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APPLICATION OF BASE ISOLATION FOR FLEXIBLE BUILDINGS

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SUMMARY

Seismic isolation enables the reduction in earthquake forces by lengthening the period of vibration of the structure. The conventional period of isolated structures is generally kept as 2 sec. Therefore; the significant benefits obtained from isolation are in structures for which the fundamental period of vibration without base isolation is short, less than 1.0 sec. This paper consists of analytical study of base-isolation for buildings with higher natural period ranging from 1.0 to 3.0 second. Different possibilities are explored to increase the feasibility of base isolation for such type of buildings. Strategies proposed in this study are (i) increasing superstructure stiffness, (ii) increasing superstructure damping and (iii) increasing flexibility of isolation system. It is observed that the effectiveness of base isolation for these buildings may be increased by incorporating such provisions.

INTRODUCTION

Seismic isolation enables the reduction in earthquake forces by lengthening the period of vibration of the structure. The typical period of isolated buildings is generally kept as 2.0 second (Constantinou [1]). Therefore the significant benefits obtained from isolation are in structures for which the fundamental period of vibration without base isolation is short, less than 1.0 second. Buildings with comparatively higher natural period attract low earthquake forces even without seismic base isolation. In the early stages of development of seismic isolation, prevention of collapse of the structure was the primary goal. Therefore, seismic isolation has mostly been used for low-rise buildings (Kelly [2]). However, later other additional considerations like comfort of occupants, functionality of important buildings during and after earthquakes, non-damage to non-structural elements and contents *etc.* have exerted an increasingly important influence. There have been proposals to use isolation to new tall buildings (Okoshi [3]) and to retrofit buildings with relatively long fixed-base periods, which are deficient in seismic resistance (Honeck [4]; Qamaruddin [5]).

There seems to be a possibility of increasing effectiveness of base isolation for relatively tall buildings by employing some strategies viz. (i) stiffening their superstructure, (ii) increasing damping in the superstructure and (iii) increasing flexibility of isolation system. The purpose of this study is to investigate the effect of implementing the above strategies in enhancing the effectiveness of base isolation to buildings with fundamental period ranging from 1.0 second to 3.0 seconds. Ten, fourteen and a twenty storey buildings are considered in this study. The isolation system considered in the study is low damping

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laminated rubber bearings combined with viscous damper. In order to see the effect of ground motion, seven real earthquake records covering different characteristics are considered for this analytical study.

THE BUILDINGS

The buildings considered for this analytical study are a ten storey, a fourteen storey and a twenty-storey building. These are reinforced concrete frame structures with masonry infill walls. Plan of fourteen and twenty storey building is part of the office building. The ten-storey building plan is the part of a hospital building. Equivalent viscous damping of the superstructure of the base-isolated building, in general, is assumed as 2 percent of critical. However, for studying the effect of superstructure damping, it is varied from 2% to 20% of critical. It is considered as 5% of critical for fixed base buildings. Infill masonry walls are considered for mass computation only and their contribution towards stiffness is neglected. In order to study the effect of superstructure stiffening, buildings with bare moment resisting frame only and the same buildings with stiffening elements like cross bracings at their end bays are analyzed. First six natural periods of these buildings with fixed base (F.B.) conditions, using ETABS model (Wilson [6]) are given in Table 1. Figures 1 to 4 show details of the buildings considered for the study. In case of stiffened 10 storey building, the braces of size 300mm x 300mm are also provided throughout the height of the building in both the bays at the two ends (Fig. 3). In order to study the 14 and 20 storey buildings with stiffened superstructure the braces of size 500mm x 500mm are provided throughout the height of the building in all the three bays at the two ends.

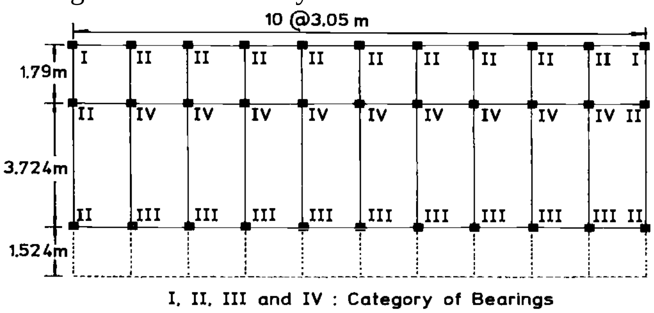

Fig. 1: Plan of 10 storey building

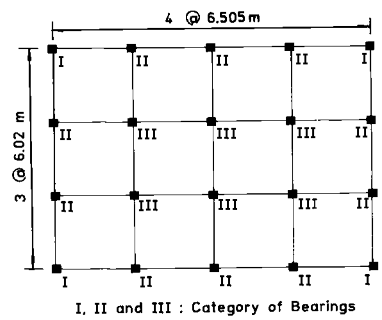

Fig. 2: Plan of 14 and 20 storey buildings

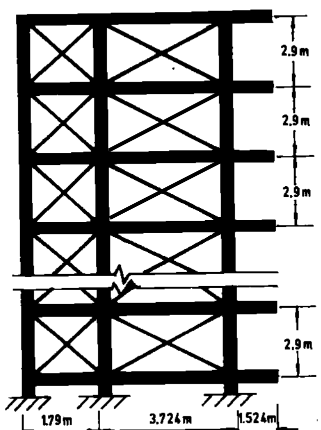

Fig. 3: Side Elevation of 10 storey building (Fixed-Base)

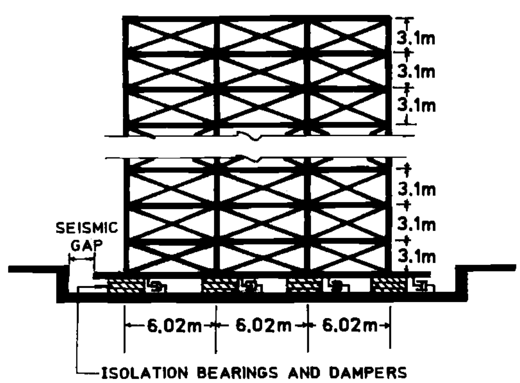

Fig. 4: Side elevation of 14 and 20 storey buildings (Base-Isolated)

Table 1 Natural Periods of the Buildings with Fixed-Base Condition

Mode No.	Time periods of the buildings (*sec*)					
	10 storey		14 storey		20 storey	
	Unstiffened	*Stiffened*	*Unstiffened*	*Stiffened*	*Unstiffened*	*Stiffened*
1	1.14	0.88	2.15	0.65	3.08	1.03
2	0.99	0.78	2.15	0.52	3.06	0.82
3	0.87	0.57	1.77	0.29	2.47	0.43
4	0.35	0.28	0.68	0.19	0.98	0.28
5	0.31	0.22	0.68	0.16	0.98	0.24
6	0.28	0.16	0.57	0.10	0.80	0.14

BASE ISOLATION OF THE BUILDINGS

The isolation system considered in this study comprises of low damping elastomeric bearings with external viscous dampers. Each column of the base-isolated (B.I.) building is assumed to have rubber bearing and viscous dampers at its base. The rubber bearings are grouped into different categories based on the magnitude of the vertical load transferred from different columns. As shown in plans of the buildings, bearings are grouped in 4 categories for 10 storey building and in 3 categories for 14 and 20 storey buildings. If elastomeric bearings are used as isolation systems, buckling limits the natural period to about 3 seconds (Stanton [7]). Therefore, in order to investigate the effectiveness of increasing the flexibility of seismic isolation system, two types of isolation systems are considered. One, that shifts the fundamental period of the buildings to 2 seconds and the other one shifts the fundamental period to 3 seconds. The rubber bearings are modelled as elastic element and external dampers are modelled as linear viscous element. Knowing the weight coming on the isolator and the desired time period of the base-isolated building, the horizontal stiffness of the isolator can be computed according to Kelly [8]. The equivalent viscous damping provided in the isolation system is assumed to be 10 percent of critical in all the cases. The design parameters of the isolation system provided in the buildings are given in Table 2.

Table 2 Design Parameters of Isolation Systems for the Buildings

Parameter	**Horizontal Stiffness of Bearing, K_h (*kN/m*)**								**Isolation Damping (%)**
Bearing Category	**I**		**II**		**III**		**IV**		
Isolation period	***2 sec***	***3 sec***	***2 sec***	***3 sec***	***2 sec***	***3 sec***	***2 sec***	***3 sec***	
10 storey building	453	201	750	335	1100	492	1250	559	10.0
14 storey building	2088	928	3572	1587	5911	2627	--	--	10.0
20 storey building	2986	1327	5114	2273	8427	3745	--	--	10.0

EARTHQUAKE MOTIONS CONSIDERED

In order to study effect of earthquake characteristics, seven real earthquake motions are considered in this study. Fourier spectra for these ground motions reveal that dominating frequencies covered by these ground motions ranges from 0.5 to 8.5 Hz. The selected records have a variety of peak ground acceleration (PGA) values. The salient features of these ground motions are shown in Table 3 (Chandrasekaran [9]; Uang [10]). Base isolation is recommended as a feasible solution for the zone in which expected peak ground acceleration has a minimum value of 0.4g (Lashkari [11]) and therefore the buildings are analysed for earthquake motions scaled to same peak ground acceleration of 0.4g. Based on the range of dominant frequencies, the ground motions considered are classified into two groups viz. (i) motions having dominant frequencies above 1.5 Hz only such as NE India (Berlongfer station), Uttarkashi and Koyna, and (ii) ground motions having dominant frequencies ranging from 0.5 Hz to 5.0 Hz such as

El Centro, NE India (Silchar station), Taft and Parkfield. The time history of Koyna earthquake motion was recorded close to epicenter of the shock and has relatively high acceleration pulses and frequency contents.

Table 3 : Characteristics of Earthquake Motions

Earthquake Date	M	Station	Components	PGA (m/s^2)	Underlying Strata	Dominant frequencies
NE (India) Aug. 6, 1988	6.8	Berlongfer	S76W	2.95	Sandy soil	1.5 - 3.0 Hz
			N14W	3.37		
Uttarkashi Oct. 20, 1991	6.5	Uttarkashi	N15W	2.37	Rock	2.5 - 6.5 Hz
			N75E	3.04		
Imperial Valley May 18, 1940	6.3	El Centro	S00E	3.35	Alluvium	0.1-10.0 Hz
			S90W	2.10		
NE(India) Aug. 6, 1988	6.8	Silchar	N60E	0.63	Alluvium	0.5 – 2.5 Hz
			S30E	0.89		
Koyna Dec.12, 1967	6.5	Koyna dam	Longitudinal	6.19	Rock	2.5 – 8.5 Hz
			Transverse	4.22		
Taft July 21, 1952	7.7	Kern County	N21E	1.53	12m alluvium over sandstone	0.5-5.0 Hz
			S69E	1.76		
Parkfield June 27, 1966	5.6	Cholame Shandon	N85E	4.26	Alluvium	1.0-4.0 Hz
			N05W	3.48		

M = Magnitude of earthquake; PGA = Peak ground acceleration

METHOD OF ANALYSIS

Seismic response of the base isolated buildings is obtained by means of computer programme, 3D-BASIS-TABS. The details of software are described in NCEER reports by Nagarajaiah [12] and Reinhorn [13]. The analysis is based on following assumptions:

The superstructure is elastic at all time and the non-linear behaviour is restricted in isolators only.

All frame substructures are connected at each floor level by a diaphragm, which is infinitely rigid in its own plane.

Each floor has three degrees of freedom (two translations and one rotation) attached to the centre of mass of the floor.

The isolation devices are rigid in the vertical direction and have negligible torsion resistance.

RESULTS OF THE ANALYTICAL STUDY

In the present study, time history analysis of three multi storeyed buildings is carried out for different earthquake motions scaled to same PGA of 0.4g. The results of time history analysis are interpreted in the context of objectives of the study that is (i) to investigate the effectiveness of base isolation for flexible buildings, (ii) effect of superstructure stiffening, (iii) effect of increase in superstructure damping and (iv) effect of increase in flexibility of isolation system. Effectiveness ratio (ER), which is ratio of response of fixed base to that of base isolated building, is considered as the parameter for studying the effectiveness of isolation. Greater the value of ER, more is the effectiveness of base isolation. It is assumed for this study that a base isolation system can be considered as feasible if the value of ER is close to 2.5 or more. Detailed discussion of results from this numerical study is presented in the following sections.

Effectiveness of Base Isolation with Conventional Isolation System

The effectiveness of base isolation for the buildings with bare moment resisting frames is investigated for conventional base isolation system having isolation period of 2 second. The buildings are analyzed with fixed-base and base-isolated conditions in order to study the effectiveness of base isolation. Table 4 shows the variation of ER with respect to maximum storey shear and maximum roof acceleration for the three buildings excited by different earthquake motions. Though ER is significantly high for 10 storey building, it generally varies between 1.0 and 2.0 for 14 and 20 storey buildings. It is observed that for 10 storey building, the base isolation is effective in reducing the floor accelerations for high frequency motions as well as motions with broad range of frequency contents but succeeds in reducing significantly the maximum storey shear for earthquake motions with high frequency contents only. In case of 14 and 20 storey buildings, the reduction in maximum acceleration and storey shear is insignificant even for the ground motions with high frequencies only. The ratio exceeds unity possibly due to the presence of high damping in isolation system. Floor acceleration response also follows the similar trend.

Table 4 Effectiveness Ratio for the Unstiffened Buildings
(*Base isolation with 2 sec period*)

Earthquake motion *(Scaled to 0.4g PGA)*	***Effectiveness ratio, ER***					
	10 storey		***14 storey***		***20 storey***	
	Shear	*Acceleration*	*Shear*	*Acceleration*	*Shear*	*Acceleration*
El Centro	1.76	2.85	1.29	1.34	1.83	2.13
Koyna	1.69	3.48	2.23	2.82	1.98	1.66
NE India(Berlongfer)	7.20	3.86	1.58	1.74	1.65	1.37
NE India (Silchar)	4.63	3.54	1.29	1.74	1.58	1.35
Parkfield	2.13	6.72	1.30	2.50	1.97	1.56
Taft	1.80	4.12	1.52	1.78	1.08	2.15
Uttarkashi	5.40	4.48	2.34	1.82	2.08	1.28

Table 5 shows the variation of maximum storey drift. Base isolation resulted in significant decrease of storey drift for 10-storey building. The reduction is much less for 14 and 20 storey buildings; the maximum storey drift even increases for some earthquake motions. As shown in Table 8, the maximum base displacement in all the three base-isolated buildings does not exceed 215mm. The results indicate that effectiveness of conventional base isolation for these buildings depends upon the number of storeys and the frequency contents of the input base motion. It is observed that conventional design of base isolation is generally not effective for flexible buildings.

Table 5 Maximum Storey Drift for Fixed-Base and Base Isolated Buildings
(*Base isolation with 2 sec period*)

Earthquake motion *(Scaled to 0.4g PGA)*	***Maximum Storey Drift (%)***					
	10 storey		***14 storey***		***20 storey***	
	F.B.	***B.I.***	***F.B.***	***B.I.***	***F.B.***	***B.I.***
El Centro	1.07	0.53	1.16	1.02	1.02	0.68
Koyna	0.29	0.18	0.42	0.41	0.42	0.40
NE India(Berlongfer)	0.75	0.18	0.41	0.30	0.41	0.34
NE India (Silchar)	1.55	0.38	0.97	0.71	0.95	0.73
Parkfield	0.58	0.19	0.50	0.39	0.39	0.28
Taft	0.84	0.34	0.79	0.71	0.73	0.75
Uttarkashi	0.54	0.14	0.36	0.21	0.20	0.21

Effect of Superstructure Stiffening

There is possibility of reduction of forces in relatively tall buildings by first stiffening of superstructure. Idea is that the stiffening may results in lower fixed-base period and such buildings, if base-isolated may develop smaller seismic response (Kelly [8]). This concept is studied so as to arrive at definite conclusions. In order to see the effectiveness of base isolation for stiffened buildings, the comparison is made between the fixed-base and base-isolated responses of the buildings. While implications of stiffening the superstructure of base-isolated buildings is investigated by comparing the seismic response of base isolated buildings without and with superstructure stiffening.

Effectiveness of base isolation for stiffened buildings

The stiffened buildings with fixed-base and base-isolated support conditions respectively are analyzed for different base motions scaled to same PGA of 0.4g. As observed from Table 1, the stiffening of superstructure reduces the natural periods of the building bringing it down close to that of low rise buildings. The effectiveness ratio is computed for these buildings. Table 6 shows the variation of ER with respect to storey shear and floor acceleration for the 10, 14 and 20 storeys unstiffened and stiffened buildings respectively subjected to different base motions.

It is observed from Table 4 and 6, that in case of 10-storey building, the value of ER increases significantly by stiffening for Uttarkashi, Taft, Koyna and El Centro motions while decreases for the Parkfield and NE India earthquake motions. The value of ER for stiffened 10-storey building subjected to Parkfield motion is very low. In cases of Parkfield and NE India earthquake motions, the base isolation is more effective when the building is unstiffened while for other cases it is found to be more effective for stiffened building. For Parkfield earthquake motion, this may be due the fact that the fixed-base stiffened ten-storey building has storey shear less than the storey shear of corresponding unstiffened building. However, as observed from Table 7, for NE (India) motions, increased value of storey shear for base-isolated stiffened building also contributed in reduction of effectiveness ratio. Further comparison of Table 4 and 6 shows that for 14-storey and 20 storey buildings, effectiveness ratio is always much higher for stiffened building as compared to corresponding unstiffened buildings. In case of all the three stiffened buildings, the effectiveness ratio exceeds 6.0 for Uttarkashi and NE India (Berlongfer) motions.

Table 6 Effectiveness Ratio for the Stiffened Buildings
(*Base isolation with 2 sec period*)

Earthquake motion *(Scaled to 0.4g PGA)*	***Effectiveness ratio, ER***					
	10 storey		***14 storey***		***20 storey***	
	Shear	*Acceleration*	*Shear*	*Acceleration*	*Shear*	*Acceleration*
El Centro	2.91	4.59	3.47	5.06	2.22	3.30
Koyna	3.82	5.93	4.25	6.72	5.10	5.07
NE India(Berlongfer)	6.09	5.75	7.35	5.72	6.25	4.63
NE India (Silchar)	3.79	4.78	3.75	6.18	4.41	3.72
Parkfield	1.72	6.84	2.14	2.78	4.51	3.21
Taft	3.69	5.54	3.15	4.45	1.78	2.63
Uttarkashi	10.9	9.36	7.12	5.63	6.44	3.77

Implications of superstructure stiffening

Table 7 shows the variation of maximum storey shear of stiffened and unstiffened base-isolated buildings for different ground motions. In case of 10 storey base-isolated building, it is observed that for NE India (Berlongfer) and Uttarkashi earthquake motions, the maximum storey shear increases significantly with stiffening of superstructure while for other base motions the difference is insignificant. In case of 14 and 20 storey base-isolated buildings the maximum storey shear increases significantly with superstructure stiffening for most of the base motions. The amount of increase is as high as 65 percent.

Table 8 shows the variation of maximum roof acceleration of stiffened and unstiffened buildings for different ground motions. It is observed that for all the three buildings, the difference in maximum roof acceleration is insignificant.

Table 9 shows the variation of maximum base displacement of stiffened and unstiffened buildings for different ground motions. It is observed that in general the maximum base displacement is more or less same for stiffened and unstiffened 10 storey base-isolated building. In case of 14 and 20 storey buildings, the maximum base displacement is significantly higher for stiffened buildings.

Table 7 Maximum Storey Shear of Base-Isolated Buildings
(*Base isolation with 2 sec period*)

Earthquake motion *(Scaled to 0.4g PGA)*	**Maximum storey shear (*kN*)**					
	10 storey		***14 storey***		***20 storey***	
	Unstiffened	*Stiffened*	*Unstiffened*	*Stiffened*	*Unstiffened*	*Stiffened*
El Centro	6735	6556	12751	13625	7173	10436
Koyna	2390	2522	5132	5942	4252	7051
NE India(Berlongfer)	1318	1844	3250	3613	4711	4298
NE India (Silchar)	3603	4179	7886	11909	9621	11125
Parkfield	2915	2910	5024	6508	3391	3402
Taft	4483	4316	8816	10385	9395	13615
Uttarkashi	1306	1605	2415	3811	2635	3794

Table 8 Maximum Roof Acceleration of Base-Isolated Buildings
(*Base isolation with 2 sec period*)

Earthquake motion *(Scaled to 0.4g PGA)*	**Maximum Roof Acceleration (*m/s^2*)**					
	10 storey		***14 storey***		***20 storey***	
	Unstiffened	*Stiffened*	*Unstiffened*	*Stiffened*	*Unstiffened*	*Stiffened*
El Centro	2.69	2.45	3.90	2.40	2.34	2.93
Koyna	0.98	1.12	1.30	1.20	0.92	0.96
NE India(Berlongfer)	1.40	1.81	1.85	1.40	1.63	1.31
NE India (Silchar)	2.52	2.18	3.53	2.11	3.31	2.80
Parkfield	1.08	0.99	1.01	1.27	0.94	0.97
Taft	1.95	2.07	2.58	2.11	2.41	2.04
Uttarkashi	1.60	1.46	1.49	1.44	1.30	1.28

Table 9 Maximum Base Displacement of Conventional Base-Isolated Buildings
(*Base isolation with 2 sec period*)

Earthquake motion *(Scaled to 0.4g PGA)*	**Maximum Base Displacement (*mm*)**					
	10 storey		***14 storey***		***20 storey***	
	Unstiffened	*Stiffened*	*Unstiffened*	*Stiffened*	*Unstiffened*	*Stiffened*
El Centro	215	215	164	179	74	214
Koyna	78	79	66	77	45	77
NE India(Berlongfer)	43	47	34	45	45	51
NE India (Silchar)	114	133	103	152	109	117
Parkfield	96	96	66	87	35	91
Taft	146	142	116	131	104	145
Uttarkashi	36	43	34	42	25	38

Table 10 shows the variation of maximum storey drift of stiffened and unstiffened buildings for different ground motions. It is observed that maximum storey drift is always more for unstiffened buildings. The maximum storey drift is reduced to approximately half in the case of ten storey base-isolated building while for 14 and 20 storey buildings, the reduction is enormous. The maximum interstorey drift reduced to one tenth or even less due to stiffening of the superstructure of these base-isolated buildings.

Table 10 Maximum Storey Drift in Base-Isolated Buildings
(*Base isolation with 2 sec period*)

Earthquake motion *(Scaled to 0.4g PGA)*	**Maximum storey drift (%)**					
	10 storey		***14 storey***		***20 storey***	
	Unstiffened	*Stiffened*	*Unstiffened*	*Stiffened*	*Unstiffened*	*Stiffened*
El Centro	0.53	0.20	1.02	0.10	0.68	0.21
Koyna	0.18	0.08	0.41	0.05	0.40	0.07
NE India(Berlongfer)	0.18	0.10	0.30	0.04	0.34	0.06
NE India (Silchar)	0.38	0.14	0.71	0.09	0.73	0.15
Parkfield	0.19	0.08	0.39	0.04	0.28	0.07
Taft	0.34	0.14	0.71	0.08	0.75	0.13
Uttarkashi	0.14	0.08	0.21	0.04	0.21	0.06

Effect of Superstructure Damping

Increase in superstructure damping in fixed base tall buildings have been proposed by many researchers and subsequently implemented successfully to control the wind and earthquake induced vibrations (Ciampi [14]; Constantinou [15]; Pall [16]). Recently devices have been developed which can economically increase superstructure damping up to the level of 20% (Niwa [17]). There seems to be a possibility of increasing effectiveness of base isolation for tall buildings by increasing damping in the superstructure. In order to investigate this strategy, the 10 and 14 storey base-isolated buildings are analyzed. Equivalent viscous damping in superstructure is varied in the range of 2 percent to 20 percent of critical and the corresponding reduction in response parameters is computed. Fig. 5 and 6 shows the percentage reduction in maximum roof acceleration and interstorey drift respectively due to increase in the superstructure damping for the two base-isolated buildings. It is observed from Fig. 5 that decrease in maximum roof acceleration, in the case of 14 storey building is higher than that for 10 storey building. Reduction is more for NE India (Berlongfer) and Uttarkashi base motions for both the buildings. The decrease in maximum roof acceleration, for all the base motions, is above 30 percent for 14-storey building. Fig. 6 shows that increase in superstructure damping also reduces the maximum interstorey drift and effect of superstructure damping is more in 14-storey building than the 10-storey building. Again the reduction in maximum storey drift is high for both the buildings subjected to NE India (Berlongfer) or Uttarkashi earthquake motions. In case of 10-storey building subjected to base motions with broad range of frequency contents the reduction in maximum storey drift is less than 20 percent. In case of 14-storey building, the decrease is always more than 20 percent.

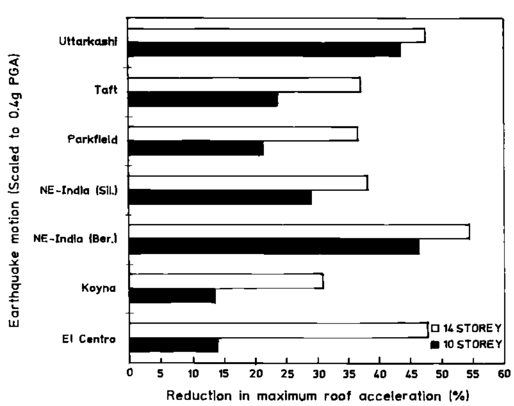

Fig. 5: Percentage decrease in maximum roof acceleration with increase in superstructure damping from 2% to 20%

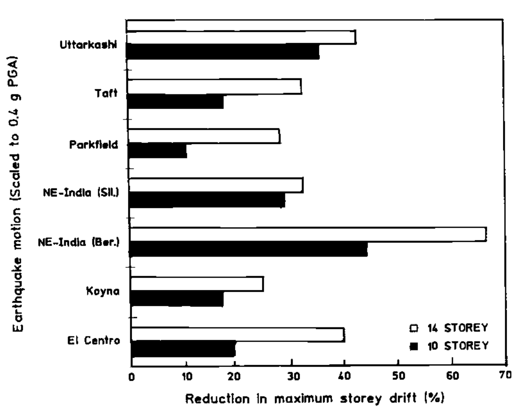

Fig. 6: Percentage decrease in maximum storey drift with increase in superstructure damping from 2% to 20%

The variation of maximum base displacement for the 10 and 14 storey base-isolated buildings with increase in superstructure damping from 2 percent to 20 percent is shown in Fig. 7 and 8. Fig. 7 shows that increase in superstructure damping has insignificant effect on maximum base displacement for the 10-storey building. In case of 14 storey building, the base displacement decreases significantly with increase in superstructure damping for El Centro, Taft and NE India (Silchar) earthquake motions while for the remaining motions, the change is insignificant.

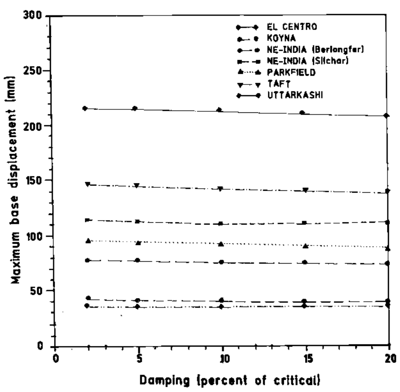

Fig. 7: Variation of maximum base displacement with superstructure damping (10 storey base isolated building)

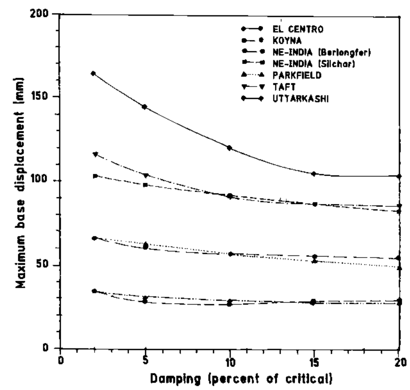

Fig. 8: Variation of maximum base displacement with superstructure damping (14 storey base isolated building)

Effect of Flexibility of Isolation System

There seems to be a possibility of increasing effectiveness of base isolation for tall buildings by further increase in the flexibility of isolation system. High damping elastomeric compounds with lower shear moduli can be used for this purpose (Kelly [18]). Shake table tests, in which the same model is tested on elastomeric bearings with different moduli has confirmed that the softer bearings are more effective in isolating low frequency earthquakes (Aiken [19]; [20]). To observe the behaviour of buildings with more flexible isolation system, the fundamental period of base isolated buildings are adopted as 2sec and 3sec respectively and the corresponding parameters of the isolation system has already been given in Table 2.

The base-isolated buildings are analyzed with base isolation system of 3.0 sec period. Table 11 presents the values of ER with respect to storey shear and roof acceleration for the three buildings. It is observed that for 10-storey building, the effectiveness ratio varies in the large range. ER with respect to shear for this building has high values for all the earthquake motions except Koyna. The value of ER for 14 storey building does not go below 2.0 for all the motions while for 20 storey building, except the Taft motion, the value of ER always exceeds 2.30.

Tables 4 and 11 clearly demonstrate that effectiveness ratio increases significantly with the increase in fundamental period from 2sec to 3sec for all the three buildings. ER with respect to roof acceleration is also increased, in general, with the increase in fundamental period of the base-isolated buildings. In fact, it is observed that the effectiveness of increasing time period is more in reducing floor accelerations than the maximum storey shear. The value of ER with respect to maximum roof acceleration reaches to the maximum value of 12.74 for 10 storey, 5.10 for 14 storey and 3.56 for 20 storey with 3 sec fundamental time period as compared to values of 6.72, 2.82 and 2.15 respectively for corresponding buildings with 2 sec time period.

Table 12 shows the percentage reduction in maximum storey shear and roof acceleration of the three unstiffened base-isolated buildings due to increase in time period from 2sec to 3sec. It is observed that the lengthening of time period results in significant reduction in maximum values of storey shear and roof acceleration both. The decrease in these response parameters is generally in the range of 30 to 50%. In some cases the response is reduced to half or even one third.

Table 11 Effectiveness ratio for the unstiffened buildings
(*Base isolation with 3 sec period*)

Earthquake motion *(Scaled to 0.4g PGA)*	***Effectiveness ratio, ER***					
	10 storey		***14 storey***		***20 storey***	
	Shear	*Acceleration*	*Shear*	*Acceleration*	*Shear*	*Acceleration*
El Centro	4.17	4.85	2.78	2.59	2.78	3.56
Koyna	2.50	4.13	3.55	5.10	2.96	2.22
NE India(Berlongfer)	10.4	5.81	2.45	3.10	3.00	2.28
NE India (Silchar)	7.26	4.62	2.05	2.70	2.36	2.32
Parkfield	5.96	12.74	3.33	3.71	2.35	2.88
Taft	3.49	5.99	2.79	2.55	1.65	1.65
Uttarkashi	9.40	6.23	4.80	3.24	3.43	1.93

Table 12 Reduction in response due to increase in time period from 2*sec* to 3*sec*

Earthquake motion *(Scaled to 0.4g PGA)*	***Reduction in maximum response (%)***					
	10 storey		***14 storey***		***20 storey***	
	Shear	*Acceleration*	*Shear*	*Acceleration*	*Shear*	*Acceleration*
El Centro	57.7	41.3	53.6	48.5	45.5	40.2
Koyna	32.5	12.2	37.1	44.6	49.4	25.0
NE India(Berlongfer)	30.7	33.6	35.6	43.8	39.5	39.9
NE India (Silchar)	36.2	23.4	37.1	35.7	36.8	41.7
Parkfield	64.2	47.2	61.0	32.7	49.3	45.7
Taft	48.4	31.3	45.3	30.2	7.10	29.5
Uttarkashi	42.5	28.1	51.2	43.6	52.0	33.8

Table 13 shows the maximum base displacements for the three base-isolated buildings with base isolation system corresponding to time period of 2 second and 3 second. Maximum base displacement is generally higher for the three base-isolated buildings with 3sec time period. However, difference between the two displacements is low, less than 50mm. Therefore; it can be observed that increase in time period of these buildings does not result in excessive seismic gap requirement.

Table 13 Maximum base displacement of the base-isolated buildings

Earthquake motion *(Scaled to 0.4g PGA)*	***Base Displacement (mm)***					
	10 storey		***14 storey***		***20 storey***	
	2 sec	*3 sec*	*2 sec*	*3 sec*	*2 sec*	*3 sec*
El Centro	215	196	164	151	74	102
Koyna	78	106	66	90	45	65
NE India(Berlongfer)	43	51	34	54	49	56
NE India (Silchar)	114	160	103	142	109	137
Parkfield	96	69	66	51	35	53
Taft	146	158	116	138	104	147
Uttarkashi	36	38	34	28	25	25

DISCUSSION OF RESULTS

Three buildings of 10 to 20 storey are analyzed in this study. The buildings are excited by seven real earthquake motions of different characteristics but scaled to same peak ground acceleration of 0.4g. The results obtained from the analytical study are discussed in the following paragraphs.

Effect of superstructure stiffening

Seismic response of the three base-isolated buildings with and without superstructure stiffening shows that stiffening of superstructure affect the response of base-isolated tall buildings. It is observed that base isolation results in significant reduction in structural response for stiffened buildings as compared to unstiffened one for all the earthquake motions. However, comparison of response of the base isolated buildings with and without stiffened superstructure shows that there is no significant change in the structural response, though the influence of superstructure stiffening is more in case of taller buildings. The maximum roof acceleration and the maximum storey drift reduce with the stiffening of the superstructure while storey shear and base displacement of the base-isolated building increases due to stiffening of the superstructure. Therefore, in situations where the floor acceleration or interstorey drifts are important parameters, the superstructure stiffening of base-isolated buildings has beneficial effects.

Effect of Increase in Superstructure Damping

It is observed that increase in the damping succeeds in lowering down the seismic response of these buildings with unstiffened superstructures. Separation between fundamental periods of these buildings with fixed-base and base-isolated support conditions is low which may lead to more contribution of higher modes for these buildings and hence increase in superstructure damping becomes more beneficial. The effectiveness of superstructure damping is seen to be more for taller buildings.

However, increase in superstructure damping from 2% to 20% do not generally results in very high decrease of seismic response of the three base-isolated buildings. This is possibly due to lesser participation of higher modes in the base-isolated buildings. The increase in superstructure damping, in case of 14 storey building, produce negligible effect on maximum base displacement for high frequency earthquake motions. While for same building, there is some decrease in the base displacement for base motions possessing low frequency contents.

Effect of Increase in Flexibility of Isolation System

It is observed that base isolation, which is not that effective for relatively tall buildings, with conventional base isolation system of 2sec, may become feasible for earthquake motions with high frequency contents as well as with broad range of frequency contents by increasing isolation period to 3.0 seconds. Maximum displacement at isolation level generally increases with increase in flexibility of the isolation system though the difference in the displacements is not significant. The lower increase in the displacement may be due to presence of 10% isolation damping which is sufficiently large amount to control the displacement at the isolation level. Looking into greater reduction in shear and acceleration, this small increase in maximum base displacement is not of much consequence.

CONCLUSIONS

An attempt is made to investigate the strategies that may result base isolation effective for the buildings having fundamental time period ranging from 1.0 to 3.0 sec. Three buildings having 10, 14 and 20 storeys are analyzed in this study. Three approaches are explored viz. increase in (i) superstructure stiffness, (ii) superstructure damping and, (iii) flexibility of isolation system. The conclusions based on this analytical study are as follows:

Stiffening of superstructure affects the response of the base-isolated buildings. Base isolation results in significant reduction in structural response of stiffened buildings as compared to unstiffened one.

There is no significant difference between the response of the base isolated buildings with and without superstructure stiffening though the influence of superstructure stiffening is more in case of taller buildings.

Stiffening of superstructure of base-isolated buildings results in reduction of the maximum roof acceleration and the maximum storey drift while it increases the maximum storey shear and the maximum base slab displacement.

Increase in the damping of superstructure reduces the seismic response of base-isolated buildings though the reduction is not appreciable.
Response reduction due to increase in superstructure damping is more for high frequency base motions. Also the reduction is generally more for taller buildings.
Superstructure damping has negligible effect on maximum base displacement of base-isolated buildings.
Increase in the flexibility of isolation system is very effective in reducing the response of the buildings. However, there is a small increase in the maximum base displacement.

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