EARTHQUAKE RESISTANT DESIGN BY USING SEISMIC BASE ISOLATION

by

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EARTHQUAKE FORCE

Force due to earthquake is

\[ F = \frac{W}{g} a = W (Seismic \ Coefficient) \]

W = weight of structure;  
g = acceleration due to gravity;  
\( a \) = peak earthquake acceleration.

IS:1893-2002 provides the general principles and design criteria for earthquake loads.
CONVENTIONAL SESIMIC DESIGN

- Sufficient Strength to Sustain Moderate Earthquake
- Sufficient Ductility under Strong Earthquake

Disadvantages
- Inelastic Deformation Require Large Inter-Storey Drift
- Localised Damages to Structural Elements and Secondary Systems
- Strengthening Attracts more Earthquake Loads
NECESSITY OF STRUCTURAL CONTROL

• Increased Flexibility
  Trends toward taller and longer structures

• Increased Safety Levels
  Tall buildings, Offshore structures, Nuclear structures

• Stringent Performance Requirements
  No damage permitted, saving weight & cost is necessary

• Uncertain Dynamic Loadings
  Seismic loads, strong winds, wave loading
CONTROL STRATEGIES

• Passive Control Devices
  
  * Base isolation
  
  Tuned mass/liquied/liquid column dampers
  
  Energy Dissipating Devices such as VD, DED, FD

• Active Control Systems
  
  Active Tendons
  
  Active TMDs, AMD

• Hybrid Control Systems
  
  Combination of active & passive systems
BASE ISOLATION

- Aseismic Design Philosophy
- Decouple the Superstructure from Ground with or without Flexible Mounting
- Period of the total System is Elongated
- A Damper Energy Dissipating Device provided at the Base Mountings.
- Rigid under Wind or Minor Earthquake
Advantages of Base Isolation

- Reduced floor Acceleration and Inter-storey Drift
- Less (or no) Damage to Structural Members
- Better Protection of Secondary Systems
- Prediction of Response is more Reliable and Economical.
Ground Forces are amplified by a factor of 3 to 4 at the roof.

Forces reduced by 3 to 6 across the isolators.
Forces reduced by 8 to 12 at the roof.
The Concept of Base Isolation

- Fixed Base
- Base Isolated

Significantly Increase the Period of the Structure and the Damping so that the Response is Significantly Reduced
Elastomeric bearings

(a)
Sliding bearings

**FPS Isolator elevation**

**FPS Isolator section**
Friction Pendulum Bearing

STAINLESS STEEL CONCAVE SURFACE

SELF LUBRICATING COMPOSITE LINER

ARTICULATING SLIDER

HOUSING PLATE

CONCAVE PLATE

CROSS-SECTION
Applications of Base Isolation

• 1st application in New Zealand in 1974
• 1st US application in 1984
• 1st Japanese application in 1985
• US - 80 buildings and 150 bridges
• Japan - 1000 buildings and 500 bridges
• 1st Indian application in 2003
Figure 7.2 Foothill Communities Law and Justice Center, Rancho Cucamonga, California (photo by I.D. Aiken).
The **Washington State Emergency Operations Center at Camp Murray** is an essential facility used for the central coordination of emergency responses for the State of Washington. The building houses critical communications and computer equipment. The Friction Pendulum TM seismic isolation bearings were designed to enable the building to withstand the maximum credible earthquake for the Seattle region. The building is located 8 miles from the epicenter of the Magnitude 6.8 earthquake that shook the Seattle region on February 28, 2001. The building and all its equipment and contents remained fully operational after the earthquake.
Figure 7.3 University of Southern California, University Hospital
(Photograph by P.W. Clark).

Location: Los Angeles, California.
Isolator: LRB
Engineers: KPFF
Year: 1991
Figure 7.9 Tohoku Electric Power Company, Japan (Kelly, 1997).

Location: Sendai, Miyako Provience
Isolator: HDR
Year: 1990
Figure 7.1 Demonstration building in Indonesia (1994)

Location: 1 k.m. SW of Pelabuhan
Building: 4-Story
Isolator: 16 HDR
Manufacturer: MRPRA, UK
Bhuj Hospital (2003)

- Newly constructed after collapse of old hospital in 2001 Bhuj Earthquake
- About 200 people died in the old hospital
Bhuj Hospital (2003)

- Lead-rubber bearings & Sliding bearings
- Robinson Seismic Ltd
- Supported by PMRF

- Time History & Response Spectrum Analysis
- Provision for Torsion (Static Expression)
- Displacement Requirements for the Isolation system are over Conservative
  - **USE OF ADDITIONAL DAMPERS**
  - Same Cost of Dampers and Isolators
  - Defeat to the Purpose of Isolation
Base Shear for Isolated Structure

\[ V = \frac{K_{\text{max}} D}{R_{wl}}; \quad K_{\text{max}} = \left( \frac{2\pi}{T_i} \right)^2 \frac{W}{g}; \quad \text{and} \quad D = \frac{10ZNS_i T_i}{B} \]

\( R_{wl} = \) Coefficients Related to Capability of Structure to Sustain Inelastic Deformation without Collapse.

\( Z = \) Zone Factor

\( N = \) Coefficient Related to Proximity of Active Fault near the Structure.

\( T_i = \) Period of Isolated Structure

\( B = \) Coefficient Related to the Damping of Isolator.

\( S_i = \) Soil-Foundation Factor

Lateral force at any Level,

\[ F_i = V \frac{W_i}{\sum W_i} \]
LAMINATED RUBBER BEARINGS

NOTE: ALL DIMENSIONS ARE IN MM
FORCE-DEFORMATION CHARACTERISTICS
Design of Elastomeric Bearings

Horizontal and vertical stiffness of the bearings are expressed by

\[ K_h = \frac{GA}{t_r} \]
\[ K_v = \frac{E_c A}{t_r} \]

- \( A \) = area of the bearing
- \( t_r \) = thickness of rubber in the bearing
- \( E_c \) = instantaneous compression modulus of the rubber-steel composites
- \( G \) = shear modulus the rubber

For a bearing square in plan,

\[ E_c = 6.73S^2G \]

- \( S \) = shape factor (i.e. ratio of the loaded area to the force-free area of the rubber layer).
Fibre-Reinforced Bearings

Replace Steel Plates with Fibre Material

- Reduction in Weight
- Less Labour Intensive Manufacturing
- Vulcanisation under Pressure with Steam can be Replaced by Heating in Microwave or Autoclave
- Long Rectangular Strip Isolators
- Additional Friction Damping in Fibre

![Diagram of fibre-reinforced bearings]
MODELLING OF BASE-ISOLATED STRUCTURES
2-D Model of Isolated Building

\[ m_N \]  
\[ k_N \]  
\[ m_2 \]  
\[ k_2 \]  
\[ m_1 \]  
\[ k_1 \]  
\[ m_b \]  

Base isolator
RESPONSE TO REAL EARTHQUAKE MOTION

Consider a five-storey base-isolated building subjected to El-Centro, 1940 earthquake motion. Let the fundamental time period of the superstructure be 0.5 sec and damping of the order of 2 percent. The base isolation systems are considered namely (i) LRB system with characteristics as $T_b = 2$ sec and $\xi_b = 10$ percent and (ii) FPS system ($T_b = 2$ sec and $\mu = 0.05$).

For the base-isolated structures the response quantities of interest are the top floor absolute acceleration of the superstructure (i.e. $\ddot{x}_a = \ddot{x}_N + \ddot{x}_b + \ddot{x}_g$) and the relative base displacement ($x_b$). The absolute acceleration is directly proportional to the forces exerted in the superstructure due to earthquake ground motion. On the other hand, the relative base displacement is crucial from the design point of view of the isolation system.
Response of five-story building isolated by LRB system

Top floor acceleration (g) vs. Time (sec)

- Fixed base
- Isolated
Response of a five-story isolated by FPS system

- Top floor acceleration (g)
- $x_b$ (cm)

**Graph**:}

**Axes**:}

**Legend**: Fixed base, Isolated
Retrofitting of Historical Buildings

- Interesting constructional/architectural techniques are detected in the historical buildings and need to be preserved.
- The ageing of these structures and their wearing out due to various causes, such as humidity, ground-settlements, pollution, earthquakes, etc. as well as the lack of maintenance, make these structures much more vulnerable to earthquake action.
Mathematical Modeling

- Building idealized as rigid block with mass, $m$
- Bearings are isotropic with same properties in two horizontal directions
- System is modeled as two degrees-of-freedom system
- Design of isolation system

$$T_b = 2\pi \sqrt{\frac{m}{k_b}} \quad \text{or} \quad \omega_b = \frac{2\pi}{T_b} = \sqrt{\frac{k_b}{m}}$$

$$\xi_b = \frac{c_b}{2m\omega_b}$$

$k_b$ = lateral stiffness
$c_b$ = damping
Time variation of superstructure absolute acceleration and bearing displacement of rigid building under Kobe, 1995 earthquake motion ($T_b=2$ sec and $b = 0.1$).

Reduction in the superstructure acceleration

Peak bearing displacement are 32.57 cm and 16.58 cm in x- and y-directions of the building
## Major Retrofitting Projects

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Project and Country</th>
<th>Year</th>
<th>Isolation Systems Utilized</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Salt Lake City and County Building Utah, USA</td>
<td>1989</td>
<td>Lead rubber isolators</td>
</tr>
<tr>
<td>2.</td>
<td>Rockwell International Corporate Headquarters -Building 80</td>
<td>1991</td>
<td>Lead rubber bearings, and rubber bearing</td>
</tr>
<tr>
<td></td>
<td>Seal Beach, California, USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Campbell Hall Monmouth, Oregon, USA</td>
<td>1993</td>
<td>Lead rubber isolator, and rubber isolator</td>
</tr>
<tr>
<td>4.</td>
<td>US Court of Appeals San Francisco, USA</td>
<td>1994</td>
<td>Friction pendulum system</td>
</tr>
<tr>
<td></td>
<td>Wellington, New Zealand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Rockwell International Corporate Headquarters</td>
<td>1994</td>
<td>Lead rubber isolator</td>
</tr>
<tr>
<td></td>
<td>Seal Beach, California, USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Oakland City Hall Oakland, California, USA</td>
<td>1994</td>
<td>Lead rubber isolator, and rubber isolator</td>
</tr>
<tr>
<td>8.</td>
<td>Hughes Aircraft Building El Segundo, California, USA</td>
<td>1994</td>
<td>Lead rubber bearing, and rubber bearing</td>
</tr>
<tr>
<td>9.</td>
<td>Caltrans Traffic Management Center San Diego, California,</td>
<td>1994</td>
<td>High-damping rubber bearings</td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>Long Beach V.A. Hospital Long Beach, California, USA</td>
<td>1995</td>
<td>Lead rubber isolator, rubber isolator, and sliding bearing</td>
</tr>
<tr>
<td>11.</td>
<td>Martin Luther King, Jr. Civic Center Building Berkeley,</td>
<td>1995</td>
<td>High-damping rubber bearing, and lead rubber bearing</td>
</tr>
<tr>
<td></td>
<td>California, USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>Kerckhoff Hall, UCLA Campus Westwood Village, California,</td>
<td>1996</td>
<td>Lead rubber isolator</td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td><strong>San Francisco City Hall</strong> and Civic Center San</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Francisco, California, USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Center San Francisco, California, USA</td>
<td></td>
<td></td>
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<tr>
<td>15.</td>
<td>Head office of Himeji Shinkin Bank (Himeji Credit Bank)</td>
<td>2000</td>
<td>Rubber bearings, and dampers</td>
</tr>
<tr>
<td></td>
<td>Himeji City, Hyogo, Japan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td>Laboratory Building of Kansai University</td>
<td>2001</td>
<td>Rubber bearings, sliding bearings, and oil dampers</td>
</tr>
<tr>
<td></td>
<td>Senriyama Campus of Kansai University, Suita City, Japan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>Tokyo DIA Building Japan</td>
<td>2001</td>
<td>Rubber bearings, and viscous dampers</td>
</tr>
<tr>
<td>18.</td>
<td>Shinjuku Station West Entrance Main Building Tokyo, Japan</td>
<td>2002</td>
<td>Rubber bearings</td>
</tr>
</tbody>
</table>
Salt Lake City and County Building
Salt Lake City, Utah
Retrofitted in 1984 (LRB & N-Z)

San Francisco City Hall (1997)
San Francisco City Hall

- The original design of the building incorporates a “soft story” approach at the main floor, intended to dissipate energy.

- This alongside other discontinuities in the structural system make the dynamic characteristics of the building unfavorable.

- The Building was severely damaged during the 1989 Loma Prieta earthquake.
San Francisco City Hall

Four Retrofit Strategies were considered

- Base Isolation
- Fixed Base / Concrete Shear Walls
- Fixed Base / Steel Braced Frames
- Fixed Base / Steel Moment Frames
- Flexible Story
## San Francisco City Hall

<table>
<thead>
<tr>
<th>Option A: Base Isolation</th>
<th>Minimum Superstructure Reconstruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.23g</td>
<td></td>
</tr>
<tr>
<td>0.17g</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option B: Fixed Base/Shear Walls</th>
<th>Dome Reconstruction Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.65g* (1.2g Elastic)</td>
<td>Interior Impact</td>
</tr>
<tr>
<td>20g* (0.88g Elastic)</td>
<td></td>
</tr>
</tbody>
</table>
### San Francisco City Hall

<table>
<thead>
<tr>
<th>Option C: Fixed Base/Braced Frames</th>
<th>0.65g* (1.2g Elastic)</th>
<th>Dome Reconstruction Required</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20g* (.80g Elastic)</td>
<td>Major Interior Impact</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option D: Fixed Base/Flexible Story</th>
<th>0.50g* (1.2g Elastic)</th>
<th>Lower Story Reconstruction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20g* (.80g Elastic)</td>
<td>Shoring of Building</td>
</tr>
</tbody>
</table>
San Francisco City Hall

• Based on the results of the analysis, the Base Isolation Scheme was selected as best meeting the retrofit objectives and providing the most favorable performance for the least relative cost.

Base Isolation is considered a particularly effective strategy when applied to massive (and rather stiff) structures.
Isolation of Bridges

- Base isolation bearings serve the dual purpose of providing for thermal movement as well as protecting the bridge from dynamic loads.
- The bridge is seismically retrofitted by using the elastomeric identical bearings at pier and abutment locations.

Typical three-span continuous bridge with seismic bearings.
Damage Of Bridges During Past Earthquakes..
Mathematical modeling of isolated bridges

- The superstructure and substructure of the bridge are modelled as lumped mass system divided into number of small discrete segments
- Each adjacent segment is connected by a node
- At each node two-degrees-of-freedom is considered
- The masses of each segment are assumed to be distributed between the two adjacent nodes in the form of point masses
- The bridge superstructure and piers are assumed to remain in the elastic state during the earthquake excitation
# Properties of the bridge deck and piers

<table>
<thead>
<tr>
<th>Properties</th>
<th>Deck</th>
<th>Piers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-sectional area ($m^2$)</td>
<td>3.57</td>
<td>4.09</td>
</tr>
<tr>
<td>Moment of inertia as ($m^4$)</td>
<td>2.08</td>
<td>0.64</td>
</tr>
<tr>
<td>Young’s modules of elasticity ($N/m^2$)</td>
<td>$20.67 \times 10^9$</td>
<td>$20.67 \times 10^9$</td>
</tr>
<tr>
<td>Mass density ($kg/m^3$)</td>
<td>$2.4 \times 10^3$</td>
<td>$2.4 \times 10^3$</td>
</tr>
<tr>
<td>Length/height ($m$)</td>
<td>$3 @ 30 = 90$</td>
<td>8</td>
</tr>
</tbody>
</table>
Response under Kobe, 1995 earthquake motion ($T_b = 2$ sec and $b = 0.1$).

The base shear in the piers is significantly reduced (about 80 to 90%) compared to the conventional bridge system in the both directions of the bridge.

The maximum peak displacement of the bearing is 32.7 cm in the longitudinal direction of the bridge.
Isolation of Liquid Storage Tanks

Sloshing mass

Impulsive mass

Rigid mass

Isolation system

Foundation
LNG storage tanks

Capacity: 38 million gallons
(226 ft dia. x 106 ft. high)

Revithoussa, Athens

212 Friction Pendulum TM bearings.

The largest and heaviest tanks in the world to use seismic isolation
2-D model of base isolated liquid storage tank
Time variation of response quantities of liquid storage tank under Kobe, 1995 earthquake motion ($T_b = 2$ sec and $\xi_b = 0.1$)
- Time variations of various response quantities such as:
  - Normalized base shear \( \frac{F_s}{W} \) where \( W \) is the effective weight of the tank
  - Relative sloshing displacement (i.e. \( x_c = u_c - u_b \))
  - Impulsive displacement (i.e. \( x_i = u_i - u_b \))
  - Relative bearing displacement (i.e. \( x_b \))

- Observation
  - The base isolation is quite effective in reducing the base shear and impulsive displacement of the liquid storage tank
  - As a result of isolation, sloshing displacement increases
  - The peak bearing displacement in the isolator is found to be of the order of the 31.18 cm
  - Thus, the base isolation is quite effective in seismic retrofitting of the existing liquid storage tanks
CONCLUDING REMARKS

• The concept of base isolation and various base isolation systems proposed in the past are reviewed.

• The practical application of base isolation had demonstrated.

• The base-isolated structures performed well during the 1994 Northridge and 1995 Kobe earthquakes.

• Base isolation can also be used for retrofitting of structure.
CONCLUDING REMARKS

• The effectiveness of the base isolation is investigated for structures such as historical buildings, bridges and liquid storage tanks.

• The analytical seismic response of retrofitted structures was significantly reduced when compared with the corresponding structure.

• The base isolation is the best strategy for seismic protection of existing historical structures.

For further Details:
• For further Details:

• V.A. Matsagar and R.S. Jangid, “Base isolation for seismic retrofitting of structures”, *Practice Periodical on Structural Design and Construction, ASCE, USA, Vol. 13*, pp. 175-185,
Building-Moving Base Isolation Improvement Method

Case Study

- Takenaka Corporation moved the laboratory building (1973) of Kansai University Japan
- A reinforced concrete four-story existing structure
- Total weight of approximately 2,000 tons
- Dimensions of 16.4 x 29.1 meters
- Height of 13.6 meters
- Approximately moved eight meters to the west, to install a base isolation system
- The moving of the building was carried out in 15 hours over two days
- The installation of the base isolation system took one month
- Possible to achieve base isolation improvements while maintaining the building in a normal state that allows the building to function normally while work is being carried out
Construction procedure for the Building-Moving Base Isolation Improvement Method

1. Earth retaining and pile work

• 44 new earth retaining H-shaped steel piles put in place where the building was to be moved
2. Excavation work

• The earthen floor slab of the first floor was broken up
• A new structural slab was laid, strengthened with beams
• Excavation was carried out while strengthening existing piles on the base under the existing building and the new site of the building
3. Cut existing piles and construct foundations

- Foundations in areas except around existing piles was constructed
- A temporary base was installed, the existing piles cut, and then new foundations constructed around existing piles
4. Building-moving work

- A roller-lift device was installed, and the temporary base removed.
- The building was then moved approximately eight meters by eight 50-ton propelled hydraulic jacks on the transfer roadbed.
- The stroke of the jacks is 20 centimeters.
5. Base isolation work

• The base isolation system - rubber bearings (diameter 600 millimeters, seven locations)
• Sliding bearings (diameter 450 to 30 millimeters, 11 locations)
• Oil dampers (four locations) will be installed under the existing foundations
6. Completion

- The remaining retaining walls was completed
- The surrounds of the building closed off with expanding metal plates