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# INELASTIC STRENGTH AND DISPLACEMENT DESIGN SPECTRA BASED ON GREEK EARTHQUAKE RECORDS

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## SUMMARY

Elastic and inelastic spectra are derived, based on greek earthquake records. A representative sample of acceleration records is carefully selected based on magnitude, distance and peak ground acceleration criteria, and is grouped into three main categories based on soil conditions (rock, stiff and medium/soft soil). Using software developed in-house, elastic (pseudoacceleration, pseudovelocity and displacement) as well as inelastic (strength and displacement) spectra are computed for various critical damping values and ductility levels. After appropriate scaling, mean spectra are computed both irrespective of, as well as for, each soil condition, and comparisons with existing seismic code provisions are made. Finally, the corresponding force reduction ($q_\mu$) and displacement reduction ($\eta$) factors are computed, and appropriate analytical relations, suitable for design purposes, are proposed.

## INTRODUCTION

It is a well-known fact that elastic and inelastic spectra, either of pseudoacceleration or displacement, play a key role in modern Earthquake Engineering practice. Displacement-based design, is based on the existence of displacement spectra for different damping ratios (usually much higher than the 5% value incorporated in current seismic codes), while in pushover analysis a target displacement is necessary and it can be realistically evaluated only through a proper displacement spectrum. Recent works by Tolis and Faccioli [1] and Bommer and Elnashai [2] are among the first major contributions in this direction. On the other hand, elastic acceleration spectra play a major role in "conventional" force-based design that is still adopted by all modern seismic codes internationally.

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In the present study, a carefully selected and properly processed sample of greek strong motion records is used as a base for the evaluation of both elastic (pseudoacceleration, pseudovelocity, displacement) and inelastic (strength and displacement) spectra, using specially developed software. The spectra are computed either for the whole sample, or for different soil conditions prescribed in the Greek Seismic Code (EAK2000), and comparisons with the design spectra proposed in the Code are presented. From the actual data, the behaviour (or force reduction) factor $q_\mu$ and displacement reduction factor $\eta$ are also evaluated, and analytical expressions for them as function of period and target ductility are proposed. Finally, key conclusions are presented, and, based on the actual results of the study, possible needs for reevaluation of some seismic code provisions are discussed.

## EARTHQUAKE GROUND MOTIONS USED IN THIS STUDY

A key factor in studies like the present one is the proper choice of a representative sample among the available strong motion records for Greece. For the selection of the sample, the strong motion database of the Institute of Engineering Seismology and Earthquake Engineering (ITSAK) was used. The database contains recordings from the permanent accelerograph network of ITSAK, which constitutes a significant part of the National Permanent Strong Motion Network, and covers the whole Greek territory. Based on both international practice in the field, as well as the personal experience of the research team, the following criteria were applied in the choice of the acceleration time histories:

- Earthquake magnitude $M_w > 5.0$ and epicentral distance 5 km < R < 100 km.
- Value of peak ground acceleration PGA ≥ 0.10g and/or strong motion having caused damage in the neighborhood of the recording site.
- Existence of sufficient geotechnical data in order to classify existing soil conditions at the recording site according to the soil categories of the Greek Seismic Code (EAK2000), which is similar to the ENV ('Prestandard') version of Eurocode 8 [3].

Due to the relatively small number of records in the database, in some cases earthquakes of magnitude somewhat less than 5 were selected, on condition that the PGA's of the horizontal motions were significant (>0.15g). The sample also includes records the178-1, kor181-1 and aml188-6 that were recorded by the corresponding accelerograph network of the Institute of Geodynamics, National Observatory of Athens. The final record sample used in the present study is presented in Table 1. It consists of 67 records of 24 strong earthquakes that occurred within the Greek territory in the last 20 years, and which were recorded by 20 stations of the permanent accelerograph network of ITSAK. For each record in the table, the date, time, geographic coordinates, magnitude, short name, and component (Longitudinal /Transverse) are given, as well as a binary code for the soil conditions (S=0 for 'soft', S=1 for 'stiff' soils). Using the geotechnical data available for each station, a soil classification according to the soil categories provided by the Greek Seismic Code (EAK2000) was achieved. The soil categories (similar to those of the 1994 Eurocode 8) are denoted as A (rock), B (stiff) and C (medium to soft). In EAK2000, two more soil categories are prescribed, namely D (soft) and X (unsuitable soils, unless special measures are taken for construction), but none of the stations belonged to these categories. Finally, for each record, the PGA is also given. The sample is deemed sufficient, ranging in terms of magnitude between 4.4 and 6.9, and in terms of PGA between 50 and 400 cm/sec$^2$. It is also noted that records in 'soft' soil conditions are more numerous than those on 'stiff' soils.

The acceleration records were suitably processed in order to eliminate to a great degree the various errors from the entire recording procedure (elimination of instrument and environmental noise, baseline – offset corrections, etc). Records on film (from analog accelerographs) were digitized using a scanner and suitable software (Scanview, ® Kinematics Inc.), a process that eliminated digitization errors. For the baseline correction, a three-step procedure proposed by Hung [4] was used. Finally, for the elimination of noise, a ramp-type bandwidth filter was used, whose high-pass limit, different for each record, is defined through a signal-to-noise procedure (a signal-to noise ratio of 2, and in some special cases of 3 was used as threshold). For the low-pass filter limit, the corresponding terminal frequency was 27 Hz for analogue records and 50 Hz for digital ones (with a roll-off of 2Hz and 3 Hz correspondingly).

*Table 1. Recorded earthquake ground motions used in this study*

| NUM | DATE | OR.TIME | LAT | LONG | M | SM-RECORD | MP | S | Soil category (EAK2000) | $A_g$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 62078 | 200321 | 40.8 | 23.2 | 6.4 | the178-1n | L | 0 | **C** | 137.2 |
| | | | | | 6.4 | the178-1n | T | 0 | | 144.1 |
| 2 | 22481 | 205338 | 38.22 | 22.93 | 6.6 | kor181-2n | L | 0 | **C** | 233 |
| | | | | | 6.6 | kor181-2n | T | 0 | | 295.7 |
| 3 | 11783 | 124129 | 38.09 | 20.19 | 6.9 | arg83-1 | L | 1 | **B** | 173.3 |
| | | | | | 6.9 | arg83-1 | T | 1 | | 142.5 |
| 4 | 32383 | 235106 | 38.33 | 20.22 | 6.2 | arg83-7 | L | 1 | | 179.8 |
| | | | | | 6.2 | arg83-7 | T | 1 | | 219.2 |
| 5 | 32483 | 41732 | 38.18 | 20.32 | 5.4 | arg183-8 | L | 1 | | 240.1 |
| | | | | | 5.4 | arg183-8 | T | 1 | | 285.3 |
| 6 | 82683 | 125210 | 40.51 | 23.92 | 5.1 | pol183-2 | L | 1 | **A** | 90.8 |
| | | | | | 5.1 | pol183-2 | T | 1 | | 49.2 |
| 7 | 102584 | 94916 | 36.83 | 21.71 | 4.8 | pel184-1 | L | 0 | **A** | 166.6 |
| | | | | | 4.8 | pel184-1 | T | 0 | | 172.7 |
| 8 | 91386 | 172434 | 37.03 | 22.2 | 5.9 | kal186-1 | L | 0 | **B** | 229.3 |
| | | | | | 5.9 | kal186-1 | T | 0 | | 263.9 |
| 9 | 91586 | 114130 | 37.04 | 22.13 | 5.4 | kal186-8 | L | 0 | | 233.8 |
| | | | | | 5.4 | kal186-8 | T | 0 | | 137.1 |
| | | | | | 5.4 | kal286-2 | L | 0 | **B** | 159.5 |
| | | | | | 5.4 | kal286-2 | T | 0 | | 254.3 |
| 10 | 101688 | 123406 | 37.95 | 20.9 | 5.8 | zak188-4 | L | 0 | **C** | 133 |
| | | | | | 5.8 | zak188-4 | T | 0 | | 147.2 |
| | | | | | 5.8 | aml188-6 | L | 0 | **C(B)** | 81.9 |
| | | | | | 5.8 | aml188-6 | T | 0 | | 156.6 |
| 11 | 122190 | 65744 | 40.98 | 22.34 | 6.1 | ede190-1 | L | 0 | **C** | 100.1 |
| | | | | | 6.1 | ede190-1 | T | 0 | | 94.4 |
| 12 | 32693 | 114516 | 37.66 | 21.39 | 4.9 | pyr193-6 | L | 0 | **B** | 105.6 |
| | | | | | 4.9 | pyr193-6 | T | 0 | | 221.5 |
| 13 | 32693 | 115613 | 37.69 | 21.43 | 4.8 | pyr193-7 | L | 0 | | 98 |
| | | | | | 4.8 | pyr193-7 | T | 0 | | 118 |
| 14 | 32693 | 115815 | 37.49 | 21.49 | 5.4 | pyr193-8 | L | 0 | | 162.9 |
| | | | | | 5.4 | pyr193-8 | T | 0 | | 425.8 |
| 15 | 71493 | 123149 | 38.24 | 21.78 | 5.6 | pat193-2 | L | 0 | **B** | 143.7 |
| | | | | | 5.6 | pat193-2 | T | 0 | | 192.5 |
| | | | | | 5.6 | pat393-2 | L | 0 | **B** | 164.2 |
| | | | | | 5.6 | pat393-2 | T | 0 | | 388.6 |
| 16 | 50495 | 3411 | 40.54 | 23.63 | 5.4 | pol95-6 | L | 1 | **A** | 136.1 |
| | | | | | 5.4 | pol95-6 | T | 1 | | 97.4 |
| 17 | 51395 | 84715 | 40.16 | 21.67 | 6.5 | koz95-1 | L | 1 | **A** | 211.7 |
| | | | | | 6.5 | koz95-1 | T | 1 | | 137.4 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 18 | 51595 | 41357 | 40.07 | 21.67 | 5.2 | chrom013 | L | 0 | **C (B)** | 157 |
| | | | | | 5.2 | chrom013 | T | 0 | | 132.1 |
| 19 | 51795 | 41426 | 40.07 | 21.61 | 5.2 | chrom032 | L | 0 | | 116.7 |
| | | | | | 5.2 | chrom032 | T | 0 | | 130.3 |
| 20 | 51995 | 64850 | 40.03 | 21.62 | 5 | karp001 | L | 0 | **B** | 185.2 |
| | | | | | 5 | karp001 | T | 0 | | 262.2 |
| 21 | 61195 | 185195 | 39.96 | 21.58 | 4.4 | karp009 | L | 0 | | 119.4 |
| | | | | | 4.4 | karp009 | T | 0 | | 82.8 |
| | | | | | 4.4 | kentr063 | L | 0 | **B** | 125.1 |
| | | | | | 4.4 | kentr063 | T | 0 | | 100.1 |
| 22 | 80596 | 224642 | 40.06 | 20.66 | 5.5 | konl0032 | L | 0 | **C** | 382 |
| | | | | | 5.5 | konl0032 | T | 0 | | 383 |
| | | | | | 5.5 | konu1007 | T | 1 | **A** | 168.4 |
| 23 | 111897 | 130753 | 37.33 | 20.84 | 6.6 | zak97-3 | L | 0 | **C** | 114.9 |
| | | | | | 6.6 | zak97-3 | T | 0 | | 129.4 |
| 24 | 90799 | 115651 | 38.15 | 23.62 | 5.9 | a299-1 | L | 1 | **B** | 108.1 |
| | | | | | 5.9 | a299-1 | T | 1 | | 155.6 |
| | | | | | 5.9 | a399-1 | L | 1 | **B** | 258.6 |
| | | | | | 5.9 | a399-1 | T | 1 | | 297.2 |
| | | | | | 5.9 | a499-1 | L | 1 | **A** | 118.6 |
| | | | | | 5.9 | a499-1 | T | 1 | | 107.9 |
| | | | | | 5.9 | kert99-1 | L | 1 | **B** | 214.4 |
| | | | | | 5.9 | kert99-1 | T | 1 | | 179.5 |
| | | | | | 5.9 | rfn1 | L | 1 | **A** | 81.4 |
| | | | | | 5.9 | rfn1 | T | 1 | | 101.4 |
| | | | | | 5.9 | splb1 | L | 0 | **B** | 342 |
| | | | | | 5.9 | splb1 | T | 0 | | 318.9 |

For the computation of spectra, the INELSP-2k program, developed at the Civil Engineering Department of University of Thessaloniki, was used. The software was developed primarily for the computation of inelastic spectra, but can also be used for the computation of elastic ones. The spectra were evaluated for the period range 0.01 to 3.0 sec, using a smaller step ($\Delta T$=0.025 sec) for shorter periods ($T \leq 0.5$ sec), that gradually increases to $\Delta T$=0.20 sec for $T > 2.0$ sec.

## ELASTIC SPECTRA

The records selected were used for the computation of elastic spectra, either for each soil category or for the whole sample. The 67 records are classified as follows: in soil category A (rock), 13 records (19%), in category B (stiff soils), 36 records (54%) and in category C (medium to soft soils) 18 records (27%). In order to estimate the spectral shape, rather than the absolute spectral values, all records were scaled according to the mean spectral intensity (SI) that corresponds to each of the three soil categories, or to the whole sample. The mean spectral intensity is defined as the area under the pseudovelocity spectrum between 0.10 and 2.5 sec and it has been found to be (Nau & Hall [5], Kappos and Kyriakakis [6]) a very suitable scaling factor, especially for periods longer than 0.5 sec. Additionally, the elastic spectra were computed for the whole range of values of the equivalent damping coefficient ($\zeta$), that is of interest in displacement-based or seismic isolation design (i.e. $0 \leq \zeta \leq 30\%$). The results of the analyses are presented in the form of mean pseudoacceleration ($S_{pa}$, Figure 1), pseudovelocity ($S_{pv}$, Figure 2) and displacement ($S_d$, Figure 3) spectra, either for the whole sample, or separately for each soil category.

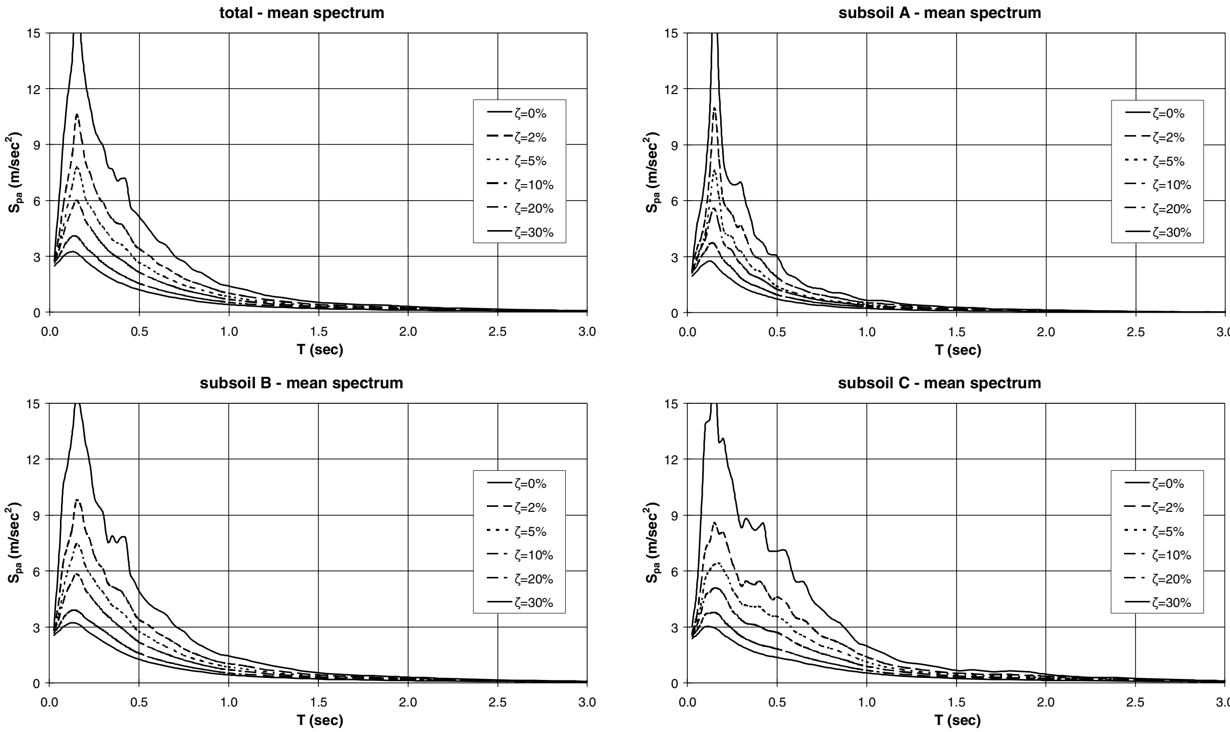


**Fig. 1 Mean elastic pseudoacceleration spectra**

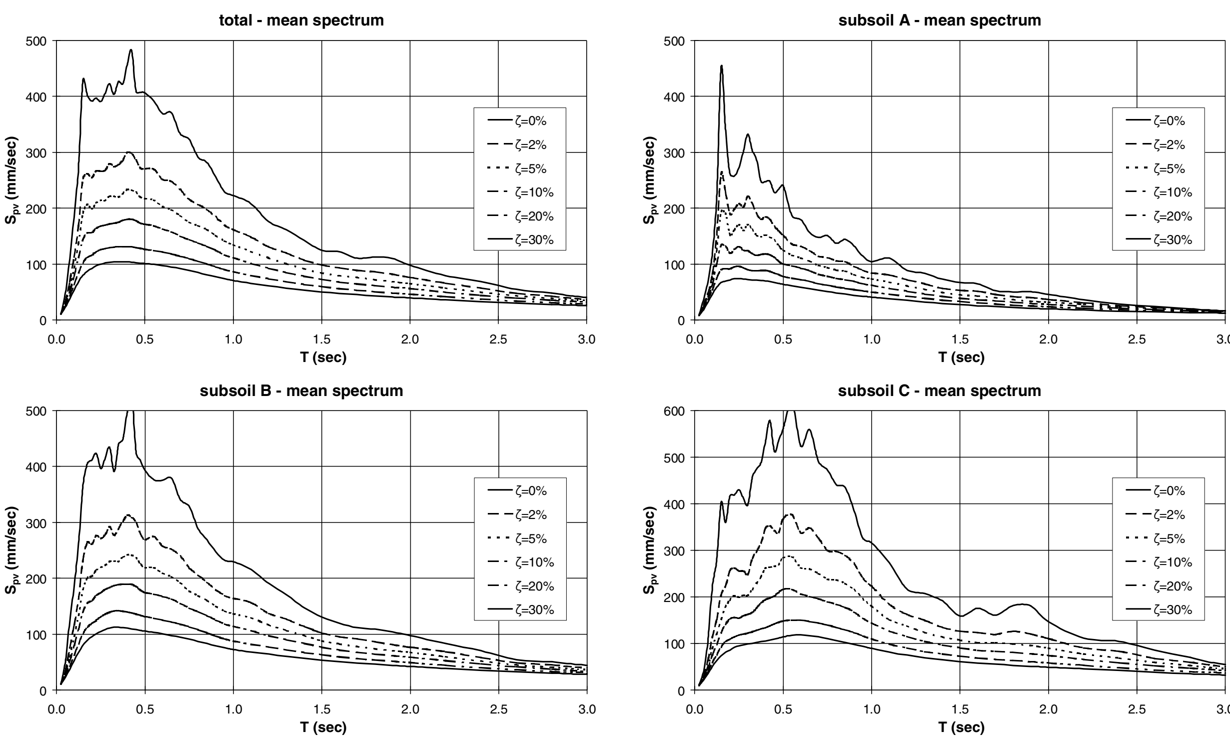


**Fig. 2 Mean elastic pseudovelocity spectra**

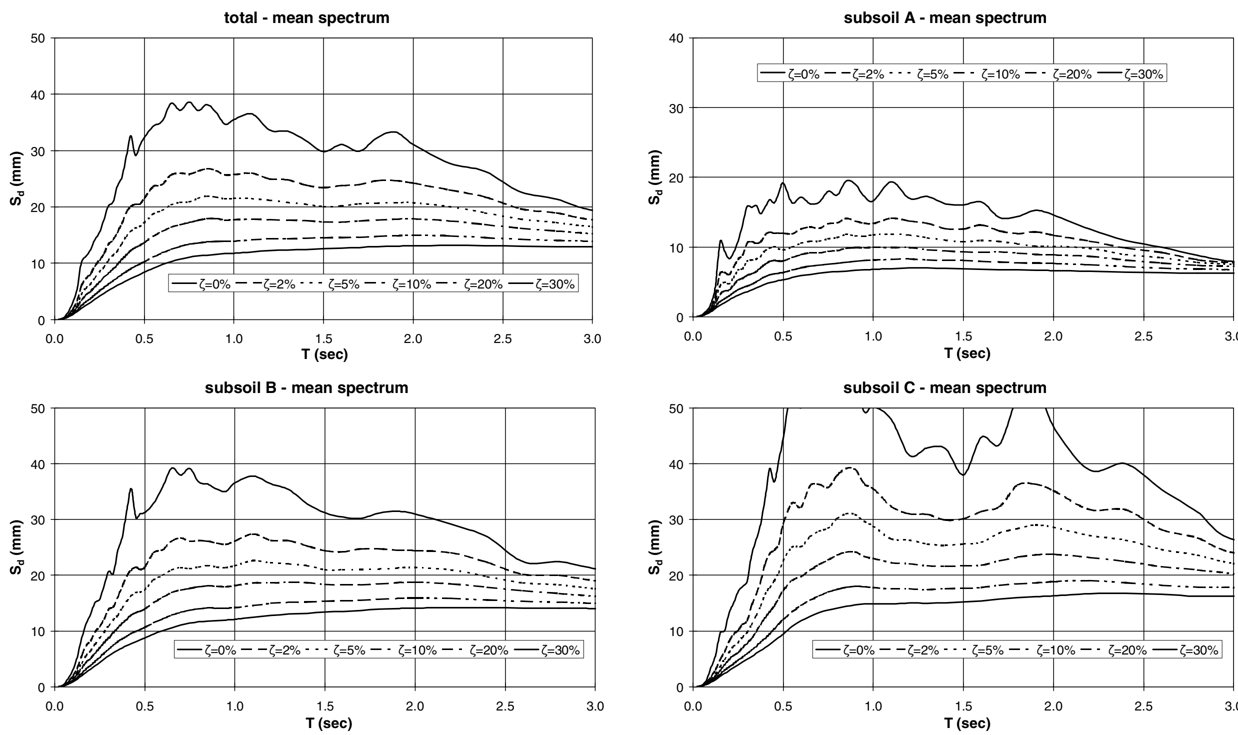


**Fig. 3 Mean elastic displacement spectra**

From the spectra derived from the whole sample, it is noted that the strong ground motions that occurred in Greece since the 70s have a high frequency content, with the peaks of both the spectral pseudo-accelerations and pseudovelocities lying in the short period range (i.e for $T \leq 0.3$ sec and $T \leq 0.6$ sec, for $S_{pa}$ and $S_{pv}$, respectively). The same trend is also observed for the displacement spectra, with a tendency for stabilization after approximately the period of 0.8 sec and beginning of the decreasing branch after the period of 2.0 sec. As expected, the influence of damping becomes greater for lower values of ζ. The soil conditions affect, as also expected, in a qualitative way the frequency content of the spectra, which becomes richer for increasingly softer soils (i.e. for smaller values of shear stiffness G). This trend becomes obvious by comparing, for example, the pseudoacceleration spectra corresponding to soil categories A and C in Figure 1. It is however noteworthy, that the quantitative differentiations are not so great, and the descending branch of the spectra starts from the range of small periods (0.2 to 0.3 sec for pseudoacceleration, 0.6 to 0.7 sec for pseudovelocity, and approximately 2.0 sec for displacement spectra). It is noted that these period values are not compatible with those normally prescribed in modern seismic codes. A clear effect of different soil conditions is that the slope of the descending branch in the pseudoacceleration spectra becomes milder for softer soils (i.e. going from soil category A to category C). On the other hand, the amplification in the range of spectral peaks (short period range) is considerably larger for stiffer soils, e.g. for the usual ζ=5% damping case, the peak spectral amplification is approximately 3.7 for soil category A, and only 2.2 for soil category C. As far as the spectral values of the response quantities are concerned, a comparison among the different spectra for different soil categories in Figures 1 to 3 indicates that (on the mean) the peak spectral pseudoaccelerations become smaller for softer soils (i.e. from soil category A to category C), while the opposite is observed for the corresponding pseudovelocity and displacement peak spectral values. These remarks have direct implications for seismic design, since they are not fully compatible with current trends in seismic codes (see Kappos [7]), which prescribe increased values of both PGA and spectral amplifications for softer soils. As anticipated, the spectral pseudovelocity and, especially, displacement values in the medium-to-long period (T>0.5 sec) range are higher for softer soils.

In Figure 4, a comparison is given between the elastic spectra ($S_{pa}$, $S_{pv}$, $S_d$) for different soil categories proposed in the EAK2000 Seismic Code (for ζ=5% damping), and the mean spectra derived in the present study. For comparison purposes, all spectra are scaled to the same peak ground acceleration (0.1g). In the pseudoacceleration case (Figure 4a), the different shape (higher frequency content) of the derived vs. Code spectra is obvious. Another remark, with serious practical implications for seismic design, is the significant overestimation by EAK2000 of the pseudovelocities and, most important, of spectral displacements. As becomes obvious from the comparison of the displacement spectra (Figure 4c), the displacement values that are compatible with the elastic pseudoacceleration spectra of the Greek Seismic Code (and the 1994 Eurocode 8) are too conservative, largely overestimating the displacement spectra derived from actual greek earthquake motions in the present study (with the exception of the T<0.3 sec range, which is of no special importance for civil engineering structures). Hence, provided that the sample of earthquake records selected in this study is representative of seismic hazard in Greece, a need for a suitable revision of the code spectra becomes obvious, especially if the latter are to be used in displacement-based design procedures (e.g. in pushover analysis for a target displacement that is evaluated from the corresponding elastic code spectrum).

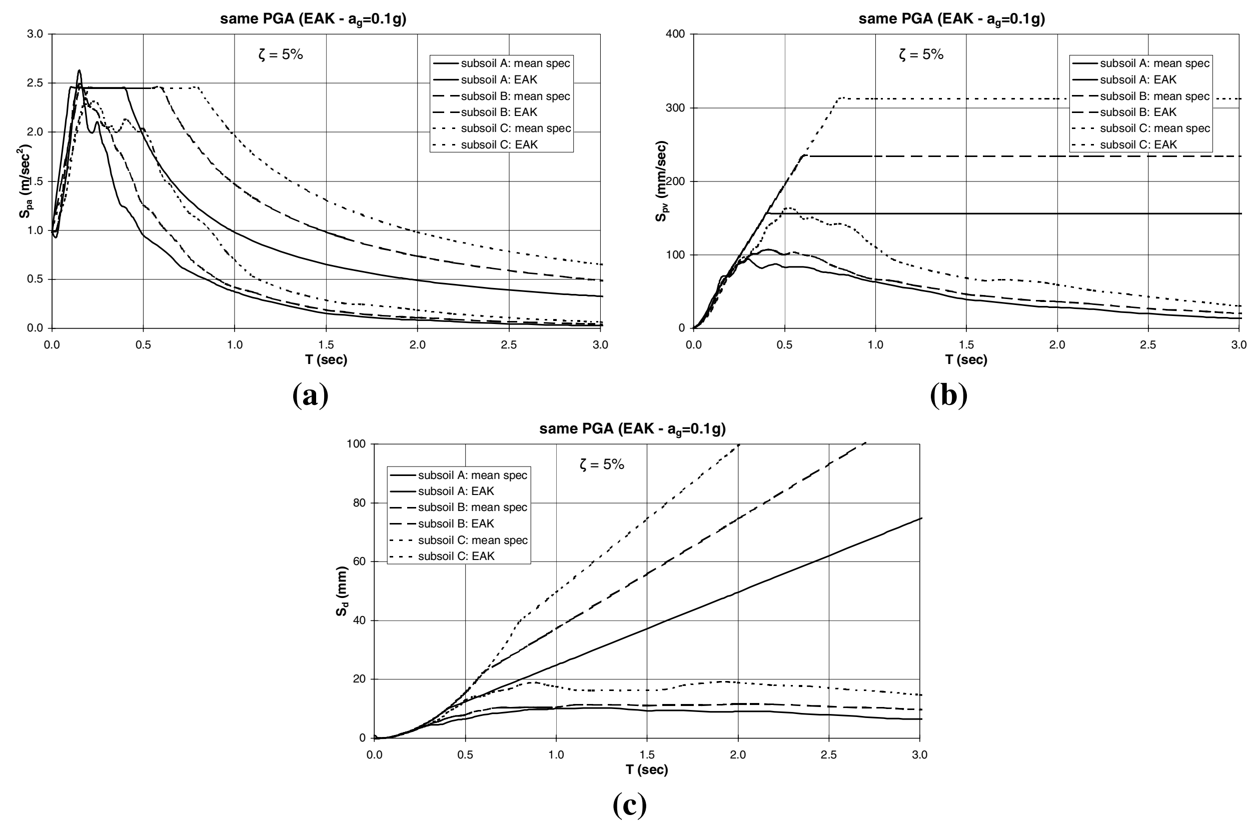


**Fig. 4 Comparison between mean elastic (a) acceleration, (b) velocity and (c) displacement spectra and Greek seismic code (EAK) provisions**

## INELASTIC SPECTRA

Current seismic design practice incorporates the concept of inelastic behaviour of a structure during the design earthquake, but in a way that the ductility demands remain within prescribed limits, for which special design measures are taken in the critical zones of the structural elements. It is therefore extremely useful, from the designer's point of view, to compute constant target ductility ($\mu$) inelastic spectra, from which the strength of a structure can be evaluated, necessary for a prescribed ductility demand to be met. Such a spectrum can be evaluated either through an interpolation process between constant strength spectral curves, or, more accurately, by an iterative computation of the level of strength $F_y$ assigned to a structure of given period, until the target ductility is achieved within an accepted tolerance (e.g. 5% error). The latter approach was adopted in the present study, and implemented in the in-house developed software (INELSP-2k). In constant ductility spectra, strength is usually expressed either as a base shear coefficient $C_y = F_y/W$ (where $W=m \cdot g$ is the weight of the structure), or as $C_y = F_y/(m \cdot a_g)$; in the former case records have to normalized to the same intensity (SI in the present study) if mean spectra are to be developed.

The inelastic strength ($C_y$) and displacement ($S_d$) spectra that were computed either for each soil category or for the whole sample of earthquake ground motions are presented in Figures 5 and 6. As in the elastic spectra case, the accelerograms have been scaled to the mean spectral intensity (SI) of the corresponding soil category. A degrading stiffness model (more representative of the inelastic behaviour of reinforced concrete structures than the elastoplastic one) was used [8]. In the model, a strain-hardening ratio of 5% (common for R/C structures) and a damping ratio of $\zeta$=5% are used; a discussion of the effect of hysteretic model parameters on response spectra can be found elsewhere [9]. Inelastic spectra were computed for four ductility levels, namely $\mu$=1.0 (elastic behaviour), 2.0 (low ductility level), 3.5 (medium ductility level) and 5.0 (high ductility level).

From Figure 5, it is clear that the shape of the inelastic spectra differs from that of the corresponding elastic ones. In general inelastic spectra are smoother, and this trend becomes more apparent for higher ductility levels. For $\mu \geq 3.5$ the strength demands (for a given $\mu$) usually decrease with increasing period. Inelastic behaviour reduces drastically strength demands in rock soil conditions, but, irrespective of soil conditions, the reduction in relation to the elastic case is very significant in the medium to high period range. From a practical point of view, it is important to note that for $\mu \geq 3.5$ the influence of the ductility level on strength demand is small. As a consequence, in medium to high ductility structures, small reduction of strength can lead to significant increase in ductility demands.

Of great practical importance are also the inelastic displacement spectra (Figure 6), especially in view of the recent concepts for displacement-based design. A first observation is the fact that the ductility level $\mu$ affects very little the displacement for periods up to 2.5 sec, and this is more true the stiffer the soil is. Of course, as expected, displacement demands increase for softer soils. A noteworthy characteristic, of a more or less general nature, is the fact that in the low period (T<0.5 sec) range, inelastic displacements are higher than the corresponding elastic ($\mu$=1) ones, while for higher periods displacements are either approximately equal (equal displacement rule) or elastic displacements are slightly larger.

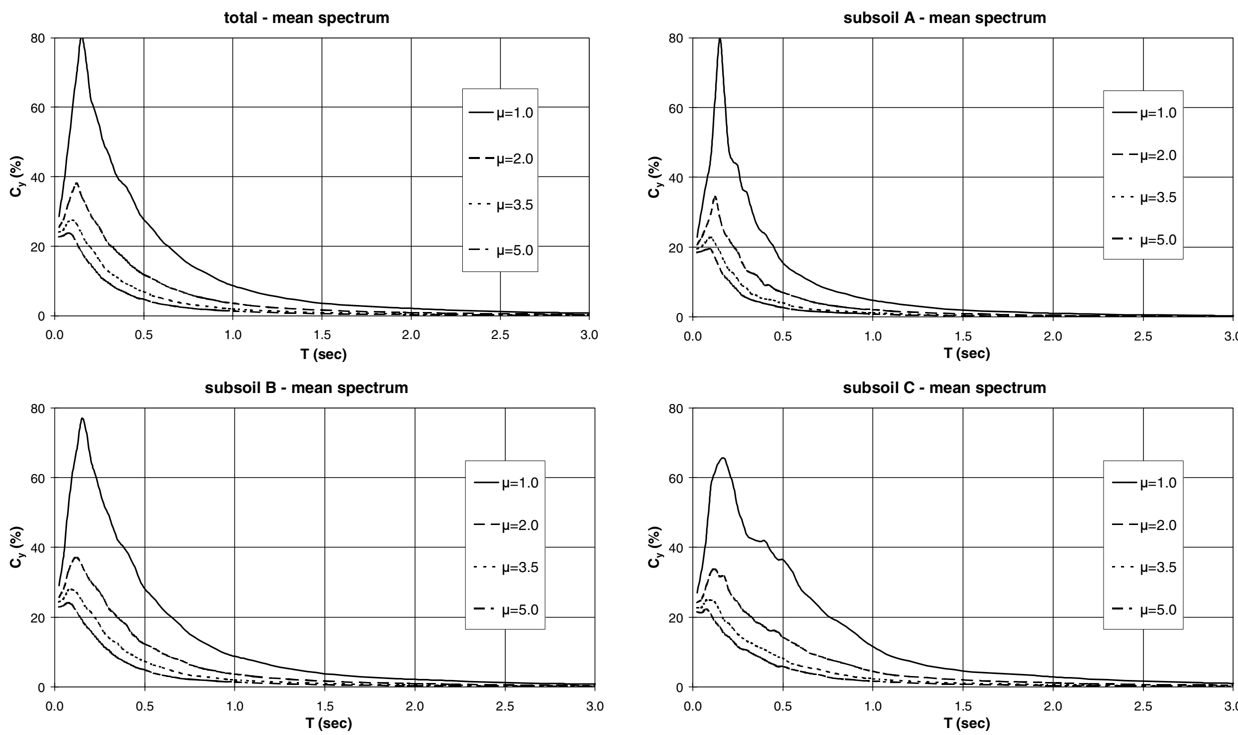


**Fig. 5 Mean inelastic strength spectra**

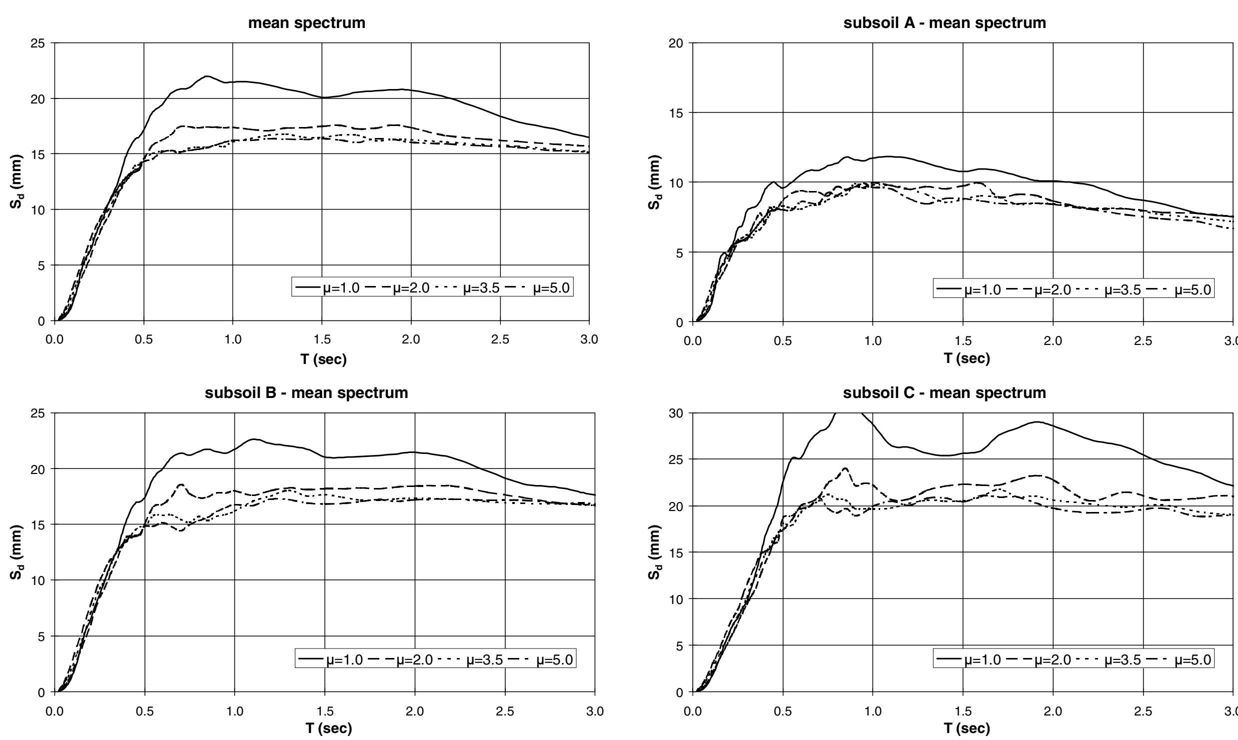


**Fig. 6 Mean inelastic displacement spectra**

## EVALUATION OF BEHAVIOUR FACTORS

From the derived spectra, the ductility-dependent component $q_\mu$ (Kappos [7], [8]) of the behaviour (force reduction) factor q, can be evaluated, as the ratio of the elastic to the inelastic spectral ordinates:

$$q_\mu = \frac{C_{y,el}}{C_{y,in}} \qquad (1)$$

The behaviour factors evaluated from the whole sample of records are presented in Figure 7. The general shape of the curves is similar, irrespective of the ductility level: Values of $q_\mu$ increase for periods up to $T_1 \approx 0.50$ sec, they tend to stabilize to a value of $q_\mu \approx 1.20\ \mu$ for periods up to $T_2 \approx 2.5$ sec, and then decrease slightly for higher periods.

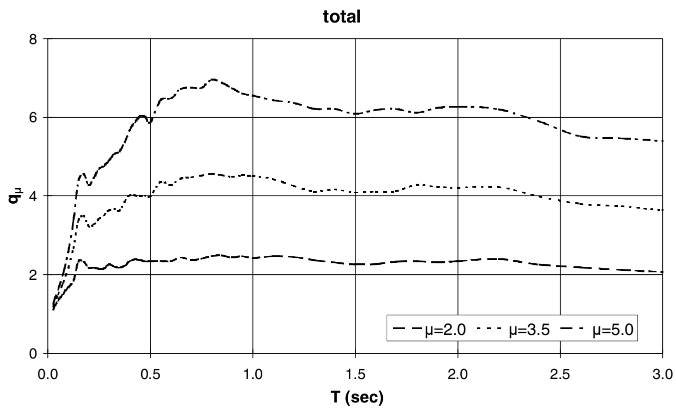


**Fig. 7 Mean values of behaviour factor $q_\mu$**

The evaluation of an analytical formula for the computation of $q_\mu$ as a function of T and μ is important for design practice. Such relationships, based on a different set of earthquakes, were proposed by Miranda and Bertero [10], and their application by Kappos [8] in the past to a (smaller than that of the present study) database of Greek records gave rather satisfactory results. An effort has been made for the computation of a new, and simple, if possible relationship, based on the sample of Greek earthquakes used in this study. Such a relationship should fulfill the following limit conditions:

1. From the definition of $q_\mu$ (eq.1), it is obvious that its value should be equal to 1 for structures behaving elastically, irrespective of their period:

$$q_\mu = q_\mu(T, \mu_i = 1) = 1 \qquad (2)$$

2. For very rigid systems whose yield displacement tends to zero (i.e. $u_y \to 0$, $T \to 0$), even a small reduction in the lateral strength that keeps the system in the elastic range results in large ductility demands. Thus, in such systems, the inelastic strength demand is the same as the elastic strength demand, and therefore the strength reduction factor should satisfy the following condition:

$$q_\mu = q_\mu(T \to 0, \mu_i) = 1 \qquad (3)$$

3. For very flexible systems, (i.e. $T \to \infty$), regardless of their strength, the maximum relative displacement tends towards the maximum ground displacement. Therefore for any ground motion, the inelastic strength demand is equal to the elastic strength demand divided by the ductility, and the following relation holds:

$$q_\mu = q_\mu(T \to \infty, \mu_i) = \mu_i \qquad (4)$$

On the basis of analysis using specialized software, the following expression for $q_\mu$ is proposed:

$$q_\mu = \frac{1}{A + \dfrac{B}{\mu} + C \ln T + D(\ln T)^2} \tag{5}$$

Where, for the entire sample, coefficients *A=-0.03239, B=0.90529, C=-0.00017* and *D*=0.03473, with a correlation coefficient (between the computed and actual data) $r^2$=0.990. Similar analyses were carried out for each soil category, and corresponding coefficients were derived.

In Figure 8, a 3D and a 2D graph of the actual data and the proposed analytical expression for $q_\mu$ (eq. (5)) are presented for the case of the entire record sample. From the graphs, it is clear that the proposed relationship satisfies to an acceptable degree the limit conditions (3) and (4). In practice, use of the proposed relation will be necessary only for μ>1, but anyway, from the graphs it is obvious that it fulfills acceptably (but of course, not strictly) also the limit condition (2) for the μ=1 case (elastic behaviour).

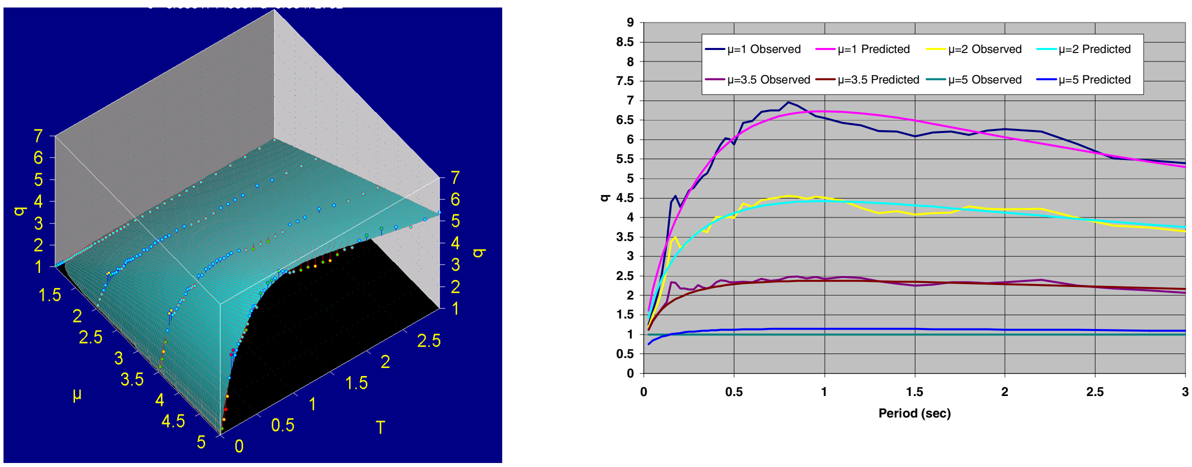


**Fig. 8 Proposed behaviour factor $q_\mu$ as function of T and μ**

The displacement reduction factor $\eta$ (or $\Delta_\mu$ or $C_\mu$) is defined as the ratio of the values of inelastic to the corresponding ones of the elastic displacement spectra:

$$\eta = \frac{S_{d,in}}{S_{d,el}} \tag{6}$$

The displacement reduction factors $\eta$ that are evaluated using the elastic and inelastic spectra derived in this study for the whole sample of earthquake motions are presented in Figure 9, for different ductility levels. The value of $\eta$ is significantly greater than 1 (i.e. inelastic displacements greater than elastic ones) in the short period range, decreases sharply up to a period of T≈0.15÷0.20sec, and then stabilizes to values somewhat less than 1 for the rest of the period range. This trend is general, and very little affected by the ductility level. In the very low period range, as discussed, values of η are significantly greater than 1, and they agree to a satisfactory degree with an observation already mentioned by other researchers (e.g. Miranda [11]), that for T→0 $\eta \rightarrow \mu$.

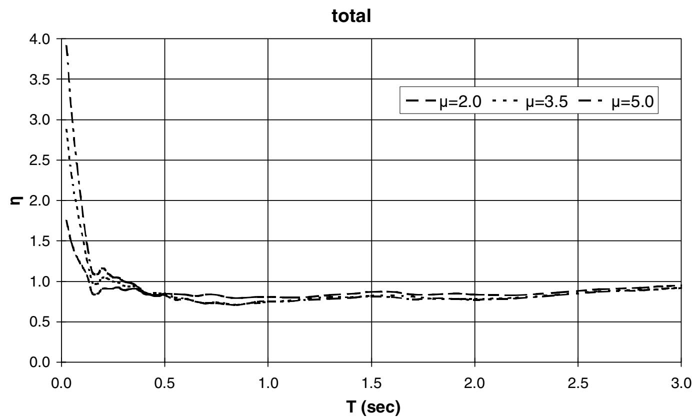


**Fig. 9 Mean displacement reduction factor *η***

The evaluation of an analytical expression for $\eta$ as a function of period T and ductility μ would be useful for design purposes. From its definition (eq. 6), it is obvious that for elastically behaving systems, the value of η should be :

$$\eta = \eta\ (T, \mu_i = 1) = 1 \tag{7}$$

Already from the first attempts for the evaluation of inelastic displacement spectra (e.g Veletsos & Newmark.[12]), it was observed that in the long period range (T > 1÷2 sec), the spectral displacements of elastic and inelastic systems were practically the same, i.e. the following condition holds :

$$\eta = \eta(T \to \infty, \mu_i) = 1 \tag{8}$$

In the medium and short period range, inelastic displacements depend largely on the period of the system, and especially in the very low range, inelastic displacements are significantly larger than the corresponding elastic ones.

Based on the limit conditions mentioned above, and after carrying out analysis with specialized software, the following expression is proposed for the displacement reduction factor $\eta$ :

$$\eta = A + B\mu^2 \ln\mu + C\mu^{2.5} + D\frac{\ln\mu}{\mu^2} + E(\ln T)^2 + F\frac{\ln T}{T} + \frac{G}{T} + \frac{H}{T^{1.5}} + \frac{I}{T^2} \tag{9}$$

Where coefficients *A, B, C, D, E, F, G, H* and *I* have values of 0.88647, 0.01118, -0.00699, -0.44647, 0.05058, 0.01388, -0.07401, 0.05861 και -0.00562 respectively, leading to a correlation coefficient of $r^2 \approx 0.62$ between the analytical expression and the actual data.

In Figure 10, a 3D and a 2D graph of the actual data and the proposed analytical relationship for $\eta$ (eq. (9)) are presented for the case of the entire record sample. From the graphs, it is clear that the proposed relation satisfies to an acceptable degree limit condition (8). In practice, use of the proposed relationship will be necessary only for μ>1, but anyway, from the graphs it is obvious that it fulfills also, to a satisfactory degree, limit condition (7) for the μ=1 case (elastic behaviour).

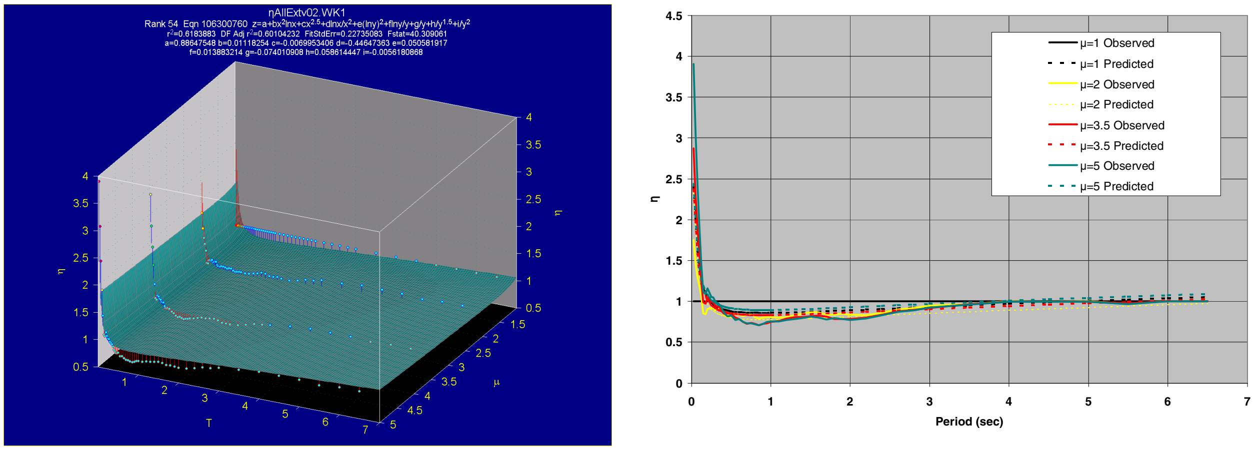


**Fig. 10 Proposed displacement reduction factor *η* as function of T and μ**

## CONCLUSIONS

From the analyses performed within the present study, the following conclusions can be drawn:

1. The strong ground motions that occurred within the Greek territory from the 70s to date have a high frequency content, with spectral peaks in the short period range.
2. The slope of the descending branch of the elastic pseudoacceleration spectra is milder for softer soils (i.e. from soil category A to category C), while the spectral amplification in the spectral peak (sort period) range is significantly higher in stiff soils. On the other hand, the peak spectral pseudo-accelerations become smaller for softer soils, while the opposite holds for the corresponding peak pseudovelocities and displacements. These observations are not fully compatible with current trends in seismic codes, which prescribe increased values of both PGA and spectral amplifications for softer soils.
3. Comparing the elastic pseudoacceleration spectra derived in this study with those provided by the Greek seismic Code EAK2000 (which is similar to the ENV version of Eurocode 8), the former are found to have a clearly higher frequency content, while the EAK2000 provisions lead to a great overestimation of the pseudovelocity and, especially, of displacement spectra, which has serious implications in modern, displacement-based design procedures.
4. Inelastic strength and displacement spectra are smoother than the corresponding elastic ones, particularly for higher ductility levels. Inelastic behaviour results in drastically reduced strength demands in rock sites, while, regardless of soil conditions, strength demand is very low in the medium and long period range. For medium and high ductilities, the influence of the ductility level on the strength demand is small.
5. The ductility level affects very little the value of the inelastic spectral displacement for periods up to approximately 2.5 sec, particularly for stiffer soil conditions. As anticipated, displacement demands are higher for softer soils.
6. In the short period range, up to approximately 0.5 sec, inelastic spectral displacements are higher than the corresponding elastic ones. For longer periods, displacements are either approximately equal (equal displacement rule) or elastic displacements are the larger ones.
7. Values of behaviour factor $q_{\mu}$ increase for periods up to $T_1 \approx 0.50$ sec, tend to stabilize to a value of $q_{\mu} \approx 1.20\ \mu$ for periods up to $T_2 \approx 2.5$ sec, and then decrease slightly for longer periods. An analytical expression for $q_{\mu}$ as a function of period T and ductility level μ is proposed.
8. Values of the displacement reduction factor $\eta$ are significantly greater than 1 (i.e. inelastic displacements greater than elastic ones) in the very short period range, decrease sharply up to a period of T≈0.15÷0.20sec, and then stabilize to somewhat less than 1 for the rest of the period range. An analytical expression for $\eta$ as a function of period T and ductility level μ is proposed.

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