International Workshop on the Uncertainties in Nonlinear Soil Properties and their Impact on Modeling Dynamic Soil Response, March 18-19, 2004, California, US

Nonlinear soil models for site response; European experience

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Site Response Analysis

Input Ground Motion

Source And Path Characteristics

Site Characterization

Geomorphologic and Geotechnical Conditions, Topographical Features, Soil Stratification, Nonlinear Inelastic Characteristics of Soils

Soil Model

Nonlinear Inelastic Cyclic Behavior of Soils

Site Response Analysis

1D and 2D

The purpose of site response analysis governs the needed accuracy

- Microzonation and scenario
- Site specific studies

Site Characterization

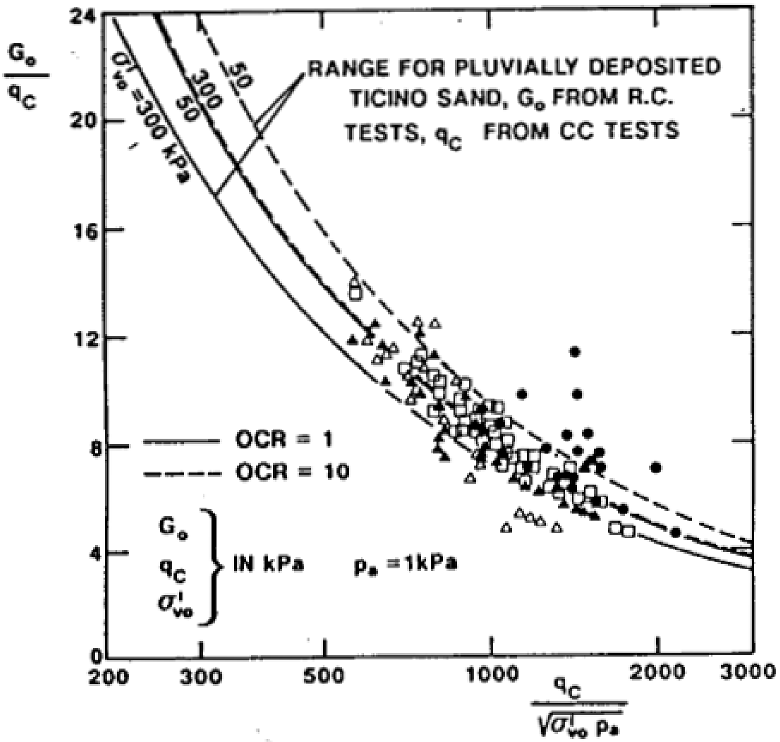
Significant number of detailed geological and geotechnical investigations were conducted to determine the soil stratification and properties of soil layers. (Calosi et al., 2001; Pitilakis et al., 1999, Marcellini et al., 1995).

In most cases these investigations are composed of in-situ and laboratory testing programs. In-situ tests can be considered as composed of three categories.

1. The first category is SPT and CPT penetration tests. These tests are utilized to identify the properties of soil layers as well as to estimate shear wave velocity profiles (Iyisan, 1996; Baldi et al. 1989 Jamiolkowski et al., 1988)

2. The second category of tests is expansion tests used to estimate medium strain range soil properties (i.e. pressuremeter, Ghionna et al., 1994)

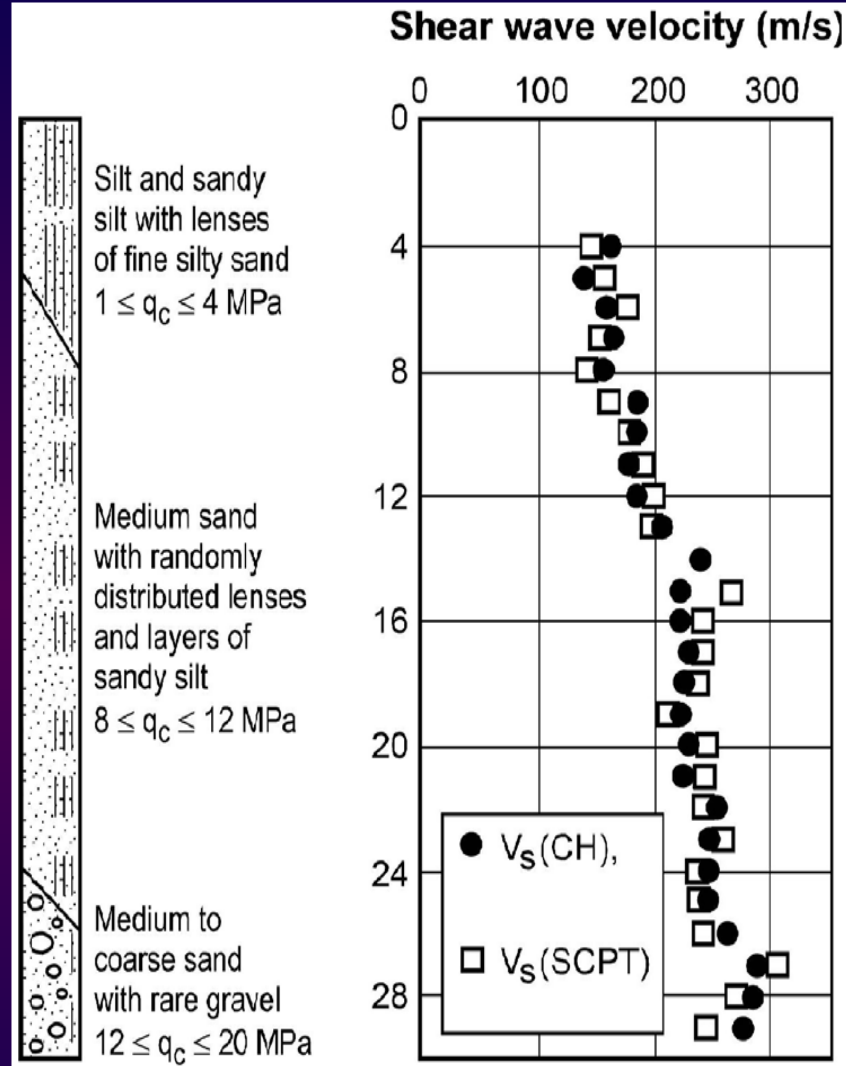
3. The third category of tests are seismic wave velocity measurements based on down-hole, cross-hole, and PS logging, SASW methodology (Lai et al., 2002; Bessason el al.,1998; Mancuso, 1994; Raptakis et al., 1994). More recently ambient noise array measurements were also utilized (Louie, 2001; Kind et al., 2000; Milana et al., 1996)



	SITE	SOIL	G_o SOURCE	BOREHOLE
△	VIADANA	MEDIUM SAND	CROSS-HOLE	4017
▲	VIADANA	MEDIUM SAND	SEISMIC CONE	4017
□	S. PROSPERO	MEDIUM SAND	SEISMIC CONE	16 17
●	GIOIA TAURO	SAND WITH GRAVEL	CROSS-HOLE	209 219

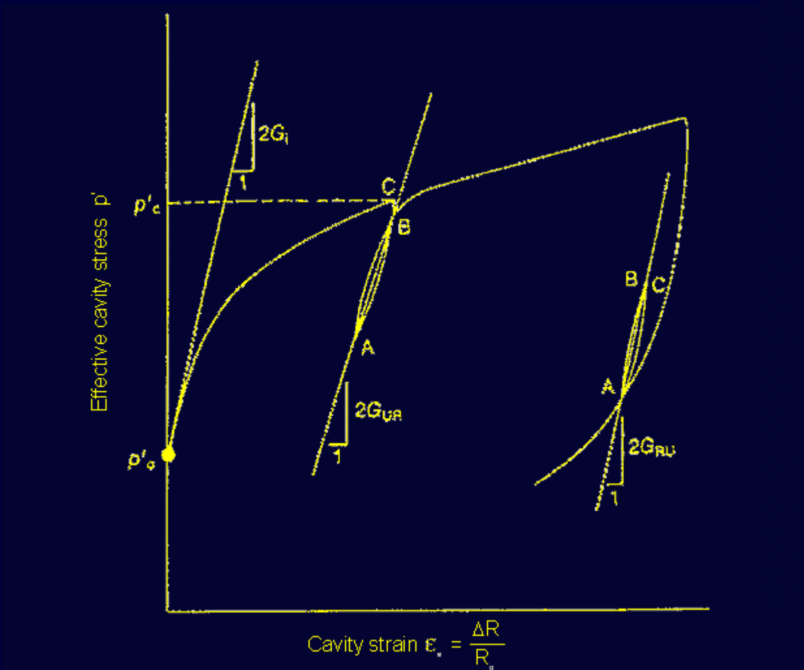
DEPTH BELOW G.L. CONSIDERED: 5.5 TO 43.5 m

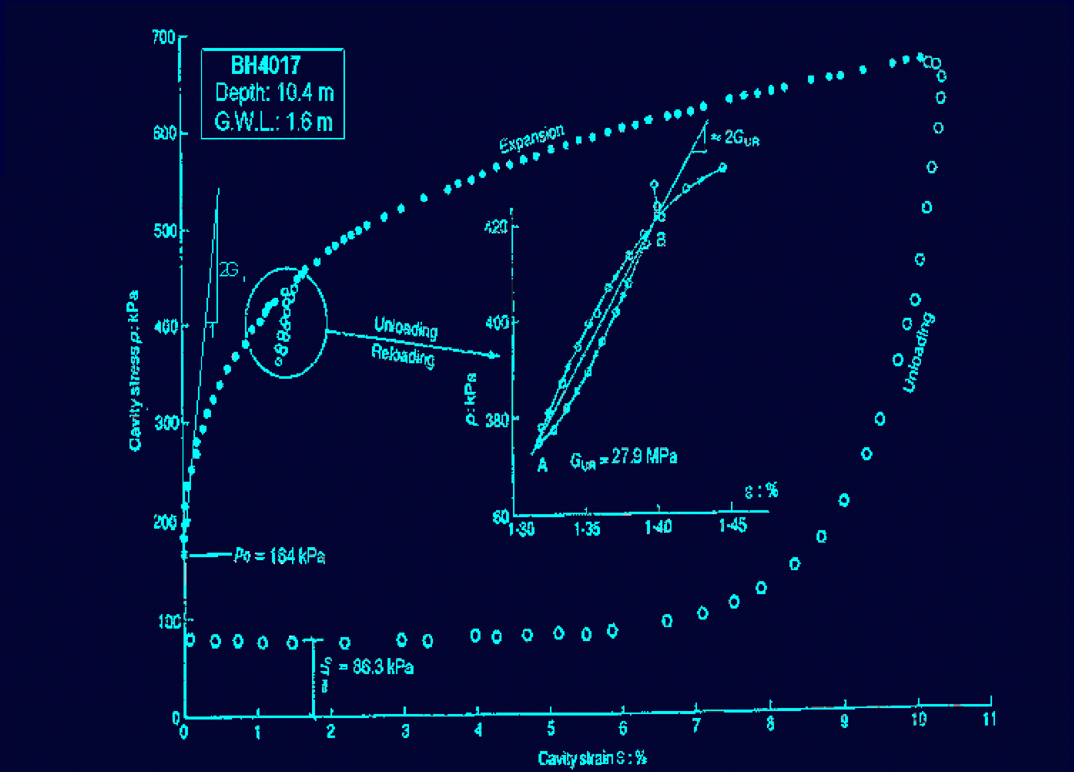
Jamiolkowski et al., 1988



Jamiolkowski et al., 1998

Insitu Large strain tests



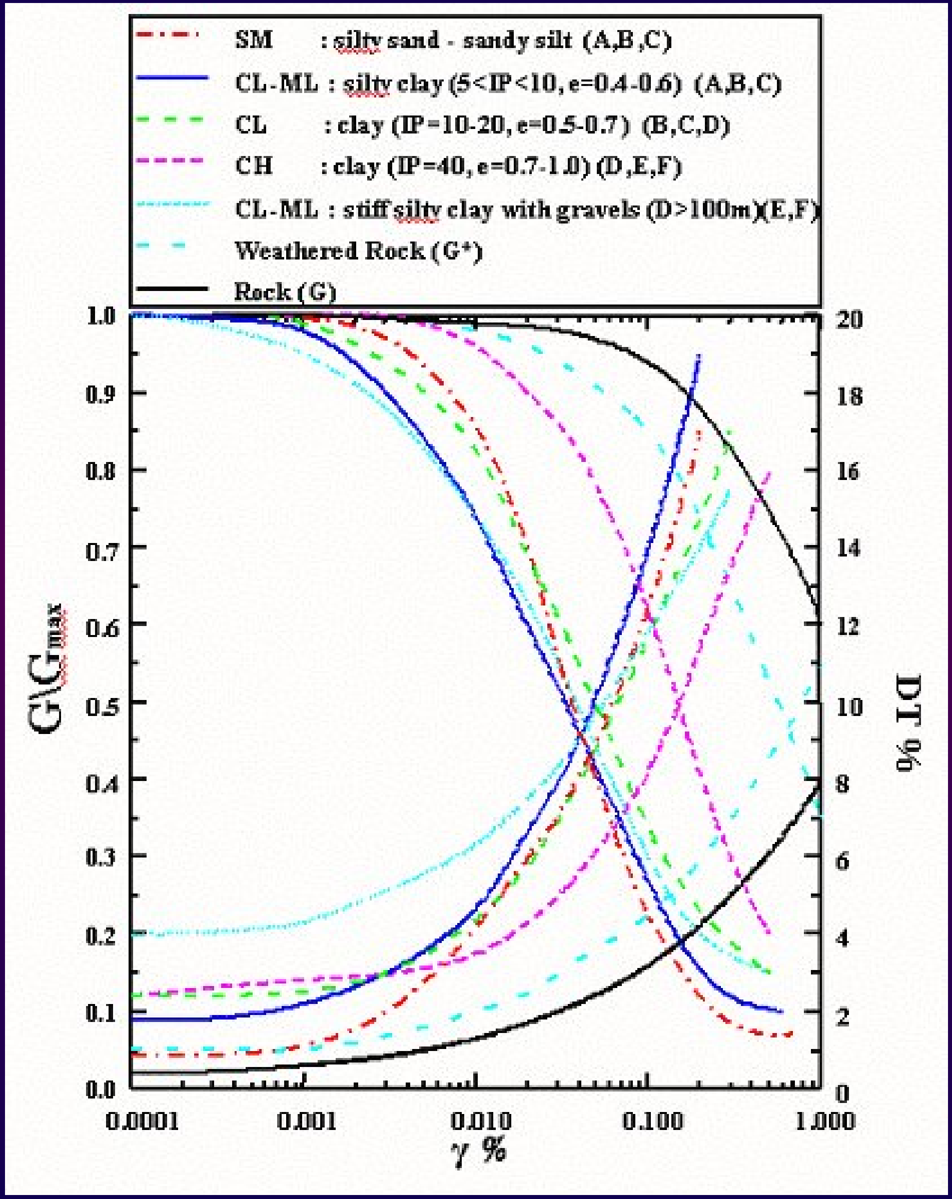


Selfboring pressuremeter SBR

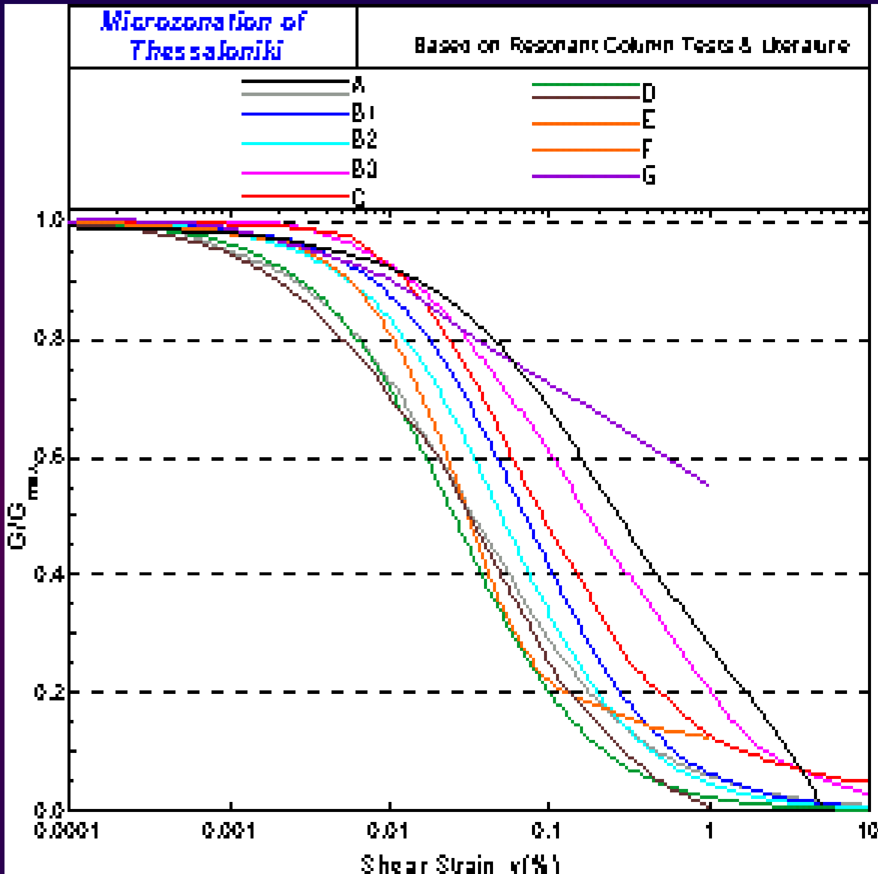
Selfboring pressuremeter SBR
Bellotti et al., 1989

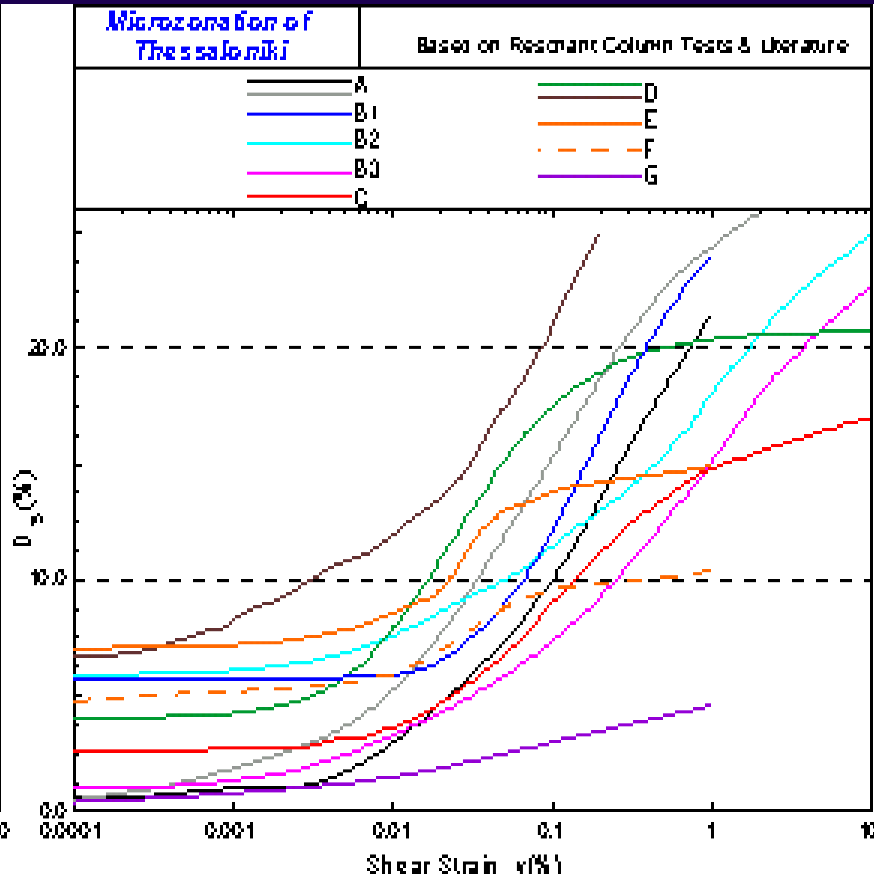
Laboratory Tests

- Triaxial Tests
- Simple shear
- Resonant Column
- Torsional Shear Test

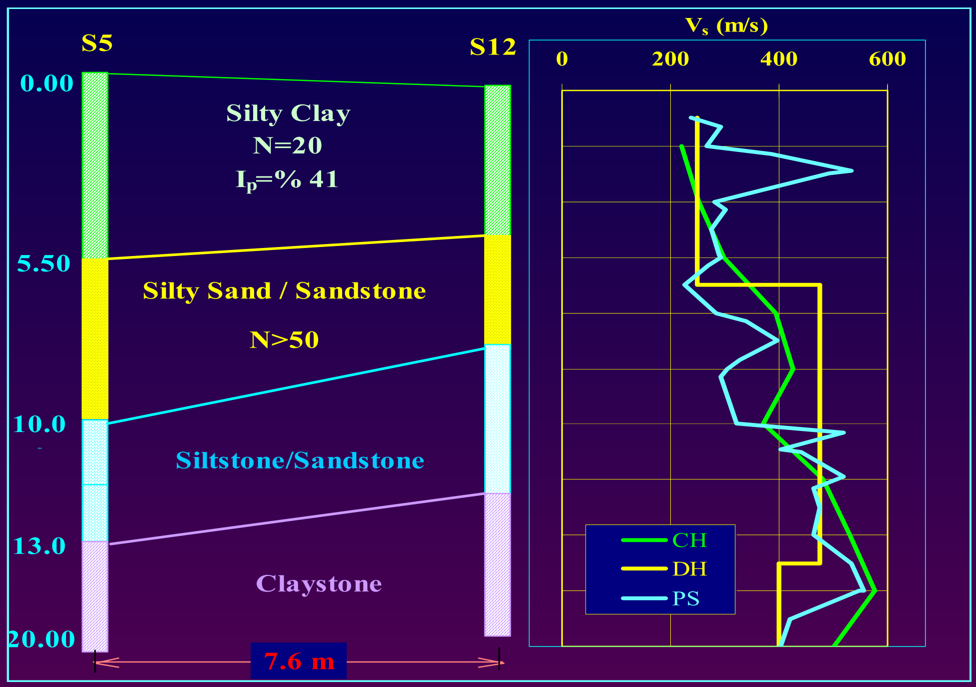


Pitilakis et al., 1999

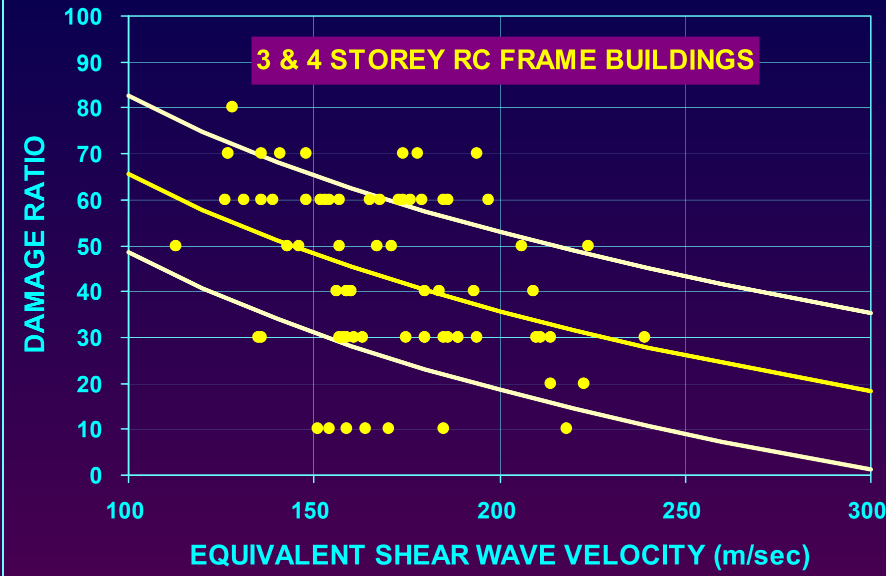

Microzonation of Thessaloniki
Based on Resonant Column Tests & Literature
A
B1
B2
B3
C
D
E
F
G
1.0
0.8
0.6
0.4
0.2
0.0
G/G max
0.0001
0.001
0.01
0.1
1
10
Shear Strain, γ(%)


Microzonation of Thessaloniki
Based on Resonant Column Tests & Literature
A
B1
B2
B3
C
D
E
F
G
20.0
10.0
0.0
D s (%)
0.0001
0.001
0.01
0.1
1
10
Shear Strain, γ(%)

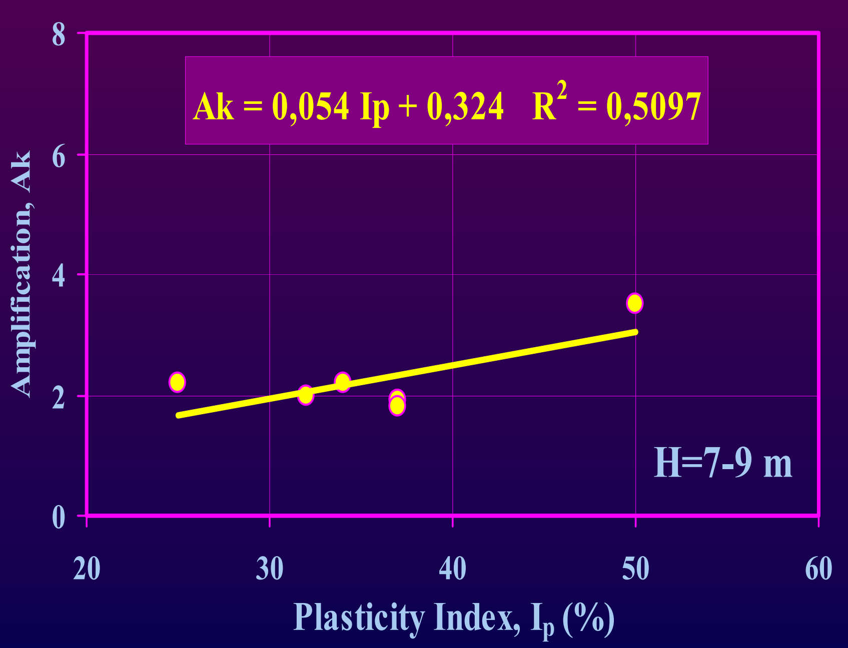
Formation	Description		V_S (m/s)	V_P (m/s)	Q_S
A	Surficial	Artificial Fills, demolition materials and debris parts	200-350 (250)	400-1700	8-20 (15)
B1		Very Stiff sandy-silty clays to clayey sands, low plasticity	300-400 (350)	1900	15-20 (20)
B2		Soft sandy-silty clays to clayey sands, low to medium plasticity	200-300 (250)	1800	20-25 (20)
B3		Stiff to hard high plasticity clays	300-400 (350)	1800	20-40 (30)
C		Very soft buy mud and silty sands	120-220 (180)	1800	20-25 (25)
D		Alluvium deposits, sandy-silty clays to clayey sands-silts, low strength and high compressibility	150-250 (200)	1800	15-25 (20)
E	Subbase	Stiff to hard sandy-silty clays to clayey sands	350-700 (600)	2000	6-30 (30)
F		Very stiff to hard low to medium plasticity clays to sandy clays Overconsolidated with rubbles and thin layers of gravels	700-850 (750)	3200	50-60 (60)
G		GreenSchists and Gneiss	1750-2200 (2000)	4500	180-200 (200)



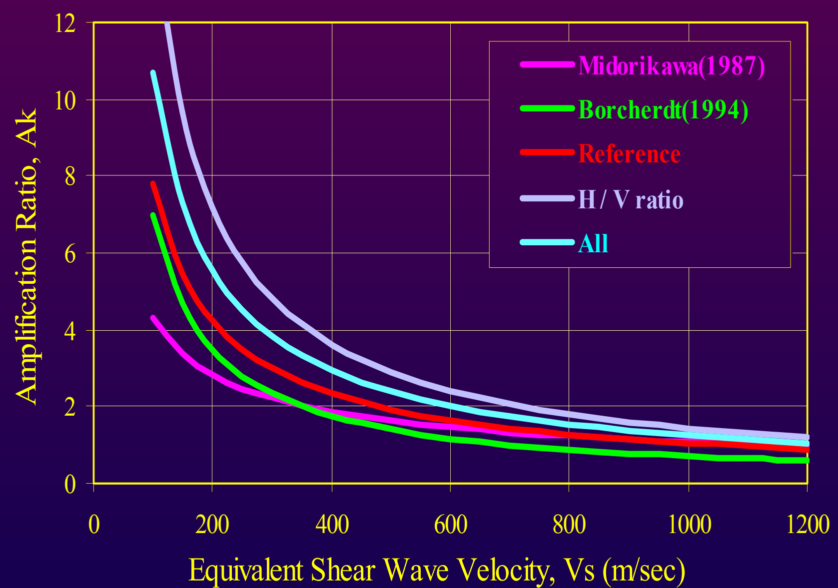
S5
S12
0.00
5.50
10.0
13.0
20.00
Silty Clay
N=20
I_p=% 41
Silty Sand / Sandstone
N>50
Siltstone/Sandstone
Claystone
7.6 m
V_s (m/s)
0
200
400
600
CH
DH
PS



3 & 4 STOREY RC FRAME BUILDINGS
DAMAGE RATIO
100
90
80
70
60
50
40
30
20
10
0
100
150
200
250
300
EQUIVALENT SHEAR WAVE VELOCITY (m/sec)



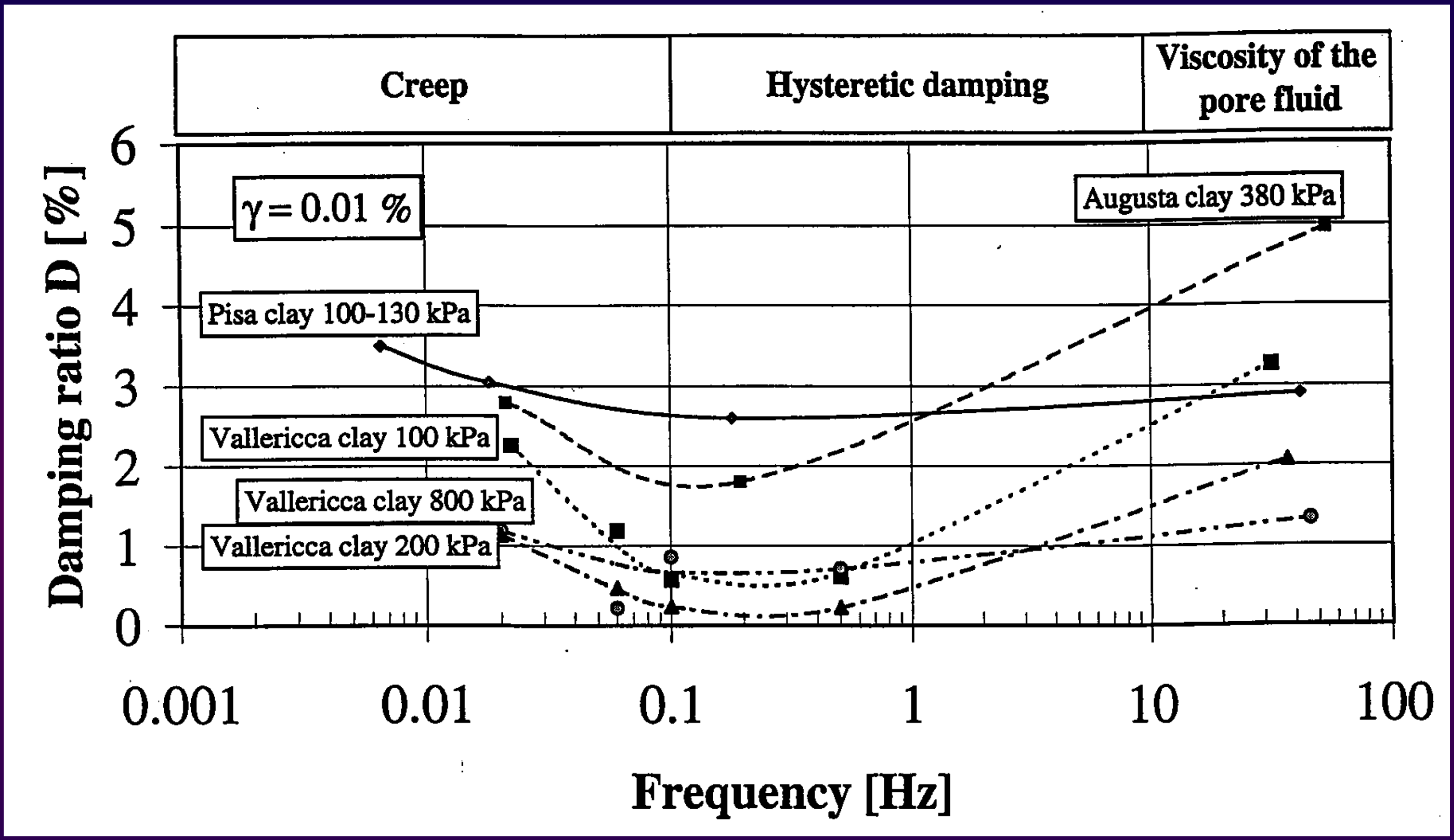
Ak = 0,054 Ip + 0,324 R^2 = 0,5097
H=7-9 m
Amplification, Ak
8
6
4
2
0
20
30
40
50
60
Plasticity Index, I_p (%)



Midorikawa(1987)
Borcherdt(1994)
Reference
H / V ratio
All
Amplification Ratio, Ak
12
10
8
6
4
2
0
0
200
400
600
800
1000
1200
Equivalent Shear Wave Velocity, Vs (m/sec)

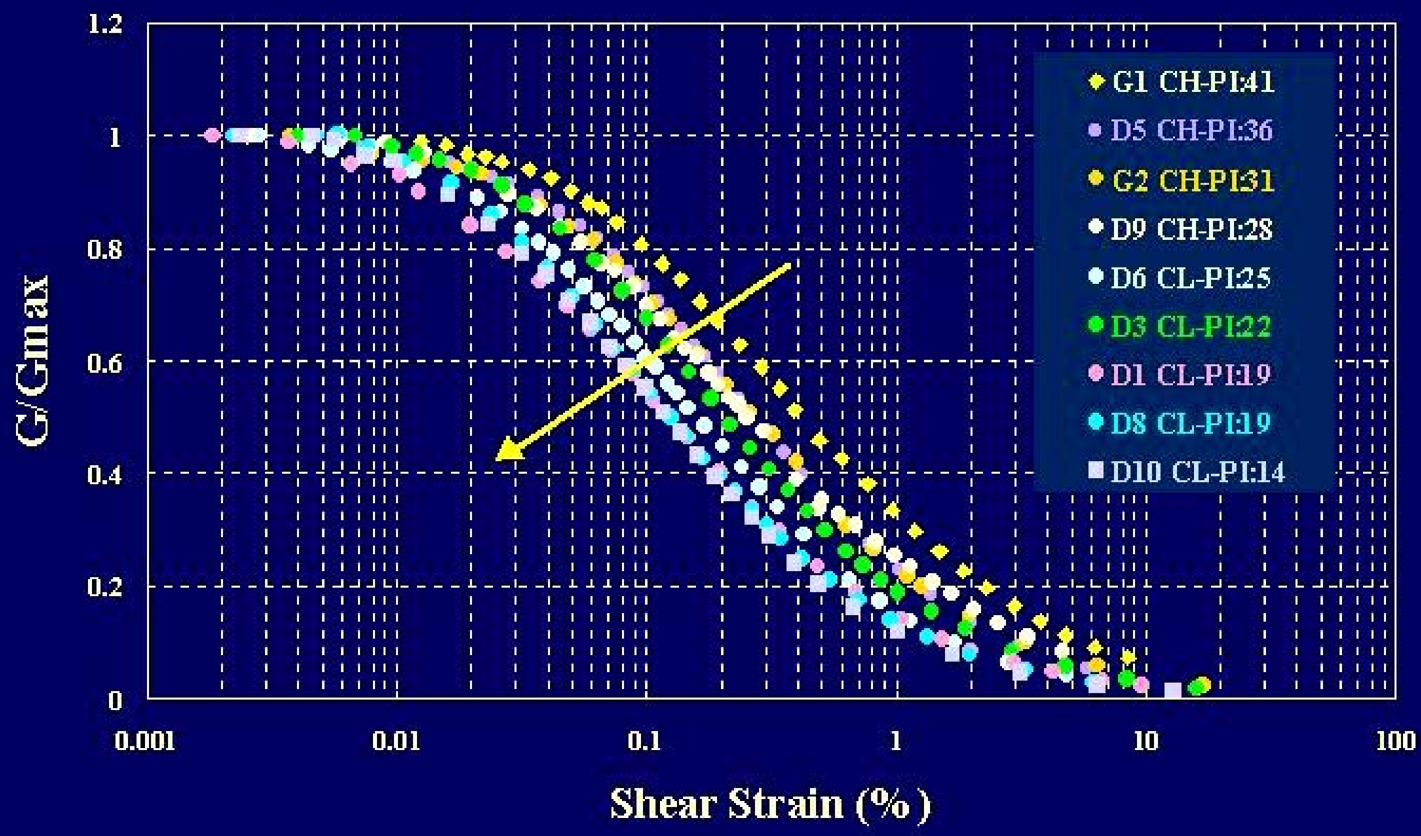
The behavior of soils subjected to cyclic loading has been studied utilizing laboratory tests such as cyclic triaxial, cyclic shear, cyclic torsional triaxial, resonant column and bender elements by large number of European researchers (i.e. Ansal, et al., 2001; Vrettos & Savidis, 1999; d'Onofrio et al., 1999; Puci & Lo Presti, 1998; Viggiani & Atkinson, 1995; Lo Presti et al., 1993; Talesnick & Frydman, 1992; Georgiannou et al., 1991; Hight et al., 1983; Andersen et al., 1980).

Various experimentally determined formulas, relationships and proposed design curves are available to obtain reasonable estimates for empirical modeling of soil behavior (Okur & Ansal, 2001; Vrettos and Savidis, 1999; Kallioglou et al., 1999; Sagaseta, et al., 1991).



Damping ratio vs. frequency (Lo Presti et al., 1997, Cavallaro et al., 1998, D'Onofrio et al., 1999;

Effect of soil plasticity to shear modulus



$$\frac{G}{G_{maks}} = \frac{35.09}{\dfrac{\gamma_a}{1 - 0.99\exp(-18.97 \quad PI^{-1.27})} + 34.74}$$

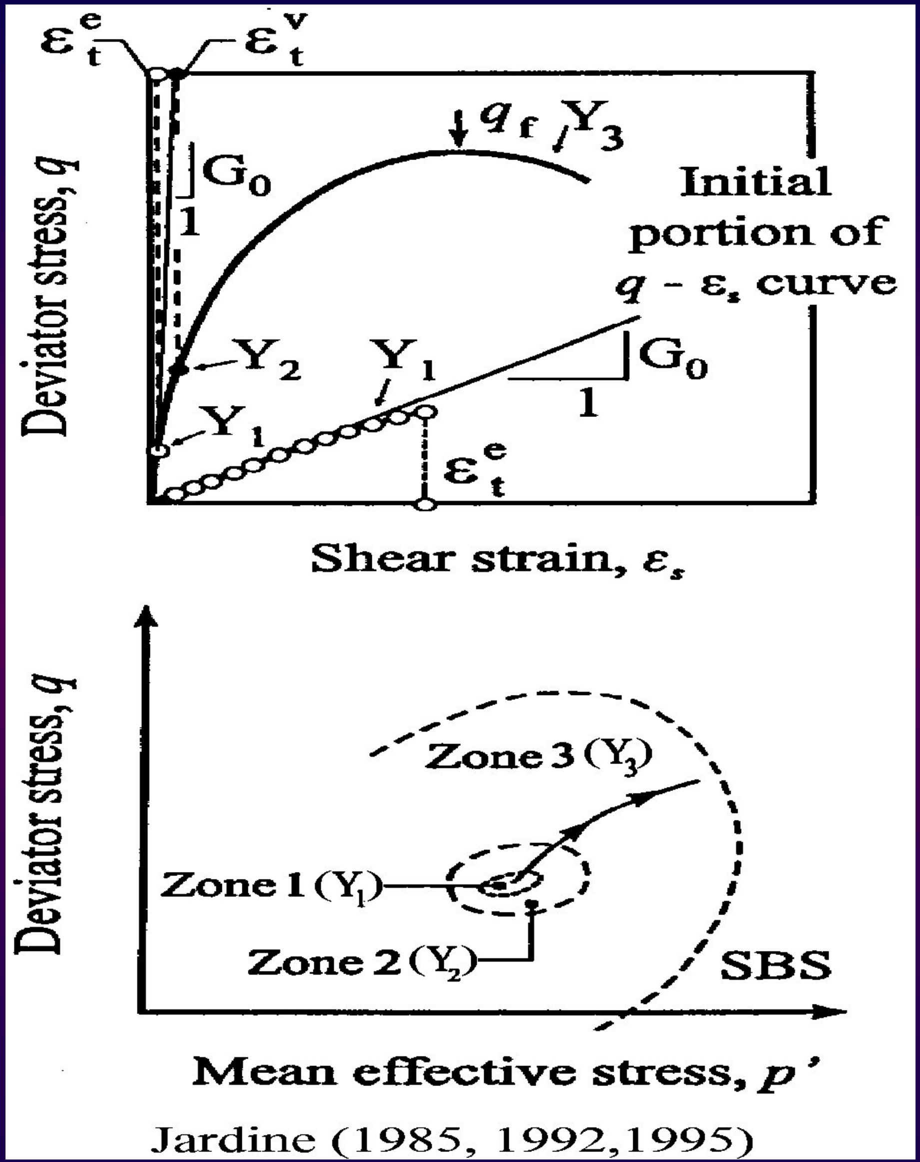
Soil Models

constitutive modelling of geomaterials in three main families:

equivalent linear models,
simplified cyclic non-linear models,
advanced cyclic non-linear models.

Jardine's qualitative model considers in addition to the State Boundary Surface (SBS, *Y3*), two other kinematic sub-yield surfaces (*Y1* and *Y2*) which are located inside the SBS and are always dragged with the current stress point.

On the contrary the SBS is relatively immobile so that any sharp change of the Effective Stress Path (ESP) from the *Y3* inwards leaves its position unchanged except in soils with highly developed fabric in which the collapse of the structure can cause the SBS to



Zone 1: for all practical purposes, the soil exhibits a linear stress-strain response.

Zone 2: When soil is strained beyond ε_t^l the ESP penetrates into Zone 2. In this zone the stress-strain response becomes non-linear.

Zone 3: the stress-strain response of soils becomes highly non-linear. G, E and D depend to a great extent on the shear stress and strain level.

Vermeer’s Model Mestat & Riou (2002)
Elastoplastic with two strain hardening mechanism

a. Purely deviatoric
b. Purely volumetric

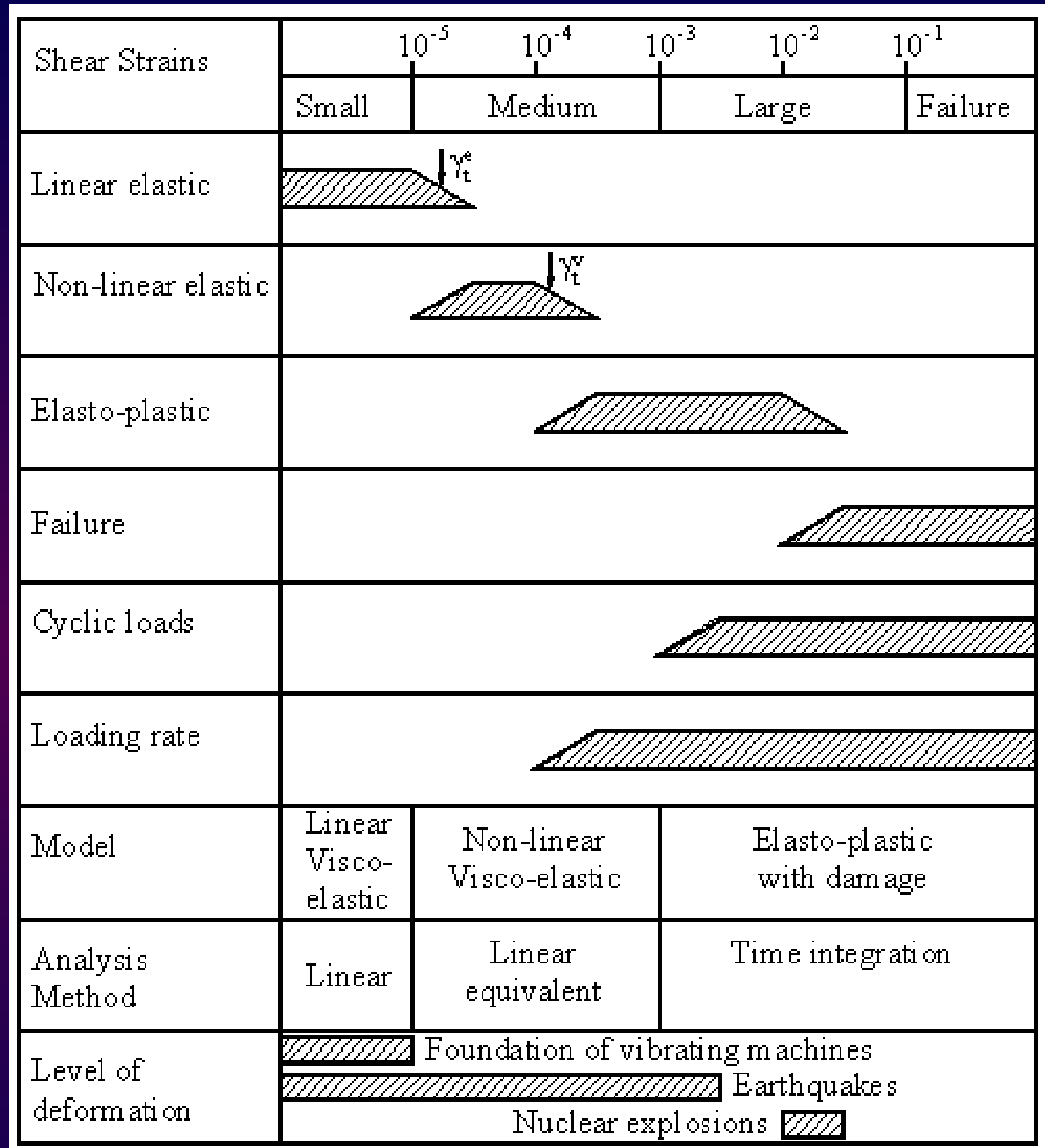
Methodology to determine the necessary model parameters

Some finite element packages

(i.e. Sigma/w; Z-Soil; Sage-Crisp; Flac, Plaxis, Gefdyn, Dynaflow, Joyner, 1975) that contain various soil models

(linear-elastic, anisotropic linear-elastic, nonlinear-elastic ‘hyperbolic’, elasto-plastic based on Tresca & Mohr-Coulomb failure criterion, strain-softening based on Von Mises failure criterion, Cam-clay, modified Cam-clay ‘Critical State’; Schofield model)

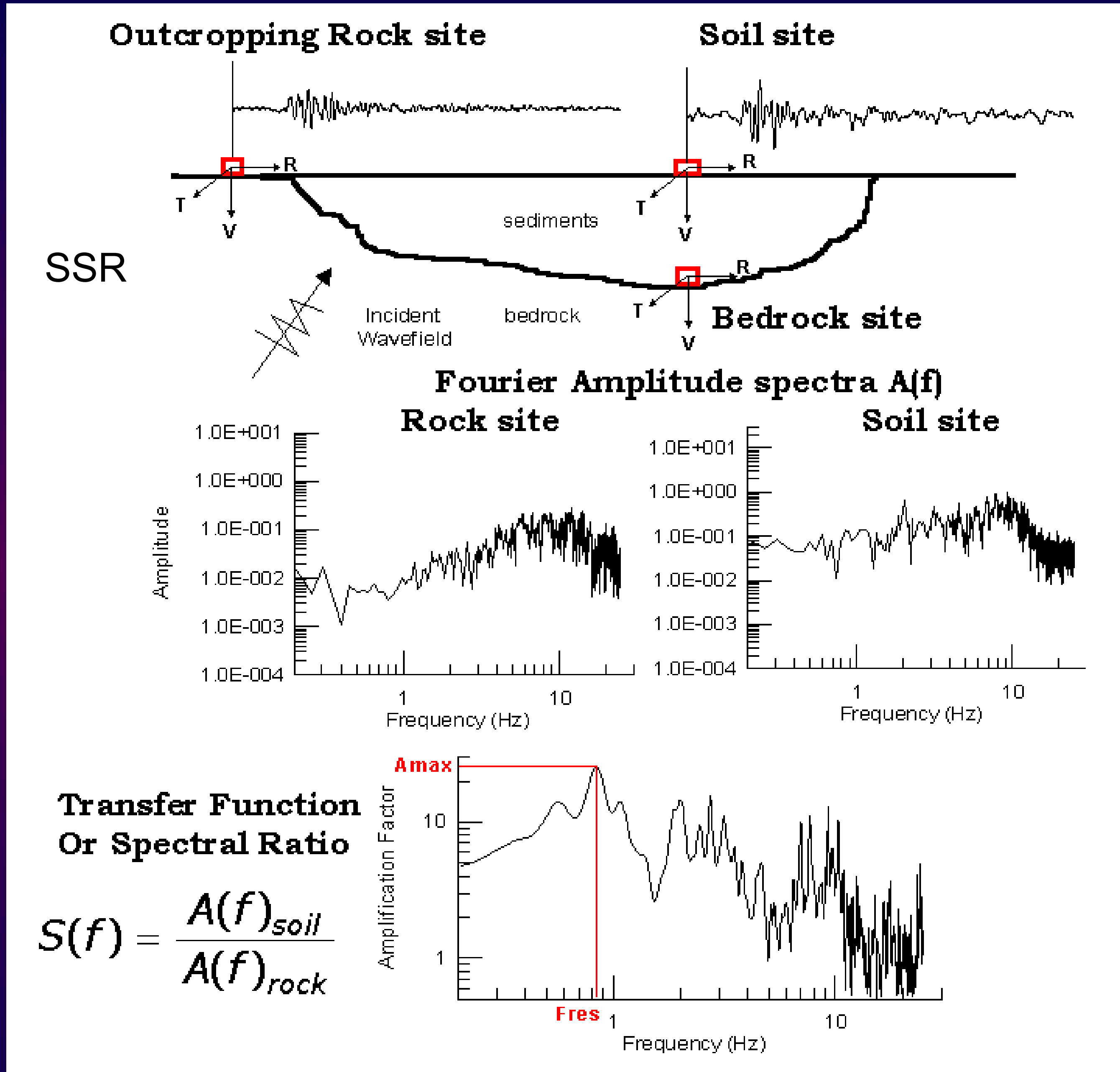
used to analyze some case studies (Beyen & Erdik, 2004; Siyahi et al., 2004; Yang et al., 2002; Mestat & Riou, 2002; Wieland & Malla, 2002; Biarez et al, 1998; Calabresi et al., 1993).



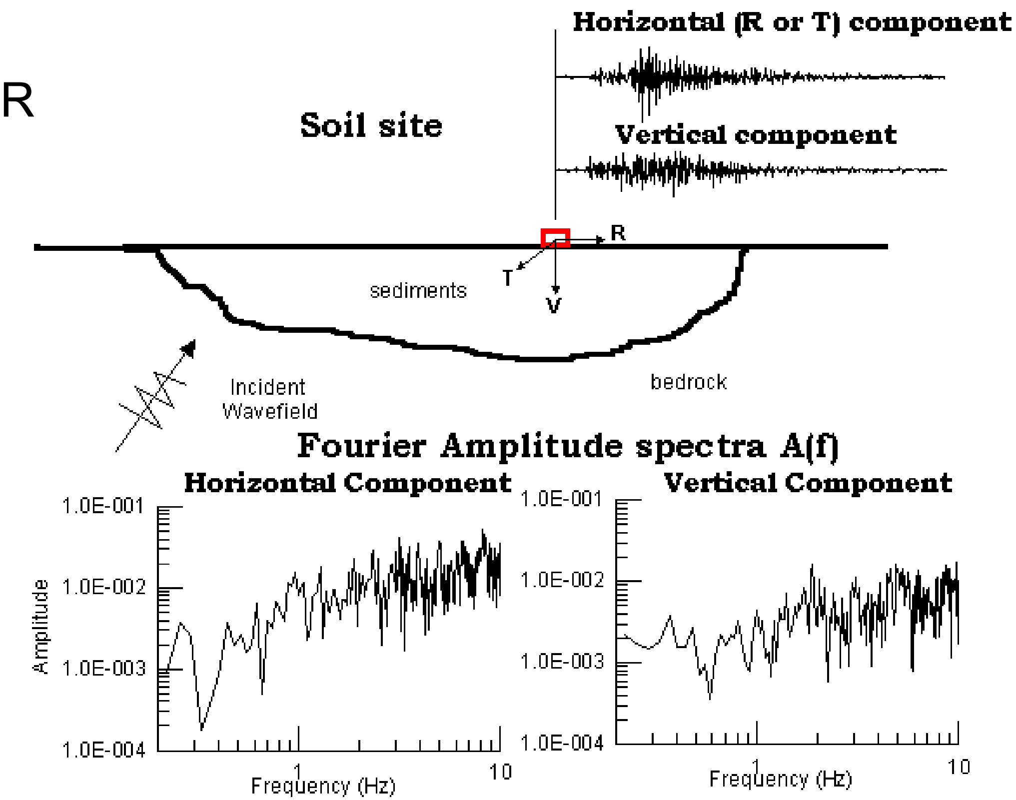
Ishihara, 1996

Site Response Analysis

- The ground motion records obtained from broad spectrum of earthquakes have been utilized for estimating the site amplification;
- by determining the generalized inversion GIT (Parolai et al., 2000)
- based on SSR, HVSR spectral ratios (Dimitriu, et al., 1999; Raptakis et al., 1998; Theodulidis & Bard, 1995).
- Ambient noise measurements were also utilized to assess the site conditions (Teves-Costa et al., 1996; Ansal et al., 2001; Bard, 1998)
- One and two dimensional analysis

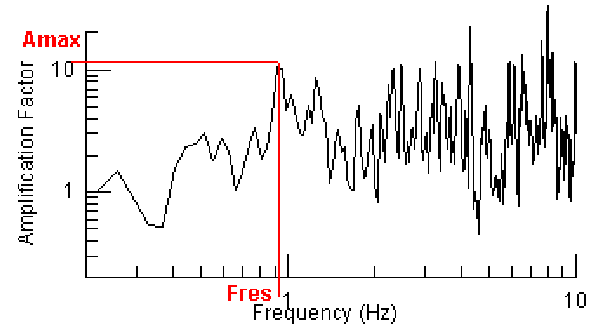

SSR
Outcropping Rock site
Soil site
R
T
V
sediments
Incident Wavefield
bedrock
Bedrock site
Fourier Amplitude spectra A(f)
Rock site
Soil site
Amplitude
1.0E+001
1.0E+000
1.0E-001
1.0E-002
1.0E-003
1.0E-004
1
10
Frequency (Hz)
Transfer Function
Or Spectral Ratio
$$S(f) = \frac{A(f)_{soil}}{A(f)_{rock}}$$
Amax
Amplification Factor
10
1
Fres
Frequency (Hz)

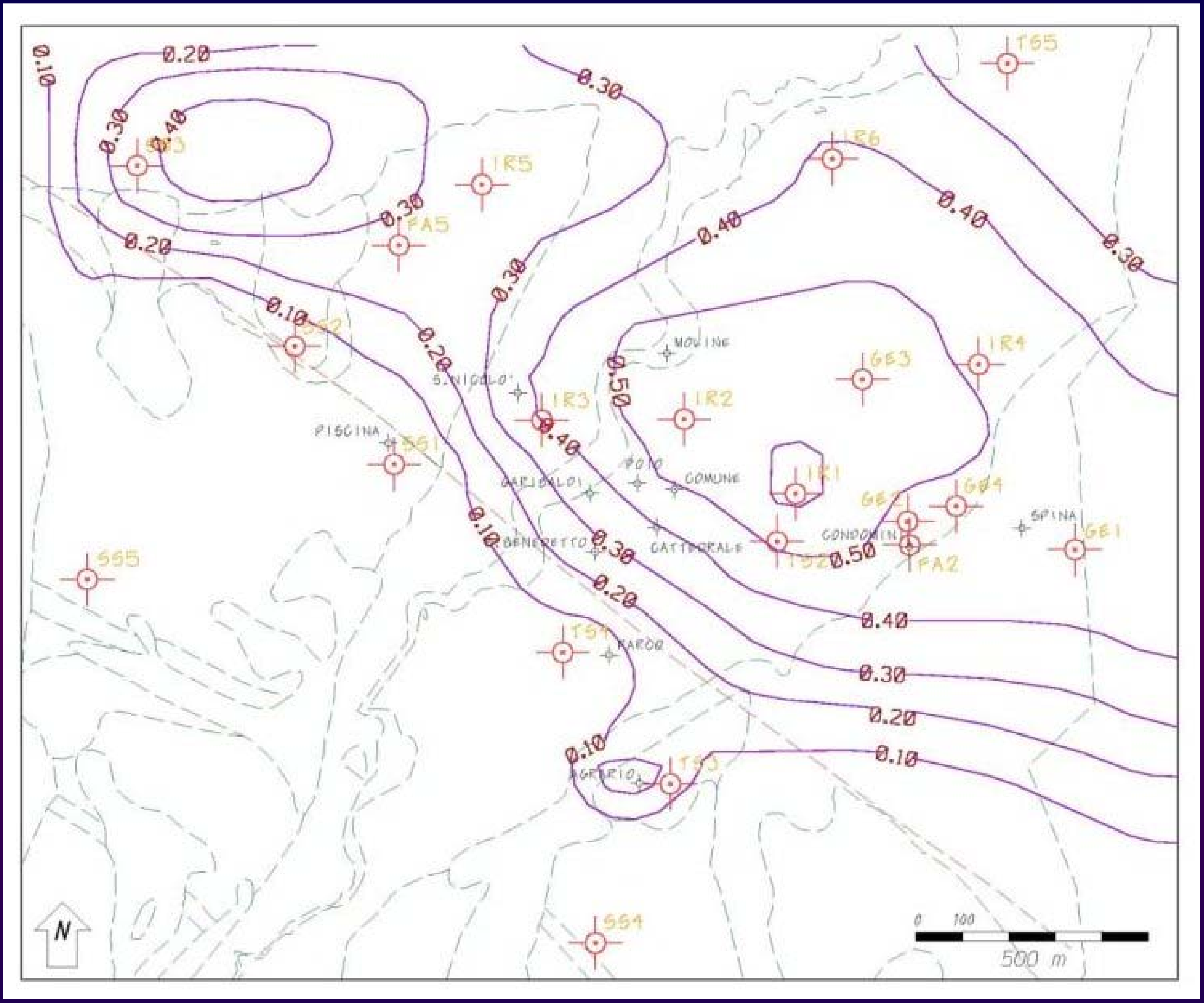
HVSR



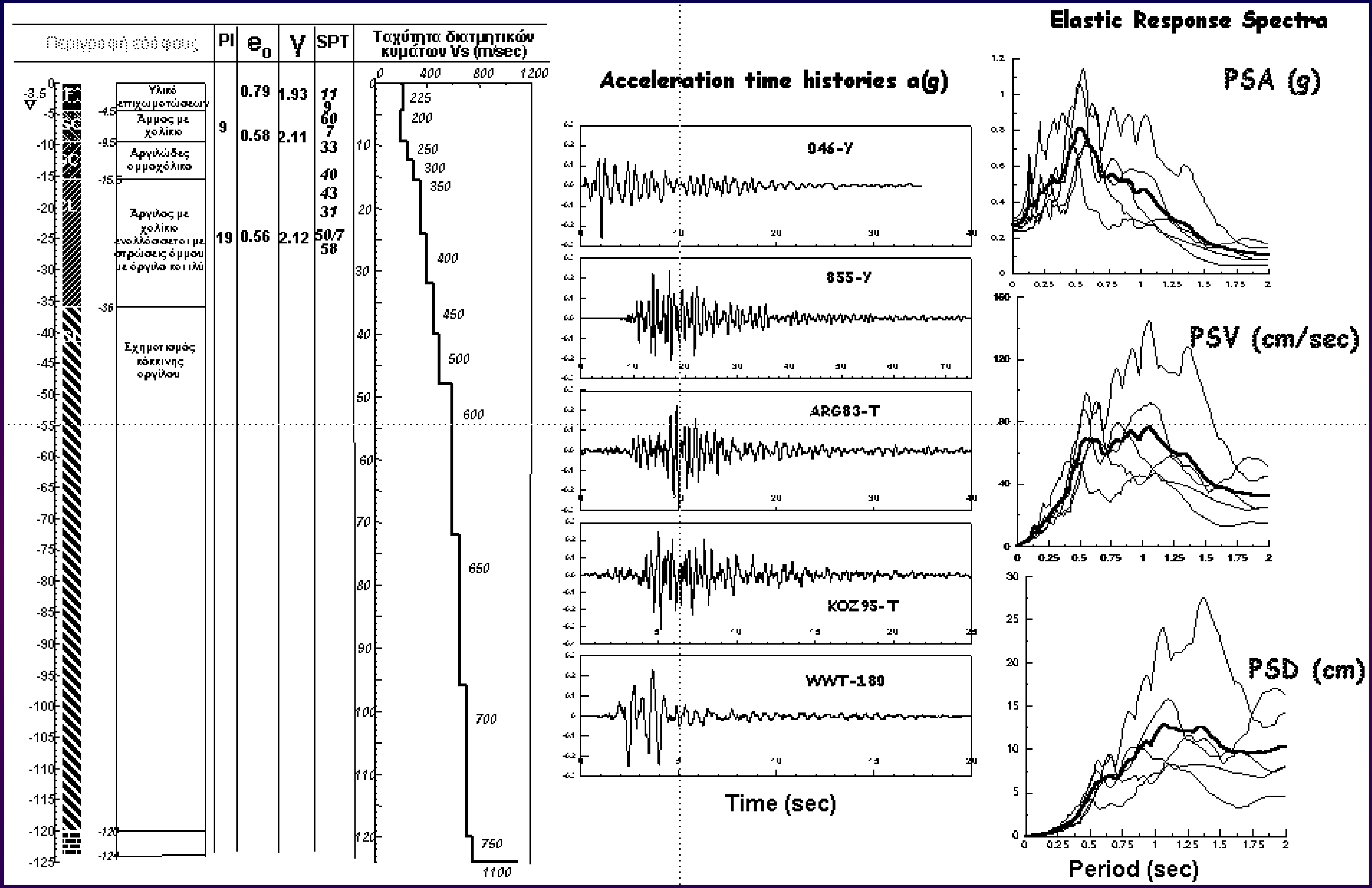
Transfer Function Or Spectral Ratio

$$S(f) = \frac{A(f)_{horizontal}}{A(f)_{vertical}}$$



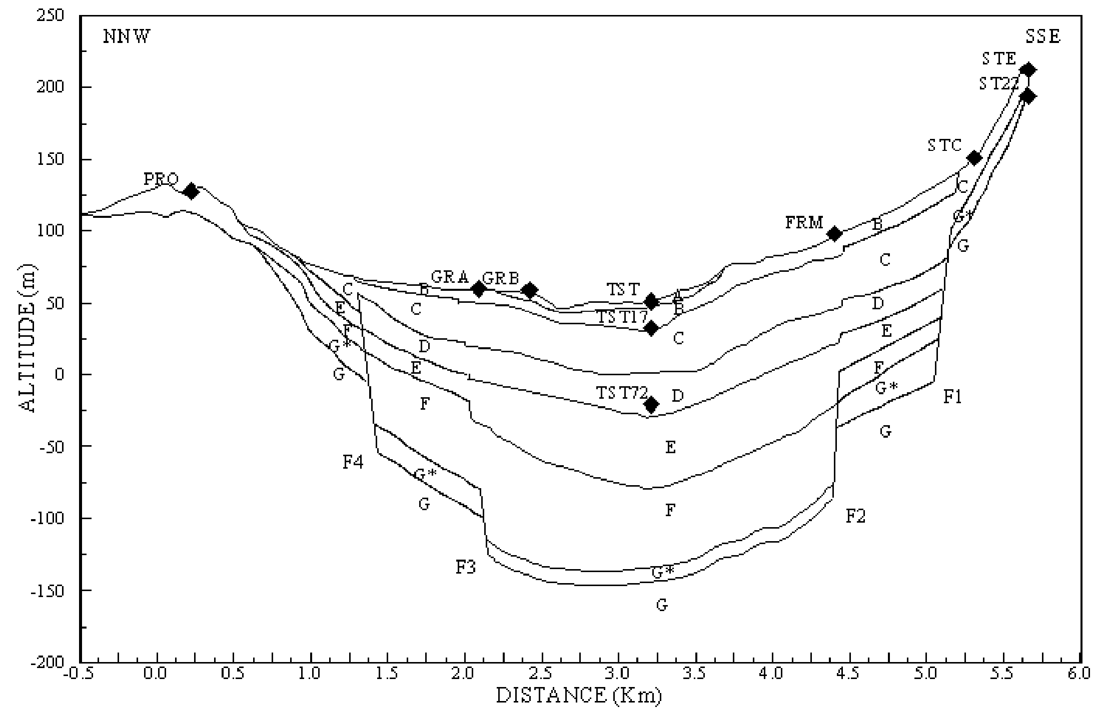


Fabriano: soils natural period map obtained by microtremors (Nakamura method) and weak motion data (Marcellini & Pagani, 2004)

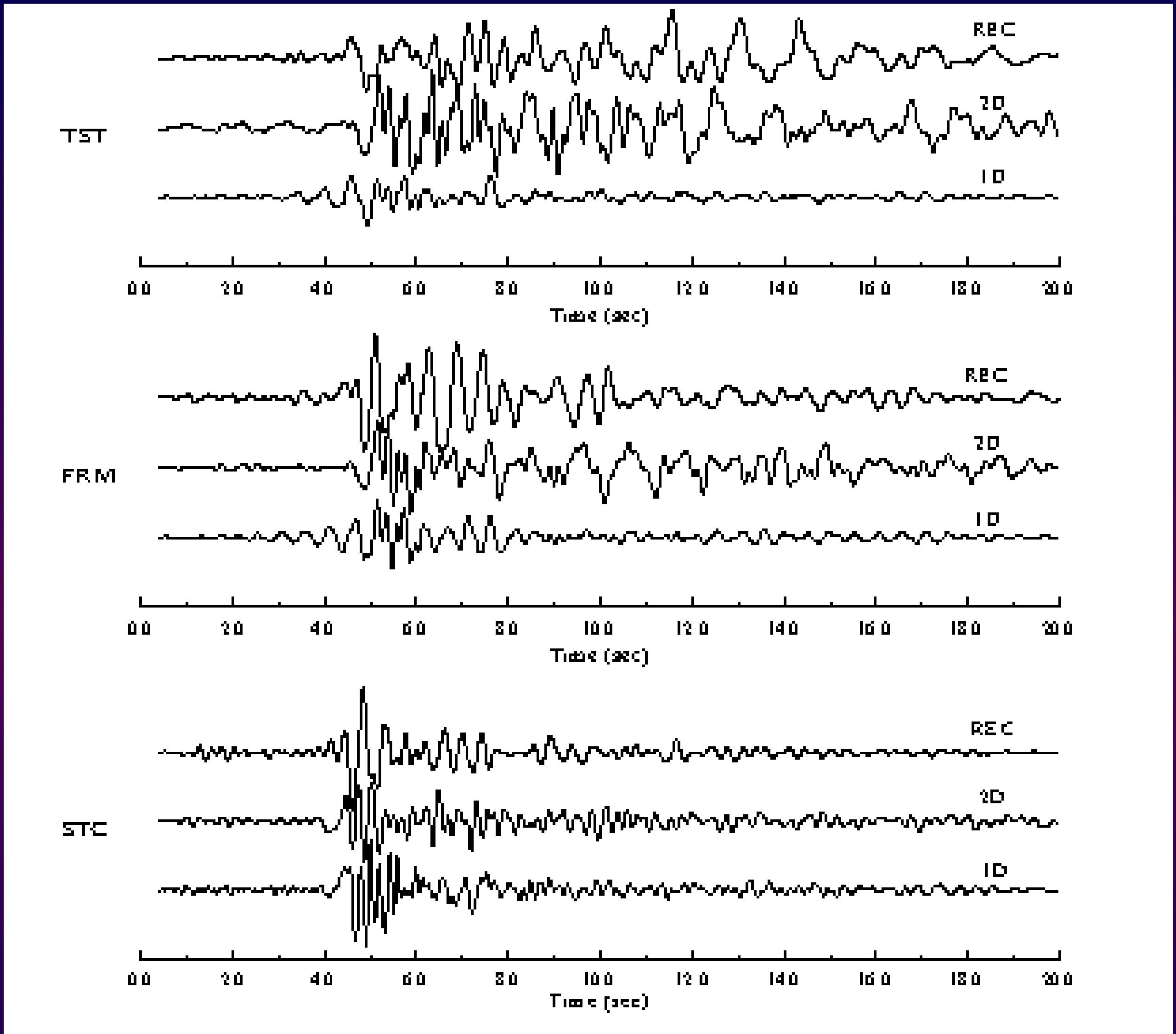


Typical example of 1D analysis using 5 input motions, all scaled to the design outcrop acceleration (PHGA=0.25g)

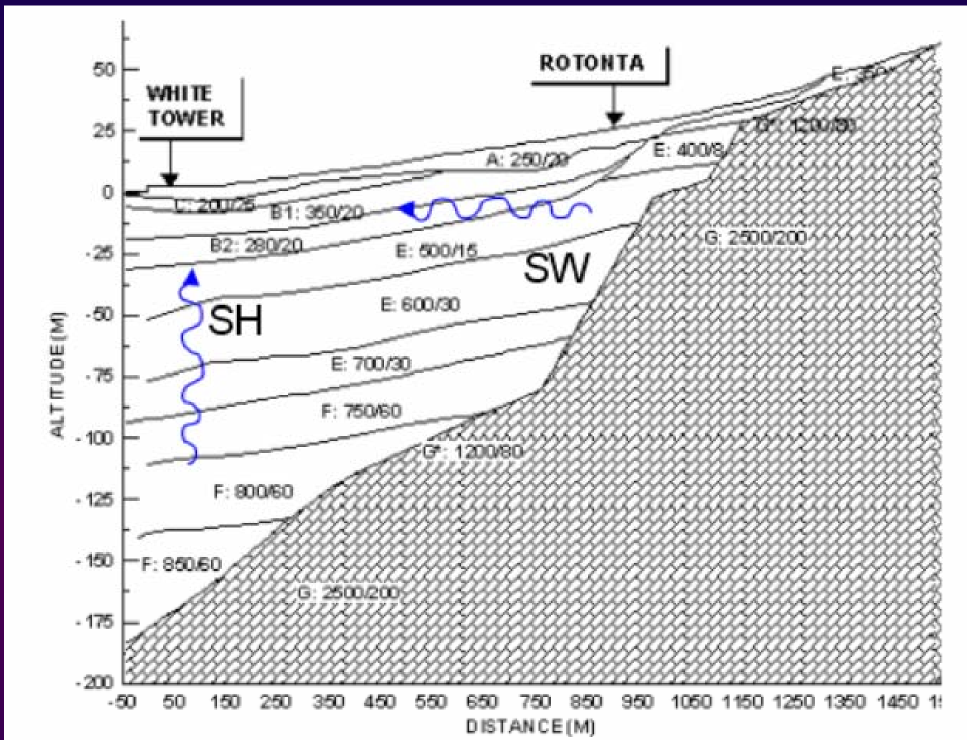
EUROSEISTEST valley cross-section and strong ground motion instrumen-tation array layout amplification (Chavez-Garcia et al., 2000)



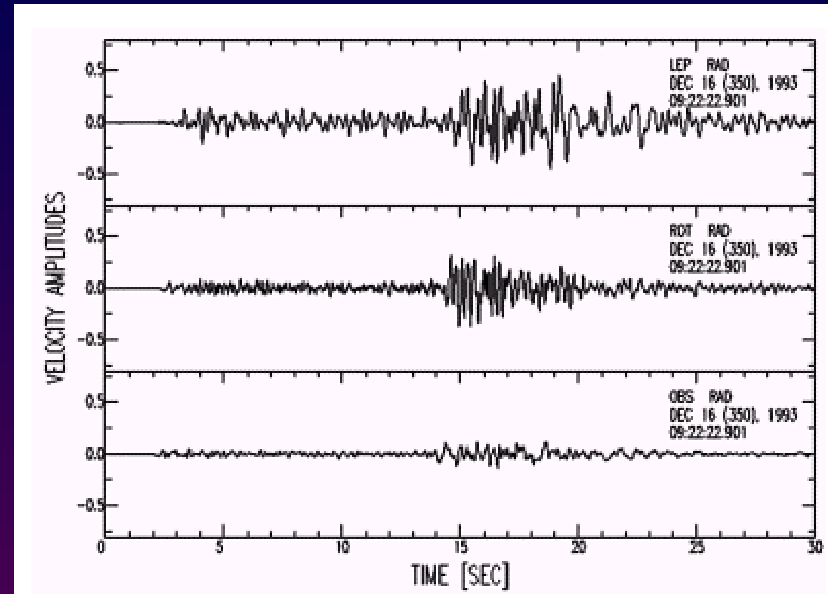
Layer	Description	S-wave	Density	Q_S
A	Silty, clayey sand	130	2.05	15
B	Silty sand and sandy clay	200	2.15	25
C	Marly silt and silty sand	300	2.075	30
D	Marly, sandy clay and clay silt	450	2.100	40
E	Alternating sublayers of clayey, silty sand and sandy clay with stones and gravels	650	2.155	60
F	Alternating sublayers of clayey, silty sand and sandy clay with stones and gravels	800	2.20	80
G*	Weathered schist bedrock	1250	2.50	100
G	Gneiss basement	2600	2.60	200

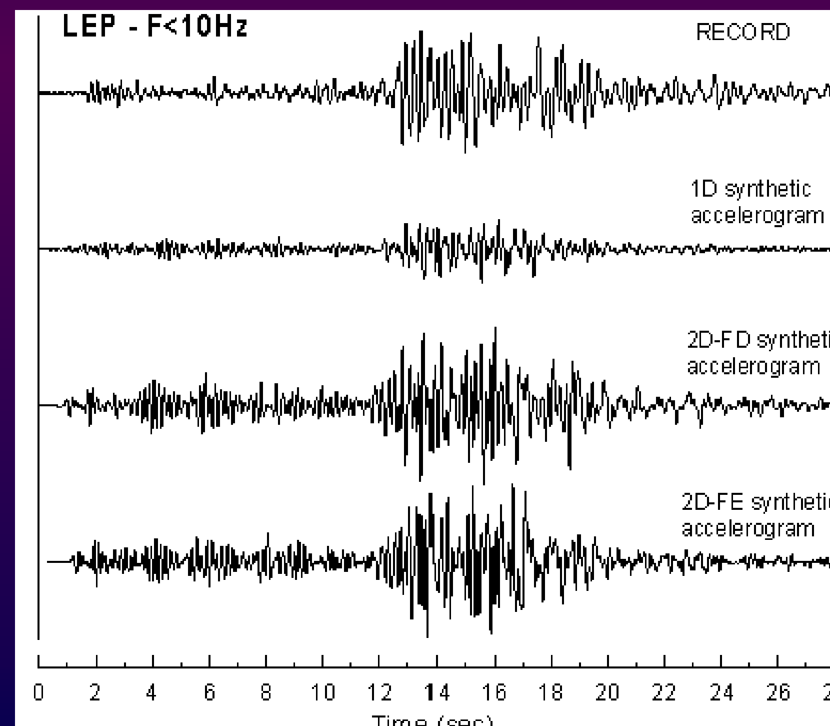


Variation of the ratio of acceleration response spectra along the EUROSEISTEST cross-section

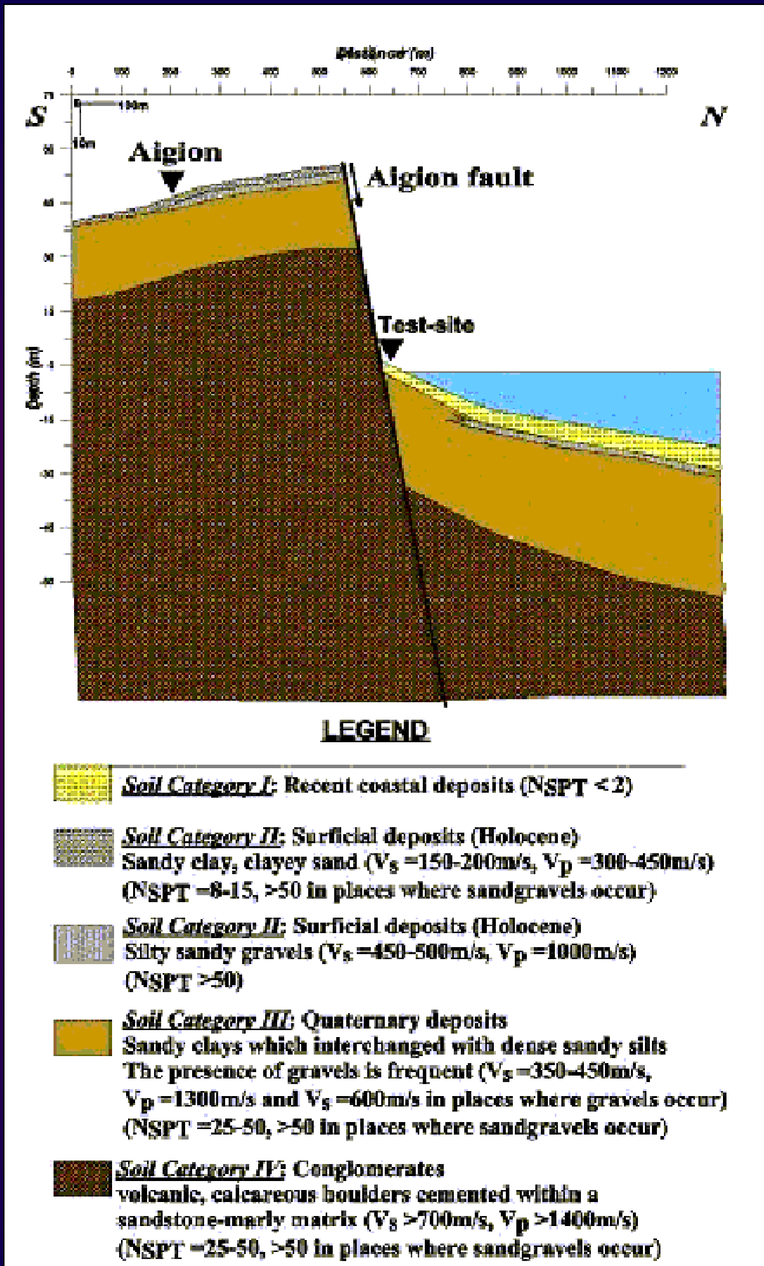


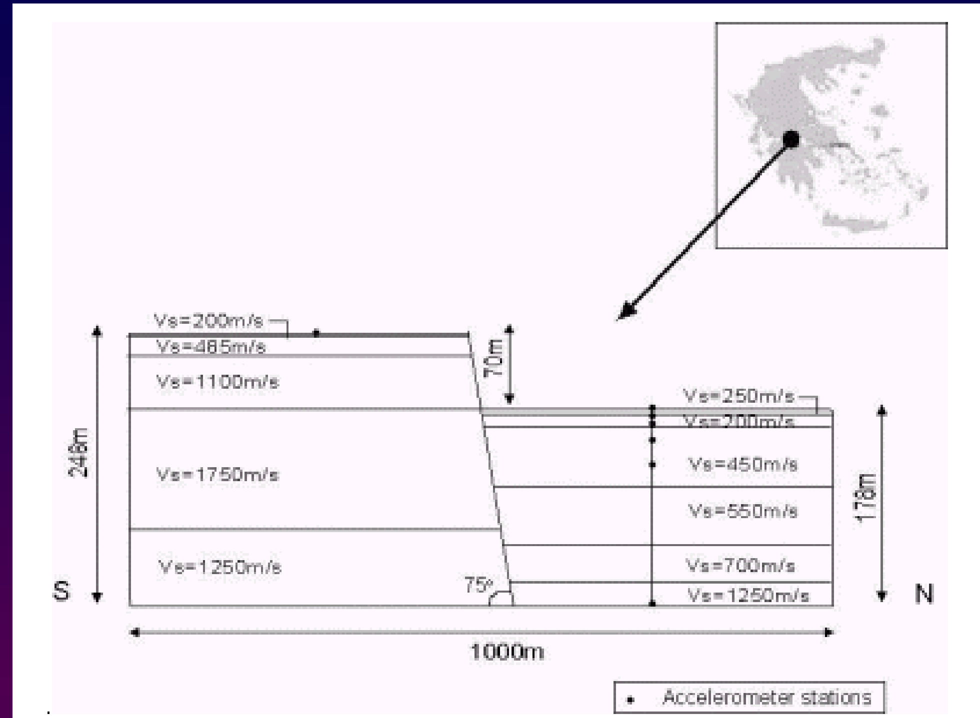
Typical geotechnical cross-section in the historical centre of Thessaloniki (Anastasiadis et al., 2001



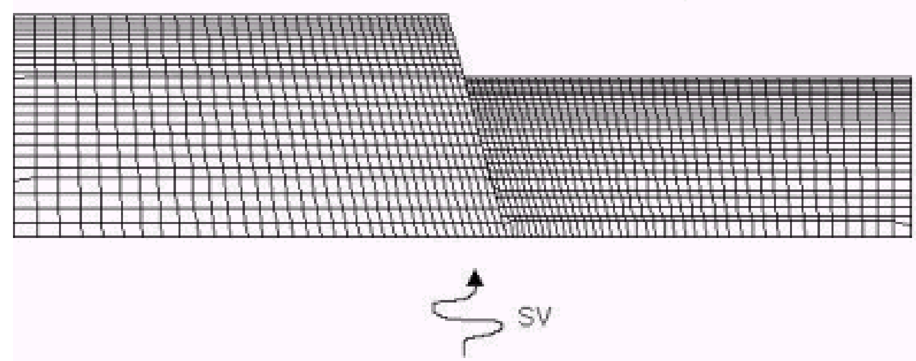


Radial (left) components and models Mw=4.8, R>100km event (16.12.93) recorded at 3 stations along the cross-section (Raptakis et al., 2003a)

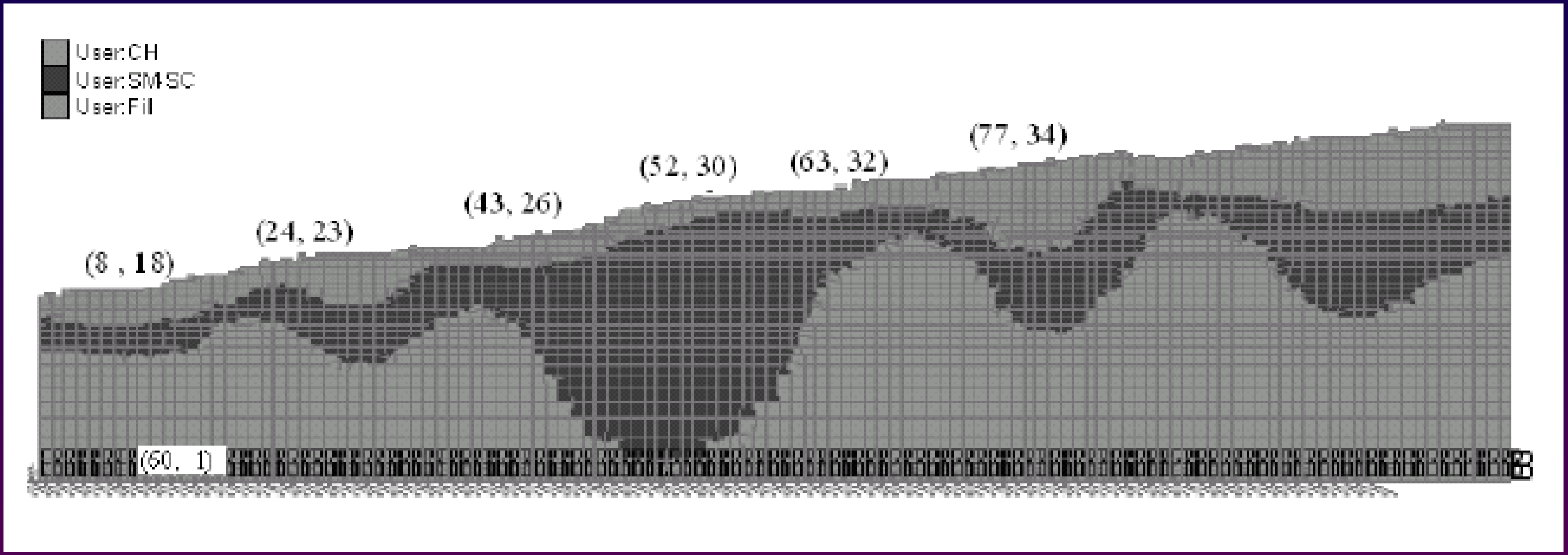




MODEL	INPUT (RICKER WAVELET)
Linear elastic model with global damping ξ=2%	f = 0.88, 1.43 & 3 Hz
Linear elastic model with global damping ξ=1%	f = 3 Hz
Equivalent linear model with damping according to soil layer	f = 3 Hz



Finite difference discretization



Model Geometry and Boundary conditions of Soil Profile

FLAC (Fast Lagrangian Analysis of Continua, 2000) for the site response analysis

A Case Study for an Applied Project

Site Conditions

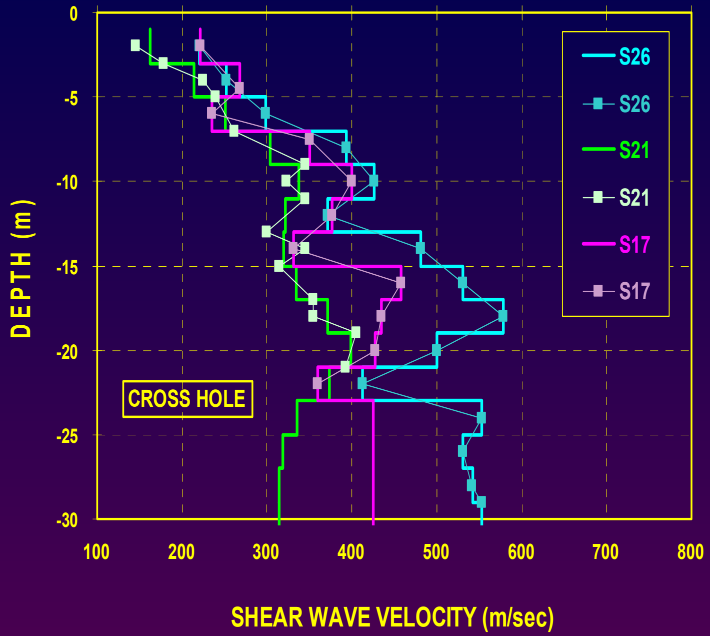
- **borings were conducted to determine soil stratification**
- **insitu seismic down-hole, cross-hole and suspension PS logging seismic wave measurements were conducted at four locations to obtain shear wave velocity profiles**

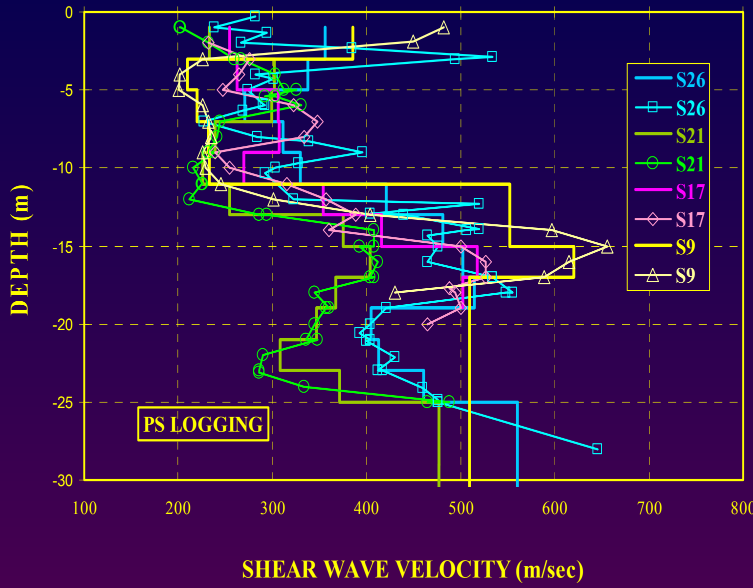
Site Response Analysis

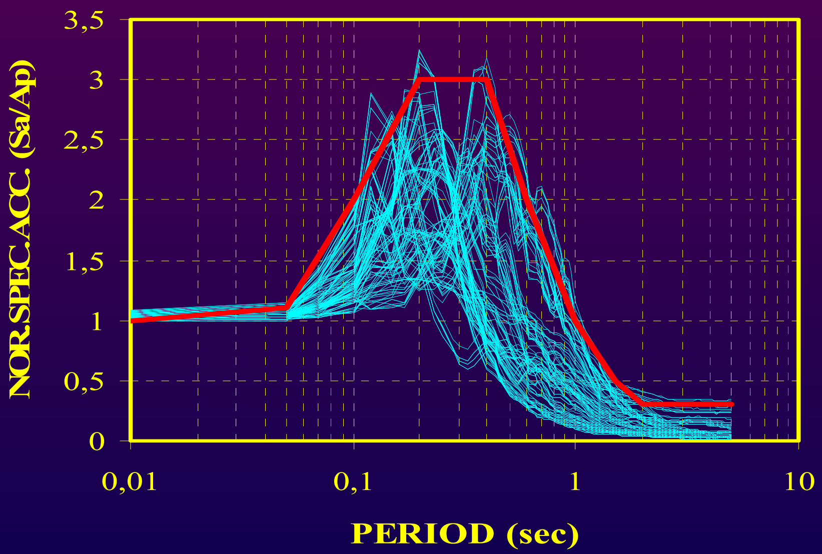
- site response analysis were conducted using 20 earthquake acceleration records obtained in Turkey and in the near vicinity of Bursa
- a total of 140 site response analysis were conducted for five shear wave profiles obtained for seven soil profiles

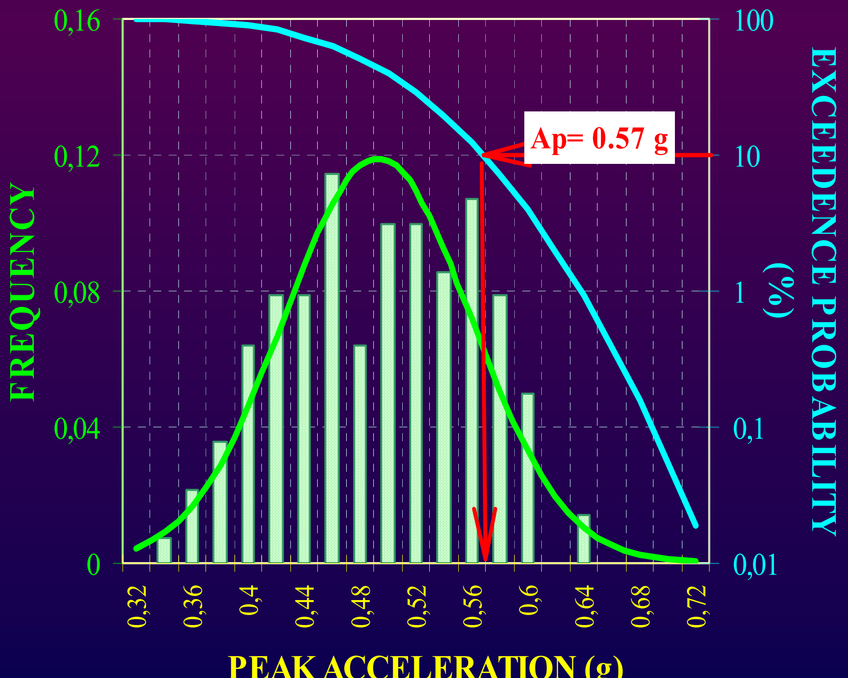
Design EQ Characteristics

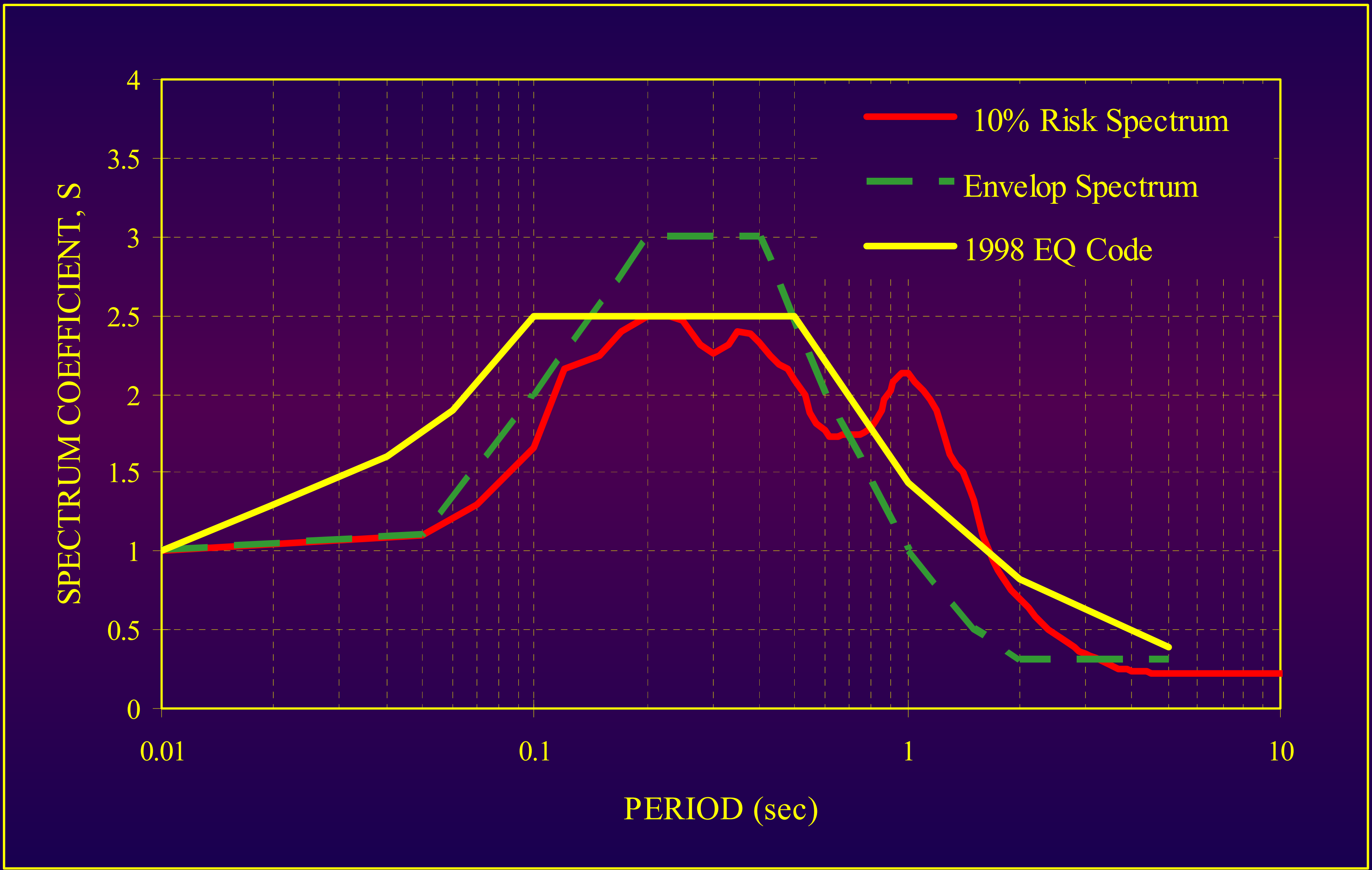
- the variation of the calculated peak accelerations and the normalised acceleration spectra on the ground surface are evaluated by using normal probability density function


DEPTH (m)
SHEAR WAVE VELOCITY (m/sec)
CROSS HOLE
S26
S26
S21
S21
S17
S17

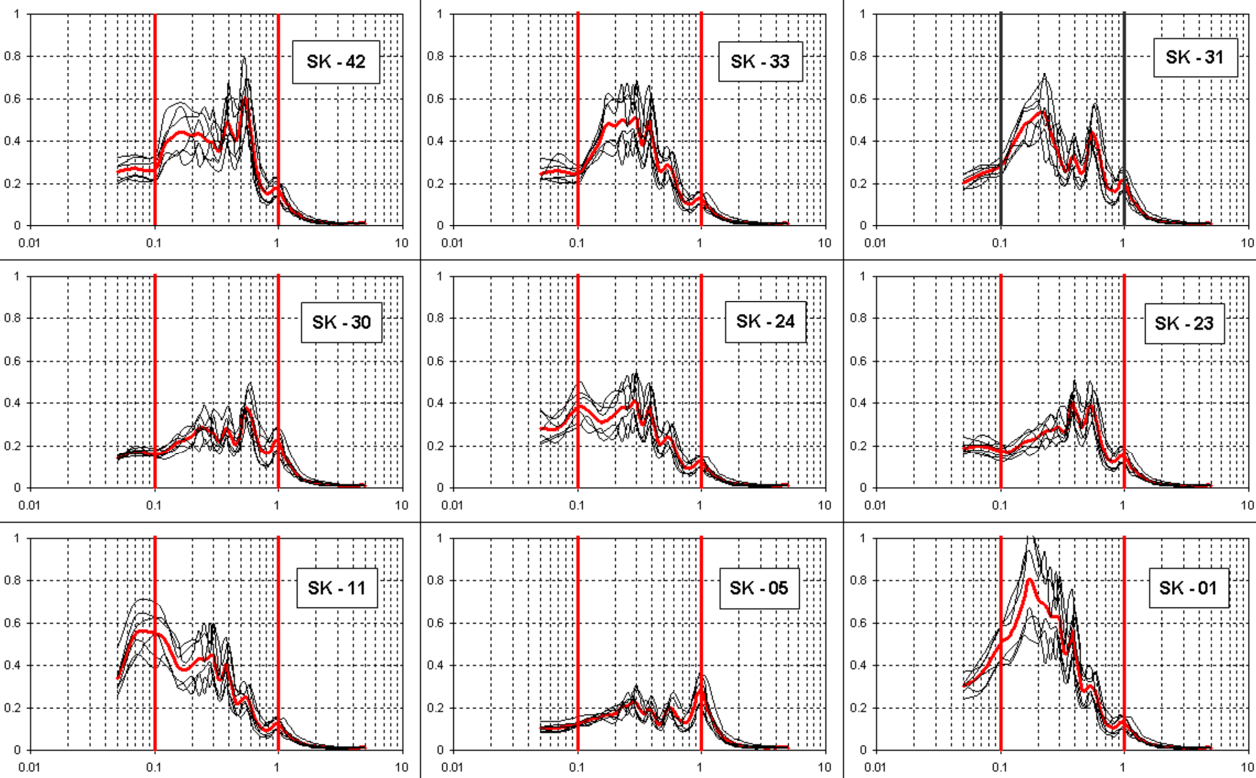

DEPTH (m)
SHEAR WAVE VELOCITY (m/sec)
PS LOGGING
S26
S26
S21
S21
S17
S17
S9
S9

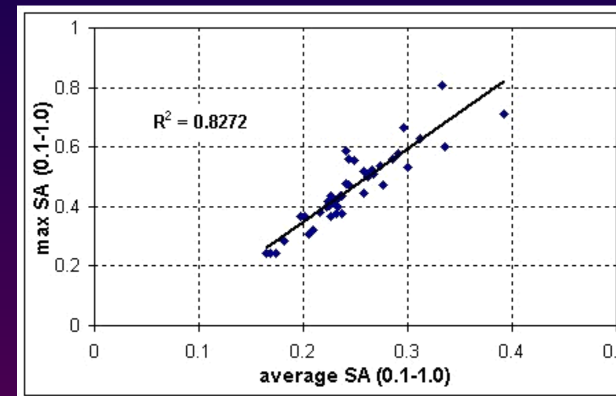

NOR.SPEC.ACC. (Sa/Ap)
PERIOD (sec)

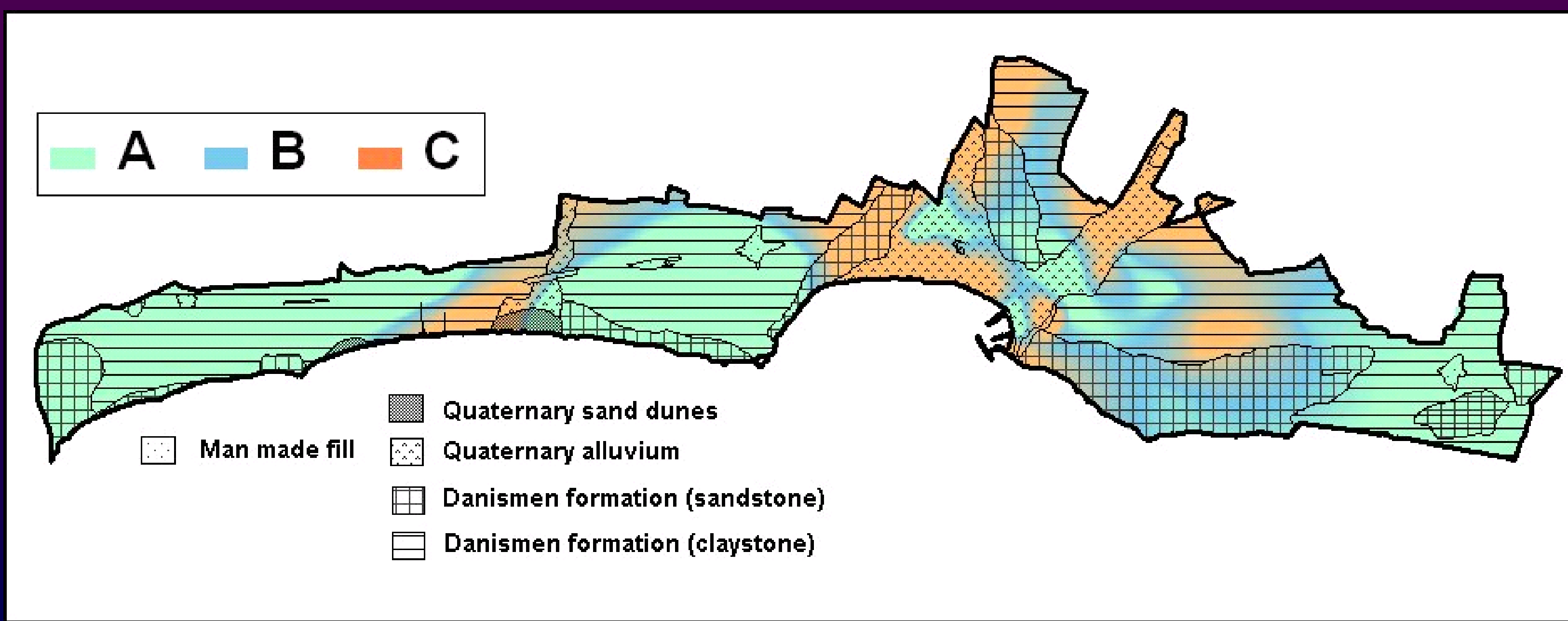

FREQUENCY
EXCEDENCE PROBABILITY (%)
PEAK ACCELERATION (g)
Ap= 0.57 g



SPECTRUM COEFFICIENT, S
4
3.5
3
2.5
2
1.5
1
0.5
0
0.01
0.1
1
10
PERIOD (sec)
10% Risk Spectrum
Envelop Spectrum
1998 EQ Code


SK - 42
SK - 33
SK - 31
SK - 30
SK - 24
SK - 23
SK - 11
SK - 05
SK - 01
0.01
0.1
1
10


R^2 = 0.8272
max SA (0.1-1.0)
average SA (0.1-1.0)


A
B
C
Quaternary sand dunes
Man made fill
Quaternary alluvium
Danismen formation (sandstone)
Danismen formation (claystone)

Discussion

- The need for more realistic soil models arise from the necessity of making better predictions for assessing the ground motion characteristics on the ground surface.
- The problem is very complex since the four components of the site response analysis, input motion, site characterization, soil model and numerical analysis can have significant effect on the calculated final results.
- The improvements in the site response analysis is not only limited with the improvements in the soil models.

- the complexity and diversity of soil stratification and the variation of soil properties for different soil layers can introduce significant limitations for conducting a realistic site response analysis
- one dimensional wave propagation analysis cannot explain the recorded earthquake motions in the existence of complex site conditions

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