Special issues on Seismic Isolation

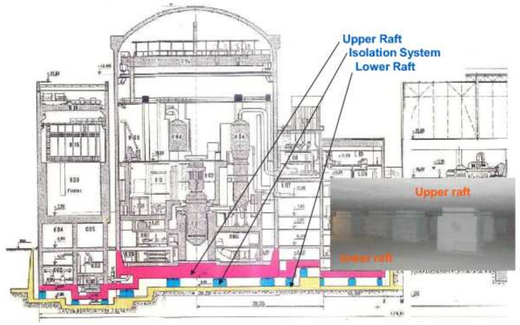
Ioannis Politopoulos
Commissariat à l'Energie Atomique, CEA Saclay, France

- **Non-isolated modes' response of seismically base isolated structures**

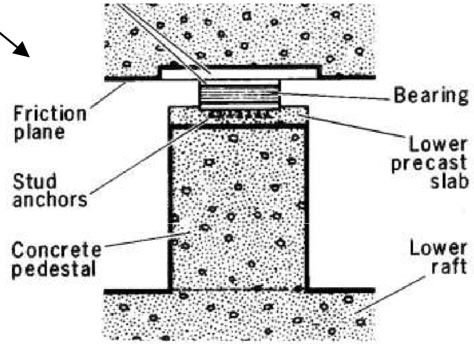
- **Sensitivity of seismically base isolated structures and their equipment**

Nuclear facilities on isolation bearings

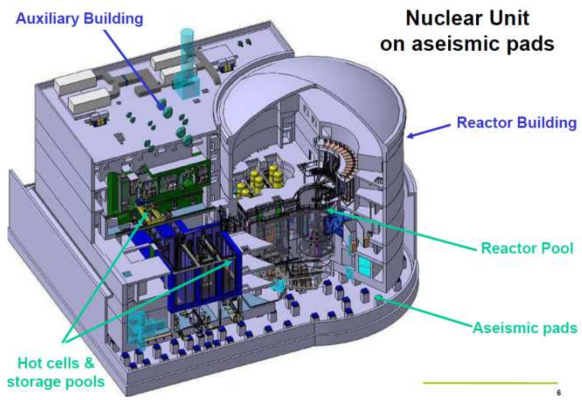
- Cruas-Meysse NPP, France (LDRB, late 70's)



- Koeberg NPP, South Africa (LDRB with friction plate, late 70's)



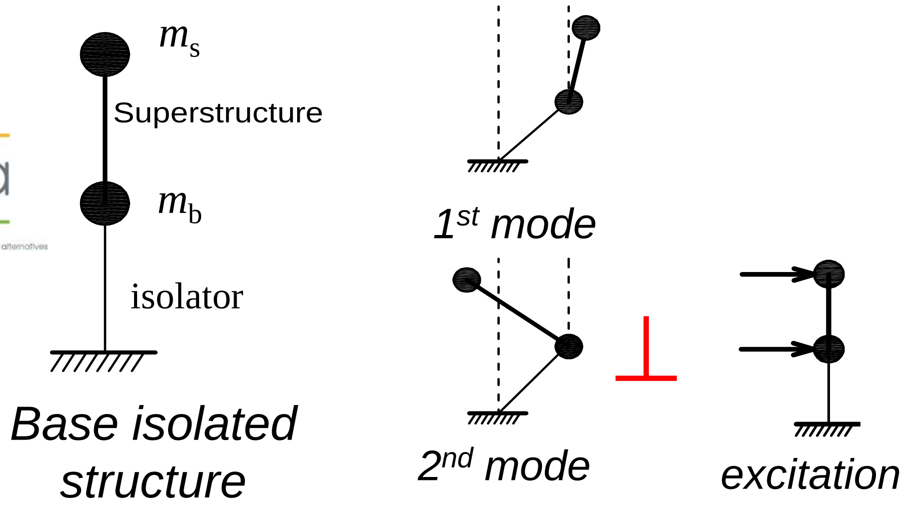
- La Hague fuel storage pool, France (LDRB)
- STAR Cadarache, France (LDRB)
- George Bessel II enrichment facility, France (LDRB)
- JHR France (LDRB, under construction, L≈100 m, H≈45 m, W≈110000 t)

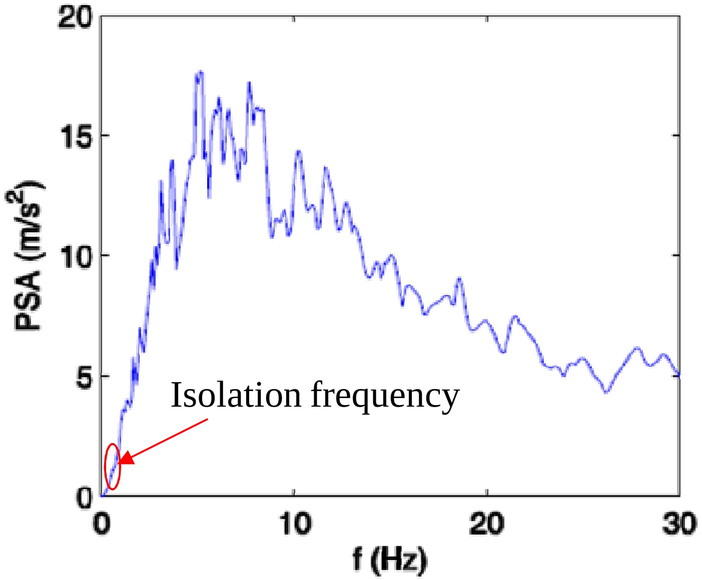


- ITER (Tokamak), France (LDRB, under design, L≈100 m, H≈70 m, W≈350000 t)
- Several concepts under study for GEN 4 NPP in France, Japan, Italy.

Non-isolated modes' response of seismically base isolated structures

Base (*horizontal*) isolation principle (*linear elastic bearings*)





Ground response spectrum

<u>If the superstructure is stiff:</u>

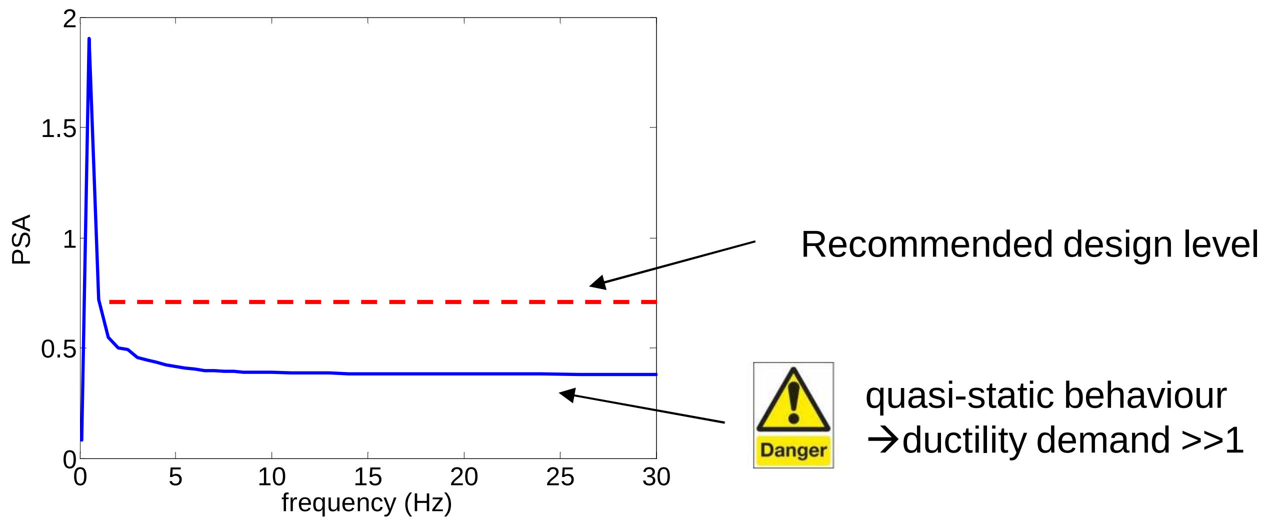
1) Isolated modes: quasi-rigid superstructure low frequency modes

2) Non-isolated modes (other than isolated modes): quasi-orthogonal to horizontal seismic excitation

Additional requirement for industrial plants (e.g. Nuclear facilities)

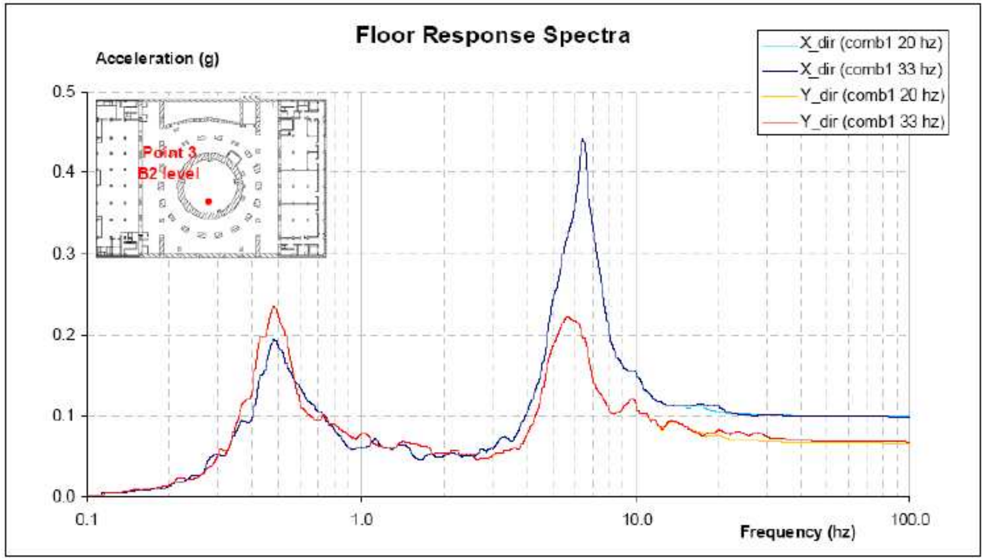
- Proper function of equipment (pumps, core, control rods, electric cabinets, pipes, crane bridge, stability of containers etc.)

- Importance of Floor Response spectra (FRS)

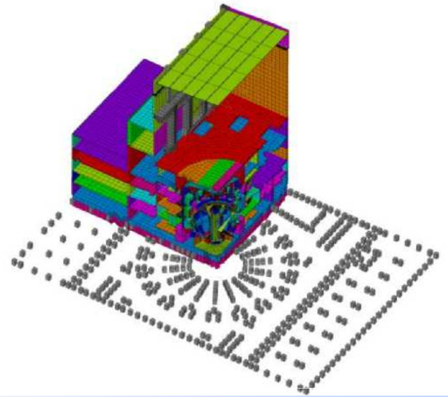


<u>Ideal floor spectrum ≈ Rigid body floor spectrum</u>

Amplification of non-isolated modes response. Why?



Example: ITER (fusion experimental reactor) [Combesure et al, 2010]



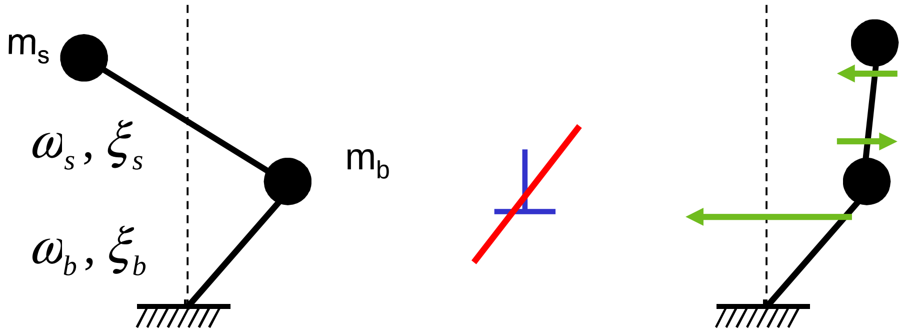
- High base « damping » : Viscous dampers, friction devices, elastoplastic devices

- Base rocking of large foundation: horizontally propagating waves (inclined waves, surface waves), embedded foundation

- Coupling between vertical excitation and horizontal response (plants with complex geometry)

- Linear viscous damping $\xi_b >> \xi_s$

[Kelly 1999, Politopoulos 2008, etc.]

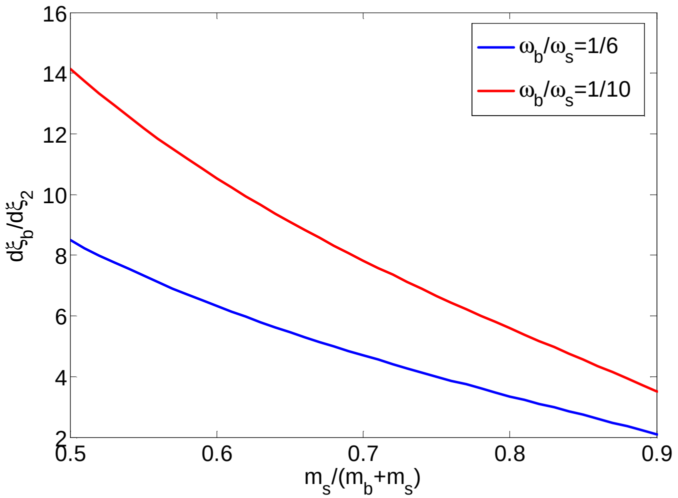


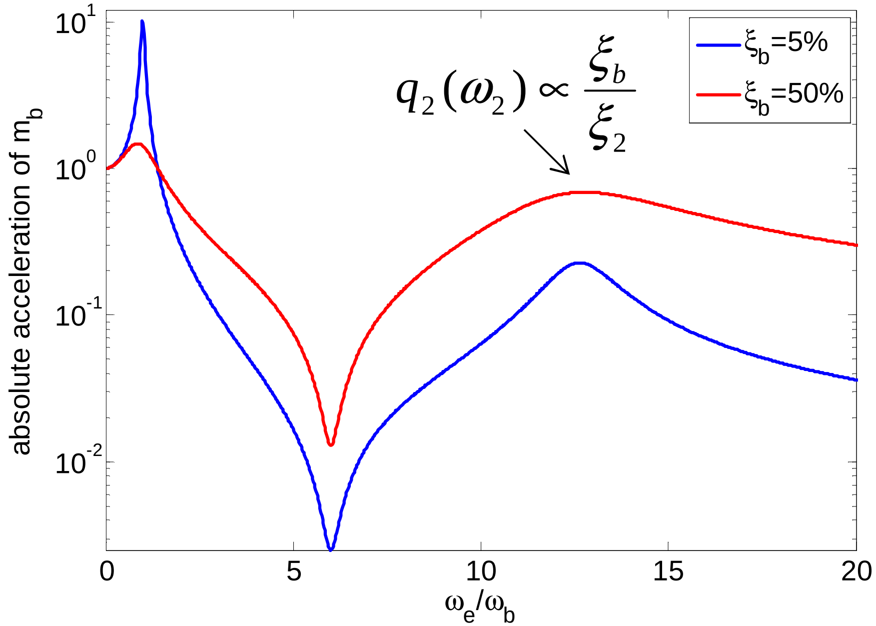
2nd mode

Damping forces due to the 1st mode's response

[Kelly, 1999]

$$\ddot{q}_1 + 2\xi_1\omega_1\dot{q}_1 + \omega_1^2 q_1 = -L_1\ddot{x}_g - \lambda_1\dot{q}_2$$
$$\ddot{q}_2 + 2\xi_2\omega_2\dot{q}_2 + \omega_2^2 q_2 = -L_2\ddot{x}_g - \lambda_2\dot{q}_1$$



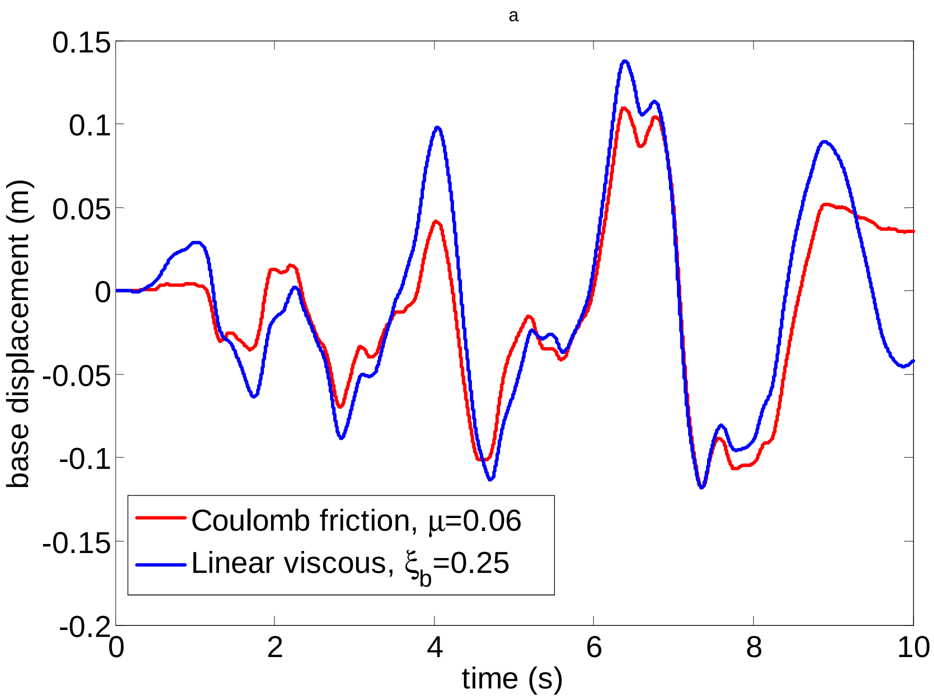


- Friction

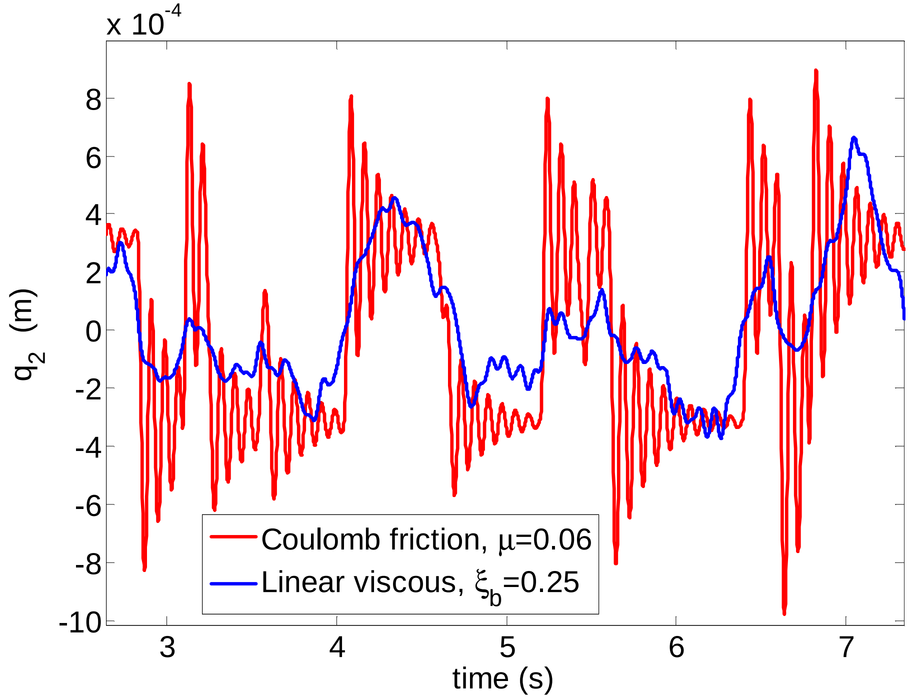
$$\ddot{q}_1 + 2\xi_1\omega_1\dot{q}_1 + \omega_1^{\,2} q_1 = -L_1\ddot{u}_g + \tilde{\phi}_1(1)F_{nl}(q_1, q_2)/m_1$$

$$\ddot{q}_2 + 2\xi_2\omega_2\dot{q}_2 + \omega_2^{\,2} q_2 = -L_2\ddot{u}_g + \tilde{\phi}_2(1)F_{nl}(q_1, q_2)/m_2$$

$$F_{nl}(q_1, q_2) = -\mu g(m_b + m_s)\,\mathrm{sgn}(\dot{x}_{bg}) = -\mu g(m_b + m_s)\,\mathrm{sgn}(\dot{q}_1\tilde{\phi}_1(1) + \dot{q}_2\tilde{\phi}_2(1))$$

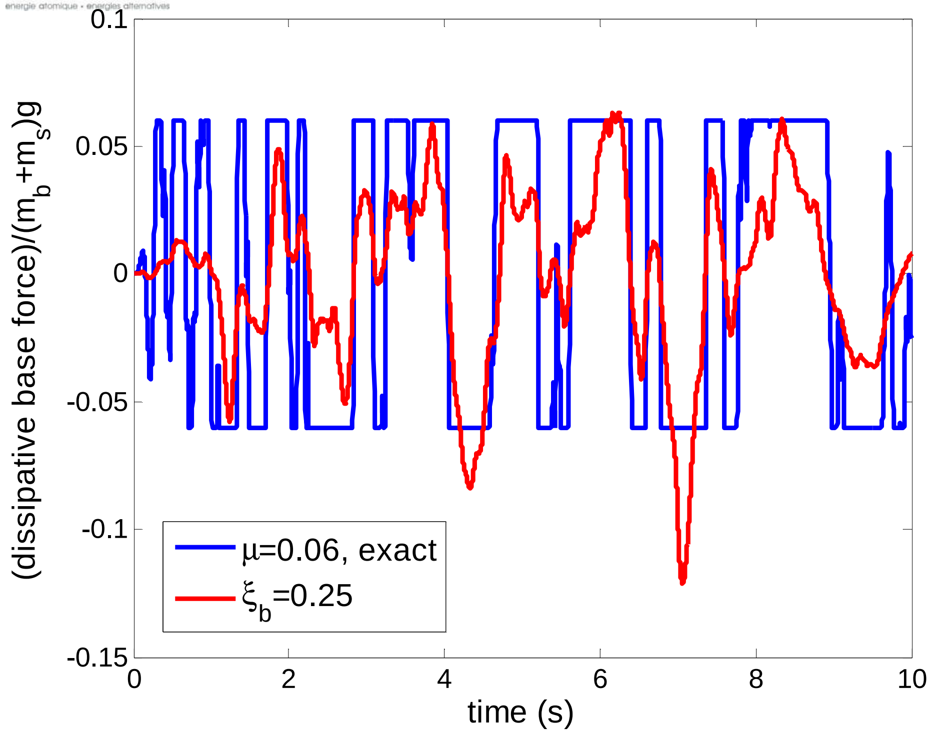


Base displacement

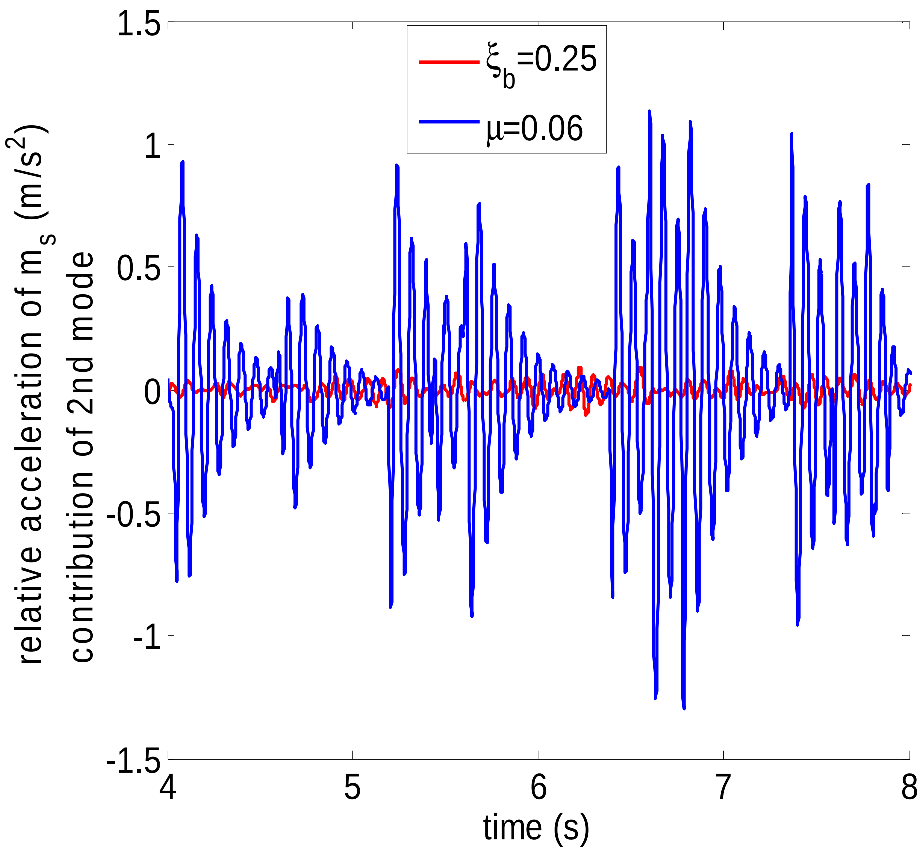


Generalized displacement of the 2nd mode

High base energy dissipation 3/5



dissipative base force (friction or viscous)

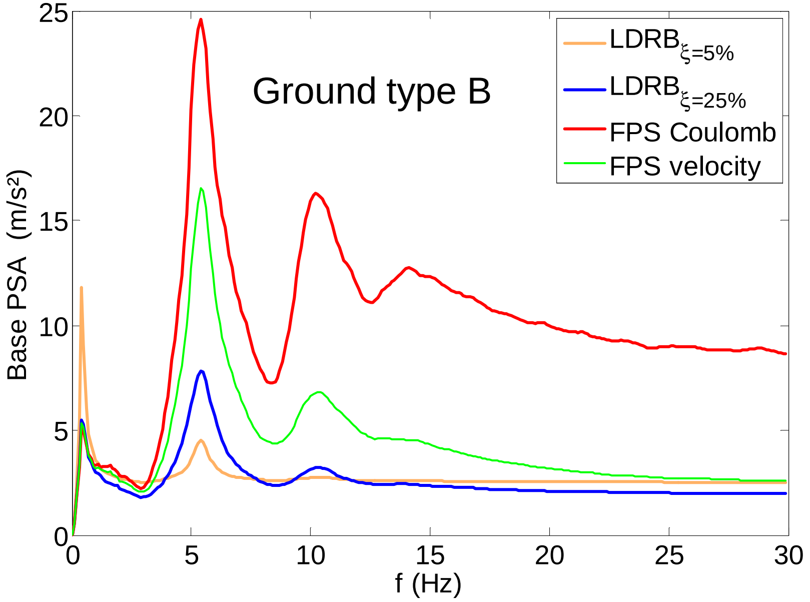


2nd mode acceleration

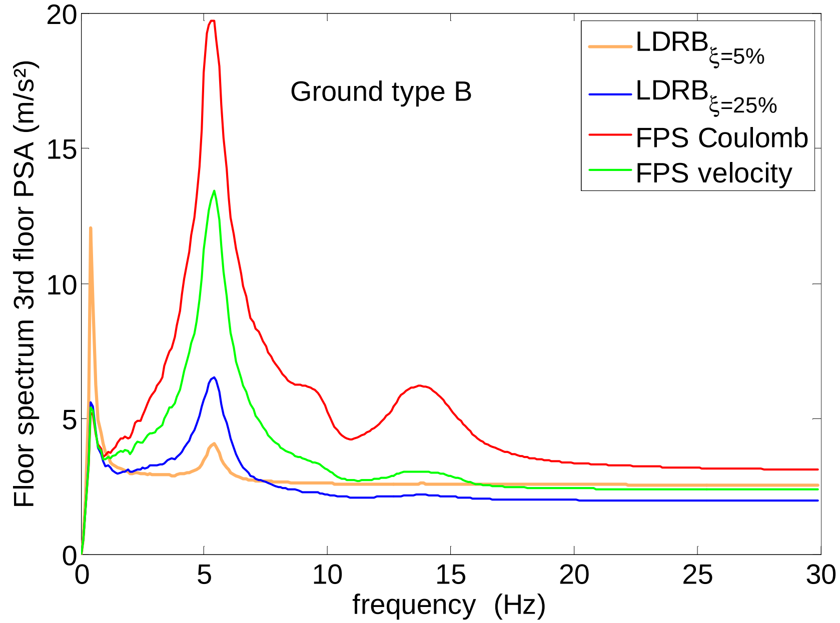
High base energy dissipation

- Linear viscosity vs friction (or elastoplasticity, or NL viscosity $f=cv^{\alpha}$, $\alpha<1$)
  - Example: 4storey shear building (f_{s1}=3 Hz, f_b=0.4 Hz)
    - LDRB (ξ_b=5%)
    - LDRB (ξ_b=25%)
    - FPS (Coulomb dry friction)
    - FPS (velocity dependent friction)

    } same mean peak base displacement
    - Excitation: 100 white noise Kanai-Tajimi filtered signals (PGA=0.6 g)



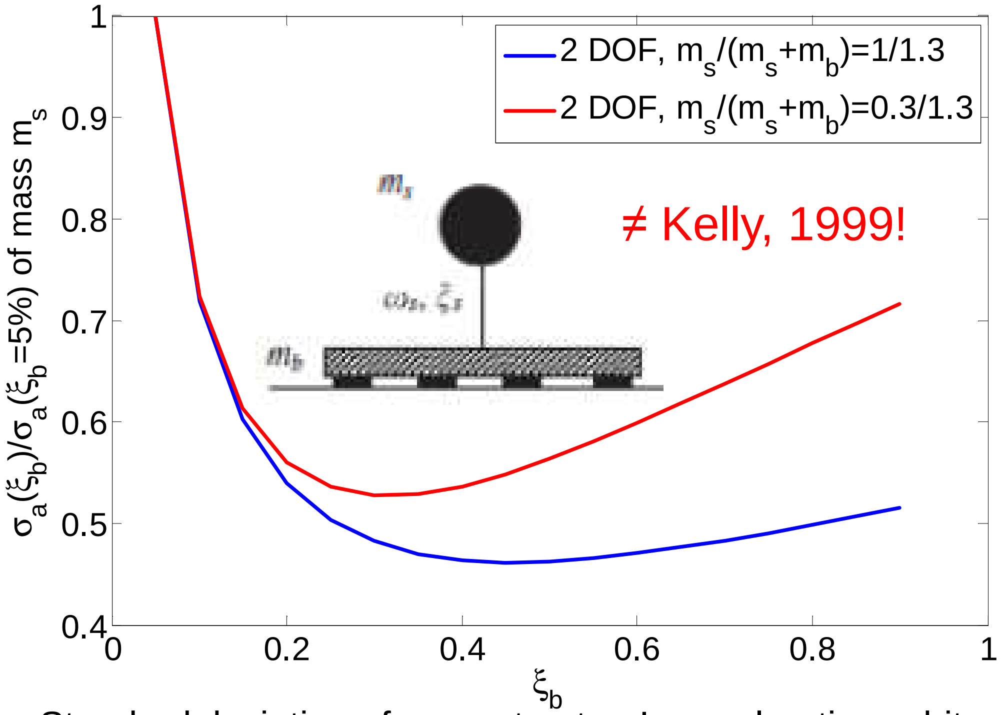
Mean base floor spectrum



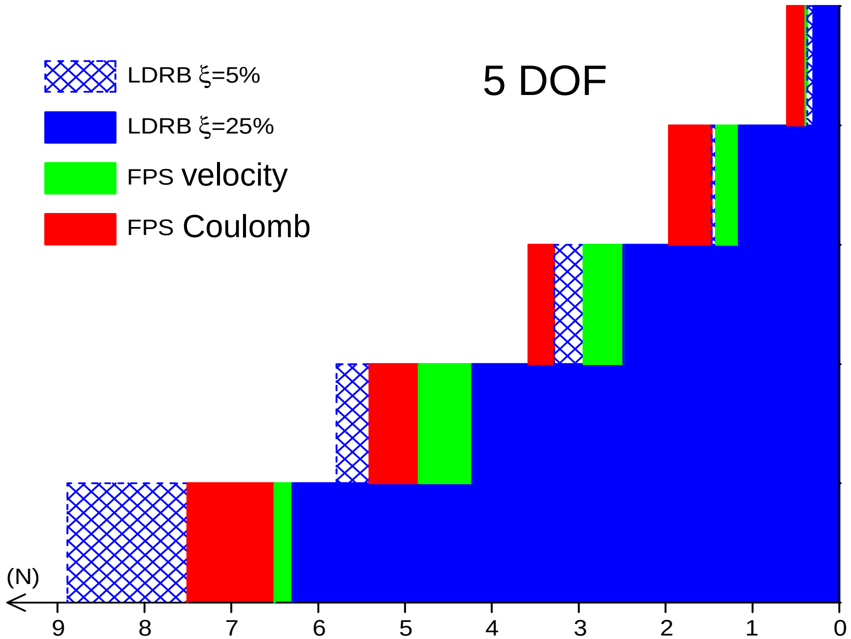
Mean 3rd floor spectrum

High base energy dissipation 5/(

- Influence on storey forces
  - Kelly, 1999 (2 DOF): adverse effects even of linear viscous damping
  - Winters and Constantinou, 1993 (MDOF): friction > linear viscous
  - Actually: « reasonable » linear viscous damping does not increase storey shears



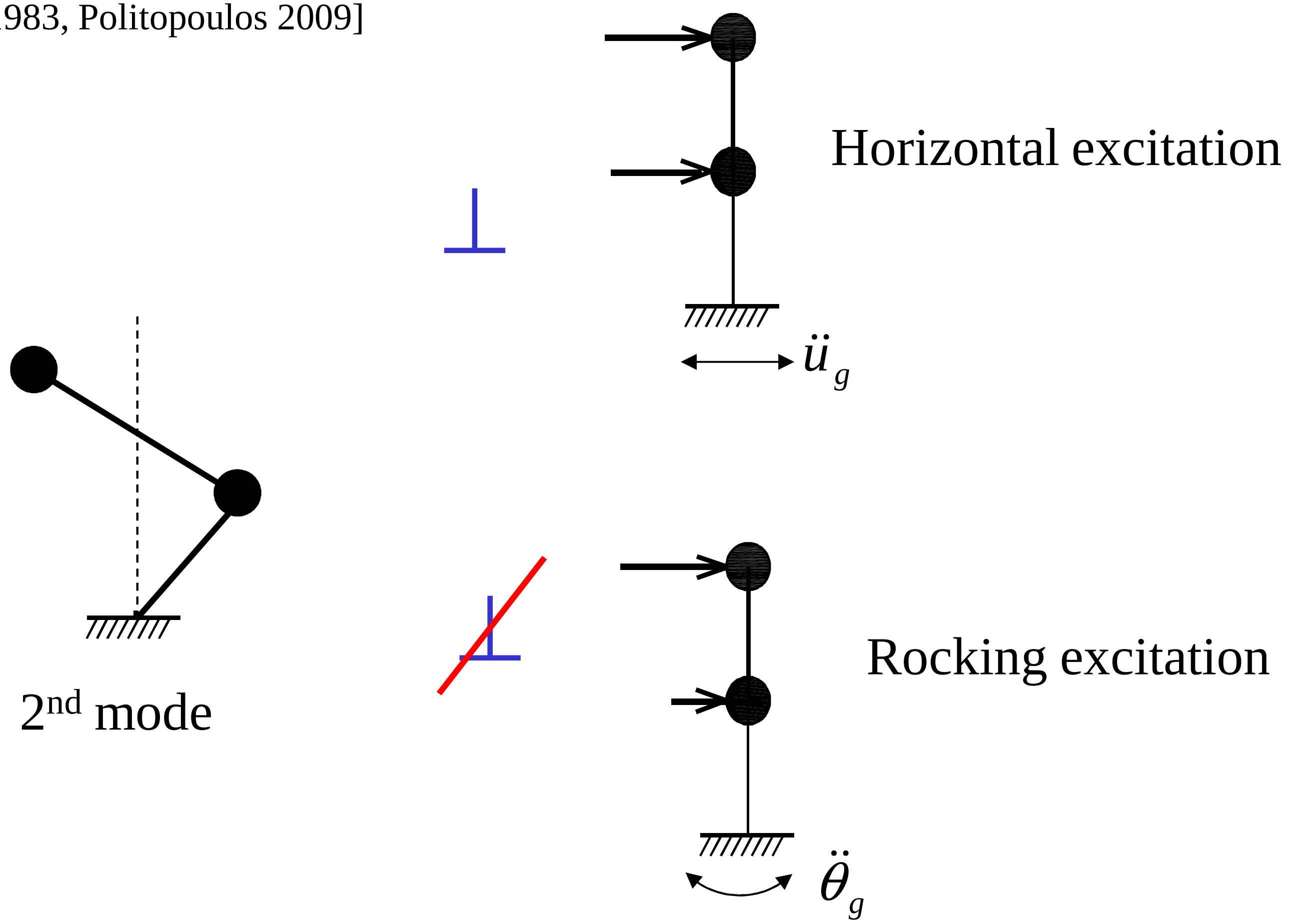
Standard deviation of superstructure's acceleration, white noise excitation (≈ Kanai-Tajimi)



Mean storey total shear force distribution

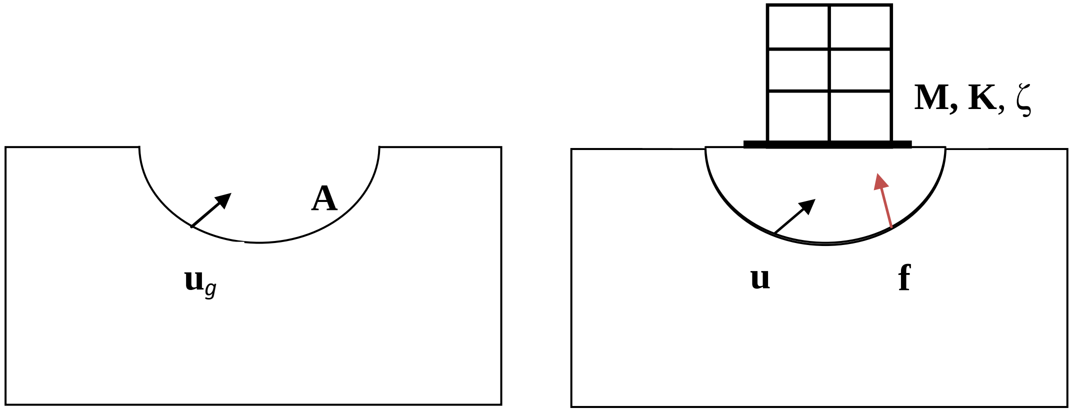
Base rocking

[Wolf et al. 1983, Politopoulos 2009]



Base rocking may appear in both conventional and base-isolated structures but, the relative contribution of responses due to horizontal and rocking inputs respectively are very different.

Base rocking due to kinematic soil-structure interaction 1/3

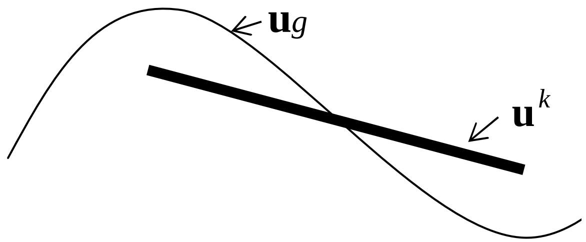


Soil impedance: $\mathbf{f} = \mathbf{A}(\mathbf{u} - \mathbf{u}_g)$

Displacement decomposition: $\mathbf{u} = \mathbf{u}^i + \mathbf{u}^k$

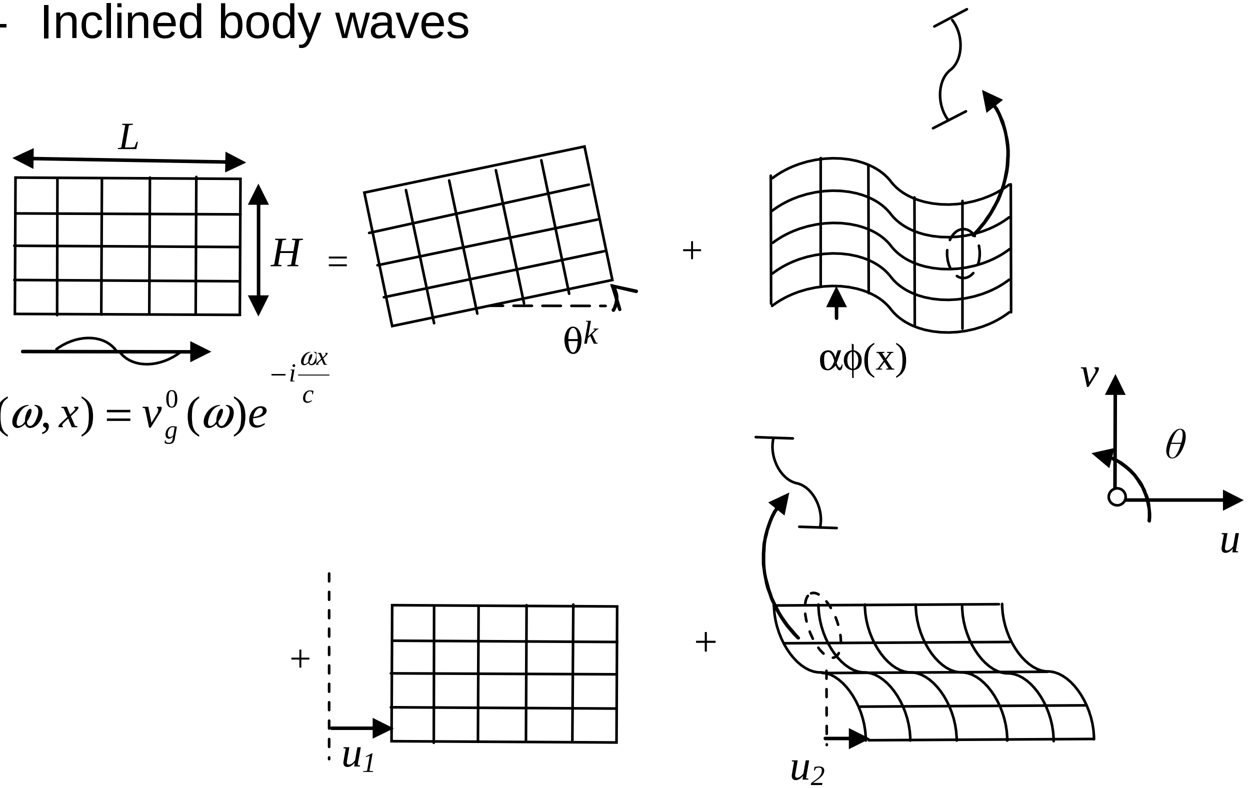
Kinematic interaction: $\left[(1+2i\zeta)\mathbf{K} + \mathbf{A}(\omega)\right]\mathbf{u}^k = \mathbf{A}\mathbf{u}_g$

Inertial interaction: $\left[-\omega^2\mathbf{M} + (1+2i\zeta)\mathbf{K} + \mathbf{A}(\omega)\right]\mathbf{u}^i = \omega^2\mathbf{M}\mathbf{u}^k$



Base rocking due to kinematic soil-structure interaction 2/3

- Horizontally propagating waves
  - Surface waves (Rayleigh waves)
  - Inclined body waves



$$v_g(\omega, x) = v_g^0(\omega) e^{-i\frac{\omega x}{c}}$$

Shear base isolated building: Decomposition of the structure deformation to elementary shape functions

Base rocking due to kinematic soil-structure interaction 2/3

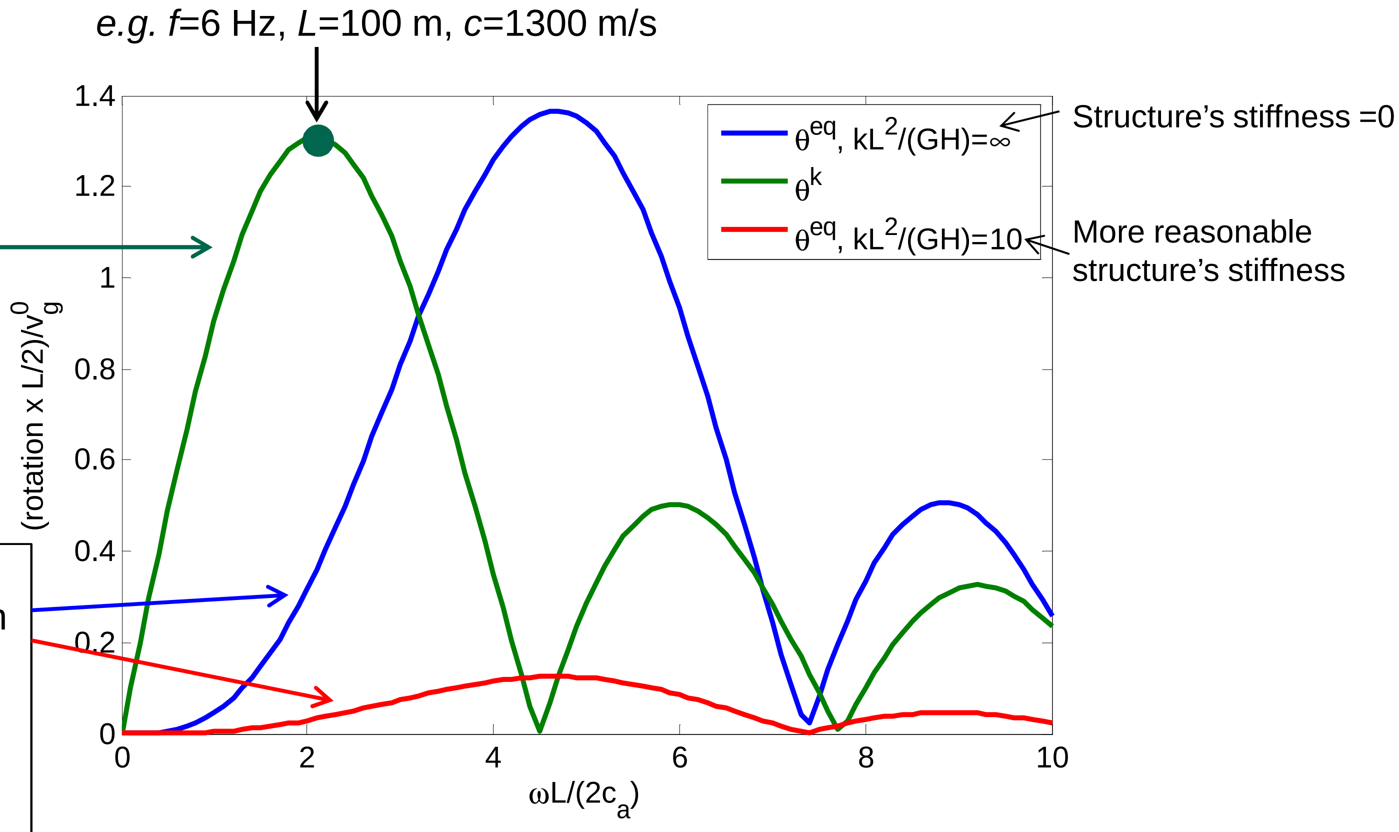
- Horizontally propagating waves

rigid body rotation

$$\theta^k = \frac{2}{L}\int_{-L/2}^{L/2} v_g x dx$$

equivalent rotation due to the structure's deformation (resulting in the same generalized modal forces)

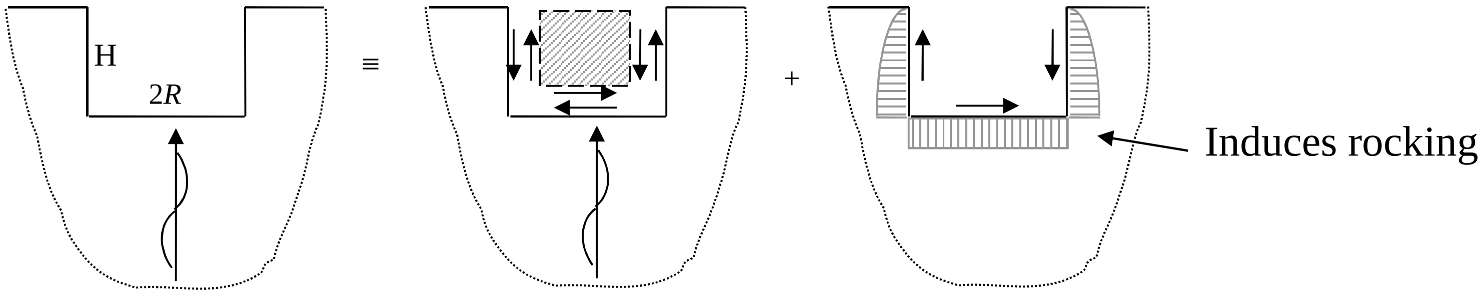
$$\theta^{eq} \approx \frac{\alpha}{L}\int_0^L \phi' dx$$

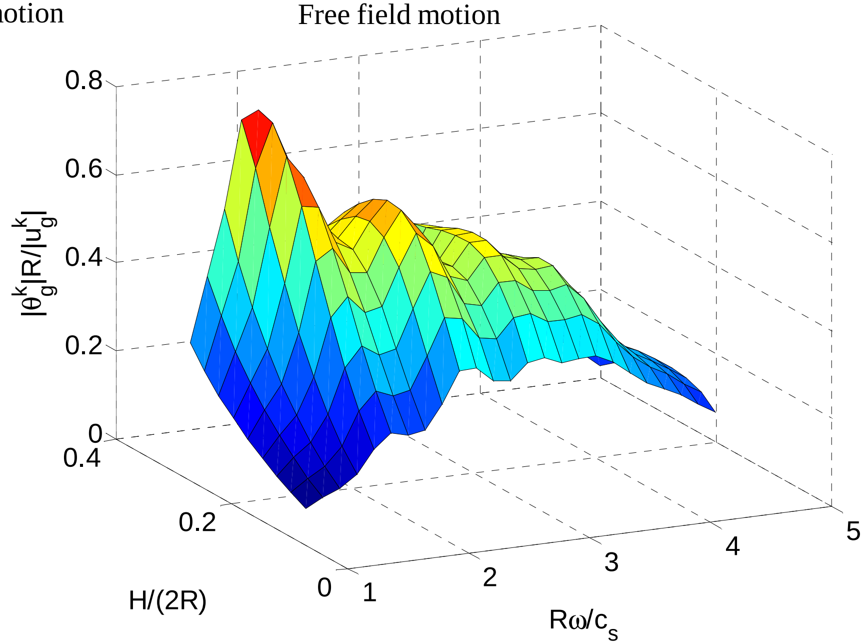


Amplitude of effective rocking input transfer function

Base rocking due to kinematic soil-structure interaction 3/3

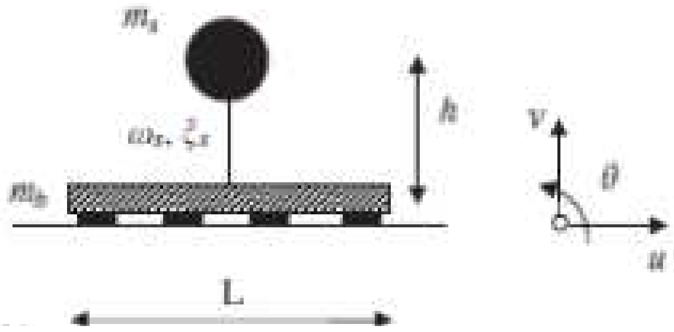
- Embedded foundation (even in the case of vertically propagating S-waves)

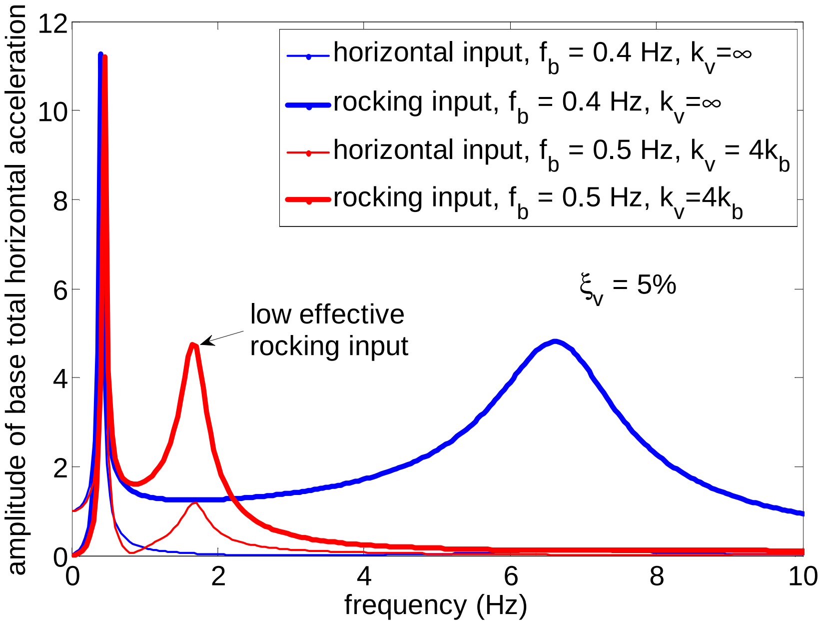




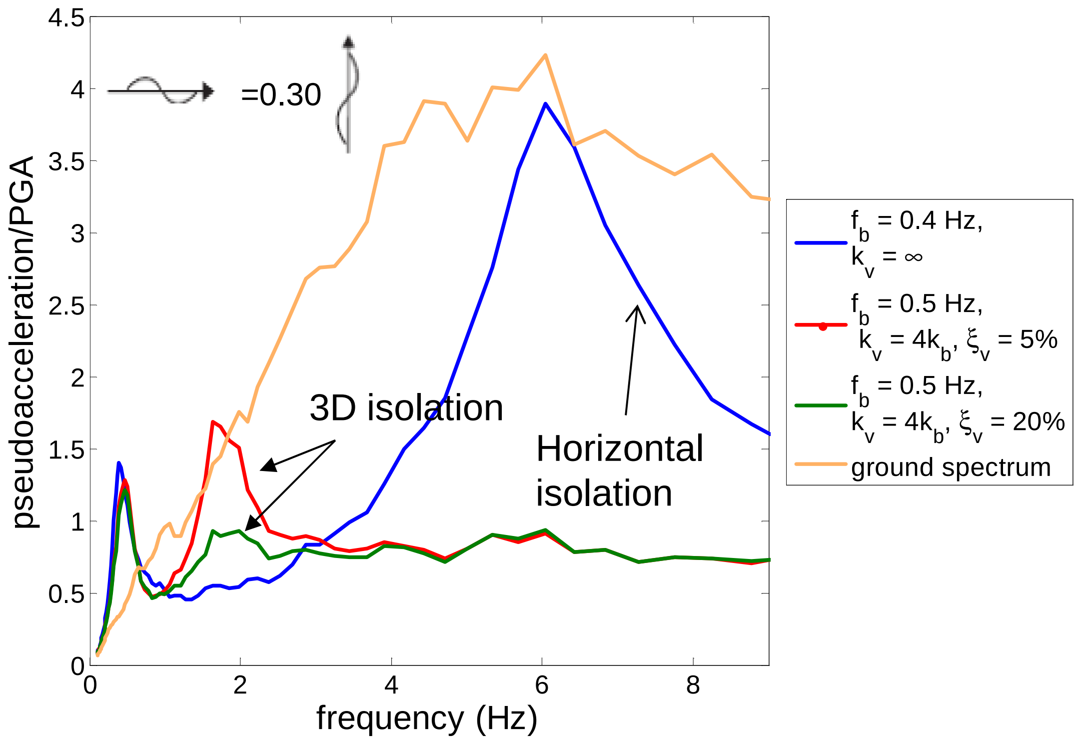
Effective rocking input (rigid base mat, flexible side walls)

Base rocking: 3D (6D?) isolation ?



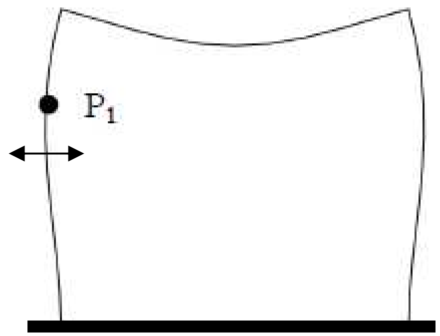


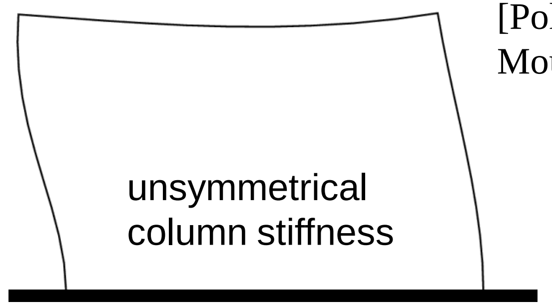
Base acceleration transfer function



Base acceleration spectrum

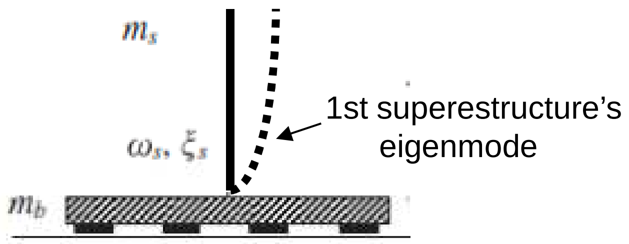
Horizontal response due to vertical excitation 1/2





[Politopoulos and Moussalam, 2012]]

Superstructure's modes which are excited by the vertical earthquake component

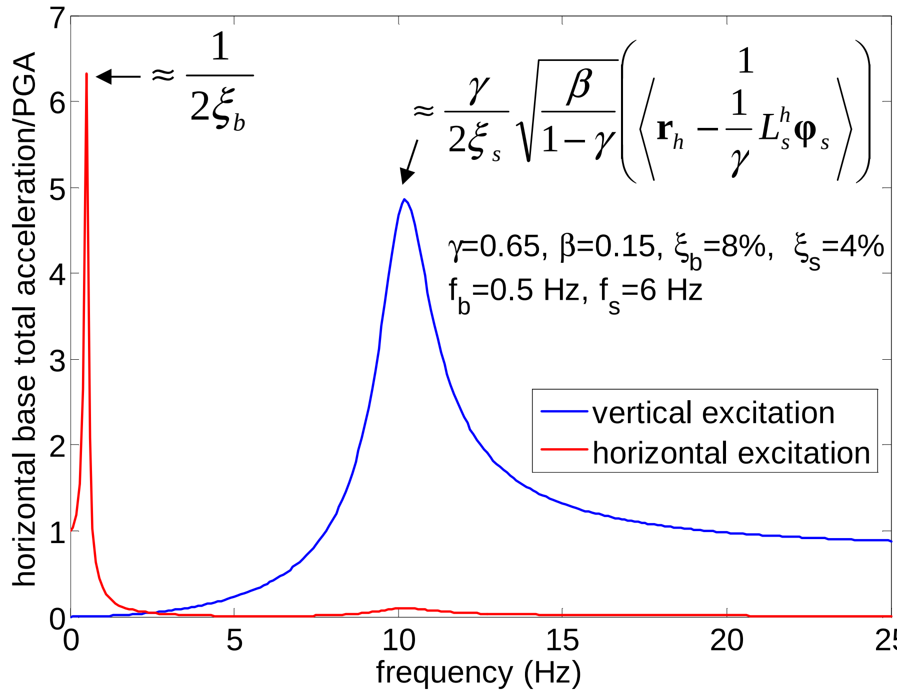


$$\gamma = m_s^h / m_{total} \qquad \beta = m_s^v / m_s^h$$

L_s^h : 1st modal horizontal contribution factor

r_h: unit horizontal vector

$\boldsymbol{\varphi}_s$:1st superstructure's mode shape

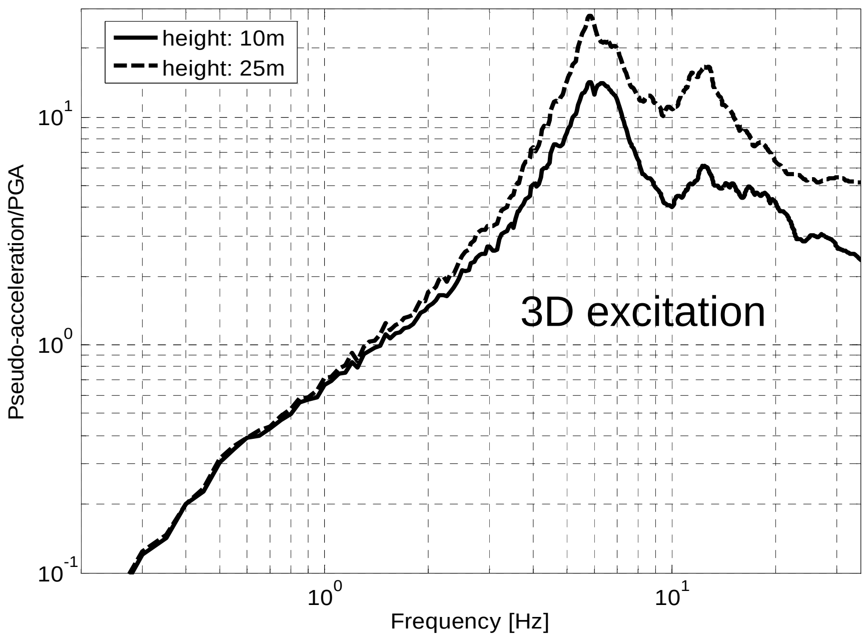


Transfer function between horizontal response acceleration and ground acceleration

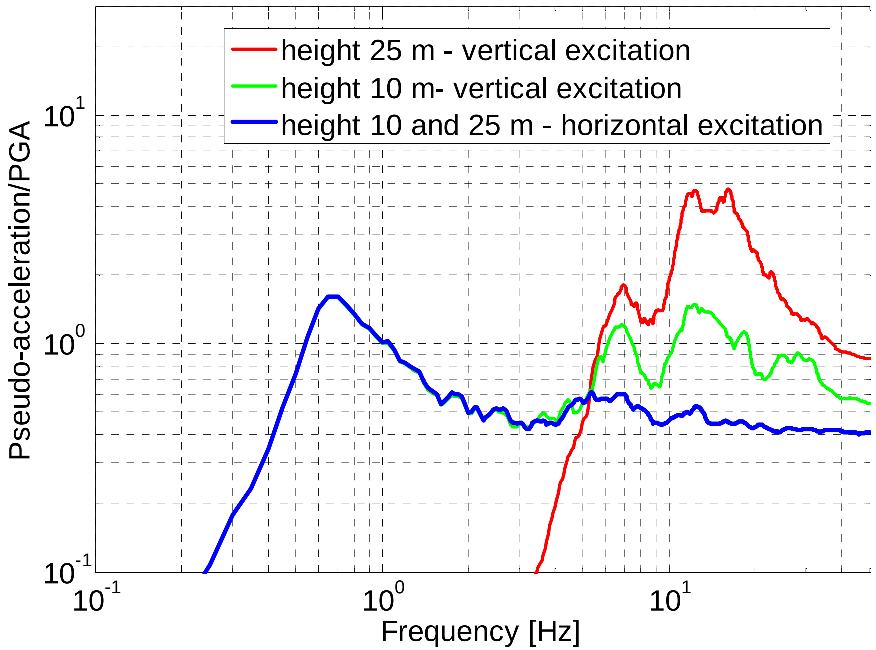
Horizontal response due to vertical excitation 2/2

Vertical-horizontal coupling may appear in both conventional and base-isolated structures but, the relative contribution of responses due to horizontal and vertical inputs respectively are very different.

Horizontal floor response spectra of a 3D FE model
of an actual nuclear plant (horizontal + vertical excitation)
[Moussallam, 2010]



Conventional building



Base isolated building

Conclusions 1/2

- Linear viscous damping
  - Maximum acceleration, elastic force in the superstructure: favourable effect, in general.
  - Floor spectra: amplification in the vicinity of non-isolated modes (but FRS isolated < FRS conventional)

- Friction (or elastoplastic) devices
  - Moderate increase of the first storey shear force compared to the viscous damping case
  - More pronounced amplification of upper storeys shear force
  - Floor spectra: significant amplification in the vicinity of non-isolated modes (friction > linear viscous)
  - Smoother nonlinearity (e.g. velocity dependent friction) results in milder amplification

- The response of base isolated structures with large dimension foundations may exhibit important amplification in the vicinity of the lower non isolated eigenfrequencies due to base rocking induced by the kinematic interaction.

- Even in the case of a flexible system (structure and foundation), kinematic interaction corresponding to the rigid body assumption has the most important contribution to the effective rocking input.

- Full three dimensional isolation, without anti-rocking devices, improves significantly the response to rocking excitation. This is achieved at the price of a, low frequency, moderate response amplification to horizontal input that may be attenuated by means of additional vertical damping.

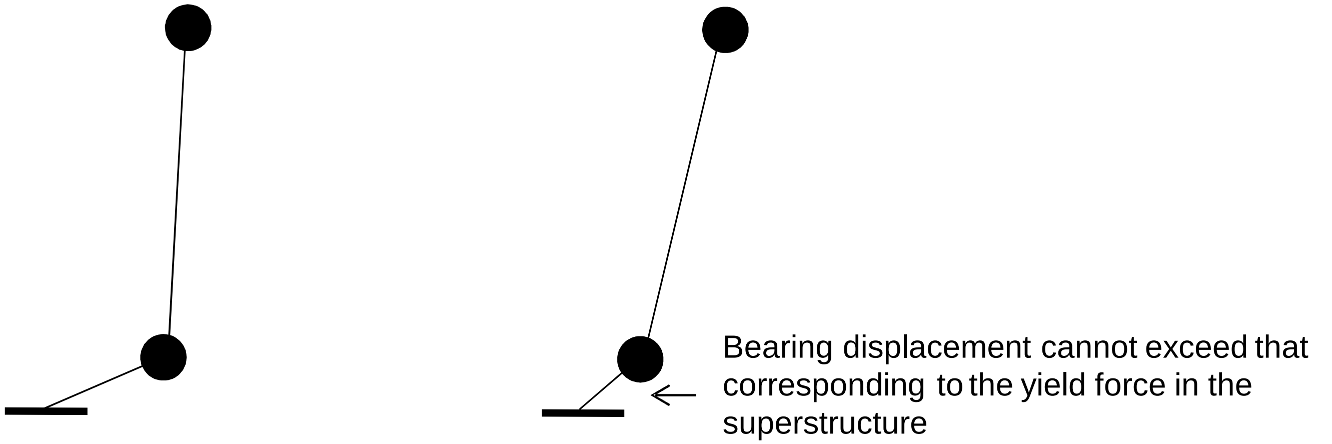
- In complex structures, the horizontal response of non-isolated modes may be amplified due to coupling with vertical excitation. However, the reduction of the floor spectra values of base isolated buildings with respect to those of conventional buildings remains substantial.

- A possible remedy against non-isolated modes' amplification could be mixed base isolation systems combining passive and semi-active devices

Sensitivity of seismically base isolated structures and their equipment

Ductility demand in the superstructure

•Isolation devices = soft storey → High ductility demand if the stiff part of the system (superstructure) yields while the isolation devices remain quasi-elastic [Pinto and Vanzi 1992, Politopoulos and Sollogoub 2005]



elastic system

Elastic bearings -yielding in the superstructure

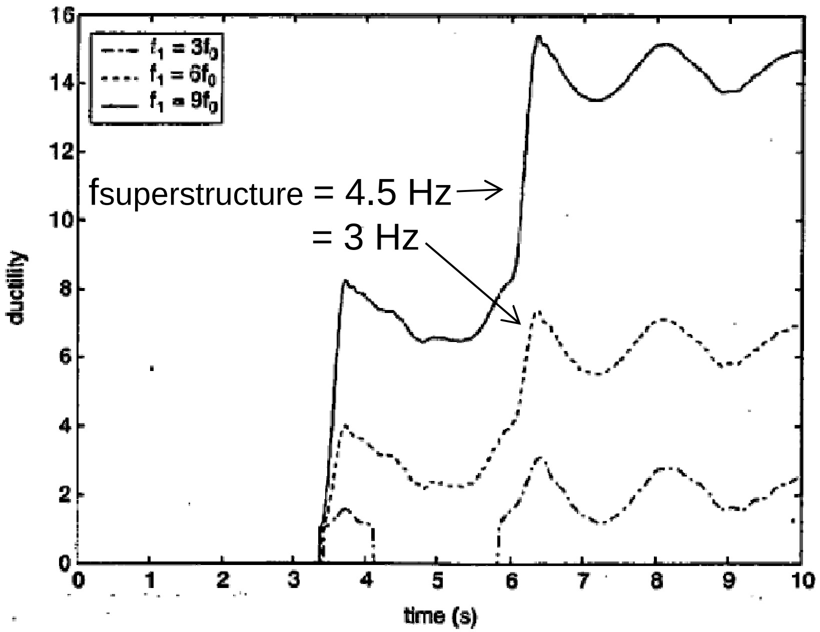
•Possible because most regulations impose that the isolation devices should withstand higher seismic loadings (MCE return period 2400 y, FEMA 356) than the superstructure (BDE, return period 475 y, FEMA 356)

•Smaller *q* or *R* for base isolated structures

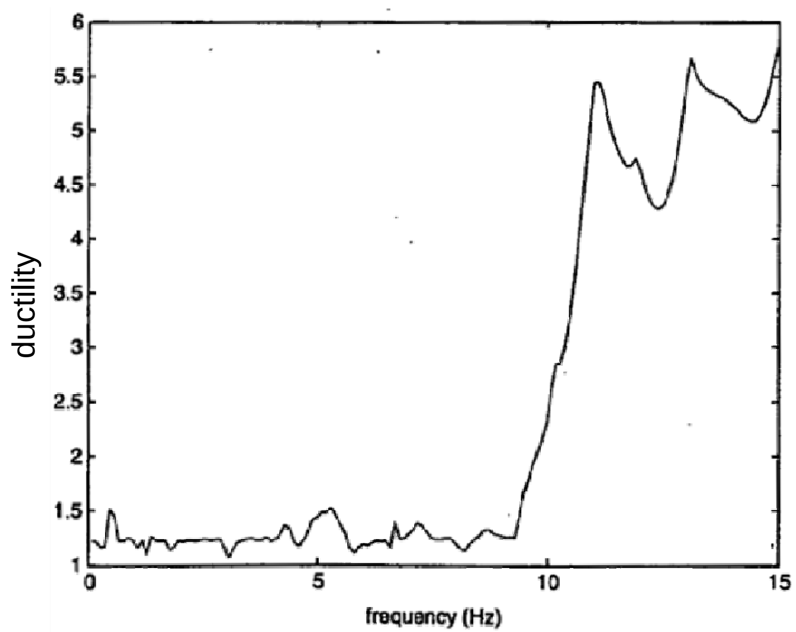
****However, recall that the strength of NPP reactor buildings is, often, determined by other loadings > seismic loadings*

Ductility demand in the superstructure

Ductility demand (El Centro , NS,1940) if the excitation level=1.2 design level
[Politopoulos and Sollogoub, 2005]



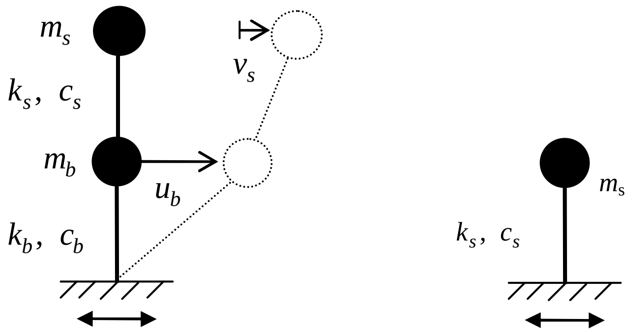
Base isolated structure



Conventional structure

Actual excitation ≠ design excitation

What happens if the excitation is slightly different from that considered for the design?



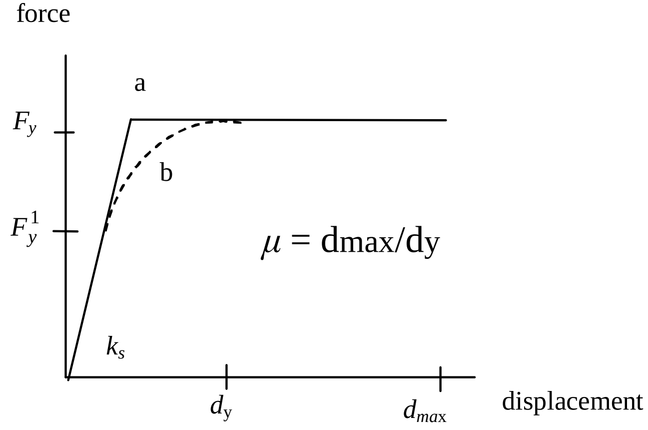
Base isolated structure conventional structure

Random variables for main structures.

Random variable	Probability distribution	Mean	ÇOV
Peak ground acceleration	lognormal	1	0.2
Frequency of excitation	normal	2.95	0.2
Ductility capacity-1	lognormal	3 Characteristic $\mu capacity = 3.6$	0.25
Yield force	normal	$F_{y\ characteristic}/0.835$	0.10
Stiffness of structure (k_1)	normal	k_1	0.10
Stiffness of bearings (k_0)	normal	$k_0 = (2\pi f_0)^2(m_1 + m_0)$	0.20

1000 artificially generated signals
Updated Latin Hypercube Monte Carlo simulations

Design method of the main structures



<table>
<tr><td colspan="2">Response modification factor (or behaviour factor) $R = R_o R_d \xrightarrow[\text{simplified bilinear model}]{} R = R_d$</td></tr>
<tr><td colspan="2">Conventional structure ($R_d > 1$, $R_d = 2.5$ in this study)</td></tr>
<tr><td><u>Practical (or common) method</u>
$F_y = m_s PSA(f)/R_d \qquad f \le f_0$
$F_y = m_s \left[PSA(\infty)\left(1 - \frac{f_0}{f}\right) + \frac{PSA(f_0)}{R_d}\frac{f_0}{f} \right] \qquad f > f_0$
where:
PSA(f): value of the mean pseudoacceleration spectrum of the reference signals at frequency f
f_0 = 5 Hz in this study</td><td><u>“Exact” method</u>
Assumed $\mu_{capacity} = (R_d^2 + 1)/2$
Trial and error nonlinear iterative procedure to determine
$F_y \Rightarrow median\ \mu_{demand} = \mu_{capacity}$ for the reference signals</td></tr>
<tr><td colspan="2">Isolated superstructure ($R_d = 1$)
F_y = mean $F_{\max}$ for the reference signals (considering a linear superstructure)</td></tr>
</table>

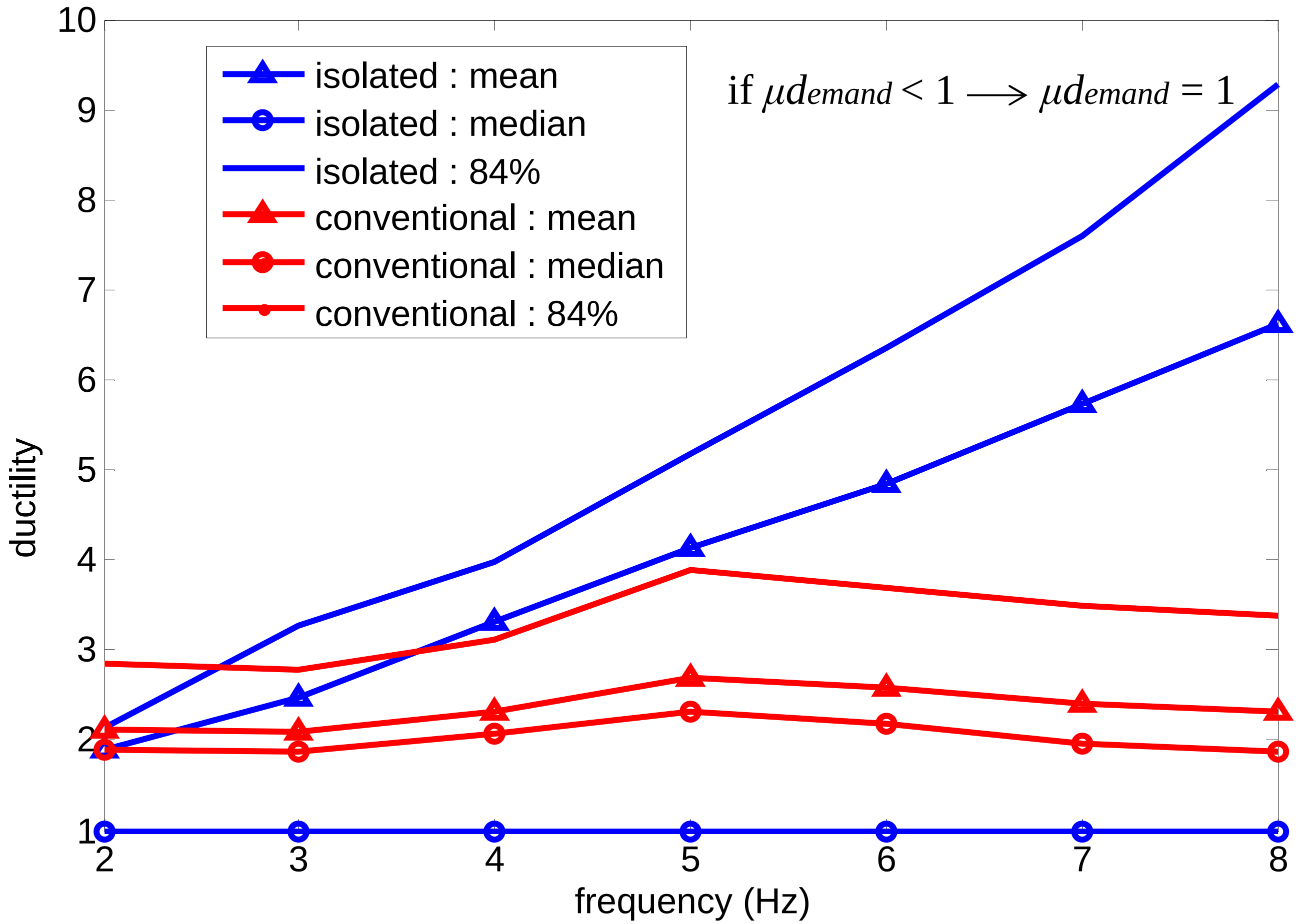
Dyctility demand (1000 signals)

elastic-perfectly plastic superstructure on « linear elastic » LDRB

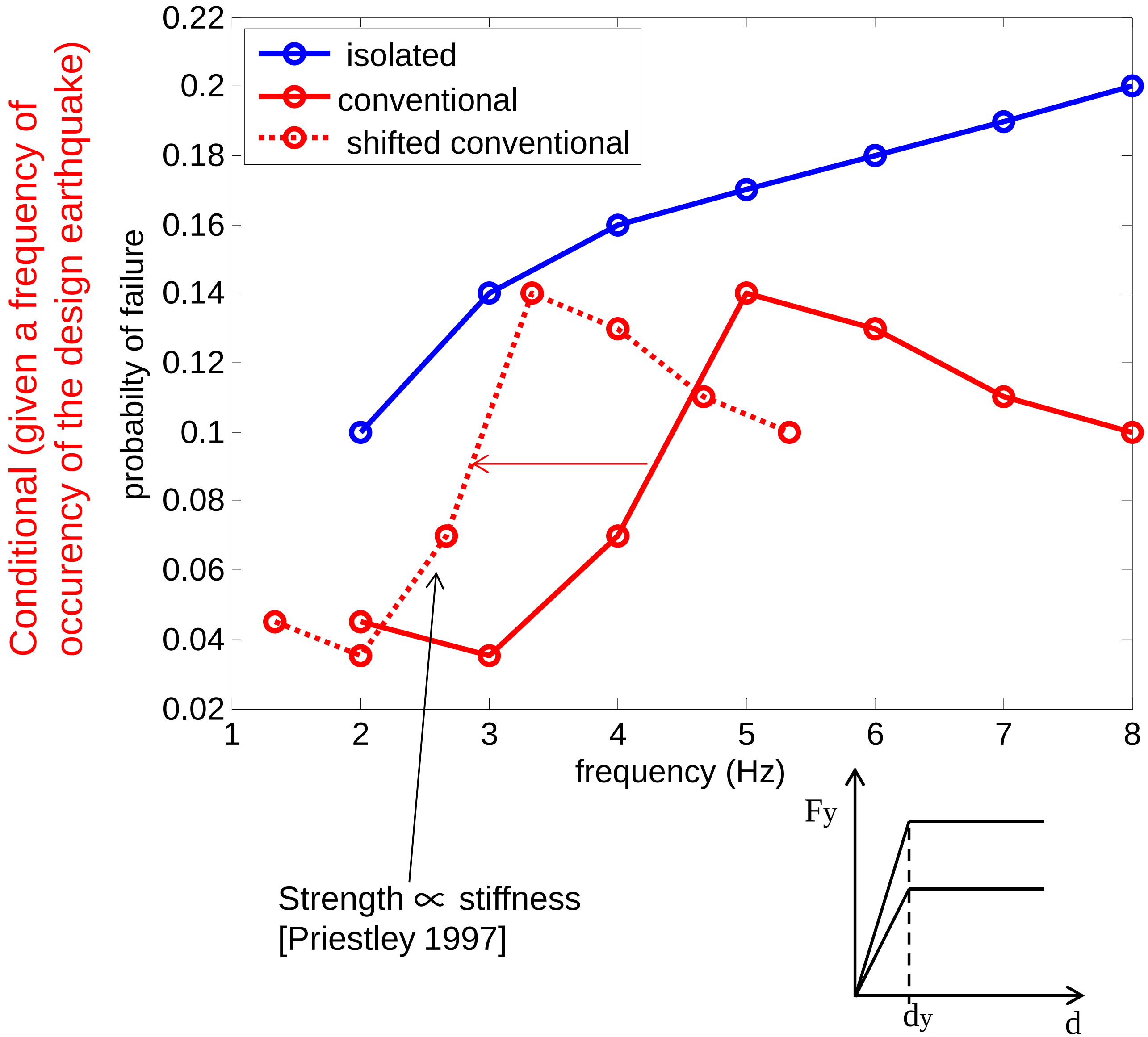
practical method : strength = mean elastic spectrum (x mass)/$\sqrt{2\mu - 1}$ (for $f < 5$ Hz)

conventional $\mu > 1$ isolated $\mu = 1$

characteristic $\mu capacity$ (95% probability of exceedance) = 3.6

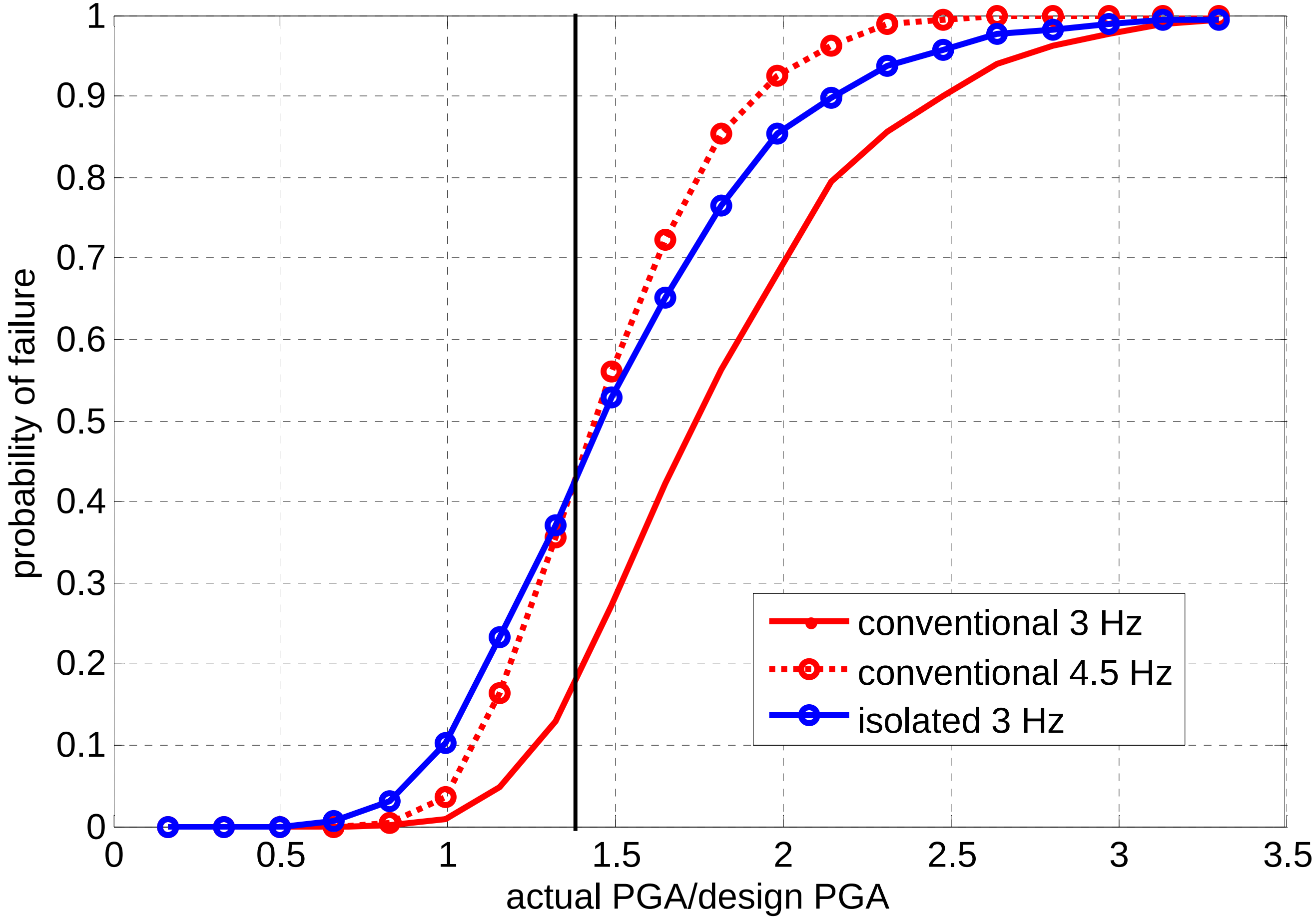


Failure probability



Fragility curves (1000 signals/PGA)

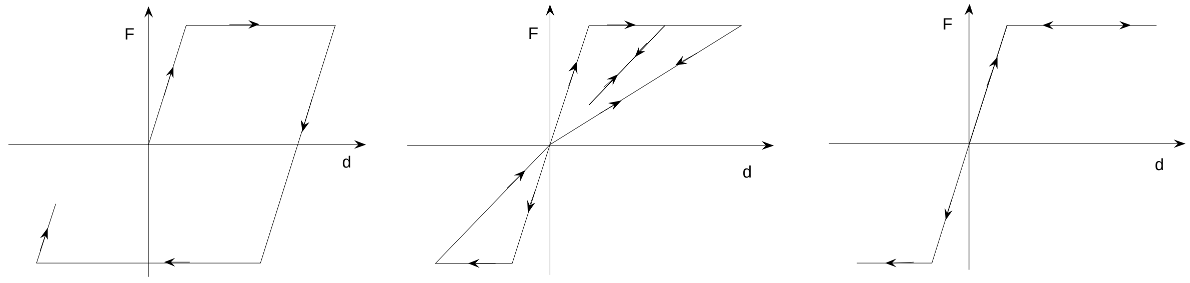
imposed PGA (no longer considered as a random variable)



Influence of superstructure's and bearings constitutive laws

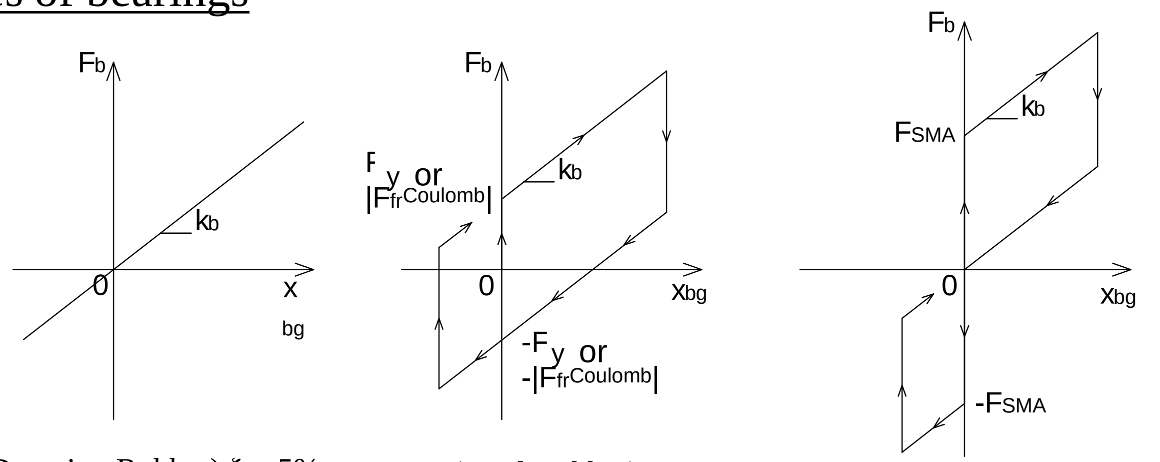
Superstructure's constitutive laws

[Politopoulos and Pham, 2009]



(a) elastoplastic (b) origin oriented (c) nonlinear elastic

Types of bearings



LDRB (Low Damping Rubber) ξ = 5%
LDRB (Low Damping Rubber) ξ = 25 %

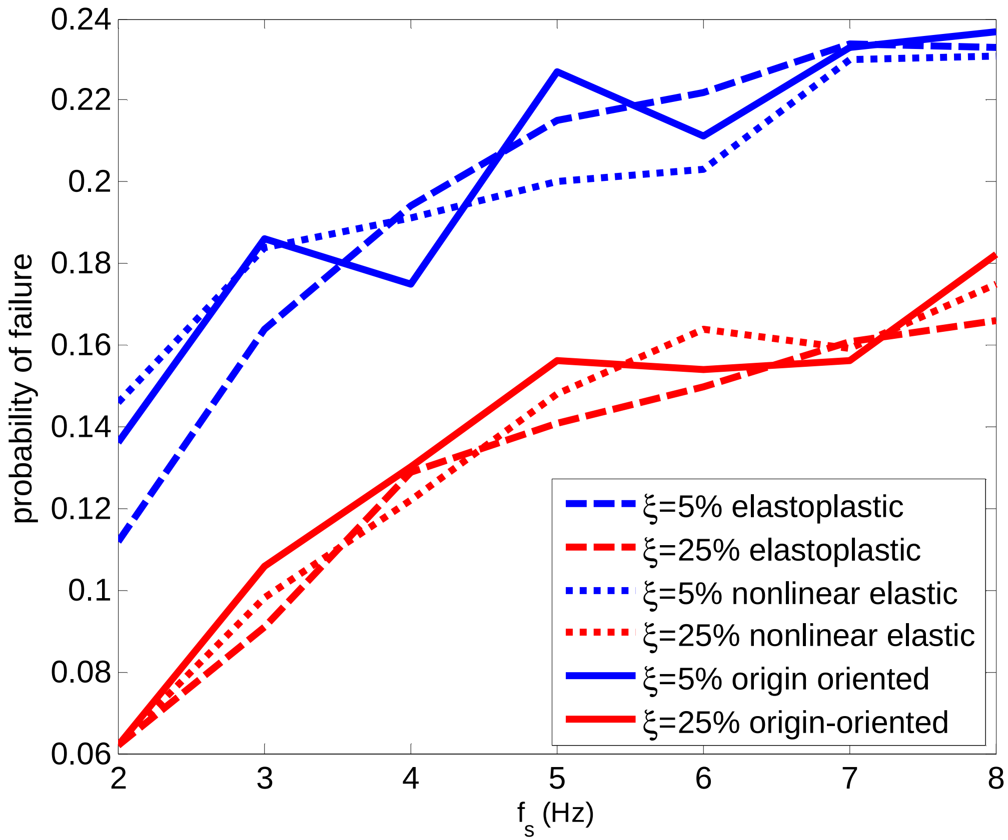
LRB (Lead Rubber)
FPS (Friction Pendalum) Coulomb

SMA (Shape Memory Alloys)

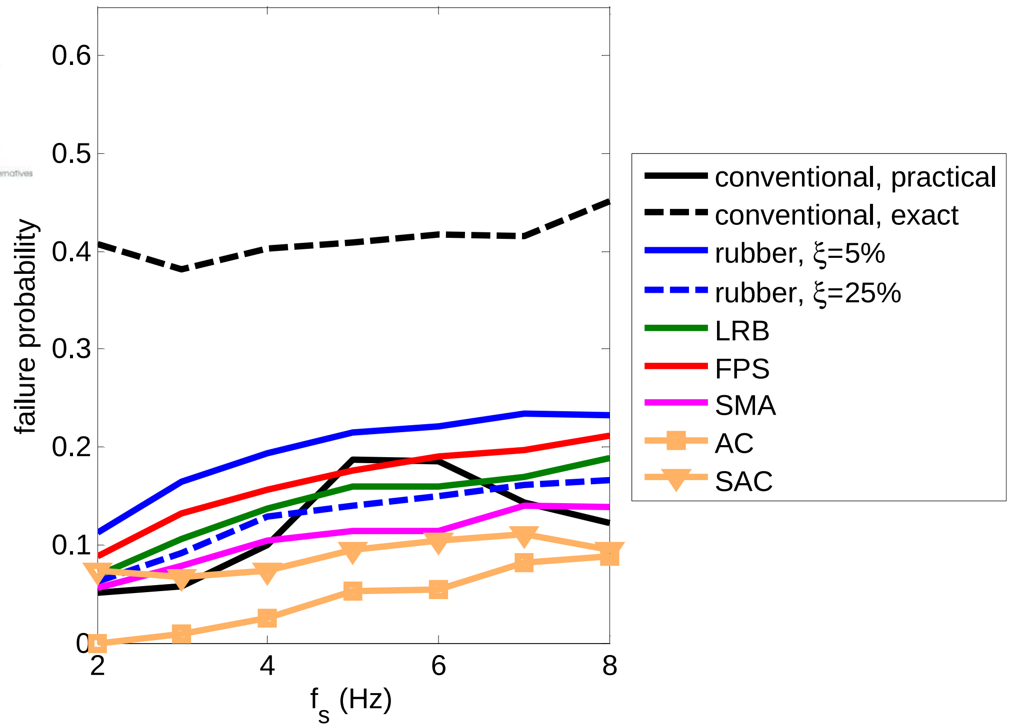
+ velocity dependent FPS, Active Control (AC), Semi-active Control (SAC)

Influence of the superstructure's constitutive law

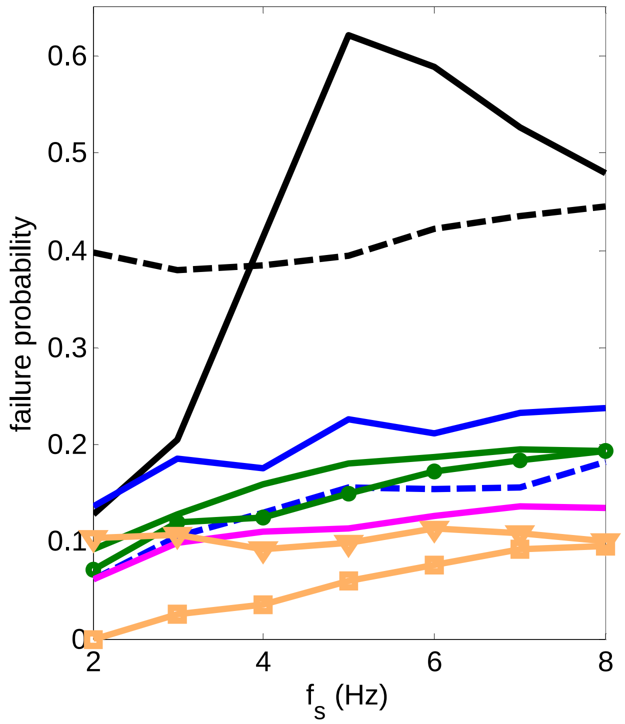
Elastomeric bearings LDRB (with and without additional linear viscous damping)



Influence of the type of bearings



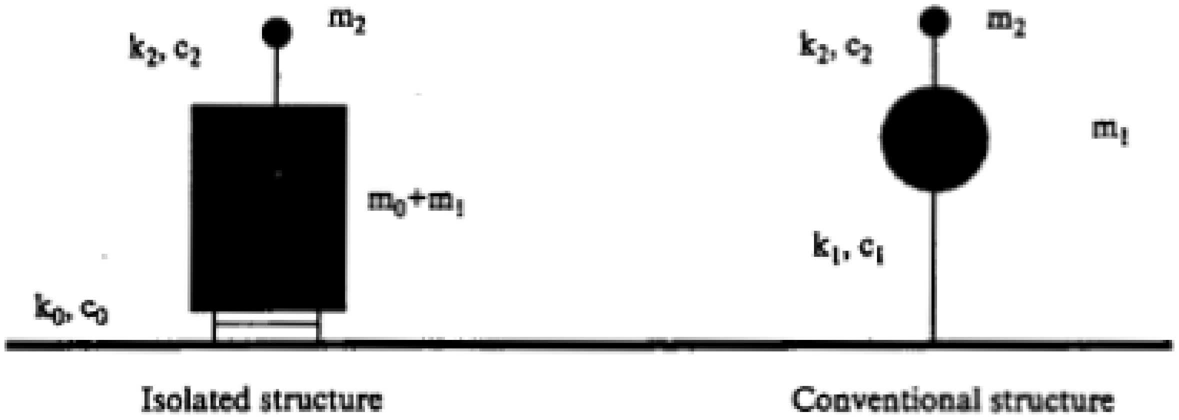
Elastoplastic superstructure

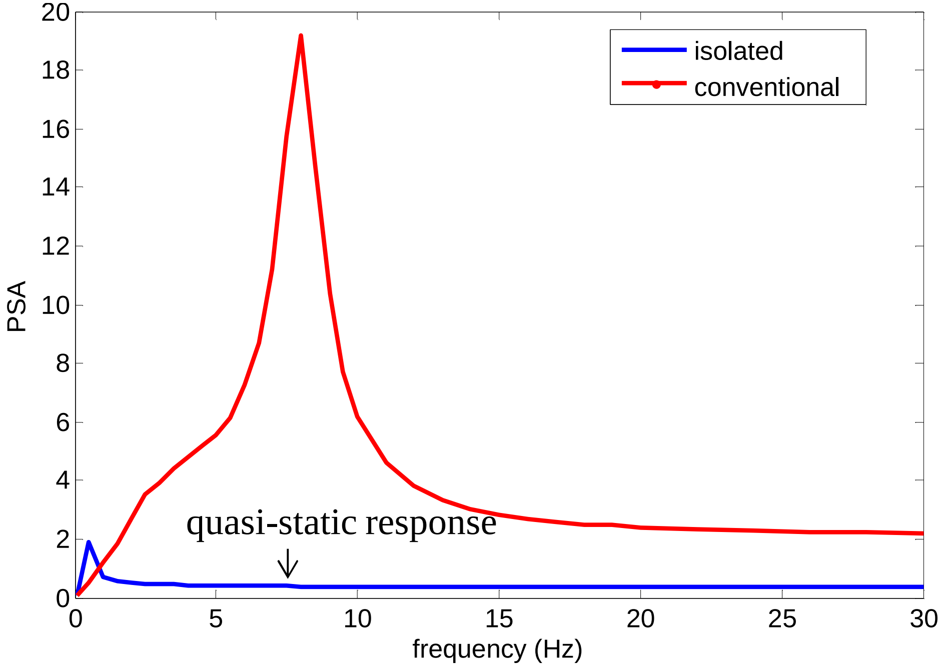


Origin-oriented superstructure

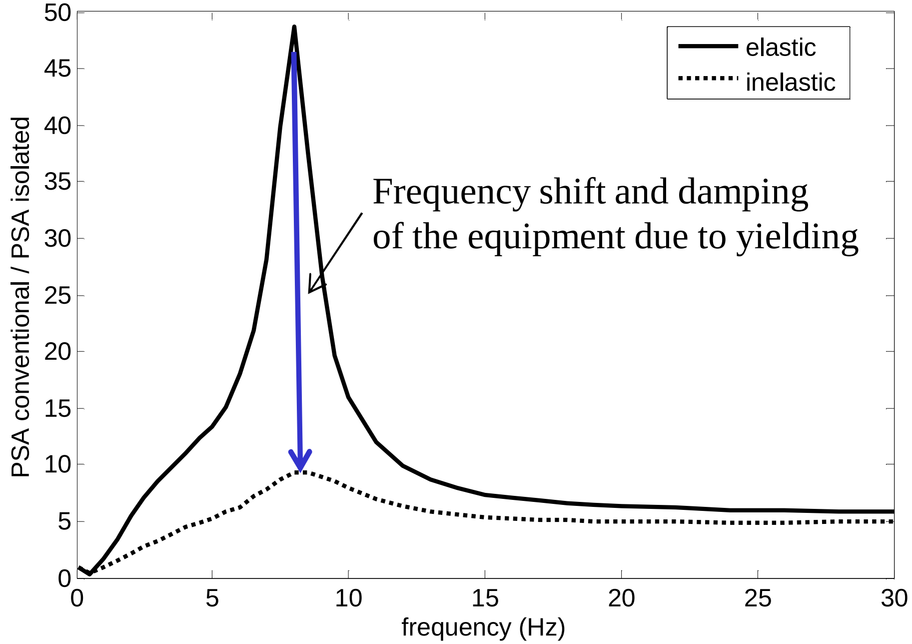
General trend: CA<CSA≈SMA< Rubber $_{\xi=25\%}$ ≈LRB≈ FPS< Rubber $_{\xi=5\%}$

Non-linear equipment on a linear base-isolated structure (LDRB)





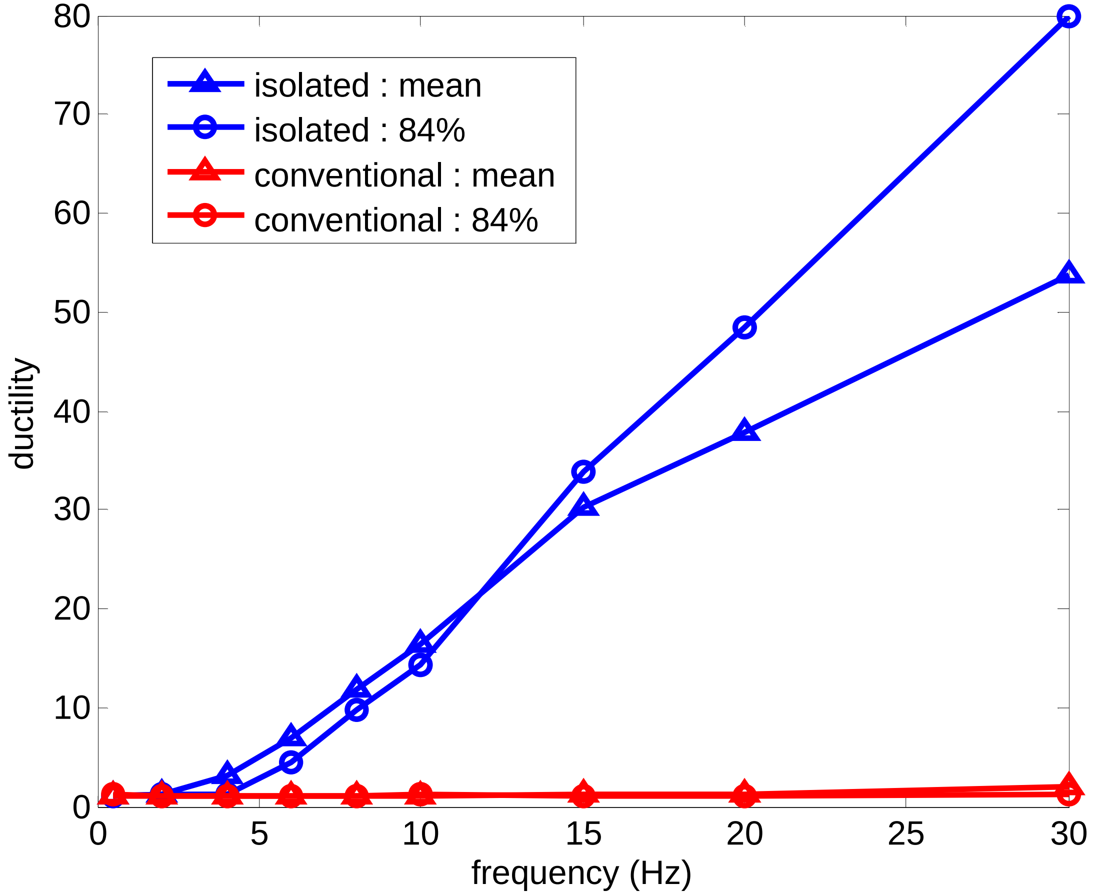
Mean elastic floor spectra



Ratios of mean elastic and inelastic (for $\mu_{demand} = 3$) floor spectra

Equipment ductility demand (1000 signals)

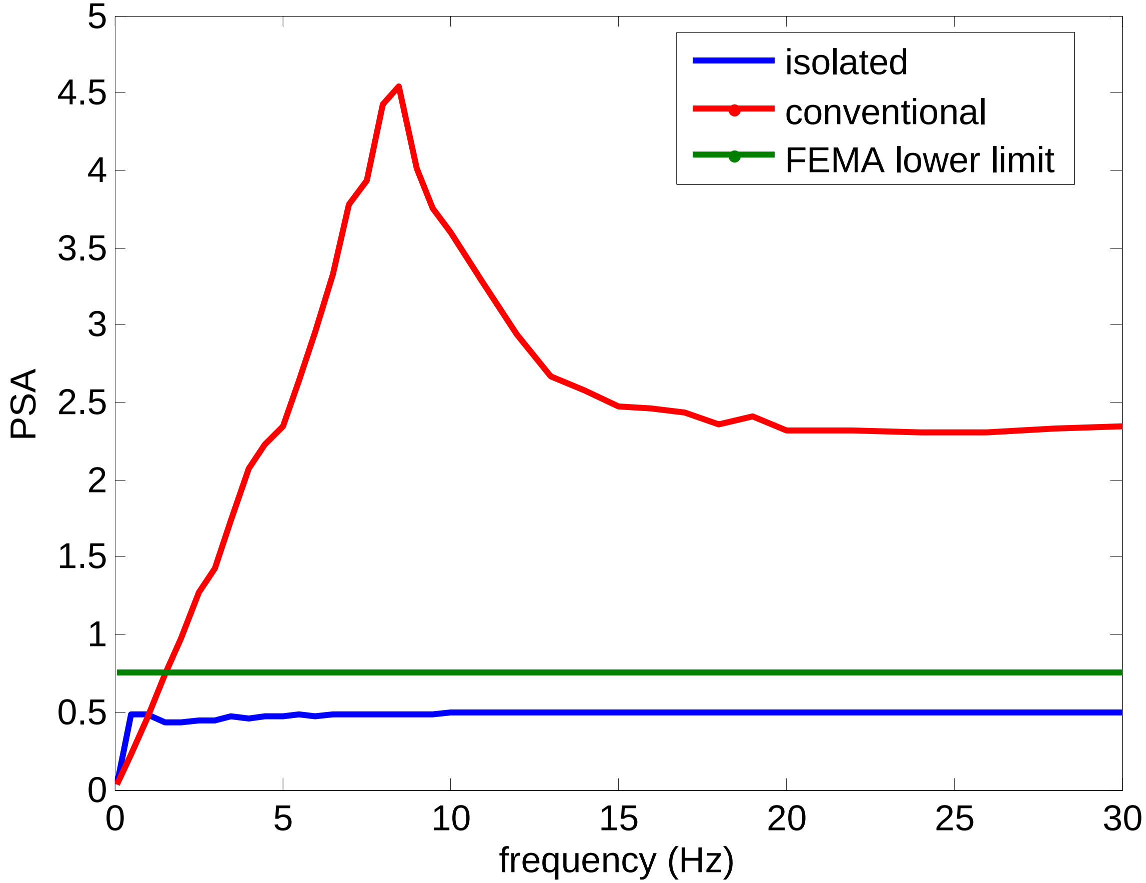
Elastic-perfectly plastic equipment/ linear elastic (superstructure +LDRB), strength = mean elastic floor spectrum (x mass) ⟶(q (or R) = 1)
characteristic $\mu_{capacity}$ (95% probability of exceedance) = 3



Ductility demand

Additionnal margin for equipment design

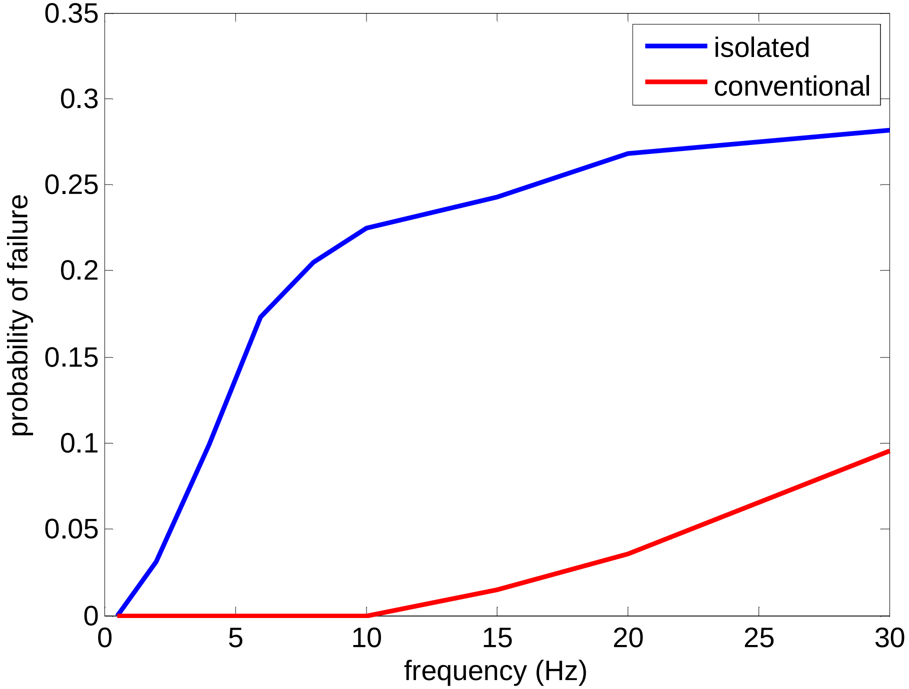
FEMA 368 (part 6, general provisions): component min $F_y = 0.75$ PGA



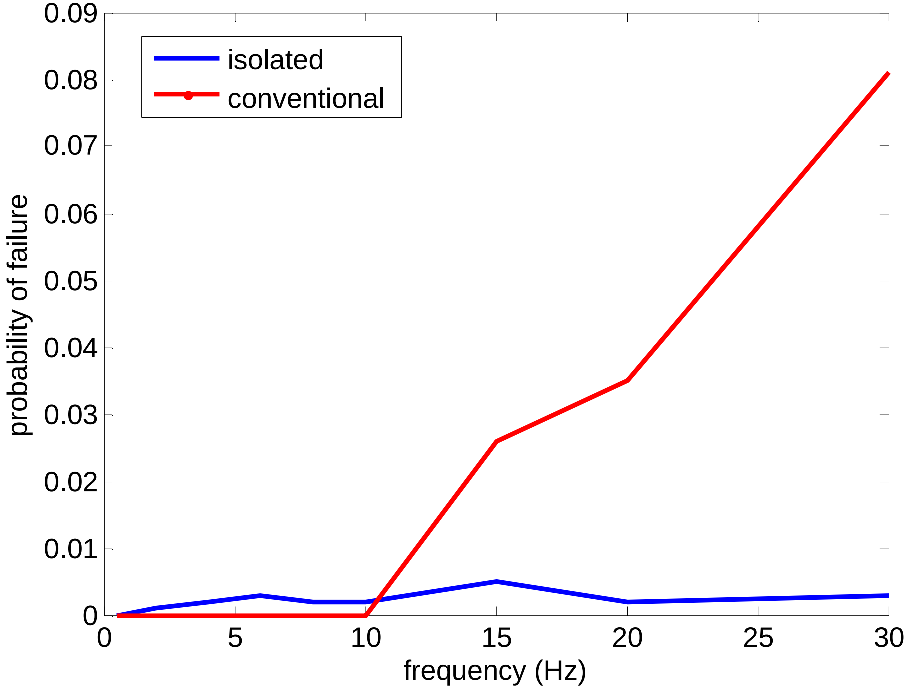
Inelastic floor spectra ($\mu_{demand} = 3$)

Failure probability

Conditional probability (given a frequency of occurrence of the design earthquake)



Equipment designed according to the mean elastic floor spectra FEMA 368 (part 13)



Equipment designed taking into account the FEMA 368 (part 6) lower force bound

Conclusions

- Base isoloated structures are more sensitive than conventional structures if yielding occurs in the superstructure while the bearings exhibit a quasielastic behavior.

- Reduced *q* or *R* values→yielding in the superstructure is less frequent than in conventional buildings but when it occurs ⟶ high ductility demand.

- The failure probability of seismically isolated structures, designed according to modern regulations, is not influenced significantly by the precise cyclic behaviour of the constitutive law considered of the superstructure. In fact, different nonlinear force-displacement relationships with the same skeleton curve result in similar probability failures.

- In particular, low damping rubber bearings result in higher failure probabilities than bearings having a capability of significant energy dissipation.

Conclusions

- Conventional structures designed so that in the mean they really exhibit the assumed design inelastic demand are more vulnerable than isolated structures. **This is not always the case when conventional structures are designed according to common force reduction methods, especially in the case of elastoplastic behaviour** *(valid only under the assumption of design and detailing ensuring equivalent ductility capacities for both isolated and conventional structure).*

- Floor spectra with a wide frequency range of quasistatic behaviour

⟶ high equipment ductility demand if designed according to the results of the dynamic analysis (*e.g. part 13 (isolated structures) of FEMA 368*).

- The consideration of a lower bound of the design force *(e.g. as recommended by part 6 (general provisions) of FEMA 368)* results in a safer equipment design.

I thank you for your attention