Revisiting seismic demand and structure capacity

G. Michele Calvi

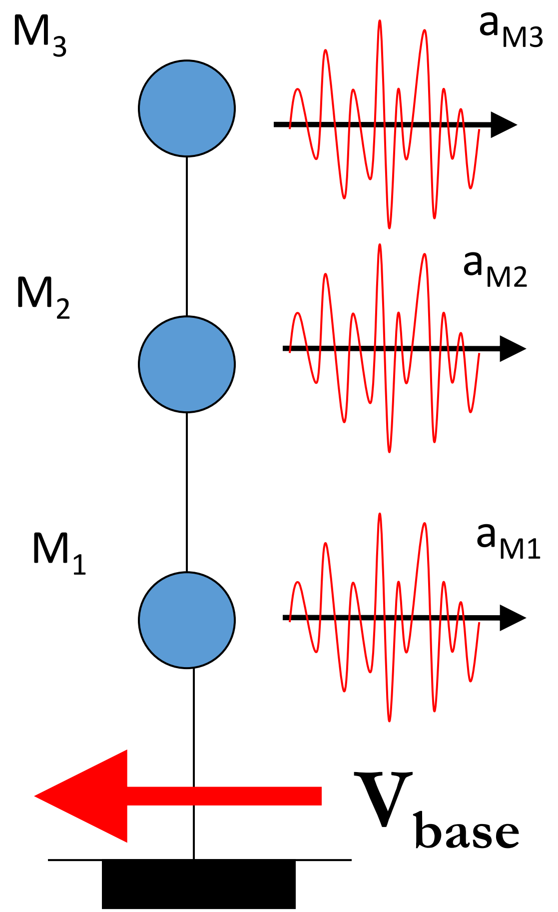
Eucentre Foundation and IUSS
Pavia, Italy

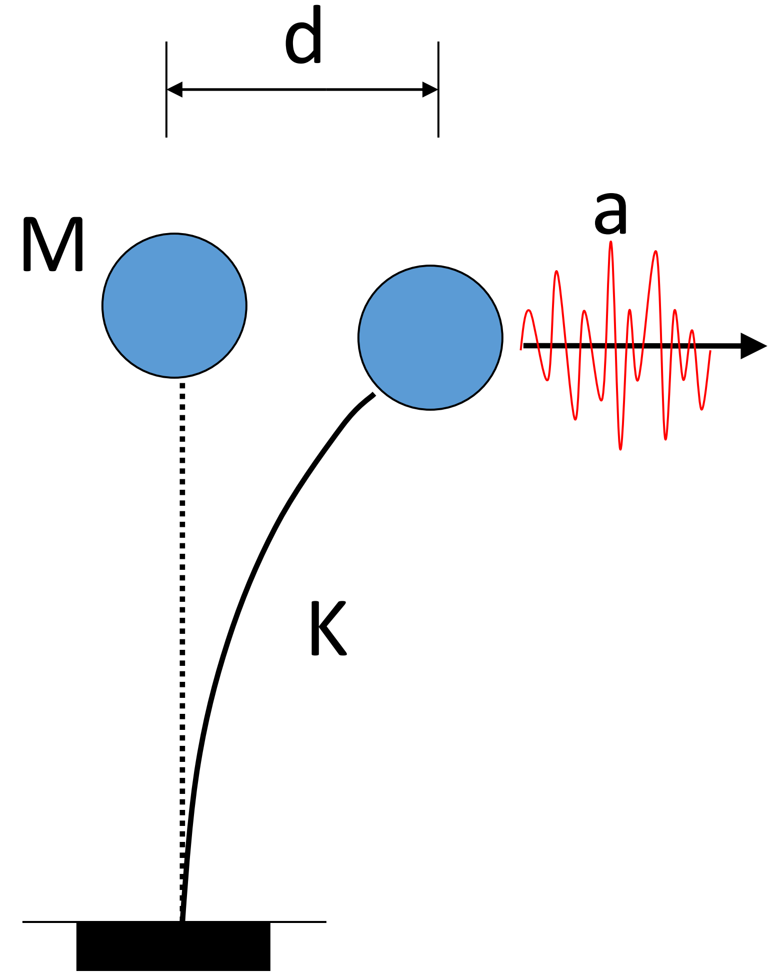
With Vitor Silva (GEM Foundation) and Daniela Rodrigues (Eucentre)

concept of elastic response spectrum

peak value
of a response parameter
of all possible linear single-degree-of-freedom systems
to a particular component of ground motion

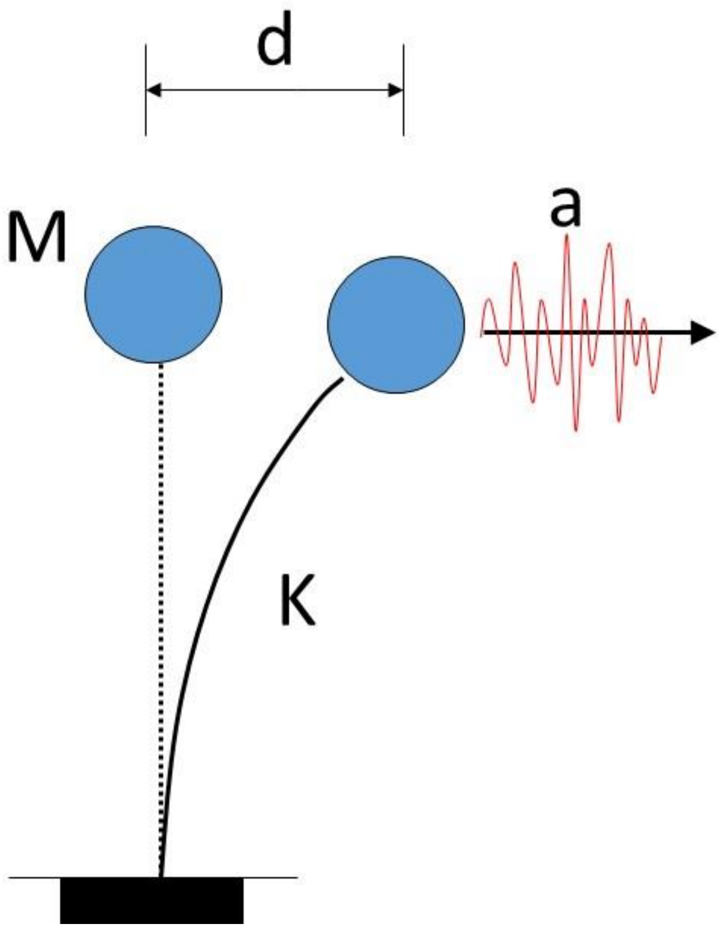
- K. Suyehiro, Japan, 1926
  a "*Vibration Analyzer*" to record the maximum amplitudes of deflection of a set of rods with periods between 0.22 and 1.81 seconds
- Von Karman, Biot, Hudson, Fung, Popov, …
- Veletsos, Newmark, Hall, …





$$V_{base} = \Sigma M_i a_{Mi}$$

$$M \times a = K \times d$$



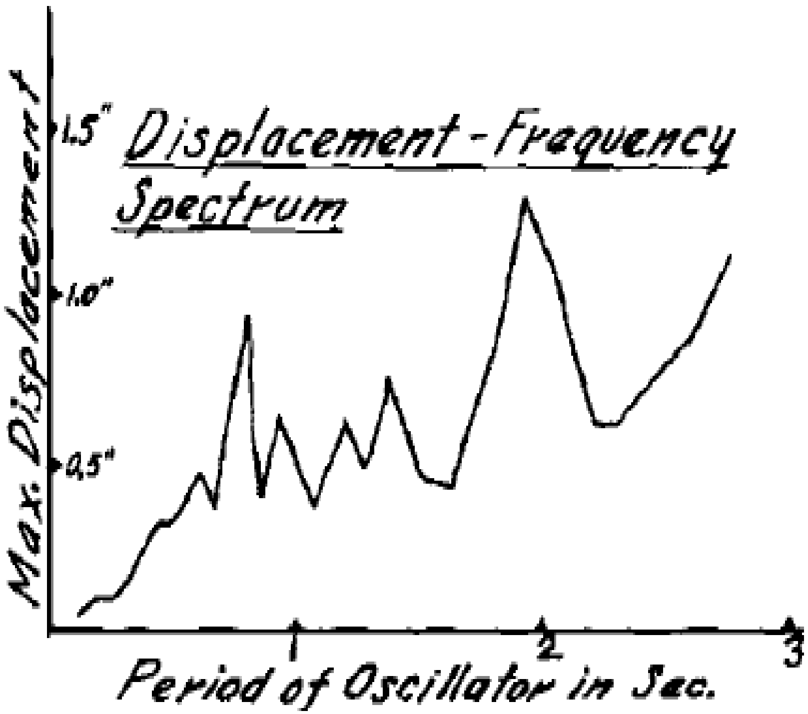
$$M \times a = K \times d$$

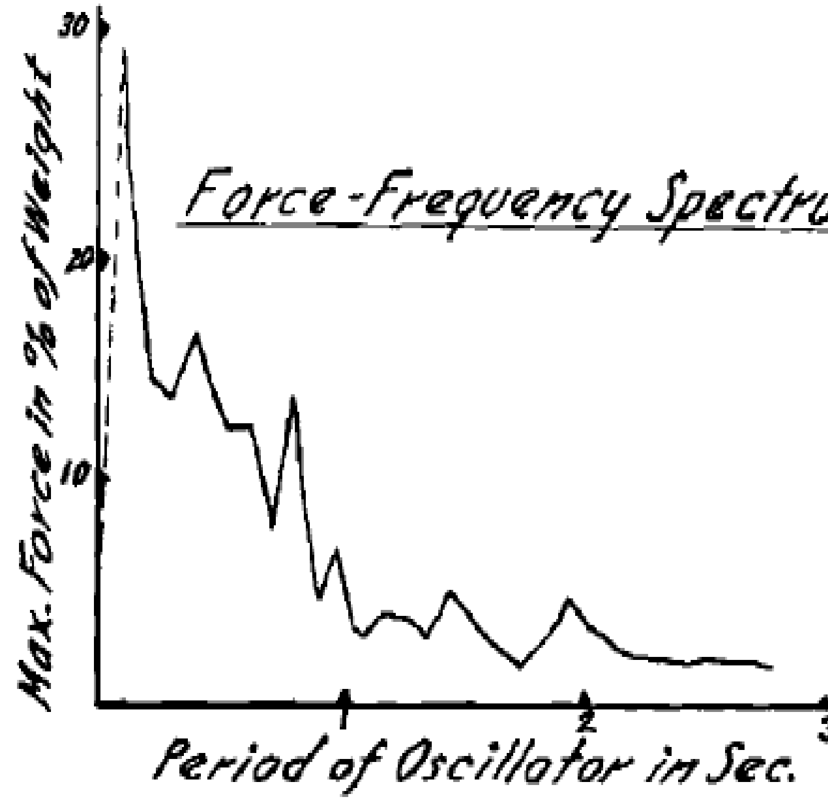
$$a / d = K / M$$

$$K / M = 4\pi^2 / \mathrm{T}^2$$

$$a / d = 4\pi^2 / \mathrm{T}^2$$

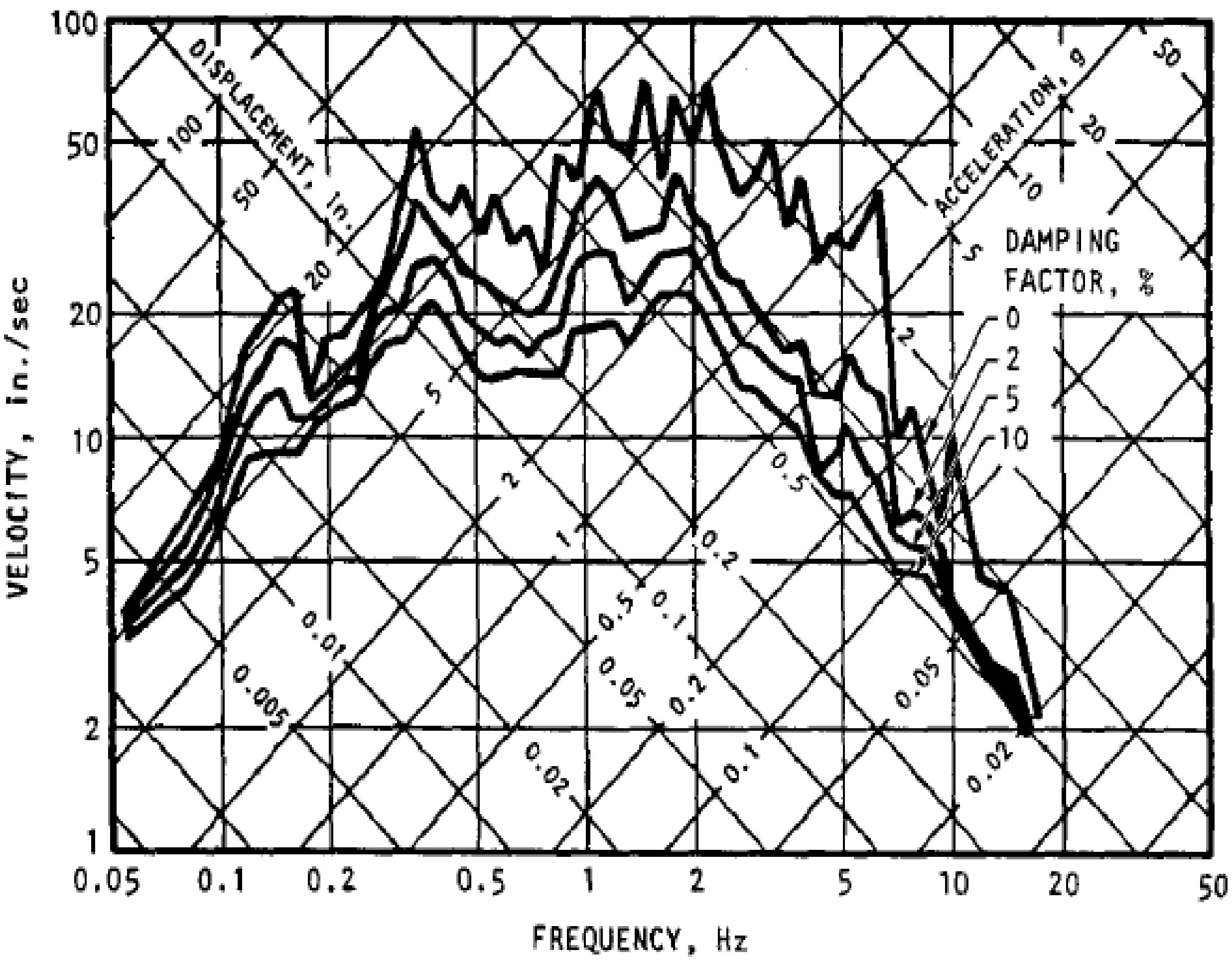
The damping term in the equilibrium equation enters as a correction factor





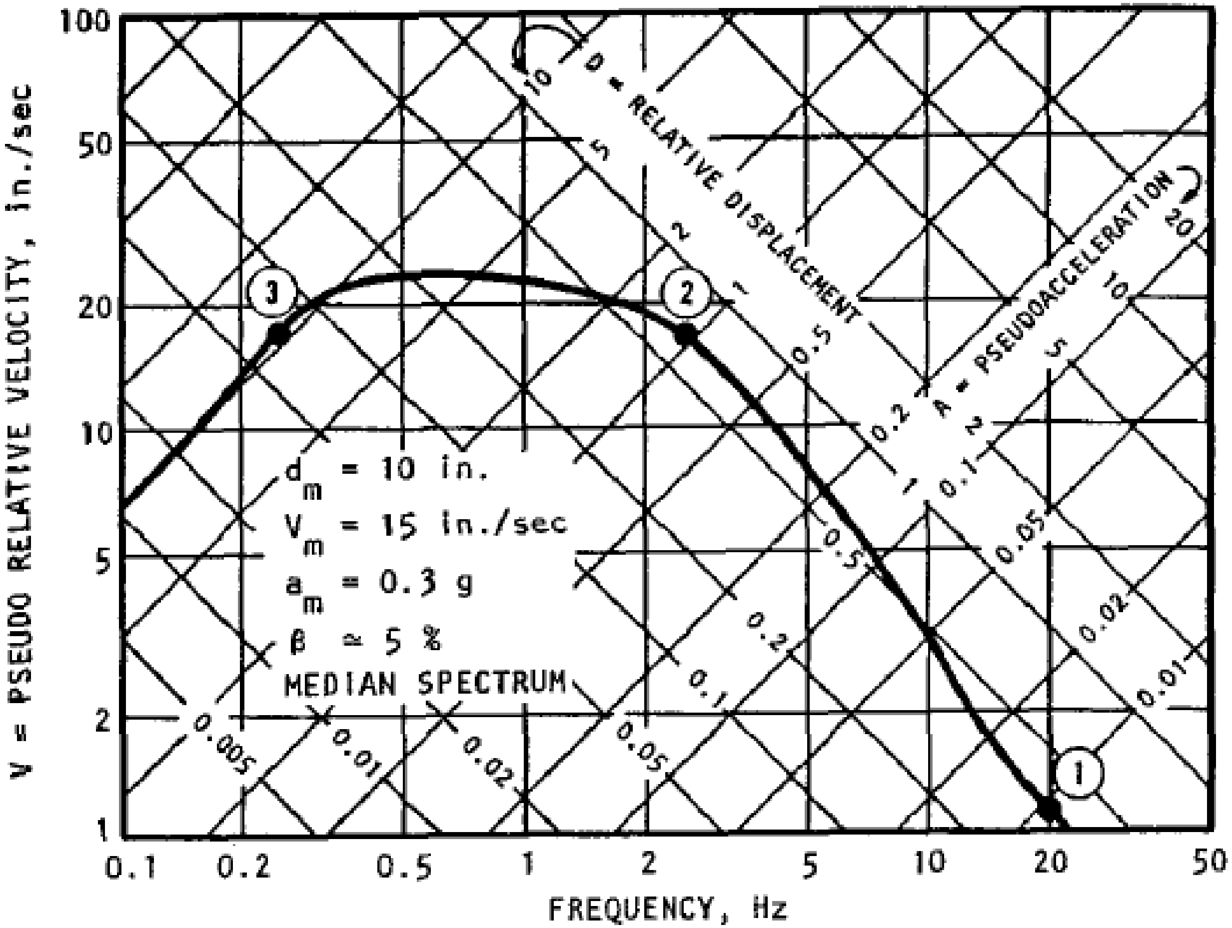
Displacement and acceleration response spectra for a component of the Los Angeles earthquake of 2 October 1933

Housner (1941)



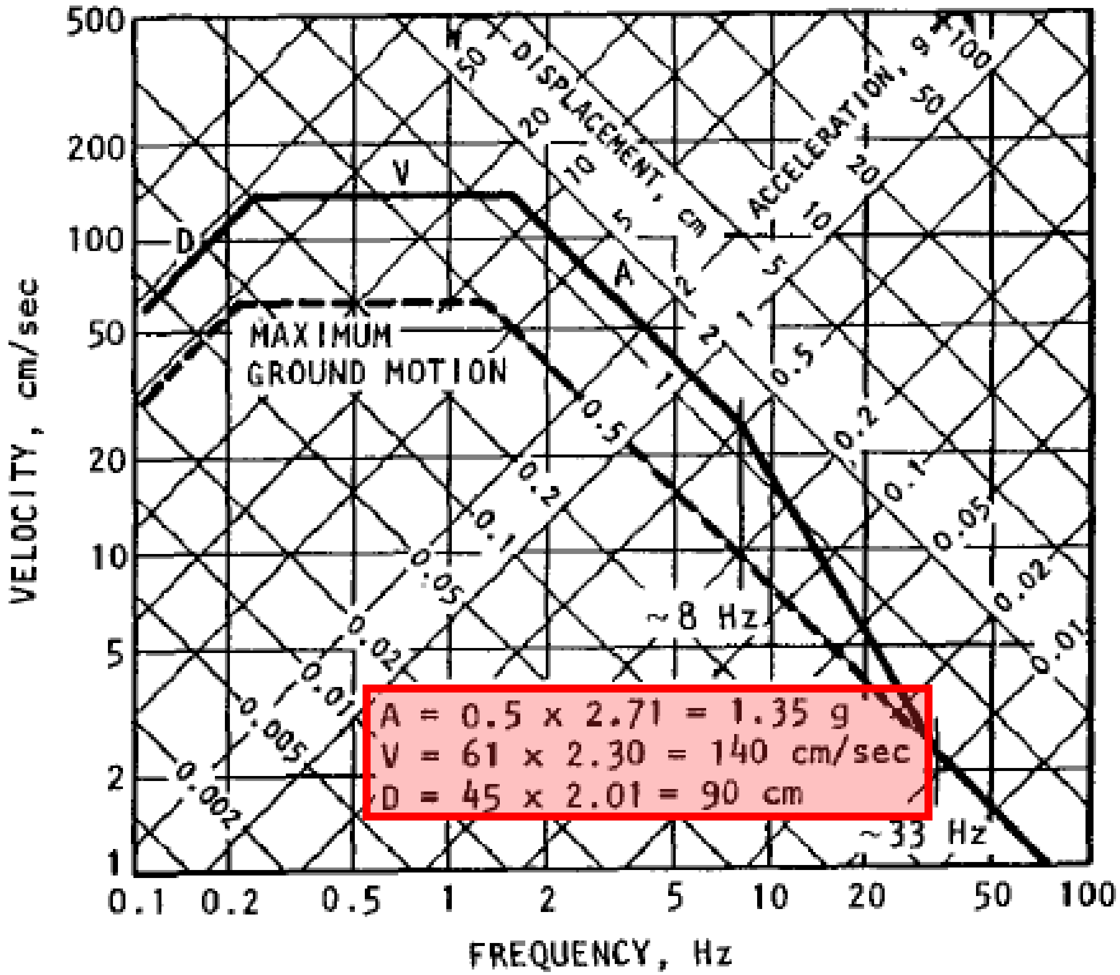
Response spectra from the NS El Centro record

Newmark and Hall, 1982



"Typical response spectrum"

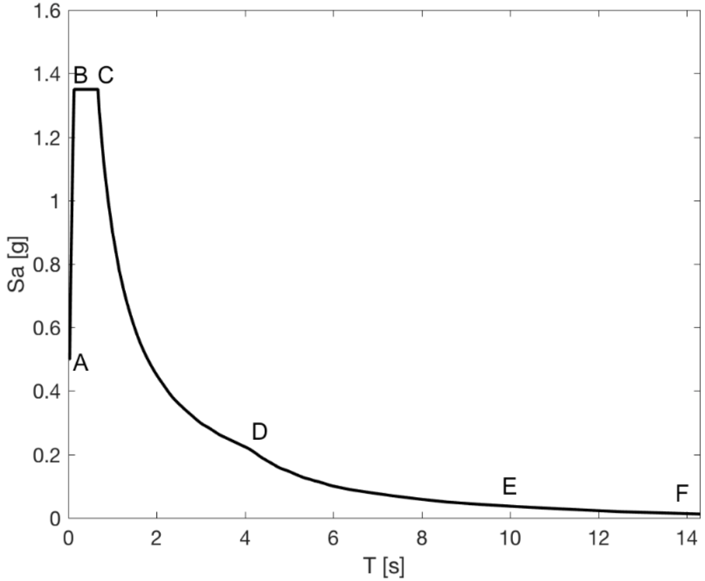
Newmark and Hall, 1982



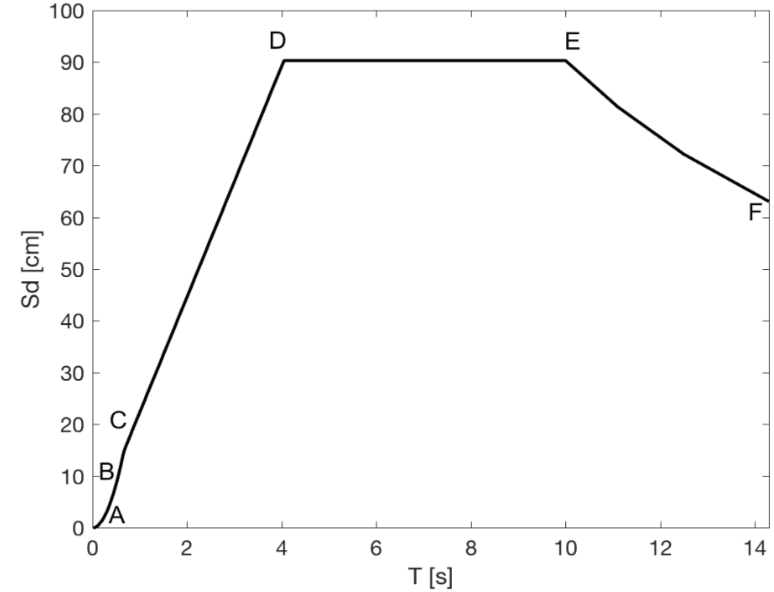
Elastic design spectrum for 0.5 g PGA, 5% damping and one sigma cumulative probability

Newmark and Hall (1982)

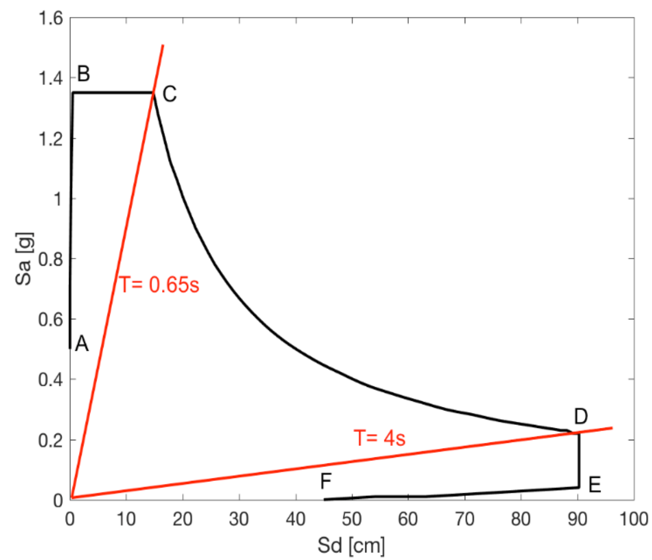
Newmark's design spectrum shown as:



acceleration spectrum



displacement spectrum



combined acceleration – displacement spectrum

Ratio between maximum spectral acceleration and PGA

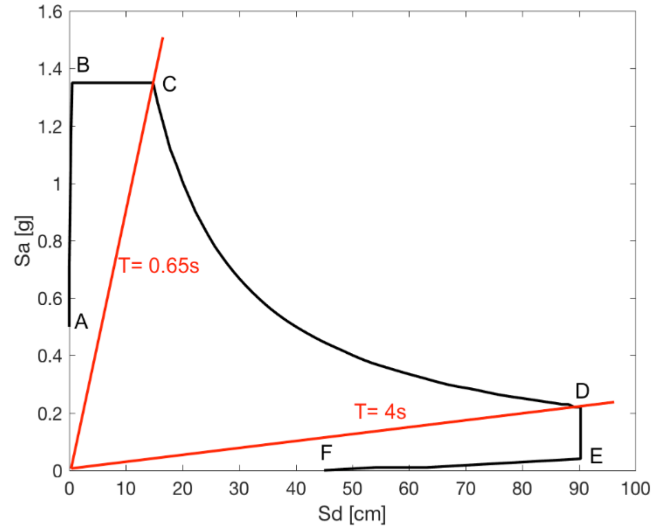
2.71?
2.5?
3.0?

Is it relevant?

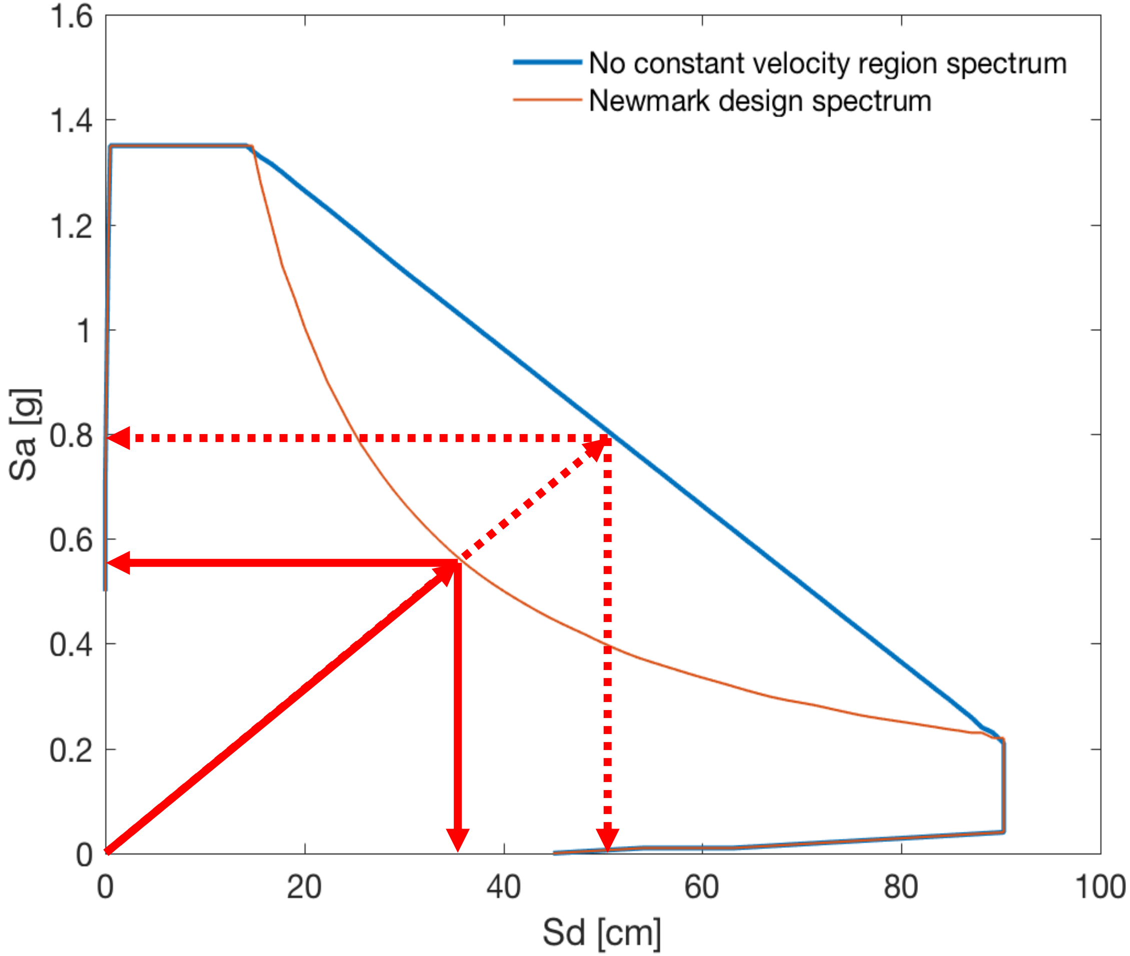
Maximum spectral displacement and corner period

$$T_D = 1.0 + 2.5\left(M_w - 5.7\right)$$

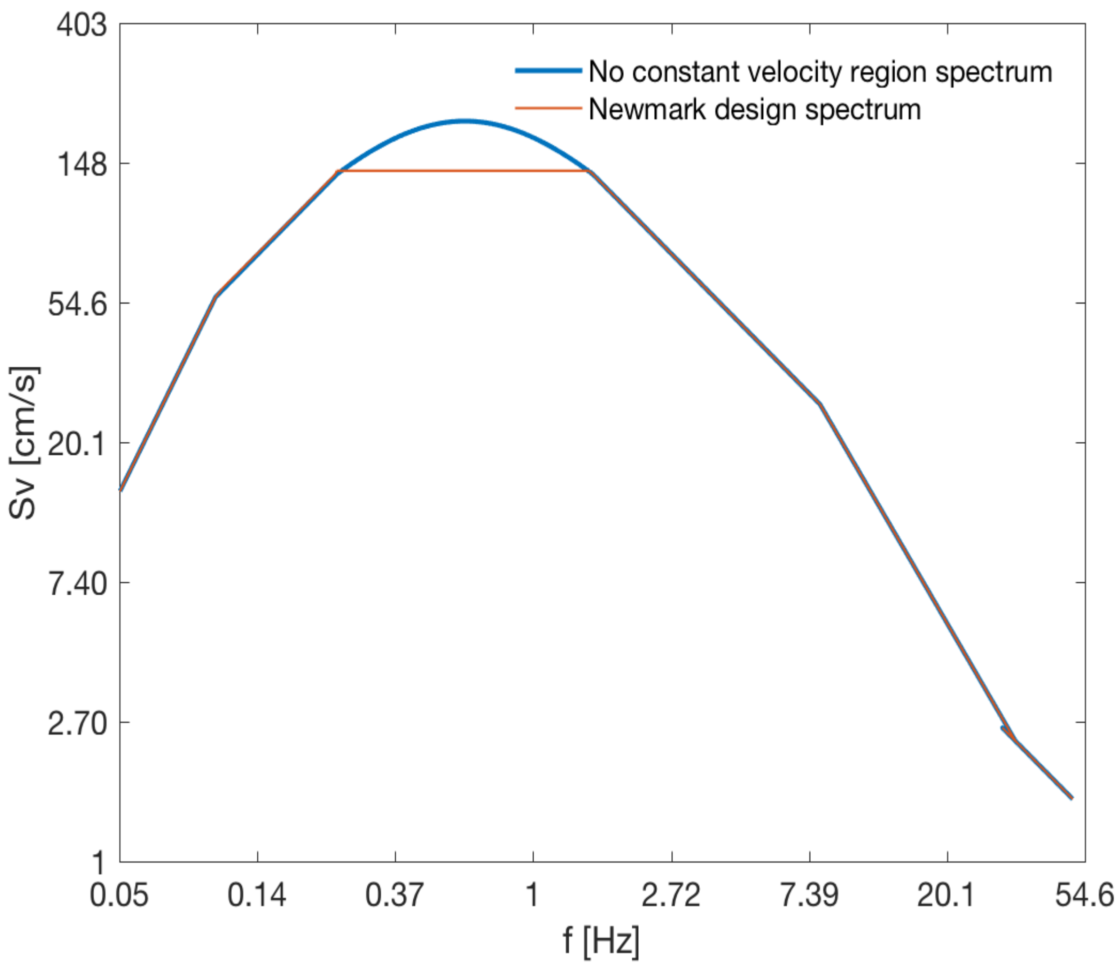
$$\Delta_D = C_S \cdot \frac{10^{\left(M_W - 3.2\right)}}{r}$$

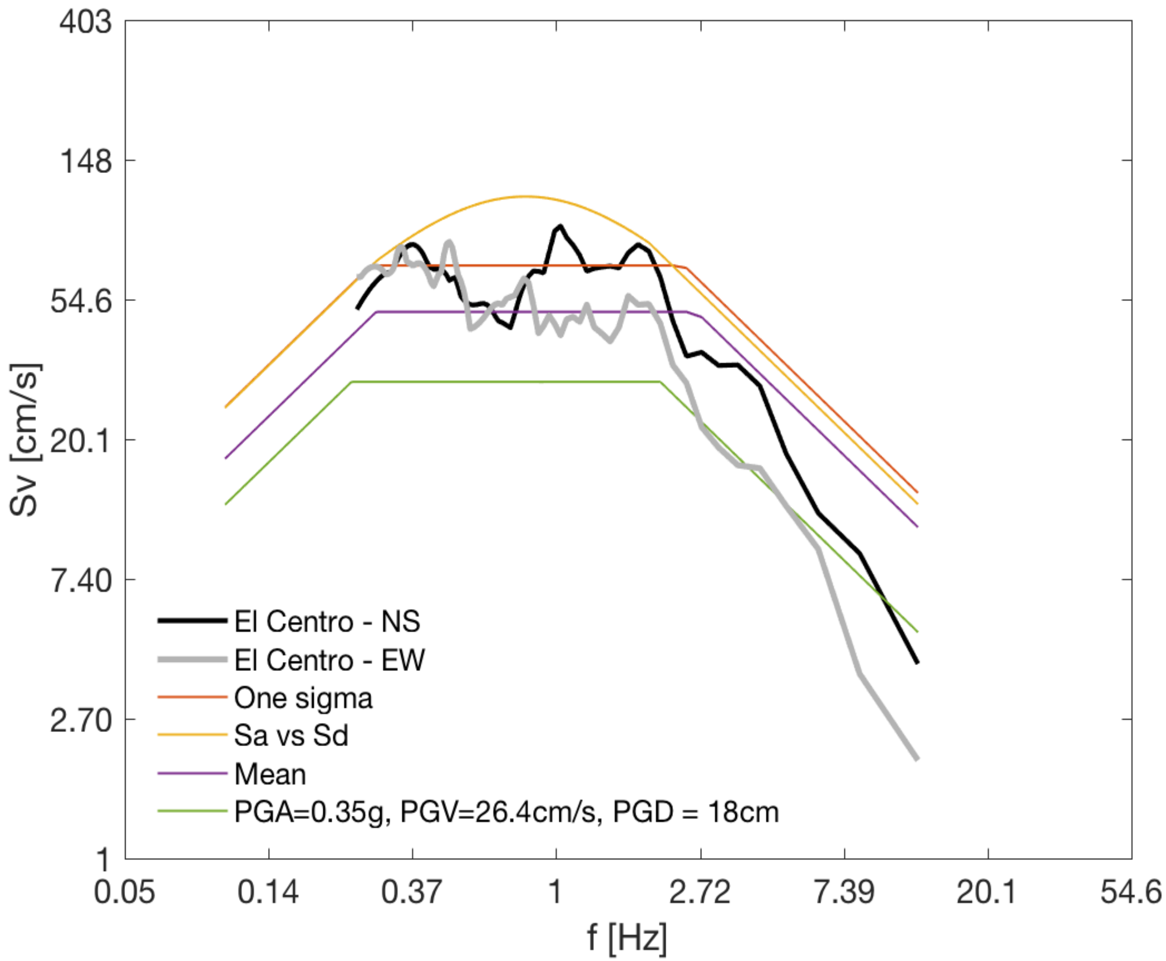


Why constant velocity?

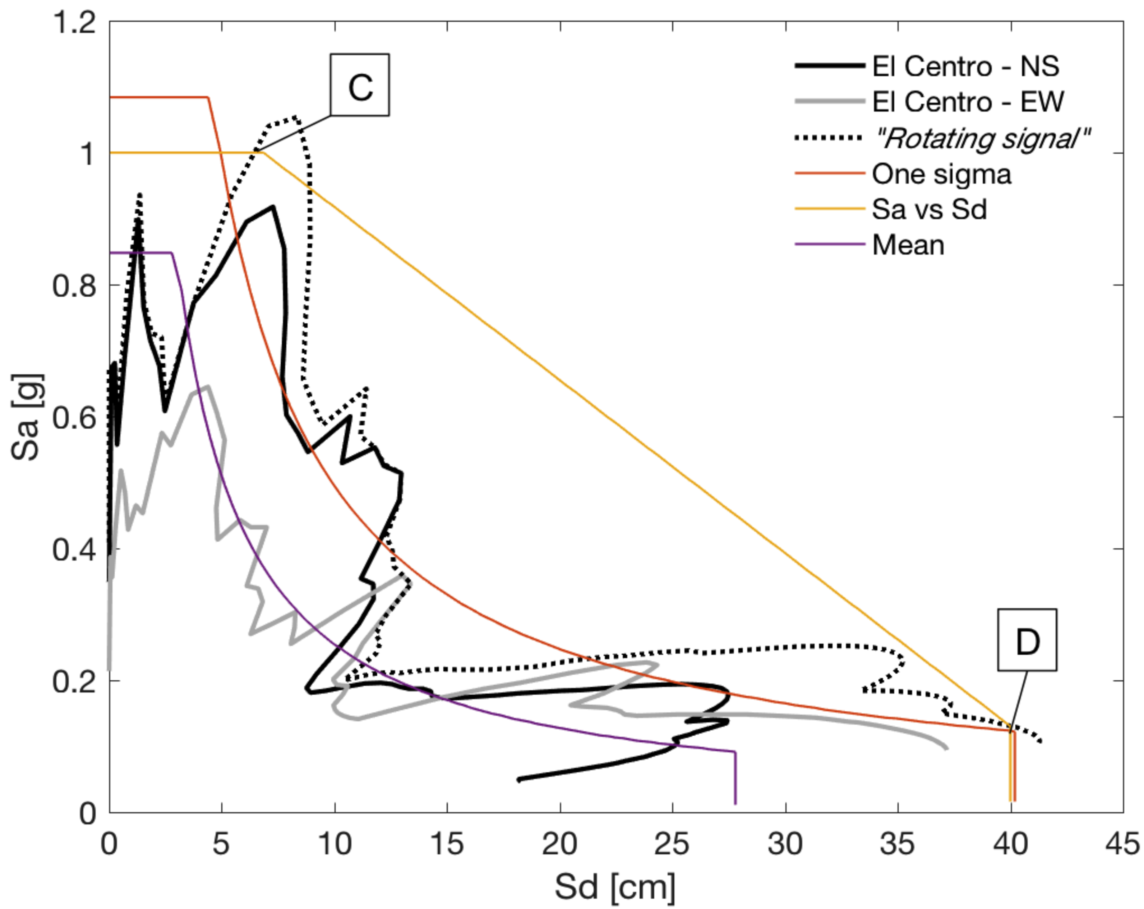


Why constant velocity?

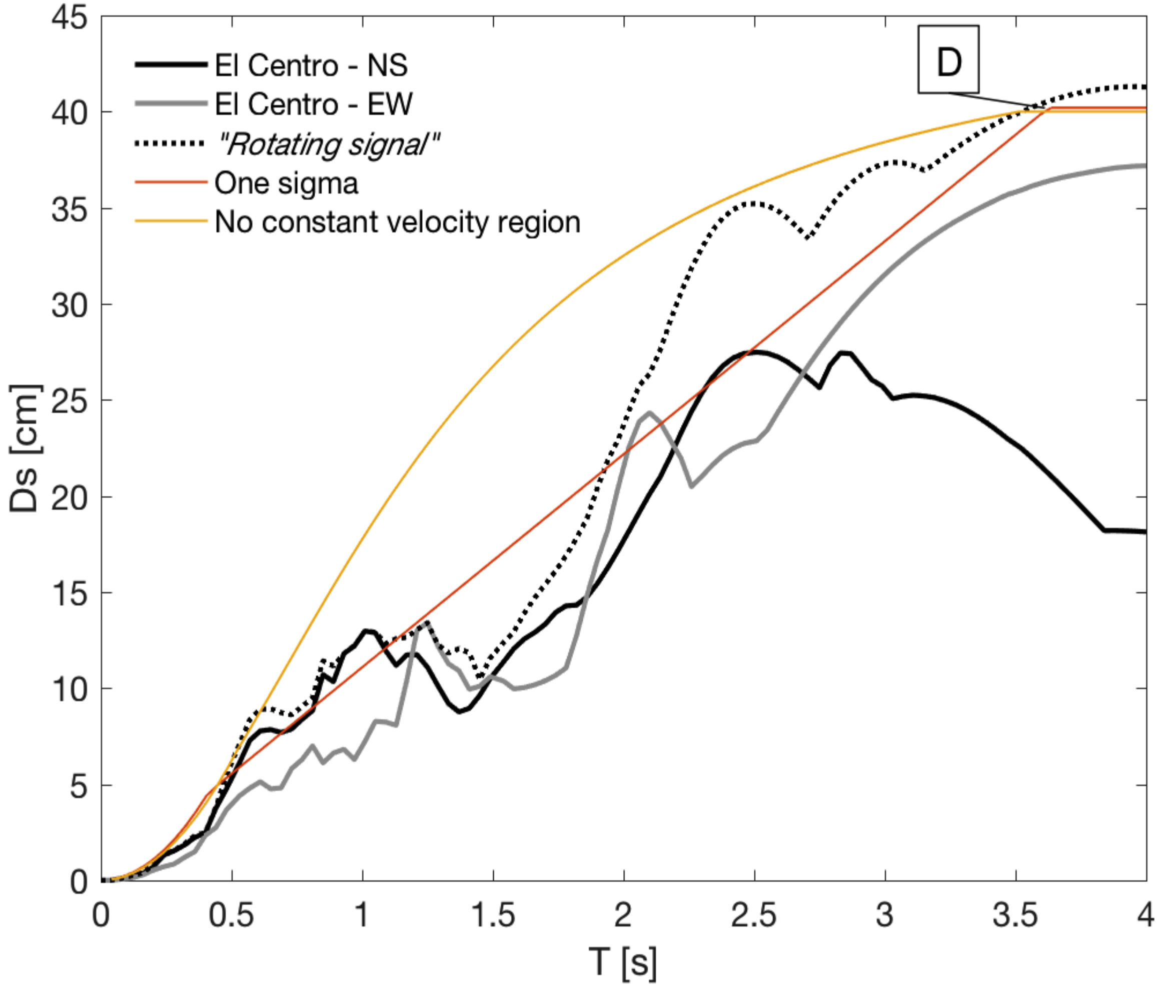




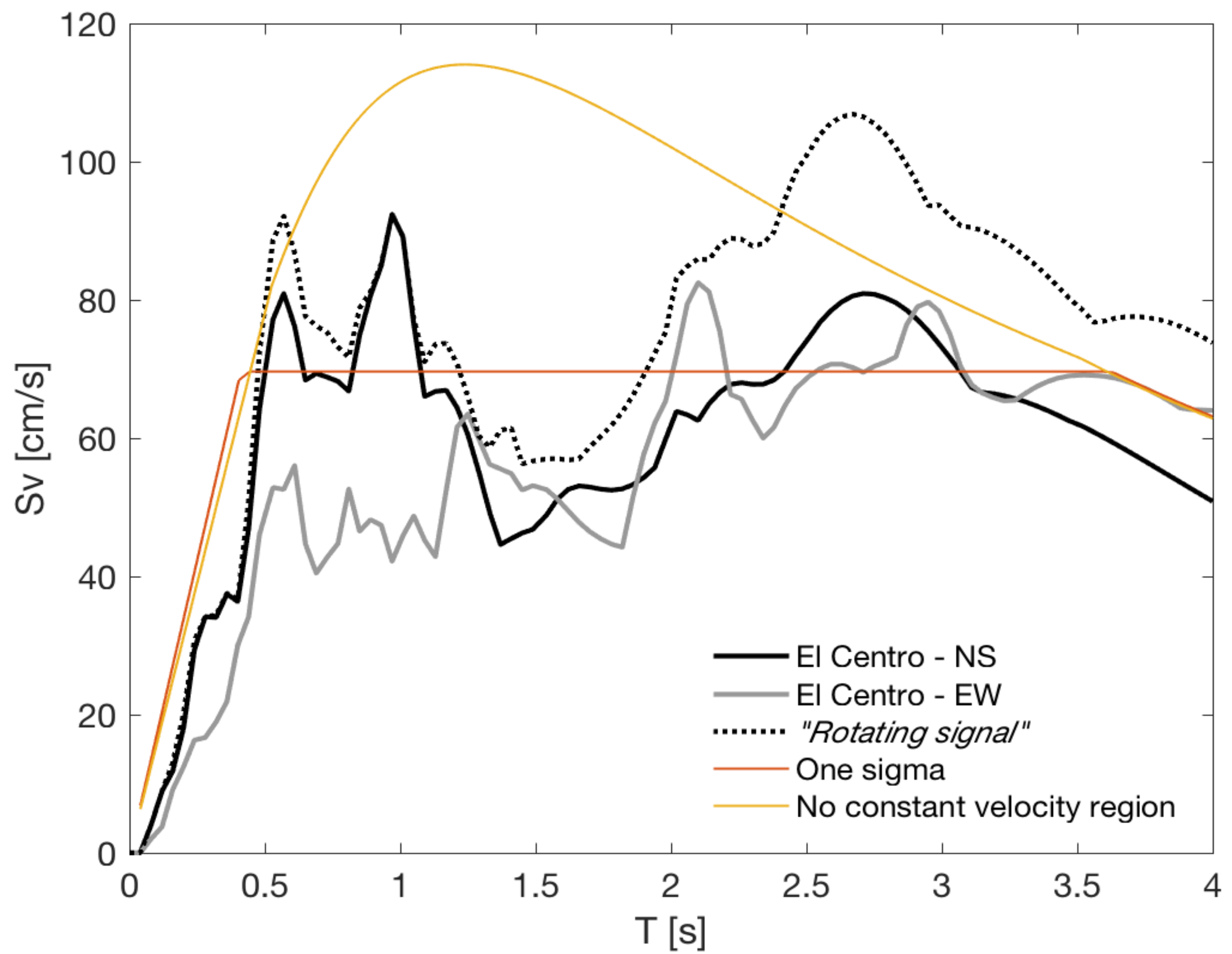
Spectra from El Centro records and Newmark design spectra



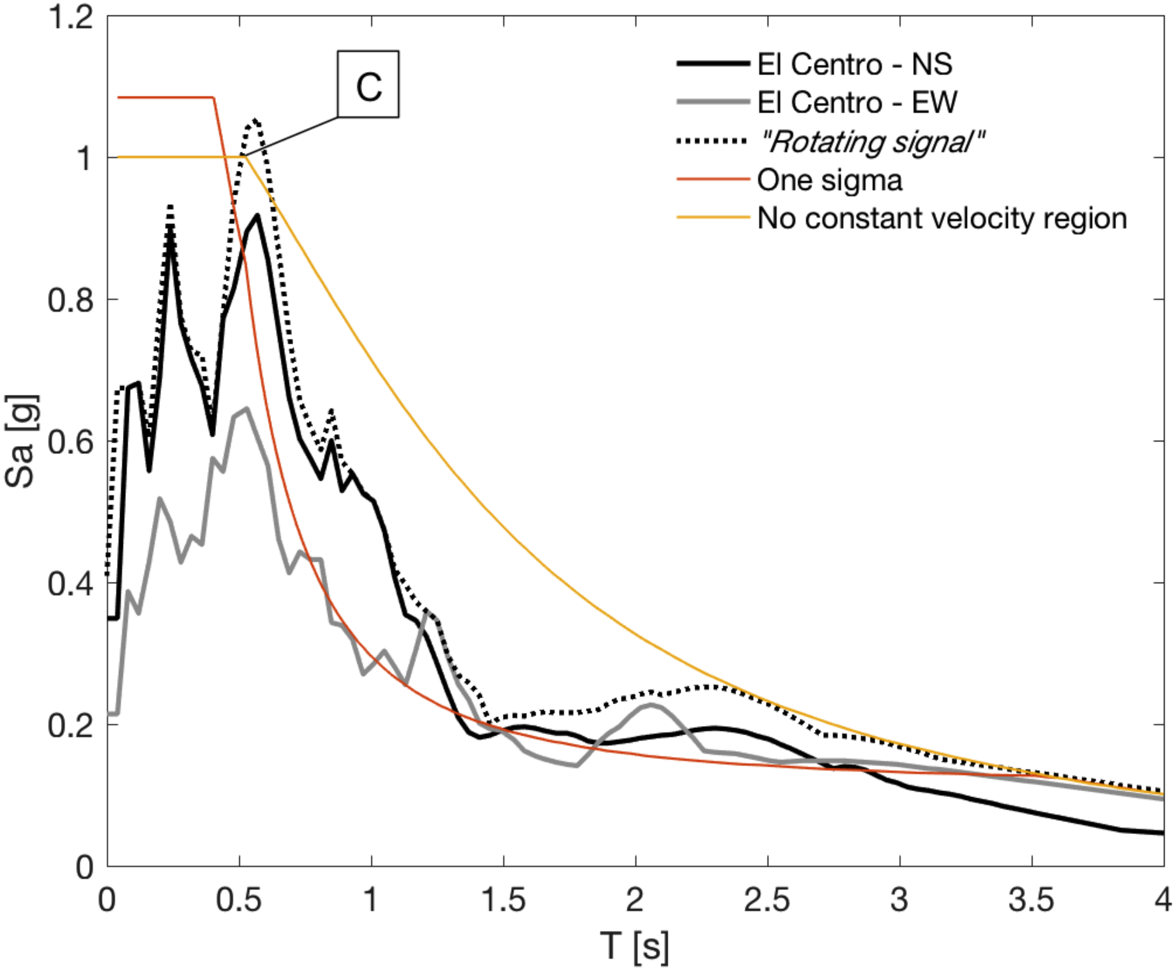
Combined Sa - Sd spectra from El Centro records and Newmark design spectra



Displacement spectra



Velocity spectra



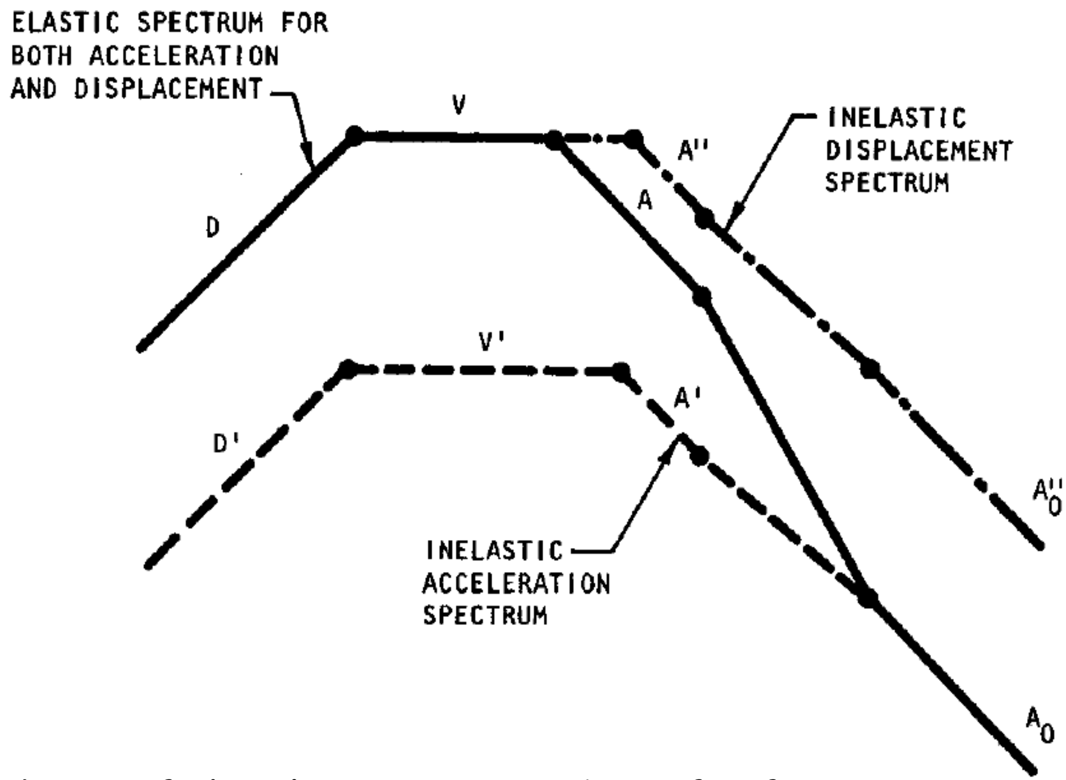
Acceleration spectra

Combination of the two horizontal components

- peak values of acceleration and displacement are the same for the same distance and magnitude
- the two recorded horizontal components of a ground motion, usually show different values of peak spectral acceleration and displacement
- often mix the larger demand in acceleration with the smaller displacement and vice versa

- Adopt the envelope spectrum?
- Calculate the ordinate resulting from the square root of the sum of the squares?

A rotating signal



- 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.

Correction to account for non linear response

DBD

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

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

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

With $C \approx 0.4 - 0.6$

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

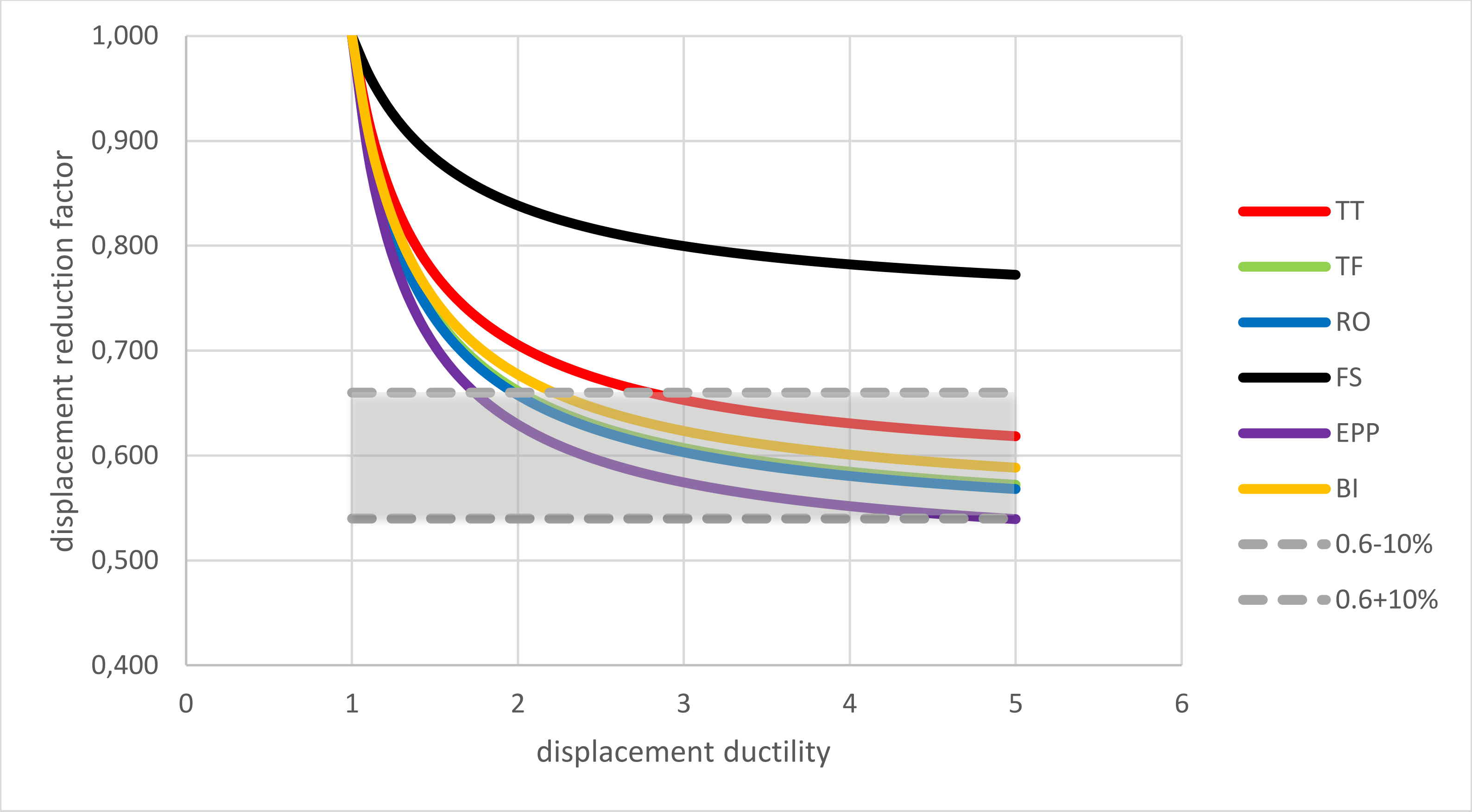
Hybrid Prestressed Frame (FS, β=0.35): $\xi_{eq} = 0.05 + 0.186\left(\frac{\mu-1}{\mu\pi}\right)$

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

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

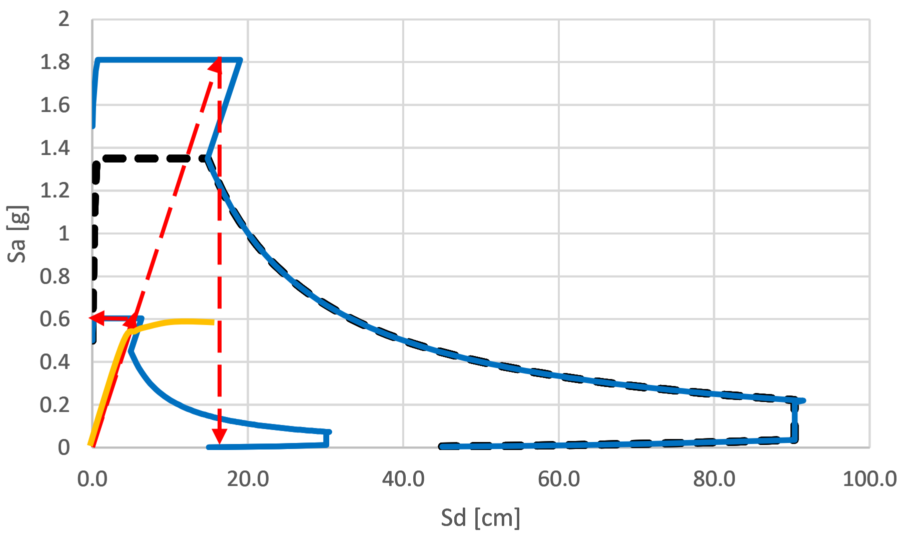
Correction of the elastic design spectrum to account for energy dissipation

displacement reduction factor $\eta_\xi \approx 0.6$ +/- 10%



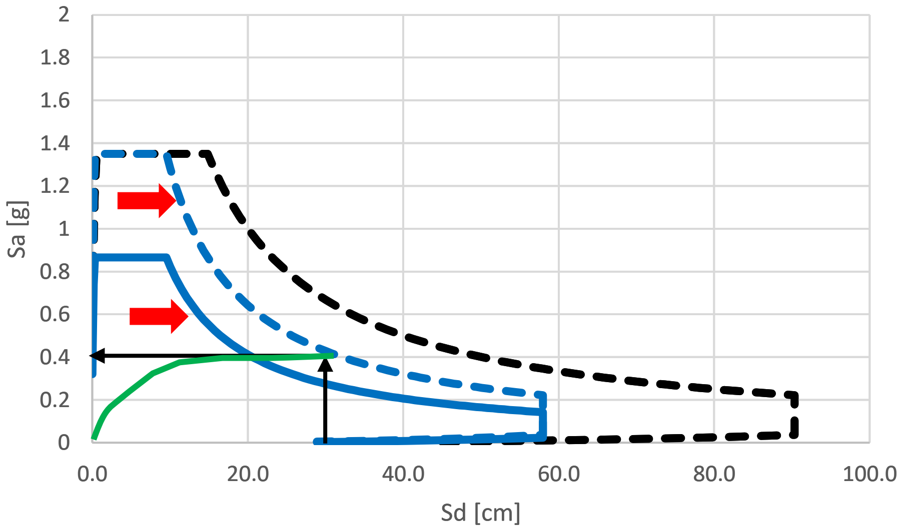
Acceleration-based non-linear design

1) Elastic spectrum
2) Non linear acceleration spectrum
3) Non linear displacement spectrum
4) Enter structure period (e.g. 0.5 s)
5) Read acceleration demand (e.g. 0.6 g)
6) Read displacement demand (18 cm)
7) Possible resulting design curve



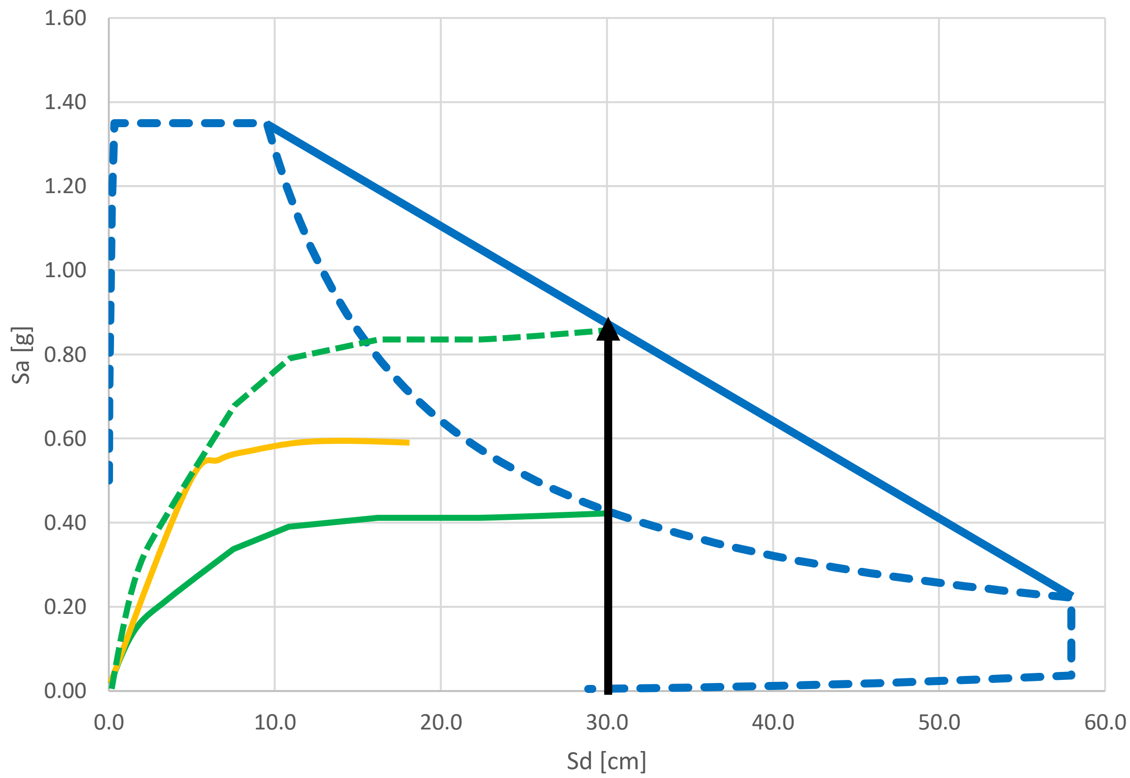
Displacement-based non-linear design

1) Elastic spectrum
2) Reduce spectrum applying displacement reduction factor (e.g. ξ=15%)
3) this?
4) or this?
5) Enter design displacement (e.g. 30 cm)
6) Read design acceleration (e.g. 0.4 g)
7) Possible resulting design curve



Displacement-based non-linear design

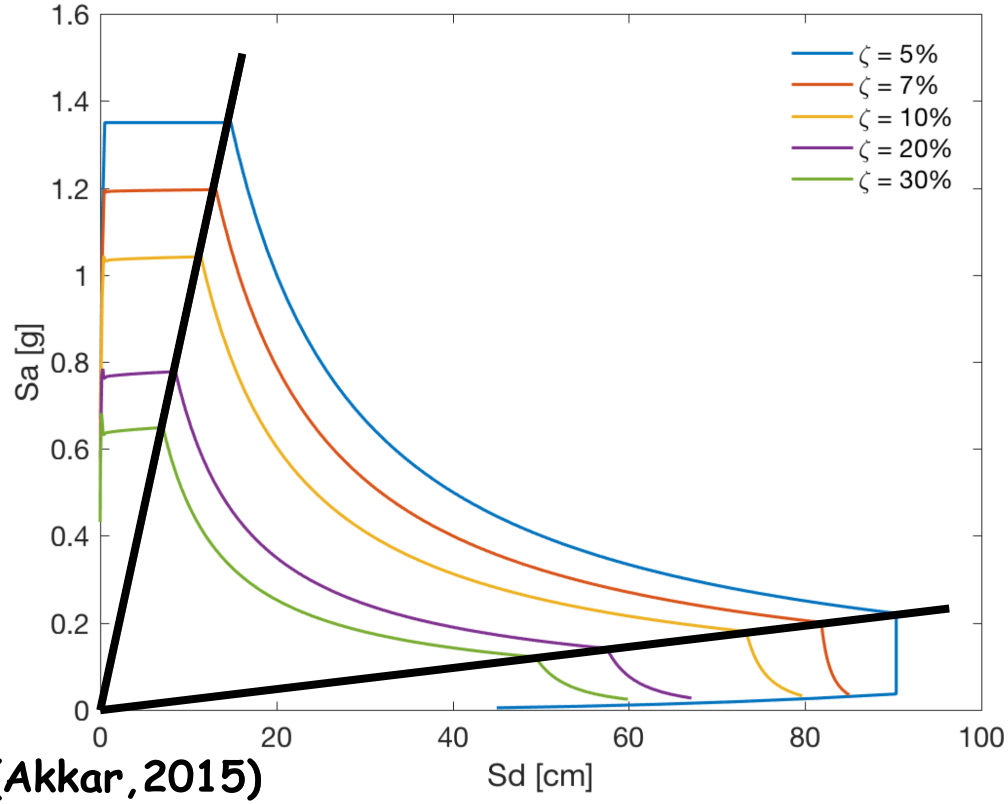
1) Comparison of possible design curves
2) With a different shape of the constant velocity region
3) The design curve may change



Correction of the elastic design spectrum to account for energy dissipation

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

$$\xi = \xi_0 + \xi_h = \xi_0 + C\left(\frac{\mu-1}{2\pi\mu}\right)$$



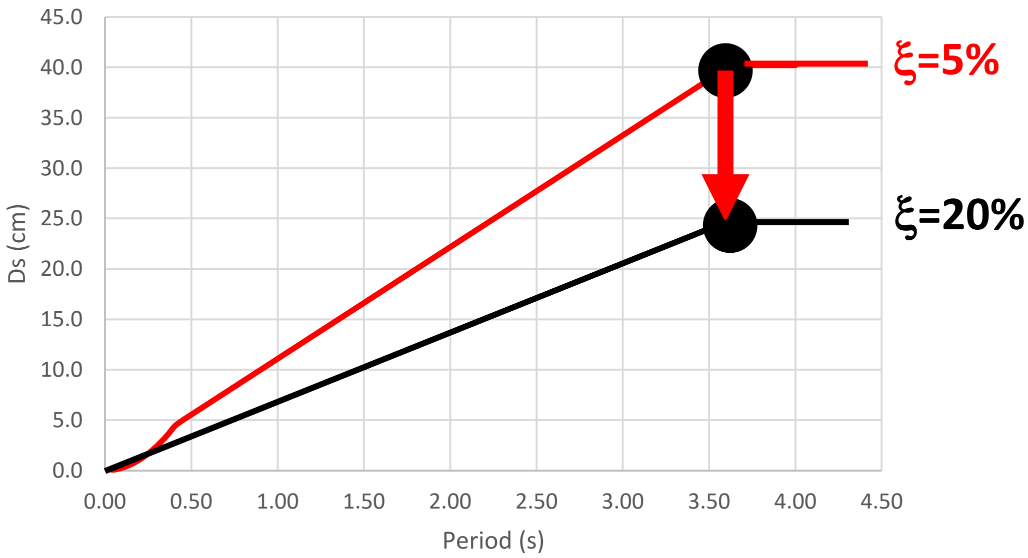
(Akkar, 2015)

Essentially conservation of corner periods

WHY?

Consider the correction of a displacement spectrum to account for energy dissipation:

1. Corner period
2. Goes here
3. Thus producing a reduced spectrum



i.e.:

- Reduce displacement
- Conserve period
- Acceleration reduces proportionally to displacement as

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

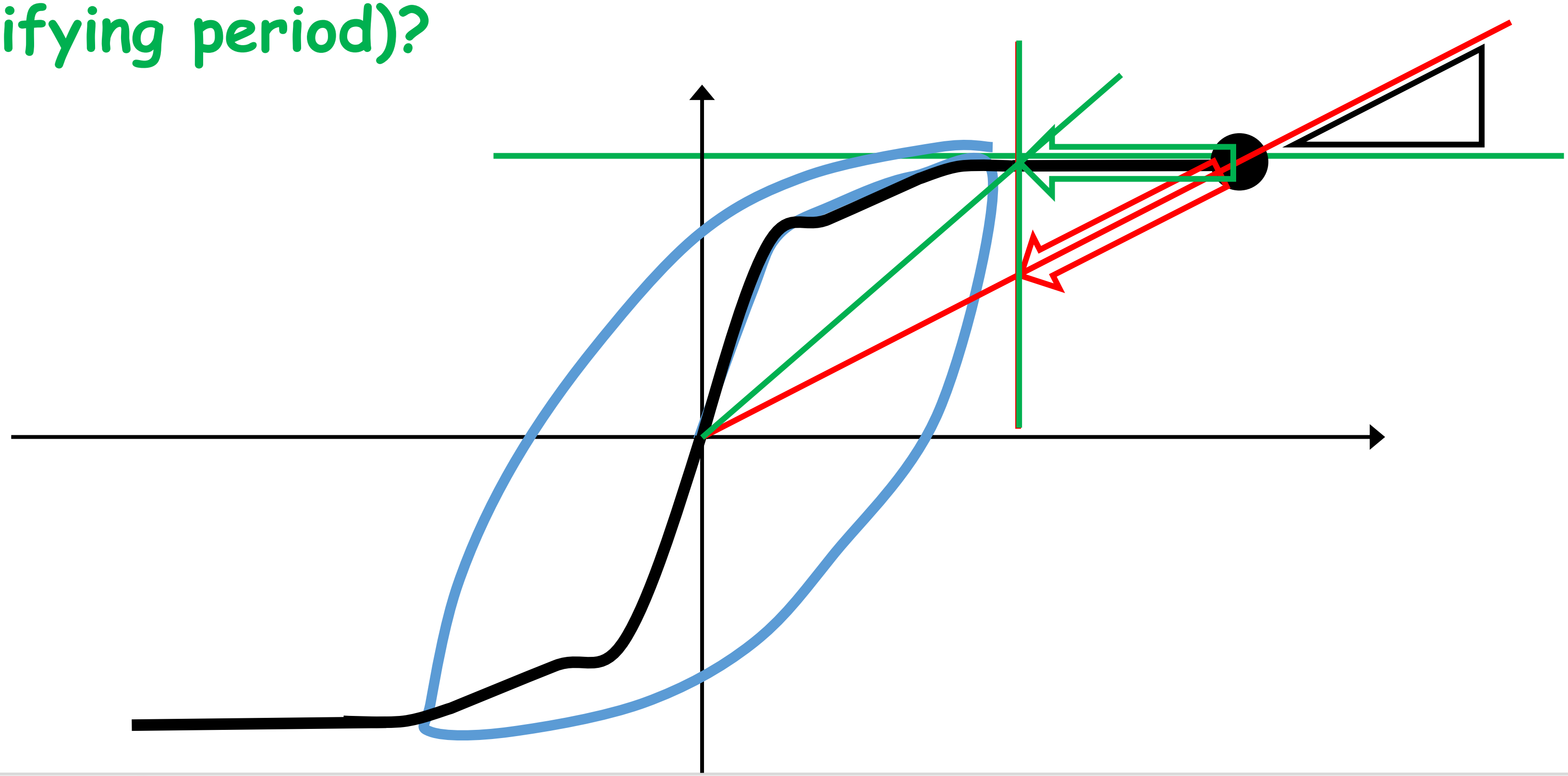
Assume a pushover curve

And an associated energy dissipation cycle

Becaus of equivalent damping, should this point

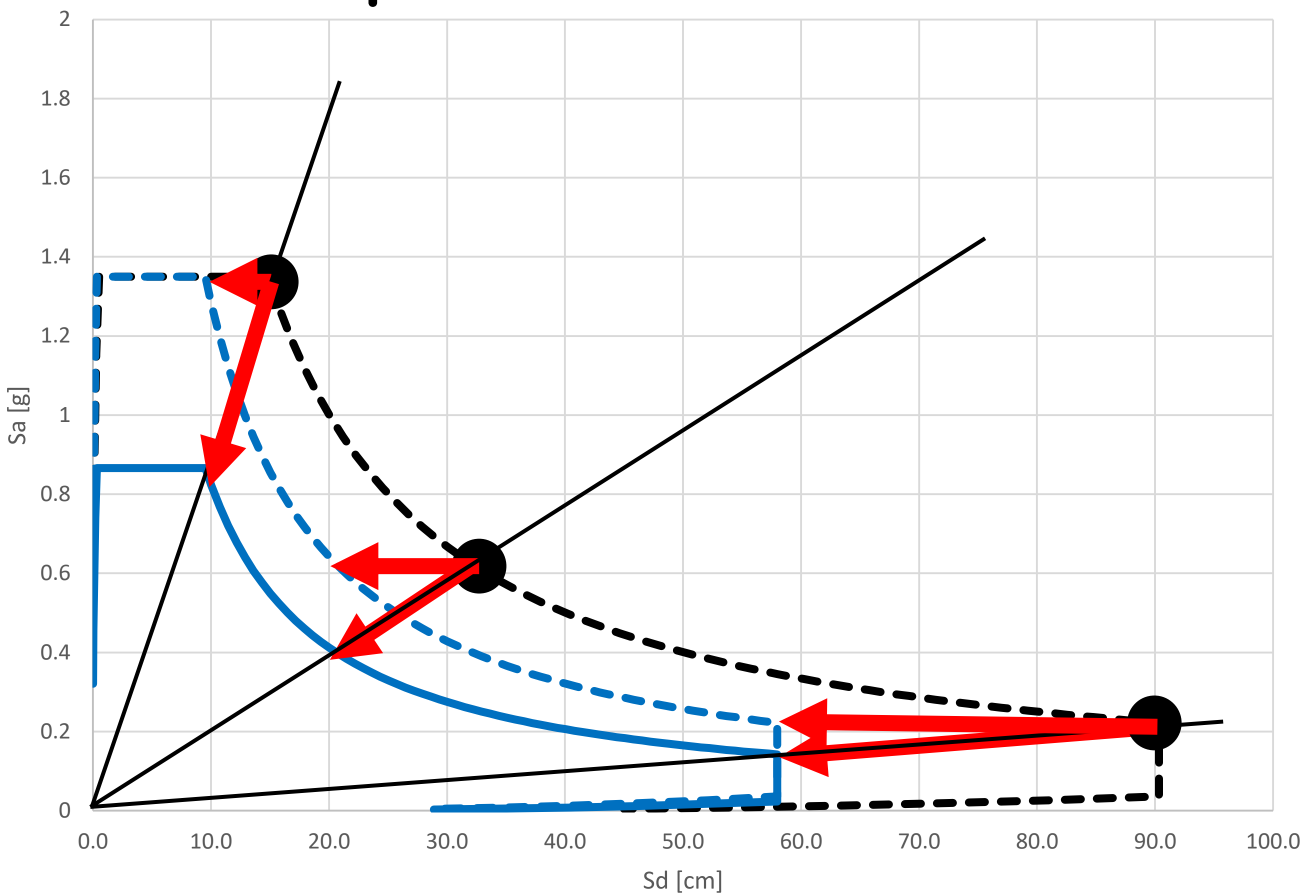
Go here (reducing displacement, conserving period, modifying acceleration)?

Or here (reducing displacement, conserving acceleration, modifying period)?



Displacement reduction factor

In today's application this point
Goes here
But it should rather go here
And the reduced spectrum is rather different



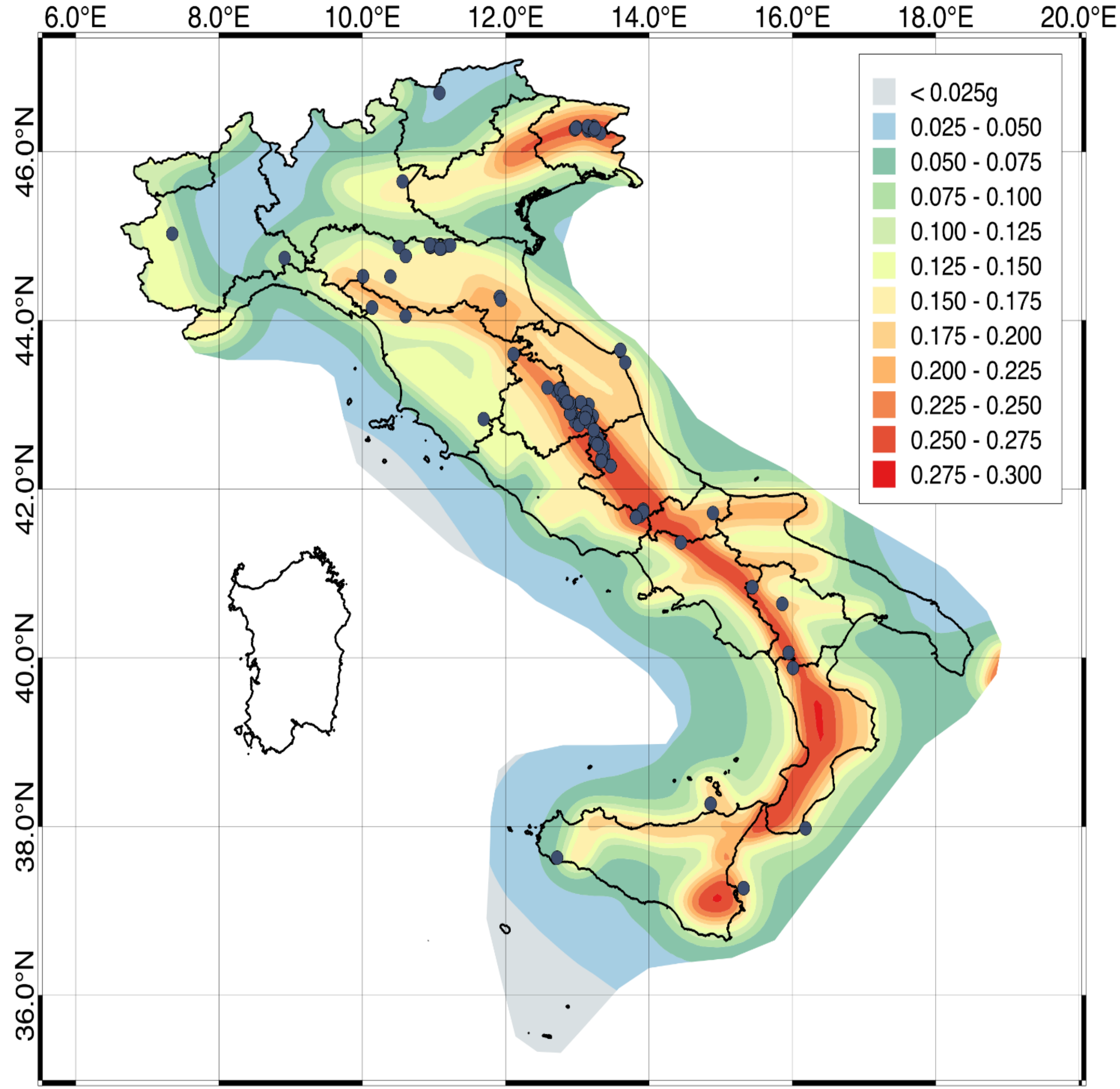
Re-definition of elastic design spectra

- Abandon peak ground acceleration as a key parameter
- Spectra based on two points:
  - maximum spectral acceleration and displacement with the corresponding periods of vibration
- Abandon constant velocity
- Shape of the intermediate region function of a single parameter
- Points and shape defined as a function of:
  - magnitude
  - distance from epicenter or fault
  - source mechanism
  - expected duration or number of significant cycles
  - soil type
  - other factors?

360 two components records

Year	Magnitude	No. of Records	Min Distance (km)	Max Distance (km)
1972	4.8	2	7.69	11.44
1976	4.5-6.4	29	1.91	85.41
1977	5.3	4	6.15	11.43
1978	5.2-6.1	5	9.15	46.64
1979	5.9	3	4.59	43.51
1980	4.6-5.0	4	5.83	16.65
1981	4.9-5.2	9	9.45	21.38
1982	4.6	1	8.07	8.07
1984	4.7-5.9	18	5.34	68.11
1990	5.6-5.8	5	26.65	65.26
1996	5.4	2	13.25	16.45
1997	4.5-6.0	52	0.96	79.50
1998	4.8-5.6	17	5.14	66.04
2000	4.5-4.8	3	1.71	7.56
2001	4.7-4.8	2	2.54	18.62
2002	5.7	1	41.06	41.06
2003	4.8	1	17.06	17.06
2004	5.3	1	14.37	14.37
2008	4.9	1	9.13	9.13
2009	4.6-6.3	38	0.73	49.17
2012	4.7-5.9	42	1.72	67.35
2013	4.9-5.2	8	4.37	81.30
2016	4.5-6.5	99	2.58	94.27
2017	4.6-5.5	13	5.24	28.85

Epicenters (on a 10 % in 50 y hazard map)

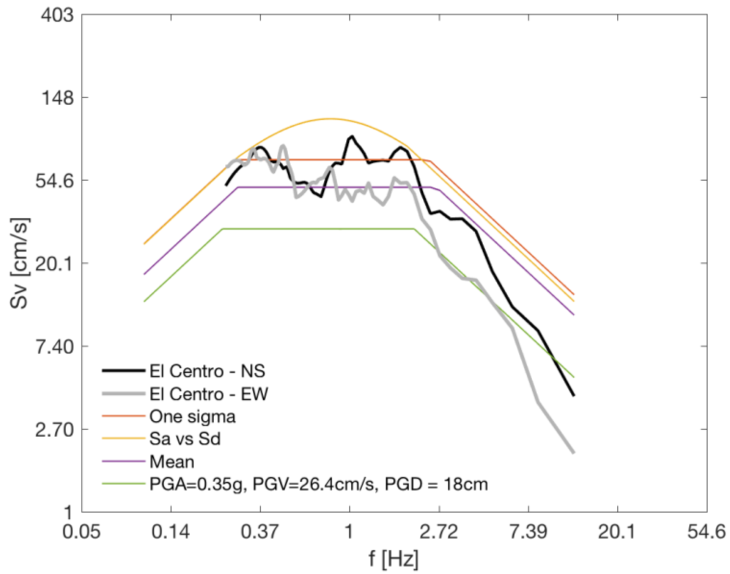


Twenty bins

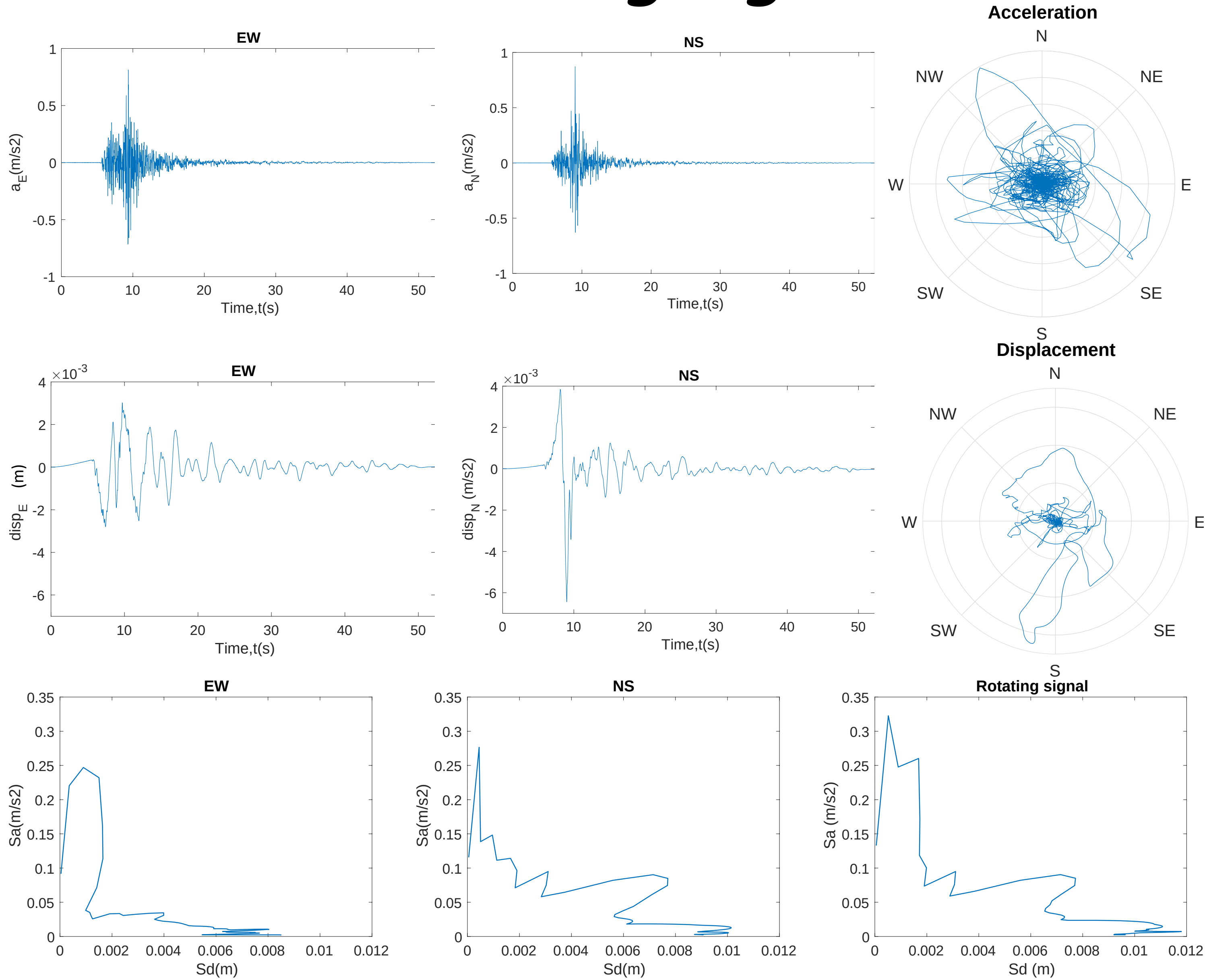
Number of available records	r<10 km	10<r<20 km	20<r<30 km	30<r<50 km	50 km<r
6.0 < M < 6.5	8	3	5	17	14
5.5 < M < 6.0	15	38	27	24	11
5.0 < M < 5.5	34	46	11	7	4
4.5 < M < 5.0	54	42	0	0	0

Combination of the two horizontal components

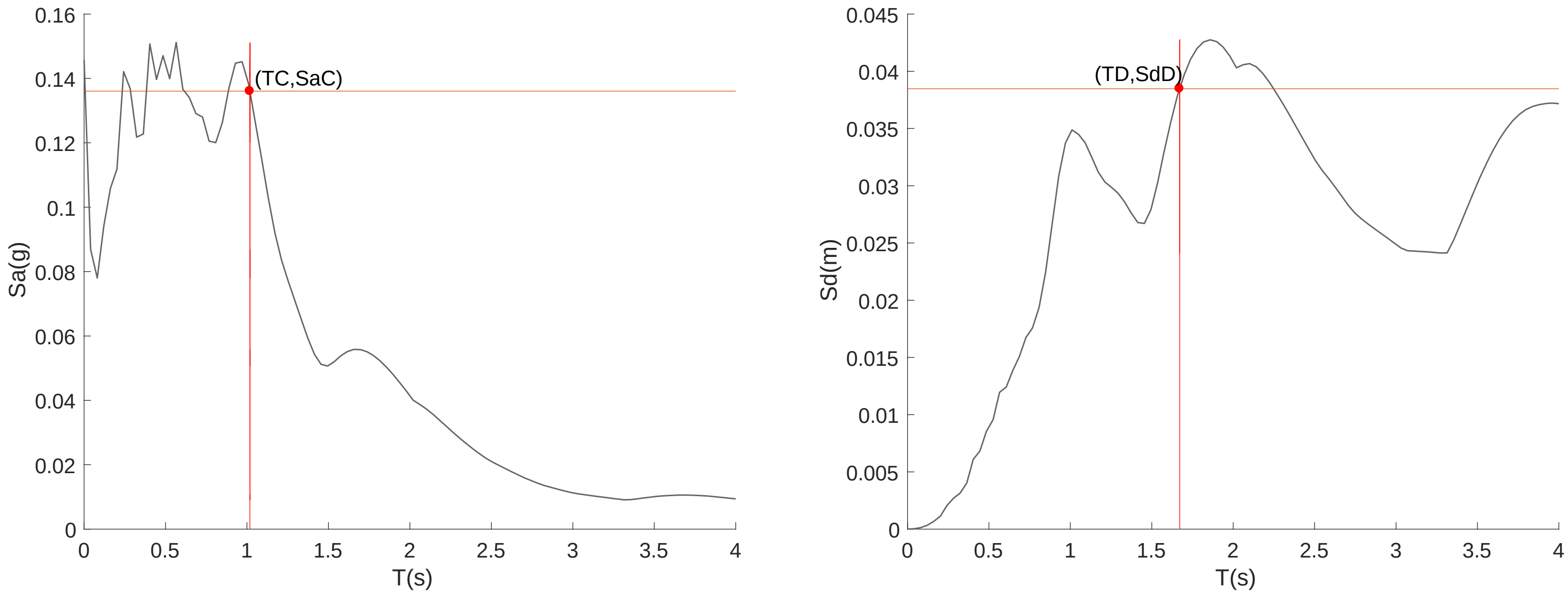
- derive one single horizontal acceleration signal from recorded ground motions, combining the two components instant by instant
- nothing to do with the combination of actions on buildings, resulting from their response in different directions



Components and rotating signal



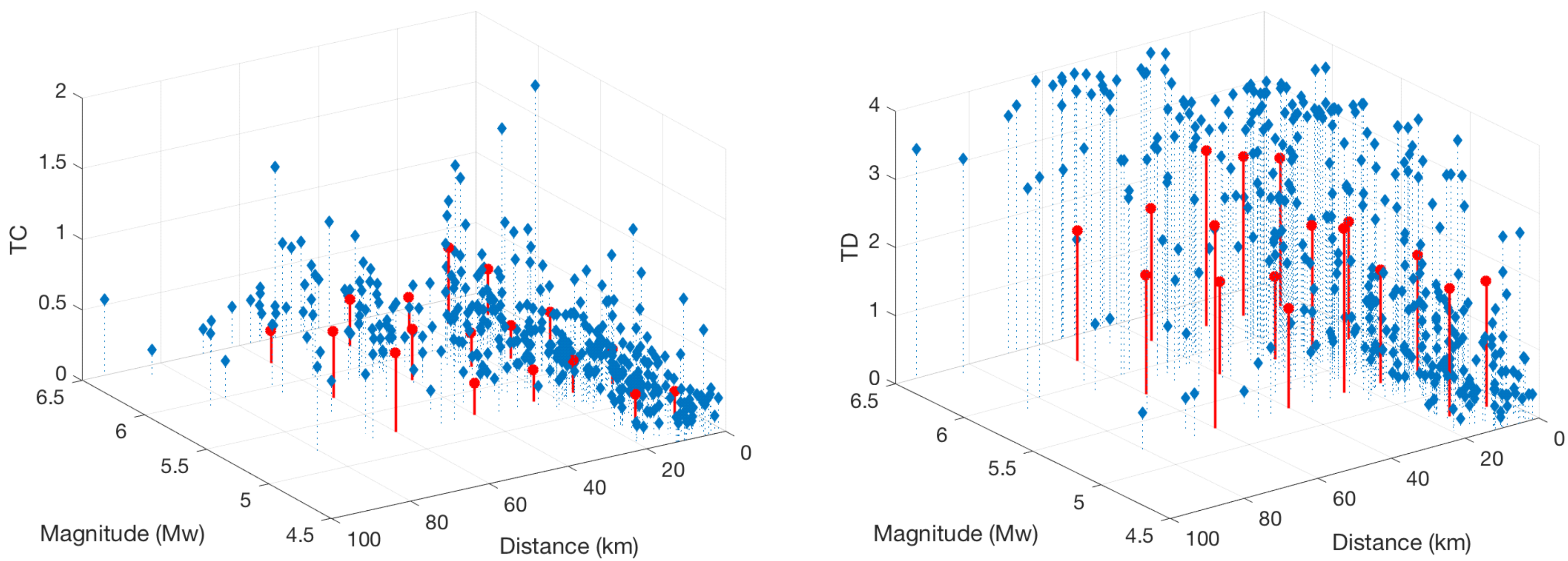
Definition of T_C T_D S_{aC} S_{dD}



Horizontal lines at 90 % of the maximum values

Points adopted at the first (displacement) and last (acceleration) intersection

Calculation of T_C and T_D



Mean values of T_C and T_D for each magnitude-distance bin compared with all available data

Definition of the interpolation function of T_C

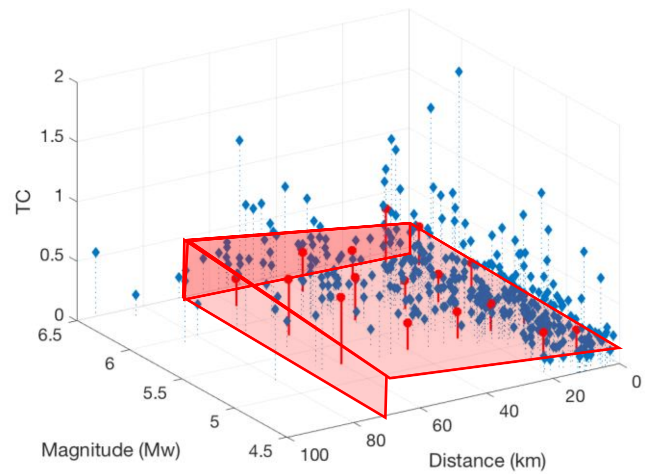
T_c interpolated by a plane surface resulting by the combination of two lines

At the maximum considered distance (r = 70 km):

$$T_{C(r=0)} = k_{TCo} - k_{TC1}(6.5 - M)$$

At M = 6.5:

$$T_{C(M=6.5)} = k_{TCo} - k_{TC2}(70 - r)$$



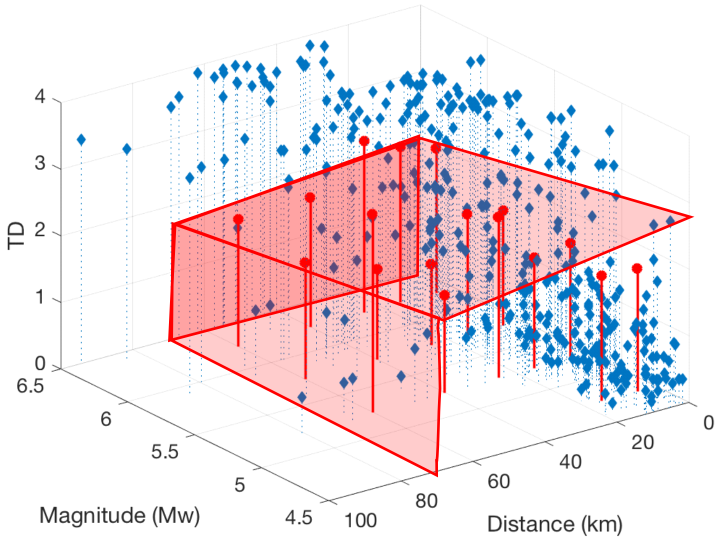
k_{TC0} is the value of T_C at M = 6.5 and r = 70
k_{TC1} is the rate of change of T_C with M
k_{TC2} is the rate of change of T_C with r

Equation of the surface:

$$T_C = \frac{\left(k_{TCo} - k_{TC1}(6.5 - M)\right)\left(k_{TCo} - k_{TC2}(70 - r)\right)}{k_{TCo}}$$

Definition of the interpolation function of T_D

T_D interpolated by a plane surface resulting by the combination of two lines



At the maximum considered distance (r = 70 km):

$$T_{D(r=0)} = k_{TDo} - k_{TD1}(6.5 - M)$$

At M = 6.5:

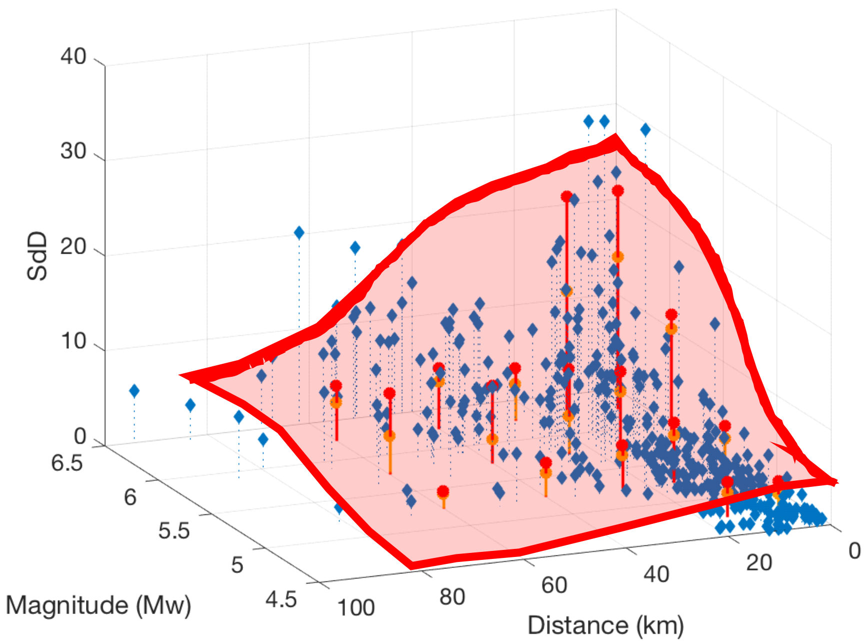
$$T_{D(M=6.5)} = k_{TDo} - k_{TD2}(70 - r)$$

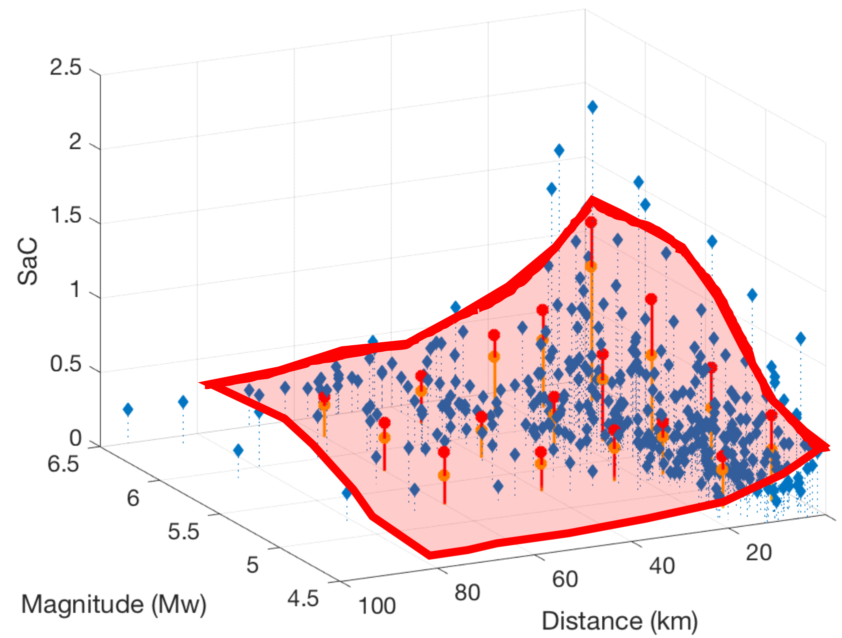
k_{TD0} is the value of T_C at M = 6.5 and r = 70
k_{TD1} is the rate of change of T_C with M
k_{TD2} is the rate of change of T_C with r

Equation of the surface:

$$T_D = \frac{\left(k_{TDo} - k_{TD1}(6.5 - M)\right)\left(k_{TDo} - k_{TD2}(70 - r)\right)}{k_{TDo}}$$

Calculation of S_{dD} and S_{aC}



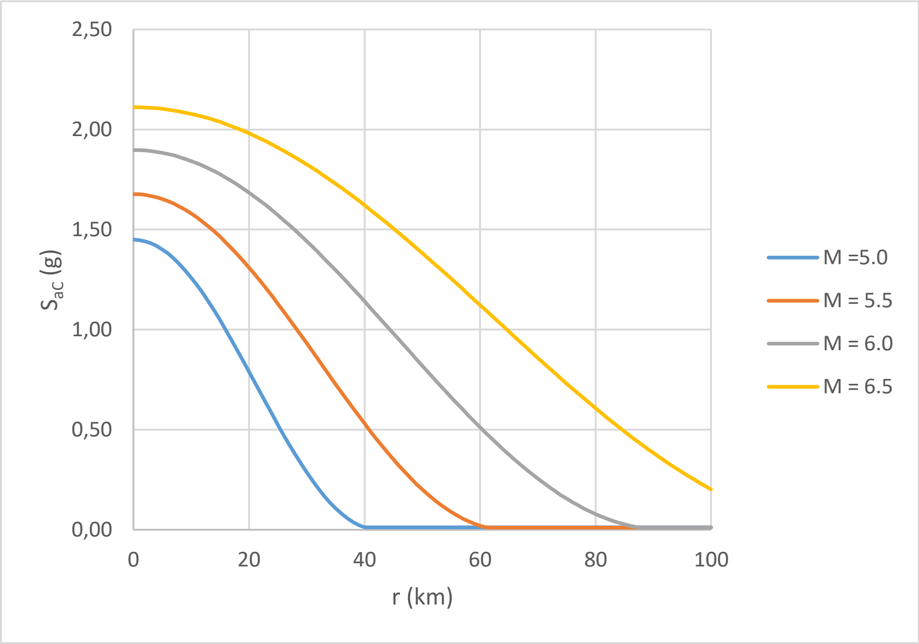


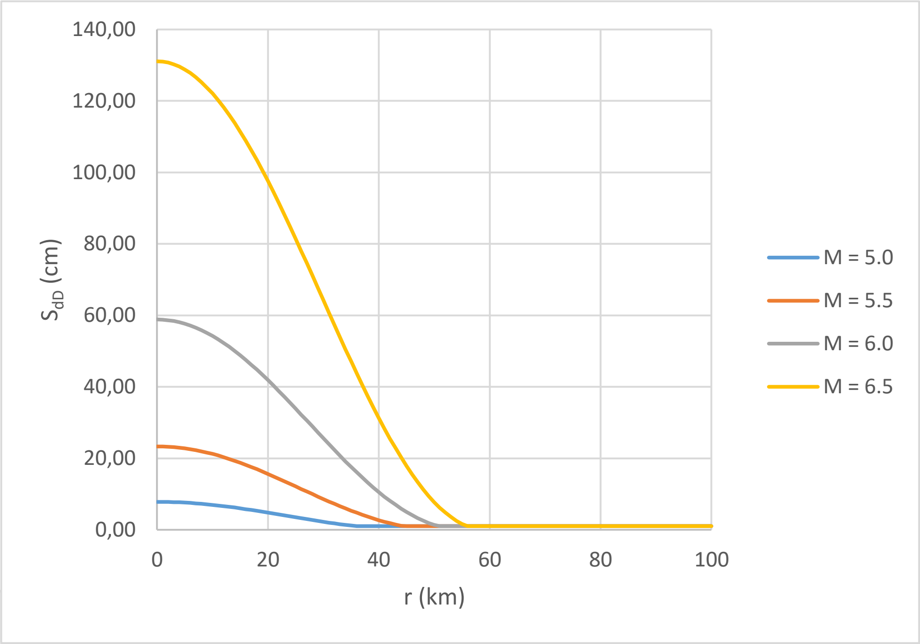
Mean and +1σ values of S_{dD} and S_{aC} for each magnitude-distance bin compared with all available data

Definition of a general equation for the interpolation of S_{aC} and S_{dD}

an over damped sinusoidal equation instead of a linear equation

$$S = k_0 + k_1 e^{-k2(f(x))} \cos k_3(f(x))$$





Definition of the interpolation function of S_{aC}

At r = 0:

$$S_{aC(r=0)} = k_{a0} + k_{a1} e^{-k_{aM2}(6.5-M)} \cos \frac{\pi}{2k_{M3}} (6.5 - M)$$

k_{a0} a minimum threshold value of S_{aC}, at minimum magnitude, at the epicenter (r = 0)

k_{a1} a value that summed to k_{a0} will give the value of S_{ac} at r = 0 and M = 6.5, i.e. the maximum spectral acceleration

k_{aM2} a factor that increases or reduces damping

k_{aM3} a factor that normalizes the range of magnitude

Definition of the interpolation function of S_{aC}

At M = 6.5:

$$S_{aC(M=6.5)} = k_{a0} + k_{a1} e^{-k_{ar2}(r)} \cos \frac{\pi}{2K_{r3}} (r)$$

k_{a0} a minimum threshold value of S_{aC}, at maximum magnitude (M = 6.5), at maximum distance (r = 70 km)

k_{a1} a value that summed to k_{a0} will give the value of S_{ac} at r = 0 and M = 6.5, i.e. the maximum spectral acceleration

k_{ar2} a factor that increases or reduces damping

k_{ar3} a factor that normalizes the range of distance

Definition of the interpolation function of S_{aC}

Resulting combined equation for the S_{aC} surface

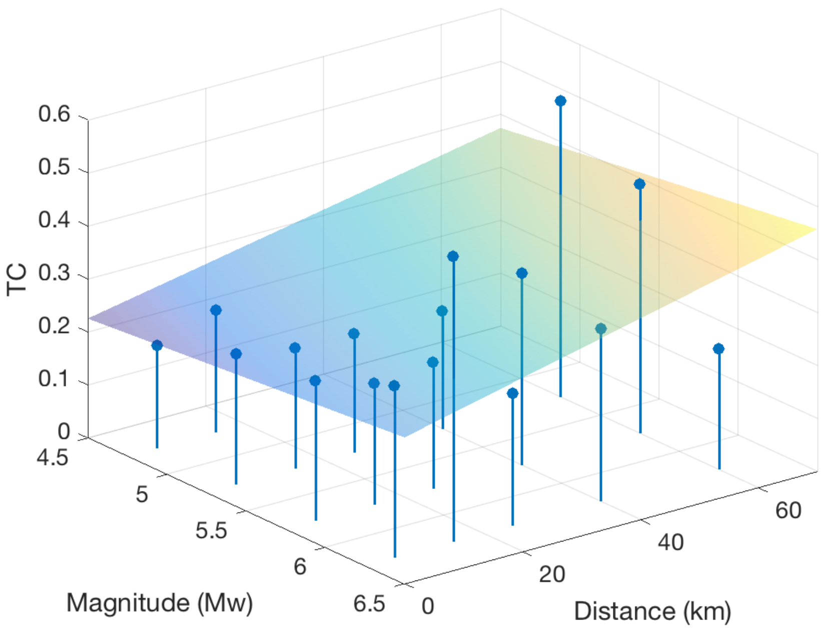
$$S_{aC} = \frac{S_{aC}(M)_{(r=0)} S_{aC}(r)_{(M=6.5)}}{S_{aC(M=6.5,r=0)}} = \frac{S_{aC}(M)_{(r=0)} S_{aC}(r)_{(M=6.5)}}{k_{a0} + k_{a1}}$$

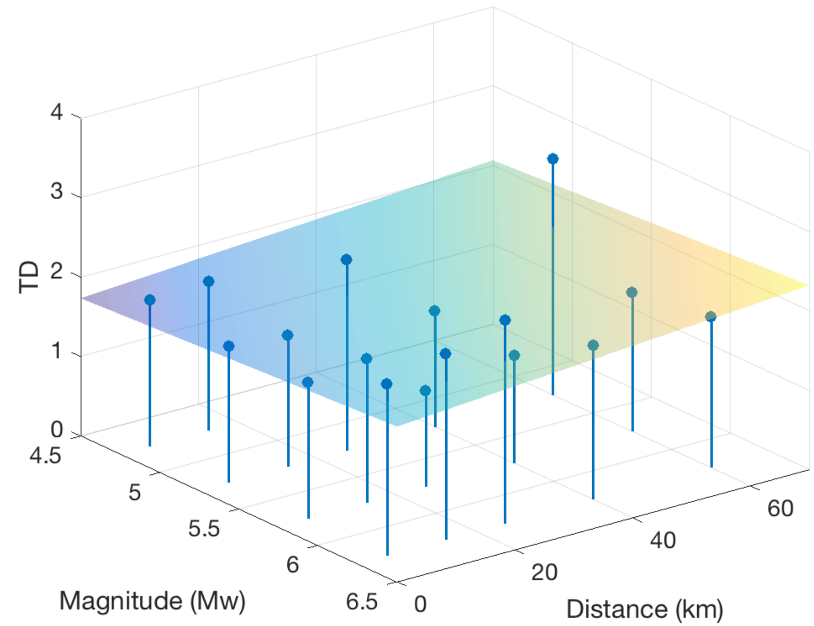
Definition of the interpolation function of S_{dD}

Identical form and parameters

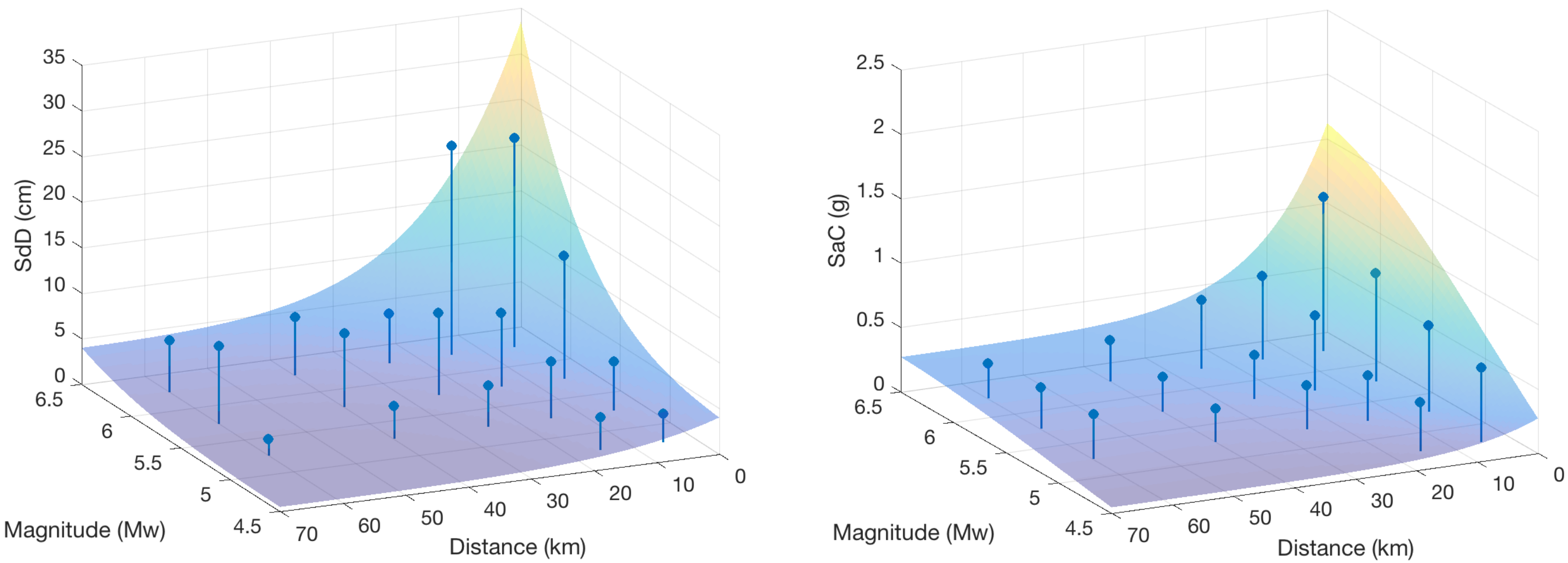
$$S_{dD} = \frac{S_{dD}(M)_{(r=0)} S_{dD}(r)_{(M=6.5)}}{S_{dD(M=6.5, r=0)}} = \frac{S_{dD}(M)_{(r=0)} S_{dD}(r)_{(M=6.5)}}{k_{d0} + k_{d1}}$$

Best fit interpolation of T_C and T_D





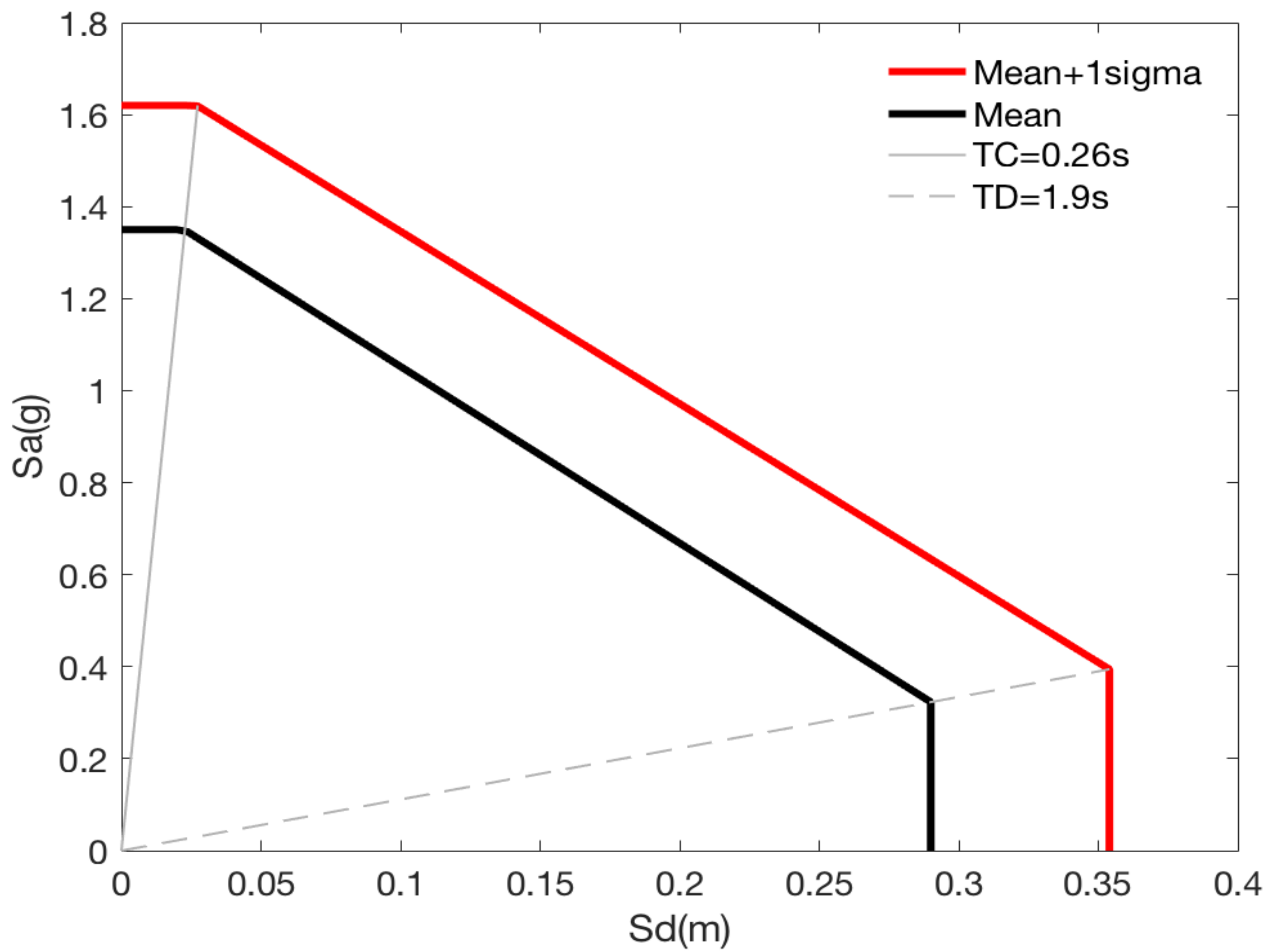
Best fit interpolation of S_{aC} and S_{aD}



Summary of optimal parameters

Parameter		Mean	+1s	Used
T_C	k_{TC0} (value of T_C at M = 6.5 and r = 70) [s]	0.46	0.61	$\boxed{0.46}$
	k_{TC1} (rate of change of T_C with M)	0.042	0.053	0.042
	k_{TC2} (rate of change of T_C with r)	0.0028	0.0034	0.003
T_D	k_{TD0} (value of T_D at M = 6.5 and r = 70) [s]	2.27	2.69	$\boxed{2.27}$
	k_{TD1} (rate of change of T_D with M)	0.13	0.11	0.13
	k_{TD2} (rate of change of T_D with r)	0.0053	0.0043	0.005
S_{aC}	k_{a0} (value of S_{aC}, at minimum magnitude and zero distance) [g]	0.2	0.27	$\boxed{0.27}$
	k_{a1} (value to be summed to k_{a0} to obtain S_{ac} at r = 0 and M = 6.5) [g]	1.15	1.35	$\boxed{1.35}$
	k_{aM2} (magnitude-acceleration damping correction factor)	0.5	0.48	0.48
	k_{ar2} (distance-acceleration damping correction factor)	0.11	0.09	0.09
S_{dD}	k_{d0} (value of S_{dD}, at minimum magnitude and zero distance) [cm]	2.5	4.0	$\boxed{4.0}$
	k_{d1} (value to be summed to k_{d0} to obtain S_{dD} at r = 0 and M = 6.5) [cm]	25.0	29.5	$\boxed{29.5}$
	k_{dM2} (magnitude-displacement damping correction factor)	1.39	1.55	1.55
	k_{dr2} (distance-displacement damping factor)	0.09	0.07	0.07
S_{aC}/S_{dD}	k_{M3} (factor that normalizes the valid range of magnitudes, 4.5 – 6.5) [Mw]	-	-	2.0
	k_{r3} (factor that normalizes the valid range of distances, 0 – 70) [km]	-	-	70

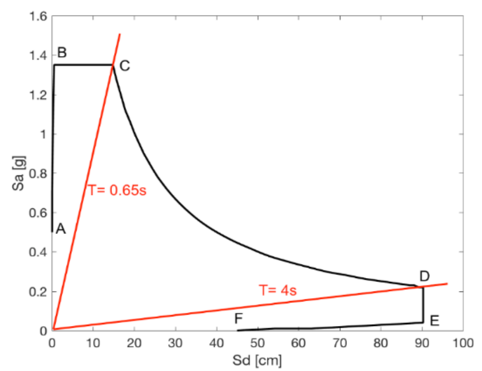
Mean and + 1s spectra for M = 6.5 and r = 0. Corner periods kept equal to the mean values to conserve the shape.



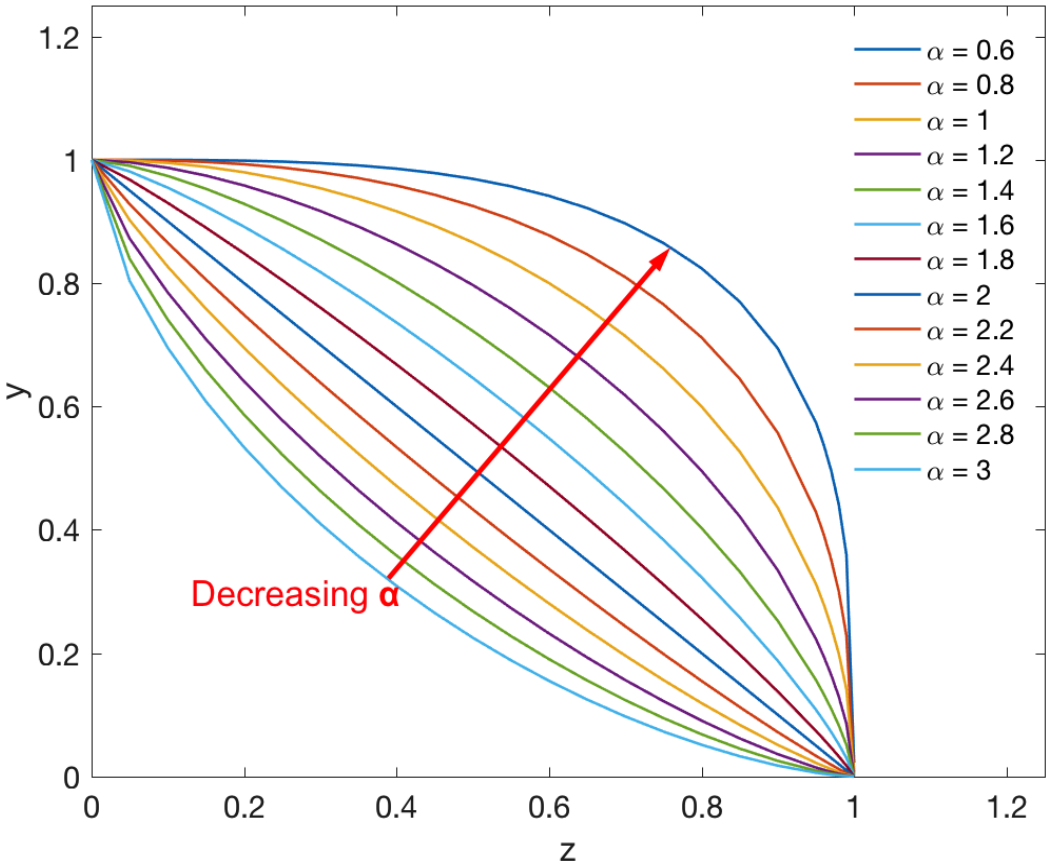
Spectral shape in the intermediate period region

Design spectra first defined as a function of two points:

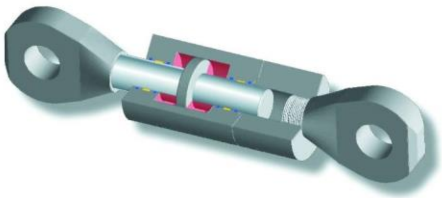
- the longest period (T_C) at which the spectral acceleration will be at the peak amplification (S_{aC})
- the shortest period (T_D) at which the spectral displacement will reach its maximum value (S_{dD})



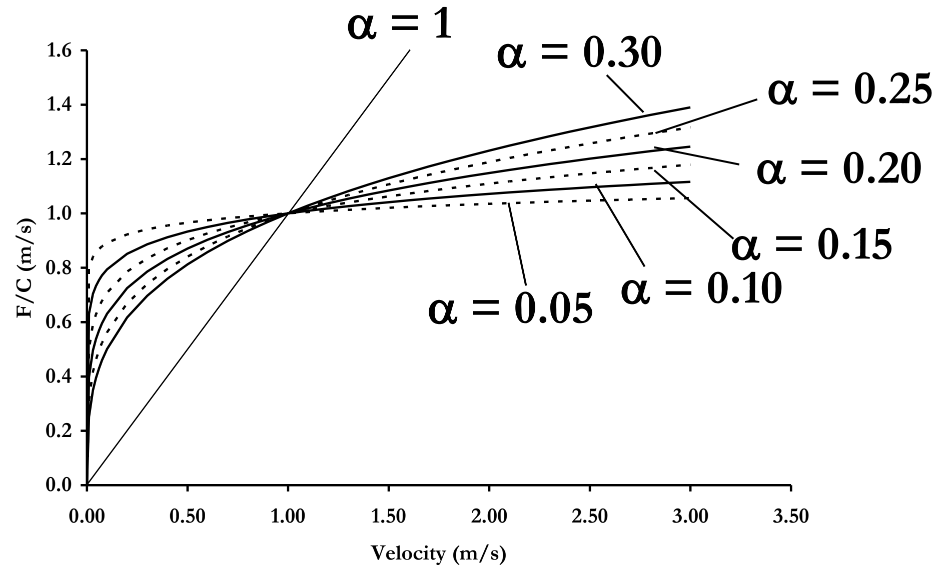
In the intermediate region shape defined by a parameter α:

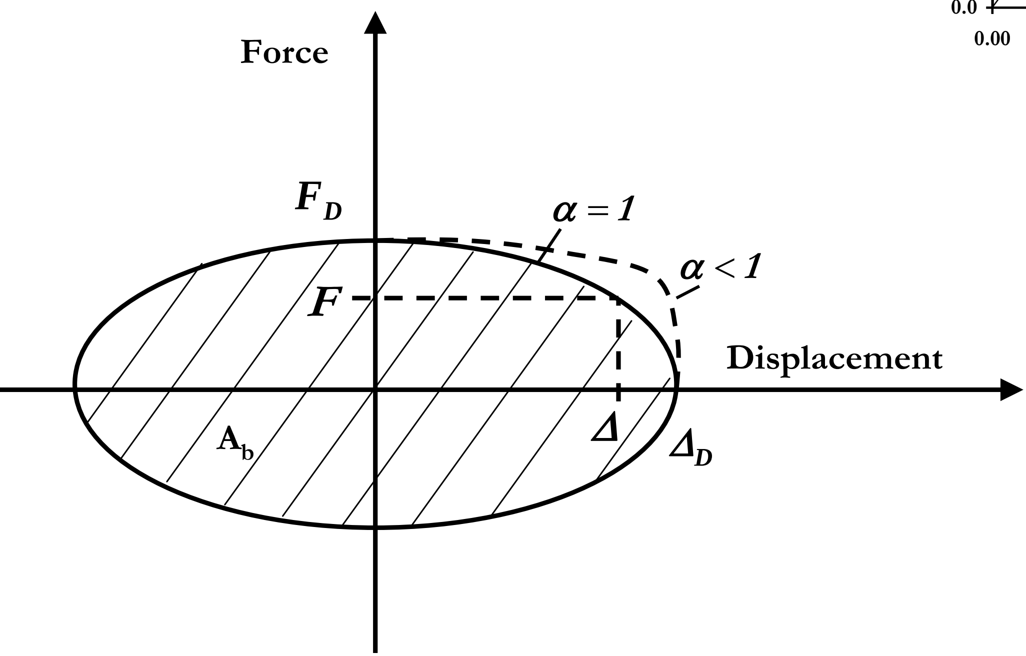


Hydraulic Devices



$$F = C \cdot V^{\alpha}$$





$$\frac{d^2 d}{dt^2} = \left(\frac{dd}{dt} \right)^{\alpha}$$

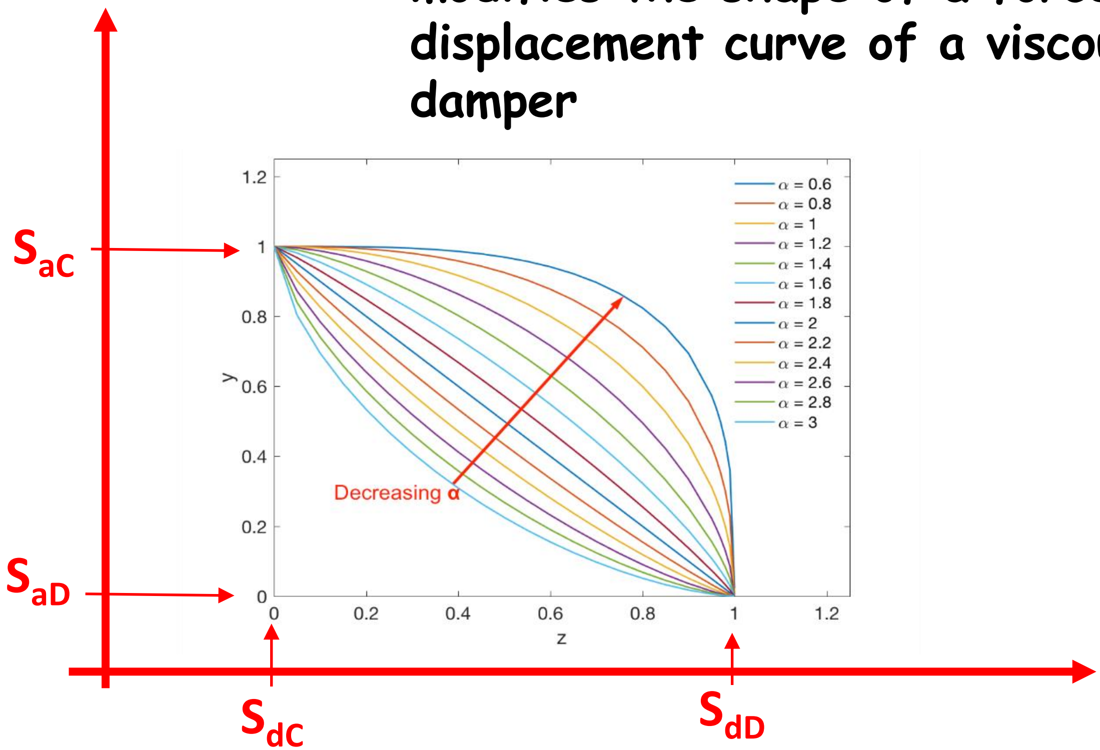
Formulation of the parameter α

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

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

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

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

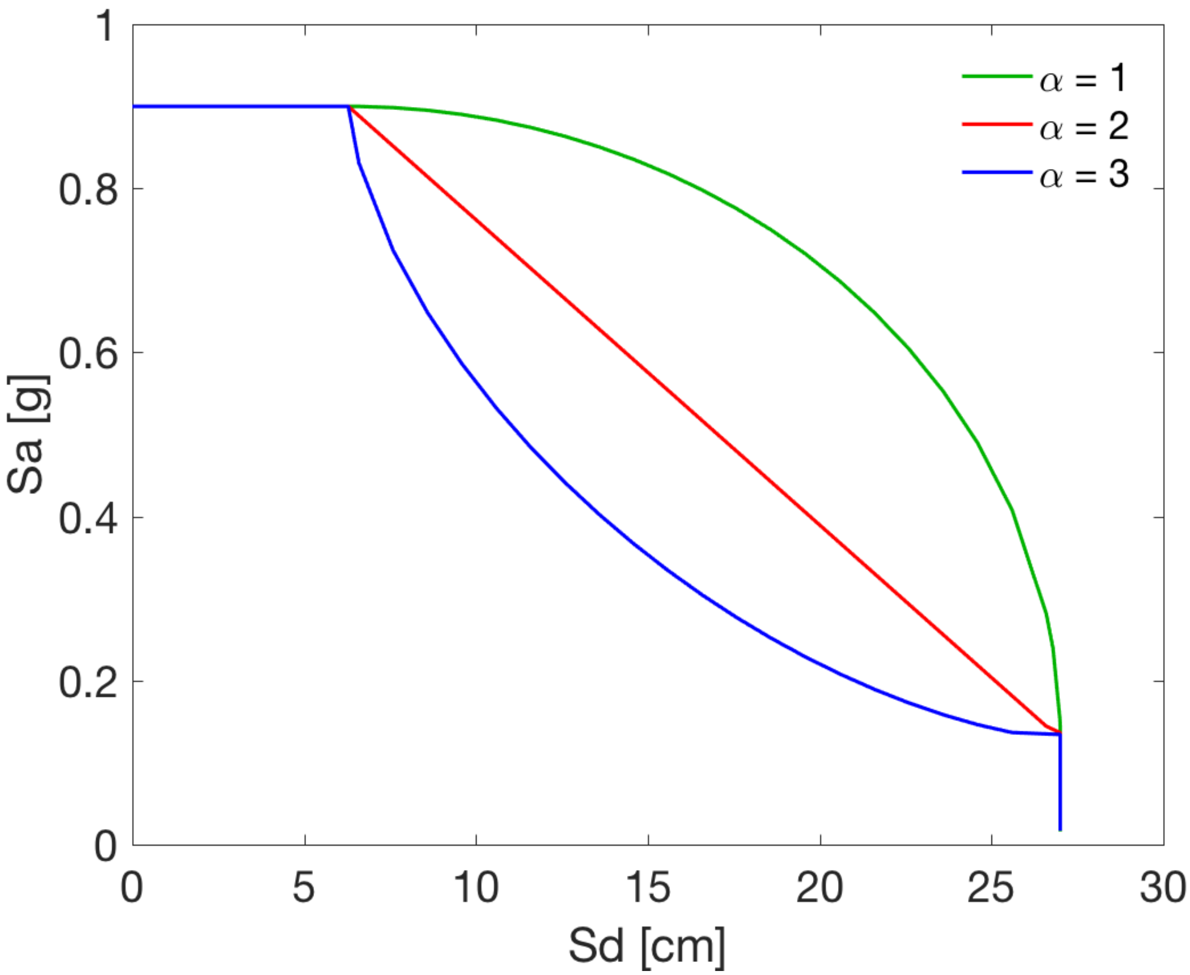


$$S_{aD} = S_{dD}\frac{4\pi^2}{T_D^2}$$

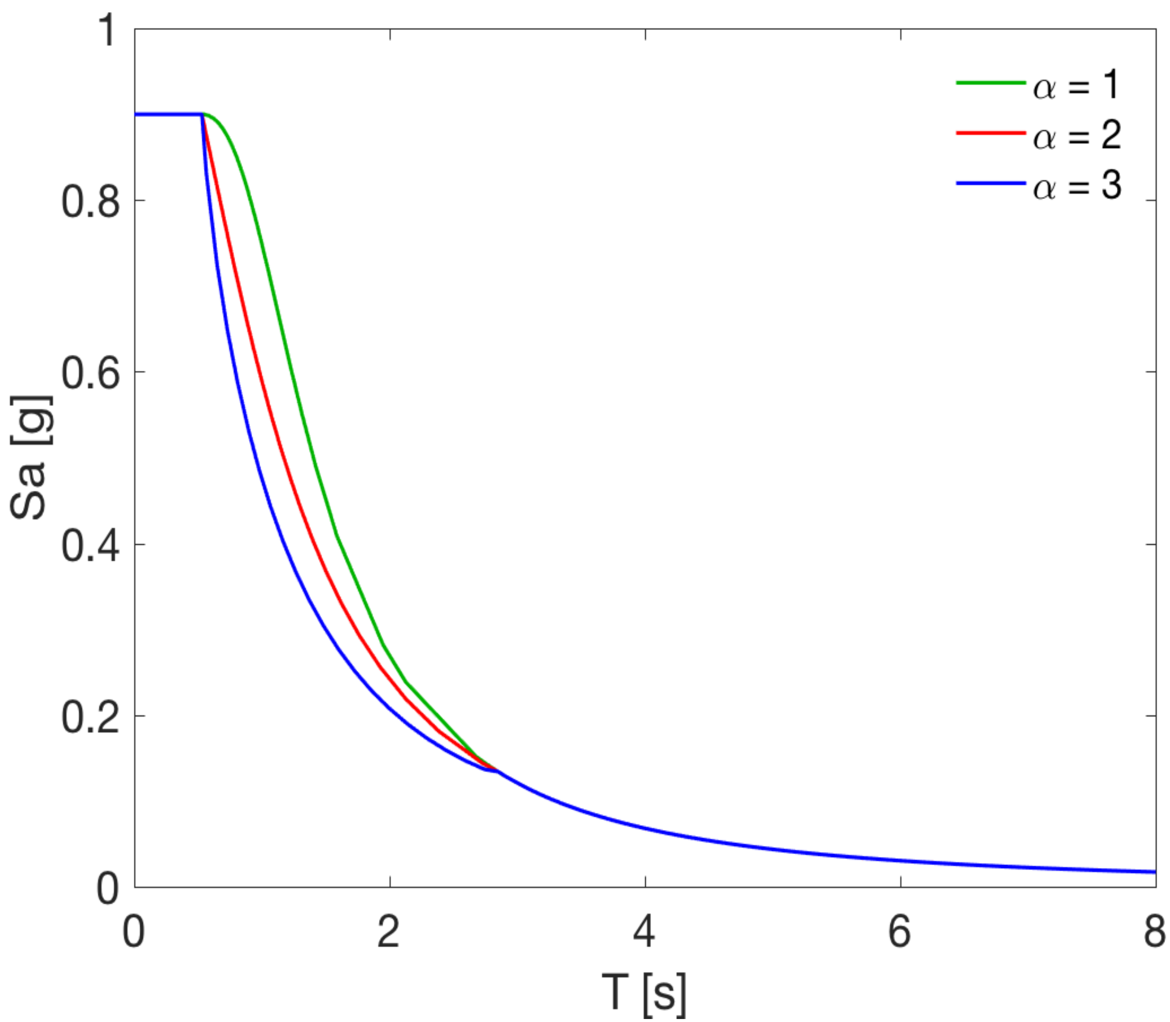
A simple transformation of coordinates:

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

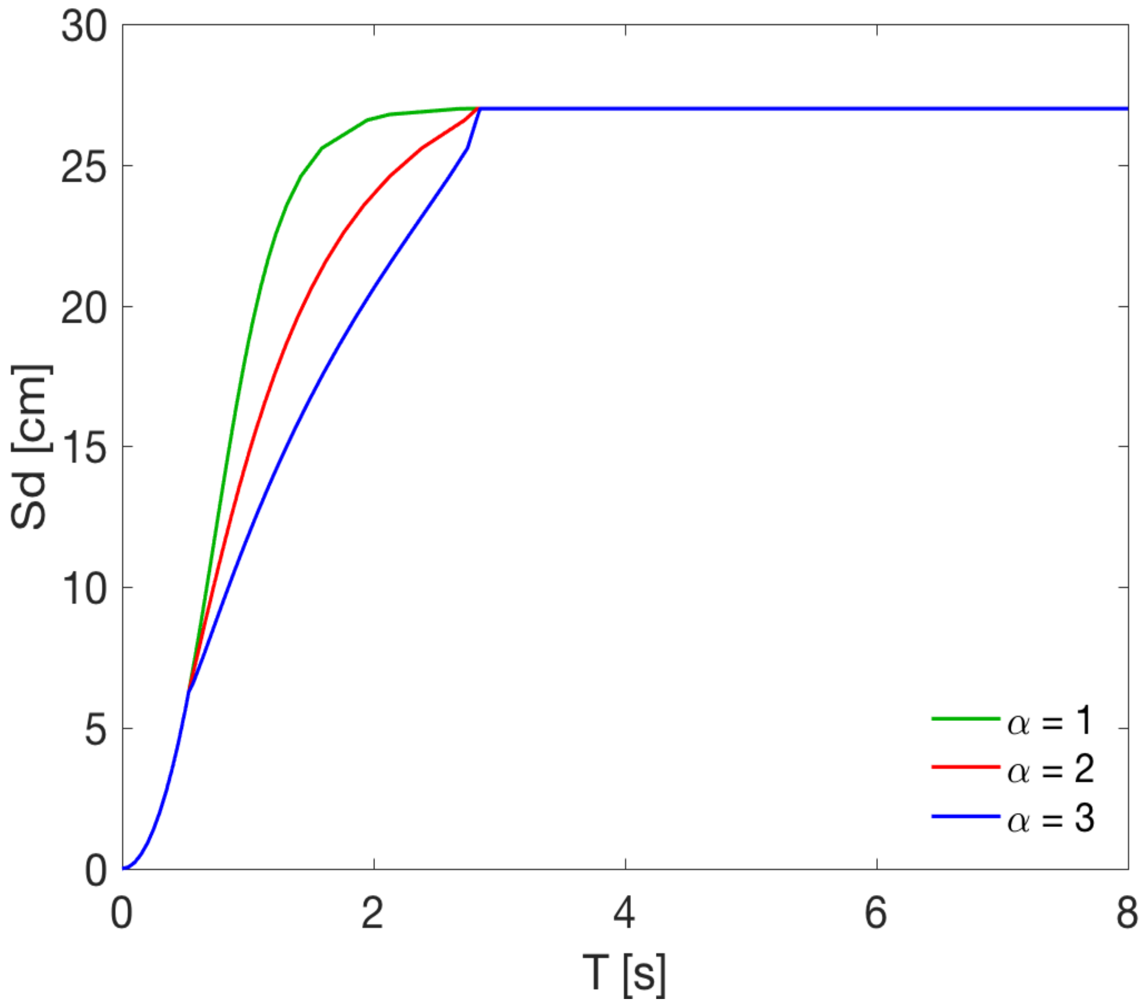
$$S_a = S_{aD} + \left(S_{aC} - S_{aD}\right)\cdot \sin^{\alpha}\left(\cos^{-1}\left(\frac{S_d - S_{dC}}{S_{dD} - S_{dC}}\right)^{\frac{1}{\alpha}}\right)$$



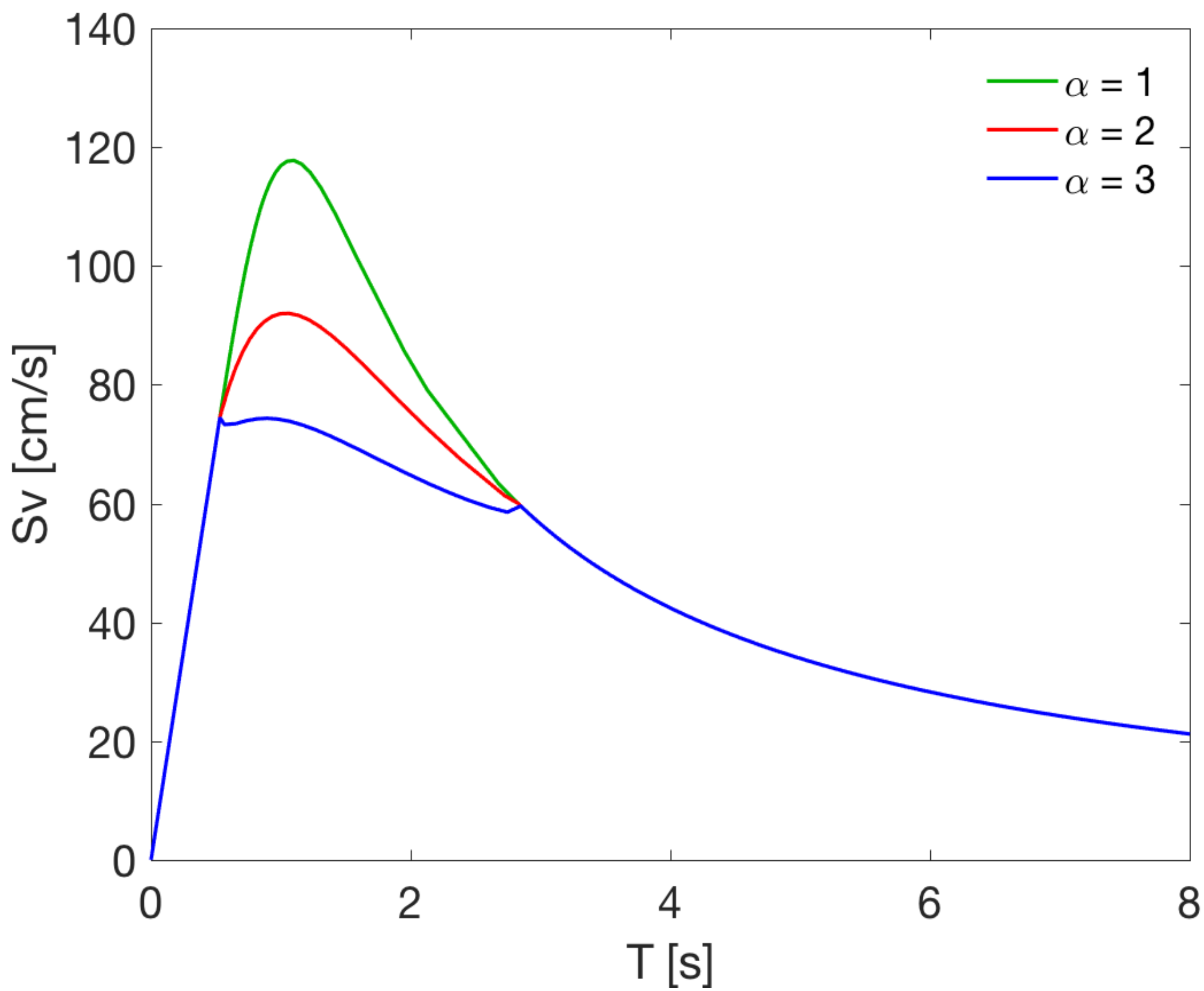
Combined Sa - Sd spectrum varying α



Acceleration spectrum varying α



Displacement spectrum varying α



Velocity spectrum spectrum varying α

Spectral shape in the intermediate period region

Calculation of the α parameter

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

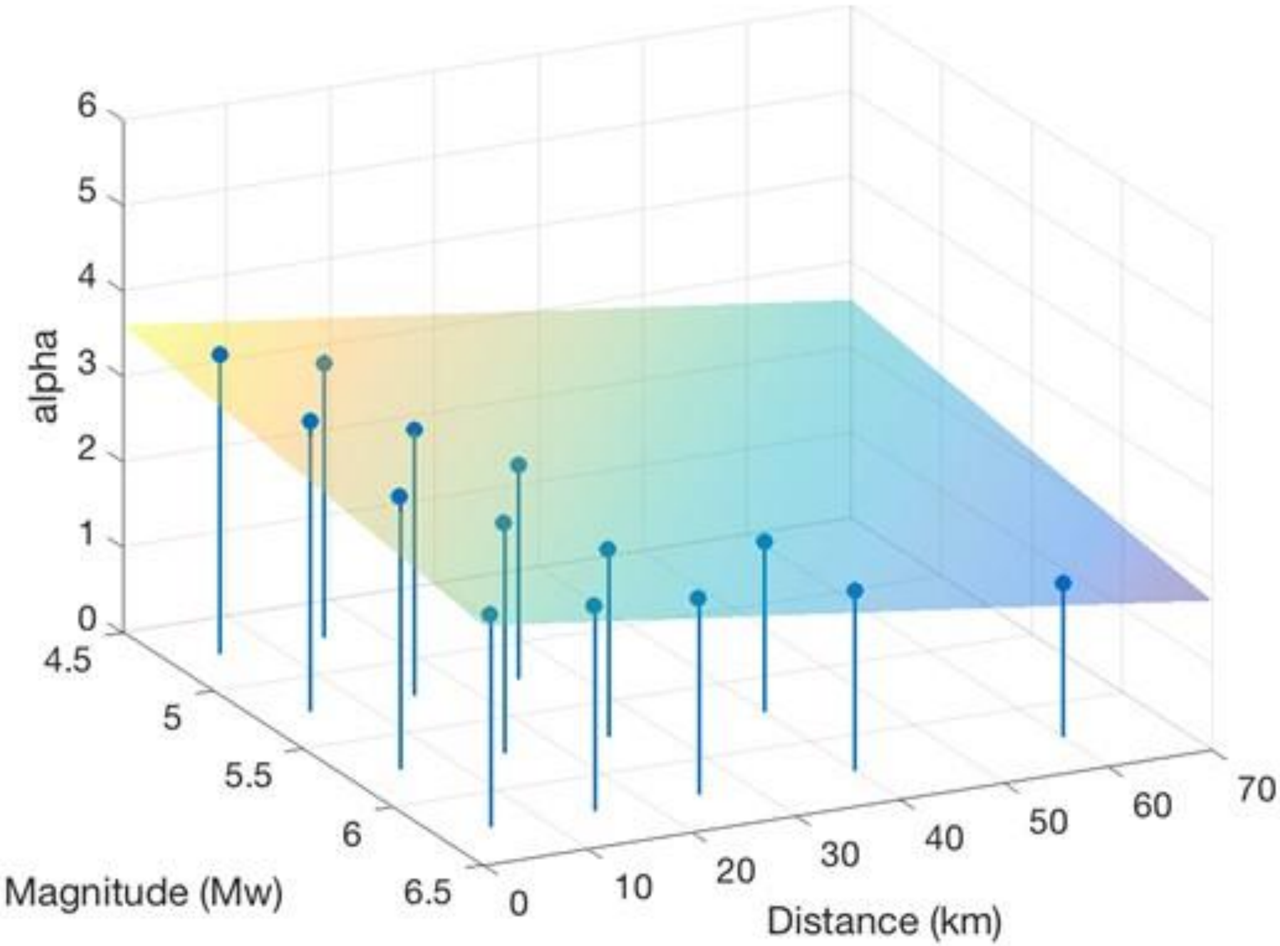
$$\alpha = k_{\alpha 0} - k_{\alpha 1}\left(M - 4.5\right) - k_{\alpha 2} r$$

Best fit

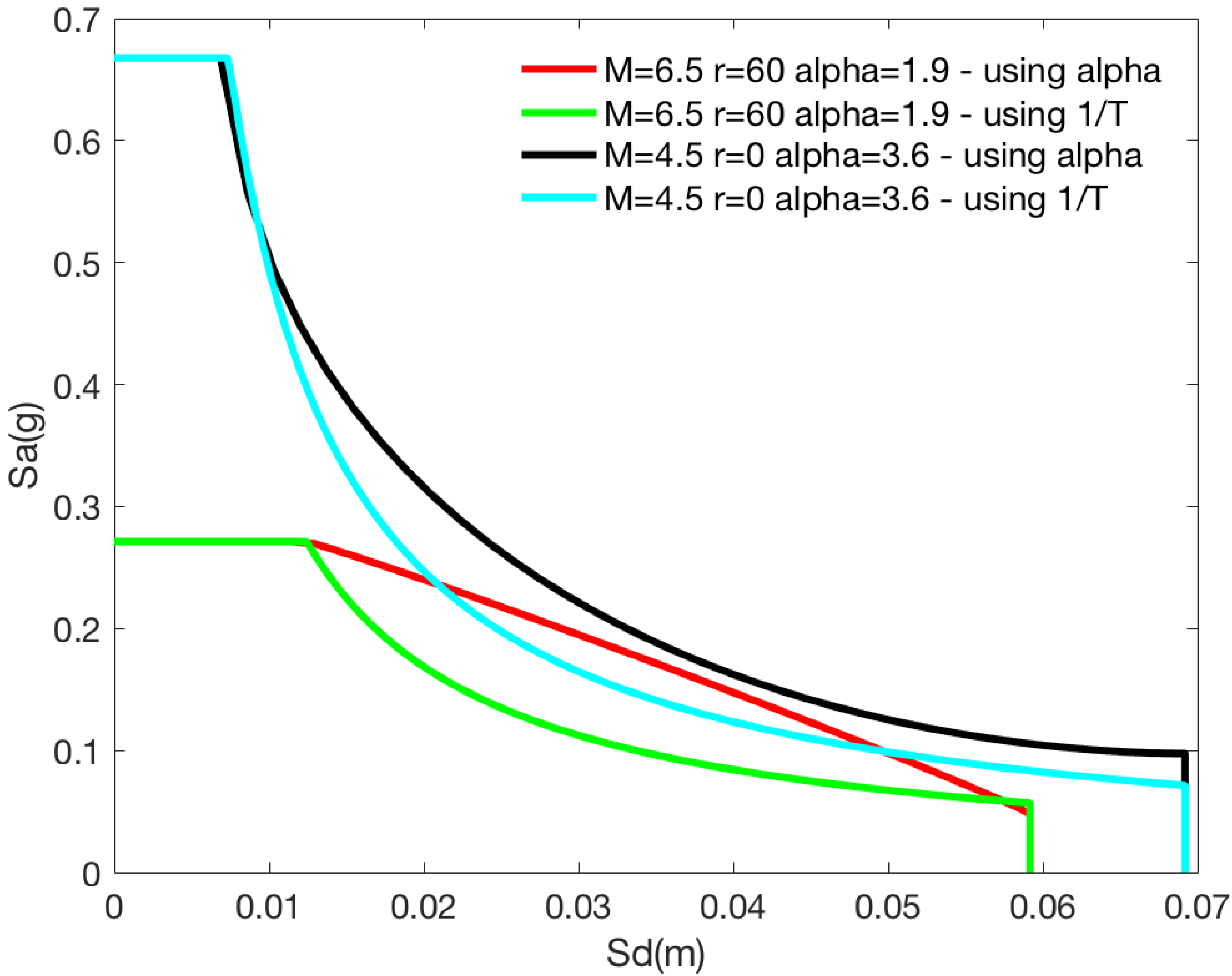
Best a value	r<10 km	10<r<20 km	20<r<30 km	30<r<50 km	50 km<r
6.0 < M < 6.5	2.5	2.4	2.3	2.1	1.8
5.5 < M < 6.0	3.2	2.7	2.2	2.0	-
5.0 < M < 5.5	3.4	3.1	2.5	-	-
4.5 < M < 5.0	3.5	3.2	-	-	-

$$\alpha = 3.6 - 0.4\,(M - 4.5) - 0.015r$$

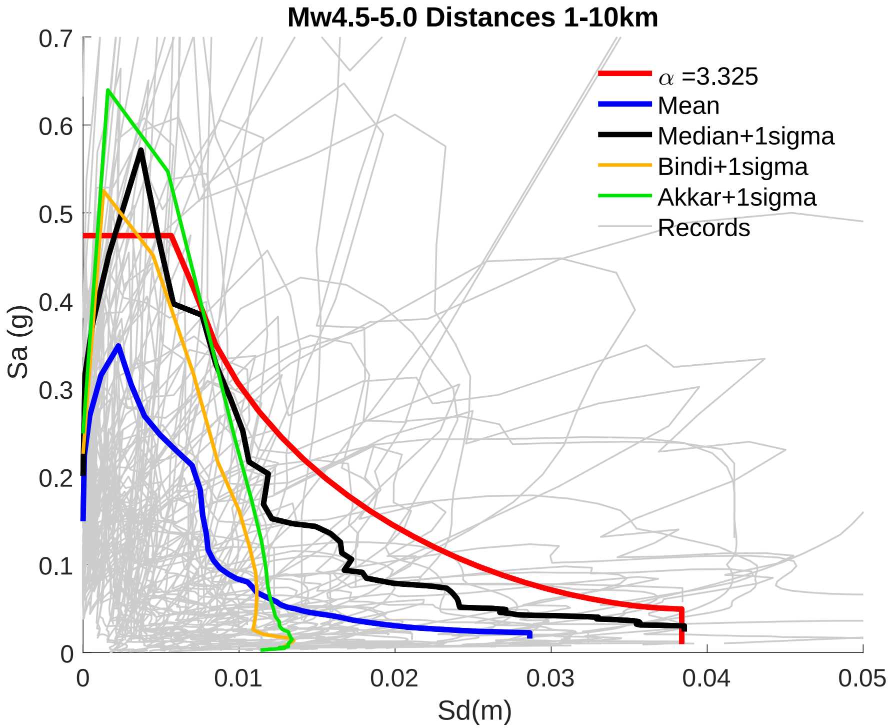
Best fitting surface of α

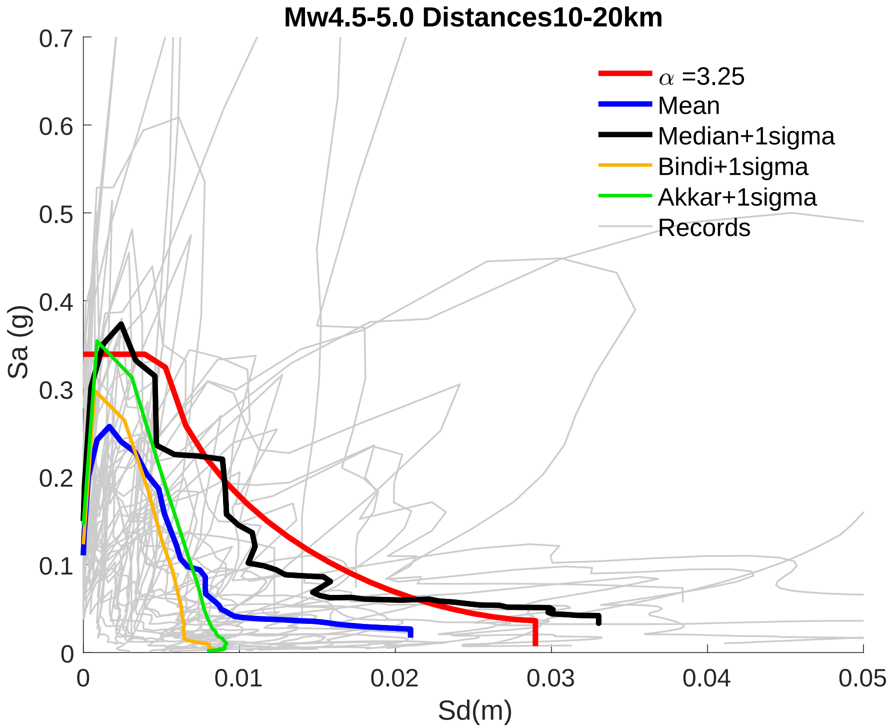


Variation of the spectral shape



Design spectra for 4.5 < M < 5.0
Compared with mean and +1σ spectra
Compared with Bindi and Akkar GMPEs





r < 10 km

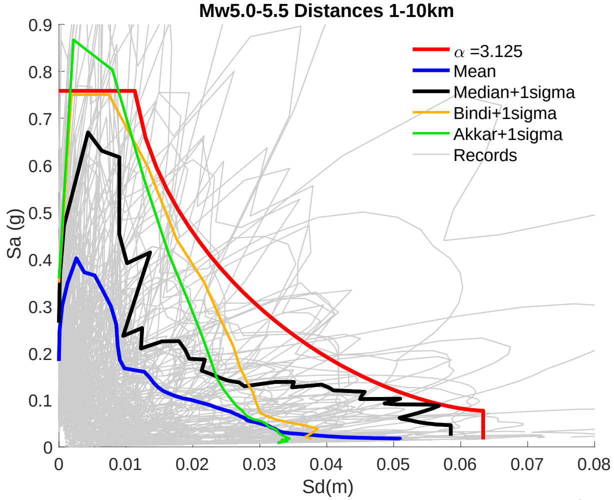
10 km < r < 20 km

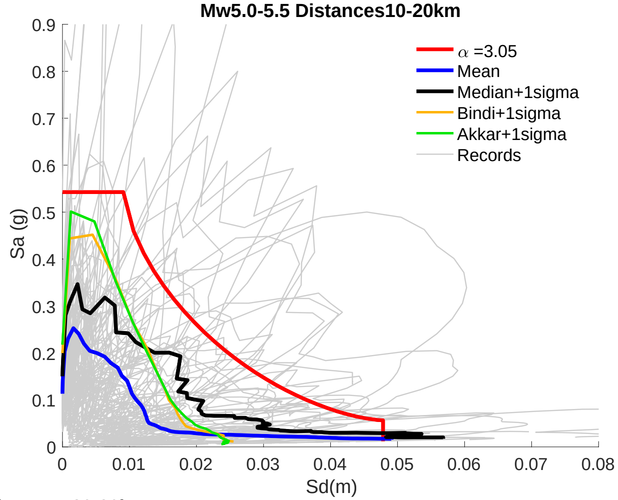
Design spectra for 5.0 < M < 5.5

Compared with mean and +1σ spectra

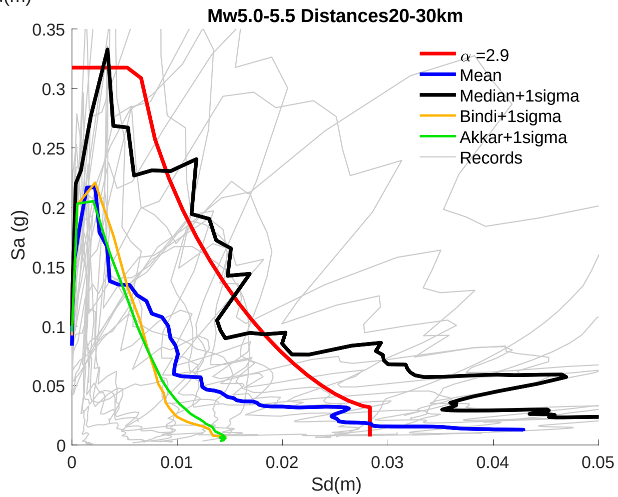
Compared with Bindi and Akkar GMPEs

r < 10 km





10 km < r < 20 km



20 km < r < 30 km

Design spectra for 5.5 < M < 6.0

Compared with mean and +1σ spectra

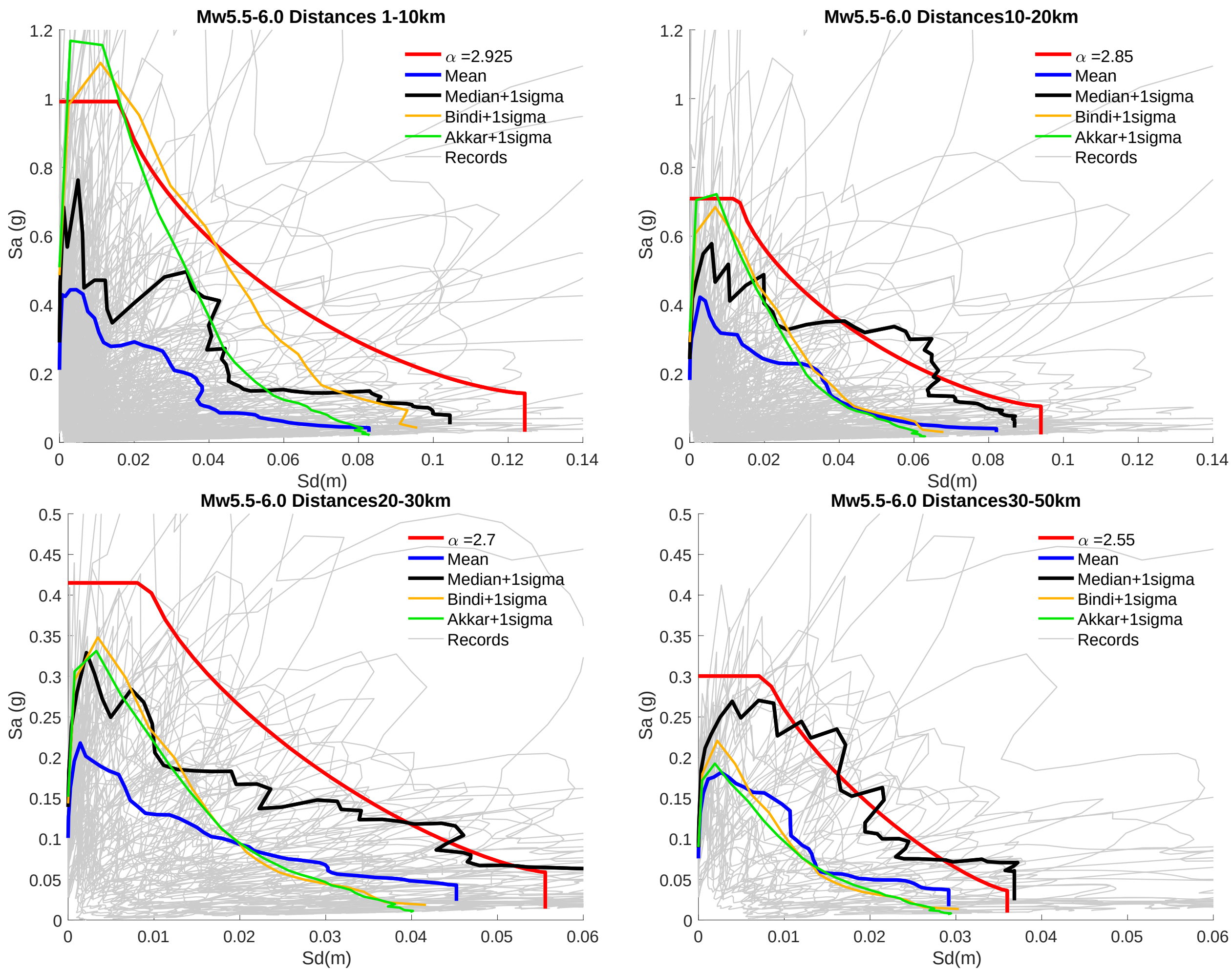
Compared with Bindi and Akkar GMPEs

< 10 km

10-20 km

20-30 km

30-50 km



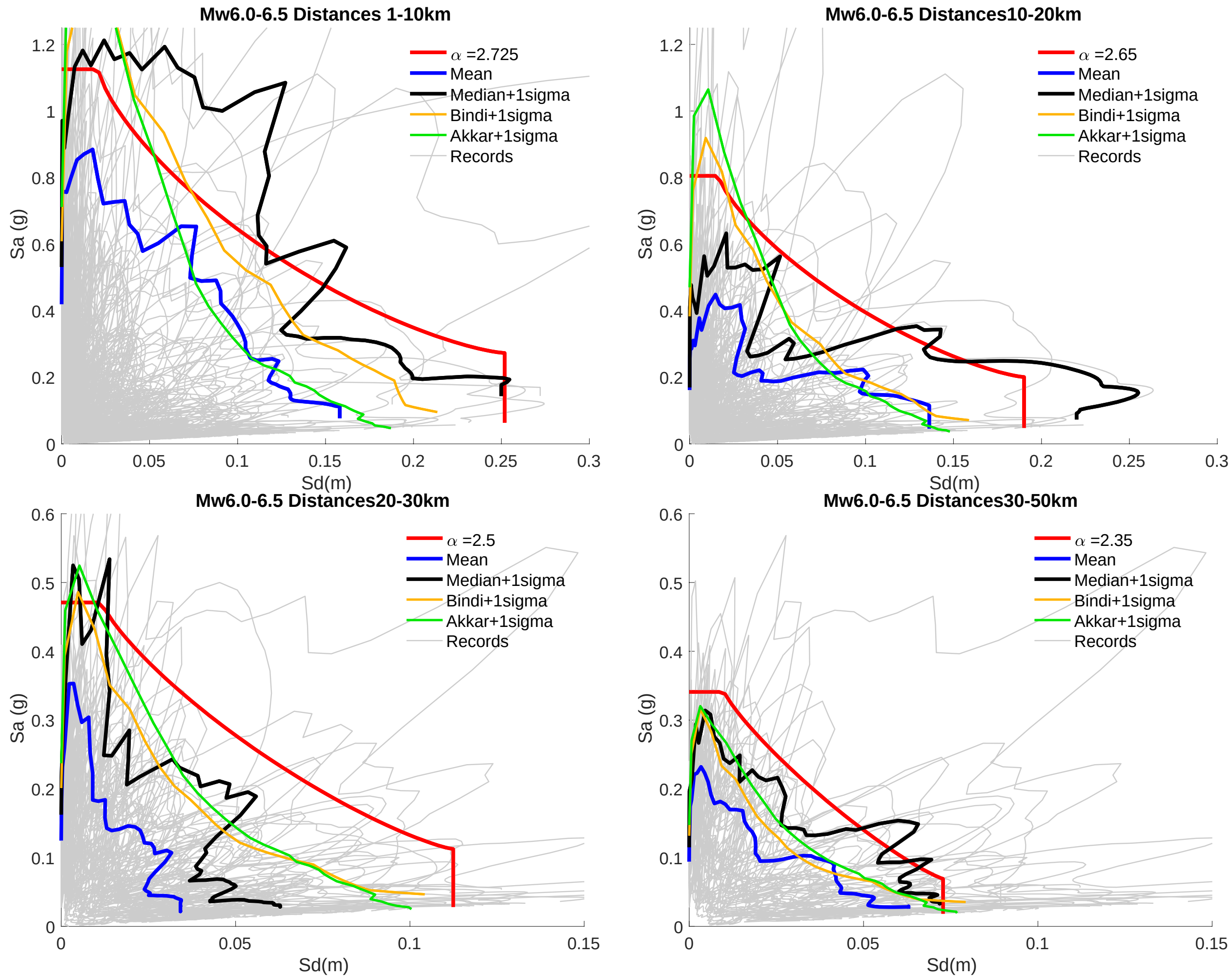
Design spectra for 6.0 < M < 6.5

Compared with mean and +1σ spectra

Compared with Bindi and Akkar GMPEs

< 10 km

10-20 km



20-30 km

30-50 km

- Performance very satisfactory
- Performance worse for low magnitude or long distance
- Performance worse when bins comprise a smaller number of records
- With acceleration amplification factor 2.5, peak values of spectral acceleration at 5 km corresponds to PGAs between 0.2 and 0.45 *g* for magnitudes between 4.5 and 6.5
- Spectral acceleration plateau do not capture single maximum recorded peaks
- Predicted maximum spectral displacements in line with DDBD at large magnitudes and small distances

Effects of spectra shapes on design (and assessment)

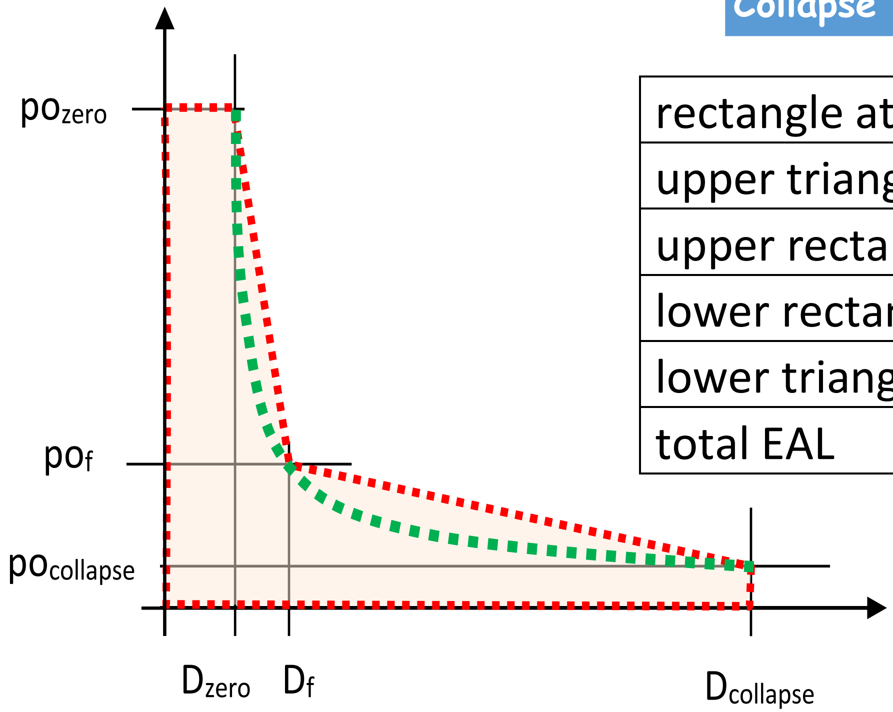
- definition of strength and displacement capacity to be attained in structural design: a rather casual business? differences of 100%
- enormous differences in the risk associated to different structures, even if they all might be above a certain threshold
- non linear time history analyses do not help in favoring a uniform risk level, since the input ground motions are derived from possibly biased design spectra
- strict application of capacity design rules fundamental

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

as a tool to design

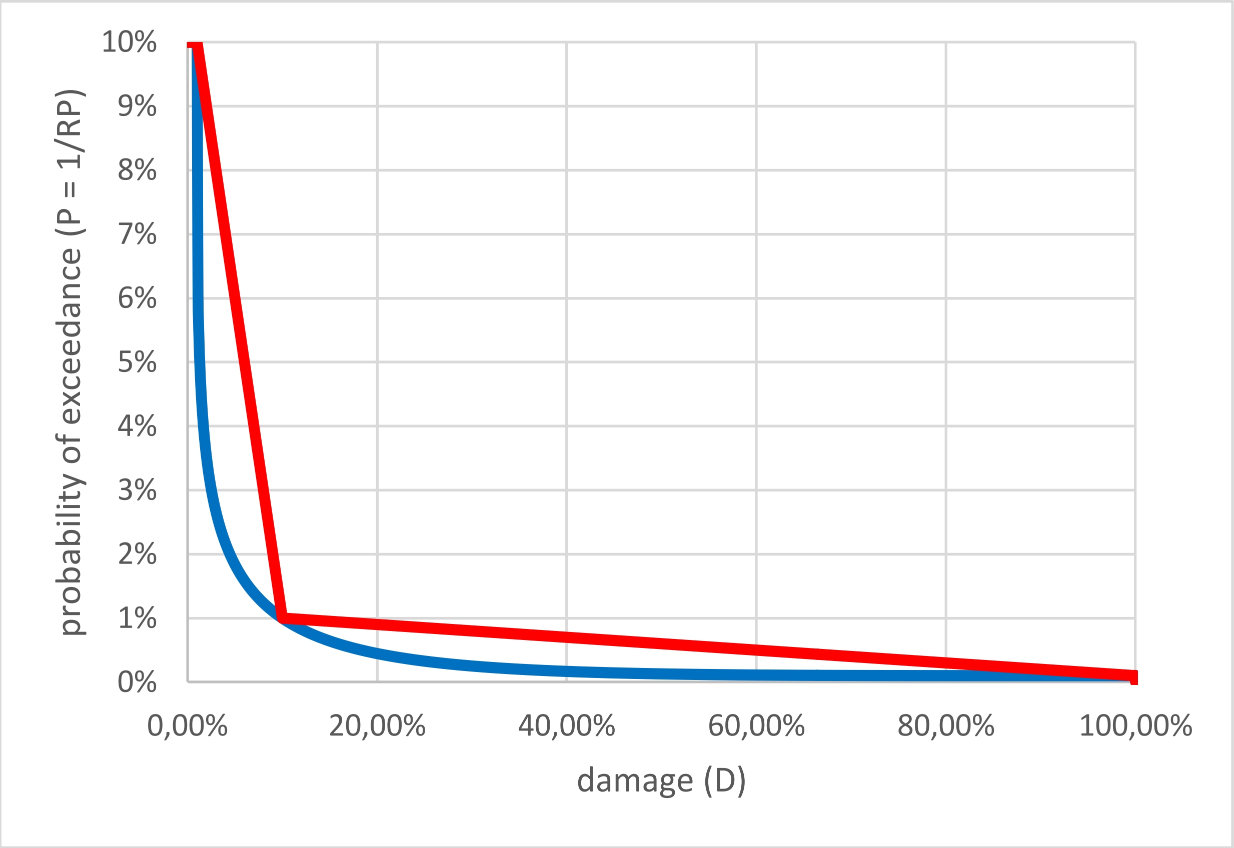
po = yearly probability of occurrence
D = level of damage
RP = return period (1/po)

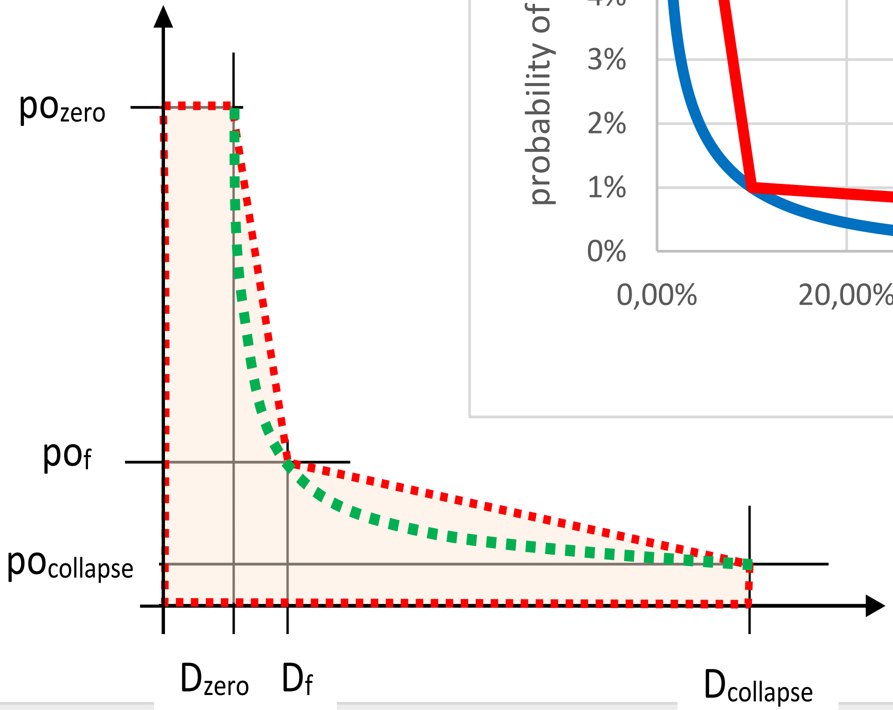
	D	RP	po
Onset of Damage (OD)	1%	10	0,1
Damage Control (DC)	10%	100	0,01
Collapse (NC)	100%	1000	0,001



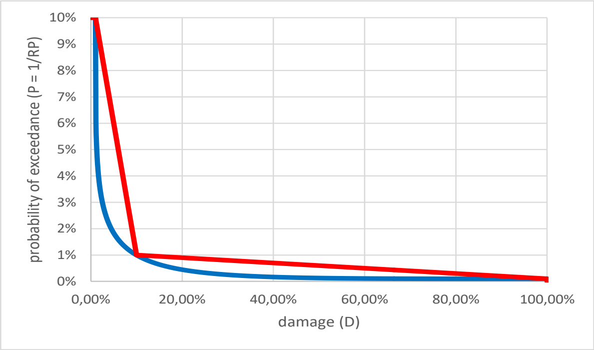
rectangle at the axes origin	0,10%	9,17%
upper triangle	0,41%	37,16%
upper rectangle	0,09%	8,26%
lower rectangle	0,09%	8,26%
lower triangle	0,41%	37,16%
total EAL	1,09%	100,00%

EAL as a tool to design





EAL as a tool to design



Derive an equation for the blue curve

Polynomial $$P = k_1 + k_2 D^{k_3}$$

With: $$P_{collapse} = k_1 + k_2$$

Or (simpler and better):

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

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

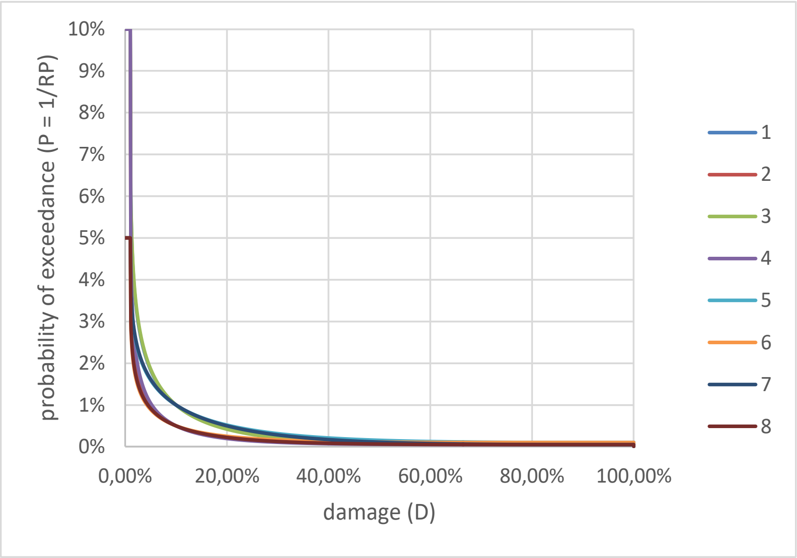
E.G.:

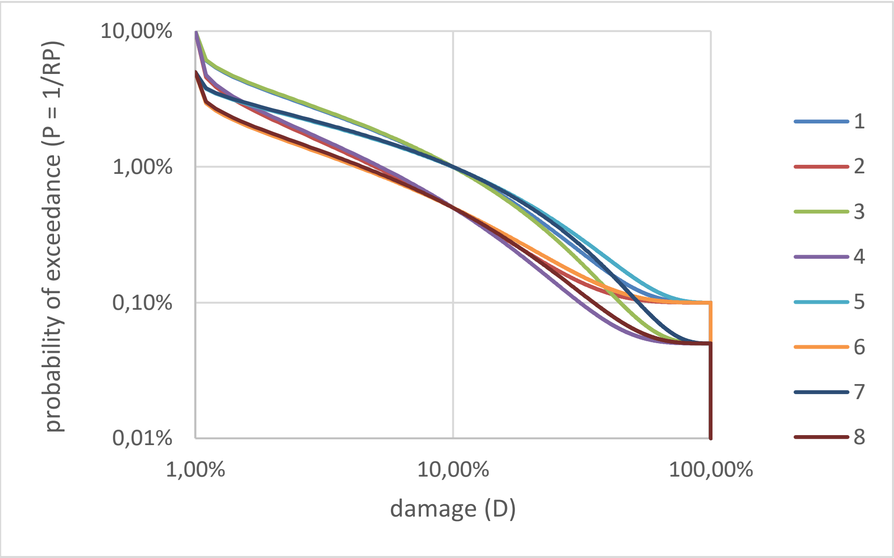
$D_{collapse}$ = 100%
D_{zero} = 1%
D_f = 10%

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

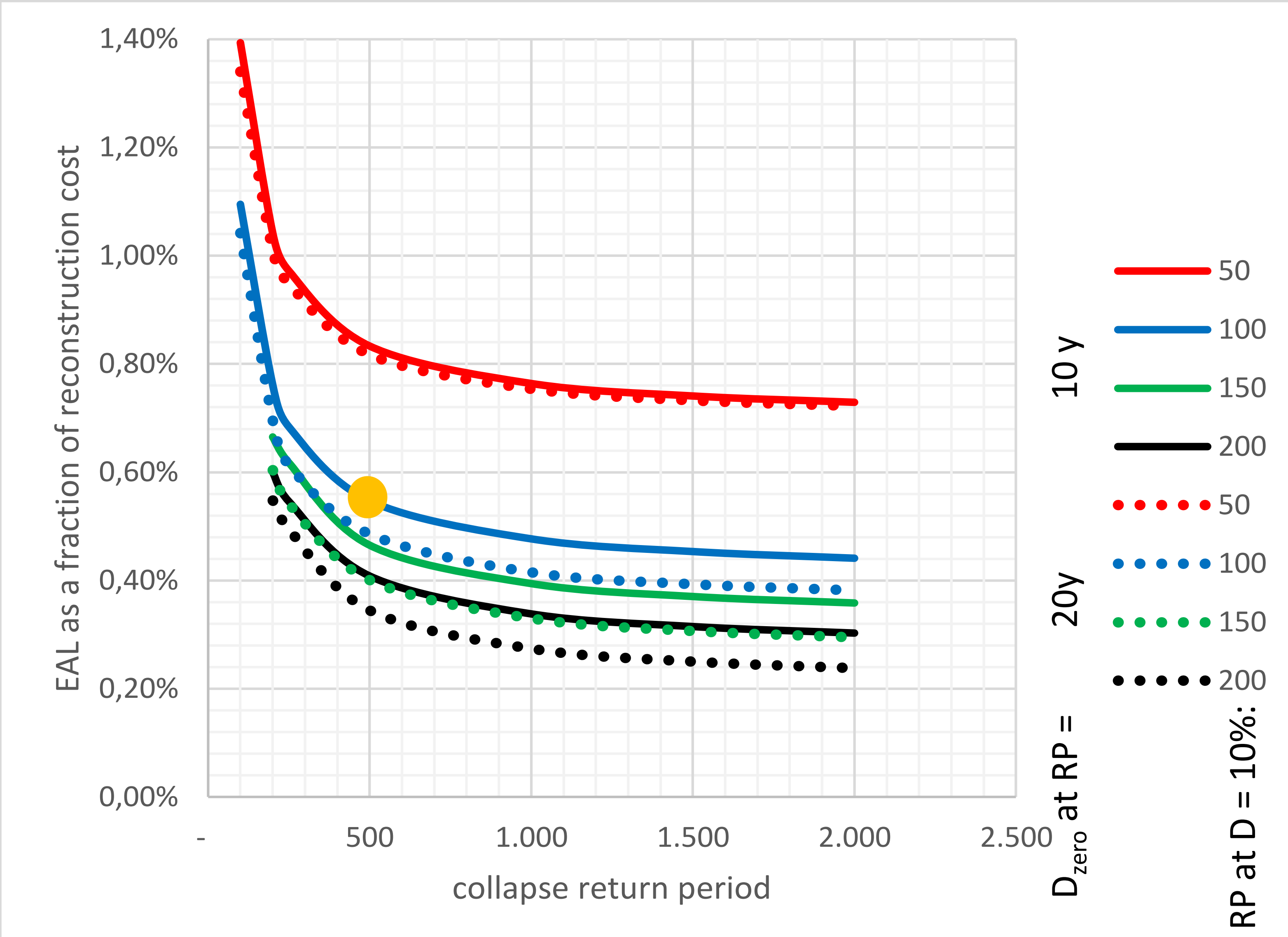
EAL as a tool to design

CASE	RP inducing D=1%	RP inducing D=10%	RP inducing D= 100%	α	EAL linear	EAL equation	Ratio
1	10	100	1000	6.92	1,09%	0,48%	44%
2	10	200	1000	8.03	0,84%	0,34%	40%
3	10	100	2000	6.85	1,07%	0,44%	41%
4	10	200	2000	7.88	0,77%	0,30%	39%
5	20	100	1000	5.85	0,82%	0,42%	51%
6	20	200	1000	7.07	0,57%	0,27%	48%
7	20	100	2000	5.77	0,79%	0,38%	48%
8	20	200	2000	6.92	0,52%	0,24%	46%





EAL as a tool to design



Definition of a capacity curve (including damping effects)

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

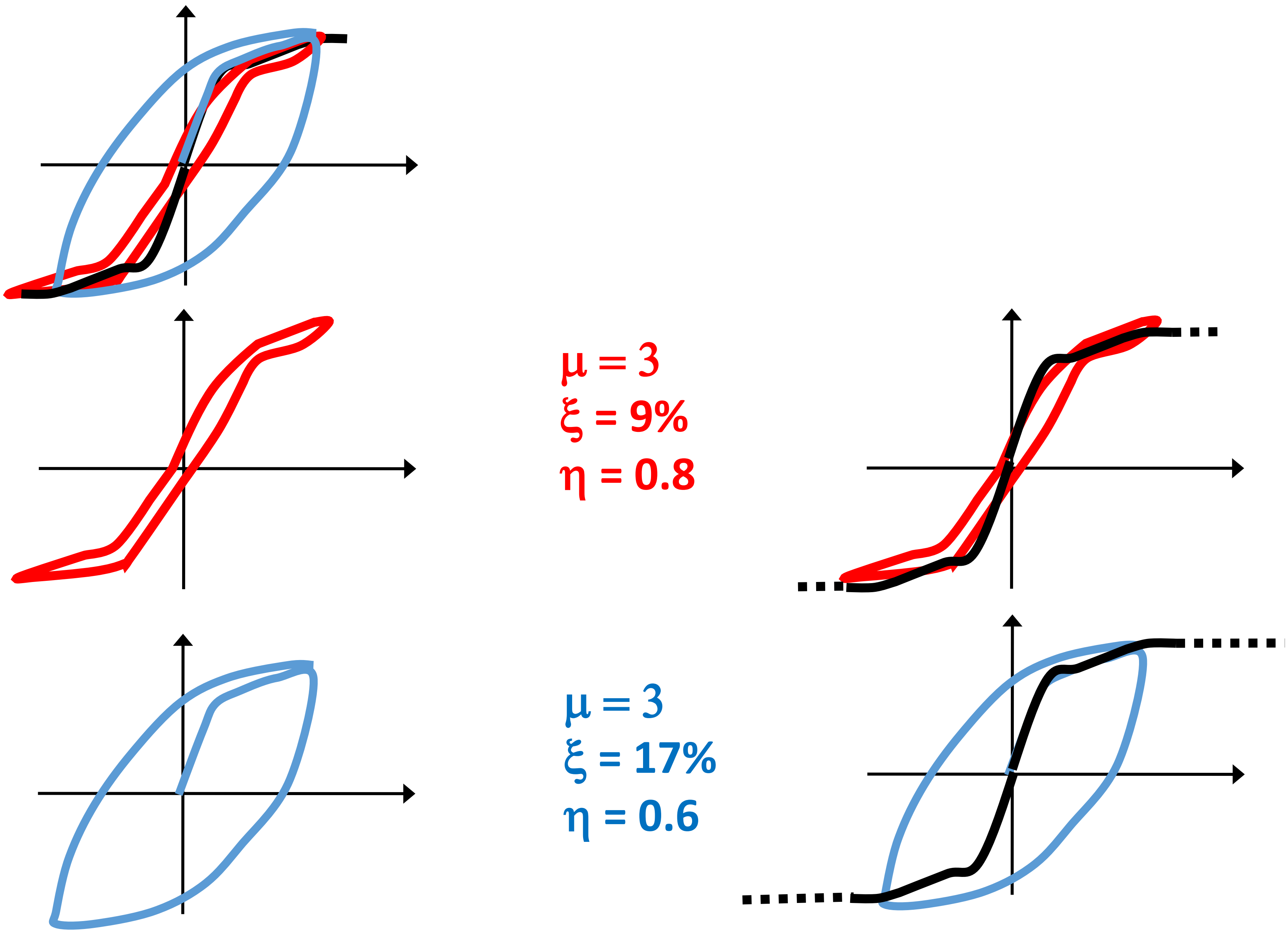
Concrete Frame Building (TF): $\xi_{eq} = 0.05 + 0.565\left(\frac{\mu - 1}{\mu\pi}\right)$

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): $\xi_{eq} = 0.05 + 0.519\left(\frac{\mu - 1}{\mu\pi}\right)$



$\mu = 3$

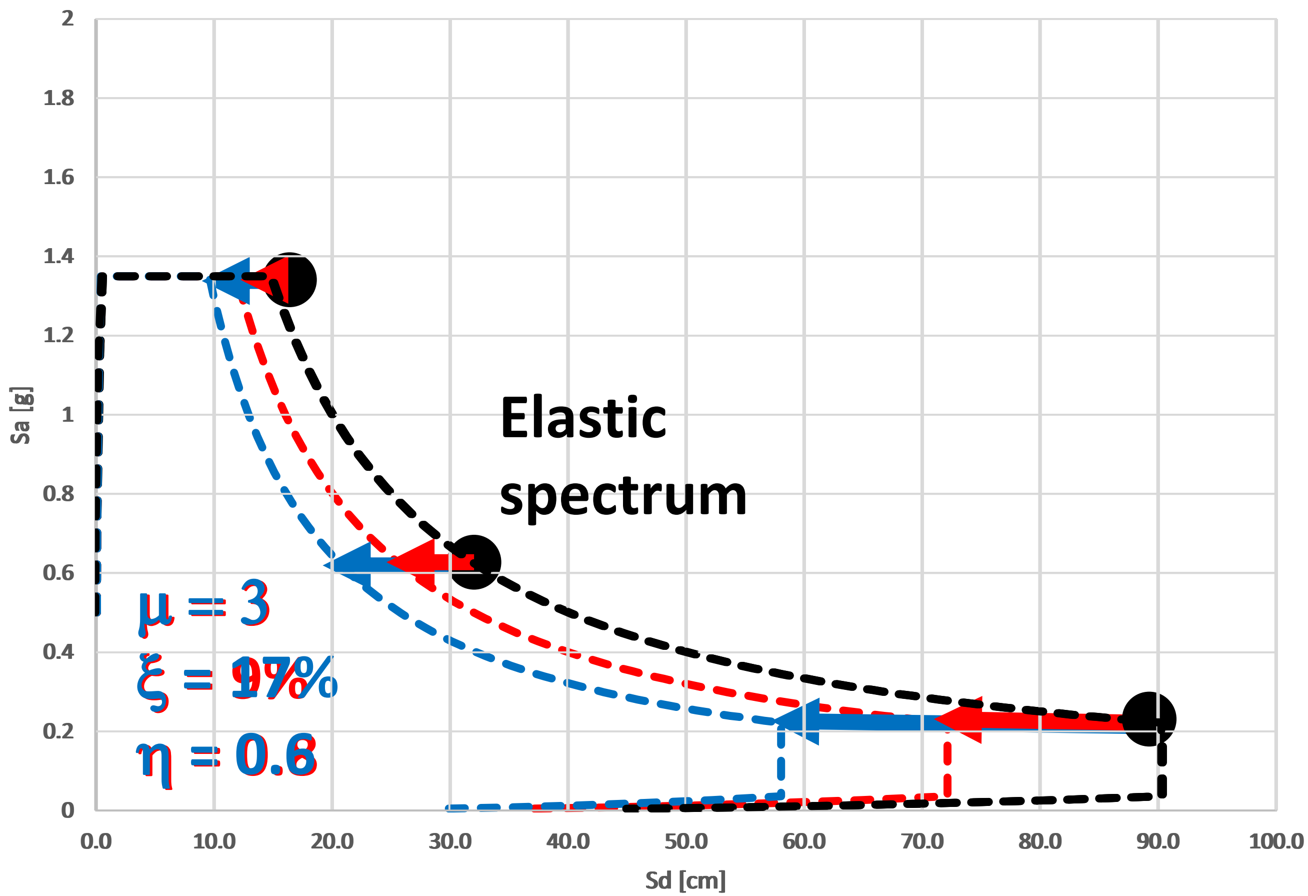
$\xi = 9\%$

$\eta = 0.8$

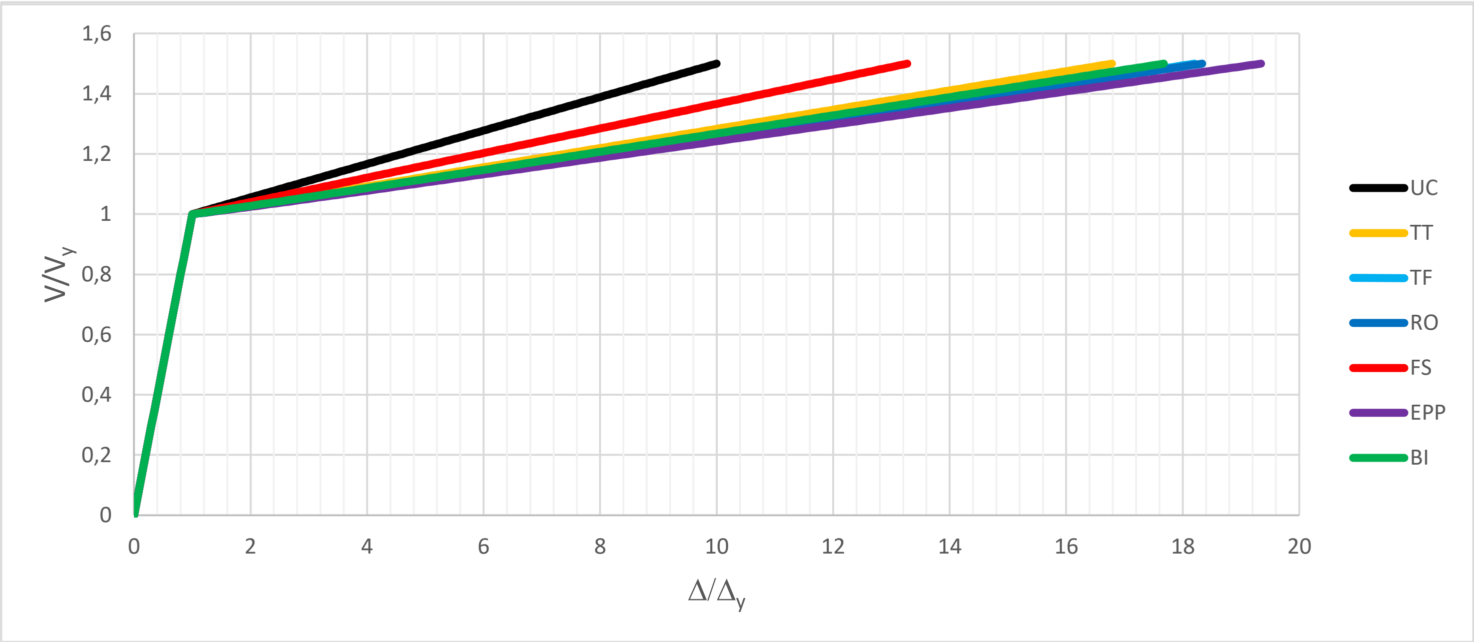
$\mu = 3$

$\xi = 17\%$

$\eta = 0.6$


Elastic spectrum
μ = 3
Sa [g]
Sd [cm]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0

Definition of a capacity curve (including damping effects)



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

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

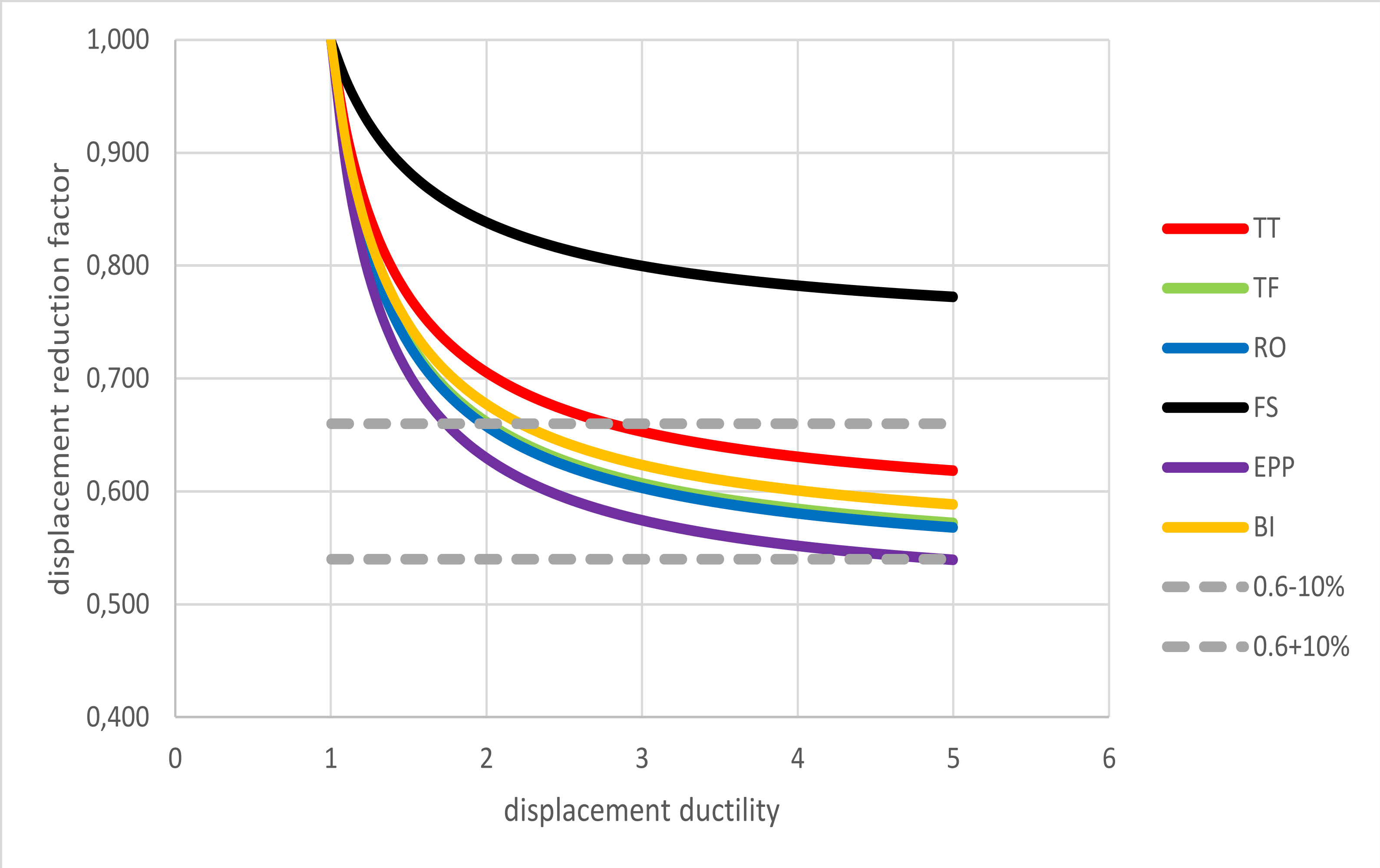
Steel Frame Building (RO): $\xi_{eq} = 0.05 + 0.577\left(\frac{\mu - 1}{\mu\pi}\right)$

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

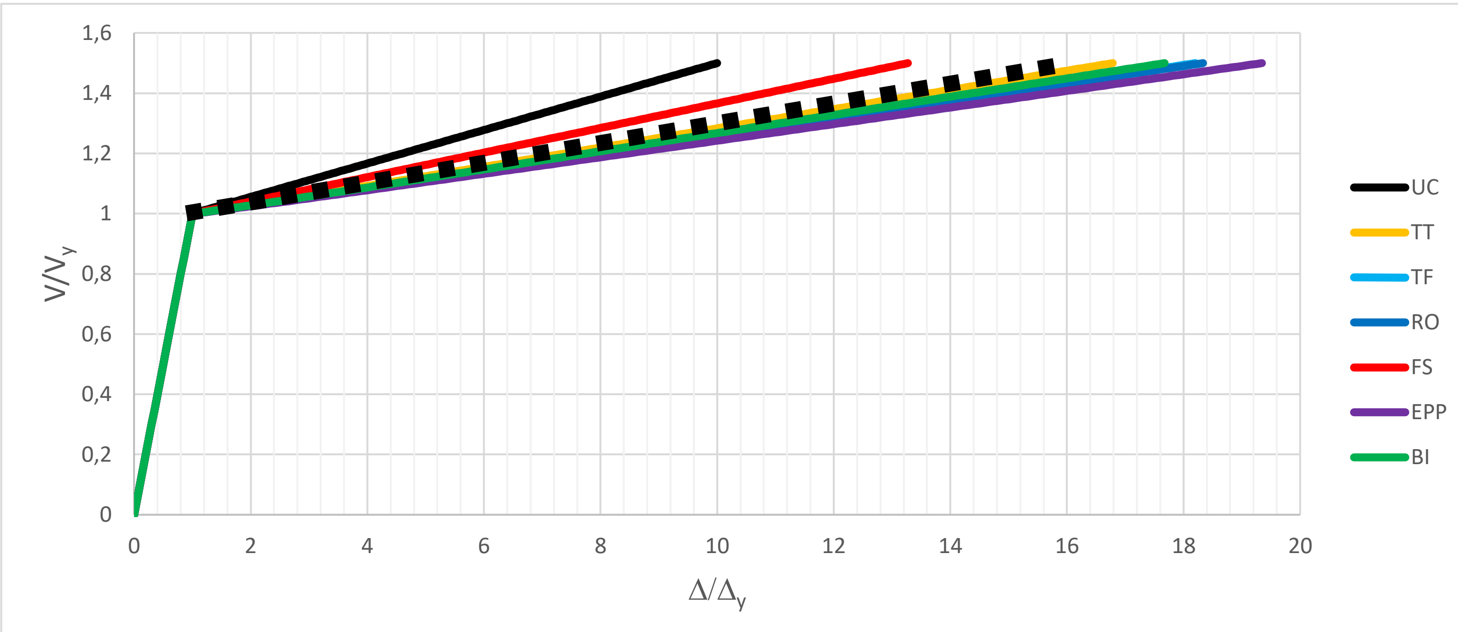
Friction Slider (EPP): $\xi_{eq} = 0.05 + 0.670\left(\frac{\mu - 1}{\mu\pi}\right)$

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

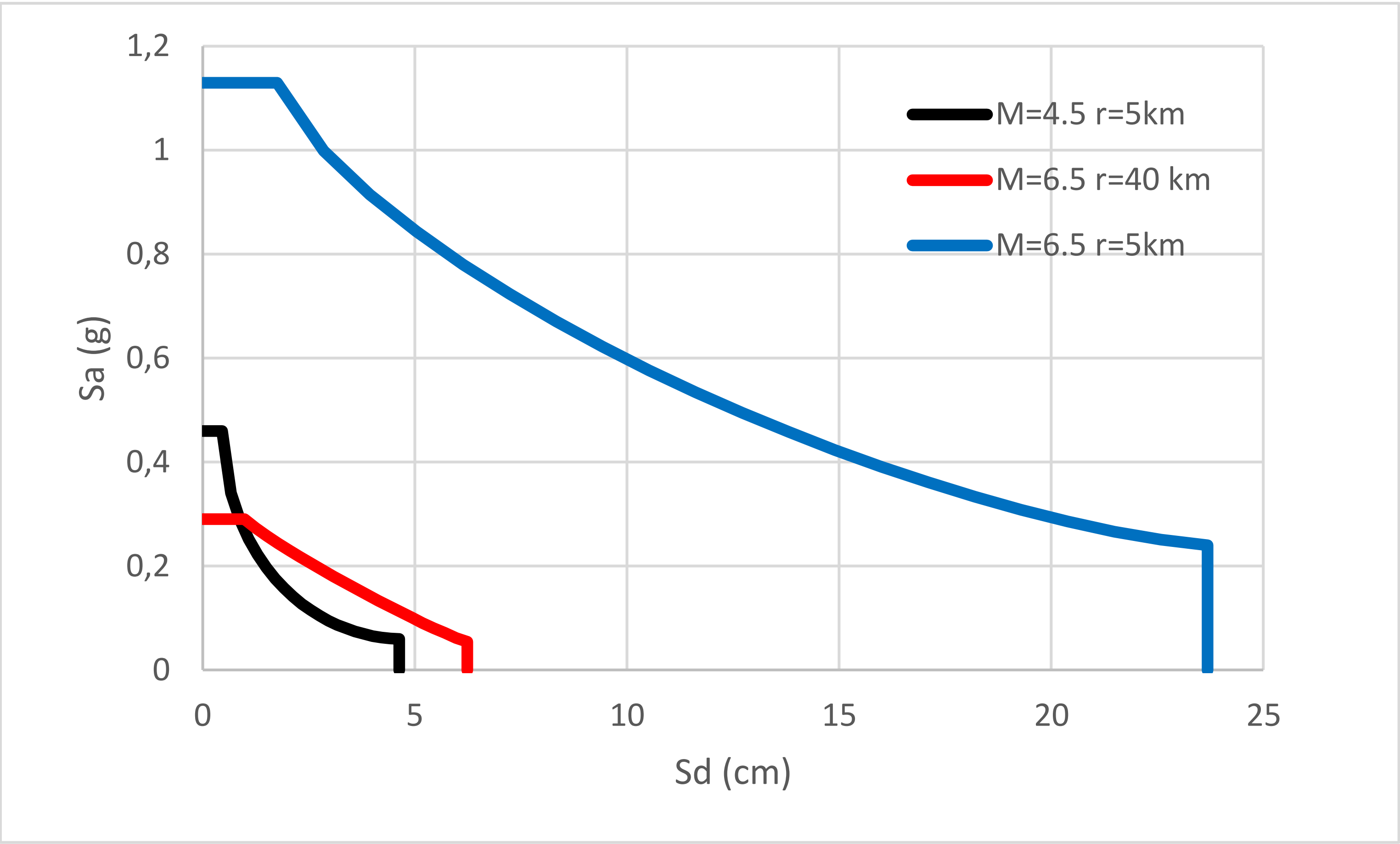
Definition of a capacity curve (including damping effects)



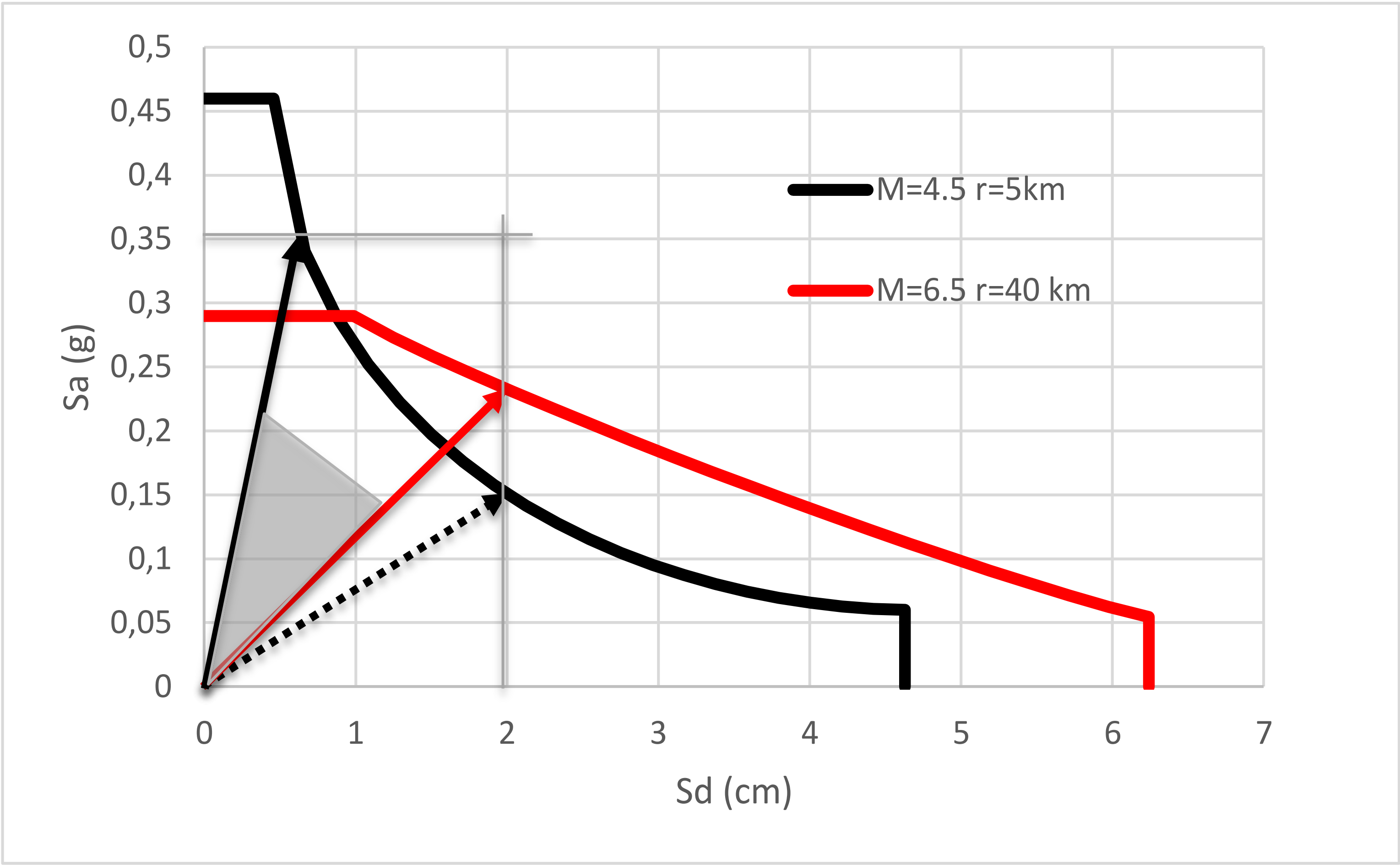
Definition of a capacity curve (including damping effects)



Effects of magnitude and distance
Possible different return period



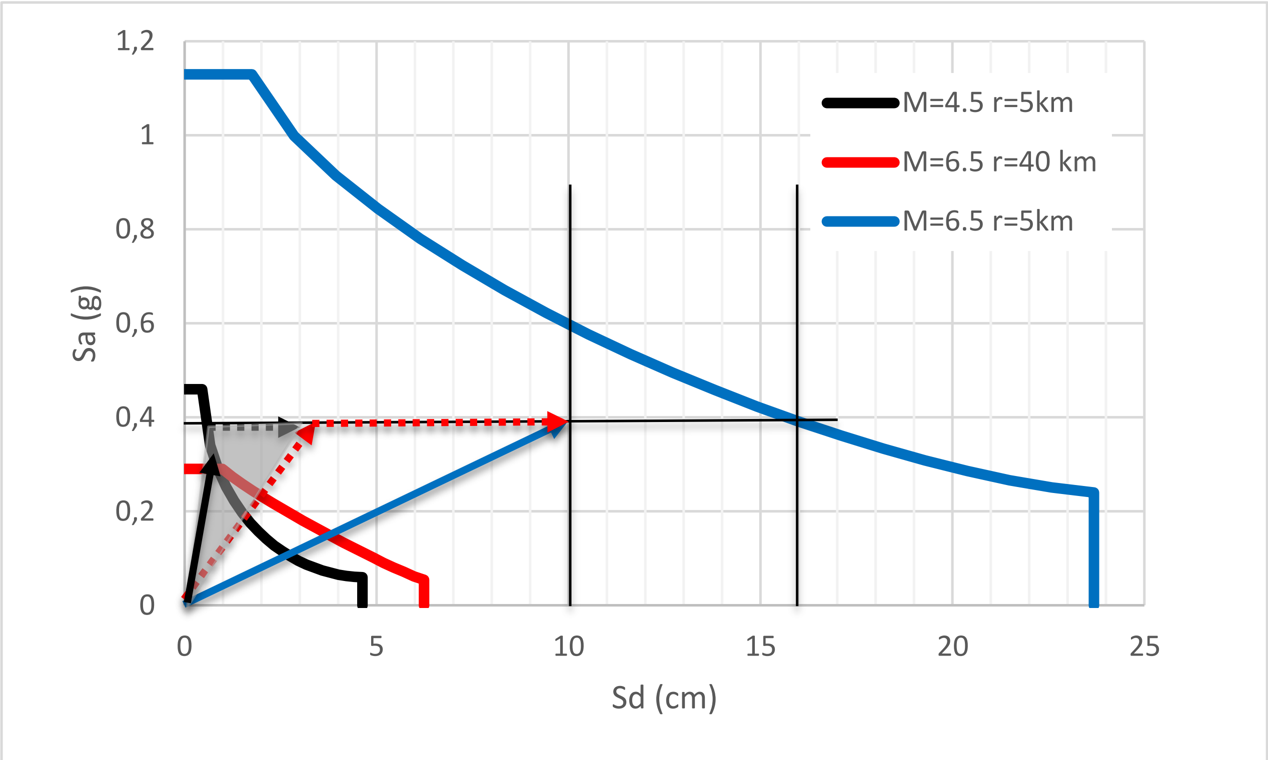
Design for frequent ground motion



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.

This input definition may foster a radical change in design philosophy, though still within a general displacement-based approach.

Progressive orientation of design towards damage limitations: to explore the possibility of a direct derivation of combined floor spectra.

The preliminary definition of a design displacement compatible with a desired damage level, possibly referred to specific classes of non-structural elements, may consent the immediate estimate of the corresponding energy dissipation and required strength.

The dependency of acceleration and displacement demand and spectral shape on magnitude and distance only should be investigated considering a much more extensive data base.

In the case of large earthquakes the distance to be considered is from epicenter, fault or focus?

The focal depth has some influence on the results?

The source mechanism and type of fault have an effect on the results or will these be included in the produced magnitude?

Local soil effect will have an impact on the spectra shape.
Recent studies demonstrate that the correction factors depends on the acceleration level.

Studies based on experimental and numerical data are under developments to provide appropriate correction factors.

Magnitude and distance have an effect on ground motion duration and number of relevant cycles.
This matter has to be included in the prediction equations, possibly together with effects of directivity.

Within the framework of design based on spectral demand and structure capacity, the effects of energy dissipation have been traditionally included in the demand side, correcting the spectra.

It seems more rational to define alternative rules to switch the consideration of dissipation on the side of capacity, consistently with its nature related to structure response, not to ground motion demand.

The equations derived can be regarded as a different form of ground motion prediction equations.
This may allow the derivation of innovative seismic hazard maps, passing directly from a probability assessment of potential events to the combination of spectra associated to each event to produce probability based design spectra.

The representation of design spectra in the combined $S_a - S_d$ form calls for the derivation of consistent ground motion time histories. Any correction to better fit a specific spectral region may be defined by an interval in both key parameters, rather than a period range.

El Centro ground motion, Imperial Valley earthquake, 18 May 1940

A fortunate unicorn or the ancestral ape of all possible ground motions?

Rather the opportunity for intelligent scientists to justify theories and models that were already in their minds