INFLUENCE OF LOW-CUT FILTER FREQUENCY ON NONLINEAR OSCILLATOR DISPLACEMENTS COMPUTED FROM NON-DEGRADING TO DEGRADING HYSTERETIC MODELS

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ABSTRACT:

Low-cut filtering used for removing the long-period noise in accelerograms is investigated for its effects on the nonlinear peak oscillator displacements. We used a suite of analog and digital accelerograms from Turkish strong-motion database and low-cut filtered each record by a set of randomly generated filter cut-offs. We computed nonlinear displacement spectra to highlight the period-dependent influence of low-cut filtering on the nonlinear oscillator response. Differences in the nonlinear oscillator response are considered by using a wide range of hysteretic models that cover non-degrading to severely degrading structural behavior. Our analyses show that inelastic spectral displacements are more vulnerable to low-cut filtering than their elastic counterparts. This can be attributed to the intricate relation between the nonlinear structural parameters, record quality and ground-motion features that increase the level of complexity between the nonlinear oscillator response and low-cut filtering. Recording type (digital / analog recording), earthquake magnitude, site classification, inelasticity level, hysteretic model as well as the variations in peak ground motion are the prominent factors about the influence of low-cut filters on peak nonlinear oscillator displacements.

KEYWORDS: record processing, nonlinear oscillator response, non-degrading / degrading hysteretic behavior, constant strength and ductility spectrum, probability

1. INTRODUCTION

Reliable spectral information is important in earthquake engineering. In structural engineering view point, consistent response spectrum will lead to robust demand estimations on structural systems. Upon the increased interest in displacement-based design and assessment procedures in earthquake engineering the estimation of peak nonlinear oscillator displacements has become an appealing research topic (ATC, 2005). This requires trustworthy long-period ground-motion information and consequentially consistent inelastic spectral shapes at long periods because nonlinear structural behavior inherently results in a period shift towards longer spectral components.

The reliability of long-period information in ground-motion records is related to the recording quality that is described by the level of long-period noise in the accelerograms. Long-period noise exhibits different features in the analog and digital recordings (Boore and Bommer, 2005) and one way of reducing its effects is to use low-cut filters. Inherently, low-cut digital filtering interferes with the general characteristics of the ground motion because the actual noise model of the record is never known. Thus, in almost all cases both the ground motion signal and the noise are lost after low-cut filtering. Moreover, only a fraction of the spectrum is not influenced by the chosen low-cut filter value due to the filter roll-off between the pass-band and filter cut-off. Spectral ranges that are least affected by the low-cut filter period (T_c) were investigated by Akkar and Bommer (2006) for elastic oscillator response. Akkar and Bommer (2006) proposed some empirical factors to be used as a fraction of T_c that vary for different site classes and recording type (i.e. digital vs. analog records). Abrahamson and Silva (1997) also proposed to use elastic spectrum for periods up to $0.8T_c$ based on the theoretical relationship between the oscillator response and digital filter behavior. Although these studies revealed versatile information about the reliable long-period spectral range for elastic oscillator response, they did not extend their observations to nonlinear oscillator response. Boore and Akkar (2003) and Bazzurro et al. (2005) conducted limited studies about the influence of different filtering types (causal vs. acausal) on the calculation of inelastic spectrum. These studies concluded that inelastic spectrum is less sensitive to the low-cut filter values when bi-directional (acausal) filters are used. Akkar and Ozen (2006) acausally filtered a set of analog ground motions using alternative low-cut filter values computed from different noise models. They showed that the elastoplastic spectra of low-magnitude rock site analog records are more sensitive to low-cut filtering such that the influence of filter cut-off commences at spectral periods significantly shorter than the chosen T_c value.

In this study we extended the findings of Akkar and Ozen (2006). We investigated the influence of low-cut filtering on the inelastic spectral displacements computed from a wide range of hysteretic models by using a set of analog and digital ground motions from Turkish strong-motion database. The inelastic spectral displacements are computed for constant strength and ductility that are used for the performance assessment and seismic design of structural systems. The randomness in the filter cut-off values is considered by generating magnitude-dependent T_c values via Monte Carlo simulations. The degree of low-cut filter influence on nonlinear displacement spectrum is observed by considering the role of ground-motion and structural parameters. We related the reliability of long-period inelastic spectrum with the uncertainty in peak ground displacements because the long-period variation is controlled by the peak ground displacement (PGD). The results presented in this short note can be further elaborated for determining reliable inelastic spectral period ranges of low-cut filtered strong-motion data.

2. GROUND MOTIONS, FILTERING PROCEDURE AND HYSTERETIC MODELS

Table 2.1 presents the strong-motion recordings used in this study. The dataset comprises of dense-to-stiff soil recordings encompassing small to large magnitude events from Turkey. There are analog and digital recordings from small and large magnitude events that are distributed almost evenly. Each ground motion was low-cut filtered by 4-pole/4-pole acausal Butterworth filter (USDP, 2008) for a set of randomly generated T_c values. This way we intended to mimic the subjective decisions of the analysts while deciding on the low-cut filter value. T_c values are generated following the log-normal distribution with upper and lower values bounded by the magnitude-dependent corner periods (T_a and T_b) of theoretical source spectrum proposed by Atkinson and Silva (2000). It is a well-known fact that the frequency content of ground motions is magnitude dependent and the guidance of a source spectrum in the generation of T_c values prevented us simulating excessive filter cut-offs that would remove a considerable amount of actual ground-motion signal. We believe that this procedure resulted in rationale filter cut-offs for each record that would also be selected by different analysts. A total of 30 T_c values were generated for each ground motion used in this study. Figure 2.1 shows an example case for the log-normal variation of the filter cut-offs simulated for the NS component of the 1976 Denizli record ($M_w = 6.1$). The left (cumulative log-normal distribution overlaid on the T_c histogram) and right (normal probability plot of the logarithm of T_c) panels justify that the randomly generated T_c values fit well to the log-normal distribution. Note that the upper and lower T_c values are bounded by the Atkinson and Silva (2000) theoretical source model that yields T_a = 7.0 sec and T_b = 1.2 sec. Accordingly, the filter cut-offs tending towards T_b would remove longer periods from this record. Figure 2.2 presents the Fourier amplitude spectra (FAS) of the same record that is low-cut filtered by the T_c values shown in Figure 2.1. The superimposed straight line that is fitted by eye shows f^2 gradient consistent with the single-corner source theory and it guides us about the decaying rate at low-frequency signals. Note that some of the low-cut filtered records decay more rapidly than the trend shown by this model whereas the rest of the FAS curves are significantly above this line. Assuming that the theoretical single-corner model holds for this record, this observation grossly indicates that the waveforms with faster decay at low frequencies have lost some part of the actual signal during the low-cut filtering whereas the others are still dominated by long-period noise. The major issue, however, is to decide the range of spectral periods for which the spectral ordinates can be used reliably regardless of the variations in filter cut-offs due to the subjectivity in the decisions of the analysts.

Table 2.1 Ground-motion data used in this study

Earthquake Date and Name	*Station Name*	*Component*	*Mw*	*Site Class*	*Distance, Rjb (km)*	*Instrument Type*
19/08/1976 - Denizli	Denizli	NS	6.1	NEHRP-D	6.43	SMA-1
06/11/1992 - Izmir	Kusadasi	NS	6.0	NEHRP-C	38.11	SMA-1
13/04/1998 - Bingol	Solhan	EW	5.2	NEHRP-C	36.92	SM-2
13/09/1999 - Kocaeli	Iznik	NS	5.8	NEHRP-D	41.24	SMA-1
12/11/1999 - Duzce	Mudurnu	EW	7.2	NEHRP-D	32.14	SMA-1
22/06/2001 - Manisa	Balikesir	NS	5.2	NEHRP-C	33.81	GSR-16
01/05/2003 - Bingol	Bingol	EW	6.3	NEHRP-C	2.23	GSR-16

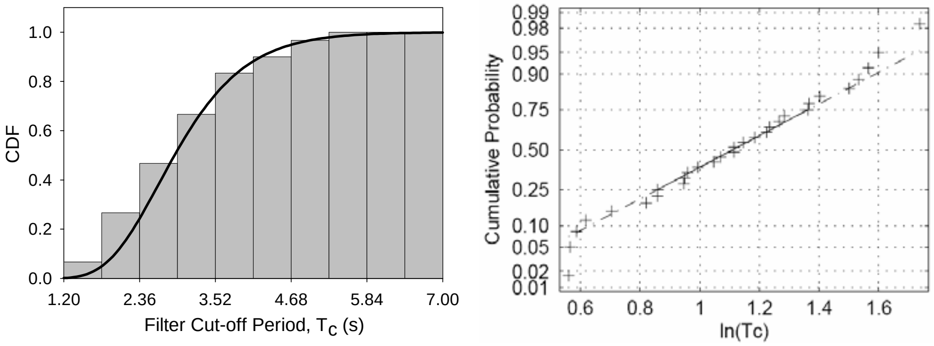


Figure 2.1 Example for the distribution of low-cut filter periods generated by log-normal distribution assumption.

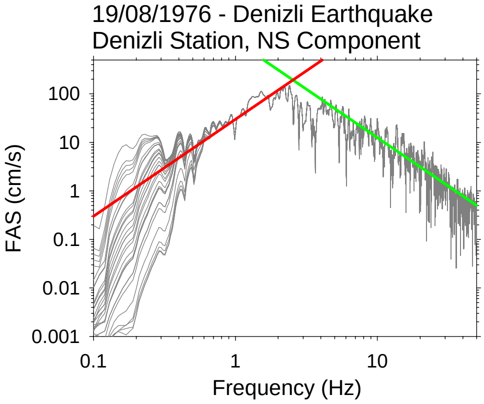


Figure 2.2 Fourier amplitude spectra of the 1976 Denizli-NS record with different low-cut filters.

We used different hysteretic models for assessing the influence of degradation on peak nonlinear oscillator displacements. In order to represent non-degrading (ND) systems, we selected bilinear hysteretic model as the reference model. The main reason for this selection is that bilinear model is simple to implement with only a few parameters (Figure 2.3.a). We classified degrading systems as only stiffness degrading (SD) systems and both stiffness and strength degrading (SSD) systems. Under cyclic excursions, SD systems generally display stable hysteretic loops with significant energy dissipation. However, SSD systems cannot maintain stable cyclic energy dissipation. Therefore, cyclic energy dissipation capacity can be employed as a convenient measure in differentiating between ND, SD and SSD systems. In this study, Clough-Johnston model (1966) was employed in order to simulate the seismic response of SD systems (Figure 2.3.b). The third model is based on the Clough-Johnston model, but with the introduction of an additional strength degradation rule. This rule is in exponential form, which is a function of displacement ductility, level and rate of degradation. The envelope curve is not bilinear; it has a descending portion beyond maximum displacement level, which indicates a reduction in strength capacity under large deformations. A simple sketch of the SSD model is illustrated in Figure 2.3.c.

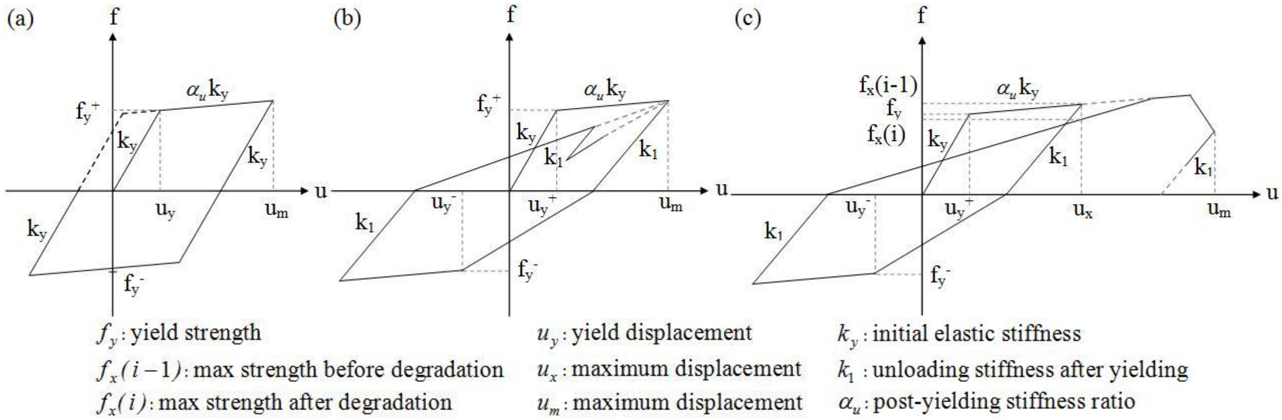
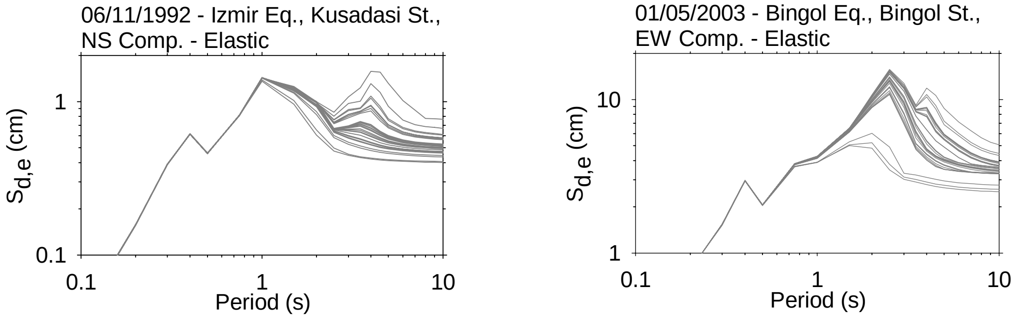


Figure 2.3 Hysteretic models used in this study: a) ND model, b) SD model, c) SSD model.

3. CASE STUDIES

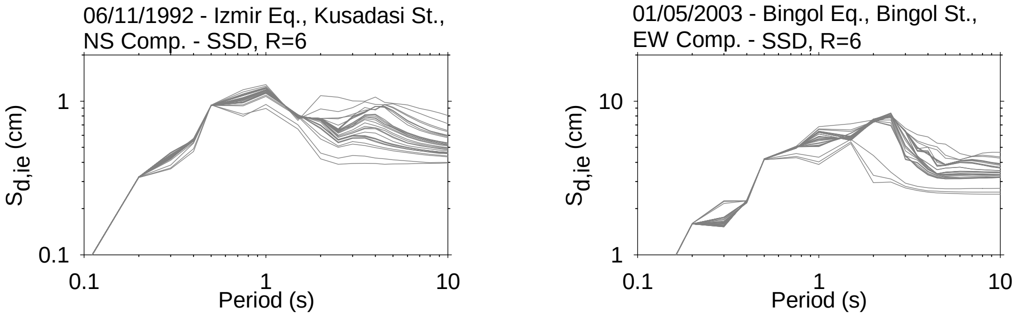
We ran a series of case studies in order to assess the influence of low-cut filtering on the nonlinear oscillator response. The oscillator responses were calculated for a classical damping value of 5%. The post-yielding stiffness ratio (α_u) is 3% in all cases. The spectra are presented up to 10 sec but we are aware of the fact that for some cases this period range will exceed the reliable periods where the low-cut filter influence is minimum (Akkar and Bommer, 2006; Abrahamson and Silva, 1997). Spectral period limit of 10 sec is imposed to satisfy the visual uniformity in the illustrations. We focused on the following seismological and structural parameters while observing the intricate relationship between the low-cut filtering and nonlinear oscillator response: (a) recording type (digital vs. analog), (b) magnitude (small vs. large), (c) dispersion on peak ground-motion values, (d) level of inelasticity (in terms of displacement ductility, μ and normalized lateral strength, R), and (e) hysteretic model (ND, SD, SSD). We used PGD as the peak ground parameter because it governs the long-period behavior of the spectrum. We chose the coefficient of variation (COV) as the dispersion index of PGD. This paper presents only a limited amount of case studies due to the spacing limitations.

In the first case study, we examined the effect of recording type on displacement response of non-degrading and degrading systems. The ground-motion records used in this comparison are Kusadasi-NS (1992) and Bingol-EW (2003) that are from the analog and digital recorders, respectively. Both of these records are from similar magnitude events ($M_w \approx 6.0$) and the variation in PGD due to low-cut filtering exhibits similar uncertainties (i.e. COV of both records are approximately 0.10). Figure 3.1 shows the linear displacement spectra ($S_{d,e}$) of these two recordings. Although the dispersion in $S_{d,e}$ due to filtering starts approximately at 1.0 sec for both records, the analog record (Kusadasi) shows a significant dispersion at longer periods when compared to the Bingol record. Figure 3.2 presents the inelastic spectral displacement of these two records computed from SSD behavior. A similar trend as in the case of Figure 3.1 is observed for the nonlinear response. The analog recording displays a more dispersive behavior with respect to the digital recording. Akkar and Bommer (2006) has already described the sensitivity of analog records to low-cut filtering with respect to digital ground motions. However, the case study presented shows that the nonlinear response triggers the low-cut filtering sensitivity towards earlier spectral periods and punishes the analog records further by larger variations in the computed displacement spectra.



(a) (b)

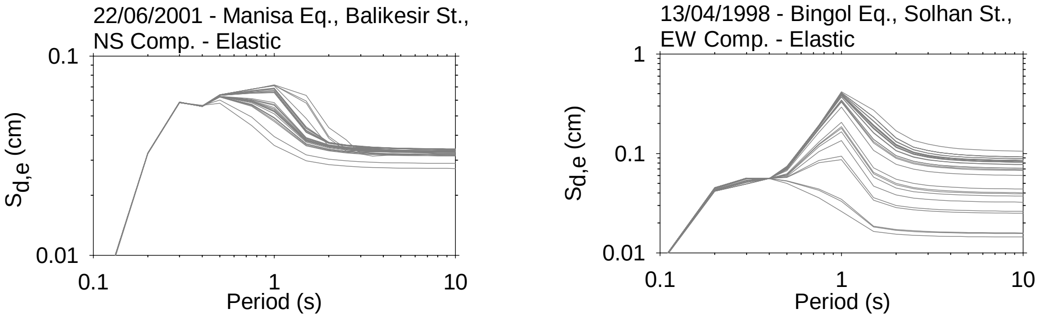
Figure 3.1 Elastic displacement spectra for a) Kusadasi (1992) NS, b) Bingol (2003) EW recordings.



(a) (b)

Figure 3.2 Inelastic displacement spectra for a) Kusadasi (1992) NS, b) Bingol (2003) EW recordings.

In the second series of case studies, we examined the effect of low-cut filtering on peak oscillator displacements by measuring the uncertainty (dispersion) in PGD. The uncertainty in PGD is quantified by COV; a dimensionless measure of dispersion that is defined as the ratio of standard deviation to mean. PGD controls the variation in the long-period displacement spectrum. Therefore, high COV values of PGD for a low-cut filtered record with a series of T_c values would imply a considerable uncertainty in the long-period spectral displacements due to low-cut filtering. We chose two digital recordings (Balikesir-NS, 2001 and Solhan-EW, 1998) of $M_w = 5.2$ from the same site class with similar source-to-site distance values for comparisons. The COV values for Balikesir and Solhan records are 0.05 and 0.64, respectively and this constitutes the major difference between these two ground motions. Figure 3.3 presents the computed $S_{d,e}$ of these records. The dispersion in $S_{d,e}$ due to different filter cut-offs commences at significantly shorter periods in the Solhan record that exhibits large COV values of PGD.



(a) (b)

Figure 3.3 Elastic displacement spectra for a) Balikesir (2001) NS, b) Solhan (1998) EW recordings.

Figure 3.4 investigates the same case for the nonlinear oscillator response (ND and SSD hysteretic models) with different levels of inelasticity (R = 2 for ND and R = 6 for SSD). This time we used the period-dependent probability curves that show the probability of occurrence of $S_{d,ie}$ within the 10% range of mean $S_{d,ie}$ [i.e.

$\Pr(0.9\overline{S}_{d,ie} \leq S_{d,ie} \leq 1.1\overline{S}_{d,ie})$]. A high probability from these curves stands for a low dispersion in the spectral displacement whereas a low probability indicates that the variation in spectral displacements is significant due to low-cut filtering. In all cases and almost for the entire spectral period range, the probability values obtained for the Solhan record (COV=0.64) are smaller than those obtained for the Balikesir record (COV=0.05). As the level of inelasticity increases and as the system characteristics shift from a non-degrading state to a degrading state, $\Pr(0.9\overline{S}_{d,ie} \leq S_{d,ie} \leq 1.1\overline{S}_{d,ie})$ decreases. This observation once again emphasizes that the filtering effects may be more prominent as the oscillator response exhibits increased levels of nonlinearity.

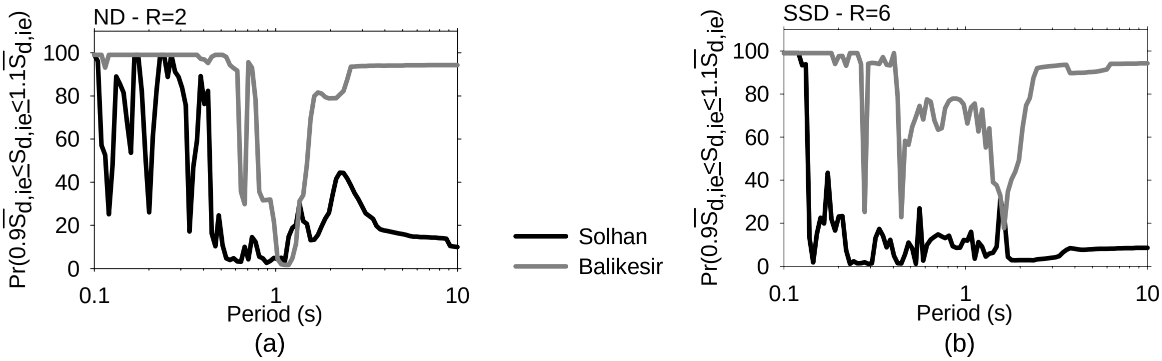


Figure 3.4 Probability curves that show occurrence rates for $\Pr(0.9\overline{S}_{d,ie} \leq S_{d,ie} \leq 1.1\overline{S}_{d,ie})$ for Balikesir (COV = 0.05) and Solhan (COV = 0.64) records using a) ND systems with R=2, b) SSD systems with R=6.

The next comparison is between two analog records of different magnitudes: the NS component of Denizli (1976) has a magnitude of 6.1 whereas the EW-Mudurnu (1999) ground motion was recorded from the Duzce earthquake (M_w = 7.2). The COV value of PGD in the small magnitude recording (Denizli-NS) is significantly smaller than the corresponding COV value of the Mudurnu record (0.07 vs. 0.35). Note that these two records pertain to the same soil group (NEHRP D). The elastic displacement spectra of these two records are compared in Figure 3.5. The comparisons indicate that the dispersion in $S_{d,e}$ in the Denizli record that is associated with low COV starts at significantly shorter periods when compared to the commencement of $S_{d,e}$ dispersion in the Mudurnu record (large COV). This observation seems to be contradictory to the previously presented case that underlines the importance of having low COV values of PGD in order to minimize the effects of low-cut filtering on peak oscillator displacements. The current case can be explained by the observations of Akkar and Bommer (2006) who stated that the rich long period frequency content of large magnitude events reduces the influence of low-cut filtering on the elastic spectral displacements. In other words, the possible large $S_{d,e}$ variation of the Mudurnu record stemming from high COV value is probably suppressed (masked) by its large magnitude. Note that this trend seems to be vanishing in the case of inelastic response (Figure 3.6). For the SSD oscillator response with R=2, the dispersion in $S_{d,ie}$ starts at very short periods (T ≈ 0.25 sec) for the Mudurnu record whereas there is no significant dispersion in the inelastic spectral displacements for T ≤ 2 sec for the Denizli record. Thus, the uncertainty in PGD is still a dominant factor for identifying the effect of low-cut filters on the nonlinear oscillator response regardless of the magnitude differences between the ground-motion records.

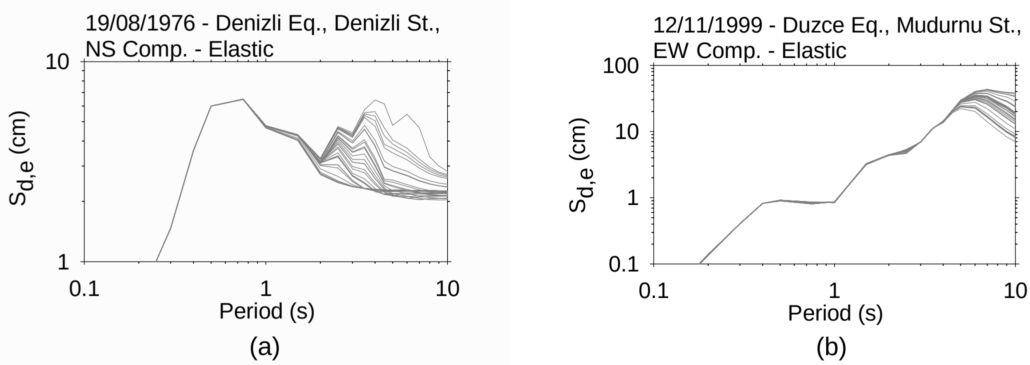
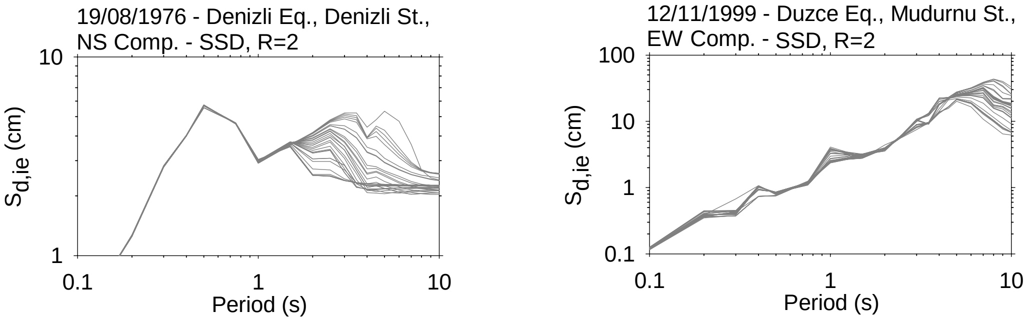


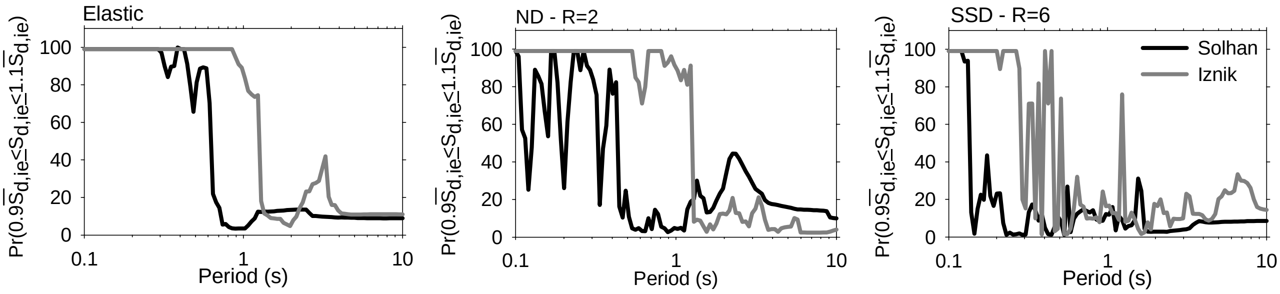
Figure 3.5 Elastic displacement spectra for a) Denizli (1976) NS, b) Mudurnu (1999) EW recordings.



(a) (b)

Figure 3.6 Inelastic SSD displacement spectra with R=2 a) Denizli (1976) NS, b) Mudurnu (1999) EW.

The final comparison in the second series of case studies is between an analog record with COV=0.21 (Iznik, 1999, NS component) and a digital record with COV=0.64 (Solhan, 1998, EW component). This cross comparison was carried out to rank the priority among the recording type and PGD uncertainty for the prominence of low-cut filtering in nonlinear spectral displacements. Note that both records are from low magnitude events but the magnitude of analog Iznik record (M_w = 5.8) is slightly larger than the Solhan record (M_w = 5.2). Figure 3.7 presents the period-dependent variation of Pr($0.9\bar{S}_{d,ie} \le S_{d,ie} \le 1.1\bar{S}_{d,ie}$) probability curves of these records for elastic and inelastic cases. The inelastic spectra are evaluated for a non-degrading, high-yield strength case (R = 2) and for a severely degrading (SSD) low-yield strength case (R=6). The plots presented here clearly show that the dispersion in the spectral displacement due to low-cut filtering is governed by the Solhan record that exhibits high COV values of PGD. When the level of inelasticity and severity in the degrading behavior are taken into consideration, the dispersion in $S_{d,ie}$ commences at very short periods for the Solhan record. This specific example advocates that, for similar levels of magnitude, the displacement spectrum of the record that possesses a higher PGD uncertainty is more sensitive to the low-cut filter values. In other words, the type of recording seems to have a lesser influence on the reliability of low-cut filtered elastic / inelastic spectral displacements when compared to the uncertainty in PGD whenever the ground motions have similar magnitude levels as in this example.



(a) (b) (c)

Figure 3.7 Probability curves for Pr($0.9\bar{S}_{d,ie} \le S_{d,ie} \le 1.1\bar{S}_{d,ie}$) for Iznik and Solhan records using a) elastic systems, b) ND systems with R=2, c) SSD systems with R=6.

4. SUMMARY AND CONCLUSIONS

We investigated the influence of low-cut filtering on the nonlinear peak oscillator displacements (inelastic spectral displacements) computed from a wide range of hysteretic models. We employed a set of analog and digital ground motions from Turkish earthquakes and ran a series of case studies with different seismological and structural parameters to achieve this objective. The variability in the low-cut filter values was taken into account by generating log-normally distributed filter cut-offs for each record using a theoretical double-corner source spectrum.

The limited number of case studies showed that the analog records, which exhibit a lower ground-motion frequency resolution with respect to the digital records are more sensitive to low-cut filtering and nonlinear response seems to trigger this sensitivity further. The variations in the nonlinear displacement spectra of low-cut filtered analog records commence at significantly shorter vibration periods with respect to their elastic counterparts. Low-cut filtering effects on the inelastic displacement spectra become more influential as the level of inelasticity increases (defined by the changes in μ and R). In other words, the variations in $S_{d,ie}$ shift to very short period ranges with respect to the chosen low-cut filter values with increasing μ and R values. This effect is further pronounced when the high level of inelasticity is associated with cyclic degradation. Another important observation of this study is the dominancy of PGD uncertainty while measuring the low-cut filtering effect on nonlinear spectral displacements. For a low-cut filtered record with different T_c values, a high level of PGD uncertainty would increase the variations in the long-period spectral response. As the level of inelasticity increases, the uncertainty in PGD becomes more apparent in the dependency of inelastic displacement spectrum on low-cut filter values.

The observations presented in this study indicate that low-cut filtering influence on the nonlinear oscillator response is complex. Therefore, the usable spectral period range of inelastic displacement spectrum should not be determined from the empirical factors that are validated for elastic oscillator response.

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