Vibration Control Techniques for Buildings

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Characteristics of Modern Buildings

♦ Large built-up area constructed on small land area
♦ Vulnerable to natural and man-made disasters
♦ Need more technical management skills
♦ Need continuous monitoring of performance
♦ Failure of such buildings has grave consequences
Critical features for good performance

♦ Expected good performance under
  – Service Loads
  – Wind Loads
  – Earthquake Loads
  – Any other vibrations

♦ May not be possible to achieve all above with conventional design

♦ Use of additional devices needed especially for vibration control
Critical features for good performance

♦ Vibration control needed under
  – Earthquake Load
  – Wind Load
  – Service Loads

♦ Earthquake and Wind loads are critical
♦ Vibration control devices can be used for both these loads
Some failures...
Need for Vibration Control

- Conventional Structures suffer extensive damage during extreme events
- Buildings and Structures having Critical facilities are required to be operational after such events
  - Ex: Hospitals, Communication networks, Life-line facilities, etc.
- Damage to Historical buildings and antique articles cannot be tolerated
- Difficult to design structures under above conditions

PREVENTION IS BETTER THAN CURE
Vibration Control-Concept

♦ Based on the idea that structure can be protected by controlling the vibration energy transmitted
  – Energy balance equation
    • Input Energy = Recoverable Energy + Energy dissipated
      \[ E_i = (E_k + E_s) + (E_\xi + E_p) \]
  – Vibration control techniques try to minimise the energy to be dissipated by structure
    • This minimises the damage
Vibration Control Systems

- **Passive control**
  - Do not need external source of energy

- **Active control**
  - Need continuous source of energy

- **Semi-active or Hybrid control**
  - Needs very less external power
Hybrid Control System

♦ Lesser Control forces are applied to control the passively controlled structure
Semi-active devices

- These are controllable passive devices
- Require less power
Passive Control Devices

- **Base Isolation**
  - Flexible layer at the base
    - Elongates time period
  - Sliding layer at the base
    - Elongates time period
    - Dissipates energy

- **Energy Dissipation**
  - Located at a suitable place in the structure
  - Dissipate energy and reduce energy transmitted to the elements of the structure
Base Isolation
Concept of Base Isolation

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BASE ISOLATION IS ONE OF THE OPTIONS
Concept of Base Isolation

♦ Preventive in concept
♦ Deflects the earthquake energy
♦ Period shift and energy dissipation are the key elements of an isolation system
♦ Accelerations and Forces in structural members reduced substantially
♦ Large displacements occur at isolator level without significant deformation in the structure
Concept of Base Isolation

Normal Structures

Base Isolated Structures

Time Period (sec)

$S_a/g$

T1 T2 T3
Concept of Base Isolation

Deformation Response Spectrum: Northridge Earthquake, 1994

Normal Structures

Base Isolated Structures
Fixed base building

Base-isolated building
Requirements of BI system

♦ Stability during design displacements
♦ Quantifiable engineering parameters
♦ Enough rigidity under in-service loads
Historical Developments

♦ History of over a century

♦ Dr. Calantarient 1909
  – Building on good soil and soft mud below. Withstood the Tokyo earthquake of 1923

♦ Late twenties and thirties – Concept of flexible first storey

♦ 1969-Fintel and Khan – Concept of first soft storey – Yielding of columns
Historical Developments...

- 1940-1984 – Roller and Spherical bearings – Problem of permanent set (PF system)
- First use of rubber in 1969 – Elementary school building in Skopje
- Elastomeric bearings (Reinforced) – 1970s: Practically possible bearings
- Sleeved pile system – 1983
**Historical Developments…**

🚀 **R-FBI, S-RF, EDF – 1980s**  
- Combine friction and elastomeric properties

🚀 **Friction Pendulum System – 1987**  
(Zayas et al.) – Restoration by gravity

🚀 **Variable Frequency Pendulum Isolator (VFPI) – 2000**  
(Pranesh and Sinha)
Modern BI Systems

♦ Elastomeric Systems
  – Laminated Rubber System (LRB)
  – New-Zealand System (NZ)

♦ Friction Systems
  – Pure-Friction Systems (P-F System)
  – Friction Pendulum System (FPS)
  – Variable Frequency Pendulum Isolator (VFPI)

♦ Combined Systems
  – Resilient Friction Base Isolation System (R-FBI)
  – Electricite-de-France System (EDF)
  – Sliding-Resilient Friction Base Isolation System (S-RF)
Laminated Rubber Bearing (LRB)

- Alternate layers of rubber and steel vulcanized together
- Stiff in vertical direction and flexible in horizontal direction
- Period lengthening and energy dissipation
- First mode rigid-body mode
- Higher mode contribution negligible
Laminated Rubber Bearing (LRB)
Pure Friction System (PF)

- Simplest system – Flat sliding surface
- Isolation system works once the static frictional force is overcome
- Isolation through sliding and energy dissipation through friction
- No restoring force mechanism
- Ends-up with large residual displacements
- Response independent of frequency and amplitude of ground motion
Pure Friction System (PF)

Structure mass

Base mass

Foundation

$km + c\dot{\theta} - \mu mg = 0$

$F - m_b\mu g = 0$
Resilient Friction Base Isolation System (R-FBI)

♦ Set of steel rings with central and/or peripheral rubber cores
♦ Very rigid in vertical direction
♦ Friction and rubber act in parallel
♦ Rubber core produces restoring effect and sliding friction causes energy dissipation
Resilient Friction Base Isolation System (R-FBI)
Electricite de France System (EDF)

- Laminated, steel reinforced neoprene pad, topped by a lead-bronze plate
- Elastomeric bearing and a friction plate act in series
- Elastomeric bearing effective for small excitation and sliding occurs for large excitations
Electricité de France System (EDF)
Sliding-Resilient Friction Base Isolation System (S-RF)

- Incorporates desirable features of EDF system and R-FBI system
- Elastomeric bearings of the EDF system are replaced by R-FBI units
- Low-level excitation – similar to R-FBI and for high level sliding in top plate
Sliding-Resilient Friction Base Isolation System (S-RF)
New-Zealand System (NZ)

- LRB with central lead core
- System provides the combined features of vertical load support, horizontal flexibility, elastic restoring force and damping in a single unit
- Lead yields at low stress in shear and behaves as an elastic plastic solid
- Large damping force due to deformation
- Mechanical properties restored
New-Zealand System (NZ)

- **Central Lead Core**
- **Steel Plates**
- **Rubber Layers**

Diagram showing a system with labeled components: $m_b$, $k_b$, $c_b$, $F$, and $x_b$.
Friction Pendulum System (FPS)

♦ Spherical sliding surface with articulated slider
♦ Isolation, energy dissipation and restoring mechanism in one unit
♦ Isolation by sliding, energy dissipation through friction and restoring force through gravity
♦ Isolation Period

\[ T = 2\pi \sqrt{\frac{R}{g}} \]
Friction Pendulum System (FPS)

♦ Lateral stiffness

\[ k = \frac{W}{R} \]

♦ Stiffness is directly proportional to weight

♦ Reduces torsional response

♦ Due to semi-spherical design uniform distribution of pressures
Friction Pendulum System (FPS)

(a) Analytical model
- Articulated slider
- Bearing material
- Sliding surface

(b) Force-deformation relation
Variable Frequency Pendulum Isolator (VFPI)

- Disadvantages of FPS are overcome
- Sliding surface geometry defined such that the frequency of isolation decreases with increase in sliding displacements
- Maximum force transmitted to structure is limited
- Very effective under different types of excitations and structures
- Effective also for low frequency ground motions
Variable Frequency Pendulum Isolator (VFPI)

♦ Geometry defined by

\[
y = b \left[ 1 - \frac{\sqrt{d^2 + 2dx_b \text{ sgn}(x_b)}}{d + x_b \text{ sgn}(x_b)} \right]
\]

♦ Frequency given by

\[
\omega_b^2(x_b) = \frac{\omega_l^2}{(1+r)^2 \sqrt{1+2r}}
\]
Variable Frequency Pendulum Isolator

- Geometry of sliding surface modified to eliminate demerits of FPS
  - Frequency decreases with sliding displacement
  - Isolator frequency depends solely on geometry
  - Restoring mechanism has a bounded value

- Two Indian Patents obtained
Linear Theory of Base Isolation

- Vibration Isolation in Mechanical Engineering is well established theory

- Base isolation theory is extension of this to buildings under earthquake loading
Problem of Vibration Isolation

\[ D_s = \frac{X}{X_{st}} = \frac{1}{\left( (1 - r^2)^2 + (2\xi r)^2 \right)^{1/2}} \]

\[ \tan \phi = \frac{2\xi r}{1 - r^2} \]

Variation of Dynamic response factor with frequency ratio
Vibration Isolation

\[ T_R = \frac{R_{\text{max}}}{F_0} \]

\[ T_R = \frac{\left[1 + (2\xi r)^2\right]^{1/2}}{\left[(1 - r^2) + (2\xi r)^2\right]^{1/2}} \]

\[ F(t) = F_0 \sin \omega t \]

\[ R(t) = kx(t) + c\dot{x}(t) \]
Transmissibility of Forces and Accelerations
Base Isolation

- Earthquake spectra similar to the harmonic spectra
- Acceleration response generally decreases with increase in time period
- Structure acceleration response can be reduced by increasing the time period
- Time period can be increased by incorporating any flexible element at the base
Linear Analysis with Base Isolation

♦ SDOF system on base isolation has an additional DOF at base
♦ Linear BI device can be represented by a spring and viscous damper
♦ Due to difference in damping between structure and BI system it is a non-classical damping case
♦ Normal modal analysis can be done to understand the system qualitatively
Equations of Motion

Structure mass-\(m_s\)

Base mass \(m_b\)

Isolation System

\(k_b, c_b\)
Equations of Motion

♦ Base Mass

\[(m_s + m_b)\ddot{x}_b + m_s\dddot{x}_s + c_b\dot{x}_b + k_b x_b = - (m_s + m_b)\ddot{x}_g\]

♦ Structure Mass

\[m_s \ddot{x}_b + m_s \dddot{x}_s + c_s \dot{x}_s + k_s x_s = - m \dddot{x}_g\]
Matrix Form

\[
\begin{align*}
M \ddot{x} + C \dot{x} + Kx &= -Mr \ddot{x}_g \\
M &= \begin{pmatrix} M & m_s \\ m_s & m_s \end{pmatrix} \\
C &= \begin{pmatrix} c_b & 0 \\ 0 & c_s \end{pmatrix} \\
K &= \begin{pmatrix} k_b & 0 \\ 0 & k_s \end{pmatrix} \\
x &= \begin{pmatrix} x_b \\ x_s \end{pmatrix} \\
r &= \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\
M &= m_b + m_s
\end{align*}
\]
Let

$$\omega_s = \sqrt{\frac{k_s}{m_s}} \gg \omega_b = \sqrt{\frac{k_b}{M}}$$

And

$$\varepsilon = O \left( \frac{\omega_b}{\omega_s} \right)^2$$

be $10^{-2}$ and damping ratios be defined by

$$\xi_s = \frac{c_s}{2 m_s \omega_s} \quad \xi_b = \frac{c_b}{2 M \omega_b}$$
Let mass ratio be defined by

\[ \nu = \frac{m_s}{M} \]

Undamped modes of vibration are

\[ \varphi^n = \begin{bmatrix} \varphi^n_b \\ \varphi^n_s \end{bmatrix}, \quad n = 1, 2 \]

Free vibration analysis can be carried out by

\[ \begin{vmatrix} k - M \omega_n^2 \end{vmatrix} = 0 \]
Characteristic equation is

\[(1 - \nu)\omega_n^4 - (\omega_b^2 + \omega_s^2)\omega_n^2 + \omega_b^2 \omega_s^2 = 0\]

Solving we get

\[
\begin{align*}
\left\{ \begin{array}{l}
\omega_2^2 \\
\omega_1^2 \\
\end{array} \right\} &= \frac{1}{2(1 - \nu)} \left\{ (\omega_s^2 + \omega_b^2) \pm (\omega_s^2 + \omega_b^2) \sqrt{1 + \frac{4v\omega_s^2 \omega_b^2}{(\omega_s^2 + \omega_b^2)^2}} \right\}
\end{align*}
\]

Using binomial series and keeping terms of O(\(\varepsilon\))
If only first term is considered then

\[
\omega_1^2 = \omega_b^2 = \omega_b^2 \left(1 - \nu \frac{\omega_b^2}{\omega_s^2}\right)
\]

\[
\omega_2^2 = \omega_s^2 = \frac{\omega_s^2}{(1 - \nu)} \left(1 + \nu \frac{\omega_b^2}{\omega_s^2}\right)
\]

If only first term is considered then

\[
\omega_b^* = \omega_b
\]

and

\[
\omega_s^* = \frac{\omega_s}{\sqrt{1 - \nu}}
\]
The mode shapes can be got from

\[
\left( K - M \omega_n^2 \right) \varphi^n = 0
\]

The mode shapes are

\[
\varphi^1 = \begin{cases} 1 \\ \varepsilon \end{cases} \quad \varphi^2 = \begin{cases} 1 \\ \left[ \frac{1 - (1 - \nu) \varepsilon}{\nu} \right] \end{cases}
\]
Mode Shapes

First Mode

Second Mode

\[ \nu \varepsilon \]

\[ 1 - \frac{(1 - \nu) \varepsilon}{\nu} \]
Observations

- Isolation Frequency remains unaltered
- Structural frequency increases significantly
- This causes frequency separation and hence isolation
- First mode is almost a rigid-body mode
- Displacement in first mode is at isolation level
- Structural deformation in the second mode
**Current Status**

More than 1000 Structures have been constructed.

**United States**
- 50 New Buildings on Base-Isolation
  - Foot Hill Communities Law and Justice Centre, California 1985
  - Hayward City Hall, December 1997
- 30 Buildings Retrofitted
  - Salt Lake City and Country Building, Utah, 1989
  - Asian Art Museum, SF, October 2000
  - City Halls at San Francisco, Los Angeles

**Isolation Systems**
LRB, HDR, HDR+PTFE Slider, FPS, FPS+Dampers

**Japan** - 500 Buildings

**Europe** - Several Buildings and Bridges

**New Zealand** - 10 Buildings (Lead Rubber Bearing)
Foothill Communities Law and Justice Center, Rancho Cucamonga, California (photo by I.D. Aiken).

Location: Rancho Cucamonga California.
Isolator: HDR
Engineers: Taylor & Gaines; Reid & Tarics.
Year: 1985
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.
University of Southern California, University Hospital
(Opened by P.W. Clark).

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

Location: Sendai, Miyako Provience
Isolator: HDR
Year: 1990
The U.S. Court of Appeals is a 350,000 sq. ft. building listed in the National Register of Historic Places. The building has an elaborate granite exterior and interiors of marble, decorative plaster and hardwoods. Installation of 256 Friction Pendulum TM bearings completed in June 1994, it became the largest building in the world to have been retrofitted with seismic isolators.
Demonstration building in Indonesia (1994)

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

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

- Lead-rubber bearings & Sliding bearings
- Consultants - Robinson Seismic Ltd, New-Zealand
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
Energy Dissipating Devices
Passive Energy Dissipation Systems

♦ Some Devices
  – Metallic Dampers
  – Friction Dampers
  – Viscoelastic Dampers
  – Viscous Fluid Dampers
  – Tuned Mass Dampers (TMD)
  – Tuned Liquid Dampers (TLD)
Metallic Dampers

- Energy dissipation through inelastic deformation of metals
  
  - Examples
    - ADAS damper
    - Lead extrusion damper
    - Torsion beam
    - Flexure beam
  
  - Incorporated so that maximum energy dissipation occurs at these elements
Friction Dampers

- Energy dissipation by dry sliding friction between two solids
  - Examples
    - Limited Slip Bolt
    - X-braced Friction damper
    - Energy dissipating restraint
    - Slotted Bolt Connection
Viscoelastic Dampers

- Viscoelastic materials used for energy dissipation
  - Typically copolymers or glassy substances
  - Dissipate energy when subjected to shear deformation
Viscous Fluid Dampers

- Movement of piston against a viscous fluid under pressure causes energy dissipation
  - Fluid – silicon gel
  - Fluid can pass through orifices
    - Higher energy dissipation
  - Examples
    - Viscous damping wall
    - Taylor devices fluid damper
Tuned Mass Damper

- Consists of a small mass, spring and damper attached to the main structure
  - Response of main structure can be controlled by tuning its frequency with TMD mass
  - Suitable for wind vibrations
TMD in sky scraper at Tapei

Weight = 660 t, diameter = 5.5 m
Tuned Liquid Damper

- Uses liquid for providing dynamic parameters
  - Sloshing results in energy dissipation
  - Liquid provides mass
  - Nonlinear behaviour
  - More practical than TMD
Buildings Using Dampers

- McConnel Library (Friction Damper)
- Izazaga building (brace damper)
- WTC Twin towers (Viscoelastic)
- Citycorp Center, NY (TMD)
Sky scraper at Taipei, Taiwan
Passive Control – Current Status

♦ Developed countries have formulated design guidelines and incorporated in codes
♦ Many structures using the control techniques have been built
♦ Testing & evaluation procedures are available
♦ Currently devices not manufactured on large scale
Active, Semi Active and Hybrid Control Devices

♦ Active Mass Dampers (AMD)
  – TMD controlled by actuators

♦ Semi-active Variable Stiffness (SAVS)
  – Stiffness controlled by actuator force

♦ Hybrid Mass Damper (HMD)
  – Combination of TMD and actuator

♦ Semi-active Hydraulic Damper (SAHD)
  – Controllable, electromagnetic, variable orifice fluid damper
Semi-active hydraulic damper

(cross-section view of Unit 6 & 7 reactor bldgs)
Active Mass Damper
Active Mass Damper
Electro-rheological damper
Concluding Remarks

♦ Base Isolation is a relatively new concept which is effective under most earthquake motion.
♦ Period-lengthening, Energy-dissipation and Restoring mechanism are important requirements of BI System.
♦ Suitable for low to medium rise buildings and effective during earthquakes having high frequency content.
♦ Many systems not effective under low frequency ground motion and near-field ground motion (VFPI an exception).
♦ One of the best options for retrofitting historical monuments.
Concluding Remarks

- Vibration Control leads to safer & serviceable structures after an earthquake
- Different control techniques are effective under different conditions
- Base isolation techniques are not suitable under wind excitations
- TMD & TLD are not very effective under earthquake excitations
- Semi-active are feasible and effective devices
- Developing countries like India should concentrate their research in this area
Any Questions ??