Towards a practical loss-based design approach and procedure

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Main objective of seismic design:

Minimize total investment, including construction and total losses during the structure life

Difficult to pursue:

Little correlation between loss and strength
Better, but still inadequate, with displacement

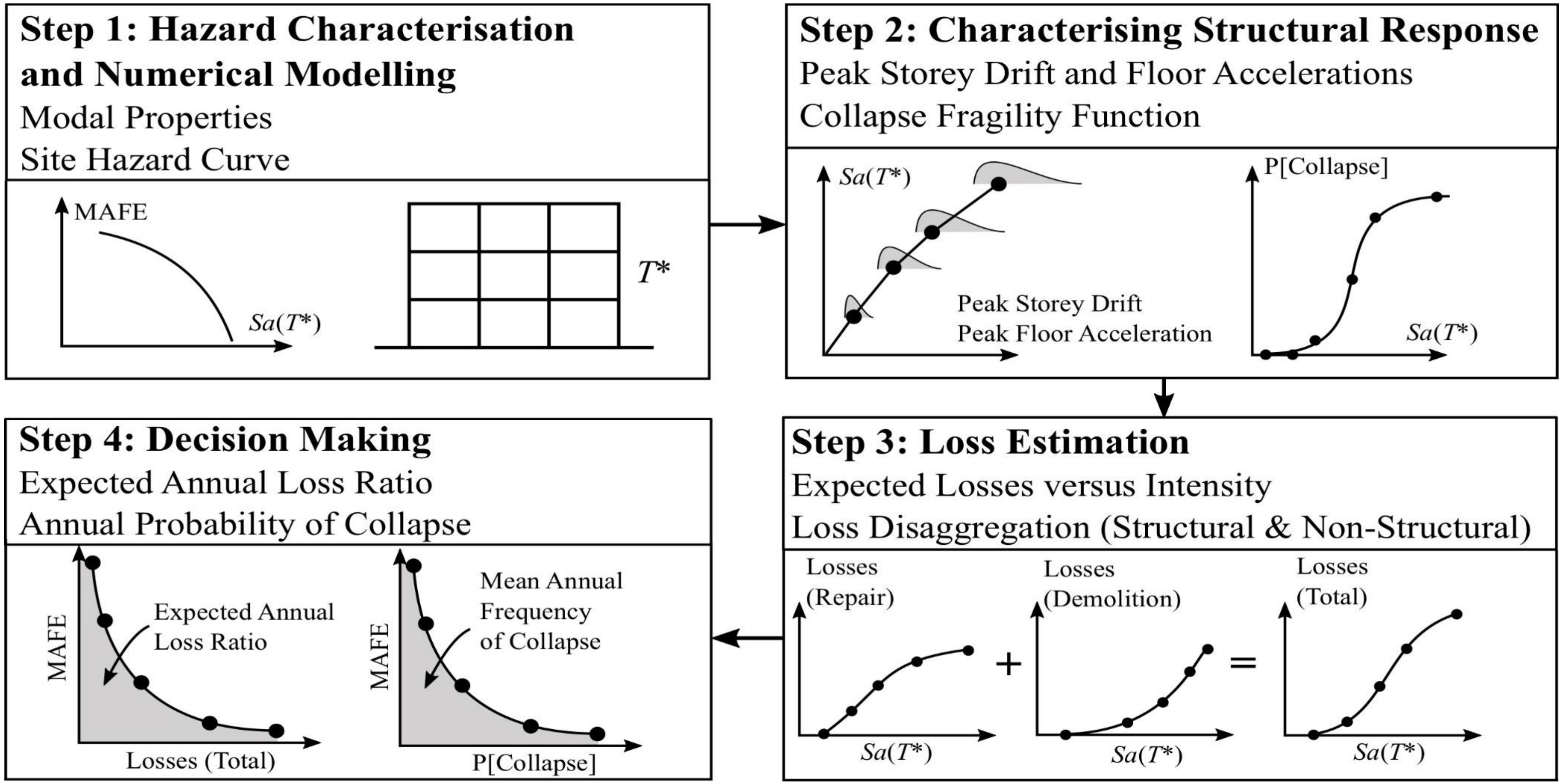
It is essential:

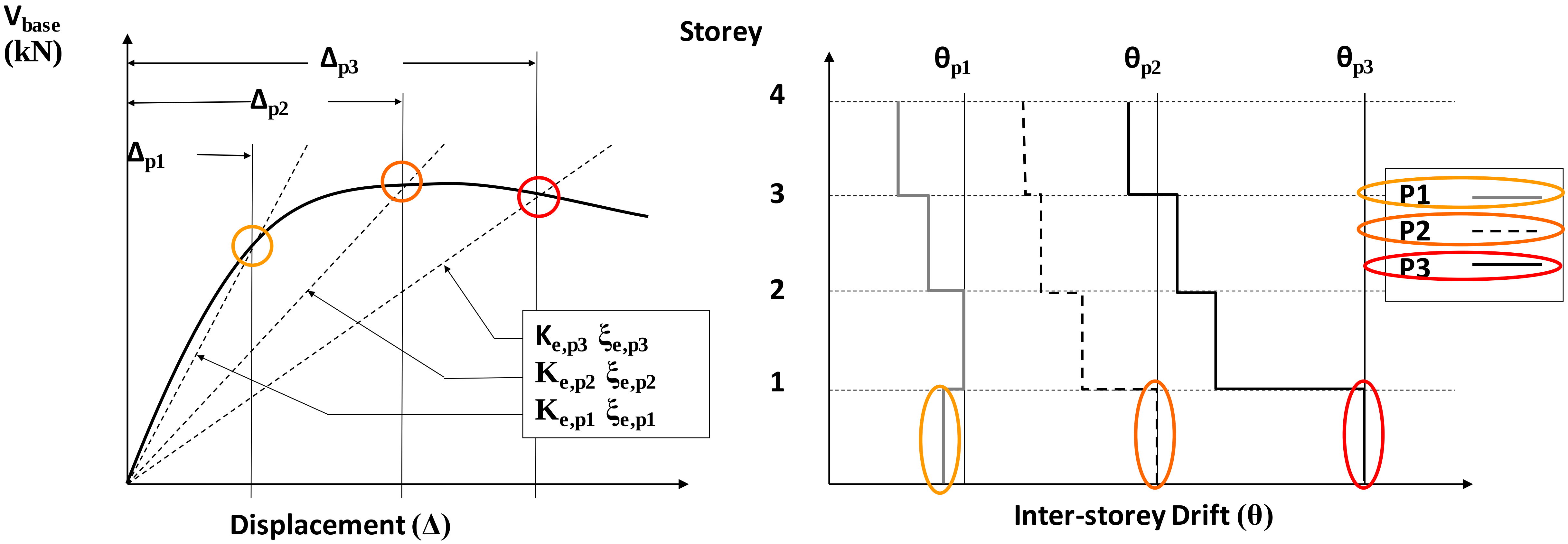
Proper definition of input
Selection of structural system
Consistent design of non-structural elements

A possible reference framework: FEMA P58 (PEER PBEE methodoly)

Focus on assessment of existing buildings

Not on structural and NS systems selection





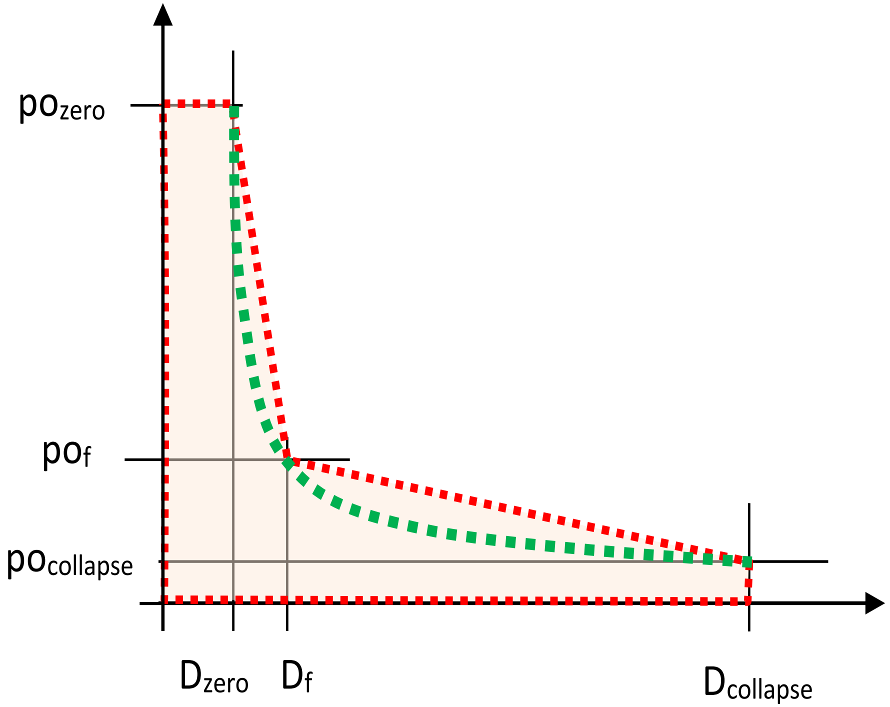
From hazard to response parameters:
What is the likely drift if Sa(T) is 1.0g ?

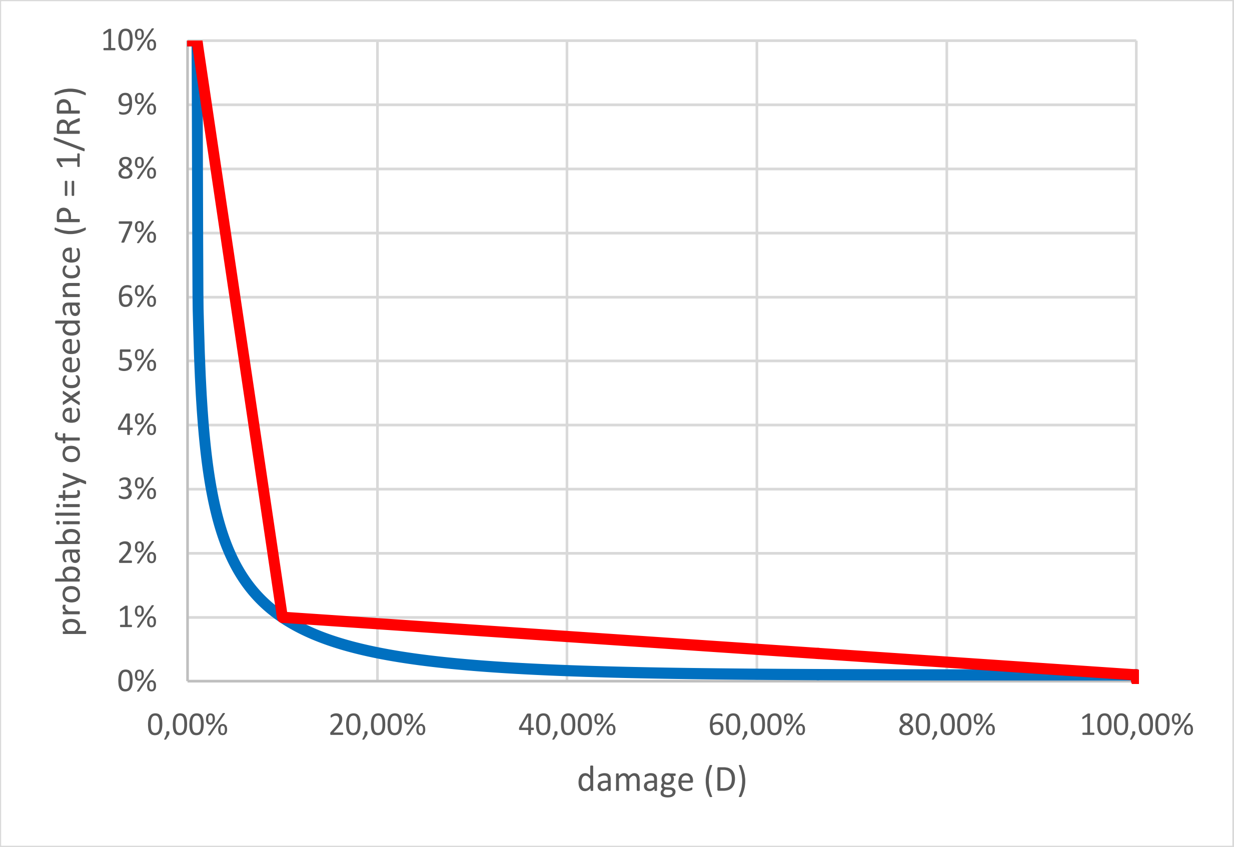
traditional question:
"what will be the response of the structure to a given input ground motion"

proper question:
"what will be the earthquake that will induce a given performance"

EAL (expected annual loss) = $\int(po \times D)dD$

as a tool to design

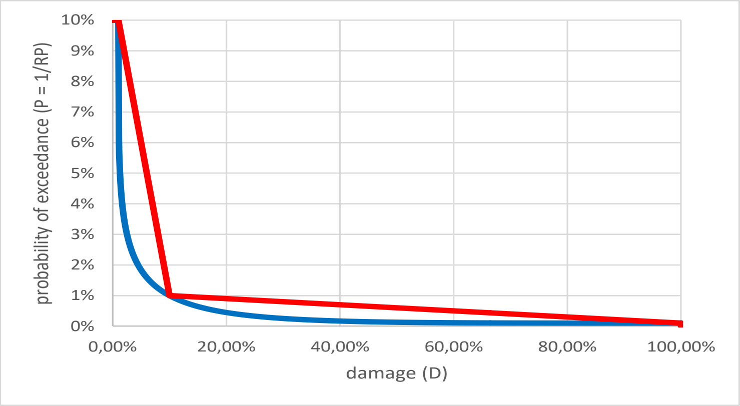




po = probability of occurrence **D = damage level**

EAL as a tool to design

Derive an equation for the blue curve



$$P = P_{collapse} + \left(P_{zerodamage} - P_{collpase}\right) \cdot \sin^{\alpha}\left(\cos^{-1}\left(\frac{D - D_{zero}}{D_{collapse} - D_{zero}}\right)^{\frac{1}{\alpha}}\right)$$

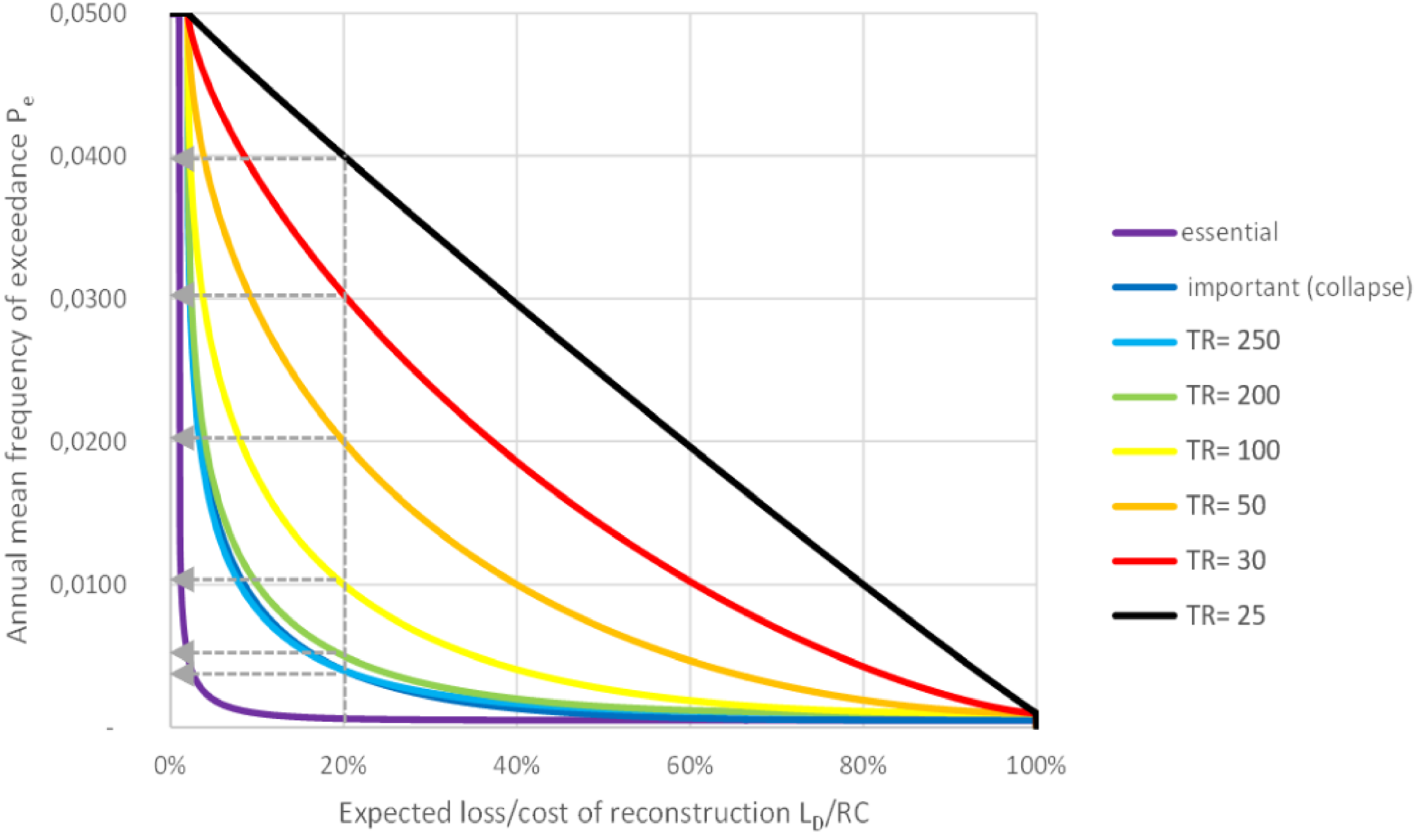
forced to pass through the two extreme points and governed by the single parameter α to pass through the f point.

E.G.:

$D_{collapse}$ = 100%
D_{zero} = 1%
D_f = 10%

$P_{collapse}$ = 1/1000
$P_{zerodamage}$ = 1/10
$P_{zerodamage}$ = 1/100

$$P_e = P_{eC} + (P_{e0} - P_{eC}) \cdot sin^{\alpha}\left(cos^{-1}\left(\frac{L_D - L_{D0}}{L_{DC} - L_{D0}}\right)^{\frac{1}{\alpha}}\right)$$



L_{D0} = 2%

L_{DC} = 100%

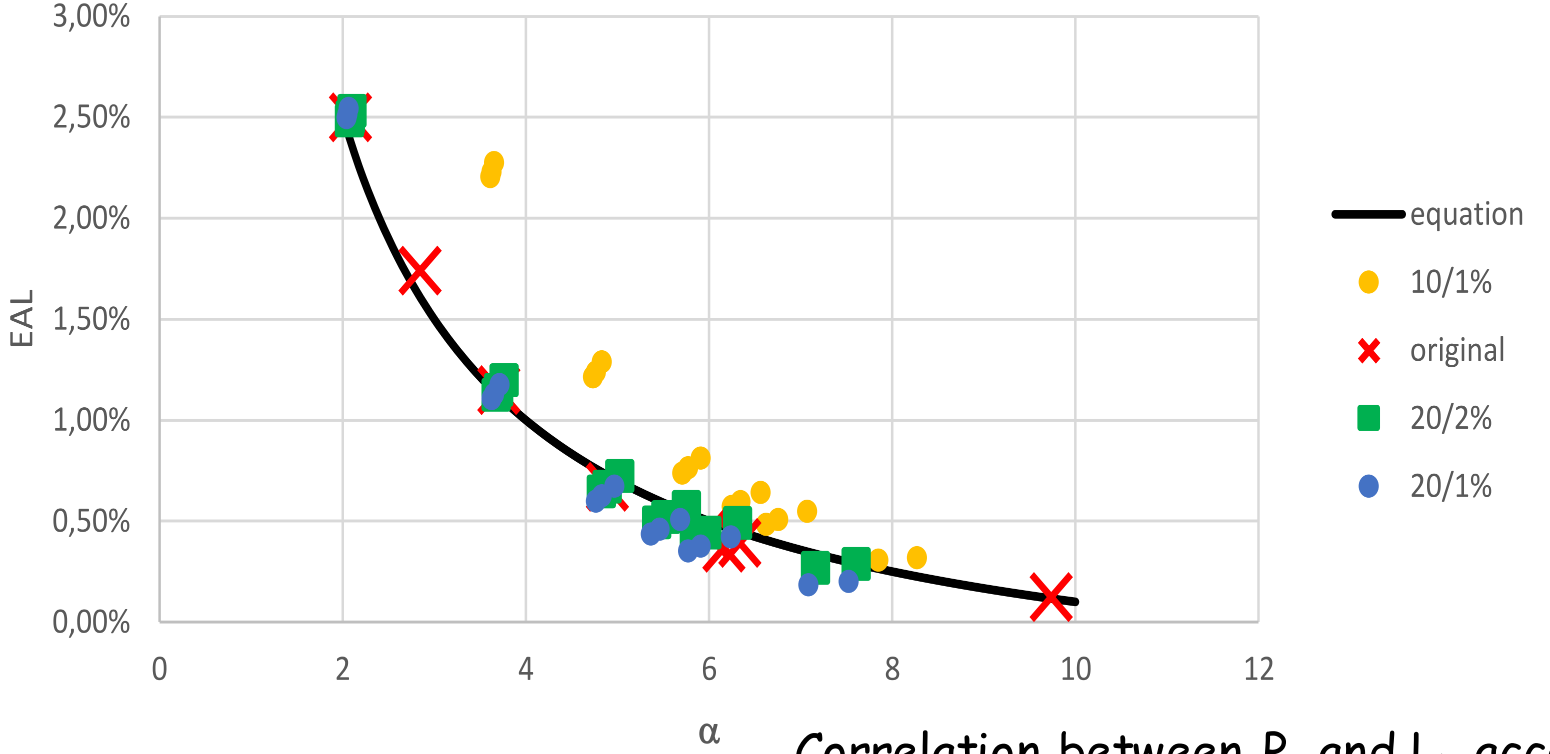
P_{e0} = 5% T_{RC} = 20 years

P_{eC} = 0.05 % T_{RC} = 2000 years

L_{Df} = 20%

	a=9.7	a=6.2	a=6.3	a=5.9	a=4.9	a=3.7	a=2.8	a=2.1
EAL	0.12%	0.37%	0.39%	0.44%	0.67%	1.15%	1.74%	2.50%

$$\alpha = \frac{6\%}{EAL + 0.5\%} \qquad EAL = \frac{6\%}{\alpha} - 0.5\%$$

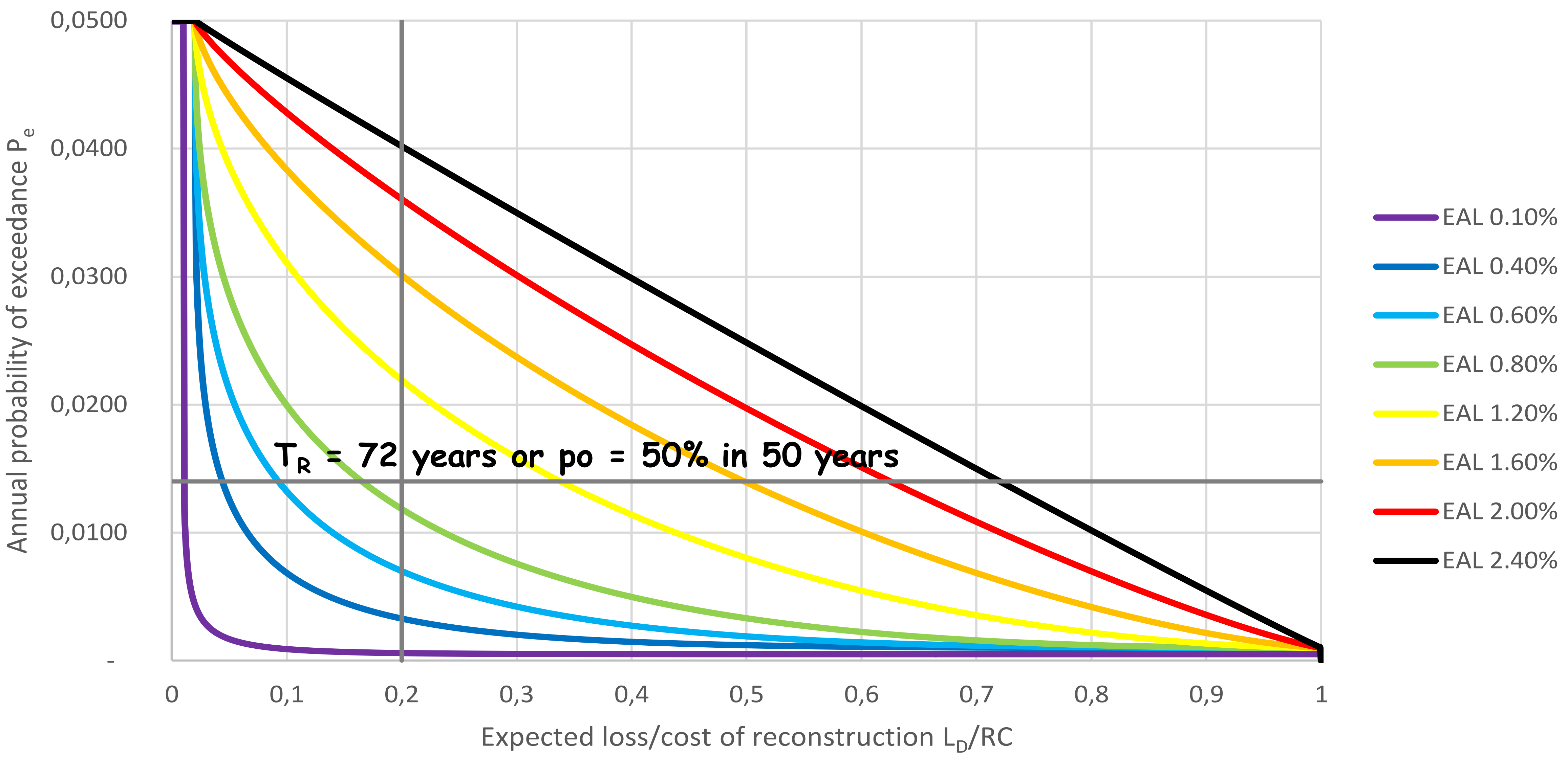


yellow dots: 1% loss at T_{RO} = 10 years

green squares: 2% loss at T_{RO} = 20 years

blue dots: 1% loss at T_{RO}= 20 years

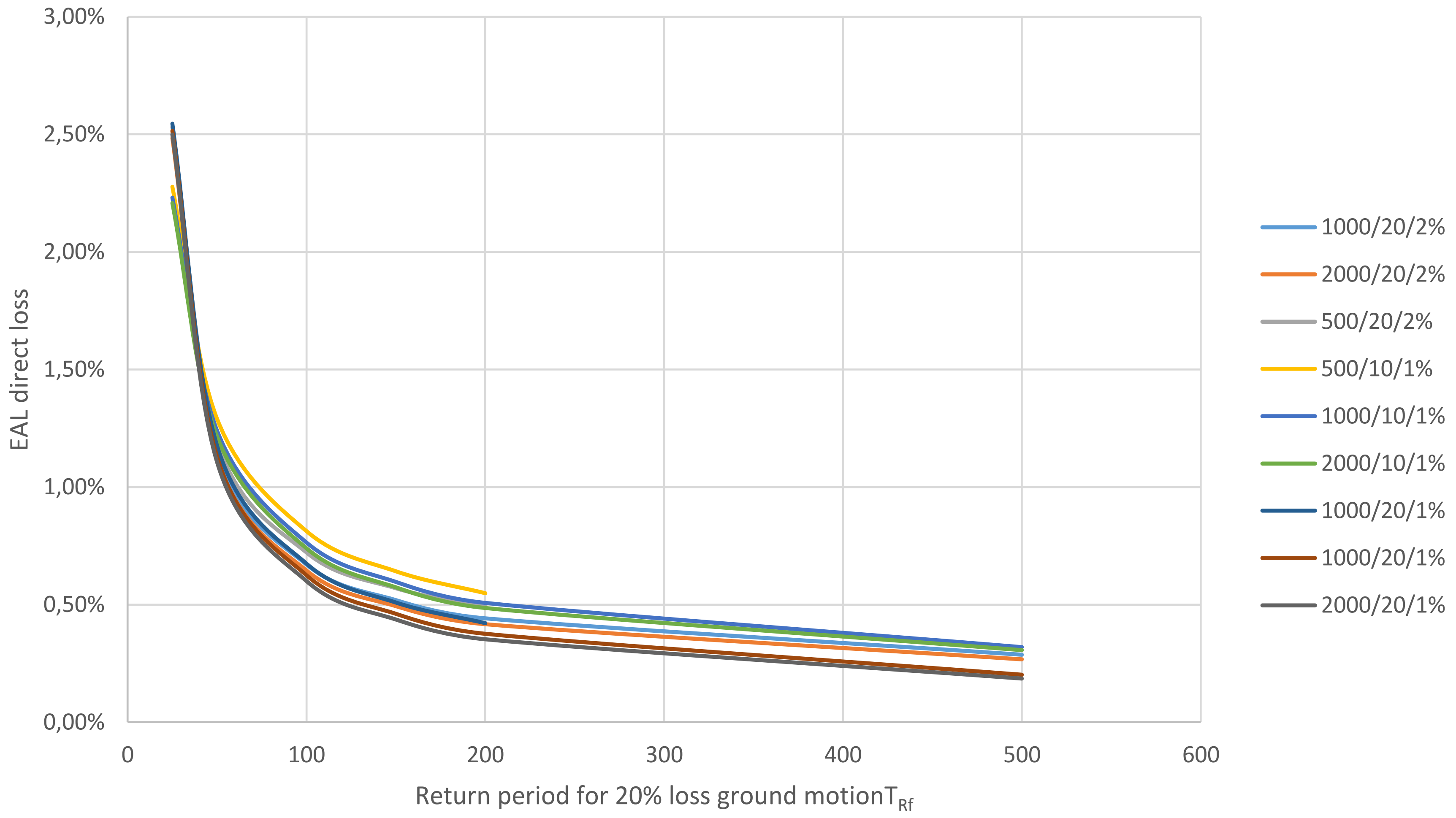
Correlation between P_e and L_D according to Eq. (2) for different EAL values



a code-conforming building may be characterized by an EAL in the range of 1.0 %

	EAL=0.1%	EAL=0.4%	EAL=0.6%	EAL=0.8%	EAL=1.2%	EAL=1.6%	EAL=2.0%	EAL=2.4%
$P_{ef}(\delta_i = 0.5\%)$	0.06%	0.33%	0.70%	1.18%	2.19%	3.01%	3.60%	4.02%
$T_{Rf}(\delta_i = 0.5\%)$ [years]	1700	305	143	84	46	33	28	25

Relationship between the annual probability of exceedance of shaking and EAL in order to respect **a drift threshold of 0.5%**



Correlation between EAL and damage control point f, as a function of the return periods of the ground motion inducing collapse and inducing the onset of damage

Loss estimation

Indirect (business interruption) losses may dominate

Residential:

- Cost of homeless relocation C_{rl}=35 €/d,
- Cost of reconstruction C_R=1000 €/sqm (100 % direct loss)
- Average area per person S_p=25 sqm
- Total time of reconstruction T_{rc}=2 y=730 d

$$\frac{L_{IM(res)}}{C_R} = \frac{C_{rl} \cdot T_{rc}}{S_p \cdot C_R} = \frac{35 \cdot 730}{25 \cdot 1000} = 1.02$$

Societal cost is about 0.14 $\%R_C$/d
i.e ratio between indirect and direct cost ≈ 1

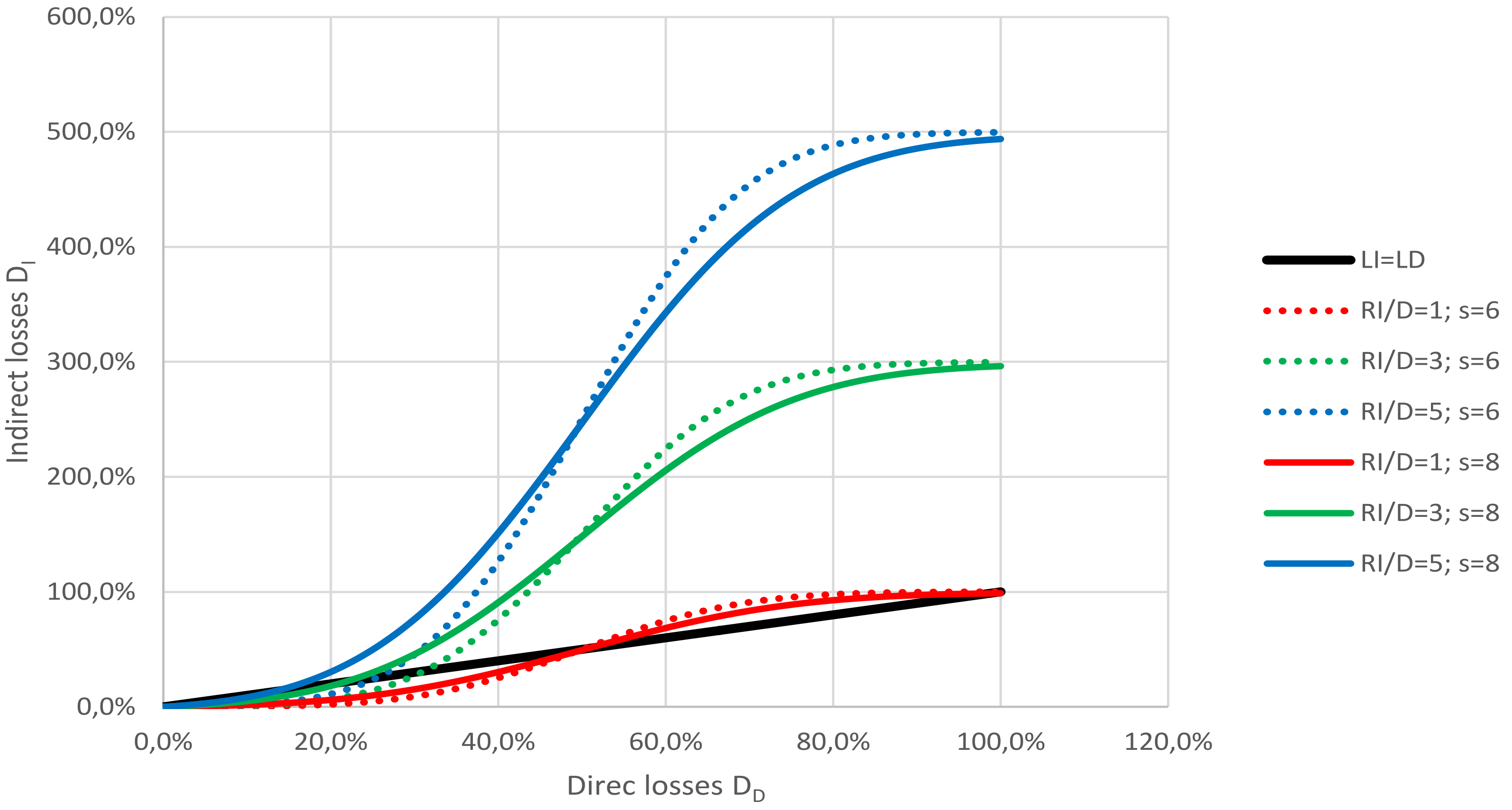
Bridges:

- number of vehicles (N_v) crossing the bridge,
- required detour length (D_d [km])
- unitary cost per added travelled km (C_{km})
- time required to reconstruct or repair the bridge (T_{rc})

$$\frac{L_{IM(bridge)}}{C_R} = \frac{N_v \cdot D_d \cdot C_{km} \cdot T_{rc}}{C_R}$$

Societal cost is about 0.3–0.8 $\%R_C/d$
i.e ratio between indirect and direct cost ≈ 2 – 5

Correlation between indirect and direct cost

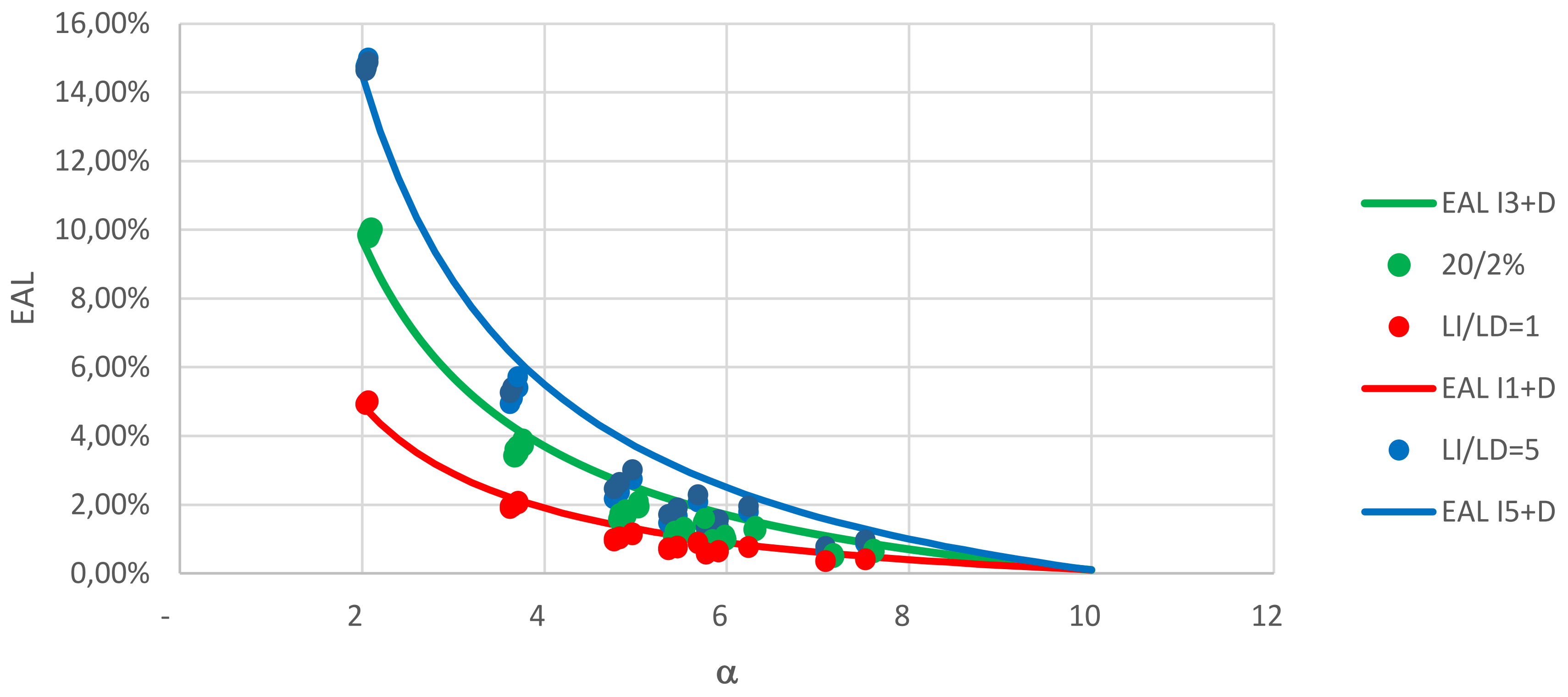


$$\mathbf{L_I = \frac{R_{I/D}}{\sigma\sqrt{2\pi}} \int_0^1 e^{-\frac{L_D^2}{2\sigma^2}} dL_D}$$

EAL including indirect loss

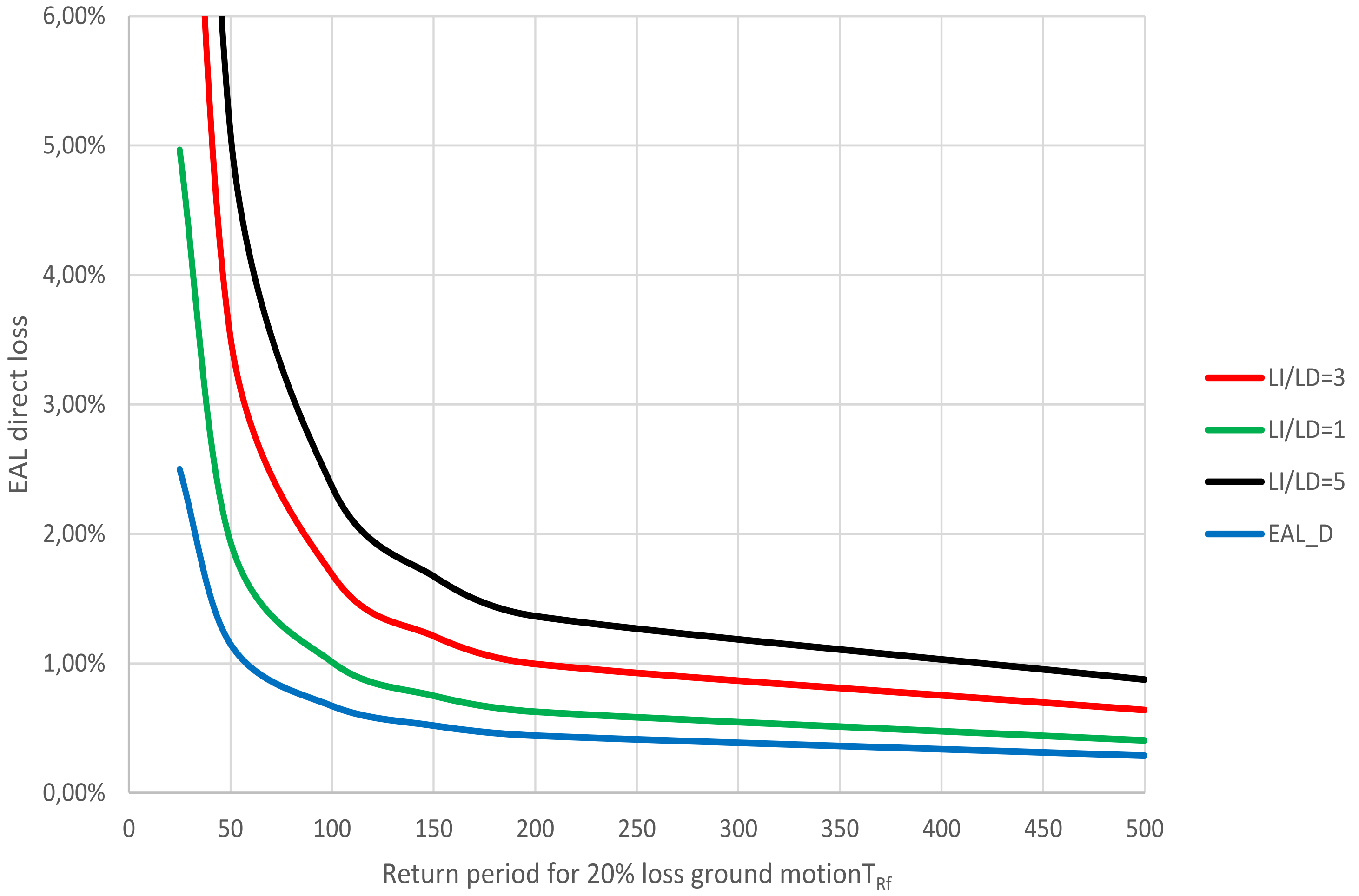
$$EAL = \frac{6\%}{\alpha} - 0.5\%$$

$$\alpha = \frac{6\%}{EAL + 0.5\%}$$



$$EAL_{I+D} = 0.06\left(1 + R_{I/D}\right)\left(\frac{10-\alpha}{10\alpha}\right) + 0.001 \qquad \alpha = \frac{0.06\left(1 + R_{I/D}\right)}{EAL_{I+D} + 0.006\left(1 + R_{I/D}\right) - 0.001}$$

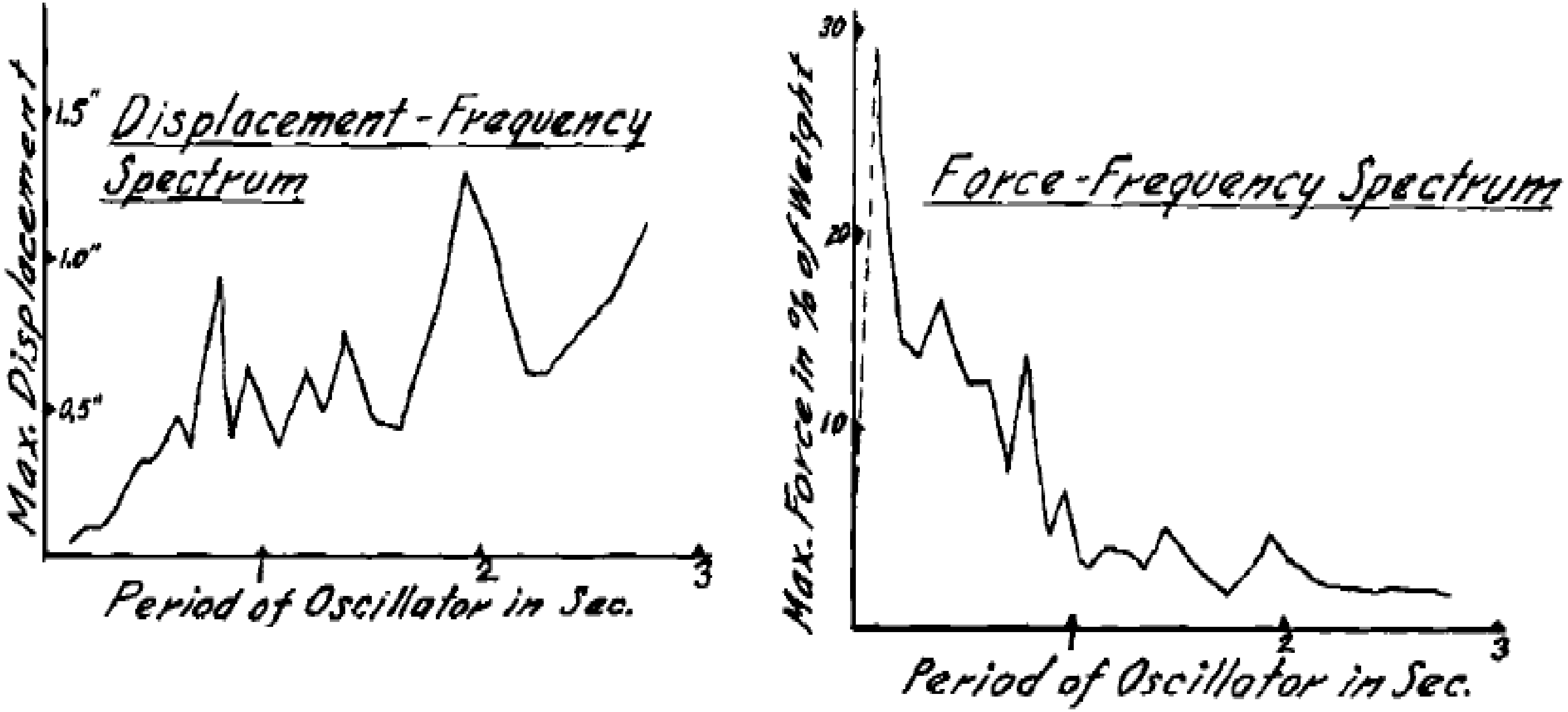
Correlation between EAL and return period of a ground motion inducing 20% of R_C direct loss



Correlations between loss, response parameters and input ground motion

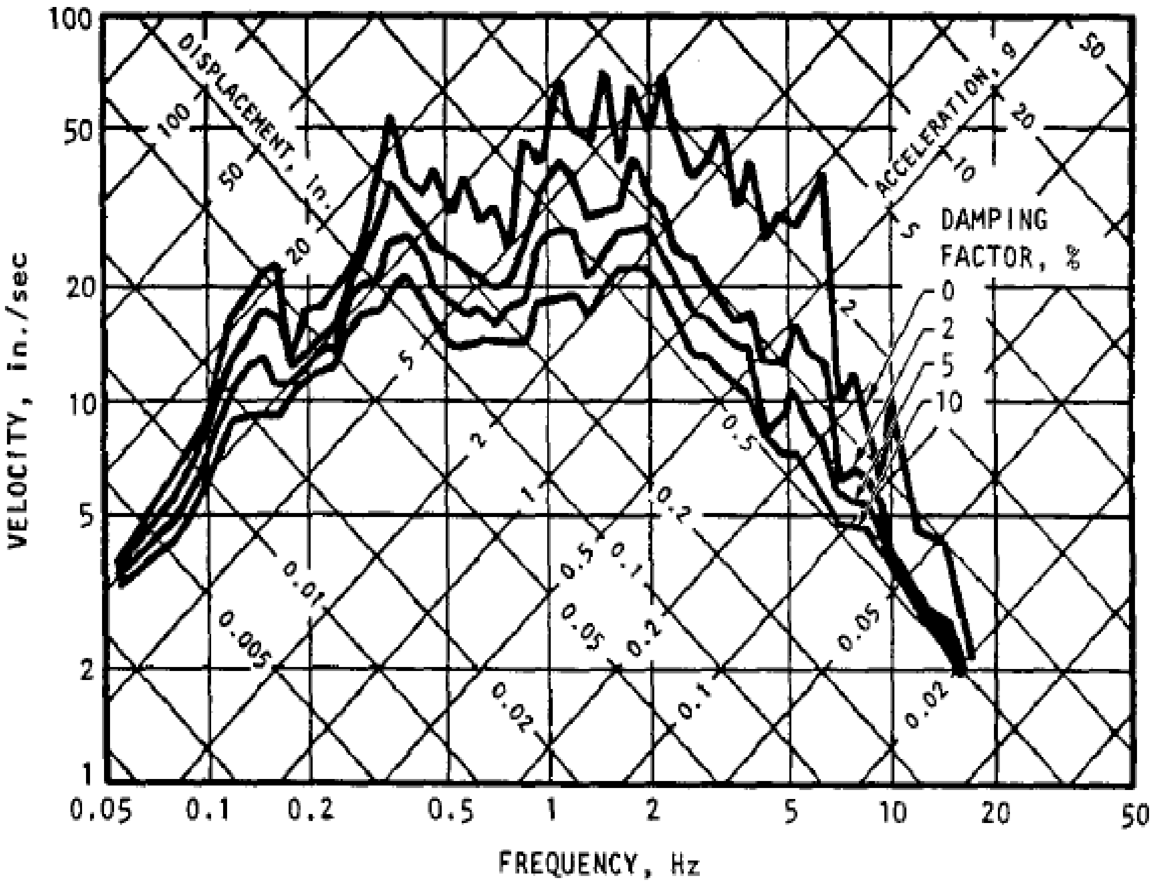
1
Definition of seismic input

in the form of appropriate design spectra

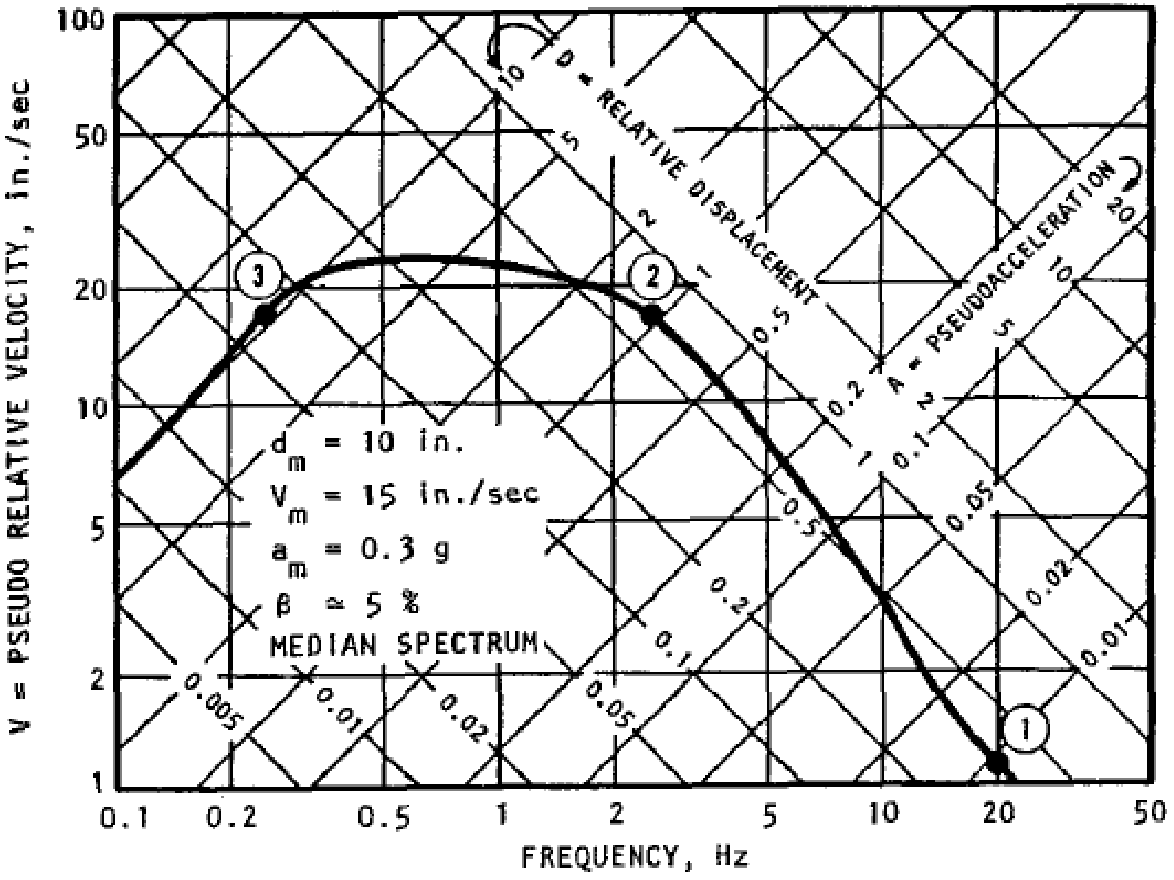


Displacement and acceleration response spectra for a component of the Los Angeles earthquake of 2 October 1933

Housner (1941)

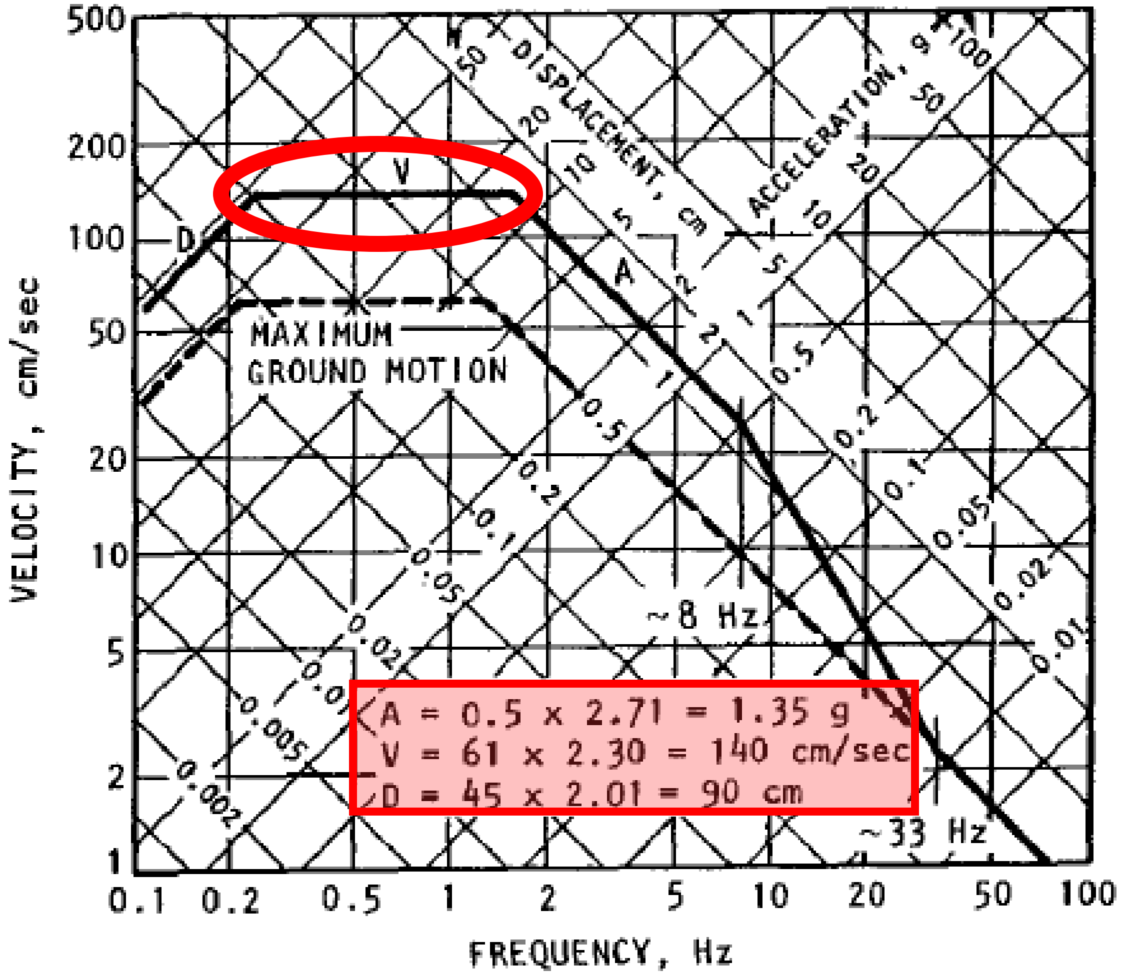


Response spectra from the NS El Centro record



"Typical response spectrum"

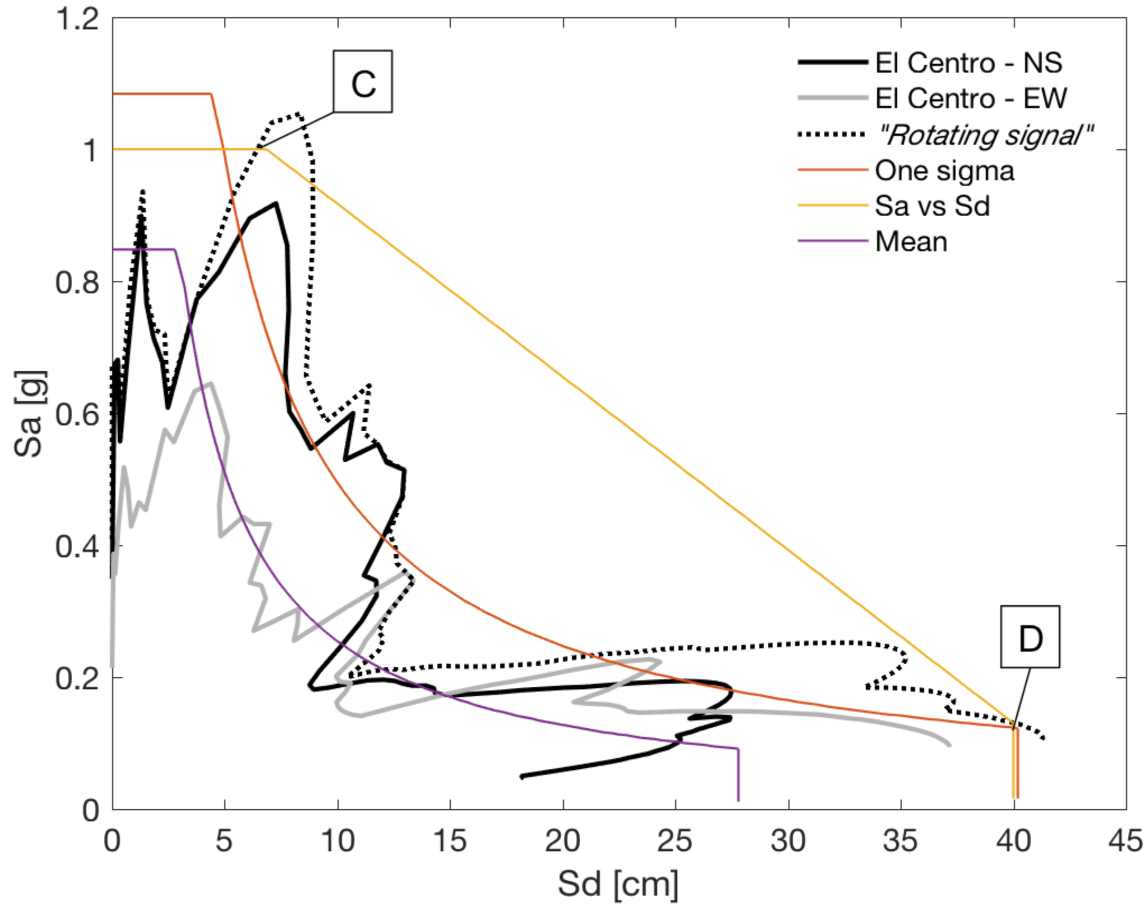
Newmark and Hall, 1982



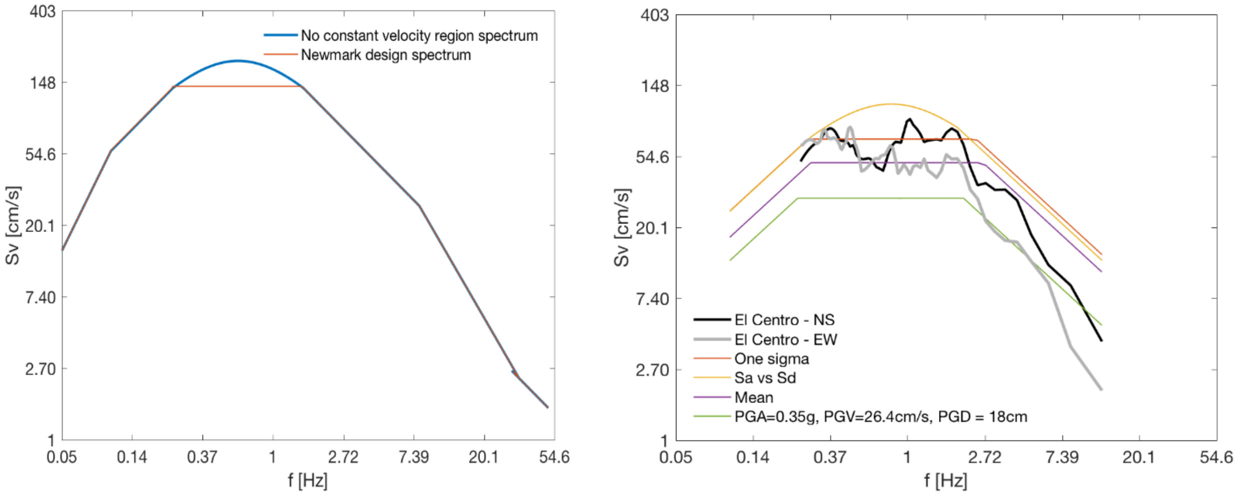
Why constant velocity?

Elastic design spectrum for 0.5 g PGA, 5% damping and one sigma cumulative probability

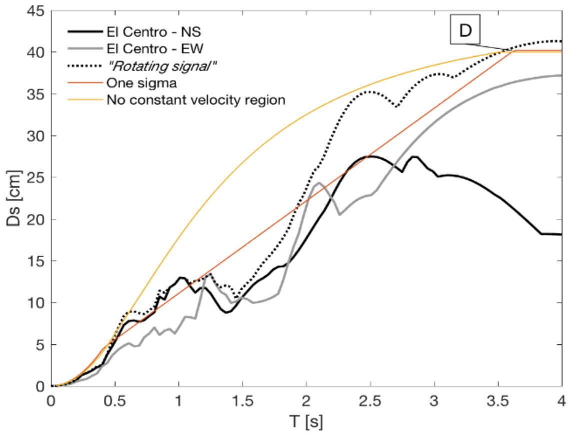
Newmark and Hall (1982)



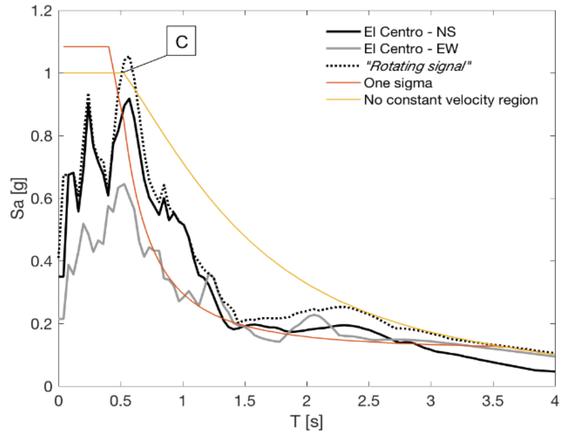
Combined Sa - Sd spectra from El Centro records and Newmark design spectra



Tri-partite log-scale spectra



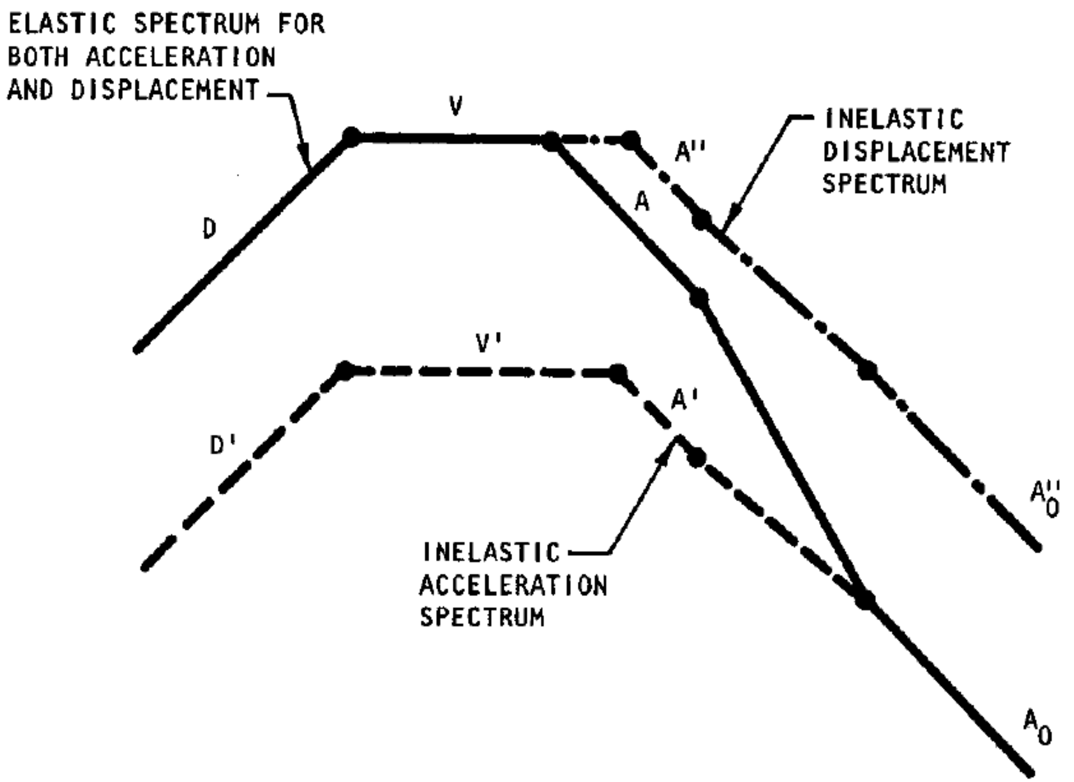
Displacement spectra



Acceleration spectra

Correction to account for non linear response:

Traditional approach



- Divide the ordinate of the elastic spectrum by μ for frequencies up to 2 Hz (regions D and V) to obtain the acceleration inelastic spectrum.
- Do the same in the frequency range between 2 and 8 Hz (region A), dividing by $(2\mu-1)^{0.5}$ instead of μ.
- Keep the same acceleration in the elastic and inelastic spectrum for frequencies higher than 33 Hz.
- Link linearly the ordinates at 8 and 33 Hz in the logarithmic plot.
- To obtain the inelastic displacement spectrum multiply all the ordinates of the inelastic acceleration spectrum by μ.

DBD

Correction of the elastic design spectrum to account for energy dissipation only

displacement reduction factor $$\eta_\xi = \left(\frac{0.07}{0.02+\xi}\right)^{0.5}$$

$C \approx 0.4 - 0.6$

equivalent hysteretic damping $$\xi = \xi_0 + \xi_h = \xi_0 + C\left(\frac{\mu - 1}{\pi\mu}\right)$$

$\eta_\xi \approx 0.6$ +/- 10%

Concrete Wall Building, Bridges (TT): $\xi_{eq} = 0.05 + 0.444\left(\frac{\mu-1}{\mu\pi}\right)$

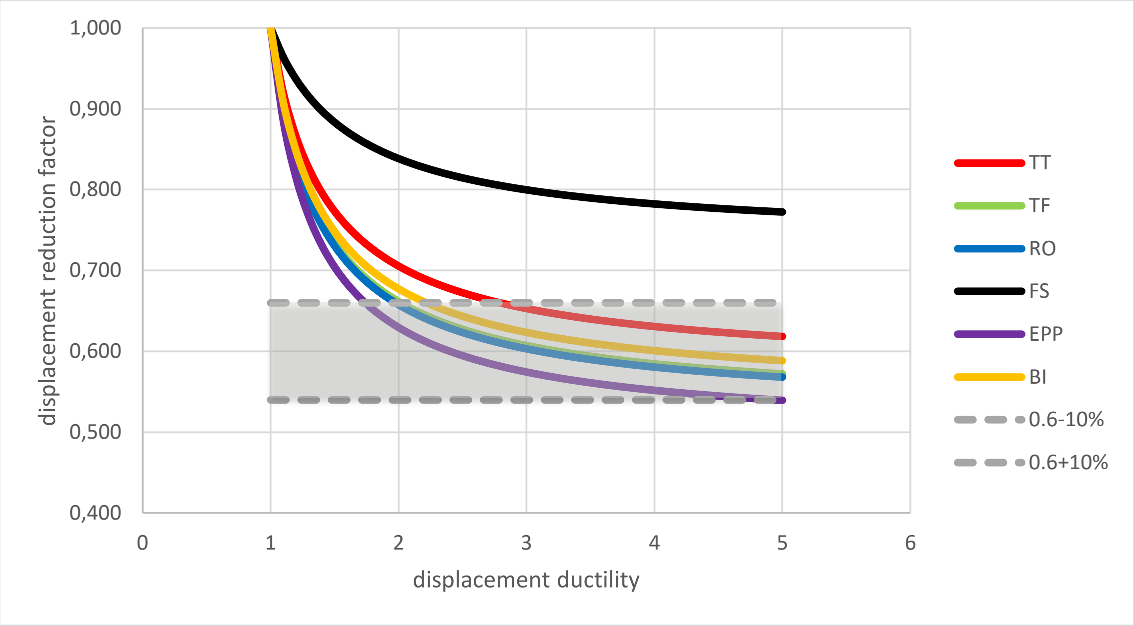
Concrete Frame Building (TF): $\xi_{eq} = 0.05 + 0.565\left(\frac{\mu-1}{\mu\pi}\right)$

Steel Frame Building (RO): $\xi_{eq} = 0.05 + 0.577\left(\frac{\mu-1}{\mu\pi}\right)$

Hybrid Prestressed Frame (FS, β=0.35): $\xi_{eq} = 0.05 + 0.186\left(\frac{\mu-1}{\mu\pi}\right)$

Friction Slider (EPP): $\xi_{eq} = 0.05 + 0.670\left(\frac{\mu-1}{\mu\pi}\right)$

Bilinear Isolation System (BI, r=0.2): $\xi_{eq} = 0.05 + 0.519\left(\frac{\mu-1}{\mu\pi}\right)$

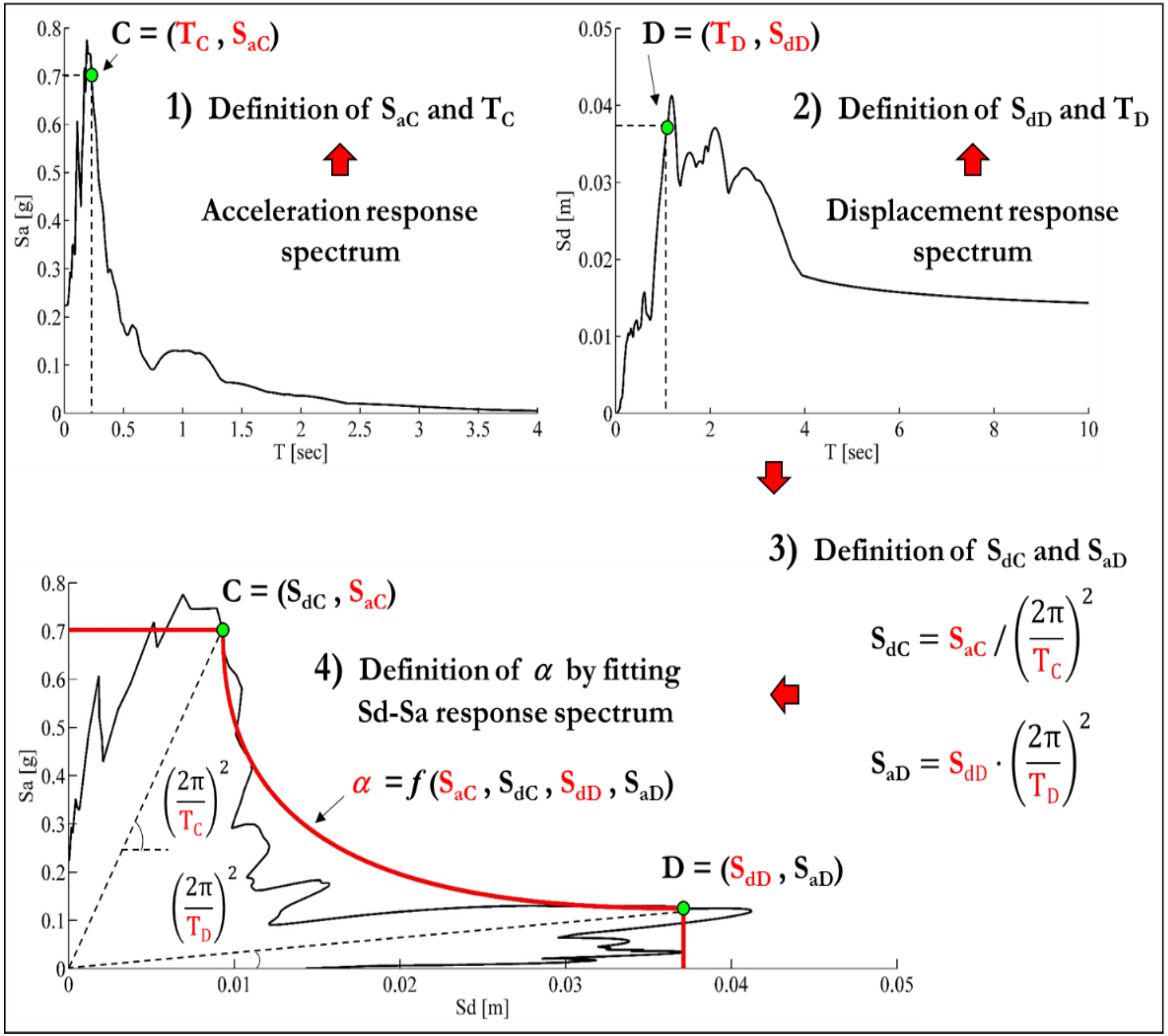


Definition of design and assessment spectra

Point C (T_C, S_{aC})

Point D (T_D, S_{dD})

α: shape of curve between C and D



The assumption of constant velocity force the position of points C and D

Formulation of the parameter α

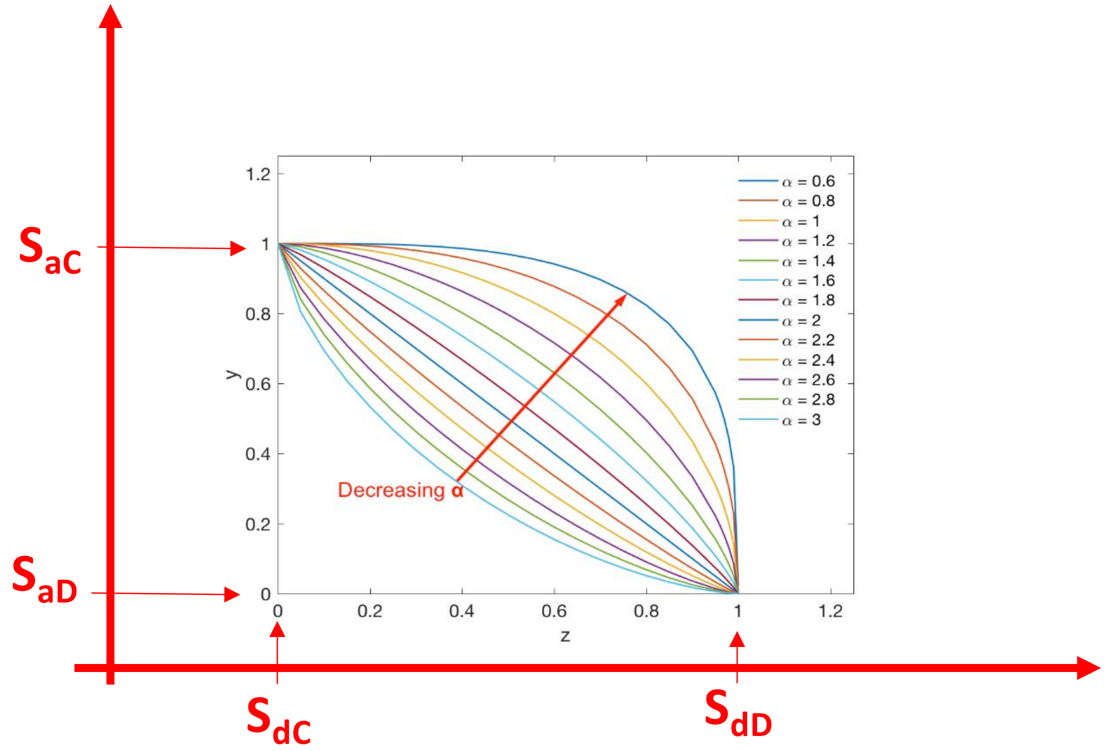
analogy with the function that modifies the shape of a force – displacement curve of a viscous damper

$$y = \sin^{\alpha} t$$

$$z = \cos^{\alpha} t$$

$$y = \sin^{\alpha}\left(\cos^{-1}\left(z^{1/\alpha}\right)\right)$$

$$S_{aD} = S_{dD}\frac{4\pi^2}{T_D^2}$$



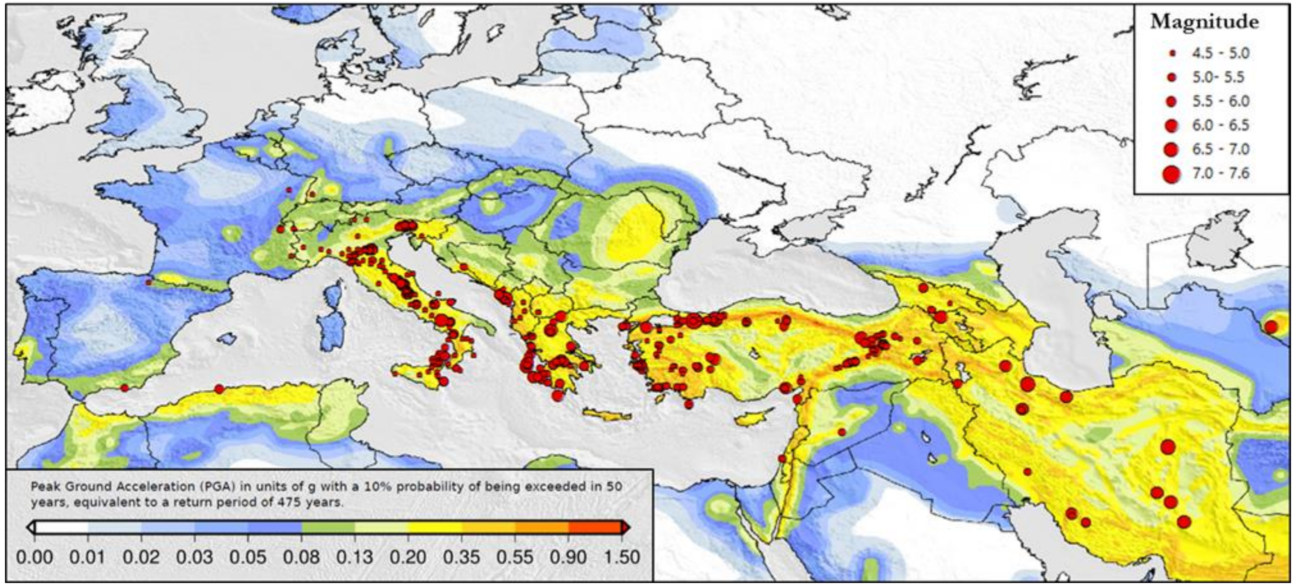
$$S_{dC} = S_{aC}\frac{T_C^2}{4\pi^2}$$

A simple transformation of coordinates:

$$S_a = S_{aD} + \left(S_{aC} - S_{aD}\right)\cdot \sin^{\alpha}\left(\cos^{-1}\left(\frac{S_d - S_{dC}}{S_{dD} - S_{dC}}\right)^{\frac{1}{\alpha}}\right)$$

Assumed key parameters:

Magnitude
Distance
Soil type



3433 couples of records from 387 events

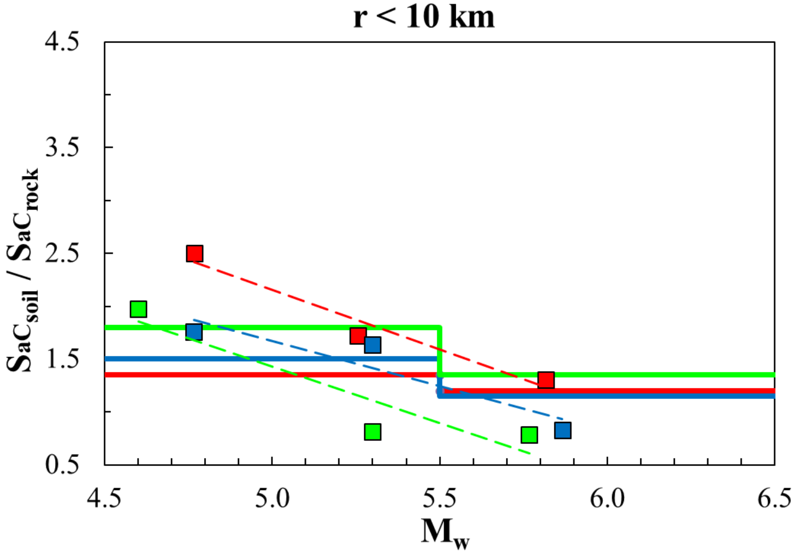
Soil class	M_w	r (km)						
		<10	10-20	20-30	30-40	40-50	50-60	>60
A	7.0-7.6	1	-	-	-	-	-	-
	6.5-7.0	1	2	1	1	-	-	-
	6.0-6.5	6	3	1	4	2	1	7
	5.5-6.0	4	5	11	5	11	6	19
	5.0-5.5	11	14	25	12	19	14	41
	4.5-5.0	11	19	31	27	35	34	61
B	6.5-7.0	5	1	3	1	1	1	2
	6.0-6.5	19	18	6	13	6	7	17
	5.5-6.0	18	25	34	22	22	22	32
	5.0-5.5	44	74	50	70	54	49	109
	4.5-5.0	57	114	103	75	86	80	156
C	7.0-7.6	1	-	1	-	-	-	-
	6.5-7.0	1	-	1	-	-	-	-
	6.0-6.5	6	3	4	14	4	5	7
	5.5-6.0	27	21	23	18	14	11	19
	5.0-5.5	25	34	43	37	43	32	45
	4.5-5.0	35	78	58	50	67	41	79
D	6.5-7.0	1	-	-	-	-	-	-
	6.0-6.5	-	1	-	1	2	-	-
	5.5-6.0	3	1	2	1	1	5	2
	5.0-5.5	2	1	1	4	2	8	13
	4.5-5.0	9	11	2	3	3	7	12
E	6.5-7.0	-	-	-	-	1	-	1
	6.0-6.5	2	-	-	3	-	2	1
	5.5-6.0	2	2	5	1	2	1	4
	5.0-5.5	3	9	6	10	1	1	7
	4.5-5.0	3	5	8	9	2	3	5

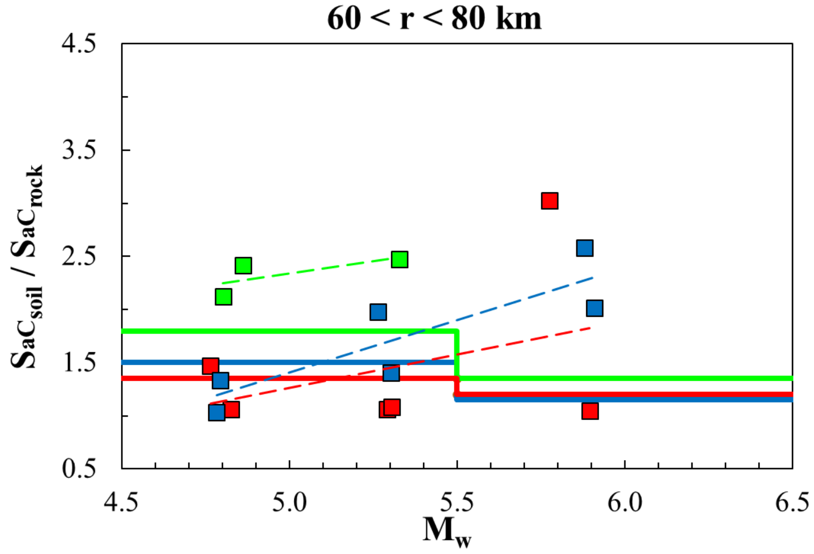
Soil amplification

Depends on Magnitude Distance

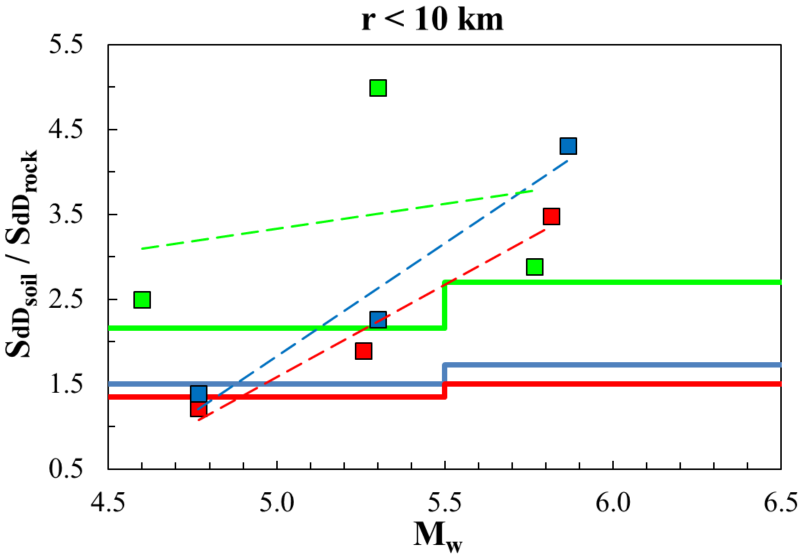
is different on acceleration and displacement

Maximum spectral acceleration (S_{aC})





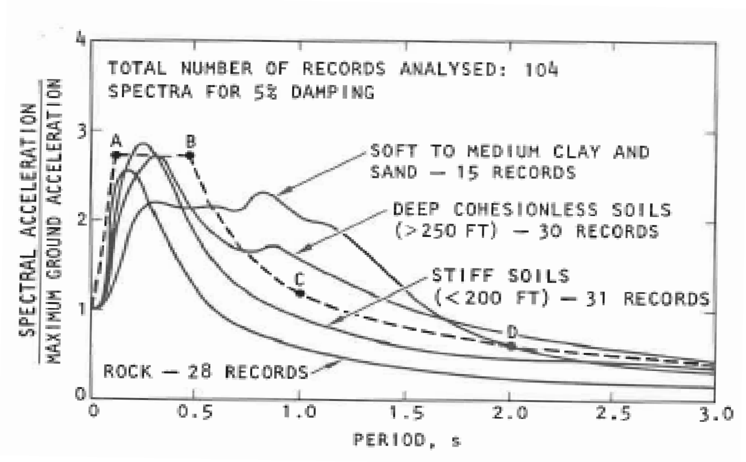
Maximum spectral displacement (S_{dD})

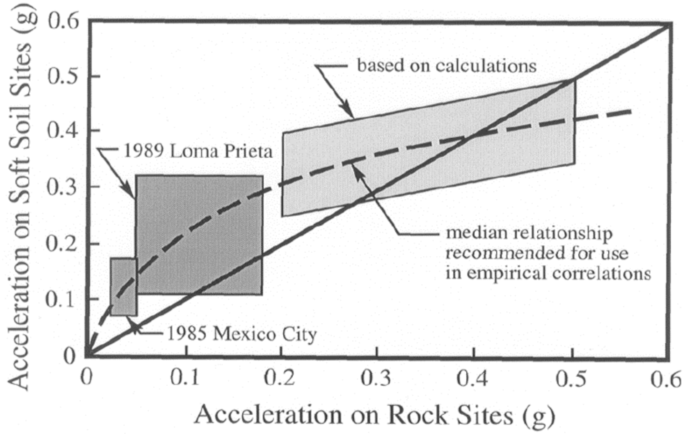


Calvi and Andreotti (2019)
- Soil class B (stiff soils)
- Soil class C (soft soils)
- Soil class D (very soft soils)

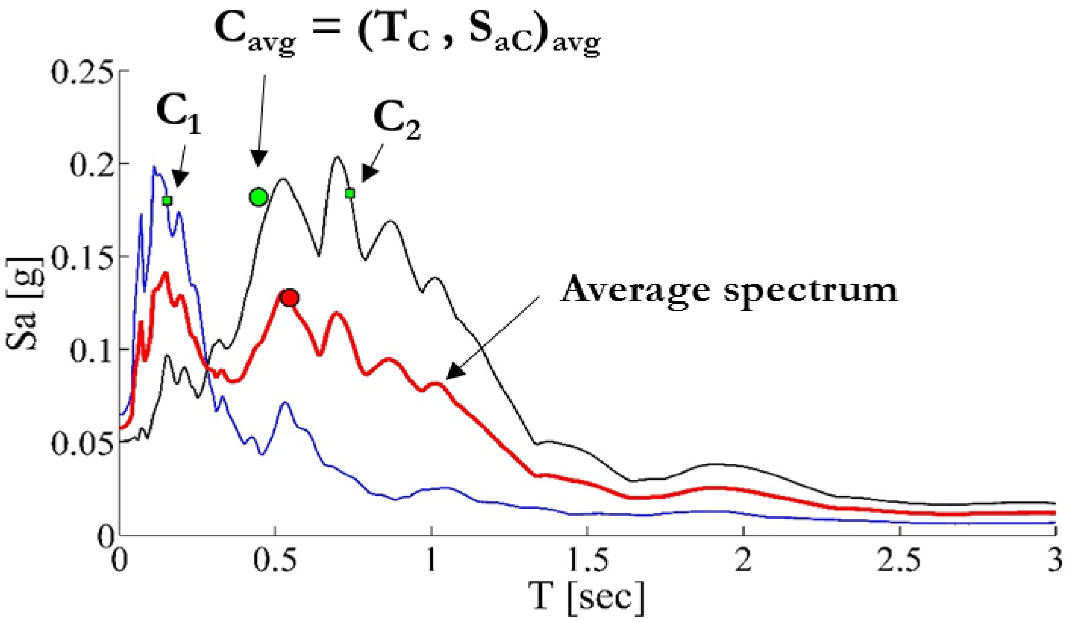
Eurocode 8 (CEN, 2006)
- Soil class B
- Soil class C
- Soil class D

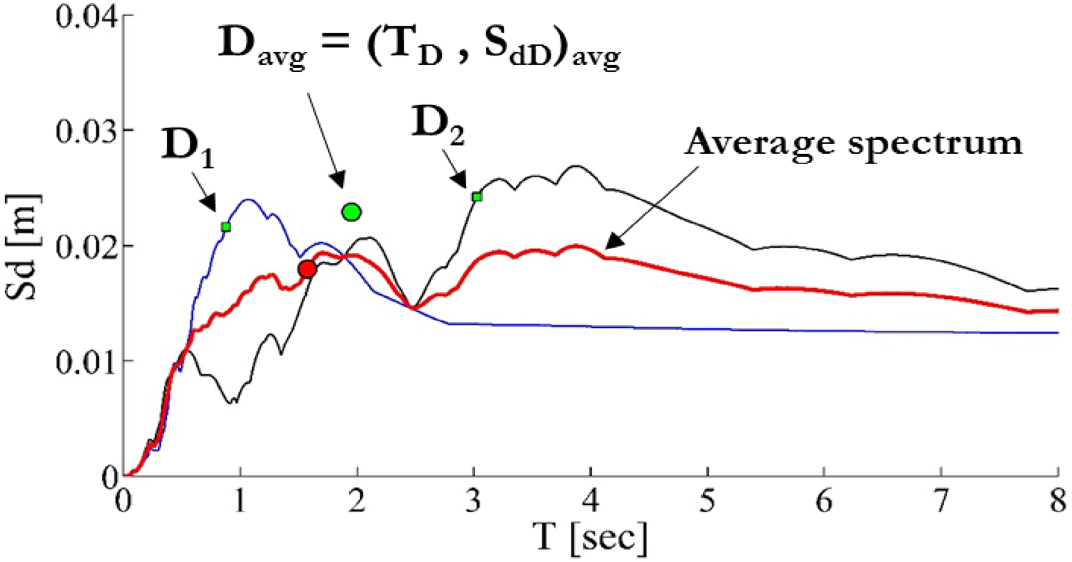
Effect known but not appropriately recognized in codes





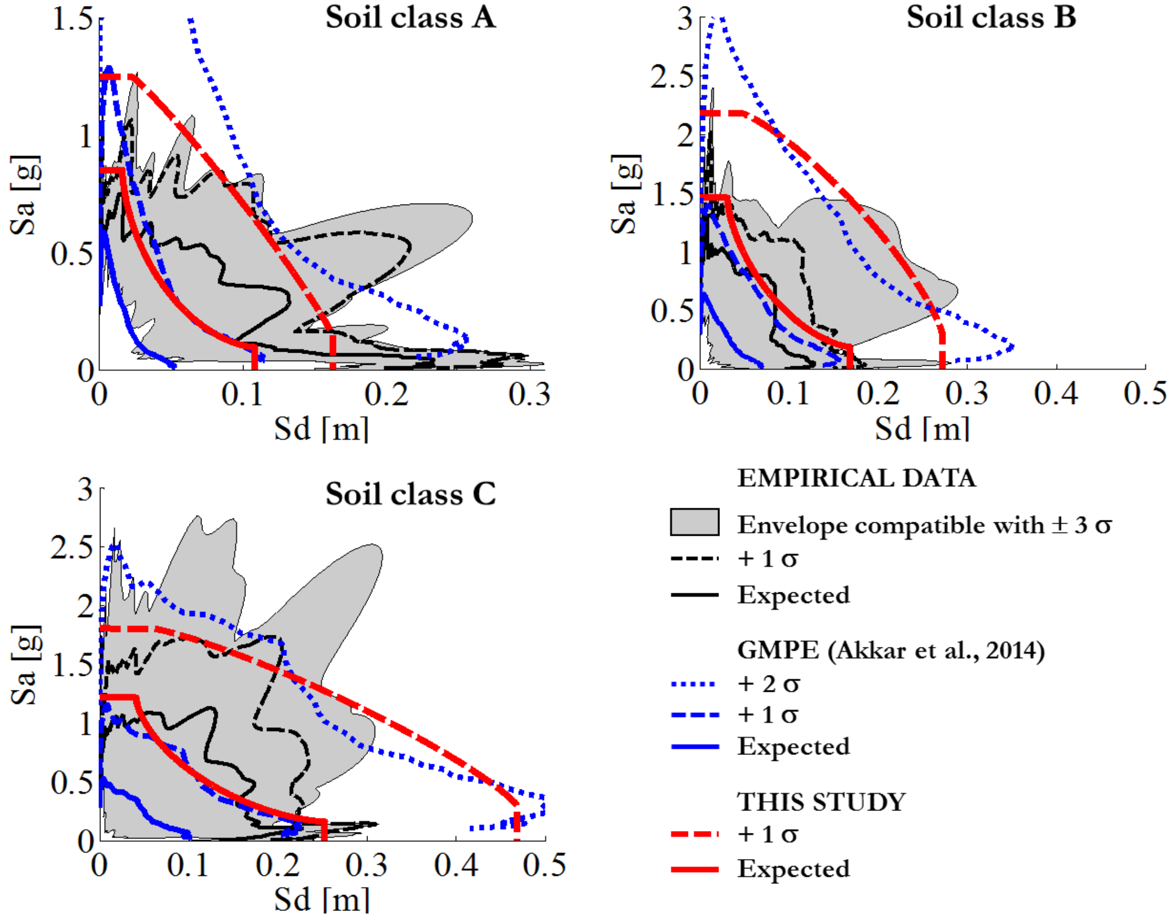
Average of peaks is different from peak of average



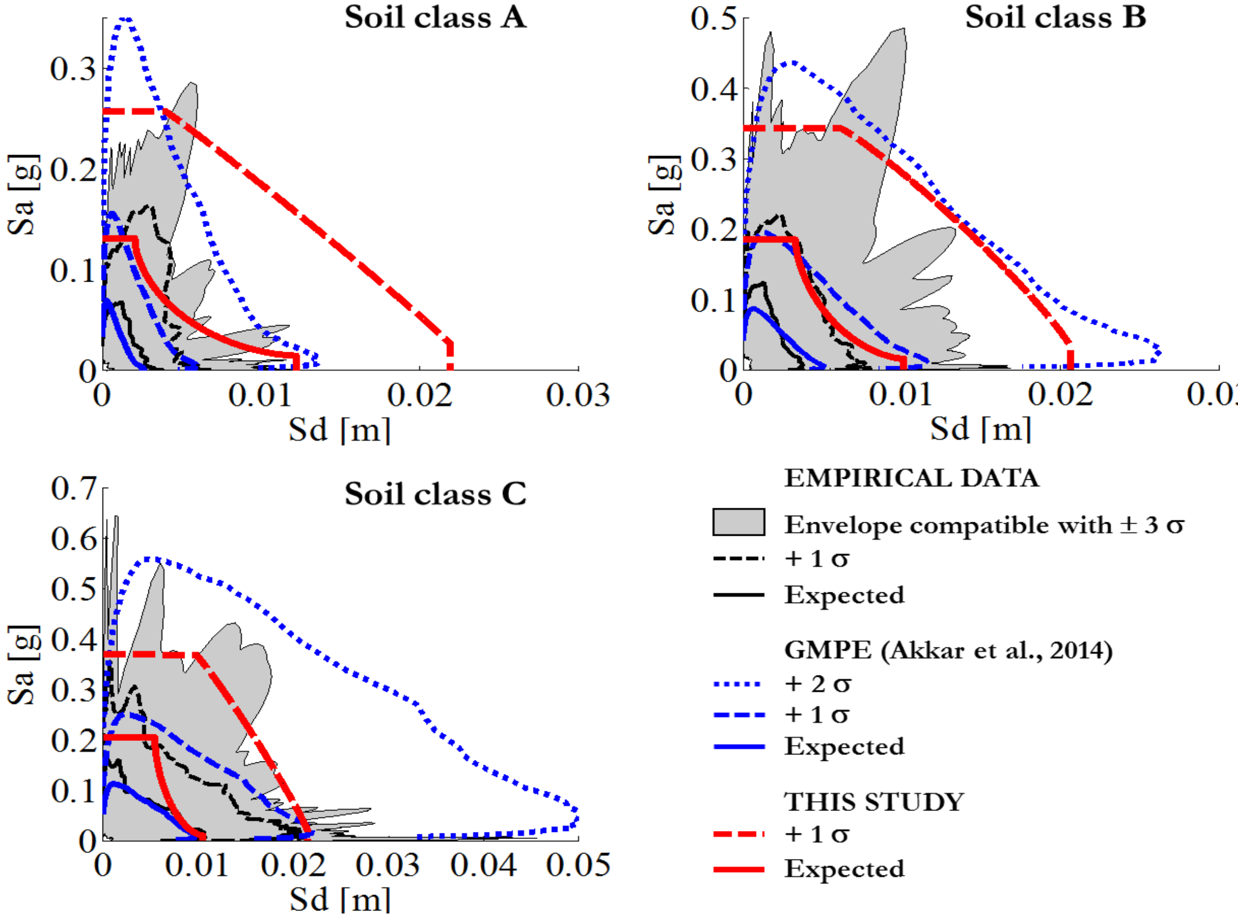


Resulting spectra

Distance: r < 10 km
Magnitude: 6.0 < M < 6.5



Distance: 20 < r < 30 km
Magnitude: 5.0 < M < 5.5

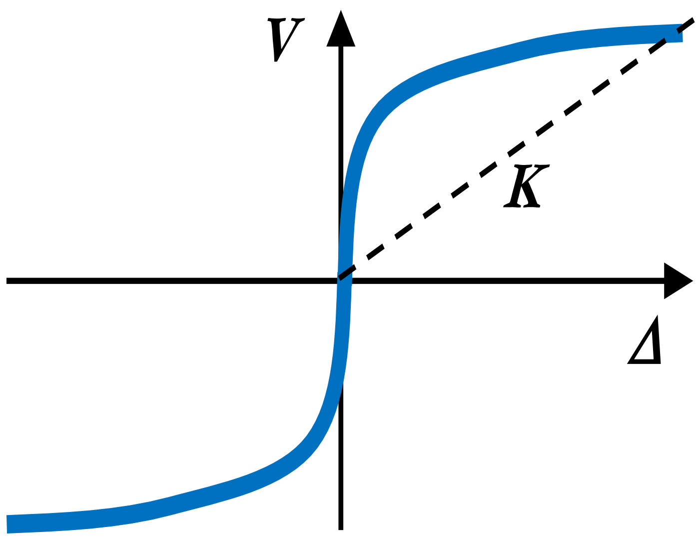


2
Accounting for energy dissipation

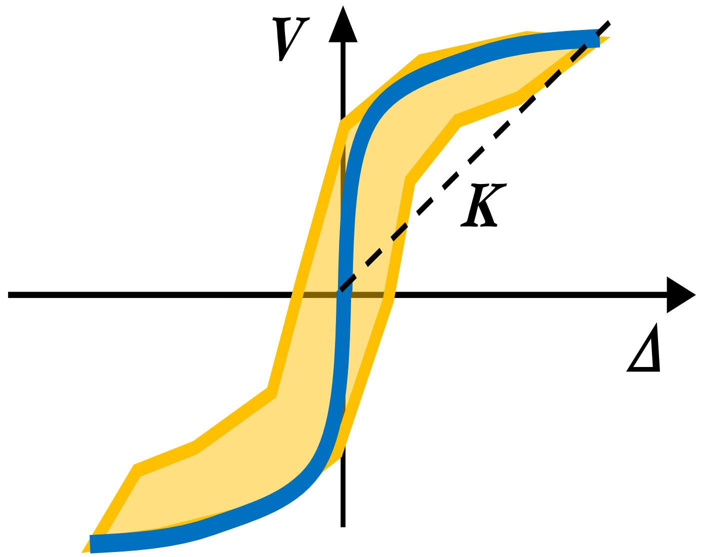
why a structural parameters is accounted for on the demand side?

An increased dissipation capacity reduces the expected displacement demand for the same sets of ground motions

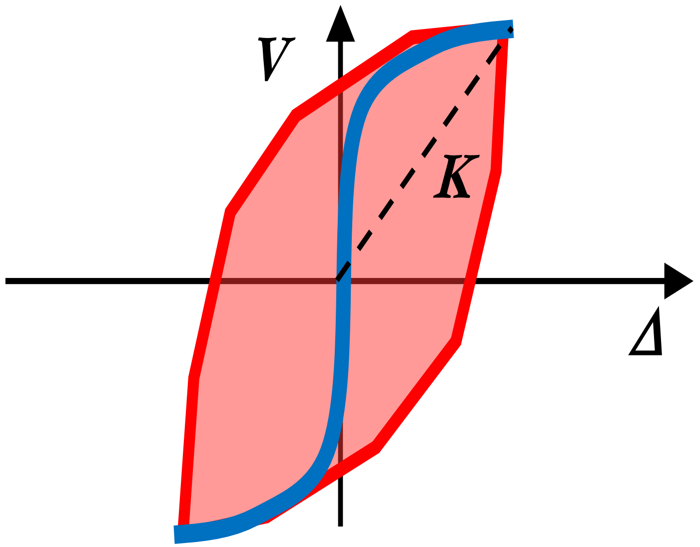
Non-linear elastic response
(ξ_e = 5%, η_x = 1)



Moderately dissipative structure
(ξ_e = 15%, η_x = 0.75)



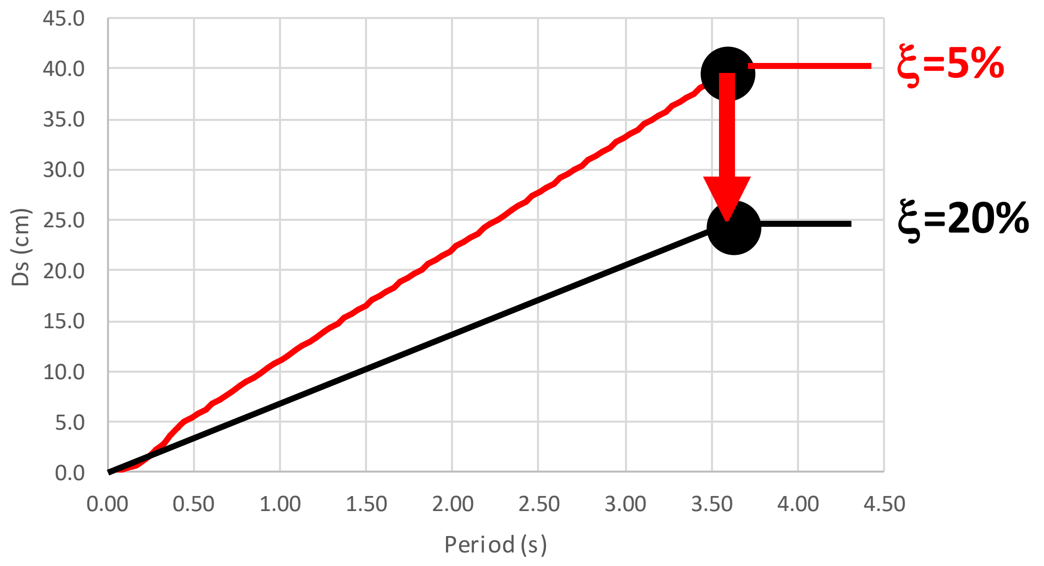
Highly dissipative structure
(ξ_e = 26%, η_x = 0.5)



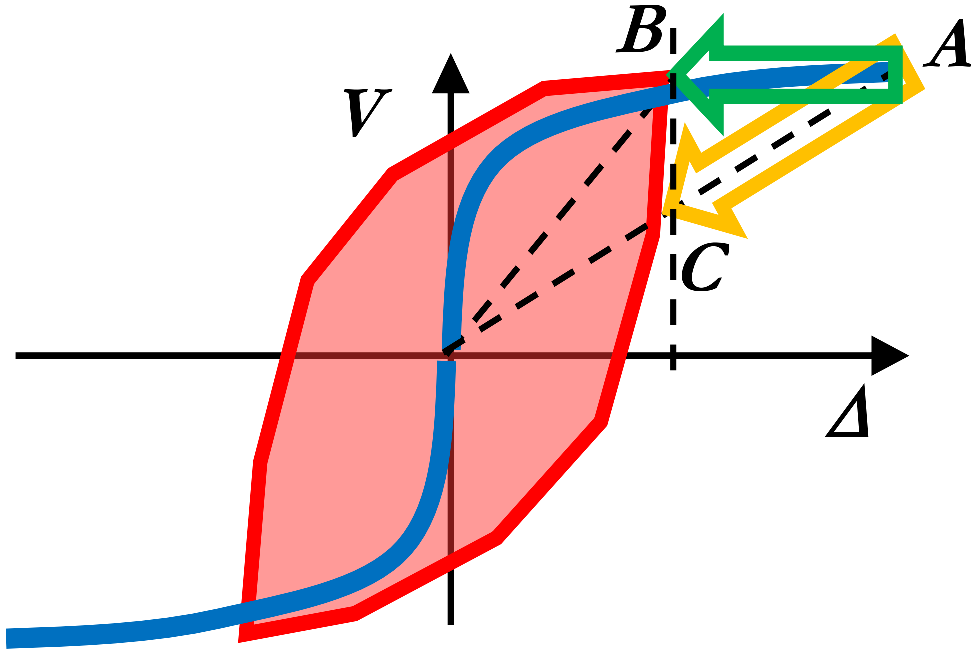
Current practice:

- ❑ Reduce displacement
- ❑ Conserve period
- ❑ Acceleration reduces proportionally to displacement:

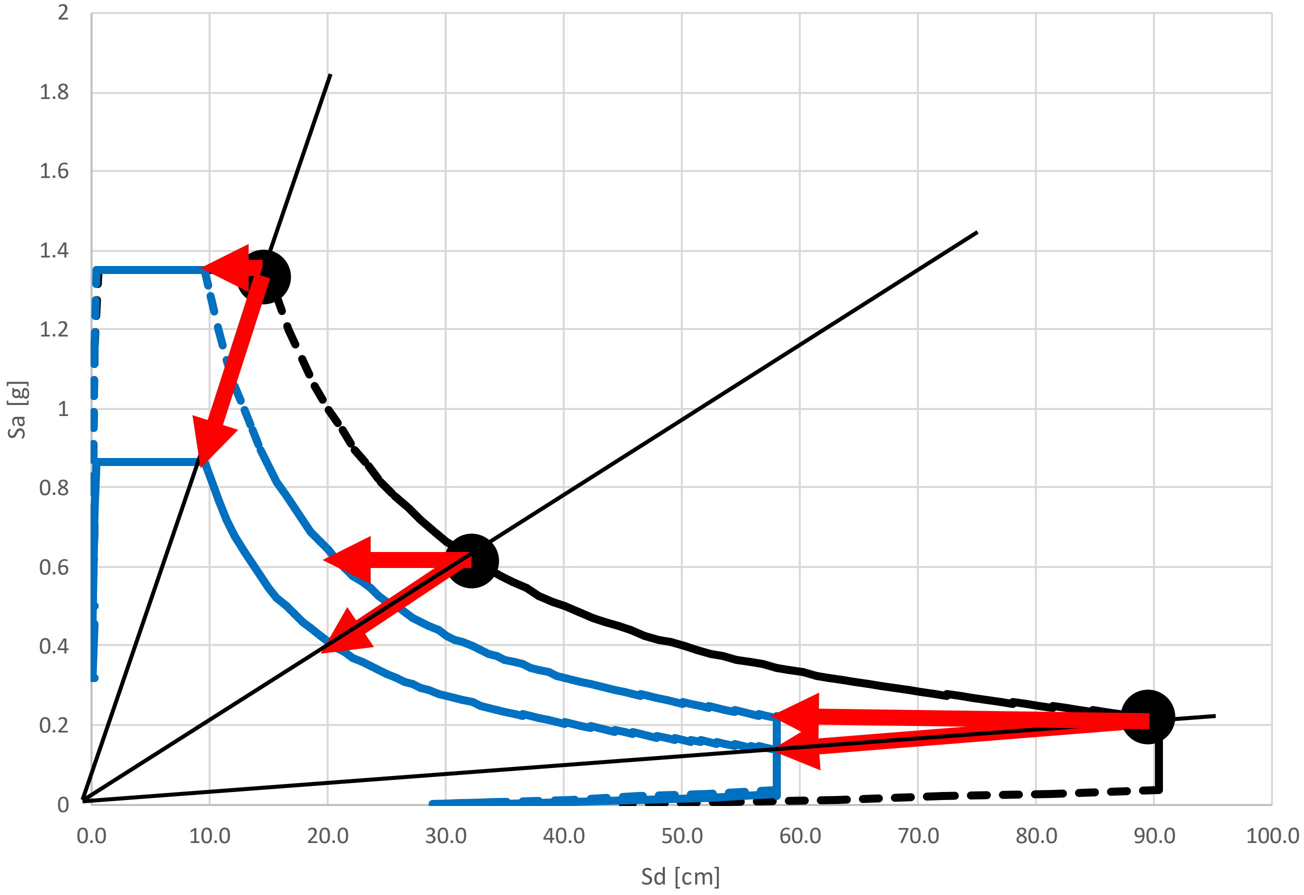
$$S_a = \frac{4\pi^2}{T^2} S_d$$

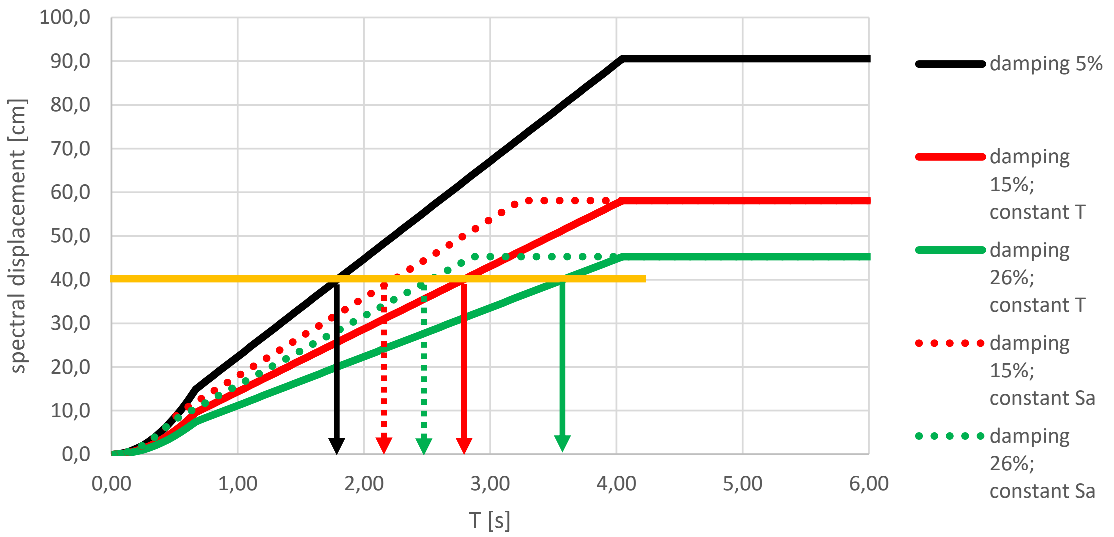


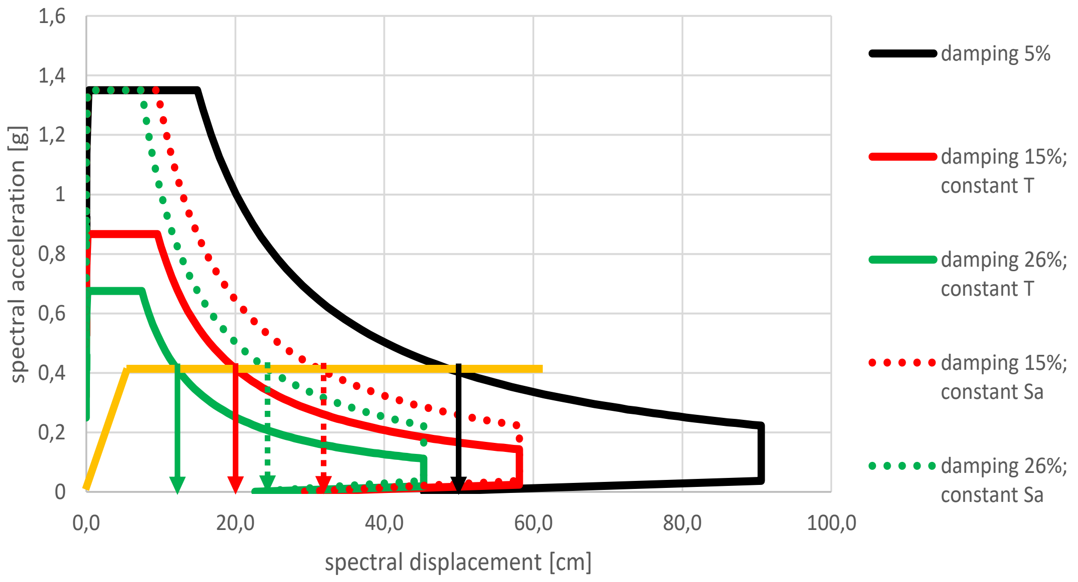
Is it correct to reduce displacement conserving period or acceleration?



Relevant effects on spectrum shape, design period and displacement capacity

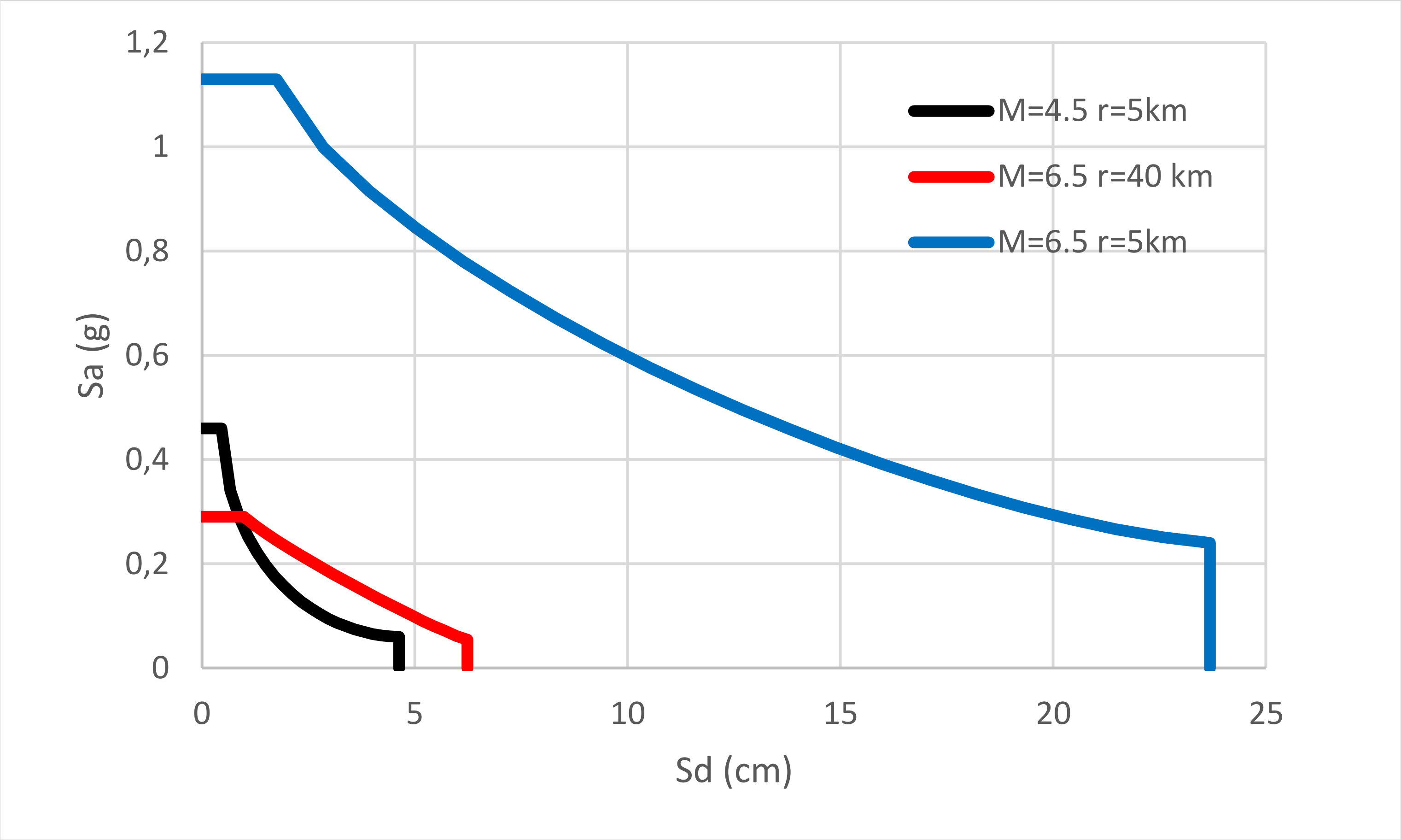






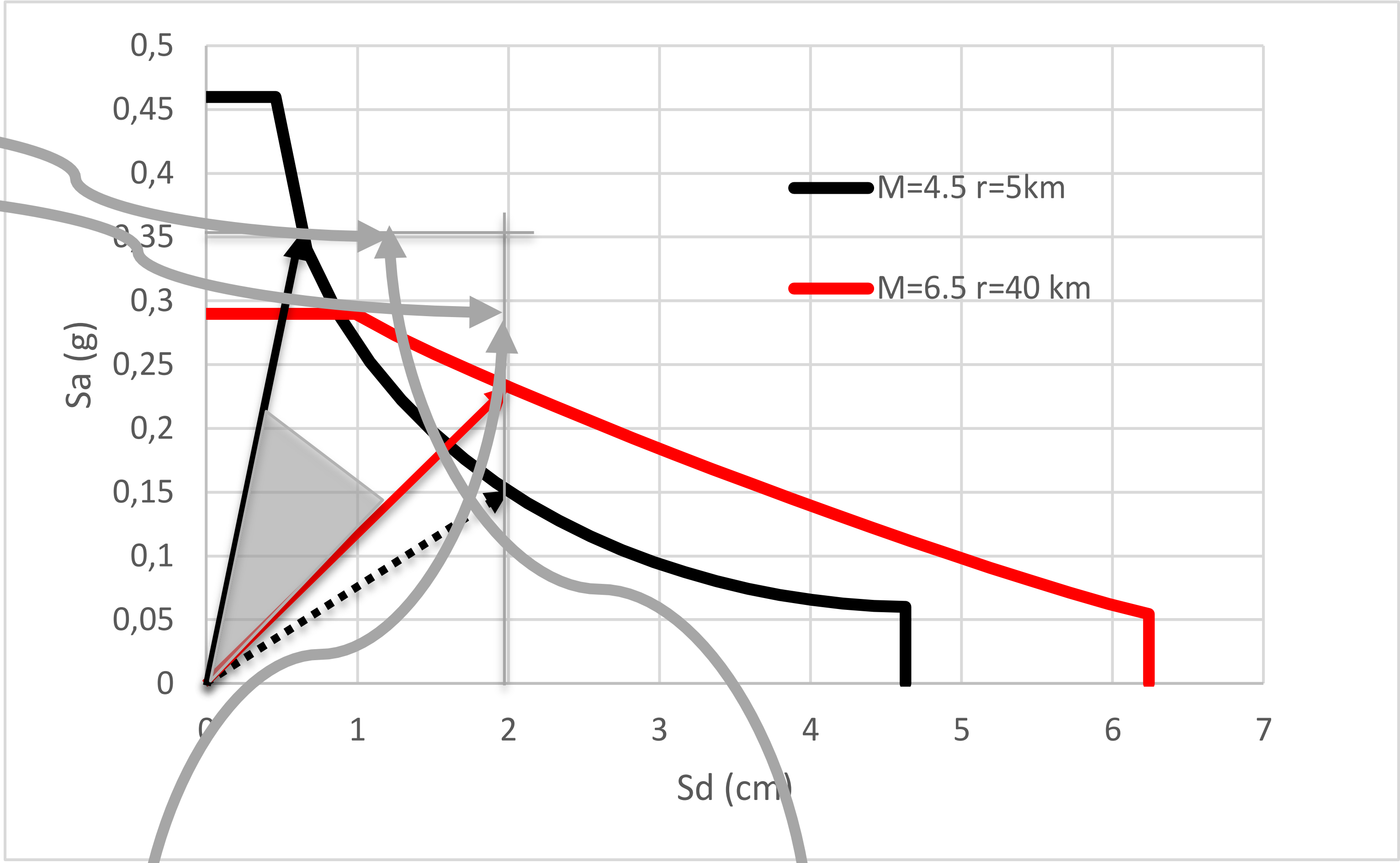
3
Design for loss control

Effects of magnitude and distance
Possible different return period



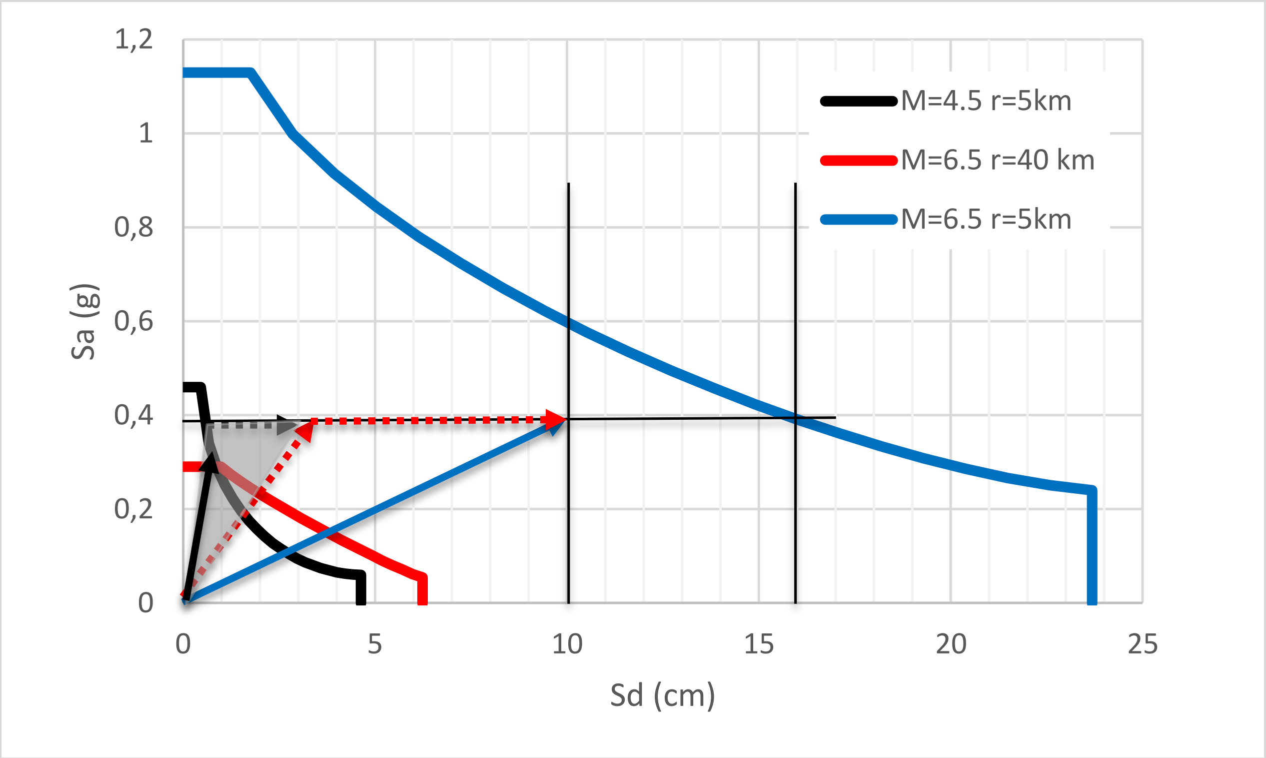
Design for frequent ground motion

Floor acceleration and displacement limits imposed by accepted level of non structural damage



Design for elastic response,
Δ_d < 20 mm; S_{ad} = 0.35 g

Design for rare ground motion



Design for Δ_d =100 mm.
Elastic response impossible and not compatible with design for frequent event.
Consider correction factor η = 0.6.

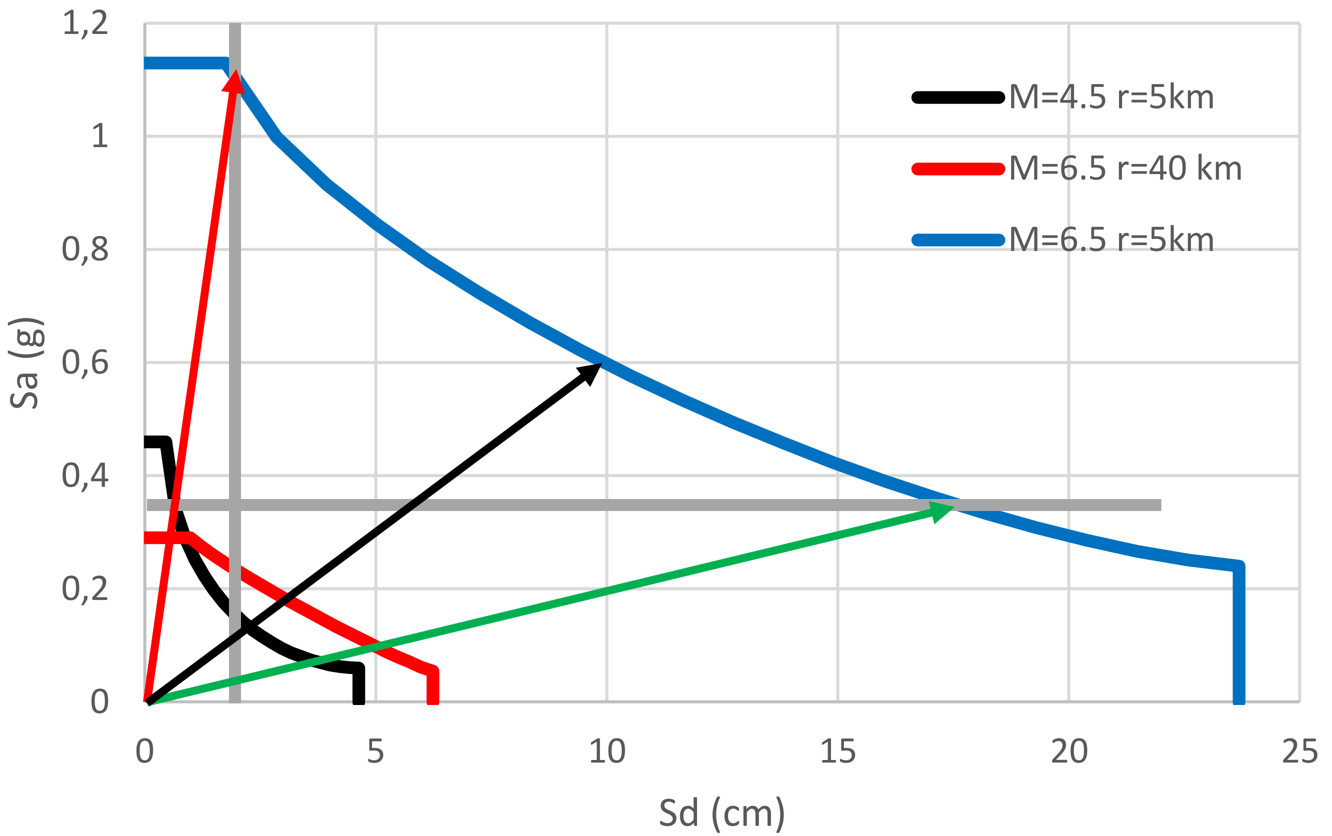
Design for continued use in case of rare ground motion

Strong structure: Limit displacement, accept high floor acceleration

Deformable structure: Limit displacement, accept high floor acceleration

Intermediate solution

Isolation or tuned mass



Displacement-based design can be considered established as today's best tool

Performance-based design can be considered definitely accepted as a rational framework, but is far from being applicable

Simplified loss-based design may be the solution

Design

1. Set conventional damage onset, say for example 2% of the replacement cost (R_c) at the 20-year return period event (T_{R0}).
2. Set collapse T_{RC} or P_{eC}; possibly T_{RC} = 1000 years (P_{eC} = 0.001) for standard constructions.
3. Calculate ratio between maximum possible indirect losses and R_C ($R_{I/D}$, possibly 1 to 5 times).
4. Set the design EAL_{D+I}, which considers both the direct and indirect loss. This could be in the range of 0.1% for essential buildings and in the range of 2% for standard buildings, however any value could be set depending on the anticipated magnitude of $R_{I/D}$, building importance and seismicity of the region.
5. Calculate the α value corresponding to $R_{I/D}$ and $EAL_{D+I,\,design}$.
6. Set the direct damage ratio (or loss, L_{Df} possibly 20 %) to be associated with the damage control return period (T_{Rf}) or probability of exceedance (P_{ef}) and find P_{ef}.
7. Associate a maximum floor acceleration and equivalent displacement to be respected in order to ensure that the direct damage ratio L_{Df} will not be exceeded.
8. For the given seismic intensity to be considered, associate a combined acceleration-displacement spectrum associated to P_{ef}.
9. Identify a structure whose initial secant-to-yield period falls with the feasible range according to the combination of points 7 and 8.
10. Associate a combined acceleration-displacement spectrum corresponding to P_{eC} and design for collapse.

Assessment

1. As in the case of design, set conventional damage onset, say for example 2% of the replacement cost (R_c) at the 20-year return period event (T_{R0}).
2. Calculate structure strength and dissipation and displacement capacity of the structural system.
3. Associate a combined acceleration-displacement spectrum passing through the collapse point and calculate the associated P_{eC}.
4. Define a damage control point. This could be based on floor acceleration or drift limits or both. The issue is to correlate it to a potential loss level, say L_{Df} = 20%.
5. Associate a combined acceleration-displacement spectrum passing through the damage control (f) point and calculate the associated P_{ef}.
6. From P_{ef} and L_{Df} obtain α.
7. From α calculate EAL_D.
8. Estimate the ratio between maximum indirect and direct loss $R_{I/D}$, based on the construction use.
9. From $R_{I/D}$ calculate EAL_{I+D}.
10. Design possible strengthening measure to decrease P_{eC} and recalculate both EALs, repeating steps 6-9.
11. Design possible measures to decrease P_{ef} and recalculate both EALs, repeating steps 6-9.
12. While P_{eC} will have to be taken below code values, to protect human life, the value of P_{ef} depends on economic considerations, therefore it will be appropriate to calculate the breakeven time, considering the cost of intervention and the EAL reduction.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