Displacement-based risk-targeted design of base-isolated structures

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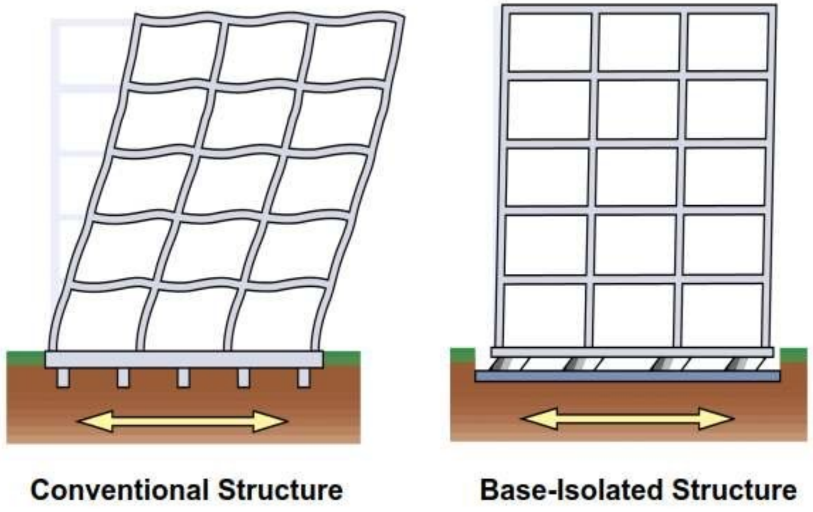
ROSE
Centre for Training and Research on Reduction of Seismic Risk

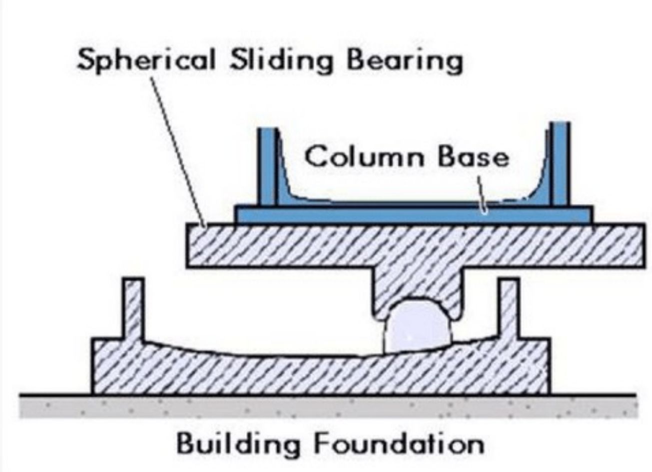
Overview

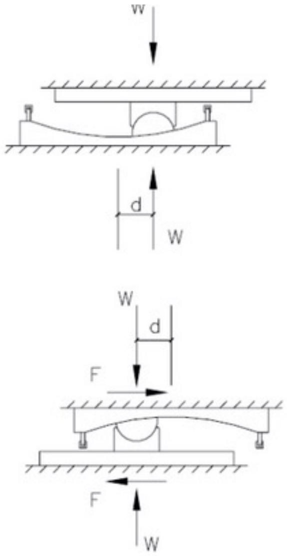
- Base isolation systems and design of isolators
- Potential issues encountered in practice
- Friction pendulum bearing systems
- Risk-based design procedure formulation
- Case study example

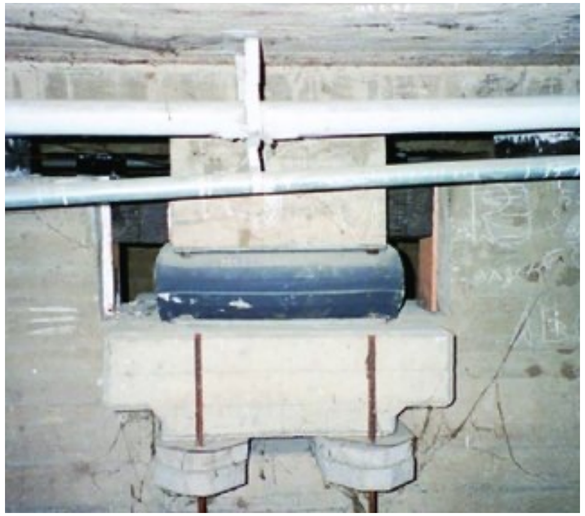
Base isolation systems

- Base isolation gained popularity in the 1960s, with the first use on a school in Skopje
- The 1980s saw the development of the friction pendulum bearing (FPB) system



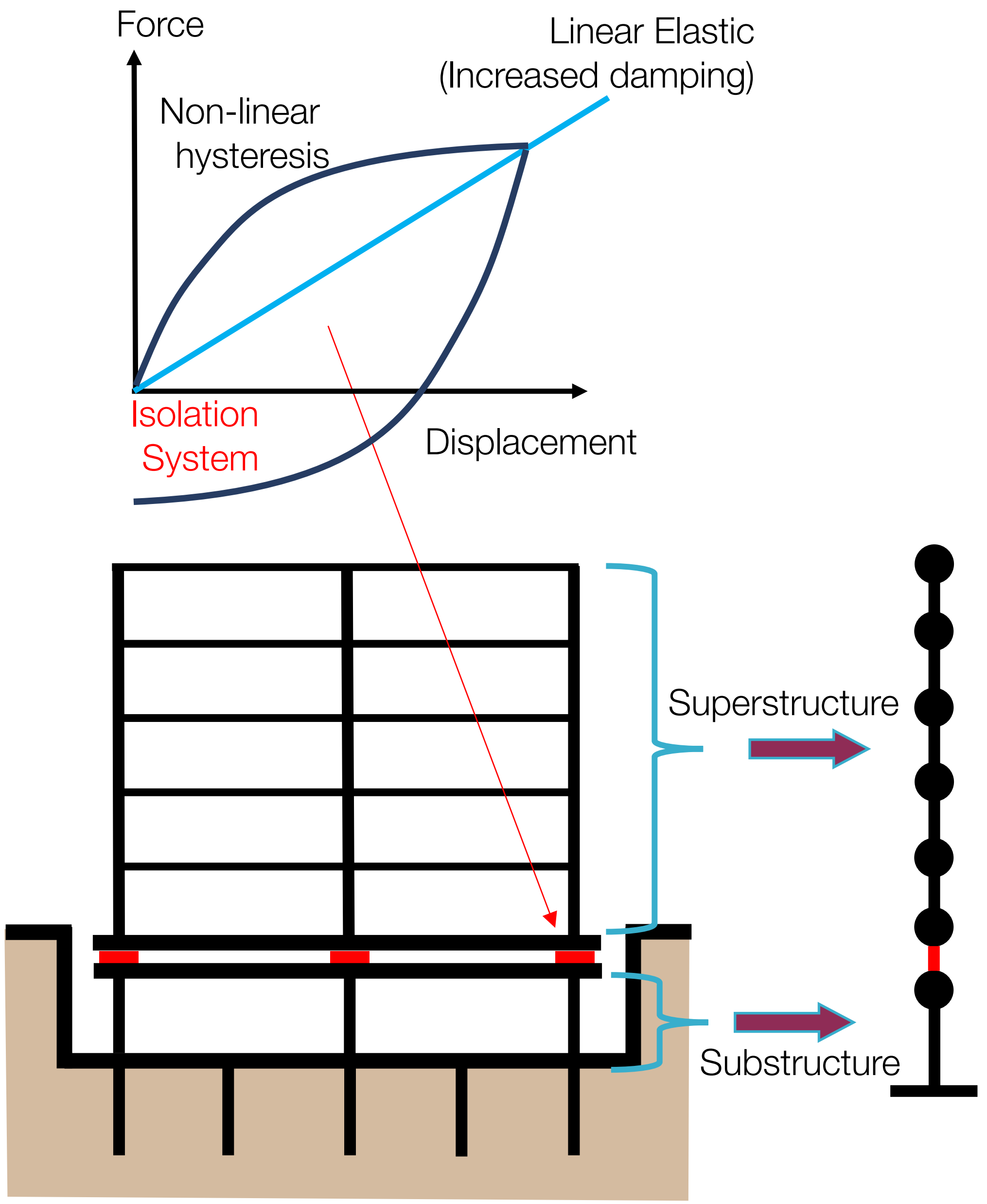






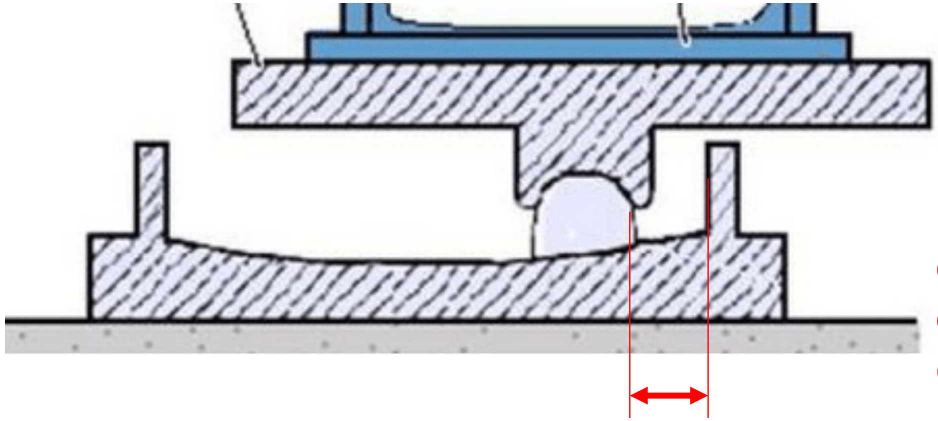
Design of isolators

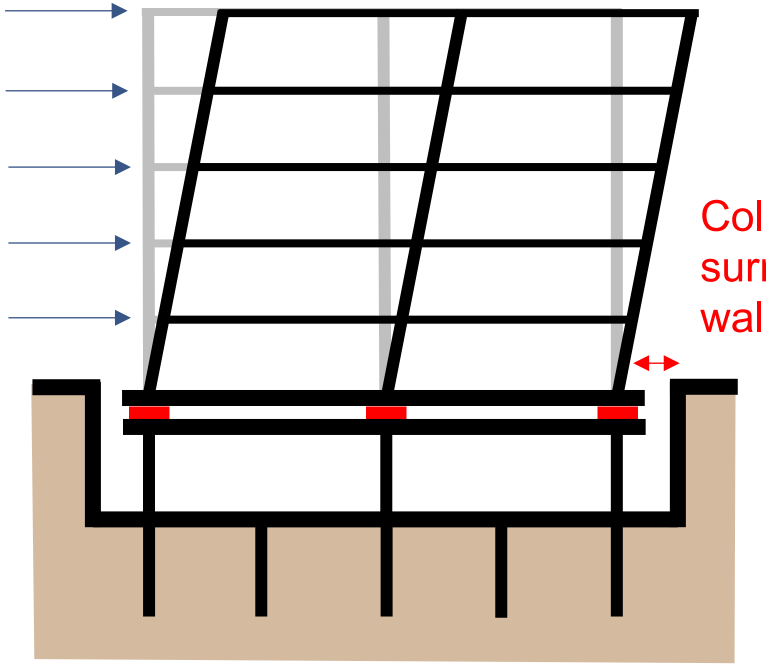
- Several codes of practice exist worldwide, each following more or less the same procedure
- An isolator bearing is trialled and can be modelled:
  - Non-linear hysteretic behaviour
  - Linear springs with increased damping
- Superstructure and substructure are to be modelled as linear elastic with non-dissipative behaviour
- The response at a given shaking intensity is checked to determine the suitability
- At the life safety limit state, Italian building requires isolators to withstand all demands without issues
- Analysis is trial and error with numerical analysis required to check result



Potential issues

- The difficulty with this intensity-based approach to design is that it verifies performance at a specific hazard level
- It doesn't give any comprehensive control of overall risk
- Devices may perform quite poorly at levels of shaking different than those they were design for
- In particular:
  - Device reaching its maximum displacement capacity
  - Crashing into the moat wall



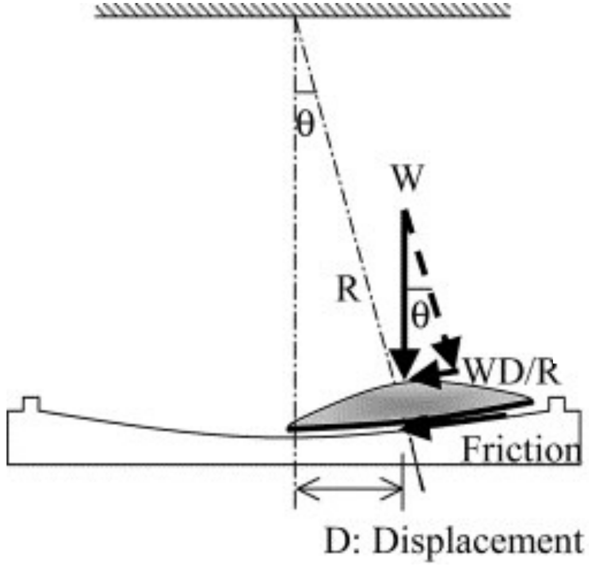


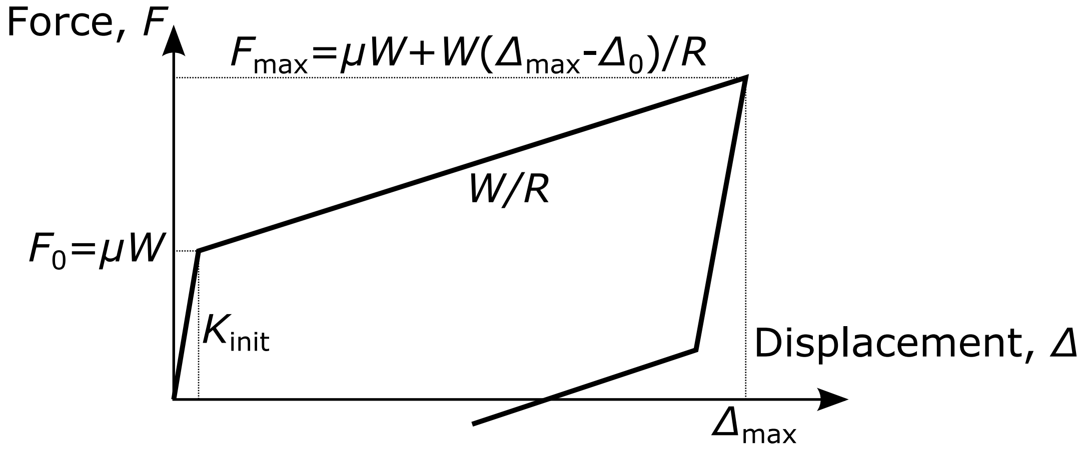
FPB isolator properties

- One of the biggest advantages of using FPB isolation systems is that the period of vibration is fixed for a given device

$$T_{iso} = 2\pi\sqrt{\frac{R}{g}}$$

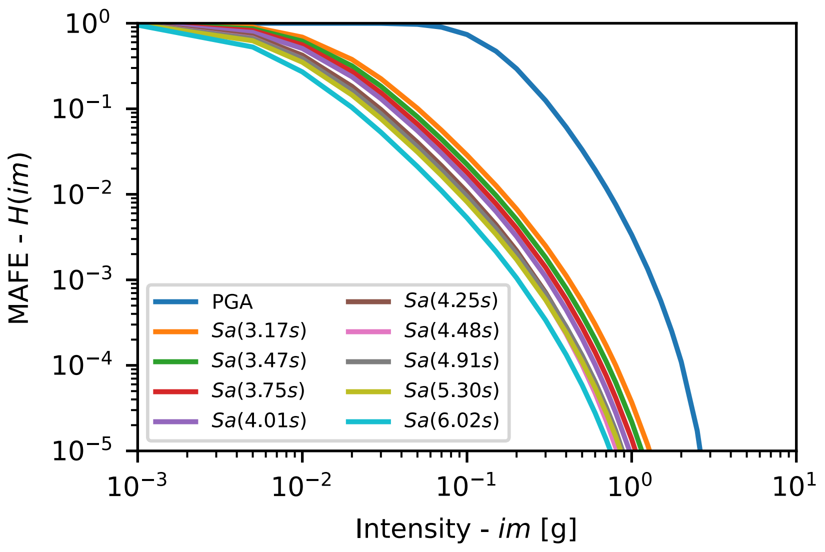
- It is a function of the radius of curvature of the sliding surface
- It is independent of the superstructure's mass and dynamic properties
- The initial activation force is a function of the friction coefficient of the sliding surface

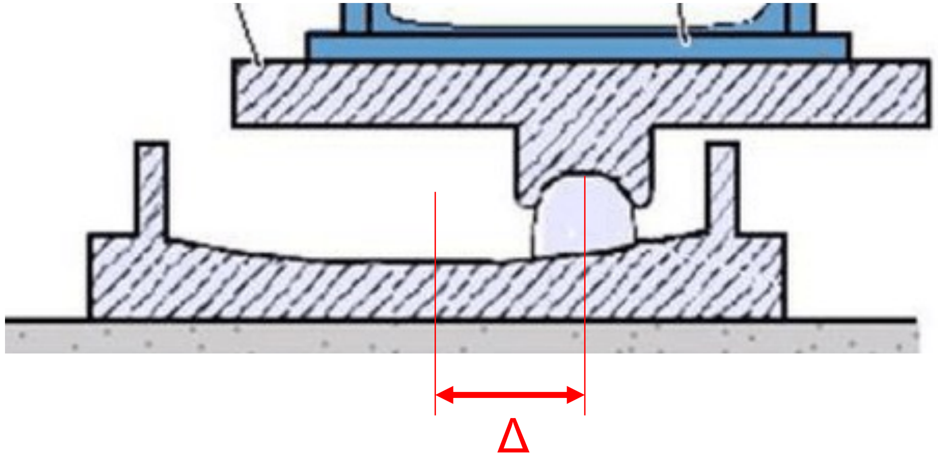




Risk-based design procedure

- To overcome the limits of intensity-based design of isolators, a risk-based design procedure is proposed
- It capitalises on the mechanical properties of FPB isolators to give a closed-form solution
- The displacement-based risk metrics can be easily checked knowing just the bearing properties and the site hazard
- It utilises mean annual frequency of exceedance (MAFE) as its performance metric





$$\lambda_\Delta = \int_0^{+\infty} P[\Delta| > \Delta_{lim} IM = im]|dH(im)|$$

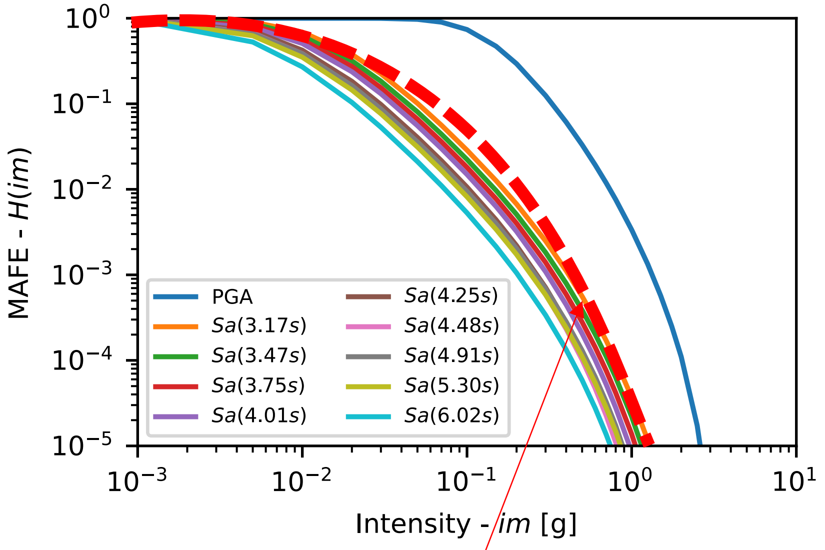
Risk-based design procedure

- Using a simplified fit of the hazard curve, a closed-form solution for MAFE can be obtained:

$$\lambda_\Delta = \sqrt{p}k_0^{1-p}[H(im)]^p \, exp\left(0.5pk_1^2\beta_\rho^2\right)$$

$$p = \frac{1}{1+2k_2\beta_\rho^2}$$

- It essentially relies on the ability to predict the median intensity (and dispersion) associated with exceeding a given displacement demand, Δ
- This requires a ***demand-intensity*** model for the structural system

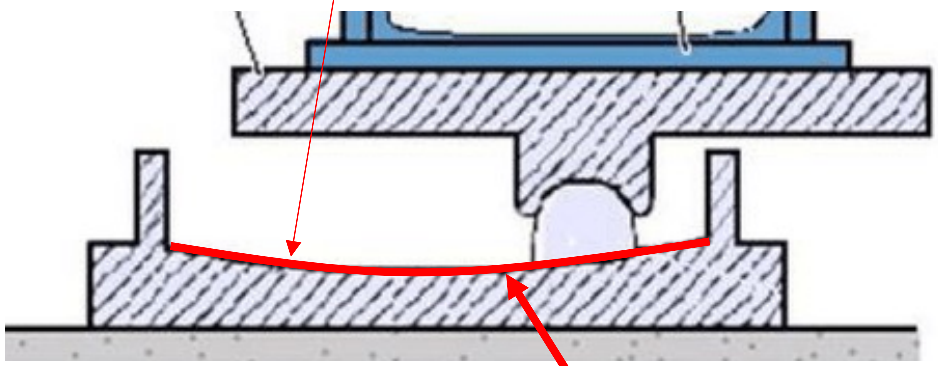


$$H(im) = k_0 \exp(-k_1 \ln im - k_2 \ln^2 im)$$

Demand-intensity model for FPB systems

- Since base isolated systems with FPB isolators are governed by the behaviour of these bearings, the model can be simplified
- This can be written in terms of the bearing's geometric and friction surface properties
- These are properties that can be selected from a manufacturer's catalogue of available devices

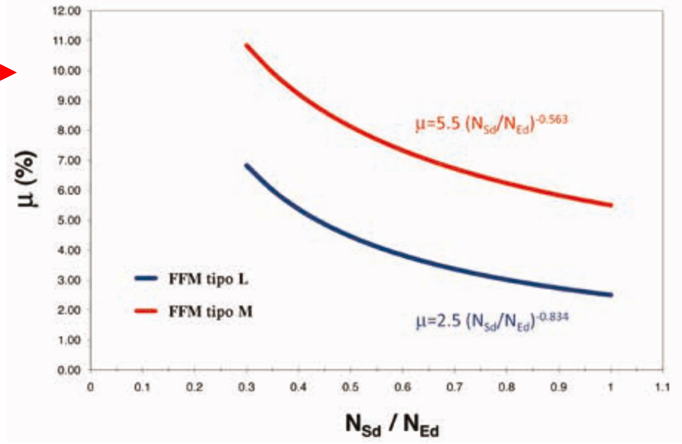
Radius of curvature, *R*



FIP INDUSTRIALE
leading technologies

Attrito minimo		Attrito medio		SPOSTAMENTO ±200 mm					
Sigla isolatore	N_{Ed} kN	Sigla isolatore	N_{Ed} kN	D mm	Y mm	Z mm	H mm	n	W kg
FIP-D L 280/400 (3100)	1000			460	570	460	108	4	85
FIP-D L 370/400 (3100)	1500	FIP-D M 370/400 (3100)	270	490	600	490	114	4	110
FIP-D L 470/400 (3100)	2000	FIP-D M 470/400 (3100)	670	520	690	530	109	4	130
FIP-D L 550/400 (3100)	2500	FIP-D M 550/400 (3100)	980	540	710	540	106	4	140
FIP-D L 630/400 (3100)	3000	FIP-D M 630/400 (3100)	1340	560	730	560	125	4	170
FIP-D L 720/400 (3100)	3500	FIP-D M 720/400 (3100)	1730	580	750	580	121	4	180
FIP-D L 810/400 (3100)	4000	FIP-D M 810/400 (3100)	2150	600	770	600	128	4	210
FIP-D L 1000/400 (3100)	5000	FIP-D M 1000/400 (3100)	3100	640	890	690	152	4	290
FIP-D L 1150/400 (3100)	6000	FIP-D M 1150/400 (3100)	3950	670	920	710	146	4	310
FIP-D L 1350/400 (3100)	7000	FIP-D M 1350/400 (3100)	4850	700	950	730	150	4	360
FIP-D L 1450/400 (3100)	8000	FIP-D M 1450/400 (3100)	5500	720	970	740	176	4	430

Catalogue specified friction coefficient *μ* as a function of axial load and surface type



Demand-intensity model for FPB systems

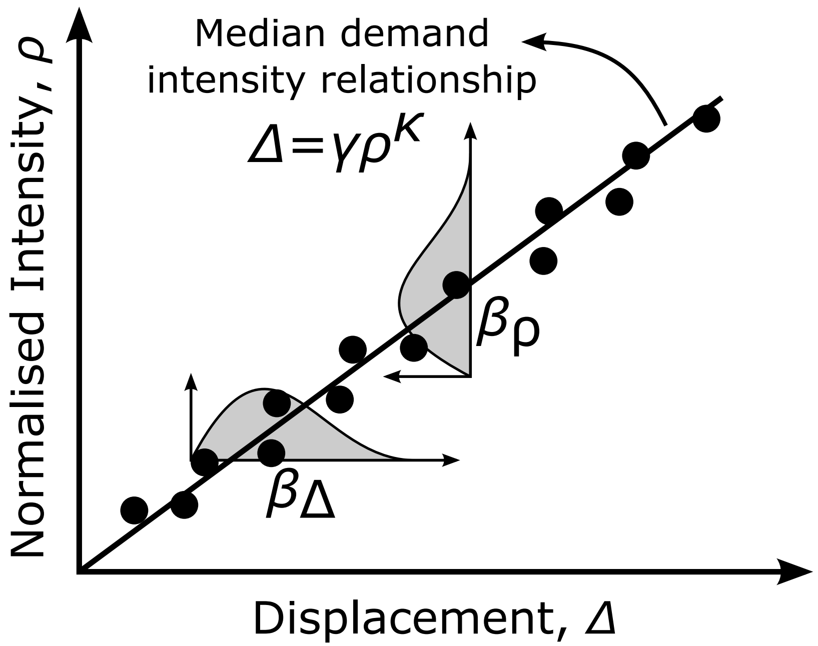
- The demand intensity model simply relates the seismic intensity required to exceed a given demand threshold
- The first step proposed by O'Reilly ey al. (2022) was to normalise the intensity by the friction coefficient

$$\rho = \frac{Sa(T_{iso})}{\mu}$$

- This is then plotted versus the FPB device displacement to give the demand-intensity model as:

$$\rho = \left(\frac{\Delta}{\gamma}\right)^{1/\kappa}$$

- where the coefficients γ and κ are assumed to be a function of the device properties
- The dispersion is denoted β



O'Reilly GJ, Yasumoto H, Suzuki Y, Calvi GM, Nakashima M. Risk-based seismic design of base-isolated structures with single surface friction sliders. Earthquake Engineering & Structural Dynamics 2022. DOI: 10.1002/eqe.3668.

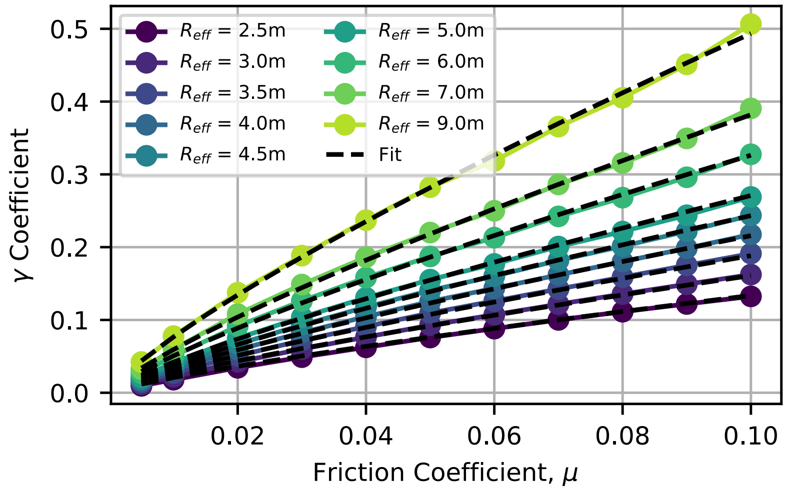
Demand-intensity model for FPB systems

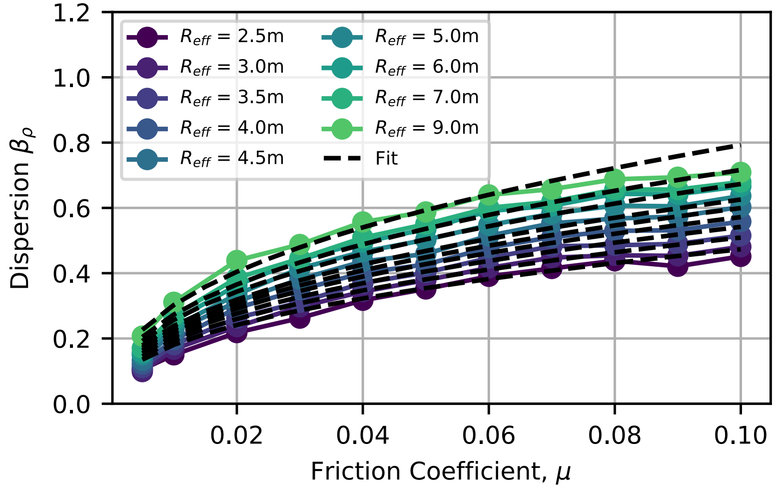
- O'Reilly et al. (2022) conducted a parametric study to quantify these coefficients as:

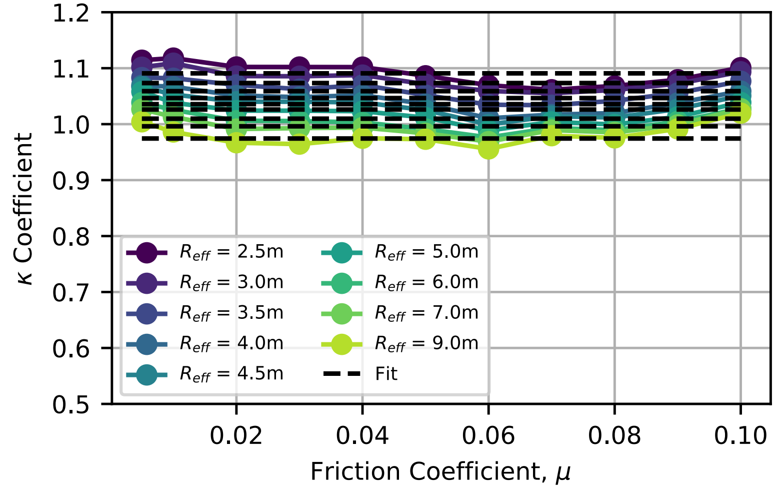
$$\gamma = 0.337\mu^{0.808}R^{1.02}$$

$$\kappa = 1.183R^{-0.088}$$

$$\beta_\rho = 0.857\mu^{0.418}R^{0.403}$$







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Procedure

Identify an isolator device

Step 1: Identify the site location and a suitable hazard model

Step 2: Identify what the design requirements for the isolation system are (i.e., displacement limit Δ_{lim})

Step 3: Select an FPB device by choosing an initial R and μ

Step 4: Determine the IM by computing T_{iso}

Compute risk of failure using simplified demand-intensity and risk models

Step 5: Get the hazard curve for IM = $Sa(T_{iso})$ from PSHA and fit the model described by Eq. (4)

Step 6: For the selected R and μ, identify the demand-intensity model parameters γ, κ and β_{ρ} from Eqs. (7), (8) and (9), respectively

Step 7: With the demand-intensity model parameters computed, identify ρ from Eq. (6) for the displacement Δ = Δ_{lim}

Step 8: Compute the seismic vulnerability via median intensity $Sa(T_{iso})$ required to exceed Δ_{lim} from Eq. (5)

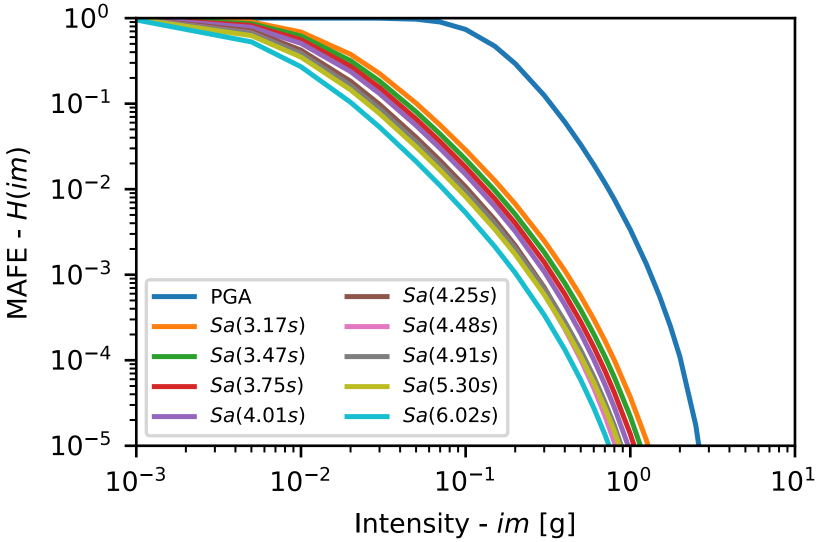
Step 9: Compute the MAFE of exceeding this displacement threshold, λ_{Δ}, from Eq. (2)

Case study example

- The proposed method can be used quickly in design situations to test whether a particular isolation system is suitable before a more thorough analysis
- Let us try:
  - Building located in L'Aquila, Italy
  - Displacement threshold of Δ_{lim} = 0.4m
  - FPB isolators μ = 3% and R = 4m
- Since the isolator bearings are R = 4m, the period of vibration is:

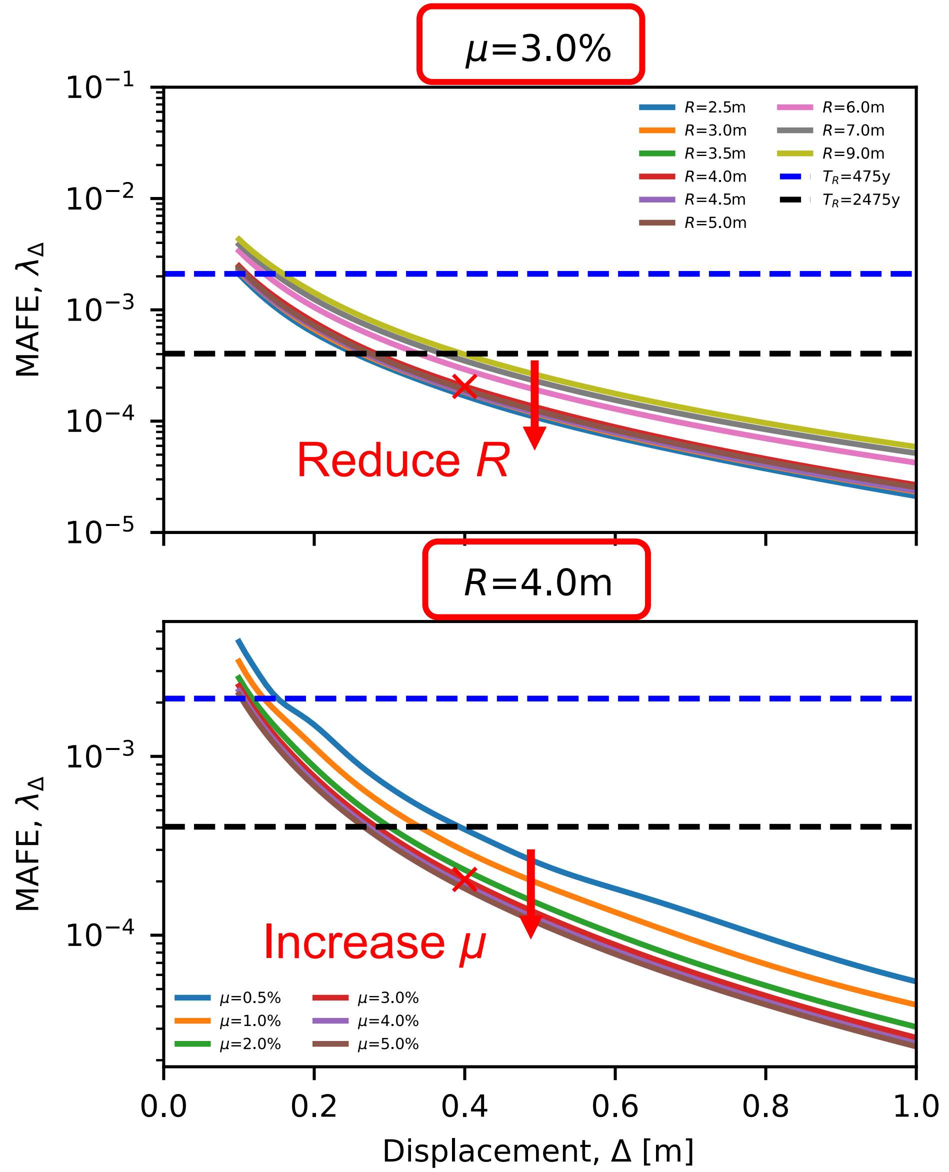
$$T_{iso} = 2\pi\sqrt{\frac{R}{g}} = 2\pi\sqrt{\frac{4}{9.81}} = 4.01s$$

- Seismic hazard curve identified using the SHARE hazard model



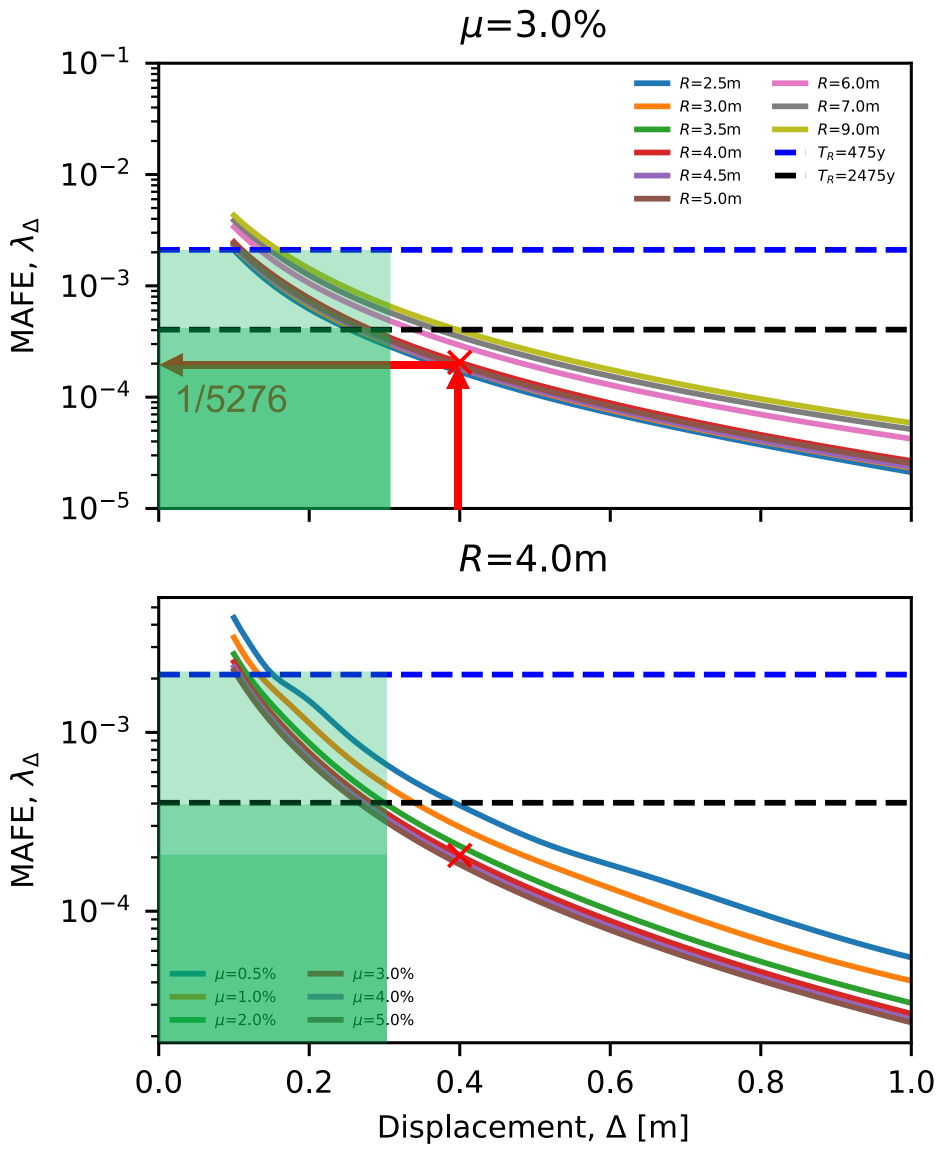
Case study example

- Using the site hazard and candidate FPB isolator properties, the approach described previously was implemented to estimate the MAFE of the target displacement threshold of Δ_{lim} = 0.4m
- This MAFE is shown via the red crosses
- This is the failure rate that can be checked against prescribed thresholds
- Repeating the same exercise for different FPB isolator and displacement combinations, the demand-hazard curves can be generated
- It can be observed that:
  - For a given μ, the MAFE can be lowered by reducing R
  - For a given R, the MAFE can be lowered by *increasing* μ



Case study example

- Examining the risk for the chosen FPB isolation system, the MAFE is 1.895×10^{-4} which corresponds to a return period of 5276 years
- If a designer wants a displacement threshold of 0.3m and MAFE of 2475 years, only FPB isolators with $R < 6$m and $\mu > 3\%$ would be suitable
- For a less stringent MAFE of 1/475 years, all isolation systems would meet the objectives for a 0.3m displacement threshold
- For an MAFE of 1/5000 years and a 0.3m displacement threshold, none of the FPB isolators would work



Conclusions

- The proposed procedure presented offers an effective and simple way to select FPB bearings for a risk-targeted seismic design of structures with isolators
- It is simpler than current design methods used in building codes, which often involve trial and error processes **after numerical verification analyses**
- It is risk-targeted, which current methods are not
- Knowing the FPB isolation system and the displacement threshold, the risk of device failure in existing buildings in a given region can be quickly estimated, allowing us to identify the isolated structures at an unacceptably high level of risk