Seismic Base Isolation for Buildings in Regions of Low to Moderate Seismicity: Practical Alternative Design

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Abstract: Although Dhaka city has experienced any moderate to large earthquakes in the past, some recent ground shakings are certainly indications of its earthquake source and vulnerability. In addition, microseismicity data also supports the existence of at least four earthquake source points in and around Dhaka. However, it is important to appropriately consider the seismic lateral load effect in structural design. A newly adopted technology of seismic design is to isolate the superstructure from the substructure with the use of a base isolator. This paper covers the design of base isolators for a building located in Dhaka, Bangladesh, along with its structural and economic feasibility. A time history is generated for Dhaka, adjusting peak ground acceleration as per seismic region from a nearby recorded earthquake. The response spectrum curve based on the site geology of Dhaka is also generated from this time history. Linear static as well as dynamic (time history and response spectrum) analyses have been carried out for both isolated and nonisolated buildings. Similar analyses have also been repeated for buildings with different heights but similar plan areas. The study reveals that for low-to medium-rise buildings, isolation can reduce seismic force along with some savings in structural cost of the building, though incorporating base isolators increase the overall price and installation cost. A meticulous review indicates that savings may be in the order of 5–10% of the total structural cost of the respective building. **DOI: 10.1061/(ASCE)SC.1943-5576.0000093.** © *2012 American Society of Civil Engineers.*

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Introduction

It may come as a surprise that the rubber foundation elements can actually help minimize earthquake damage to buildings, considering the tremendous forces these buildings must endure in a major quake. Contrasting the conventional design approach based on an increased resistance (strengthening) of the structures, the seismic isolation concept is aimed at a significant reduction of dynamic loads induced by the earthquake at the base of the structures themselves (Micheli et al. 2004). Seismic isolation separates the structure from the harmful motions of the ground by providing flexibility and energy dissipation capability through the insertion of the isolating device, known as isolators (BI), between the foundation and the building structure (Ismail et al. 2010). The invention of lead rubber bearings (LRB, 1970s) and high damping rubber bearings (HDRB, early 1980s) gave a new dimension to the seismic base-isolation design of BI structure (Islam 2011b, d). A significant amount of both past and recent research in the area of base isolation has focused on the use of elastomeric bearings, such as HDRB and LRB. Jangid (2007) and Providakis (2008) investigated seismic responses of multi-storied buildings for near-fault motion isolated by LRB. Dall'Asta and Ragni (2006, 2008); Bhuiyan et al. (2009) covered experimental tests, analytical models, and nonlinear dynamic behavior of HDRB. Although it is a relatively recent technology, seismic isolation for multi-storied buildings has been well evaluated and reviewed (Baratta and Corbi 2004; Hong and Kim 2004; Matsagar and Jangid 2004; Komodromos 2008; Lu and Lin 2008; Spyrakos et al. 2009; Polycarpou and Komodromos 2010). Base isolators with hardening behavior under increasing loading have been developed for medium-rise buildings (up to four stories) and sites with moderate earthquake risk (Pocanschi and Phocas 2007). Nonlinear seismic response evaluation was performed by Balkaya and Kalkan (2003). Resonant behavior of base-isolated high-rise buildings under long-period ground motions was studied by Ariga et al. (2006) and long-period building responses by Olsen et al. (2008). Deb (2004); Dicleli and Buddaram (2007); Casciati and Hamdaoui (2008); and Di Egidio and Contento (2010) have also made strides in the field of isolated systems. Komodromos et al. (2007); Kilar and Koren (2009); and Islam et al. (2011a) focused on the seismic behavior and responses through the dynamic analyses of isolated buildings.

Though the application of base isolators is similar all over the world, there is a lack of proper research to implement the device practically for local buildings in the Dhaka, Bangladesh, region as per the local requirements. So thorough study in this area is a critical concern. Site specific earthquake data are also very important in seismic design. Linear static and linear dynamic response spectrum analyses have been carried out. However, the time domain method

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has been employed for considering nonlinearities present in the structural systems. Isolator design is governed by a relatively small number of equations and does not require extensive numerical computation; therefore, the design can be performed using only spreadsheet tools. A combined model of HDRB and LRB have been adopted to explore the feasibility of the design. Preliminary exploration of the suitability of incorporating isolator has been done with equivalent static analysis. Dynamic analysis has been performed to satisfy the displacement limitation and economic contribution.

The system is ideal for areas of low to moderate seismicity, such as Dhaka. The sophisticated finite element software SAP 2000 has been found compatible for analysis and design of 10-storied residential building in Dhaka for the case study. The displacement behaviors for fixed and isolated buildings were discussed at different levels. Base shear and overturning moments were also compared for these cases. Finally, net cost savings realized by using isolators for this building and several other buildings with varying story numbers have been evaluated. Regions with low to moderate

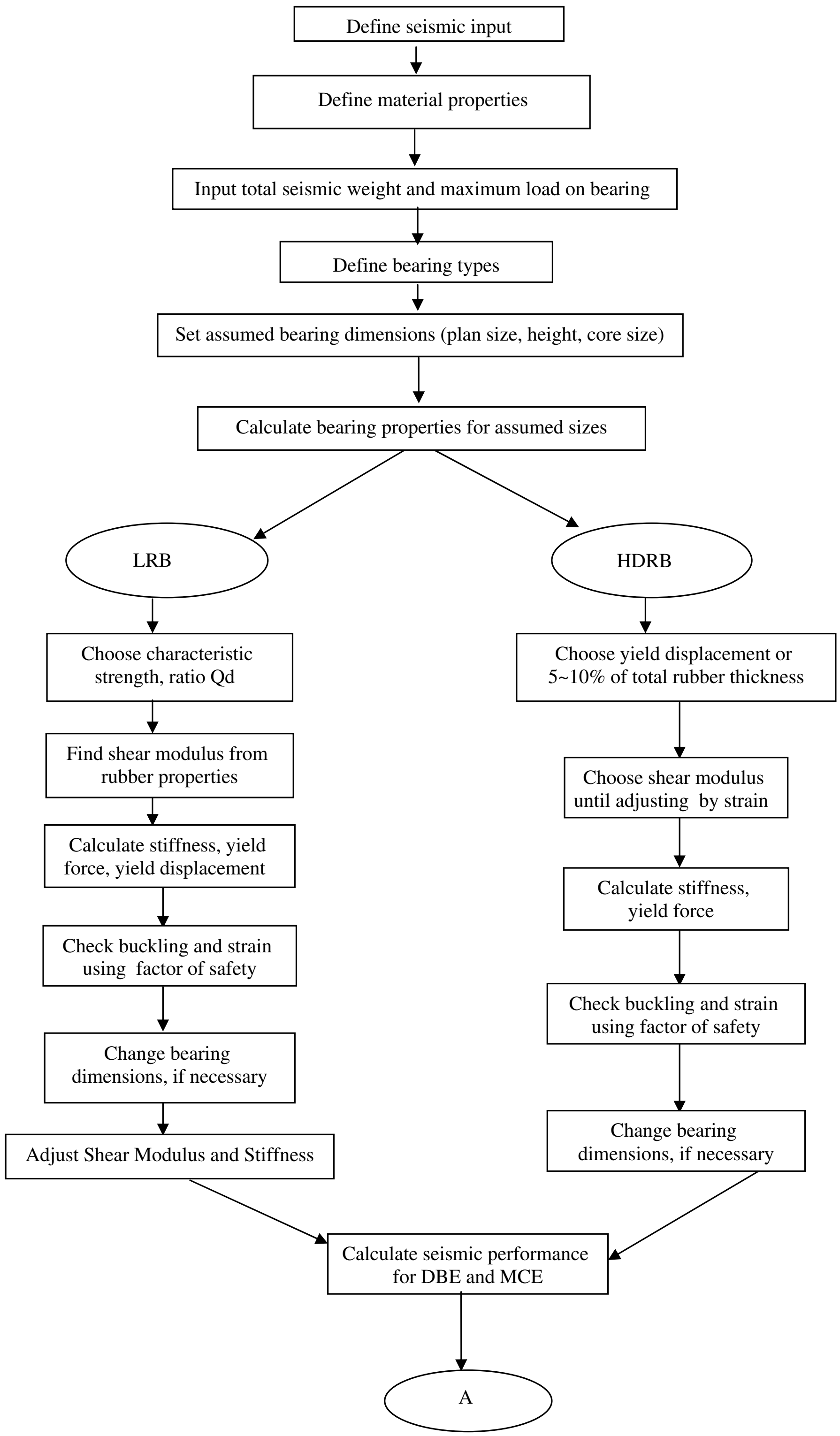

Fig. 1. Design of Isolator Properties

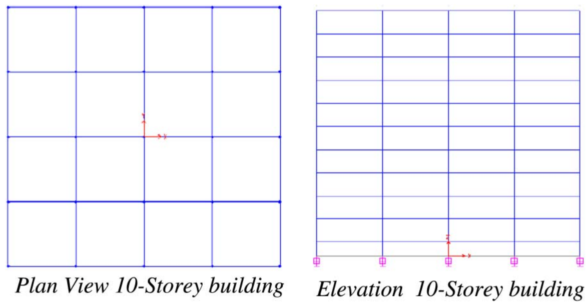

Fig. 2. Plan & Elevation of the Building (Fixed- or Isolated-Based)

earthquake risk in the United States are also prone to seismic hazard.

Many places in the Midwestern areas of the U.S. (Southern Illinois, Kentucky, Southern Indiana, etc.) experience low to moderate seismicity. However, for building construction in these zones, seismic base-isolation can be a suitable alternative as it ensures building flexibility and drastically reduces lateral forces. Moreover, using this system is cost-effective. These sites can also benefit from implementation of this base-isolation system, especially in buildings such as museums and data centers.

Isolation System Evaluation

Evaluation of base-isolated structures has been done through dynamic analysis with response spectrum and time history. Here SAP2000 program has been used for both types of analysis, provided a linear elastic structure is appropriate. For this HDRB and LRB are designed as per different properties and following the static design procedure. They were then linked at the building structures and analyzed.

Isolation Design Flow Chart

Design has been done by Excel spreadsheet formulated and by the equations and conditions. Here flow charts for sequential isolator design are given for both HDRB and LDRB (Fig. 1).

Implementation of the Design Procedure

The case provided in this section is based on design requirements, using the spreadsheet developed in the Excel program. Total seismic load and loads on maximum loaded columns have been obtained by the following consideration.

The 10-story residential building located in Dhaka of four spacing at 7.62 m c/c in both directions is required to design for an earthquake (i.e., it is assumed that the effect of the earthquake is greater than that of wind). Given that: $f'c = 28$ MPa; $fy = 414$ MPa; deadload (excluding self weight) = 4.8 KPa; live load = 2.4 KPa; slab thickness = 150 mm; exterior corner columns are all $C1 = 750\ \text{mm} \times 750\ \text{mm}$; exterior middle columns are all $C2 = 950\ \text{mm} \times 950\ \text{mm}$; interior columns are all $C3 = 1{,}000\ \text{mm} \times 1{,}000\ \text{mm}$; grade beams are $\text{GB} = 300\ \text{mm} \times 375\ \text{mm}$ each; and beam $B1 = 525\ \text{mm} \times 825\ \text{mm}$ each; beam $B2 = 600\ \text{mm} \times 900\ \text{mm}$ each; beam $B3 = 550\ \text{mm} \times 900\ \text{mm}$ each. The plan and elevation of the building are given in Fig. 2.

A model of the building shown above was prepared and loaded as described in the problem. For equivalent static analysis of the conventional fixed-based building, procedures described in the Bangladesh National Building code [BNBC (1993)] have been adopted. But for isolated buildings, the response modification factor (Kelly 2001) has been taken as $R_I = 2.0$ and the importance coefficient has also been chosen as 1.0, as per occupancy category in Table 1, which denotes how the values of I or, I' are tabulated. After equivalent static analysis, the following results are obtained (Table 2).

The design base shear for earthquake loading is greater than that for wind loading and the structural time period is within the reasonable value (1.0 sec.) for isolating (Table 2). Again lateral load due to wind is less than 10% of the weight of the building requirement. So we can incorporate isolator at the base of the structure to justify and confirm its economic feasibility against conventional fixed-based design.

Isolation Design

Rubber Isolators have been designed here considering vertical load, isolator types, and different properties.

Material Definition

The material definitions are shown in Table 3. This is basic information used for the design process. The range of properties for rubber is restricted and some properties are related to others, such as the ultimate elongation, material constant, and elastic modulus being all functions of shear modulus (Kelly et al. 2006). The design is based on the tabulated values.

Project Definition

The project definition for the building is shown in Table 4. The information provided defines the seismic loads and the structural data required for evaluating performance.

Isolator Types and Load Data

Types of isolators and loads acting on the column base subjected to the bearings are defined in Table 5. HDRB and LRB have been assigned at the middle ($C3$) and outside column ($C1$ and $C2$) bases, respectively, assuming their suitability at their respective link positions.

Table 1. Structure Importance Coefficient (Nonisolated & Isolated)

Occupancy category	Function of the structure	I	I'
1. Essential facilities	Needed after the emergency (hospitals, fire and police stations, emergency vehicle garages, aviation control towers, communication centers, fire suppressing equipment. etc.)	1.25	1
2. Hazardous facilities	Housing toxic or explosive substances	1.25	1
3. Special occupancy	Schools > 300 students, universities > 500 students, any buildings > 5,000 occupants, occupants restricted > 50	1.00	1.00
4. Standard occupancy	Occupancies not listed in 1–3 and towers belongings to utilities	1.00	1.00
5. Low-risk structures	All utilities, except towers	1.00	1.00

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Table 2. Data Obtained after Static Analysis without Using Isolator

Data Analyzed	Values
Structural time period	0.913 sec
Design base shear (EQ load)	4,565 KN
Design base shear (wind load)	2,698 KN
Maximum top story displacement (EQ load)	13.63 mm
Maximum top story displacement (wind load)	6.63 mm
Total weight of building	127,766 KN
Governing axial load under column $C3$	7,215 KN
Governing axial load under column $C2$	4,546 KN
Governing axial load under column $C1$	2,544 KN

Table 3. Material Properties used for Isolator Design

Elastomer properties	Unit	Value
Shear modulus	KPa (Ksf)	400 (8.21)
Ultimate elongation	%	650
Material constant, k	—	0.87
Elastic modulus	KPa (Ksf)	1,350 (27.36)

Table 4. Seismic Characteristics for Structural Analysis

Seismic properties	Value
Seismic zone factor	0.15
Soil profile type	S3
Seismic coefficient, C_A	0.22
Seismic coefficient, C_V	0.32
Isolated lateral force coefficient, R_I	2
Fixed base lateral force coefficient, R	8
Importance factor, I	1
Seismic coefficient, C_{AM}	0.35
Seismic coefficient, C_{VM}	0.55

Table 5. Isolator Types & Load Data

Bearing types and load data	LRB	HDRB	Total
Type	Isolator1	Isolator1	
No. of bearings	16	9	25
Average DL + SLL (KN)	4,035	7,024	
Maximum DL + LL (KN)	4,546	7,215	
Maximum DL + SLL + EQ (KN)	4,603	7,220	
Seismic weight W (KN)			127,766
Total wind load (KN)			2698

Table 6. Isolator Dimensions

Bearing dimensions	LRB	HDR
Plan dimension (mm)	800	950
Layer thickness (mm)	10	10
No. of layers	16	16
Lead core size (mm)	150	175
Shape (S = square; C = circular)	C	C
Total height (mm)	240	240

Isolator Dimensions

The isolators are introduced by the plan size and rubber layer configuration (Table 6). For lead rubber bearings, an extra parameter lead core size is covered.

Isolator Performance

Two things are needed to make changes: (1) the status of the isolation bearings to support the loads safely, and (2) the performance of the isolation system. The isolation bearing status is checked by the factors of safety as F.S. exceeding 1.0 shows satisfactory performance. The performance of the isolated structure has been evaluated for the design basis earthquake (DBE) and the maximum credible earthquake (MCE) [International Conference of Building Officials (ICBO) 1997]. The DBE in this scenario considers the seismic coefficients $C_A = 0.22$ and $C_V = 0.32$. To check the performance against the MCE, the coefficient values of C_{AM} and C_{VM} for $Z = 0.15$ and soil profile S3 are 0.35 and 0.55, respectively.

Properties for Analysis

The design procedure provides a plot of the hysteresis curves for each of the isolator types as designed for displacements up to the MCE total displacement level. These plots (Fig. 3) show the bilinear properties to be used for system evaluation. The properties used to develop the hysteresis loop are taken in a format suitable for the SAP program. The use of these properties is discussed later in these guidelines. A detailed sketch and other characteristics of the designed isolators are given in Figs. 4 and 5.

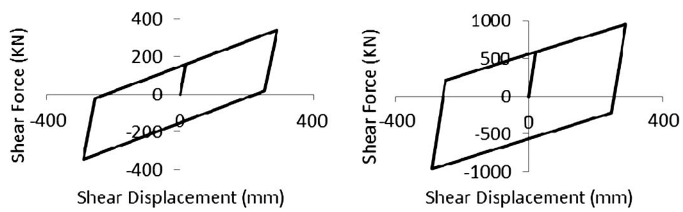

Fig. 3. Hysteresis of isolator LRB (left) & HDRB (right)

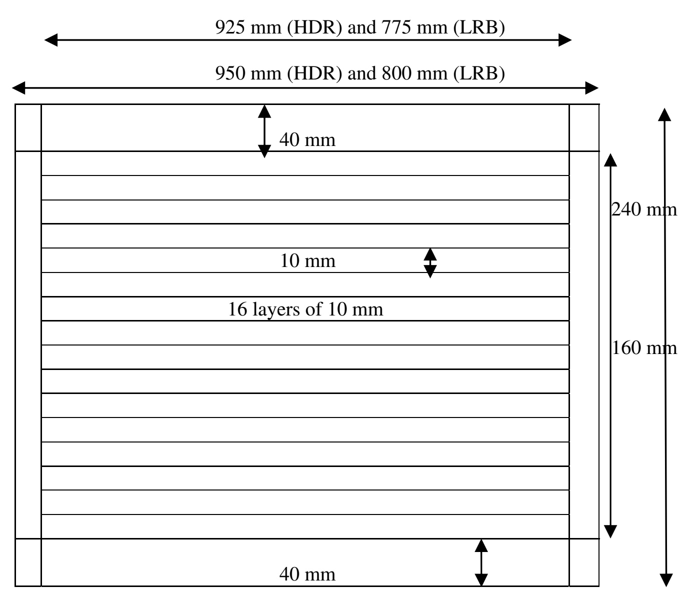

Fig. 4. High damping rubber bearing and lead rubber bearing dimensions

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Fig. 5. Isolator view

Dynamic Analysis

Assigning the properties to the isolators, the bearings are linked and the structure with the isolator is analyzed by SAP2000 (CSI 2004).

Sample Earthquake Used in the Analysis

Since there is a lack of recorded earthquake data for Dhaka, the construction of an appropriate time history for this area is critical. In this study, the Natore earthquake record has been properly modified for the Dhaka region. This earthquake is chosen because its time history represents the closest point from Dhaka where any sort of ground shaking has ever been recorded. Collected data (Islam et al. 2011e) for recent earthquake at Station ID = ALTUS S/N 2,928; Channel 1 = 06th Jan 2009 16:04:03 (GMT); Magnitude = 4.0; Place = Natore.

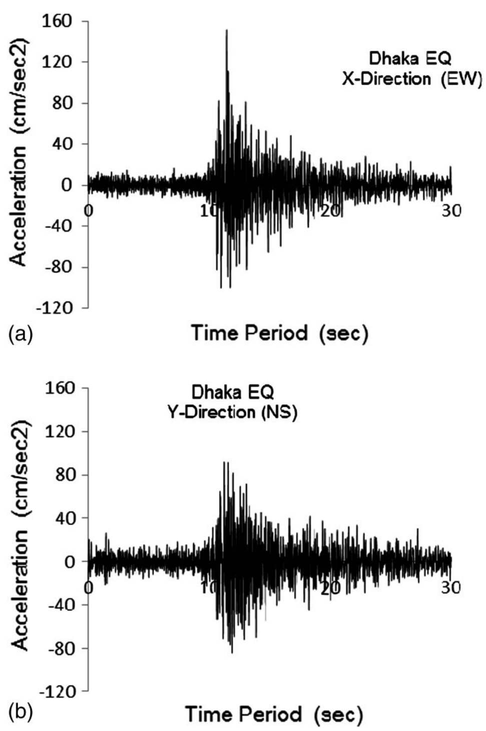

Fig. 6. Time History for Dhaka EQ: (a) *X*-direction; (b) *Y*-direction

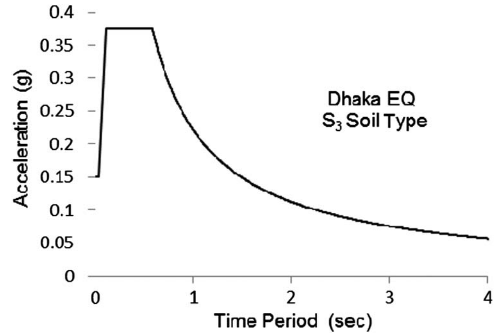

Fig. 7. Acceleration response spectrum for S3 soil for Dhaka

Table 7. Results of Dynamic Analysis (without Using Isolators)

	Response spectrum analysis	Time history analysis
Design base shear (KN) in *X* direction	22,221	19,610
Design base shear (KN) in *Y* direction	16,666	14,528
Design base moment (KN-m) in *X* direction	143,114	123,726
Design base moment (KN-m) in *Y* direction	87,047	76,880
Top story displacement in UI direction (mm)	67.1	35
Top story displacement in U2 direction (mm)	40.1	31.7

A time history for Dhaka city (Longitude 90°24′ and Latitude 23°3′) has been generated here by scaling up to the maximum acceleration limit for Dhaka from the Natore record (Fig. 6).

From the above time history, soil characteristics, site location, seismic coefficients, along with the generated time history following Duhamel's integral 5% damped response spectrum, has been established. Fig. 7 (Islam et al. 2011c, 2011f) shows the values of the acceleration response spectrum. Dynamic analysis for the response spectrum and time history has been performed for the fixed base structure (Table 7) to determine the governing type of analysis. Then, after linking them with the properties of isolators from the isolation system design procedure and at the respective column base, dynamic analysis is again performed.

Response Spectrum Analysis

The response spectrum analysis follows the usual procedure for this method of analysis with two modifications to account for in the isolation system:

1. Springs with effective stiffness of the isolators are modeled to connect the base level of the structure to the ground.

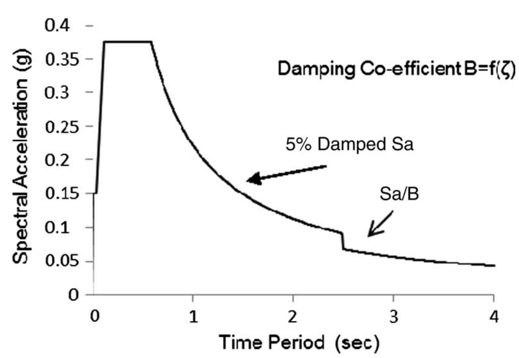

Fig. 8. Composite response spectrum for Dhaka EQ (isolated building)

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2. The response spectrum is modified to account for the damping provided in the isolated modes to use a composite spectrum. The 5% damped spectrum has been reduced by the *B* factor in the isolated modes (Fig. 8).

Response spectrum analysis has been performed for Dhaka for S3 soil profile assigning the generated response spectrum curve.

Time History Analysis

A nonlinear time history analysis was also performed by choosing an appropriate time history (i.e., ground motion that resembles the site condition of Dhaka) (Fig. 6). Each building model and damping system configuration was analyzed for the 30-s duration of each record at a time step of 0.005 s.

Dynamic Analysis without Isolators

The following findings were attained from dynamic analysis (Table 7). A comparison of the dynamic analysis result (Table 7) with the static analysis result (Table 2) clarify that dynamic analysis by response spectrum method governs among the three types of analysis. Therefore, response spectrum analysis plays the leading role here to justify feasibility.

Static and Dynamic Analysis with Isolators

Linear static as well as nonlinear dynamic analysis of the building structure with isolators shows the subsequent results of the mentioned structural parameters (Tables 8 and 9). All the values of maximum (top) displacements (Table 8) lie below the isolator design displacement of 292.61 mm for the MCE level of ground excitation. So the isolator properties are satisfactory. Again response spectrum analysis denotes the governing role through the analysis of the structure (Table 9).

Table 8. Results of Dynamic Analysis (Using Isolators)

	2.85 sec	
Structural period for mode 1	Isolator displacement (mm)	Total structure drift (mm)
UI Direction (static analysis)	151.6	56.3
U2 Direction (static analysis)	145.8	53.1
U1 Direction (response spectrum analysis)	134.4	35.4
U2 Direction (response spectrum analysis)	83.3	31.2
U1 Direction (time history analysis)	119.1	30.1
U2 Direction (time history analysis)	73.8	28.6

Table 9. Base Shear and Base Moment after Dynamic Analysis Using Isolator

	Response spectrum analysis	Time history analysis
Design base shear (KN) in *X* direction	8,842.5	7,803.2
Design base shear (KN) in *Y* direction	5,526.9	4,837.3
Design base moment (KN-m) in *X* direction	49,923.7	43,932.1
Design base moment (KN-m) in *Y* direction	30,955.67	26,930.8

Economic Implications

There are both direct and indirect costs and cost savings related with the system. Though the installation of the isolation system adds more to the initial costs than a nonisolated system, the use of isolators reduces the reinforcement requirement of a building and ultimately reduces the total cost. So the cost for isolators and the cost of changes to the structural configuration is potentially the largest component of the initial cost and is a function of the building layout.

Cost Analysis for the Ten-Story Building

For the 10-story demo building, savings from the reinforcement requirement along with cost are determined.

Keeping the member section unchanged, savings come up to 17.38% from reinforcement. But for detailing, the additional cost

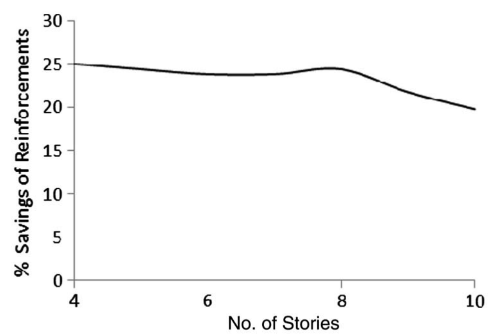

Fig. 9. Percentage savings of reinforcement in beams and columns versus different stories

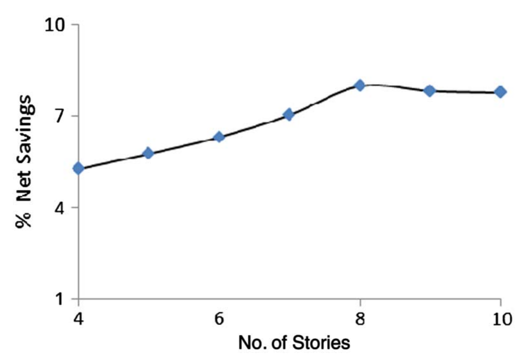

Fig. 10. Percentage of net cost savings in isolation system versus number of stories

Table 10. Net Cost Savings in the Isolated Building

No. of stories	Savings from beams and columns in U.S. dollars ($)	No. of isolators	Isolator costs in U.S. dollars ($)	Net savings in U.S. dollars ($)	Net savings (% of reinforcement cost)
10	40,980	25	24,926	16,054	7.75

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is about 3% with the required amount for fixed base structure. Mild steel (MS) rod steel price was taken as \$0.65 per kg.

Isolator cost depends on the layer thickness, number of layers, isolator diameter, etc. The values of different components are analyzed based on the results taken from the 10-story building. Cost per isolator has been collected from the Holmes Consulting Group Ltd. Along with the price installation cost is to be added at around 3%.

Though reinforcement savings of beams and columns decreases the building cost in isolated systems, isolators add a significant cost. Here for the sample 10-story building, cost savings excluding the isolator costs are mentioned in Table 10.

For the same plan area, the building has been analyzed for 4, 5, 6, 7, 8, and 9 stories to represent a comparative generalized relationship for savings in reinforcement and cost mentioning percentage with the value for fixed-base buildings (Fig. 9). Apart from this, the percentage of net cost savings for isolated (with isolation cost) buildings against nonisolated buildings with varying stories is in Fig. 10. It is worth noting that for every building, properties of HDRB and LRB are designed separately and the structures were analyzed after linking the bearings properly.

Concluding Remarks

Seismic base isolators increase the building costs with its price as well as installation cost. Reinforcements required for grade beams increase slightly (5–7%) than for similar sections installed without isolators. But the cost reduction for reinforcement in upper floors for horizontal and vertical members (i.e., beams and columns) makes up for that cost. Thus, reinforcement yields a cost savings of 19–25%. Considering isolator and reinforcement yields a net cost savings of of 5–10%. Again, using isolator member sections can be decreased, depending on architectural requirements. The rate of cost savings decreases as the number of stories increases.

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Notations

The following symbols are used in this paper:

B = damping coefficient;
$B1$, $B2$, $B3$ = different beam types;
$C1$, $C2$, $C3$ = different column types;
C_A = seismic coefficient corresponding to the constant-acceleration region = C_{AD} at DBE;
C_{AM} = seismic coefficient corresponding to the constant-acceleration region at MCE;
C_V = seismic coefficient corresponding to the constant-velocity region = C_{VD} at DBE;
C_{VM} = seismic coefficient corresponding to the constant-velocity region at MCE;
DBE = design basis earthquake;
HDRB = high damping rubber bearing;
LRB = lead rubber bearing;
MCE = maximum capable earthquake; and
ζ = damping ratio.

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