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EVALUATION OF DRIFT DEMAND ON THE BASIS OF NONLINEAR RESPONSE OF BUILDING STRUCTURES LOCATED AT SEISMICALLY ACTIVE REGIONS

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ABSTRACT

This study aims at the assessment of seismic drift response of building structures located in seismically active regions. The displacement-based design approach which correlates observed damage of a structure to its drift ratio constitutes a basis for the research. The ground motion data, recorded during Marmara Earthquake (August 17th., 1999) and Duzce Earthquake (November 12th., 1999) in Turkey, are used. In general, it is observed that the increase in base shear strength coefficient, C_y decreases the nonlinear displacement demand for single-degree-of-freedom (SDOF) systems. The same ground motion data are applied for a representative building in Turkey which is modeled as a regular reinforced concrete frame. The corresponding building acts as a multi-degree-of-freedom (MDOF) system. The nonlinear response of a selected frame under the ground motion data is investigated. It is examined that the nonlinear displacement response of the selected building frame increased, when the intensity of the maximum ground velocity increment, ΔV_{max} increased. The main emphasis of this study is to find a solution within the physical characteristics of the building structures in order to control excessive drift demands which are observed at high levels of ground velocity, V. The effects of base shear strength, C_y; initial period of the structure, T; characteristic period of ground motion, T_g and structural damping ratio are investigated. It is observed that in order to avoid excessive nonlinear displacement demands, an increase in base shear strength, C_y is beneficial to improve the performance of the building.

Keywords: drift demand, nonlinear response, ground velocity change, ground velocity, base shear strength

INTRODUCTION

The assessment of seismic drift response of building structures located in seismically active regions is considered in this study. For this purpose, ground motion data obtained from recording stations located in a seismically active region in Turkey will be used. The concept of ground velocity increment, ΔV and its effects on the nonlinear displacement response of building structures will be investigated in the light of the displacement-based design approach which correlates observed damage of a structure to its drift ratio.

The ground motion records presented in this paper were recorded at Izmit recording station during the Marmara Earthquake (August 17th, 1999) and at Duzce recording station during the Duzce Earthquake (November 12th, 1999). The nonlinear displacement response of single-degree-of-freedom (SDOF) systems will be calculated for different values of base shear strength coefficient, C_y and initial period, T. Nonlinear displacement responses of a SDOF system with periods ranging from 0.1 sec to 2.0 sec

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for base shear strength coefficients, C_y of 10% - 20 % - 30 % are calculated for both Degrading-Stiffness and Elasto-Plastic models shown in Figure 1. A viscous damping of 2% of critical damping is assumed.

The nonlinear displacement demand is compared with the linear displacement response spectra developed by Lepage (Lepage, 1997) who considered ground motions with low (less than 0.75m/sec) ground velocities. In this paper the nonlinear displacement response spectra for NS Component of Duzce Record (November 12th, 1999), where the value of $\triangle V$ exceeds the threshold level of 0.75 m/s, is examined. It is observed that large nonlinear displacements develop for periods less than T_g especially for low base shear strength coefficient values, C_y (Figure 11). A nonlinear displacement spectrum model is introduced based on the concept of maximum ground velocity increment ($\triangle V_{max}$) which is the absolute value of the change in velocity between two consecutive velocity maxima of different signs.

Nonlinear behavior of representative buildings in Turkey which are modeled as MDOF (multi-degree-of-freedom) systems has been investigated for ground motions recorded during recent earthquakes in Turkey (Ozturk, 2003). A sample building plan (BLDG), which provides an insight to the building stock in Turkey, is provided below (Figure 2). It has to be emphasized that the analyzed building (BLDG) is proportioned with respect to the base shear strength coefficient, C_y and the initial period, T.

The dynamic analysis results and the nonlinear behavior of a representative frame (FRAME) of five-story building modeled as MDOF (multi-degree-of-freedom) system will be demonstrated. The representative frame is aligned in the EW direction (Figure 2). It has a base shear strength coefficient, C_y value of 0.11. It is analyzed for the ground motions which are given in Table 1. The floor plan of the reinforced concrete frame building is given in Figure 2. Typical story height is three meters for the building (BLDG). The unit weight of the building is taken as 800 kg/m^2 (approx. 8kN/m^2) which is common in Turkey. The analyses were conducted using both static and dynamic versions of LARZ program (Saiidi, 1979a and 1979b; Lopez, 1988). The static version was used to define the base shear strength coefficient, C_y of the model frame while the dynamic version of the program helps to define the nonlinear response of the frame and its response histories during the ground motion.

Two response-history analyses are provided below corresponding to two acceleration records provided in Figures 3 and 4. The introduced ground motions are NS component of Izmit Record (August 17th, 1999; Marmara Earthquake) and NS component of Duzce Record (November 12th, 1999; Duzce Earthquake), respectively. The nonlinear displacement response histories of the investigated frame (FRAME) under these ground motions are given in Figures 5 and 6 and; large nonlinear displacements are observed for ground motion with large values of ground velocity increment, $\triangle V$.

DEFINITION OF GROUND VELOCITY INCREMENT AND INVESTIGATION OF ITS EFFECT ON THE OBSERVED NONLINEAR DISPLACEMENT RESPONSE

The acceleration-time history and the calculated velocity history for NS component of Duzce record of November 12th, 1999 are shown in Figures 4 and 7, respectively. The quantity $\triangle V_{max}$ is calculated as the largest difference obtained by integration between maximum and minimum velocity values. The maximum values of $\triangle V_{max}$ are given in Table 1.

In the nonlinear displacement response spectra for NS component of Duzce Record (November 12th., 1999) used in this study (Figure 11), it is observed that the maximum displacement demand of a SDOF system and the damage potential of the ground motion increase especially for periods less than

T_g. It is observed that for ground motion records with comparatively higher values of $\triangle V$, there is an increasing requirement for the base shear strength of a SDOF system, if response is to remain within the bound given by Lepage (Lepage, 1997).

The idealized displacement response spectrum, S_d (i.e. Figure 11) is obtained using:

$$S_d = \frac{F_a.\alpha.g.T^2}{(2\pi)^2} \quad \text{for } T<T_g \tag{1}$$

$$S_d = \frac{F_a.\alpha.g.T_g}{(2\pi)^2}.T \quad \text{for } T\geq T_g \tag{2}$$

where:

F_a : acceleration amplification factor (a value of 3.75 for systems with 2% damping factor is representative of a wide range of ground motions);
g : acceleration of gravity;
α : peak ground acceleration expressed as a coefficient of the acceleration of gravity;
T_g : characteristic period for ground motion, it may be defined as the period at which the assumed constant acceleration region ends;
T : period of vibration

Equations 1 and 2 reflect regions of nearly constant acceleration (for $T< T_g$) and nearly constant velocity (for $T> T_g$). These generalizations relate to observations made by Newmark (Newmark, 1970).

The characteristic period for ground motion, T_g is the period where the energy response spectrum, for a damping factor of 10%, tends to level off. The characteristic period, T_g, closely corresponds to the period where the nearly constant velocity response region starts.

According to Lepage (Lepage, 1997), nonlinear-response displacement, D_{max} may be estimated from a linear-response spectrum using:

$$D_{\max} = \frac{F_a.\alpha.g.T_g}{(2\pi)^2}.T \tag{3}$$

Equations 1 -3, which provide idealized nonlinear-response maxima, are based primarily on response spectrum determined for a viscous damping of 2% of the critical. They emphasize that for a given earthquake intensity and frequency content, the period of the system is the most significant parameter. The straight line for the idealized displacement response spectrum in the linear displacement response spectra (i.e. Figure 11) is extended to the origin for $T<T_g$. In order to evaluate the envelope of the nonlinear displacement spectra maximum from the linear displacement spectra, the slope of the line is multiplied by $\sqrt{2}$. For reinforced concrete systems T_{eff} may be defined as $\sqrt{2}$ times the period that corresponds to uncracked member section properties. The formula is given as below in Equation 4.

$$T_{eff} = T\sqrt{2} \tag{4}$$

For an idealized nonlinear-response spectra of a system in general (Lepage, 1997):

$$D_{\max} = k.T_{eff} \tag{5}$$

where, k : slope of straight line,
T_{eff} : effective structural period of the system

The values of k for the investigated ground motion records are provided in Table 1.

NONLINEAR MODELS USED IN ANALYSES AND THE CORRESPONDING NONLINEAR DISPLACEMENT RESPONSE SPECTRA

Two hysteresis models are used to characterize nonlinear response: the Degrading-Stiffness model, and the Elasto-Plastic model which are shown in Figure 1.

The Elasto-Plastic (a version of the Bilinear model) model is characterized by two parameters. They are the initial stiffness K_y, and the yield strength V_y. This model, although not representative of the actual response for most structures, is very useful as a frame of reference since it has been used extensively in previous studies and, it represents a reasonable upper bound for energy dissipation.

The Degrading-Stiffness model used in this study is characterized by four parameters. In addition to two parameters used in the Elasto-Plastic model, it requires additional parameters to define the secondary stiffness, K_u, and the unloading stiffness-reduction parameter ψ. The model can be considered as a simplification of the Takeda model (Takeda, Sozen and Nielsen, 1970), and it is based on the "Modified Clough Model" described by Otani (Otani, 1981). The stiffness during unloading and subsequent reloading, is equal to K_r, and is given by:

$$K_r = K_y \left(\frac{D_y}{D_{\max}} \right)^{\psi} \tag{6}$$

where, K_y : initial stiffness;
D_y : yielding displacement;
D_{max} : previously attained maximum displacement in the direction concerned;
ψ : unloading stiffness-reduction parameter.

The value of the parameter ψ controls the capacity of the idealized hysteresis loops to dissipate energy. Its values may range from 0.2 to 0.6. A value of 0.4 was initially proposed (Takeda, Sozen and Nielsen, 1970). A damping coefficient of 2% of critical damping is applied during the nonlinear analysis. The damping coefficient was assumed to be unchanged during the entire analysis. The corresponding sample nonlinear time histories are given in Figures 8 - 10 for NS component of Duzce record of November 12th, 1999 (for C_y values of 10%, 20% and 30%).

Nonlinear displacement response spectra are given in Figure 11 for NS component of Duzce record of November 12th, 1999. They are calculated for base shear strength coefficients, C_y of 10% - 20% and 30%. The definition of base shear, C_y is given below:

$$C_y = \frac{ShearStrength}{Weight} = \frac{V}{W} \tag{7}$$

The period range applied is T=0.1 – 2.0 sec for the nonlinear displacement spectra. It is observed that for low values of C_y , an excessive nonlinear displacement demand develops for NS Component of Duzce Record of November 12th, 1999 (Figures 8 – 10). The high displacement demand emphasizes the destruction potential of the seismic wave for certain combinations of building properties. In Figure 11 lines are drawn using Equation 8 which is developed in order to provide an upper bound to determine nonlinear displacement, Δ_m values (Ozturk, 2003):

$$\Delta_m = \frac{V_{ground}^{\ 2}}{\pi \beta g}(1+T) \tag{8}$$

where, V_{ground} : maximum ground velocity,

β : coefficient used to define base shear strength as a function of weight,

T : initial period of the structure

DESCRIPTION OF SAMPLE BUILDING AND ANALYSES OF THE SELECTED FRAME

The properties of the reinforced concrete five-story building (BLDG) is described below. It is proportioned considering the effects of variation of base shear strength coefficient, C_y and initial period, T. Identification of the investigated frame (FRAME) is given in Table 2.

The floor plan of the building (BLDG) is presented in Figure 2. The investigated reinforced concrete frame (FRAME), which is aligned in the EW direction, was proportioned to have base shear strength coefficient, C_y value of 0.11 (for a linear mode shape). The yield strength of steel, f_y is 220 MPa, and the concrete strength, f'_c is 16 MPa. The maximum nonlinear displacement response values and general information about the frame described above are given in Table 2. The total weight of the building is 15360 kN. The spans of the frame are four meters in length. The initial calculated period, T of the frame is 0.57 sec. As tabulated in Table 2, the investigated frame (FRAME) has a longitudinal column reinforcement ratio, ρ_{column} value of 1% and its beams have longitudinal reinforcement ratio, ρ_{beam} of 1.5 %. The columns have a dimension of 550mm by 550mm and; the beams have a width of 250mm and a depth of 400mm.

Static analysis was applied in order to evaluate the base shear strength coefficient, C_y of the five-story building frame (FRAME) defined above. The static version of the program LARZ (Saiidi, 1979a and 1979b; Lopez, 1988) was used. The base shear strength coefficient value, C_y will provide very valuable information with the initial period, T of the building, in order to assess the nonlinear behavior of the building. It is known that these two parameters are correlated with the maximum nonlinear displacement response of building structures (Shibata and Sozen, 1976; Shimazaki and Sozen, 1984; Lepage, 1997; Ozturk, 2003).

Dynamic version of the program LARZ (Saiidi, 1979a and 1979b; Lopez, 1988) is used in order to obtain the nonlinear displacement histories of the frame. A simplified version of Takeda model (Takeda, Sozen and Nielsen, 1970) is used to define the nonlinear behavior of reinforced concrete structures. The nonlinear displacement response histories are given in Figures 5 and 6 for the selected ground motion records provided in Table 1.

The effects of ground velocity increment, ΔV on the reinforced concrete frame (FRAME) can be traced in the nonlinear displacement histories (Figures 5 and 6). In Figure 6; it is observed that comparatively large nonlinear displacements are observed following the ground velocity increment patterns in the NS component of Duzce Record (November 12th, 1999, Duzce Earthquake).

RESULTS AND CONCLUSIONS

The concept of ground velocity increment, ΔV which is observed mainly in seismically active and near-fault regions is investigated in this study. The nonlinear behavior of a SDOF system under NS Component of Duzce Record (November 12th, 1999, Duzce Earthquake) is provided in Figures 8 – 10. It is observed that for a ground motion with a large intensity of the ground velocity increment, ΔV ; the nonlinear displacement demand of the single-degree-of-freedom system with a low value of base shear strength coefficient, C_y exceeds the displacement spectrum proposed by Lepage (Lepage, 1997) in the region where $\frac{T}{T_g} < 1.0$ and $\Delta V > 0.75$ m/s.

where, T : structural period in sec
T_g : characteristic period for ground motion
ΔV : ground velocity increment

Accordingly, Equation 8 developed for estimation of the maximum nonlinear displacement, Δ_m in the region where $\frac{T}{T_g} < 1.0$ and $\Delta V > 0.75$ m/s is proposed (Ozturk 2003).

In addition, this study aims at providing an insight to the characteristics and the behavior of building structures located in seismically active regions in Turkey. A reinforced concrete frame (FRAME) of a sample building (BLDG) is investigated (Figure 2). The selected frame has a base shear strength coefficient, C_y value of 0.11. Two ground motion records, which are NS Component of Izmit Record for Marmara Earthquake (ΔV_{max}=0.35 m/sec) and; NS Component of Duzce Record for Duzce Earthquake (ΔV_{max}=1.0 m/sec), are introduced. The corresponding nonlinear displacement-time histories are provided for FRAME (Figures 5 and 6). It is observed that the nonlinear displacement demand of the investigated building frame (FRAME) increased, when the intensity of the maximum ground velocity increment, ΔV_{max} increased (Figures 5 and 6).

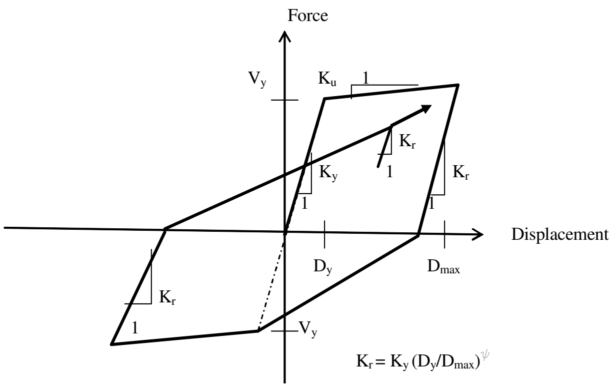
Table 1 Maximum change in ground velocity, ΔV_{max} and; elevated slope, $k\sqrt{2}$ for described ground motions

Name of the earthquake	*Name of ground motion components*	*Maximum Change in Velocity, ΔV_{max} (in m/sec)*	$k\sqrt{2}$ *, elevated slope (in mm)*
Marmara Earthquake	Izmit - NS	0.35	140
Duzce Earthquake	Duzce - NS	1.00	300

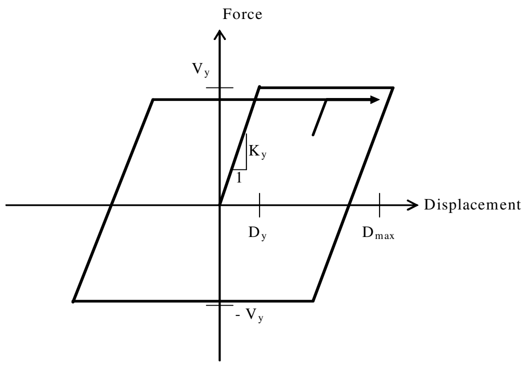
Table 2. Information for Designated Frame in EW direction: FRAME of Building Plan (BLDG)

Designation of the Frame	***FRAME***	
Story Column Height, m Span Length, m	3 4	
Column Information ρ_{column}, %	1 %	
Beam Information ρ_{beam}, %	1.5 %	
From Static Analysis Base Shear Strength Coefficient, C_y in W%	11	
Weight, W in kN	15360	
Period of the Building, T in sec	0.57	
f_y in MPa	220	
f'_c in MPa	16	
Maximum Nonlinear Displacement Response of the Building, in m	Roof Drift, m	Mean Drift Ratio, %
Izmit Record-NS Component Marmara Earthquake (ΔV_{max}=0.35 m/sec)	0.10	0.7
Duzce Record-NS Component Duzce Earthquake (ΔV_{max}=1.0 m/sec)	0.20	1.3

*Unit Weight of BLDG is 800 kg/m^2



Degrading-Stiffness Model



Elasto-Plastic Model

Figure 1 Hysteresis Models Used in this Study

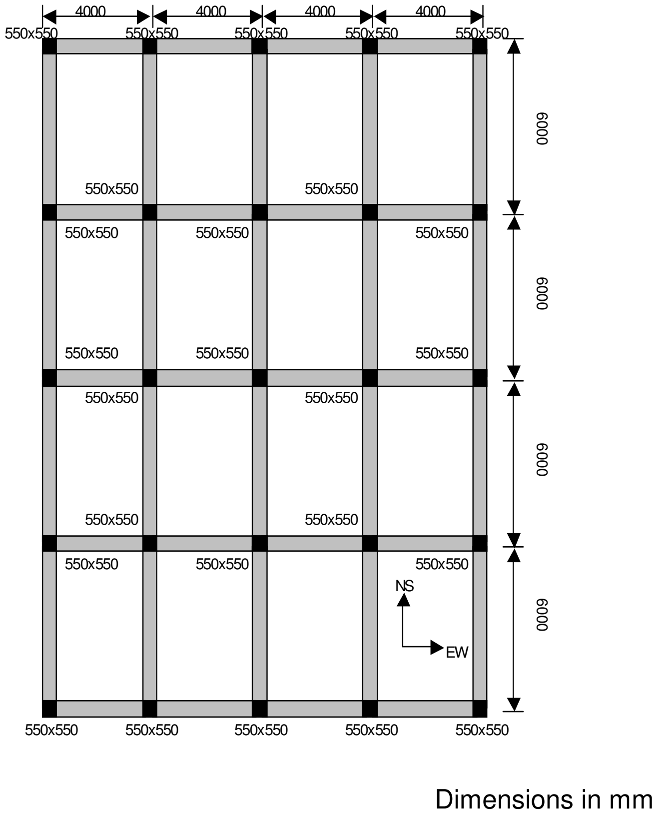


Figure 2 Floor plan of BLDG (the investigated FRAME is located in the EW direction)

Column Dimensions : 550 mm x 550 mm

Beam Dimensions : 250 mm x 400 mm in the EW direction

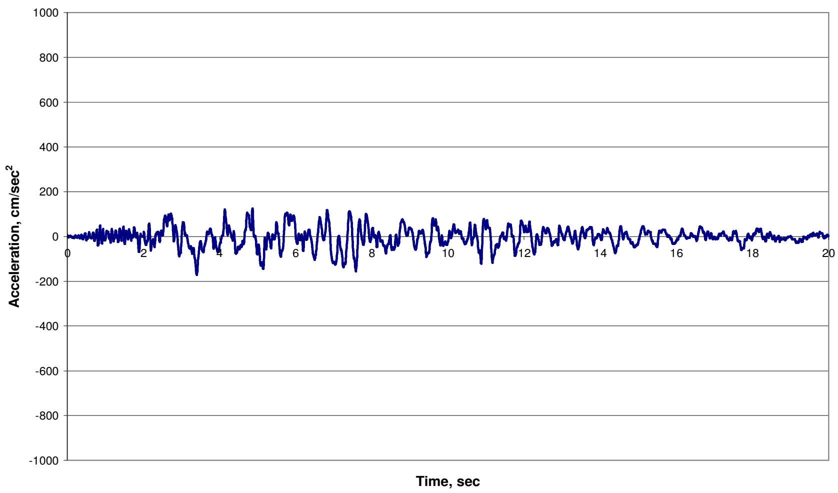


Figure 3 Acceleration-Time History of NS Component of Izmit Record (ΔV_{max}=0.35 m/sec) (Marmara Earthquake, August 17th, 1999)

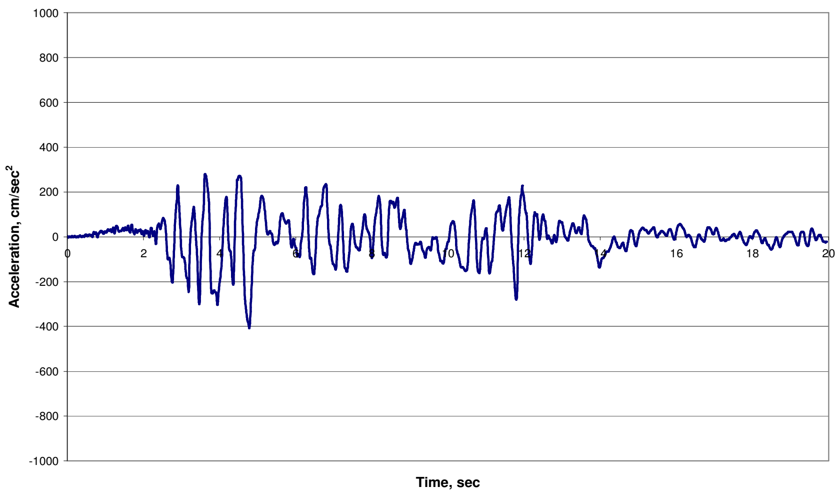


Figure 4 Acceleration-Time History of NS Component of Duzce Record (ΔV_{max}=1.0 m/sec) (Duzce Earthquake, November 12th, 1999)

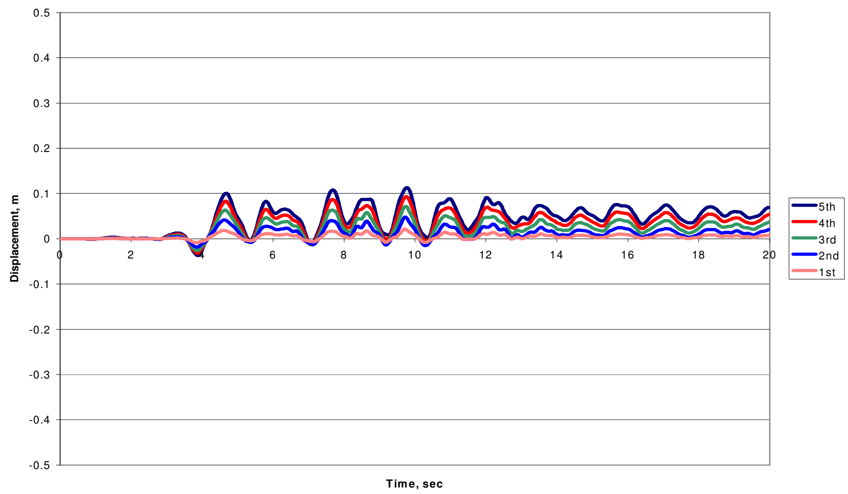


Figure 5 Nonlinear Displacement-Time History of FRAME at each Story (C_y=0.11) (Marmara Earthquake, NS Component of Izmit Record, ΔV_{max}=0.35 m/sec)

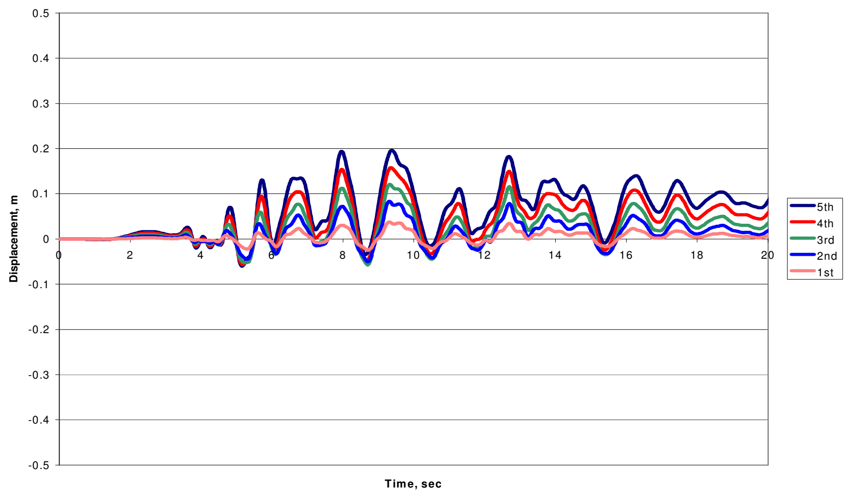


Figure 6 Nonlinear Displacement-Time History of FRAME at each Story (C_y=0.11) (Duzce Earthquake, NS Component of Duzce Record, ΔV_{max}=1.0 m/sec)

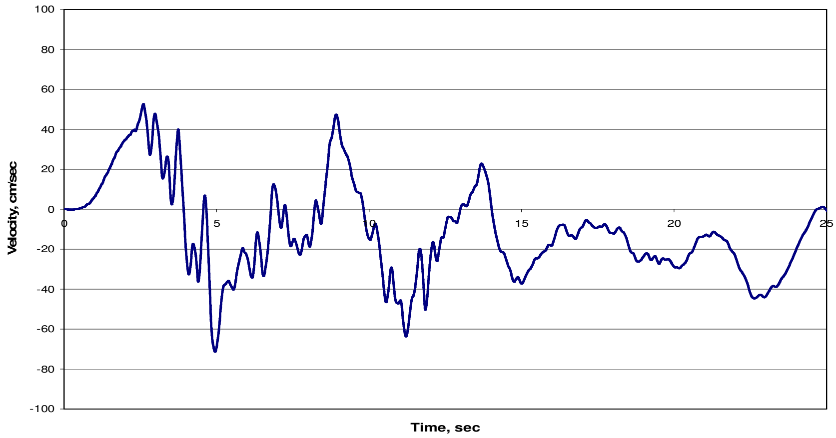


Figure 7 Velocity-Time History of NS Component of Duzce Record (Duzce Earthquake, November 12th, 1999)

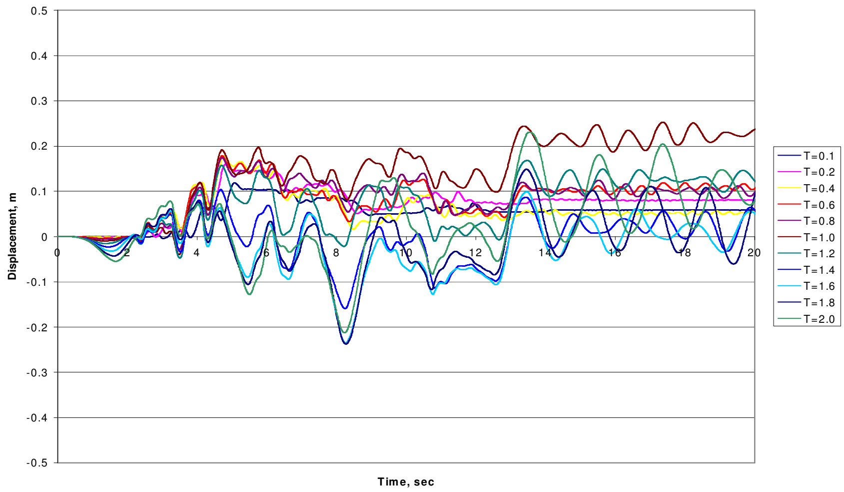


Figure 8 Nonlinear Displacement Histories of a SDOF system for 10% Base shear strength and; *T*= 0.1 - 2.0 sec (NS Component of Duzce Record, Duzce Earthquake, November 12th, 1999)

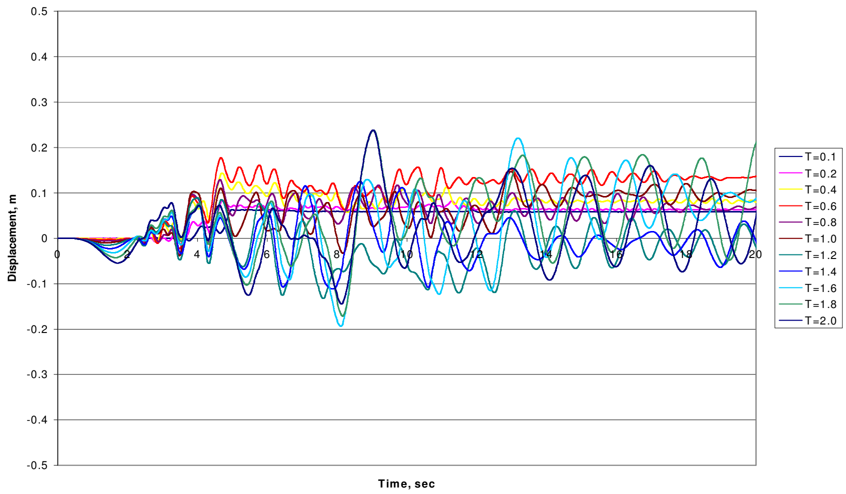


Figure 9 Nonlinear Displacement Histories of a SDOF system for 20% Base shear strength and; *T*= 0.1 - 2.0 sec (NS Component of Duzce Record, Duzce Earthquake, November 12th, 1999)

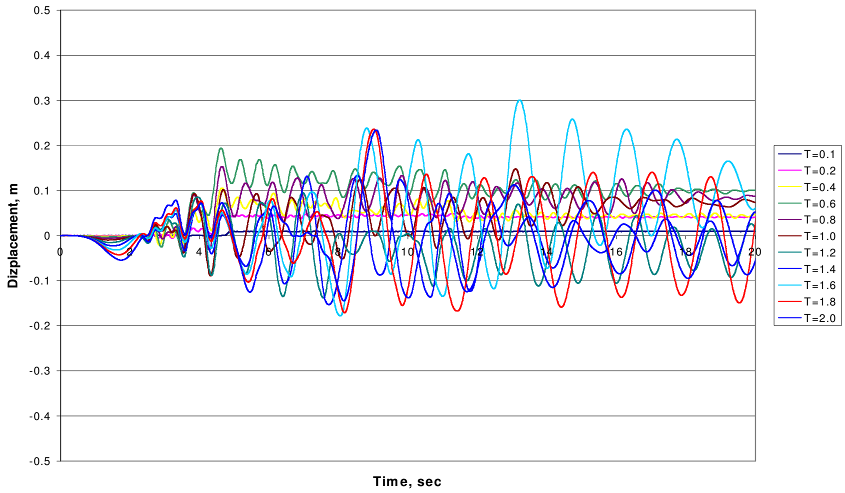


Figure 10 Nonlinear Displacement Histories of a SDOF system for 30% Base shear strength and; *T*= 0.1 - 2.0 sec (NS Component of Duzce Record, Duzce Earthquake, November 12th, 1999)

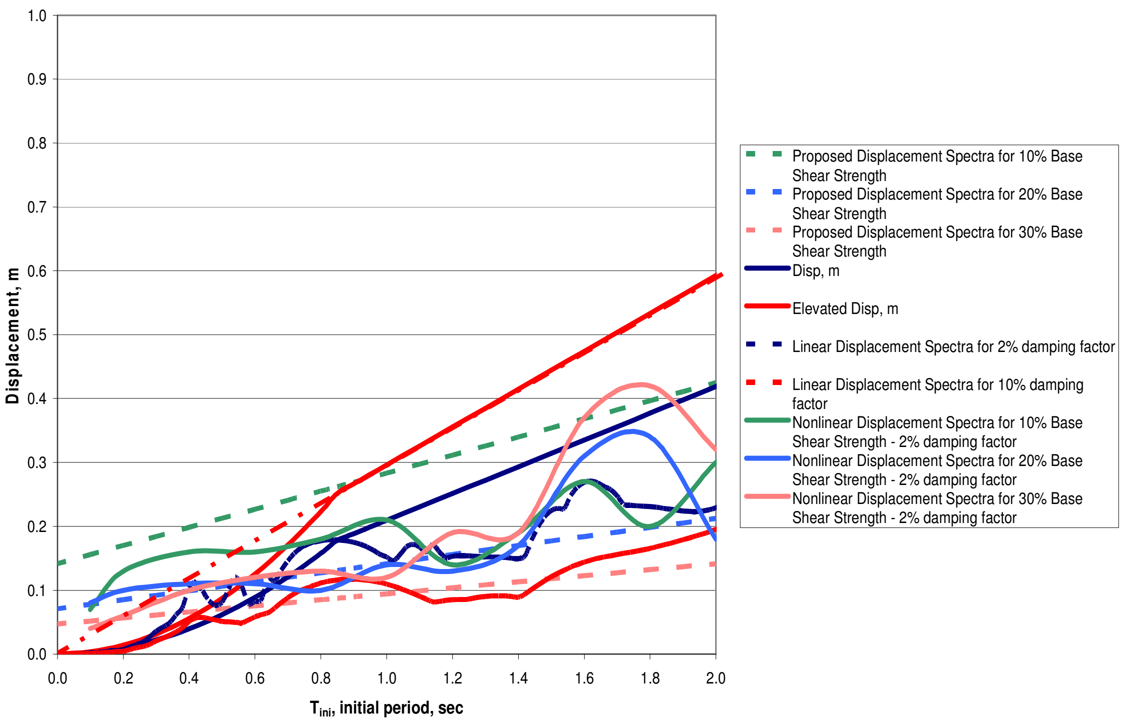


Figure 11 Nonlinear Displacement Spectra for NS Component of Duzce Record (Duzce Earthquake, November 12th, 1999)

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