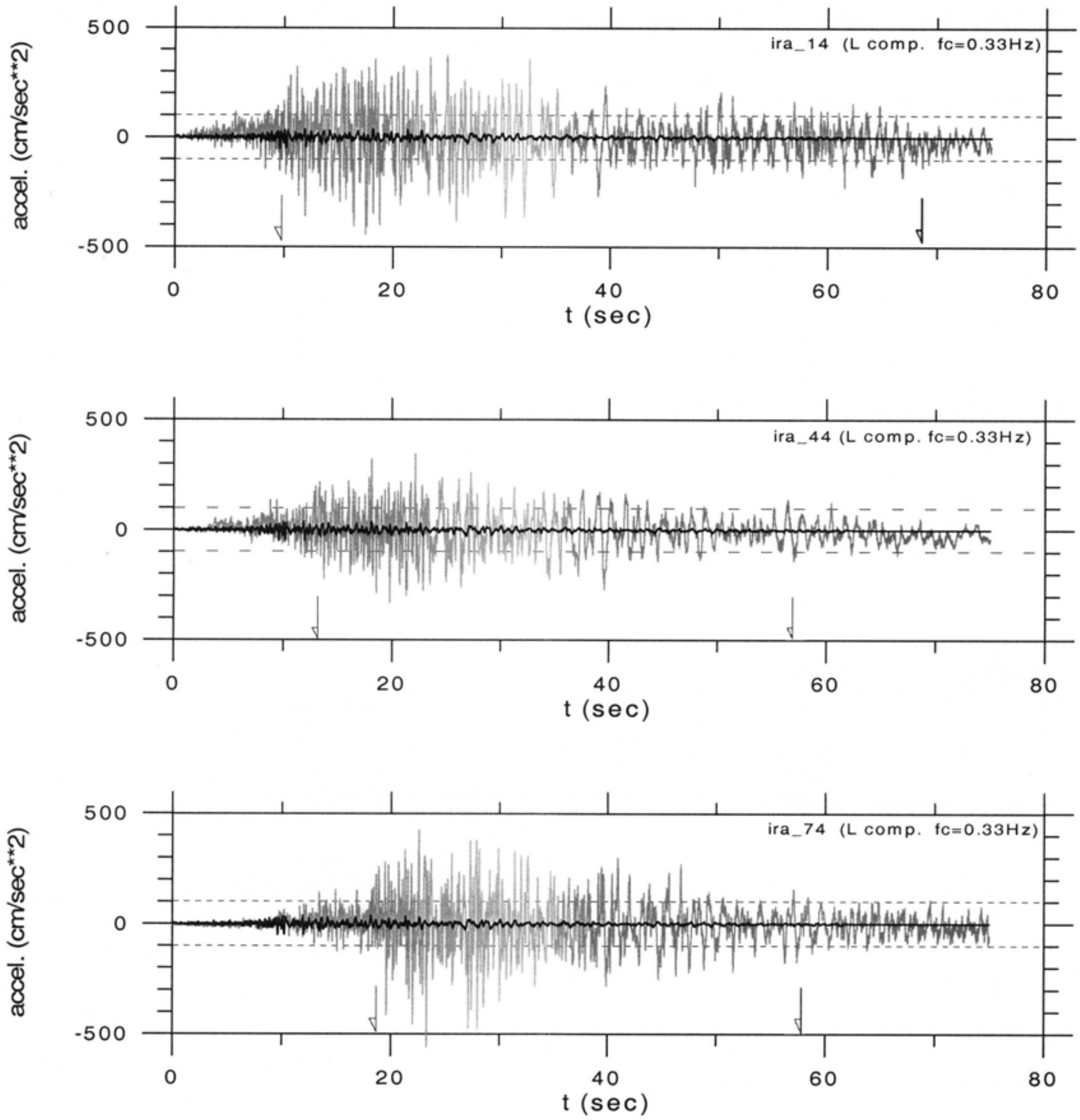

Figure 2: Recording of the 23/5/1994 (M6.1) EGF element event (black line); simulated acceleration time history of the target event (M7.8) for three rupture scenarios for the city of Iraklio (grey line).

RESULTS

In this study EGF simulation results using only one horizontal component, the one with the highest peak ground acceleration recorded at Iraklio, are shown. In Figure 2 acceleration time history of the element event (M6.1) together with simulated strong motion of the target event (M7.8) for three rupture scenarios are given. Strong motion duration - time span between the first and last peak with acceleration ≥0.10g - varies from about 40sec to 60sec, depending on the rupture scenario. The shortest strong motion duration, 40sec, comes from the S(7,4) scenario of unilateral rupture while the longest one, 60sec, from the S(1,4). The highest PGA, 0.50g, appears at the case of S(7,4) and the lowest PGA, 0.30g, at the S(4,4) for bilateral rupture.

Pseudoacceleration response spectra -5% damped- for the three aforementioned rupture scenarios are shown in Figure 3. In the same Figure elastic design spectra for the seismic zone category III of the Greek seismic code – where the site of Iraklio falls – are given for soil categories A & B (Greek Seismic Code, 2000). Spectral values of the target event exceed those imposed by code provisions for almost all periods, especially in the range 0.15sec≤T≤0.7sec and 1.0sec≤T≤1.8sec. The highest spectral acceleration, around 2g, is observed at 0.3sec.

Empirical predictive models for pseudoacceleration based on subduction zone strong motion data have been published for various regions of the world. In this study two of them were used in order to compare their results with those of the simulated target event. One model was proposed by Theodulidis and Papazachos (1990) [TP90] and was based mainly on thrust fault intermediate depth events (40km≤h≤160km) of several subduction zones worldwide, while the other (Molas and Yamazaki , 1996) [MY96] was based on Japanese data from interplate events (0.1km≤h≤200km). As shown in Figure 4, average plus one standard deviation spectral accelerations predicted by the [TP90] model are in very good agreement with simulated ones for periods up to 1.5sec. For longer periods simulated values are up to 2 times higher. On the other hand, average plus one standard deviation spectral accelerations predicted by the [MY96] model are in good agreement with simulated ones for periods greater than 0.7sec, while for shorter periods they are up to 2 times lower. However, an envelope of both empirical predictive models gives spectral acceleration values which are in agreement with the simulated ones.

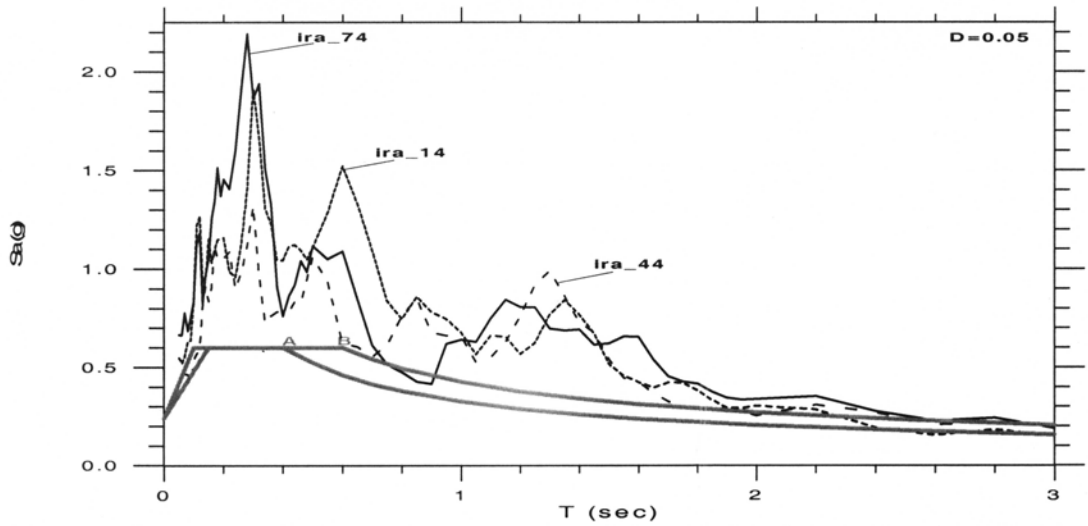

Figure 3: Pseudoaccelertion response spectra of the simulated time histories (Fig. 2) in comparison with elastic design spectra of Greek Seismic Code(2000) [Zone III, Soil Categories A, B].

The new trend of seismic code provisions towards displacement-based design led to definition of displacement response spectra attenuation relations in Europe (Bommer and Elnashai, 1999) [BE99]. For the target event, M=7.8 & R=40km, average plus one standard deviation spectral displacement values predicted by the [BE99] model, are shown in Figure 5. In the same Figure, spectral

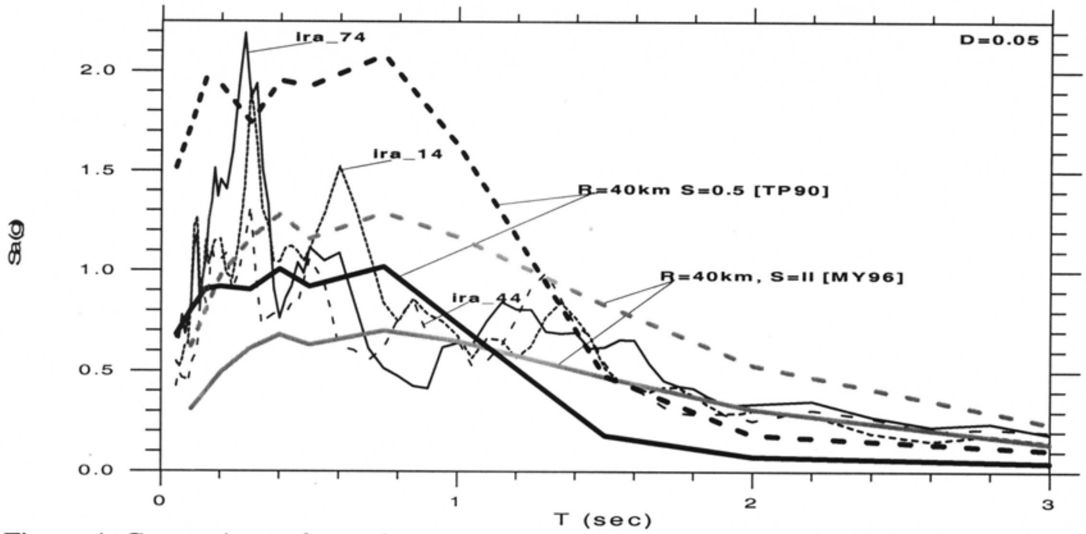

Figure 4: Comparison of pseudoacceleration response spectra of the simulated time histories (Fig. 2) with average +1σ spectra proposed by the [TP90] and [MY96] empirical models.

displacements of the simulated target event for the examined three rupture scenarios, are given. For short to intermediate periods, T<1sec, the latter fall between the average and plus one standard deviation of those predicted by the [BE99] model. However, for longer periods simulated spectral displacements are much higher than the empirical ones especially in periods around 1.5sec where they reach up to 2.5 times higher values.

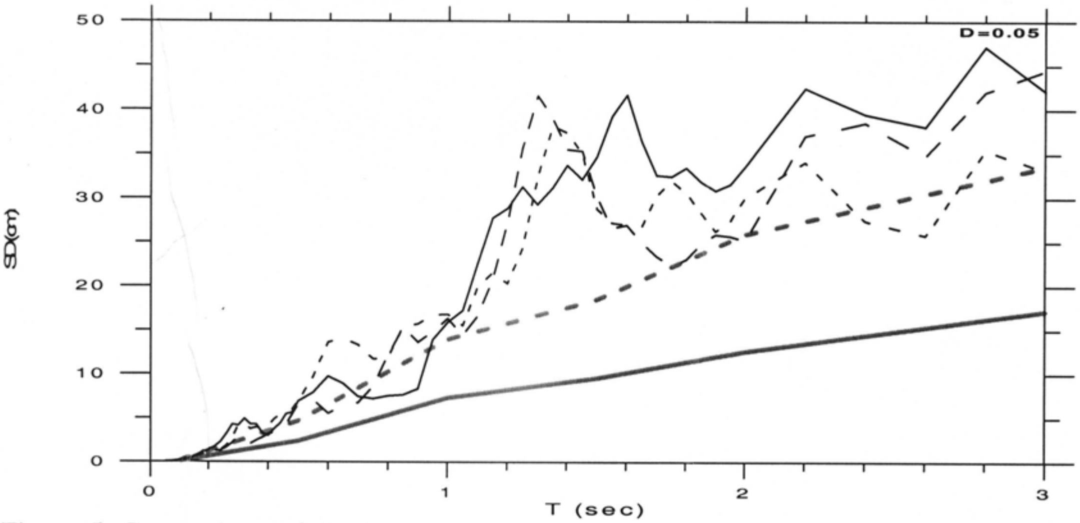

Figure 5: Comparison of displacement response spectra of the simulated time histories (Fig. 2) with average +1σ spectra proposed by the [BE99] empirical model.

DISCUSSION AND CONCLUSIONS

In this study strong ground motion in the near field of a large intermediate depth subduction zone earthquake (M7.8) at the southern Aegean area is estimated, using the empirical Green's function method. For this purpose, as element event strong ground motion of a moderate magnitude event (M6.1) recorded at the city of Iraklio-Crete island (Greece) is used.

Simulated strong ground motion for three rupture scenarios, two unilateral and one bilateral, gave PGAs ranging between 0.5g and 0.3g. Strong motion duration - time span between the first and last peak with acceleration ≥0.10g – for the unilateral rupture scenario S[7,4] has the shortest value, ~40sec, that is in agreement with the rupture directivity towards the city of Iraklio while the longest strong motion duration, ~60sec, corresponds to the scenario S[1,4]. According to Papazachos and Papazachou (1997) from the earthquake of October 1856 (M7.8),"*...the city of Iraklio and the surrounding area suffered the largest destructions. From the 3620 houses, which the city had at that time, only 18 were standing up and were inhabitable*". Estimated values of PGA and strong motion duration of the target event seem to be reasonable and in agreement with the damage caused in the past. Furthermore, according to the same authors, "*...in Rhodos, the earthquake lasted from 40sec up to 90sec and caused destructions in 8 villages where 2000 houses became uninhabitable...*". Although Rhodos island is at a distance of about 200km from the target event fault, strong motion duration seems to be consistent with the estimated one.

Comparison of spectral accelerations of the target event for all three rupture scenarios with empirically predicted ones (average $+1\sigma$) based on two predictive models showed good agreement. Extrapolating empirical predictions at the far field, ~650km, and using the [TP90] model, expected PGA for a target event (M7.8) on stiff soil conditions, may take values of about 0.05g. Such small PGA values hardly can justify macroseismic intensities observed, ~VII+ of Mercalli scale, for instance at the northern Egypt (Alexandria). However, the long duration, ~90sec, that the October 1856 (M7.8) event lasted at this area (Papazachos and Papazachos 1997), as well as site effects due to Nile delta deposits, might have strongly amplify weak ground motion leading to a "mini" Mexico City (event of 1985) phenomenon.

It was found that at short and intermediate periods, $0.15sec \leq T \leq 0.7sec$, simulated target event give much higher, up to 3 times, spectral values than the elastic design spectra proposed by the Greek seismic code. In this case ductility demands that may be imposed by the target event are about 3. It is interesting to note that apart from the short and intermediate periods, also at long periods, $T \approx 1.5sec$, target event gives up to 3 times higher spectral values than those of the seismic code. This discrepancy is also obvious in the comparison of simulated spectral displacements with empirically predicted ones by the [BE99] model (Figure 5). Such spectral values could have strong implication to multi-storey buildings (say >10 stories) as well as to flexible long period structures.

Results of the present study show the reliability - although qualitatively - of the EGF approach and are encouraging in simulating strong ground motion of large intermediate depth subduction zone earthquakes in SE Europe. However, small to moderate magnitude intermediate depth events should be recorded at selected sites where strong motion of the target events are going to be simulated. For this purpose, high resolution accelerographs must be deployed at selected sites of southern Greece as well as of eastern Mediterranean cities.

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