Response of Sliding Structure with Restoring Force Device to Earthquake Support Motion

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ABSTRACT: *Seismic performance of a symmetrical space frame structure resting on sliding bearing with restoring force device is studied considering all the six degrees of freedom. The sliding support is modeled as a fictitious spring with two horizontal degrees of freedom. In non-sliding phase the horizontal stiffness of sliding bearing is considered as very large whereas it is equal to zero during sliding phase. The El Centro, Turkey and Mexico earthquakes are adopted as the input motion. The response quantities obtained from the analysis are the acceleration, base shear, bending moment and displacement. In this study, the response of the isolated structure is compared with the response of the structure fixed at the base. Response of the isolation system with restoring force device is also compared with the response of the isolation system without restoring force device. In addition, the effects of coefficient of friction of sliding material, time period of the superstructure and the number of storeys on response of structure are also investigated. It is concluded from the study that the sliding bearing with restoring force device reduces the earthquake response of the structure. The restoring force device reduces the sliding and residual displacements without transmitting additional forces into the structure. Response of the isolated structure varies with the coefficient of friction of sliding material, time period of superstructure and number of storeys. Also, there exists an optimum coefficient of friction of sliding material for acceleration, base shear and bending moment at which acceleration, base shear and bending moment attains a minimum value.*

Keywords: Sliding structures; Base isolation; Seismic performance; Restore force

1. Introduction

Base isolation is widely used as an aseismic design measure to protect the structures from possible severe damage during destructive earthquakes. The main concept in base isolation is to shift the fundamental frequency of structural system from the predominant energy content of the earthquake ground motion. This is generally achieved by introducing a flexible layer (or isolator) between the superstructure and the foundation. A great number of base isolation systems has been proposed to study their effectiveness. An extensive review of the base isolation for structures was provided by Buckle and Mayes [1]. Isolation devices are essentially classified into two types - rubber bearing and sliding bearing. Although rubber bearing has been used extensively in base isolation systems, sliding bearing has recently found increasing applications. The most attractive feature of the sliding bearing is its effectiveness for a wide range of frequency of the excitation. The simplest sliding bearing is the pure friction type referred to as *P-F* system. In this system, rollers or sliders are provided between the foundation and base of the structure. The shear force transmitted to the structure across the isolation interface is limited by keeping the coefficient of friction as low as practical. This results in large sliding and residual displacements, which may be difficult to incorporate in structural design. The practical effectiveness of sliding bearings can be enhanced by adding suitable restoring mechanism to reduce the displacements to manageable levels. Several systems have been suggested by Chalhoub and Kelly [3], Bhasker and Jangid [2] and Zayas et al [11] to accommodate restoring mechanism in a structure isolated by sliding systems. They are in the form of high-tension springs, laminated rubber bearings or by using friction pendulum systems which provides restoring mechanism by gravity. The sliding systems perform very well under a variety of severe earthquakes and are quite effective in reducing high superstructure acceleration without inducing large base displacement. Because the non-sliding and sliding phases exist alternatively, the dynamic behaviour of a sliding structure is highly nonlinear. Mostaghel and Tanbakuchi [7] developed a mathematical model for a single degree of freedom (*DOF*) structure to study the effectiveness of sliding support in isolated structures. Yang et al [10] studied the response of the multi *DOF* structures on sliding supports using fictitious spring to the foundation floor. The spring was assumed to be bilinear with a very large stiffness in the non-sliding phase and zero stiffness in the sliding phase. Jangid and Londhe [4] and Jangid [5] analyzed the structure resting on sliding bearing assuming different equations for non-sliding and sliding phases. Vafai et al [9] analyzed multi *DOF* structure on sliding supports by replacing fictitious spring in the model of Yang et al [10] with a link of rigid perfectly plastic material. In all these analyses the structure was modeled as shear building with only one (horizontal) *DOF* for each floor. Krishnamoorthy and Saumil [6] studied the seismic response of a space frame structure isolated at the base without restoring force device. They considered all the six *DOFs* at each node. In the present study on the seismic performance of space frame structures resting on sliding bearings incorporated with restoring force device all beam and column elements are assumed to be of six - *DOFs* (three translations and three rotations) at each node. The sliding support is modeled by using a fictitious spring beneath each column. Parameter analysis was performed to study the effects of coefficient of friction of sliding material, time period of the superstructure and number of storeys on response of the structure for various values of isolation period of the restoring force device.

1.1. Analytical Modeling

A symmetrical space frame structure resting on sliding type of bearing is shown in Figure (1). F_x, is the mobilized frictional force under the base of each column due to ground acceleration. When the structure is resting on sliding type of bearing like sand with a coefficient of friction equal to μ then the mobilised frictional force, F_x, at base of each column will be resisted by the frictional resistance, F_s. This frictional resistance is equal to the product of the weight on each column, W, and the friction coefficient, μ (i.e. $F_s = \mu W$) and acts opposite to the direction of sliding. When the mobilized frictional force, F_x, at the base is less than the frictional resistance, F_s, (i.e. $|F_x| < F_s$) the structure will not have relative movement at the base and this phase of structure is known as the non-sliding phase. However, when the mobilized frictional force, F_x, is equal to or more than the frictional resistance, F_s, (ie. $|F_x| \geq F_s$) the structure starts sliding at the base and this phase of the structure is known as sliding phase. When the structure is in sliding phase and whenever reverses its direction of motion (when the velocity at the base is equal to zero), then the structure may again stop its movement at the base and enters the non-sliding phase or may slide in opposite direction. In the present study, a fictitious spring is used in order to model the sliding and non-sliding phases. This spring is assumed as fixed at one end and connected to the base of the bottom column at the other end. When the structure is in non-sliding phase, the stiffness of the spring is assigned a very high value so that the structure will not slide relatively to the ground at base whereas when the structure is in sliding phase, stiffness of spring is made equal to zero to allow the sliding of the structure at base. Thus the stiffness of the spring may be equal to zero or very high value depending on the phase of the structure.

1.2. Modeling the Structure, Sliding Bearing and Restoring Force Device

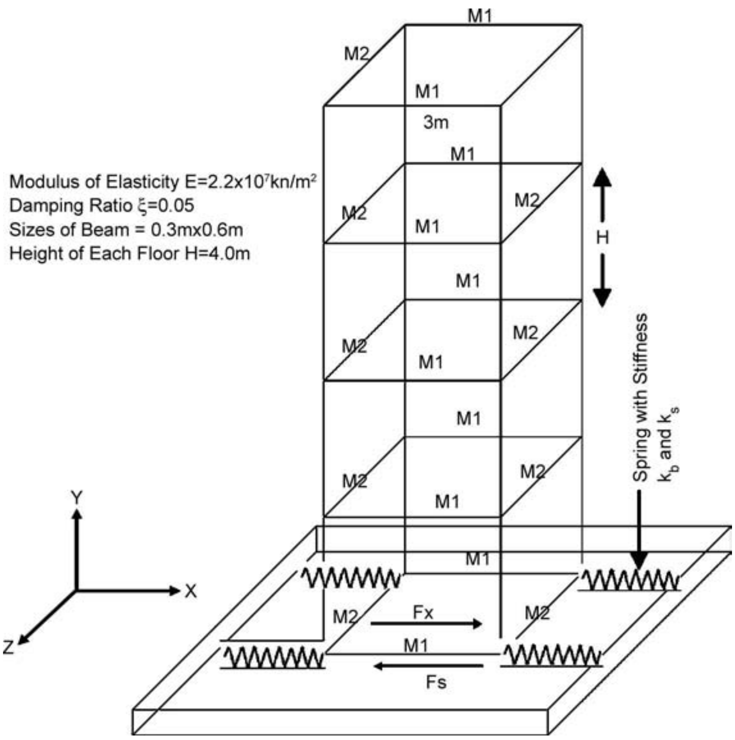
The structure is divided into number of elements consisting of beams and columns connected at nodes. Each element is modeled using two noded frame element with six degrees of freedom at each node i.e., three translations along X, Y and Z axes and three rotations about these axes. For each element, the stiffness matrix $[k]$ and consistent mass matrix $[m]$ in global direction are obtained. The overall mass matrix $[M]$ and stiffness matrix $[K]$ for the entire structure is then obtained by assembling mass matrix $[m]$ and stiffness matrix $[k]$ of each element. The overall dynamic equations of equilibrium for the entire structure as proposed by Paz [8] can be expressed in matrix notations as

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F(t)\} \qquad (1)$$

where [M], [C] and [K] are the overall mass, damping, and stiffness matrices, respectively. The damping of the superstructure is assumed as Rayleigh type and the damping matrix [C] is determined using the equation $[C]=\alpha[M]+\beta[K]$ where α and β are the Rayleigh constants. These constants can be determined if the damping ratio for each mode is known. $\{\ddot{u}\},\{\dot{u}\},\{u\}$ are the vectors of relative acceleration, relative velocity and relative displacement at nodes. $F(t)$ is the nodal load vector. $\{u\}=\{u_1, v_1, w_1, \theta_{x1}, \theta_{y1}, \theta_{z1}, u_2, v_2, w_2, \theta_{x2}, \theta_{y2}, \theta_{z2}, \ldots u_n, v_n, w_n, \theta_{xn}, \theta_{yn}, \theta_{zn}\}$ where n is the number of nodes. The nodal load vector, $F(t)$ is calculated using the equation

$$\{F(t)\}=-[M]\{I\}\ddot{u}_g(t) \qquad (2)$$

Where [M] is the overall mass matrix, {I} is the influence vector, and $\ddot{u}_g(t)$ is the ground acceleration. As already explained, the sliding support is modeled using a fictitious spring with two horizontal *DOF*. These *DOFs* are the translations along *X* and *Z* directions. The spring is attached to the base of the bottom column as shown in Figure (1). The restoring force device may be in the form of high tension springs or laminated rubber bearings. The restoring force device is modeled as a spring with stiffness k_b.



Size of column and load on each beam for various time period

Time Period (sec)			0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Case (1)	Mass (kN.sec^2/m^2)	M1	3	3	3	3	3	3	3	3	3	3
		M2	2	2	2	2	2	2	2	2	2	2
	Column Size (m)	B	1.62	1.05	0.8	0.70	0.60	0.48	0.42	0.38	0.35	0.32
		D	1.62	1.05	0.8	0.70	0.60	0.48	0.42	0.38	0.35	0.32
Case (2)	Mass (kN.sec^2/m^2)	M1	0.03	0.42	1.05	1.82	3.0	4.35	6.0	8.7	10.0	12.0
		M2	0.02	0.28	0.70	1.21	2.0	2.90	4.0	5.8	6.7	8.0
	Column Size (m)	B	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
		D	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6

Size of column and load on each beam for various number of storeys

Number of Storeys	Case (1)				Case (2)				Case (3)			
	Mass (kN.sec^2/m^2)		Size (m)		Mass (kN.sec^2/m^2)		Size (m)		Mass (kN.sec^2/m^2)		Size (m)	
	M1	M2	B	D	M1	M2	B	D	M1	M2	B	D
1	3	2	0.25	0.25	7.5	5.0	0.32	0.32	3	2	0.6	0.6
2	3	2	0.34	0.34	5.0	3.33	0.39	0.39	3	2	0.6	0.6
3	3	2	0.44	0.44	3.75	2.5	0.47	0.47	3	2	0.6	0.6
4	3	2	0.6	0.6	3.0	2.0	0.6	0.6	3	2	0.6	0.6

Figure 1. Four storey symmetrical space frame structure.

This spring is also attached to the base of bottom column as shown in Figure (1). The stiffness of sliding bearing, k_s, and restoring force device, k_b, are added to the stiffness matrix of the structure at corresponding *DOF* to obtain the stiffness matrix of the structure resting on sliding bearing with restoring force device. The isolation period, T_b, is defined as

$$T_b = 2\pi\sqrt{\frac{m_c}{k_b}} \tag{3}$$

where m_c is the mass on each column, k_b is the stiffness of restoring force device, and T_b is the isolation period.

1.3. Sliding and Non-Sliding Phases of the Structure

The structure resting on sliding type of support passes through two types of phases i) non-sliding phase and ii) sliding phase.

1.4. Modeling the Non-Sliding Phase

In the non-sliding phase the frictional resistance, F_s, is greater than the mobilized frictional force, F_x. At the beginning, before the structure starts sliding, the displacement of the structure at the base is equal to the displacement of foundation. Hence, the relative displacement between the base of the structure and the foundation remains constant and is equal to zero. The relative acceleration and relative velocity of the base is also equal to zero. When the structure enters the sliding phase, it slides relatively to the ground. When it again enters the non-sliding phase after sliding to some distance say, u, the relative acceleration and relative velocity again becomes zero, and the relative displacement remains constant and is equal to, u, during this phase. Hence, when the structure is in non-sliding phase, the relative acceleration $(\ddot{u}_b)$ and relative velocity $(\dot{u}_b)$ is equal to zero and the relative displacement (u) at base is constant during this phase. The stiffness of the spring, k_s, at the base of each column is considered as very large ($k_s = 1\text{x}10^{15} kN/m$) during this phase. The dynamic equation of motion for the non-sliding phase is the same as given in Eq. (1). However, [K] is the stiffness matrix of the structure including stiffness of sliding bearing, k_s (k_s being very high value) and stiffness of restoring force device, k_b. [M] is the consistent mass matrix of the whole structure.

1.5. Modeling the Sliding Phase

When the mobilized frictional force, F_x, overcomes the frictional resistance, F_s, the system enters the second phase and starts sliding. The mobilized frictional force, F_x, at base is equal to, F_s, and remains constant during this phase. The stiffness of the sliding bearing, k_s, is considered as zero ($k_s = 0$). The dynamic equations of motion for the structure during this phase is

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F(t)\} - \{F_{xmax}\} \tag{4}$$

Where, $[K]$ is the stiffness matrix of the structure including stiffness of the fictitious spring k_s (k_s being equal to zero) and stiffness of restoring force device, k_b $\{F_{xmax}\}$ is the vector with zeros at all locations except those corresponding to the horizontal *DOF* at the base of the structure. At these degrees of freedom, the vector $\{F_{xmax}\}$ will have values equal to F_s.

1.6. Criteria for Phase Change

The system is in non-sliding phase if the mobilized frictional force at the interface of sliding bearing is less than the frictional resistance (ie. $|F_x| < F_s$). However the system starts sliding as soon as the mobilized frictional force attains the frictional resistance (ie. $|F_x| \geq F_s$). During sliding phase, whenever the relative velocity at the base becomes zero, the phase of the motion is checked to determine whether the system remains in the sliding phase or sticks to the foundation, i.e. when the relative velocity of the base mass is equal to zero and $|F_x| < F_s$, the system enters to non-sliding phase otherwise even if the relative velocity is equal to zero and $|F_x| \geq F_s$, the system remains in sliding phase only.

1.7. Determination of Displacements and Acceleration by Newmark Method

The frictional force mobilized in the sliding system is non-linear function of the system response and hence the response of the isolated structural system is obtained in the incremental form using Newmark's method. In this method, from the response at time t the response at time $t + \Delta t$ is determined. Owing to its unconditional stability, the constant average acceleration scheme (with $\beta = 1/4$ and $\gamma = 1/2$) is adopted.

1.8. Determination of Mobilized Frictional Force and Member Forces

Forces in each member of the structure are obtained using the equation $[k]\{q\}$, where $[k]$ is the element stiffness matrix and $\{q\}$ is the nodal displacement vector of each element. The horizontal force, F_{bc}, at the bottom node of the column in contact with the sliding bearing is the base shear under each column. Similarly the damping force, F_d, at each node can also be obtained using the equation $[C]\{\dot{u}\}$ where $[C]$ is the overall damping matrix and $\{\dot{u}\}$ is the vector of nodal velocity. The mobilized frictional force F_x, under each column when the system is in non-sliding phase, is determined using the equation

$$F_x = F_{bc} + F_{bs} + F_d - F \tag{5}$$

Where F is the applied force at base of each column due to ground acceleration (ie. $F = -M_F \ddot{u}_g$, where M_F is the base mass and $\ddot{u}_g$ is the ground acceleration). F_{bs} is the horizontal force in the restoring force device. This force is equal to the stiffness of restoring force device, k_b, multiplied by the relative displacement of the structure at base. It is to be noted that the relative acceleration and relative velocity at base are equal to zero when the system is in non-sliding phase.

1.9. Determination of Frictional Resistance

The frictional resistance, F_s, is obtained using the equation $F_s = \mu W$, where μ is the coefficient of friction of the sliding material and W is the load on each column in contact with bearing.

2. Numerical Study

The response of a four storey symmetrical space frame structure resting on sliding bearing with restoring force device subjected to El Centro, Turkey and Mexico earthquakes is obtained. The response quantities obtained from the analysis are the top floor absolute acceleration, base shear, bending moment at base of bottom column, relative displacement at top and relative base displacement. The response of the isolated structure is compared with the response of the structure fixed at base to study the effectiveness of the sliding bearing as isolation system. The response of the isolation system with restoring force device is also compared with the response of the isolation system without restoring force device to study the effectiveness of using restoring force device in a sliding bearing. In addition, the effect of the coefficient of friction of base material, effect of time period of the superstructure, and the effect of number of storeys on response of structure are also investigated. The effect of beam size to column size ratio on response of the structure is also studied in order to study the effect of the beam stiffness on response of the structure. The space frame structure considered for the study is shown in Figure (1). The various parameters considered for the study are also shown in this figure.

Rayleigh constants, α and β are calculated using the first two modes considering the damping ratio of 0.05.

2.1. Effect of Beam Stiffness on Response of the Structure

As already discussed, in the present analysis, the space frame structure is divided into number of beams and columns and six *DOFs* are considered at each node instead of modeling the structure as a shear model with only one horizontal *DOF* at each floor. In the analysis of structures using a shear type of model, the effect of the stiffness of the beam on the response of the structure is neglected and its stiffness is assumed as considerably large in comparison with the stiffness of the column. In order to study the effect of stiffness of the beam on response of the structure, a space frame structure shown in Figure (1) is analyzed by varying the size of the beam from $0.3m \times 0.3m$ to $0.3m \times 2.1m$. The size of the column is kept constant as $0.6m \times 0.6m$ for all sizes of the beam considered. The time period of the restoring force device, $T_b = 1sec$ and coefficient of friction of base material is equal to 0.05. The other geometric and material properties are shown in Figure (1). The base displacement, top displacement, top floor acceleration, base shear and bending moment at the base of the bottom column for various ratios of beam size to column size for El Centro earthquake is tabulated in Table (1). As observed from the table, the response of the structure varies with beam size to column size ratio. However, the response will not change much with beam size to column size ratio when the ratio is more than 6. Thus the stiffness of beam will have the effect on the response of the base isolated structure and the analysis considering the effect of stiffness of beam may be more realistic as compared with the analysis neglecting the stiffness of beam.

2.2. Time History Response

Figures (2) to (4) show the variation of response with time for a structure fixed at base, isolated with restoring force device and isolated without restoring force device subjected to El Centro, Turkey and

Table 1. Response of Isolated structure for various values of beam to column ratio.

Sl. No.	Ratio of Beam to Column Size	Base Displacement (mm)	Top Displacement (mm)	Acceleration (m/sec^2)	Base Shear (kN)	Bending Moment (kN.m)
1	0.5	25.76	67.8	2.98	51.80	264.14
2	1.0	38.82	54.45	2.80	70.67	197.28
3	1.5	39.60	52.58	3.56	82.14	195.15
4	2.0	42.53	51.93	3.35	80.72	180.25
5	2.5	43.22	51.24	3.18	78.67	171.17
6	3.0	43.44	50.90	3.09	77.60	166.83
7	3.5	43.53	50.73	3.04	77.02	164.65

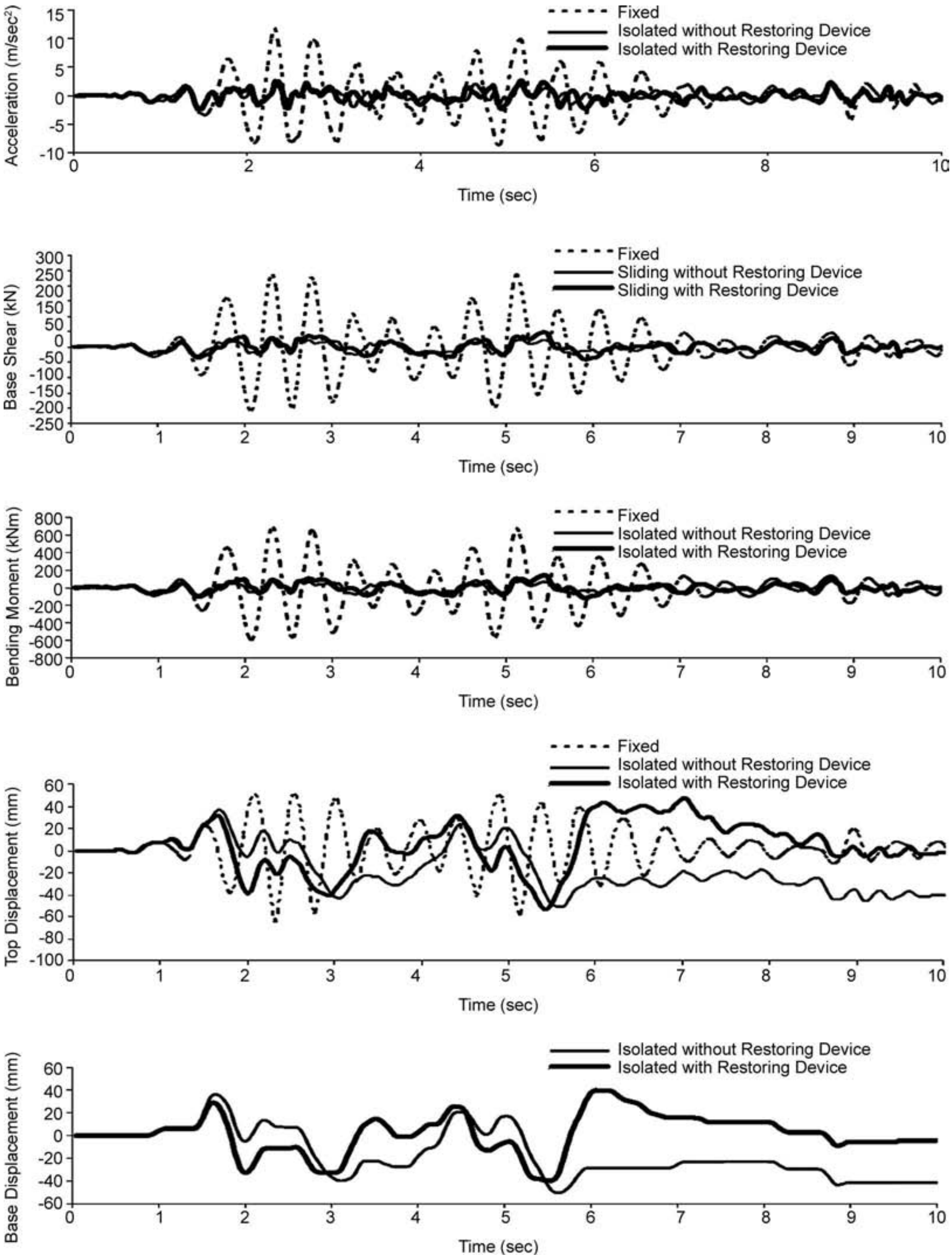


Figure 2. Variation of response with time for a structure subjected to El Centro earthquake.

Mexico earthquakes respectively. In the analysis it is assumed that the time period of the superstructure, $T_s = 0.5sec$, time period of the isolation system, $T_b = 1.5sec$ and coefficient of friction of base material, $\mu = 0.05$. As tabulated in Figure (1), the mass on each beam $M1 = 3kNsec^2/m^2$ and $M2 = 2kNsec^2/m^2$ and the sizes of each column is equal to $0.6m \times 0.6m$. Isolation without restoring force device implies that stiffness $k_b = 0$ (T_b = &). As observed from figures, the acceleration, bending moment and base shear decreases considerably due to isolation for all three types of earthquakes considered in the study. Also, there is not much change in top acceleration, bending moment and base shear for the structure isolated at base without restoring force device and isolated with restoring force device. The maximum relative top displacement of isolated structure with and without restoring force device is almost the same as the maximum relative top displacement of the structure fixed at the base for the El Centro and Mexico earthquakes, whereas for the Turkey earthquake, the maximum relative top displacement

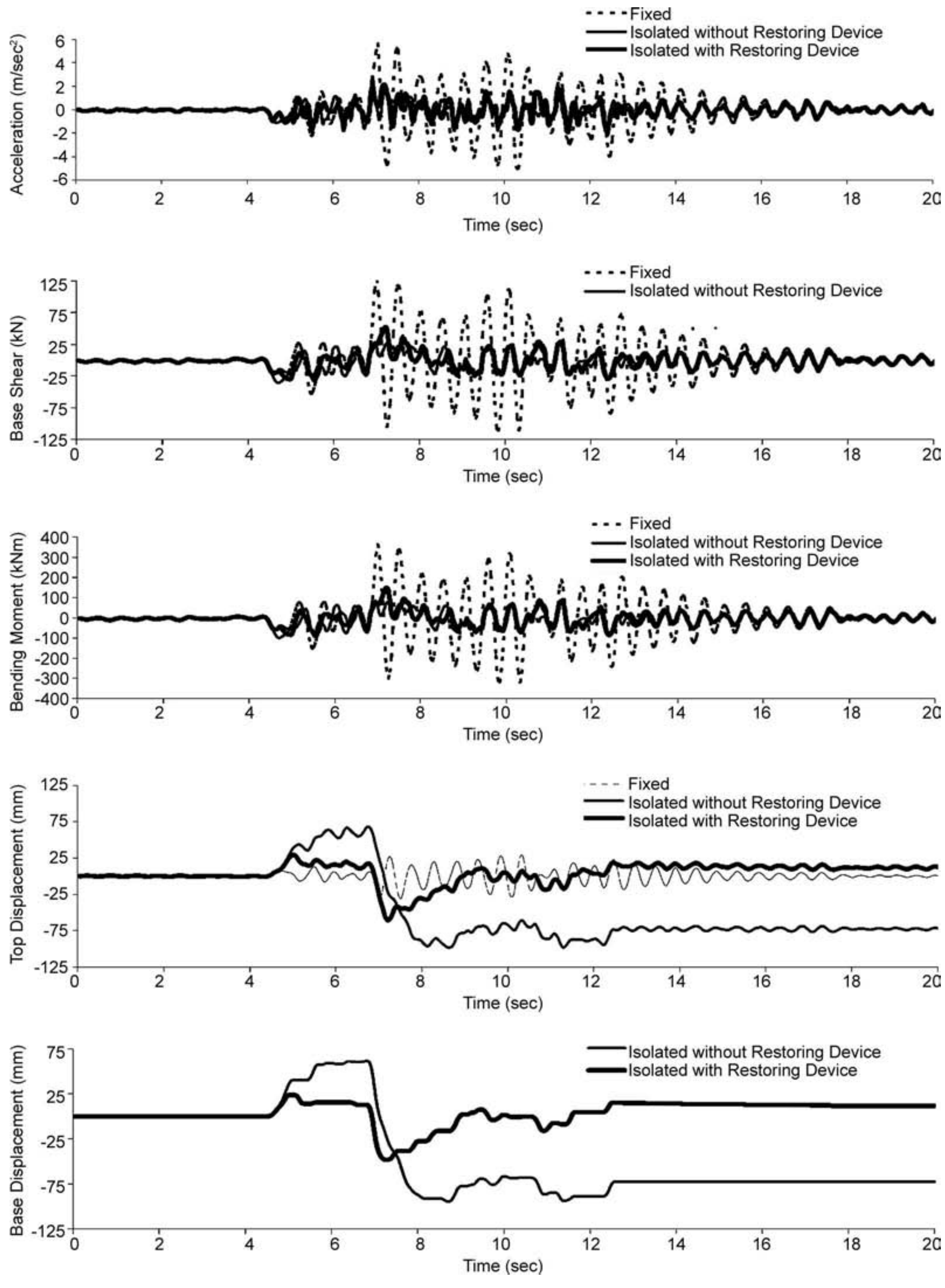


Figure 3. Variation of response with time for a structure subjected to Turkey earthquake.

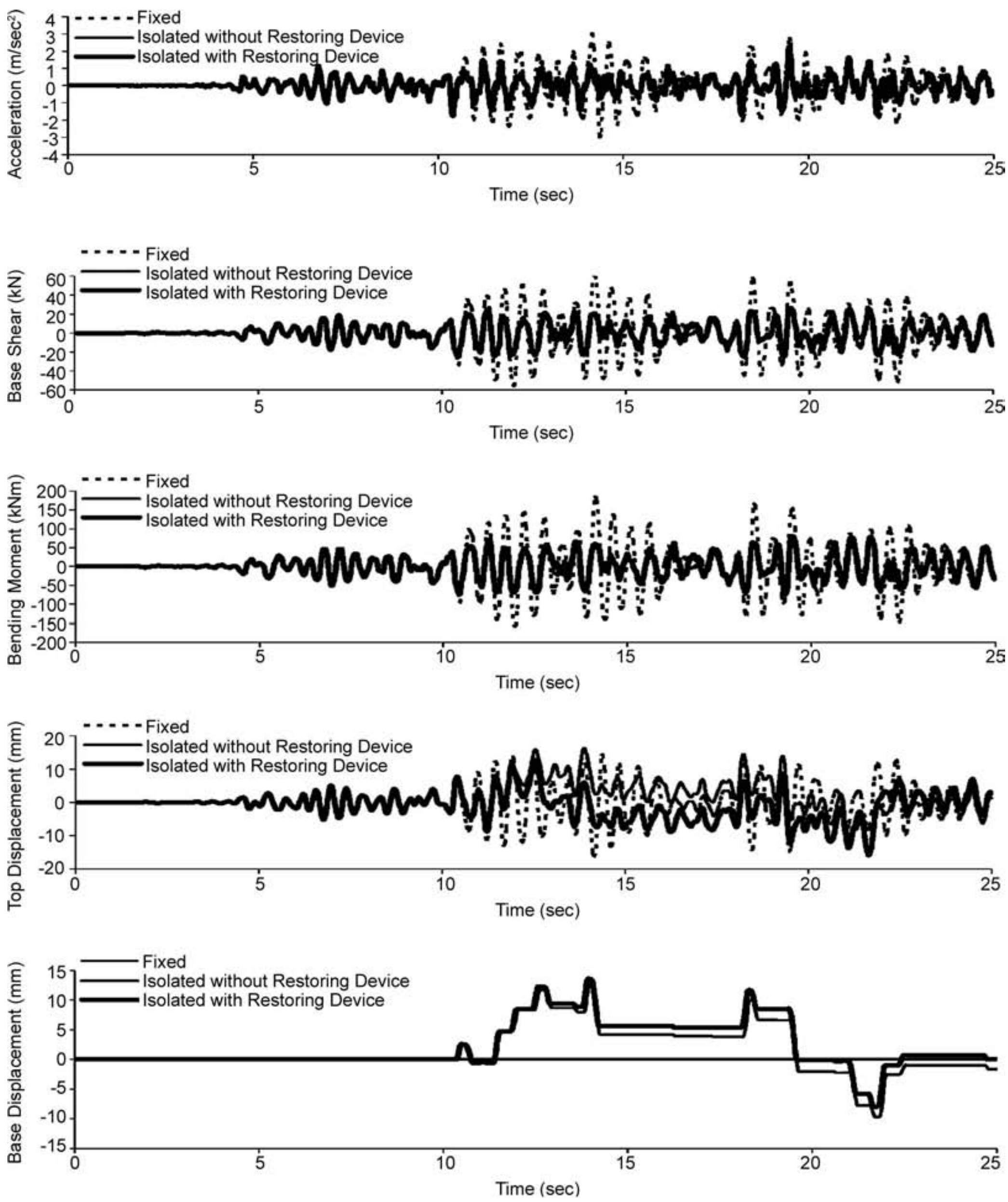


Figure 4. Variation of response with time for a structure subjected to Mexico earthquake.

of the isolated structure is more than that of the structure fixed at base. The residual base displacement (displacement at base at the end of earthquake) for a structure isolated with restoring force device is less than the residual displacement of structure isolated without restoring force device for all three types of earthquakes.

Thus the restoring force device in the isolation system reduces the sliding displacement without transmitting additional accelerations and forces into the superstructure. Further, the structure isolated without restoring force device shifts to a new position whereas the structure isolated with restoring force device comes almost to original position after the end of the earthquake.

2.3. Effect of Coefficient of Friction of Base Material

Depending on the choice of material for sliding surface, a wide range of coefficient of friction of base material can be obtained. The influence of the coefficient of friction of the base material has been investigated by analysing a one storey and four storey space frame structure with sliding bearing for different coefficient of friction of base material. For the problem chosen, time period of the superstructure is equal to $0.5 sec$. The mass on beam $M1 = 3kNsec^2/m^2$ and $M2 = 2kNsec^2/m^2$ for the four storey structure and $M1 = 7.5kNsec^2/m^2$ and $M2 = 5.0kNsec^2/m^2$ for the one storey structure. The size of the column is equal to $0.6m \times 0.6m$ for four storey and $0.32m \times 0.32m$ for one storey structure. Figures (5) to (7) show the variation of response with coefficient of friction of base material for four storey and one storey structure for various values of $T_b = 1sec$, $1.5sec$ and $2.0sec$ when the structure is subjected to El Centro, Turkey and Mexico earthquakes respectively. It can be observed from these figures that as the coefficient of friction of the base material, μ, increases, the acceleration, base shear and bending

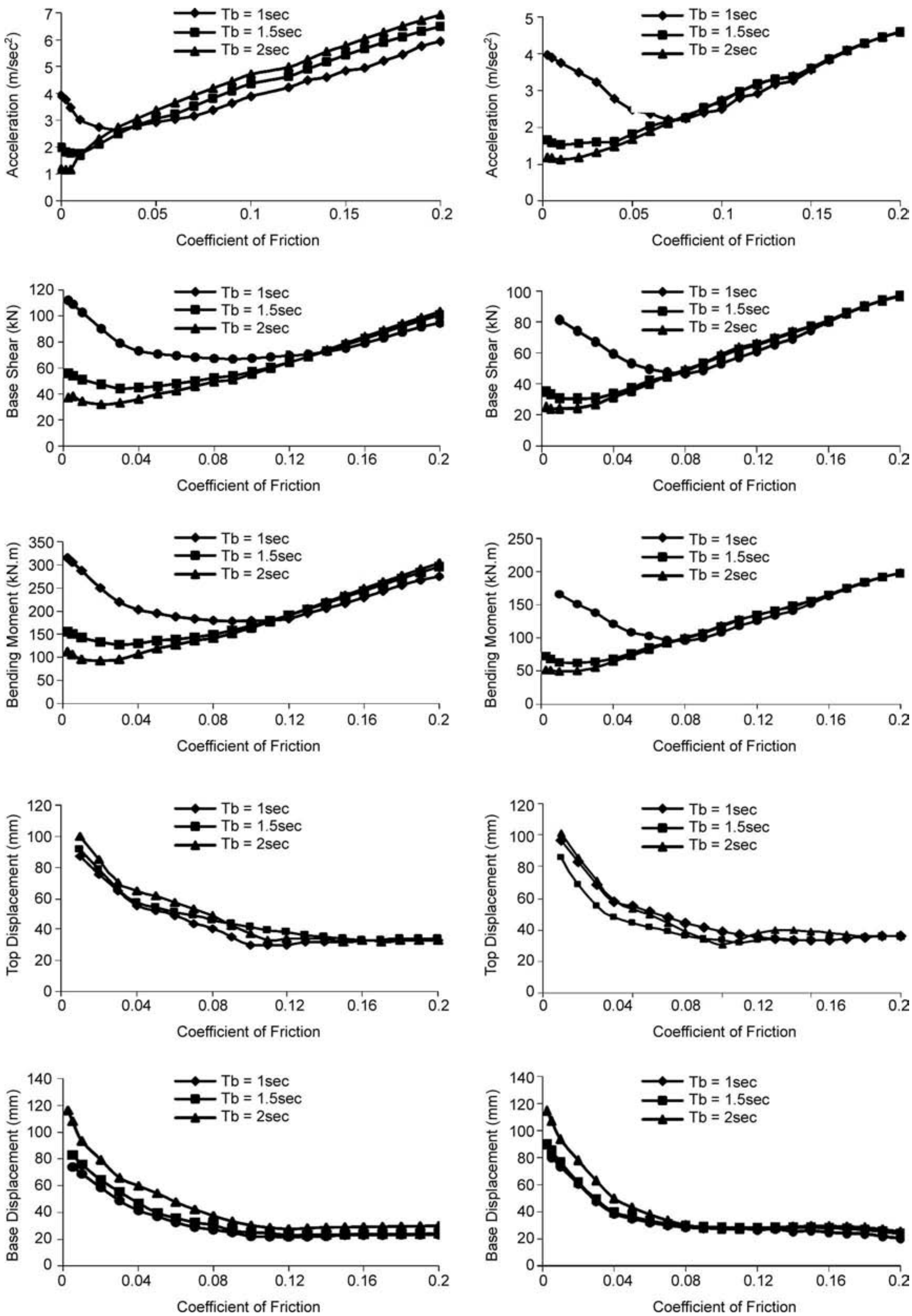


Figure 5. Variation of response with coefficient of friction of base material for El Centro earthquake.

moment first decreases to a minimum value and then increases with increase in value of μ. This indicates that there exists a value of μ at which the acceleration, bending moment and base shear attains a minimum value. This is the optimum value of μ. It can also be observed from the figures that the optimum value of μ decreases as the value of T_b increases for both one storey and four storey structures. It can also be observed from figures that the acceleration, base shear and bending moment decreases as the value of T_b increases up to a certain value of μ and beyond this value of μ, the acceleration, base shear and bending moment either increases (as in the case of El Centro earthquake) or

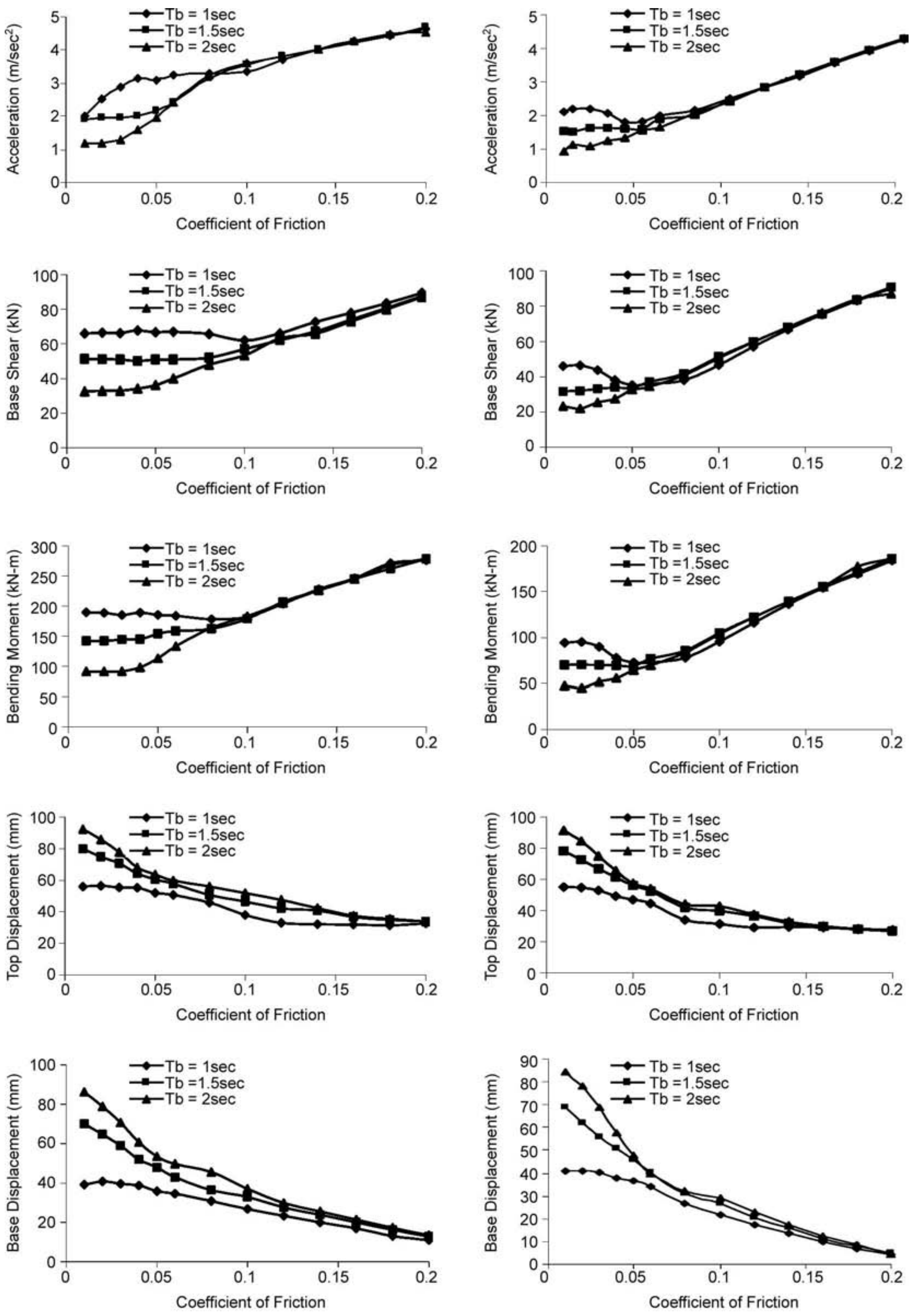


Figure 6. Variation of response with coefficient of friction of base material for Turkey earthquake.

will not change much (as in the case of Turkey and Mexico earthquakes) with increase in value of T_b. The top and base displacement of the structure decreases as the coefficient of friction of base material increases. The top and base displacement also increases as the value of T_b increases.

2.4. Effect of Time Period of Superstructure

Time period of the structure is the most important property for evaluating the dynamic response of the structure. Time period varies from 0.1*sec* to 1.0*sec* for most typical building structures. For base isolation

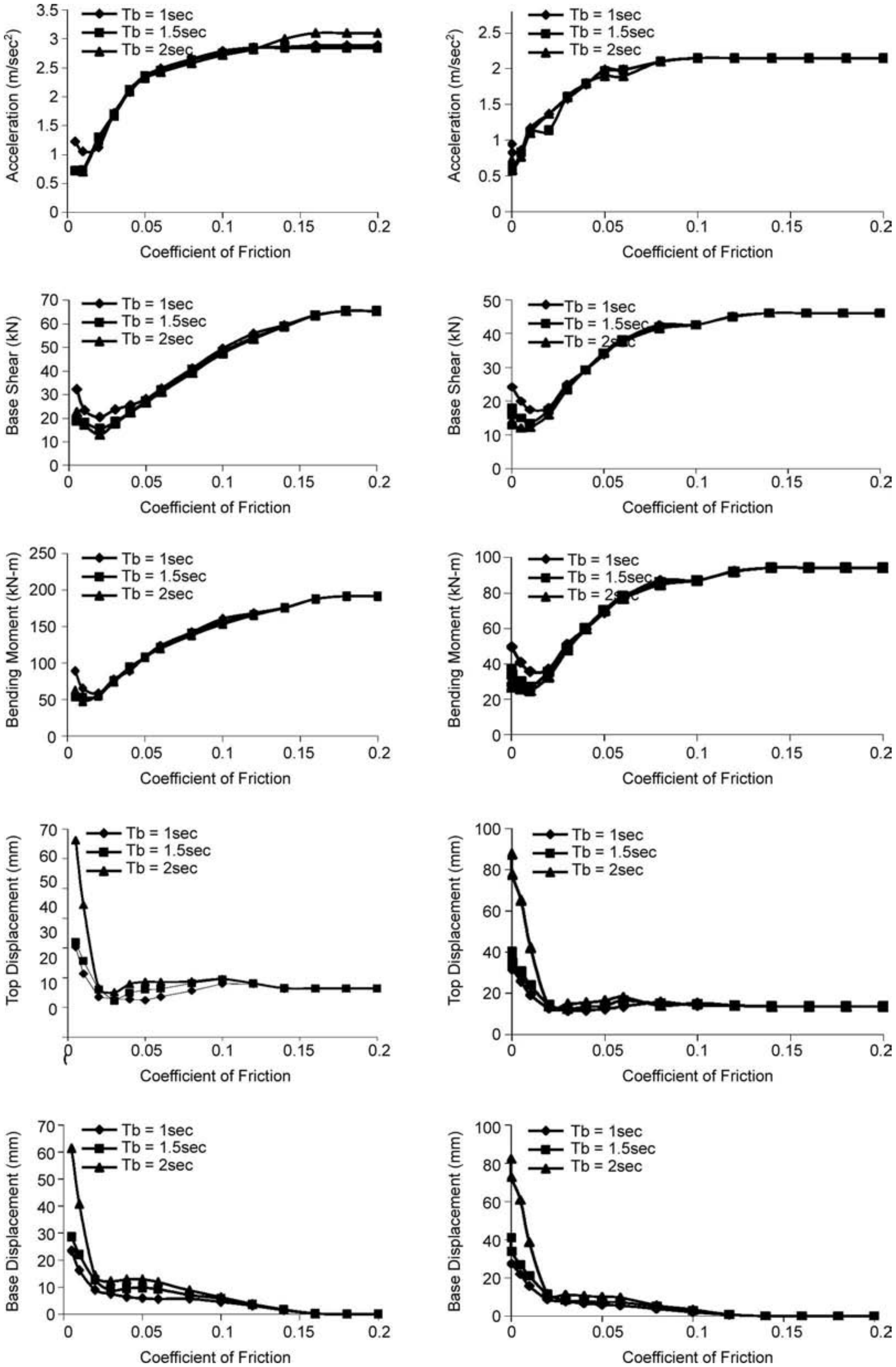


Figure 7. Variation of response with coefficient of friction of base material for Mexico earthquake.

to be effective, time period of the structure is to be shorter than the time period of the restoring force device. The time period of the restoring force device is chosen as 1.0*sec* and the time period of the structure changes from 0.1*sec* to 1.0*sec* at interval of 0.1*sec*. The time period, T_s, of the structure varies either due to the change in mass on structure, the change in stiffness of structure or due to the change in both stiffness of structure and mass on structure.

In the present study, time period of the structure, T_s, is varied by varying only the stiffness of the column keeping mass on the structure constant in one case (case 1) and in another case (case 2) changing the mass on structure keeping the column stiffness constant.

The variation of maximum response with time period for the four storey space frame structure isolated at base when it is subjected to El Centro, Turkey and Mexico earthquakes, is shown in Figure (8). The response of the structure fixed at base is also shown in the same figure. As seen in Figure (1), the mass on beam is kept same whereas the size of the column varies from $1.62m \times 1.62m$ for $T_s = 0.1sec$ to $0.32m \times 0.32m$ for $T_s = 1.0sec$ for case 1. In this case, the size of beam is taken as 0.3m (width) $\times$ 0.6m (depth) when the size of column is less than $0.6m \times 0.6m$. When the size of column is more than $0.6m \times 0.6m$ (as in the case of T_s less than 0.5*sec*), the width of beam is 0.3m whereas the depth of beam is equal to the size of the column (ie $0.3m \times 1.62m$ for $T_s = 0.1sec$). In case 2, the size of column is same for all values of T_s whereas the mass on each beam varies from $M1 = 0.03kN.sec^2/m^2$ and $M2 = 0.02kN.sec^2/m^2$ for $T_s = 0.1sec$ to $M1 = 12kN.sec^2/m^2$ and $M2 = 8.0kN.sec^2/m^2$ for $T_s = 1.0sec$. The value of coefficient of friction of base material μ is equal to 0.05.

For case 1, the acceleration, base shear and bending moment varies with time period for the structure both isolated at base and fixed at base. However, the effect of time period of the structure is more significant for the structure fixed at base as compared with the structure isolated at the base. For case 2, the effect of time period on acceleration is almost the same as in case 1. However, the base shear and bending moment increases with increase in time period for the structure both fixed and isolated at the base.

The top displacement for the structure fixed at base is almost identical for both case 1 and 2 and in both cases, it increases with increase in time period. For isolated structure, the top displacement increases with time period for case 1, whereas it will not change much for case 2. The base displacement in case 1 increases slightly when time period is increased from 0.1*sec* to 0.3*sec* and with further increase in time period, the base displacement decreases for El Centro and Turkey earthquakes and do not change much for Mexico earthquake.

For case 2, the base displacement decreases when time period is increased from 0.1*sec* to 0.2*sec* and then remains almost the same with further increase in the time period. It can also be observed from Figure (8) that the effect of time period on acceleration and base displacement is almost the same when time period is varied either by varying the stiffness or mass on the structure whereas the effect of time period on base shear and bending moment is more significant when time period is varied by changing the total mass on the structure than by varying the stiffness of the structure.

2.5. Effect of the Number of Storeys

Figure (9) shows the variation of response of the structure with number of storey. The various number of storeys considered for the study are equal to 1, 2, 3 and 4.

Again three cases are considered while varying the number of storeys. The various sizes of column and mass on each beam considered for each case are tabulated in Figure (1). In case 1, the mass on each beam is kept the same and the size of the column are varied so as to obtain time period T_s = 0.5*sec* for all number of storeys. In case 2, the mass on each beam is varied in order to obtain the total mass on the structure ($42.5kN.sec^2/m^2$) which is the same for different number of storeys. The sizes of column are also varied in this case to obtain the value of T_s = 0.5*sec* for all number of storeys. In case 3, the mass on each beam and the sizes of each column are the same for all number of storeys. Thus in case 1, the time period of the structure is the same for different storeys whereas the total mass on the structure and column sizes varies with number of storeys. In case 2, total mass on the structure and the time period of the structure is the same whereas the sizes of column varies with number of storeys. In case 3, the total mass on the structure and time period changes whereas the size of column will not vary with number of storeys. The value of T_s, of the structure increases as the number of storeys increases in this case. The various time period of the structure, T_s, for this case is equal to 0.11*sec*, 0.16*sec*, 0.37*sec* and 0.50*sec* for one, two, three and four storey respectively.

It can be observed from the Figure (9) that for case 1, the acceleration and top displacement will

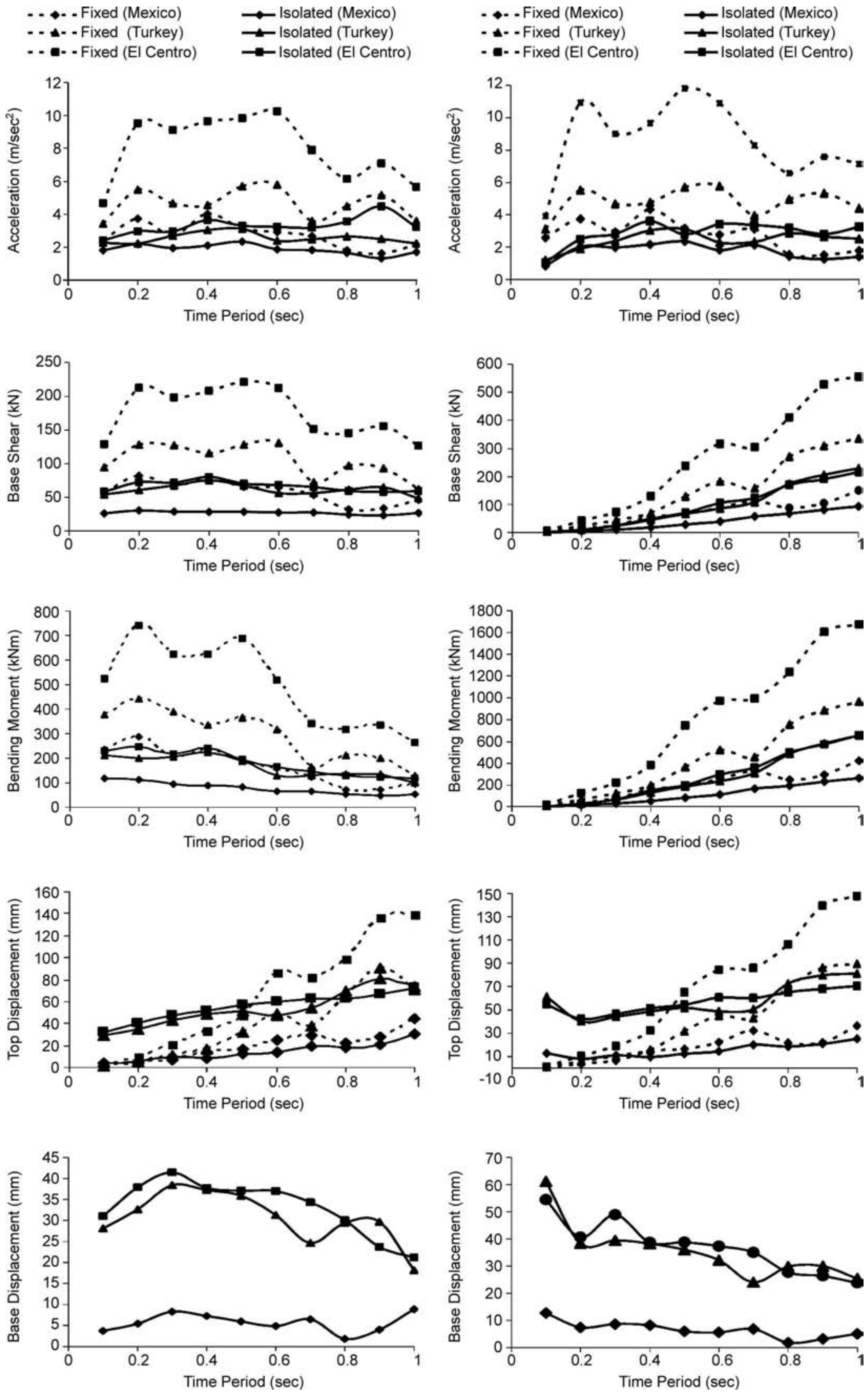


Figure 8. Variation of response with time period.

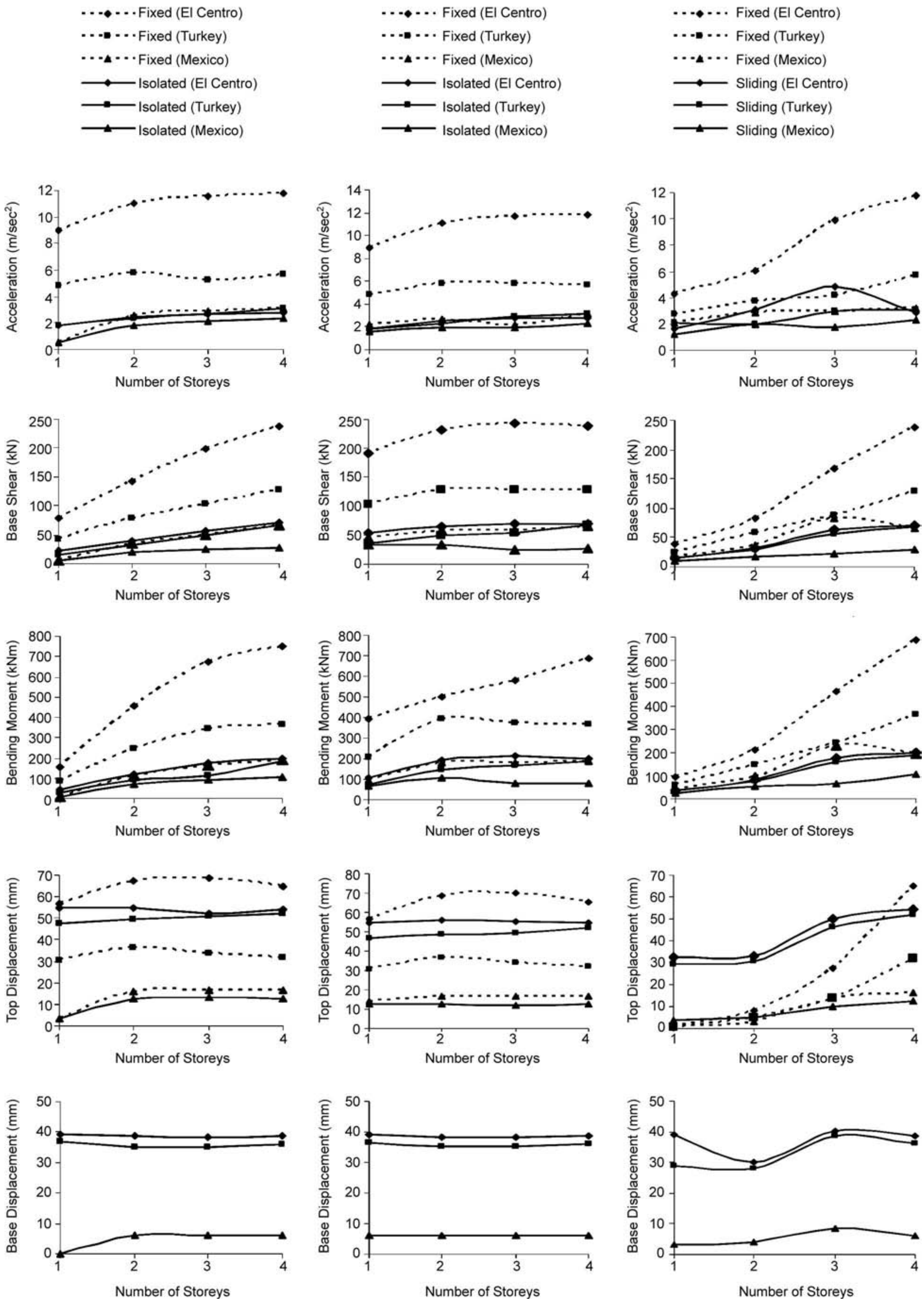


Figure 9. Variation of response with number of storeys.

not change much with increase in number of storeys for the structure fixed and isolated at the base. The base shear and bending moment increases with increase in number of storeys for the isolated and fixed base structure. The base displacement will not vary much with increase in number of storeys. In case 2, the acceleration, base shear, bending moment, top displacement and base displacement will not vary much with number of storeys. For case 3, the acceleration, base shear, bending moment, top displacement and base displacement increases as number of storeys increases.

3. Conclusions

In this paper, the seismic performance of a symmetrical space frame structure resting on sliding type of bearing with restoring force device is studied. The effects of coefficient of friction of sliding material, vibration period of the superstructure and number of storeys on response of the structure are also studied.

Based on the study, it is concluded that the sliding bearing with restoring force device is effective in reducing the earthquake response of the structure. The restoring force device reduces the base displacement without transmitting additional forces into the structure. The restoring force device also helps the structure to come to its original position after the end of earthquake. Response of the structure isolated at the base varies with the coefficient of friction of base material, time period of superstructure and number of storeys. The top and base displacement of the structure decreases with increase in coefficient of friction of base material whereas there exists an optimum coefficient of friction of sliding material for acceleration, base shear and bending moment at which acceleration, base shear and bending moment attains a minimum value. This optimum value decreases with increase in isolation period. The effect of time period of superstructure and number of storeys on response of fixed and isolated structure also depends on the mass on beam and sizes of column at each time period and at each number of storey(s). Also, the stiffness of beam will have the effect on the response of the base isolated structure and the analysis considering the effect of stiffness of beam may be more realistic as compared with the analysis neglecting the stiffness of beam.

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