16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3072

Registration Code: S-P1465642214

BEHAVIOR OF BASE ISOLATED BUILDINGS SUBJECTED TO NEAR FIELD EARTHQUAKES

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Abstract

Most of the base-isolated buildings are designed and tested for design basis far-field ground motion. This leaves a scope for investigation of seismic vulnerability of bases isolated buildings under near-field effects. Typically a near-field earthquake is identified as large amplitude, low frequency, short duration, a pulse type ground motion known for its high damage potential and ductility demand due to its whiplash effect. The present study seeks to investigate the effectiveness of base isolation system for seismic hazard mitigation of buildings, especially under near-field effects. For the study response, history analysis is carried out for a ten storey building frame, both fixed base and isolated, subjected to near-field ground motions, and the same structure is also subjected to a set of far-field ground motions. Two levels of earthquakes are used i.e. design level (scaled to have PGA = 0.2g) and extream level (scaled to have PGA = 0.4g). The selected response parameters for the comparative study are peak values of floor displacement, acceleration and base shear. The result of the study highlights that (i) for the two levels of PGA of earthquake considered in the study, the results in base shear, top floor absolute acceleration and maximum storey drift are significant for far-field earthquake and near-field earthquake with directivity effect, (ii) for the near-field earthquake with fling step effect, percentage reduction in the above response quantities is considerably reduced indicating that the base isolation proved to be ineffective for this type of near-field earthquake, (iii) the time history of the top storey displacement for near-field earthquake with fling step effect is distinctively different than those for other earthquakes and (iv) force-deformation loop of the isolator differ widely with earthquakes, for the near-field earthquake with fling step effect. The hysteresis curve is narrow with large displacement especially for the higher level of PGA.

Keywords: Far field earthqukae, Near-field earthquake, Base isolation, inelastic deformation, Base isolated structure

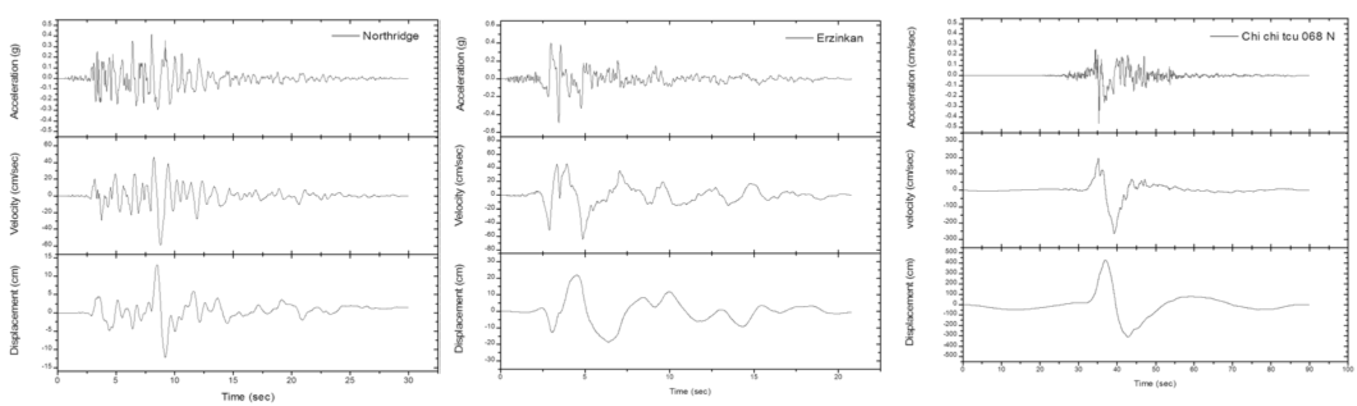
1. Introduction

A base-isolated building has been analyzed and designed mostly for far-field earthquakes with design level earthquake, in which the superstructure remains linear, and isolator goes into the non-linear state. A primary concern in the base-isolated structure is the isolation displacement and acceleration of the building. A lot of studies have been carried out for far-field earthquakes on base isolated structures. Recently, the behavior of the base-isolated building for the near-field earthquake has become a topic of considerable interest because of the impulsive type of excitation experienced by the structure. The behavior of base isolation and base-isolated buildings under such earthquakes could be significantly different as compared to far-field earthquakes. For such type of excitations, even under relatively less peak ground acceleration, superstructure may get into inelastic range.

Near-field earthquakes consist of a major portion of fault energy in the form of pulses. These pulses tend to have maximum Fourier spectrum in limited periods whereas far-field earthquakes have maximum Fourier spectrum in the broad range of periods. Near field earthquakes are associated with two major effects namely, directivity effect and fling step effect. These effects are based on three main active parameters of near-field ground motions which are rupture mechanism, slip direction of rupture relative to the site and residual ground displacement. When the direction of propagation of rupture is aligned towards the site or having a small angle between them and when the velocity of fault rupture is close to shear wave velocity of the site then it is called forward directivity effect. Due to this effect, large amplitude pulses with the long period and short duration are generated which are highly destructive in nature. Fling step effect is accompanied by permanent ground displacement resulting from tectonic deformations. It produces large amplitude unidirectional velocity pulse and a monotonic step in displacement time history.

Figure 1 shows the comparison between far field, near field (Directivity effect) and near field (fling step effect) earthquakes by comparing their time histories of acceleration, velocity, and displacement. It can be clearly observed that there exists cyclic type wave in the time histories of the far-field earthquake. Near field earthquakes comprise of a low-frequency pulse in the acceleration time history and coherent pulses in velocity and displacement time histories. Monotonic step in displacement time history for fling step effect can be seen in Figure 1 (c).

Huang and Chen [1] studied the near-field ground motion characteristics and patterns of velocity waveforms in relation to the chelungpu rupture surface of the 1999 chi-chi earthquake. Li shuang and Xie li-li [2] studied the state of the art near-field problems in civil engineering, which included inherent characteristics of near-field ground motions and influences of these on civil structures. Kalkan and Kunnath [3] investigated the consequences of well-known characteristics of near-fault ground motions on the seismic response of steel moment frames. Effects of high-amplitude pulses on structural demands were studied by considering idealized pulses.



(a) Far field (b) Near field (Directivity effect) (c) Near field (Fling step effect)

Fig. 1 Comparison of Far Field, Near Field (Directivity effect) and Near Field (fling step effect) earthquakes

Various studies have been conducted by a number of researchers on the behavior of base isolated structures subjected to near-field ground motions. Rao and Jangid [4] investigated the response of a building supported on sliding isolation systems under near-fault ground motion in two horizontal directions. Akkar et al. [5] developed theoretical expressions for estimating the ground story and maximum inter-storey drift ratios by considering varying beam to column stiffness ratios in frame buildings subjected to near-fault ground motions. Heydari and Mousavi [6] conducted an incremental dynamic analysis of a seven storey concrete building subjected to near-field and far-field ground motions for comparing the structural displacements. Jangid and Kelly [7] studied the effect of isolation damping on the performance of different isolation systems under near-fault ground motions. Jangid [8] studied analytically the response of base-isolated multi-storey buildings with lead rubber bearings for near-fault ground motions and derived an optimum value of bearing yield strength for different system parameters. Ryan and Chopra [9] conducted the nonlinear response history analysis of an isolated (lead rubber bearing) block subjected to far field and near field ground motions, using an advanced bearing model that incorporates the relation between axial load and bearing response. Osgooei [10] et al. carried out time history analyses on a 2-story reinforced concrete shear wall structure subjected to far- field and near-field earthquakes, seismically isolated, using unbonded rectangular fiber reinforced elastomeric isolator FREI and with the fixed base. Davoodi et al. [11] studied the influence of near-fault and far-fault earthquakes by considering soil-structure interaction on the maximum response of an SDOF system. Alonso-Rodríguez and Miranda [12] investigated inter-storey drift and floor acceleration demand in buildings subjected to near-fault ground motions by considering simplified building and ground motion models. Elnashai [13] conducted the analysis of the damage potential of the Kocaeli (turkey) earthquake of 17th August 1999 for which two full-scale RC structures have been designed, built and tested. Jamnani et al. [14] investigated the displacement demands of an SDOF with different fundamental period values subjected to ground motion with and without fling step effect.

Although there are a number of studies on the response behavior of base isolated buildings under near-field earthquakes, more investigations are required especially to examine; (i) the effect of the two level concept of earthquake on base isolated building for near and far field ground motions; (ii) the difference between the response characteristics of base isolated buildings under ground motions having directivity and fling step effects both in the linear and nonlinear range; (iii) the ductility demands and the isolator nonlinearity for near field earthquakes as compared to the far field one; (iv) damage states of the base isolated buildings for the upper level near field and far field earthquakes. The present study is concerned with the above objectives. For this purpose, seismic response of a 10 storey building is obtained by performing time history analysis for a set of near field and far field earthquakes. The seismic response is obtained for both fixed base and base isolated conditions. Response parameters considered for the study are, base shear, top storey absolute acceleration, maximum storey drift, peak top floor displacement and isolator displacement. RMS (root means square) values of the top floor and first floor and isolator displacement.

2. Analysis

The frame is modeled and analyzed in SAP 2000. Base isolators are modeled as support elements. Base isolator properties which have been used for the analysis of base isolated building are taken as Keff (Effective stiffness) = 713 kN/m, K1 (Initial stiffness) = 5419 kN/m, βeff (Effective damping) = 0.1, γ (Post yield stiffness ratio) = .10, FY (Yield force) = 59.61 kN, Kv (Vertical stiffness) = 200687 kN/m.

To study and calculate the nonlinear behavior of the structure, default frame hinges are defined for beams and columns according to FEMA 356 in SAP 2000. Force-deformation behavior of plastic hinge is described by 5 points A, B, C, D, and E as shown in Figure 2. Figure 3 shows the isolator characteristics with properties as modeled in SAP 2000.

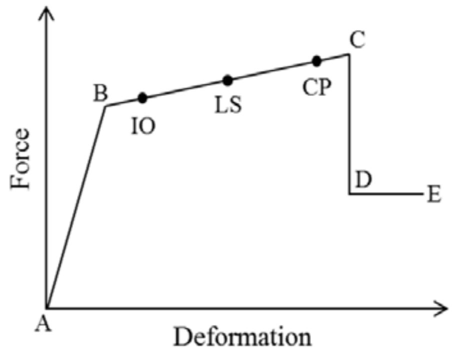


Fig. 2 Force deformation relationship of plastic hinge

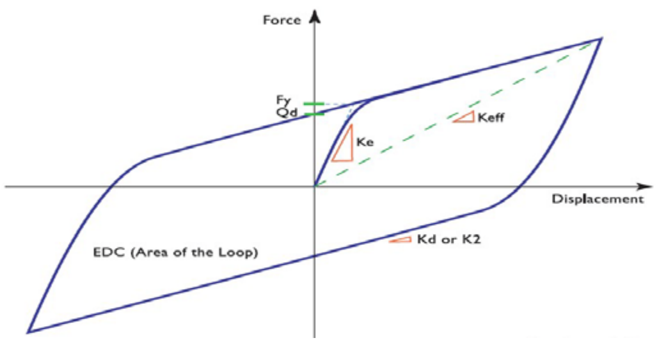


Fig. 3 Bilinear curve of isolator

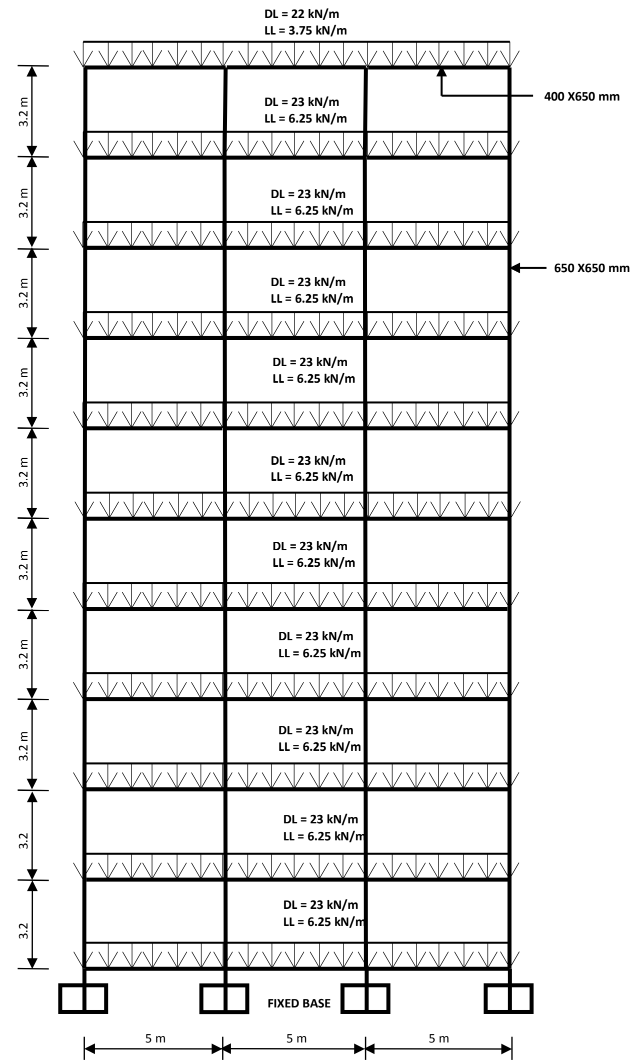


Fig. 4 Building frame details

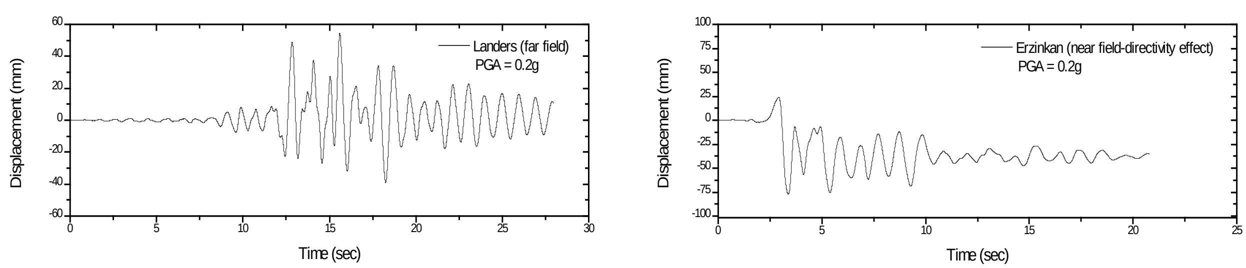
3. Numerical study

The building which has been considered for the study is a symmetrical square building consisting of 3 bays in each direction of 5 m width and 3.2 m storey height. A typical frame which is analyzed is shown in Figure 4. For the analysis, four sets of far field and near field earthquake records have been taken from PEER Strong Motion Database of Berkeley University. Out of the four near field earthquakes, two are selected with directivity effect and the other two with fling step effect. All the records have been normalized and scaled to .2g and .4g in order to obtain the two level earthquake design concept. All the relevant properties of records like PGA (peak ground acceleration), PGV (Peak ground velocity), and PGD (peak ground displacement) are given in table 1.

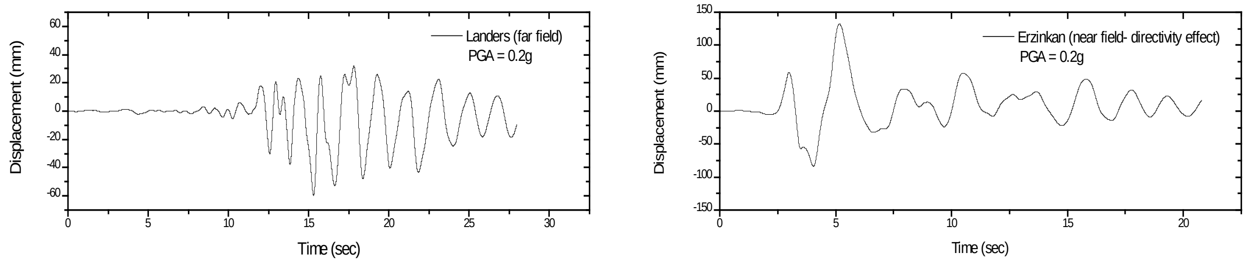
Table 1 Ground Motion Records

S.No.	Year	Earthquake	M_w	Station	Component	PGA (g)	PGV (cm/s)	PGD (cm)
Far Field Records								
1	1994	Northridge	6.7	Beverly hills	MULH, 009	0.42	58.91	13.18
2	1992	Landers	7.3	Cool water	SCE STATION 23	0.42	42.35	13.84
3	1978	Tabas	7.4	Ferdows	L	0.093	5.4	2.24
4	1987	Superstition hill	6.5	Poe road	POE 270		35.72	8.81
Near Field Records (Forward Directivity effect)								
1	1992	Erzinkan	6.69	Erzinkan	EW	0.5	64.32	21.91
2	2003	Bam	6.6	BAM	L	0.8	124.1	33.94
Near Field Records (Fling step effect)								
3	1999	Chi Chi	7.6	TCU 052	E	0.36	151.2	210.43
4	1999	Chi Chi	7.6	TCU 068	N	0.46	263.25	430.2

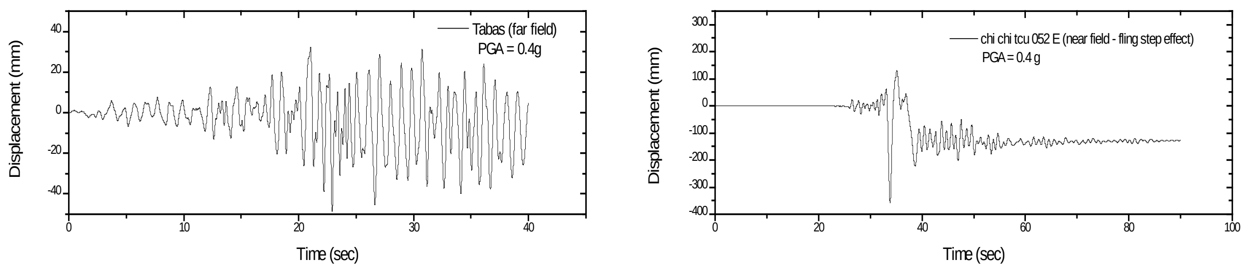
Figures 5 (a-d) show the typical time histories of top floor displacements for both far and near field earthquakes with PGAs as 0.2 g and 0.4 g. For the near field, responses for two types namely, with directivity and fling step effects are shown. It is seen from the figures that the response time history to the fling step earthquake is distinctly different than other earthquakes. Further, maximum top floor displacement (total displacement) is significantly large. This is due to the fact that the fling step effect suddenly induces a large displacement in the isolator. Figures 6 (a-f) show the typical plots of the force-displacement behaviors of the isolators under different types of earthquakes. It is seen from the figures that force displacement characteristics of the isolators are different for different types of earthquake and PGA levels. For far-field earthquakes, many cycles of isolator displacement take place which are closely spaced in the central zone. The area of the hysteresis loop widens at the higher value of PGA. For the near-field earthquake with directivity effect, the hysteresis curves elongate and become narrow at the higher value of PGA. Numbers of hysteresis cycles within the loop are fewer compared to the far-field earthquakes. For far-field earthquakes with fling step effect, the hysteresis loops are essentially narrow with fewer numbers of cycles within the loop. Isolator maximum displacement is very large.



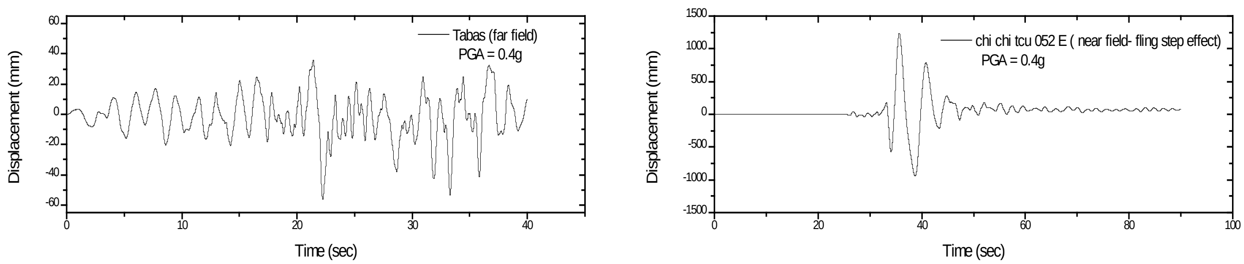
(a) Fixed base frame for PGA = 0.2g



(b) Base isolated frame for PGA = 0.2g



(C) Fixed base frame for PGA = 0.4g

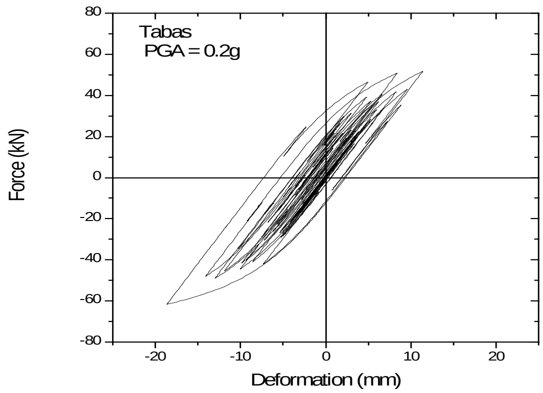


(d) Base isolated frame for PGA = 0.4g

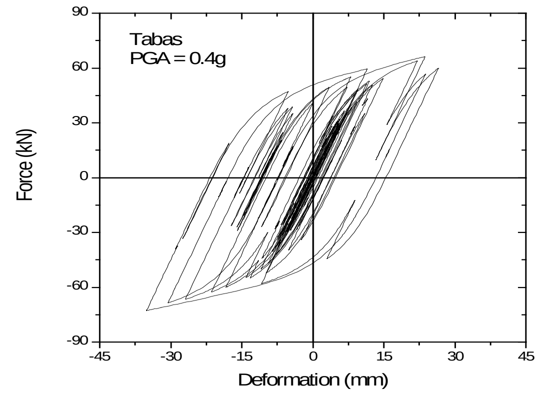
Fig. 5 Time histories top floor displacements for fixed and base isolated frames for different cases.

Some typical values of response quantities of interest are shown in table 2 for some of the earthquakes. From such values of responses, percentage reductions in the base shear, top storey absolute acceleration, maximum storey drift are depicted in the Figures 7, 8 and 9. Additionally, maximum isolator displacement and the total number of plastic hinges formed for both fixed base and base isolated conditions are shown in Figures 10 and 11.

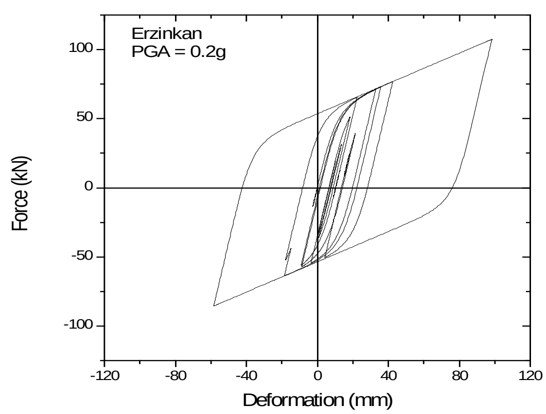
Figures 7 (a-b) shows the percentage reduction in base shear compared to fixed base condition. It is seen from the Figures 7 (a-b) that for both upper level i.e. 0.4 g and lower level i.e. 0.2 g accelerations the reductions in the base shear for far-field earthquake vary between 63% to 75%.



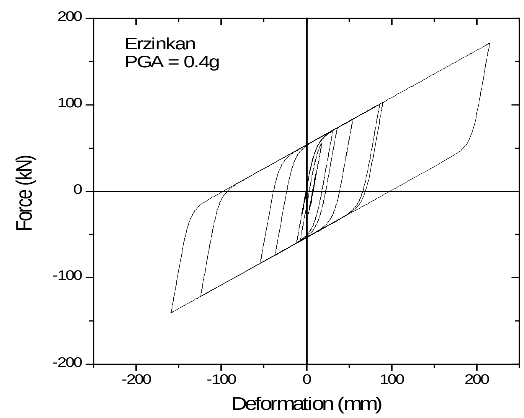
(a) Tabas (far field) ,PGA = 0.2g



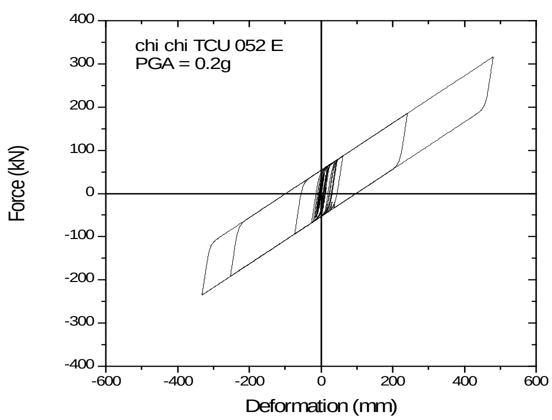
(b) Tabas (far field) for PGA = 0.4g



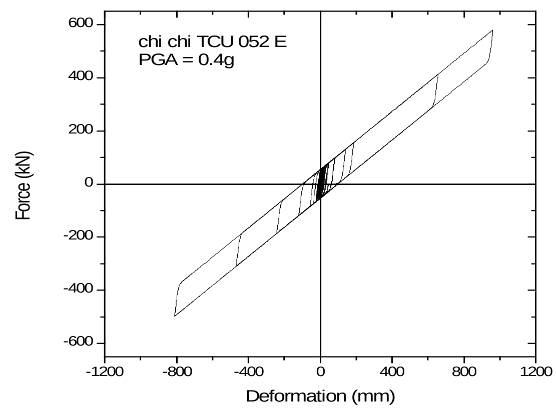
(c) Erzinkan (near field -directivity), PGA = 0.2g



(d) Erzinkan (near field -directivity), PGA = 0.4g



(e) Chi chi (near field -fling step), PGA = 0.2g

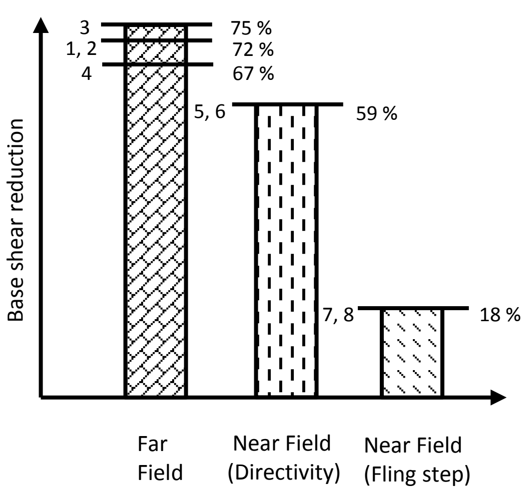


(f) Chi chi (near field -fling step), PGA = 0.4g

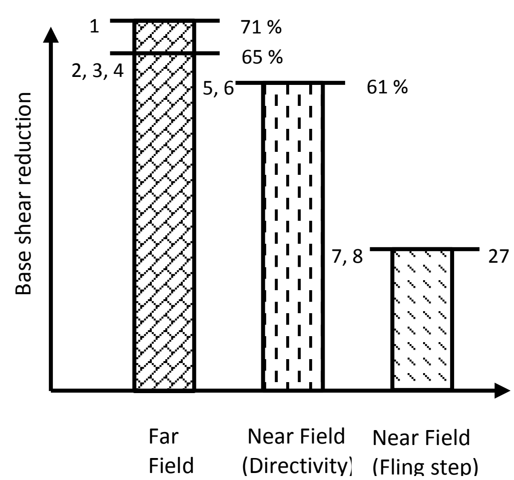
Figure 6 Force deformation curves of isolator for different earthquakes.

Table 2 Response quantities for far field and near field earthquake

EEARTHQUAKE	BUILDING TYPE	BASE SHEAR (kN)	TOP STOREY ABS. ACC. m/sec2	MAX. STOREY DRIFT mm	PEAK TOP FLOOR DISP mm	PEAK 1st FLOOR DISP mm	ISOLATOR DISP mm	NON LINEAR HINGES					
								B	IO	LS	CP	D	E
Northridge	FB	2108	5.23	29.93	166.66	16.26		113	3	0	0	0	0
Far field													
	BI	604	2.28	4.09	196.8	183.36	180	45	0	0	0	0	0
%	REDUCTION	71.35	56.41	86.33	-18.08								
Landers	FB	1422	5.06	20.88	132.9	8.8		94	0	0	0	0	0
Far field													
	BI	421	1.93	3.41	118.9	98.9	95.58	21	0	0	0	0	0
%	REDUCTION	70.39	61.86	83.67	10.53								
Chi chi TCU 052 E	FB	2780	4.64	61	360.04	40.68		91	33	5	0	1	2
Near field													
Fling step	BI	2278	2.8	43.8	1238.23	1005.55	962	92	23	2	0	0	0
Effect													
%	REDUCTION	18.06	39.66	28.2	-243.91								
Bam	FB	1828	4.77	29.58	160.6	15.6		103	0	0	0	0	0
Near field													
Directivity	BI	744	1.53	7.42	288.96	252.12	790	38	0	0	0	0	0
Effect													
%	REDUCTION	59.3	67.92	74.92	-79.93								



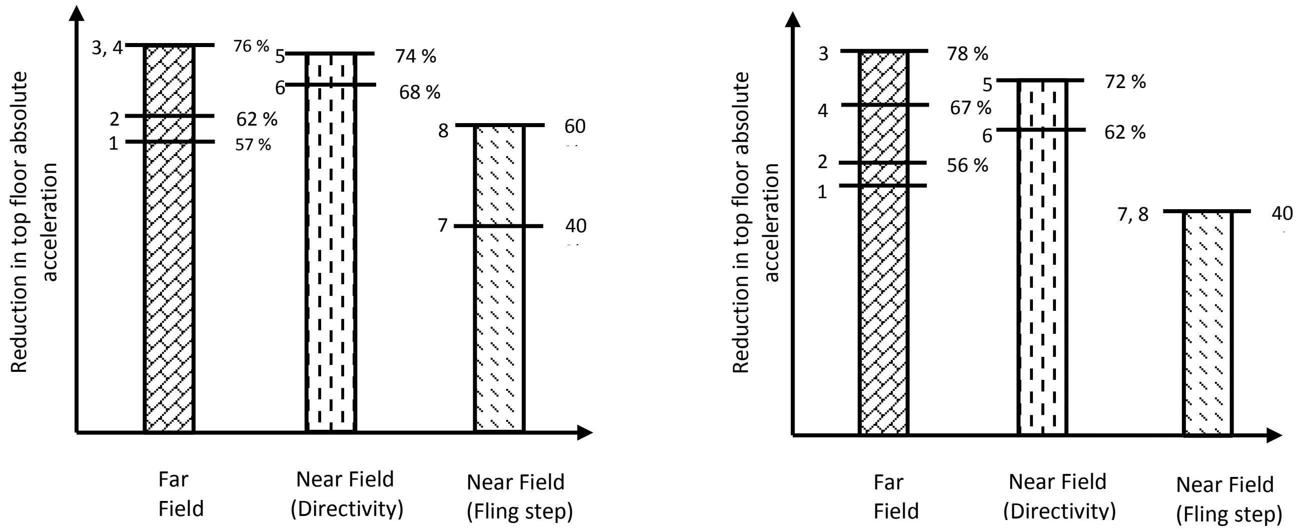
(a) PGA = 0.4g



(b) PGA = 0.2g

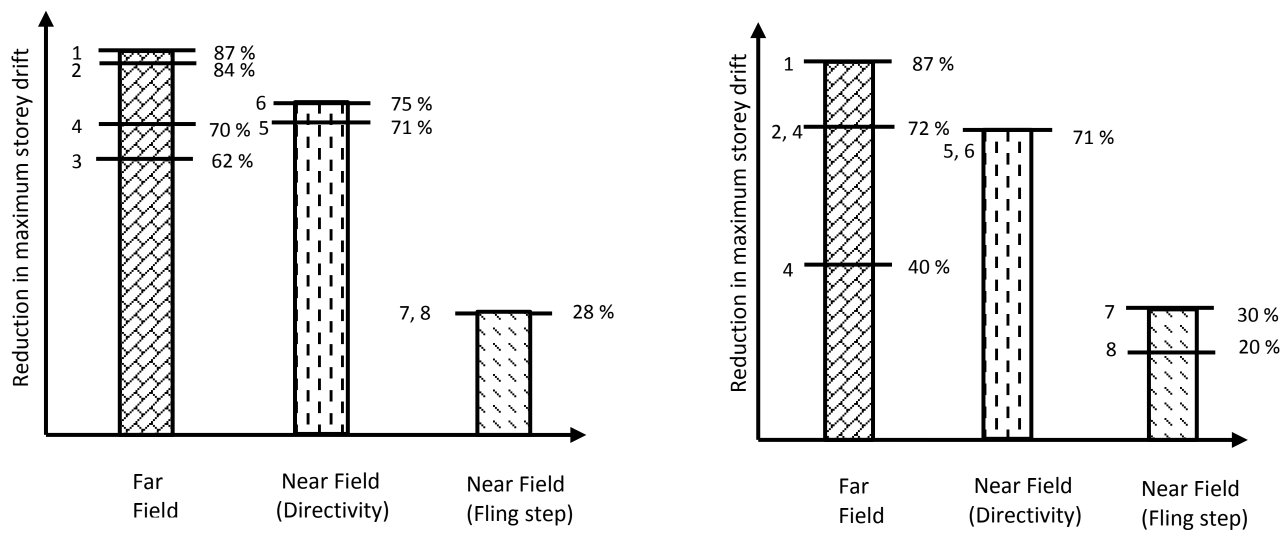
1. Northridge 2. Landers 3. Tabas 4. Superstition hill
5. Erzinkan 6. Bam 7. Chi chi TCU 052 E 8. Chi chi TCU 068 N

Figure 7 Percentage reduction in base shear.



(a) PGA = 0.4g (b) PGA = 0.2g

Figure 8 Percentage reduction in top floor absolute acceleration

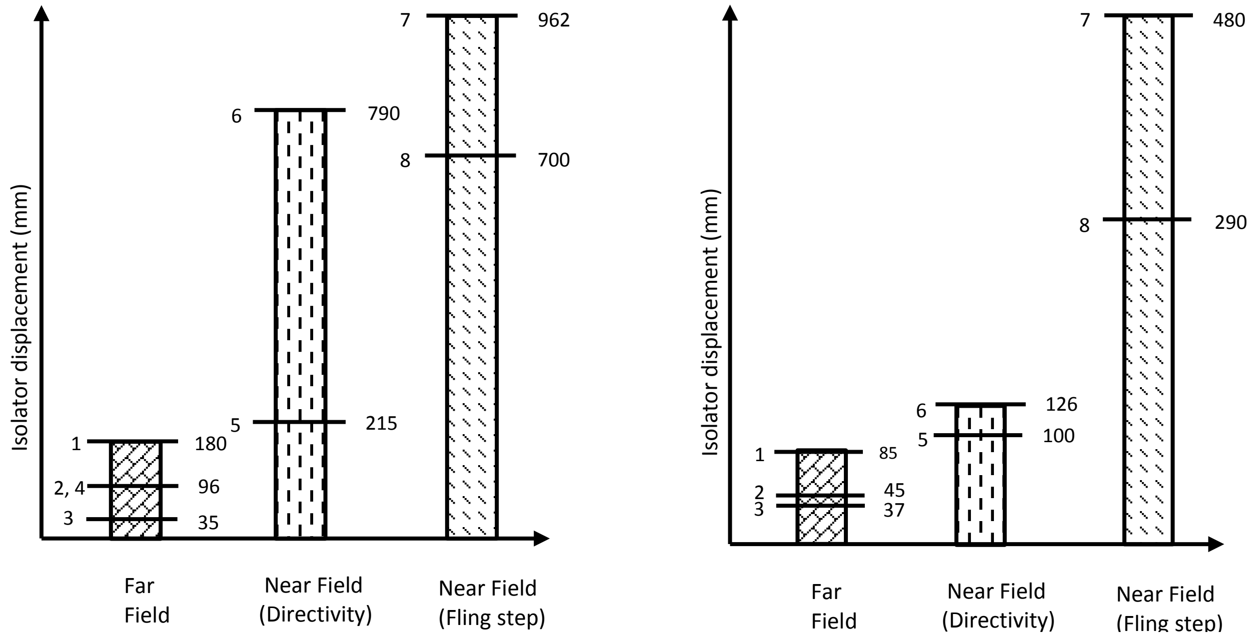


(a) PGA = 0.4g (b) PGA = 0.2g

Figure 9 Percentage reduction in máximum Storey drift

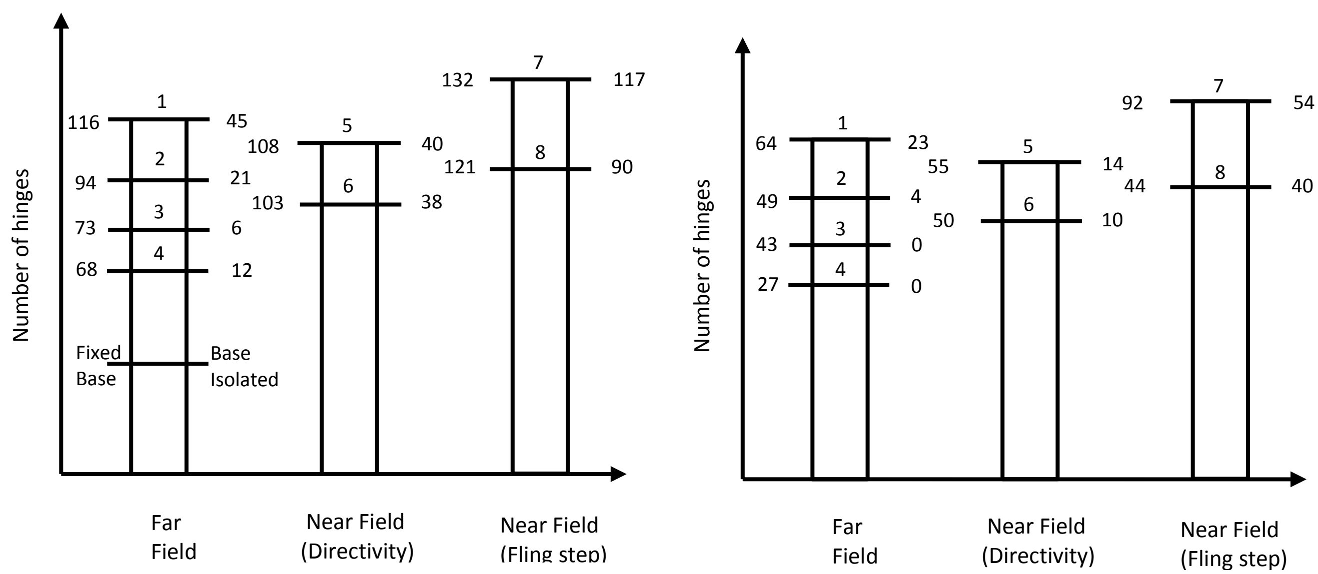
For near-field earthquake with directivity effect, the reduction in base shear response is also considerable, of the order of 60 %, for the two levels of PGA. However, for near-field earthquake with fling step effect, the reduction in base shear is drastically reduced to a value of 18 % for the PGA of 0.4g and 27 % for the PGA of 0.2g. This shows that base isolation for near-field earthquake with the fling step effect may prove to be ineffective, so far as the reduction of base shear is concerned.

Figures 8 (a-b) show the reduction of top storey absolute acceleration for the base isolated structure for the far field earthquakes. The reduction in the top storey absolute acceleration widely varies with earthquake in the range of 50 % - 78 % for both PGA levels. For the near-field earthquake with directivity effect, the response reduction of top storey absolute acceleration is found to be considerable which varies between 60 % and 74 % for both levels of PGA. For near-field earthquake with fling step effect, the effectiveness of base isolation for the reduction of top storey absolute acceleration is reduced but not as much as the case of base shear. The reduction typically varies between 40 % and 60 %.



(a) PGA = 0.4g (b) PGA = 0.2g

Figure 10 Isolator displacement



(a) PGA = 0.4g (b) PGA 0.2g

Figure 11 Number of hinges

Figures 9 (a-b) show the percentage reduction in maximum storey drift. There is a wide variation in percentage reduction in the maximum storey drift depending upon the earthquake. For far-field earthquake, the maximum reduction could be of the order of 87 % for both levels of PGA. The minimum reduction could be as low as 40 % observed for the PGA level of 0.2 g. For near-field earthquake with directivity effect, the reduction in maximum storey drift is quite significant i.e. of the order of 70 % - 78%. Base isolation is found to be quite ineffective for the reduction of storey drift for near-field earthquake with fling step effect. Reduction in maximum storey drift is found to be of the order of 20 % - 30 %. Figures 10 (a-b) show the maximum isolator displacement. Maximum isolator displacement depends on the PGA level. For earthquakes with 0.4 g, maximum isolator displacement is nearly about two times that for PGA level of 0.2g. Maximum isolator displacement considerably increases for near-field earthquakes as compared to far-field earthquakes. Out of the two types of near-field earthquakes, the fling step earthquake provides very large maximum isolator displacement especially for the upper level of PGA.

For most of the base isolated structures, it is expected that the structure will remain in elastic range for the lower level of PGA, whereas for extreme earthquake i.e. for the higher level of PGA the structure may undergo inelastic excursion. Figure 11 (a-b) compare between the plastic hinges formed for fixed base and base isolated structures. It is seen from the Figure 11 that for far-field earthquake, the number of plastic hinges formed for PGA = 0.4g is considerably greater compared to the PGA = 0.2g for fixed base structure, as it would be expected. For the far field earthquake with PGA = 0.4g, the number of hinges formed for fixed base structure varies between 68 – 116, while for the base isolated structure it is reduced to 12 – 45 showing that at higher PGA the base isolated structure gets into inelastic range, but extent of inelastic excursion is considerably reduced.

For the near-field earthquake, the same observation holds good for earthquakes with directivity effect. For earthquake with fling step effect, the number of plastic hinges formed in base-isolated structure is quite large. The inelastic excursion is nearly the same as that for the fixed base case.

For lower level of PGA, it is observed that the base isolated structure either remains in elastic range or marginally gets into inelastic range for far field earthquakes and near filed earthquakes with directivity effect. However, for the earthquakes with fling step effect, the base isolated structure significantly gets into inelastic range even for the lower value of PGA.

4. Conclusions

Behavior of base-isolated building frame is investigated for both near-field and far-field earthquakes in order to show the difference between the response characteristics of the system for the two types of earthquake. Two types of near field earthquake namely, with directivity effect and fling step effect are considered. Two levels of PGA are also considered consistent with the present earthquake design philosophy. The difference in the behavior is shown with the help of (i) percentage reduction of base shear; (ii) top storey absolute acceleration and (iii) maximum drift. Apart from these, the nonlinear excursion of base isolator and inelastic deformation of base isolated structure under different types of earthquake are highlighted.

Numerical results of a 10 storey base isolated building frame designed for earthquake lead to following conclusions:

1. For the two levels of PGA of earthquake considered in the study, the reductions in base shear, top floor absolute acceleration and maximum storey drift are significant for far-field earthquake and near field earthquake with directivity effect.
2. For the near field earthquake with fling step effect , the percentage reduction in the above response quantities is considerably reduced indicating that the base isolation prove to be ineffective for this type of near field earthquake.
3. The time history of the top storey displacement for near-field earthquake with fling step effect is distinctively different than those for other earthquakes.

4. Force-deformation loop of the isolator differ widely with earthquakes; for the near-field earthquake with fling step effect, the hysteresis curve is narrow with large isolator displacement especially for the higher level of PGA.
5. For the higher level of PGA base isolated structures undergo inelastic excursion; however, the inelastic effect is considerably reduced compared to that for fixed base structure.
6. For the near-field earthquake with fling step effect, the base isolated building frame may get into inelastic range even for the lower value of PGA.

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