# FEASIBILITY STUDY FOR SEISMIC BASE ISOLATION DESIGN OF A HIGH-RISE BUILDING

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**ABSTRACT:**

This paper summarizes a feasibility study for the use of seismic base isolation for a high-rise (30 stories, 102 m) reinforced concrete building, which has planned to be constructed in Istanbul. The plausibility and effectiveness of base isolated system designs with LRB (Lead Rubber Bearing) and HRB (High-Damping Rubber Bearing) have been investigated by comparing them with the conventional fixed base model. The design of structures is based on local and international codes. Cost-effectiveness of the solutions for the selected performance levels, e.g. user comfort in terms of floor accelerations and displacements as well as architectural benefits in terms of structural members designed are explored in comparison to the conventional design.

**KEY WORDS:** Reinforced Concrete, Base Isolation, High-Rise Building

# DEPREM YALITIMLI YÜKSEK BİR YAPININ FİZİBİLİTE ÇALIŞMASI

**ÖZET:**

İstanbul'da inşa edilmesi planlanan yüksek (30 kat, 102 m) bir betonarme yapının fizibilite çalışması gerçekleştirilmiştir. Çalışma hem konvansiyonel yöntemle hem de deprem yalıtımlı yapısal sistemle planlanan bir yapının incelemesini içermektedir. Çalışma kapsamında sabit temelli (konvansiyonel), LRB (Kurşun Çekirdekli Kauçuk İzolatör) yalıtımlı ve HRB (Yüksek Sönümlü Kauçuk İzolatör) yalıtımlı olmak üzere üç yapı modeli yerel ve uluslararası yönetmeliklere dayalı olarak tasarlanmıştır. Seçilen performans seviyeleri için en ekonomik çözümler tanımlanmıştır. Üç modelin yapısal maliyet ve kat ivmeleri ile yer değiştirmeler bazında kullanıcı rahatlığı açılarından karşılaştırması yapılmıştır. Ayrıca konvansiyonel ve deprem yalıtımlı iki bina türünün mimari kazanımlar ve pazarlama avantajları açısından karşılaştırması yapılmıştır.

**ANAHTAR KELİMELER:** Betonarme, Deprem Yalıtımı, Yüksek Yapı

## 1. INTRODUCTION

Miyamoto International Turkey is requested by a major development company from Japan to conduct a feasibility study of a base isolated high-rise structure planned to be constructed in Istanbul. The task requires the design of a sample building with 30 stories (h=102m) both with conventional method (fixed base system) and with base isolated system method. Within the scope of the study three comprehensive models (fixed base model, base isolated model using lead rubber bearings (LRB) and base isolated model using high-damping rubber bearings (HRB) with the same layout created for the selected sample building decided on with the consultancy of Taisei Corporation, a major general contracting and engineering company from Japan. Design of the three structures are performed according to IYBDY'08 (Istanbul High-Rise Structures' Code, 2008), DBYBHY'07 (Turkish Seismic Code, 2007) and ASCE 7-10 (Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, 2010). Upon completion of the comparative design, two alternatives (fixed base system and seismic isolated system) are compared from the perspectives of cost, user's comfort and architectural benefits.

## 2. THE SAMPLE BUILDING AND THE SITE PROPERTIES

The sample building is decided to be consist of 30 stories with 3.4m height of each floor (102 m in total). The plan dimensions of the selected building is 29.5m x 29.5m. The structural core of the building in which elevators, staircases, mechanical/electrical shafts will take place is selected to have 13.5m x 13.5m plan dimensions (182.25m², 21% of the floor area). The width of the corridor around the structural core is decided to be 1.75m (106.75m², 12% of the floor area). Rest of the floor area is reserved to be residential area (581.25m², 67% of the floor area). The typical floor plan and the layout of the isolators are shown in Figure 1. Selected materials for the structure of the building are C50 for concrete and S420a for reinforcement. The isolators are selected from the catalog of the manufacturer, a major base isolator manufacturing company from Japan.

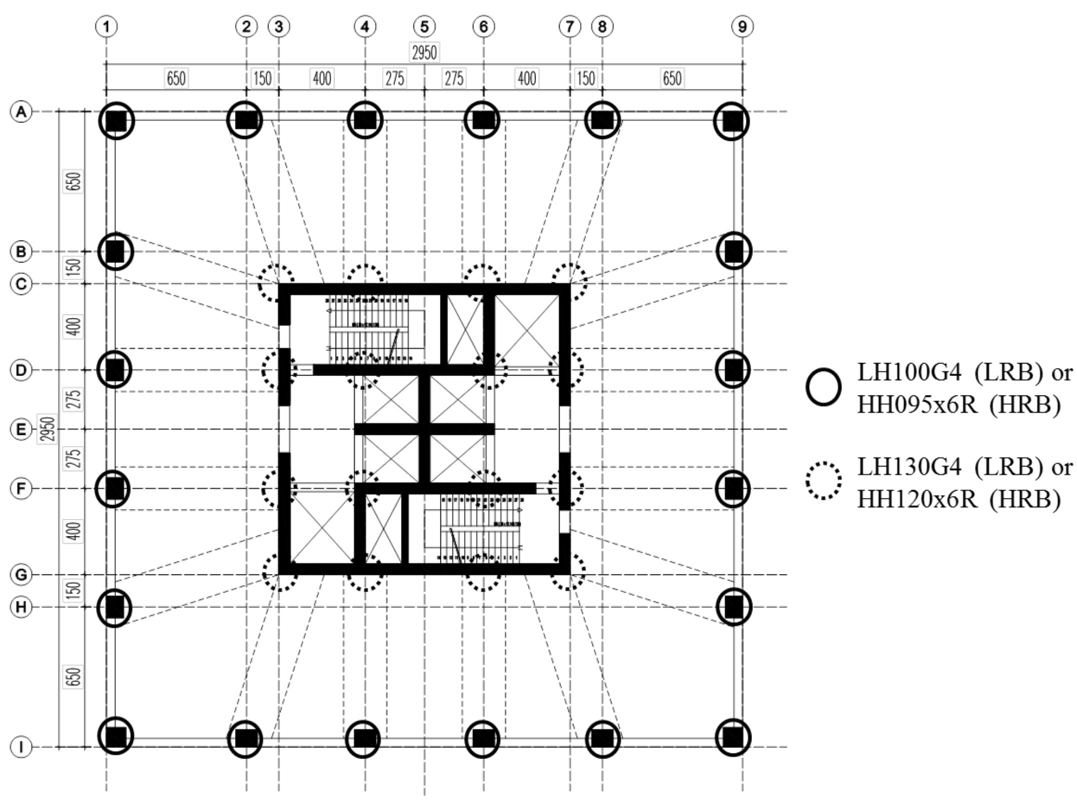

Figure 1. Typical floor plan and the layout of the isolators

Since this study is based on a sample building and the location of the building is not decided on, soil properties are assumed based on the similar buildings built in the planned region. Assumed soil class is "Z2" according to DBYBHY'07 and "C" according to IYBDY'08 with the subgrade soil modulus of 50.000 kN/m³, allowable soil stress of 500 kPa and $Vs_{30}$ of 500m/s. Seismic parameters are shown in Table 1.

Table 1. Seismic parameters assumed for the region

| DBYBHY'07 | IYBDY'08 | |
|---|---|---|
| Seismic Zone: 1 | | $S_1$: 0.39 |
| Effective Ground Acceleration Coefficient, $A_0$: 0.4g | | $S_S$: 0.88 |
| Soil Class: Z2 | | $S_1$: 0.63 |
| Spectrum Characteristic Periods: $T_A$ =0.15 sec, $T_B$ = 0.40 sec | | $S_S$: 1.25 |

IYBDY'08 is followed for the fixed base model study and ASCE'07 is followed for the base isolated model study. For the design of the fixed base model, response spectrum analysis method is used to design the cross-sections of the structural members. Design parameters for the fixed model is shown in Table 2.

Table 2. Design parameters for the fixed base model

| | |
|---|---|
| Seismic Event: | DBE (10% probability of exceedence in 50 years) |
| Structural behavior coefficient, R: | 4 |
| Structural importance factor, I: | 1 |
| Effective damping ratio, β: | 5% |
| Mass reduction factor, n: | 0.2 |

For the design of the base isolated model static analysis is performed in order to determine the axial loads on the isolators. The stresses are kept between 10-15MPa. Pushover analysis is performed in order to calculate the effective stiffnesses of the isolators, check the tensile stresses on the isolators and the P-Δ effects on the foundation as wells as the isolation level slab. During the calculation of the axial loads on the isolators, DL+LL±EQ (for DBE, R=1) is used in order to calculate the maximum compression forces and 09DL±EQ (for DBE, R=1) is used to calculate the maximum tensile forces. In pushover analysis, lateral load distribution at the superstructure defined based on the first vibration mode shape in the related direction. The structure is pushed until the isolation system reached the target displacement demand at DBE event. After the calculation of the effective stiffnesses, modal analysis is performed using DBE seismic event to design the superstructure. Isolators are designed using their non-linear properties and time-history analysis methods. Maximum isolator displacements and stresses are calculated using both MCE and DBE events.

Earthquake time history records selected for the study are shown in Table 3. Seven ground motion records from four earthquakes were selected based on matching the seismo-tectonic factors controlling the region (mechanism: strike-slip, Mw: 6.5-7.5, near field records). Geometric mean of the two components of the each record are matched to the design spectrum between 2.1 and 6.9 sec (0.5TD and 1.25TM) which satisfies the requirement of ASCE7-10.

Table 3. Selected earthquake time history records compatible with the design spectrum

| Earthquake | Fault Mechanism | Station Name / Code | Components | Distance (km) |
|---|---|---|---|---|
| 1999, M=7.14 Duzce, Turkey | Strike Slip | Lamont 362 Lamont | LAMONT362 E LAMONT362 N | 23.42 |
| | Strike Slip | CDMG 23559 Barstow | BRS000 BRS090 | 34.86 |
| | Strike Slip | USGS 5070 North Palm Spring | NPS000 NPS090 | 26.84 |
| | Strike Slip | CDMG 12149 Desert Hot Spring | DSP000 DSP090 | 21.78 |
| | Strike Slip | USGS 5071 Morongo Valley | MVH000 MVH090 | 17.32 |
| 1999, M=7.4 Kocaeli, Turkey | Strike Slip | ERD 99999 Arcelik | ARC000 ARC090 | 13.49 |
| 1979, M=6.53 Imperial Valley, USA | Strike Slip | UNAMUCSD 6604 Cerro Prieta | CPE147 CPE237 | 15.19 |

One of the spectral matching methods used in this study is based on time domain approach of Lilhanand and Tseng (1987) coded in the computer program RSPMATCH (Abrahamson, 1998). In this time domain approach, matching is accomplished by adding (subtracting) finite duration wavelets to (from) the initial time history. This approach normally provides a close fit to the target. One representative wavelet is the impulse response time-history of the SDOF oscillator reversed in time. This wavelet abruptly ceases (i.e. becomes zero) after the peak response time and thus limits the temporal extent of the modification made to the time history. Another commonly used wavelet is the tapered sinusoid with the level of tapering being period dependent. RSPMATCH alters the frequency content of the ground motion by adding pulses of motion in the form of tapered cosine waves. The end result is a ground motion of the desired frequency content and peak ground acceleration without significantly altering the time signature of the original ground motion. The second approach of spectral matching used in this study is based on velocity response spectrum-Fourier amplitude spectrum compatibility (Celep, 2007). In this method, the scale factors corresponding to each frequency are obtained by dividing the velocity response spectrum of the original record by the target pseudo velocity response spectrum. The Fourier Transform of the original record is multiplied with the scale factors in the frequency domain in order to obtain a scaled Fourier Transform. The scaled time history is obtained by computing the inverse Fourier Transform. This procedure is repeated until a satisfactory convergence is achieved between the pseudo acceleration response spectrum of the record and the target pseudo acceleration response spectrum.

## 3. STRUCTURAL MEMBERS

The structural members designed for the models are shown in Table 4.

Table 4. Sections designed for the structures

| | Floors | Fixed Base Model | Base Isolated Models |
|---|---|---|---|
| | 21~30 | 60x60cm | 60x60cm |
| | 11~20 | 80x80cm | 60x60cm |
| | 1~10 | 90x90cm | 80x80cm |
| | 21~30 | 30cm | 30cm |
| | 11~20 | 40cm | 30cm |
| | 1~10 | 50cm | 30cm |
| Edge Beams | All | 40x80cm | 30x60cm |
| Slab Thickness | All | 30cm | 30cm |
| Foundation Thickness | All | 200cm | 200cm |

Isolator properties are selected in order to provide the criteria indicated in Table 5.

Table 5. Criteria for the isolator properties

| | |
|---|---|
| Compression stresses under DL+LL | < 10-15Mpa |
| Compression stresses under DL+LL+EQ (MCE) | < 60Mpa (Maximum Allowed Compression Stress) |
| Tension stresses under 09DL+EQ (DBE) | < 1.0MPa |
| Maximum isolator displacement (MCE) | < 0.50m |
| Base shear coefficient (DBE, R=1) | < 0.10g |
| Maximum shear strain, $\gamma$ (MCE) | < 250% |

Number and layout of the isolators are determined considering the tensile forces under the structure's core. Effective stiffnesses ($K_{eff}$) are calculated by pushover analysis. With the $K_{eff}$ of the LRB isolator, natural period of the structural system is calculated as TX = 4.23sec and TY = 4.16sec. With the $K_{eff}$ of the HRB isolator, natural period of the structural system is calculated as TX = 4.86sec and TY = 4.80sec. The tensile stiffness values are assumed to be 1/15 of the compressive stiffness based on experimental study of the manufacturer for shear strain of $\gamma$=100%.

Table 6. Isolator properties used in the design

| Characteristics | | LRB | | HRB | |
|---|---|---|---|---|---|
| | | LH100G4-A | LH130G4-A | HH095X6R | HH120X6R |
| Initial Stiffness | | 20000kN/m | 33900kN/m | 13100kN/m | 20700kN/m |
| Post Yield Stiffness | | 1540kN/m | 2610kN/m | 1310kN/m | 2070kN/m |
| Effective Stiffness ($K_{eff}$) | | 2501kN/m | 4237kN/m | 1813kN/m | 2872kN/m |
| Characteristic Strength | | 250kN | 423kN | 179kN | 285kN |
| Compressive Stiffness | | 4610MN/m | 7830MN/m | 4980MN/m | 7860MN/m |
| | $(\gamma_0,\sigma_0)$ | (0.00,60.0) | (0.00,60.0) | (0.00,59.0) | (0.00,60.0) |
| | $(\gamma_1,\sigma_1)$ | (1.40,60.0) | (3.12,60.0) | (2.30,59.0) | (3.60,60.0) |
| | $(\gamma_2,\sigma_2)$ | (4.00,22.2) | (4.00,47.1) | (3.60,29.0) | (3.70,56.0) |
| Allowable tensile stress | | 1.0MPa | 1.0MPa | 1.0MPa | 1.0MPa |

## 4. ANALYSIS RESULTS

Maximum displacement demands on the isolators are calculated using the average of absolute maximum displacement values for each ground motion record. In case of the LRB model, maximum isolator displacements are 0.288m and 0.445m calculated at DBE event and MCE event respectively. In case of the HRB model maximum isolator displacements are 0.332m and 0.477m calculated at DBE event and MCE event respectively.

Floor displacements for three models under DBE seismic event are shown in Figure 2.

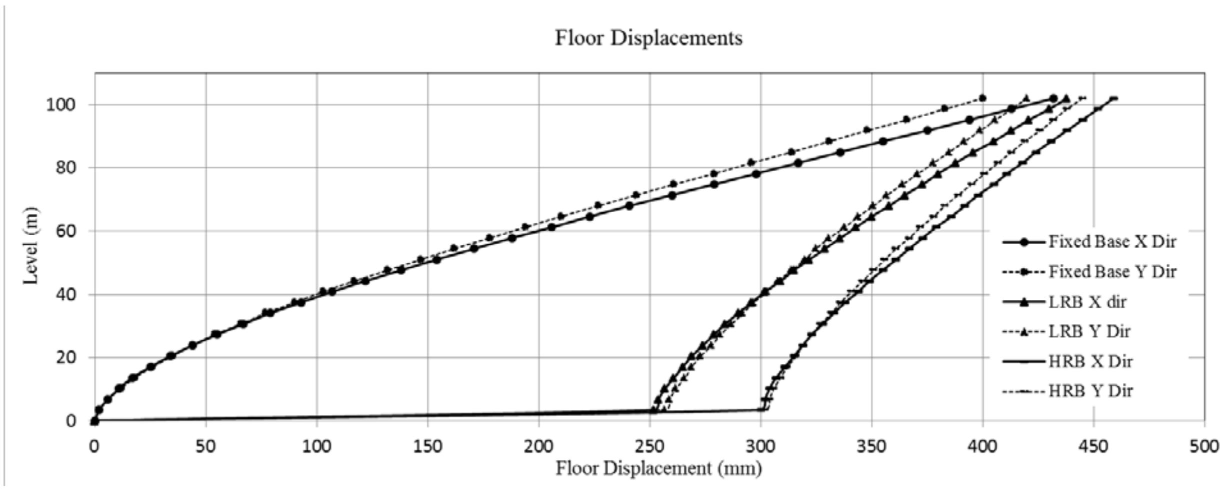


Figure 2. Maximum floor displacements (DBE)

Floor accelerations for three models are given in Figure 3. The accelerations are the average of absolute maximum acceleration values for each ground motion record.

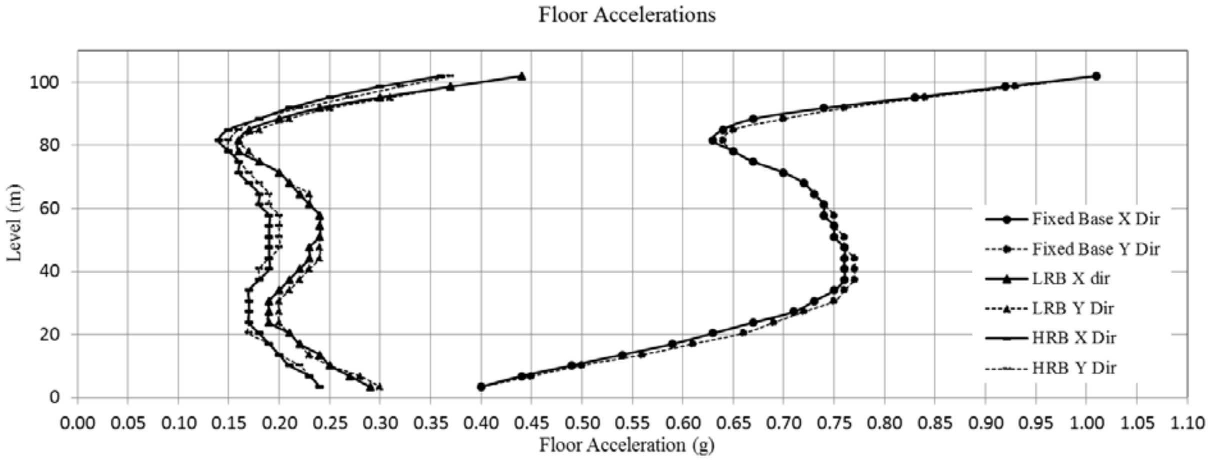


Figure 3. Maximum Floor Accelerations (DBE)

Story drift ratios for three models are given in Figure 4. The drift ratios of the base isolated models are below 0.25% which satisfies ASCE 7-10.

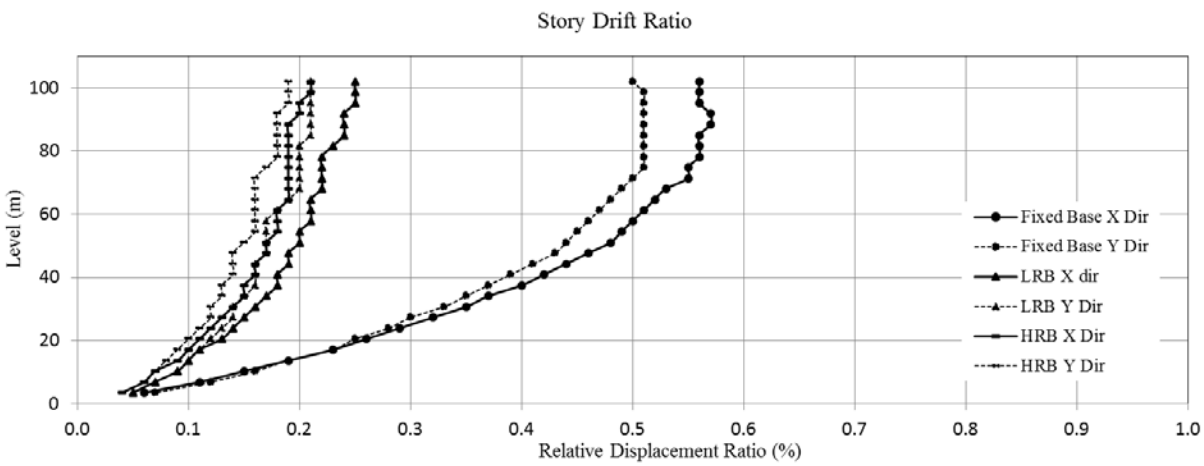


Figure 4. Story Drift Ratios

## 5. COMPARISON OF THE RESULTS FROM COMFORT PERSPECTIVE

Purpose of comparing the floor accelerations and drift ratios is to make a pre-assessment for the risks due to the non-structural elements such as ceiling, mechanical equipment, furniture, glazing etc. and residents' comfort during an earthquake.

In the base-isolation specification of Turkish Ministry of Health, target floor acceleration limit is defined as 200cm/sec². This limit is conservative for residential buildings since it is defined for the medical equipments not to be damaged and go on operation just after an earthquake. No limit is defined in the design codes for the floor acceleration in the residential buildings. However, floor acceleration is used as a parameter in order to estimate the fragility in ATC58-1. For instance suspended ceiling, bookcases & file cabinets, desktop equipments and mechanical equipment are defined to be sensitive to floor acceleration while developing fragility.

As seen on Figure 3, floor accelerations for the base isolated models are mostly below 0.30g limit. Especially for the HRB model, the values does not exceed 0.25g except the two floors on top. On the other hand, floor

accelerations in the fixed base model are above 0.60g at more than 2/3 of the building. On the top floor, it reaches 1.01g.
Story drift limit for the structures are defined differently in the various codes. Drift limit according to DBYBHY'07 and IYBDY'08 is 2.0% whereas ASCE 7-10 sets the limit as 1.5%. DBYBHY'07, IYBDY'08 and ASCE 7-10 takes only the structural damage into consideration, however Eurocode takes also non-structural risks into consideration. In Eurocode, drift limit is defined as 0.5% for buildings having non-structural elements of brittle materials attached to the structure, 0.75% for buildings having ductile non-structural elements and 1.0% for buildings having non-structural elements fixed in a way so as not to interfere with structural deformations, or without non-structural elements.
Together with the structural elements, glazing and interior partition walls are directly sensitive to story drift.
As shown in Figure 4, story drifts for the fixed base model exceeds the 0.5% limit for the buildings having non-structural elements of brittle materials attached to the structure defined in Eurocode.
From the structural performance perspective, both structures are designed code compliant, and the codes' target structural performance is the same for both design alternatives. However, since the drift ratios are much smaller in base isolated alternative, the structural damage will be at minor level compared to the fixed base conventional one.

## 6. COMPARISON OF ARCHITECTURAL BENEFITS

Structural member sections get smaller due to the decreasing story shear forces. Shearwall thickness in the first floor of the fixed base alternative is 50cm, while it is 30cm for the base isolated models. Similarly, column sections between 11th and 20th floor are 80x80cm for fixed base alternative, while they are 60x60cm for base isolated models.
However, this decrease in structural members brings only 1% gain to the architectural net area of the building for the selected architectural layout. Since this is a feasibility study, the focus is given on the financial issues. More attention on architectural concepts can be paid in order to increase the usable net areas within the structure in a real design study.

## 7. COMPARISON OF BOQ'S

Bill of quantities are calculated based on the design result. Overall summary of the cost analysis is shown in Table 7.

Table 7. Overall summary of cost analysis

| Construction Cost | Gross Floor Area | TL/m² | USD/m² | Total Cost (TL) | Total Cost (USD) |
|---|---|---|---|---|---|
| Fixed base system | 26,108m² | 274 | 127 | 7,153,890 | 3,305,253 |
| Base isolated system with LRB | 26,108m² | 319 | 147 | 8,327,246 | 3,847,370 |
| Base isolated system with HRB | 26,108m² | 307 | 142 | 8,020,465 | 3,705,630 |

The costs are studied only for the skeleton construction. Land cost, finishing, glazing, furniture, design and management costs etc. are not included in the cost analysis. As shown in Table 7, cost of the base isolated (HRB) alternative is 400.000$ higher compared to fixed base conventional system. This corresponds to 12% increase in the shell core construction. However, in case finishing, glazing, furniture and other additional costs are considered, this ratio is estimated to be in the range of 2-4%.

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