Elastic and inelastic spectra for Greek earthquakes, based on a representative set of records

C. Athanassiadou\textsuperscript{1}, A. Kappos\textsuperscript{1}, C. Karakostas\textsuperscript{2}, N. Klimis\textsuperscript{2}, V. Lekidis\textsuperscript{2}, V. Margaris\textsuperscript{2} & N. Theodulidis\textsuperscript{2}

\textsuperscript{1}Department of Civil Engineering, Aristotle University of Thessaloniki, Greece
\textsuperscript{2}Institute of Engineering Seismology and Earthquake Engineering (ITSAK), Thessaloniki, Greece

Abstract

Elastic and inelastic spectra are derived, based on a set of records representative of Greek earthquakes. For the selection of the dataset, criteria of magnitude, distance and PGA are used. Recently developed techniques are used to correct and filter the noise and other errors in the records. Based on available geotechnical information, a classification of the dataset into three soil categories, compatible to the 2004 Eurocode 8 (EC8) provisions, is made. After appropriate scaling, mean elastic and inelastic spectra are computed both irrespective of, as well as for, each soil condition, and comparisons with the EC8 design spectra are made.

Keywords: elastic spectra, inelastic spectra, strong motion accelerograms, filtering, soil classification, Eurocode 8.

1 Introduction

Elastic and inelastic spectra, either of pseudoacceleration or displacement, play a key role in modern Earthquake Engineering practice. Especially, displacement spectra form the basis of the recently developed displacement-based design and pushover analysis procedures and their adoption by seismic codes is currently underway. For the evaluation of such spectra, careful selection and proper processing of representative strong motion records are of paramount importance.
In the present work, elastic and inelastic spectra are derived, based on Greek earthquake records. A representative set of acceleration records is carefully selected based on magnitude, epicentral distance and peak ground acceleration. The records are then processed using recently developed techniques in order to correct various high and low frequency errors. Taking into account the available geotechnical information for each of the strong motion stations where the dataset came from, the records are grouped into three main categories, based on soil conditions as prescribed in EC8 [1]. The records selected are used for the computation of elastic pseudoacceleration ($S_{pa}$), pseudovelocity ($S_{pv}$) and displacement ($S_d$) spectra, for both each soil category and the whole set (i.e. irrespective of soil conditions). A detailed description of the different characteristics of the spectra and the influence of the soil conditions is presented and comparison is made between the mean elastic spectra derived in the present study and the design spectra adopted by EC8. Finally, inelastic strength ($C_y$) and displacement ($S_d$) spectra are computed, and their properties discussed. The present work is an extension of previous research that involved site classification according to the soil types prescribed in the Greek Seismic Code (Margaris [2], Athanasiadou et al. [3]).

2 Compilation of strong motion dataset

The strong motion database of the ITSAK (period 1980-2005), comprising more than 2000 records, was mainly used. To ensure a representative, and good quality, strong motion dataset, the following compilation criteria were adopted:

- Earthquake magnitude $M_w > 5.0$ and epicentral distance $5 \text{ km} < R < 100 \text{ km}$.
- Value of peak ground acceleration $\text{PGA} \geq 0.10g$ and/or strong motion having caused damage in the neighbourhood of the recording site.
- Availability of sufficient geotechnical data, to classify existing soil conditions at the recording site according to the 2004 EC8 soil categories [1].

Due to the relatively small number of records in the database, in some cases earthquakes of magnitude slightly less than 5 were selected, on condition that the PGAs of the horizontal motions were significant ($>0.15g$). After adopting the aforementioned criteria, 71 horizontal acceleration components were selected. They are records of 26 strong earthquakes that occurred in Greece in the last 25 years, recorded at 27 stations of the permanent accelerograph network of ITSAK. Three records from the accelerograph network of the Institute of Geodynamics, National Observatory of Athens were also included in the dataset.

3 Digitization and correction of strong motion data

The recordings, particularly from analog recorders, invariably contain noise that can affect and distort the signal at both high and low frequencies. It is of paramount significance to identify the presence of the noise in the digitized time-histories and to apply appropriate processing for its removal. Significant effort regarding the strong-motion data processing has been carried out by ITSAK (Margaris, [2]; Skarlatoudis et al., [4]).
The first stage of the processing is the digitization of the analog records. For this, an automated scanning procedure with a resolution of 600 dpi is used, yielding corresponding TIFF image files. The image files are then converted from raster to vector format using the Kinemetrics Scanview software (©Kinemetrics Inc., 1990). The third stage of data processing involves the generation of the uncorrected data (usually referred to as .V1 files) from the processing of the digitized records. The whole digitization procedure results in noise introduction, especially in the lower frequencies of the signals, resulting in a smaller frequency bandwidth for which reliable information can be obtained compared to data recorded from digital accelerographs (Skarlatoudis et al., [5]).

Figure 1: Fourier amplitude spectra of the ZAK 188-4 event: Horizontal components in black lines, fixed trace component in grey line.

The outset correction usually applied in both analog and digital accelerograms is the baseline correction, i.e. the existence of distortions and shifts of the baseline, which result in unphysical velocities and displacements. The procedure involves record selection, baseline determination (usually a fixed trace) and correction. For the selected dataset, the three-step baseline correction routine proposed by Hung-Chie [6] was used.

In order to remove the previously described inherent noise of the records, digital filters are used. In order to estimate the appropriate high-pass filter limits, a signal-to-noise ratio methodology is applied. At first, the Fourier Amplitude Spectra (FAS) for the uncorrected data for frequencies up to 30 Hz are computed. The same procedure is also applied for the two digitized fixed traces, which are two components of the record representing the zero acceleration traces. Since the fixed traces should be equal to zero, any non-zero value and the corresponding spectra are a result of poor recording and digitization errors. For the estimation of the characteristic frequencies of the high-pass filters that will be applied on the uncorrected data, an appropriate processing program was
written, which uses the Fourier amplitude spectra and calculates the frequencies for which the signal to noise amplitude ratio exceeds a certain threshold (Skarlatoudis et al., [4]). After testing different filters for the records, it was decided to use as cut-off frequency \( f_c \), the frequency where signal to noise ratio was 2:1 and as roll-off frequency \( f_r \), the frequency where signal to noise ratio was 3:1 (the threshold is computed using the average FAS of the horizontal components and the fixed traces). The comparison of the Fourier Amplitude Spectra (FAS) of the components and the corresponding fixed traces for one of the processed records (code name: zak188-4) is shown in Figure 1. It was recorded during the Kyllini (Southwestern Greece) mainshock (M=5.8, in 1988) at an epicentral distance of 20 Km and has a PGA value equal to 147.2 cm/s\(^2\). It is evident that the seismic signal (black lines) is higher than fixed trace noise signal (grey line) only in a certain frequency range. For the low-pass filters the characteristic frequencies of 25 and 27 Hz are used for most records in accordance with the frequency response of the recording instrument. By applying the previously calculated filters the corrected data (usually referred to as V2 files) are obtained.

![Figure 1: Comparison of Fourier Amplitude Spectra (FAS) of the components and the corresponding fixed traces for zak188-4.](image1)

**ZAK188-4 - T**

\[ \mu = 5.0 \]

![Figure 2: Inelastic displacement spectra computed for various high-pass filter limits of the zak188-4 record.](image2)

To illustrate the effect of the filtering limits applied on a record on the various spectra computed from it, different high-pass filters are applied on the zak188-4-T record, which is then used to compute the inelastic displacement (\( S_d \)) spectrum for a ductility factor \( \mu = 5 \). Five arbitrarily chosen high-pass filters are used (filters 1 to 5, with corresponding \( f_c/f_r \) values of 0.95/1.0 Hz, 0.45/0.50 Hz, 0.28/0.33 Hz, 0.20/0.25 Hz, 0.15/0.20 Hz), as well as the filtering limits computed by the previously described signal-to-noise ratio methodology (filter S/N, \( f_c/f_r : 0.344/0.477 \) Hz). As can be seen from Figure 2, the computed spectra rely heavily on the filtering limits used, and the spectrum derived by using the S/N filter, correctly converges to the max displacement value for higher periods.
(T>2.5 sec) (whereas spectra using filters with low high-pass limits, e.g. filters 4 and 5, and to a certain degree even filter 3, tend to diverge).

4 Classification of selected records according to soil conditions

The objective of this part of the work is the classification of selected representative Greek accelerograms according to the local soil conditions at the recording site, by applying the soil categorization criteria proposed in Eurocode 8 [1]. Classification of recorded accelerograms according to local soil conditions is a topic that has attracted the last 30 years a very strong scientific interest and numerous efforts have been reported (e.g. references [8, 9, 10]). It should be noted that soil classification criteria adopted by different seismic codes might be strongly dissimilar, since the basic concept adopted in each case is dependent on each country’s experience in the field. In EC8 [1] five basic ground types (A, B, C, D, E) and two specific categories (S₁ and S₂) are defined, according to their stratigraphic profile and/or the value of the parameters $V_{S30}$ (average shear wave velocity at the upper 30 meters of the soil), $N_{SPT}$ (Standard Penetration Test blowcounts) and $C_u$ (undrained shear strength).

Table 1: Site classification according to soil type.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thessaloniki (Hotel City)</td>
<td>C</td>
<td>Chromio</td>
<td>B</td>
</tr>
<tr>
<td>Corinth</td>
<td>C</td>
<td>Karpero</td>
<td>B</td>
</tr>
<tr>
<td>Argostoli</td>
<td>B</td>
<td>Kentro</td>
<td>C</td>
</tr>
<tr>
<td>Polygyros</td>
<td>A</td>
<td>Konitsa (Town Hall – Konu)</td>
<td>B</td>
</tr>
<tr>
<td>Pelekanada</td>
<td>A</td>
<td>Konitsa (Kato Konitsa – Konl)</td>
<td>C</td>
</tr>
<tr>
<td>Kalamata (Prefecture- kal186)</td>
<td>B</td>
<td>Athens (Chalandri – ath299)</td>
<td>B</td>
</tr>
<tr>
<td>Kalamata (OTE-kal286)</td>
<td>B</td>
<td>Athens (KEDE – ath399)</td>
<td>B</td>
</tr>
<tr>
<td>Zakynthos island</td>
<td>C</td>
<td>Athens (GYS – ath499)</td>
<td>A</td>
</tr>
<tr>
<td>Amaliada</td>
<td>C</td>
<td>Keratsini</td>
<td>B</td>
</tr>
<tr>
<td>Edessa</td>
<td>C</td>
<td>Rafina</td>
<td>B</td>
</tr>
<tr>
<td>Pyrgos</td>
<td>C</td>
<td>Sepolia</td>
<td>B</td>
</tr>
<tr>
<td>Patras (ETE – pat193)</td>
<td>C</td>
<td>Lefkada</td>
<td>C</td>
</tr>
<tr>
<td>Patras (St-Demetrios church – pat393)</td>
<td>C</td>
<td>Preveza</td>
<td>Not Available</td>
</tr>
<tr>
<td>Kozani</td>
<td>A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The sites of the selected recordings dataset are classified (Table 1) according to the value of $V_{S,30}$, if it is available; otherwise the values of $N_{SPT}$ and alternatively of $C_u$ (for cohesive soils) are used. In case none of the aforementioned parameters ($V_{S,30}$, $N_{SPT}$, $C_u$) was available for the sites of recording stations, categorization was based on a qualitative description of the stratigraphic profile and information from the corresponding geological map (IGME, scale 1:50,000).

The recording stations were classified in three soil categories A (rock), B (very dense sand/gravel or very stiff clay) and C (dense or medium dense sand/gravel or stiff clay) as prescribed by EC8. Any attempt for a more refined categorization is meaningless, due to the limited size of the dataset. For the Preveza station no geotechnical information was available; therefore, the two records have been used only for the computation of mean elastic and inelastic spectra irrespective of soil conditions (i.e. for the whole dataset). The remaining 69 records were classified as follows: in soil category A 10 records (14.5%), in soil category B 31 records (45%), in soil category C 28 records (40.5%).

5 Computation of elastic spectra

The selected records were used for the computation of elastic spectra, either for each soil category or for the whole sample (i.e. irrespective of soil conditions). In order to estimate the spectral shape, rather than the absolute spectral values, all records were scaled according to the mean spectral intensity (SI i.e. the area under the pseudovelocity spectrum between 0.10 and 2.5 sec) that corresponds to each of the three soil categories, or to the whole sample. Elastic spectra were computed for all values of the equivalent damping coefficient ($\zeta$), that are 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 3 left), pseudovelocity ($S_{pv}$) and displacement ($S_d$, Figure 3 right) spectra.

![Figure 3: Mean elastic pseudoacceleration spectra irrespective of soil conditions (left), and for soil category B (right).](image-url)
velocities 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 (Figure 4), 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 $\zeta$. A clear effect of different soil conditions is that the slope of the descending branch in the $S_{pa}$ 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. Also, a comparison among the different spectra for different soil categories indicates that (on the mean) the peak spectral pseudoaccelerations become smaller for softer soils, while the opposite is observed for the corresponding pseudovelocity and displacement peak spectral values. These remarks are not fully compatible with current trends in seismic codes (Kappos [10]), 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.

Figure 4: Mean elastic displacement spectra irrespective of soil conditions (left), and for soil category B (right).

Figure 5: Comparison between mean elastic acceleration (left), and displacement (right) spectra (black lines) and EC8 provisions (grey lines).
In Figure 5, a comparison is given between the elastic spectra \((S_{pa}, S_d)\) for different soil categories proposed in the EC8 Seismic Code (for \(\zeta=5\%\) 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 5 left), 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 EC8 of the pseudovelocities and, most important, of spectral displacements. As becomes obvious from the comparison of the displacement spectra (Figure 5 right), the displacement values that are compatible with the elastic pseudoacceleration spectra of EC8 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).

6 Computation of inelastic spectra

The computed inelastic strength \((C_y)\) and displacement \((S_d)\) spectra are presented in Figures 6 and 7. 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 (Kappos [11]). In the model, a strain-hardening ratio of 5\% (common for R/C structures) and a damping ratio of \(\zeta=5\%\) are used. 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).

![Graphs](image)

Figure 6: Mean inelastic strength spectra irrespective of soil conditions (left), and for soil category B (right)

From Figure 6, 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 \(\mu\geq3.5\) 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 7), especially in view of the recent concepts for displacement-based design. It is observed 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 feature, of more or less general nature, is that in the low period range \( (T<0.5 \text{ sec}) \), 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.

Figure 7: Mean inelastic displacement spectra irrespective of soil conditions (left), and for soil category B (right).

7 Conclusions

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

(1) The strong ground motions that occurred in Greece 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, while the spectral amplification in the spectral peak (short period) range is significantly higher in stiff soils. On the other hand, the peak \( S_{\text{pa}} \) values 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 Eurocode 8, the former are found to have a clearly higher frequency content, while the EC8 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.

References


