Effect of Soil-Structure Interaction on Performance of Sliding Low-Cost Base Isolators

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1. Background
   - Base Isolation
   - Pure-Friction Base Isolation(PFBI)
   - Soil-Structure Interaction (SSI)
   - Our Research Goals

2. Analytical Model

3. Results and Conclusion

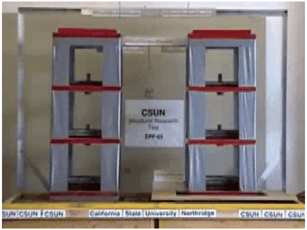
Base Isolation

- A layer of low stiffness between the structure and foundation

[Nakagawa and Shimazaki, 2015]

Base Isolation

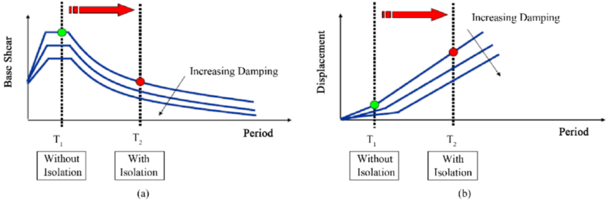
- A layer of low stiffness between the structure and foundation
- Decouples the superstructure from its foundation



Source: Valentin Shustov

Base Isolation

- A layer of low stiffness between the structure and foundation
- Decouples the superstructure from its foundation
- Increases the natural period of the structure



[Barmo et al., 2015]

Elastomeric Base Isolators

- Most commonly used isolation system
- High vertical stiffness but low horizontal stiffness

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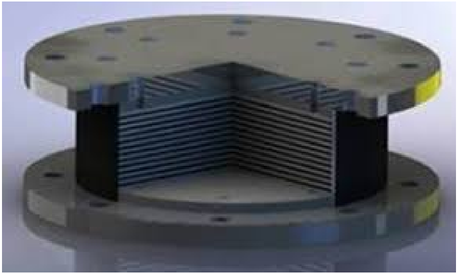

High Damping Rubber Bearing

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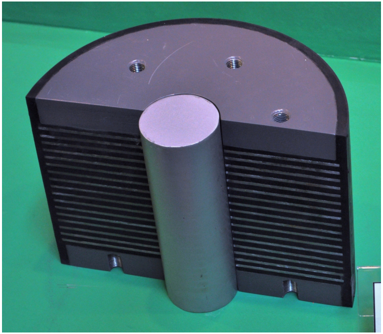

Lead-Plug Rubber Bearing

Sliding Base Isolators

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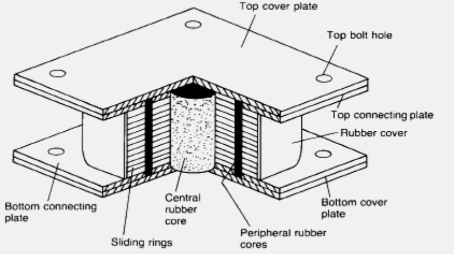


Resilient Friction Base Isolation[Mostaghel and Khodaverdian, 1987]

Sliding Base Isolators

- Sliding elements between structure and foundation
- Restoring forces provided by springs, bearings or curved surface
- Examples:

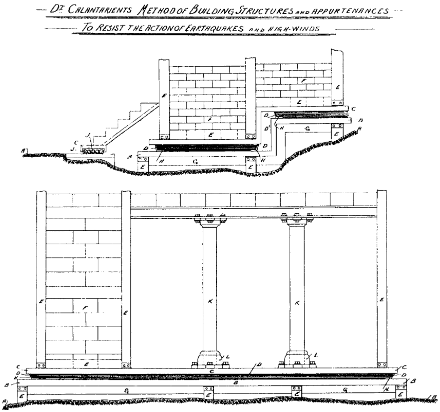
Friction Pendulum System

Introduction to PFBI

- Purely sliding interface between structure and foundation
- No restoring forces!
- Commonly used interface materials include sand, marble, terrazzo, etc.

History of PFBI

- Earliest proposal dates back to 1909 by Johannes Calantarients



Calantarients’ design using talc as the isolating material

History of PFBI

- Earliest proposal dates back to 1909 by Johannes Calantarients
- In the 1930 Dhubri earthquake, masonry buildings that slid on their foundation survived [Gee, 1934]
- Similar phenomenon was observed in the aftermath of the 1979 Tangshan earthquake
- Since then PFBI have been studied both theoretically and experimentally for over half a century [Qamaruddin, 1998]

Need for PFBI

- Masonry buildings have very poor earthquake safety records [Arya et al., 1977]
- However, conventional base isolators are too expensive to apply to small masonry buildings
- They are also too bulky and require highly skilled construction workers
- PFBI provides a low-cost yet effective solution for rural masonry buildings

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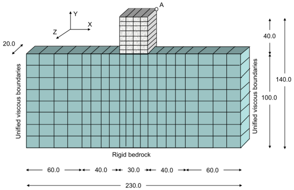

FEM model of a soil-structure system [Hatzigeorgiou and Beskos, 2010]

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- Also, SSI analyses often involve large finite element meshes which are computationally expensive to solve
- Hence they are oft ignored in day-to-day analyses

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2 Analytical Model

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Our Research Goals

- Present a simple, continuous and completely analytical model of PFBI+SSI
- A parametric study of structural response under near as well as far fault seismic records

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2. **Analytical Model**
   - Soil Model
   - Friction Model
   - Analytical Model
   - Equations of Motion
3. Results and Conclusion

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Table 5-1. Lumped Representation of Structure-Foundation Interaction at Surface for Circular Base

Motion	Equivalent Spring Constant	Equivalent Damping Coefficient
Horizontal	$k_x = \frac{32(1-\nu)GR}{(7-8\nu)}$	$c_x = 0.576 k_x R\sqrt{\rho/G}$
Rocking	$k_\psi = \frac{8GR^3}{3(1-\nu)}$	$c_\psi = \frac{0.30}{1+B_\psi} k_\psi R\sqrt{\rho/G}$
Vertical	$k_z = \frac{4GR}{(1-\nu)}$	$c_z = 0.85 k_z R\sqrt{\rho/G}$
Torsion	$k_t = 16GR^3/3$	$c_t = \frac{\sqrt{k_t I_t}}{1+2I_t/\rho R^5}$

Note: ν = Poisson's ratio of foundation medium; G = shear modulus of foundation medium; R = radius of circular basemat; ρ = mass density of foundation medium; $B_\psi = 3(1-\nu)I_O]/(8\rho R^5)$; I_O = total mass moment of inertia of structure and basemat about the rocking axis at the base; and I_t = polar mass moment of inertia of structure and basemat.

Lumped Representation of SSI (ASCE 4-16)

Soil Model

- If soil is assumed to be uniform upto a depth of foundation dimension, simplified soil spring methods can be used as per ASCE 4-16

Table 5-2. Lumped Representation of Structure-Foundation Interaction at Surface for Rectangular Base

Motion	Equivalent Spring Constant	Equivalent Damping Coefficient
Horizontal	$k_x = 2(1+\nu)G\beta_x\sqrt{BL}$	Use the results for circular base with the following equivalent radius R:
Rocking	$k_\psi = \frac{G}{1-\nu}\beta_\psi BL^2$	
Vertical	$k_z = \frac{G}{(1-\nu)}\beta_z\sqrt{BL}$	for translation (1) $R = \sqrt{BL/\pi}$
Torsion	Use Table 5-1 with $R = 4\sqrt{BL(B^2+L^2)/6\pi}$	for rocking (2) $R = 4\sqrt{BL^3/3\pi}$

Note: ν and G are as defined previously; B = width of the basemat perpendicular to the direction of horizontal excitation; L = length of the basemat in the direction of horizontal excitation; and β_x, β_ψ, β_z = constants that are functions of the dimensional ratio, L/B. See Fig. 5-1.

Lumped Representation of SSI (ASCE 4-16)

Conventional Friction Model

- Conventional friction models involve different sets of equation for sliding and non-sliding phases [Nanda et al., 2016]
- This discontinuous model requires convoluted logic to solve as we constantly have to check if the motion is in stick phase or slip phase after every $\dot{x}_b = 0$

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Non-Sliding Phase

$$\ddot{x}_t + 2\varepsilon\omega_n\dot{x}_t + \omega_n^2 x_t = -\ddot{x}_g$$

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Sliding Phase

$$\ddot{x}_t + \ddot{x}_b + 2\varepsilon\omega_n\dot{x}_t + \omega_n^2 x_t = -\ddot{x}_g$$
$$\ddot{x}_b - 2\varepsilon\omega_n\theta\dot{x}_t - \omega_n^2\theta x_t + \mu(1+\theta)g\,\mathrm{sgn}\left(\dot{x}_b\right) = -\ddot{x}_g$$

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Sliding Condition

$$\left| 2\varepsilon\omega_n\theta\dot{x}_t + \omega_n^2 x_t - \frac{\ddot{x}_g + \ddot{x}_b}{\theta} \right| > \mu\left(1 + \frac{1}{\theta}\right) g$$

Arctangent Friction Model

- Friction force is modeled as:

$$F_f = \mu mg * sign(v_{rel})$$

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Actual model

$$sign(v_{rel}) = \begin{cases} 1 & v_{rel} > 0 \\ -1 & v_{rel} < 0 \\ [-1, 1] & v_{rel} = 0 \end{cases}$$

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Arctangent model [Leine and Nijmeijer, 2013]

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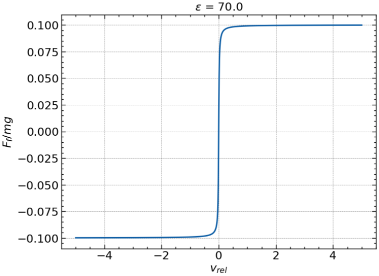

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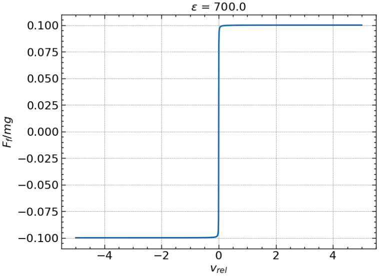

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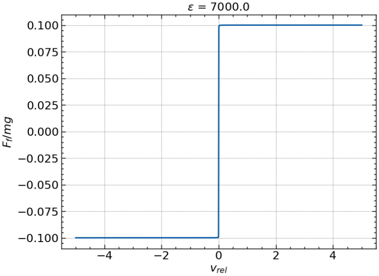


Effect of ϵ

Representative Masonry Building

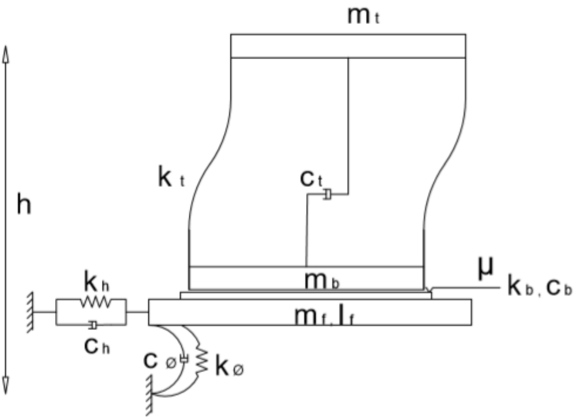
System Parameters

Soil Properties	
Density	1800 kg/m^3
Poisson's ratio	1/3
Shear wave velocity	300 m/s
Foundation Properties	
Length	9.5 m
Width	7 m
Mass	30,000 kg
Moment of inertia	200,000 kgm^2

System Parameters

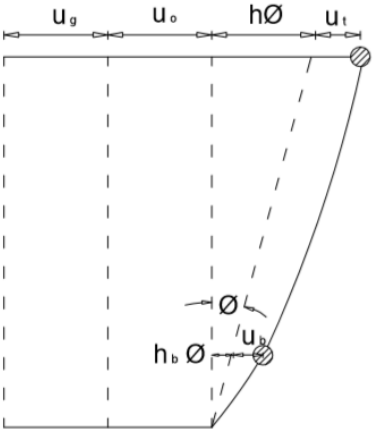
Base Isolator Properties	
Coefficient of friction	0.1
Damping ratio	1%
Structure Properties	
Top mass	35,000 kg
Bottom mass	20,000 kg
Superstructure time period	0.3 s
Damping ratio	5%
Height	2.2 m

Simplified Analytical Model



4-DOF simplified model

Simplified Analytical Model



Degrees of Freedom

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2. Analytical Model
   - Soil Model
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3. Results and Conclusion

Equations of Motion

$$\boldsymbol{M}\ddot{\boldsymbol{u}} + \boldsymbol{C}\dot{\boldsymbol{u}} + \boldsymbol{K}\boldsymbol{u} + \boldsymbol{F_f} = -\boldsymbol{M}\boldsymbol{r}\ddot{u}_g$$

Equations of Motion

$$\boldsymbol{M\ddot{u}} + \boldsymbol{C\dot{u}} + \boldsymbol{Ku} + \boldsymbol{F_f} = -\boldsymbol{Mr}\ddot{u}_g$$

where

$$\boldsymbol{M} = \begin{bmatrix} m_t & 0 & m_t & m_t h \\ 0 & m_b & m_b & 0 \\ m_t & m_b & m_t + m_b + m_f & m_t h \\ m_t h & 0 & m_t h & m_t h^2 + I_f \end{bmatrix}$$

Equations of Motion

$$\boldsymbol{M}\ddot{\boldsymbol{u}} + \boldsymbol{C}\dot{\boldsymbol{u}} + \boldsymbol{K}\boldsymbol{u} + \boldsymbol{F_f} = -\boldsymbol{M}\boldsymbol{r}\ddot{u}_g$$

where

$$\boldsymbol{K} = \begin{bmatrix} k_t & -k_t & 0 & 0 \\ -k_t & K_b + k_t & 0 & 0 \\ 0 & 0 & k_o & 0 \\ 0 & 0 & 0 & k_\phi \end{bmatrix}$$

Equations of Motion

$$\boldsymbol{M\ddot{u}} + \boldsymbol{C\dot{u}} + \boldsymbol{Ku} + \boldsymbol{F_f} = -\boldsymbol{Mr}\ddot{u}_g$$

where

$$\boldsymbol{C} = \begin{bmatrix} c_t & -c_t & 0 & 0 \\ c_t & c_b + c_t & 0 & 0 \\ 0 & 0 & c_o & 0 \\ 0 & 0 & 0 & c_\phi \end{bmatrix}$$

Equations of Motion

$$\boldsymbol{M\ddot{u}} + \boldsymbol{C\dot{u}} + \boldsymbol{Ku} + \boldsymbol{F_f} = -\boldsymbol{Mr}\ddot{u_g}$$

where

$$\boldsymbol{F_f} = \begin{bmatrix} 0 \\ \mu(m_b + m_t)g * sign(\dot{u_b}) \\ 0 \\ 0 \end{bmatrix}$$

Equations of Motion

$$\boldsymbol{M\ddot{u}} + \boldsymbol{C\dot{u}} + \boldsymbol{Ku} + \boldsymbol{F_f} = -\boldsymbol{Mr}\ddot{u_g}$$

where

$$\boldsymbol{r} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

Equations of Motion

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where

$$\boldsymbol{u} = \begin{bmatrix} u_t \\ u_b \\ u_o \\ \phi \end{bmatrix}$$

Solution to EOMS

- Solver used: Backward Difference Formula (BDF)
- Absolute tolerance $= 10^{-8}$
- Relative tolerance $= 10^{-8}$

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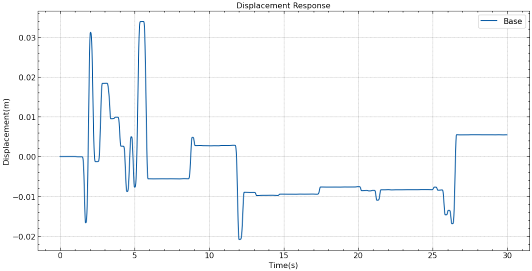
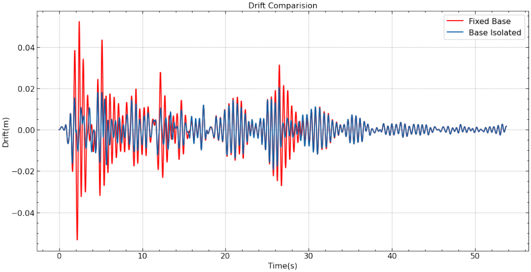
- Solver used: Backward Difference Formula (BDF)
- Absolute tolerance = 10^{-8}
- Relative tolerance = 10^{-8}
- Solved for 20 earthquakes, 10 near-fault and 10 far-fault, each scaled from 0.1 to 1.0g
- Response Parameters Studied:
  - Inter-story Drift Ratio (IDR)
  - Peak Sliding Displacement (PSD)

Sliding Displacement History



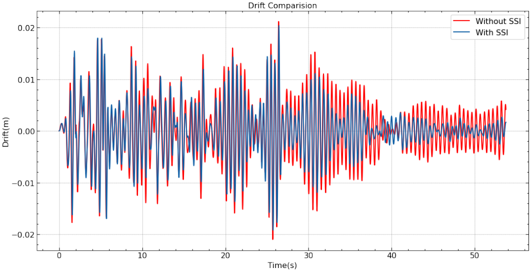
Base displacement history showing typical stick-slip behaviour

Comparision: Fixed vs Sliding Base



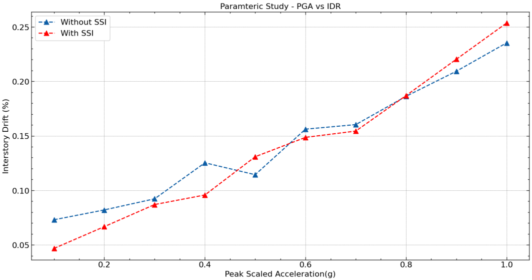
Drift: Fixed vs Sliding Base

Comparison: With SSI vs Without SSI



Drift: With SSI vs Without SSI

SSI effects on IDR



SSI does not always cause response reduction

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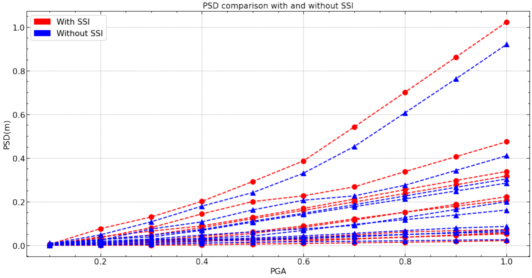
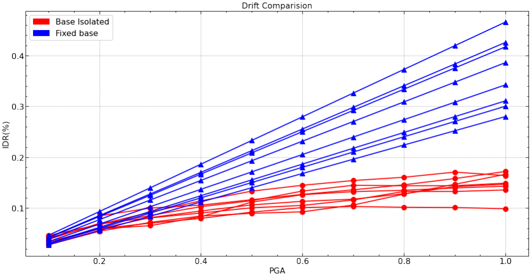
   - Typical Response Patterns
   - Parametric Study
   - Conclusion

Parametric Study: PSD vs PGA



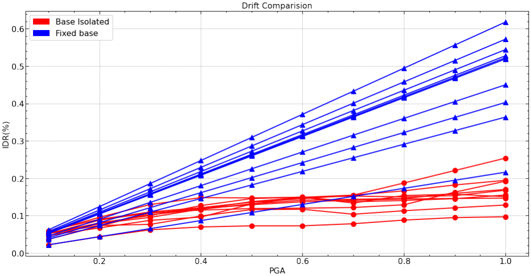
Comparison of PSD with and without SSI

Parametric Study: IDR vs PGA



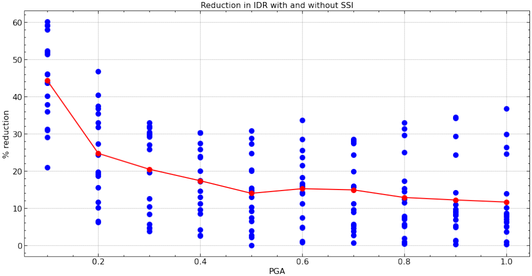
Near Fault

Parametric Study: IDR vs PGA



Far Fault

Parametric Study: % Reduction in IDR vs PGA



Reduction in IDR due to SSI for different PGAs

Conclusions

- When SSI is not considered in design the PSD will be underestimated.
- The % response reduction in IDR due to base isolation is more for far fault earthquakes vs near fault earthquakes.
- The effect of SSI is greater in lower PGAs as compared to higher PGAs.
- The response of a building considering SSI is not always smaller than that without considering SSI.

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Thank You!