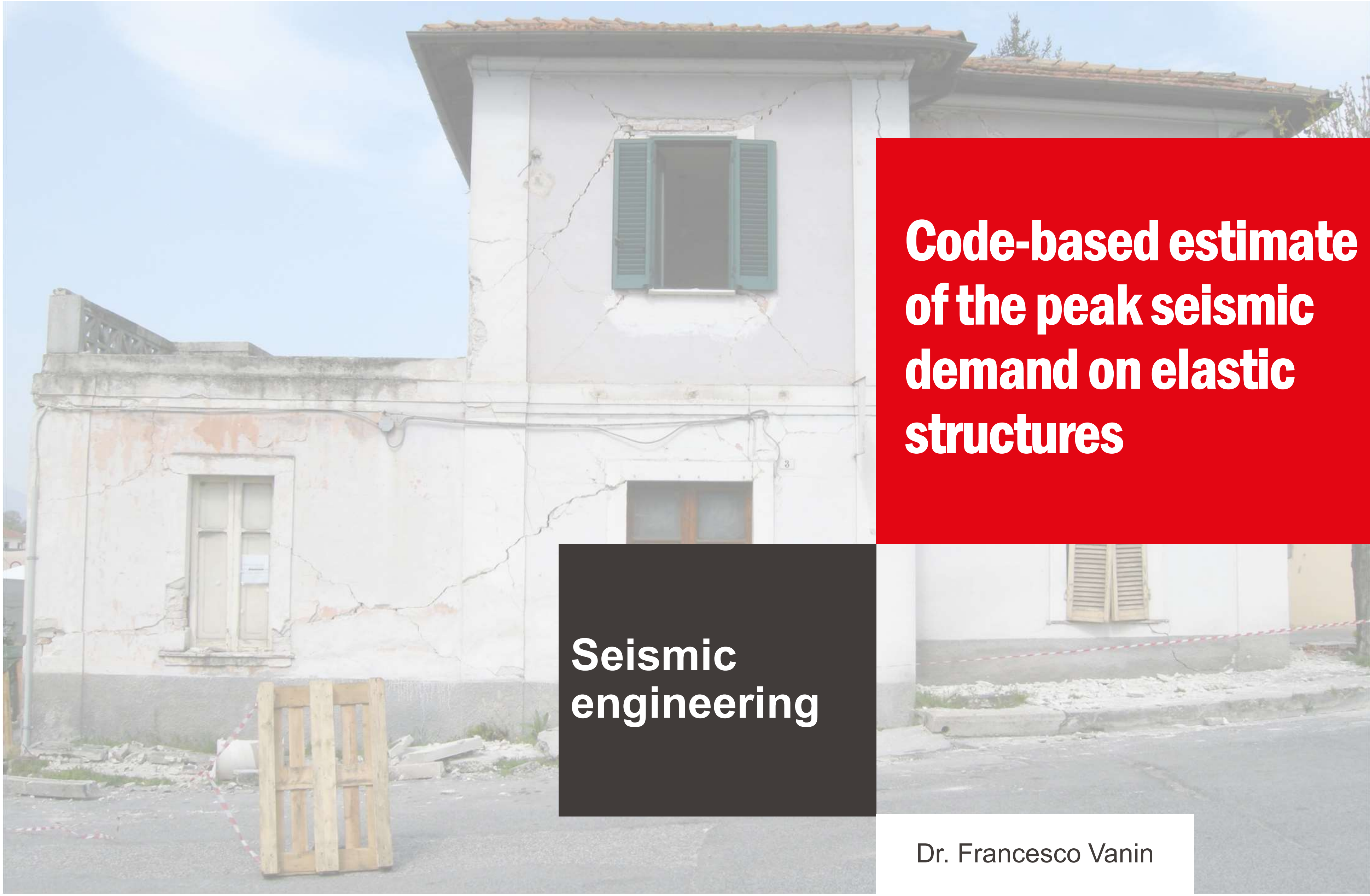


EPFL

Code-based estimate of the peak seismic demand on elastic structures

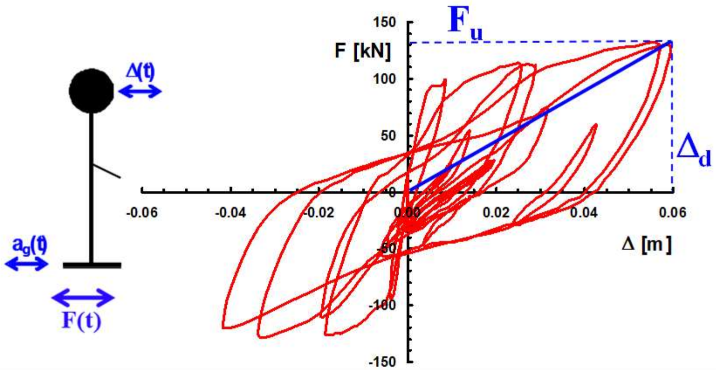
Seismic engineering

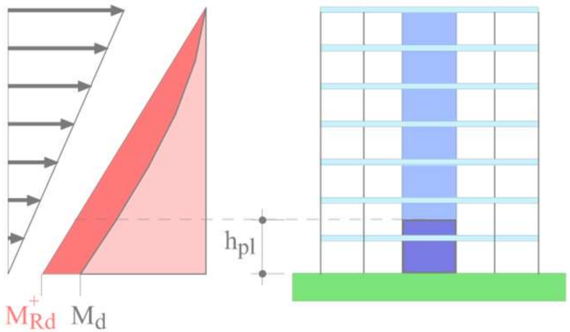
Dr. Francesco Vanin

Course objectives

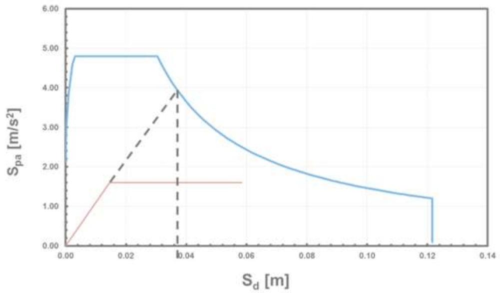
Know typical failure modes of structures during earthquakes.

Know how to estimate the peak forces and displacements of structures subjected to earthquakes.





Know how to design new buildings with reinforced concrete walls.



Know the basic elements of a displacement-based evaluation of existing structures.

Objective and Content

Objective:

- Know how to estimate the peak forces and displacements of elastic structures subjected to an earthquake.

Content:

- Response spectra for a given accelerogram
- Response spectra in the code SIA 261
- Formulae for estimating the fundamental period of a building

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Elastic response spectra

Elastic response spectra

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Definition « Response Spectra »

A response spectrum represents for SDOF systems with different periods, subjected to the same base acceleration, the maximum value of the absolute response for a certain damping coefficient.

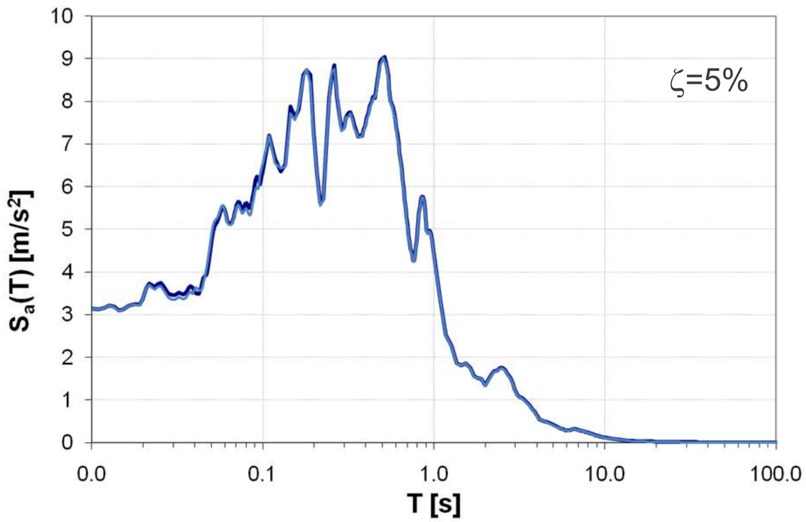
Response spectra can be calculated for many different quantities, e.g.:

- The absolute acceleration S_a
- The relative velocity S_v
- The relative displacement S_u
- The pseudo-acceleration S_{pa}
- The pseudo-velocity S_{pv}

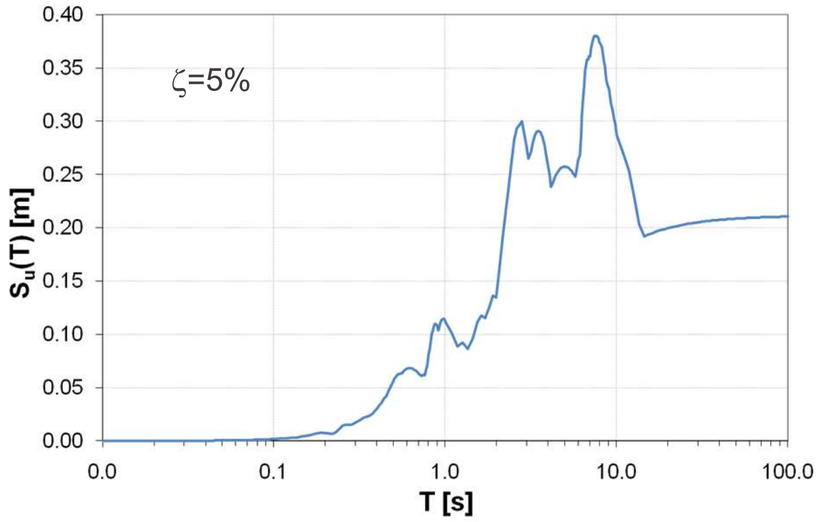
S_u and S_{pa} are the most frequently used spectral values.

Elastic response spectra

Response spectra for the **absolute** acceleration

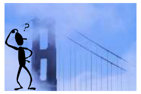


Response spectra for the **relative** displacement



Approximate relationship between S_a and S_u:

$$S_u(\omega) \cong \frac{1}{\omega^2} S_a(\omega)$$



One question…

Which of the following statements is correct?

A. For very flexible structures, the relative acceleration between mass and soil is zero and the relative displacement is not zero.

B. For very rigid structures, the absolute acceleration is zero and the relative displacement is also zero.

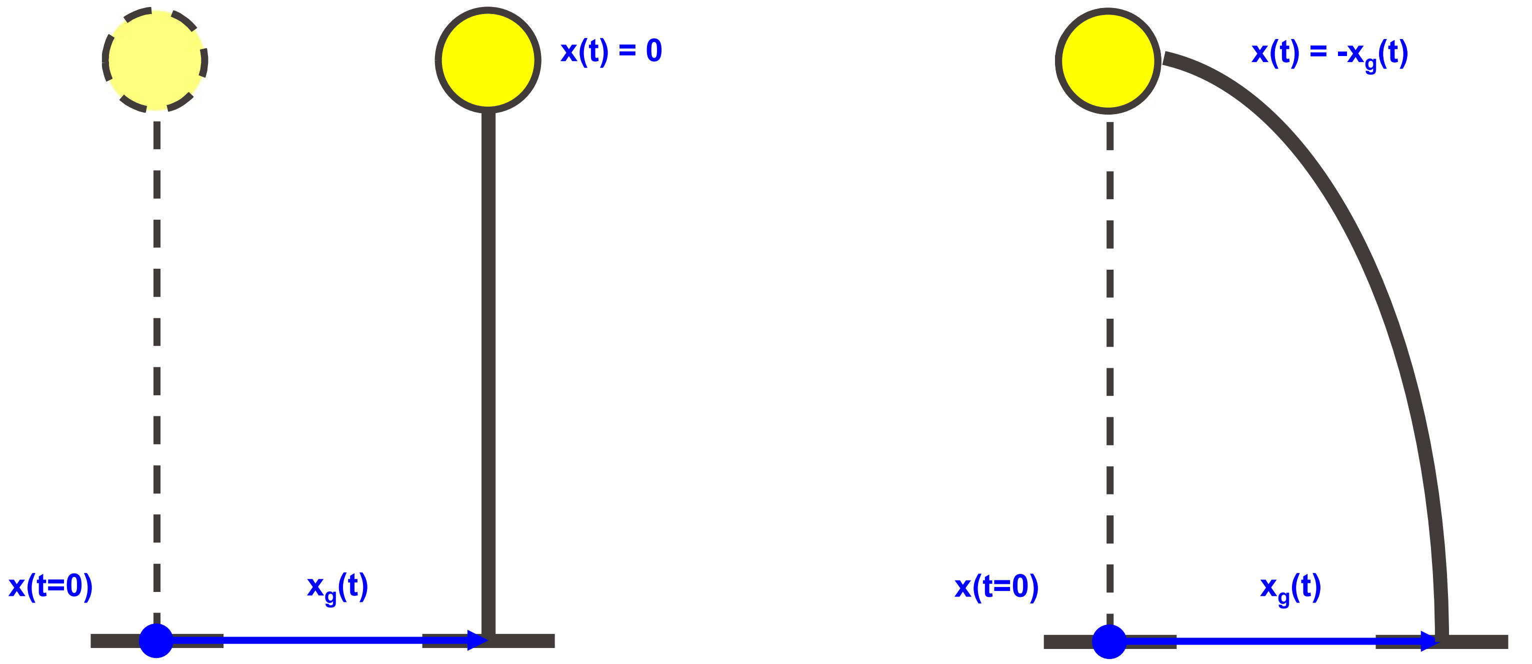
C. For very rigid structures, the absolute acceleration is zero and for very flexible structures, the relative displacement is zero.

D. For very flexible and very rigid structures the spectral values are independent of the damping ratio

Elastic response spectra: Limit values

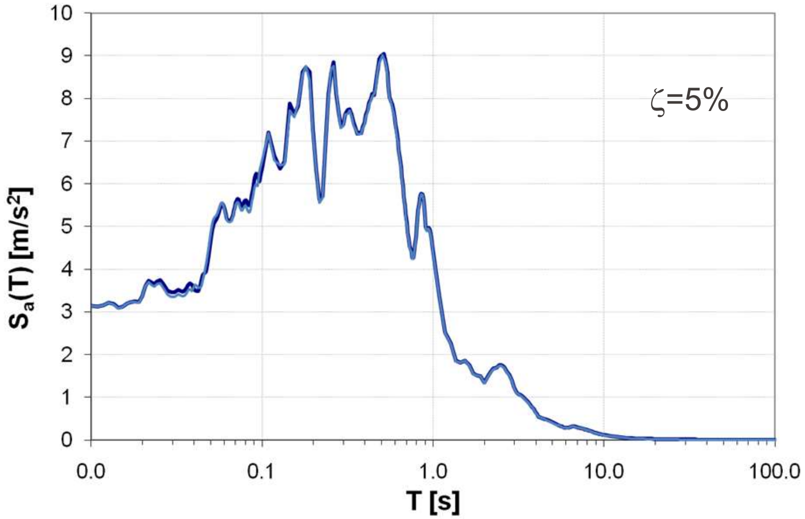
Very rigid systems
(f → ∞, T→ 0)

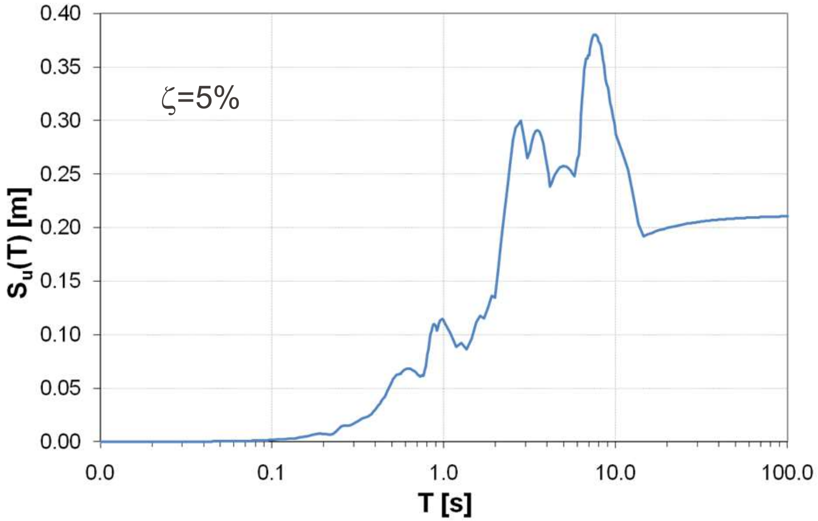
Very flexible systems
(f → 0, T→ ∞)



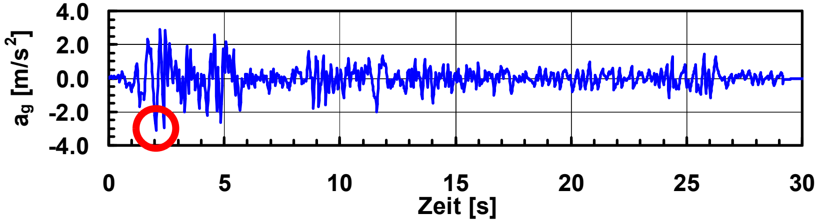
Elastic response spectra

Spectral values for T→0 and T→∞



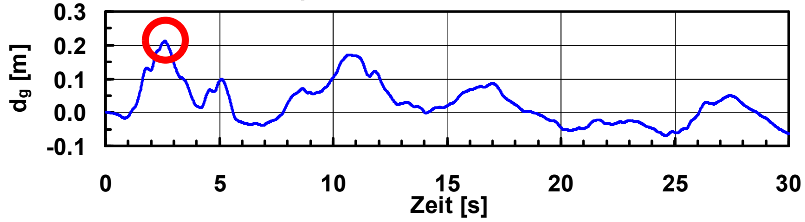


Ground acceleration



$a_{g,max}$ = 3.13 m/s²

Ground displacement



$d_{g,max}$ = 21.1 cm

Elastic response spectra

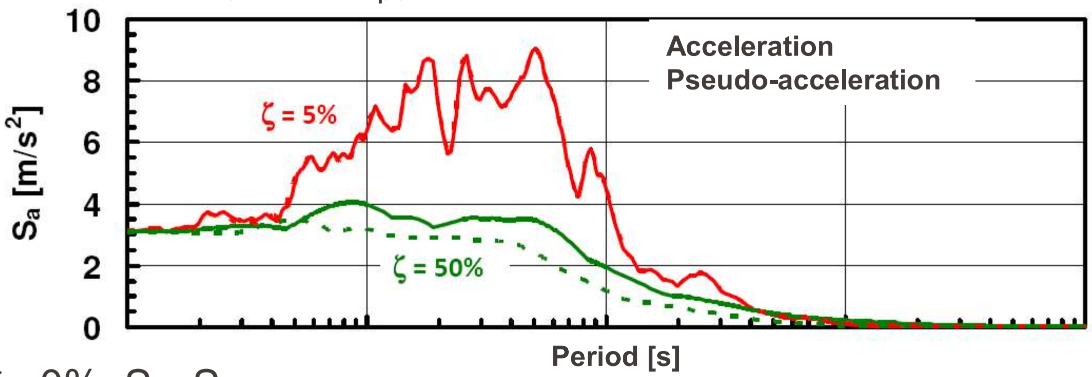
Pseudo-acceleration S_{pa}

Definition of the pseudo-acceleration: $S_{pa} \equiv \omega^2 S_u$

The pseudo-acceleration is a measure for the base shear:

$$F = kS_u = k\left(S_{pa} / \omega^2\right) = mS_{pa}$$

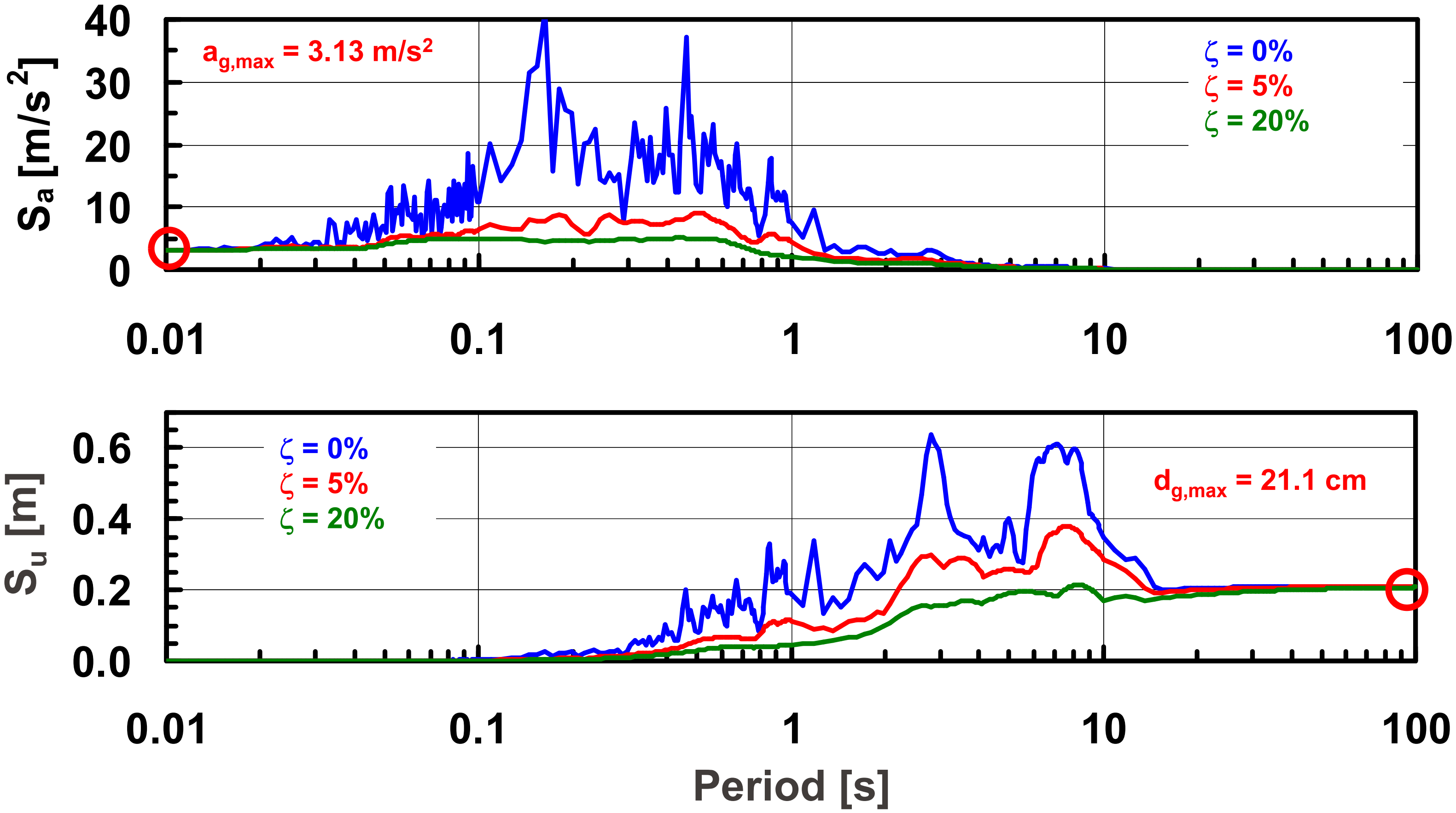
Relationship between S_a and S_{pa}:

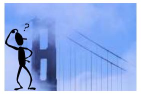


- Damping ζ= 0%: S_a=S_{pa}
- Damping ζ< ~20%: $S_a \approx S_{pa}$

Elastic response spectra

Effect of damping ratio on spectral values





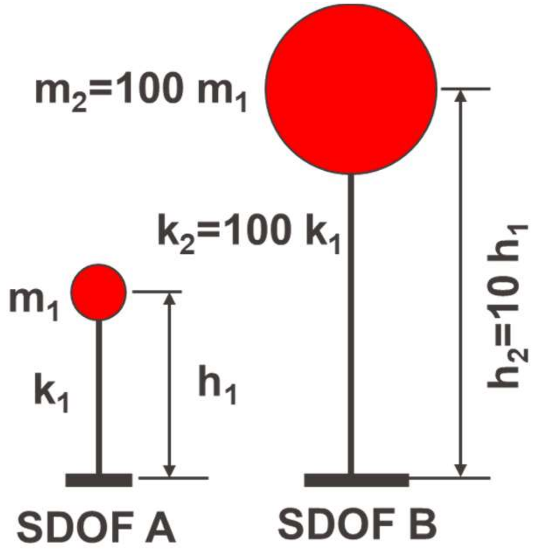
One question…

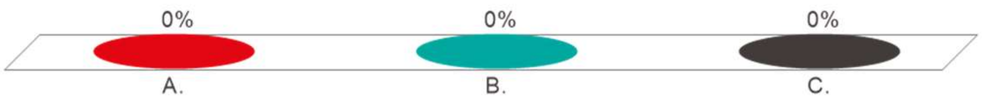
Two SDOF systems A and B are subjected to the same ground motion. Which of the following statements is correct? Assume for both structures the same damping ratio.

A. Both systems are subjected to the same top displacement.

B. System B is subjected to a larger displacement at the top because it is much taller.

C. System B is subjected to a smaller displacement at the top because it is much stiffer.





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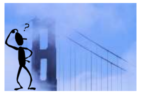


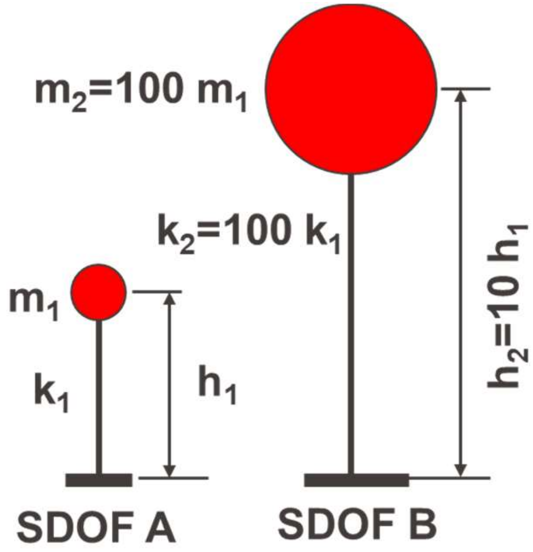
One question...

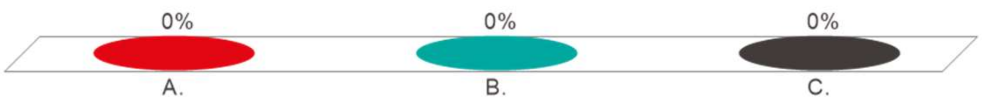
Two SDOF systems A and B are subjected to the same ground motion. Which of the following statements is correct? Assume for both structures the same damping ratio.

A. The absolute accelerations at the top and the base shear force is the same.

B. The absolute acceleration at the top and the base shear force of System B is larger than of System A.

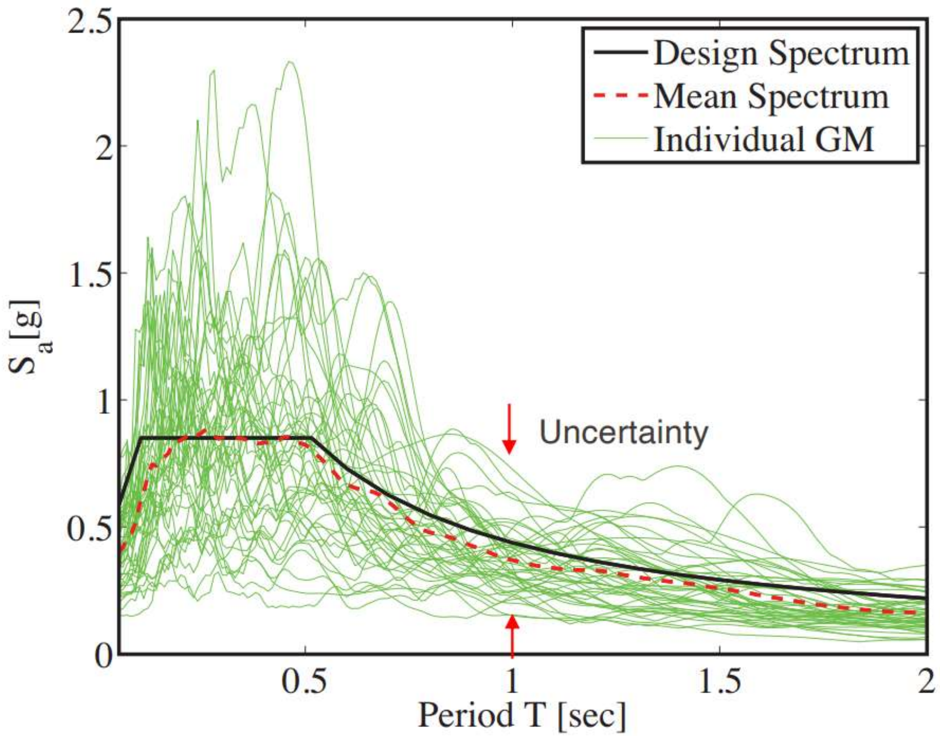
C. Both systems are subjected to the same absolute acceleration at the top, but the base shear force is not the same.

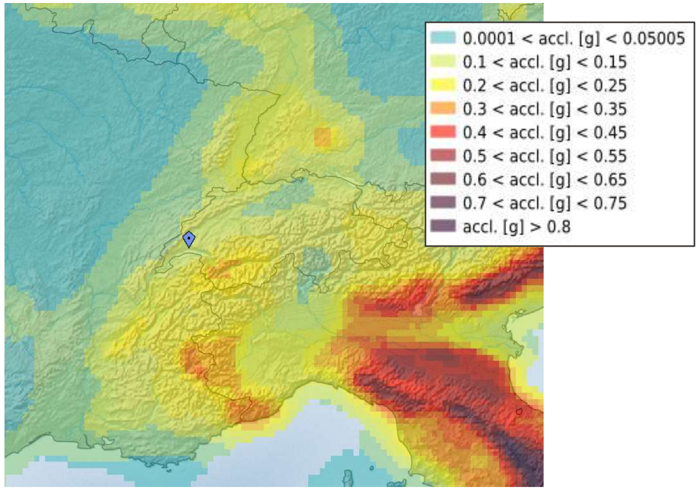


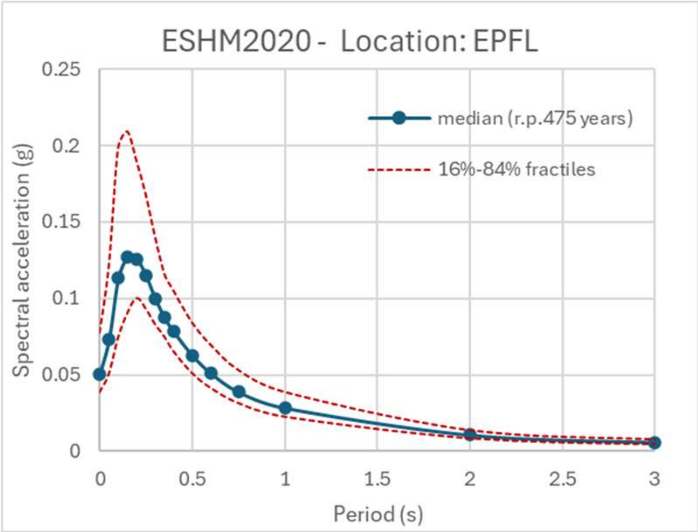


Elastic response spectra in the code SIA 261

Elastic spectra from hazard models







Elastic response spectra in SIA 261

Elastic response spectra in the Swiss code SIA 261

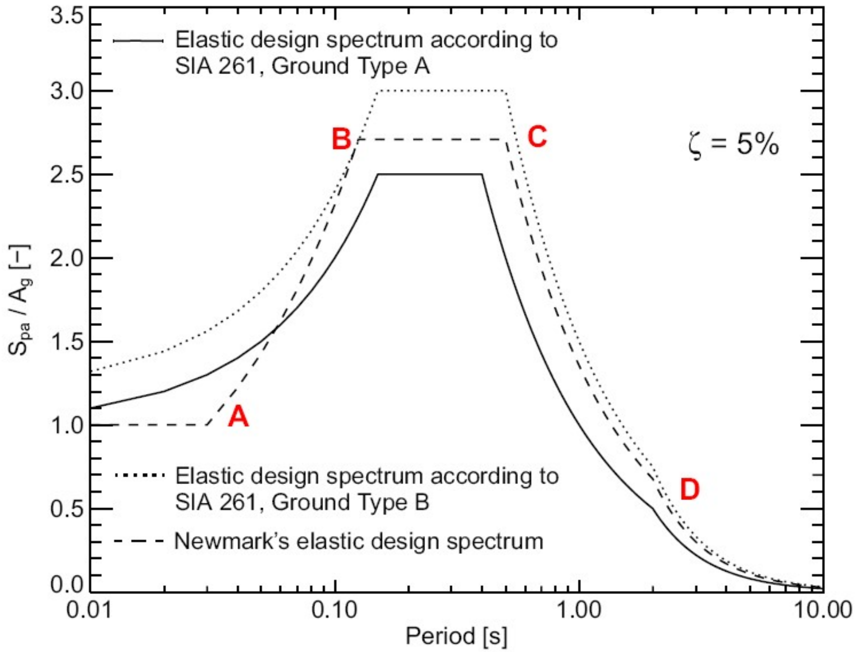
- Codes define the seismic hazard by means of response spectra.
- Spectra are defined for a return period of 475 ans → For this return period, structures should not collapse.

Objective:

- Know the shape of the acceleration and displacement response spectra as defined in SIA 261
- Know the parameters which are used to define the spectra

Elastic response spectra in SIA 261

- Elastic response spectra are typically based on Newmark spectra: Newmark N.M., Hall W.J. (1982) « Earthquake spectra and design », EERI Monograph, Earthquake Engineering and Research Institute, USA.
- Newmark spectra are smooth spectra.
- Often only three corner periods are used T_B, T_C, T_D (Newmark defined also a corner period T_A).



Newmark spectra:
$T_B<T<T_C$: S_{pa} constant
$T_C<T<T_D$: S_{pv} constant
$T_D<T$: S_u constant

Elastic response spectra in SIA 261

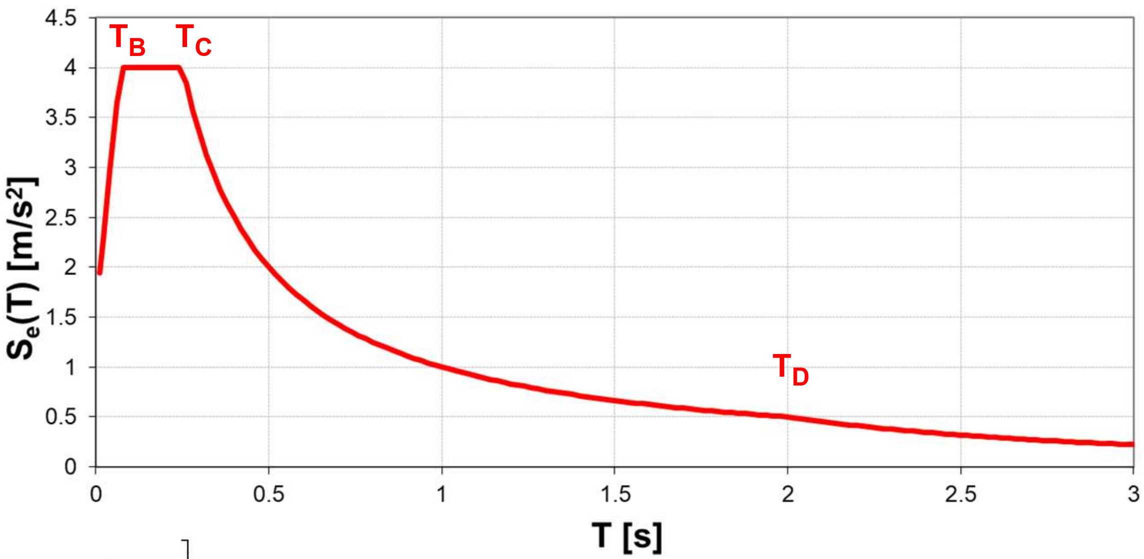
- Response spectra defined for horizontal pseudo-accelerations S_{pa}.
- Two types of spectra
  - Elastic response spectrum S_e (Notation in SIA 261: S_e=S_{pa})
  - Inelastic design spectrum S_d

- The elastic response spectrum is defined as a function of
  - Seismic zone (peak ground acceleration on rock a_{gd})
  - Soil class (corner periods T_B, T_C, T_D and soil parameter S)
  - Damping (parameter η)

- The spectrum of the vertical component of the ground motion can be estimated as 0.7 x the horizontal spectrum.

Elastic response spectra in SIA 261

Definition of elastic response spectrum in SIA 261



$$S_e = a_{gd}\, S \left[1 + \frac{(2{,}5\,\eta - 1)\,T}{T_B} \right] \qquad (0 \le T \le T_B)$$

$$S_e = 2{,}5\; a_{gd}\, S\, \eta \qquad (T_B \le T \le T_C)$$

$$S_e = 2{,}5\; a_{gd}\, S\, \eta\, \frac{T_C}{T} \qquad (T_C \le T \le T_D)$$

$$S_e = 2{,}5\; a_{gd}\, S\, \eta\, \frac{T_C\, T_D}{T^2} \qquad (T_D \le T)$$

a_{gd} = Peak ground acceleration on rock (dependent on seismic zone Z1a, Z1b, Z2, Z3a, Z3b)

S = Parameter for soil class

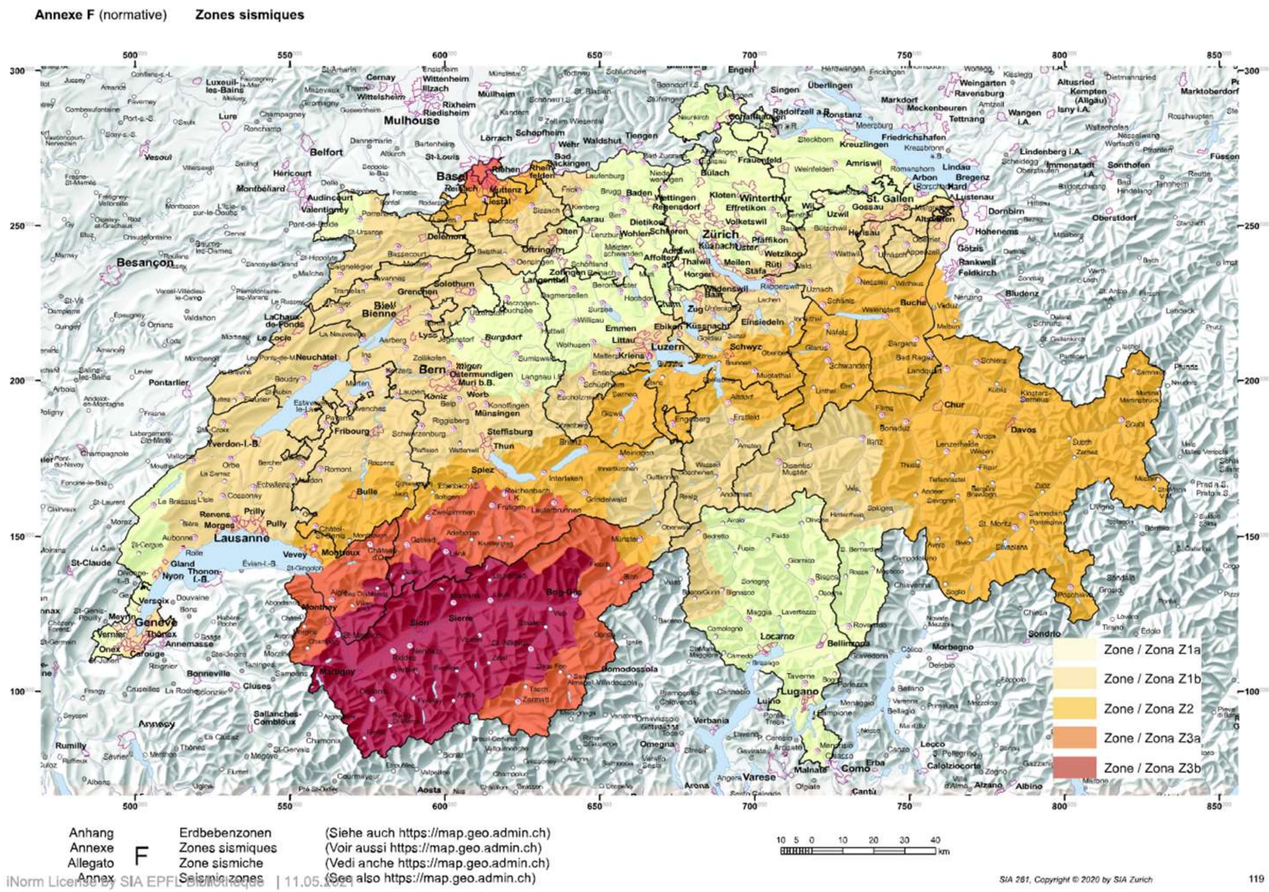
η= Correction factor to account for damping

T_B, T_C, T_D = corner periods (as a function of the soil class)

Elastic response spectra in SIA 261

Five seismic hazard zones with the following peak ground accelerations on rock a_{gd} :

- Zone 1a $a_{gd}=0.6\ m/s^2$
- Zone 1b $a_{gd}=0.8\ m/s^2$
- Zone 2 $a_{gd}=1.0\ m/s^2$
- Zone 3a $a_{gd}=1.3\ m/s^2$
- Zone 3b $a_{gd}=1.6\ m/s^2$



Map available at map.geo.admin.ch/
(https://shorturl.at/gqsvP)

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Elastic response spectra in SIA 261

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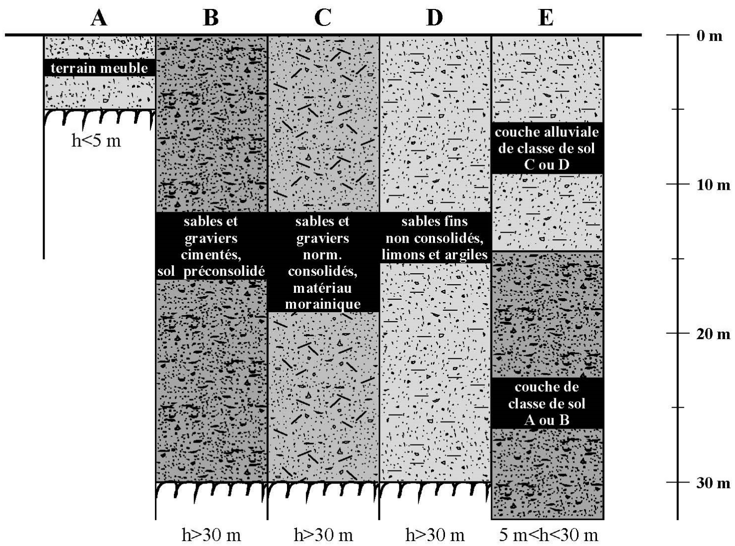
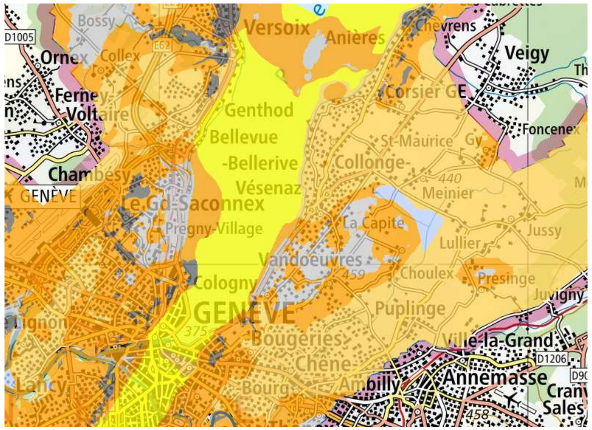
Soil classes in SIA 261 (2020)

- 6 soil classes
- For very soft soils (class F) particular investigations are necessary

Classe de terrain de fondat.	Description du profil stratigraphique	$v_{s,30}$ m/s	N_{SPT} nombre de coups/ 0,3 m	c_u kN/m²	S	T_B s	T_C s	T_D s	l_g m
A	Rocher ou formation géologique similaire avec une couverture de terrain meuble d'au plus 5 m d'épaisseur en surface	> 800	–	–	1,00	0,07	0,25	2,0	600
B	Dépôts de sable et gravier très compact ou d'argile très ferme, d'une épaisseur d'au moins quelques dizaines de mètres, caractérisés par une augmentation progressive des propriétés mécaniques avec la profondeur	500 à 800	> 50	> 250	1,20	0,08	0,35	2,0	500
C	Dépôts de sable et gravier moyennement compact à compact ou d'argile ferme, d'une épaisseur de quelques dizaines à plusieurs centaines de mètres	300 à 500	15 à 50	70 à 250	1,45	0,10	0,4	2,0	400
D	Dépôts de terrain meuble non cohésif lâche à moyennement compact (avec ou sans couches cohérentes tendres) ou à prédominance de terrain meuble cohésif de consistance tendre à ferme	< 300	< 15	< 70	1,70	0,10	0,5	2,0	300
E	Couche superficielle de terrain meuble correspondant à la classe C ou D avec une épaisseur comprise entre 5 m et 20 m et une valeur moyenne de v_s < 500 m/s, reposant sur un matériau plus ferme avec une valeur v_s > 800 m/s	–	–	–	1,70	0,09	0,25	2,0	500
F	Dépôts à structure sensible, organiques ou très tendres (par ex. tourbe, craie lacustre, limon mou) d'une épaisseur supérieure à 10 m	–	–	–	–	–	–	–	–



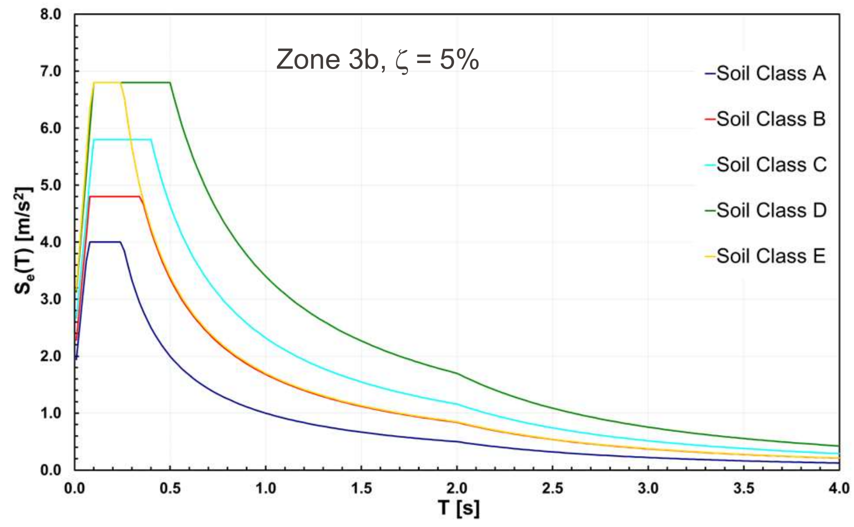


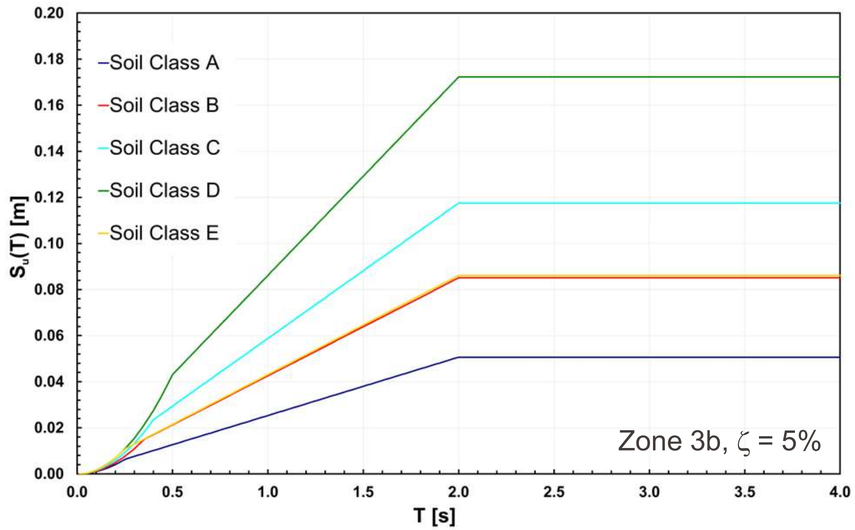
Map available at map.geo.admin.ch/

(https://shorturl.at/tKMY8)

Elastic response spectra in SIA 261

Effect of soil class on the shape of response spectra





Elastic response spectra in SIA 261

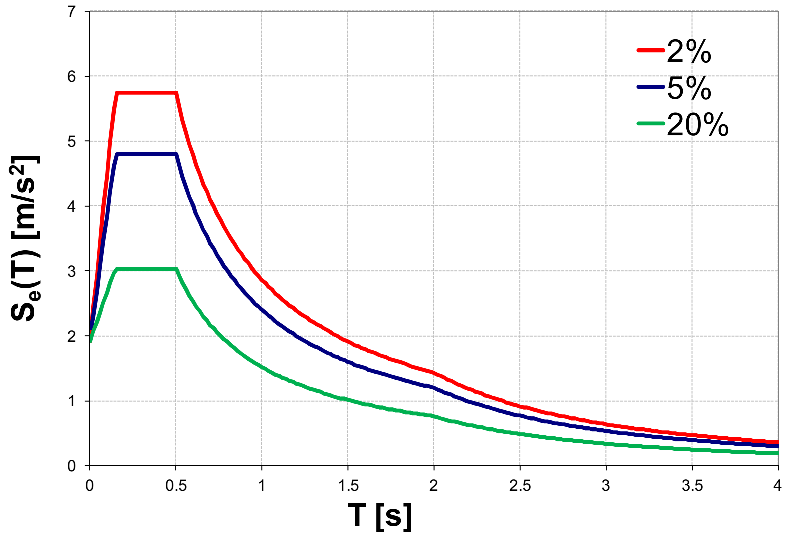
Damping

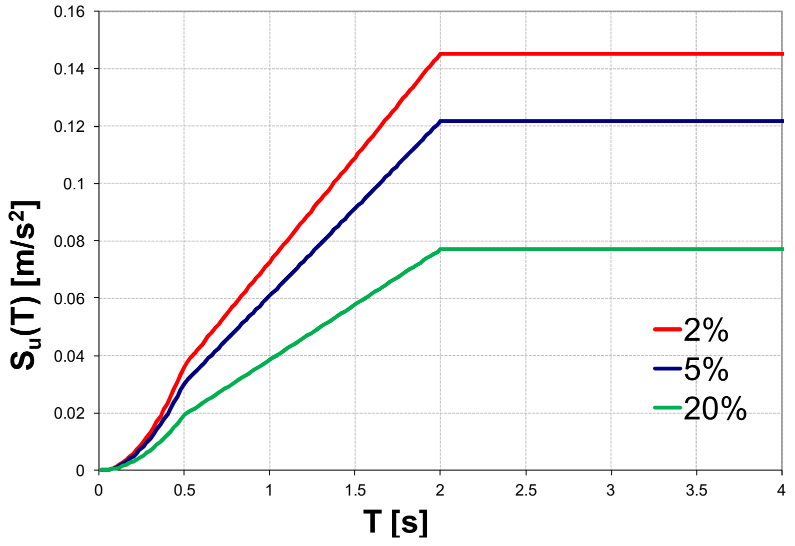
- Elastic spectra are defined for a damping ratio of ζ=5%
- Damping ratio depends on
  - Structural system
  - Material
  - Non-structural elements
  - …
- For buildings: Typically ζ=5%
- For damping coefficients different from 5% the elastic design spectra is multiplied by a factor η for periods $T>T_B$:

$$\eta = \sqrt{\frac{0.1}{0.05+\varsigma}} \geq 0.55$$

Elastic response spectra in codes

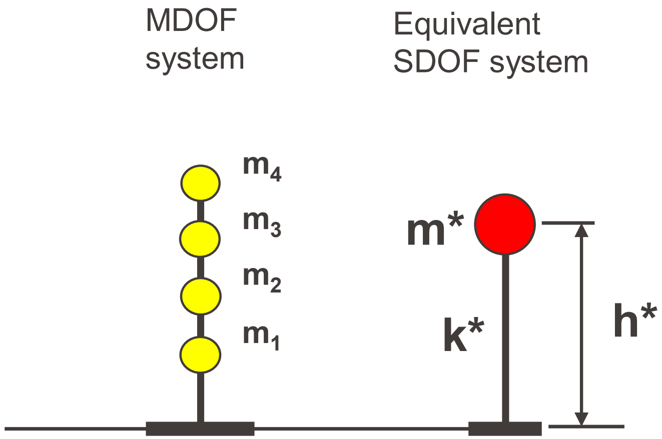
Effect of damping ratio on elastic spectra





Estimating the fundamental period of a building

Fundamental period of a building



- The seismic response of a building is dominated by its first mode (=fundamental mode).
- The simplest model representing the dynamic behaviour of a building is a linear system SDOF system, which has the same period as the first mode of the building.

Fundamental period of a building

Fundamental period of a building

- Key input parameter to code-based seismic design of structures

→Needs to be estimated at the beginning of the design process.

- Different approaches for estimating the fundamental period:
  - Empirical equations
  - Rayleigh method
  - Simplified Rayleigh method
  - Finite element calculations

Fundamental period of a building

Empirical equations for the fundamental period

- As a function of the number of storeys (n):

$$T_1 = \frac{n}{10} \quad [s] \qquad\qquad f_1 = \frac{10}{n} \quad [Hz]$$

- As a function of the building height (SIA 261):

$$T_1 = C_t H^{0.75} \quad [s]$$

  - H= Building height in [m]
  - Factor accounting for the structural system:
    - Steel moment resisting frames C_t = 0.085
    - RC moment resisting frames C_t = 0.075
    - All other types of structures C_t = 0.050

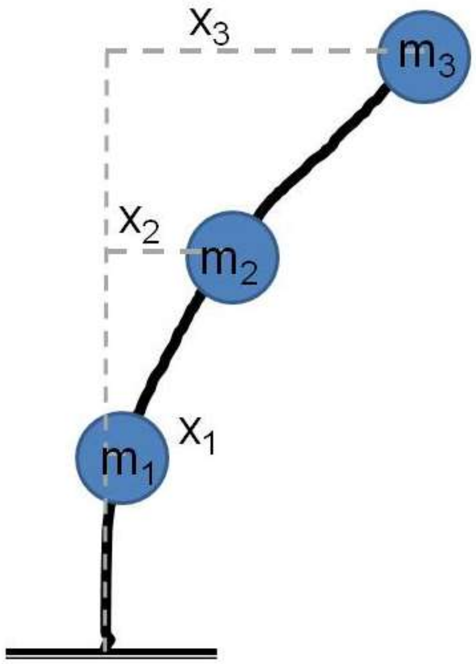
- Equations were developed for force-based design. → To be conservative, they tend to underestimate the actual period.
- Equations were developed for structures in areas of high seismicity. → For areas of low seismicity, these equations underestimate the actual period often by large.
- It is in general not recommended to use these equations (only as very first estimate).

Fundamental period of a building

Rayleigh method

- Method for estimating the fundamental period
- Based on the conservation of energies (potential energy = kinematic energy).
- Rayleigh quotient:

$$\omega_1^2 = \frac{x^T K x}{x^T M x}$$

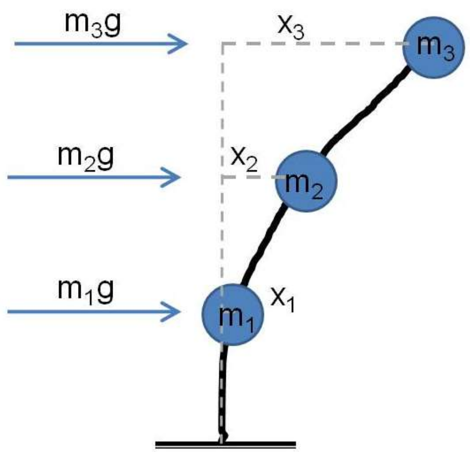


- x = Eigenvector of fundamental mode
- K = Stiffness matrix
- M = Mass matrix

→ Course “Dynamique des structures”

Fundamental period of a building

Simplified Rayleigh method (SIA 261)



- The fundamental period can be estimated as (SIA 261, Equation 40):

$$T_1 = 2\sqrt{x_{top}}$$

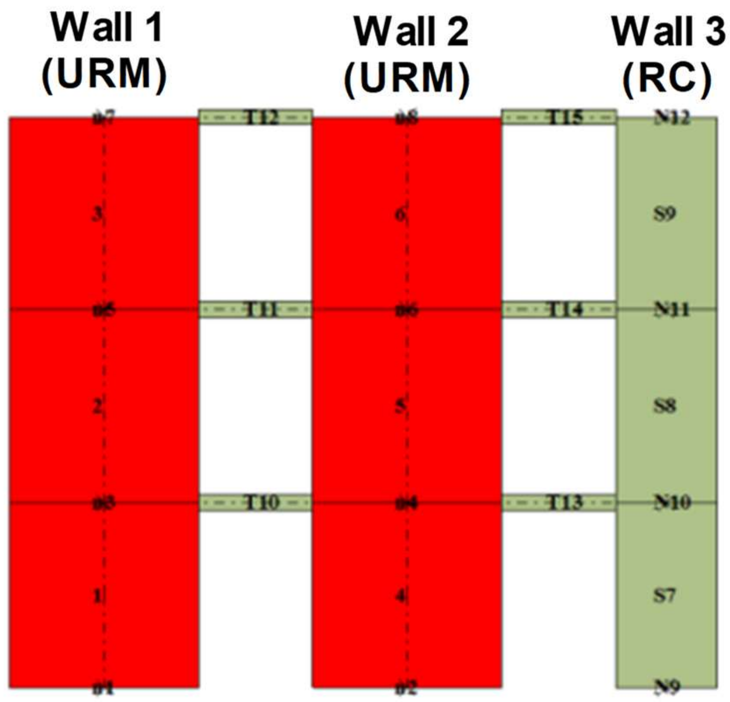
- x_{top} (in m) is the fictive horizontal top displacement when the vertical loads are applied as horizontal loads.
- Vertical loads = selfweight G_k and quasi-permanent loads $\psi_2 Q_k$
- Show that this formula is exact if applied to a SDOF system:

Fundamental period of a building

Finite element analysis

Numerical model of the structure with «a mean stiffness up to the point of yield» (SIA 261, 16.5.5.2)

→ typically $EI_{eff} = 0.3\text{-}0.5\ EI_{gross}$
$GA_{eff} = 0.3\text{-}0.5\ GA_{gross}$



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