DISPLACEMENT AMPLIFICATION FACTORS FOR DEGRADING SYSTEMS SUBJECTED TO NEAR-FAULT GROUND MOTIONS

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SUMMARY

The displacement demands of single-degree-of-freedom degrading systems subjected to near-fault ground motions are studied. The investigation included models with 5 percent damping, three levels of strength and stiffness decay and five ground motions. The results show that stiffness and strength degradation tend to increase the maximum inelastic displacements above those observed for nondegrading systems. They also show that the additional displacement amplification is more significant for short period systems. Average amplification factors in the order of two were obtained at short periods, though factors as high as four were observed for individual records. At long periods, a small or no additional amplification was observed.

INTRODUCTION

Recent earthquakes have shown that near-fault ground motions can produce spectral demands significantly larger than those considered in current design provisions. In addition, they can contain large displacement pulses that can have severe damaging effects on structures. The destructive nature of these types of events can have a significant impact on the performance of older structural systems. The last often lack strength and ductility, and are prone to severe damage or collapse under strong ground motions.

In recent years, displacement-based procedures have been favored by many within the engineering community, because they permit, albeit approximately, a direct evaluation of the damage and performance of a structure during ground shaking. In the United States, such procedures have been explicitly incorporated into the guidelines for seismic evaluation and rehabilitation of existing of buildings [ATC-33]. These procedures require realistic estimates of the displacement demands of systems that may exhibit significant strength and stiffness deterioration of the hysteresis loops. Most earthquake response studies have considered elasto-plastic, bi-linear or stiffness degrading hysteresis models, which are not representative of the response characteristics of older construction. A few studies on systems with degrading characteristics [Al-Sulaimani and Roessett, 1984; Rahnam and Krawinkler 1993, Gupta and Kunnath, 1998] suggest that the inelastic displacements can be much larger than those of systems without degradation.

The purpose of this paper is to study the effects of near-fault ground motions on the displacement demands of single-degree-of-freedom (SDOF) systems with degrading characteristics. The study considered models with three different decay levels which were analysed for five ground motions. The results are examined in terms of spectral displacements and displacement amplification factors.

DESCRIPTION OF THE SYSTEMS STUDIED

The nonlinear model used in this study included strength and stiffness degradation with increasing deformation amplitude and with loading cycles. The degradation rate is controlled by six parameters that can be adjusted to obtain systems with various levels of degradation. In Figure 1, the hysteretic responses of systems with three plausible decay levels are shown. The responses were obtained for the same loading history which consisted of

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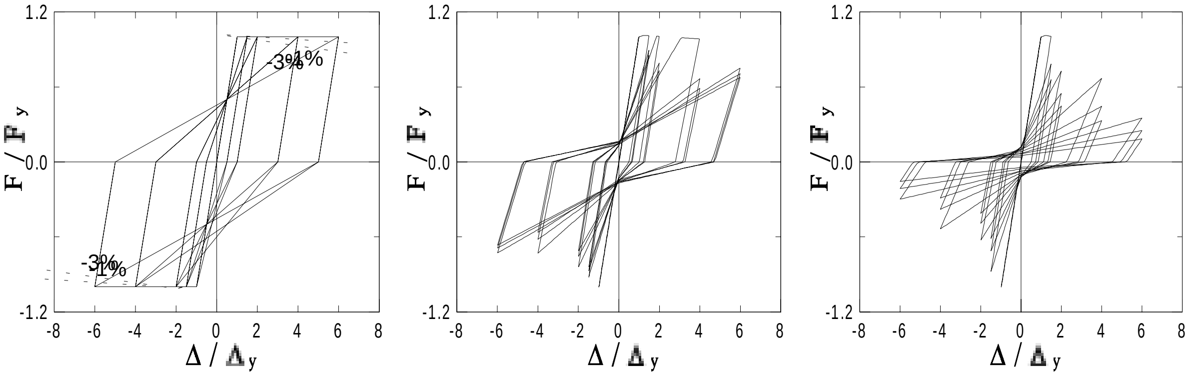
three full cycles at displacement amplitudes of 1.5, 2, 3, 4 and 6 times the yield displacement. For simplicity, they have been called nondegrading, moderate and high degrading models in accordance with their strength decay level. The nondegrading model (see Figure 1a) is, in fact, a stiffness degrading system with no strain hardening, but it has no strength decay characteristics. The system with moderate decay level (Figure 1b) has a negative post-yield stiffness equal to one percent of the elastic stiffness. In addition, the strength of the system is assumed to decrease with repeated cycles of equal deformation amplitude, but its hysteretic response becomes stable after approximately three cycles as shown in the figure. For the system with high degradation (see Figure 1c), a higher rate of strength degradation with displacement amplitude (3 percent of the initial stiffness) and with loading cycles were assumed.



(a) nondegrading (b) moderate degradation (c) high degradation

Figure 1: Hysteretic response characteristics of the degrading systems studied.

GROUND MOTIONS

Table 1 shows the main characteristics of the records studied. The Erzincan, Kobe-JMA, Takatori and Los Gatos records correspond to the component perpendicular to the fault derived from the original recordings. The Lucerne record corresponds to the original N90E component. Also shown in Table 1 is the characteristic period of the ground motions, T_g. This period was calculated for all, but the Lucerne record, as that corresponding to the peak of the input energy spectrum of a 5 percent damped linear elastic system. For the Lucerne record, T_g thus defined resulted in a value of 0.08 seconds, which is well below the practical range of interest. Thus, it was decided to define T_g based on the second largest peak, which resulted in the value reported in the Table.

In Figure 2, the 5 percent damping, elastic response spectra for each record and the design spectra constructed according to the 1997 NEHRP provisions (BSSC, 1997) are compared. The last were constructed for a rock site in a region where the spectral accelerations were maxima at 0.2 seconds, in accordance with the provisions. It can be seen that the components for the Kobe, Takatori and Los Gatos motions have both spectral acceleration and displacement ordinates considerably higher than the design values over a wide range of periods. The spectral values for the Erzincan record are not as high, but they are larger than the design values for periods between one and 3 seconds. The Lucerne component resulted in spectral ordinates lower than those of the design spectrum in the period range of practical interest.

Table 1. Ground motions selected for study

Earthquake	Station and Component	Epicentral Distance (Km)	P.G.A. (g)	T_g (sec)
March 13, 1992 Turkey Earthquake	Erzincan (Fault Normal)	6.7	0.432	2.08
January 17, 1995 Hyogo-Ken Nambu Earthquake, Japan	Kobe–JMA (Fault - Normal)	3.4	1.088	0.92
	Takatori (Fault Normal)	4.3	0.786	1.22
June 28, 1992 Landers Earthquake, U.S.A.	Lucerne N90E	*	0.864	1.58
October 17, 1989 Loma Prieta Earthquake, U.S.A.	Los Gatos (Fault Normal)	3.5	0.718	0.76

* Not available

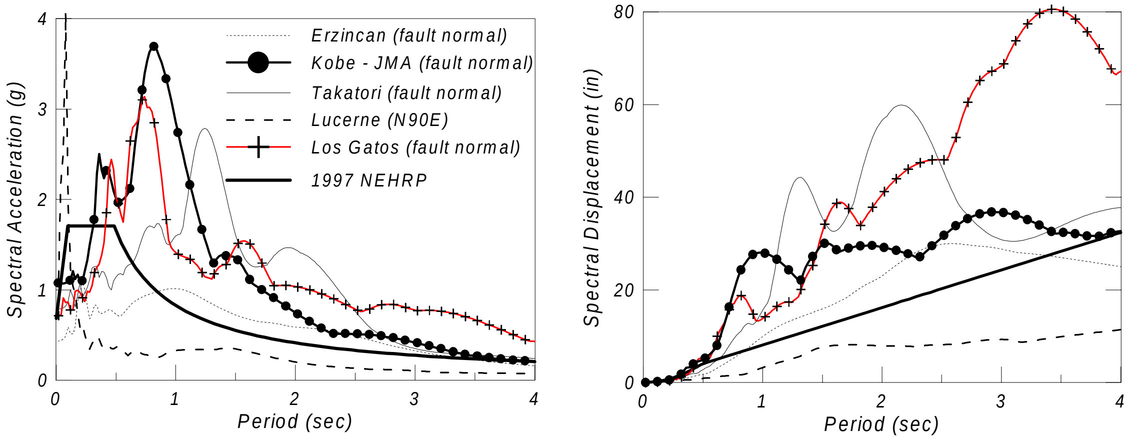
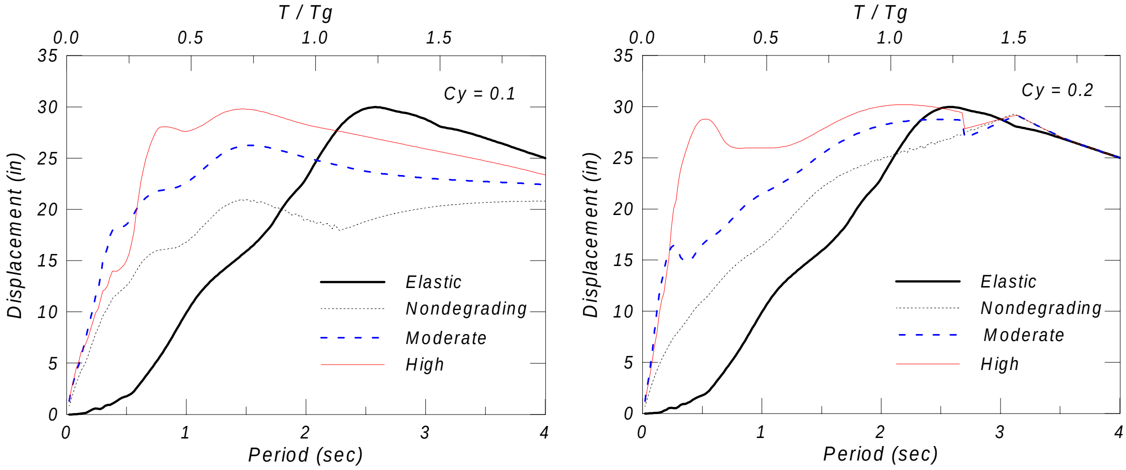


Figure 2 Comparison of elastic response spectra of ground motions studied with the design spectra according to the 1997 NEHRP provisions.

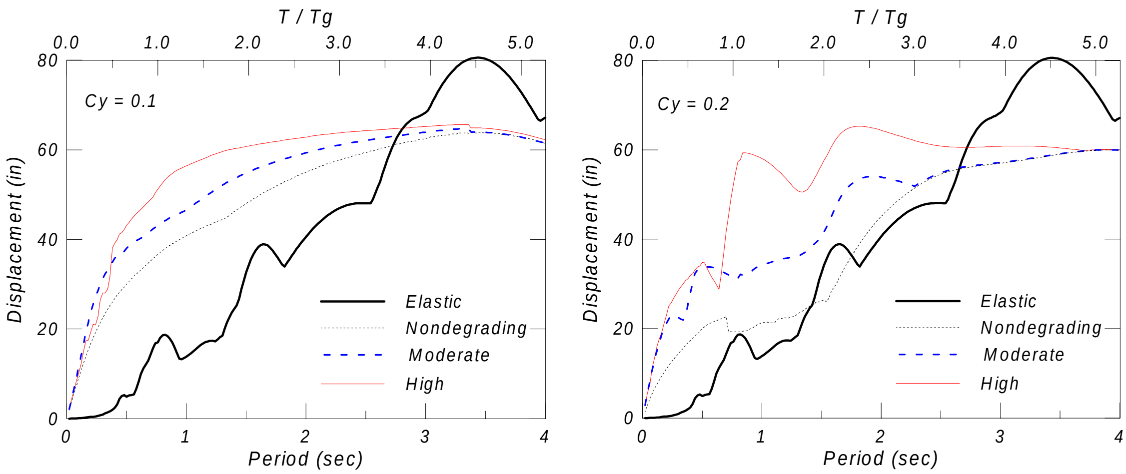
CALCULATED DISPLACEMENT RESPONSE

Response spectra were computed for each of the ground motions presented in Table 1 using the hysteresis models shown earlier in Figure 1. The spectra were computed for a 5 percent viscous damping using strength coefficients C_y (yield strength divided by the weight of the oscillator) of 0.05, 0.1, 0.2 and 0.4.

The displacement response spectra for Erzincan and Los Gatos are compared for oscillators with strength coefficients of 0.1 and 0.2 in Figure 3. The corresponding displacement amplification factor, DAF, e.g., the ratio between the inelastic and the elastic displacements is shown in Figure 4. These records yielded the largest displacement amplification factors, while the Los Gatos component resulted in the largest spectral displacements. It can be seen that the inelastic displacements of the degrading oscillators tend to be larger than those of the nondegrading system. This additional amplification varies with the period and the strength of the system, but it tends to be larger as the degrading characteristics of the system become more severe. These results are consistent with those obtained in previous studies [Al-Sulaimani and Roessett, 1984; Rahnam and Krawinkler 1993, Gupta and Kunnath, 1998].



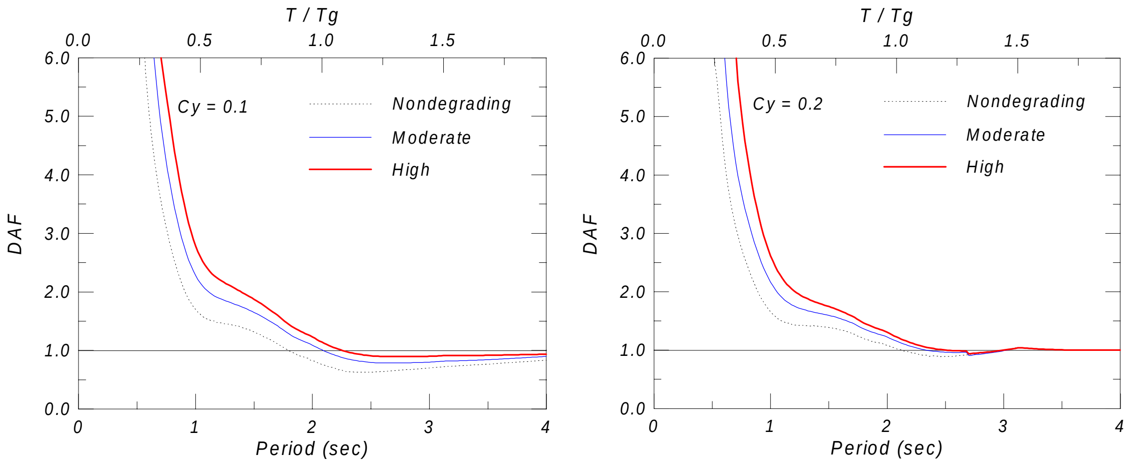
a) Erzincan



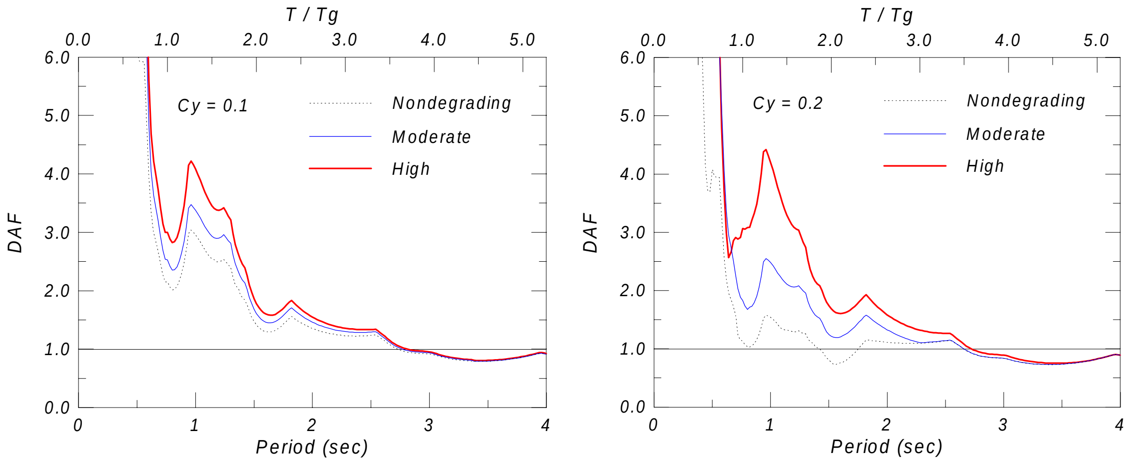
b) Los Gatos

Figure 3: Displacement response spectra: a) Erzincan and b) Los Gatos.

It may be noted that for periods greater than the characteristic period of the ground motion, T_g, the elastic spectrum provides an upper bound of the inelastic displacements computed for the nondegrading system subjected to Erzincan. Similar results have been found in past studies on bi-linear and stiffness degrading hysteresis models [Shimazaki and Sozen, 1985; Qi and Moehle, 1991]. The data for Erzincan (and also for the Takatori and Lucerne records) suggest that degrading systems follow similar trends. For the Los Gatos record, however, inelastic displacements larger than the elastic can be observed for T/T_g ratios as large as 3.5 for a strength coefficient of 0.1, irrespective of the degrading characteristics of the systems (see Figures 3 and 4). For a strength coefficient of 0.2, the inelastic displacements of the nondegrading system are comparable, but tend to be larger than the elastic for periods greater than T_g. The displacement of the degrading systems significantly exceed the elastic displacements for the same period range and strength coefficient. A reason for this result can be found in the shape of the input energy spectrum and the definition of T_g [Qi and Moehle, 1991]. As mentioned earlier, the characteristic period was chosen as that corresponding to the peak of the input energy spectrum. It was observed, however, that the energy spectrum for the Los Gatos record contained three peaks of similar amplitude at approximately 0.72 seconds (the chosen value of T_g), 1.7 and 2.9 seconds. As the system yields, its effective period elongates into the region of the second and third peaks of the energy spectrum which can result in inelastic displacements larger than the elastic. This result has important implications in the calculation of spectral displacements for inelastic systems, particularly for older structures which are often weak in comparison to modern construction. The data obtained for Los Gatos has also been observed for other ground motions, and show that T_g (as defined here) does not represent the limit where inelastic displacements are bounded by the elastic spectrum for these types of ground motions. Additional correlation studies between the definition of T_g and the corresponding input energy spectrum are needed, if T_g is to be used as such limit for ground motions of this nature.



a) Erzincan



c) Los Gatos

Figure 4: Displacement amplification factors: a) Erzincan and b) Los Gatos.

It must be noted that the intensity of these near-fault motions was generally quite high and resulted in very large spectral displacements. In Figure 5, the calculated response for an oscillator with initial period of one second and moderate decay characteristics subjected to Los Gatos is compared for strength coefficients of 0.1, 0.2 and 0.4. For the weakest system (C_y = 0.1), the inelastic displacements are so large that the oscillator exhibited nearly total loss of strength and would collapse by the end of the record. Even for a strength coefficient of 0.2, not an uncommon value found in older construction, the maximum displacements are very large and the strength loss is significant. Only when the strength coefficient is increased to 0.4, the displacements are reduced to levels that might be tolerable, although significant strength loss can be expected. These results show how damaging this type of motion can be and further emphasize the need to reliably estimate the displacement demands to prevent severe damage or collapse of degrading systems.

As noted earlier, the degrading systems tended to develop inelastic displacements larger than those of a nondegrading oscillator with the same initial period and strength. In the following, the effect of the degrading characteristics on inelastic displacements will be evaluated by comparing the displacement ratio obtained for the degrading systems and those without degradation, or the degrading–to–nondegrading displacement amplification

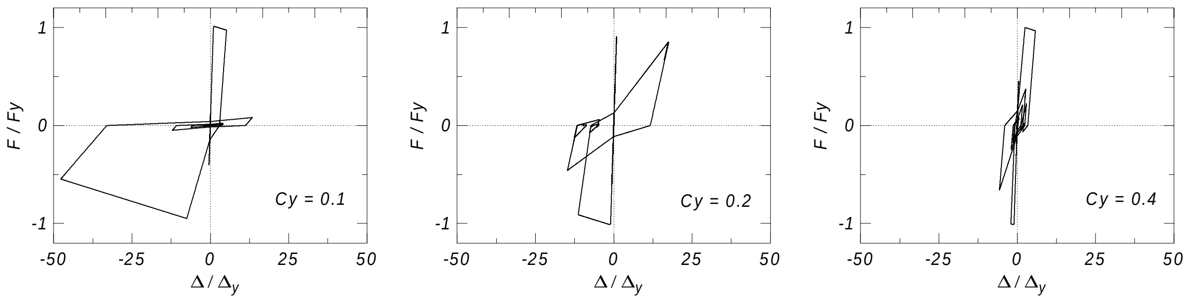
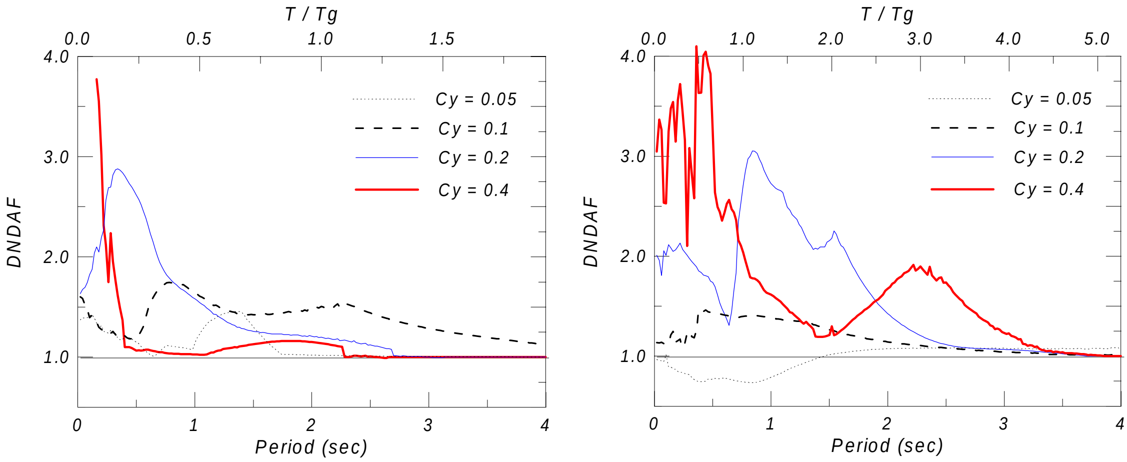


Figure 5: Hysteretic response for an oscillator of moderate decay characteristics and different strength coefficients subjected to the Los Gatos record (T = 1 second).

factor, DNDAF. In Figure 6, the DNDAFs calculated for oscillators with high degradation characteristics (Figure 1c) subjected to the Erzincan and Los Gatos motions are compared for different strength coefficients. The data show scatter, but generally, the factors tend to be larger for short period systems. In addition, the maximum amplification factors are observed for short period systems with high strength levels.

It may also be noted that the maximum values of the amplification factors obtained for these two motions are comparable in magnitude, even though the maximum inelastic displacements computed were significantly different (see Figure 3). The amplification reaches peak values of about four at short periods and are close to unity at long periods. The peak values for the other records were similar in magnitude or smaller.

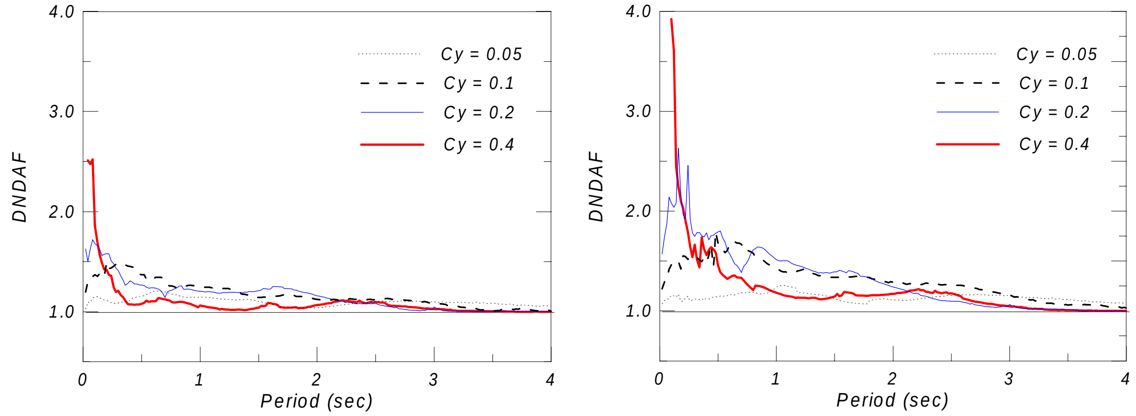


a) Erzincan

b) Los Gatos

Figure 6: Degrading–to–nondegrading displacement amplification factors (DNDAF) for systems with high degradation subjected to the Erzincan and Los Gatos records.

The average DNDAFs for the five records considered in this study are shown in Figure 7. In the figure, the factors have been grouped according to the degrading characteristics of the system. It can be seen that, on average, the factors obtained for systems with high degrading characteristics tend to be higher than those of systems with moderate decay levels, but by a small margin. Also, as observed for the individual motions, the average factors are larger at short periods and are close to unity at long periods. Peak values of the average factors of two or less are obtained for periods within the practical range of interest (at very short periods they are larger) which are smaller than those observed for the individual motions. The significant discrepancy between the average values and those obtained for the individual motions reflect the scatter of the data. Cleary, additional motions should be included to obtain better estimates of mean response values.



a) Moderate b) High

Figure 7: Average degrading–to–nondegrading displacement amplification factors (DNDAF) for systems with moderate and high degradation characteristics.

The results presented above are consistent with a parallel study conducted by the authors on twelve far-field records on both firm and soft soils. The amplification factors obtained here are comparable to those found in that study, despite that the spectral displacements of the near-fault records considered here were much higher. These findings suggest that the additional amplification observed for degrading system is not significantly influenced by the characteristics of the ground motion. Rather, the strength and degrading characteristics of the system are more important.

SUMMARY AND CONCLUSIONS

The effect of near-fault ground motions on the inelastic displacement demands of stiffness and strength degrading systems was studied. The results show that the maximum inelastic displacements of degrading systems tend to be larger than those of a nondegrading oscillator with the same initial period and strength. The additional displacement amplification depends on the period, strength and degrading characteristics of the systems, but tends to be larger at short periods. Peak amplification values as high as four were obtained at periods below one second for some records, with average amplification factors of two. At long periods, the factors tend to be close to unity.

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