Optimization of Triple Pendulum Bearing Design

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Loss from Earthquakes

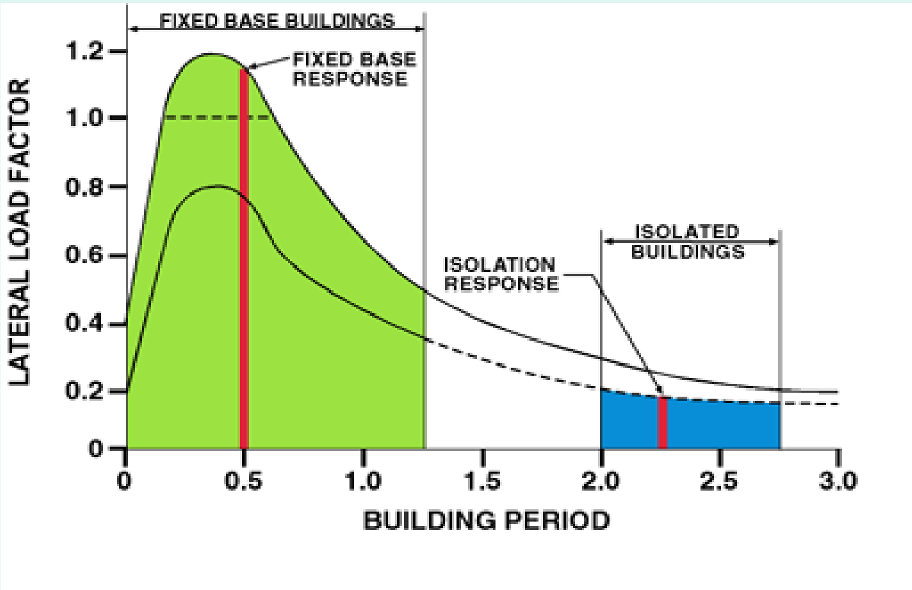
Death Dollars and Downtime

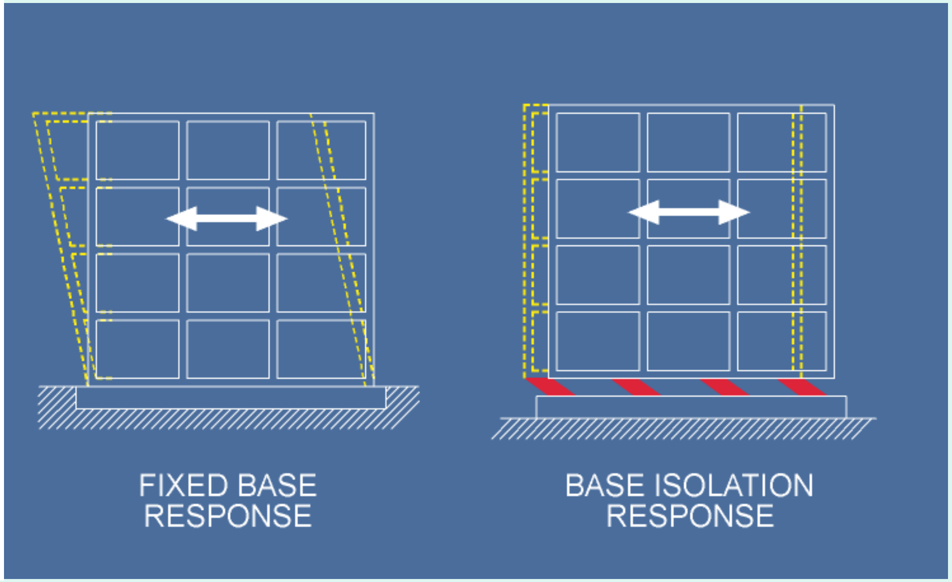
- Death
  - All code designed buildings are designed for minimum of “life safety” for design basis eq
- Dollars
  - Building contents and architectural components account for ~ 80% of building cost
  - Damage to these systems are caused by high floor accelerations
- Downtime
  - Monetary loss due to suspended use of a building because of necessary repairs (tenancy or work)

Base Isolation Benefits

Basic concept of base isolation viewed two ways

1) Shift of building period from predominate earthquake frequencies, decreasing the amount of energy entering the building system
2) Change in first mode shape, concentrating deformation in the isolation layer

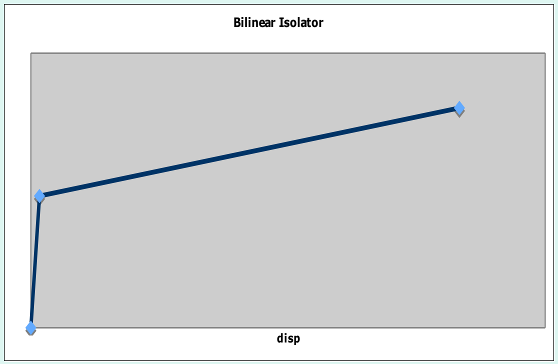


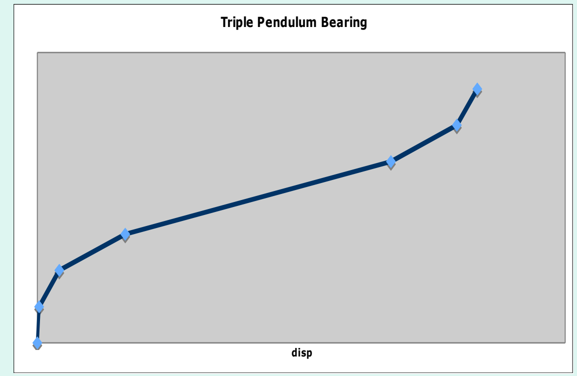


Single Friction Pendulum Bearings and Lead Rubber Bearings

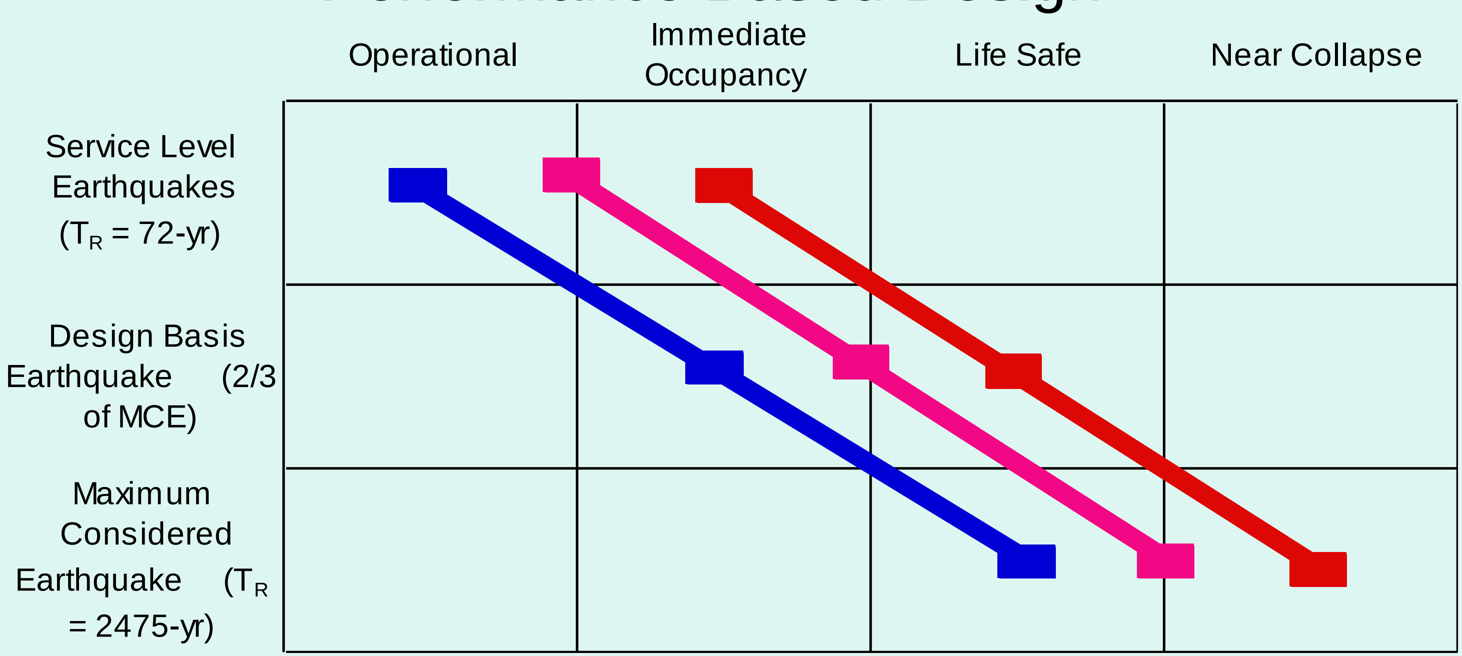
Vs.

Triple Friction Pendulum Bearings



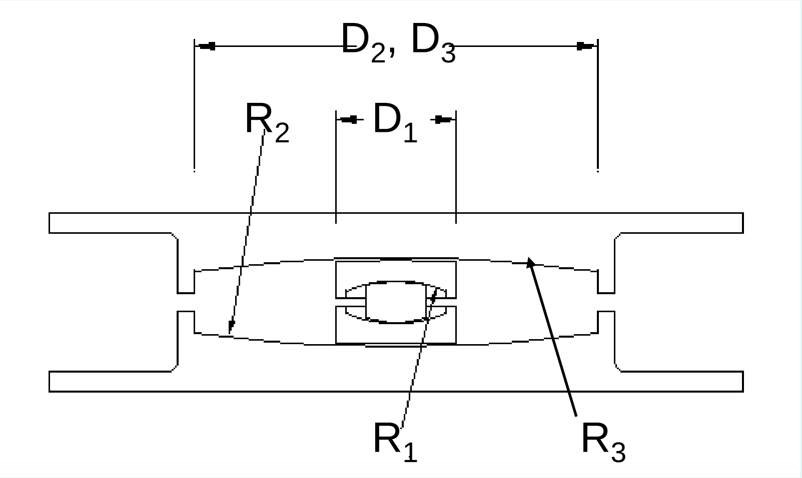


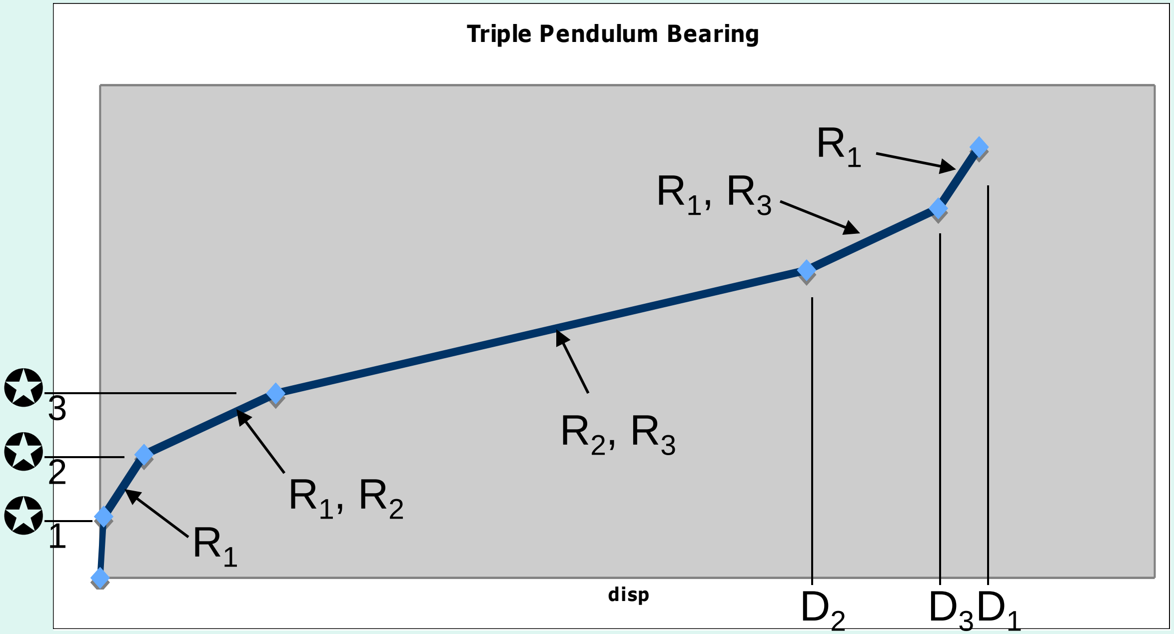
Performance Based Design



Triple Pendulum Bearing Parameters

9 independent parameters
- 3 effective radii
- 3 friction coefficients
- 3 diameters





Triple Pendulum Movie - Kobe

QuickTime™ and a
H.264 decompressor
are needed to see this picture.

Optimization Goal

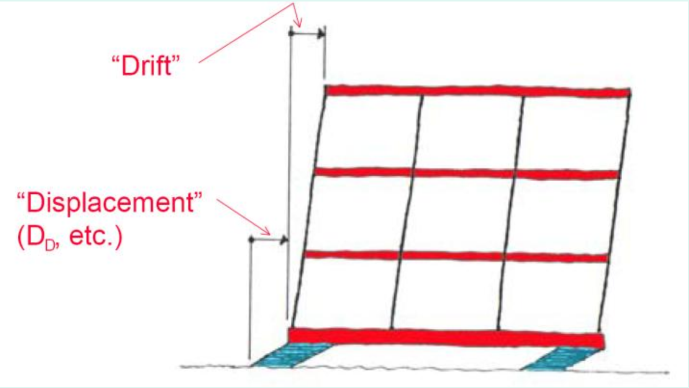
Minimize engineering response parameters

- Floor accelerations
- Interstory drift
- Minimize for 2 design levels - service level and design basis level earthquakes
- Neglect diameters as parameters (only for behavior in maximum considered earthquakes)

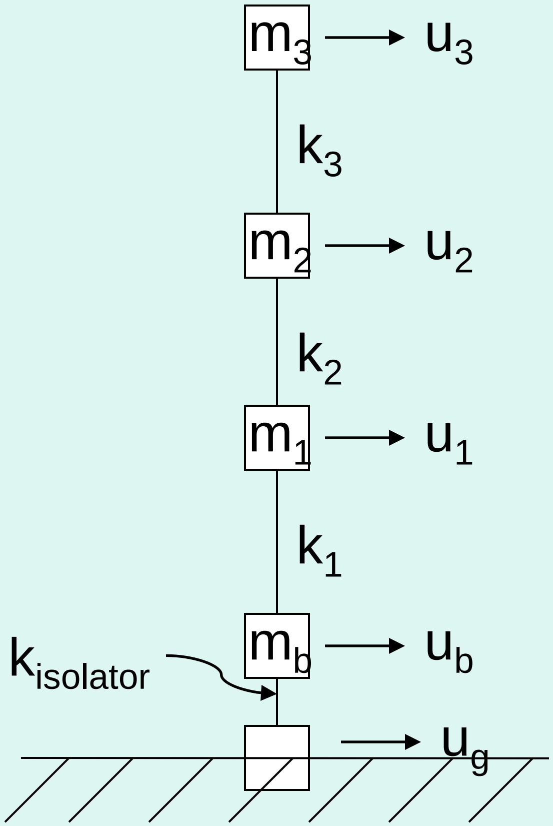
$$w_1\left(\frac{SA_{0.5\max 50\%}}{SA_{0.5 input 50\%}}\right)+w_2(\Delta_{\max 50\%})+w_3\left(\frac{SA_{0.5\max 10\%}}{SA_{0.5 input 10\%}}\right)+w_4(\Delta_{\max 10\%})$$

While limiting certain responses

- Maximum isolator displacement
- Maximum interstory drift



Building Model



$$M\ddot{u}+C\mathring{u}+Ku=-M\ddot{u}_g$$

$$M=\begin{bmatrix} m_b & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 \\ 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & m_3 \end{bmatrix}$$

$$C=\begin{bmatrix} a_0 m_b + a_1(k_{iso}+k_1) & -a_1k_1 & 0 & 0 \\ -a_1k_1 & a_0m_1 + a_1(k_1+k_2) & -a_1k_2 & 0 \\ 0 & -a_1k_2 & a_0m_2 + a_1(k_2+k_3) & -a_1k_3 \\ 0 & 0 & -a_1k_3 & a_0m_3 + a_1k_3 \end{bmatrix}$$

$$K=\begin{bmatrix} k_{iso}+k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1+k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2+k_3 & -k_3 \\ 0 & 0 & -k_3 & k_3 \end{bmatrix}$$

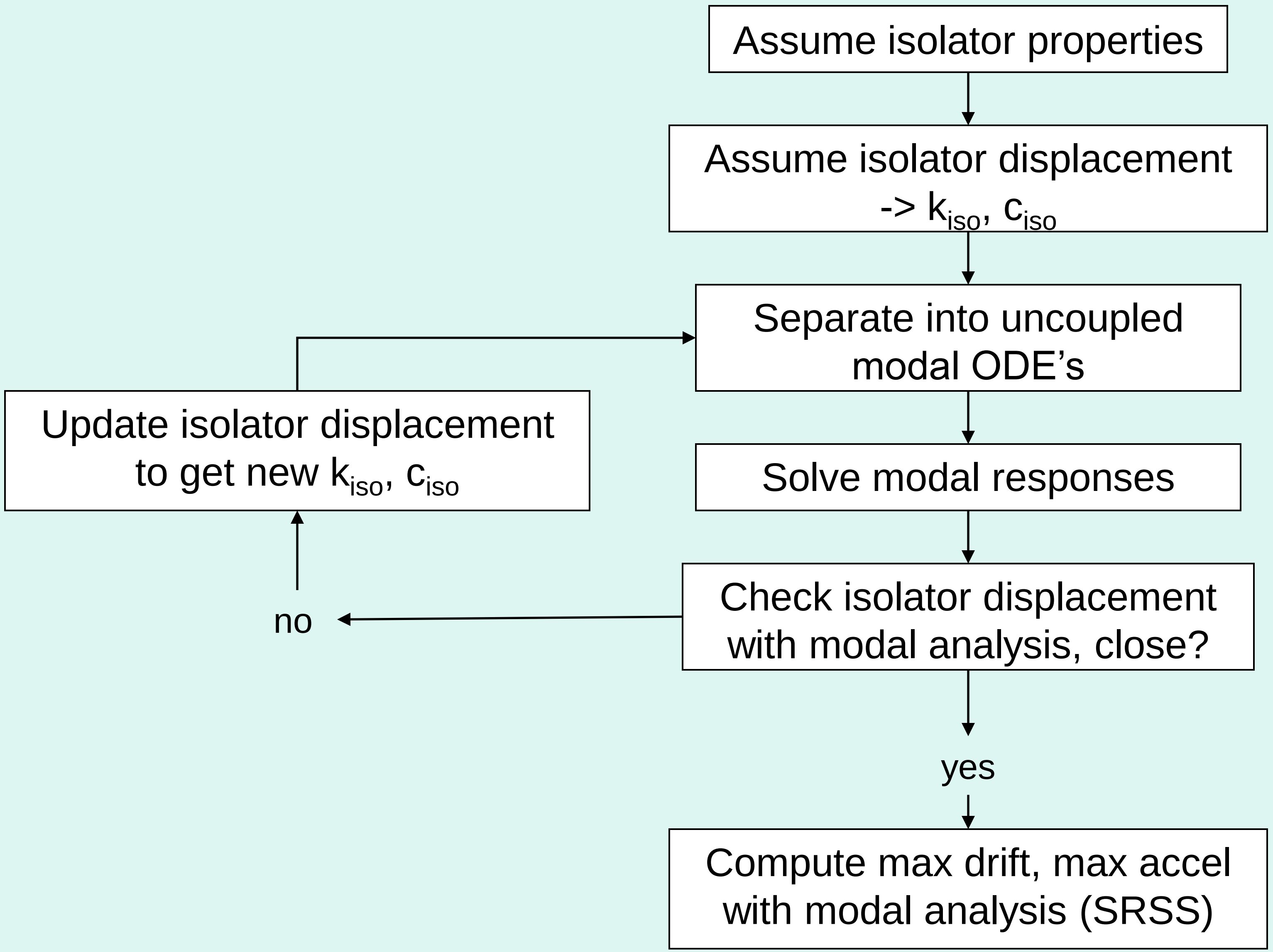
Isolator stiffness and the damping coefficients are the only varying quantities

Sine Pulses to Approximate Near Fault Earthquakes

QuickTime™ and a
decompressor
are needed to see this picture.

Makris and Black

Solution for Response to a Sine Excitation



Solution for Response to a Sine Excitation

Modal equation:

$M_n\ddot{u}+C_n\mathring{u}+K_nu=-M_n\ddot{u}_g=p(t)$

For sine 'B' $\ddot{u}_g=\omega_p v_p\cos(\omega_p t)$

$M_n\ddot{u}+C_n\mathring{u}+K_nu=-M_n\omega_p v_p\cos(\omega_p t)$ $t<T_p$

$= 0$ $t<T_p$

Solution (Chopra Ch3):

$$u_n(t)=C\sin(\omega_p t)+D\sin(\omega_p t)\in 0<t<T_p$$

$$C=\frac{M_n w_p v_p}{K_n}\frac{2\varsigma_n(\omega_p/\omega_n)}{[1-(\omega_p/\omega_n)^2]^2+[2\varsigma_n(\omega_p/\omega_n)]^2}$$

$$D=\frac{M_n w_p v_p}{K_n}\frac{1-(\omega_p/\omega_n)^2}{[1-(\omega_p/\omega_n)^2]^2+[2\varsigma_n(\omega_p/\omega_n)]^2}$$

$$u_n(t)=e^{-\varsigma_n\omega_n t}[A\sin(\omega_{Dn}t)+B\sin(\omega_{Dn}t)]\in t>T_p$$

$$A=u_n(T_p)$$

$$B=\frac{u_n(T_p)-\varsigma_n\omega_n u_n(T_p)}{\omega_{Dn}}$$

Optimization Gradient

$$J = w_1\left(\frac{SA_{0.5\max 50\%}}{SA_{0.5input50\%}}\right) + w_2(\Delta_{\max 50\%}) + w_3\left(\frac{SA_{0.5\max 10\%}}{SA_{0.5input10\%}}\right) + w_4(\Delta_{\max 10\%})$$

$$J = f(SA_{0.5\max 50\%}, \Delta_{\max 50\%}, SA_{0.5\max 10\%}, \Delta_{\max 10\%}) = f(\rho)$$

$$\rho = g(k_{iso50\%}, c_{iso50\%}, k_{iso10\%}, c_{iso10\%}) = g(\psi)$$

$$\psi = h(\mu_1, \mu_2, \mu_3, R_1, R_2, R_3) = h(u)$$

$$J = f(\rho(\psi(u)))$$

$$\partial J = \left(\frac{\partial J}{\partial \rho}\right)\left(\frac{\partial \rho}{\partial \psi}\right)\left(\frac{\partial \psi}{\partial u}\right)$$

Partial derivatives δJ/δρ and δψ/δu are easily found; however δρ/ δψ depends on both the modal expansion, the resulting ODE’s and the modal combination (SRSS used). Find this through finite difference.

Constraints

- $R_1 < R_2$, $R_1 < R_3$, R's $\in (0, +\infty)$
- $\mu_1 < \mu_2 < \mu_3$, $\in (0, +\infty)$
- $\Delta < \Delta_{max}$
- $u_b < u_{bmax}$

Implement logarithmic barriers as seen in class

- $b(R_1) = -\varepsilon \log((R_1-0)(R_1-R_2))$
- $b(R_i) = -\varepsilon \log((R_i-0)(R_i-200))$
- $b(\mu_i) = -\varepsilon \log((\mu_i-0)(\mu_i-1))$
- $b(\mu_1) = -\varepsilon \log((\mu_1-0)(\mu_1- \mu_2))$
- $b(\mu_2) = -\varepsilon \log((\mu_2-0)(\mu_2- \mu_3))$
- $b(\Delta) = -\varepsilon \log((\Delta-0)(\Delta-\Delta_{max}))$
- $b(u_b) = -\varepsilon \log((u_b -0)(u_b - u_{bmax}))$

State of the Project

- Code is currently being de-bugged in MATLAB
- Plan to compare results with
  - Varying pulse types (sine, cosine)
  - Varying initial parameters
  - Varying building characteristics (number of stories, stiffness, damping)
  - Varying importance weights in the optimization function

Questions?