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Earthquake Response of Multistory Masonry Building with Friction Base Isolation

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Abstract. Although confined masonry and reinforced masonry construction have had good behavior in strong earthquakes occurred during the last decade, but the unreinforced masonry construction has had poor safety performance records during the past earthquakes. In view of this, a friction base isolation (FBI) system for multistory masonry building is considered here in which a clear smoothened surface is created between the superstructure and the sliding substructure. The earthquake response of the multistory masonry buildings with a FBI system subjected to the Koyna and El Centro earthquake ground motions is computed through a multi-mass-spring-dashpot mathematical model. The parameters involved in the seismic analysis are the number of stories of the building, the coefficient of friction and the type of earthquakes. The results are presented through graphs in terms of non-dimensional lateral force coefficient and drift to story height ratio plotted against the number of stories for different coefficients of friction and earthquakes. These plots show the reduction in response of the base isolated multistory masonry buildings compared with corresponding conventional buildings.

Key words: masonry buildings; friction base isolation; El Centro earthquake; sliding material; interfloor discontinuity; lateral force coefficient.

1. Introduction

Present design provisions (Earthquake Resistant Regulation 1992) are based on the assumptions of inelastic behavior of structures in the case of a major earthquake occurrence because it is not economically feasible to design structures elastically for such situations. Recent earthquakes in China, India, Iran, Japan, Turkey, USA and the former USSR have shown that unreinforced masonry structures strengthened (not fully reinforced) as recommended by the design codes of various countries to provide non-collapse masonry construction did not perform satisfactorily during severe ground motion. Perhaps, in view of this fact, a number of base isolation techniques have been developed (Skinner, *et al.* 1975a, 1975b and 1980, Megget 1978 and Kelly 1986) in the last four decades in which the superstructure is joined to its substructure through flexible structural and / or energy dissipation devices. Perhaps, masonry buildings cannot be isolated economically by these techniques in developing countries. In view of these problems, the friction base isolation (FBI) scheme has been developed for masonry buildings during the last fifteen years.

Damage study of buildings during the Dhubri earthquake of Assam in 1930 and in Bihar-Nepal earthquake in 1934 indicated that those buildings where movement occurred between the superstructure and substructure suffered less damage than those buildings in which no such freedom existed (Joshi 1960). From these observations of masonry structural response to severe

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ground motion, the FBI concept was first introduced by Qamaruddin (1978) for the construction of masonry buildings. The concept of the FBI system established through analytical and experimental studies (Arya, *et al.* 1981, Qamaruddin 1978, Qamaruddin, *et al.* 1984, 1986a and 1986b) made mainly for masonry buildings. In such buildings, a clear smoothened surface is created between the superstructure and the substructure at the plinth level on which the superstructure sits and is free to slide except for frictional resistance. This discontinuity at the plinth level enables the building to dissipate a part of the seismic energy by sliding.

The concept of the FBI system was further strengthened by investigations (Lee 1984) made after the catastrophic Tangshan earthquake of 1976 in China. A similar mathematical model, as first proposed by Qamaruddin (1978), was presented by some researchers (Mostaghel, *et al.* 1983a and 1983b) a few years later for solving the problem of two-degree-of-freedom structures supported on a sliding substructure and subjected to harmonic and earthquake support motions. The seismic capacity of multistory masonry buildings with interfloor discontinuity at different story levels together with the sliding substructure was also investigated by Qamaruddin, *et al.* (1986c). Recently attempts were made to suggest mathematical models (Bingze, *et al.* 1990 and Qamaruddin, *et al.* 1990) for frictional base isolated multistory masonry buildings subjected to earthquakes, but a simple mathematical model for seismic response analysis of multistory masonry buildings with sliding substructure is presented in the present study. The results of the theoretical studies carried out for the seismic response of multistory masonry buildings with sliding substructure are presented in this paper.

2. Mathematical model

A multistory masonry building with a friction base isolation system may be idealized as a multi-degree-of-freedom discrete model (Fig. 1) for computing its seismic response. A thin layer of sliding material is interposed between the contact surfaces of the bond beam of the superstructure and the plinth band of the substructure. The spring action in the mathematical model is assumed to be provided by the shear walls. The internal damping is represented by a dashpot which is parallel with the spring. The bottom mass of the sliding system is assumed to rest on a plane with dry frictional damping to permit sliding of the superstructure. The coefficient of friction between the sliding surfaces is assumed to remain constant throughout the motion of the structure. The building material is considered as elastic. Throughout the ground motion due to earthquake, the behavior of the system is taken as linear. The building is subjected to only one horizontal component of the ground motion at a time. For response computation, one degree of translational freedom per mass of the model is considered in the same direction as the ground motion. The sliding displacement at the contact surface between the superstructure and the substructure without overturning and/or tilting is assumed to be unrestrained.

3. Equations of motion

The equations of motion for multi-degree of friction base isolated system (Fig. 1) are written in matrix form as:

$$[M][\ddot{x}]+[C][\dot{x}]+[K][x]=[F]-[\ddot{x}_g][M] \tag{1}$$

where [M], [C] and [K] are the mass, damping and stiffness matrices, respectively of the sliding structure; $[x]$,$[\dot{x}]$and$[\ddot{x}]$ and [F] stand for the respective vectors of relative displacement, velocity and acceleration with respect to ground and the friction force vector.

There are different phases in the motion history of the system due to the frictional resistance at its base. Initially, the bottom mass, m_o, moves with the base since there is no sliding, and the structure behaves as n-degree of freedom conventional system and therefore,

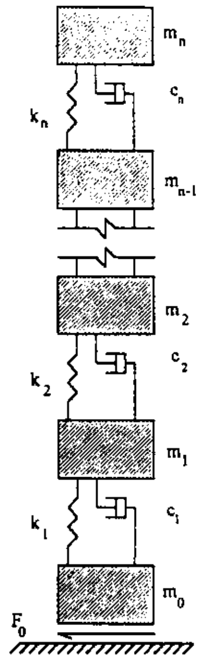

Fig. 1 Mathematical model

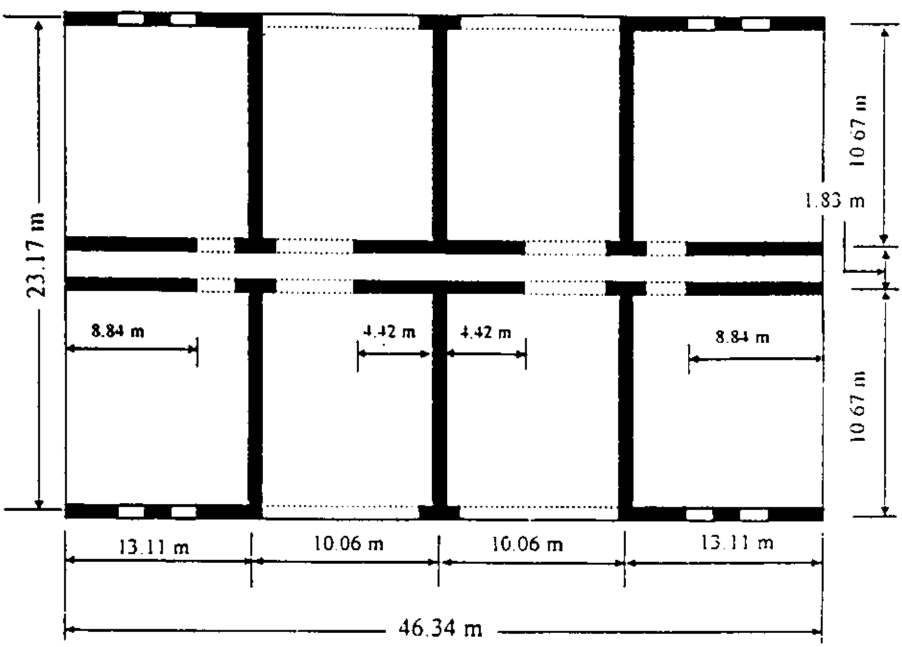

Fig. 2 Typical Plan of a Multistory Masonry Building

$$F_0 = -S_F \quad (2)$$

where F_0 represents the frictional force between the bottom mass and base, on which the sliding takes place and therefore now,

$$S_F = m_0 \ddot{x}_g + c_1(\dot{x}_0 - \dot{x}_1) + k_1(x_0 - x_1) \quad (3)$$

in which $\ddot{x}_g$ is the ground acceleration. Sliding of the bottom mass begins, if

$$|S_F| > fg\sum_{i=0}^{n} m_i \quad (4)$$

where f is the coefficient of friction and g is the acceleration due to gravity. Now, the system has (n+1) degree of freedom for which the equations of motion are given by Eq. (1). In this phase of motion,

$$F_0 = -\mathrm{Sign}(S_F)\, fg\sum_{i=0}^{n} m_i \quad (5)$$

During motion of the system, if

$$|S_F| < fg\sum_{i=0}^{n} m_i \quad (6)$$

then, the sliding of the bottom mass is stopped while the other masses continue to vibrate. Therefore, the structure again becomes an n-degree of freedom system and hence its motion would be governed by Eq. (1) Thus, the bottom mass of the system either stops or continues to slide during the ground shaking according to the conditions enumerated above.

The Runge-Kutta fourth order method is employed for numerical integration of the equations of motion since this method is self starting and the solutions are stable and accurate to a definite precision. A computer program has been developed to compute the timewise seismic response of the multistory friction base isolated building.

4. Data for computing seismic response

4.1. *Building data*

The roof and/or floor plan of a seventeen-story reinforced masonry apartment building built several years ago in Denver (USA) are shown in Fig. 2. This building has been chosen for the seismic response computation to study the efficiency of the friction base isolation system to ground shaking. In view of this, the plan of the building has been kept invariant and the masonry walls are considered as unreinforced but the number of stories of the building has been taken as 5 and 11 in addition to the existing one for parametric study. The story-height, of all the three buildings chosen in the present study, is 2.74m except the first story height which is 3.66m. The thickness of the walls up to five stories is 0.33 m whereas the walls are 0.28 m thick between six and eleven stories. 0.23 m thick walls have been provided between twelve and seventeen stories.

The values of seismic weight, story stiffness and coefficient of viscous damping are shown in Tables 1 to 3. The damping values given in the table represent 5% of critical damping. The damping is considered to be proportional to the story stiffness. The fundamental natural period of the 5, 11 and 17 story buildings is 0.27, 0.58 and 0.89 second, respectively. The coefficient of friction is an important parameter that effects the response of the sliding system considerably. In the present investigation, the values of coefficient of friction are considered between 0.10 to 0.30 with an interval of 0.05 depending upon the number of stories of the chosen buildings. It is assumed that a coefficient of friction less than 0.10 will be difficult to obtain in actual building construction and for a value greater than 0.30 practically no sliding may occur in most real earthquakes.

Table 1 Data for five story masonry building

Story level	Seismic weight (kN)	Story stiffness (kN/m)	Damping coefficient (kN-sec/m)
6	8995		
		5500913	2197
5	9285		
		5500913	2197
4	9285		
		5500913	2197
3	9285		
		5500913	2197
2	9932		
		4486847	1793
1	8013		

Table 2 Data for eleven story masonry building

Story level	Seismic weight (kN)	Story stiffness (kN/m)	Damping coefficient (kN-sec/m)
12	8415		
		4657323	3322
11	8705		
		4657323	3322
10	8705		
		4657323	3322
9	8705		
		4657323	3322
8	8705		
		4657323	3322
7	8705		
		4657323	3322
6	8995		
		5500913	3849
5	9285		
		5500913	3849
4	9285		
		5500913	3849
3	9285		
		5500913	3849
2	9932		
		4486847	3146
1	8013		

4.2. Earthquake data

The earthquake response has been computed employing the El Centro earthquake of May 18, 1940 (N-S component) and the Koyna earthquake of December 11, 1967 (longitudinal component). The Koyna accelerogram was recorded close to the epicenter of the shock and has high acceleration pulses and frequency content. The El Centro accelerogram has relatively lower acceleration pulses as well as frequency content. The influence of the accelerogram on the structural response has been studied with these two different earthquakes.

5. Earthquake response

The response of the multistory masonry buildings was computed for the various combinations of the parameters as mentioned before. The quantities of interest for estimating realistic forces and displacements for friction base isolated buildings are: absolute accelerations which determine

Table 3 Data for seventeen story masonry building

Story level	Seismic weight (kN)	Story stiffness (kN/m)	Damping coefficient (kN-sec/m)
18	6250		
		3813732	3814
17	8125		
		3813732	3814
16	8125		
		3813732	3814
15	8125		
		3813732	3814
14	8125		
		3813732	3814
13	8125		
		3813732	3814
12	8415		
		4657323	4657
11	8705		
		4657323	4657
10	8705		
		4657323	4657
9	8705		
		4657323	4657
8	8705		
		4657323	4657
7	8705		
		4657323	4657
6	8995		
		5500913	5501
5	9285		
		5500913	5501
4	9285		
		5500913	5501
3	9285		
		5500913	5501
2	9932		
		4486847	4487
1	8013		

the interfloor forces; and the maximum relative displacement of the superstructure at the base so that the extent of sliding of the superstructure to be allowed for in design may be known.

The results of the response computation are presented in the form of plots. The maximum interfloor lateral force (F_i) is non-dimensionalized to obtain the lateral force coefficient (F_c) follows:

$$(F_c)_i = \frac{F_i}{\sum_{j=1}^{n} W_j} \qquad (7)$$

The lateral force coefficient is plotted against the number of story for these buildings subjected to the Koyna and the El Centro earthquakes for different values of the coefficient of friction, as shown in Figs. 3 to 8. The story-wise variation of story drift to story height ratio (story-drift ratio) with different values of coefficient of friction is plotted for the multistory buildings subjected to El Centro and Koyna earthquakes as shown through Figs. 9 to 14.

6. Discussion of results

The effect of different parameters on maximum seismic response of the friction base isolated multistory buildings is discussed with reference to Figs. 3 to 14 in the following paragraphs.

6.1. Effect of coefficient of friction

It is seen from Figs. 3 to 8 that generally the story-wise lateral force coefficient (F_c) increases as the coefficient of friction increases in all the parametric combinations, though this trend is not seen in top stories of few cases of the buildings. Because, the resistance against sliding of the system decreases as the coefficient of friction between the sliding surfaces decreases, a building of larger inertia force in the superstructure gets reduced. It is significantly noted from Figs. 4 through 8 that the variation of F_c lies approximately between a narrow band of 0.15 to 0.45 in the bottom stories.

6.2. Influence of number of stories

It is observed from Figs. 3 to 8 that the lateral force coefficient decreases as the number of building stories increases in the cases of buildings subjected to the Koyna and the El Centro earthquakes.

6.3. Effect of different earthquakes

The magnitude of the lateral force coefficient is greater in the case of five-story FBI building subjected to the Koyna earthquake than the corresponding values of F_c for the El Centro earthquake as shown in Figs. 3 and 7. But in the case of the same building with fixed base, this tend is opposite. But, unlike the observations made for the five-story FBI building, the magnitude of F_c in the case of eleven and seventeen story FBI buildings (Figs. 4, 5, 7 and 8) is approximately same for all the combinations of the coefficient of friction and the earthquakes. It is very significantly observed from Figs. 3 to 8 that the lateral force developed in the five and eleven story buildings with fixed base subjected to the Koyna earthquake is greater than that of the El Centro earthquake. But, the lateral force values in the case of seventeen story buildings with fixed base subjected to the El Centro earthquake is greater than the corresponding values of the lateral force for the Koyna earthquake.

6.4. Effect of structural system

The seismic response of the FBI buildings with eleven and seventeen stories is much less than that of conventional (fixed base) buildings subjected to the El Centro earthquake for coefficient of friction varying from 0.10 to 0.30 as observed from Figs. 4 and 5. Although the seismic response in the case of five-story FBI building is less than that of corresponding conventional building

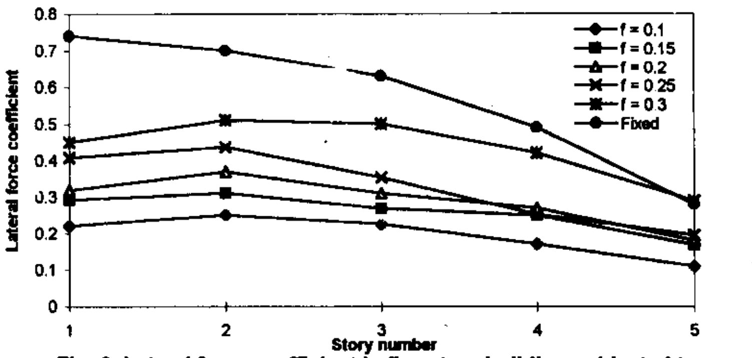

Fig. 3 Lateral force coefficient in five story building subjected to El Centro earthquake

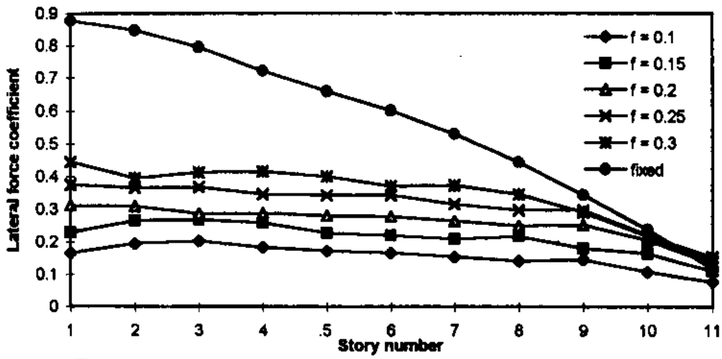

Fig. 4 Lateral force coefficient in eleven story building subjected to El Centro earthquake

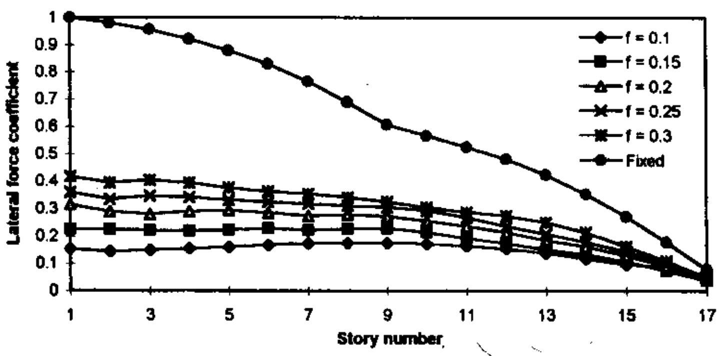

Fig. 5 Lateral force coefficient in seventeen story building subjected to El Centro earthquake

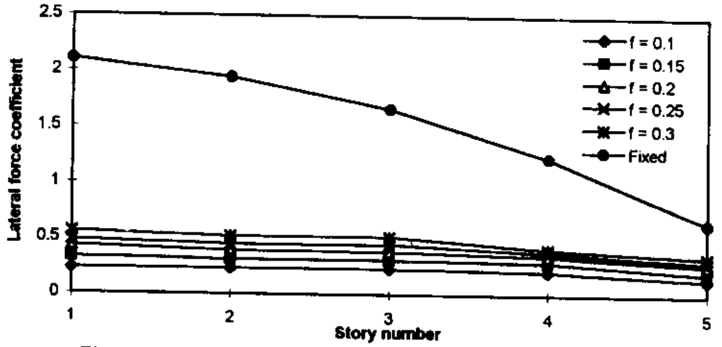

Fig. 6 Lateral force coefficient in five story building subjected to Koyna earthquake

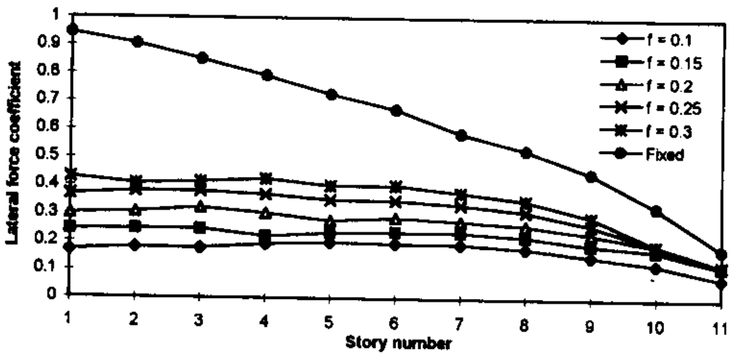

Fig. 7 Lateral force coefficient in eleven story building subjected to Koyna earthquake

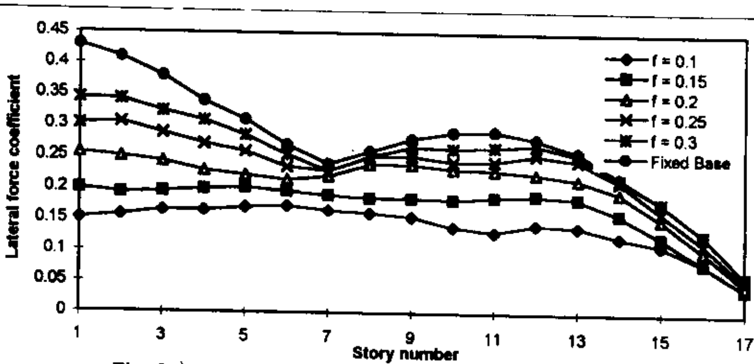

Fig. 8 Lateral force coefficient in seventeen story building subjected to Koyna earthquake

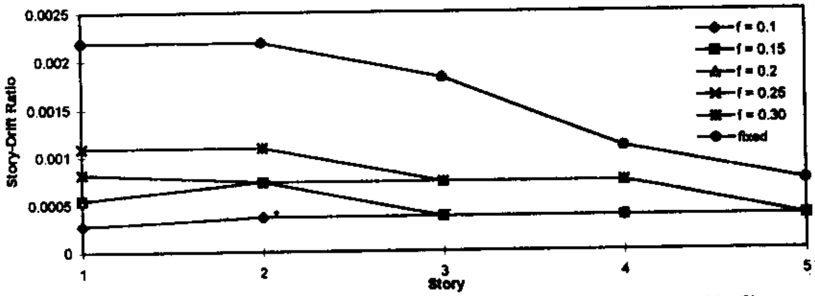

Fig. 9 Variation of story-drift ratio in five story building subjected to El Centro earthquake

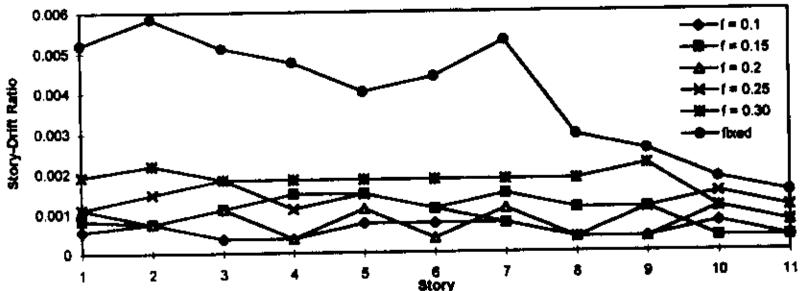

Fig. 10 Variation of story-drift ratio in eleven story building subjected to El Centro earthquake

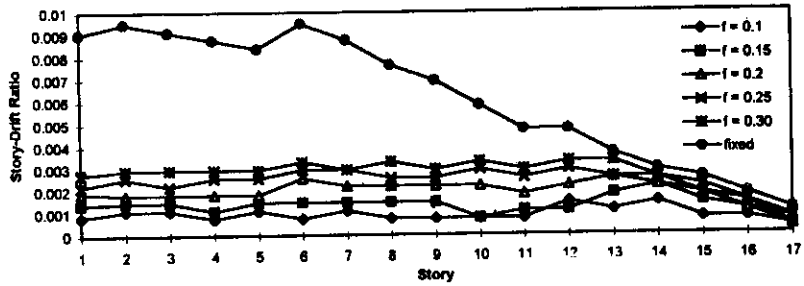

Fig.11 variation of story-drift ratio in seventeen story building subjected to El Centro earthquake

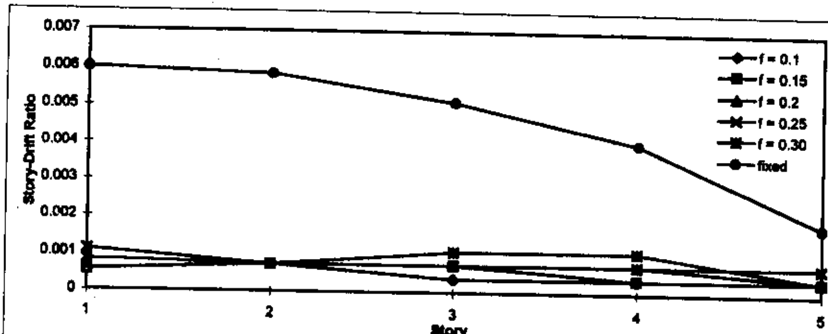

Fig.12 Variation of story-drift ratio in five story building subjected to Koyna earthquake

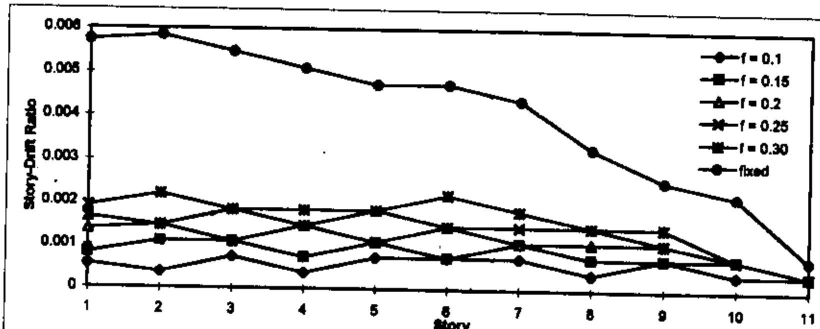

Fig. 13 Variation of story-drift ratio in eleven story building subjected to Koyna earthquake

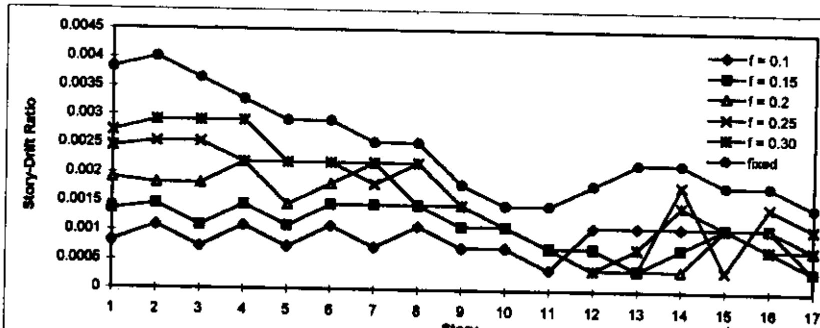

Fig. 14 Variation of story-drift ratio in seventeen story building subjected to Koyna earthquake

subjected to El Centro earthquake (Figs. 3), but not as much as in the eleven and seventeen stories buildings. It is important to note from Figs. 3 and 6, 7 and 8 that the trend of seismic response variation in the case of five and seventeen story buildings with FBI system as compared to that of the conventional buildings subjected to the Koyna earthquake is quite different from the corresponding building cases of the subjected to the El Centro earthquake.

6.5. Story-Drift Ratio

The story-wise variation of story drift to story height ratio (story-drift ratio) with coefficient of friction in the case of five-, eleven-, and seventeen-story buildings subjected to the El Centro and Koyna earthquake is shown in Figs. 9 to 14. It is seen from these figures that there is no definite trend in the variation of story drift/story height ratio as the values of coefficient of friction increase. But, in the case of five-, eleven-, and seventeen-story buildings, there is not much variation in the drift ratio as the number of story increases. For example, the drift ratio lies between a narrow band of 0.00025 to 0.00075 in five-story building with the FBI system whereas this variation is much in the case of similar building but with fixed base (Fig. 9). This trend is observed for all the multistory buildings studied except in the seventeen story building subjected to the Koyna earthquake. It is also observed from these figures that the story-wise variation of the drift ratio for a particular value of the coefficient of friction is small in the case of all the three buildings. But, this variation is large for similar buildings with fixed base.

6.6. Maximum relative displacements

The maximum sliding displacements of the superstructure relative to the base of the buildings from five- to seventeen- stories subjected to the Koyna earthquake vary from 97 mm to 111 mm whereas this variation is between 73 mm to 128 mm in the case of the El Centro earthquake.

7. CONCLUSIONS

The multistory masonry buildings utilizing a friction base isolation (FBI) system are subjected to reduced seismic force during an earthquake compared to similar buildings with fixed base. The story-wise variation of the drift ratio for a particular value of the coefficient of friction is small in the case of all the three buildings, but this variation is large for similar buildings with fixed base. The maximum displacements of the superstructure relative to the base of the buildings are likely to be small enough which could be provided on the plinth. Further investigation has to be undertaken to study the applicability of the FBI system for a wide range of time periods and other important parameter of multistory buildings.

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