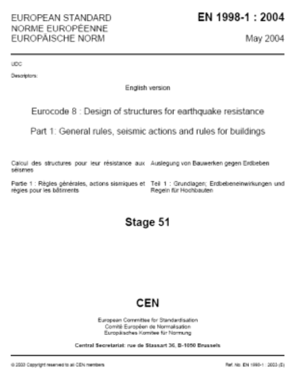
Design seismic actions and determination of action effects using appropriate computational tools

Anastasios Sextos
Lecturer



EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1998-1 : 2004
May 2004

UDC
Descriptors:

English version

Eurocode 8 : Design of structures for earthquake resistance

Part 1: General rules, seismic actions and rules for buildings

Calcul des structures pour leur résistance aux séismes

Partie 1 : Règles générales, actions sismiques et règles pour les bâtiments

Auslegung von Bauwerken gegen Erdbeben

Teil 1 : Grundlagen; Erdbebeneinwirkungen und Regeln für Hochbauten

Stage 51

CEN

European Committee for Standardisation
Comité Européen de Normalisation
Europäisches Komitee für Normung

Central Secretariat: rue de Stassart 36, B-1050 Brussels

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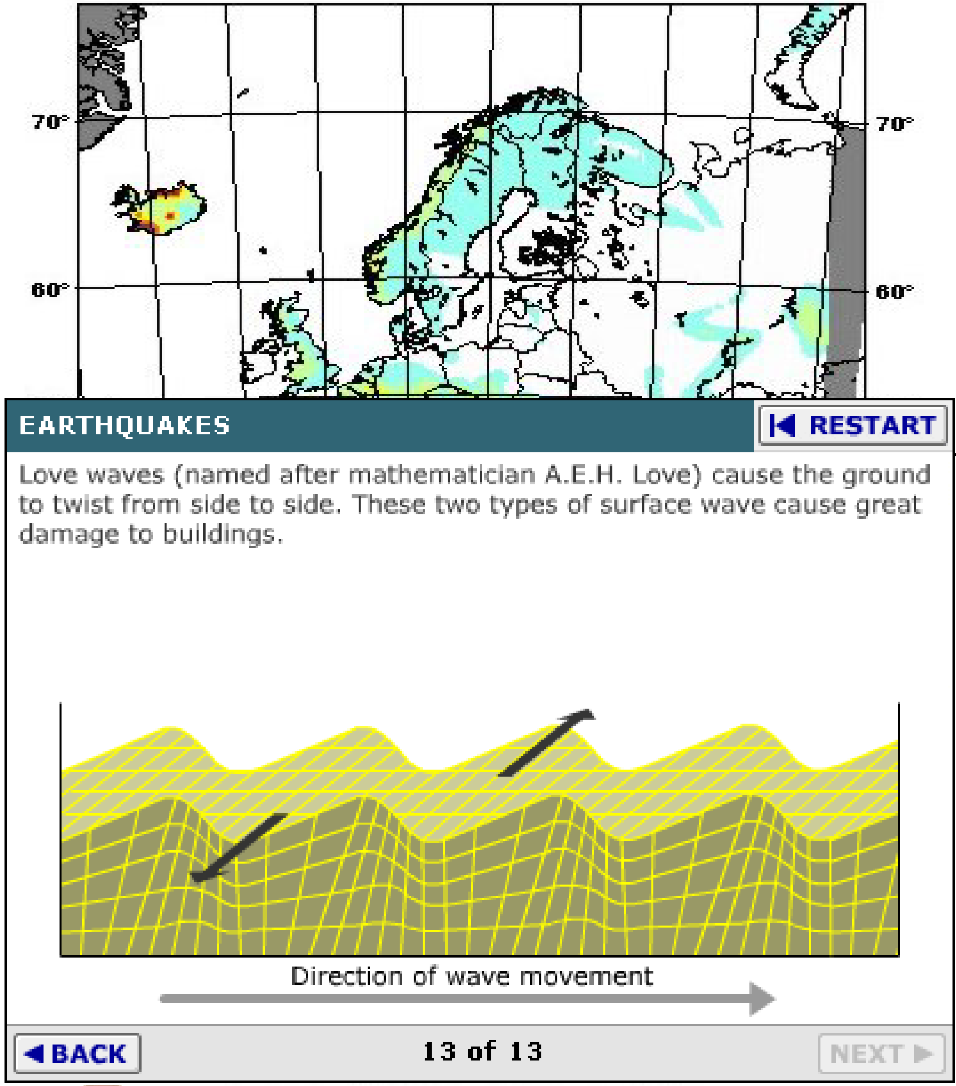
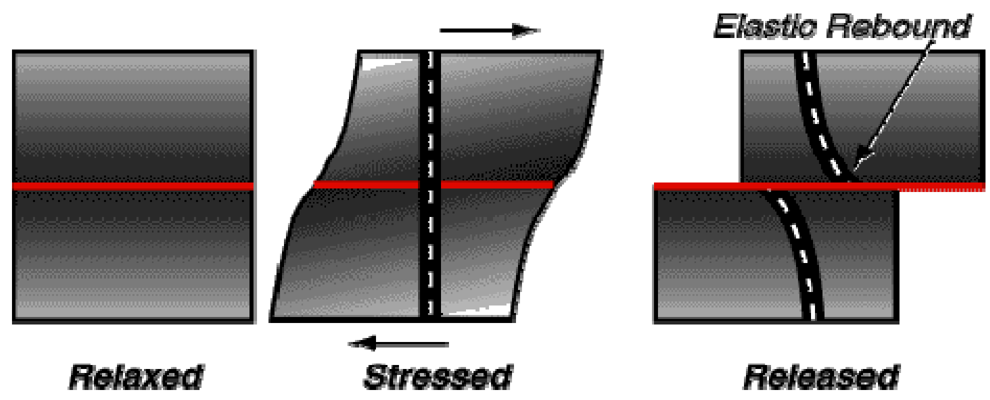
Ref. No. EN 1998-1 : 2003 (E)

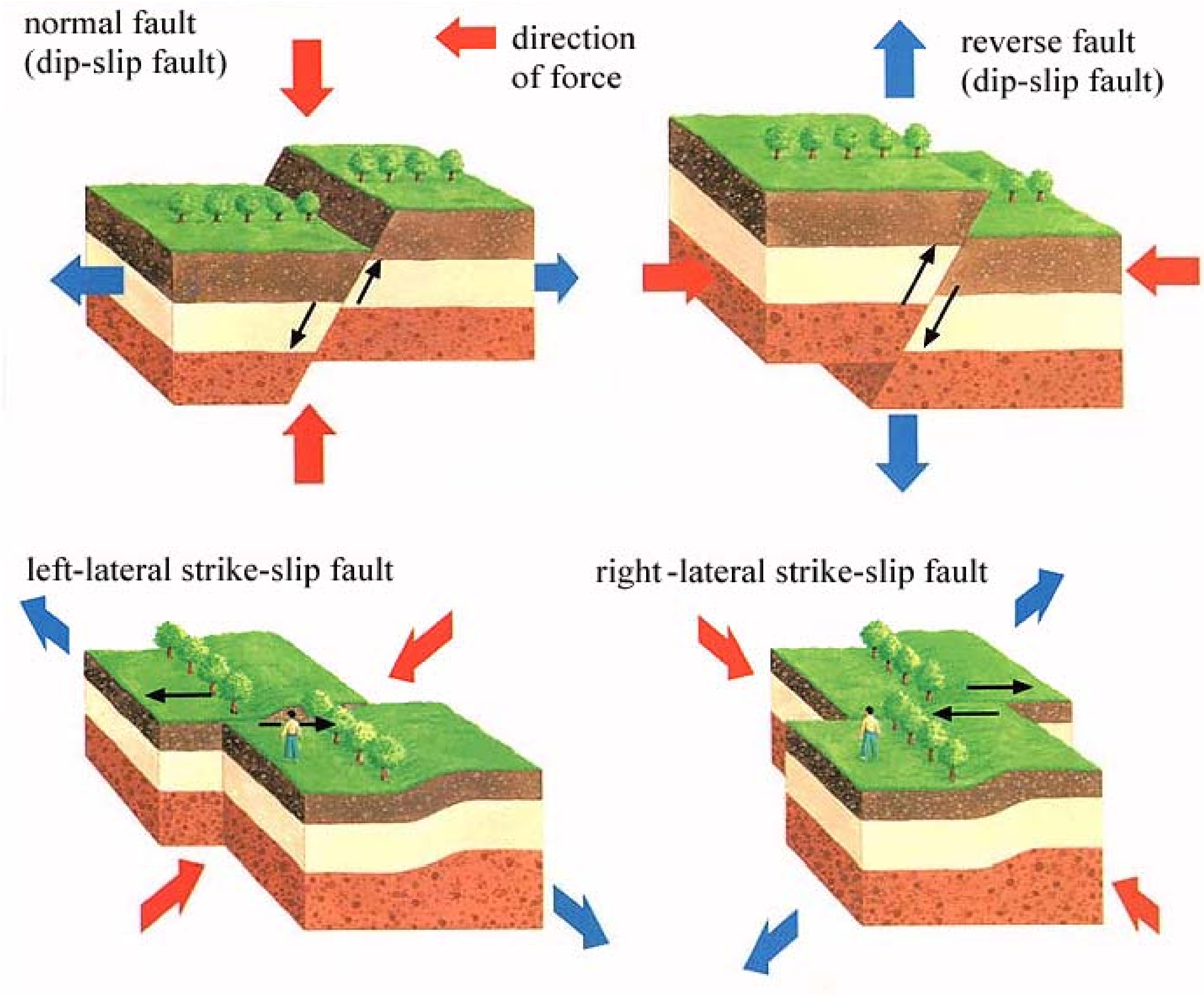
Seismicity, faults and earthquake generation





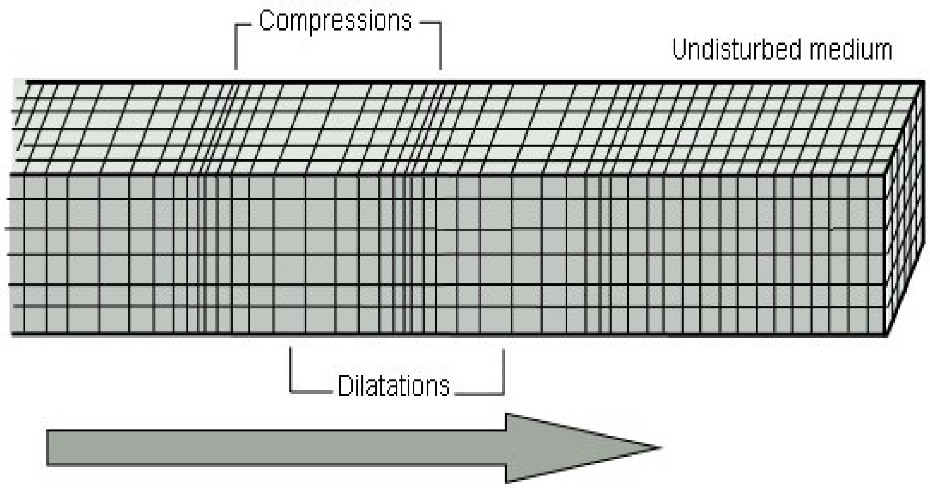
- Accumulation of stresses
- Fault zone
- Reverse, normal and strike slip
- Energy release
- Wave propagation

Seismicity, faults and earthquake generation

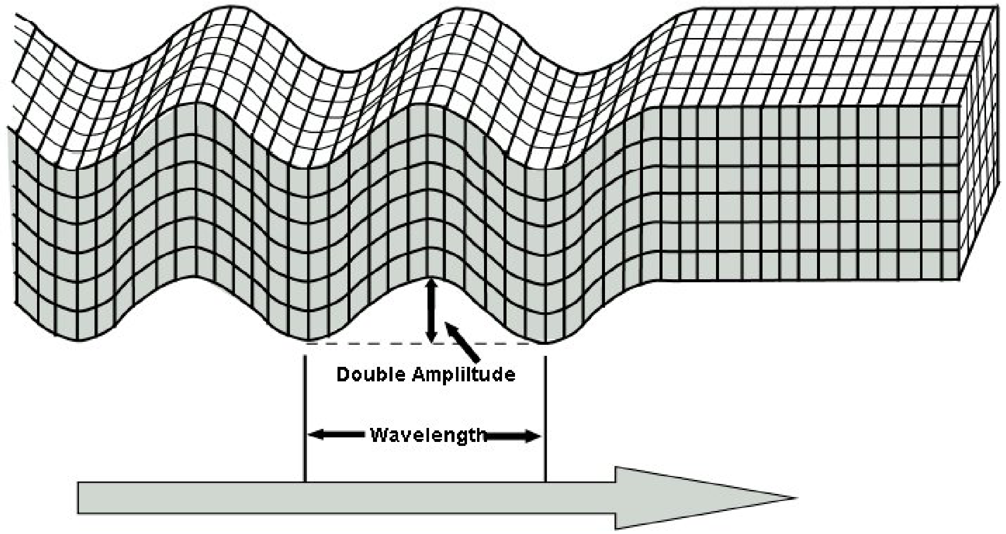


Seismicity, faults and earthquake generation

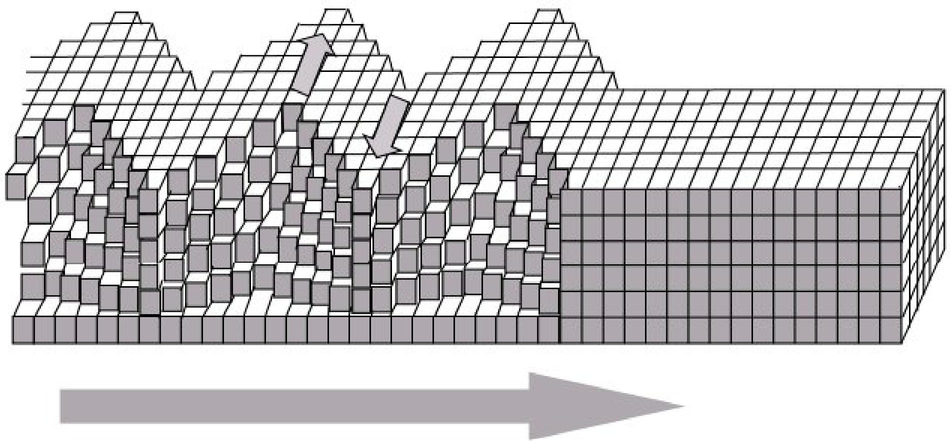
P Wave



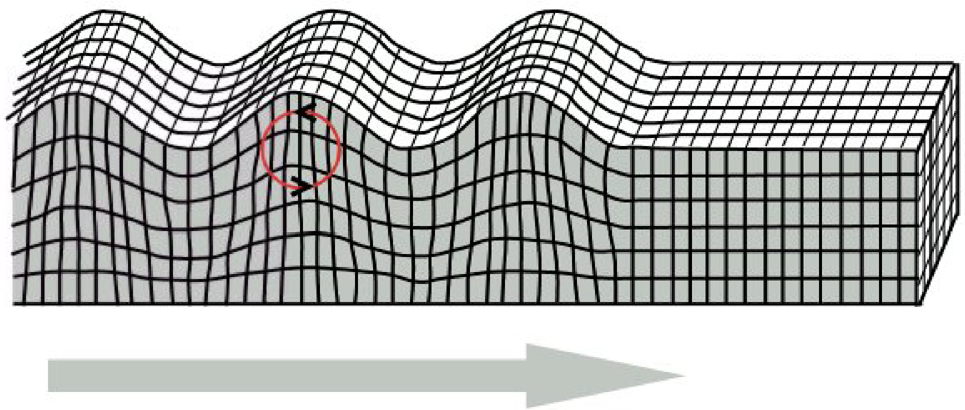
S Wave



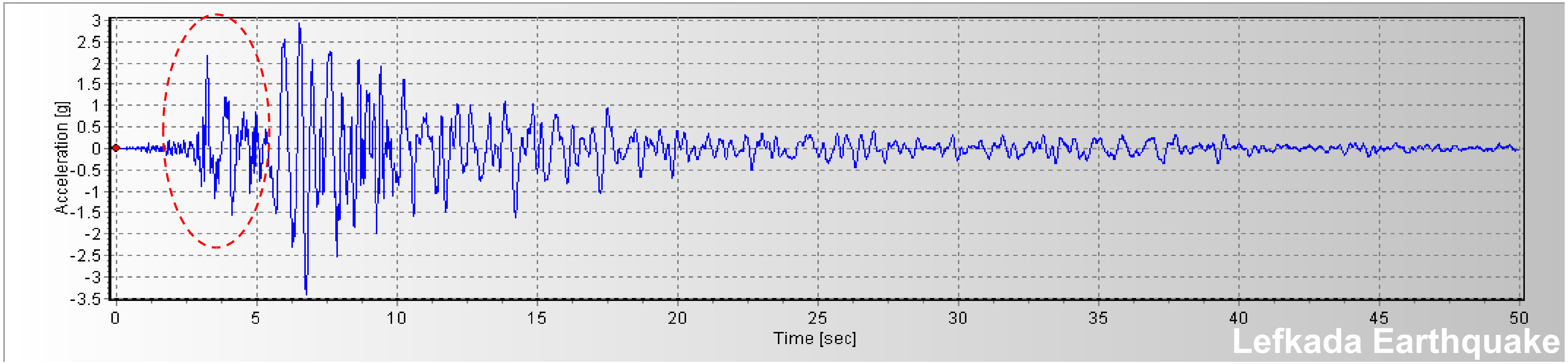
Love Wave

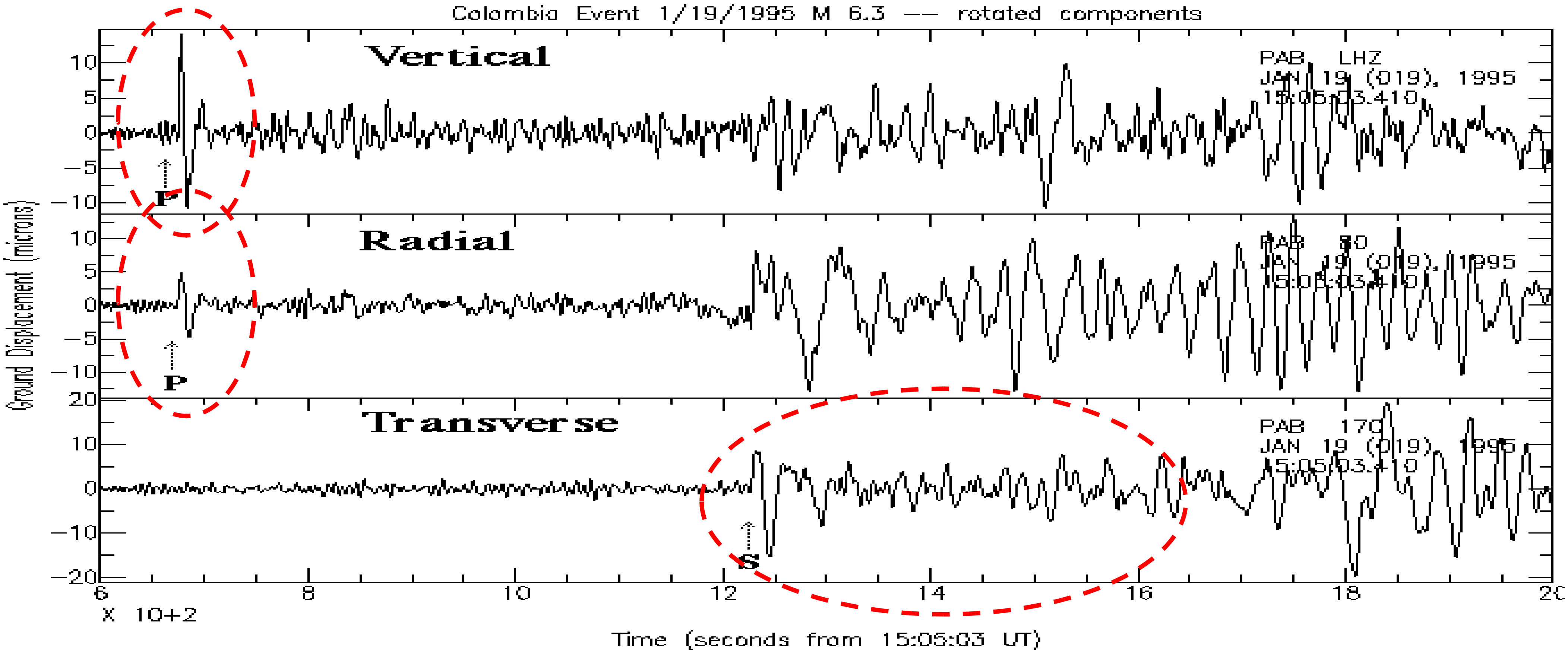


Rayleigh Wave



Seismicity, faults and earthquake generation





Seismic hazard, vulnerability and seismic risk

Seismic Hazard (SH):

A property of an earthquake that can cause damage and loss. Probabilistic Seismic Hazard Analysis (PSHA) determines the frequency (i.e. the number of events per unit of time) with which a seismic hazard is expected to occur. Typically, the seismic hazard is calculated as a *frequency* that 'a ground motion amplitude is greater than a specified value'.

Vulnerability (V):

The 'sensitivity' of a given structure under a seismic event. The probability that a structure will exhibit a specific level of damage under a given level of seismic forces

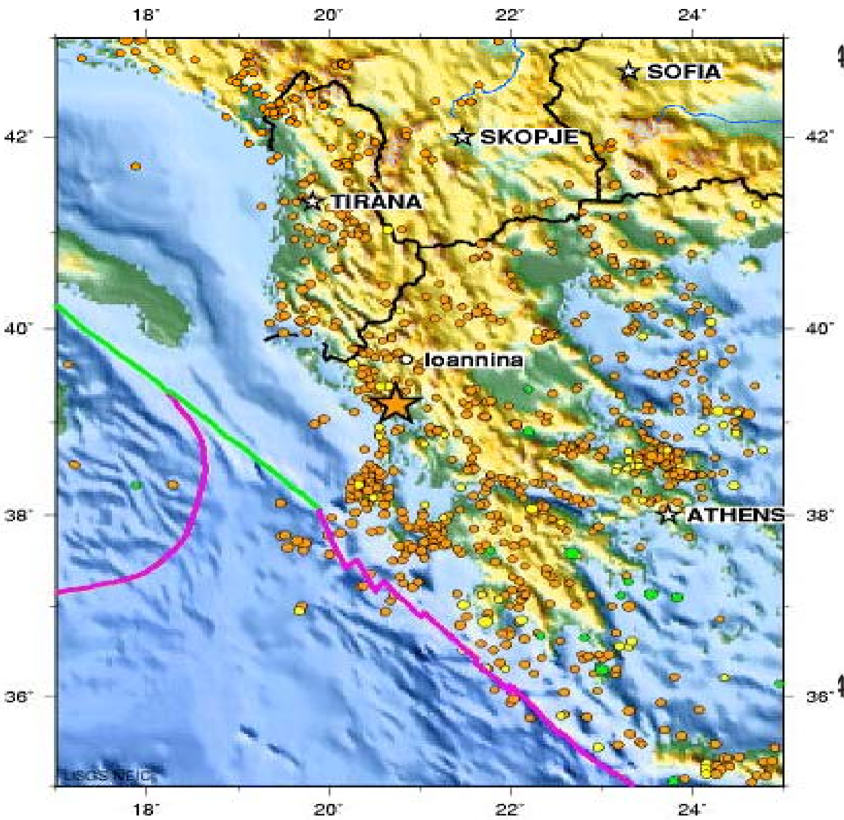
Seismic Risk (SR):

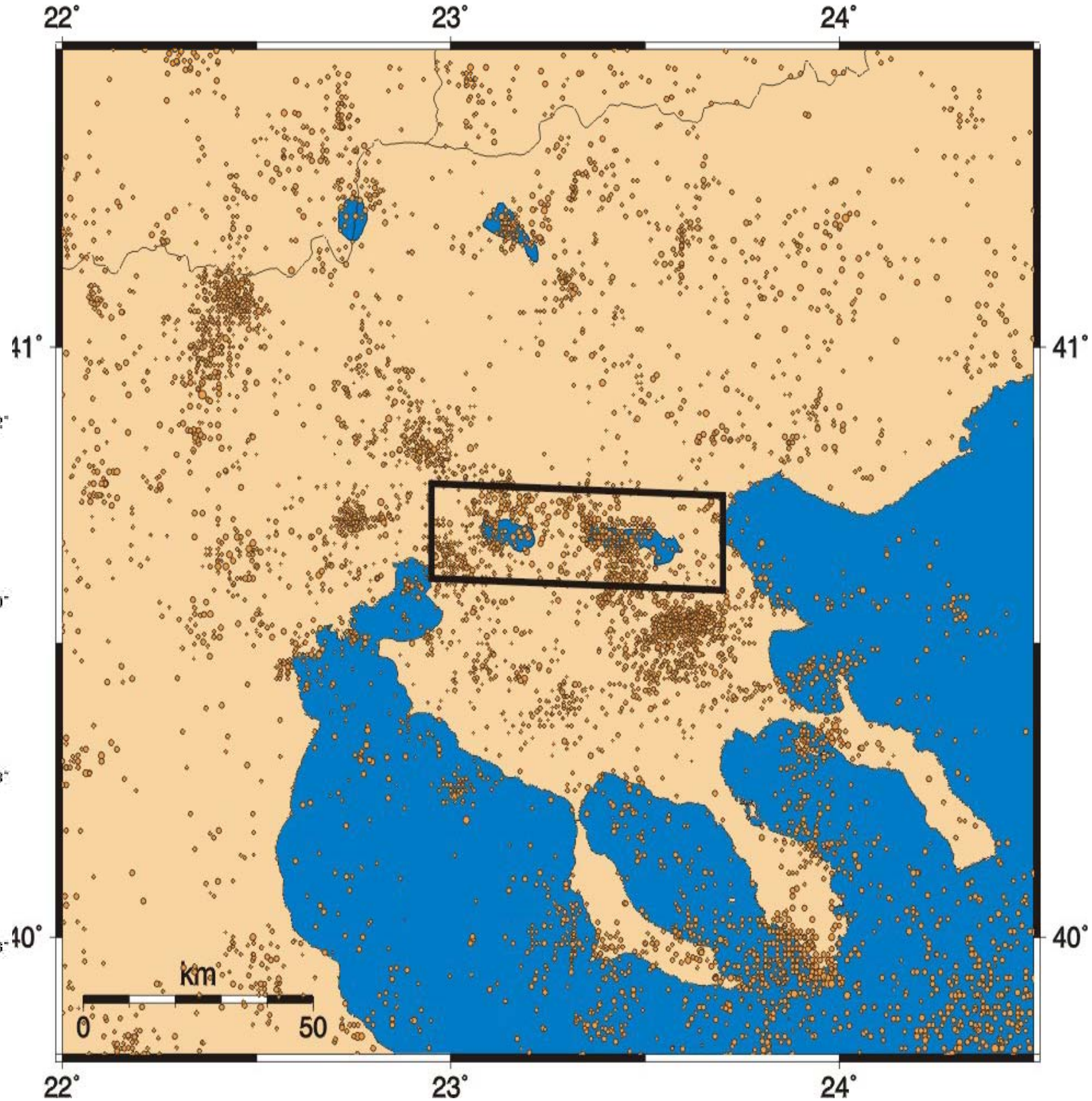
A level of loss or damage related to a given set of structures that are exposed to a particular level of seismic hazard given their own vulnerability.

Seismic Risk = Vulnerability * Seismic Hazard

Seismicity, faults and earthquake generation

Seismicity
The seismic energy released in a given time window in a given area





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Design Seismic Actions

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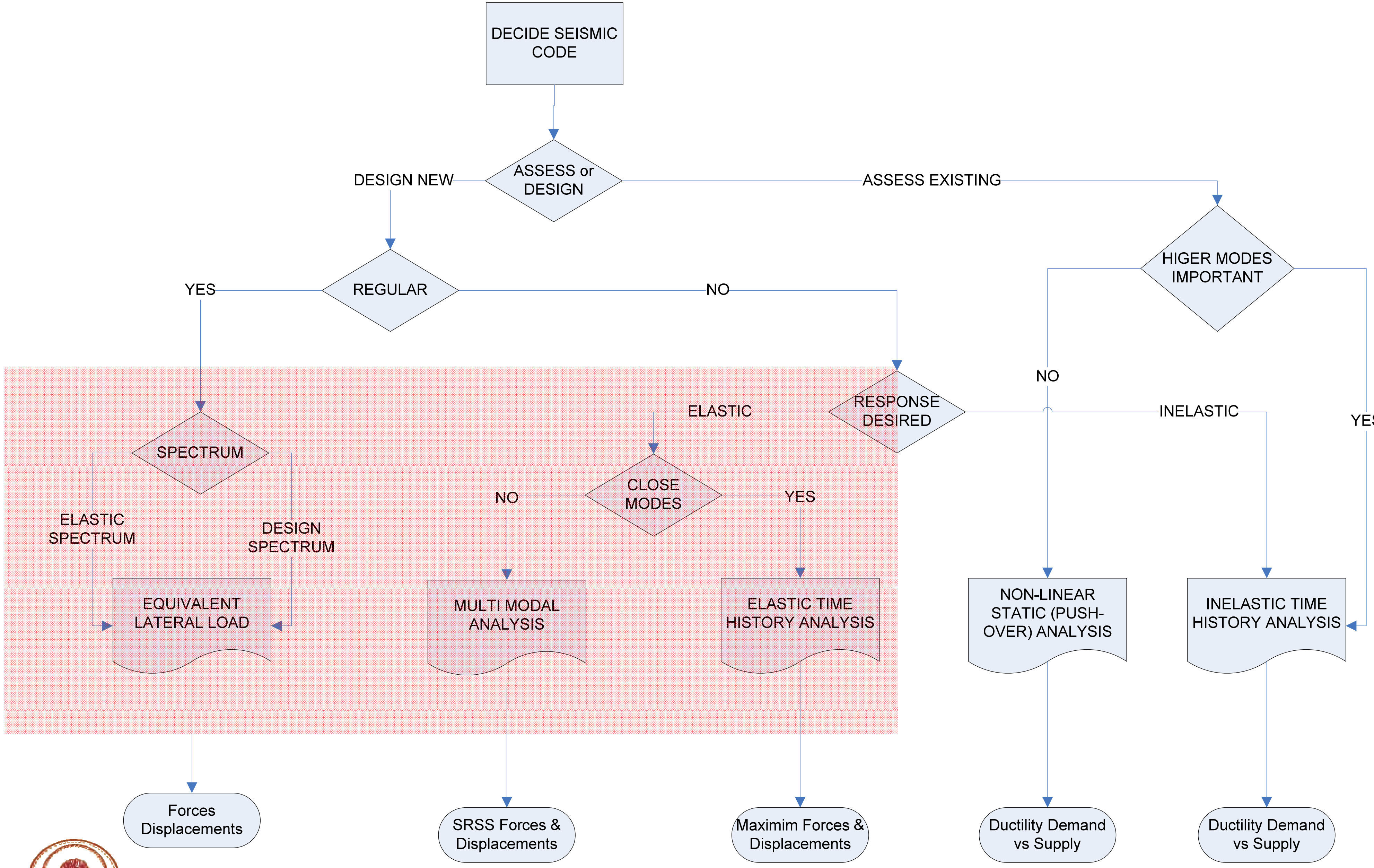
Seismic design & assessment flowchart



Eurocode 8 parts

Table 1: Eurocode 8 parts and key dates (achievement or expectation)

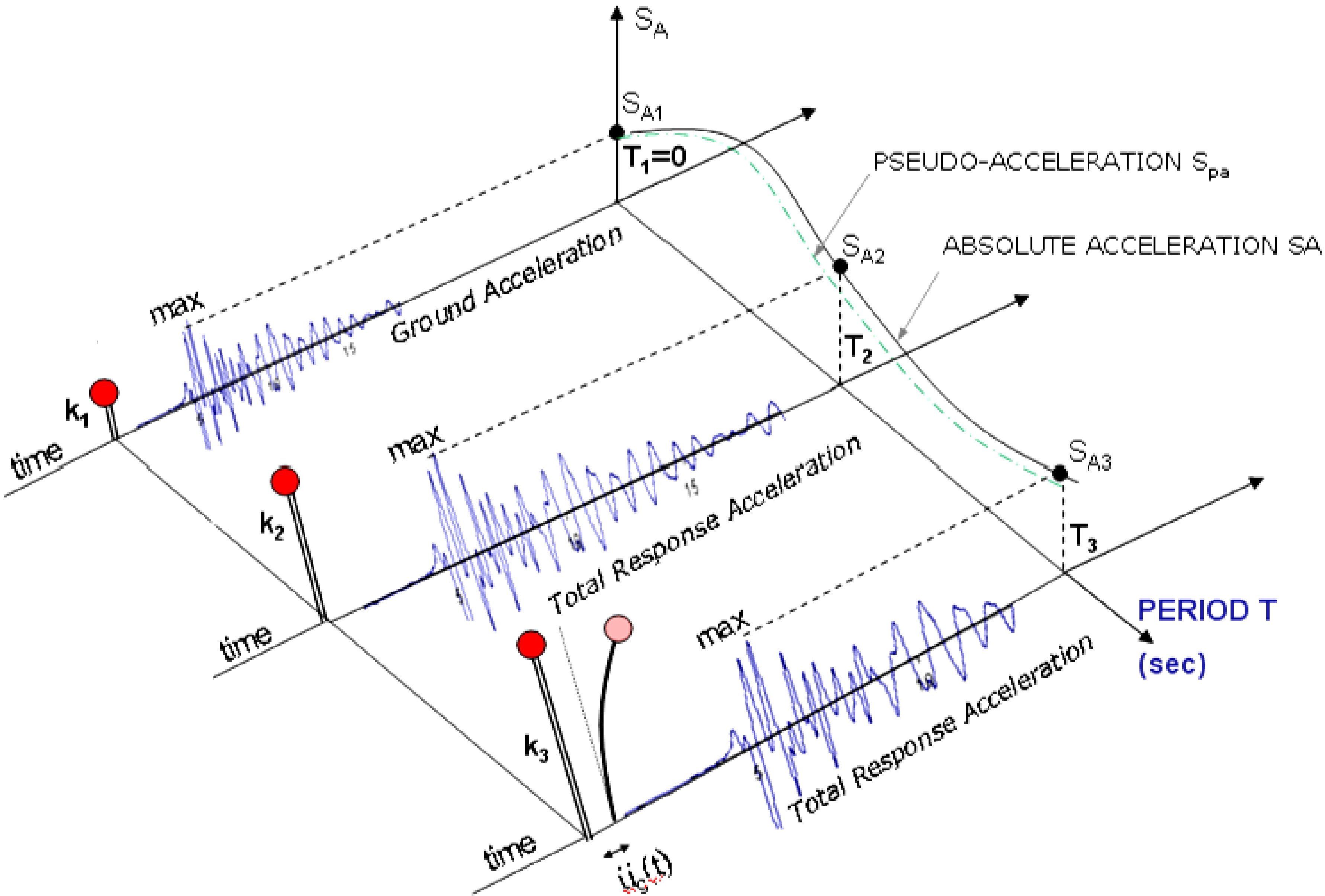
EC8 Part	Title	Approval by formal vote	Availability from CEN	National publication - National Annexes(2)
1: EN1998-1	General rules, seismic actions, rules for buildings	Feb 04(1)	Dec. 04(1)	Dec. 06
2: EN1998-2	Bridges	June 05(1)	Nov. 05(1)	Nov. 07
3: EN1998-3	Assessment and retrofitting of buildings	Feb 05(1)	June 05(1)	June 07
4: EN1998-4	Silos, tanks, pipelines	April 06(1)	July 06	July 08
5: EN1998-5	Foundations, retaining structures, geotechnical aspects	Feb 04(1)	Nov. 04(1)	Nov. 06
6: EN1998-6	Towers, masts, chimneys	March 05(1)	June 05(1)	June 07

(1): Actual achievement date

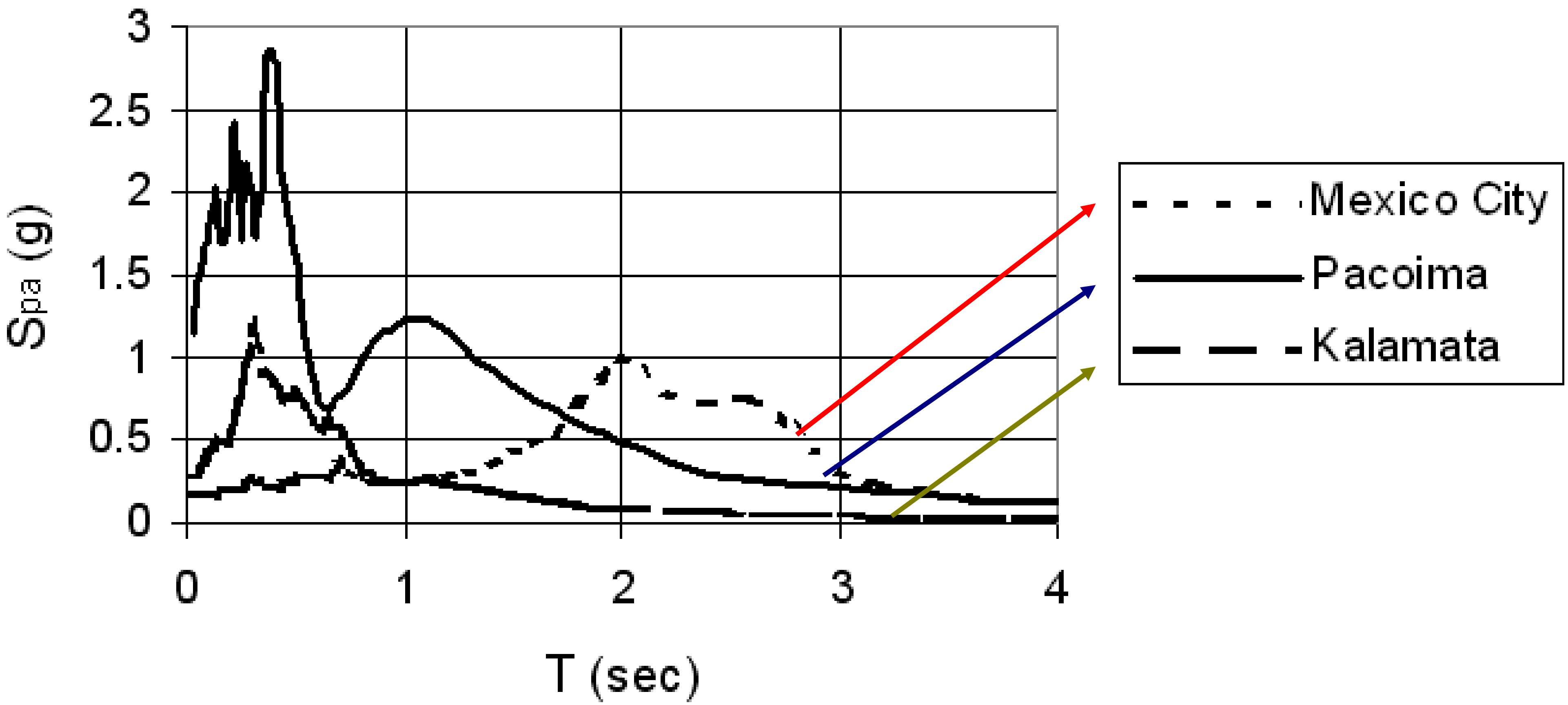
(2): Expected date of publication by CEN member states of national (translated) version of EN, with National Annex and Nationally Determined Parameters; adaptation of national provisions to allow nationally the parallel use of the EN.

* M. Fardis (2006), 1st European Conf. on Earthq. Eng. and Seismology

Response spectra

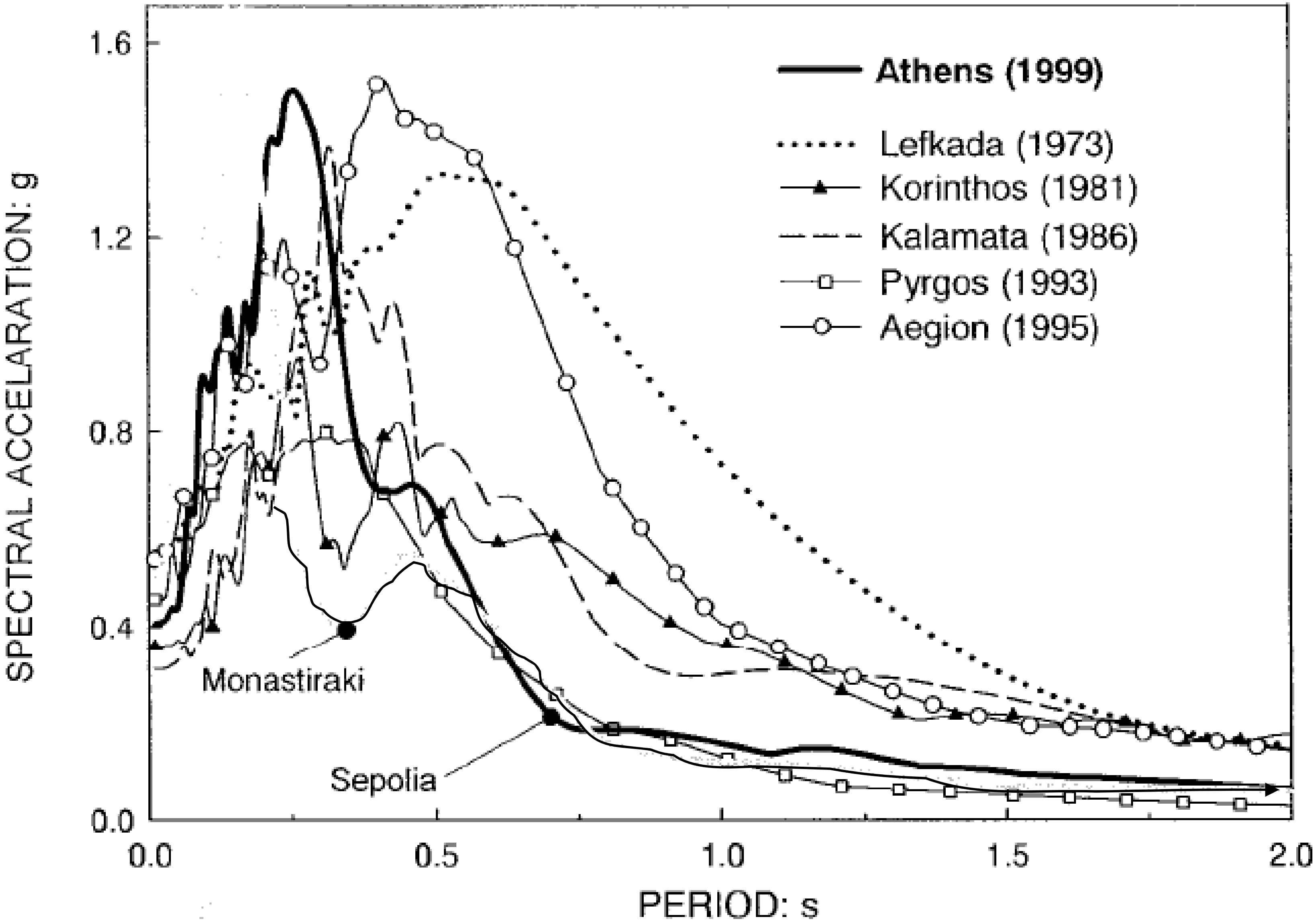


Response spectra

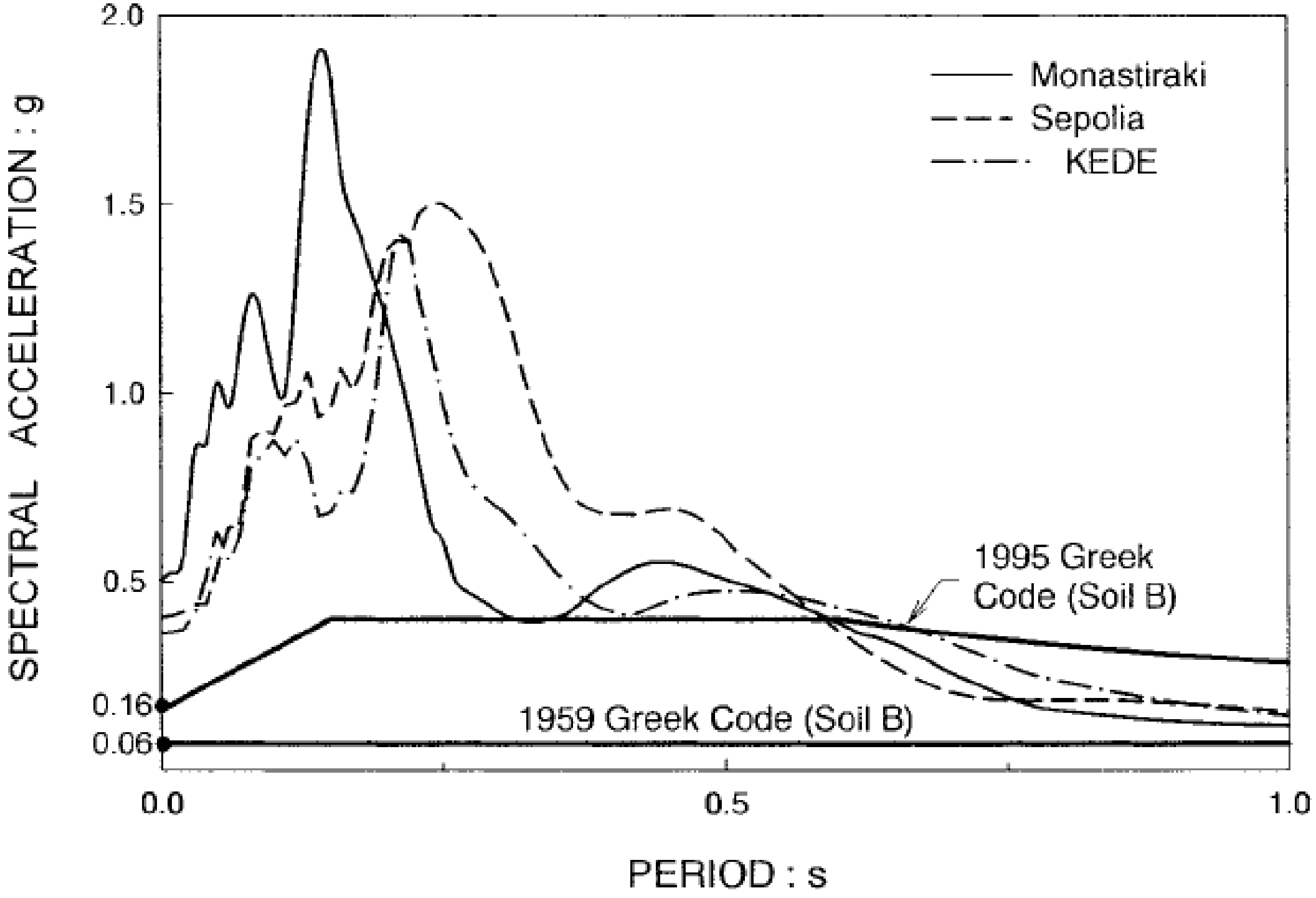


Depend on fault mechanism, epicentral distance, path and local site conditions

Response spectra

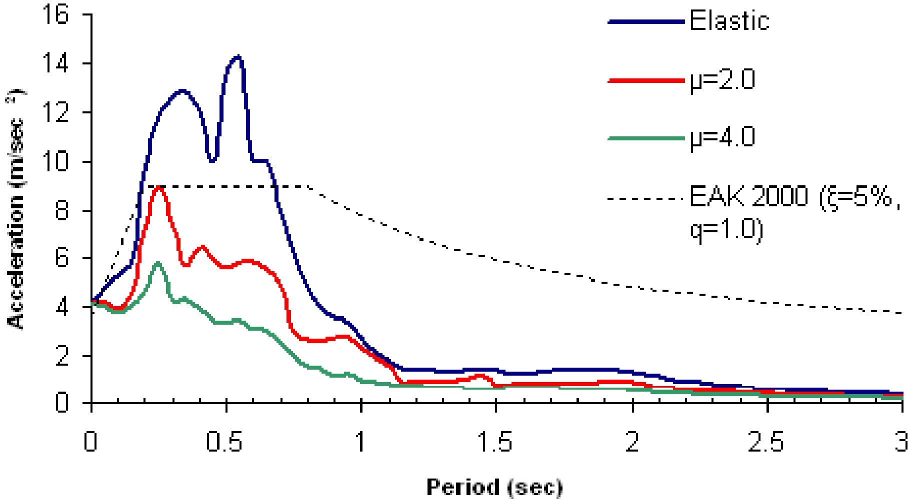


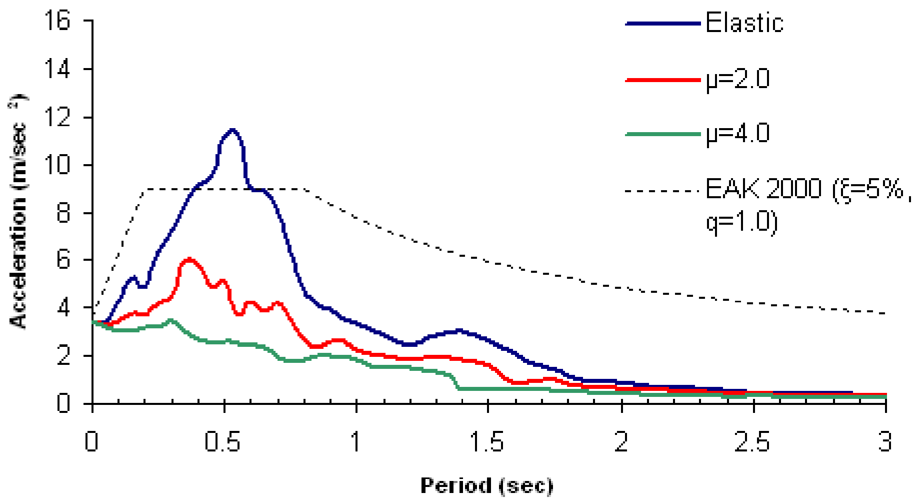
Response spectra



May well exceed seismic code prescribed spectra

Response spectra

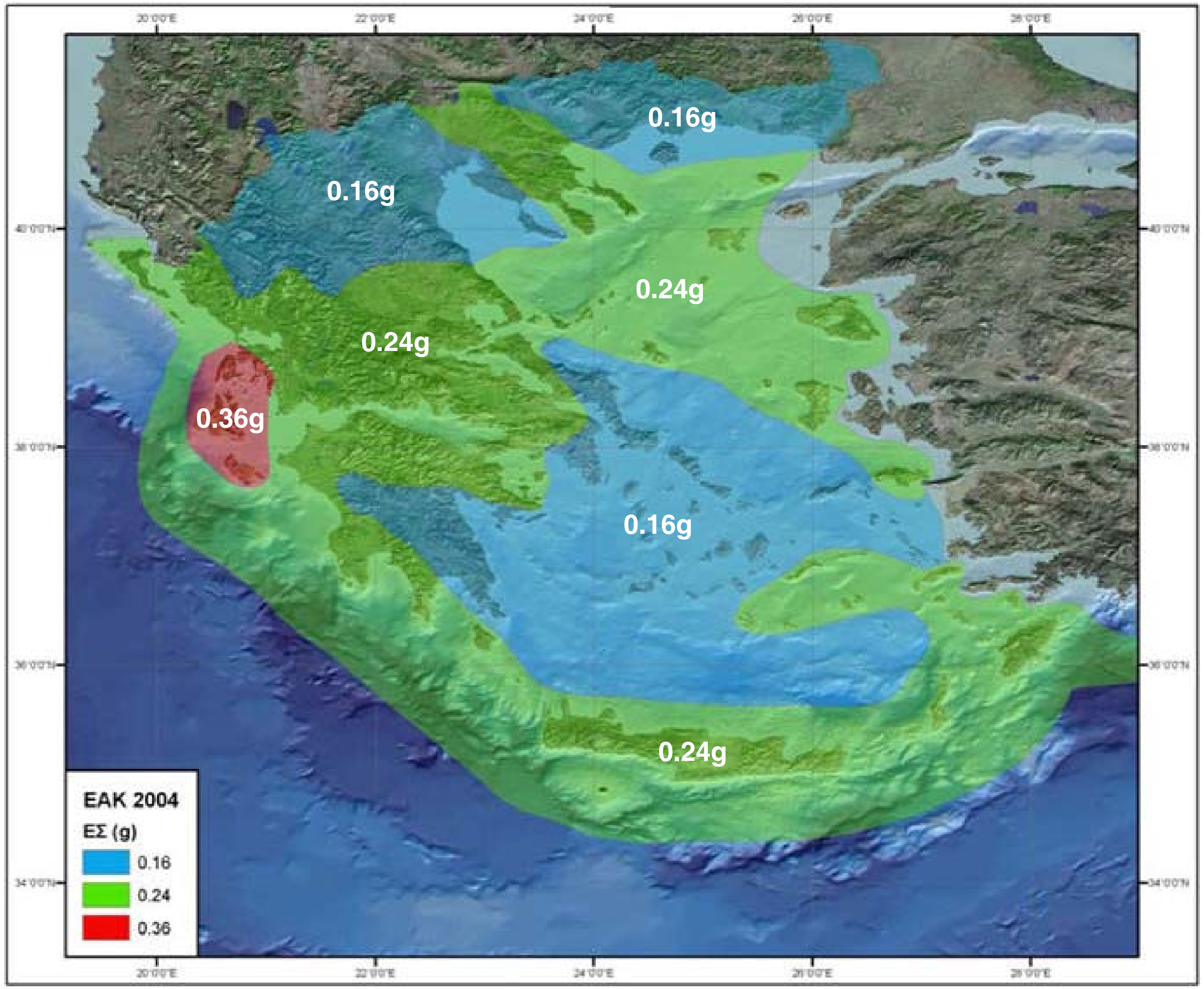


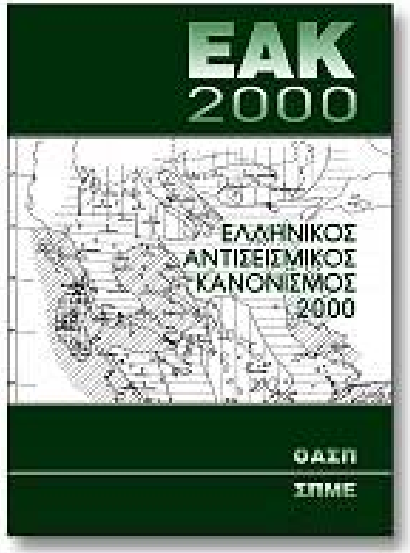


Inelastic spectra derived for ductility factors μ=2,3 and 4 by the main shock response spectrum

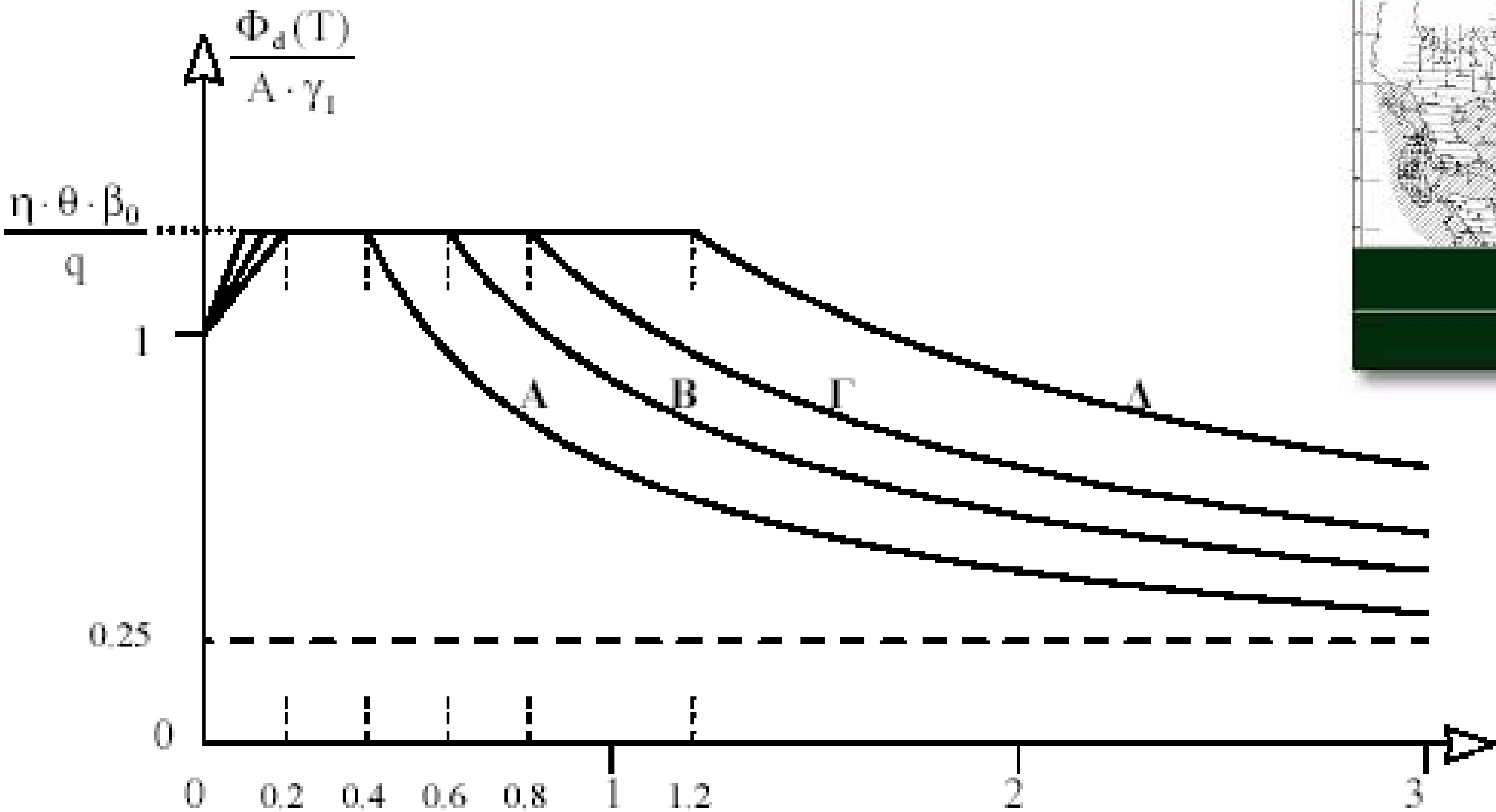
Hellenic Seismic Code

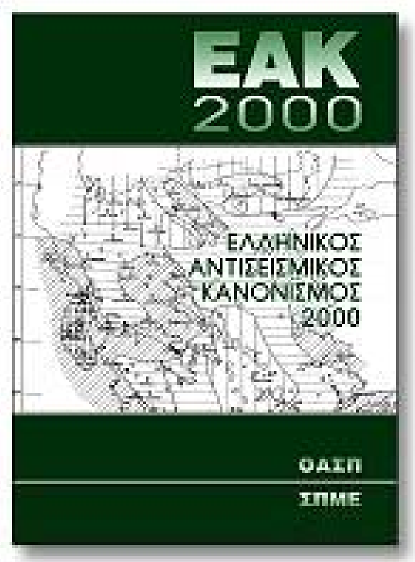
Seismic Zones for Greece (2004)



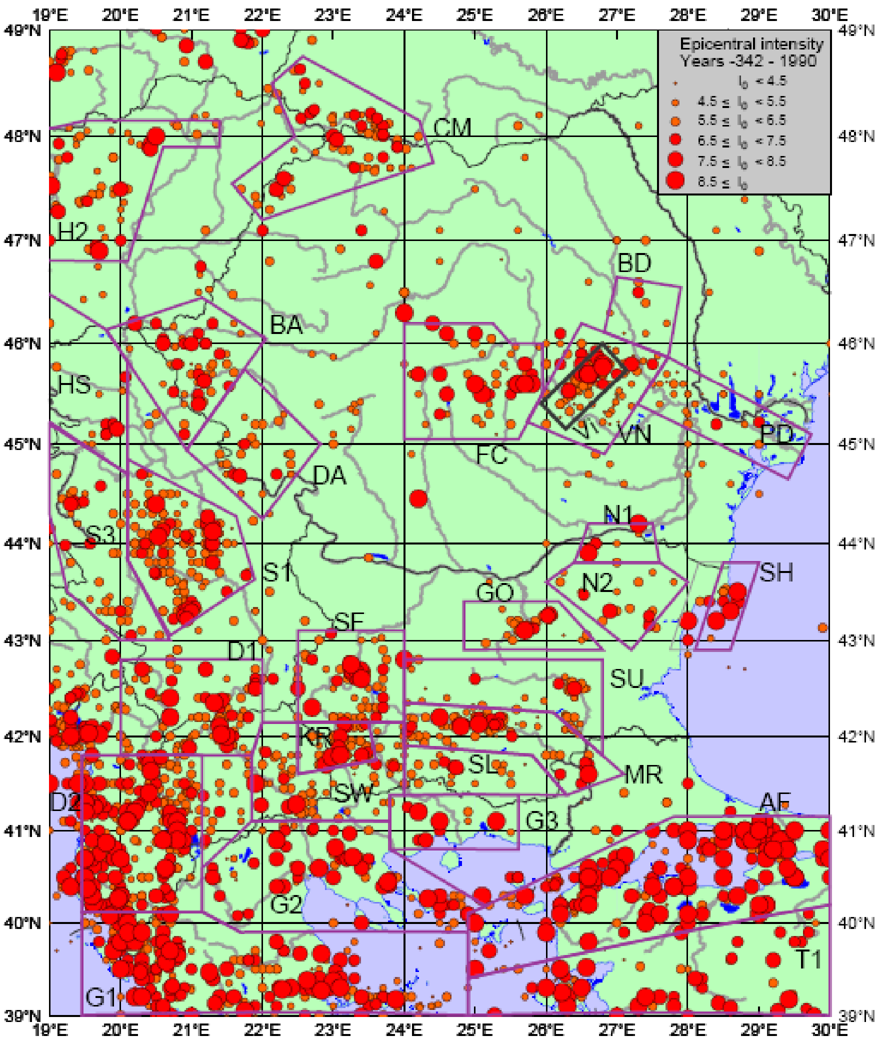


Hellenic Seismic Code

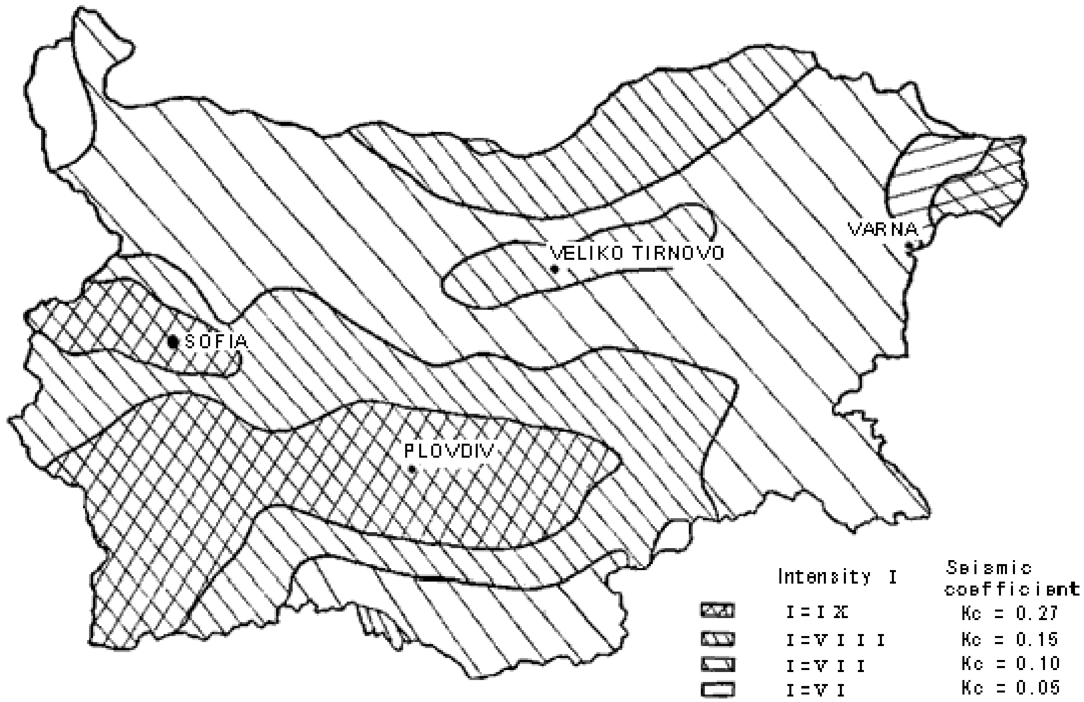




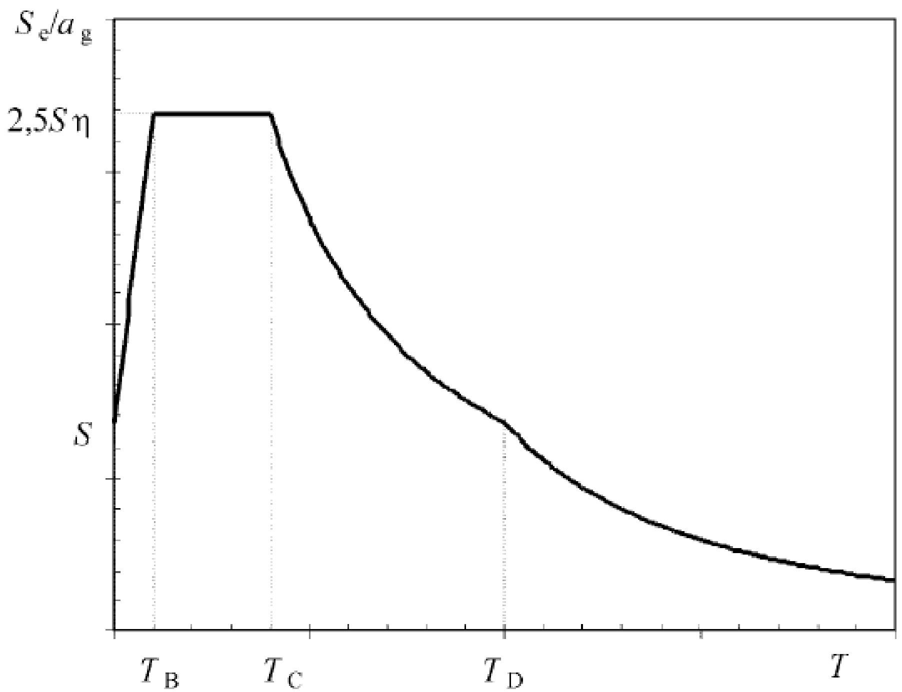
Bulgarian Seismic Code



Seismic Zones for Bulgaria



Eurocode 8 Elastic Response Spectrum



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

$$T_B \le T \le T_C : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5$$

$$T_C \le T \le T_D : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5 \left[\frac{T_C}{T}\right]$$

$$T_D \le T \le 4\text{s} : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5 \left[\frac{T_C T_D}{T^2}\right]$$

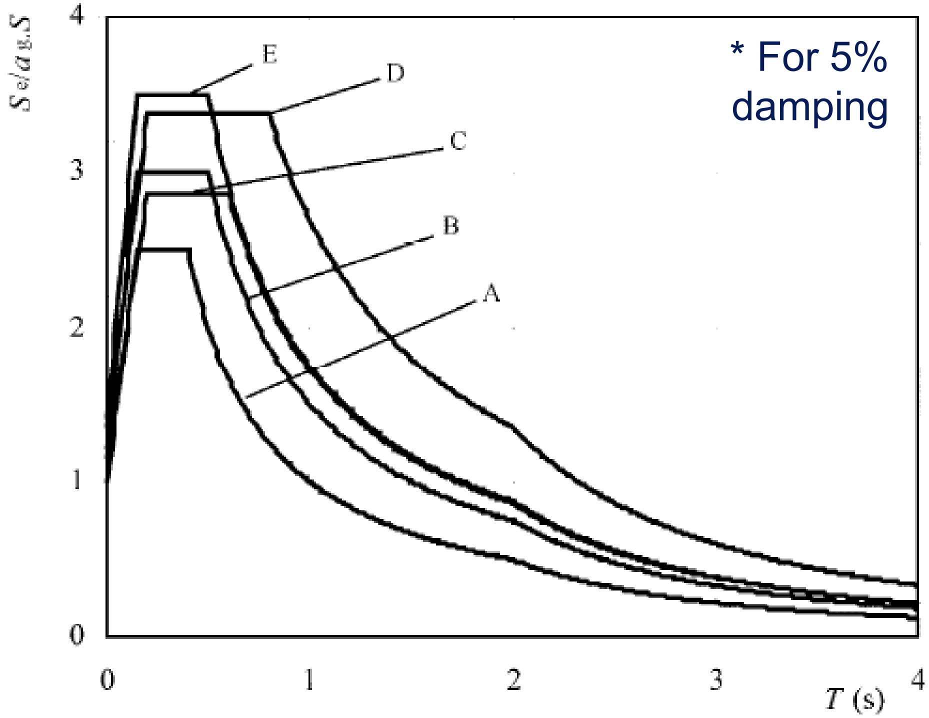
- Identical for both horizontal actions
- S = Soil factor
- α_g = design ground acceleration
- η = damping correction factor
- T_B, T_C, T_D = corner periods

DAMPING η

• RC structures (uncracked)	0.7-1.0%
• RC Structures (fully cracked)	1.0-4.0%
• RC Structures (fully cracked no yielding)	5.0-8.0%
• Prestressed concrete (uncracked)	0.4-0.7%
• Lightly stressed concrete	0.8-1.2%
• Composite	2.0-3.0%
• Steel	1.0-2.0%

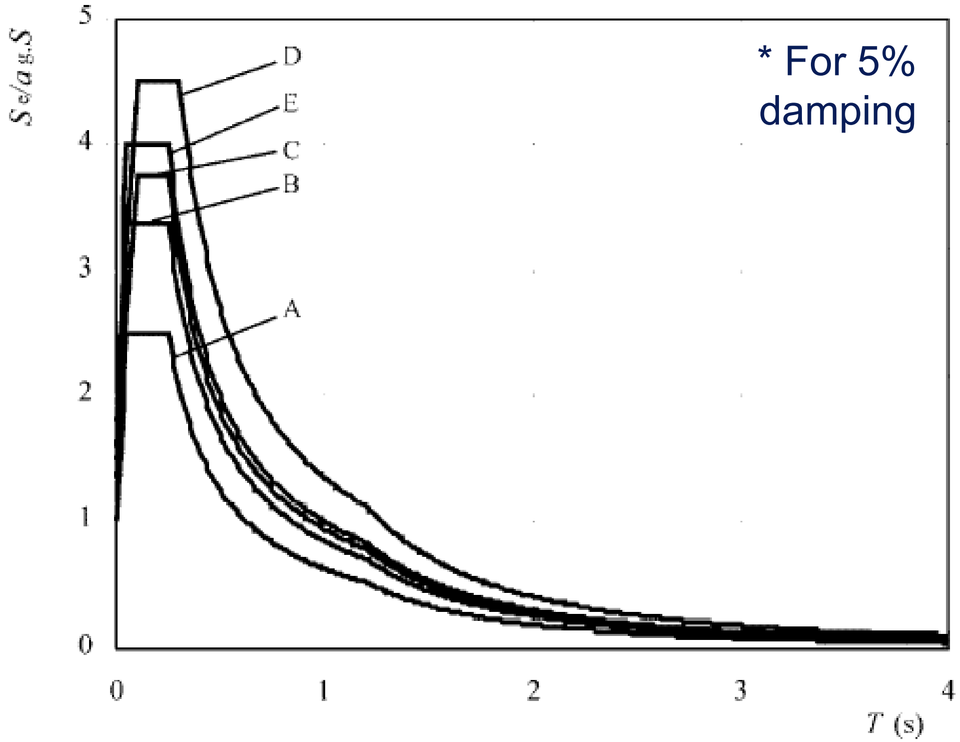
Eurocode 8 Elastic Response Spectrum: Two types of spectra

- **Type 1:** For areas exposed to earthquakes with expected surface wave magnitude $M_s > 5.5$



Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1,0	0,15	0,4	2,0
B	1,2	0,15	0,5	2,0
C	1,15	0,20	0,6	2,0
D	1,35	0,20	0,8	2,0
E	1,4	0,15	0,5	2,0

- **Type 2:** For areas exposed to earthquakes with expected surface wave magnitude $M_s \leq 5.5$



Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1,0	0,05	0,25	1,2
B	1,35	0,05	0,25	1,2
C	1,5	0,10	0,25	1,2
D	1,8	0,10	0,30	1,2
E	1,6	0,05	0,25	1,2

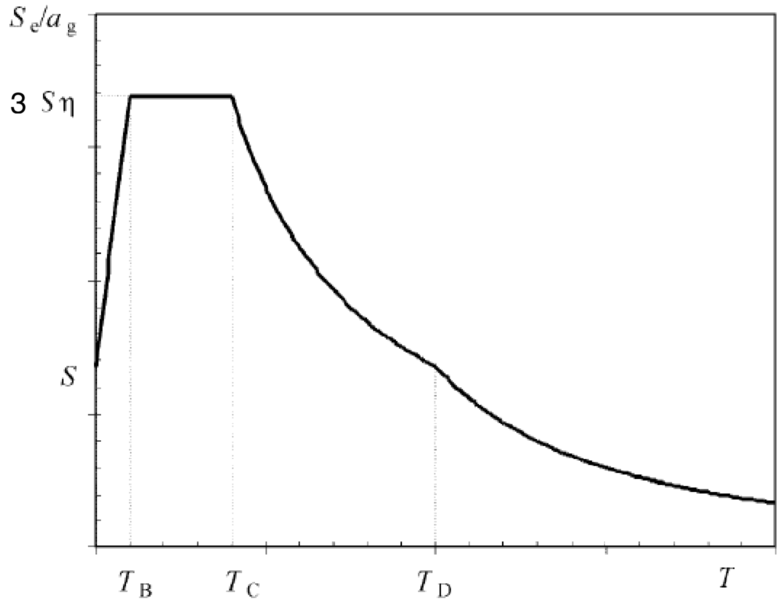
Eurocode 8 : Soil Classes, Im

Ground type	Description of stratigraphic profile	Parameters		
		$v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	> 800	–	–
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	360 – 800	> 50	> 250

Structure type	Importance factor: γ_I
Buildings	
• Hospitals, fire stations, power plants, etc.	1·4
• Schools, assembly halls, stadia, museums, etc.	1·2
• Ordinary buildings	1·0
• Agricultural buildings	0·8
Bridges	
• Critical to maintaining emergency communications.	1·3
• Average	1·0
• Not critical to maintaining emergency communications.	0·7

Eurocode 8 Elastic Vertical Response Spectrum

- shape retained
- again **Type 1** (M_s > 5.5) and **Type 2** (M_s <= 5.5) distinction is made
- but shape is not changing depending on the spectrum type neither on the soil conditions
- vertical PGA is lower than horizontal PGA



$$0 \le T \le T_B : S_{ve}(T) = a_{vg} \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 3{,}0 - 1)\right]$$

$$T_B \le T \le T_C : S_{ve}(T) = a_{vg} \cdot \eta \cdot 3{,}0$$

$$T_C \le T \le T_D : S_{ve}(T) = a_{vg} \cdot \eta \cdot 3{,}0 \left[\frac{T_C}{T}\right]$$

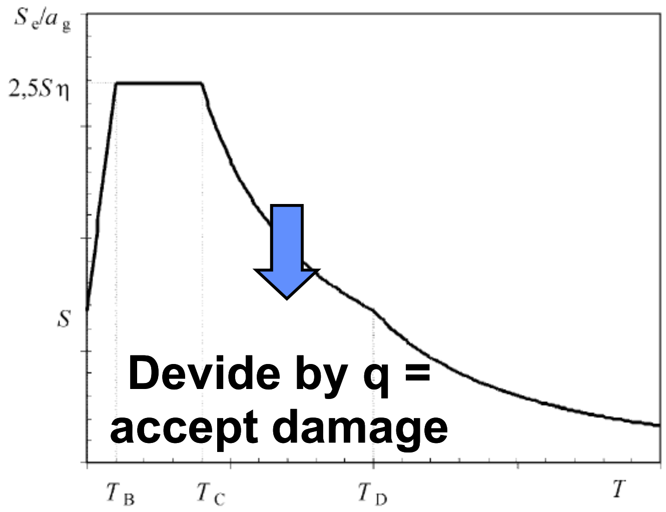
$$T_D \le T \le 4\text{s} : S_{ve}(T) = a_{vg} \cdot \eta \cdot 3{,}0 \left[\frac{T_C . T_D}{T^2}\right]$$

Spectrum	a_{vg}/a_g	T_B (s)	T_C (s)	T_D (s)
Type 1	0,90	0,05	0,15	1,0
Type 2	0,45	0,05	0,15	1,0

Eurocode 8 Design Spectrum for Elastic Analysis

EN1998-1:2004 §3.2.2.5

“To avoid explicit inelastic structural analysis in design, the capacity of the structure to dissipate energy, through mainly ductile behaviour of its elements and/or other mechanisms, is taken into account by **performing an elastic analysis** based on a **response spectrum reduced** with respect to the elastic one, hence forth called a **"design spectrum".** This reduction is accomplished by introducing the behaviour factor q”.



$$0 \le T \le T_B : S_d(T) = a_g \cdot S \cdot \left[\frac{2}{3} + \frac{T}{T_B} \cdot \left(\frac{2,5}{q} - \frac{2}{3}\right)\right]$$

$$T_B \le T \le T_C : \quad S_d(T) = a_g \cdot S \cdot \frac{2,5}{q}$$

$$T_C \le T \le T_D : S_d(T) \begin{cases} = a_g \cdot S \cdot \frac{2,5}{q} \cdot \left[\frac{T_C}{T}\right] \\ \ge \beta \cdot a_g \end{cases}$$

$$T_D \le T : \quad S_d(T) \begin{cases} = a_g \cdot S \cdot \frac{2,5}{q} \cdot \left[\frac{T_C T_D}{T^2}\right] \\ \ge \beta \cdot a_g \end{cases}$$

Eurocode 8 Design Spectrum for Elastic Analysis

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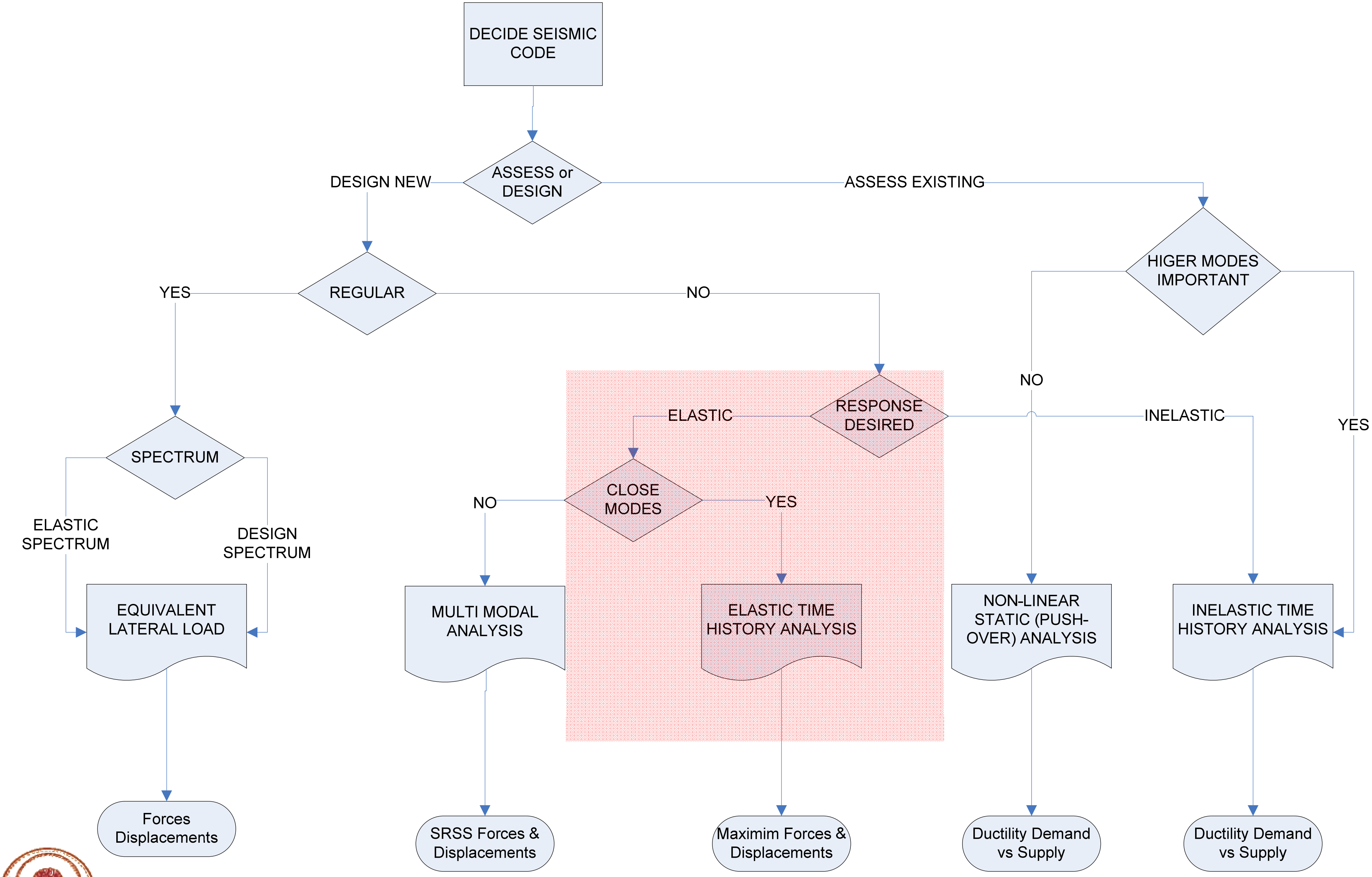
$$T_D \le T : \quad S_d(T) \begin{cases} = a_g \cdot S \cdot \frac{2,5}{q} \cdot \left[\frac{T_C T_D}{T^2} \right] \\ \ge \beta \cdot a_g \end{cases}$$

Building type	**Behaviour factor: *q***
Reinforced concrete	
• Frame system	5·0
• Dual system	4·5–5·0
• Wall system	4·0–5·0
• Core system	3·5
• Inverted pendulum system	2·0
Steel	
• Moment resisting frame	5·0–8·0
• Concentric braced frame	4·0
• Eccentric braced frame	5·0–8·0
• Cantilever structures	2·0
• Moment resisting frame with concrete/masonry infills	2·0

Seismic design & assessment flowchart



Eurocode 8 Alternative representation of Seismic Action

Time History representation

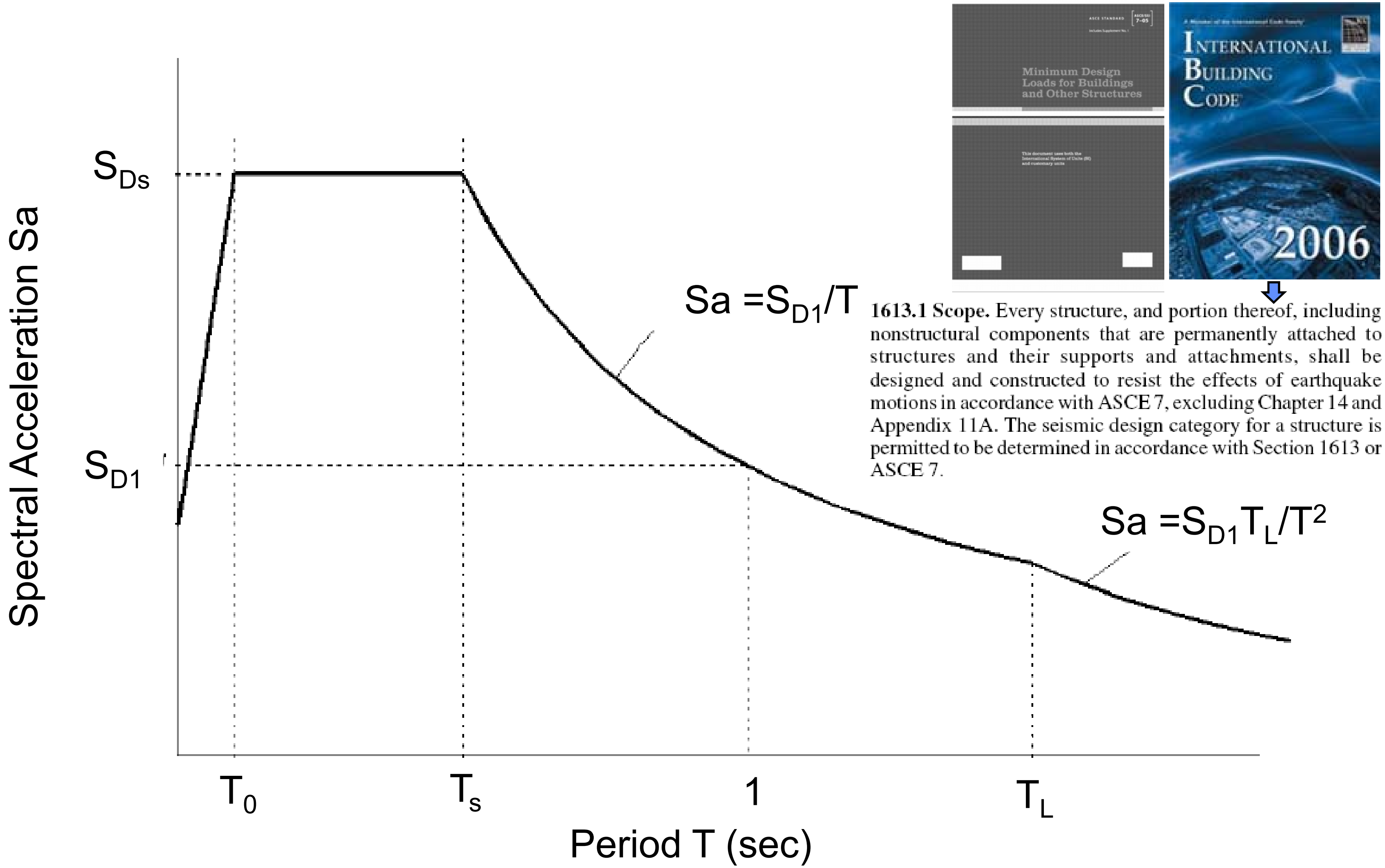
- Accelerograms may be either artifficial or recorded
- The three components are necessary
- Same accelerogram cannot be used simultaneously along both horizontal directions
- Duration should be consistent with the magnitude of the earthquake (minimum duration is 10sec unless specific site response analysis is made)
- The suite of artificial accelerograms should observe the following rules:

(1) A minimum of 3 records is used

(2) The mean of the zero period spectral acceleration response (i.e. PGA) should not be less than αg*S for the specific site

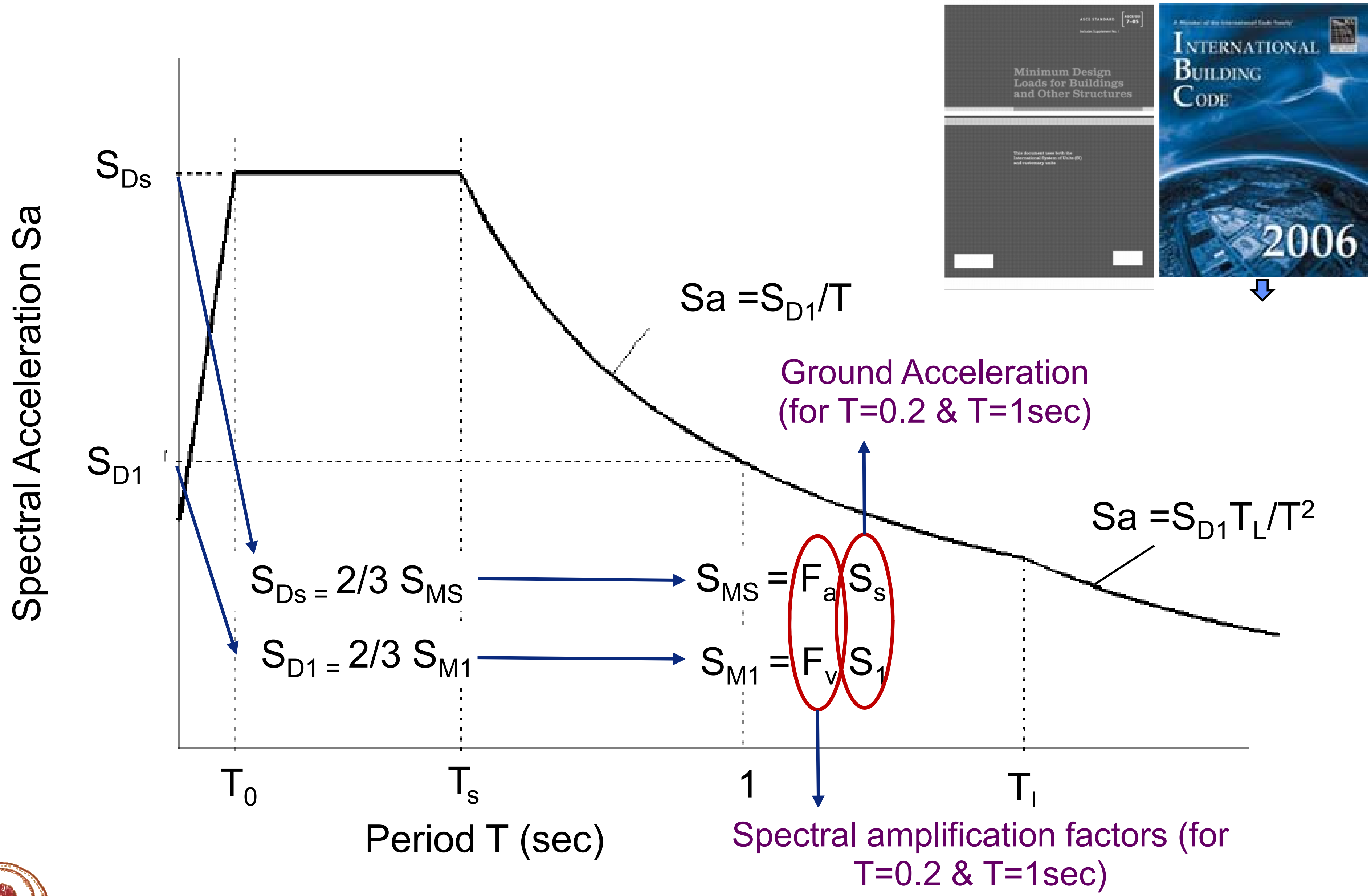
(3) In the range of periods between 0.2T1 and 2T1, where T1 the fundamental period of the structure in the direction where the accelerogram will be applied: no value of the mean 5% damping elastic spectrum (as calculated by all time histories) should be less than the 90% of the corresponding value that would have been derived using the 5% damping elastic response spectrum

U.S. International Building Code (2006) - ASCE standard 7



1613.1 Scope. Every structure, and portion thereof, including nonstructural components that are permanently attached to structures and their supports and attachments, shall be designed and constructed to resist the effects of earthquake motions in accordance with ASCE 7, excluding Chapter 14 and Appendix 11A. The seismic design category for a structure is permitted to be determined in accordance with Section 1613 or ASCE 7.

U.S. International Building Code (2006) - ASCE standard 7



U.S. International Building Code (2006) σε συνδυασμό με ASCE standard 7

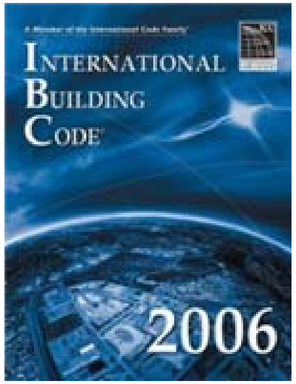


TABLE 1613.5.3(1)
VALUES OF SITE COEFFICIENT F_a [a]

SITE CLASS	MAPPED SPECTRAL RESPONSE ACCELERATION AT SHORT PERIOD				
	$S_s \le 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \ge 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	Note b	Note b	Note b	Note b	Note b

Spectral Amplification Factors F_a & F_v (for T=0.2 & T=1sec)
Function of soil condition and earthquake intensity

VALUES OF SITE COEFFICIENT F_V [a]

SITE CLASS	MAPPED SPECTRAL RESPONSE ACCELERATION AT 1-SECOND PERIOD				
	$S_1 \le 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \ge 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	Note b	Note b	Note b	Note b	Note b

a. Use straight-line interpolation for intermediate values of mapped spectral response acceleration at 1-second period, S_1.
b. Values shall be determined in accordance with Section 11.4.7 of ASCE 7.

U.S. International Building Code (2006) - ASCE standard 7

Soil categories

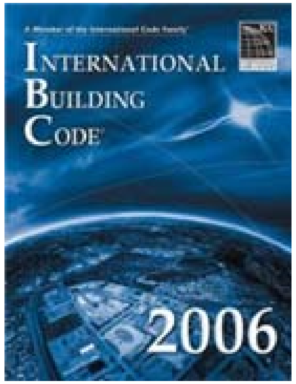


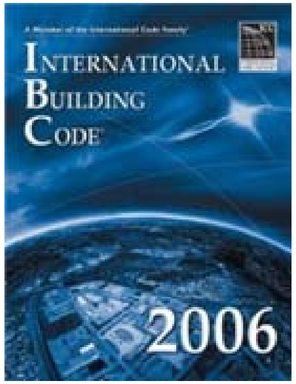
TABLE 1613.5.2
SITE CLASS DEFINITIONS

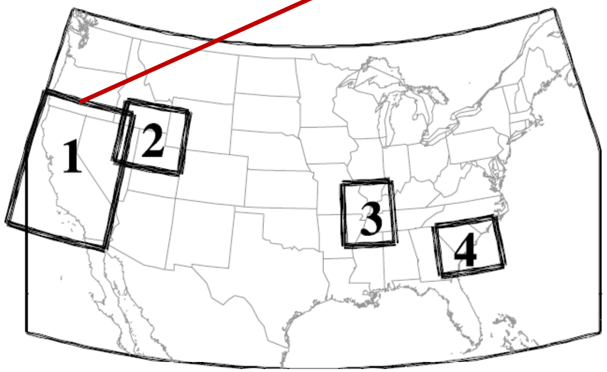
SITE CLASS	SOIL PROFILE NAME	AVERAGE PROPERTIES IN TOP 100 feet, SEE SECTION 1613.5.5		
		Soil shear wave velocity, $\bar{v}_s$, (ft/s)	Standard penetration resistance, $\bar{N}$	Soil undrained shear strength, $\bar{s}_u$, (psf)
A	Hard rock	$\bar{v}_s > 5{,}000$	N/A	N/A
B	Rock	$2{,}500 < \bar{v}_s \le 5{,}000$	N/A	N/A
C	Very dense soil and soft rock	$1{,}200 < \bar{v}_s \le 2{,}500$	$\bar{N} > 50$	$\bar{s}_u \ge 2{,}000$
D	Stiff soil profile	$600 \le \bar{v}_s \le 1{,}200$	$15 \le \bar{N} \le 50$	$1{,}000 \le \bar{s}_u \le 2{,}000$
E	Soft soil profile	$\bar{v}_s < 600$	$\bar{N} < 15$	$\bar{s}_u < 1{,}000$
E	—	Any profile with more than 10 feet of soil having the following characteristics: 1. Plasticity index $PI > 20$, 2. Moisture content $w \ge 40\%$, and 3. Undrained shear strength $\bar{s}_u < 500$ psf		
F	—	Any profile containing soils having one or more of the following characteristics: 1. Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. 2. Peats and/or highly organic clays ($H > 10$ feet of peat and/or highly organic clay where H = thickness of soil) 3. Very high plasticity clays ($H > 25$ feet with plasticity index $PI > 75$) 4. Very thick soft/medium stiff clays ($H > 120$ feet)		

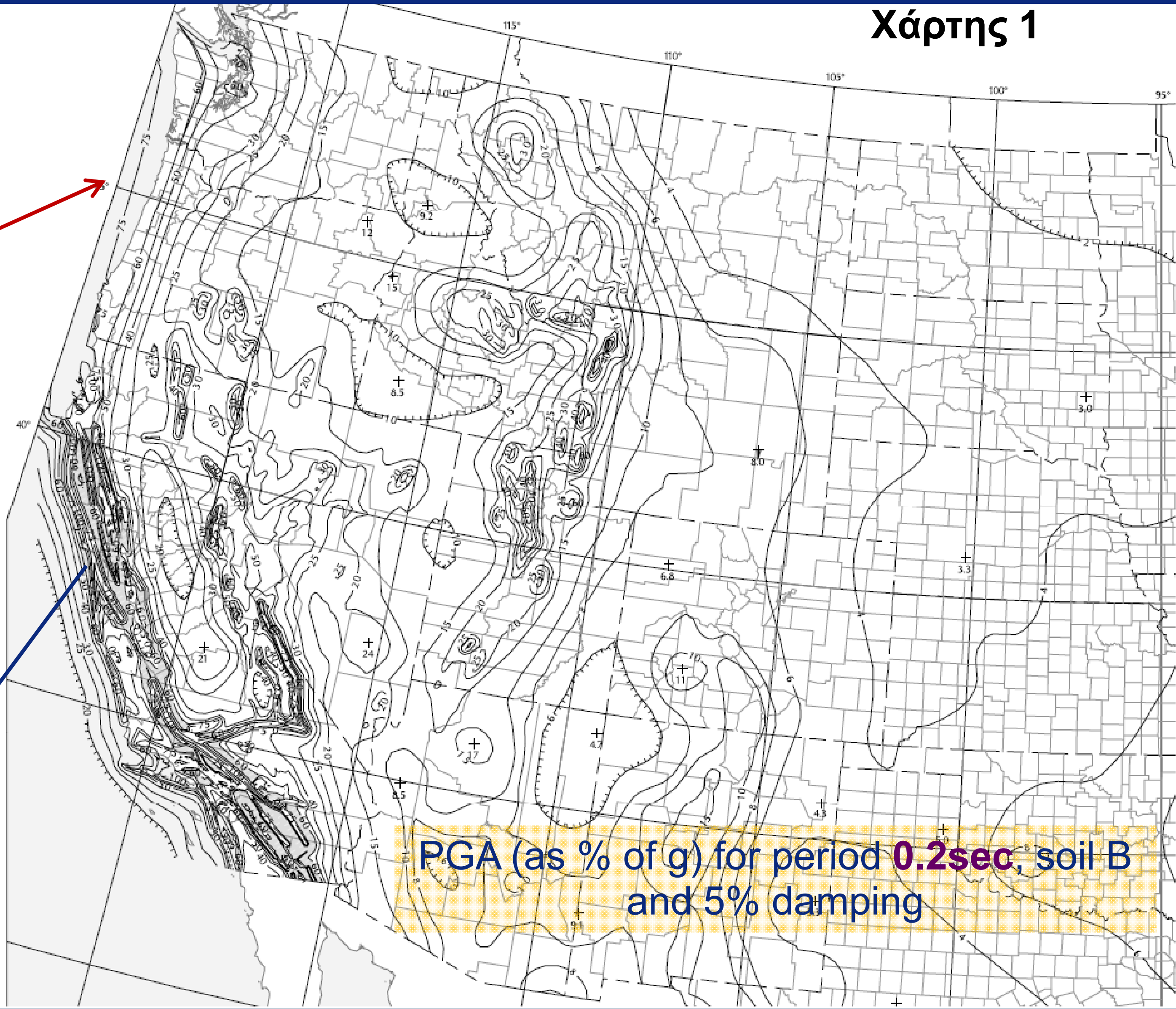
For SI: 1 foot = 304.8 mm, 1 square foot = 0.0929 m^2, 1 pound per square foot = 0.0479 kPa. N/A = Not applicable

U.S. International Building Code (2006) σε συνδυασμό με ASCE standard 7

PGA (S_1 για T=0.2sec)







Χάρτης 1

Values up to 200% g = 2g

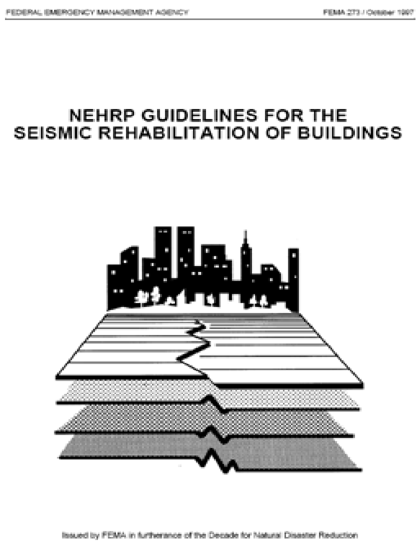
PGA (as % of g) for period **0.2sec**, soil B and 5% damping

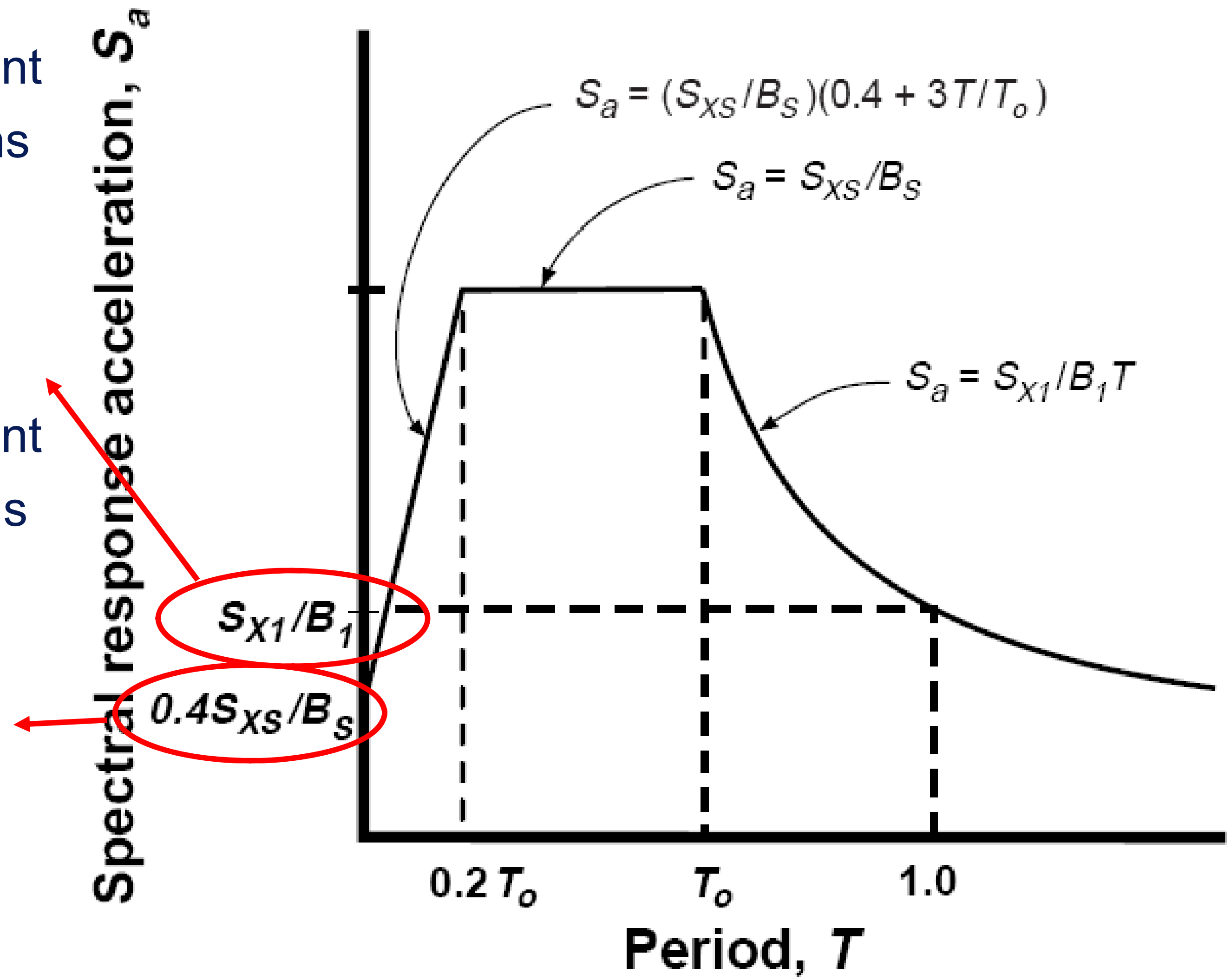
U.S. Seismic Codes: FEMA 273

B_1 = damping Coefficient

S_{x1} = (Site Response Coefficient F_v depending on soil conditions and seismicity) * (ground acceleration S_1 at T=1sec)

S_{xs} = (Site Response Coefficient F_a depending on soil conditions and seismicity) * (ground acceleration S_s at T=0 sec)





Again spectral acceleration is both Magnitude and Site dependent

U.S. Seismic Codes

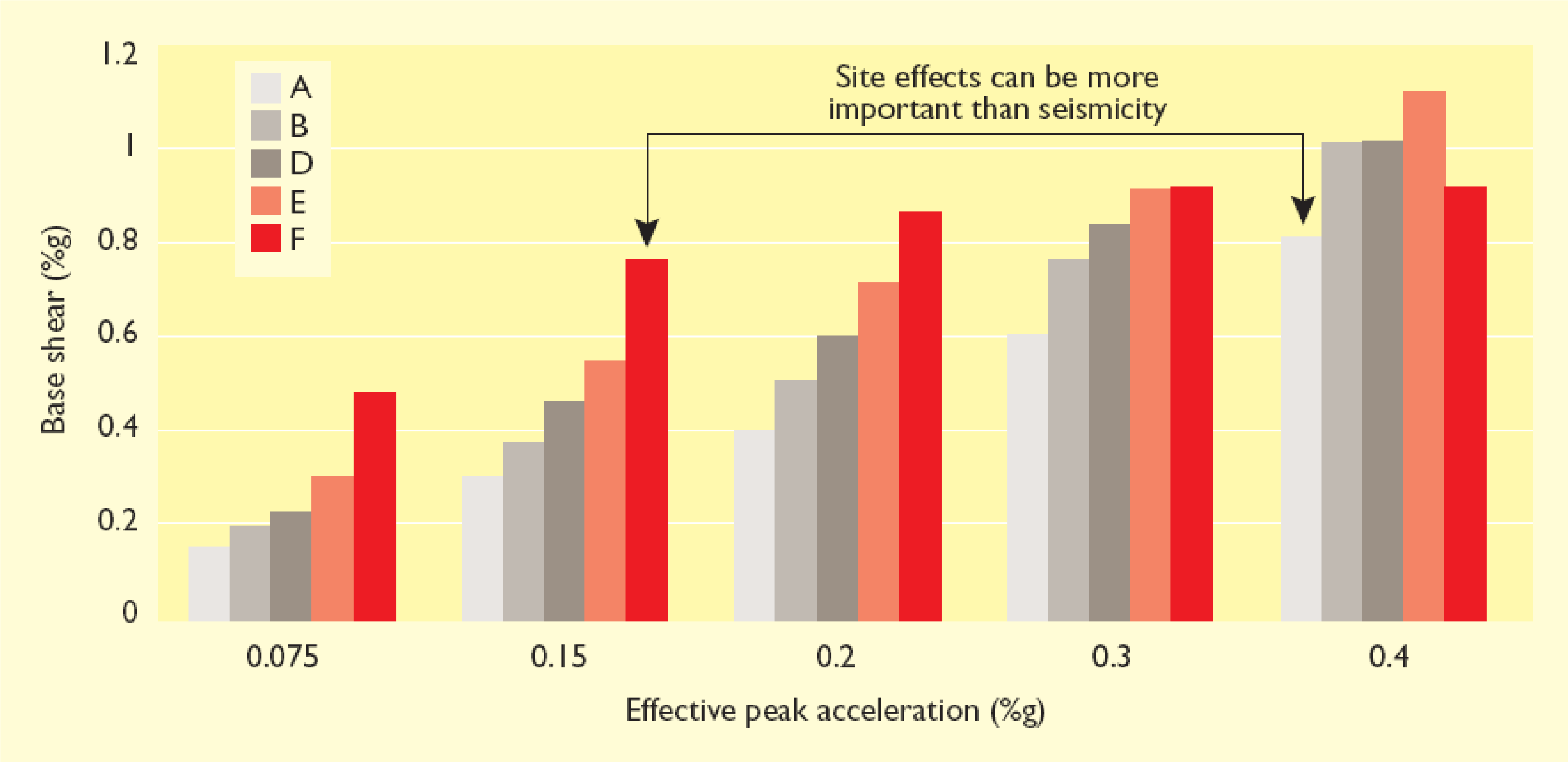


Fig. 3. US Uniform Building Code shows that horizontal earthquake force (base shear) in low seismic, soft-soil areas can be the same as high seismic, rock areas (see Table 1 for soil classes)—this 'amplitude dependence' is not accounted for in Eurocode 8

Comparative study of Seismic Codes

$V_{s,30}$ (m/sec)		180	360	760	1500
UBC/97 IBC/2000	S_E	S_D	S_C	S_B	S_A
EAK2000	D – C	C	B A	A	
EC8 (ENV1998)	C	C	B A	A	
EC8 (prEN1998) (Draft4, 2001)	D	C	B	A	
New Zealand, 2000 (Draft)	D (T>0.6s =>$V_{s,30}$<200)	C (T<0.6s =>$V_{s,30}$>200)	B	A	
Japan, 1998 (Highway Bridges)	III (T>0.6s =>$V_{s,30}$<200)	II (I) (T=0.2 - 0.6s => $V_{s,30}$=200 - 600)		I (T<0.2s =>$V_{s,30}$>600)	
Turkey/98	Z_4 – Z_3	Z_3 – Z_2	Z_3 – Z_2 – Z_1	Z_1	
AFPS/90	S_3 – S_2	S_3 – S_2 – S_1	S_1 – S_0	S_0	

- Different PGA levels
- Different Site Amplification
- Different Force reduction (behaviour) factors

Uncertainties

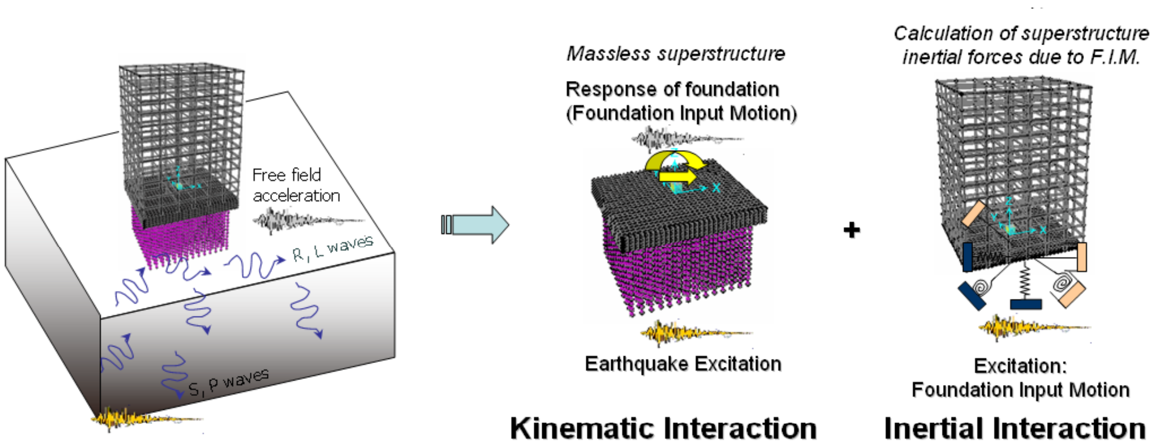
Selection of the design earthquake

- Methods to select ‘realistic’ acceleration time histories for the analysis in the time domain?
- Possible sensitivity of the structure in the selection process?
- How many accelerograms?
- Scalling?
- Natural or artificial accelerograms?
- Duration της of earthquake input?
- Spatial variability τof earthquake ground motion?

Dynamic characteristics of the structure?

For both spectral analysis and time history analysis the dynamic characteristics of the structure play an important role. However, they depend on:

Flexible soil and foundation (soil-structure interaction)

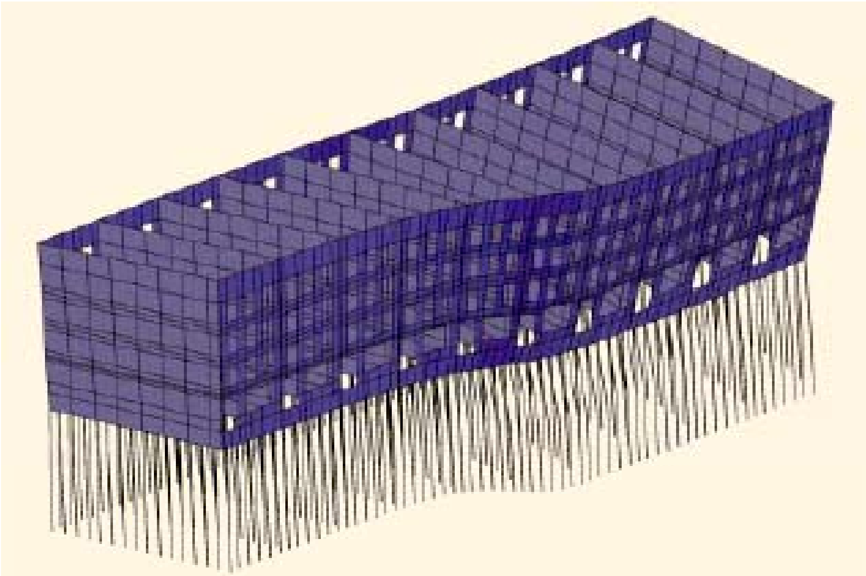


- **Fundamental period increases**
- **the modal participation factors are modified**

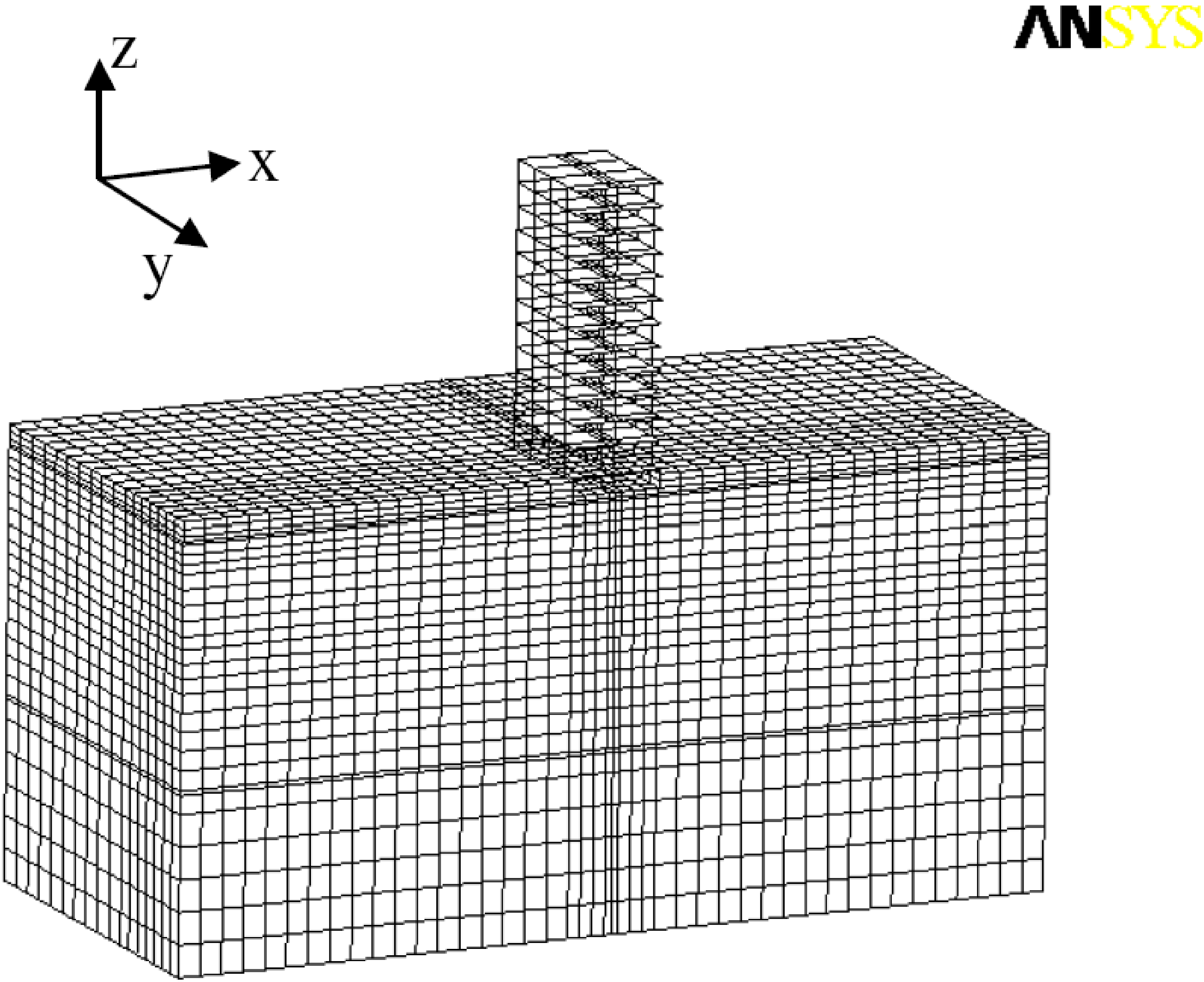
Yielding of R/C members and period elongation

- **the dynamic characteristics change in time**

Soil-structure interaction



Soil-structure interaction



Soil-structure interaction

1. Motion exhibits a significant rocking component.

2. Seismic excitation at the base of a structure founded on soft soil is generally different than the free field vibration as seismic waves are reflected and refracted on the foundation hence, radiated back to the surrounding soil.

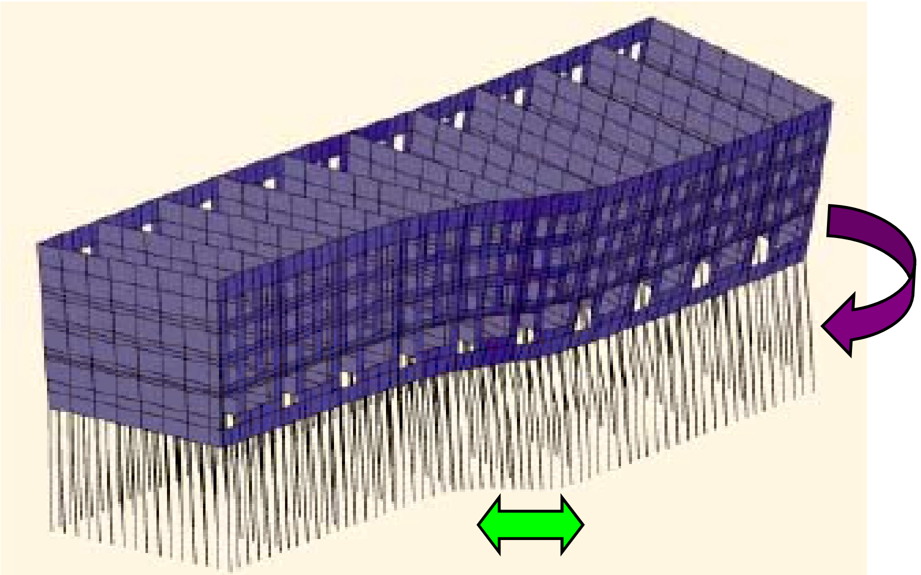
3.The fundamental period of the flexibly supported structure is expected to be higher

4. Once the structural period is shifted rightwards on the response spectrum the corresponding spectral acceleration is different.

5. Eigenmodes and modal participation factors are affected

6. An additional damping is introduced at the structure-soil interface.

Soil-structure interaction (EN 1998-5)



Inertia forces developed in the structure cause in turn displacements at the foundation relative to the free field (frequency dependent impedance – inertial interaction)

Foundation is not able to follow the imposed by soil displacement field, hence seismic motion at the base of the structure is different than that of the free field (kinematic interaction)

= Decoupling of kinematic & inertial interaction

Soil-structure interaction (EN 1998-5)

(1)P The effects of dynamic soil-structure interaction shall be taken into account in:

a) structures where P-δ (2nd order) effects play a significant role;

b) structures with massive or deep-seated foundations, such as bridge piers, offshore caissons, and silos;

c) slender tall structures, such as towers and chimneys, covered in EN 1998-6:200X;

d) structures supported on very soft soils, with average shear wave velocity $v_{s,max}$ (as defined in Table 4.1) less than 100 m/s, such as ground type S_1.

> NOTE: For a better understanding of the general effects and significance of dynamic soil-structure interaction, Annex D provides relevant information.

(2)P The effects of soil-structure interaction on piles shall be assessed according to 5.4.2 for all structures.

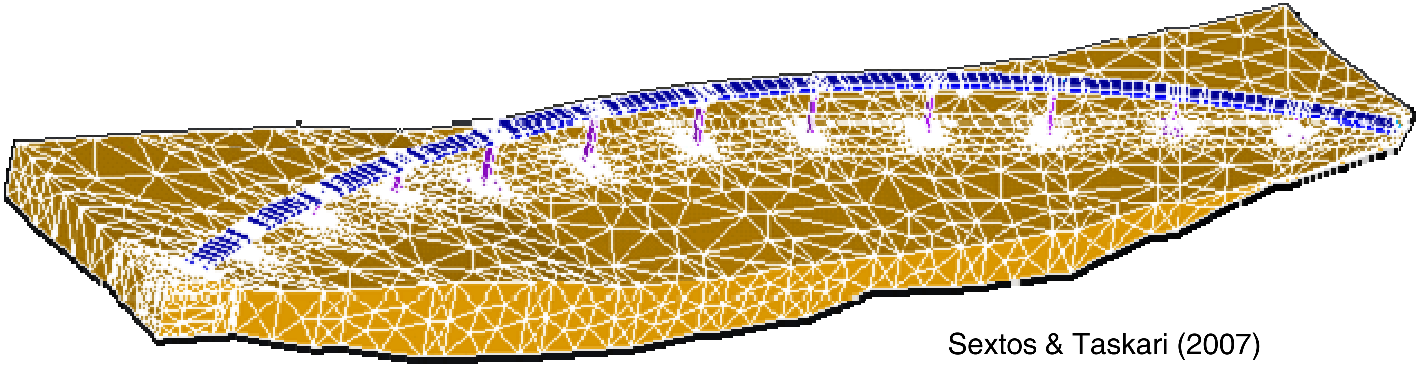
Soil-structure interaction (EN 1998-5)

Table Cl: Expressions for static stiffness of flexible piles embedded in three soil models

Soil model	$\dfrac{K_{HH}}{dE_s}$	$\dfrac{K_{MM}}{d^3 E_s}$	$\dfrac{K_{HM}}{d^2 E_s}$
$E = E_s \cdot z/d$	$0{,}60\left(\dfrac{E_p}{E_s}\right)^{0{,}35}$	$0{,}14\left(\dfrac{E_p}{E_s}\right)^{0{,}80}$	$-0{,}17\left(\dfrac{E_p}{E_s}\right)^{0{,}60}$
$E = E_s \sqrt{z/d}$	$0{,}79\left(\dfrac{E_p}{E_s}\right)^{0{,}28}$	$0{,}15\left(\dfrac{E_p}{E_s}\right)^{0{,}77}$	$-0{,}24\left(\dfrac{E_p}{E_s}\right)^{0{,}53}$
$E = E_s$	$1{,}08\left(\dfrac{E_p}{E_s}\right)^{0{,}21}$	$0{,}16\left(\dfrac{E_p}{E_s}\right)^{0{,}75}$	$-0{,}22\left(\dfrac{E_p}{E_s}\right)^{0{,}50}$

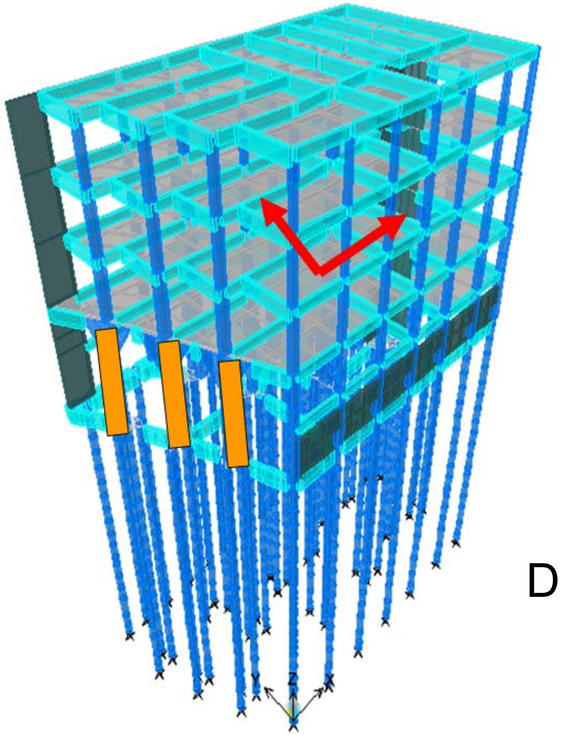
Angle of incidence? Which direction to excite along?

Which is the critical angle of earthquake excitation for curved bridges or irregular buildings?

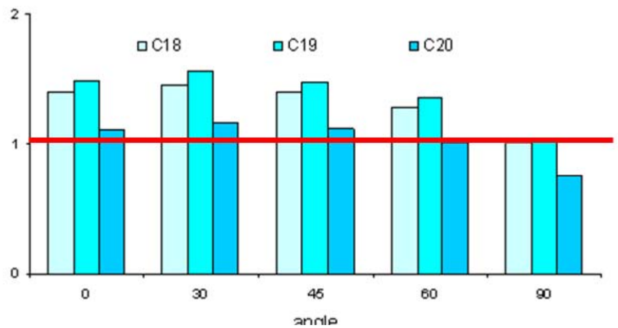


Sextos & Taskari (2007)

Sextos, Kappos & Mergos (2004)



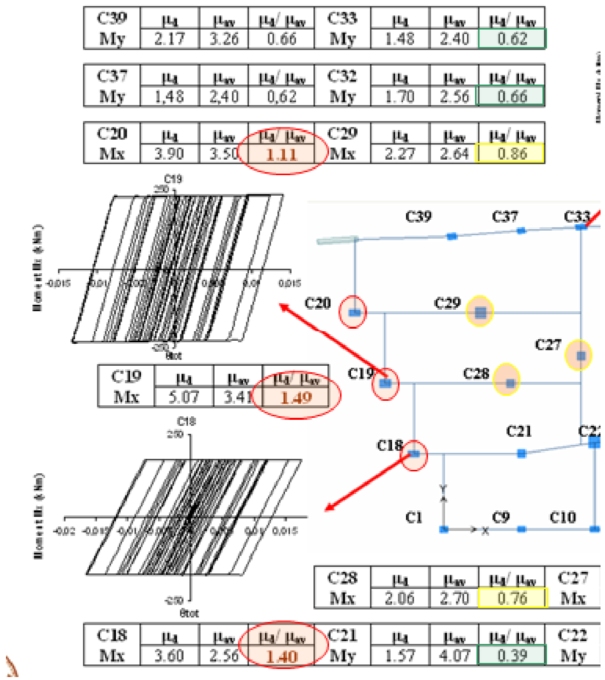
Sextos et al. (2005)



Ductility demand changes as the angle changes

n

the most critical



Computational tools

Strong Ground Motion Databases On-line

ESD – the European Strong-Motion Database: http://www.isesd.cv.ic.ac.uk

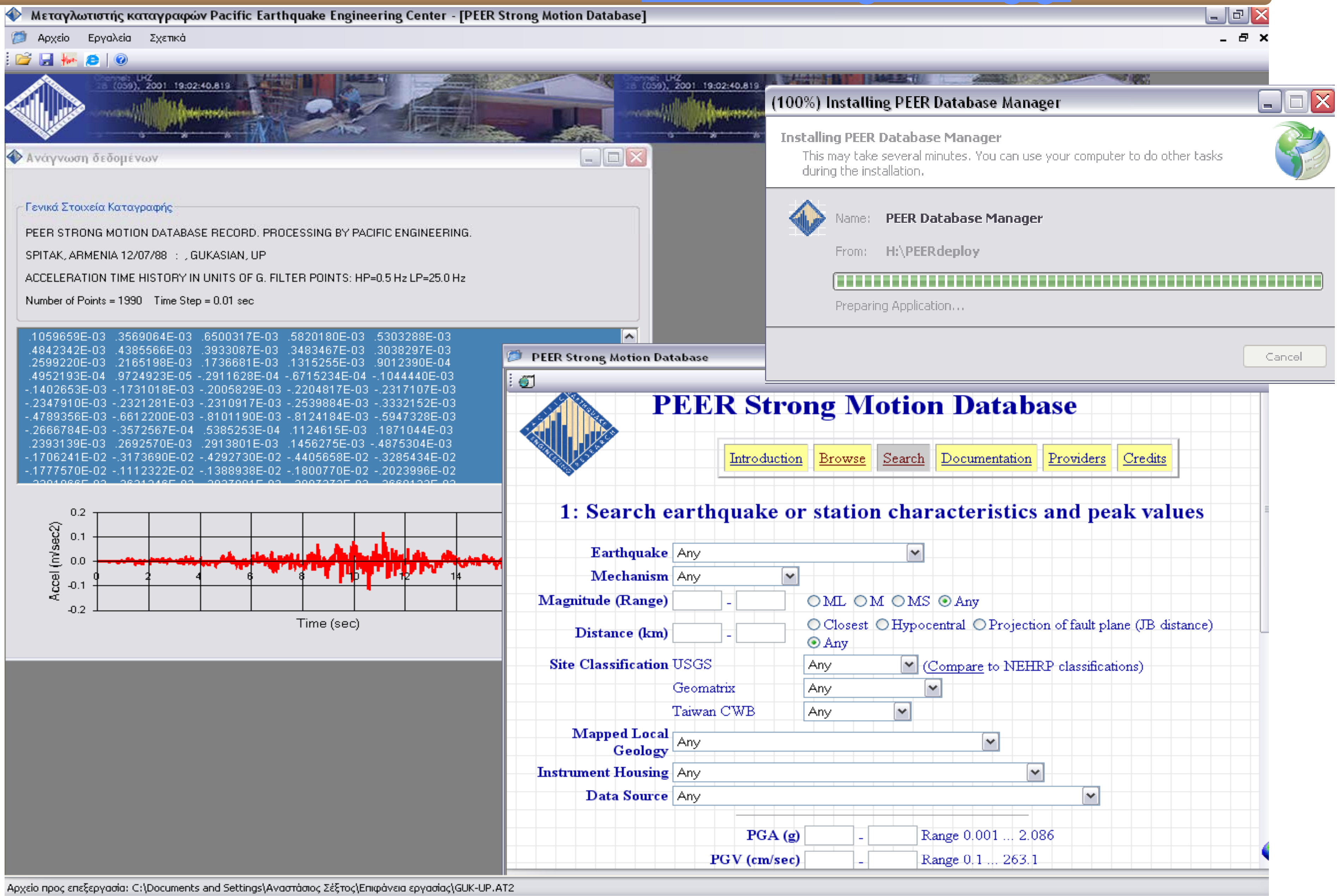
PEER Strong Motion Database: http://peer.berkeley.edu/smcat/

NIED K-NET: http://www.k-net.bosai.go.jp/

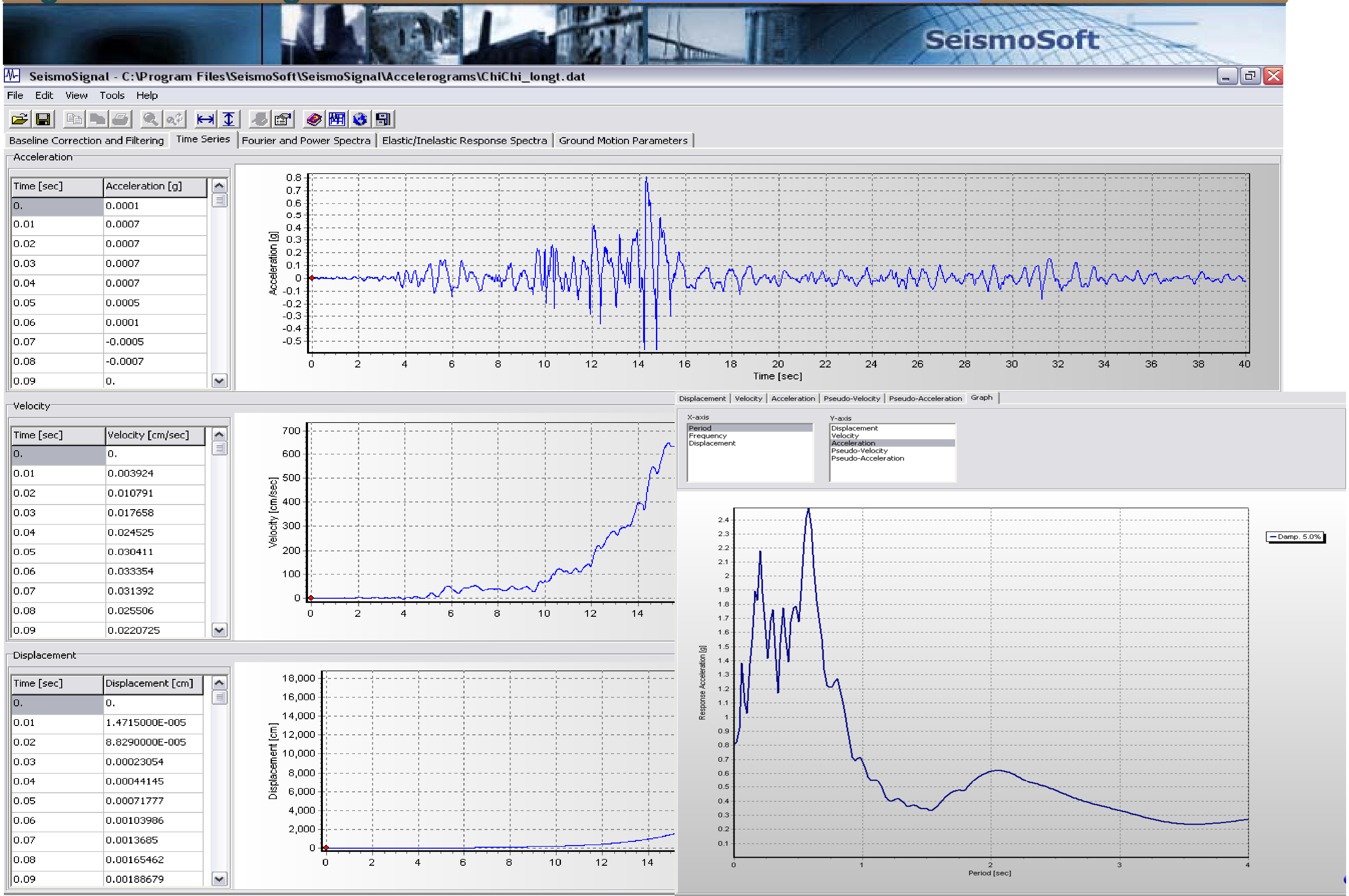
COSMOS Virtual Data Center – Consortium of Organizations for Strong-Motion Observation Systems: http://db.cosmos-eq.org

Seismic Data from the Center for Earthquake Research and Information (CERI): http://folkworm.ceri.memphis.edu/

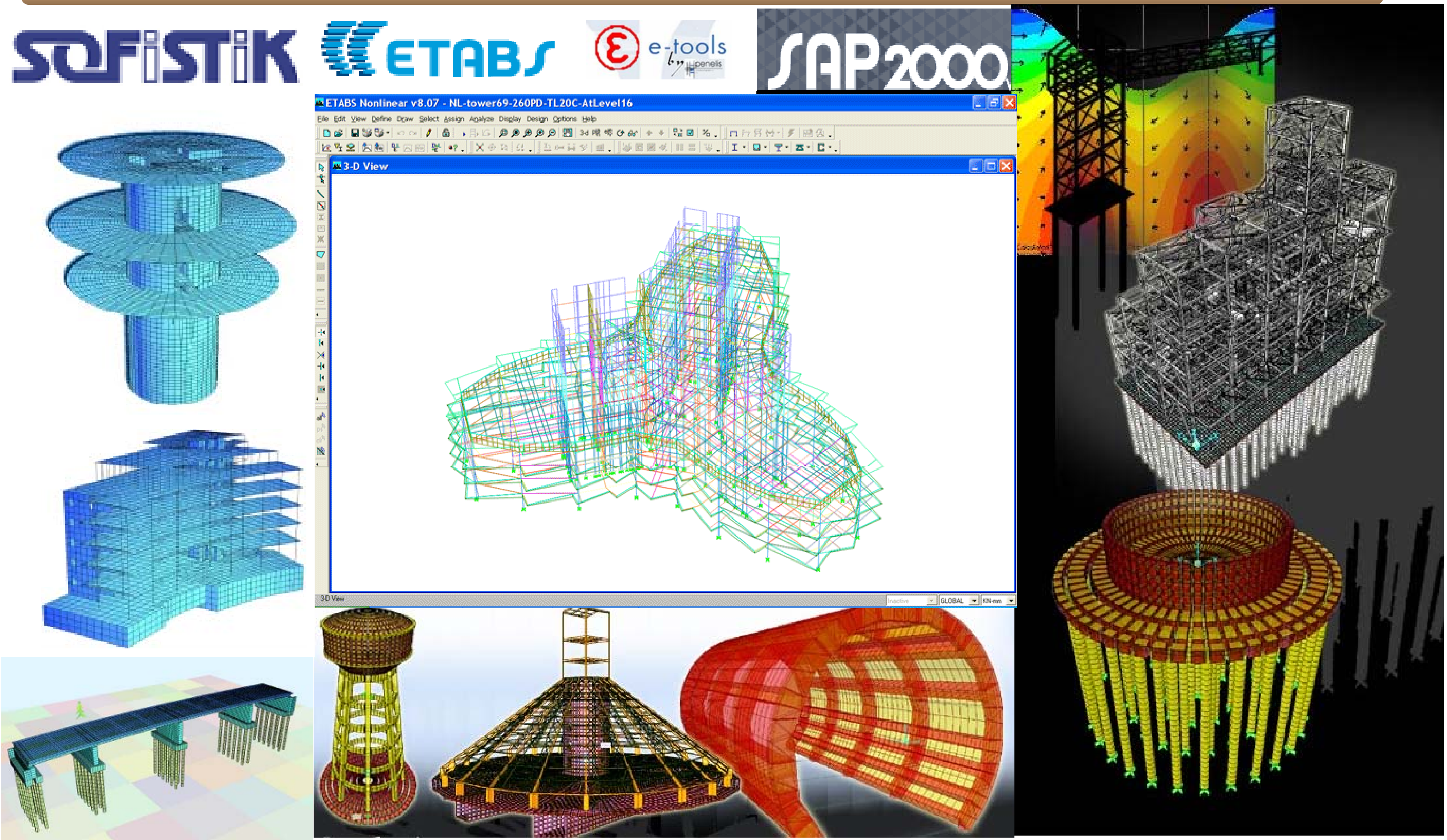
Strong Ground Motion Translators On-line: www.civilengineering.gr



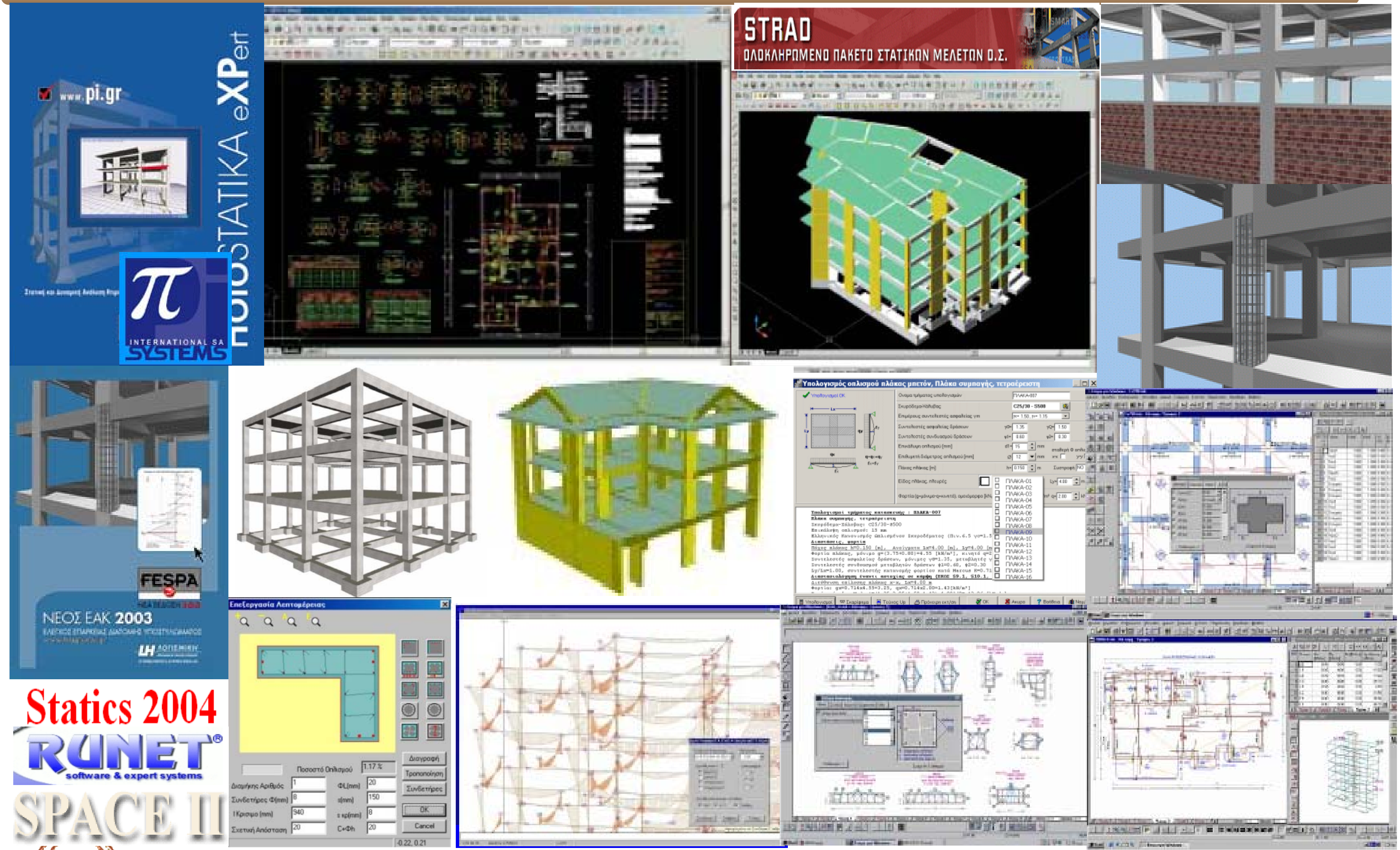
Signal Processing – Freeware on-line: www.seismosoft.com



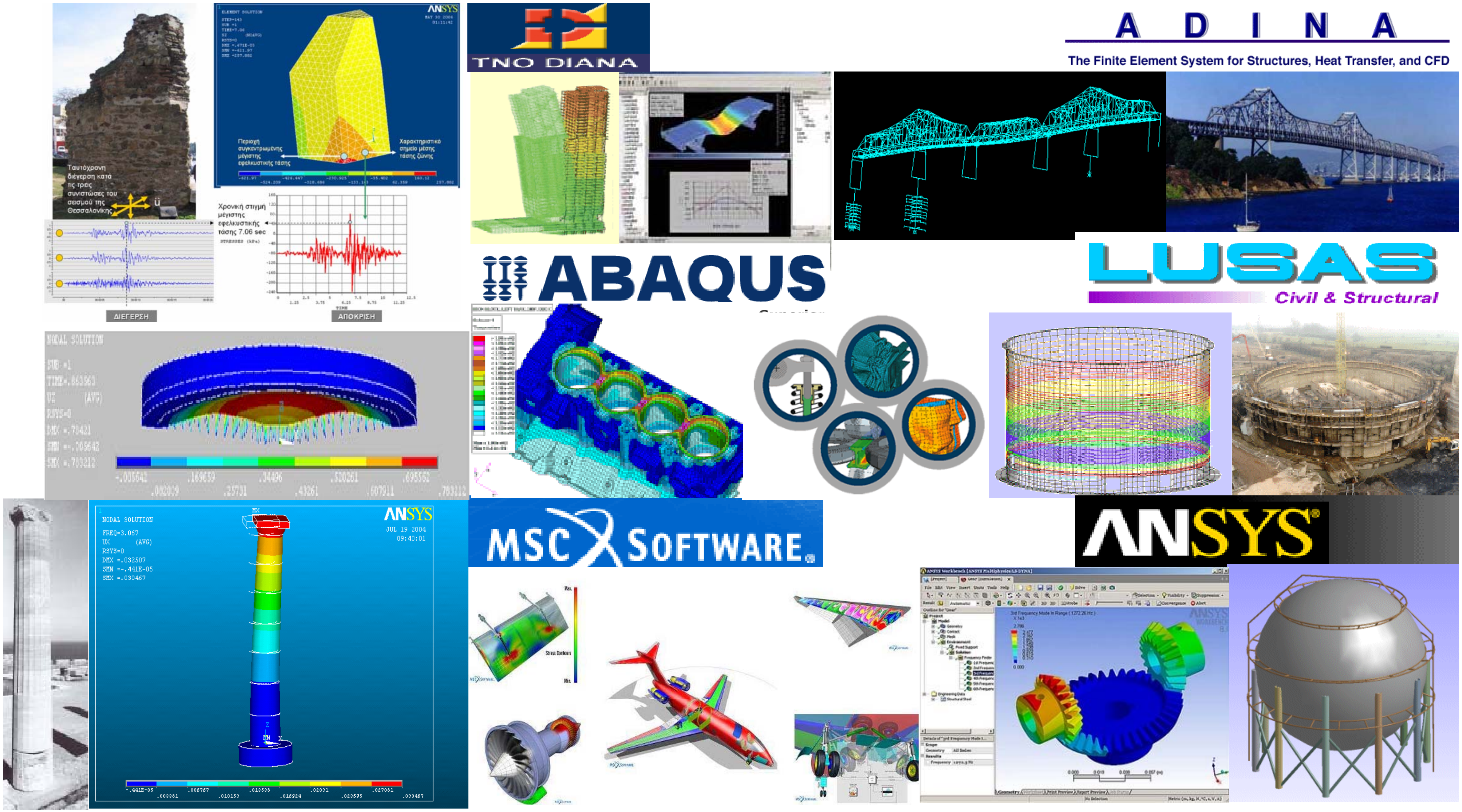
Finite Element software for the determination of action effects



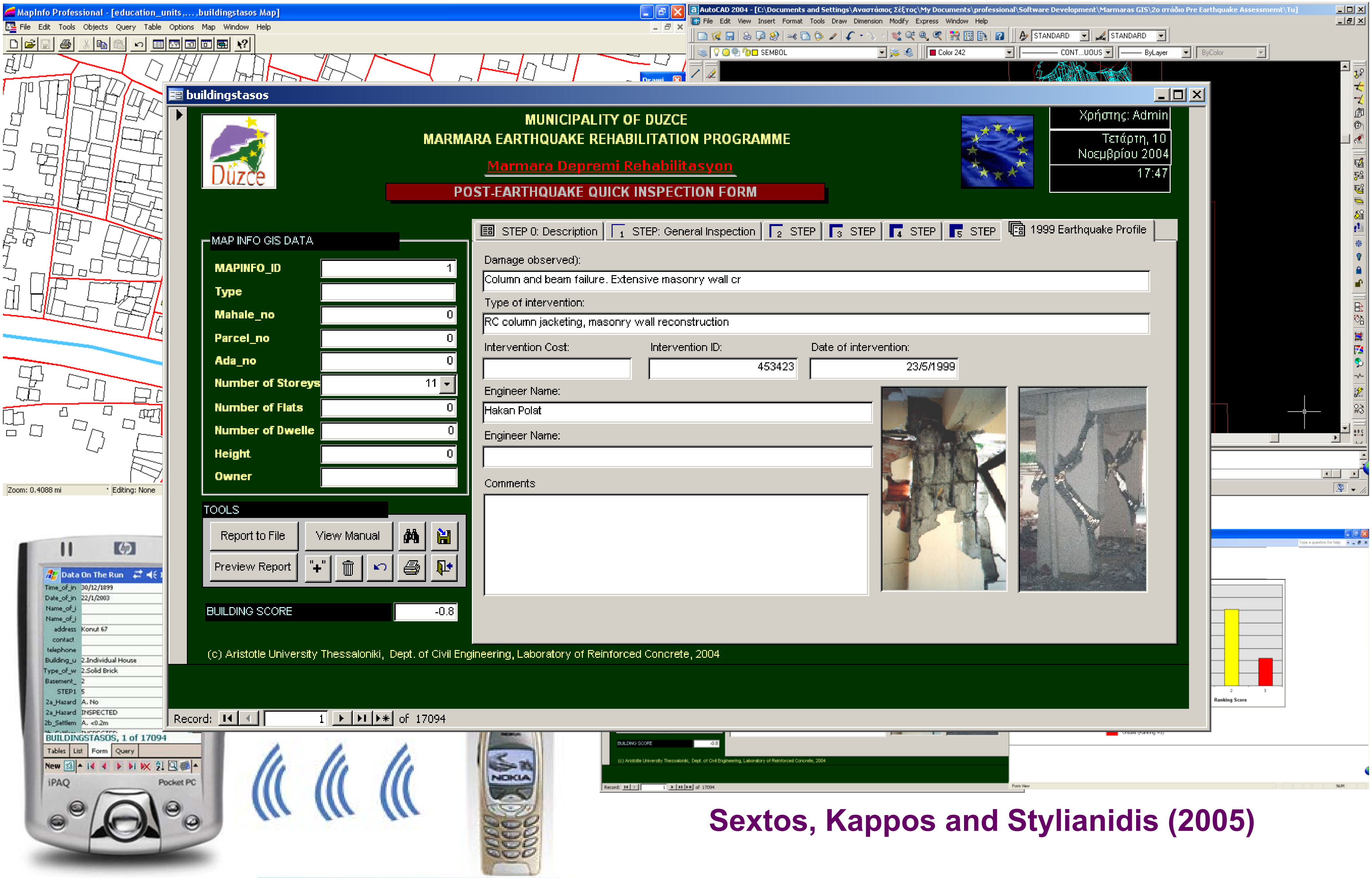
Finite Element software for the determination of action effects



Finite Element software for the determination of action effects

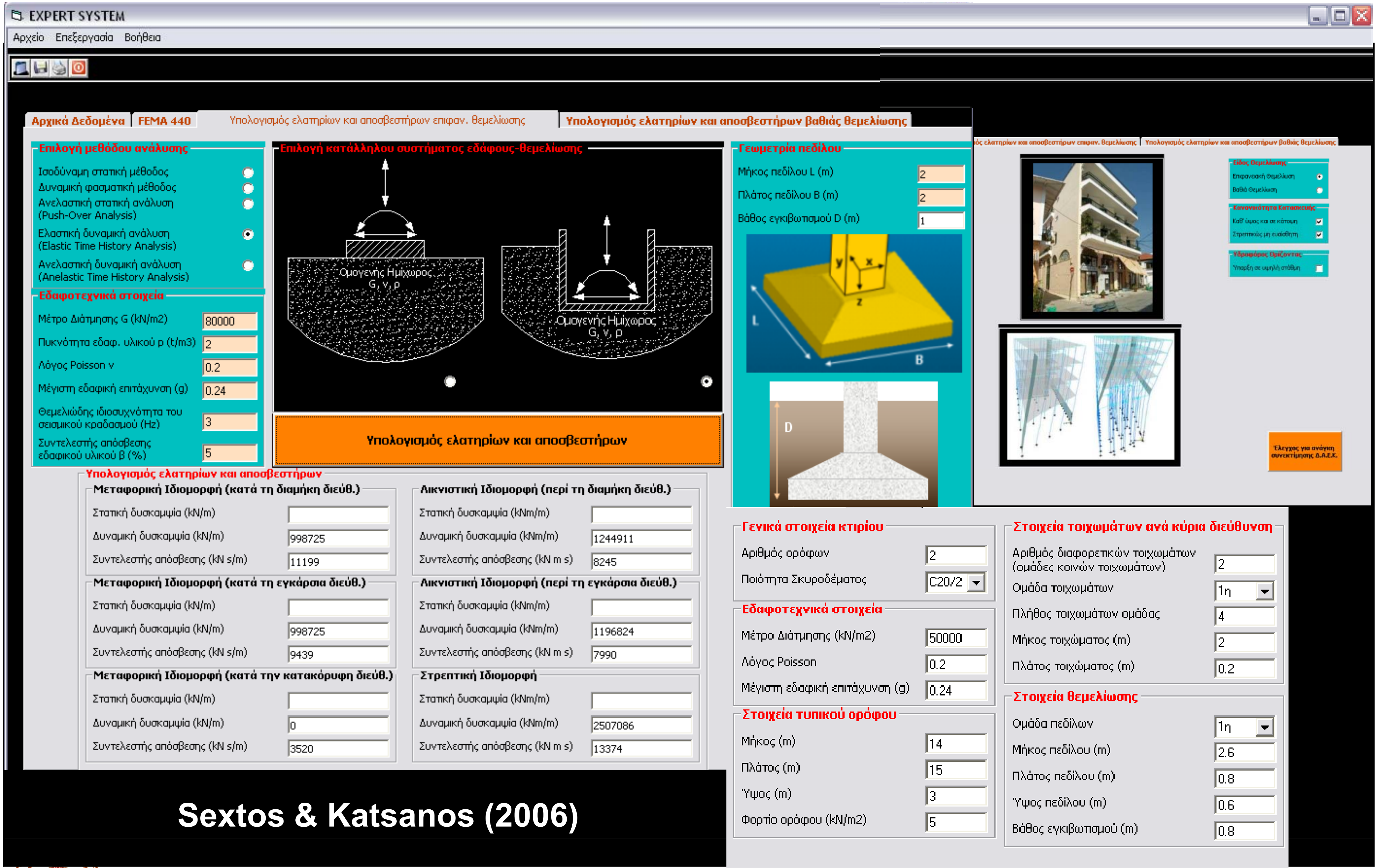


A hybrid GIS/Mobile-Database Expert System for the assessment of buildings



Sextos, Kappos and Stylianidis (2005)

An Expert System for the assessment of Soil-Structure interaction in buildings



Sextos & Katsanos (2006)

Design Seismic Actions

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1998-1 : 2004

May 2004

UDC

Descriptors:

English version

Eurocode 8 : Design of structures for earthquake resistance

Part 1: General rules, seismic actions and rules for buildings

Calcul des structures pour leur résistance aux séismes

Partie 1 : Règles générales, actions sismiques et règles pour les bâtiments

Auslegung von Bauwerken gegen Erdbeben

Teil 1 : Grundlagen; Erdbebeneinwirkungen und Regeln für Hochbauten

Stage 51

CEN

European Committee for Standardisation
Comité Européen de Normalisation
Europäisches Komitee für Normung

Central Secretariat: rue de Stassart 36, B-1050 Brussels

Ref. No. EN 1998-1 : 2003 (E)