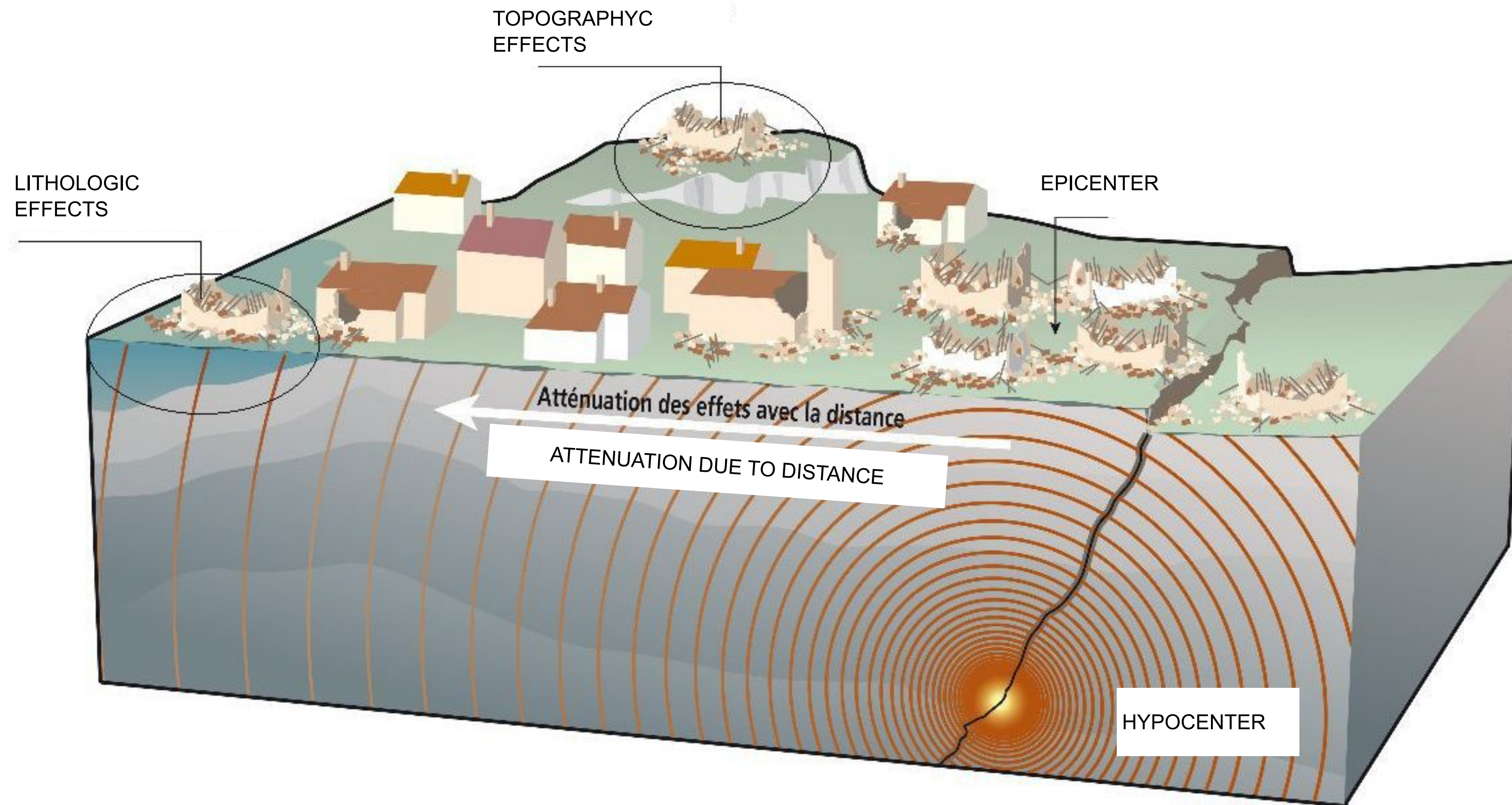


Introduction to the Seismic Risk

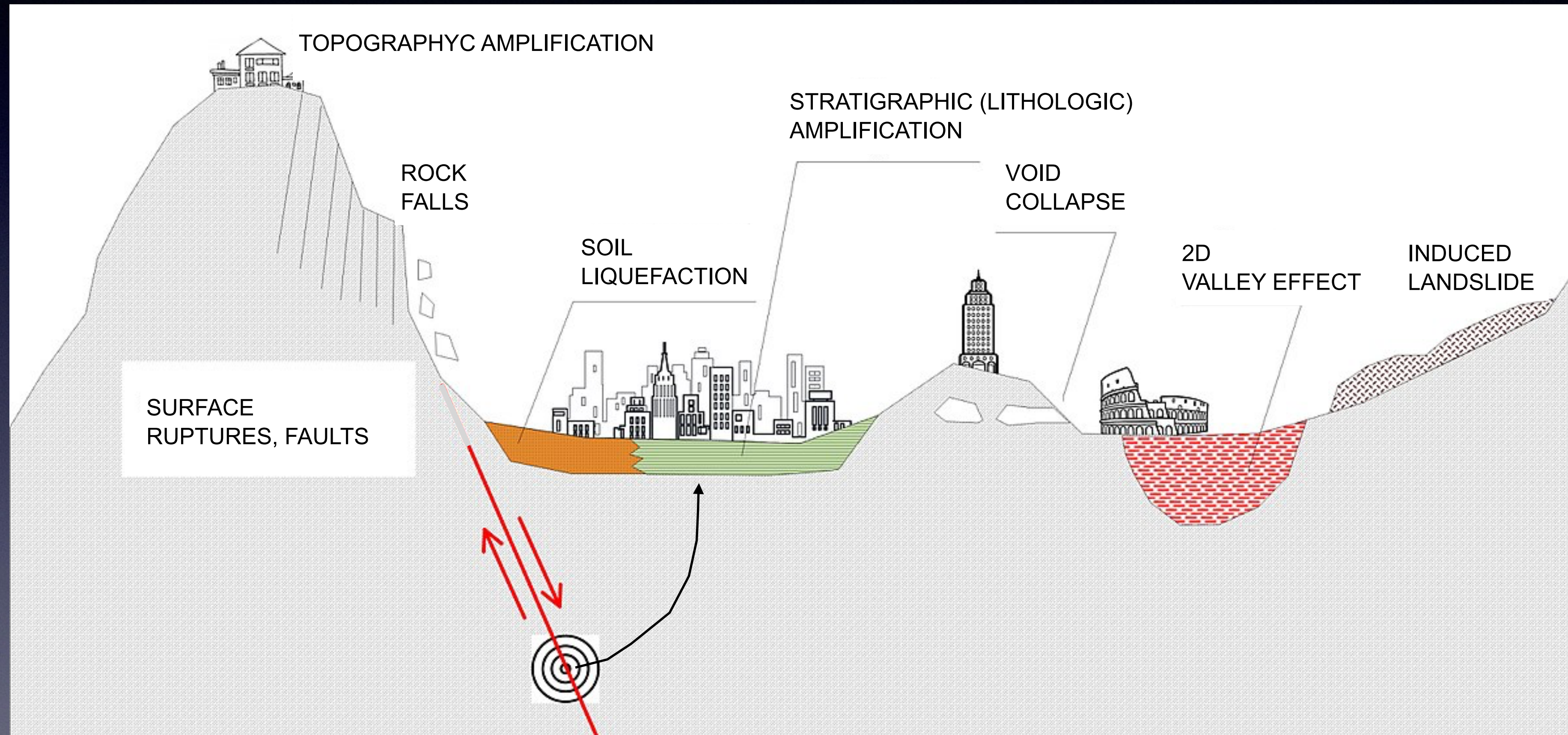
We have seen the seismic problem
but what happen locally?

Microzonation and Seismic Local Response
(RSL)

-The seismic local response

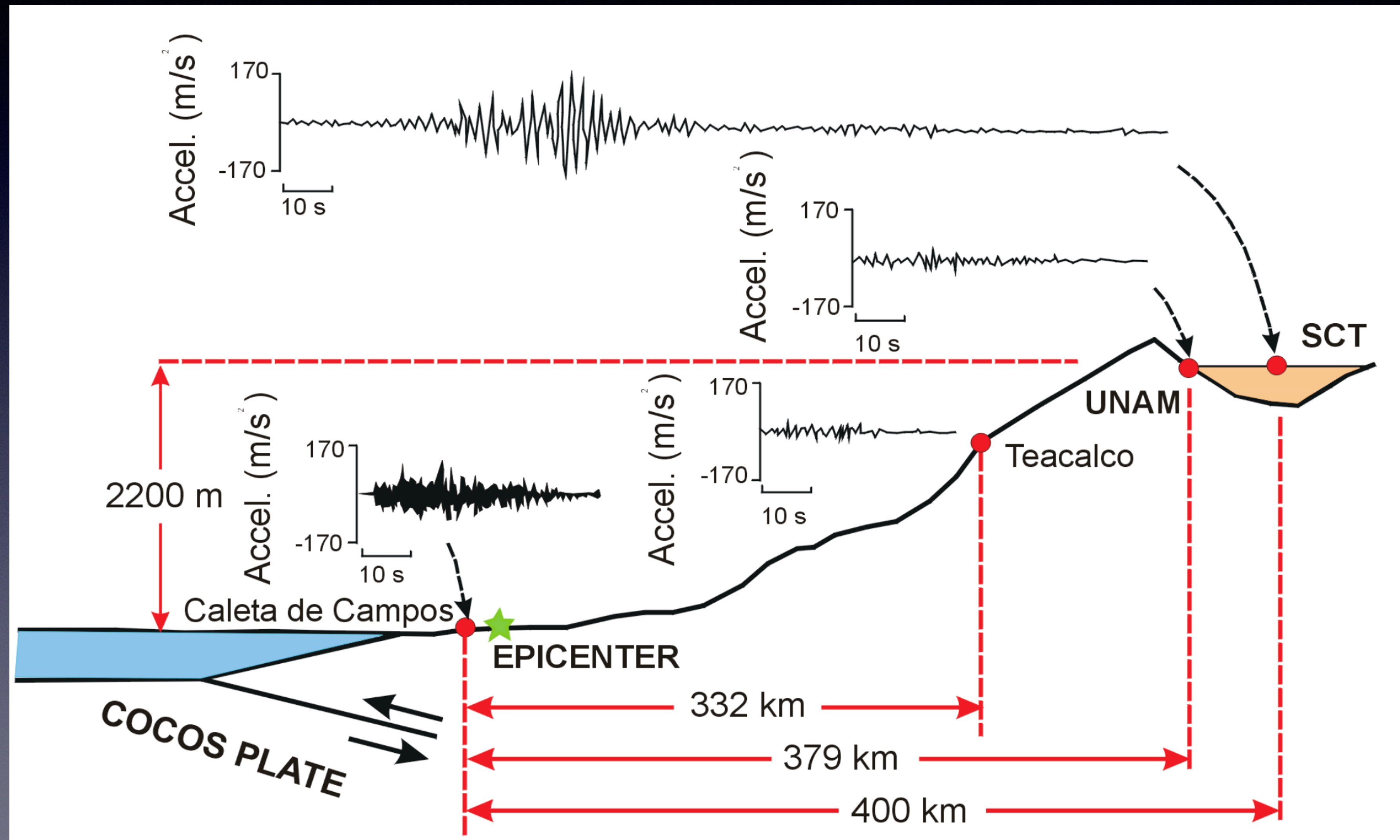


-The seismic local response : + induced effects



LOCAL CONDITIONS MODIFY THE EARTHQUAKE EFFECTS

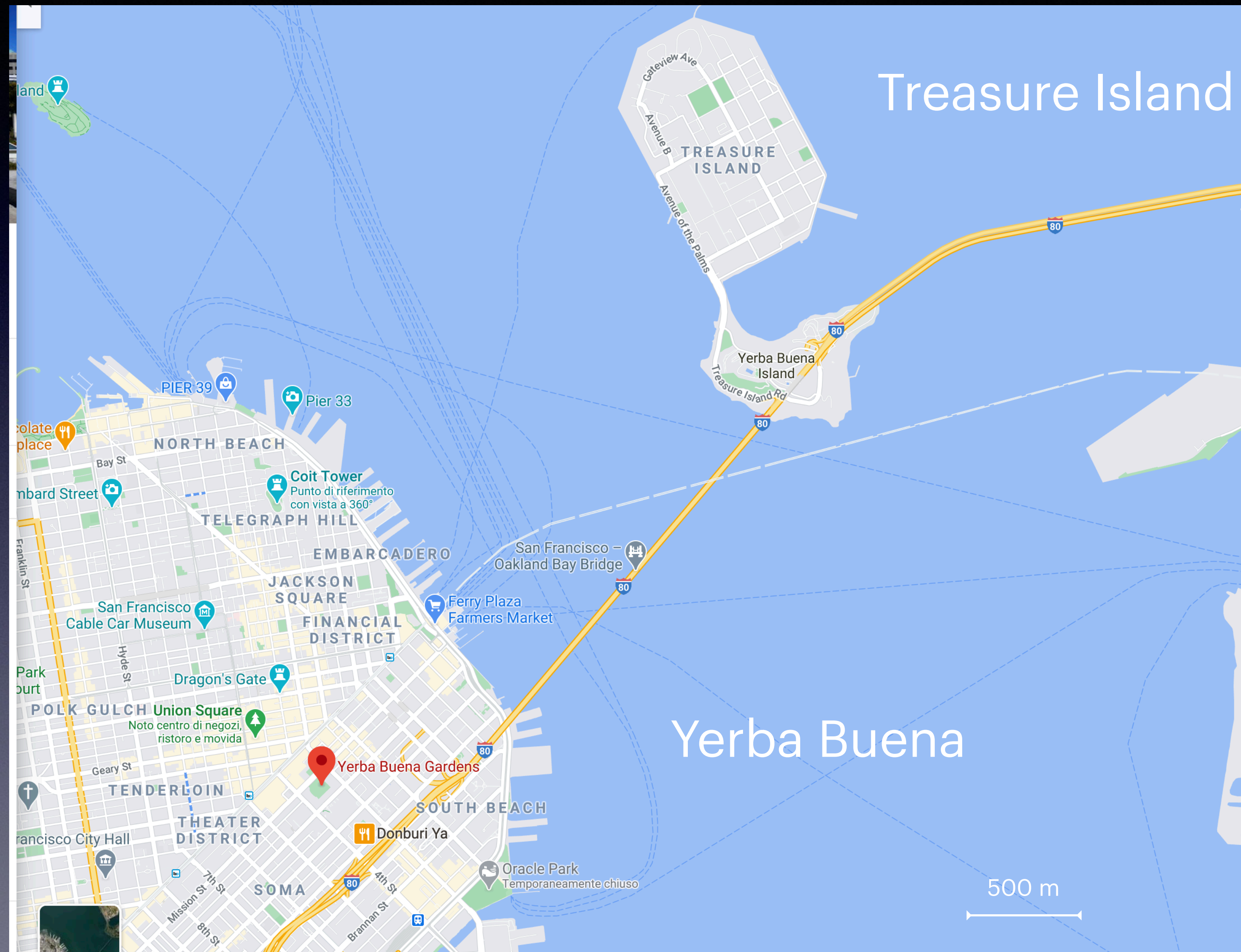
Mexico City earthquake 19/9/1985 (M= 8.1)



Loma Prieta earthquake 17/1/1989 (M=7.1)

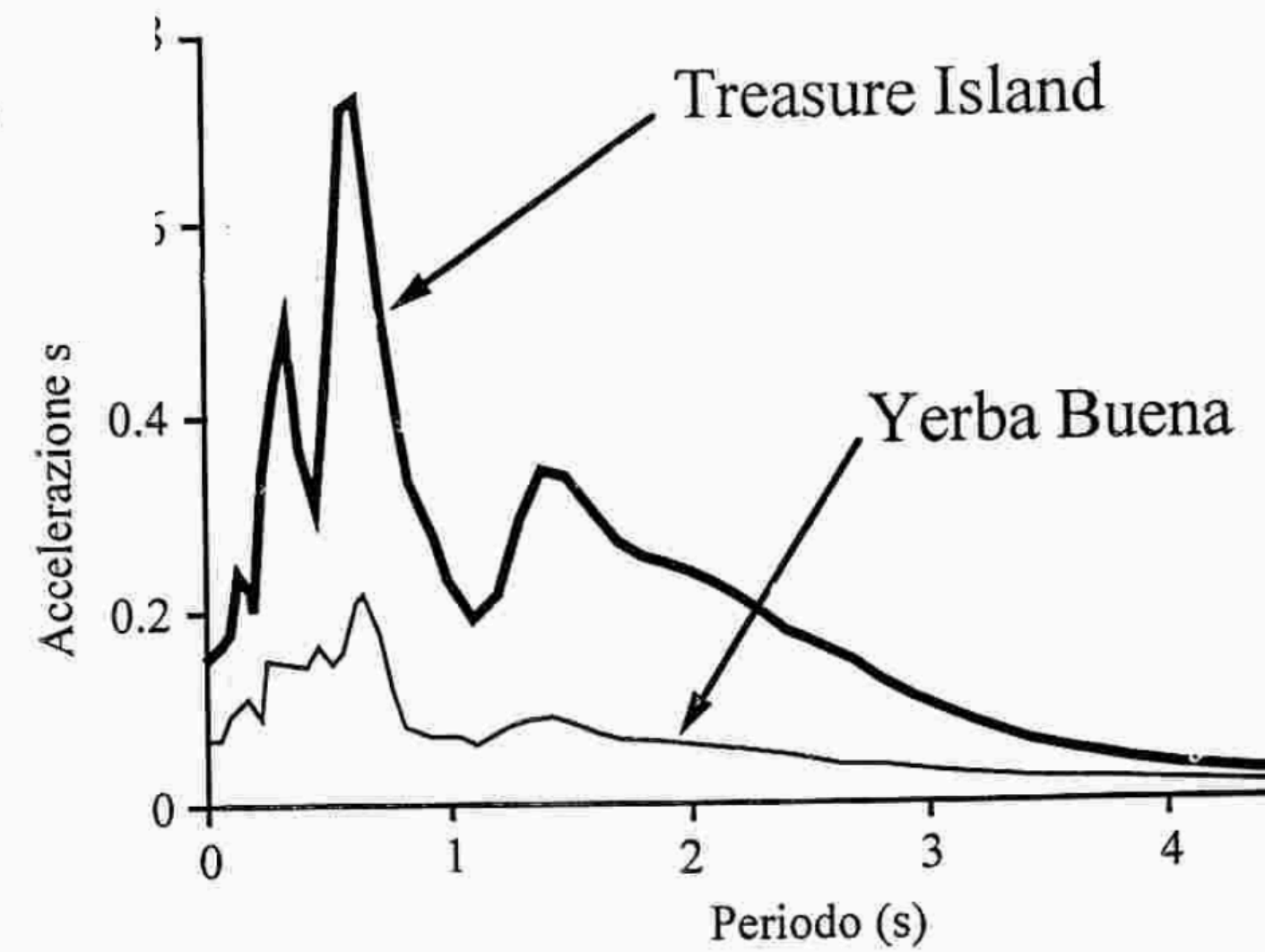
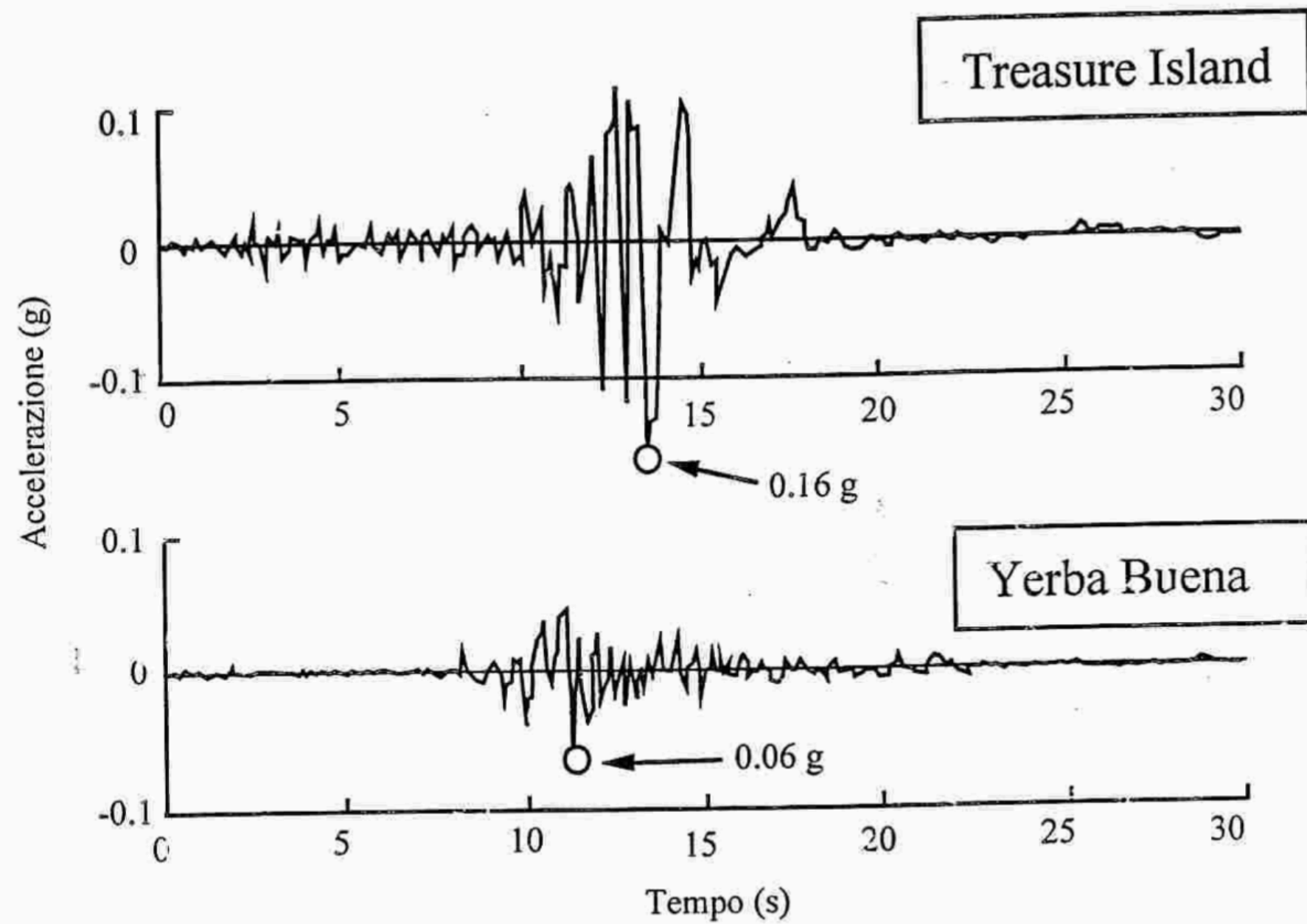


Loma Prieta - San Francisco bay (USA)



PGA 0.16 g

PGA 0.06 g



Sequenza sismica Umbria- Marche del 1997: il caso di Cesi

Cesi Bassa - IX MCS

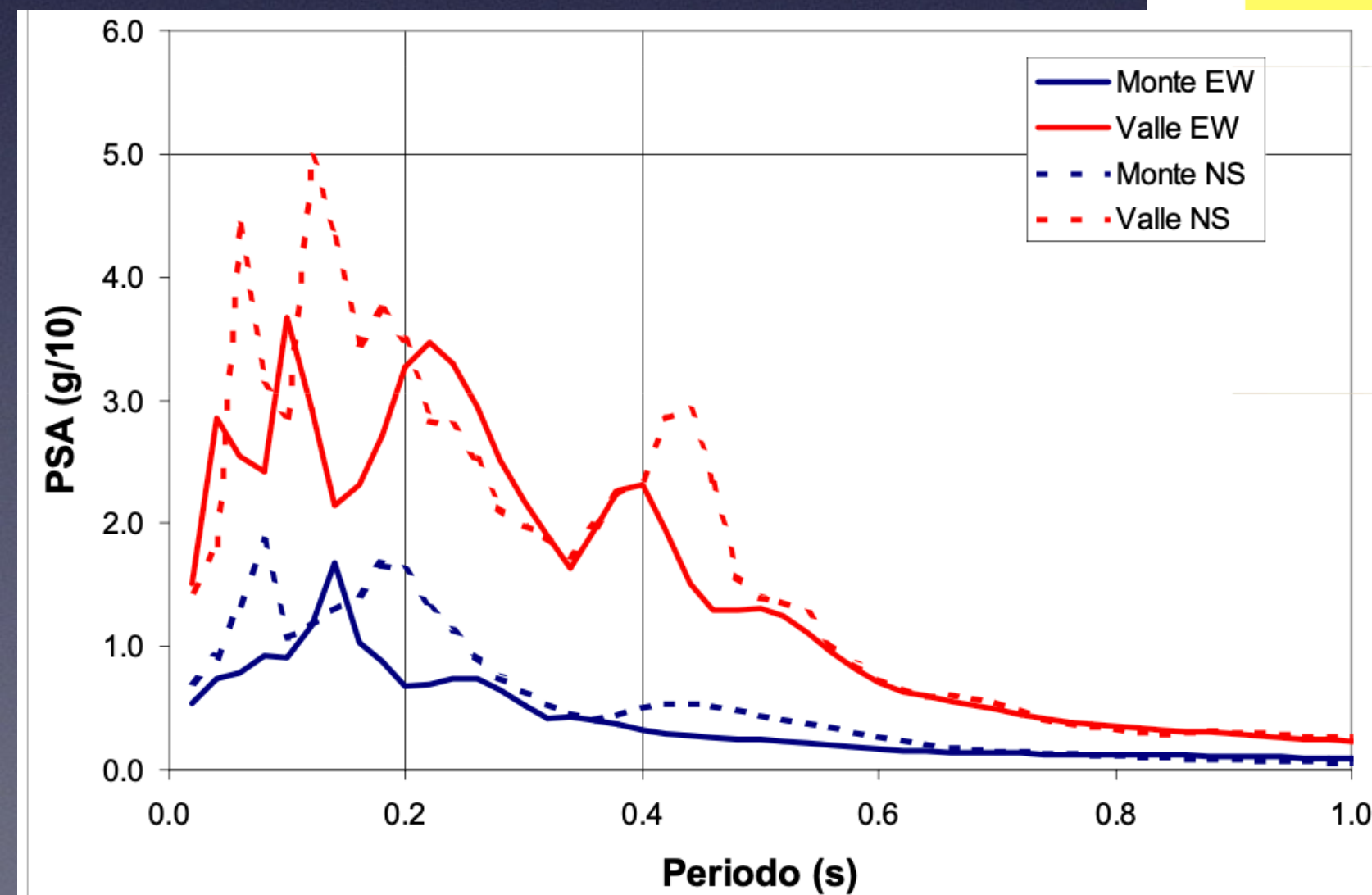
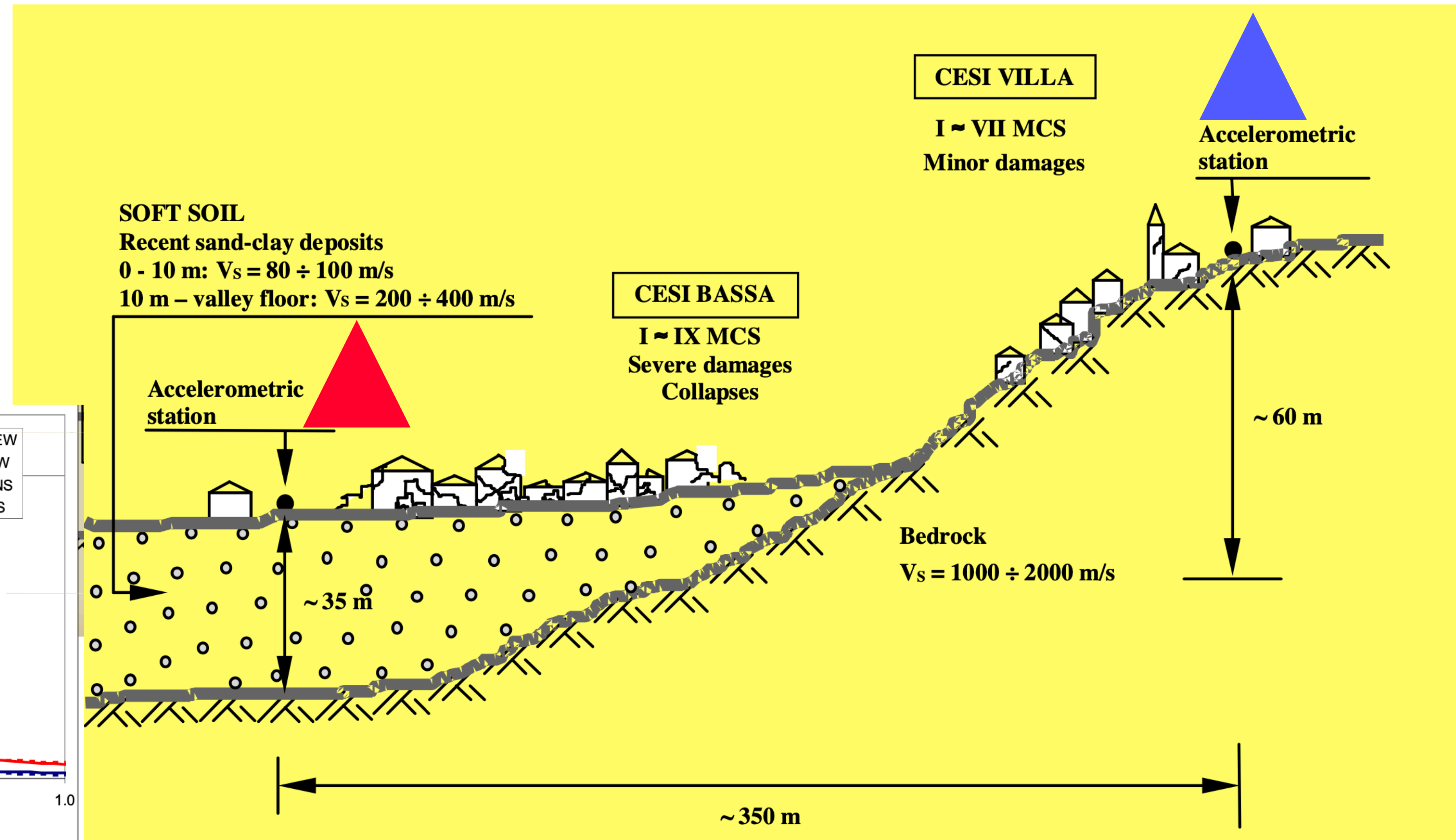


Cesi Villa - VII MCS



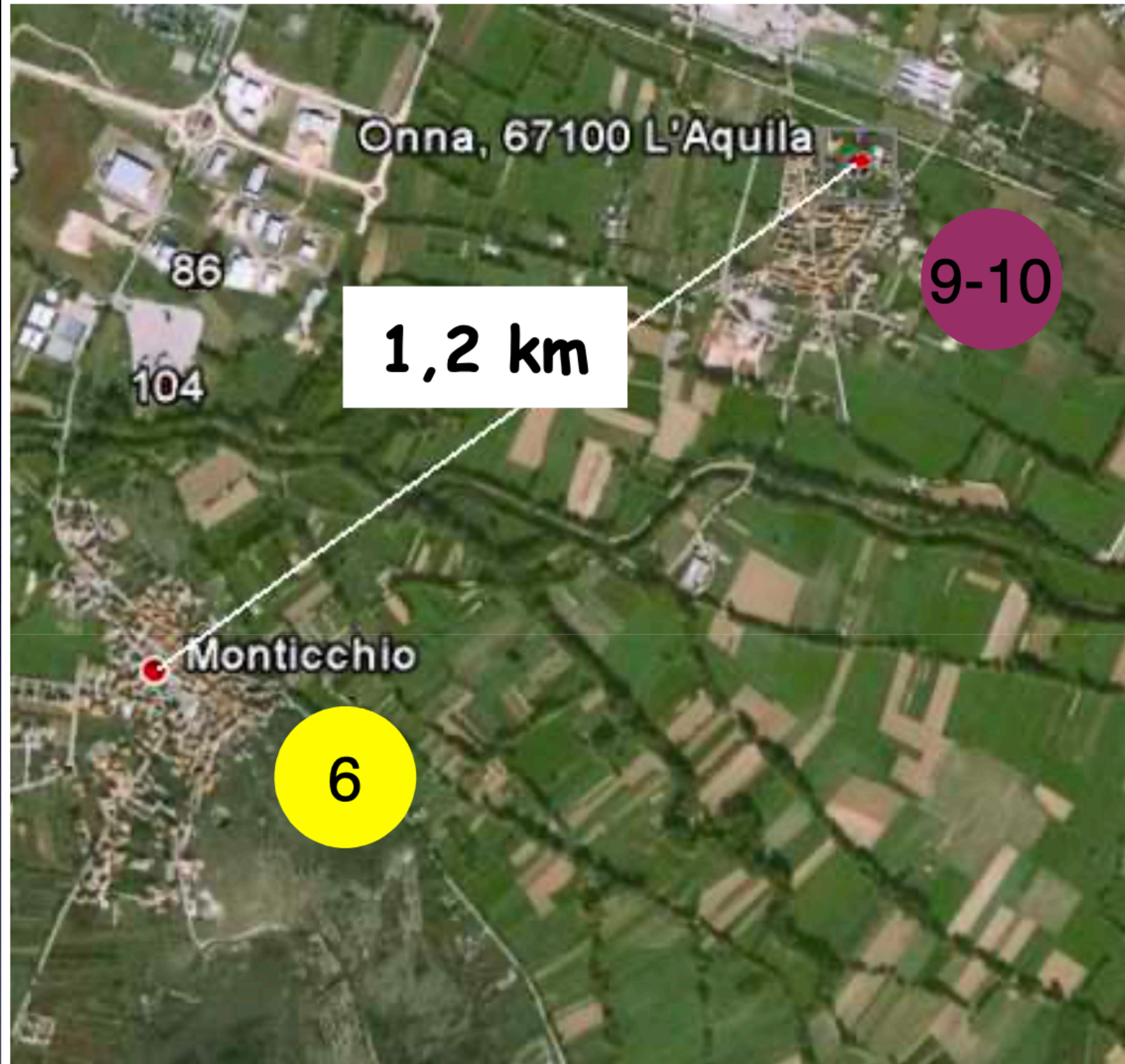
A **Cesi Bassa** i danneggiamenti corrispondono al IX grado MCS, mentre a **Cesi Villa** si hanno danni corrispondenti al VII grado MCS. La distanza tra le due aree è di poche centinaia di metri e le costruzioni non presentano differenze di vulnerabilità tali da spiegare le differenze di intensità macrosismica di due gradi osservate.

Sequenza sismica Umbria- Marche del 1997: il caso di Cesi



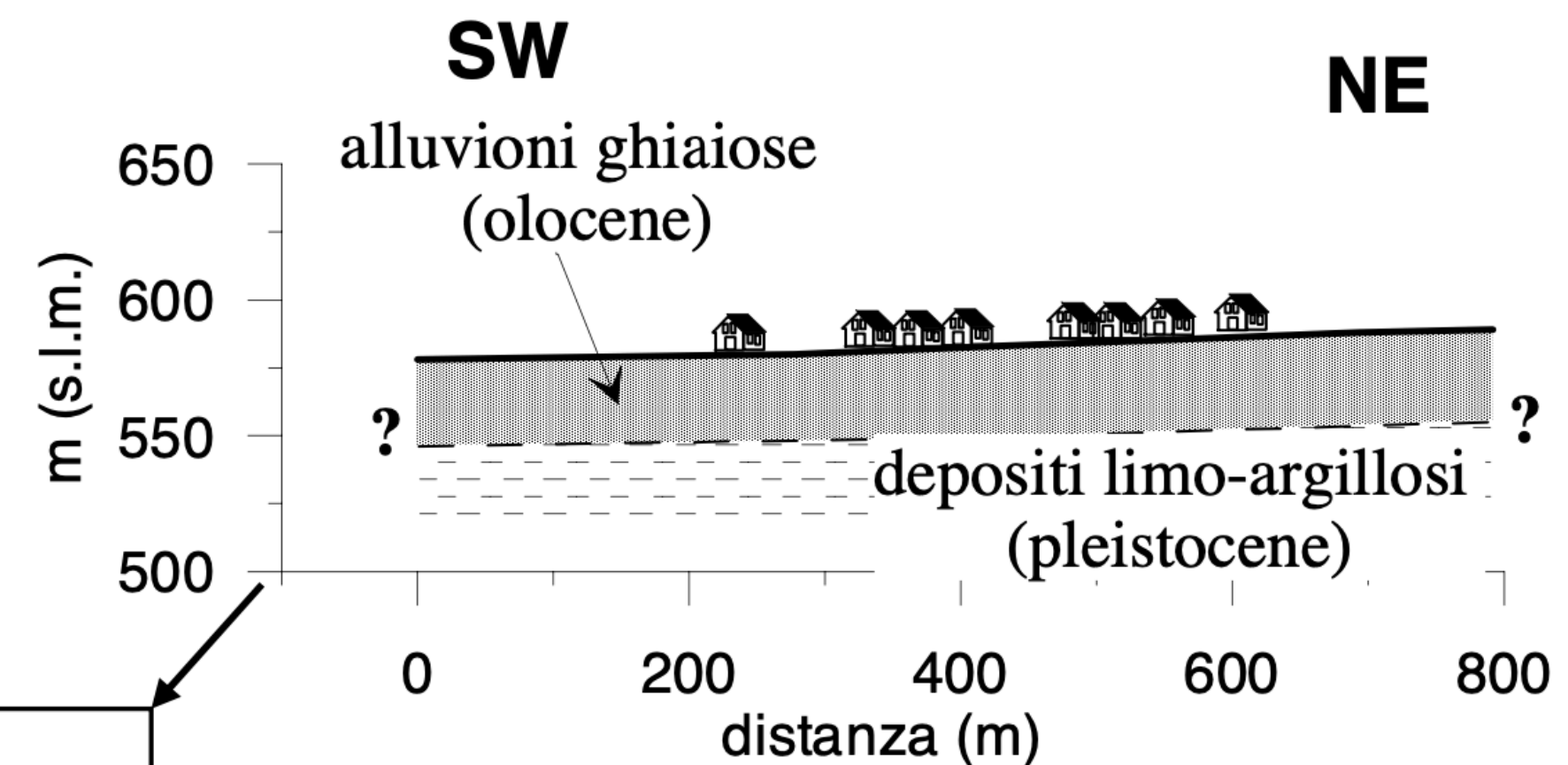
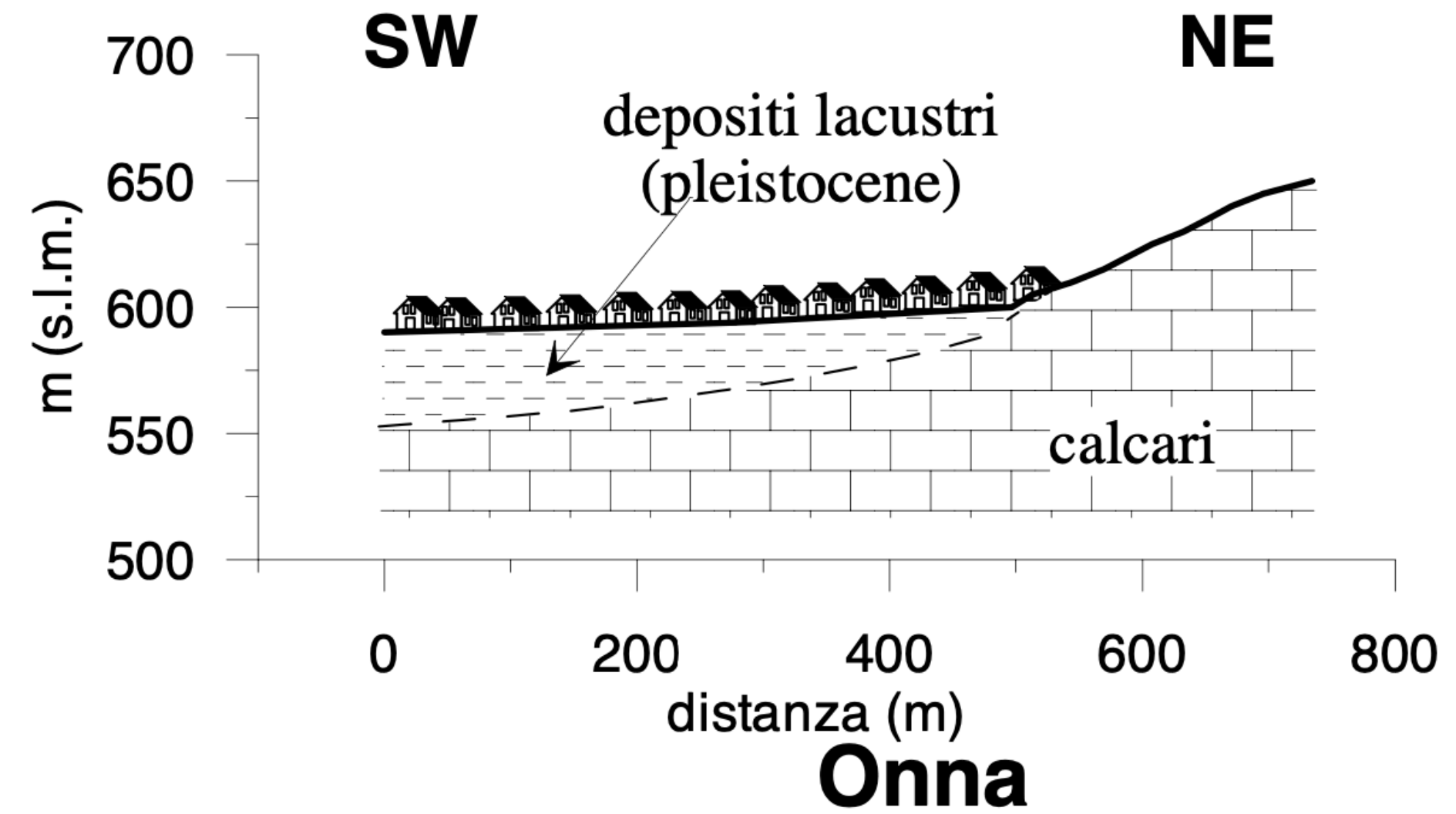
Il terremoto de L'Aquila del 06/04/2009 (M=6.3)

Monticchio



Distanza epicentrale \cong 12 km

Terremoto del 1461
Onna completamente distrutta



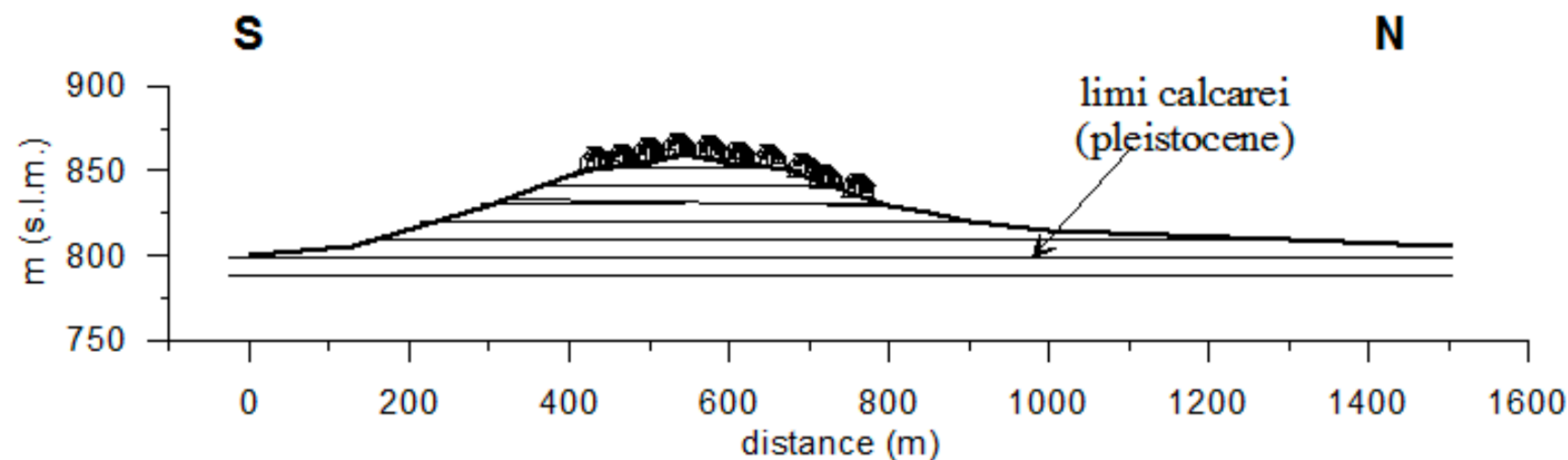
(cortesia Dott. Di Capua, INGV)

Il terremoto de L'Aquila del 06/04/2009 (M=6.3)



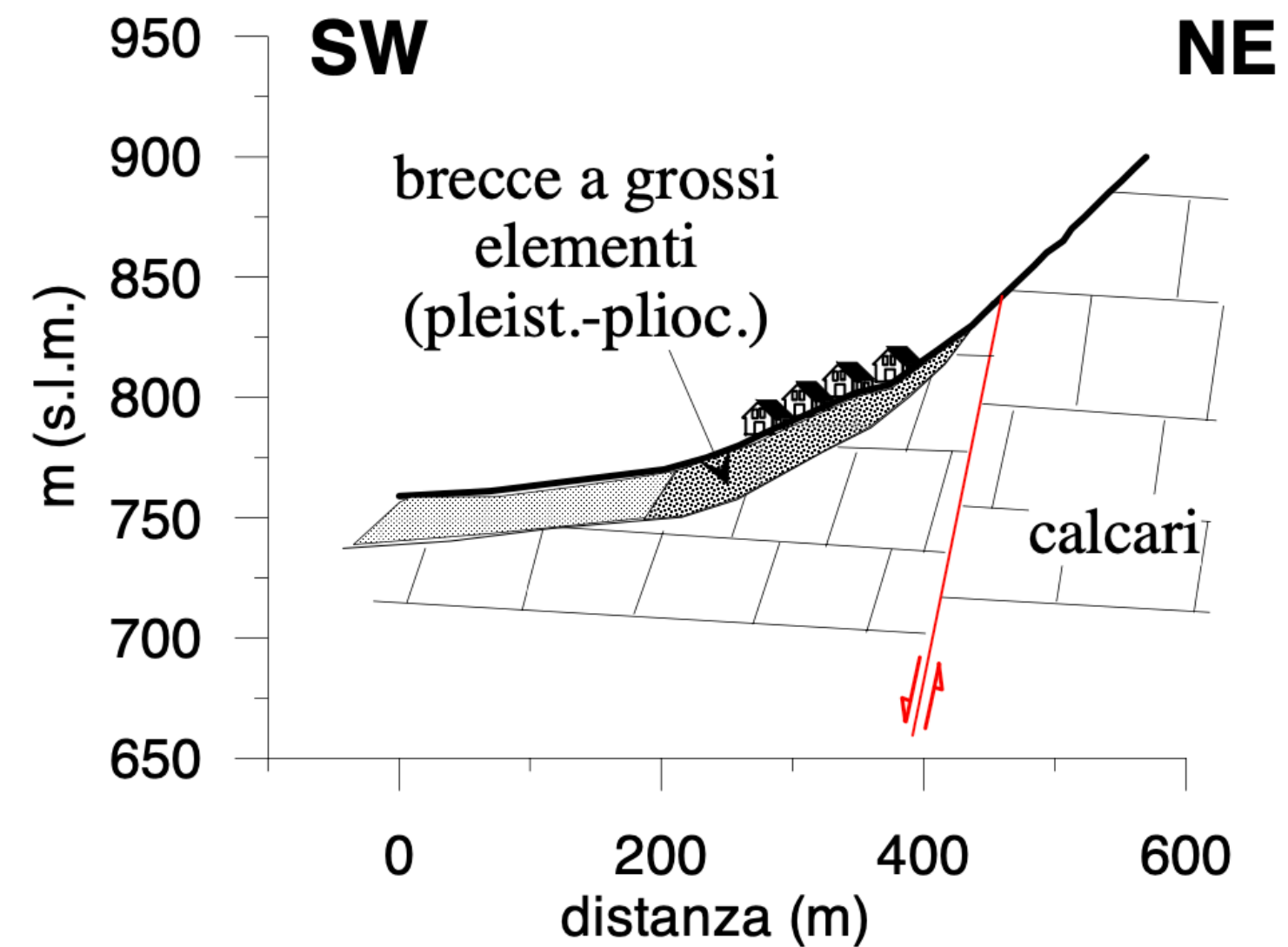
Distanza epicentrale \cong 25 km

Castelnovo
(I=IX-X MCS d=25 km)



(a)

San Pio delle Camere



Terremoti del
1461,
1703, 1762
Castelnovo
completamente
distrutta

(cortesia Dott. Di Capua, INGV)

Local geological conditions can modify the seismic motion (local amplifications)

Ground motion modification due to:

1. Lithological conditions = 'the site effect' (1D and 2D/3D)
2. Morphological conditions = 'the topographic effect'

Effects of seismic induced instabilities:

- Ruptures and faults
- Landslide (in land or submarine)
- Liquefaction
- Tsunami
- Etc.

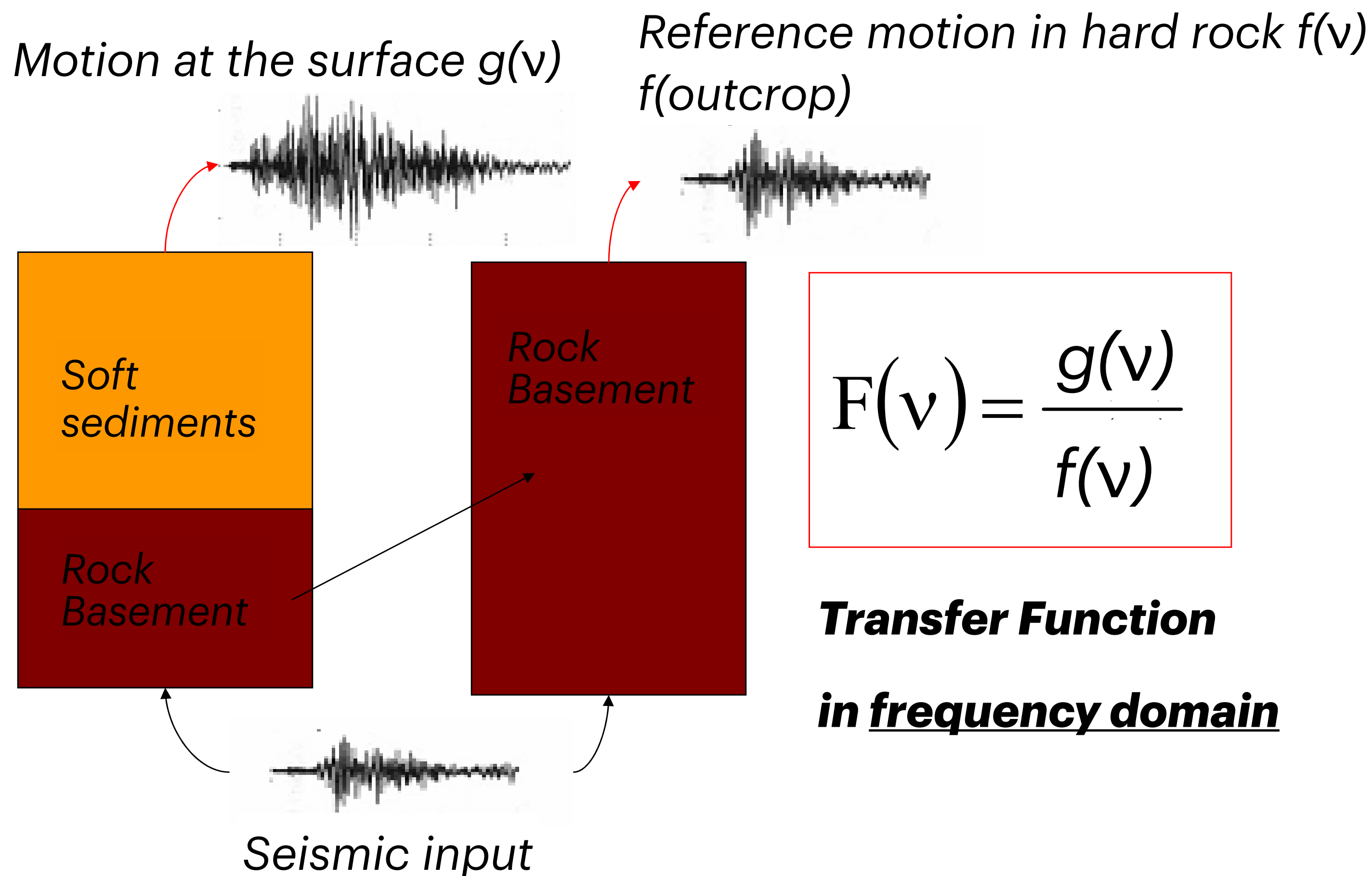
Local geological conditions can modify the seismic motion (local amplifications)

ν = frequency

1. Lithological conditions

The **TRANSFER FUNCTION** is the **spectral** ratio between the motion at the basement and the motion at the sediments ground surface

Soft soils can modify the energy propagation: a relative estimation




Local geological conditions can modify the seismic motion (local amplifications)

1. Lithological conditions

Practically the amplification function is used and assumed as the modulus of the transfer function

Amplification factor = $|F(v)|$



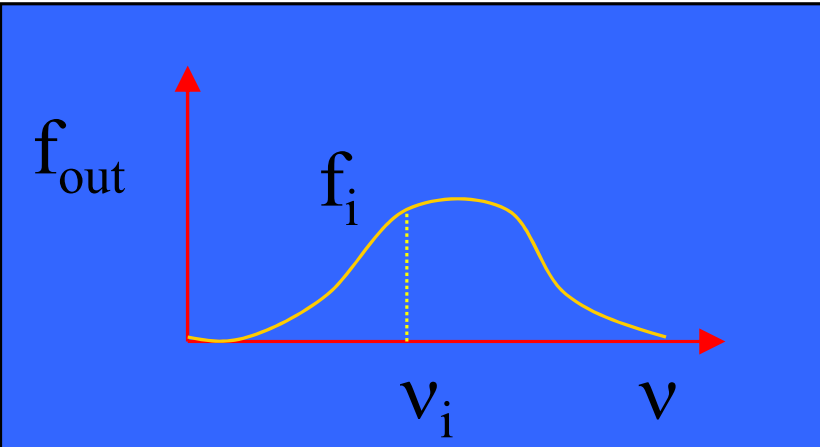
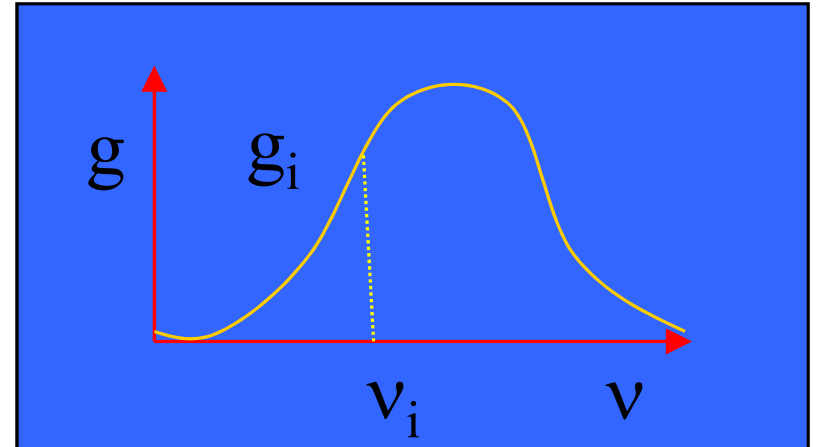
$$F_t(v) = \frac{g}{f_{out}}$$

Amplification Function $F_t(v)$


Amplification Function

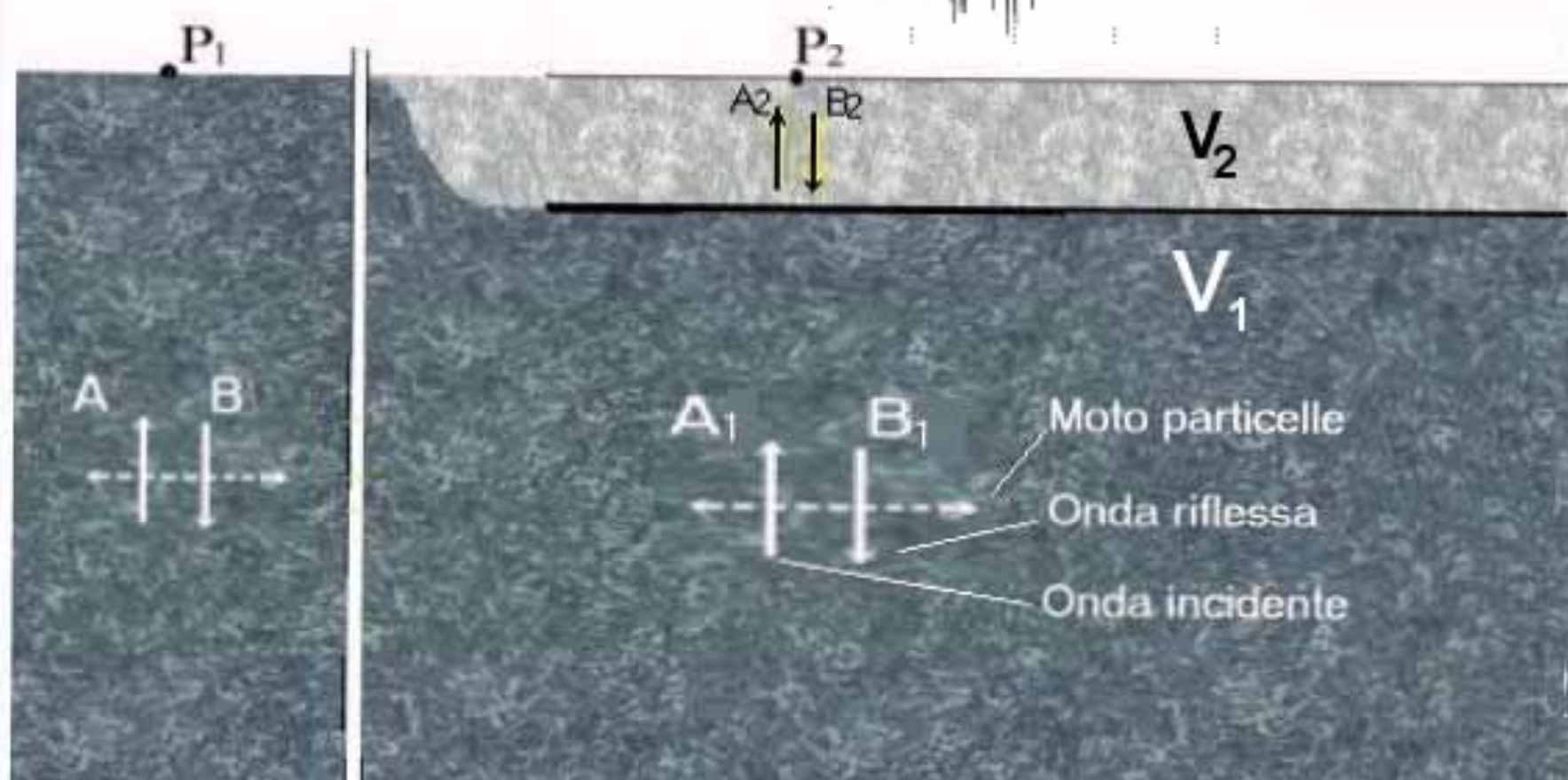
It is the spectral ratio between the motion recorded at the outcrop basement and the sediments ground surface

Spectra

Time series





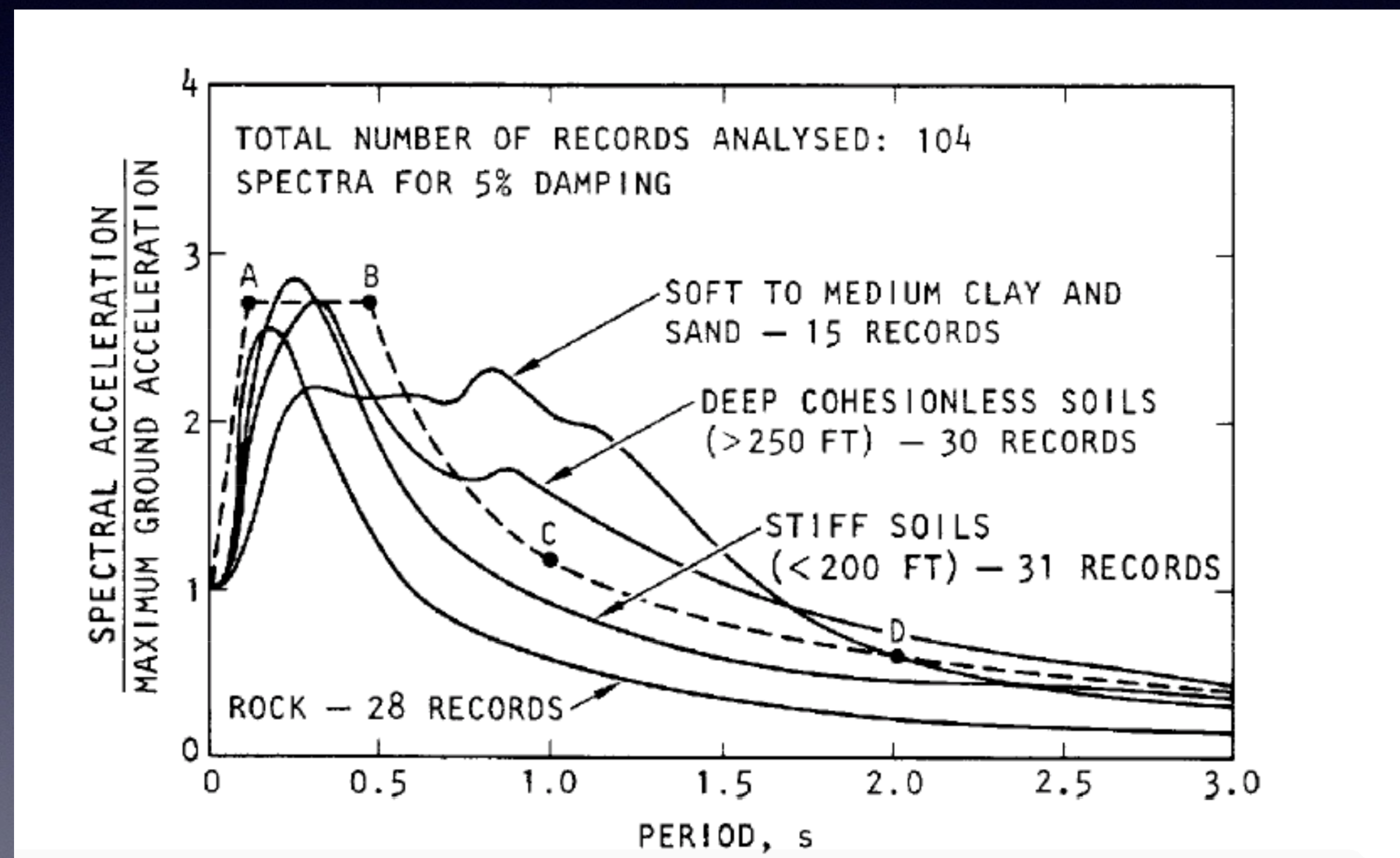
Amp. funct. ≠ Transfer funct.

Local geological conditions can modify the seismic motion (local amplifications)

1. Lithological conditions

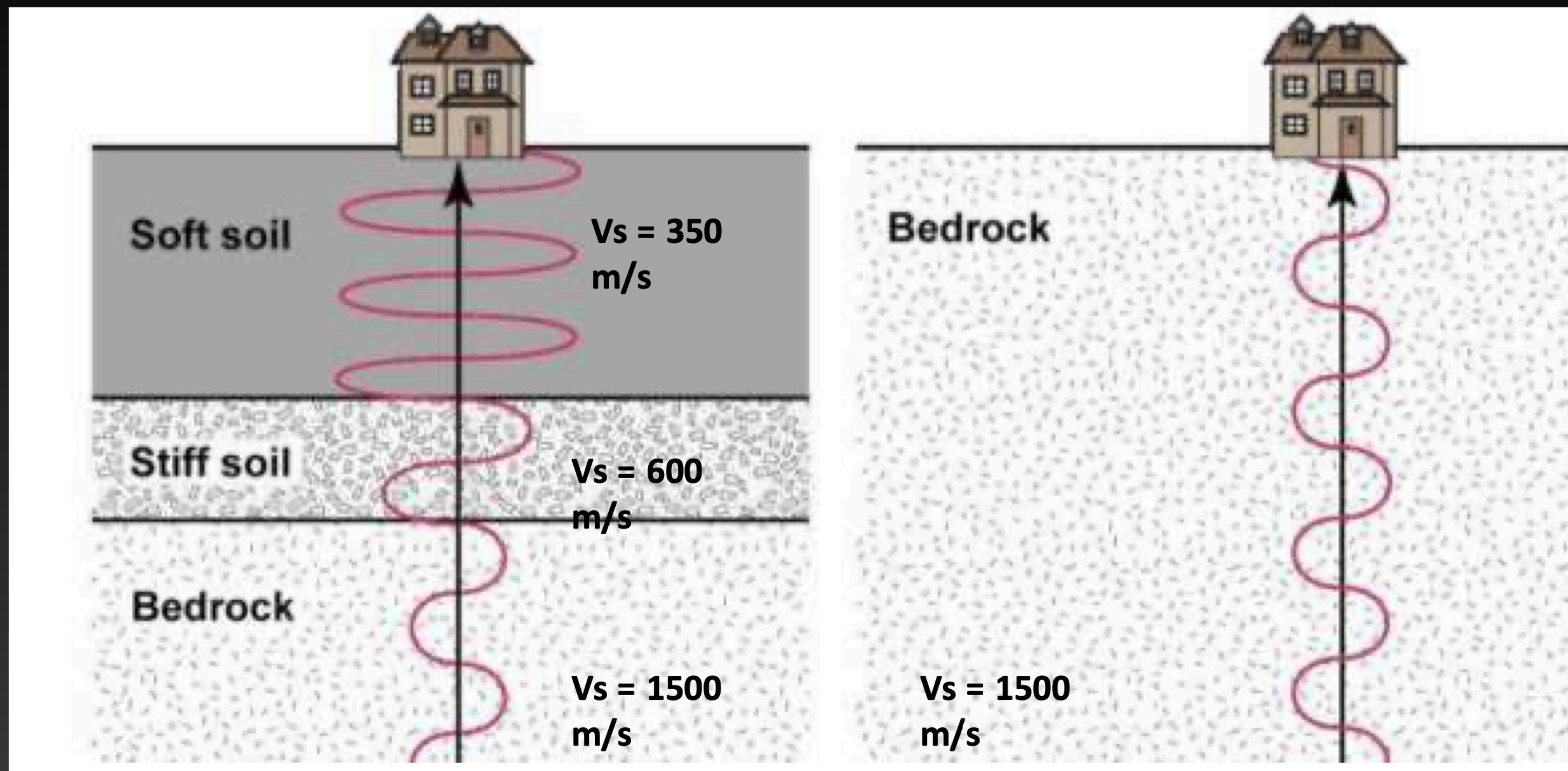
The mechanical properties of soil can deeply modify the local seismic ground motion

Due to conservation of energy, slower soils can improve the seismic acceleration (given the same magnitude and epicentral distance)



Local geological conditions can modify the seismic motion (local amplifications)

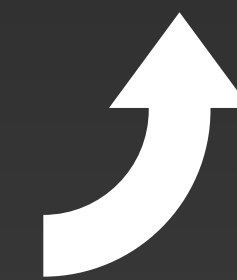
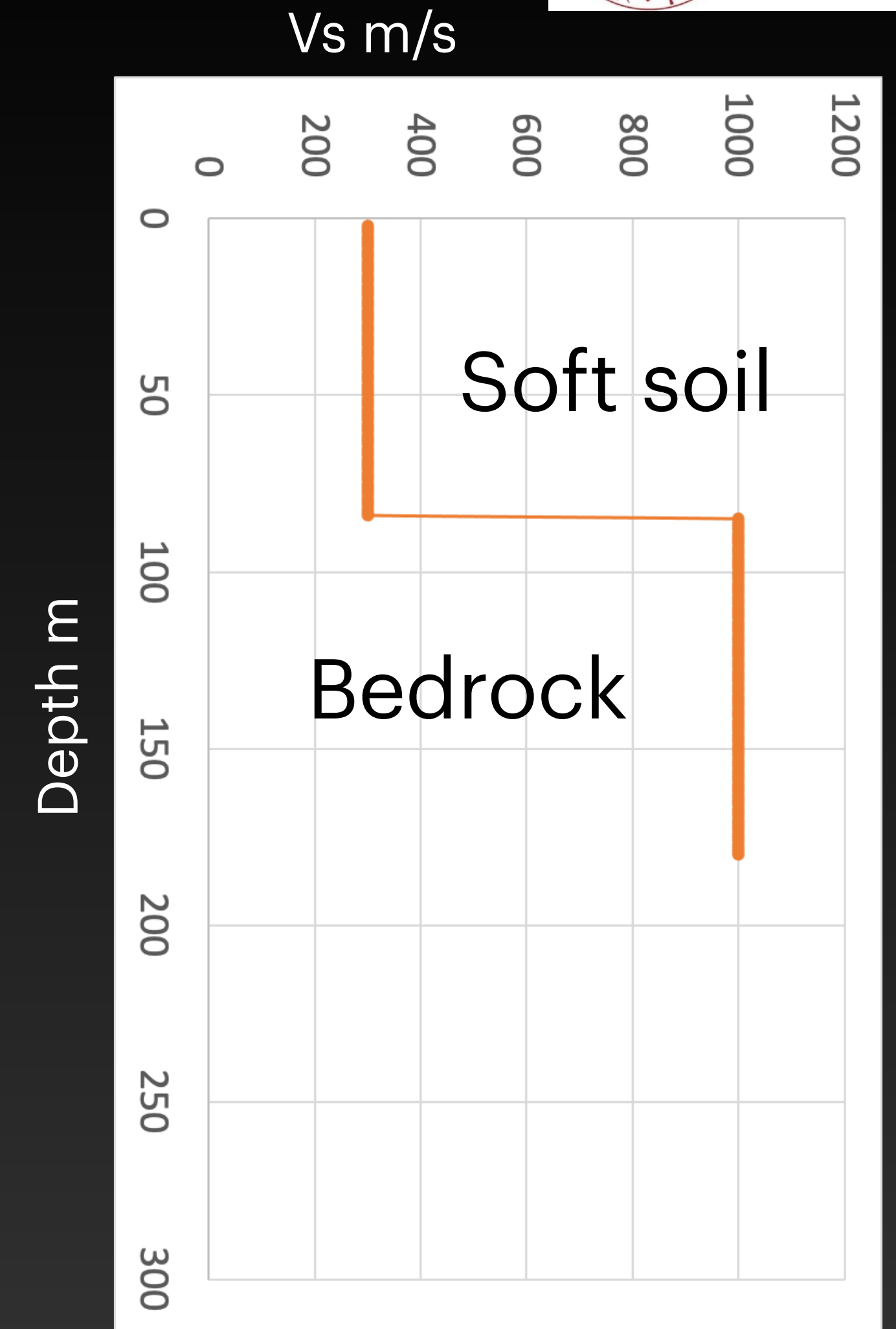
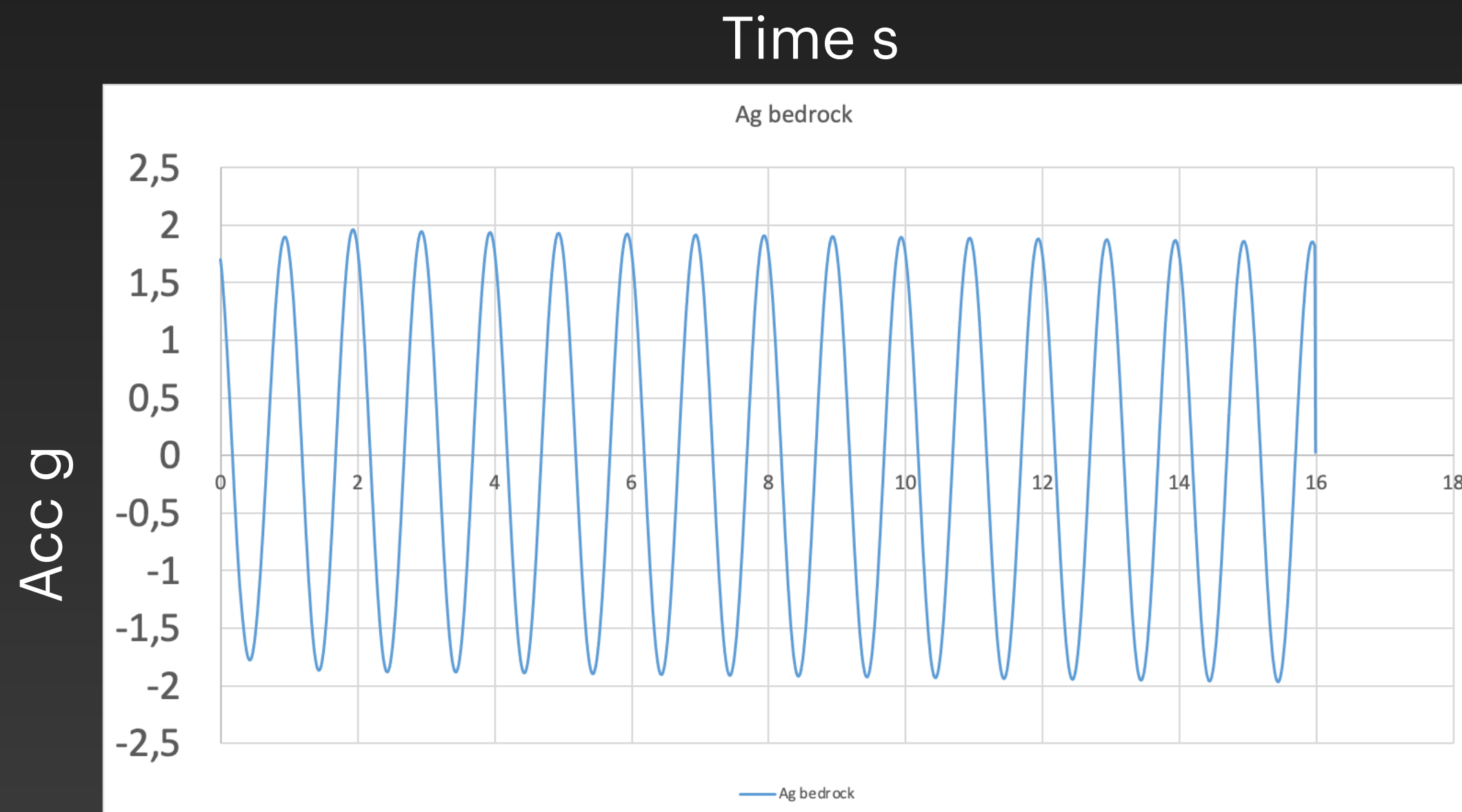
Due to conservation of energy, slower soils can improve the seismic motion !



Soft soil effect Synth example

80 m o soft soil
over an hard soil
model

Input: cosine 2g
wave at 1 Hz
frequency

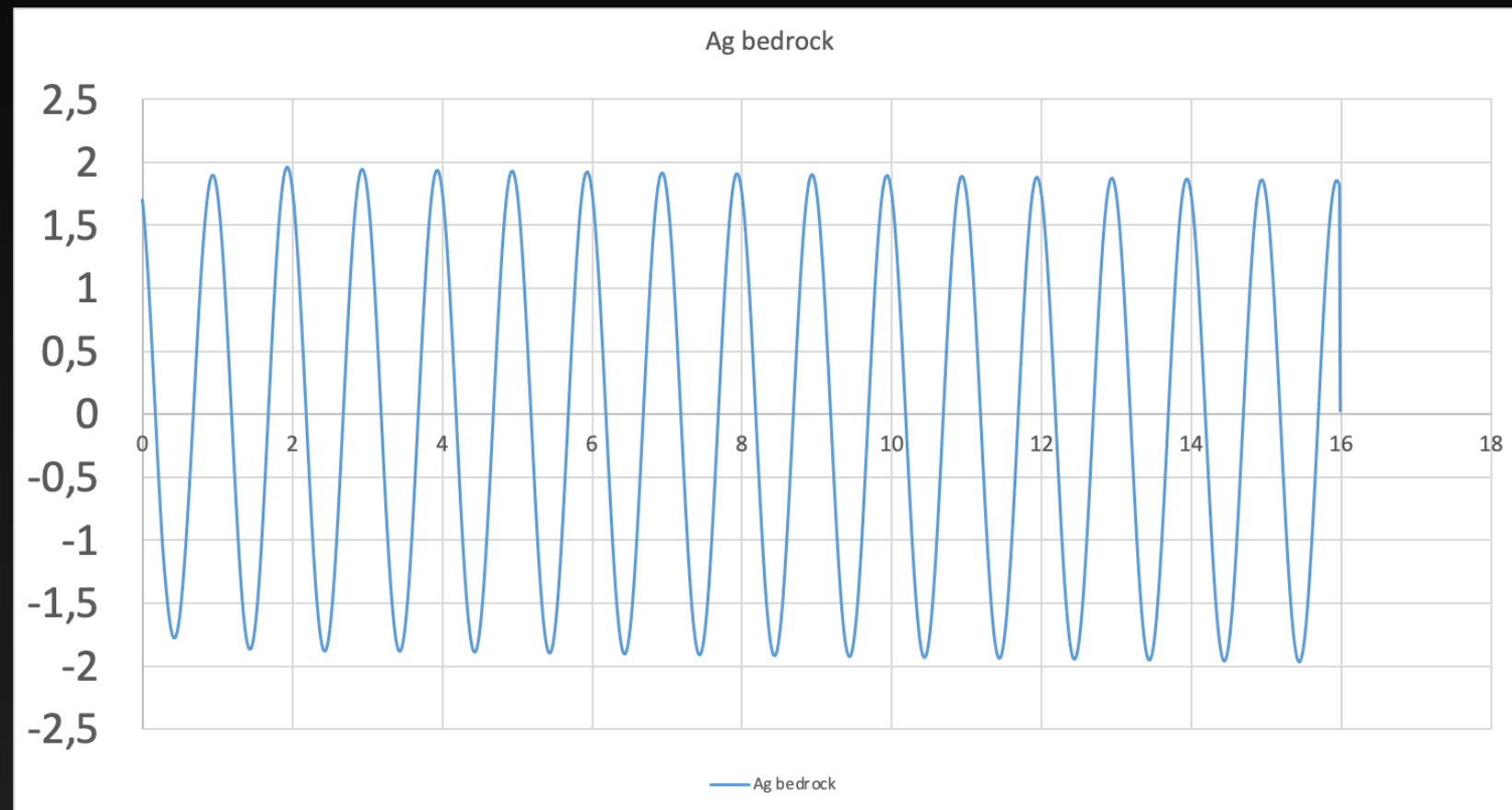


Soft soil effect

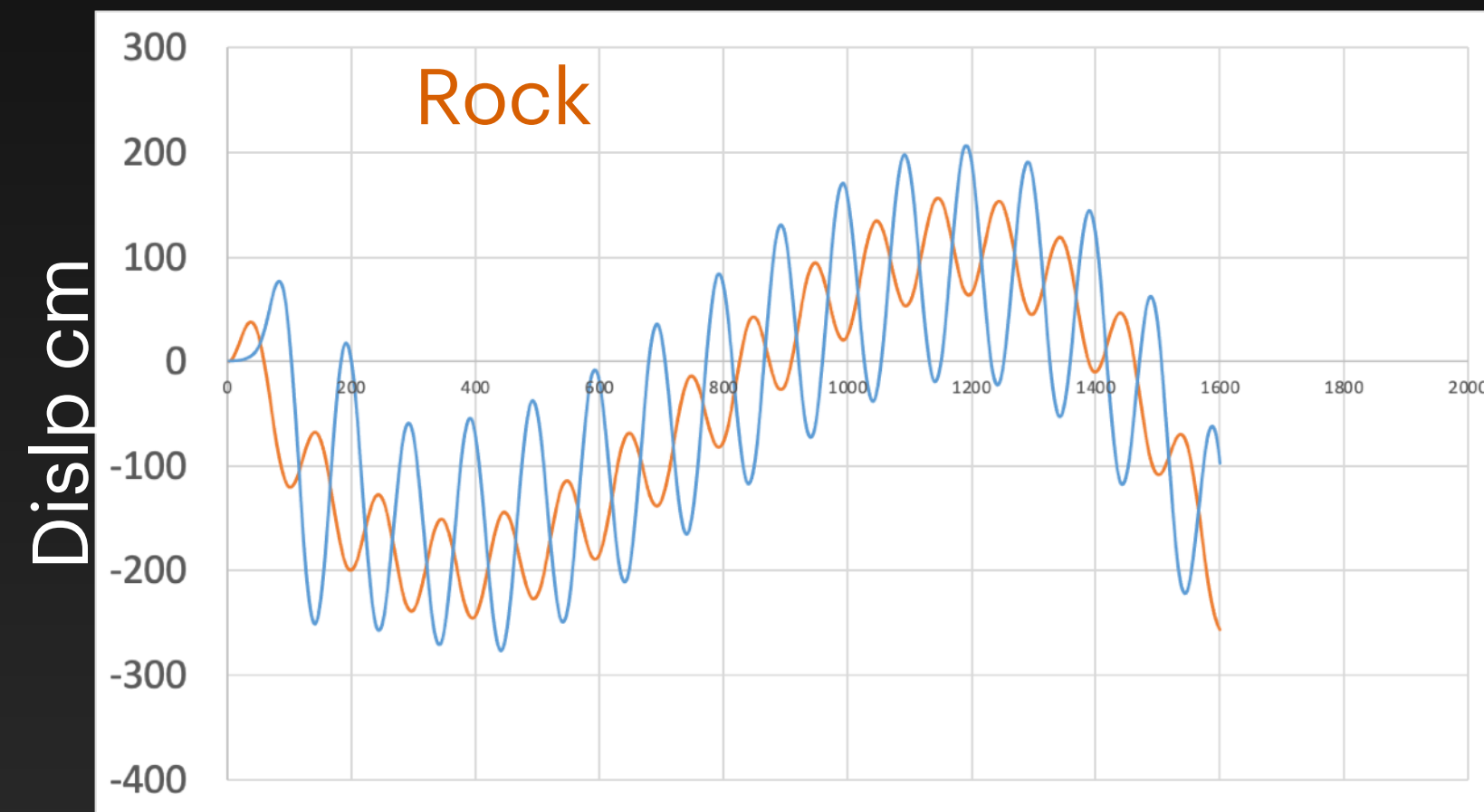
Time s

INPUT

Acc g

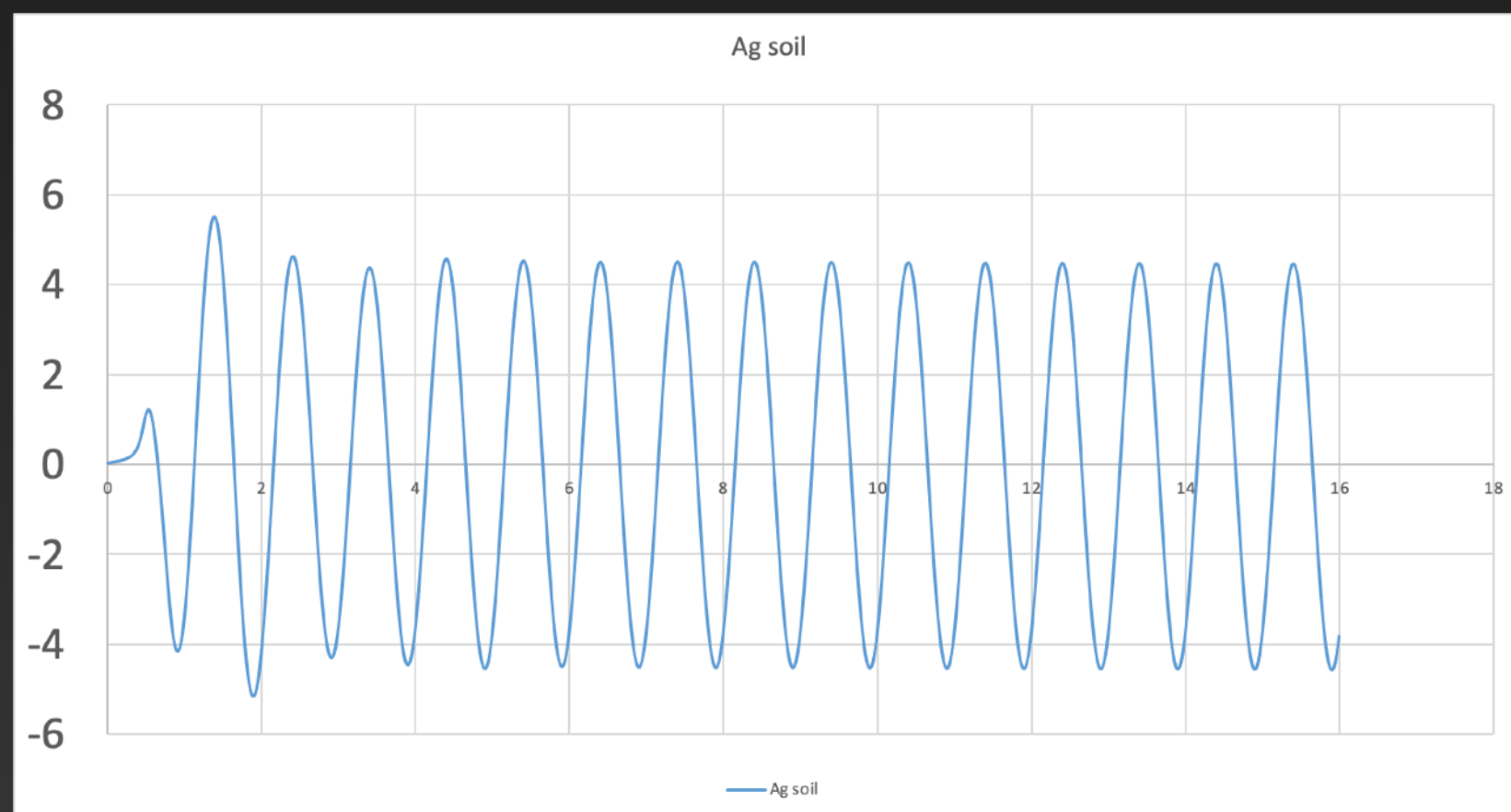


2 g Acceleration Input



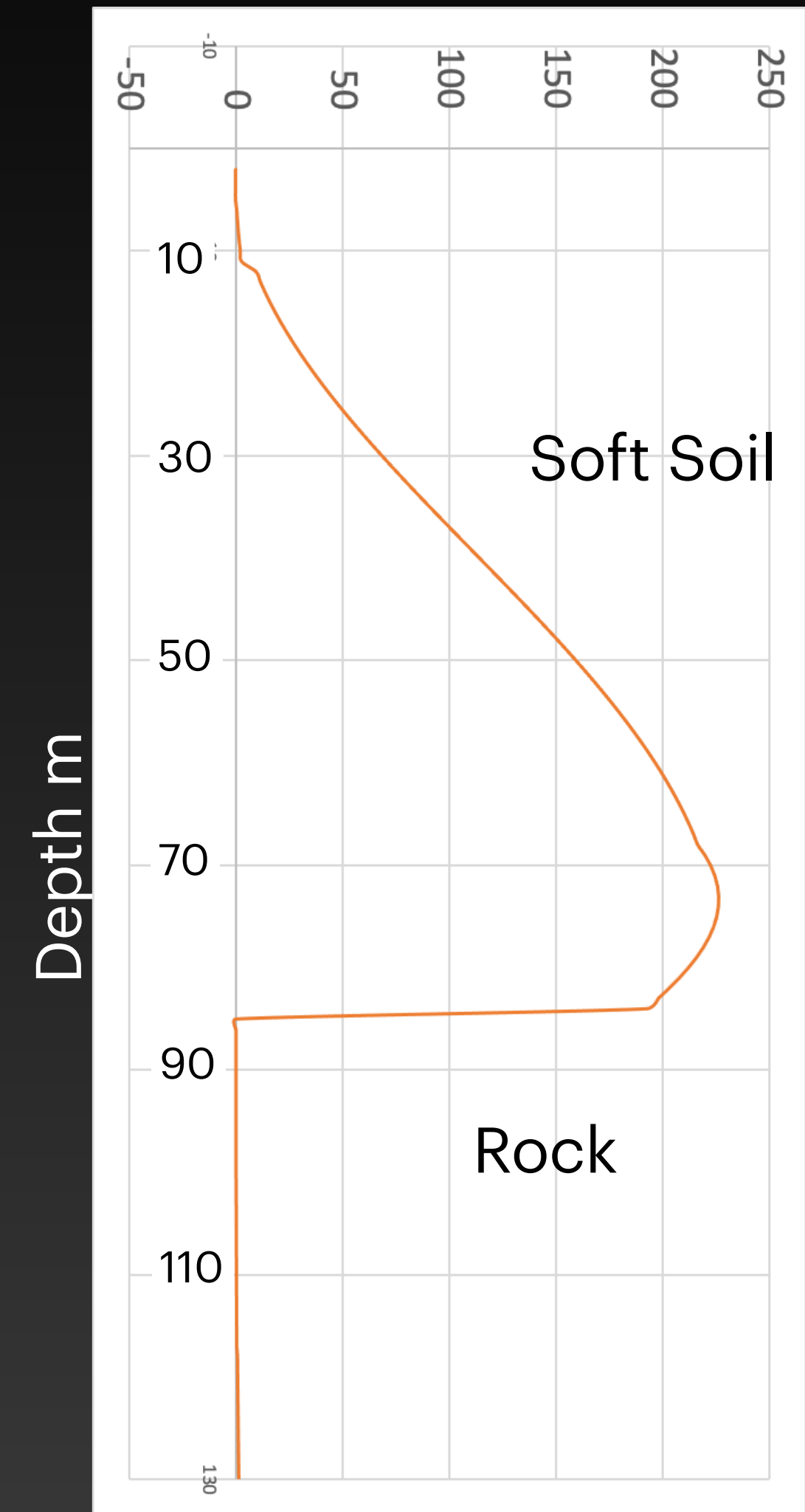
OUTPUT

Acc g



5g Acceleration At surface!

Dissipated Energy

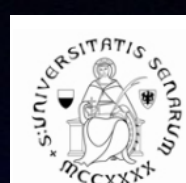


Local geological conditions can modify the seismic motion (local amplifications)

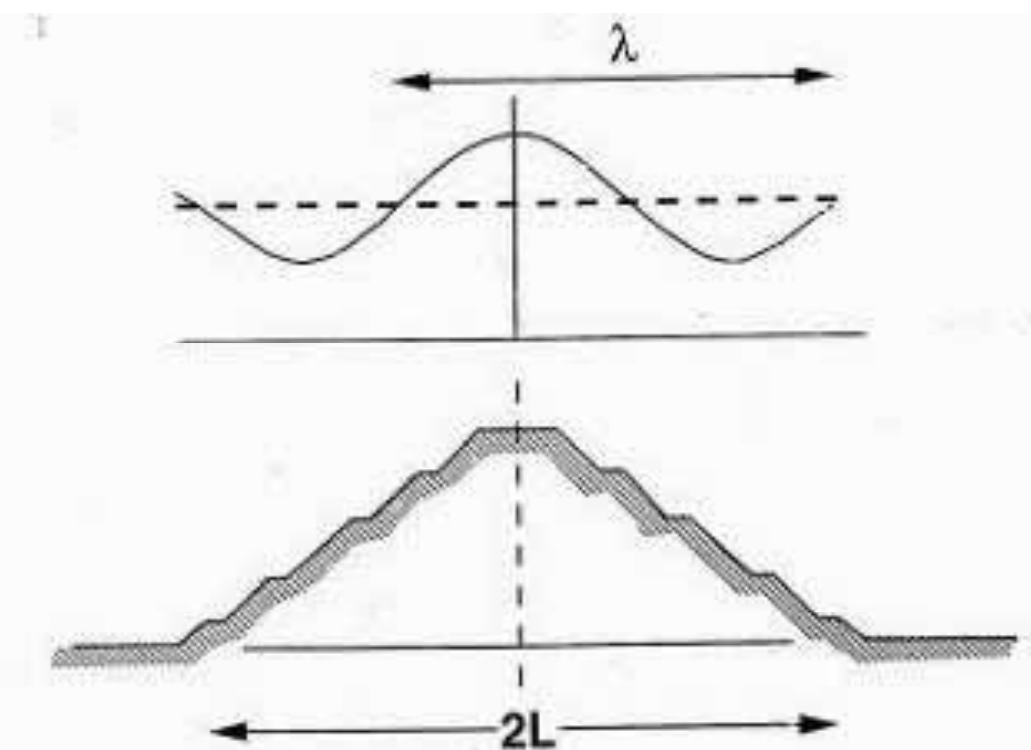
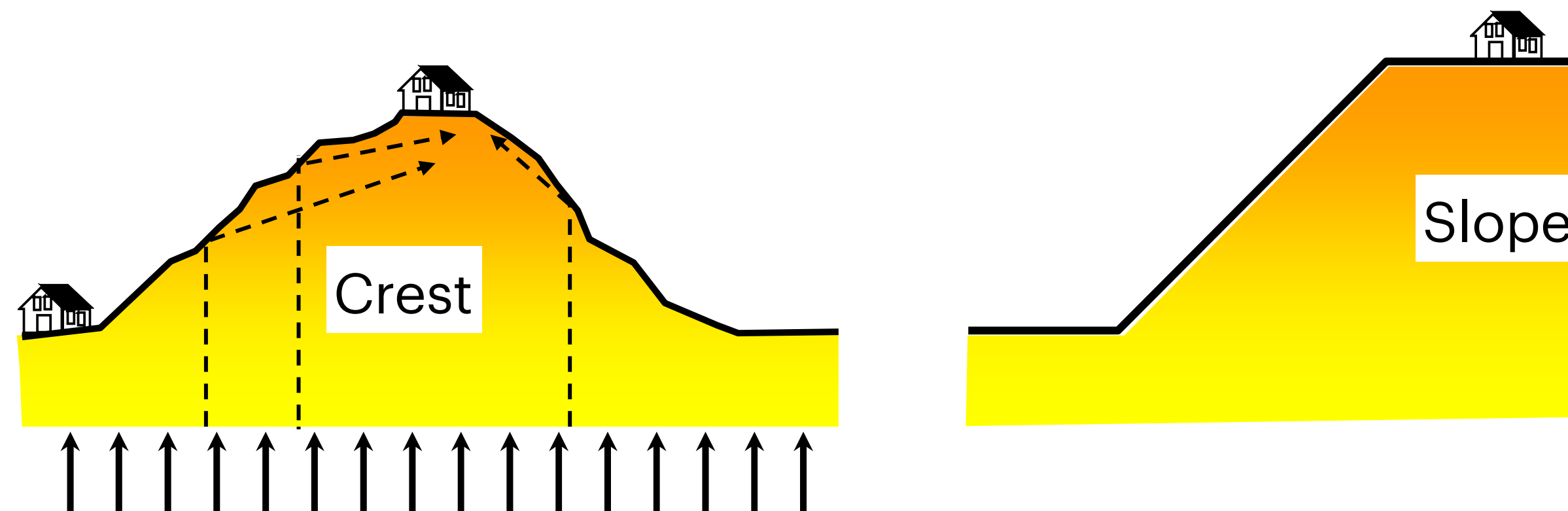
2. Topographic conditions

Topographic effects are less
Important than lithological
ones

They can happen due to
constructive interference
between reflected waves
and boundaries effects



2D effects for topographic conditions



Topographic effects can be
significant if dimensions are in
the same order of seismic
wavelength

$$2L \approx \lambda$$

>> slope >> amplification

L = hill semi-length λ = wavelength

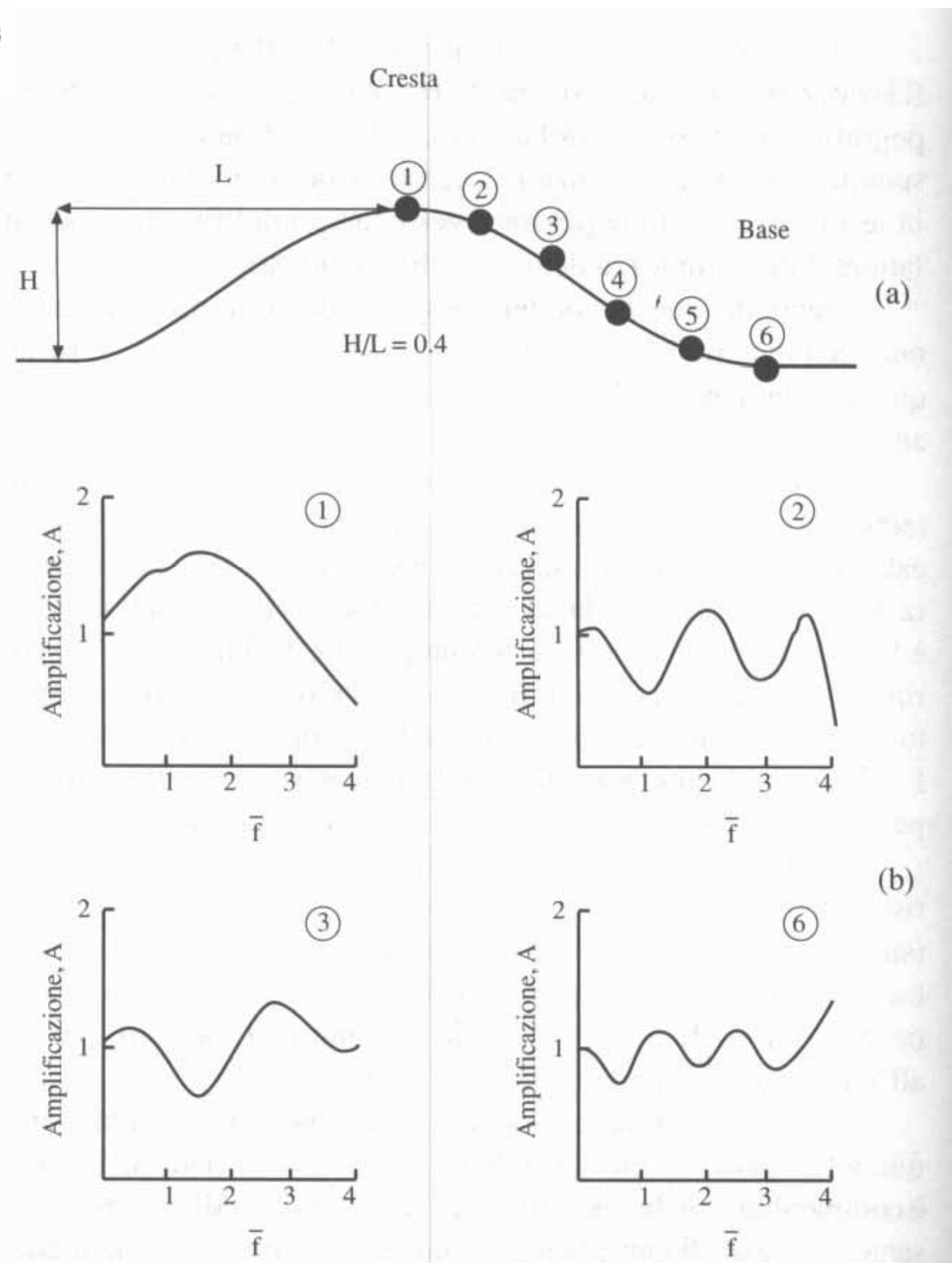


Fig. 4.16. Funzioni di amplificazione calcolate in corrispondenza di alcune postazioni di un rilievo isolato nell'ipotesi di propagazione verticale di onde SH (Geli et al., 1988).

Effects depends on waves direction and slope geometry.

The key parameter is $\beta=2L/\lambda$, being

L = half width of the mountain and

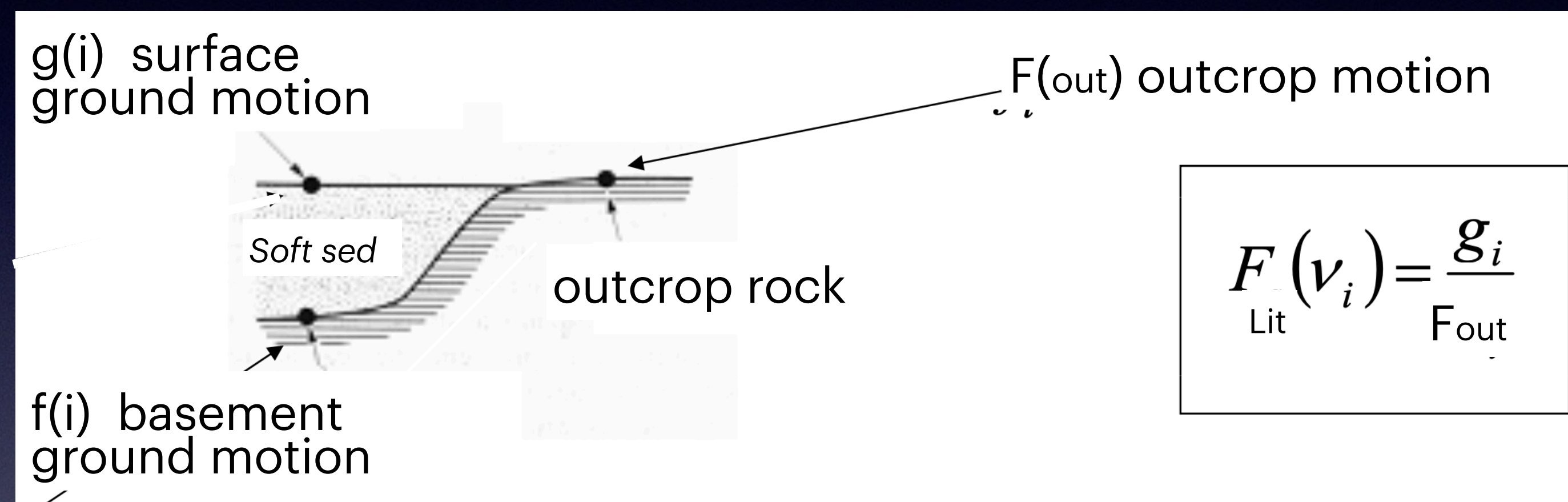
λ = seismic wavelength

(λ = velocity/frequency = c/f)

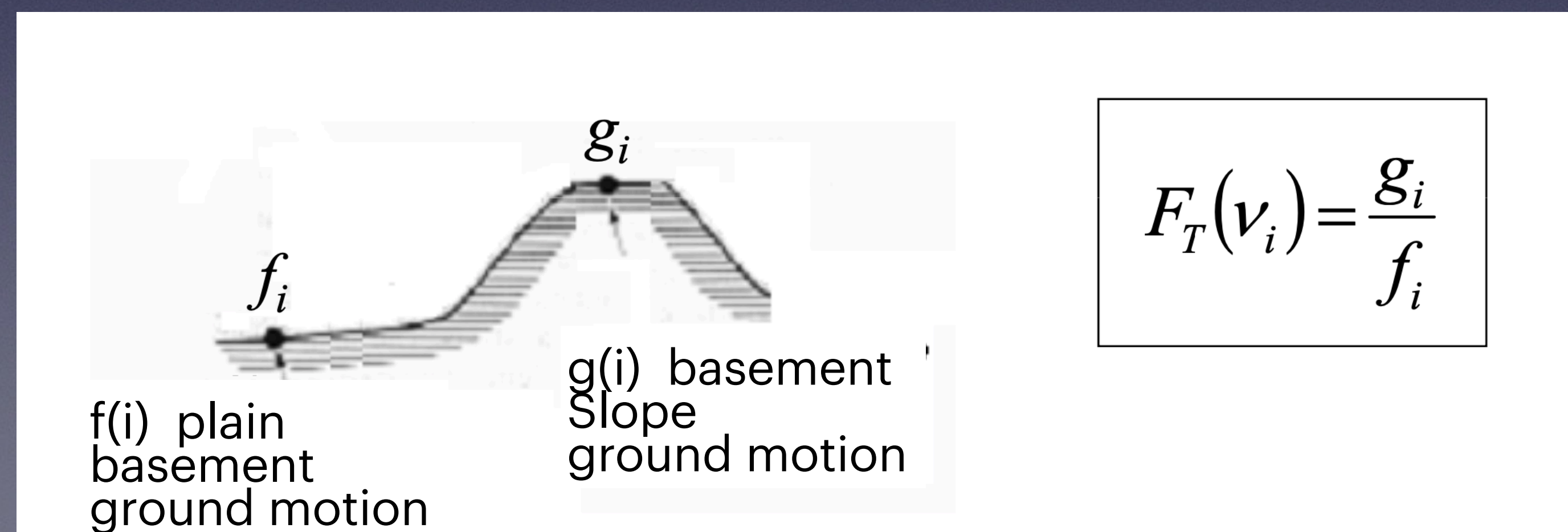
The maximum effect is for $\beta=1$, $2L=\lambda$

Local geological conditions can modify the seismic motion (local amplifications)

1. Lithological conditions



2. Topographic conditions



Local geological conditions can modify the seismic motion (local amplifications)

What it means local?

The interest scale is done by the **seismic wavelength λ** occurring,

$$\lambda = c/f = \text{velocity} / \text{frequency}$$

Example: with soil having $V_s = 300$ m/s and building frequency interest of 3 hz

$$\lambda = 300/3 = 100 \text{ m}$$

'Local' means hundreds of meters....

Local geological conditions can modify the seismic motion (local amplifications)

Dimensions are important for NORMS regulations

e.g. Italian Norms 'Norme Tecniche per le Costruzioni' NTC 2018

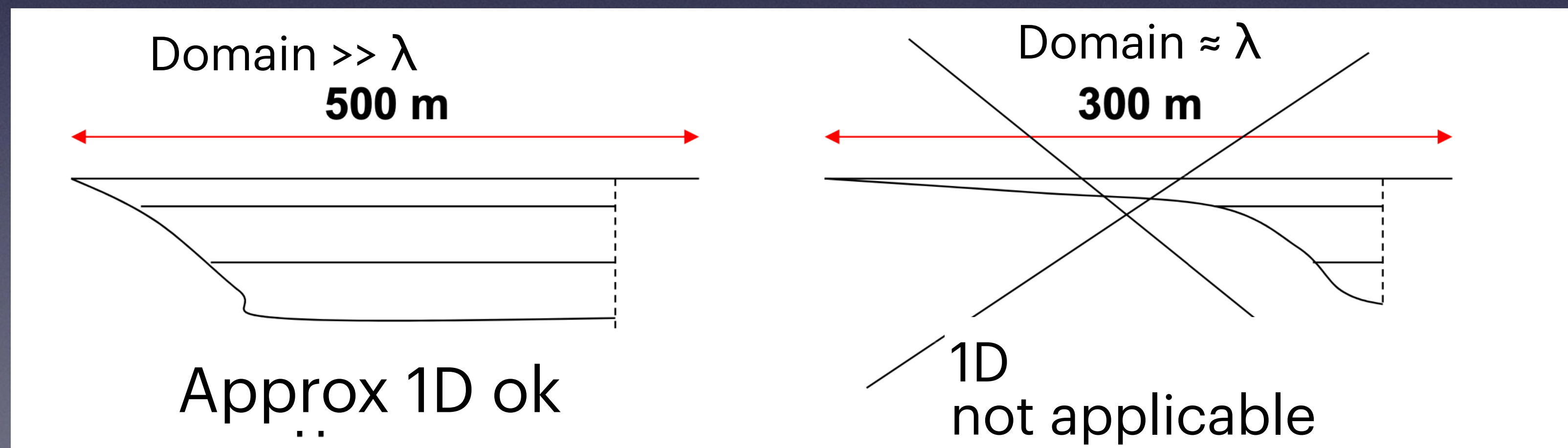
If the site can be considered as horizontal flat layered for the λ of interest = 1D,
otherwise it must be considered 2D

E_s

$V_s = 500 \text{ m/s}$

$f = 2 \text{ Hz}$

$\lambda = 250 \text{ m}$



Local geological conditions can modify the seismic motion (local amplifications)

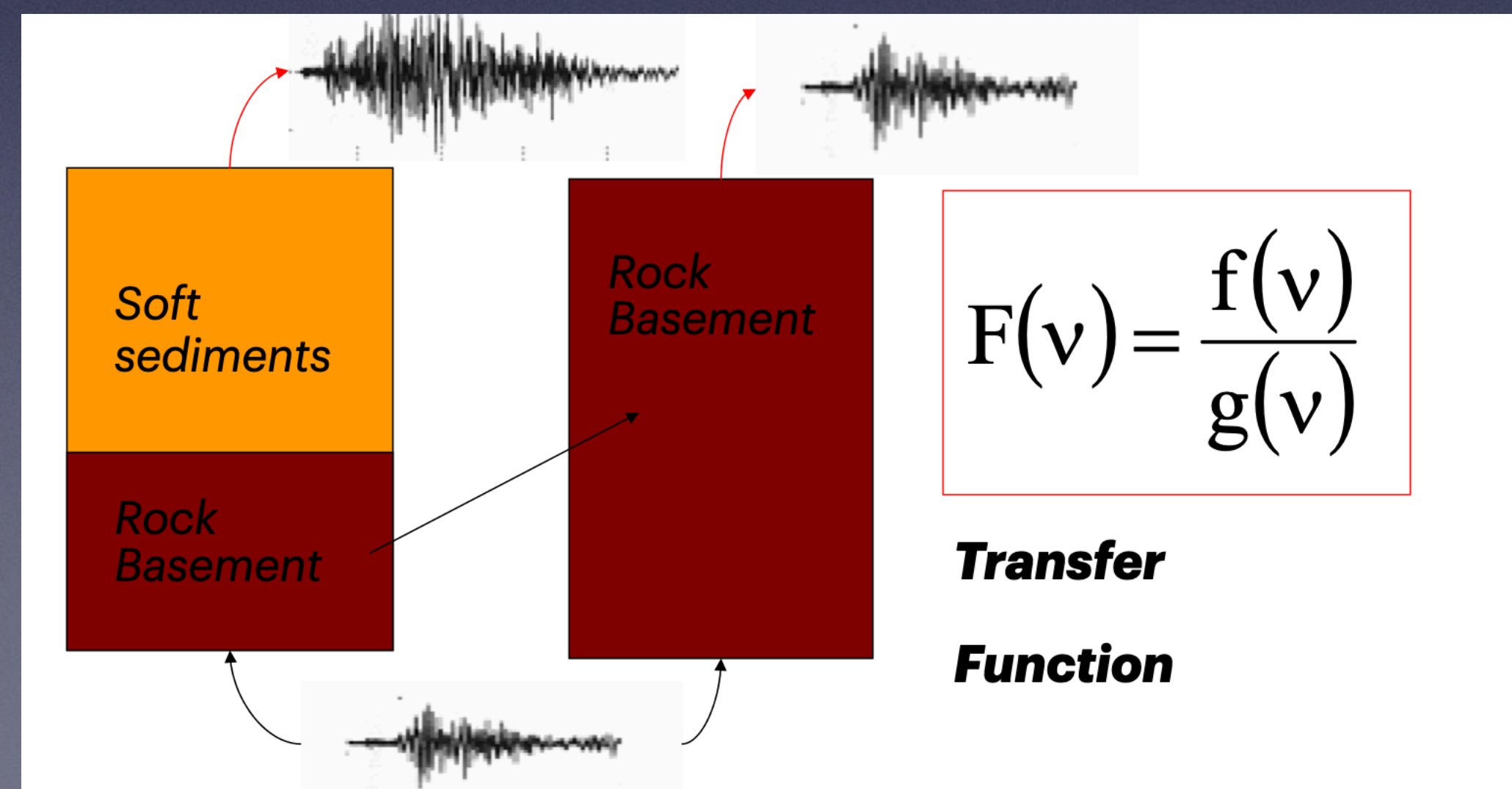
What it means 1D, 2D (3D)?

The assuming dimensions of the problem

**Some geological features are strictly
multi-dimensional,**

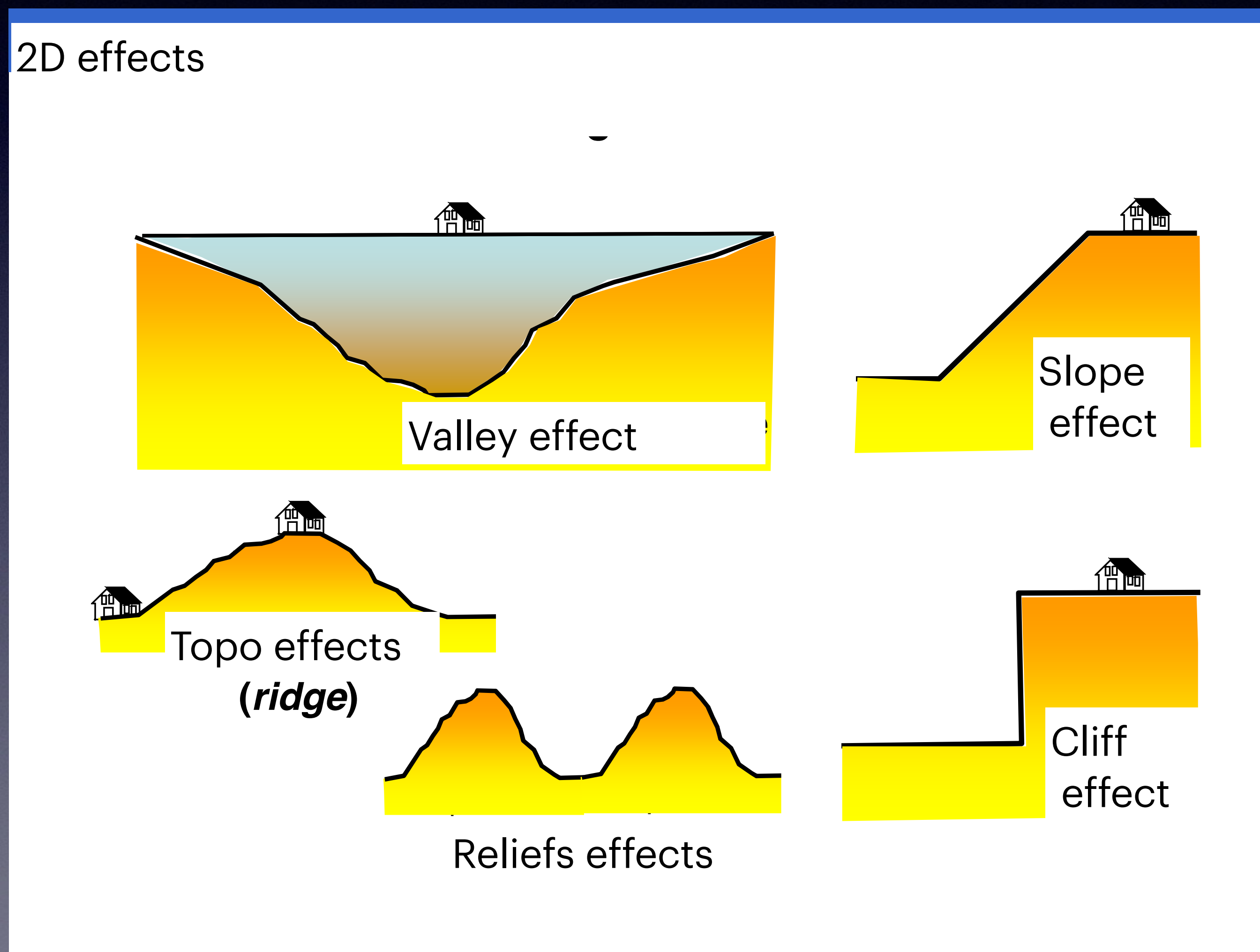
**cannot be adopted 1D simplified
assumptions...**

1D world



Local geological conditions can modify the seismic motion (local amplifications)

The 2D effects



Local geological conditions can modify the seismic motion (local amplifications)

The 'valley' 2D effects

2D effects

The energy waves can be trapped in the valley causing larger motion and bigger surface waves



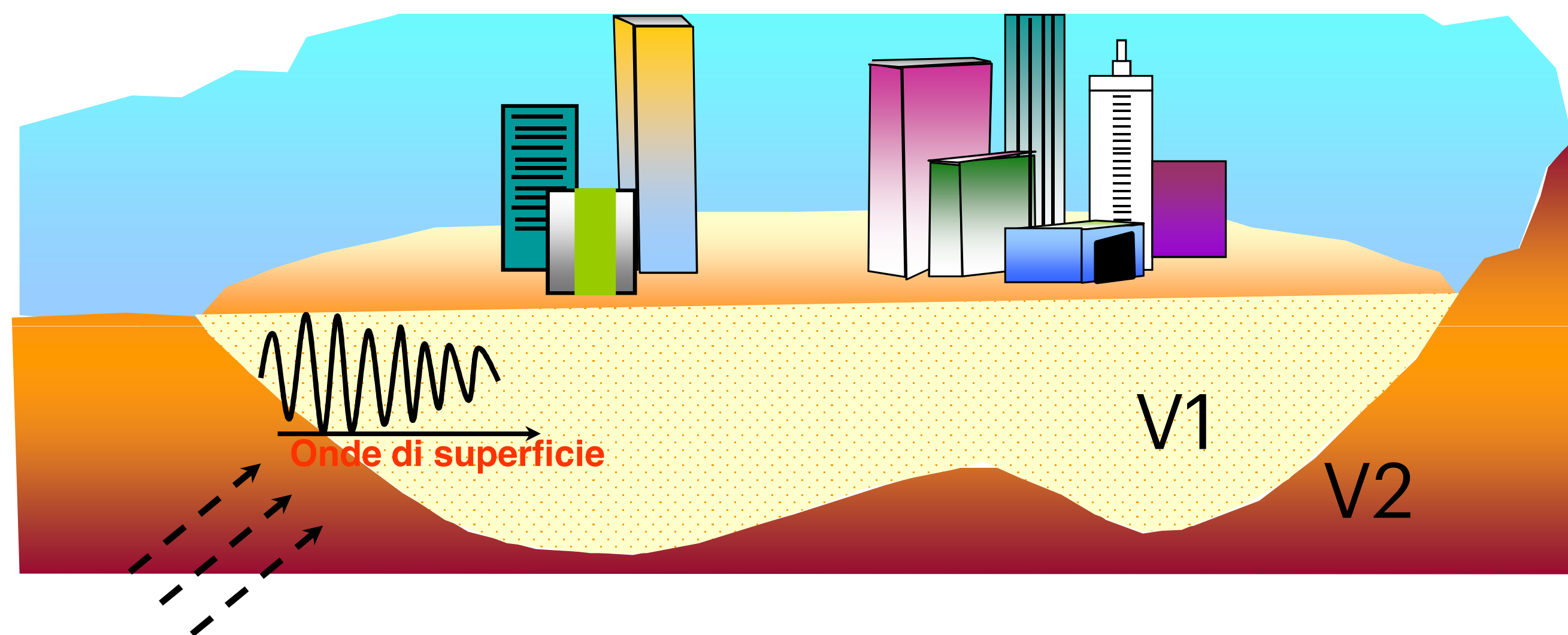
The effects depend on valley geometry and contrast between V1 and V2

Local geological conditions can modify the seismic motion (local amplifications)

The 'valley' 2D effects

2D effects

The energy waves can be trapped in the valley causing larger motion and bigger surface waves



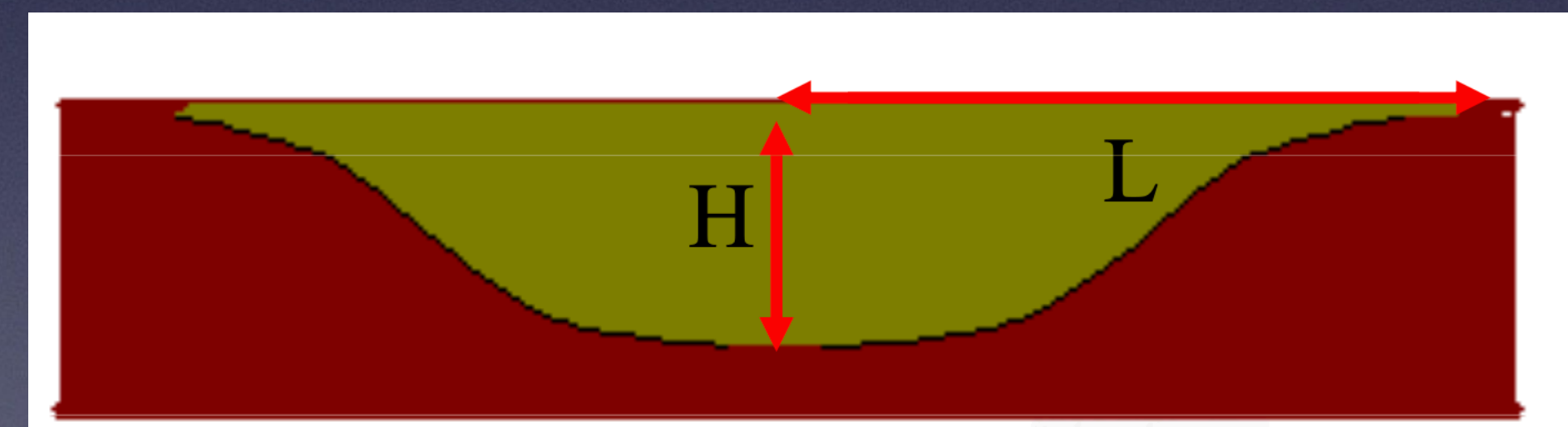
The effects depend on valley geometry and contrast between V1 and V2

SHAPE RATIO

H/L

H= thickness

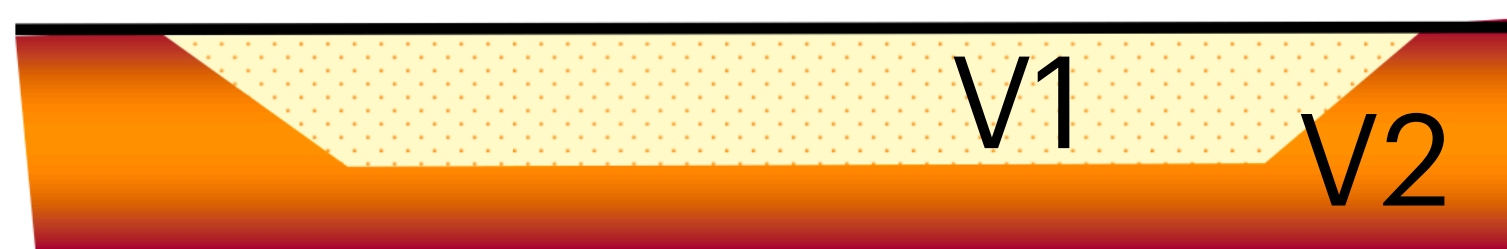
L =halfwidth



Local geological conditions can modify the seismic motion (local amplifications)

The 'valley' 2D effects

Extended valley



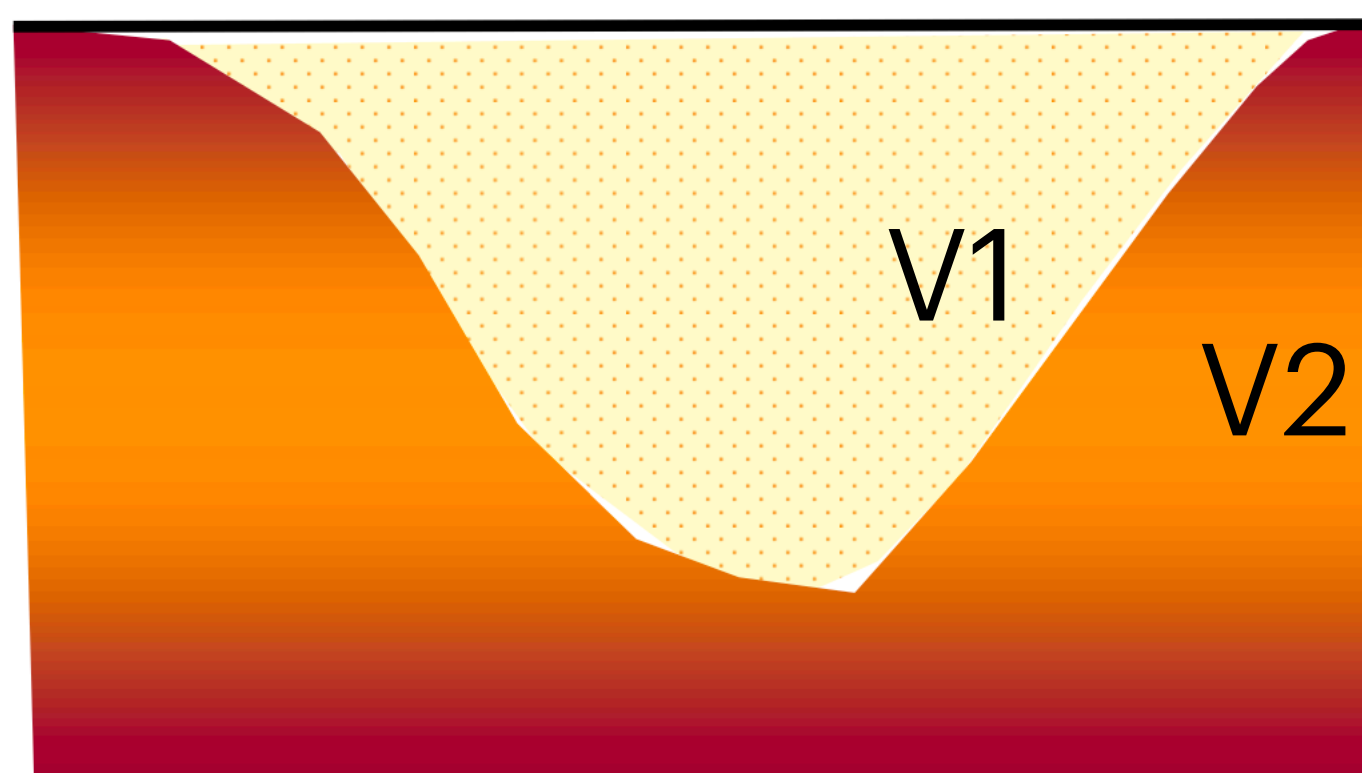
<< SHAPE RATIO

H/L

H= thickness

L =halfwidth

Deep valley



>> SHAPE RATIO

H/L

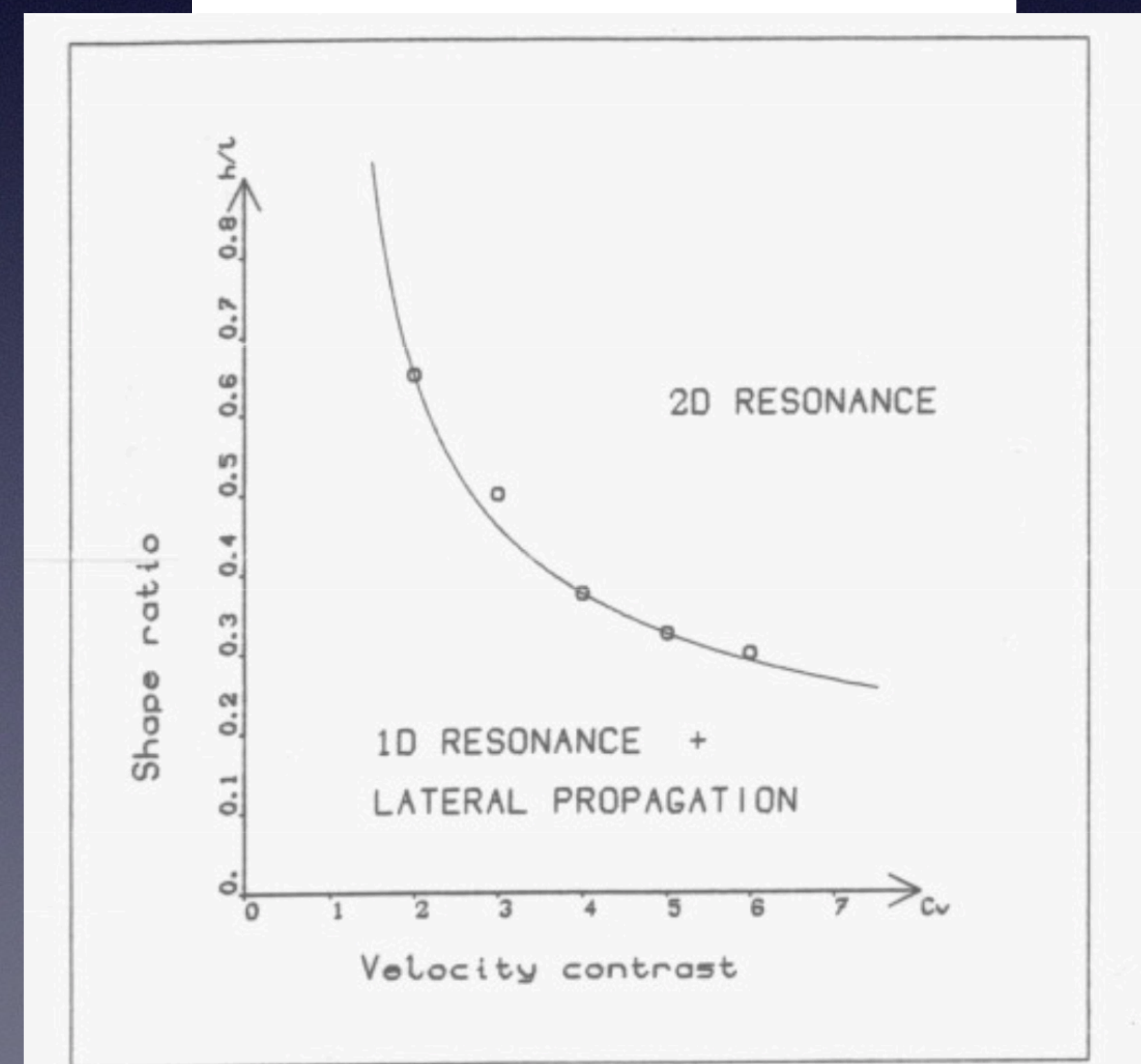
H= thickness

L =halfwidth

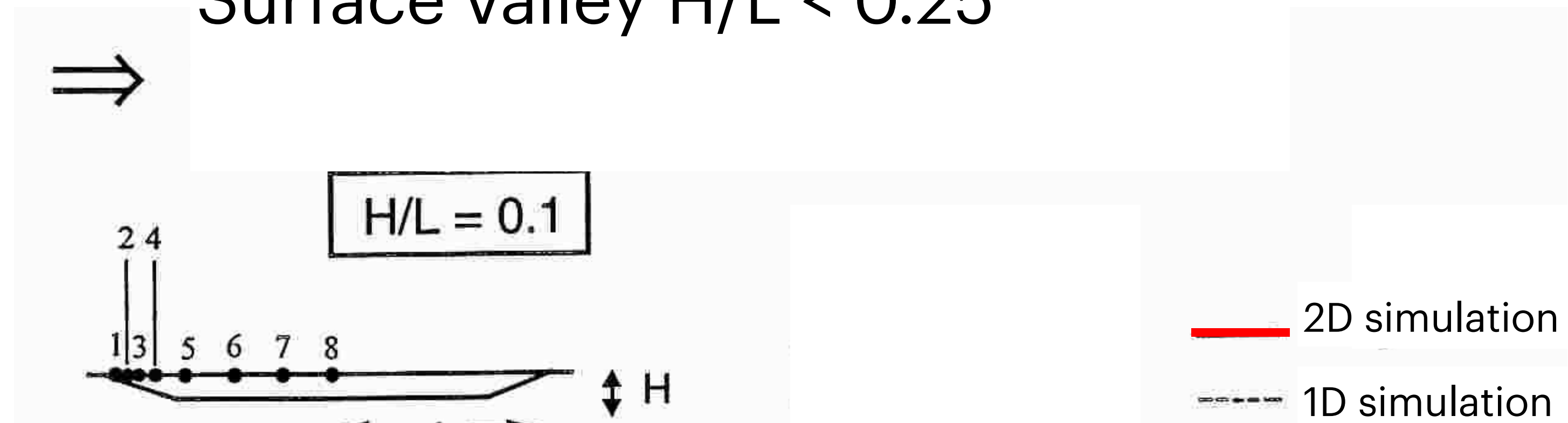
>> shape ratio

>> velocity contrast

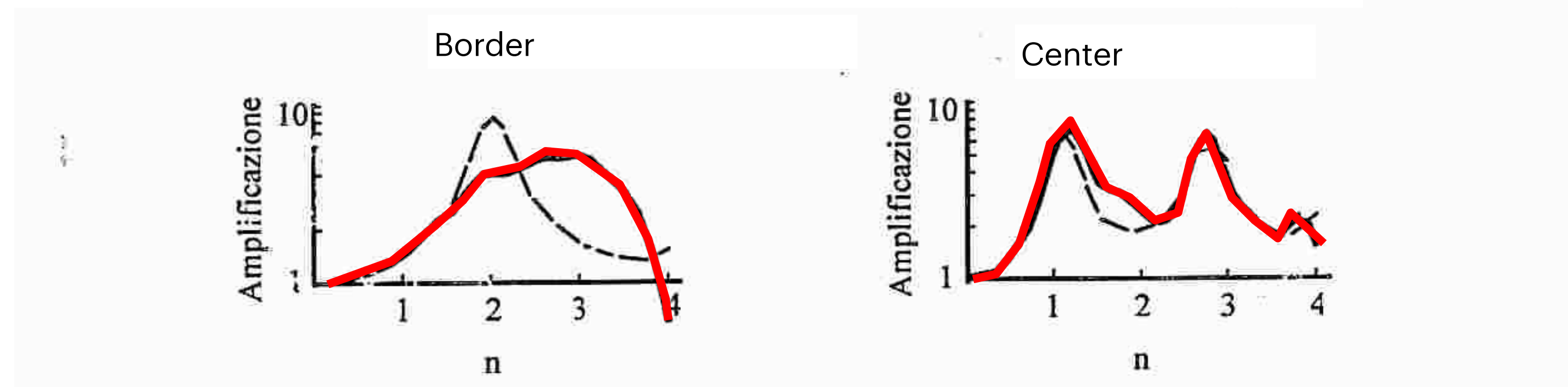
= greater amplification!



Surface valley $H/L < 0.25$



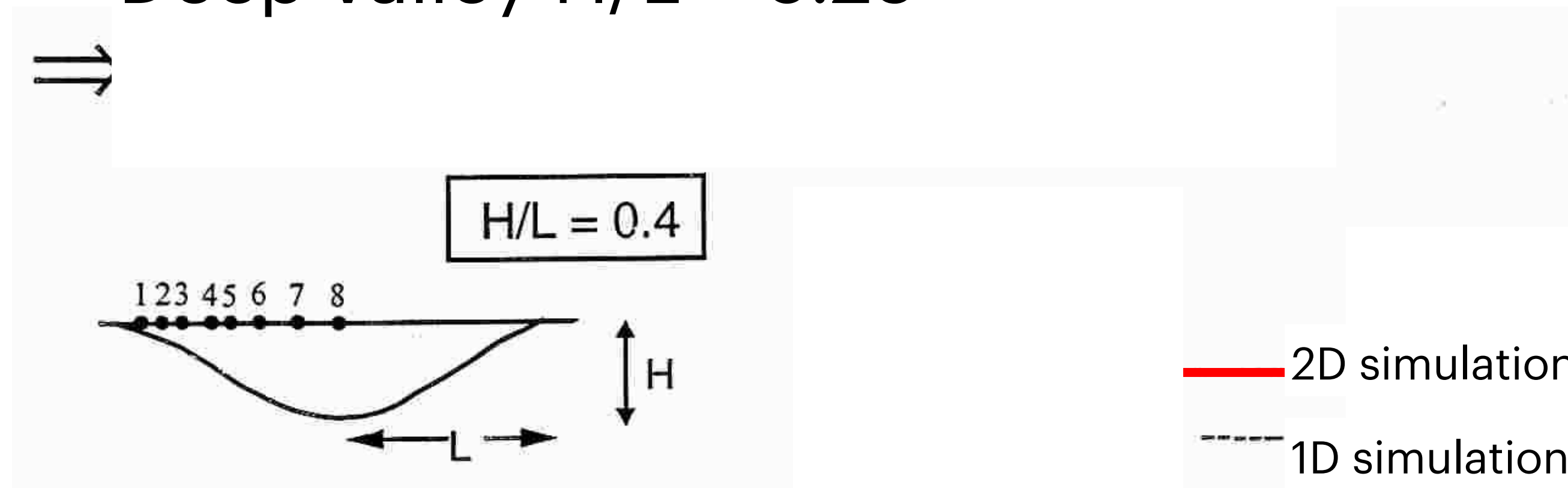
Analytic simulation



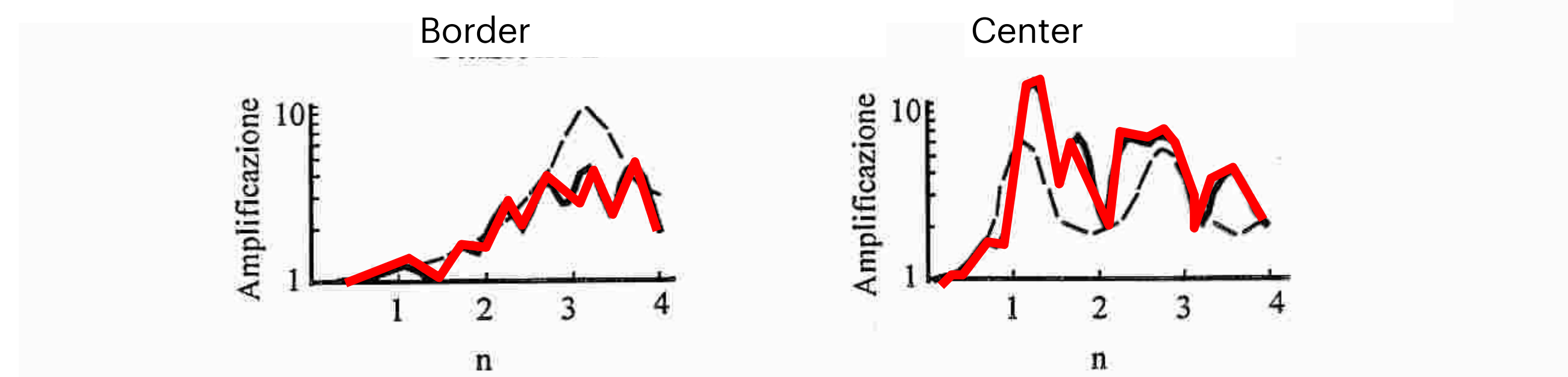
1D approx. ok for the center of the valley

(Bard & Gariel, 1986)

Deep valley $H/L > 0.25$



Analytic simulation



• 1D approximation not usable

⊖
(Bard & Gariel, 1986)

The Seismic MICROZONATION

3 LEVELS

(Italian, EU NORMS, etc.)

L1 = The seismic microzonation

(qualitative level, for city and territory planning)

L2 = semi-quantitative zoning

(adopting tables literature values, for territory planning)

L3 = quantitative Seismic Response Analysis

(for constructions design and hazard plan)

The Seismic MICROZONATION

Identify the zones capable of seismic amplification due to:

-lithological characteristics

-morphological characteristics

+

-identify possible induced effects (e.g. landslide, collapse,
liquefaction, etc.)

The Seismic MICROZONATION

Level I = Urban Planning level, mandatory for all the municipalities,
Defining zones homogenous from the geological/geomorphological points of view

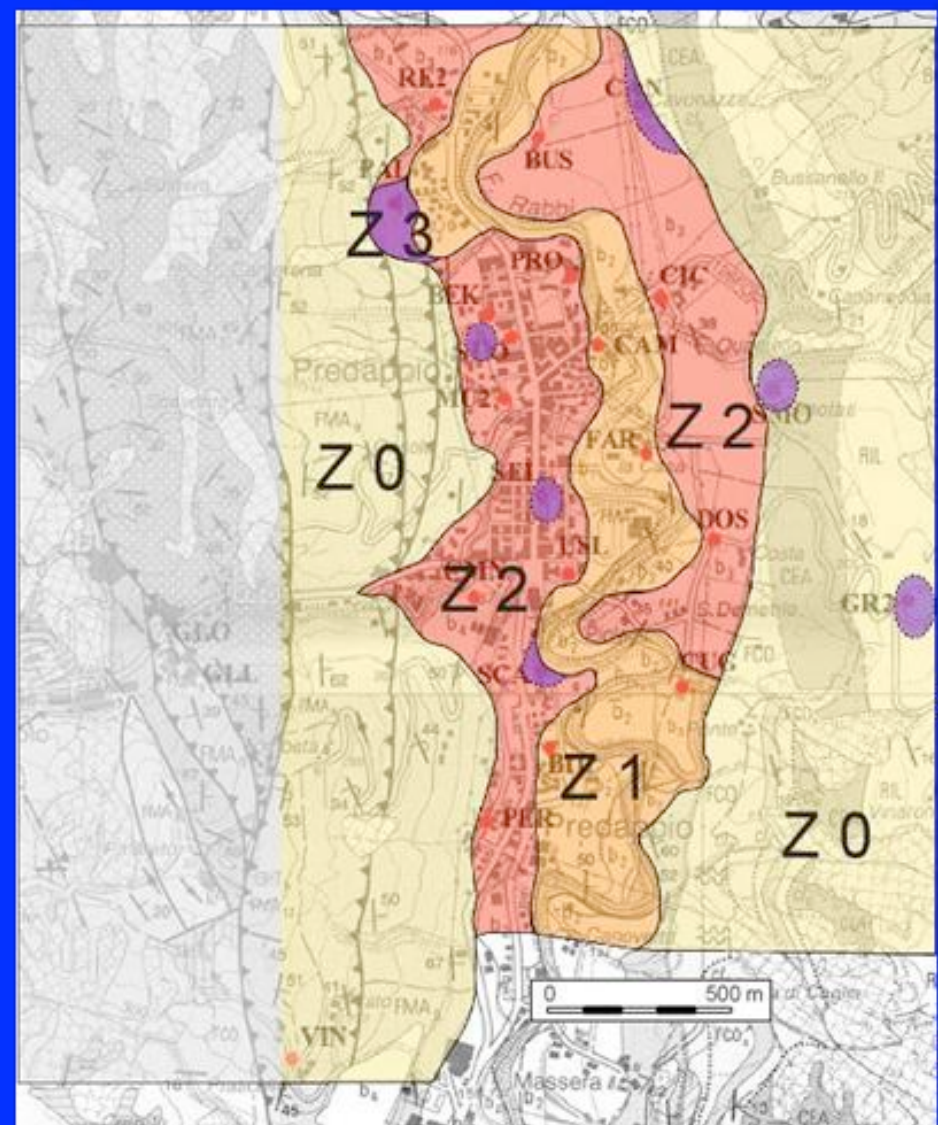
(Italian) Norms:

- define zones susceptible of amplification
- define zones potentially not stable (landslide, collapse, etc.)

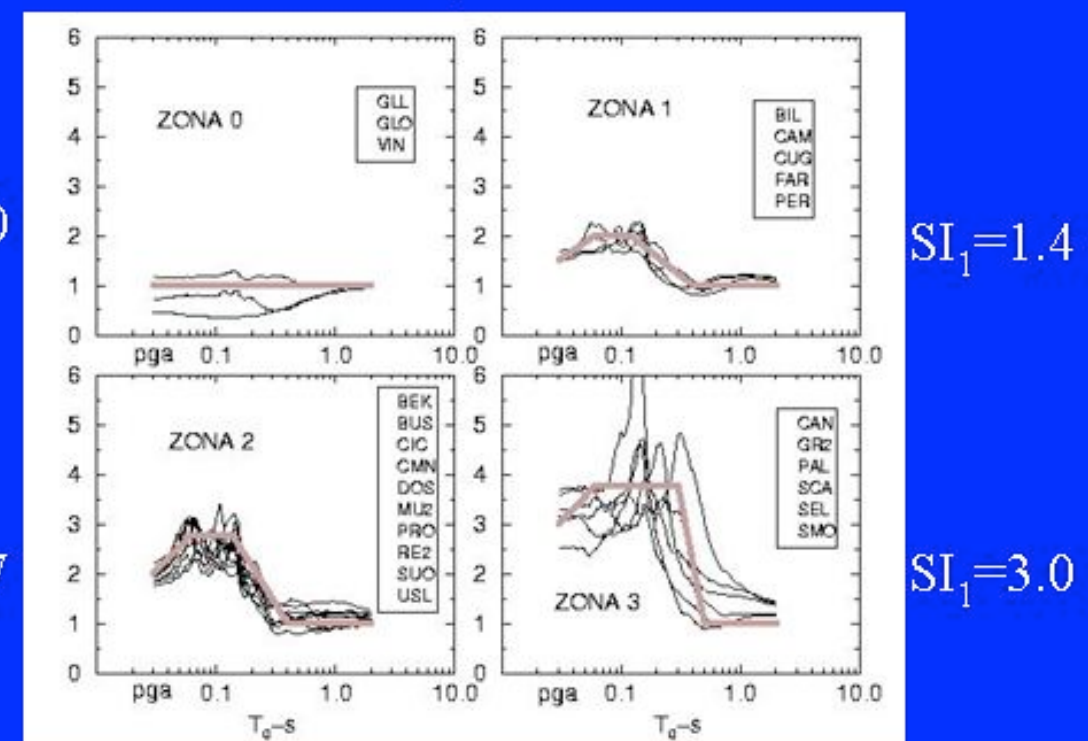
'MOPS Microzone Omogenee in Prospettiva Sismica'

The Seismic MICROZONATION

Valutazione sperimentale effetti di sito



- Z.0: riferimento
- Z.1: depositi alluvionali di spessori limitati (< 6 m)
- Z.2: terrazzi alluvionali piu' antichi
- "Z.3": spessori elevati dei sedimenti, frane quiescenti, alterazioni superficiali, ...



$S_{a_zona} / S_{a_riferimento}$

Starting from a geologic map:
Identify all the zones with the same deposits

Starting from a geomorphological map:
Identify all the zones with instabilities such:
Active and quiescent landslides,
karst voids, etc.

The Seismic MICROZONATION

Attuazione dell'articolo 11 della legge 24 giugno 2009, n.77

MICROZONAZIONE SISMICA - Livello 1

Tavola 5

Carta delle microzone omogenee in prospettiva sismica

 Foglio 1/2 - Nord

 Regione Veneto

 Comune di Schio

Soggetto realizzatore:

 TECNOLOGICA srl

 Viale Comandanti Alinari d'Europa, 9/15

 45100 ROVIGO

 MI s.r.l.

 Via Giuseppe Verdi, 1

 45100 ROVIGO

 Data: 17 Dicembre 2013

Zone Stabili (Non suscettibili di amplificazione)

Zona 1: Stratificato
 Zona 2: Granulare generato (pendo < 15°)

Zone stabili suscettibili di amplificazioni locali

Zona 3: Lapideo (pendo < 15°)
 Zona 4: Substrato di origine effusiva o metamorfica
 Zona 5: Substrato (10-15 m)
 Zona 6: Lapideo stratificato (10-15 m)
 Zona 7: Lapideo (pendo > 15°)
 Zona 8: Substrato (15-20 m)
 Zona 9: Substrato (15-20 m)
 Zona 10: Substrato (40-50 m)
 Zona 11: Substrato (20-30 m)
 Zona 12: Substrato (40-50 m)
 Zona 13: Alta frequenza di risonanza (50-200 m)
 Zona 14: Bassa frequenza di risonanza (>200 m)

Zone suscettibili di instabilità

Instabilità di versante: Attiva
 Instabilità di versante: Quiescente
 Instabilità di versante: Inattiva
 Instabilità di versante: Non definita
 Liquefazione
 Aree interessate da deformazioni dovute a faglie attive e capaci
 Cedimenti differenziali
 Sovrapposizione di zone suscettibili di instabilità differenti

Forme di superficie e sepolte

Conoide alluvionale
 Falda detritica
 Area con cavità sepolte/sinkhole
 Orlo di scarpata morfologica (>20m)
 Cresta
 Valle sepolta stretta (C<0.25)
 Valle sepolta larga (C<0.25)
 Picco isolato

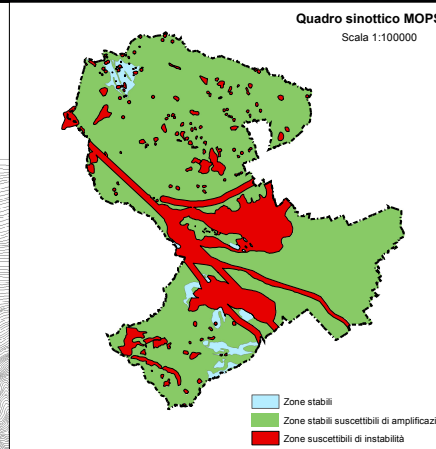
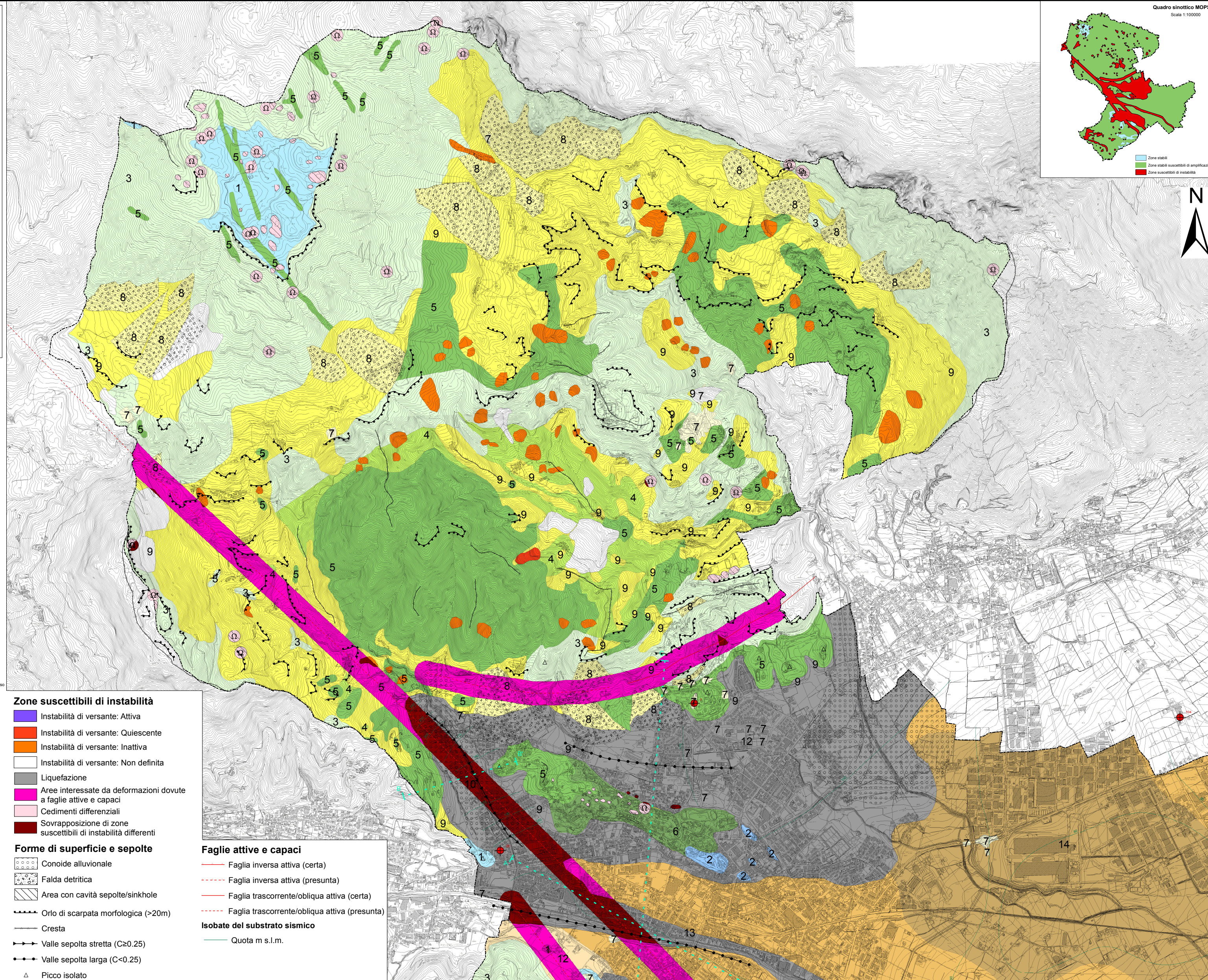
Faglie attive e capaci

Faglia inversa attiva (certa)
 Faglia inversa attiva (presunta)
 Faglia trascorrente/obliqua attiva (certa)
 Faglia trascorrente/obliqua attiva (presunta)

Isobate del substrato sismico

Quota m s.l.m.

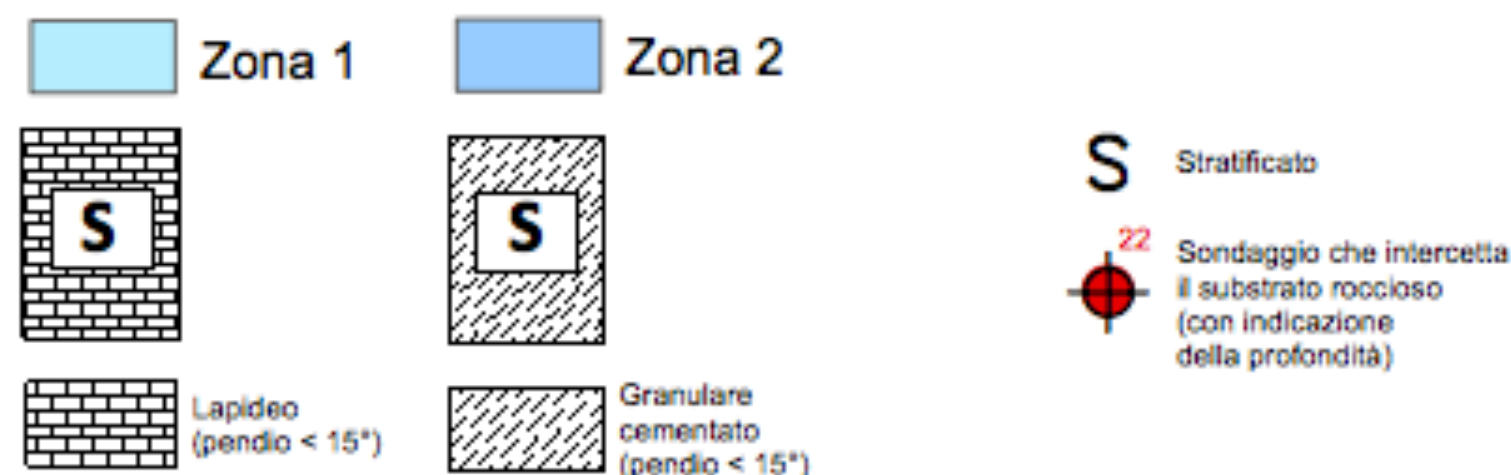
Scala 1:10000



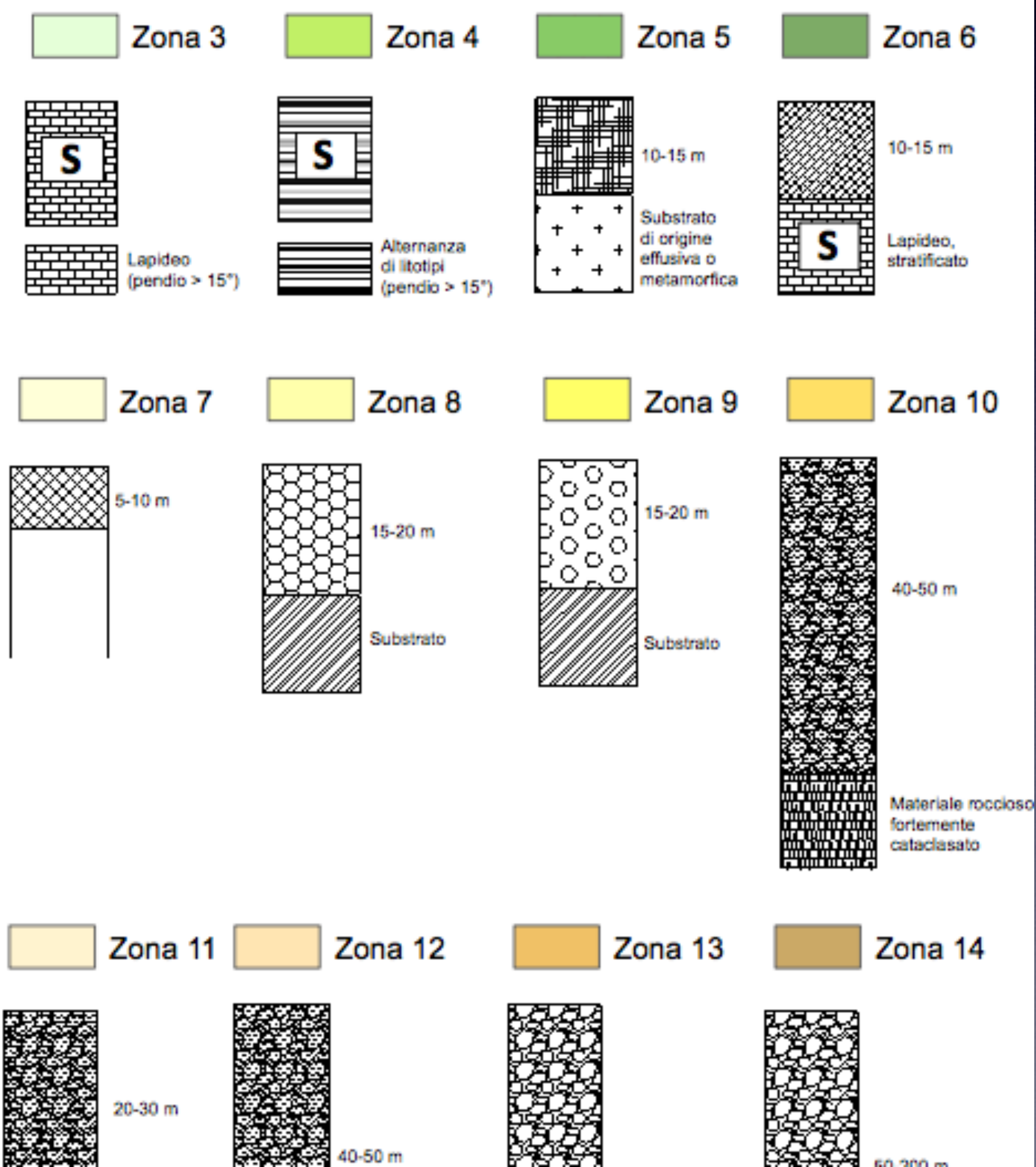
The MICROZONATION

-define zones susceptible of amplification
-define zones potentially not stable
(landslide, collapse, etc.)

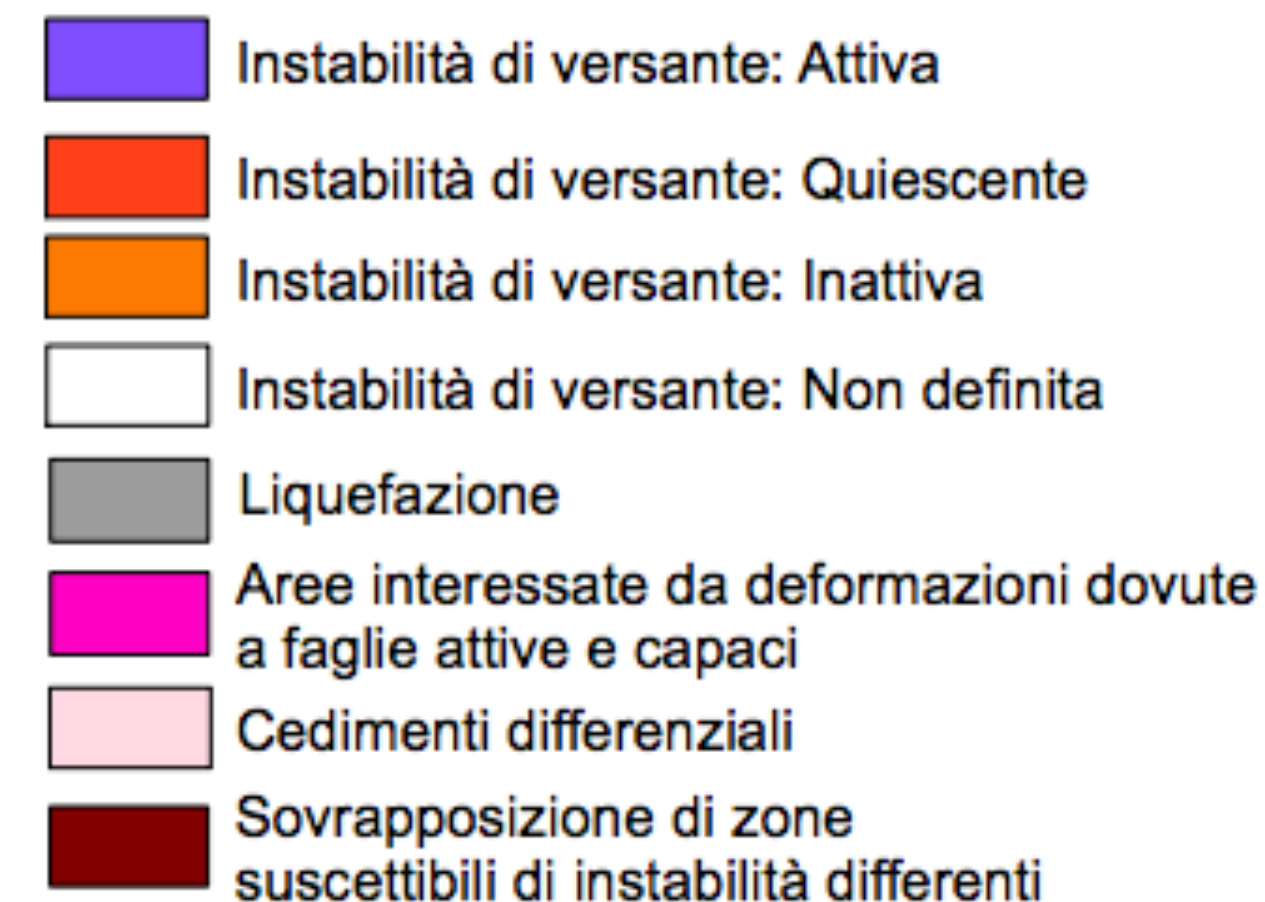
Zone Stabili (Non suscettibili di amplificazione)



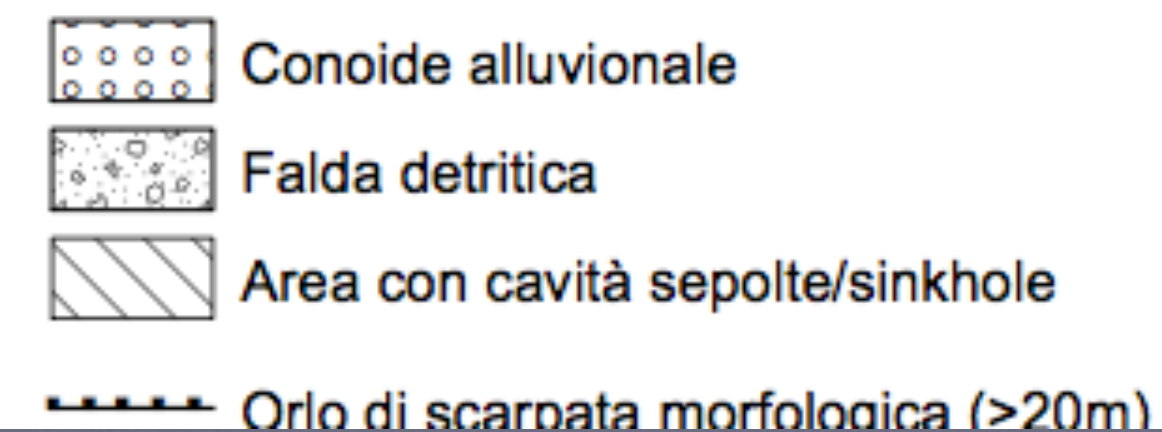
Zone stabili suscettibili di amplificazioni locali



Zone suscettibili di instabilità



Forme di superficie e sepolte



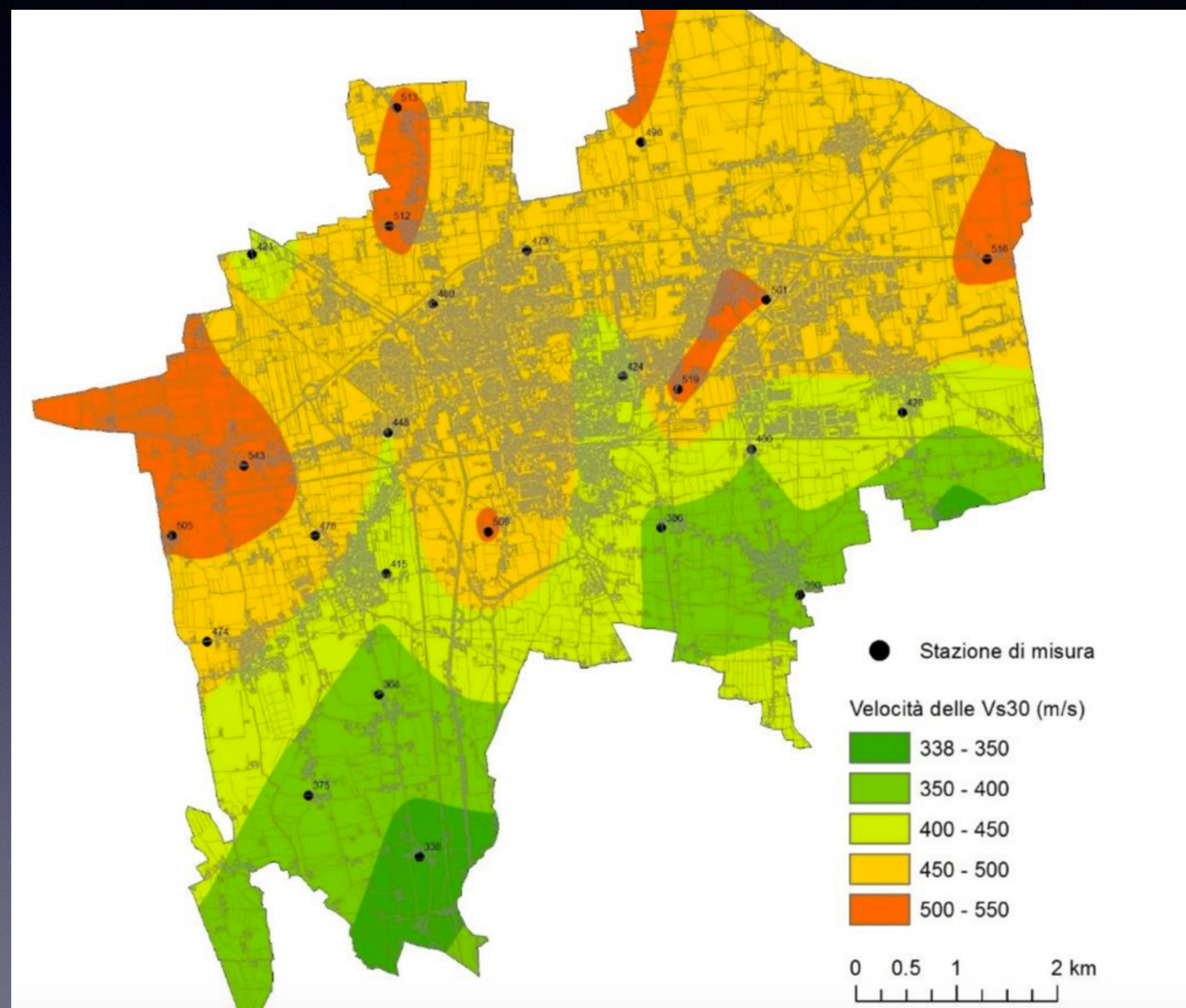
The Seismic MICROZONATION

Level 2 = Planning.

Define homogeneous zones

Basing on experimental simplified
procedures.

E.g. V_s simplified measurements, etc



The Seismic **MICROZONATION**

LEVEL 2

Using
AMPLIFICATION ABAQUS

CLAY ← Soil type

Vs30(m/s)	200	250	300
F.A. PGA	1.8	1.7	1.6
F.A. S1	1.5	1.4	1.4
F.A. S2	3.2	2.5	2.4
F.A. S3	5.3	4.3	3.7

← Vs of soil

← Amplification Factor at certain period

SAND

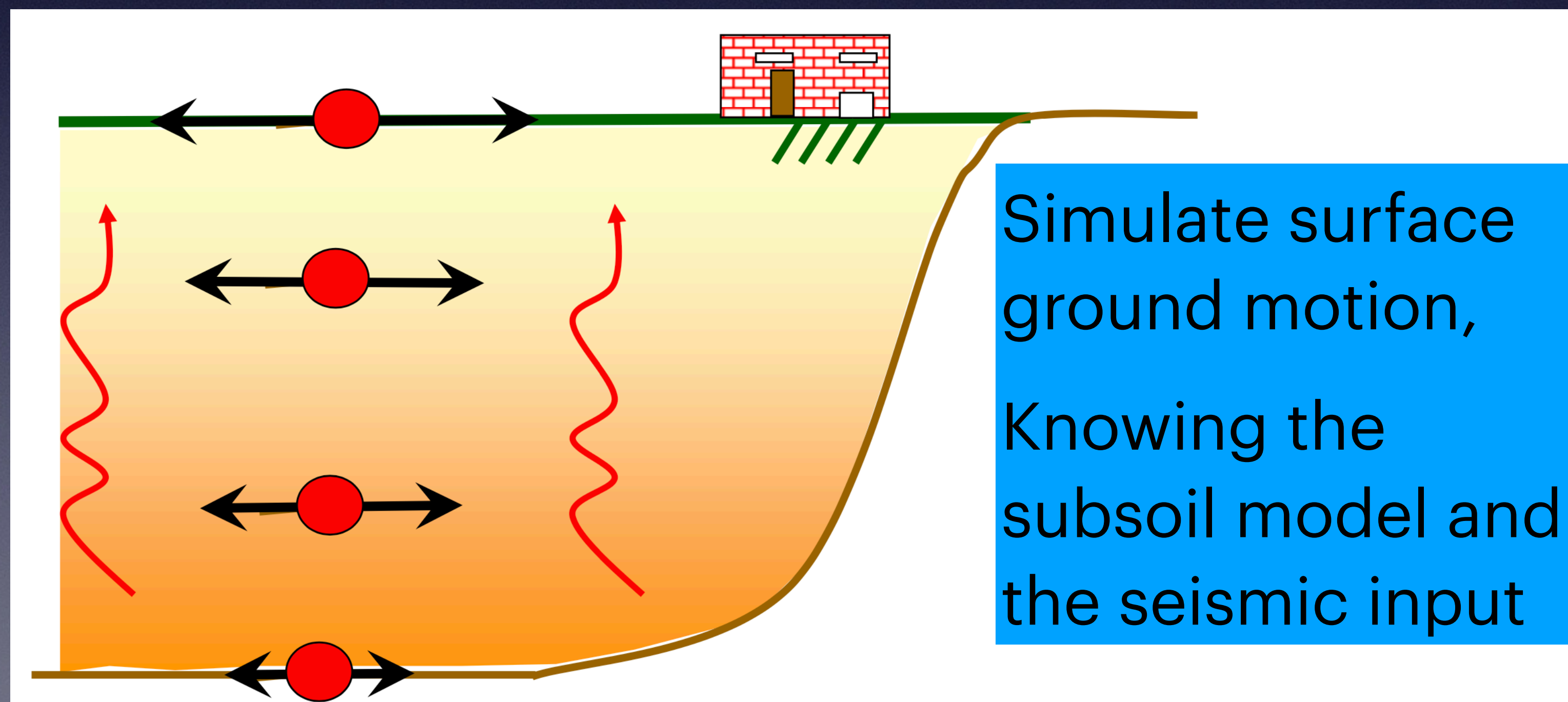
Vs30(m/s)	250	300	350
F.A. PGA	1.5	1.4	1.2
F.A. S1	1.3	1.3	1.2
F.A. S2	2.1	2.1	1.8
F.A. S3	3.8	3.8	3.1

GRAVEL

Vs30(m/s)	400	450	500	550	600
F.A. PGA	1.3	1.2	1.2	1.2	1.2
F.A. S1	1.2	1.2	1.2	1.3	1.1
F.A. S2	1.8	1.8	1.7	1.8	1.6
F.A. S3	3.1	3.1	3.1	3.1	2.8

Local geological conditions can modify the seismic motion (local amplifications)

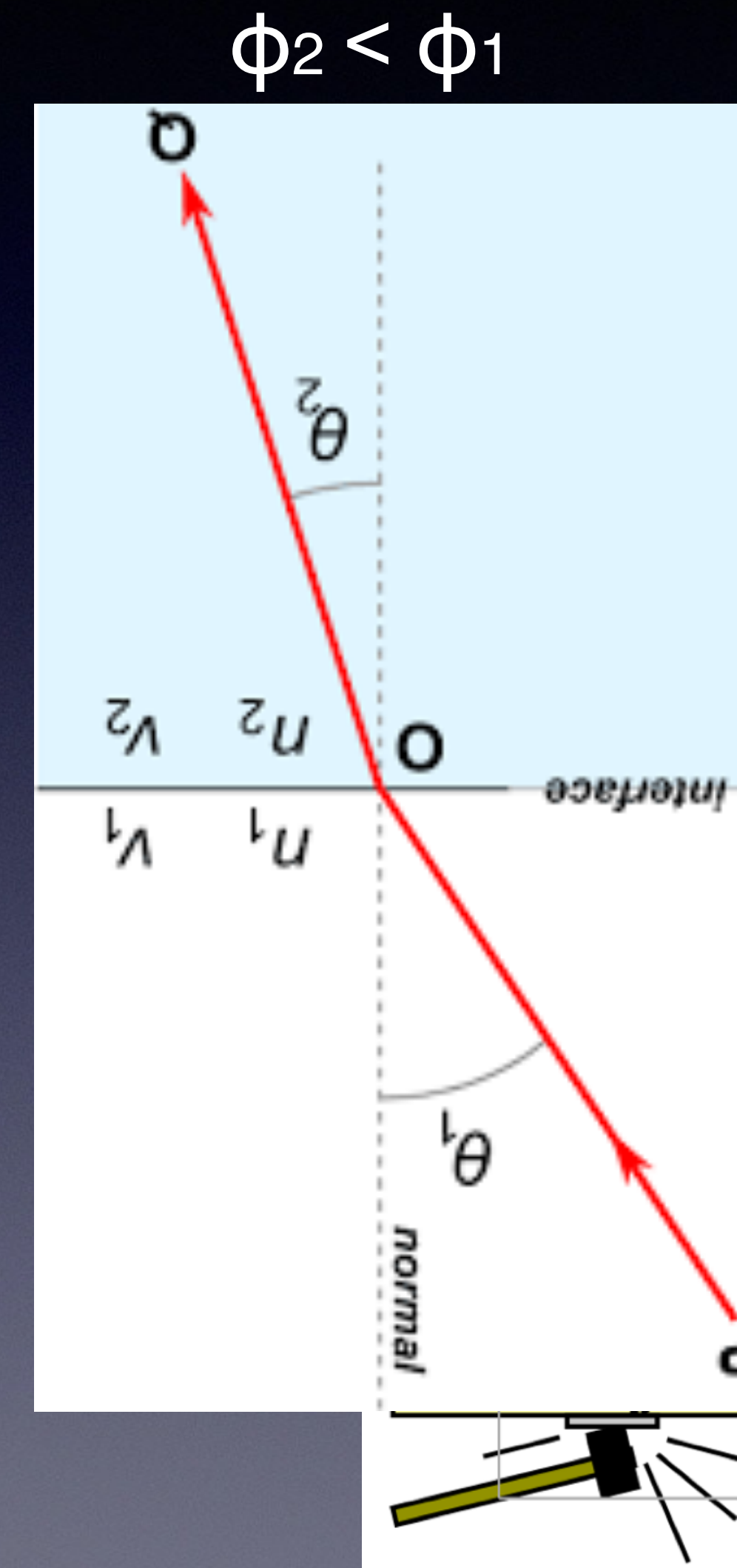
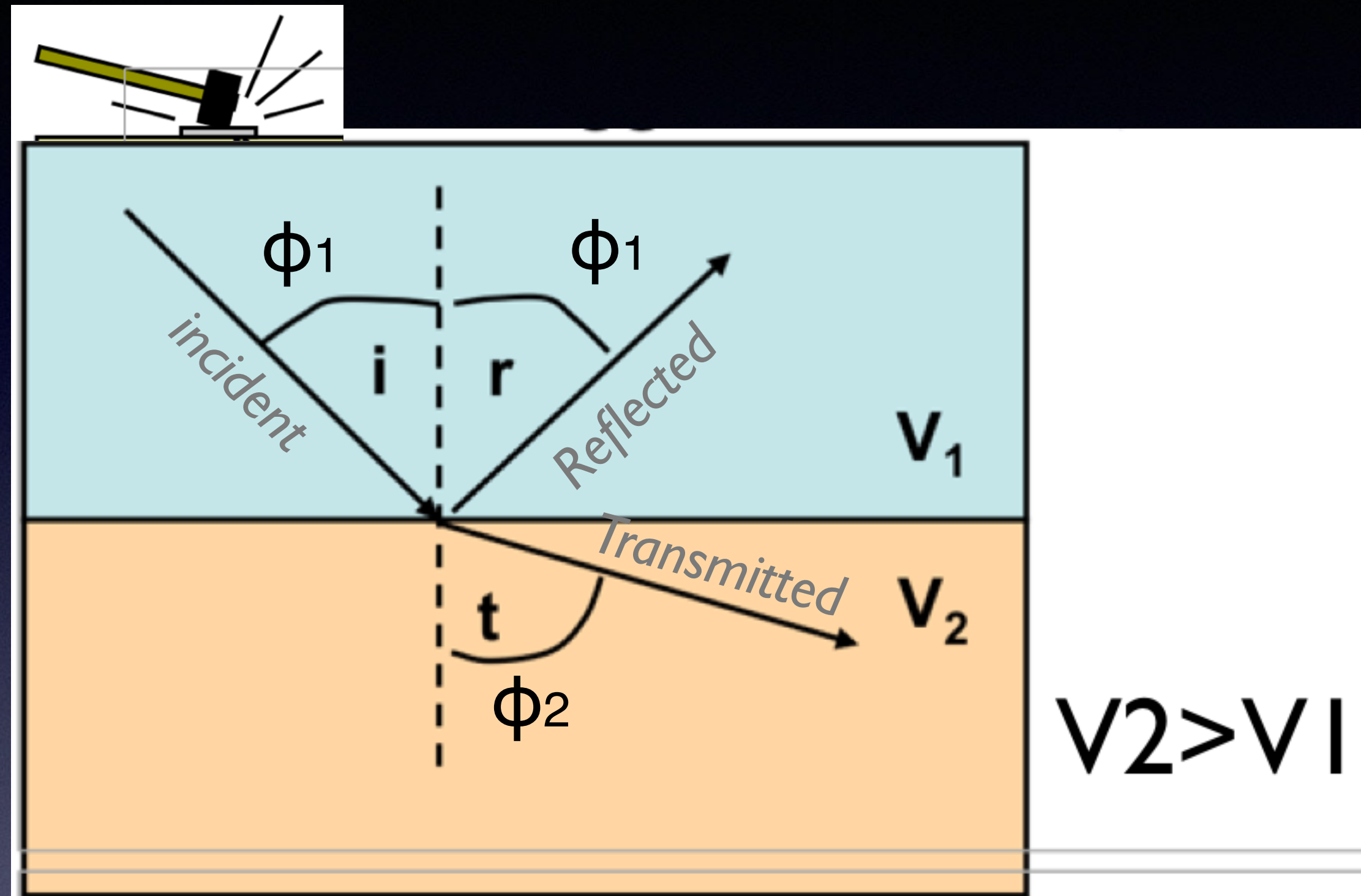
LEVEL 3 : the quantitative seismic local response
For building design and hazard planning



e.g.
the deterministic
Approach

Seismic Response Analysis

Snell Law



Impedance Contrast = $\frac{\rho_2 V_2}{\rho_1 V_1} > 1 \rightarrow t \phi_2 > i^\circ \phi_i$

density Velocity

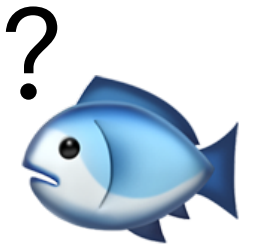
EARTHQUAKE



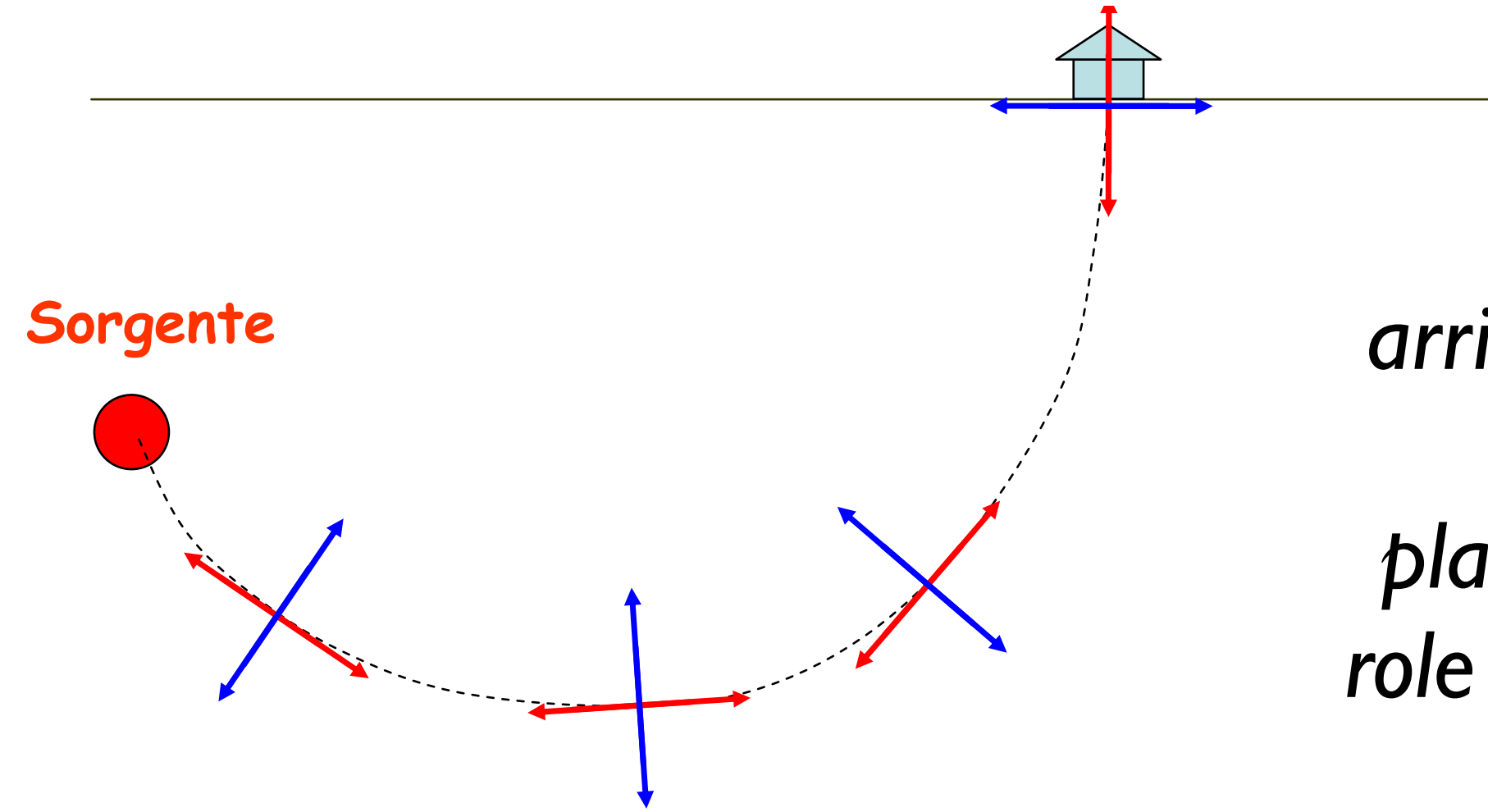
Seismic Response Analysis



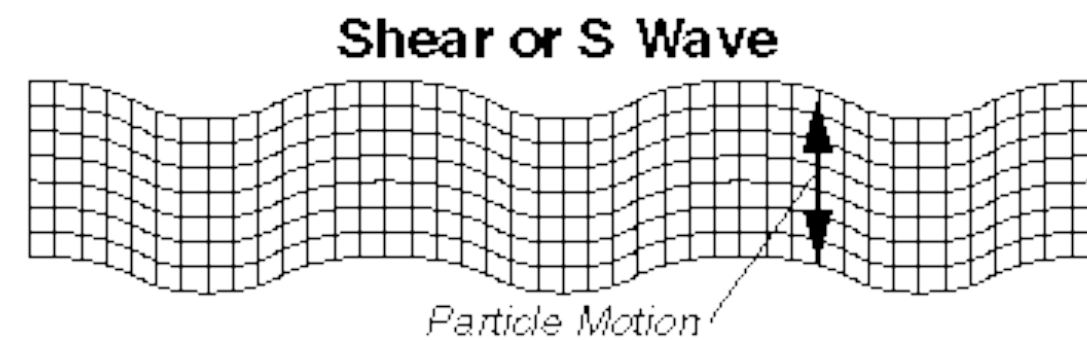
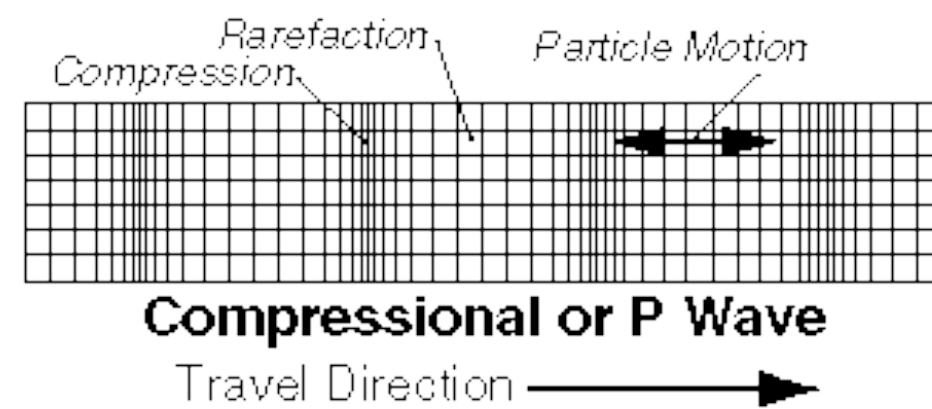
Damages are due to structures, not to earthquake...the S motion problem



Energy travel through seismic waves compressional (P) and shear waves (S)

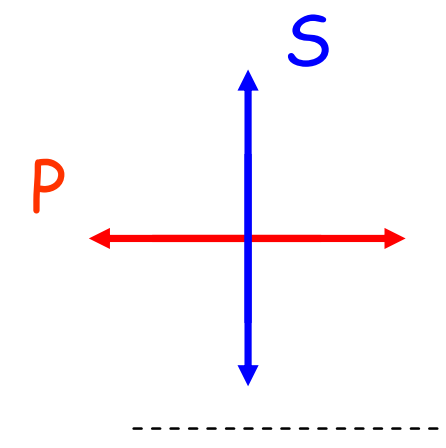


Shear waves S arrive as perpendicular to surface and play the most relevant role in building damages

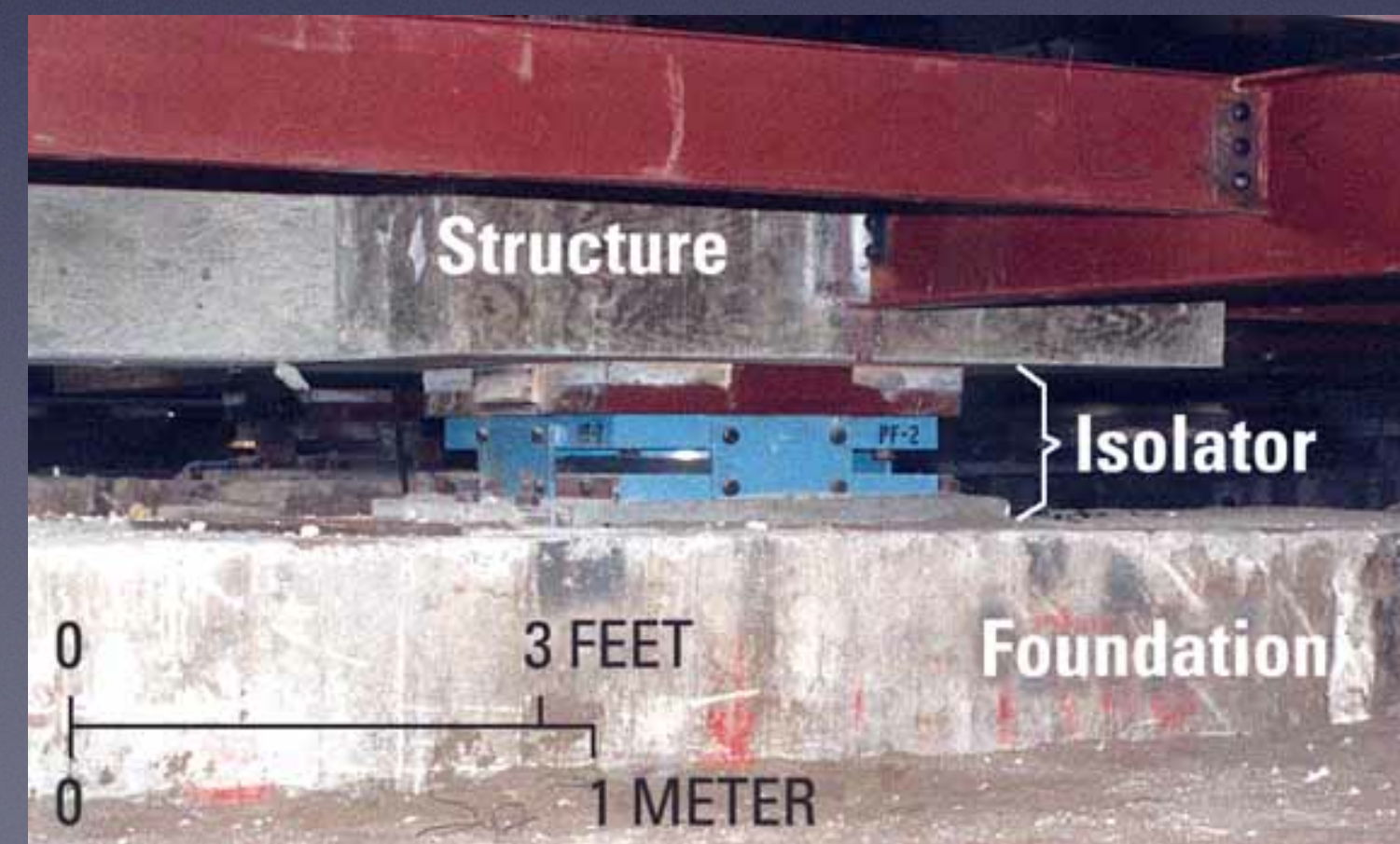


P waves
S waves

Direction of propagation



Seismic Response Analysis



Seismic Response Analysis

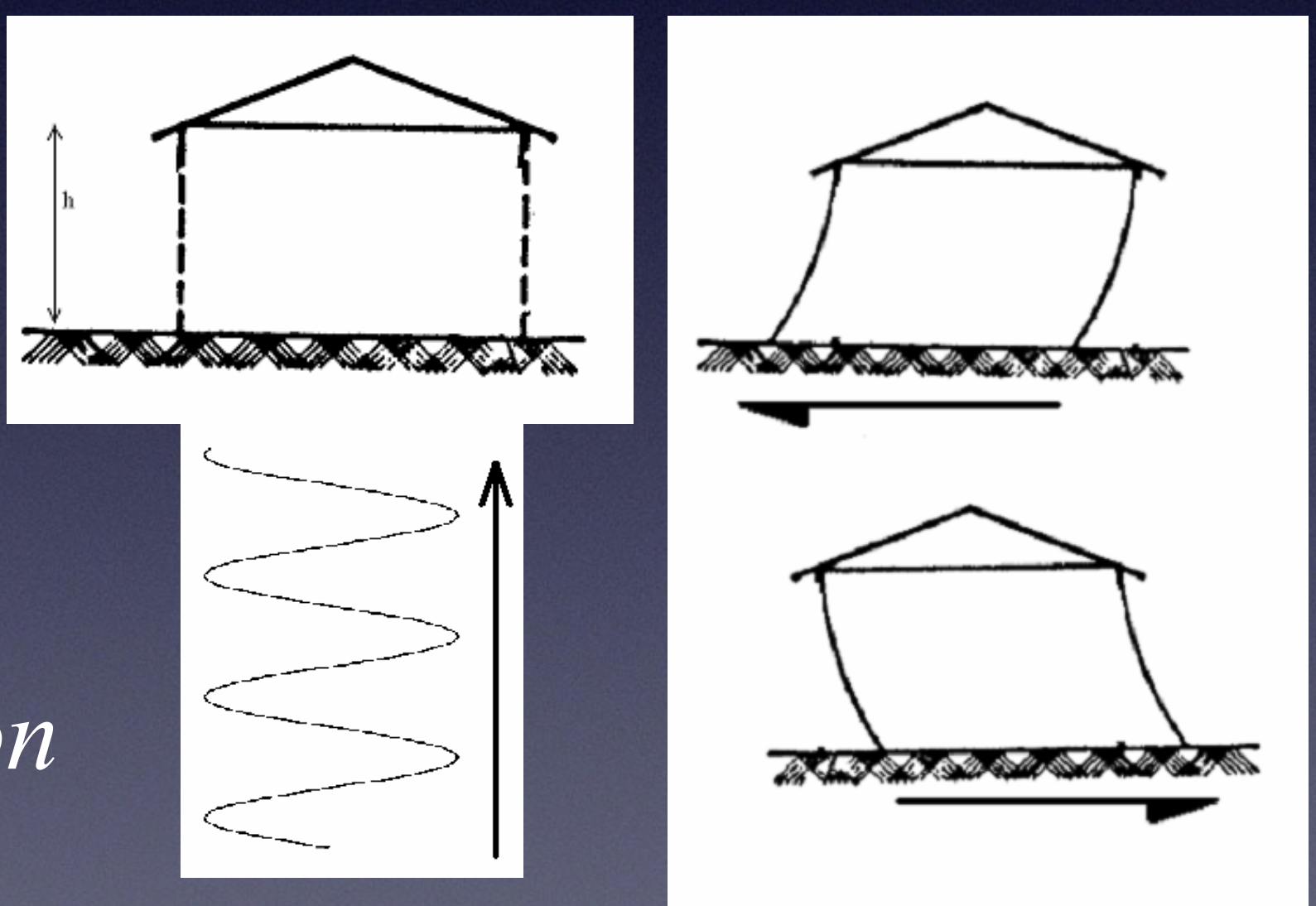
The damages is due to the relative motion between the Building parts (e.g. roof/floor)

The motion depend on the period of the structure

$n = \text{floor number}$

$$T \approx n/10$$

$T = \text{proper period of the construction}$



S waves



S waves

Alaska oil-pipes mounted on teflon slider system

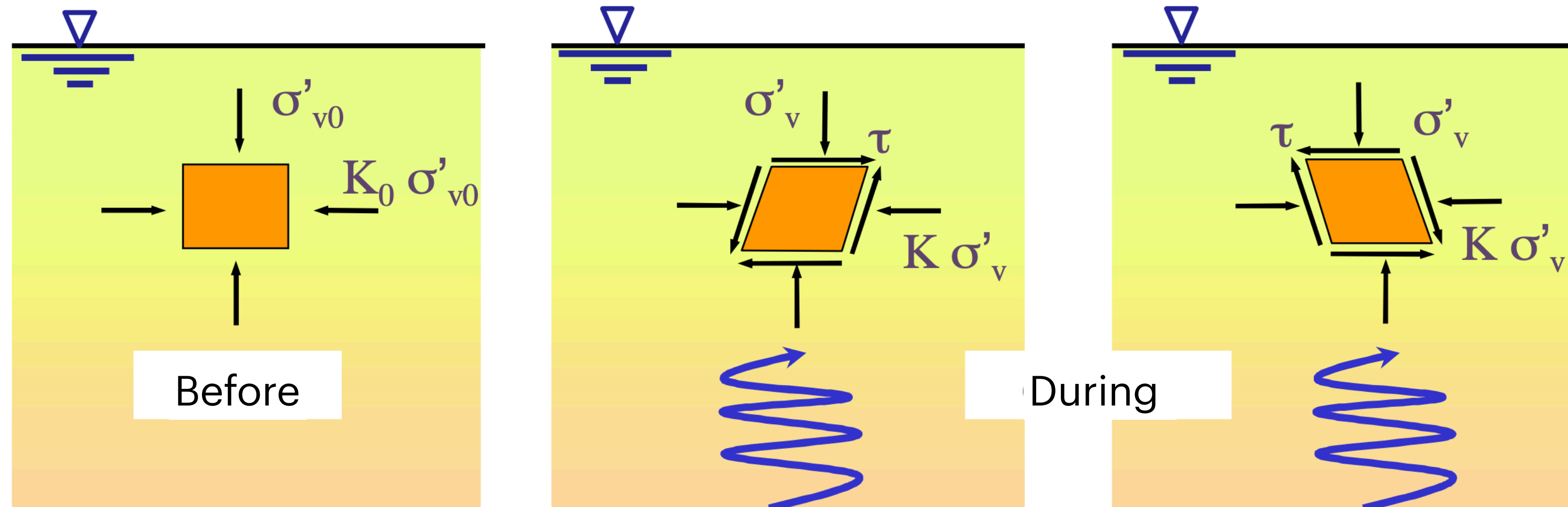


Seismic Response Analysis

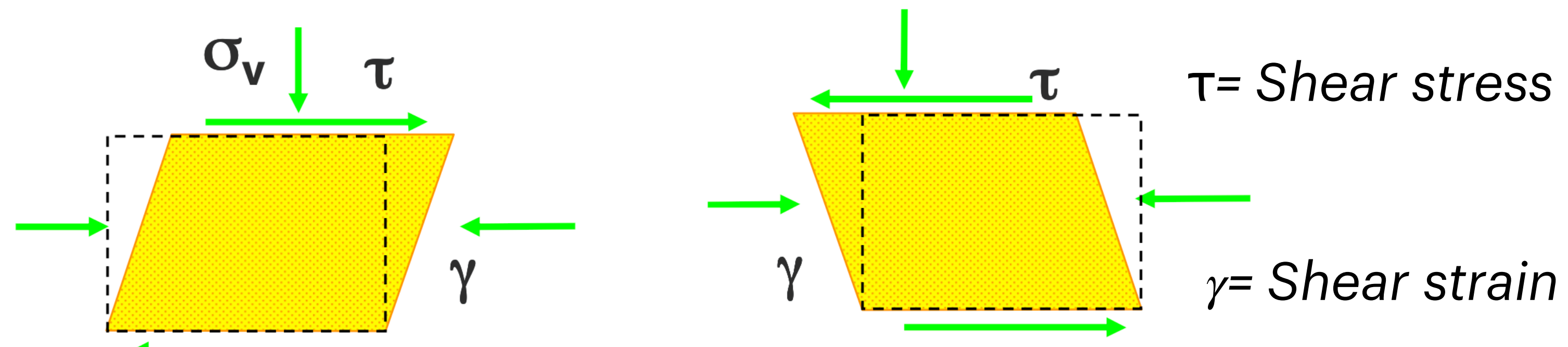
Terrain element under earthquake stress

$\sigma =$ pressure

conditions



S waves coming from the inner crust



(Undrained Conditions)

Define Soil Deformability

The seismic waves

Body waves (in geotechnics)

$$V_p = \sqrt{\frac{K + 4/3\mu}{\rho}}$$

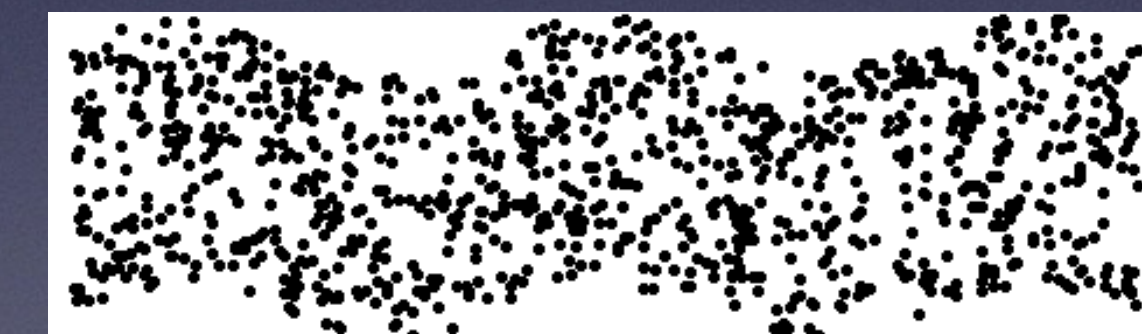
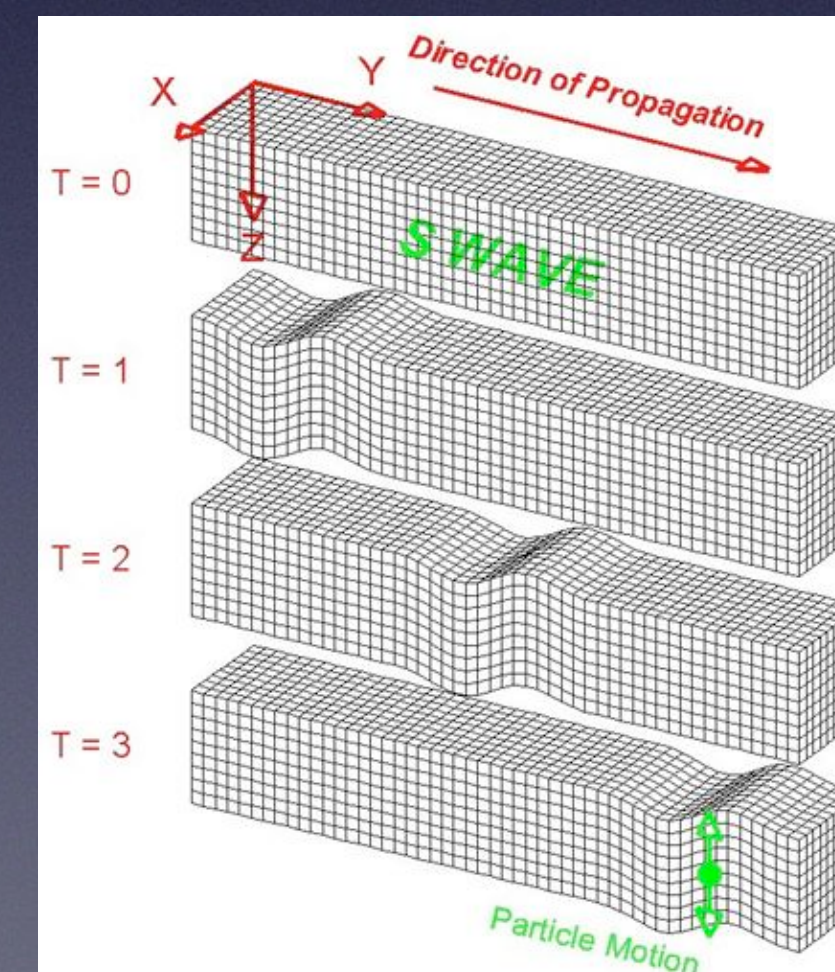
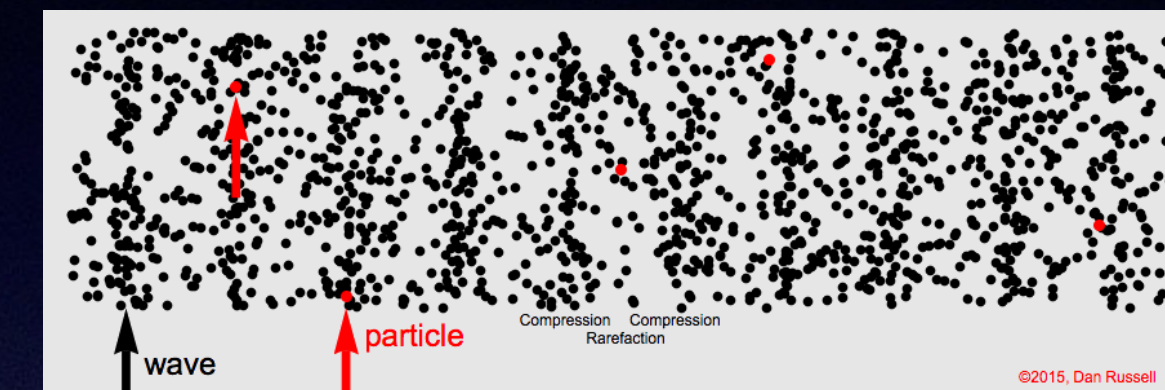
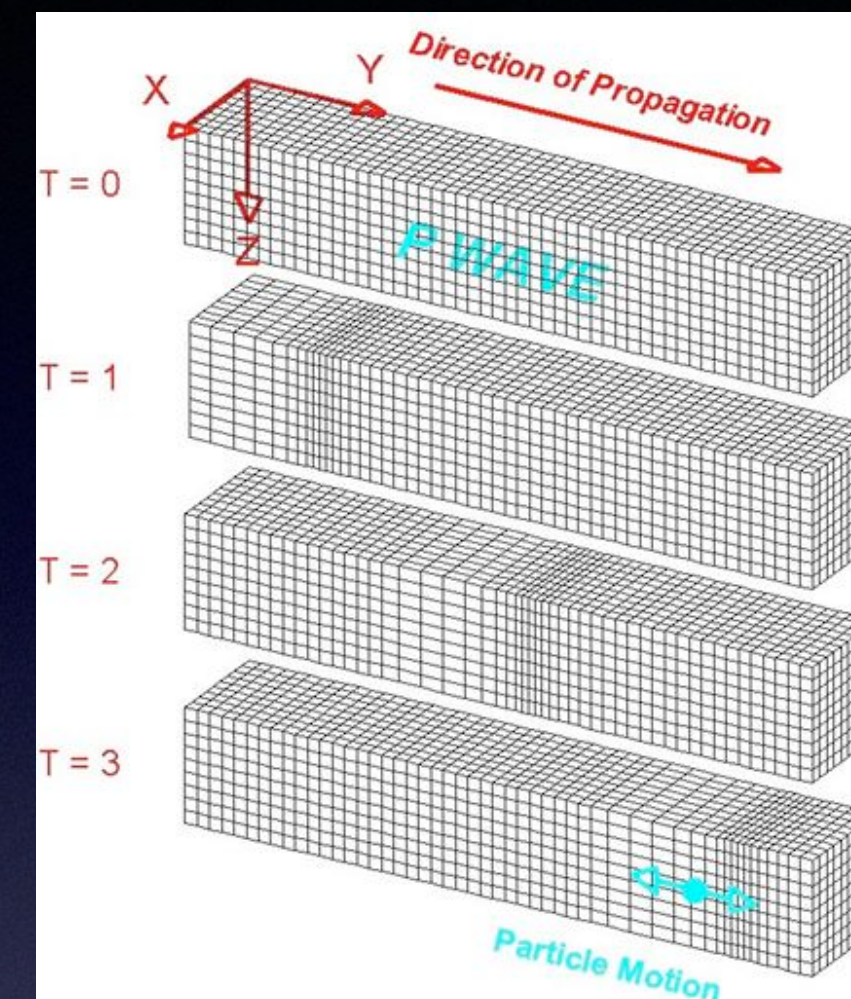
Compression modulus
(Ed in odometry)

Density

$$V_s = \sqrt{\frac{G}{\rho}}$$

Shear modulus

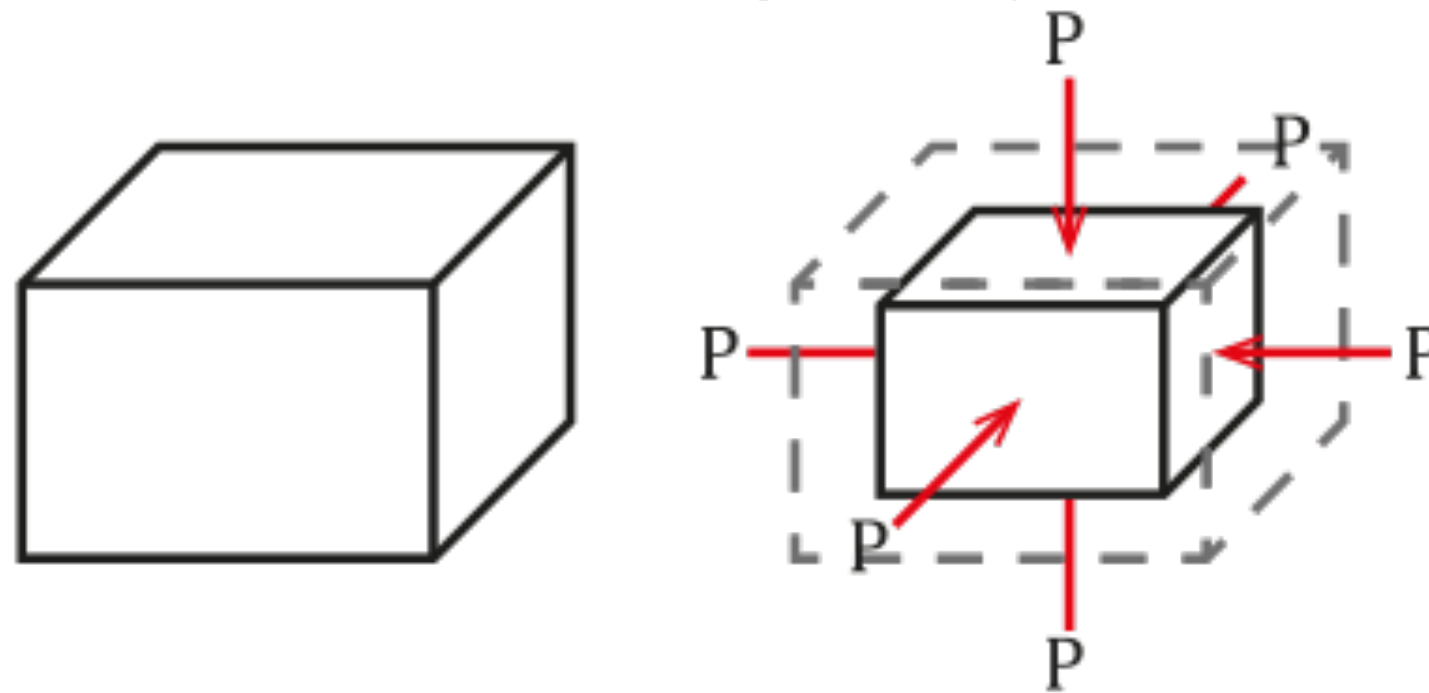
?



Body waves (in geotechnics)

K = compression modulus

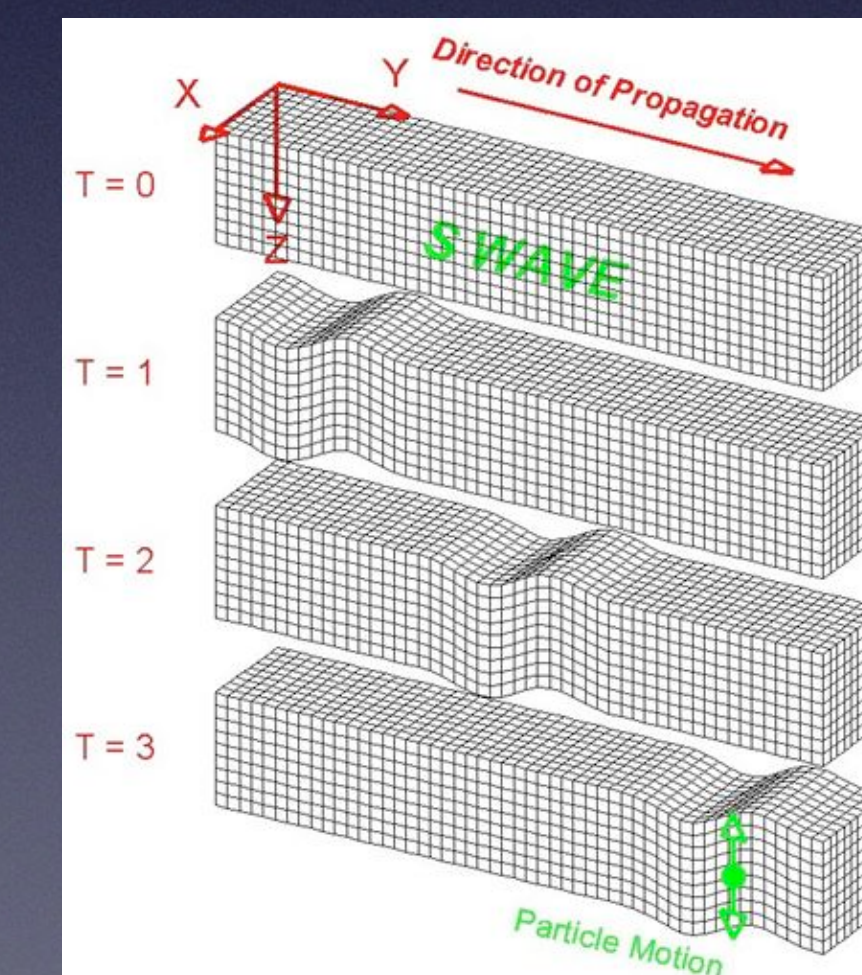
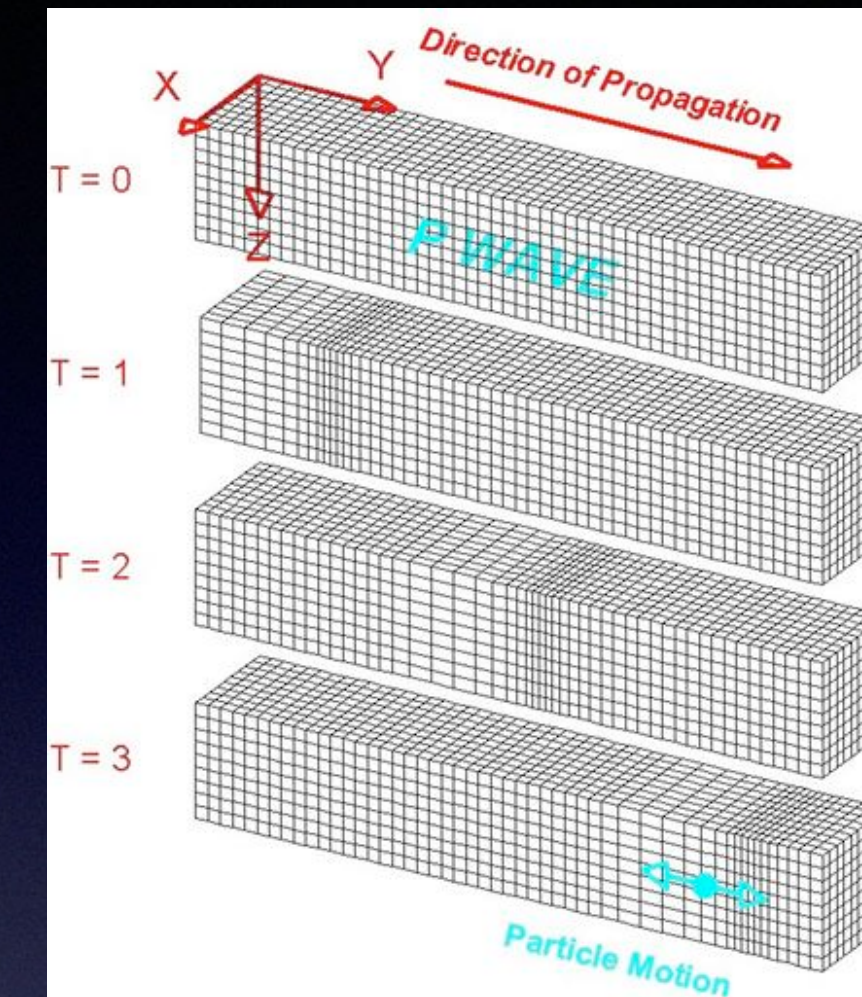
The pressure increment necessary to induce a density change



Lamè constant

Shear Modulus

$$K = \lambda + (2 G)$$



G shear Modulus

$$G = \rho V_s^2$$

Density
S waves velocity

$$G = \frac{(\rho V_p^2) (1-2\gamma)}{2(1-\gamma)}$$

P wave velocity
Poisson

$$G = \frac{E}{2(1+\gamma)}$$

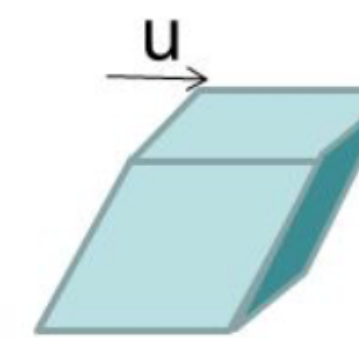
Young modulus

$$\frac{V_p}{V_s} = \sqrt{\frac{(1-\gamma)}{(0.5-\gamma)}}$$

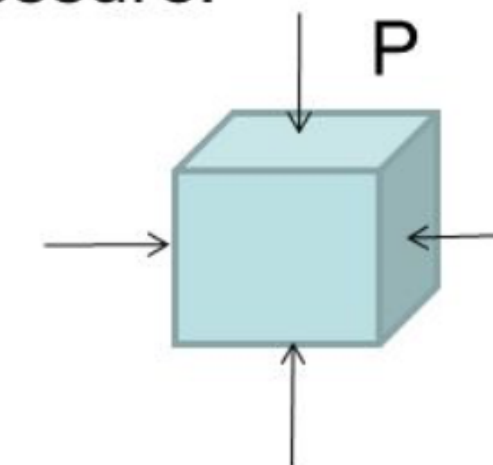
Traction:



Shear:



Hydrostatic Pressure:



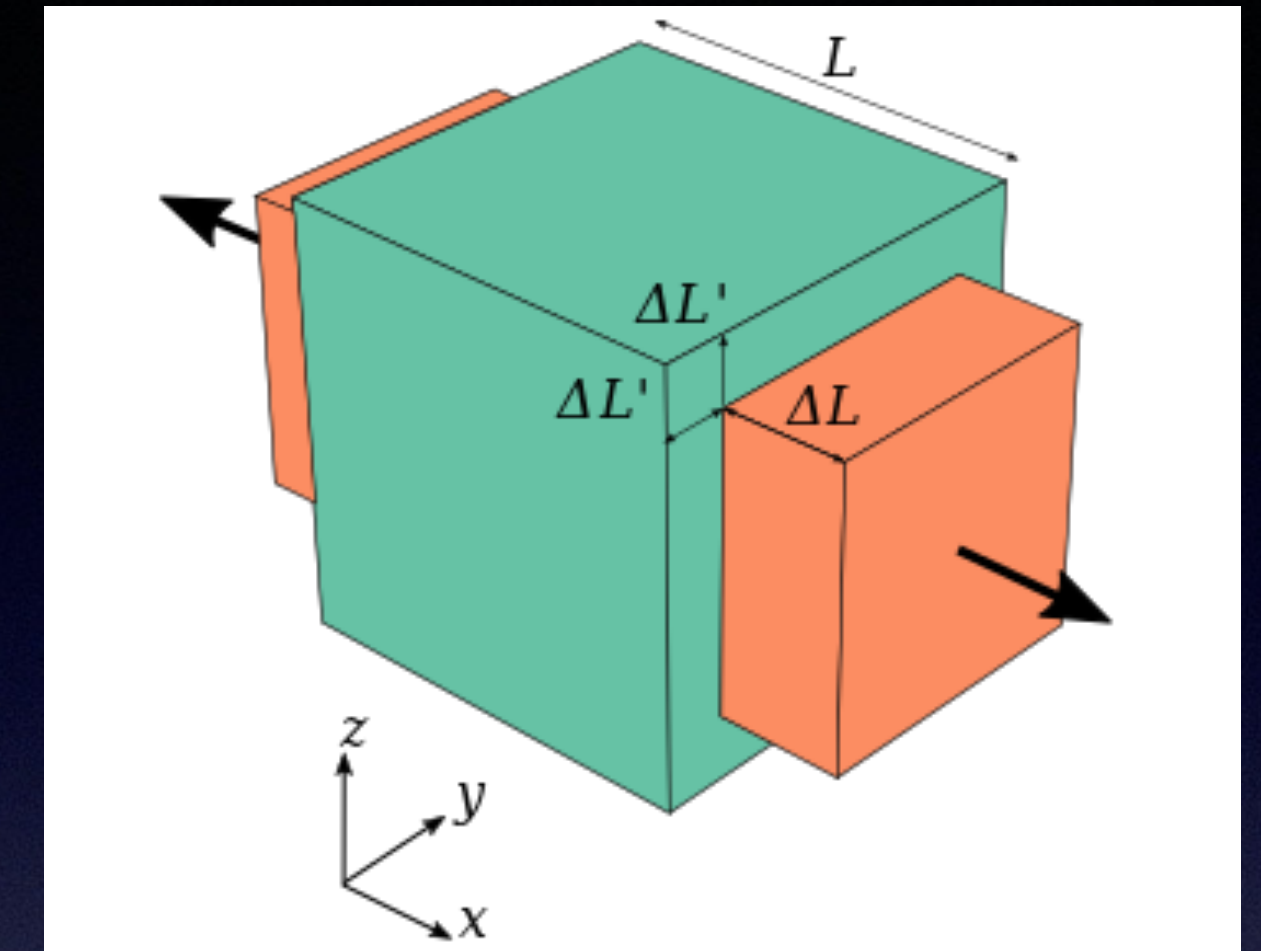
Poisson ratio γ

Ratio between the
transverse strain and
longitudinal deformation

$$\gamma < 0.5 \quad ! \quad (0.5 \text{ rubber})$$

Transverse strain

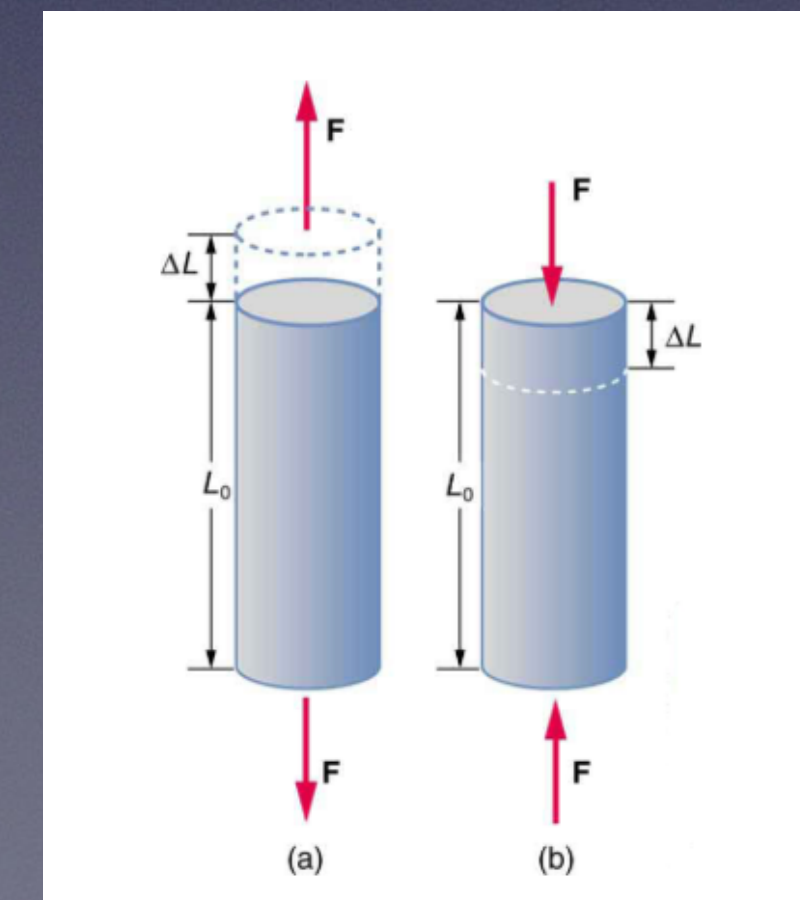
Longitudinal strain



Young modulus E

Ratio between the applied tension along
the axes and relative deformation ϵ
(e.g. spring deformation)

Applied tension σ
Deformation ϵ



Elastic waves propagating

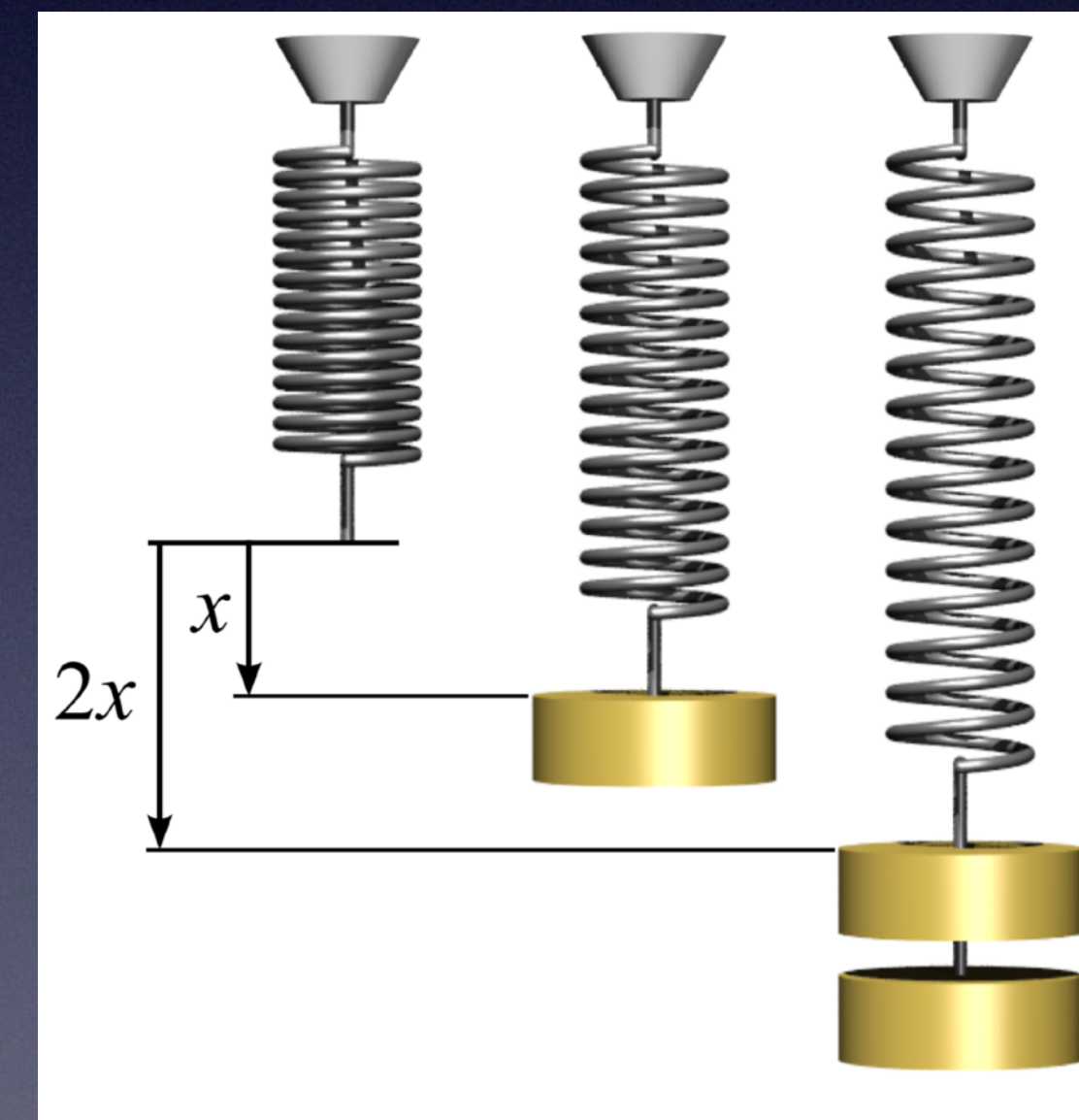
Dynamic principles - Hooke law

$$\sigma = E \varepsilon$$

Young modulus

Deformation ε

Tension



$$\sigma = K \varepsilon$$

k spring

wave motion - Wave Equation

$u, v, w =$ displacement in x, y, z

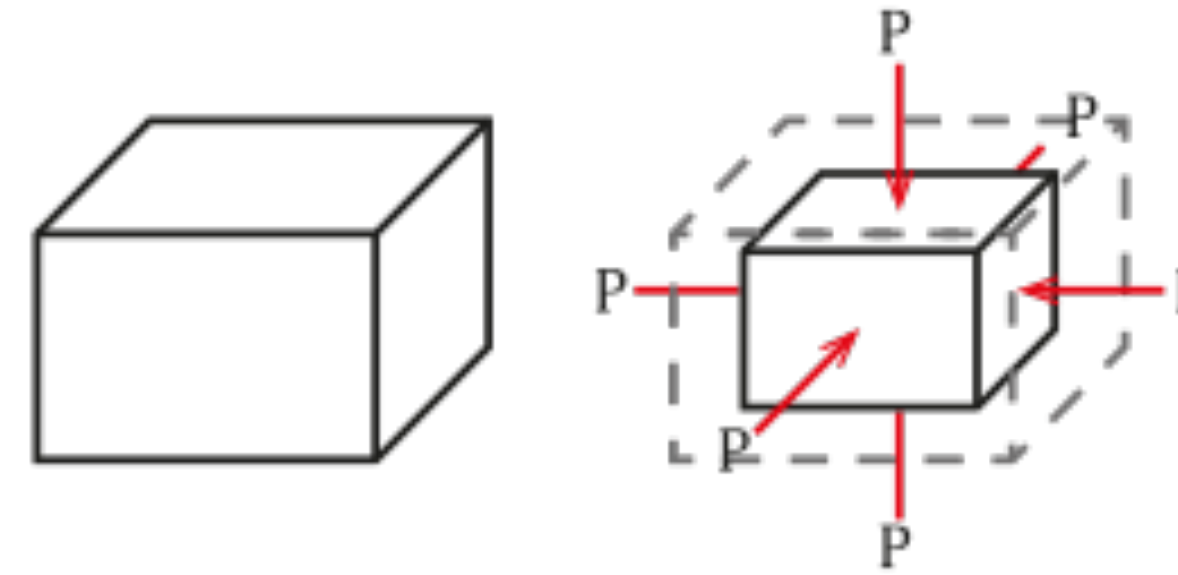
strain (ϵ) tensor

$$\epsilon_{xx} = du/dx$$

$$\epsilon_{yy} = dv/dy$$

$$\epsilon_{zz} = dw/dz$$

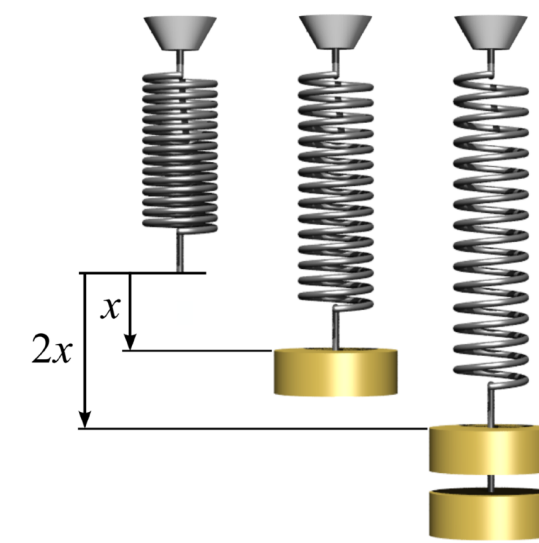
Stress-strain



...a relation between strain and stress...

Dilatation $\rightarrow \Delta = \epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}$

Hooke law (isotropic media)



Normal stress

$$\sigma_{ii} = \lambda \Delta + 2 \mu \epsilon_{ii} \quad \text{for } i = x, y, z$$

shear stress

$$\sigma_{ij} = \mu \epsilon_{ij} \quad \text{for } i \neq j$$

elastic constant of lamè

λ

μ

compress.

Shear

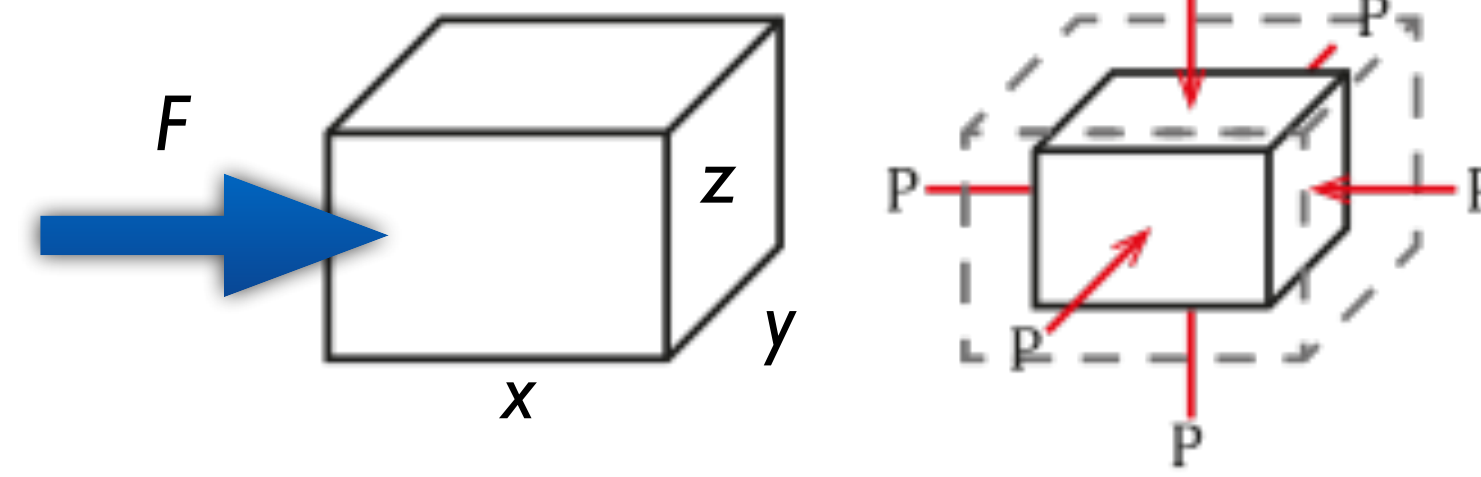
wave motion - Wave Equation

Mass of the cube $dm = \rho dx dy dz$ density

Newton Law $F = m a$

$$\rho \frac{d^2 u}{dt^2} = \frac{d\sigma_{xx}}{dx} + \frac{d\sigma_{xy}}{dy} + \frac{d\sigma_{xz}}{dz}$$

stress



Hooke law

Normal stress

dilatation

$$Es \text{ along } x \longrightarrow \rho \frac{d^2 u}{dt^2} = (\lambda + \mu) \frac{d\Delta}{dx} + \mu \Delta^2 u$$

diff for x, y, z

Dilatation

laplacian

$$\rho \frac{d^2 \Delta}{dt^2} = (\lambda + 2\mu) \nabla^2 \Delta \quad \text{Wave Equation !}$$

Lame parameters

Elastic waves in homogeneous and isotropic media

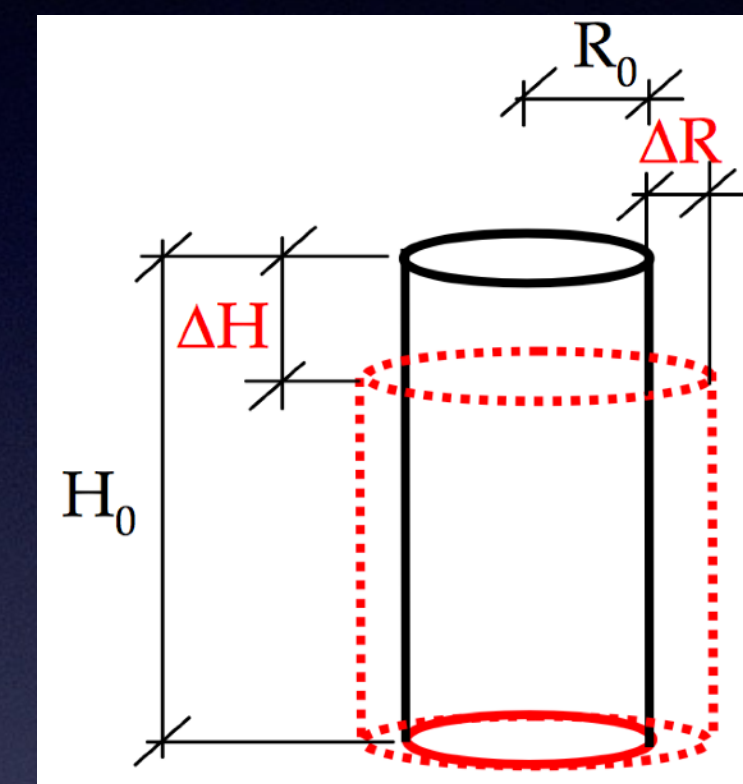
Body waves

Solution eq. diff. (Equazione d'onda)

Deformazione volumetrica

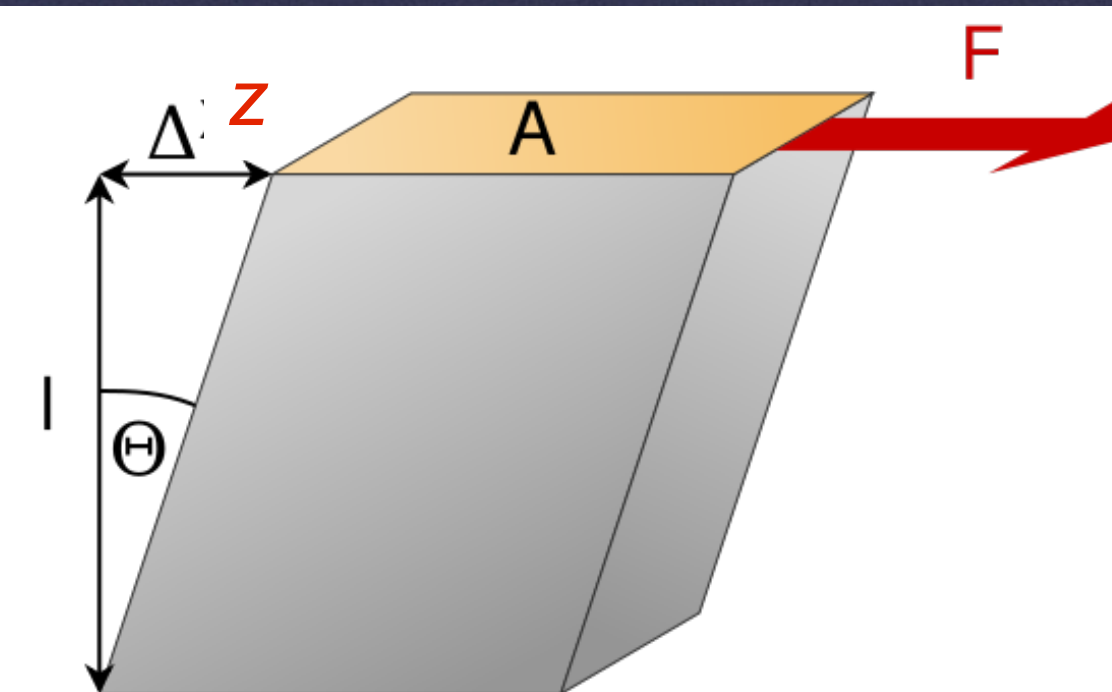
$$\text{P} \quad \frac{\partial^2 \bar{\varepsilon}}{\partial t^2} = \frac{\lambda + 2G}{\rho} \nabla^2 \bar{\varepsilon}$$

$$\varepsilon = \frac{\Delta V}{V_0}$$



$$\text{S} \quad \frac{\partial^2 \Omega_z}{\partial t^2} = \frac{G}{\rho} \cdot \nabla^2 \Omega_z$$

componenti di rotazione (x, y, z)



Elastic waves in homogeneous and isotropic media

Solution of waves equations

P

$$\frac{\partial^2 \bar{\varepsilon}}{\partial t^2} = \frac{\lambda + 2G}{\rho} \nabla^2 \bar{\varepsilon}$$

$$V_P^2$$

$$V_P = \sqrt{\frac{\lambda + 2G}{\rho}}$$

S

$$\frac{\partial^2 \Omega_z}{\partial t^2} = \frac{G}{\rho} \nabla^2 \Omega_z$$

$$V_S^2$$

$$V_S = \sqrt{\frac{G}{\rho}}$$

In fluids
 $G = 0$
 $V_S = 0$

Elastic waves in elastic homogeneous and isotropic media

In applied seismology :
The problem is solution wave equation for Shear wave

$$S \quad \frac{\partial^2 \Omega_z}{\partial t^2} = \frac{G}{\rho} \cdot \nabla^2 \Omega_z \quad \text{in } x, y \text{ e } z$$

HOOKE LAW in z

$u = \text{displacement}$

$$\rho \frac{d^2 u}{dt^2} = G \frac{d^2 u}{dz^2}$$

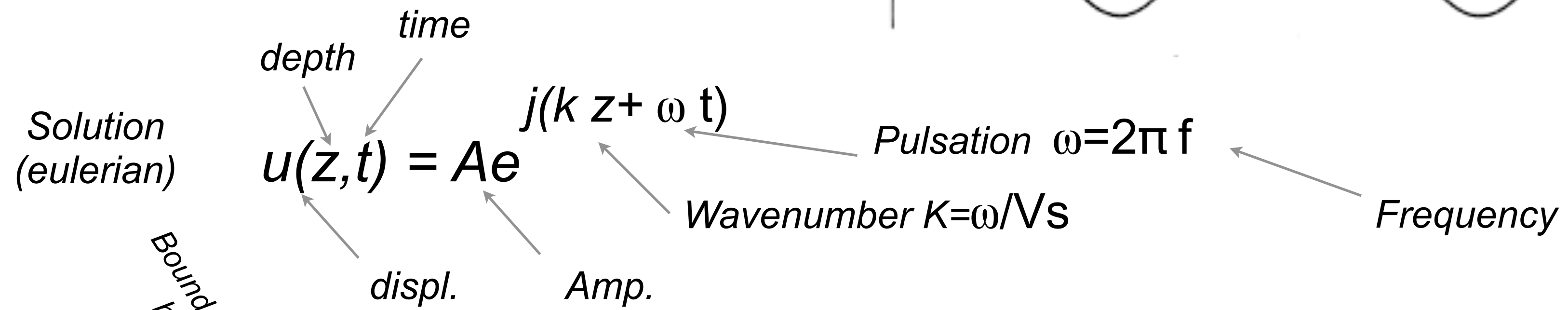
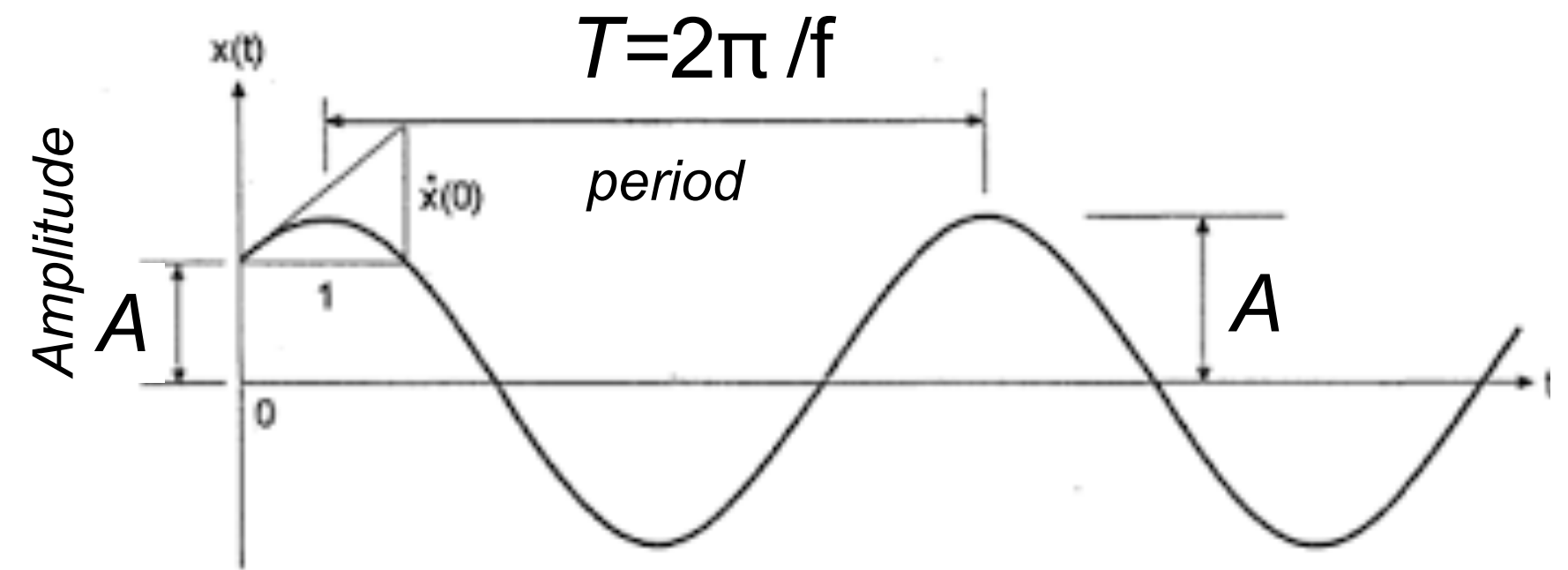
ELASTIC
WAVE
EQUATION (S)

Elastic waves in homogeneous and isotropic media

S waves equation

$$\rho \frac{d^2 u}{dt^2} = G \frac{d^2 u}{dz^2}$$

harmonic sinusoidal wave

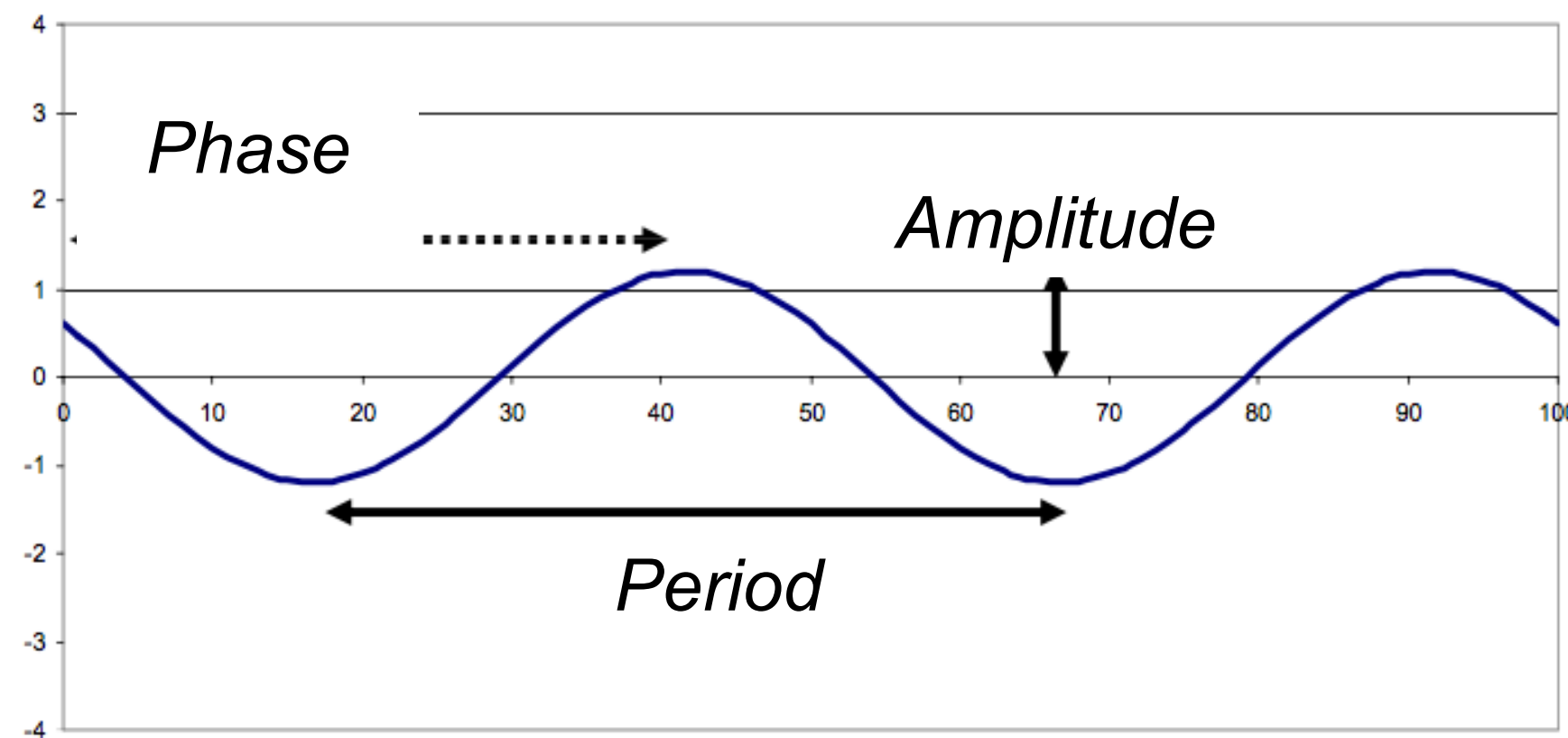


Bound. Conditions
Halfspace
 $G=0$
 $z=0$

Horizontal displacement = $u(z,t) = 2A \cos(kz) e^{j\omega t}$ Wave equation Solution

in first approximation soil can be imaged as a continuous media with linear constitutive equations (elastic or visco-elastic)

This way the spoil motion can be represented by linear combination of harmonic oscillations



$$A(t) = A_{\max} \cos(2\pi f t + \phi)$$

Eq. Wave

$$\phi = -2\pi f t_{\max}$$

phase (when arrive the maximum?)

$$T = 1 / f$$

Period (how much last the motion?)

$$f = 1 / T$$

Frequency (how much oscillation?)

$$\omega = 2\pi f = 2\pi / T$$

Pulsation


```
clear all
close all
clc
```

```
Dm=2 % Spostamento Massimo
f=1  % frequenza in Hz
fi=0.5 % sfasamento
t = 0:0.01:(2*pi); % vettore tempo
```

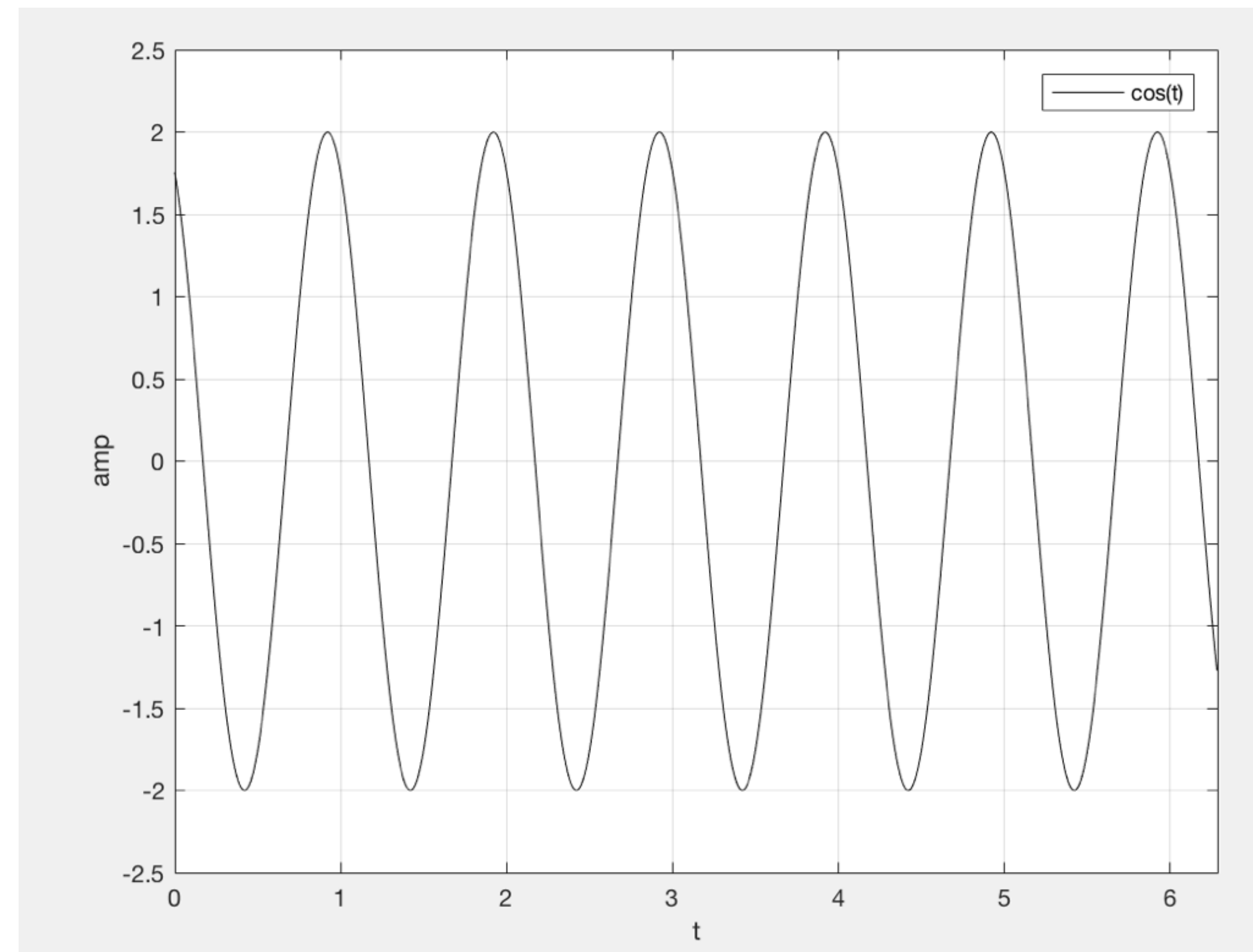
```
D=Dm*(cos(2*pi*f*t+fi)); % equazione d'onda 1D
%plot
plot(t,D,'k'); hold on;
axis([0 2*pi -2.5 2.5])
legend('cos(t)', 'Location', 'NorthEast')
xlabel 't'
ylabel 'amp'
grid on
```

$$A(t) = A_{\max} \cos(2\pi f t + \phi)$$

Spostamento

Frequenza

fase




```

clc; clear all; close all;

%2D WAVE EQUATION utt = c^2(uxx+uyy)
%with initial condition u(x,y,0) = sin(p*pi*x)*sin(q*pi*y), 0<x<1 0<y<1
% and boundary conditions u(0,y,t) = u(1,y,t)= u(x,0,t)= u(x,1,t) = 0 t>0

c = 1;
dx = 0.01;
dy = dx;
sigma = 1/sqrt(2); gamma = 1/sqrt(2); %Courant-Friedrich Stability Condition
dt = sigma*(dx/c);
t = 0:dt:1; x = 0:dx:1; y = 0:dy:1;
u = zeros(length(x),length(y),length(t));
p = 2; q = 1;

u(:,:,1) = transpose(sin(p.*pi.*x))*sin(q.*pi.*y); %u(x,y,0) = sin(p*pi*x)*sin(q*pi*y)

%u(x,y,dt)
for i=2:length(x)-1
    for j=2:length(y)-1
        u(i,j,2)= (sigma^2)*(u(i+1,j,1)-2*u(i,j,1)+u(i-1,j,1))...
            +(gamma^2)*(u(i,j+1,1)-2*u(i,j,1)+u(i,j-1,1))+2*u(i,j,1) - u(i,j,1);
    end
end

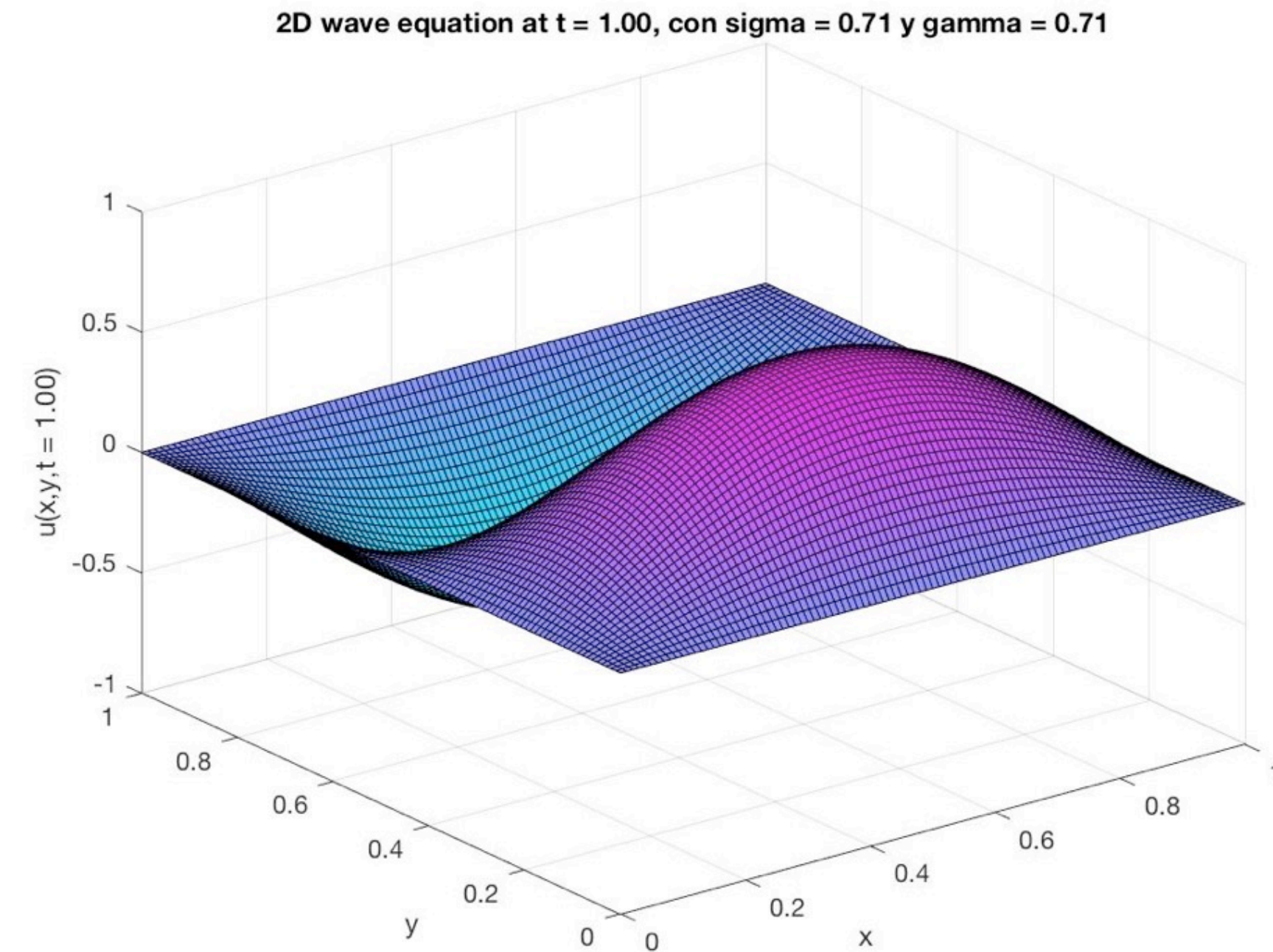
for n=2:length(t)-1
    for i=2:length(x)-1
        for j=2:length(y)-1
            u(i,j,n+1)= (sigma^2)*(u(i+1,j,n)-2*u(i,j,n)+u(i-1,j,n))...
                +(gamma^2)*(u(i,j+1,n)-2*u(i,j,n)+u(i,j-1,n)) + 2*u(i,j,n) - u(i,j,n-1);
        end
    end
end

for j=1:length(t)
    colormap(cool);
    p1 = surf(X,Y,u(:,:,j));
    title(sprintf('2D wave equation at t = %1.2f, con sigma = %1.2f y gamma
= %1.2f',t(j),sigma, gamma),'FontSize',11);
    xlabel('x','FontSize',11); ylabel('y','FontSize',11);
    zlabel(sprintf('u(x,y,t = %1.2f)',t(j)),'FontSize',11);
    axis ([0 1 0 1 -1 1]);
    pause(0.0001);
    hold on;

    if(j~=length(t))
        delete(p1);
    end
end

```

2D wave eq solution

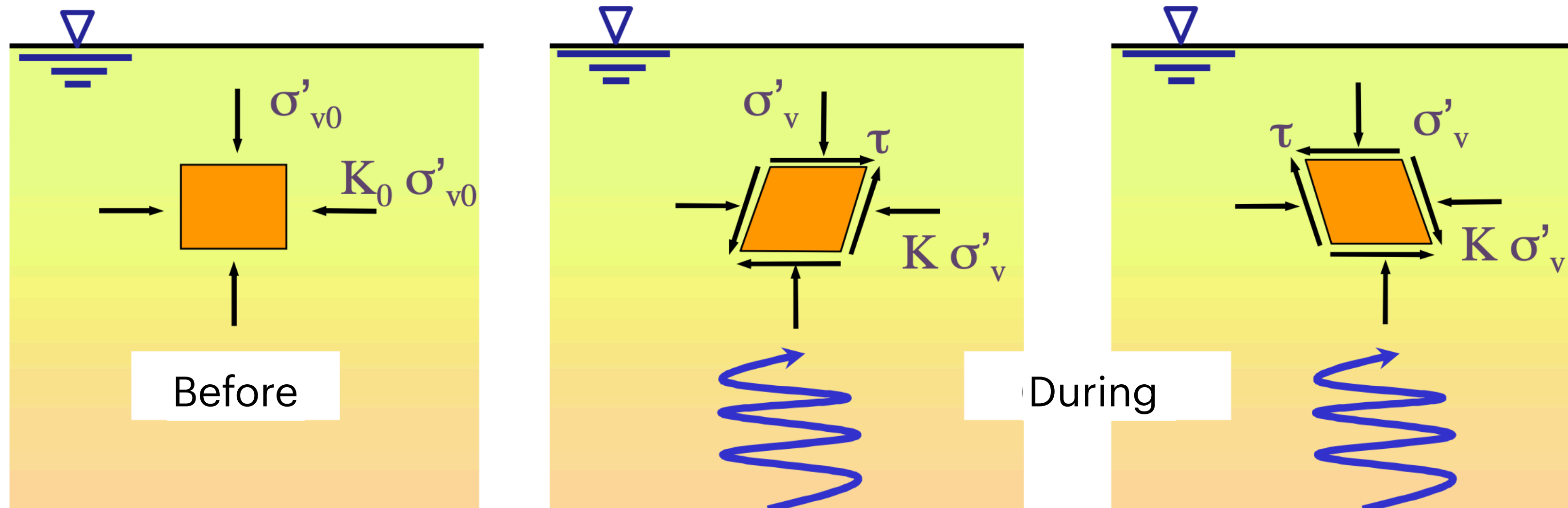


Seismic Response Analysis

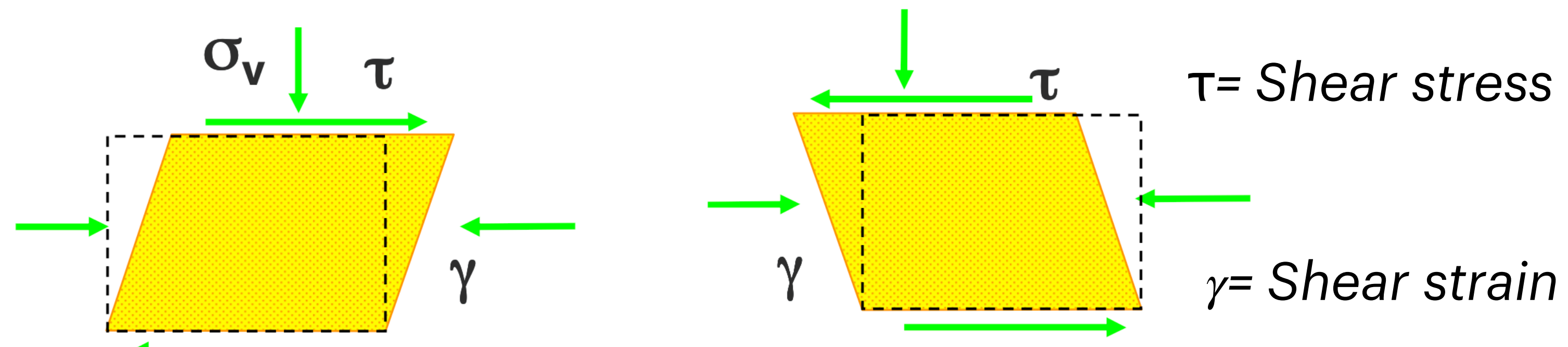
Terrain element under earthquake stress

$\sigma =$ pressure

Conditions



S waves coming from the inner crust



(Undrained Conditions)

Define Soil Deformability

Seismic waves in esalti media, isotropic and homogeneous harmonic motion

$$u(z,t) = 2A \cos(kz) e^{j\omega t}$$

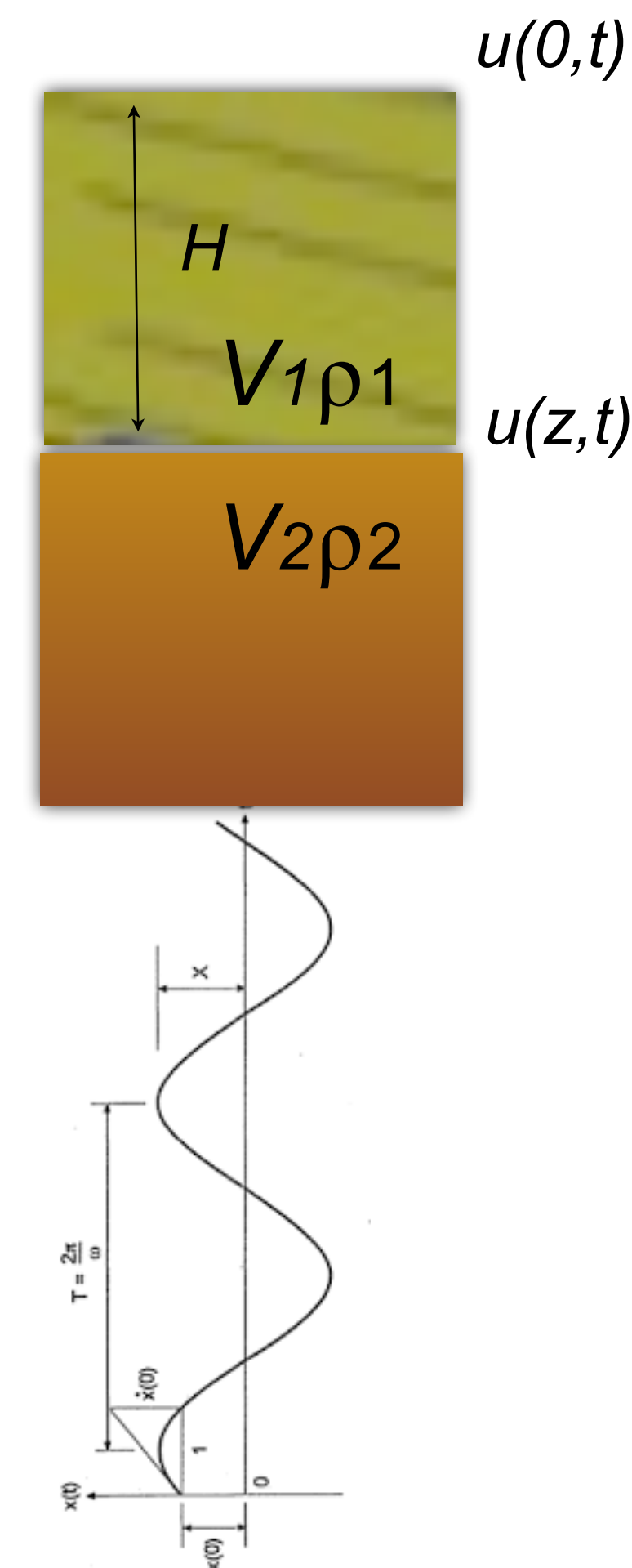
Transfer function for $z=H$

$$H(\omega) = \frac{U_{max}(0,t)}{U_{max}(z,t)} = \frac{2Ae^{j\omega t}}{2A \cos(kH)e^{j\omega t}} = \frac{1}{\cos(kH)}$$

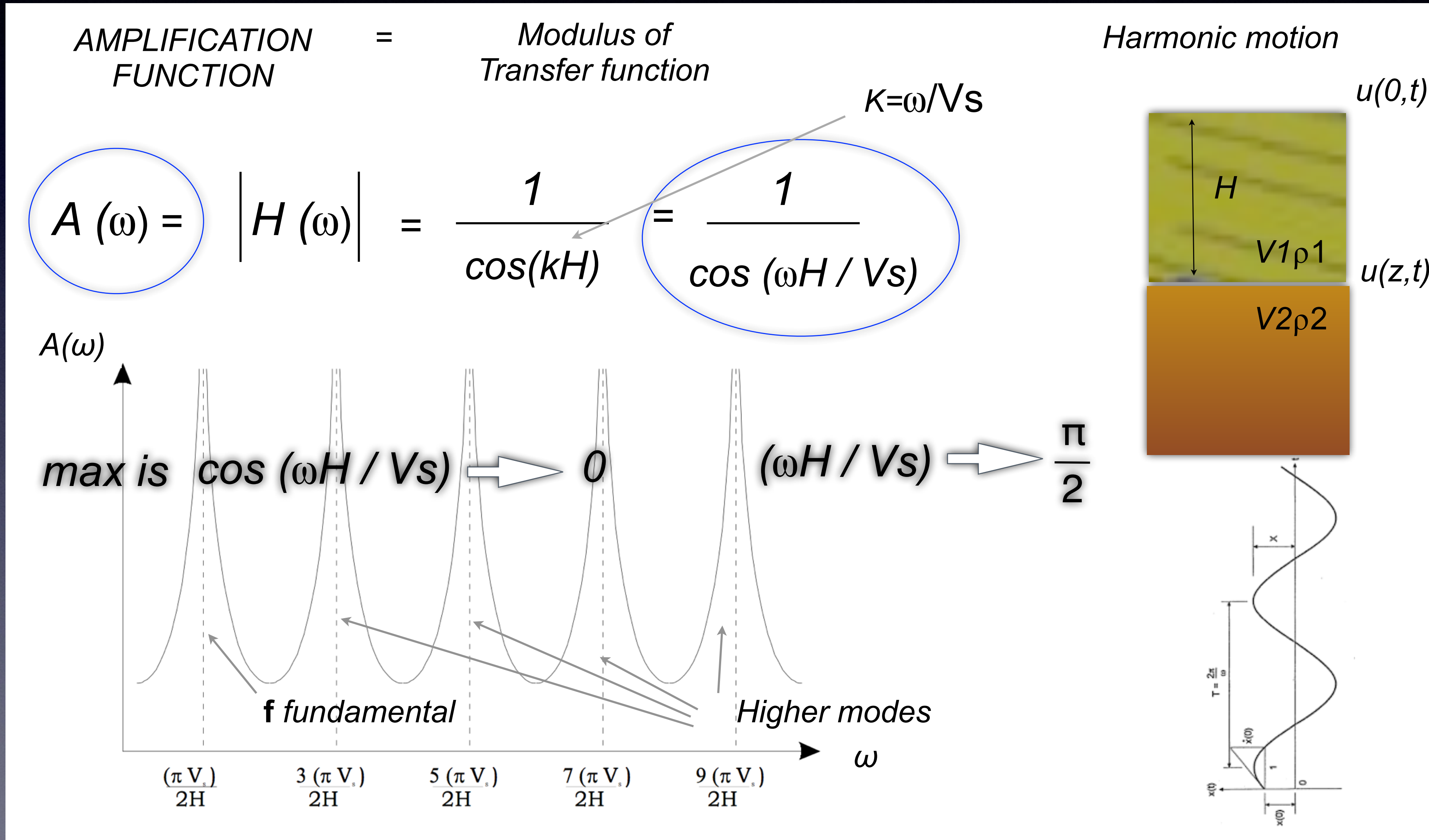
Surface

Depth

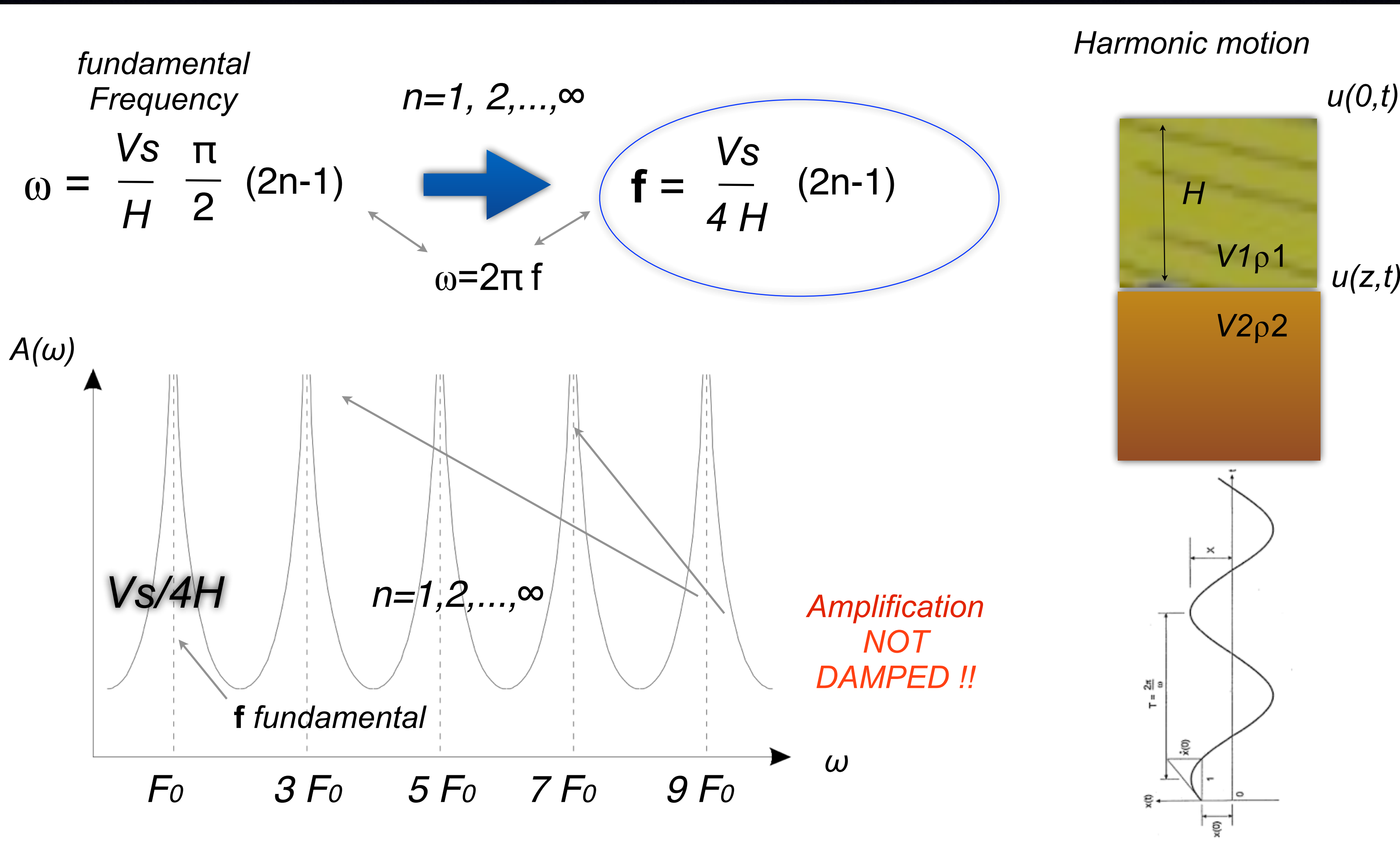
Ideal harmonic Motion



Seismic waves in esalti media, isotropic and homogeneous harmonic motion



Seismic waves in esalti media, isotropic and homogeneous harmonic motion

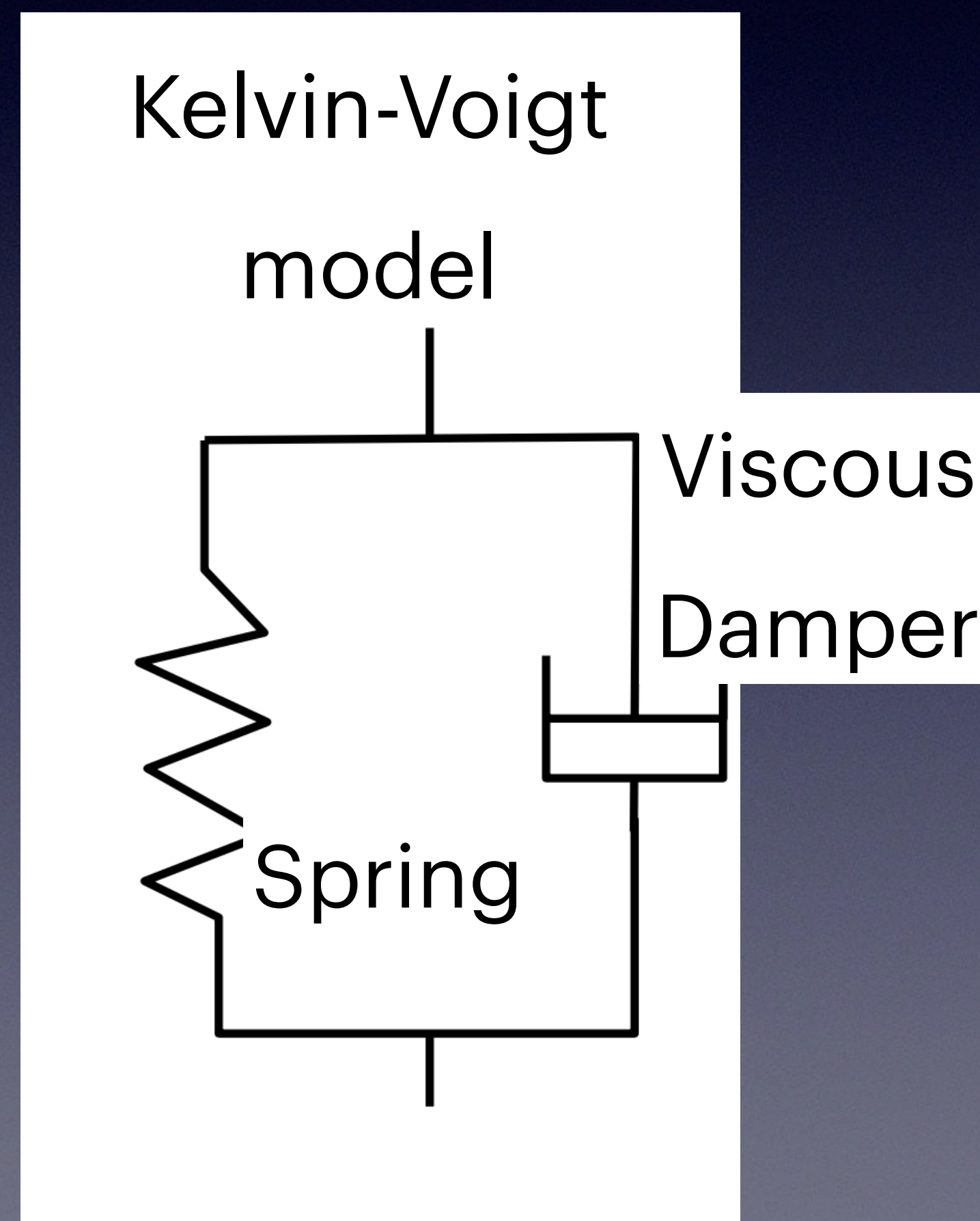


From the waves in ideal elastic homogeneous isotropic
media



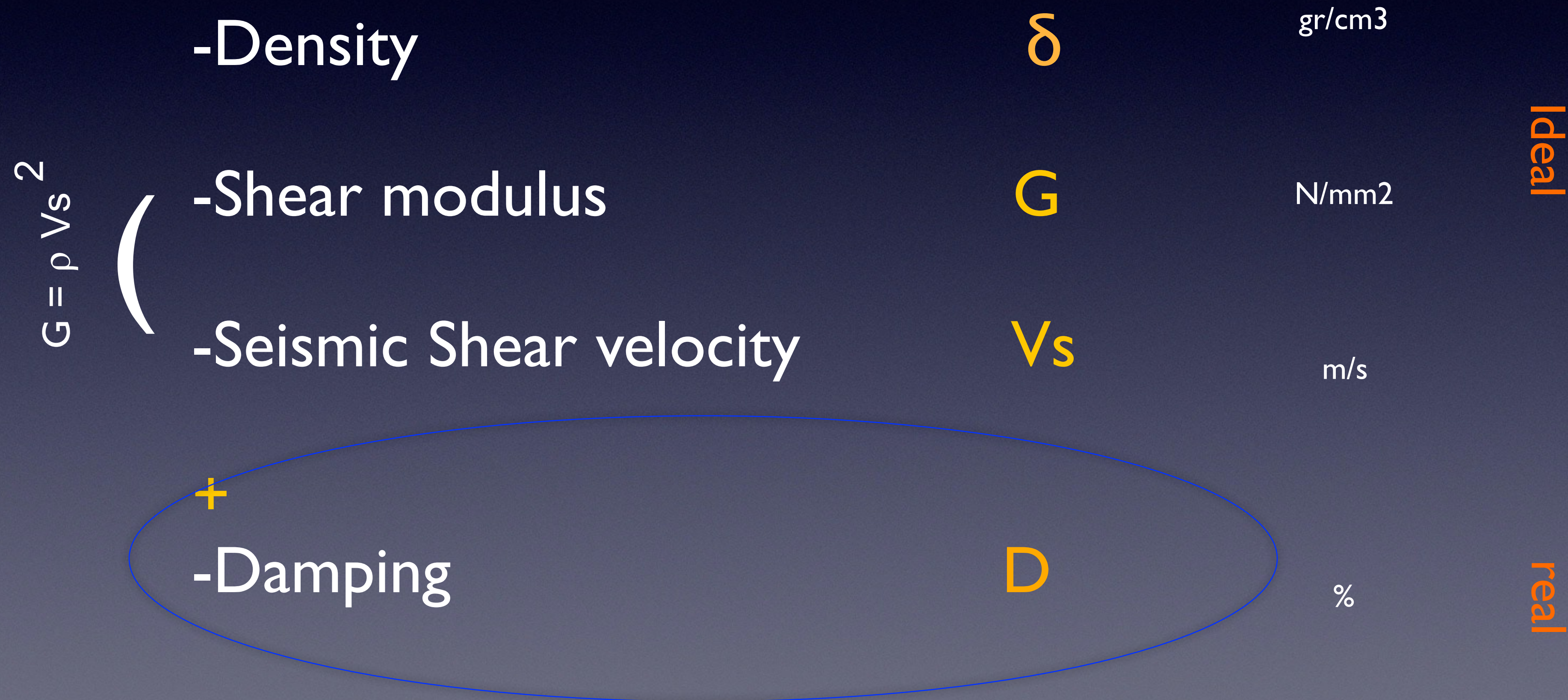
To seismic waves in a real soil
(not linear)

The soil visco-elastic model is based on a kelvin-voigt model
based on spring rigidity (G) and viscous damper (D)

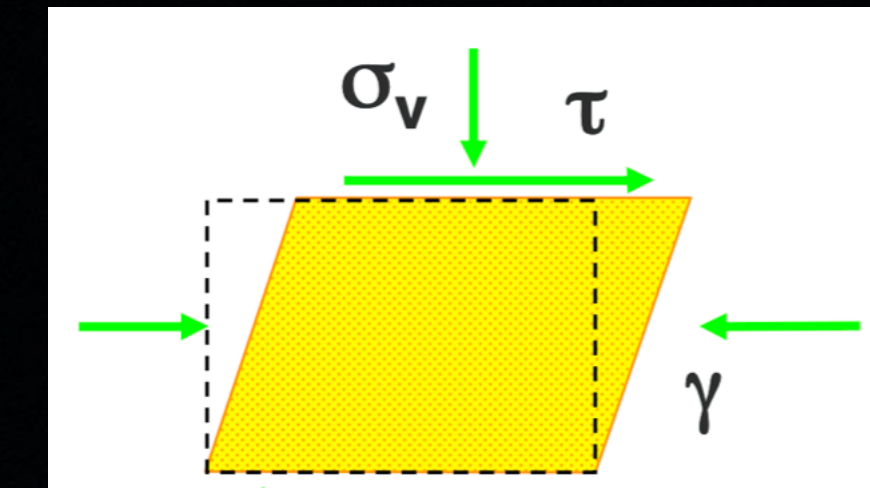


Waves propagation in the real soil

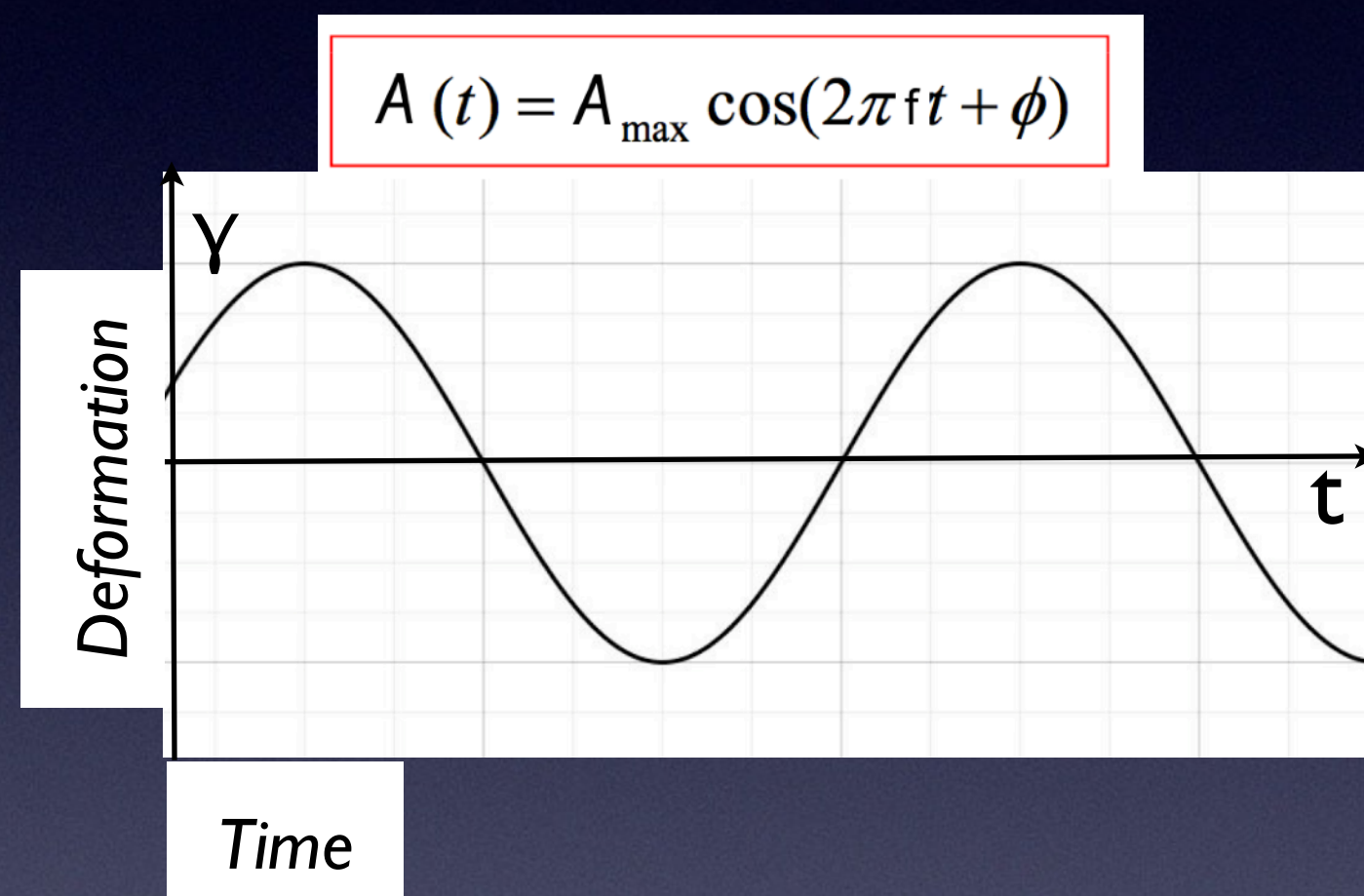
Soil parameters for seismic response analysis



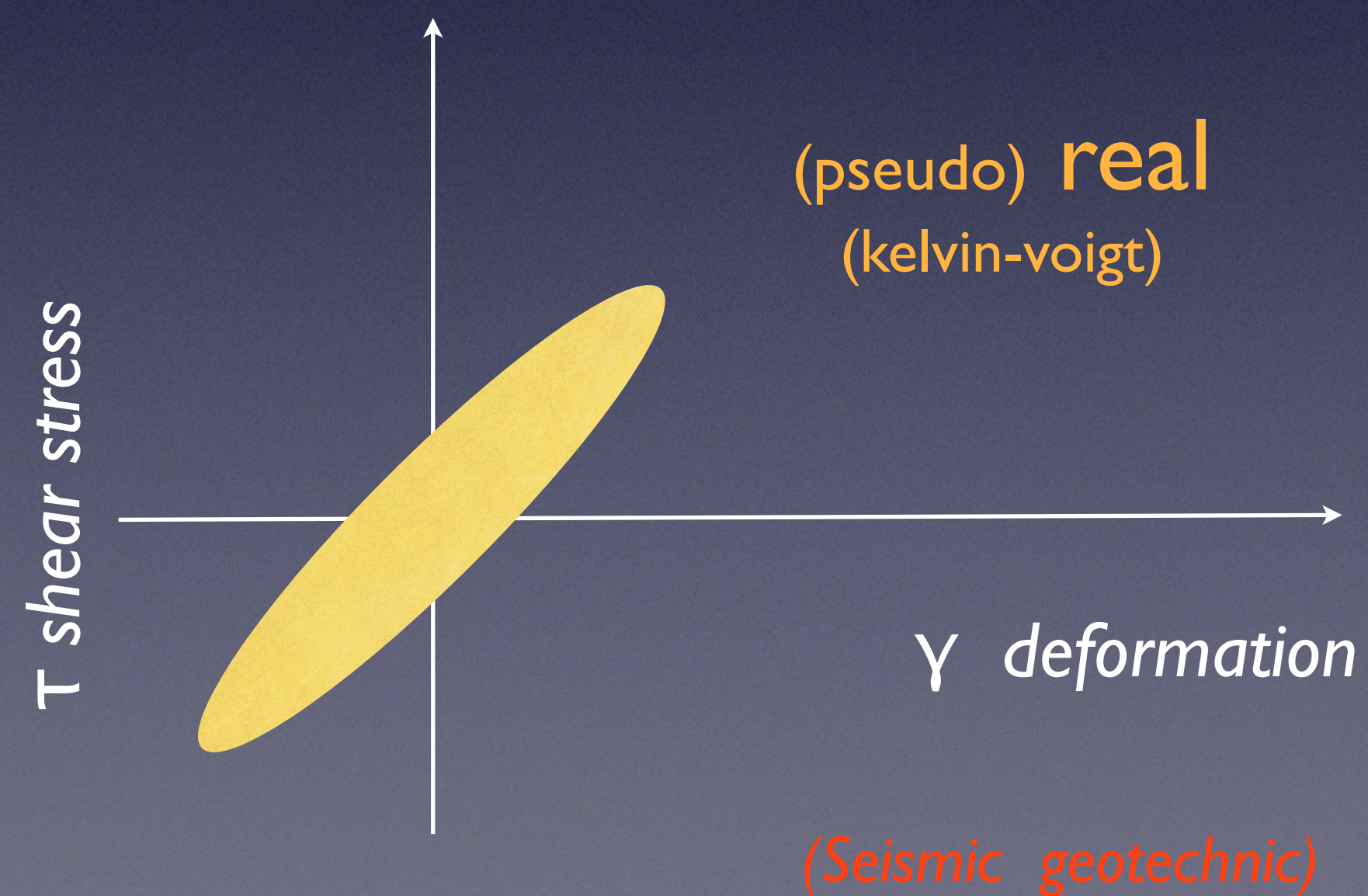
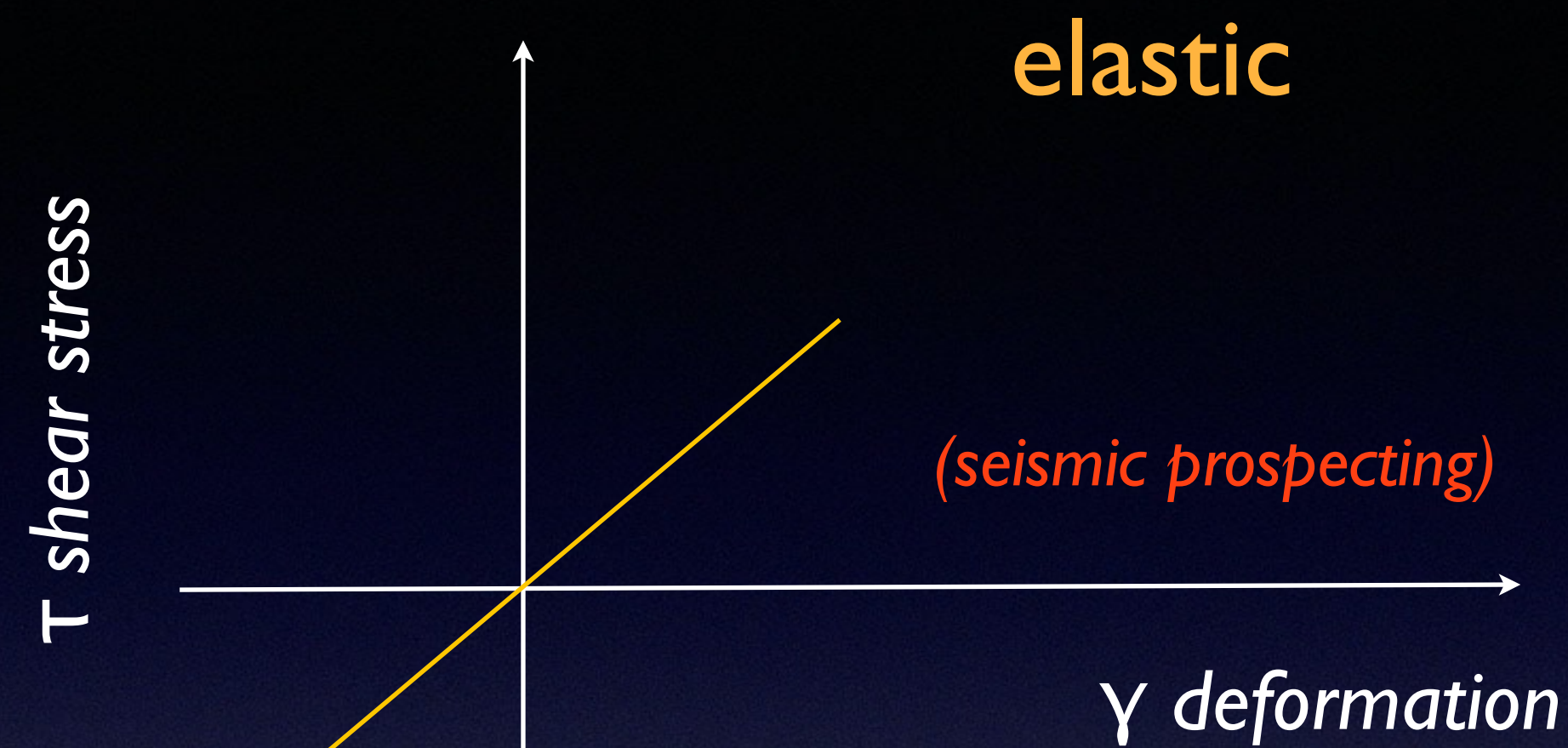
Stress (τ) and strain (γ) in cyclic loads



Small deformation
Soil is linear elastic (seismic prospecting)



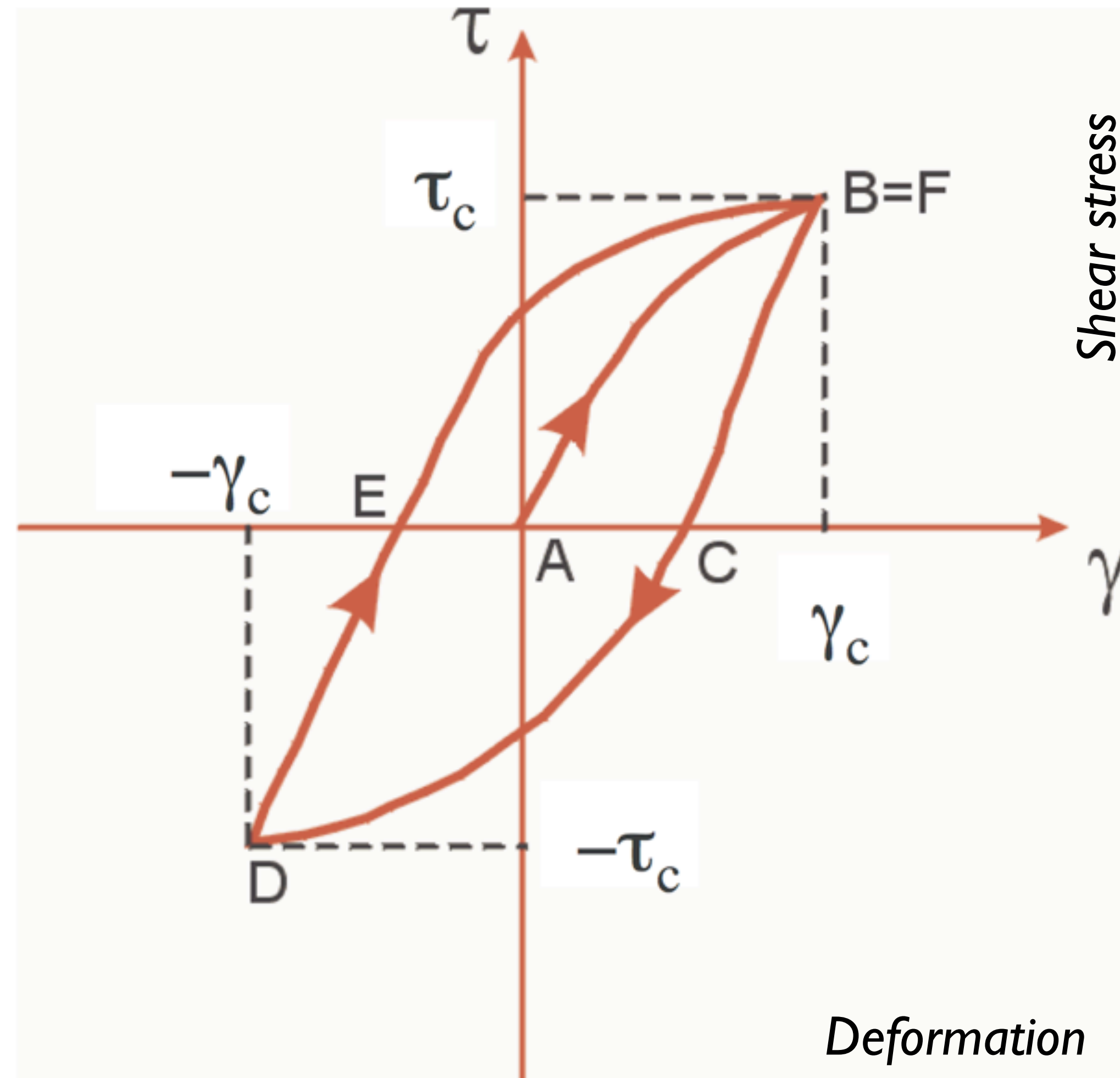
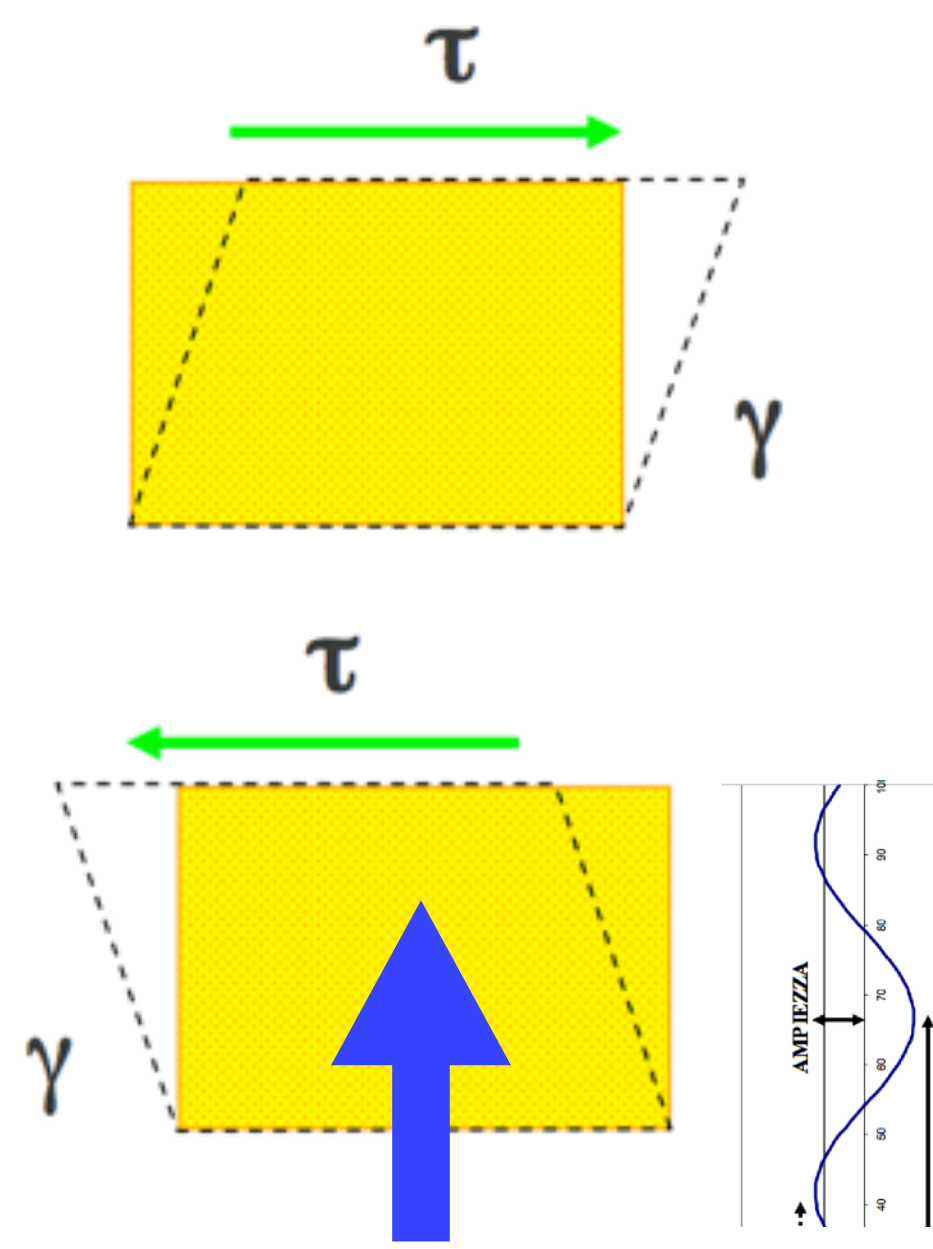
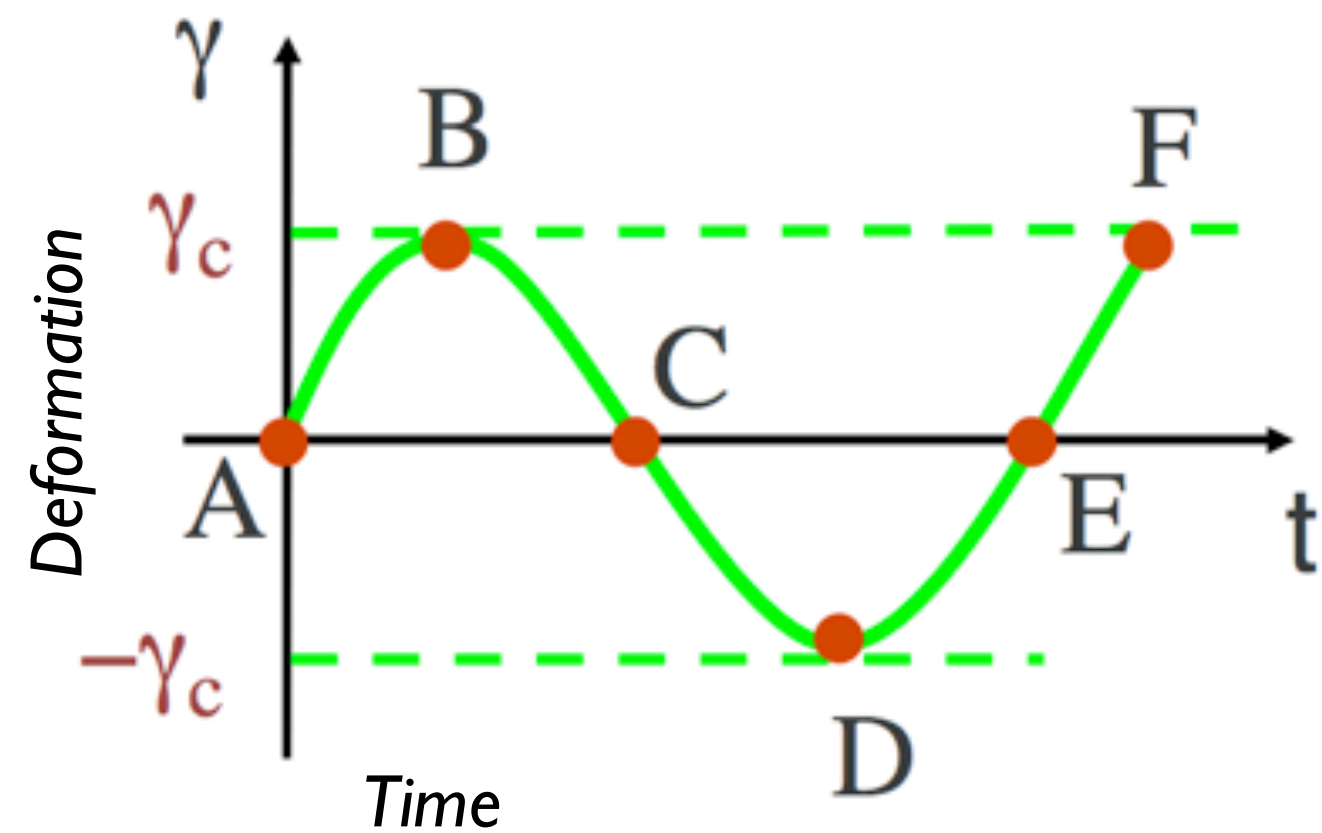
Medium to big deformation
Soil is not linear and dissipative (damped)



Geotechnical parameters in seismic motion

Response of soil to cyclic loads

Soil is not linear and dissipative (medium-big deformation)

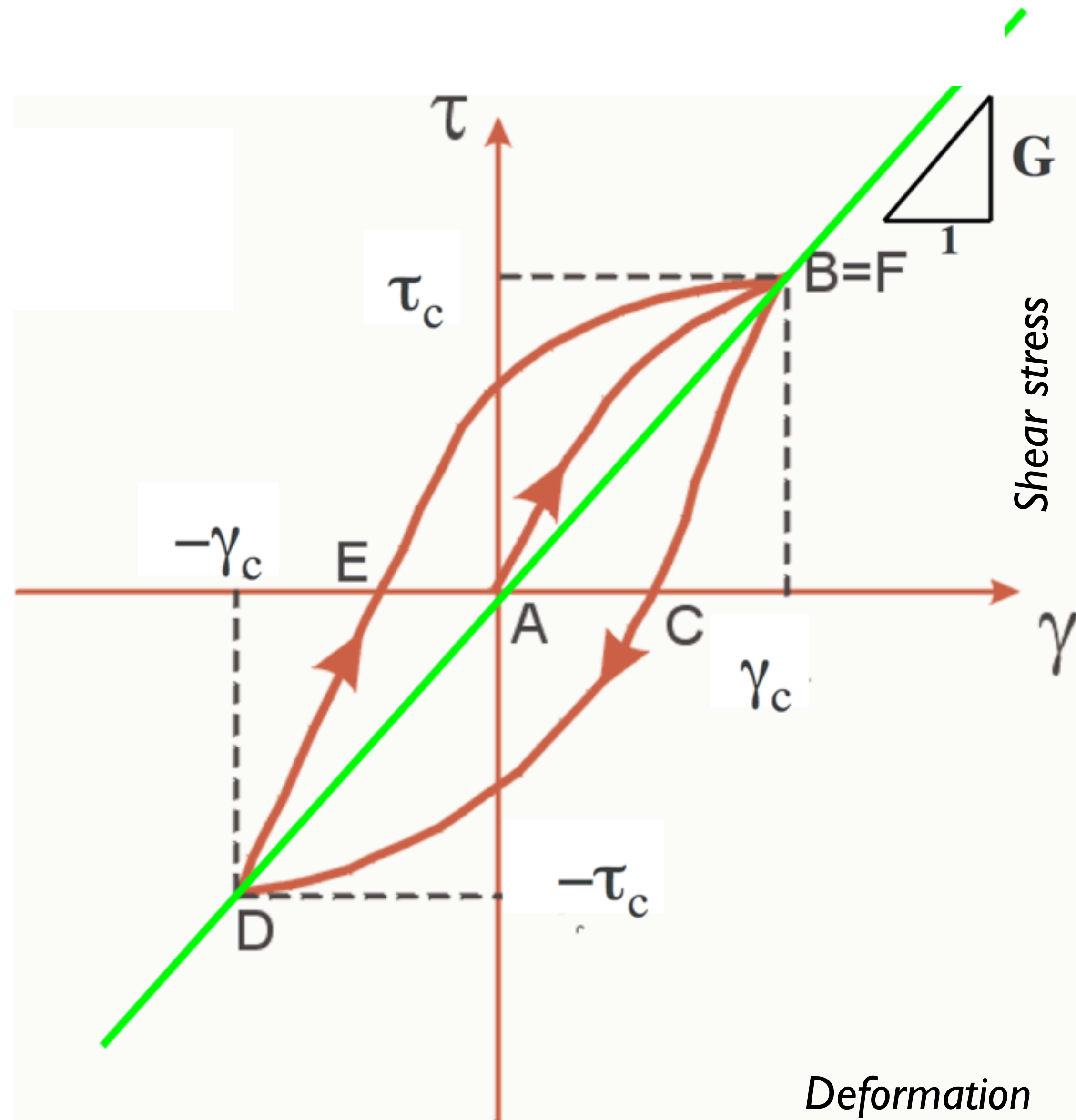


Geotechnical parameters

G modulus

$$G = \frac{\tau_c}{\gamma_c}$$

Secant
of τ - γ

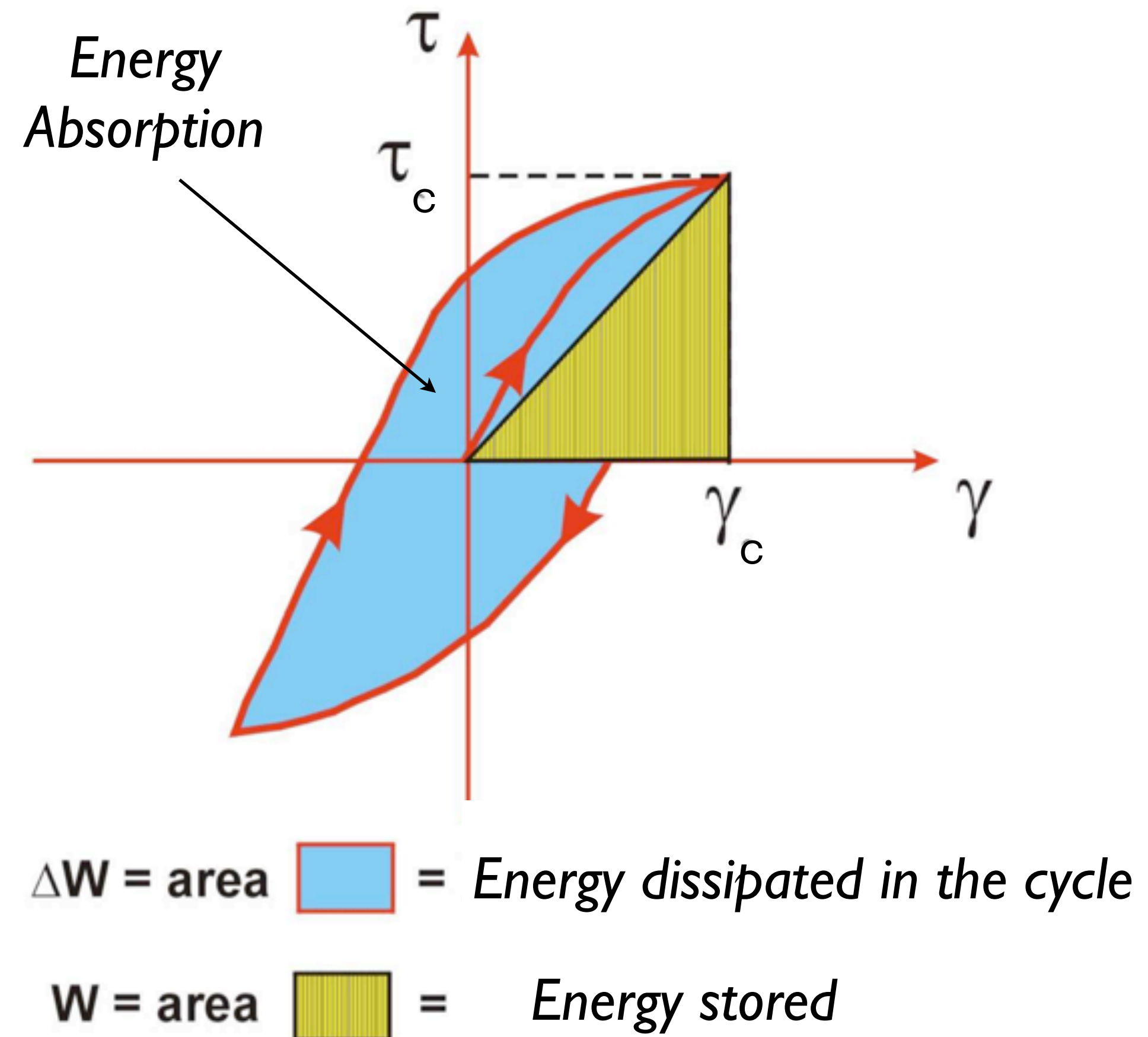


Geotechnical parameters

D Damping

$$D = \frac{1}{4\pi} \frac{\Delta W}{W}$$

Ratio between the
dissipated energy and
the elastic energy
stored



Different soils, different DAMPING



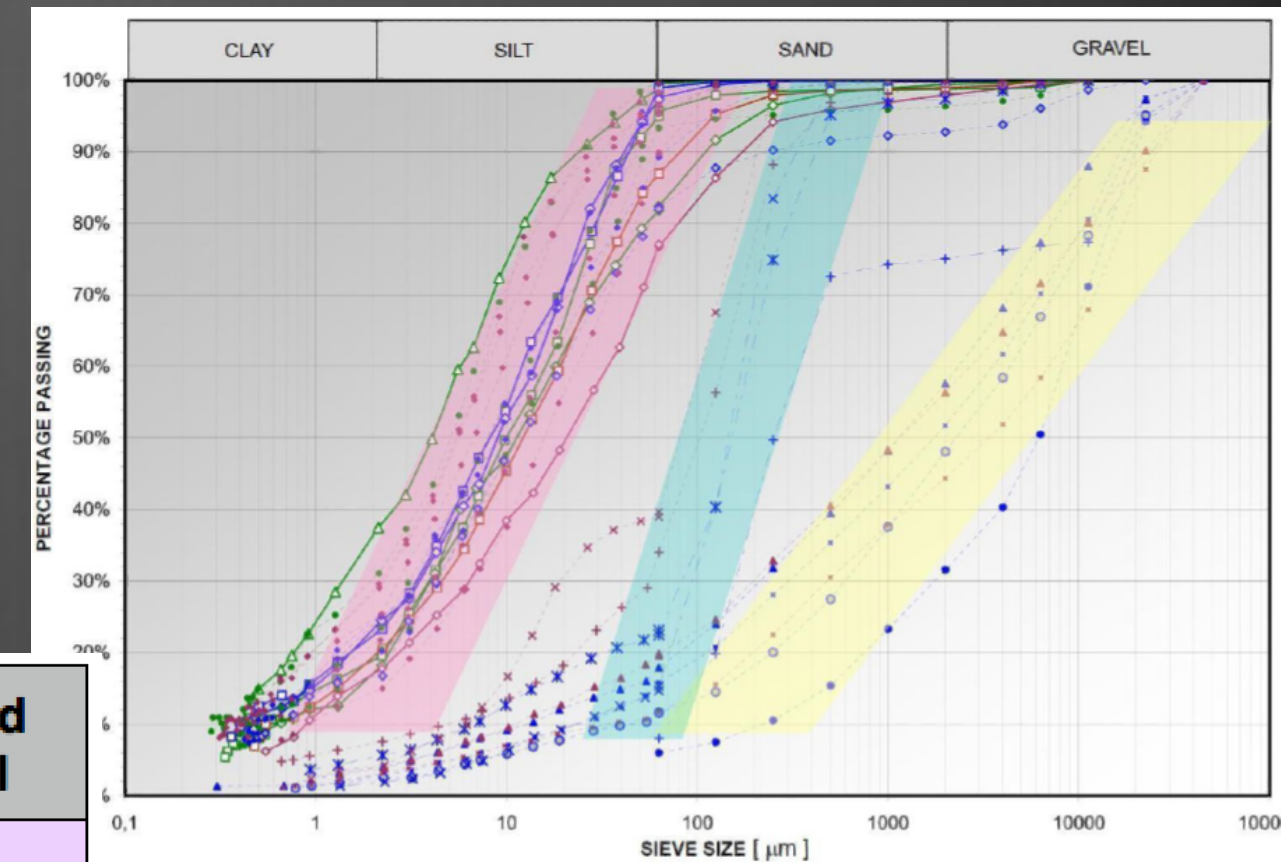
Università degli Studi di Padova

Dipartimento di Geoscienze



Indagini geofisiche e geotecniche

Indagini sismiche:
risultati ed interpretazioni



Depth (m)	Vs (m/s)	Mean Vs (m/s)	Layer type	Assigned Material
0	258	250	sand	SAND
1	253,3			
2	227,3			
4	191,7	200	silt + clay	CALYEEY SILT
6	203,5			
8	251,7			
10	312,1	350	gravel1	GRAVEL
13	365,8			
16	406,7			
21	430,4	440	gravel2	
26	443,5			
31	450,6			



Indagini geotecniche

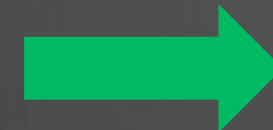
- caratteristiche fisiche
- proprietà indice
- granulometrie
- limiti di Atterberg
- edometriche
- conducibilità idraulica
- prove triassiali

Lab DAMPING with resonant column test



Indagini geotecniche

Strumentazione di
Colonna Risonante
(Lab. di geotecnica P.A.T.)



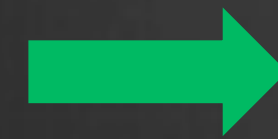
G_0 = modulo di taglio dinamico
naturale

G = modulo di taglio dinamico di
laboratorio

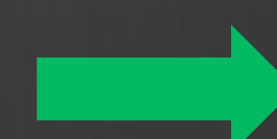
D = smorzamento



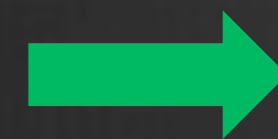
PROVE
RC



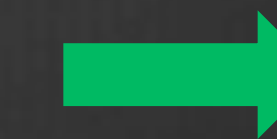
$$\begin{cases} V_s = h \cdot \omega / \beta \\ \omega = 2\pi \cdot Fr \end{cases}$$



$$G = V_s^2 \cdot \rho$$



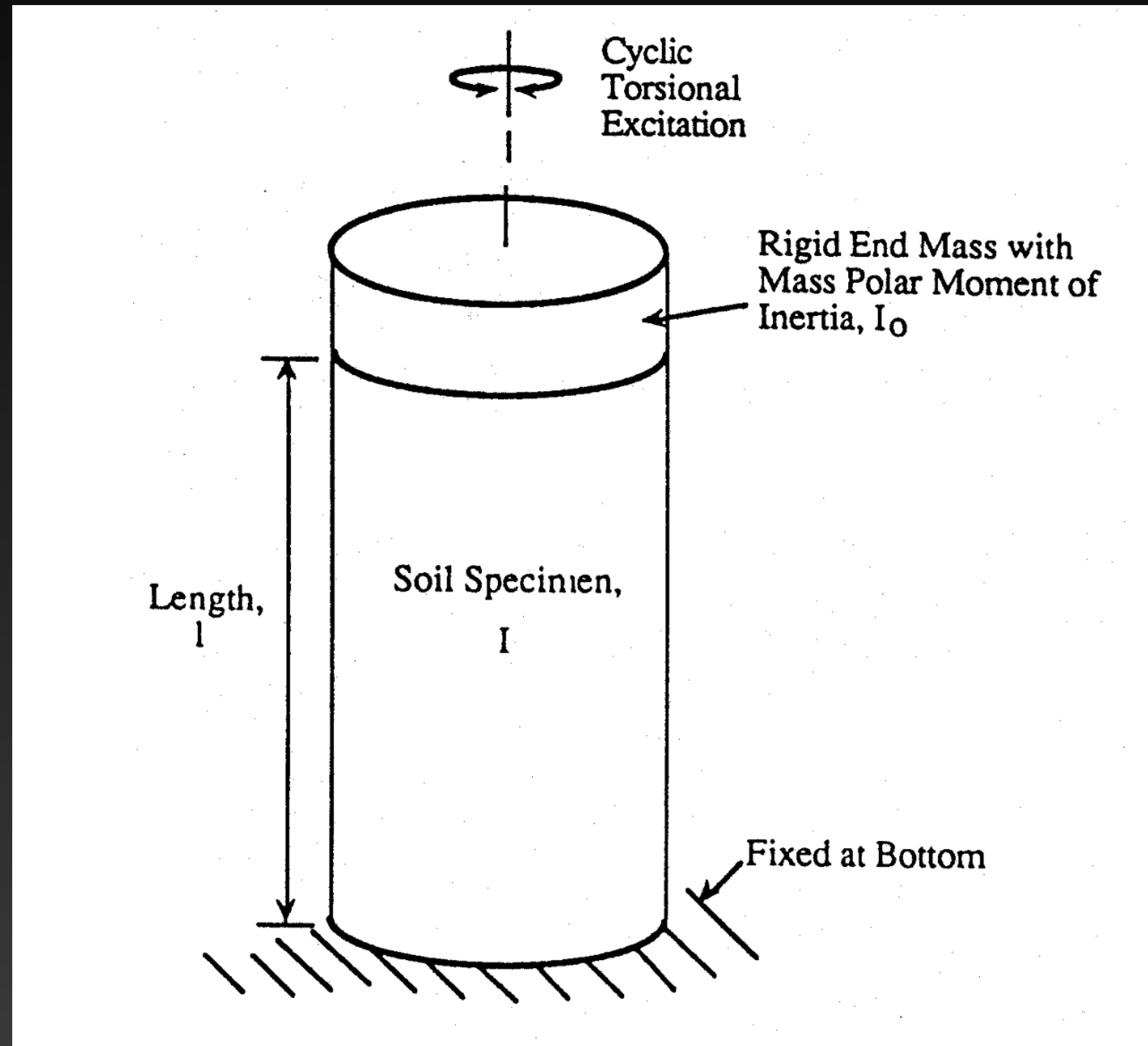
Amplitude Decay Method



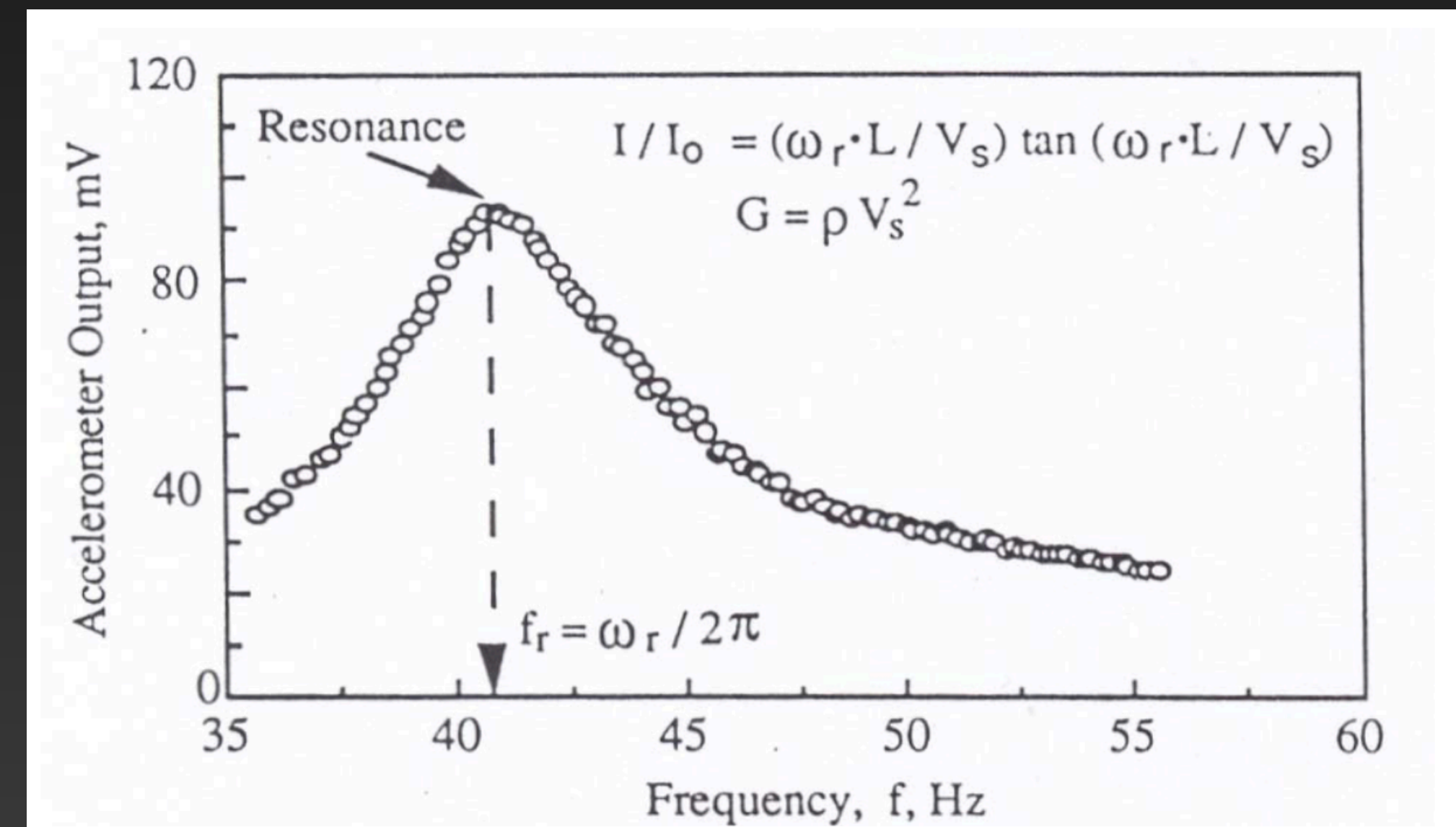
D

Lab DAMPING with resonant column test

Determining the dynamic deformation properties (shear modulus G and damping ratio D) of soils.

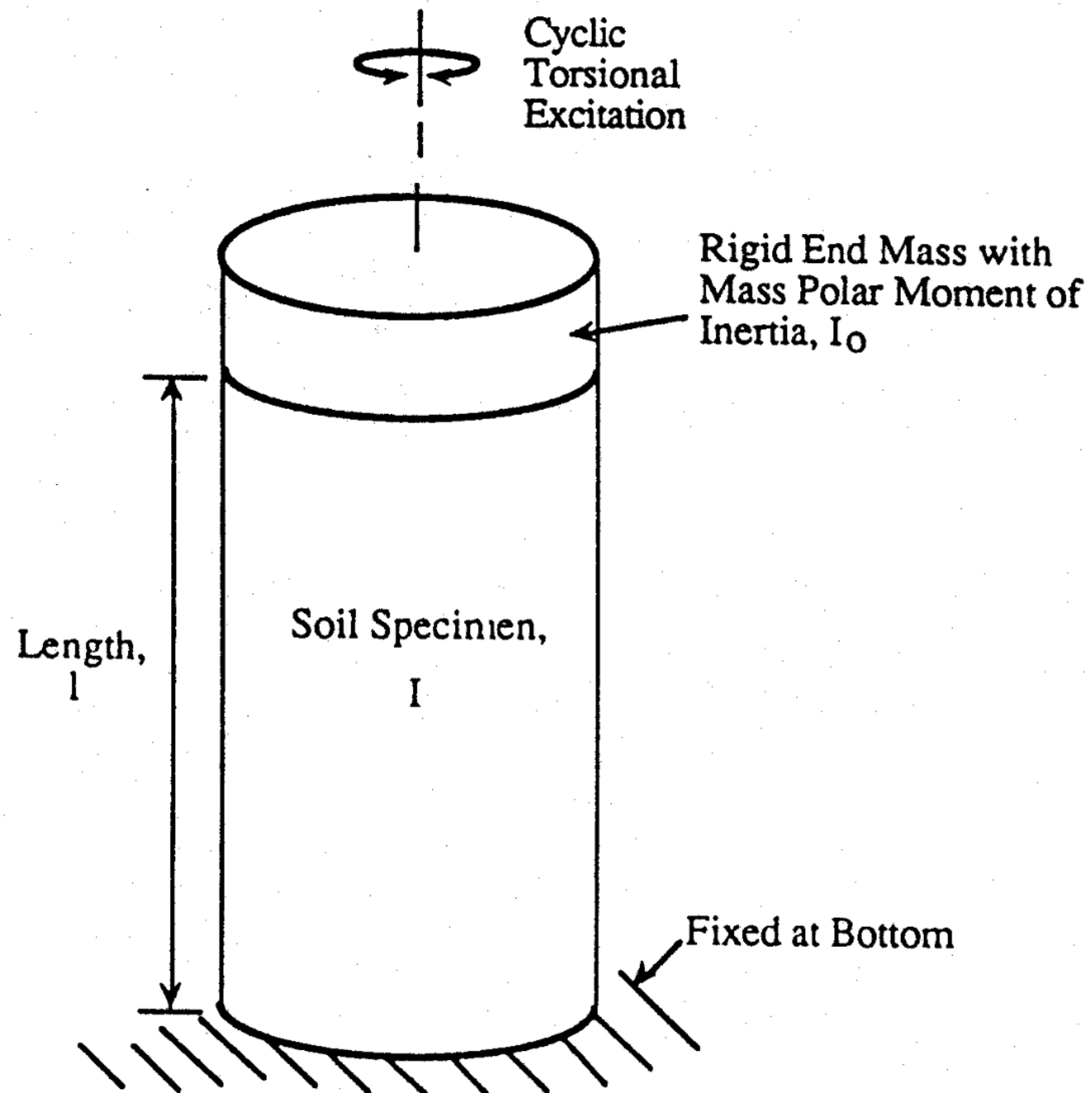


- i) prepare the specimen (density)
- ii) Apply harmonic torsional excitation to the specimen with varying frequency.
- iii) Obtain the response of the acceleration amplitude with varying frequency and find the first-mode resonance where output voltage of accelerometer is maximized.



Lab DAMPING with resonant column test

Determining the dynamic deformation properties (shear modulus G and damping ratio D) of soils.



iv) Record the resonant frequency and the amplitude of vibration.

v) Obtain the free-vibration decay curve (using an oscilloscope) by shutting off the driving force while the specimen is vibrating at the resonant frequency. (or find the frequencies where the amplitude of vibration is 0.707 times of first-mode resonance.)

vi) Repeat the process described ii) ~ v) with increasing the amplitude of torsional excitation. (in general, γ can reach about 10e-1%.)

Lab DAMPING with resonant column test

Determining the dynamic deformation properties (shear modulus **G** and damping ratio **D**) of soils.

3.1 Shear Modulus

- Calculate the shear wave velocity of soil sample, V_s , as follows:

$$\frac{\sum I}{I_0} = \frac{\omega_n \cdot l}{V_s} \tan\left(\frac{\omega_n \cdot l}{V_s}\right)$$

where

$\sum I$: sum of I_s and I_m ,

I_s : mass moment of inertia of soil,

I_m : mass moment of inertia of membrane,

I_0 : mass moment of inertia of rigid end mass at the top of sample,

l : length of the specimen,

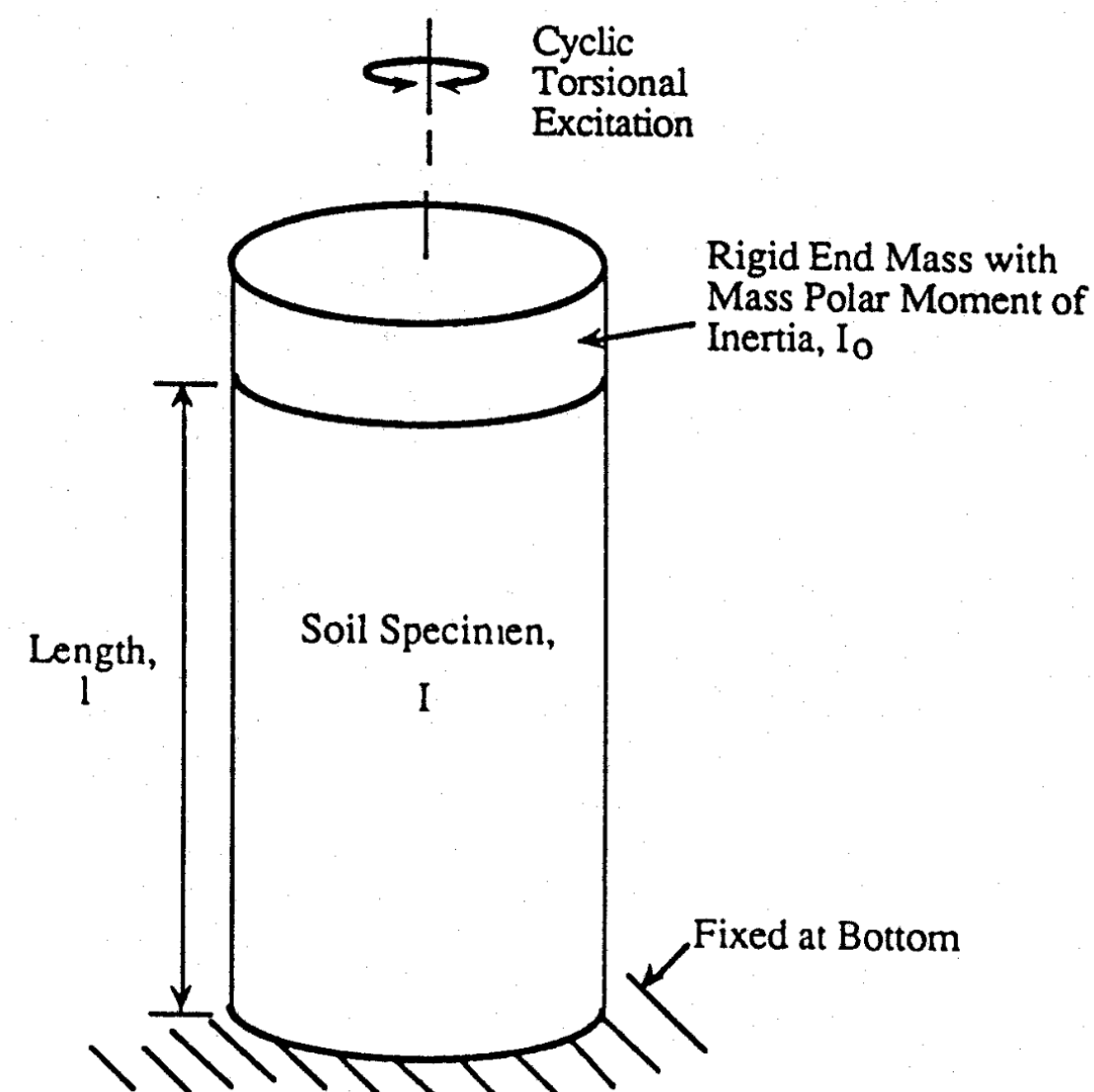
ω_n : undamped natural circular frequency of the system

- Calculate the shear modulus using shear wave velocity

$$G = \rho \cdot V_s^2$$

where

ρ : total mass density of the soil



Lab DAMPING with resonant column test

Determining the dynamic deformation properties (shear modulus **G** and damping ratio **D**) of soils.

3.2 Shear Strain

- Calculate the shearing strain

$$\gamma = r_{eq} \frac{A_c \cdot T_r^2}{4\pi^2 \cdot CF} \cdot \frac{1}{D_{ac}} \cdot \frac{1}{l}$$

where

r_{eq} : equivalent radius (0.707r or 0.67r),

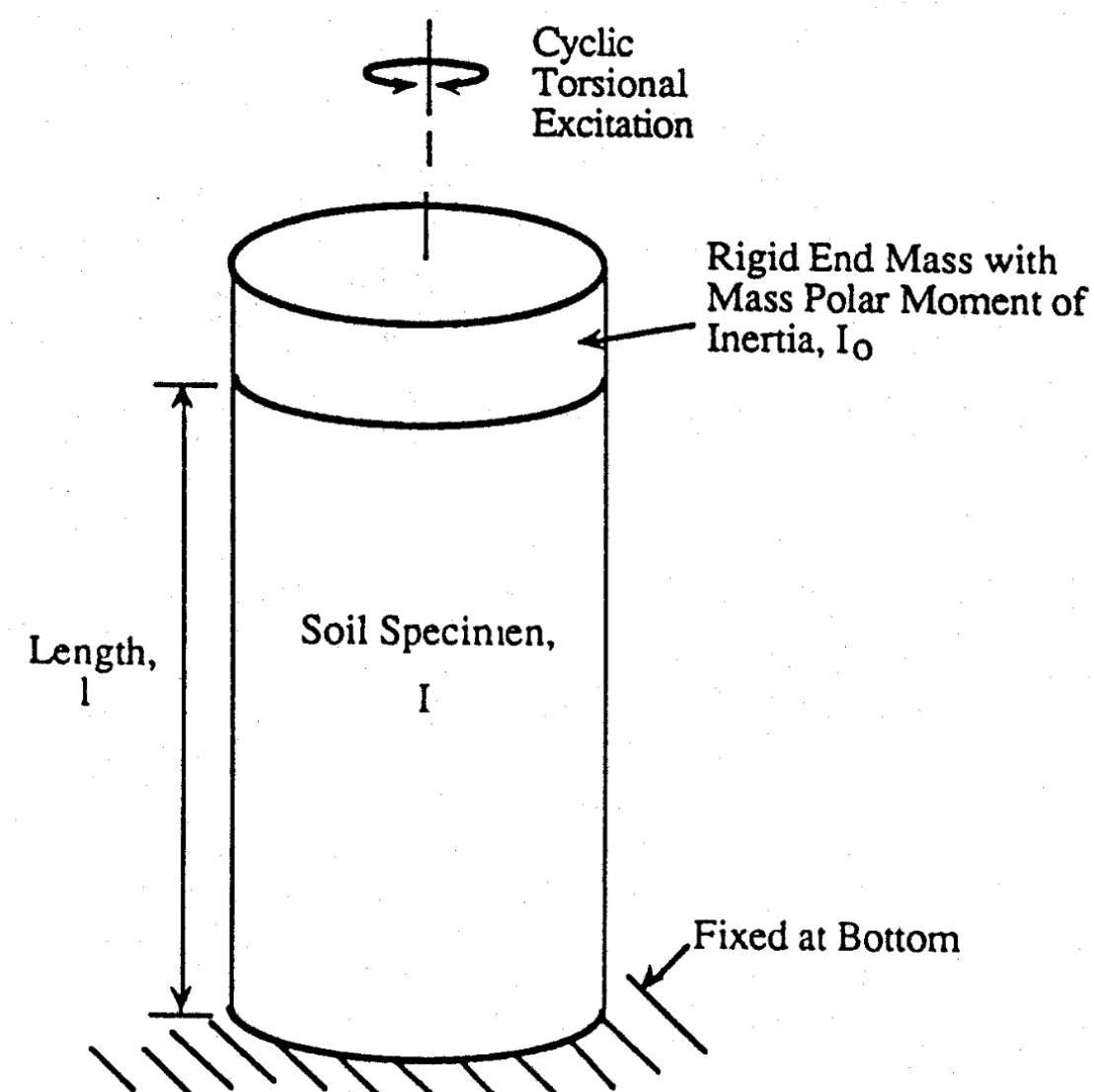
A_c : output voltage of accelerometer,

T_r : resonant period,

CF : accelerometer calibration factor,

D_{ac} : distance between the location of accelerometer and the axis of the specimen, and

l : length of specimen



Lab DAMPING with resonant column test

Determining the dynamic deformation properties (shear modulus **G** and damping ratio **D**) of soils.

3.3 Damping Ratio

- Calculate the damping ratio using free-vibration decay method or half-power bandwidth method
- Calculate the damping ratio using free-vibration decay method

$$D = \sqrt{\frac{\delta^2}{4\pi^2 + \delta^2}}$$

where

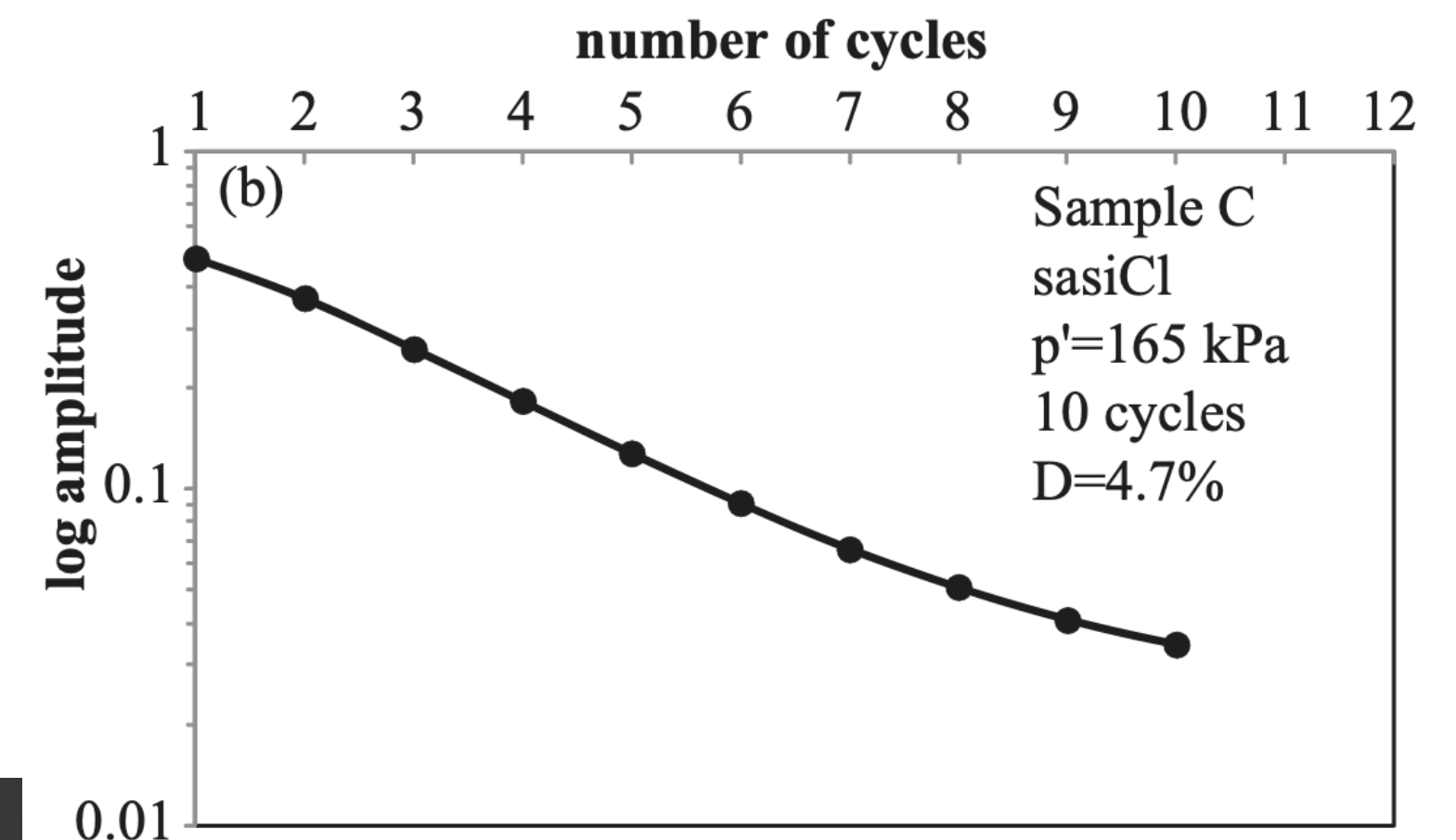
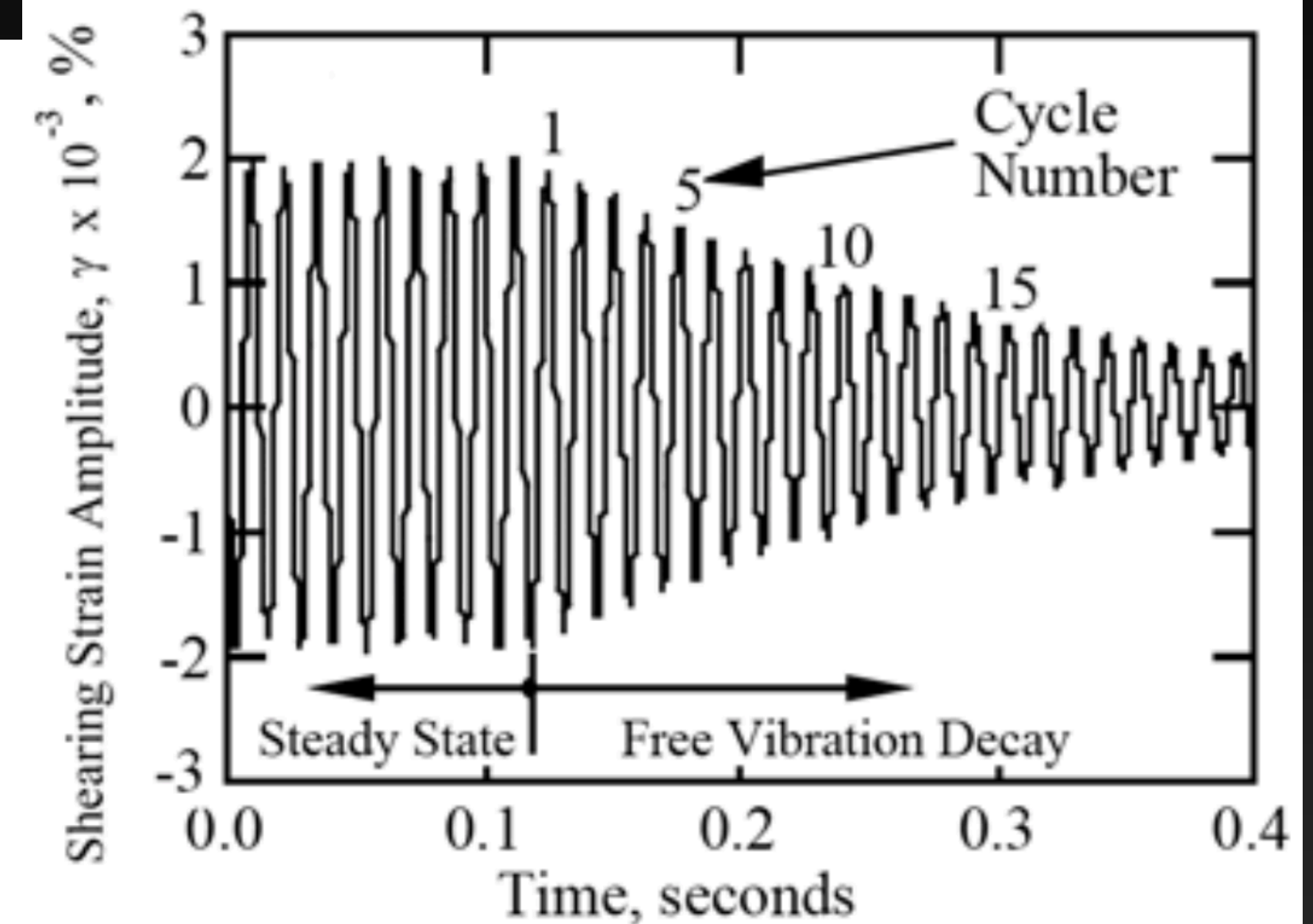
δ : logarithmic decrement of strain amplitudes, which is defined as:

$$\delta = \ln\left(\frac{Z_1}{Z_2}\right) = \frac{2\pi D}{\sqrt{1-D^2}}$$

where

Z_1, Z_2 : two successive strain amplitudes of motion, and

D : material damping ratio



Lab DAMPING with resonant column test

Determining the dynamic deformation properties (shear modulus **G** and damping ratio **D**) of soils.

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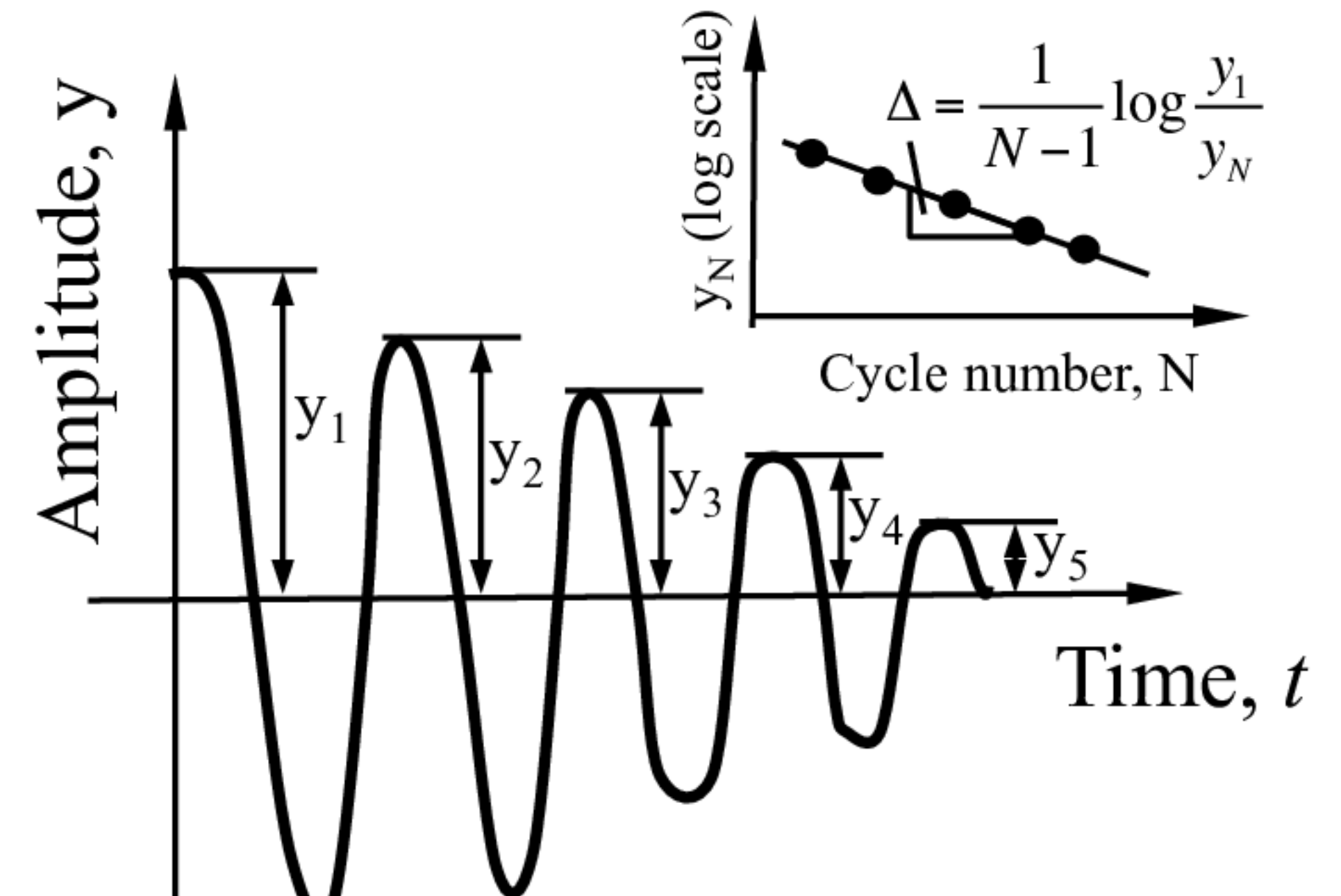
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where

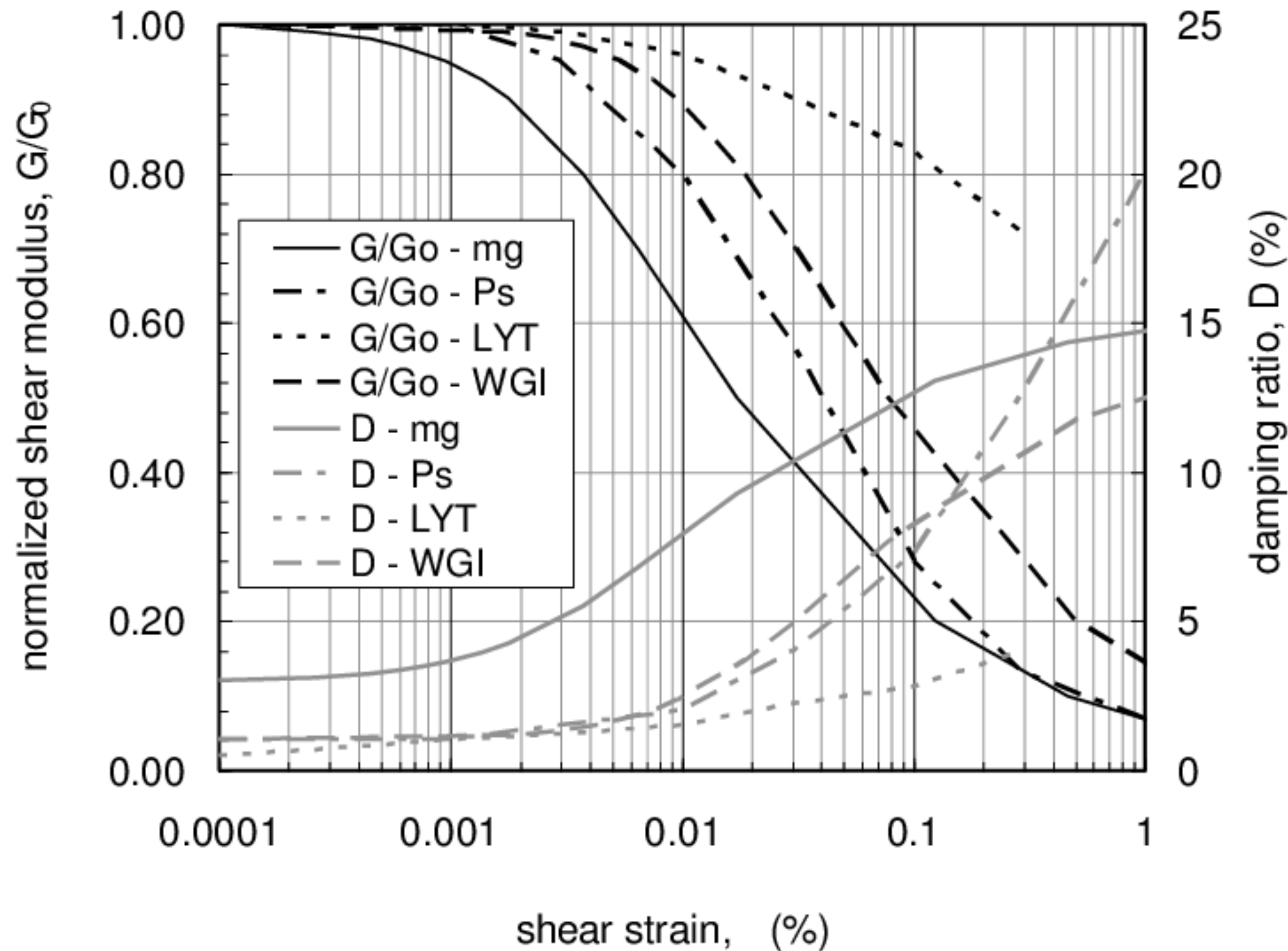
Z_1, Z_2 : two successive strain amplitudes of motion, and

D : material damping ratio



*For moderate deformation
D can be assumed as
Independent from frequency !*

Lab DAMPING with resonant column test



Different soils , different shear modulus G and damping ratio D .

Expressed in function of the shear strain γ (%)

$\gg \gamma \gg D$ (%)

$\gg \gamma \ll G$ (G/G_0)

$G_0 = G_{max} = G$ initial condition



S

Modello d'interpolazione di Yokota et al., 1981

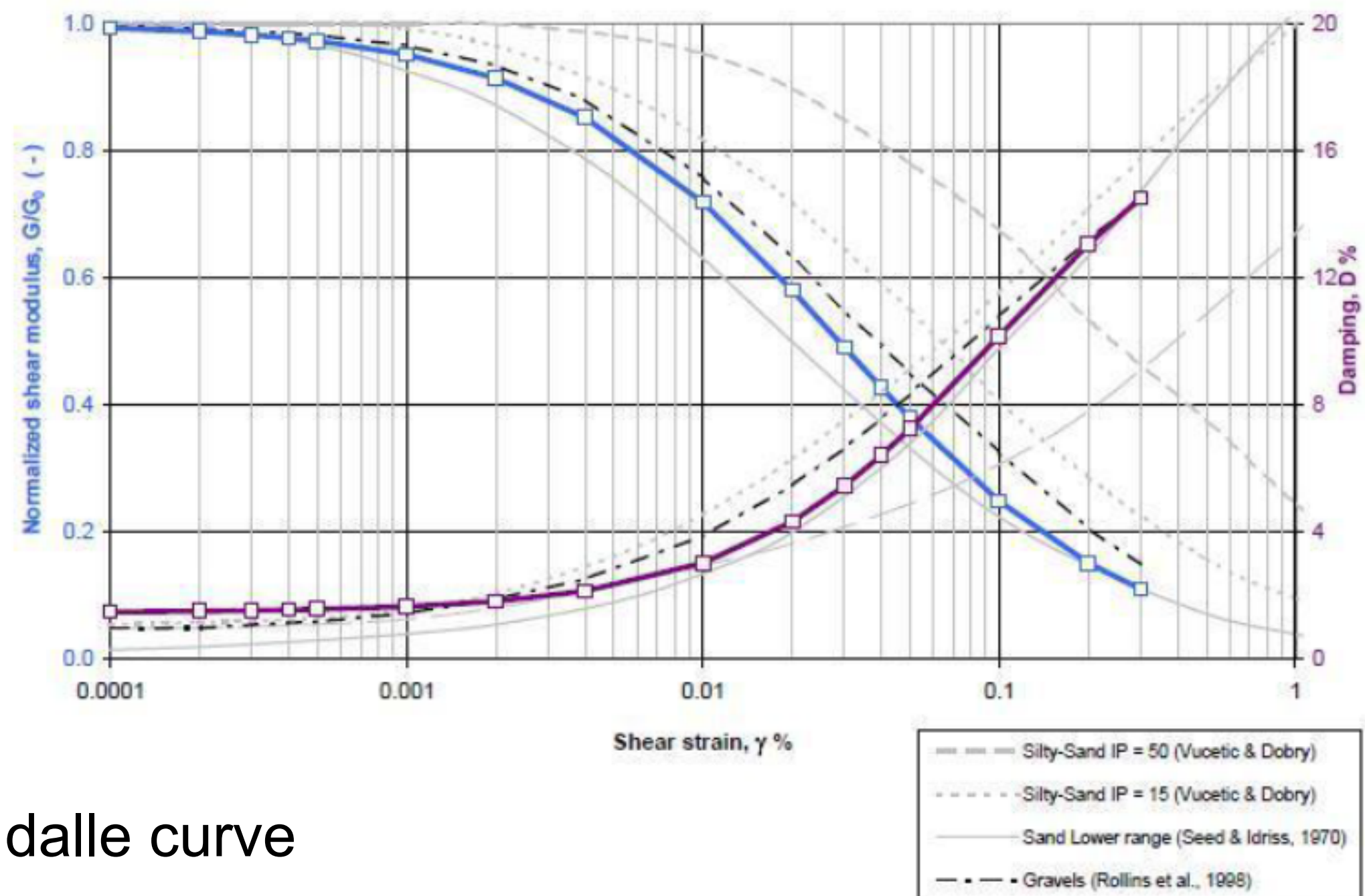
Resonant Column Tests

fitting of Yokota et al. (1981) model to experimental data obtained on 2 samples: S2-CD L (21.70-22.00 m) and S2-CD M (24.00-24.40 m) at the effective stress of 200 kPa (S2 CD L) and 300 kPa (S2 CD M) normalized using G_0 coming from the hyperbolic relationship of Hardin e Drnevich

α	β	D_{max}	λ
23.3607	0.8887	19.3231	-2.5740

γ (%)	$\frac{G(\gamma)}{G_0} = \frac{1}{1 + \alpha\gamma(\%)^\beta}$	$\frac{D}{D_{max}} = e^{-\frac{\lambda}{\gamma}}$
γ (%)	G / G_0 (-)	D (%)
0.0001	0.994	1.498
0.0002	0.988	1.519
0.0003	0.983	1.539
0.0004	0.978	1.558
0.0005	0.974	1.577
0.001	0.952	1.667
0.002	0.915	1.835
0.004	0.853	2.152
0.01	0.719	3.033
0.02	0.581	4.335
0.03	0.491	5.456
0.04	0.428	6.423
0.05	0.380	7.262
0.1	0.249	10.183
0.2	0.152	13.074
0.3	0.111	14.523

Curve di decadimento per le Sabbie

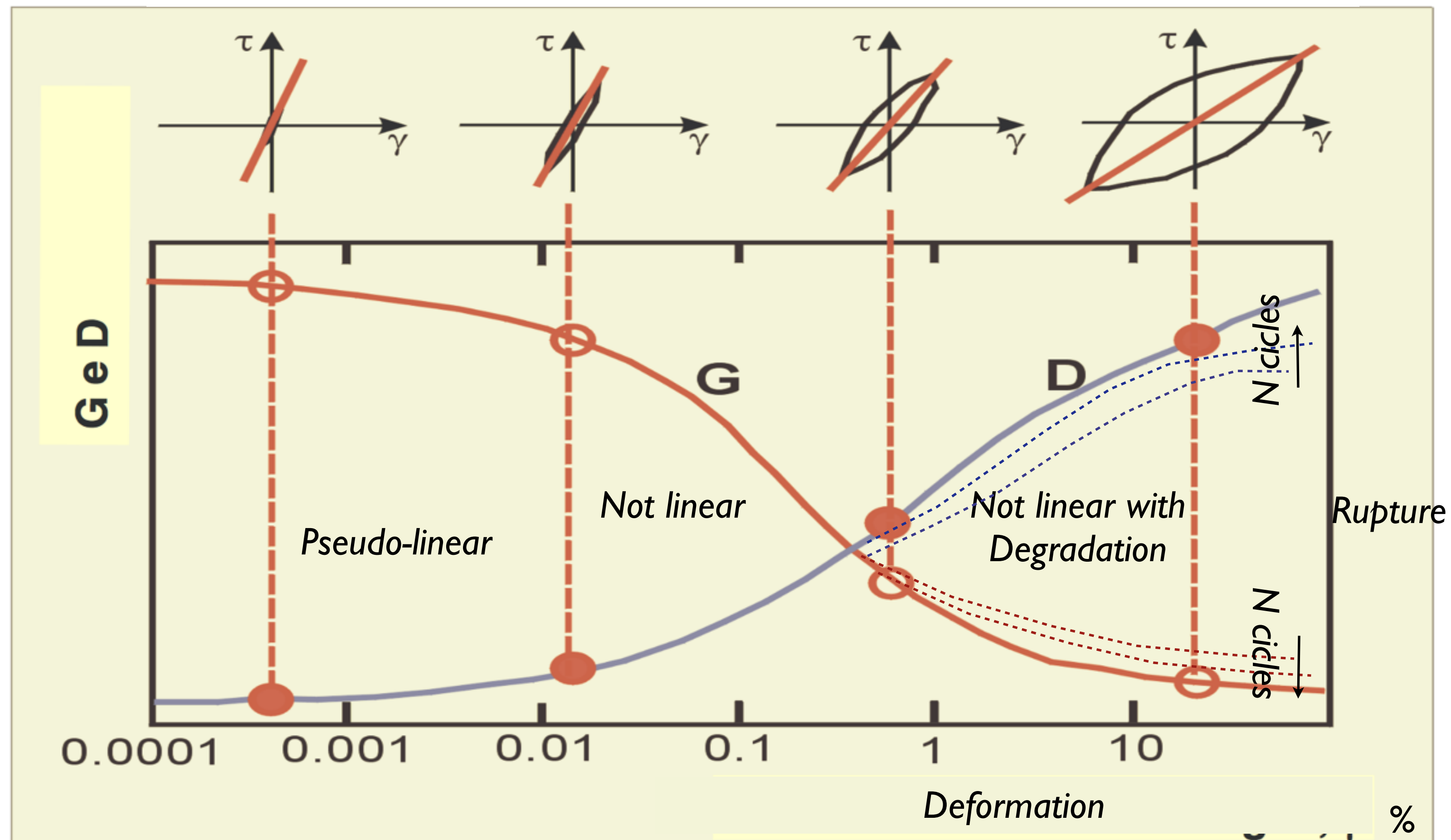


Valori selezionati dalle curve

Soil under cyclic loads

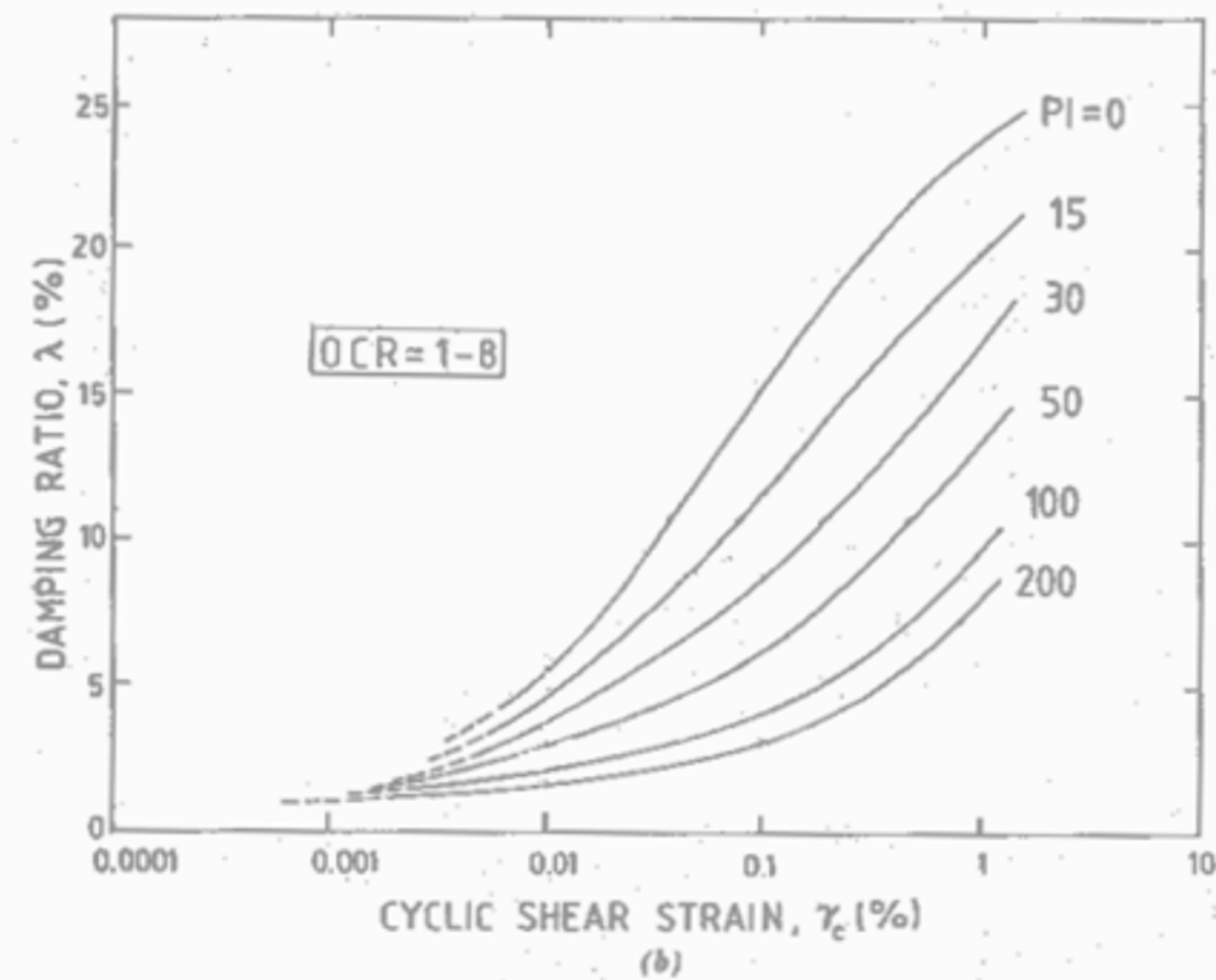
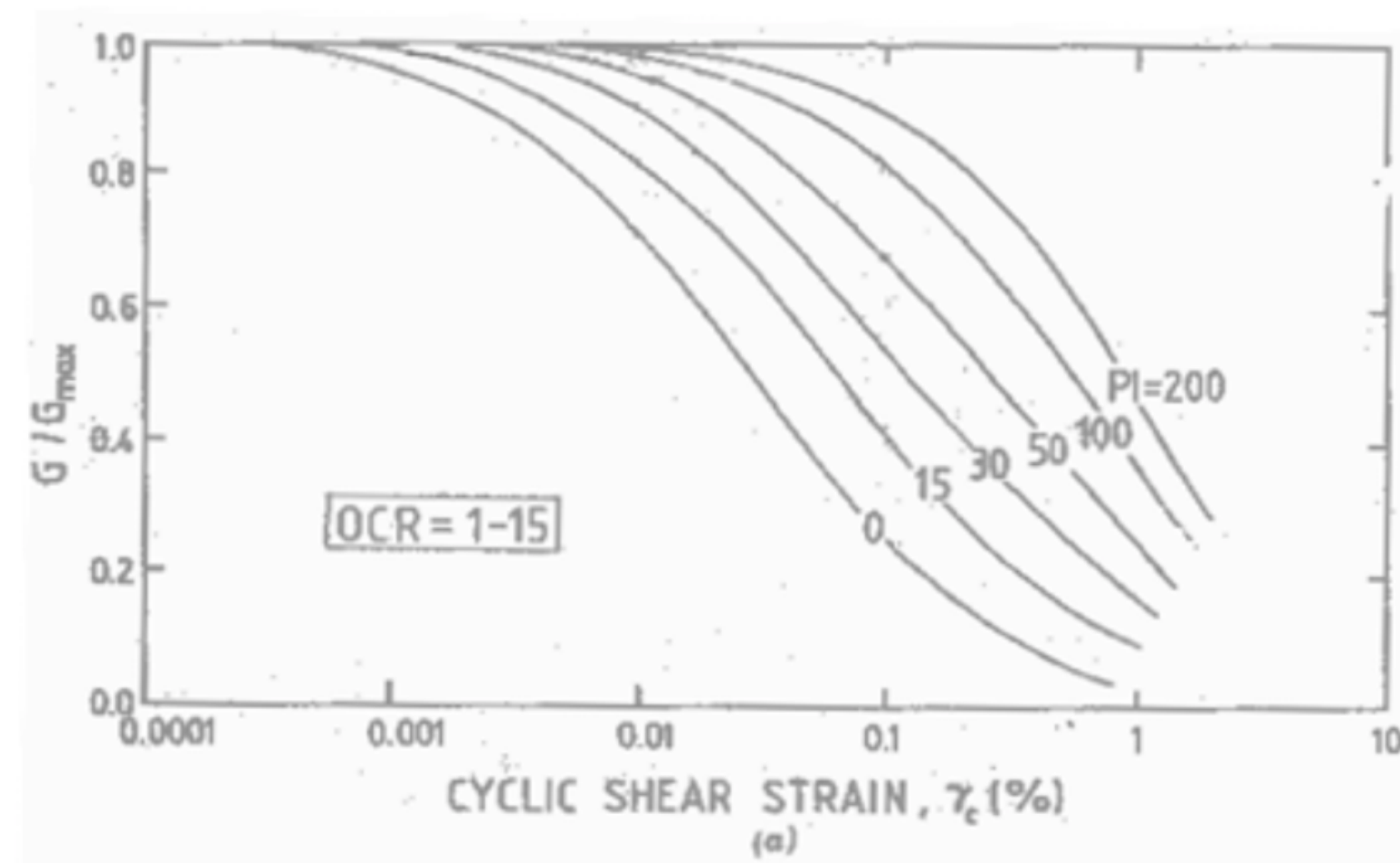
G e D vary in function of deformation γ

NOT LINEAR!

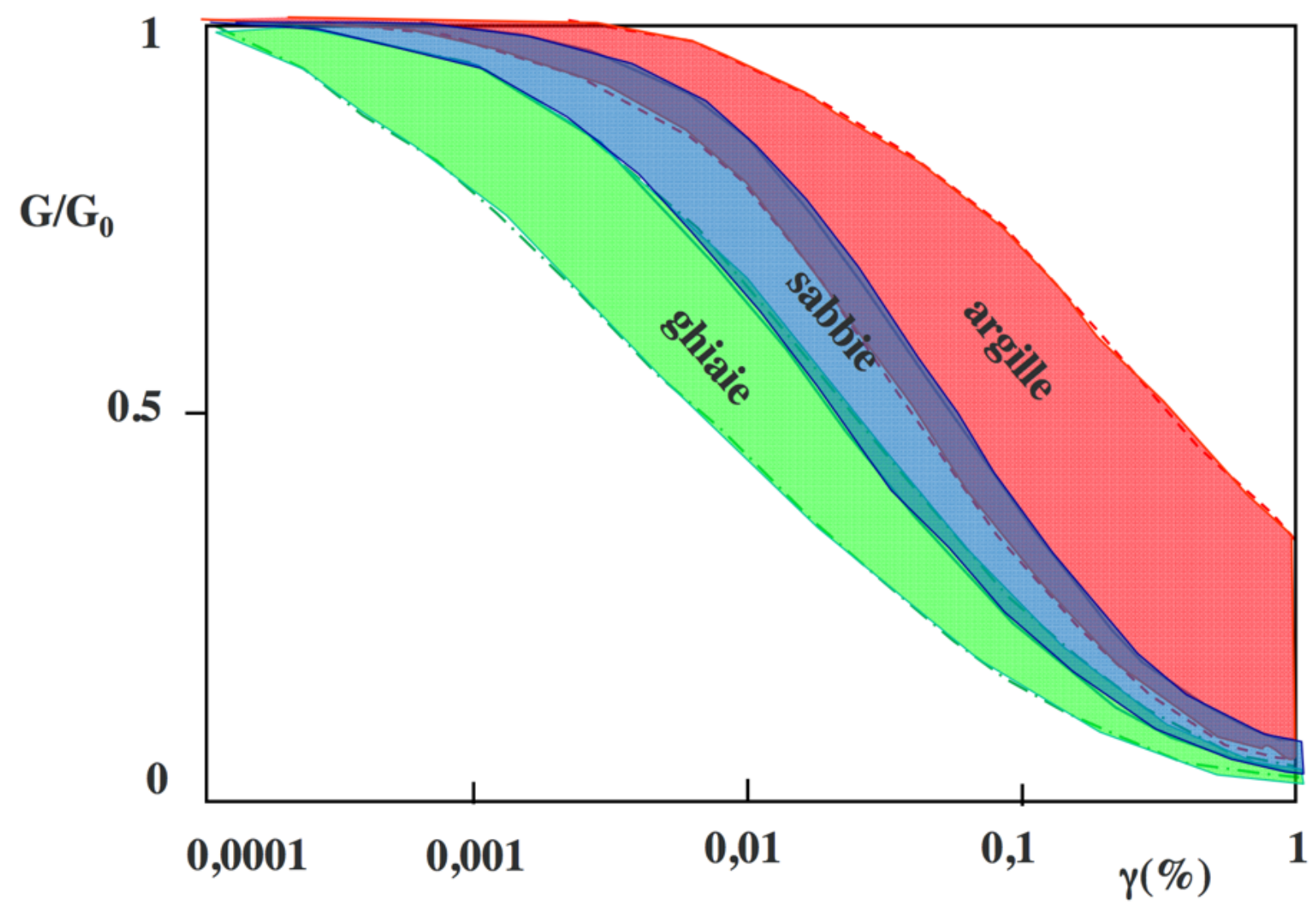


G e D curves in function of soil type

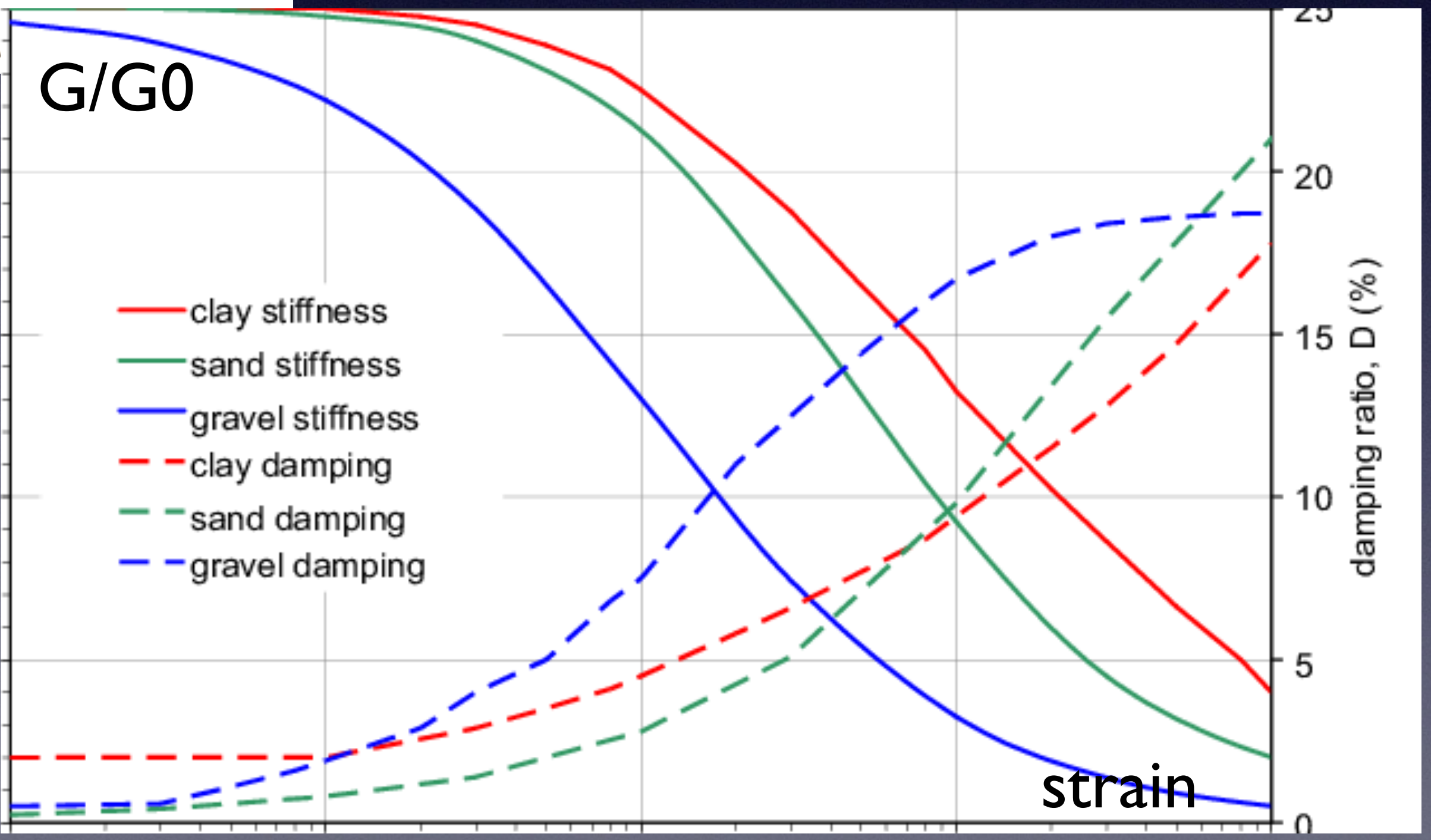
e.g. clay, sand, gravel...



Campi di variazione delle curve $G/G_0-\gamma$



(Seed et al., 1986; Dobry & Vucetic)



Soil visco-elastic homogeneous on rigid plate (kelvin-voigt)

Dynamic equilibrium equation

$$\rho \frac{du}{dt}^2 = G \frac{du}{dz}^2 + \eta \frac{du}{dt dz}^3$$

Viscosity Coefficient

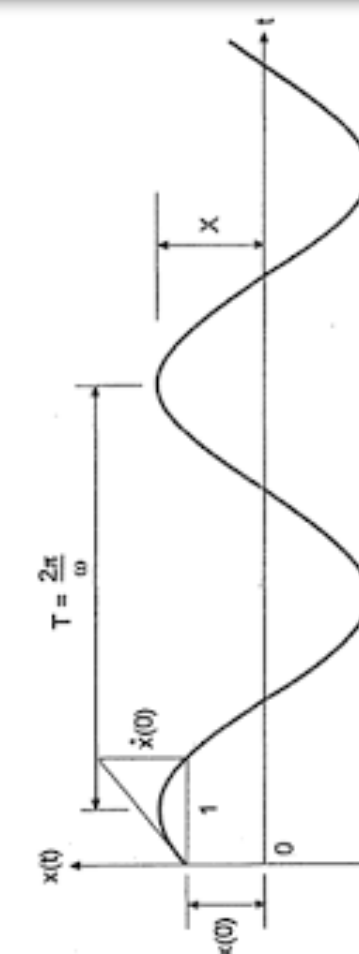
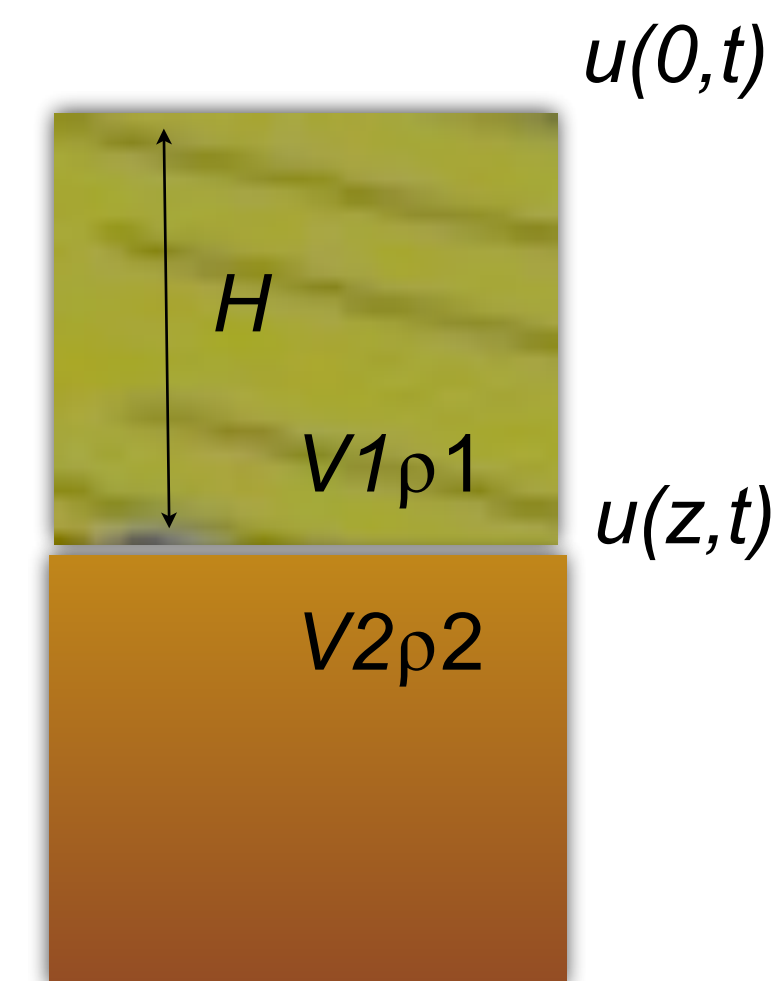
$$\eta = \frac{D (2 G)}{\omega}$$

$$D = \frac{\eta \omega}{2 G}$$

Viscosity
Frequency

DAMPING

G modulus



Soil visco-elastic homogeneous (kelvin-voigt)

Transfer Function

$$H(\omega) = \frac{1}{\cos(kH)}$$



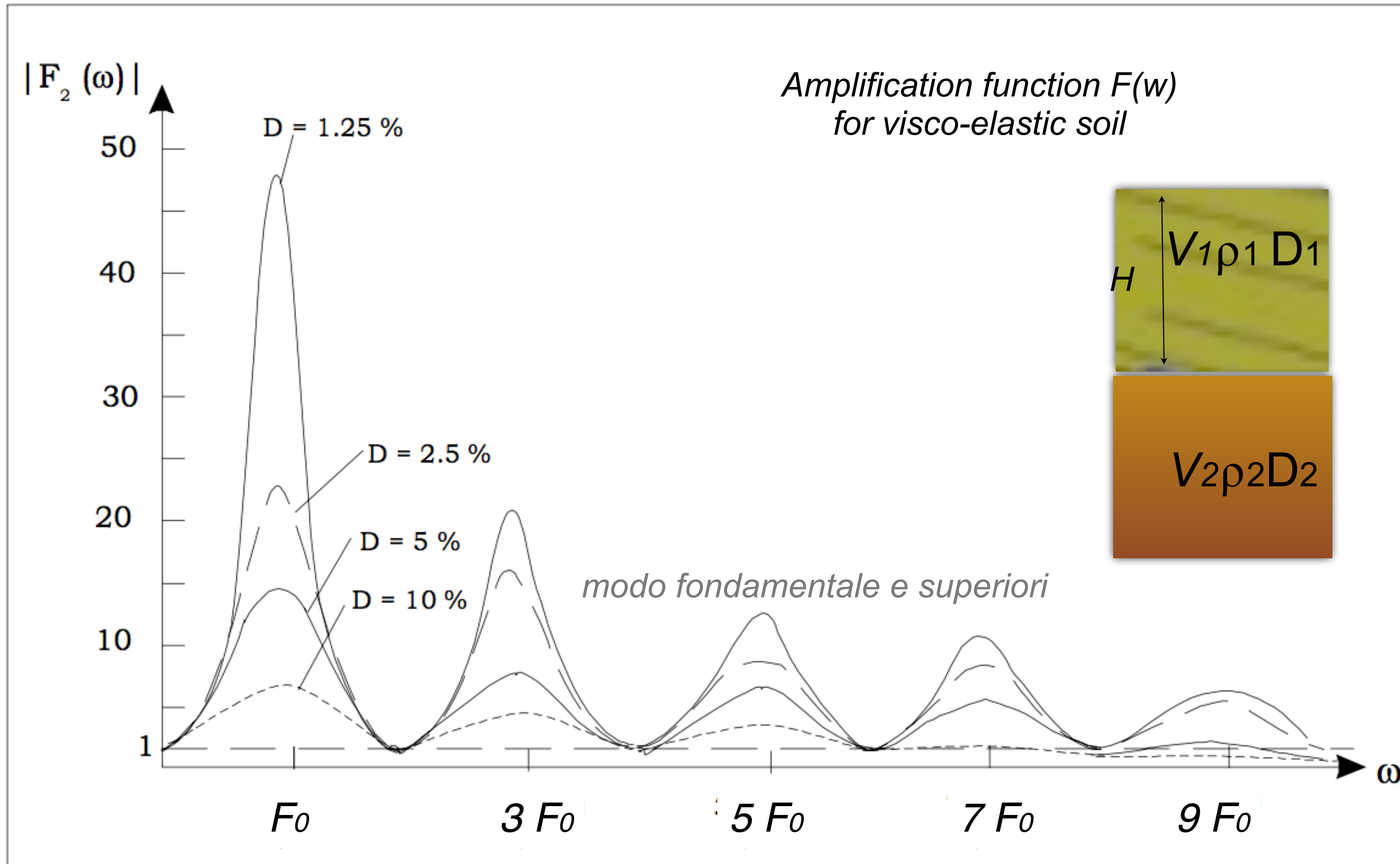
Amplification Function = $|H(\omega)|$

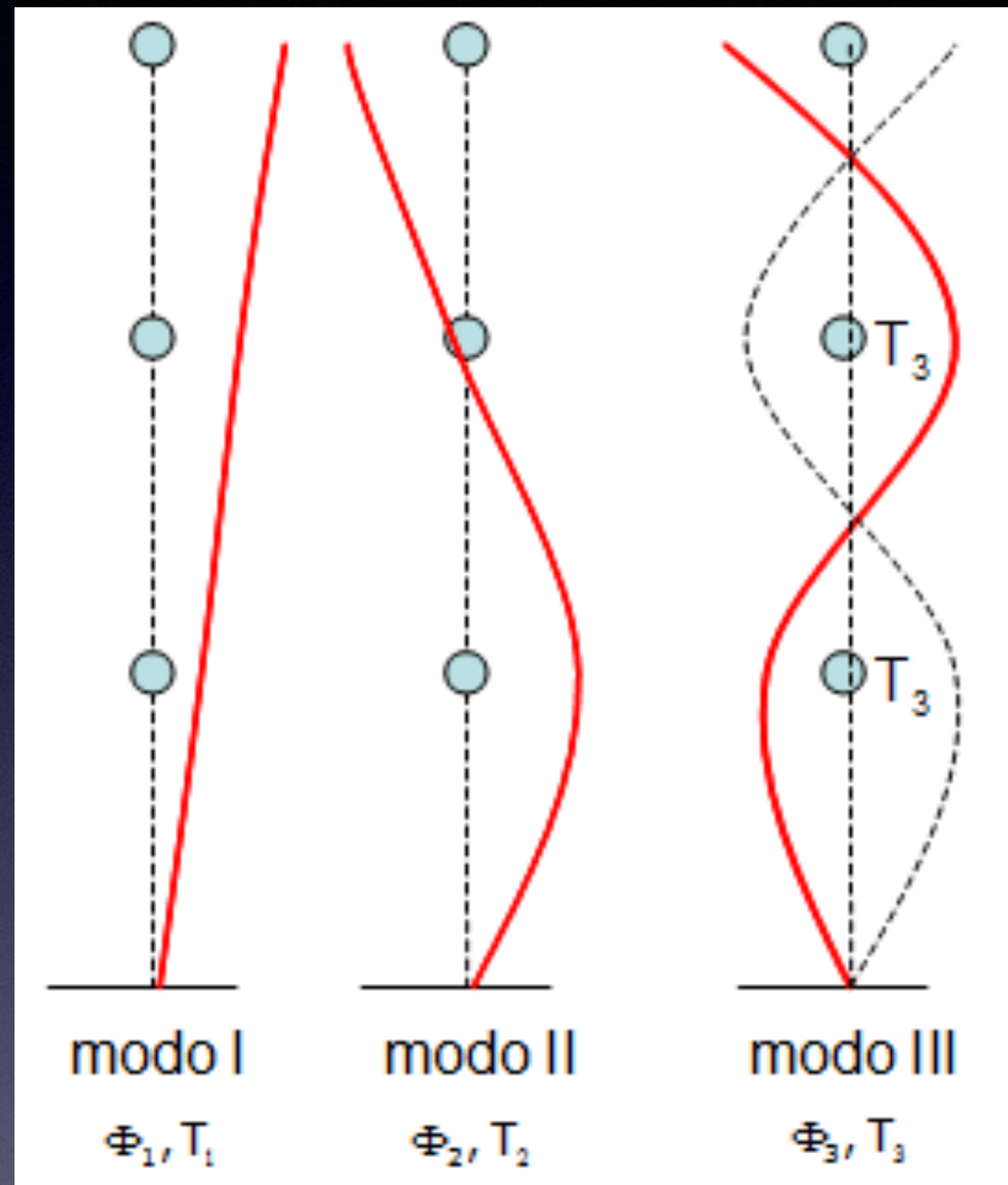
$$F(\omega) = \frac{1}{\sqrt{\cos^2\left(\frac{\omega H}{V_s}\right) + \left(D \frac{\omega H}{V_s}\right)^2}}$$

$$V_s = \sqrt{\frac{G}{\rho}}$$

D

*For moderate deformation
D can be assumed as
Independent from frequency !*





Modes

($n=1$ fundamental mode)

$$u(z,t) = Ae^{j(kz + \omega t)}$$

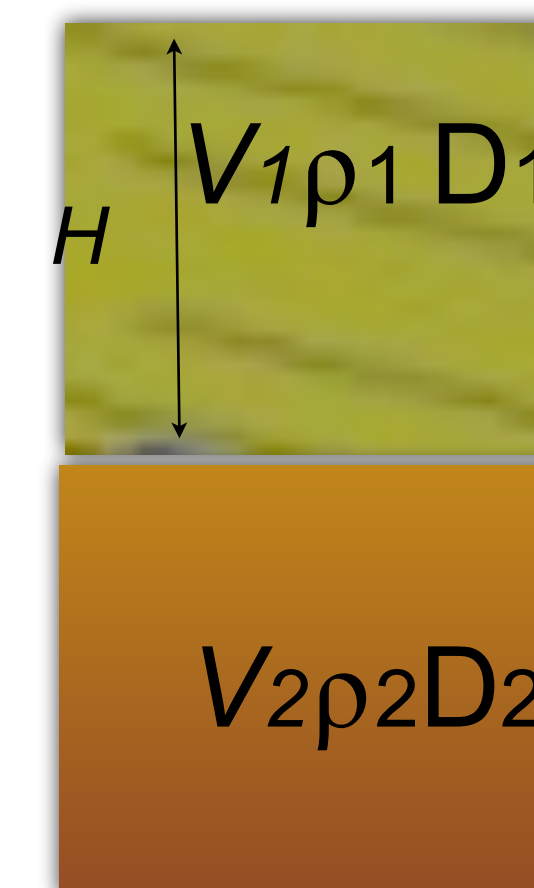
Solution

Soil visco-elastic homogeneous On rigid plate (kelvin-voigt)

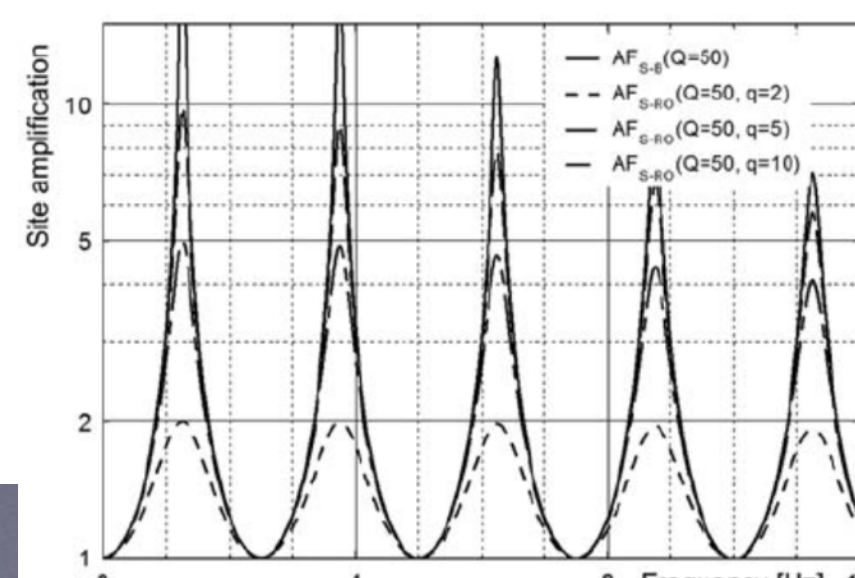
EQUAZIONE EQUILIBRIO DINAMICO

$$\rho \frac{du}{dt}^2 = G \frac{du}{dz}^2 + \eta \frac{du}{dt dz}^2$$

*Solution no more in simple formulation
Amplification factor must be approximated (Roesset ,
1970)*

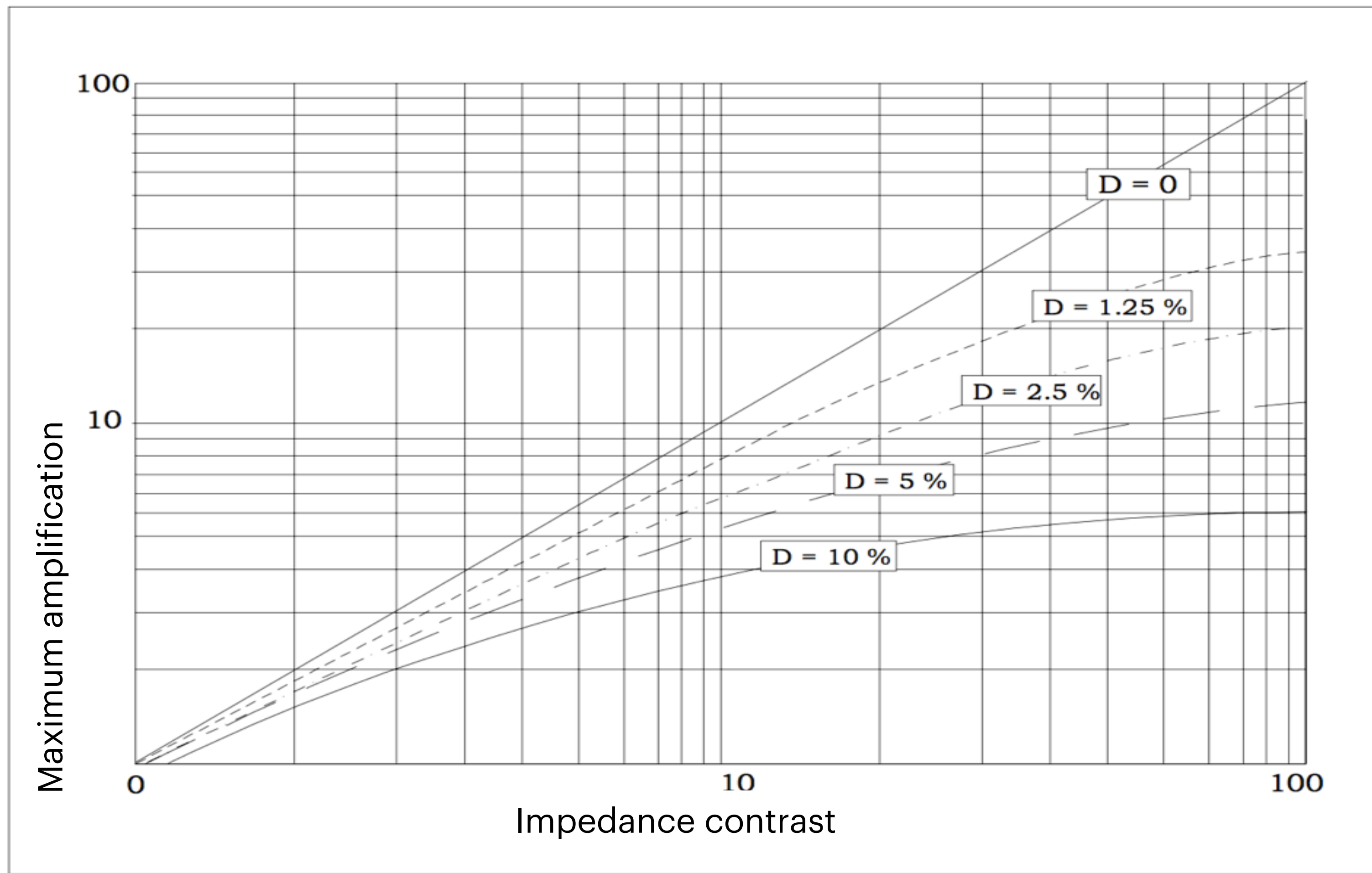


$$F_{max} \approx \frac{1}{\frac{1}{i} + (2n-1) \frac{\pi}{2} D}$$



IMPEDANCE CONTRAST

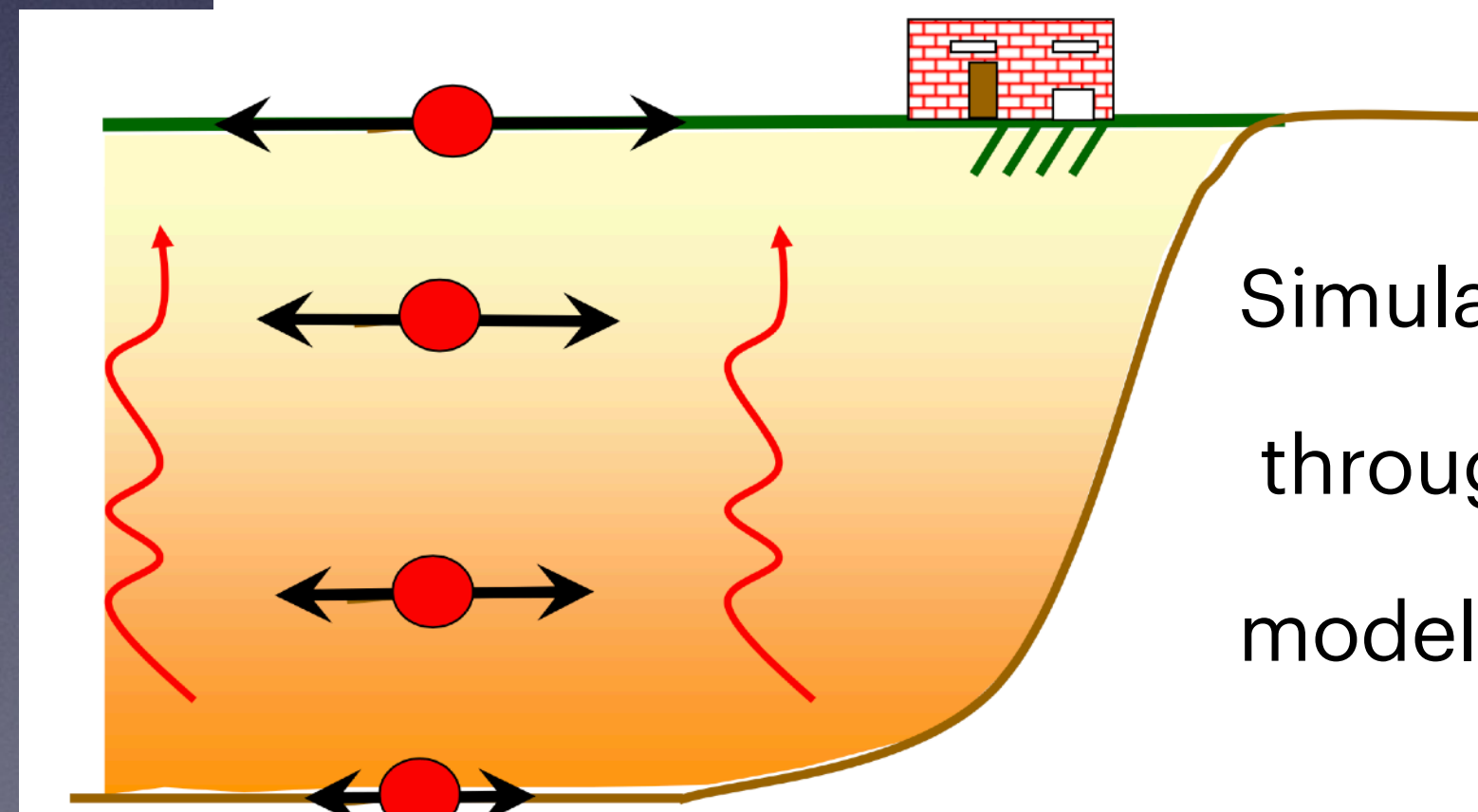
$$i = \frac{v_1 \rho_1}{v_2 \rho_2}$$



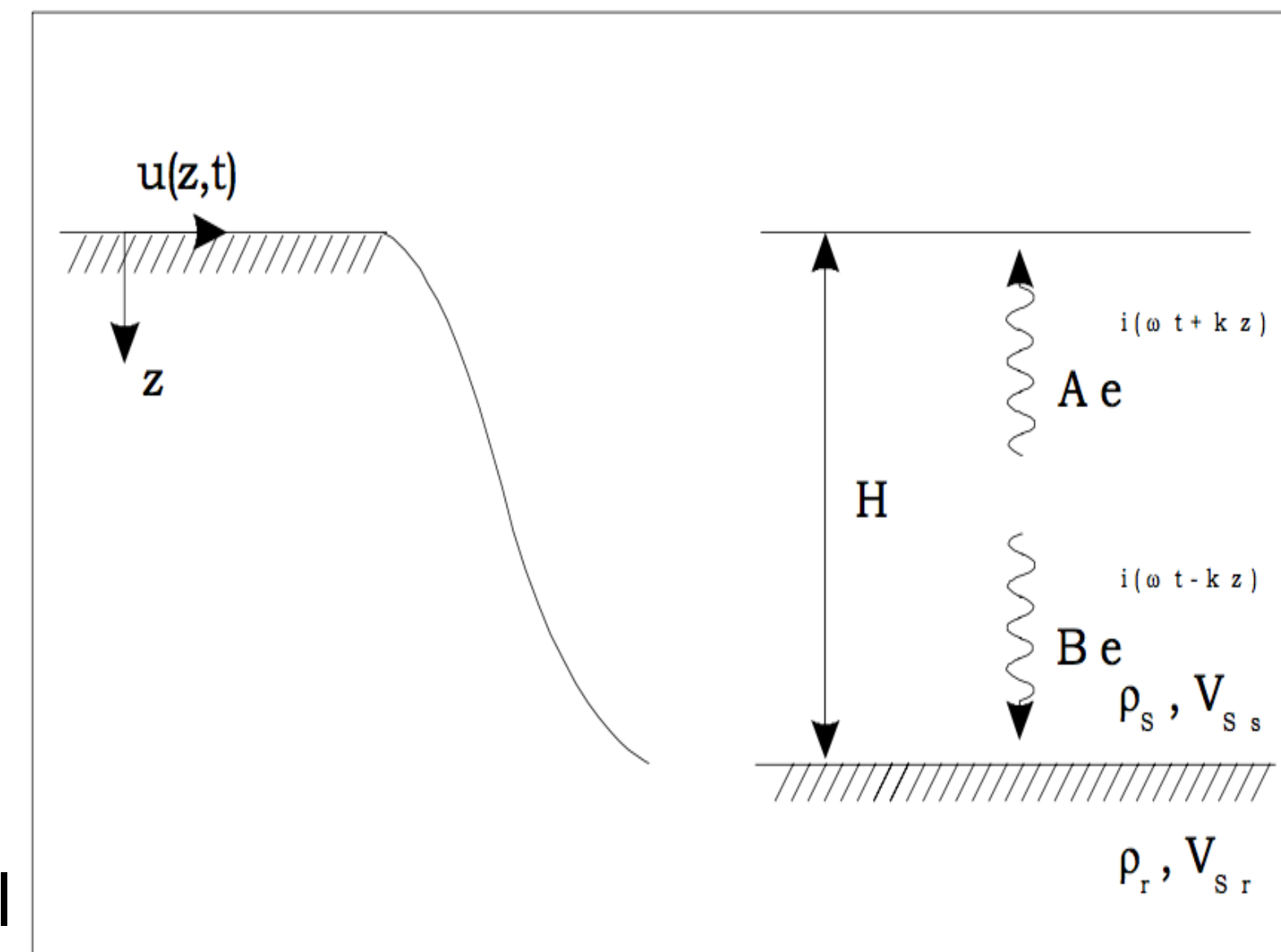
Response depends on impedance contrast and damping D

Numerical methods for Seismic response analysis

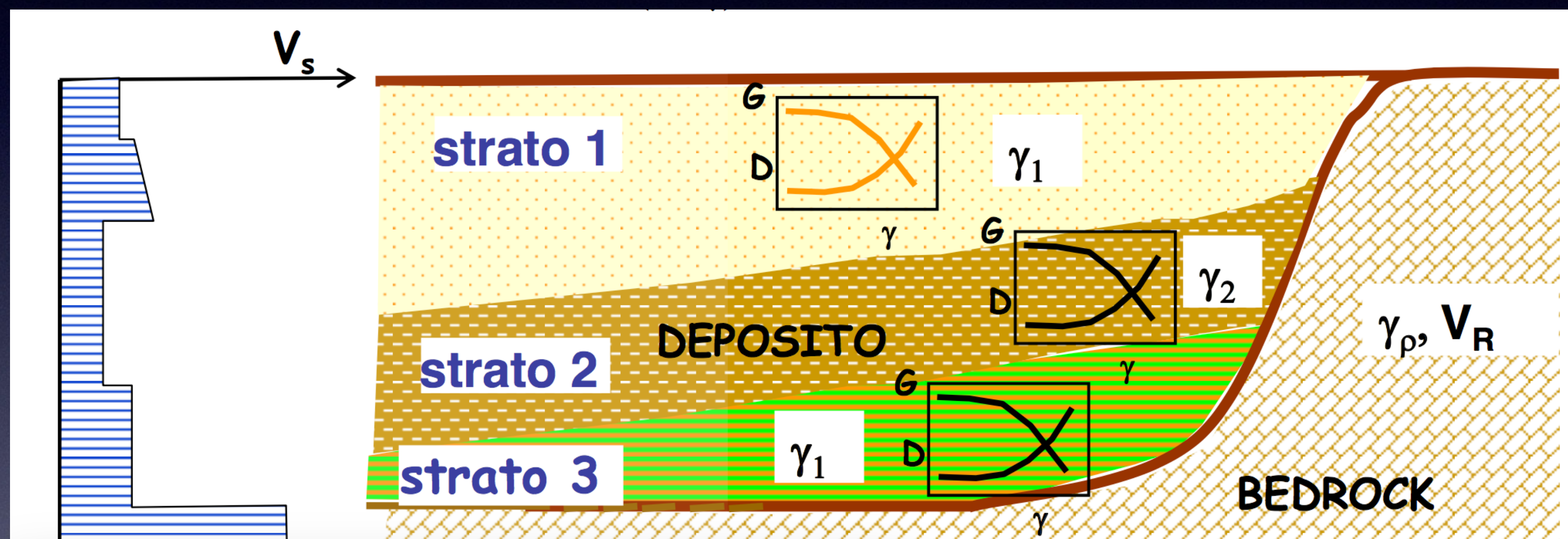
$$\rho \frac{du}{dt}^2 = G \frac{du}{dz}^2 + \eta \frac{du}{dt dz}^3$$



Simulate the motion
through a known soil
model

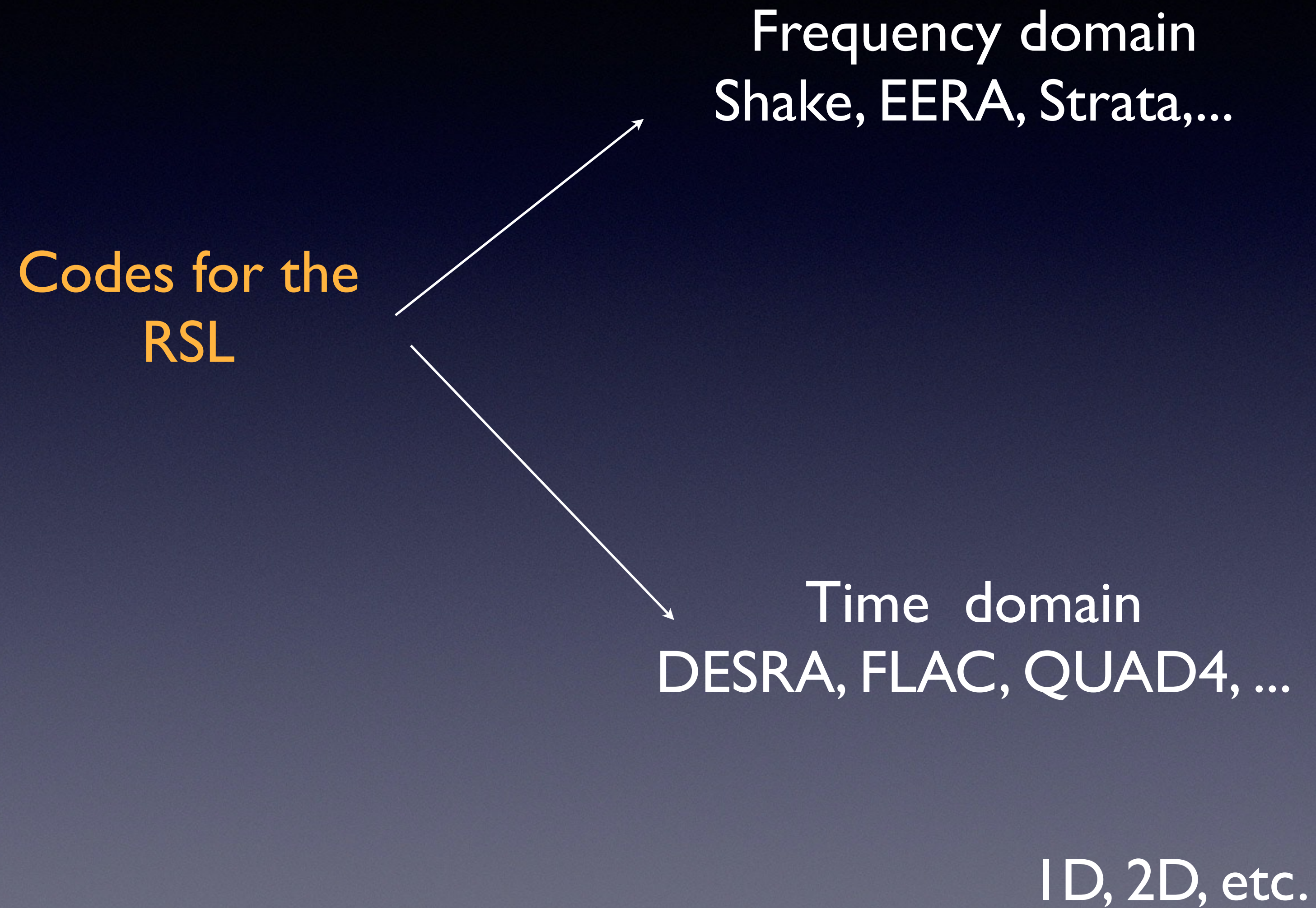


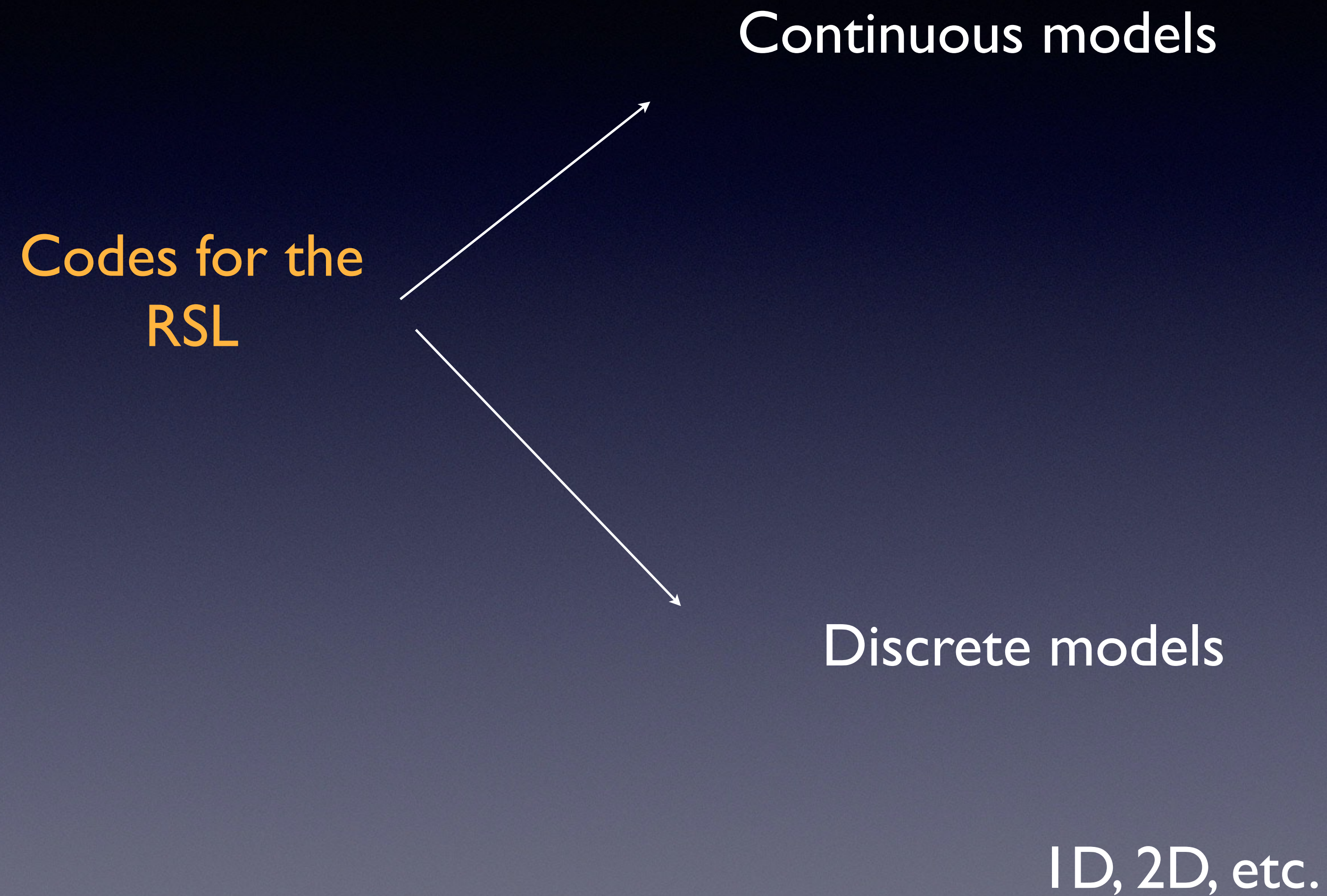
Numerical methods for Seismic response analysis



**Synthetic
Models of soil
Shaking
Based on soil
properties and a
Given earthquake as
input**

(the Deterministic approach)

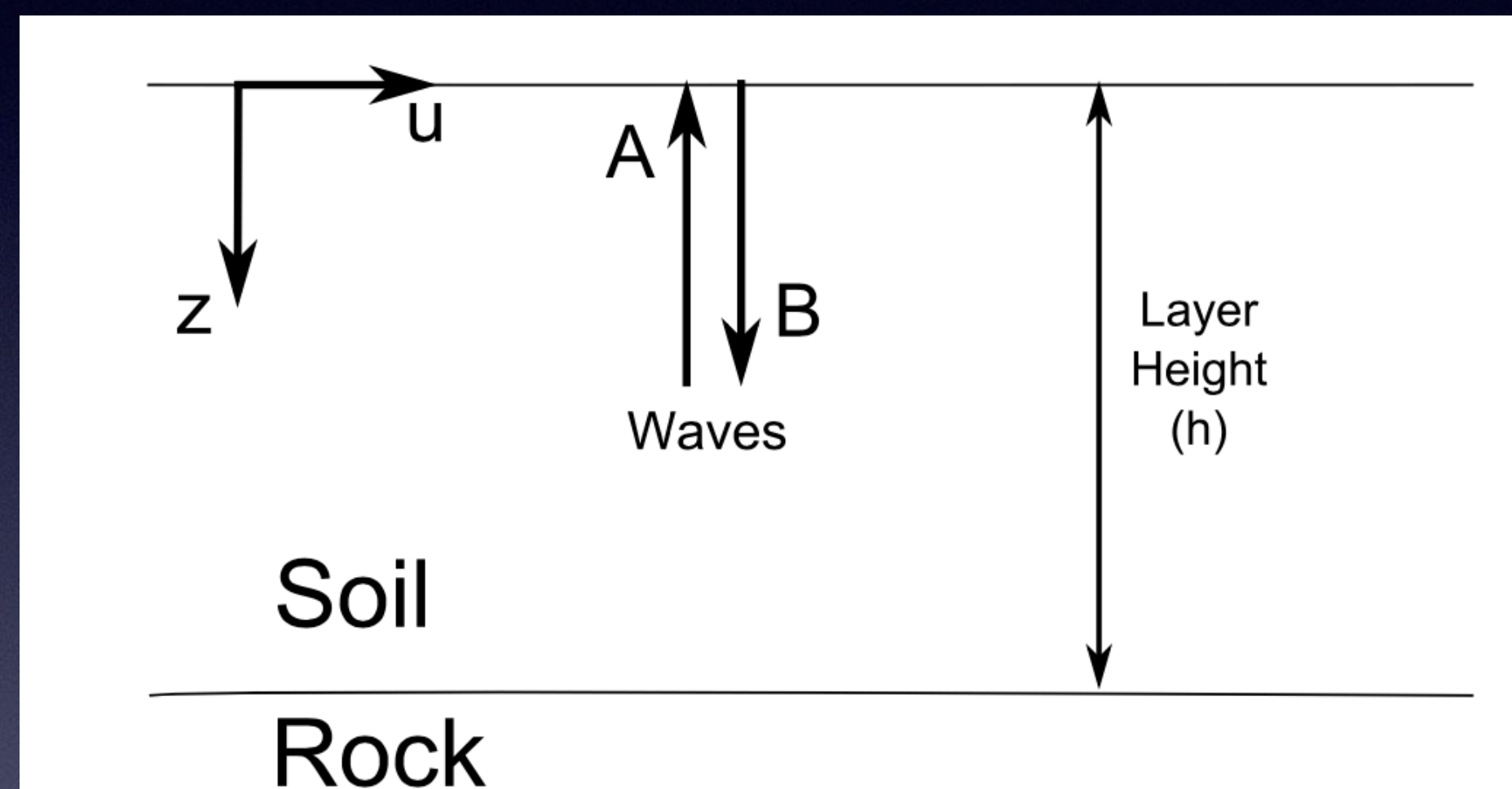




Seismic Response Analysis

Linear-equivalent methods

Iteratively consider non linearity in the response



A direct waves

B reflected waves

Multi-layers models

$$u(z, t) = A \exp [i (\omega t + k^* z)] + B \exp [i (\omega t - k^* z)]$$

A and B wave amplitudes

1	A_1	$\uparrow \downarrow B_1$	$\rho_1 h_1 G_1 D_1$
2	A_2	$\uparrow \downarrow B_2$	$\rho_2 h_2 G_2 D_2$

m	A_m	$\uparrow \downarrow B_m$	$\rho_m h_m G_m D_m$
$m + 1$	A_{m+1}	$\uparrow \downarrow B_{m+1}$	$\rho_{m+1} h_{m+1} G_{m+1} D_{m+1}$

n	A_n	$\uparrow \downarrow B_n$	$\rho_n h_n G_n D_n$
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Seismic Response Analysis

Linear-equivalent methods

Iteratively consider non linearity in the response

$$u(z, t) = A \exp [i (\omega t + k^* z)] + B \exp [i (\omega t - k^* z)]$$

$$k^* = \frac{\omega}{v_s^*}$$

$$v_s^* = \sqrt{\frac{G^*}{\rho}}$$

$$G^* = G (1 - 2D^2 + i2D \sqrt{1 - D^2}) \approx G(1 + i2D)$$

We need
the strain in each layer
(that is function of G and D)

Linear-equivalent methods

Iteratively consider non linearity in the response

$$u(z,t) = A e^{j(kz + \omega t)}$$

$$TF_{mn}^{\text{strain}}(\omega) = \frac{\gamma(\omega, z = h_m/2)}{\ddot{u}_{n,\text{outcrop}}(\omega)} = \frac{ik_m [A_m \exp(ik_m^* h_m/2) - B_m \exp(-ik_m^* h_m/2)]}{-\omega^2 (2 \cdot A_n)}$$

1	$A_1 \uparrow \downarrow B_1$	$\rho_1 h_1 G_1 D_1$
2	$A_2 \uparrow \downarrow B_2$	$\rho_2 h_2 G_2 D_2$
\dots	\dots	\dots
m	$A_m \uparrow \downarrow B_m$	$\rho_m h_m G_m D_m$
$m+1$	$A_{m+1} \uparrow \downarrow B_{m+1}$	$\rho_{m+1} h_{m+1} G_{m+1} D_{m+1}$
\dots	\dots	\dots
n	$A_n \uparrow \downarrow B_n$	$\rho_n h_n G_n D_n$

The codes compute the strain transfer Function between the layers $m, m+n$, (generally at the middle of the layer $H_m/2$)

Seismic Response Analysis

Linear-equivalent methods

Iteratively consider non linearity in the response

$$TF_{mn}^{strain}(\omega) = \frac{\gamma(\omega, z = h_m/2)}{\ddot{u}_{n,outcrop}(\omega)} = \frac{ik_m [A_m \exp(ik_m^* h_m/2) - B_m \exp(-ik_m^* h_m/2)]}{-\omega^2 (2 \cdot A_n)}$$

1	$A_1 \uparrow \downarrow B_1$	$\rho_1 h_1 G_1 D_1$
2	$A_2 \uparrow \downarrow B_2$	$\rho_2 h_2 G_2 D_2$
\dots	\dots	\dots
m	$A_m \uparrow \downarrow B_m$	$\rho_m h_m G_m D_m$
$m+1$	$A_{m+1} \uparrow \downarrow B_{m+1}$	$\rho_{m+1} h_{m+1} G_{m+1} D_{m+1}$
\dots	\dots	\dots
n	$A_n \uparrow \downarrow B_n$	$\rho_n h_n G_n D_n$

As starting condition it uses the initial values:

$$G = G_0 = G_{max}$$

$$G_{max} = \rho v_s^2$$

$$D = D_0 = D_{min}$$

Linear-equivalent methods

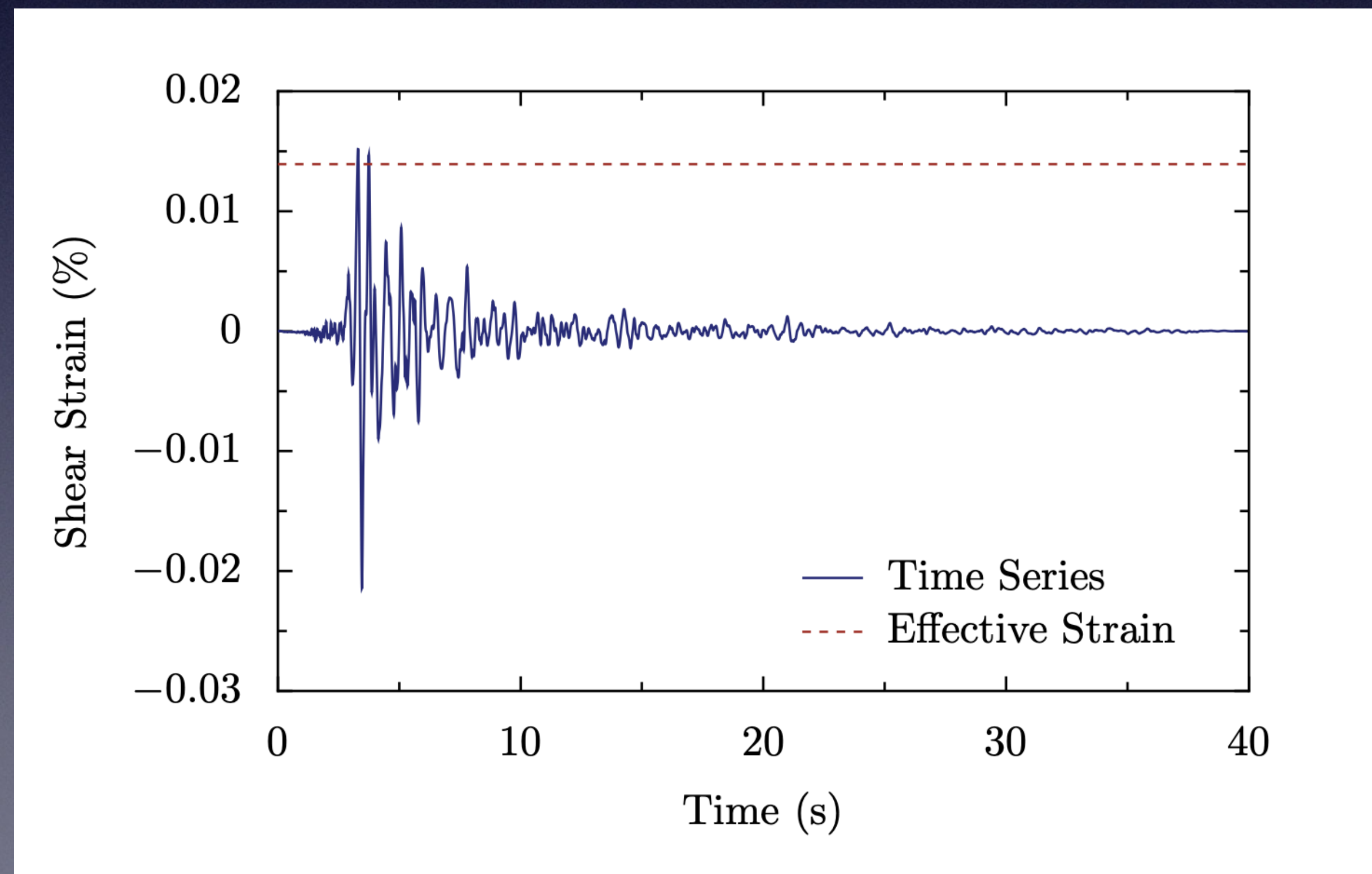
Since the maximum strain γ for G_{max} refers to a very short moment,

A more realistic effective strain is preferred

usually $\gamma_{eff}=65\%$ of γ_{max}

$$\gamma_{eff} = \beta \gamma_{max}$$

$$\beta = 0.65-0.7$$



Seismic Response Analysis

Linear-equivalent methods

1. The wave amplitudes (A and B) are computed for each of the layers
2. The strain transfer function is calculated for each of the layers.
3. The maximum strain within each layer is computed by applying the strain transfer function to the input Fourier amplitude spectrum and finding the maximum response (
4. The effective strain (γ_{eff}) is calculated from the maximum strain within each layer.
5. The strain compatible shear modulus and damping ratio are recalculated based on the new estimate of the effective strain within each
6. The new nonlinear properties (G and D) are compared to the previous iteration and an error is calculated. If the error for all layers is below a defined threshold the calculation stops.

1	$A_1 \uparrow \downarrow B_1$	$\rho_1 h_1 G_1 D_1$
2	$A_2 \uparrow \downarrow B_2$	$\rho_2 h_2 G_2 D_2$

m	$A_m \uparrow \downarrow B_m$	$\rho_m h_m G_m D_m$
$m + 1$	$A_{m+1} \uparrow \downarrow B_{m+1}$	$\rho_{m+1} h_{m+1} G_{m+1} D_{m+1}$

n	$A_n \uparrow \downarrow B_n$	$\rho_n h_n G_n D_n$
-----	-------------------------------	----------------------

In practice:

We compute for each layer

the strain γ by the

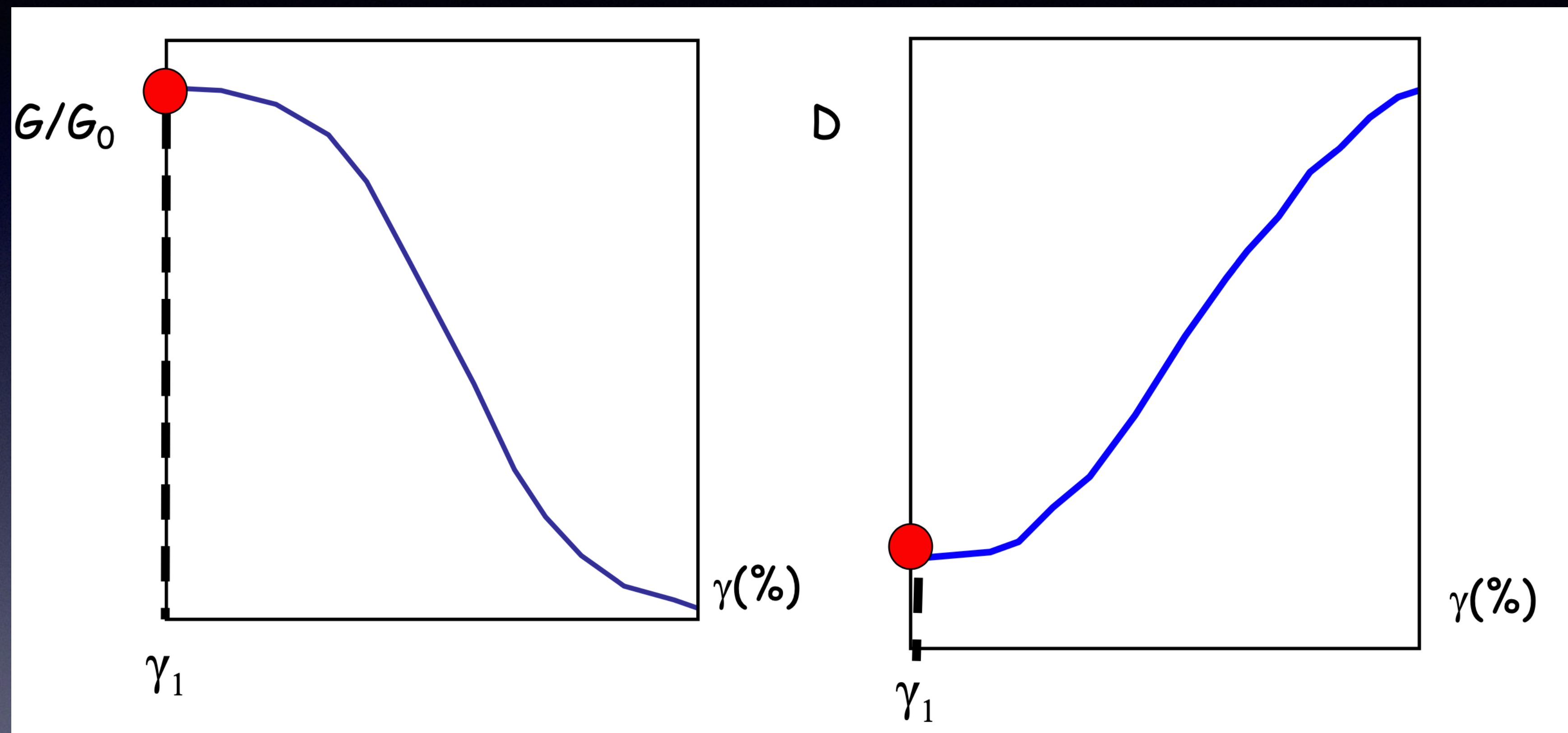
Transfer Function

starting

from G_{max} and D_0

$$G/G_0 = 1$$

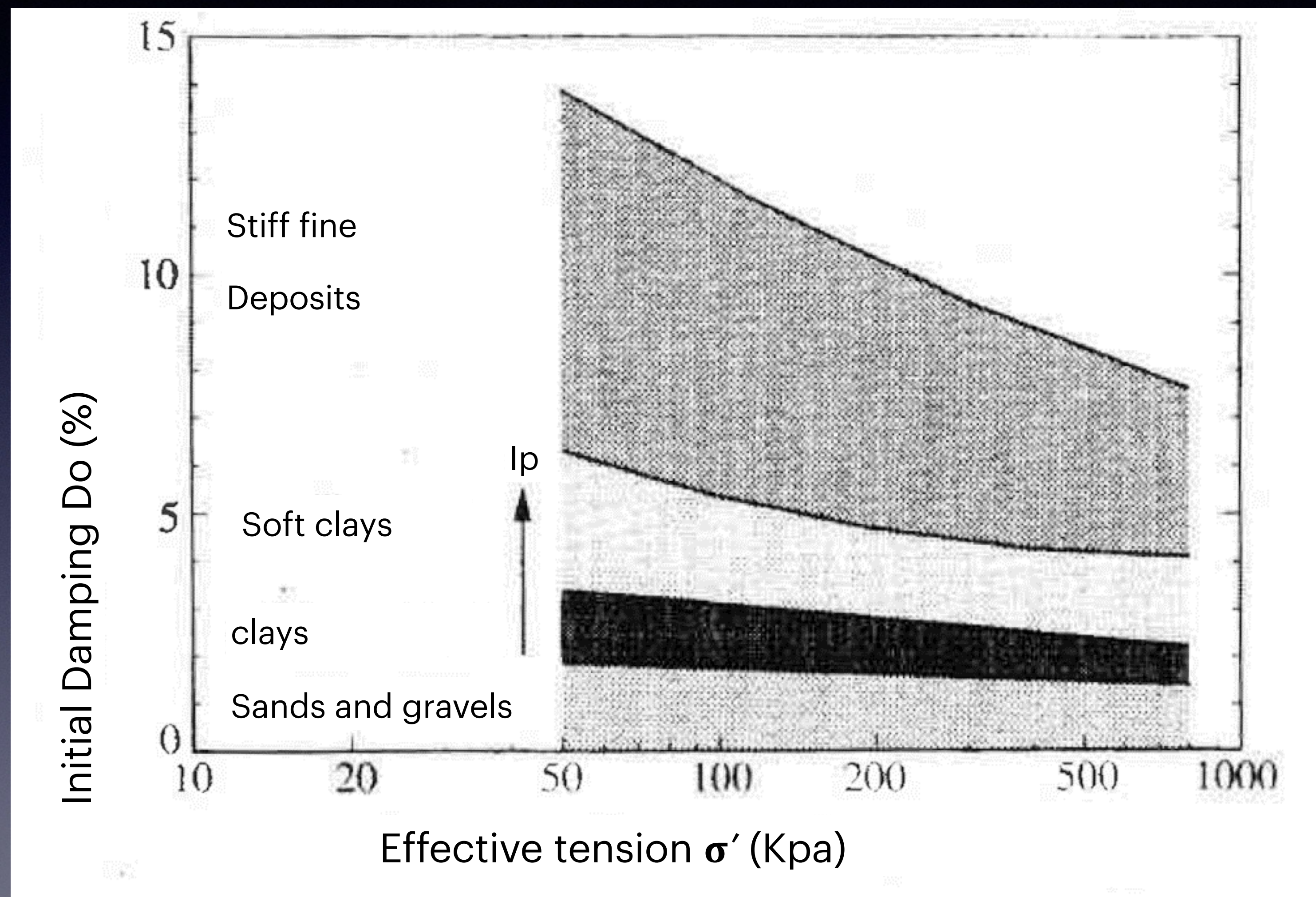
$$G_{max} = G_0 \text{ (from } V_s)$$



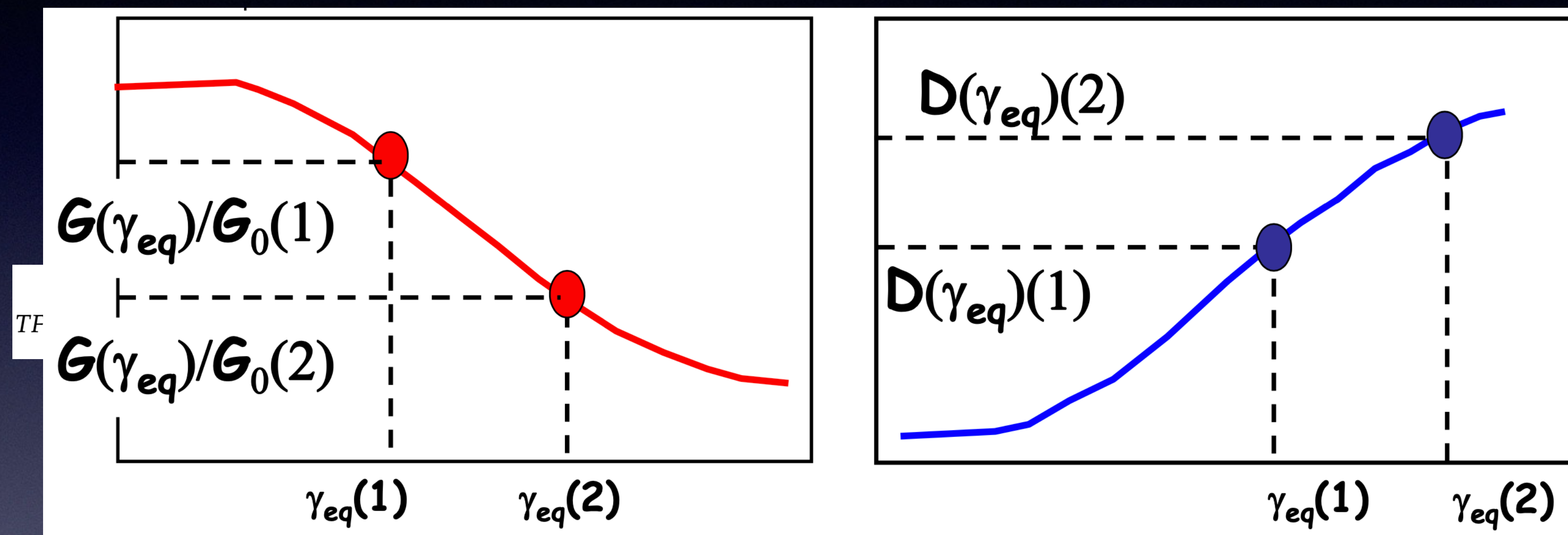
$$G_0 = G_{max} = \rho V_s^2$$

D_0 is considered $\approx 1\%$ for gravel and sands, for finer deposit it depends on effective tension σ'

(literature values are commonly used)



*The resulting G and D
At the strain level γ (i)
reached are
calculated*



*And iteratively compared to the previous one, if difference $if < error \ \varepsilon$
(G decay is not significant) \rightarrow solution converges*

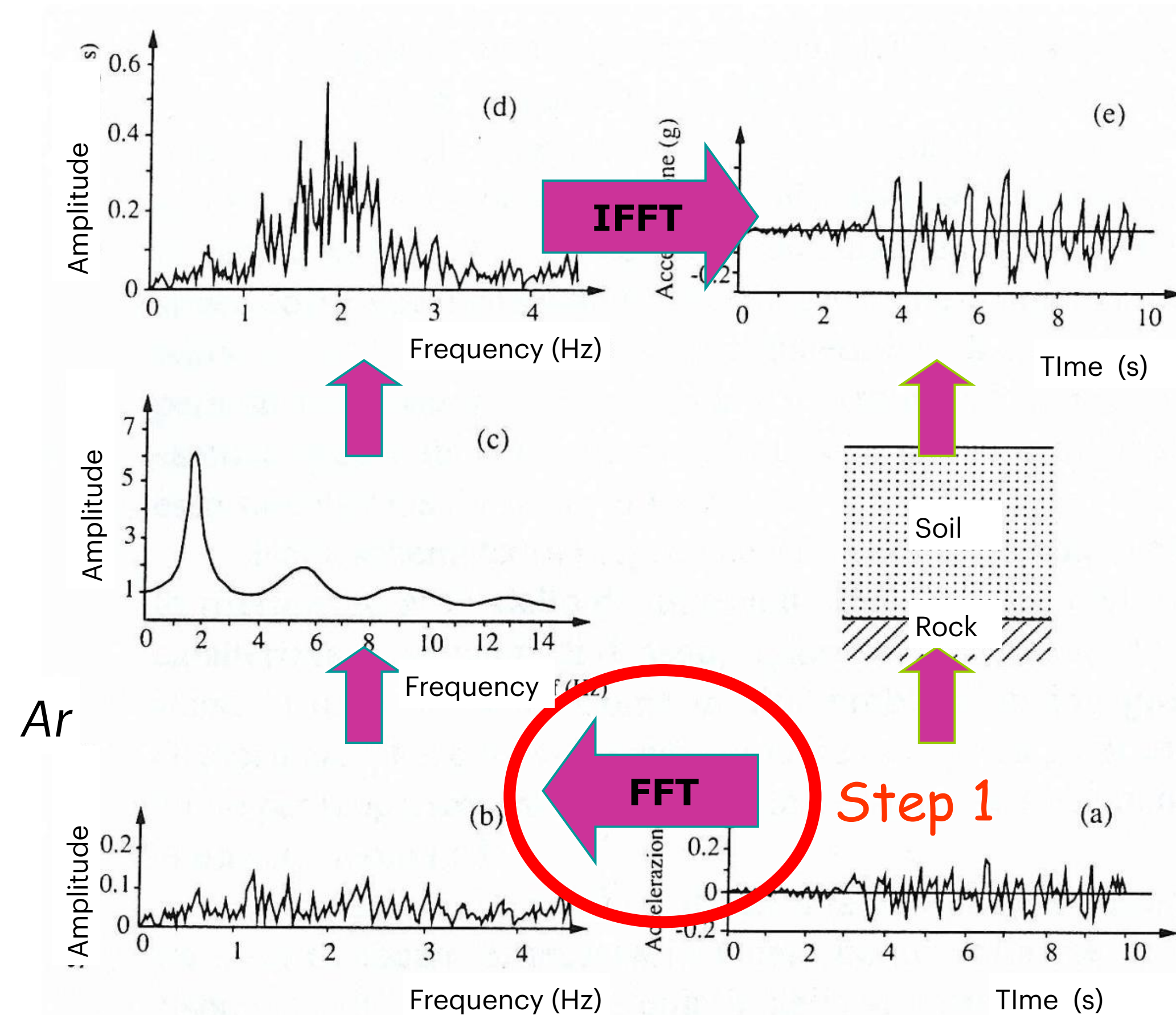
Response Analysis via transfer function computation

(in frequency domain)

Step 1

Compute the Fourier transform FFT of the input accelerogram at the base of the soil column

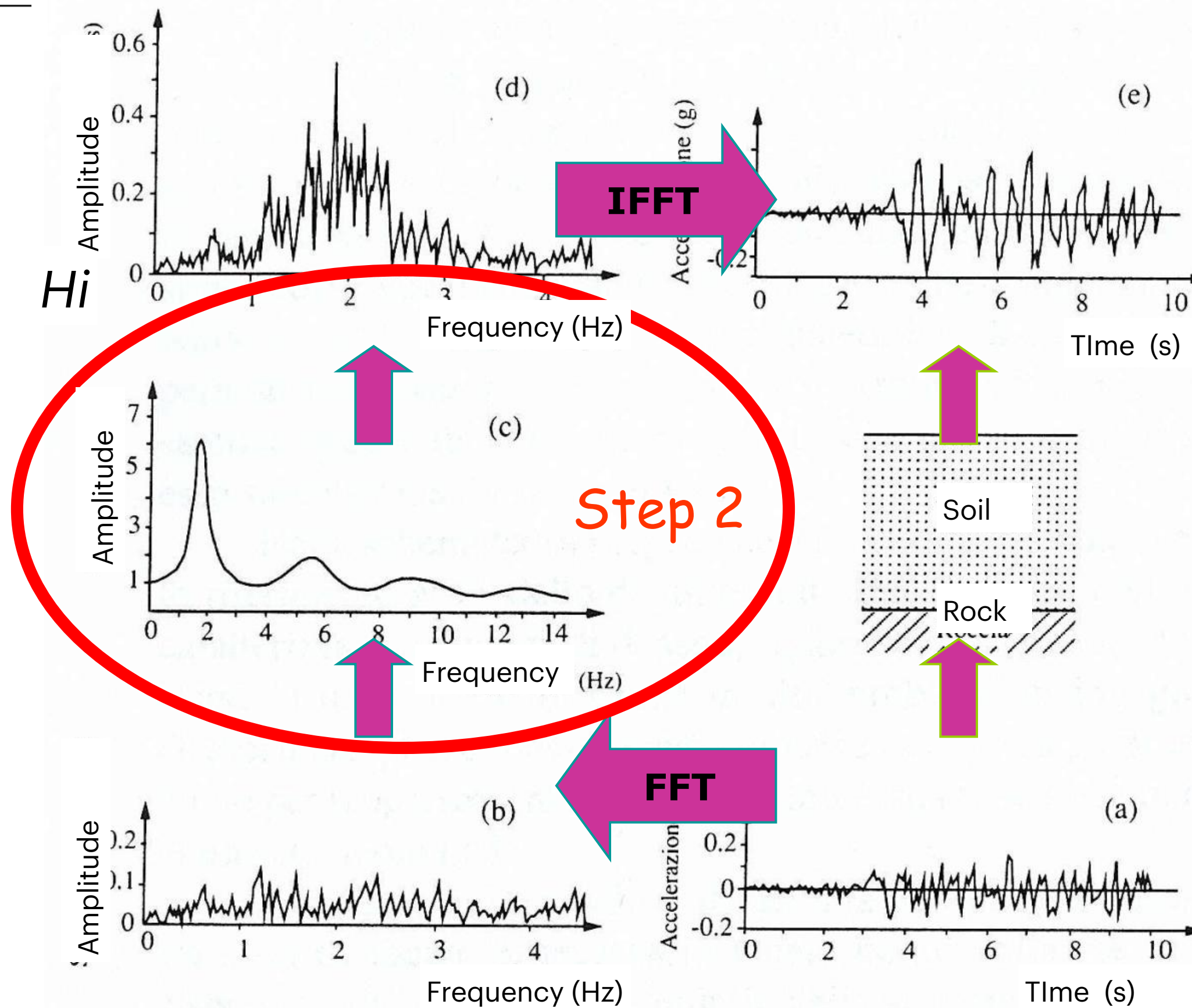
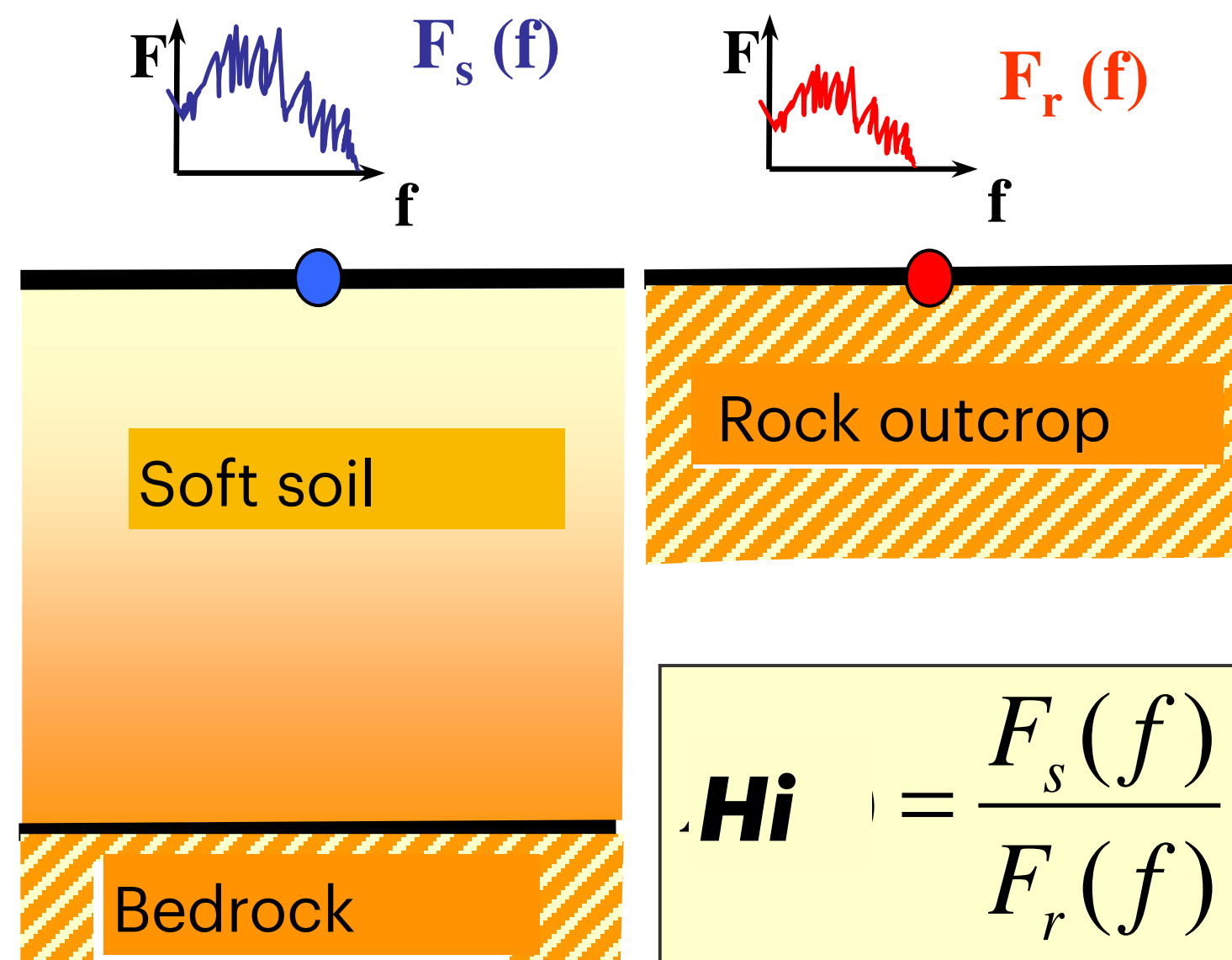
Ar (i.e. a sum of simple harmonics)



Shake/strata/EERA codes

Step 2 Compute the transfer function (amp. Function H_i) between the layers

$$TF_{mn}^{strain}(\omega) = \frac{\gamma(\omega, z = h_m/2)}{\ddot{u}_{n,outcrop}(\omega)} = \frac{ik_m [A_m \exp(ik_m^* h_m/2) - B_m \exp(-ik_m^* h_m/2)]}{-\omega^2 (2 \cdot A_n)}$$

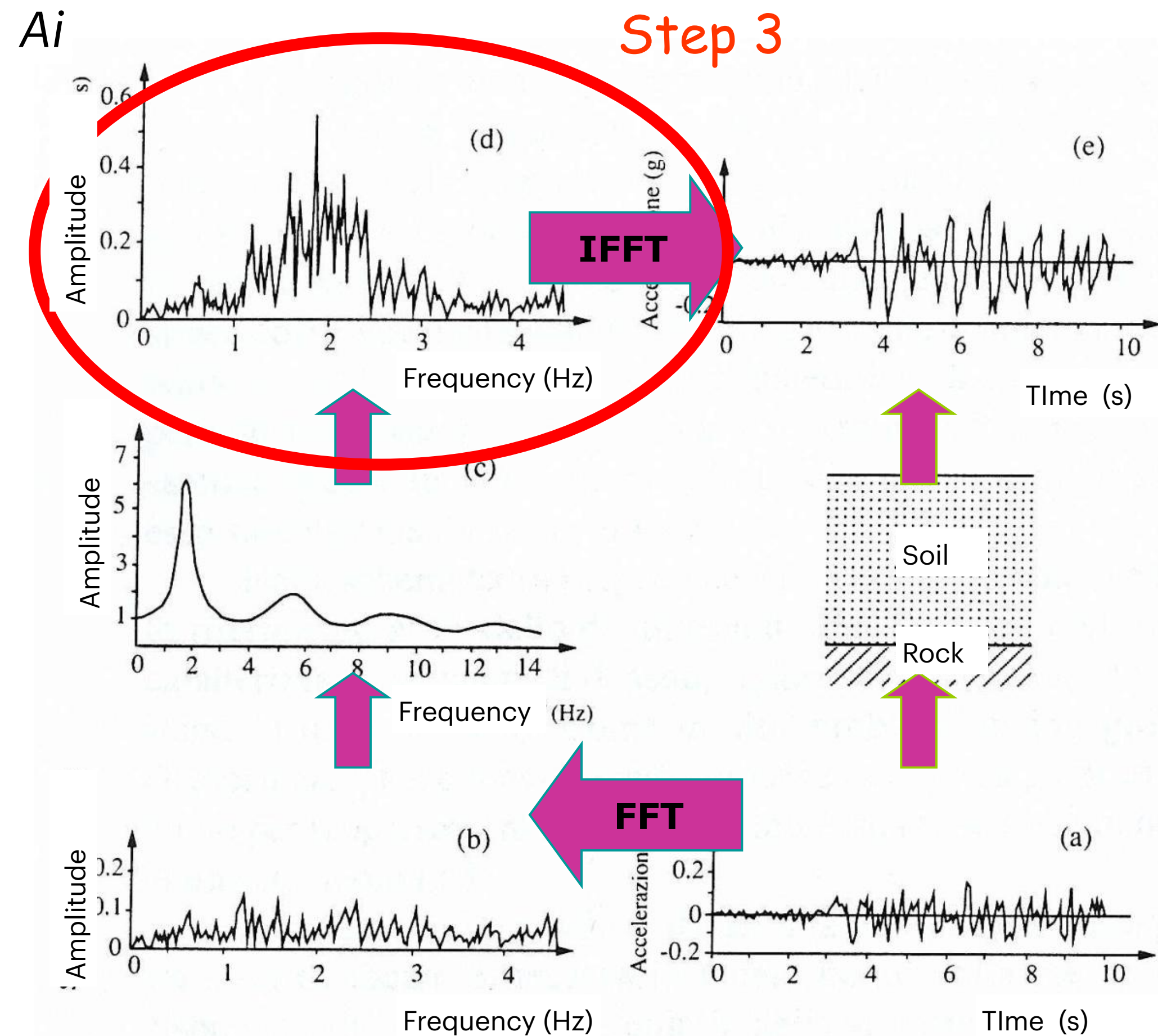


Step 3

Compute the Fourier transform
FFT of the response at surface **A_i**:

In frequency domain it is the
product of the input spectrum and
the amplification function

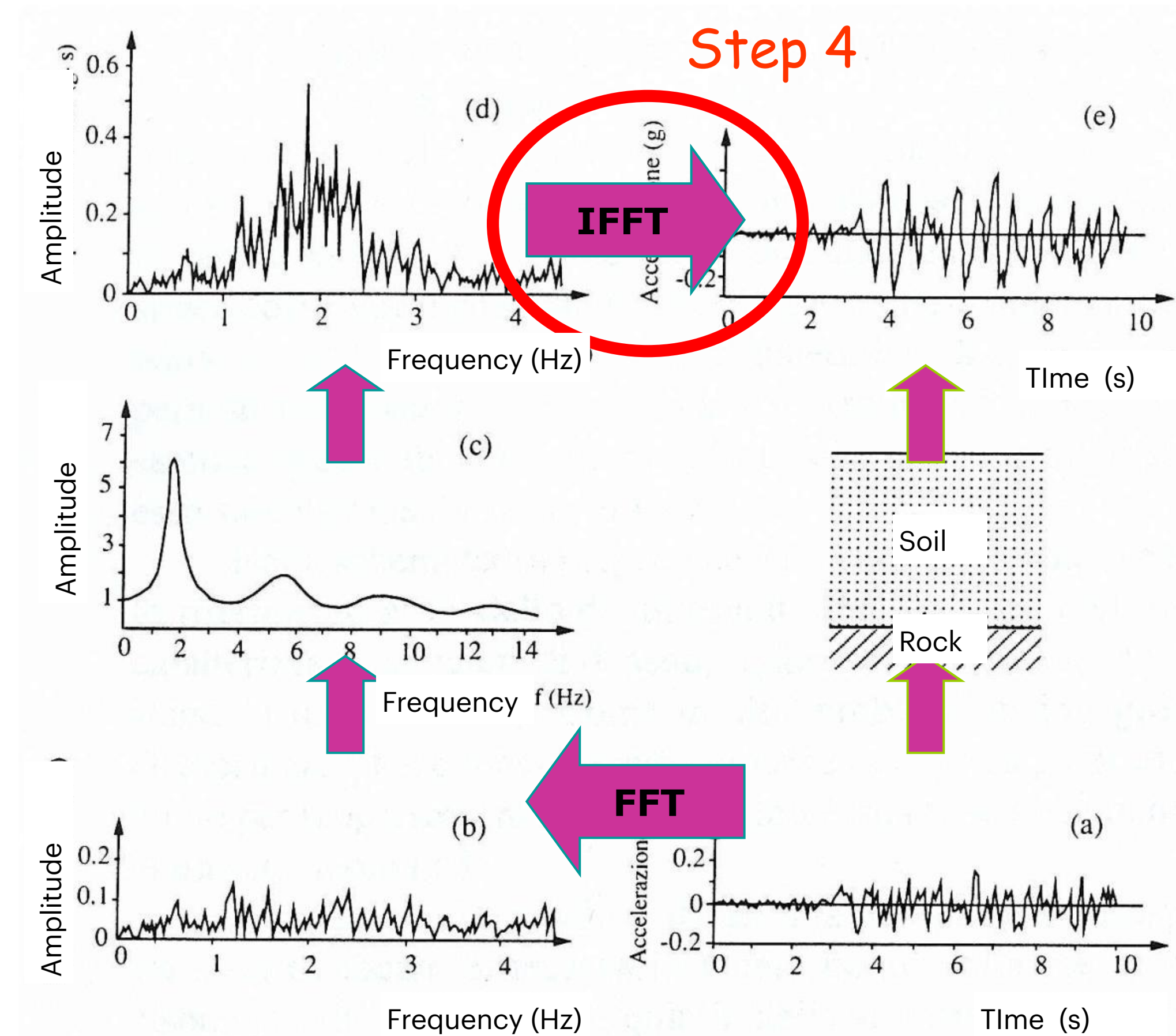
(In time domain would be the
more complex convolution)



Step 4

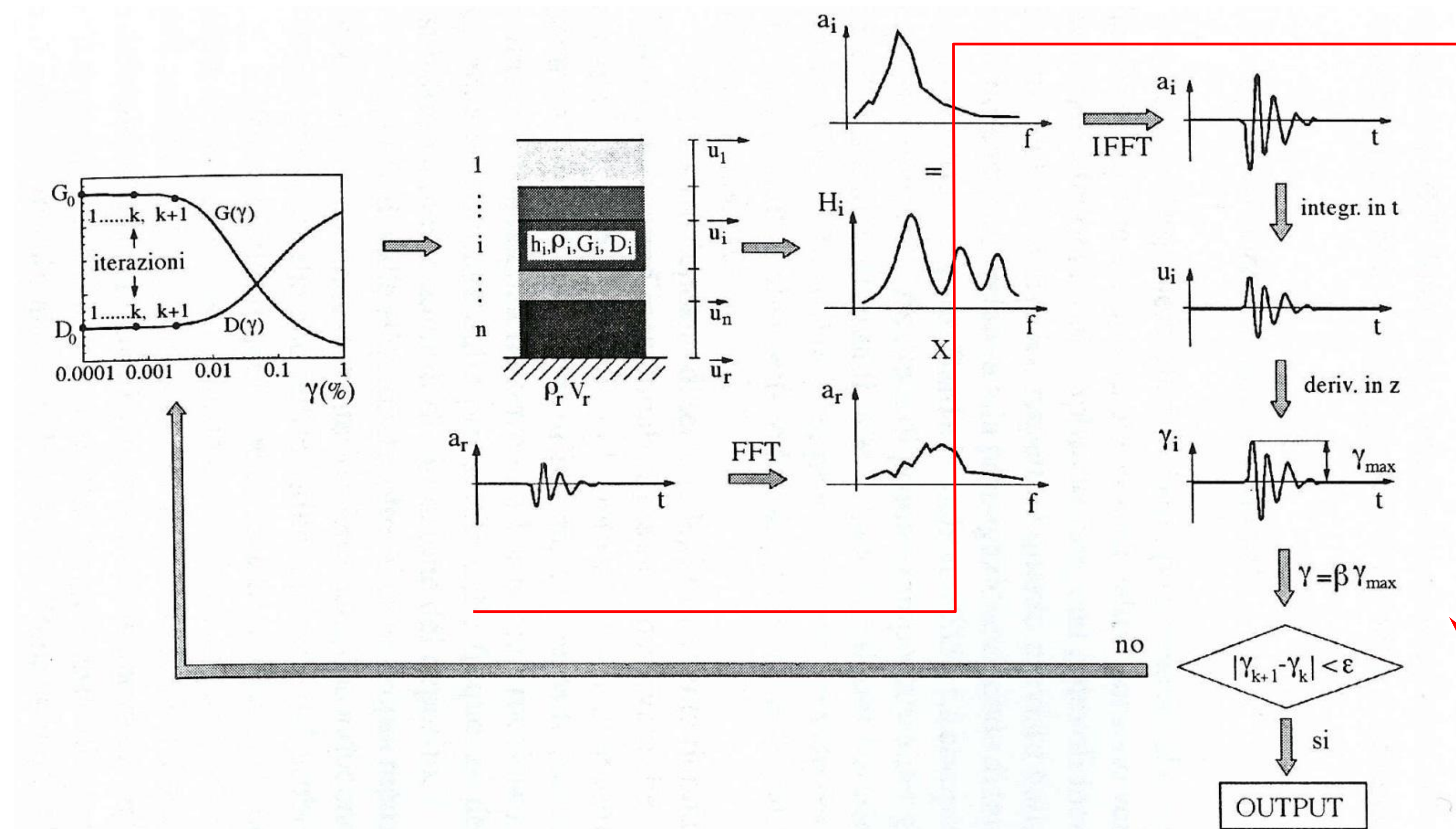
Compute the Anti Fourier transform IFFT of the response at the surface:

Obtaining the **resulting** time series **accelerogram** of the site



Shake/strata/EERA codes

The so called linear equivalent method models the visco-elastic behaviour in an iterative way: G and D parameters are updated for each strain γ computed till no significant G decay is observed.



Starting data:

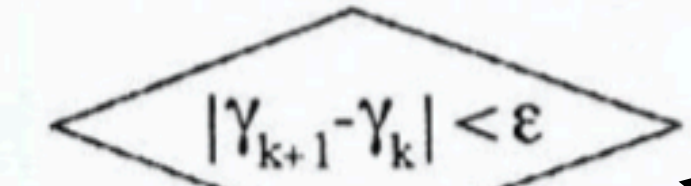
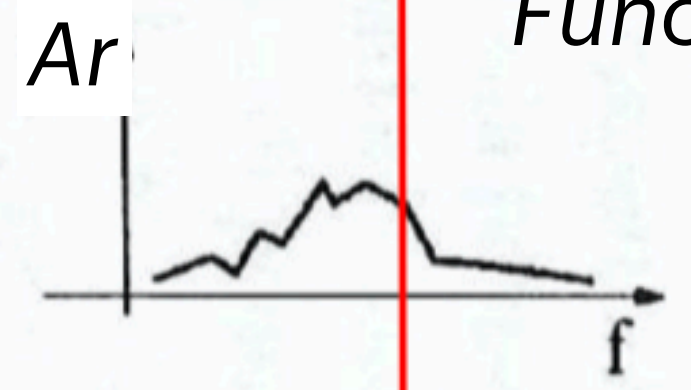
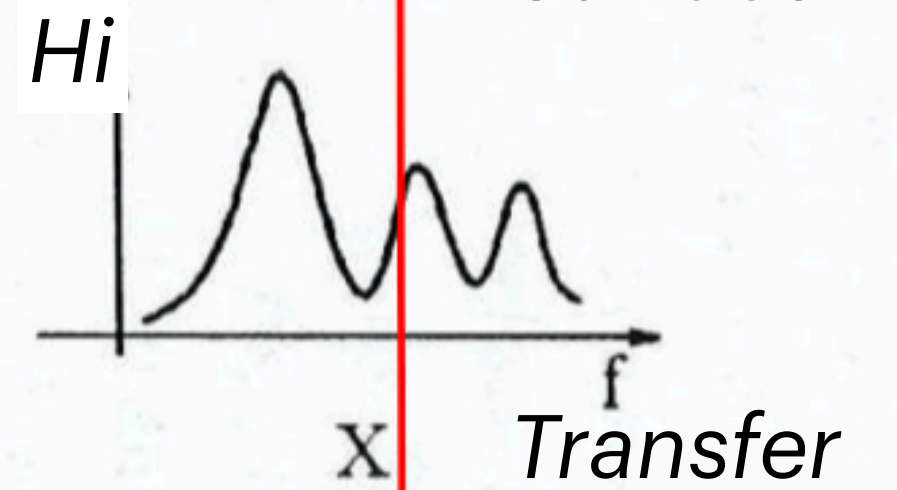
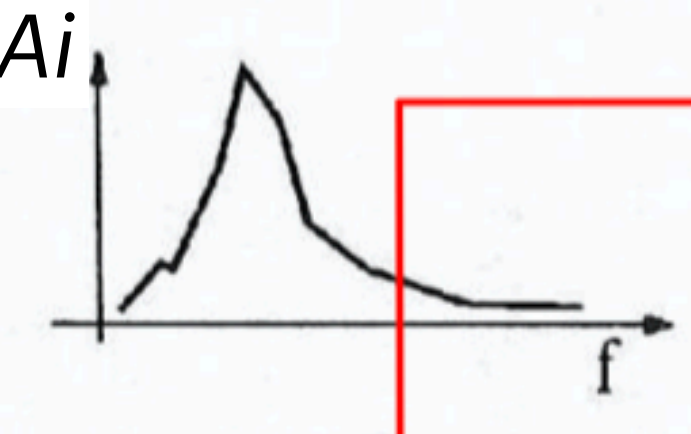
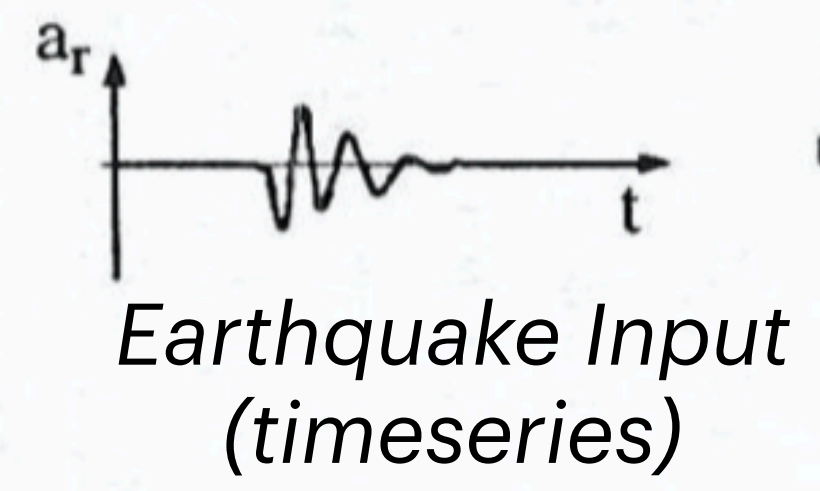
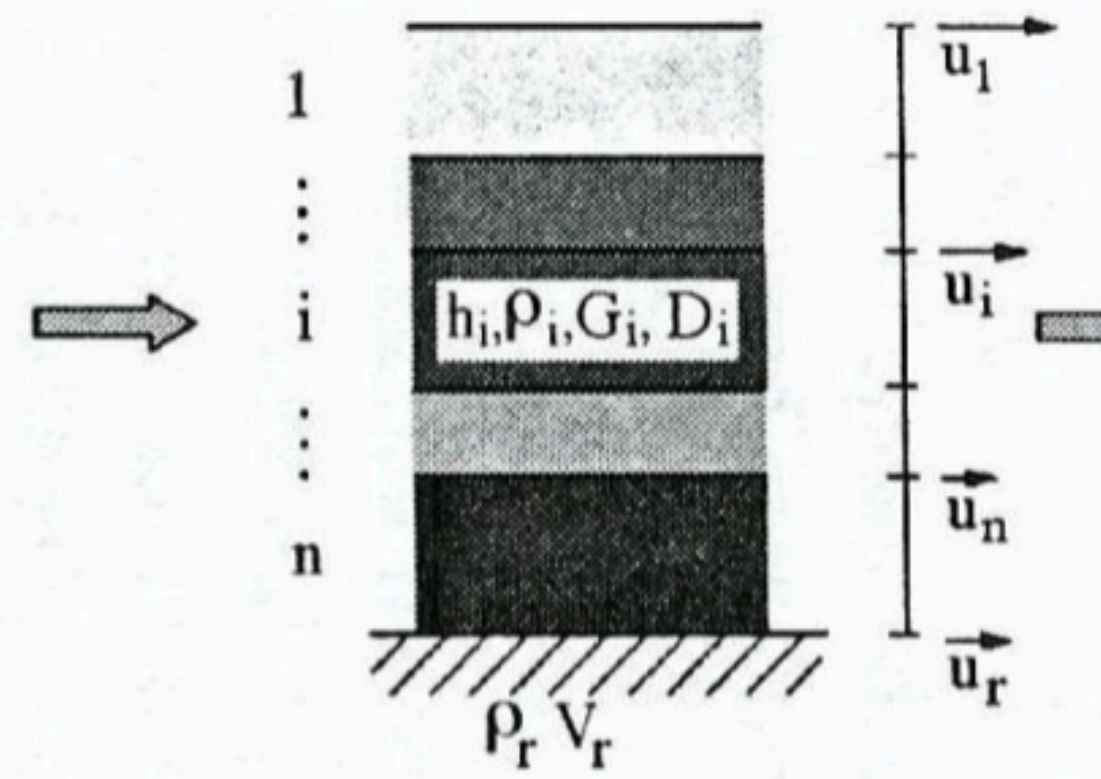
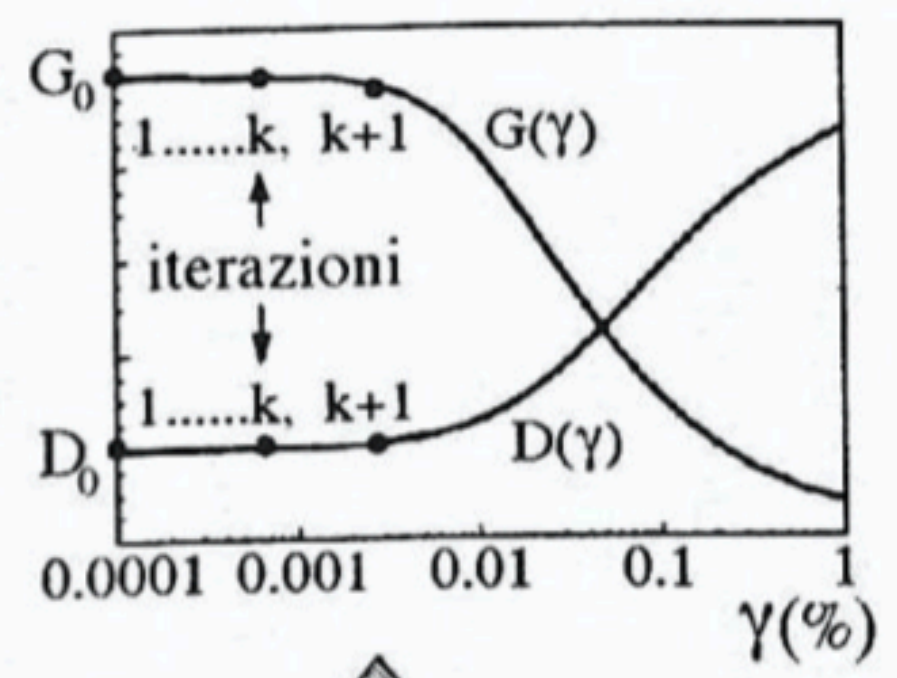
Frequency domain

Time domain

G and D curves

H and Vs Model

$$A_i = (H_i) \times (A_r)$$



OUTPUT

Acc.

Displ.

Deformation

Real Def.

$\beta = 0.65$

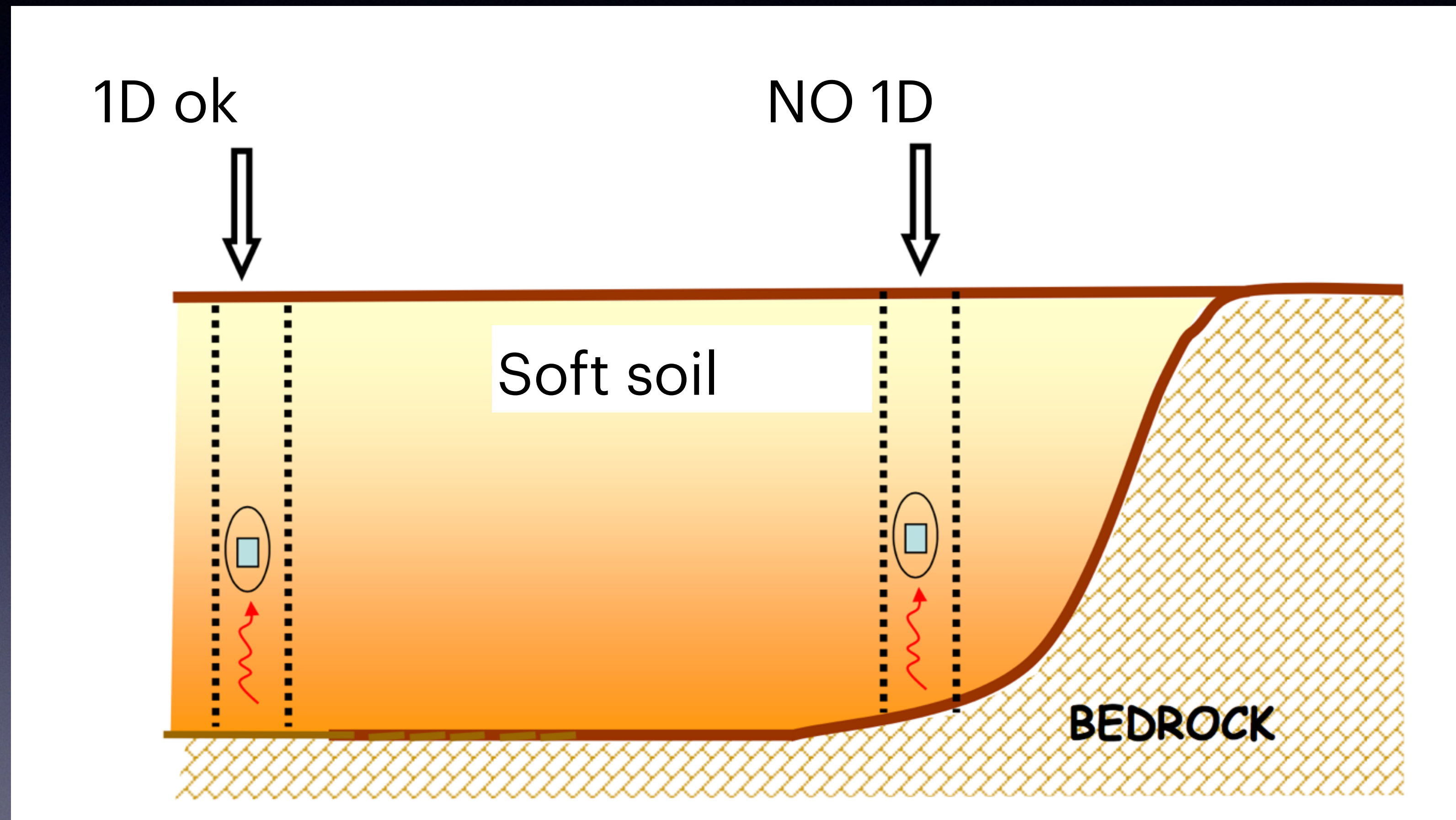
$\epsilon =$ established error

No significant changes in G, D = solution converges

Geometria	Codice di calcolo (riferimento)	Tipo di analisi		Ambiente operativo
1-D	SHAKE (Schnabel et al., 1972) SHAKE91 (Idriss & Sun, 1992)* PROSHAKE (EduPro Civil System, 1999) SHAKE2000 (www.shake2000.com) EERA (Bardet et al., 2000) NERA (Bardet & Tobita, 2001) DEEPSOIL (Hashash e Park, 2001)	TT	LE	DOS
			NL	Windows
	DESRA_2 (Lee & Finn, 1978) DESRAMOD (Vucetic, 1986) D-MOD_2 (Matasovic, 1995) SUMDES (Li et al., 1992) CYBERQUAKE (www.brgm.fr)	TE		DOS
			Windows	
2-D / 3-D	QUAD4 (Idriss et al., 1973) QUAD4M (Hudson et al., 1994) FLUSH (Lysmer et al., 1975) BESOIL (Sanò, 1996)	TT	LE	DOS
			Windows	
	QUAKE/W vers. 5.0 (GeoSlope, 2002)	TE	NL	DOS
			Windows	
DYNAFLOW (Prevost, 2002) GEFDYN (Aubry e Modaressi, 1996) TARA-3 (Finn et al., 1986)	TE	NL	DOS	
		Windows		
FLAC vers. 6.0 (Itasca, 2008) PLAXIS vers. 8.0 (www.plaxis.nl)	TE	NL	Windows	
		Windows		

TT = Tensioni Totali; TE = Tensioni Efficaci;
LE = Lineare Equivalente; NL = Non Lineare

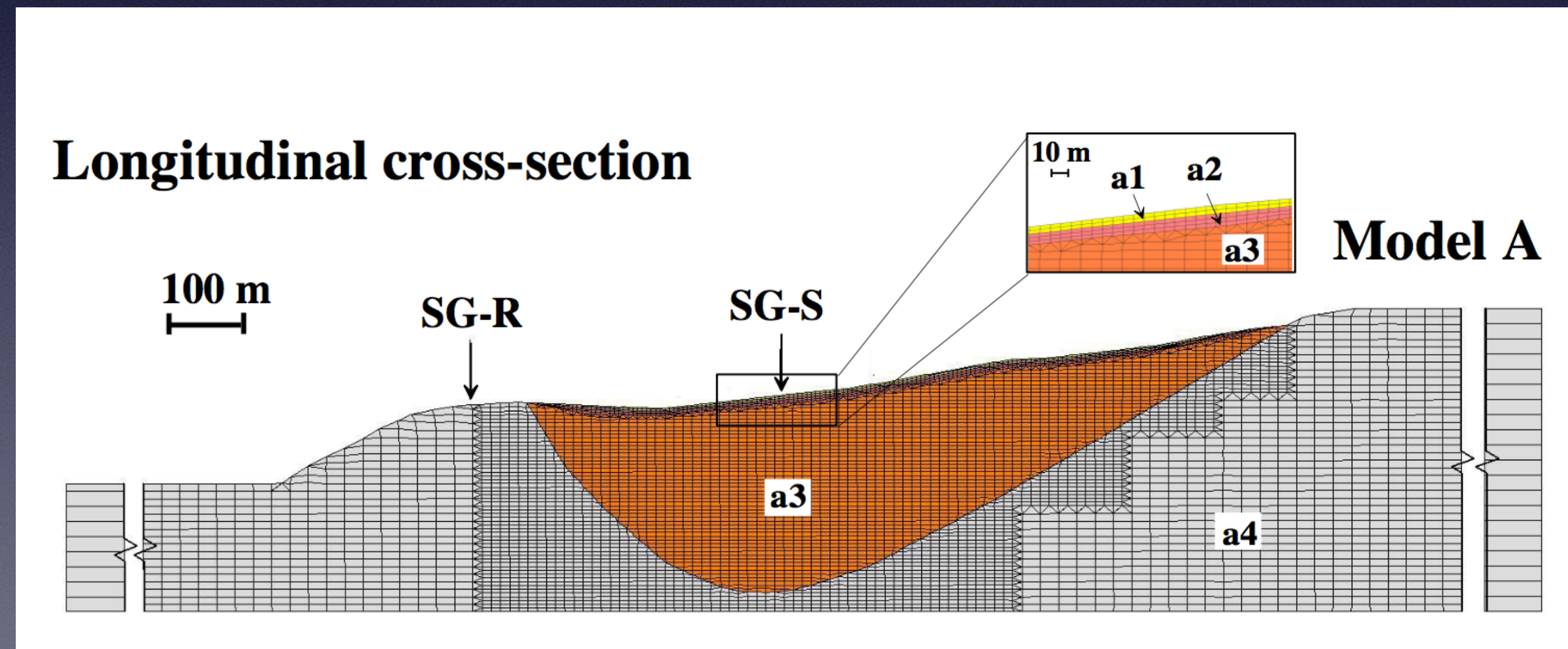
And in 2 dimensions ?



2D numeric solution For seismic response analysis

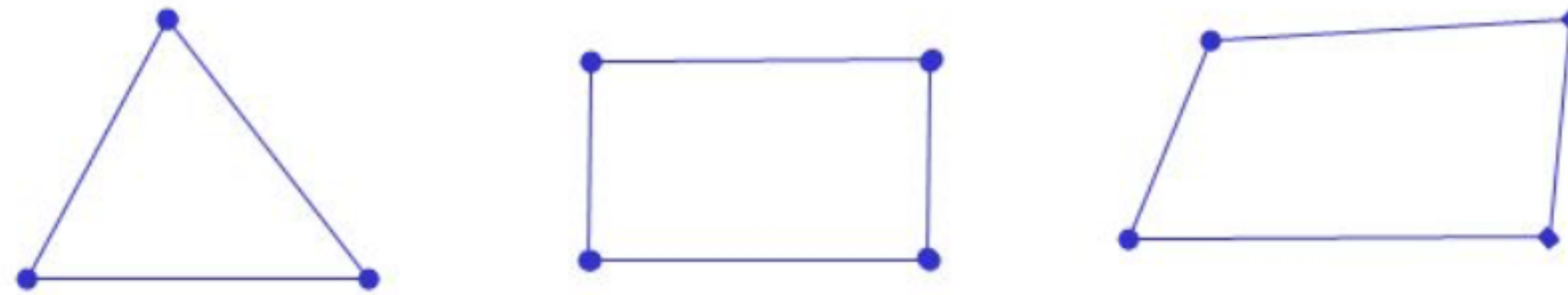
Finite elements models who discretise the space domain in fundamental elements connected by nodes. Continuous response is considered equivalent at each nodes

2D

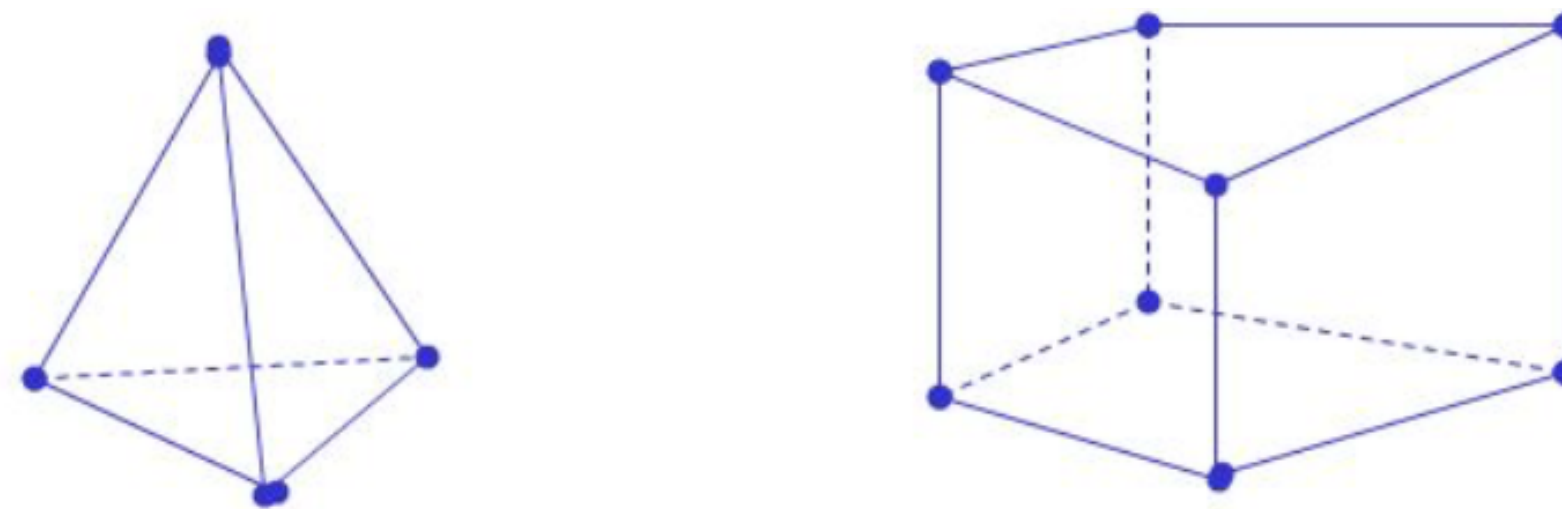


2D numeric solution For seismic response analysis

Triangular, rectangular, quadrilateral mesh for 2 D

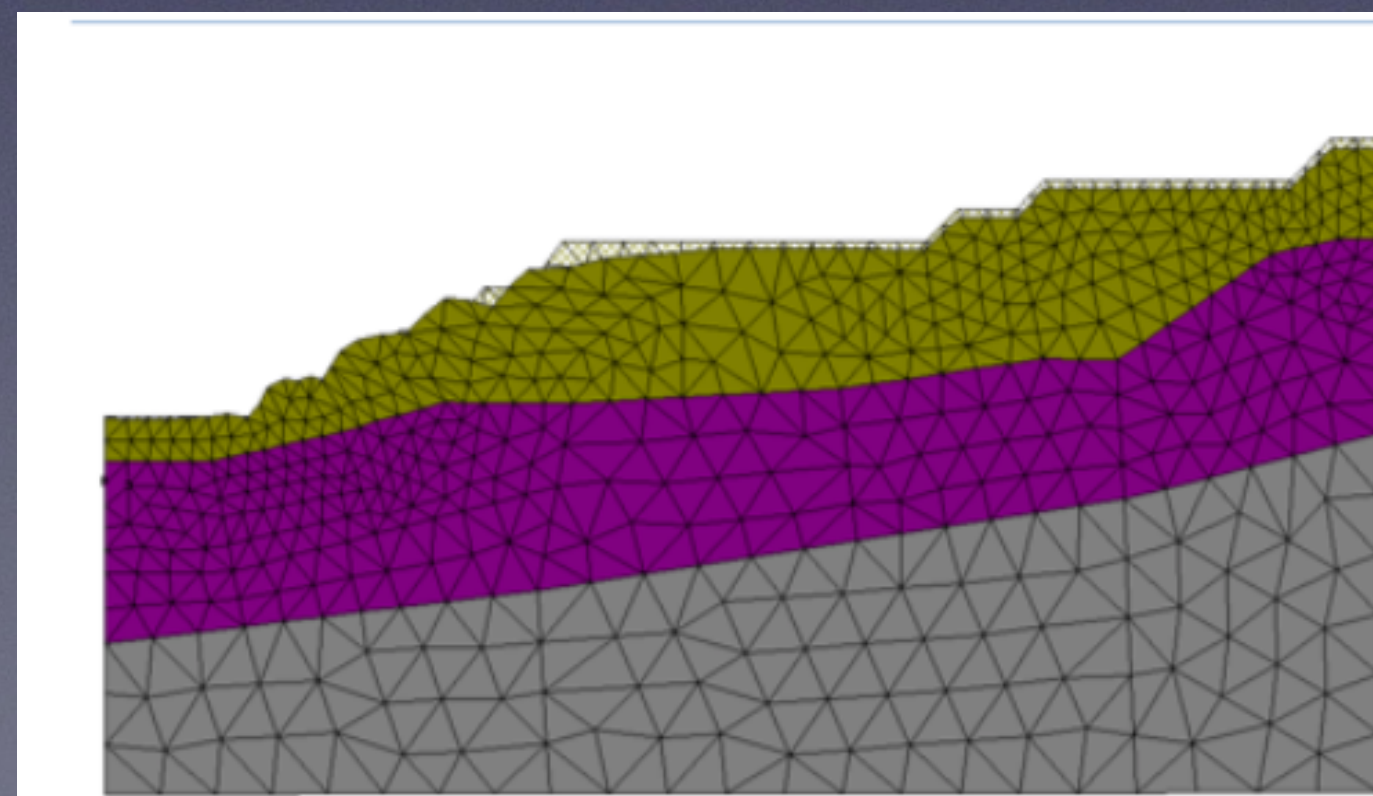


Tetrahedron, hexahedron for mesh for 3 D

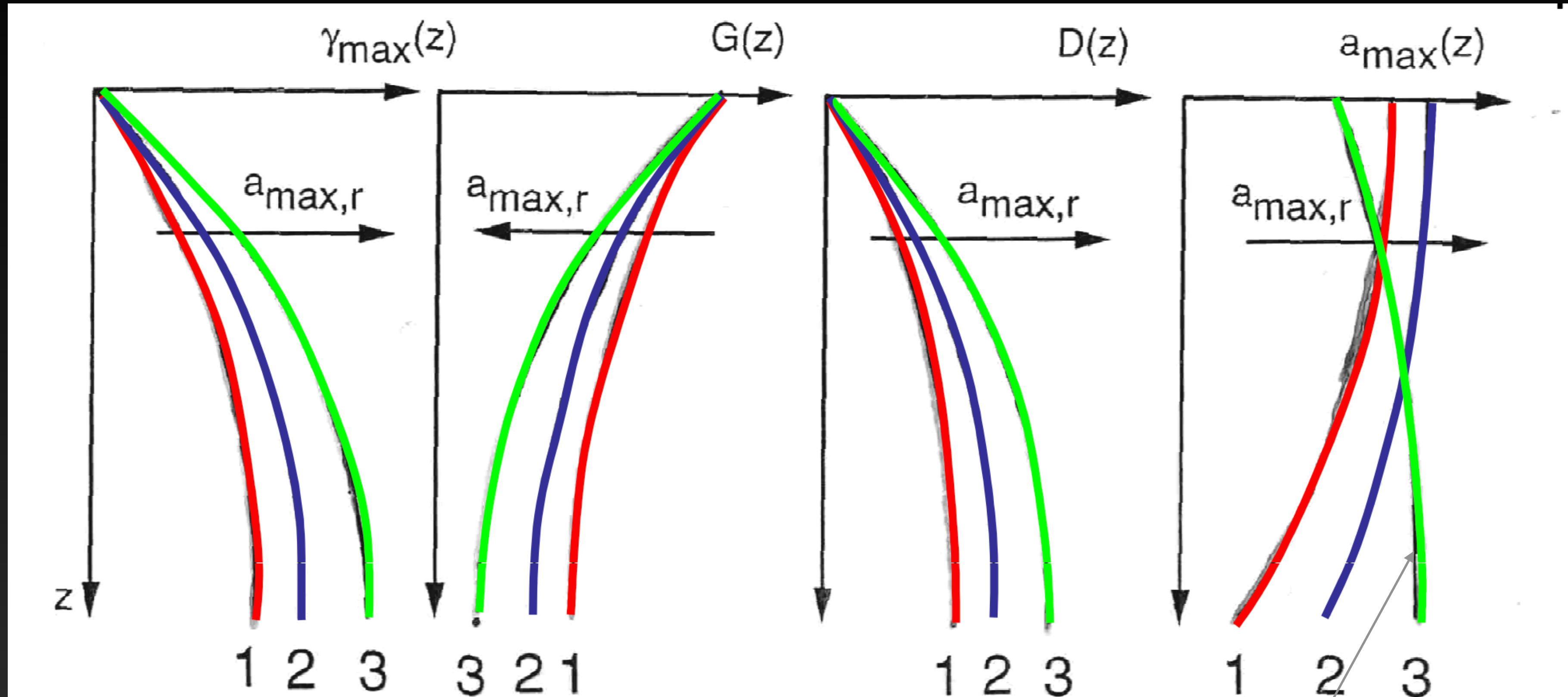


Differential equations are solved
in the discrete domain

Numerical methods to
approximate solutions in a
simplified mesh



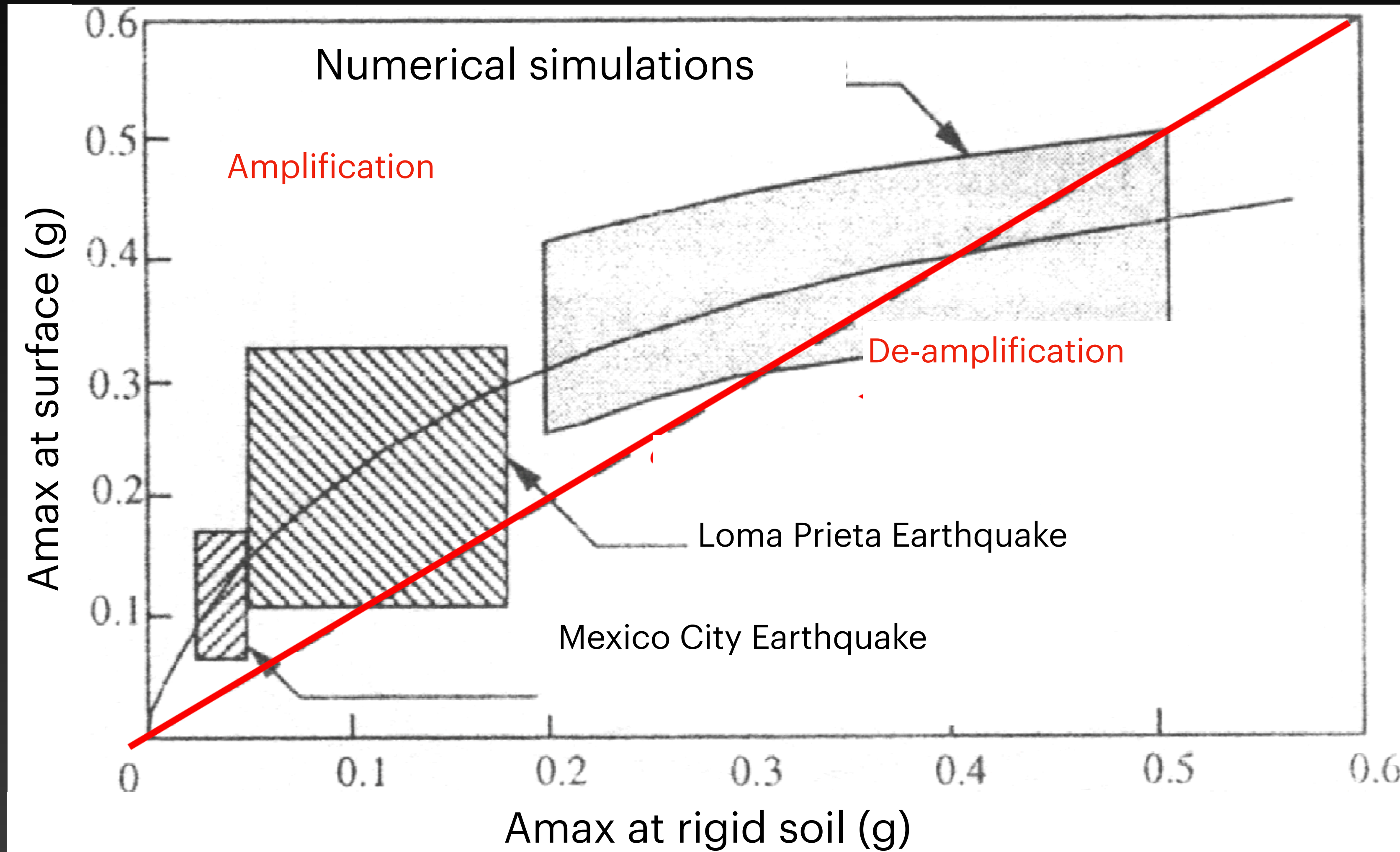
The effect of non linearity for very strong motion



- >> Acc >> deformation γ
- >> Acc >> damping D
- >> Acc << shear rigidity G

In case of very strong acceleration (3),
Amax can decrease in surface
(attenuation prevails)

Example in soft soil

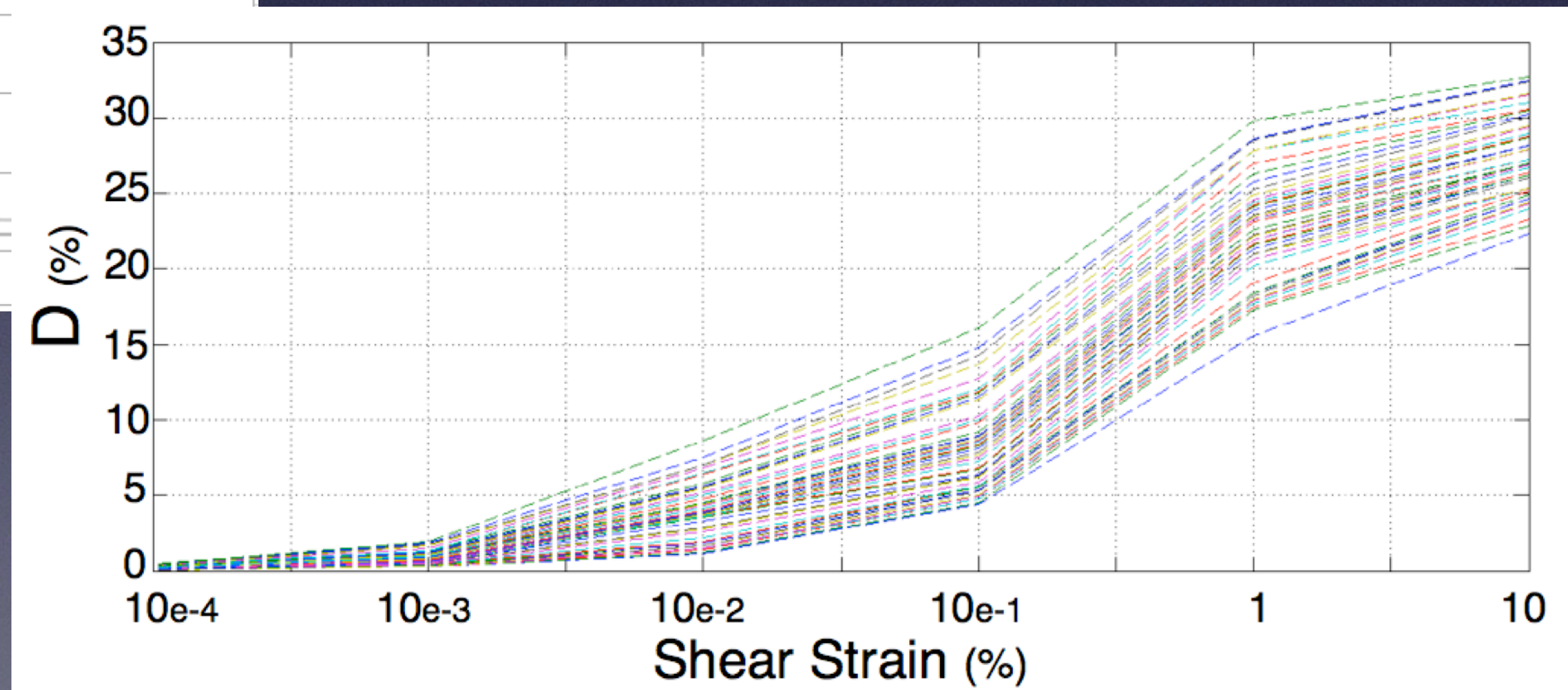
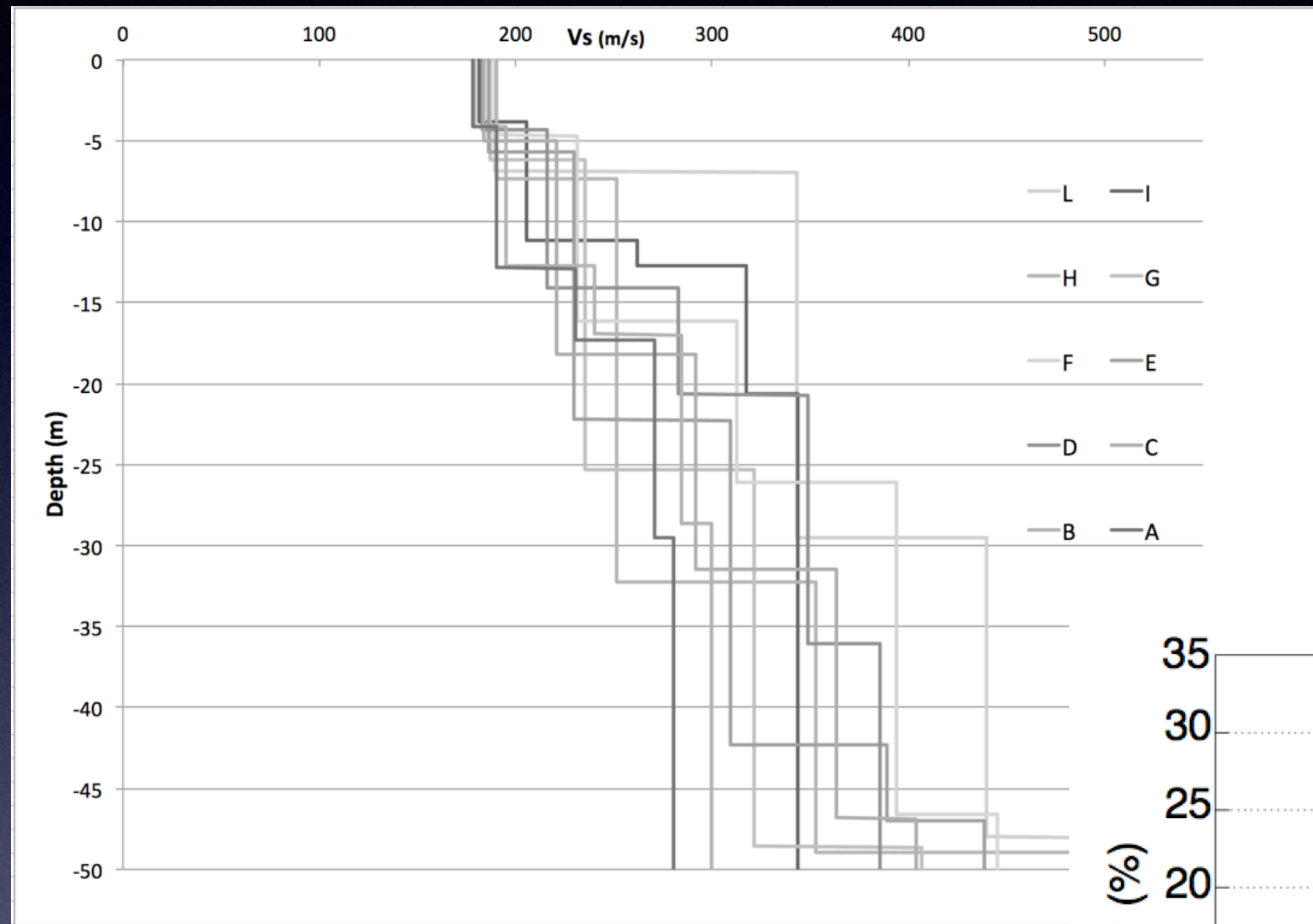


In case of very strong acceleration non linearity
Can even de-amplify the motion
(attenuation prevails)

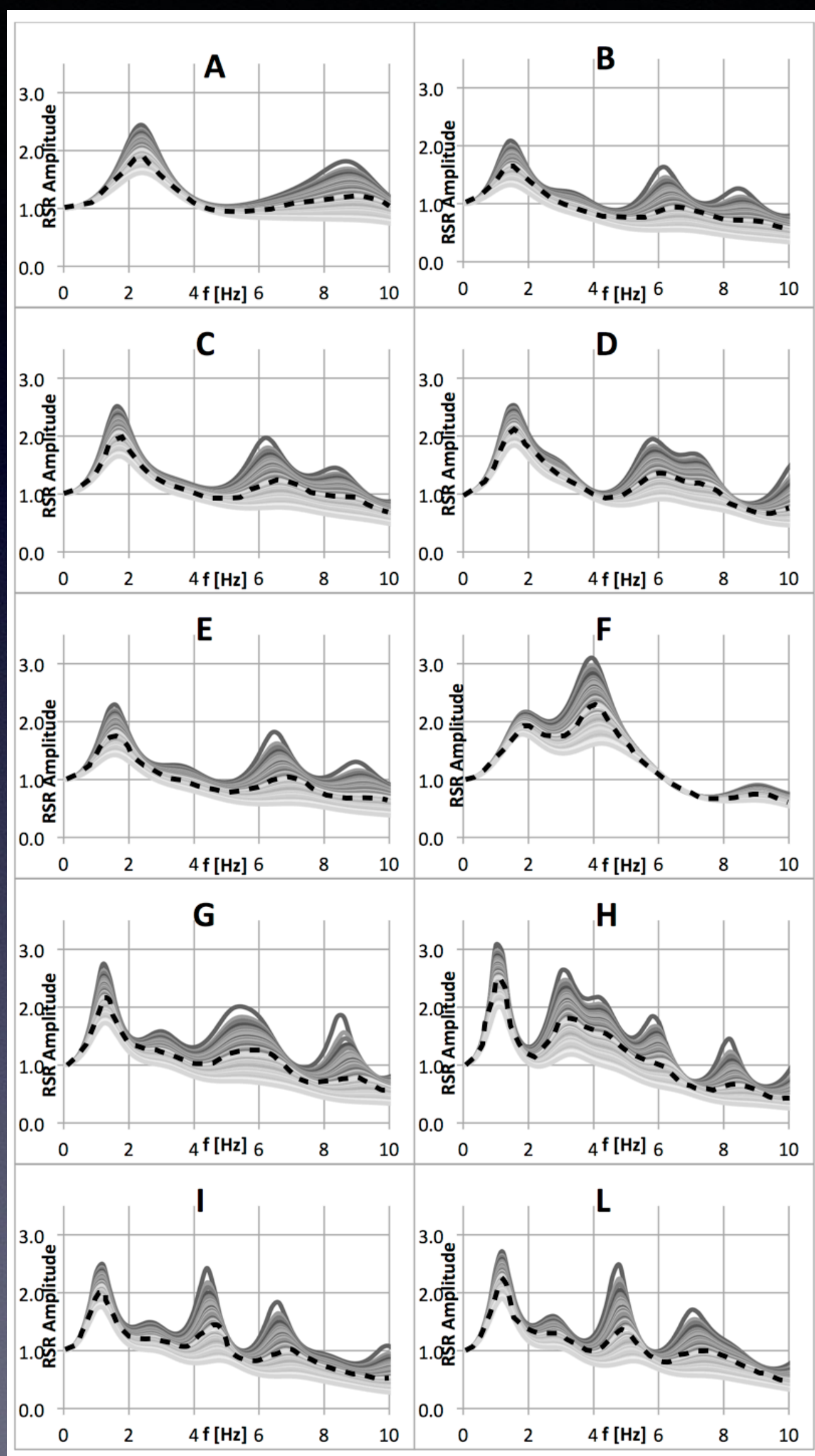
The sensitivity of G (V_s) and D

Boaga et al. 2015

Soil damping influence on seismic ground response: A parametric analysis for weak to moderate ground motion. *Soil Dynamics and Earthquake Engineering* 79 (2015) 71–79



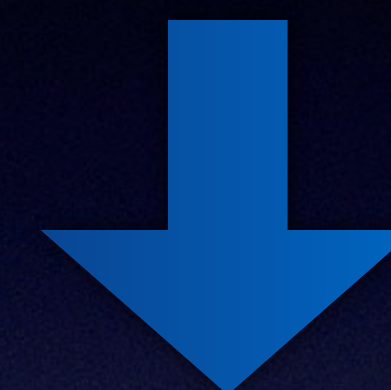
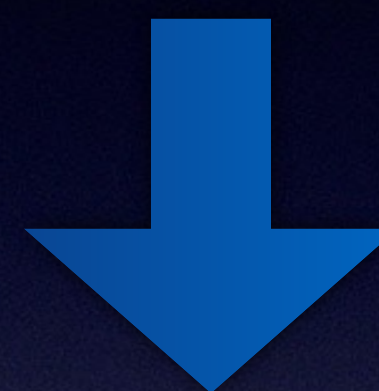
Same soil structure varying only D %



Surface response spectra

Δ PGA
+/- 20%

Small
Impedance



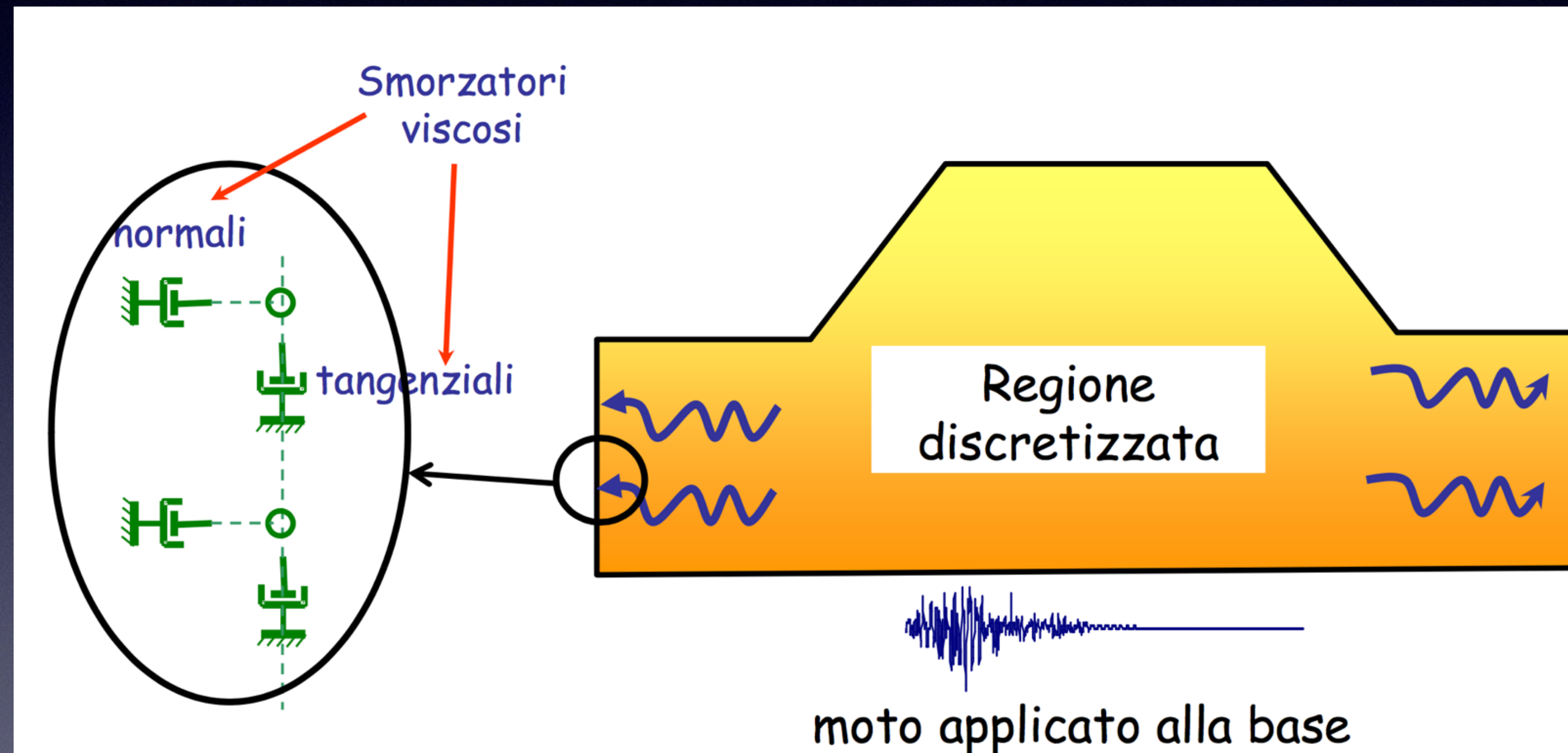
+/- 60%

High
Impedance

In case of high impedance
contrast
D factor is more important
than V_s

Extra materials

Le **frontiere laterali** devono essere in grado di modellare la perdita di energia dovuta all'allontanamento delle onde sismiche dalla regione discretizzata.
In caso contrario si generano onde riflesse che vengono artificialmente introdotte nella regione di interesse



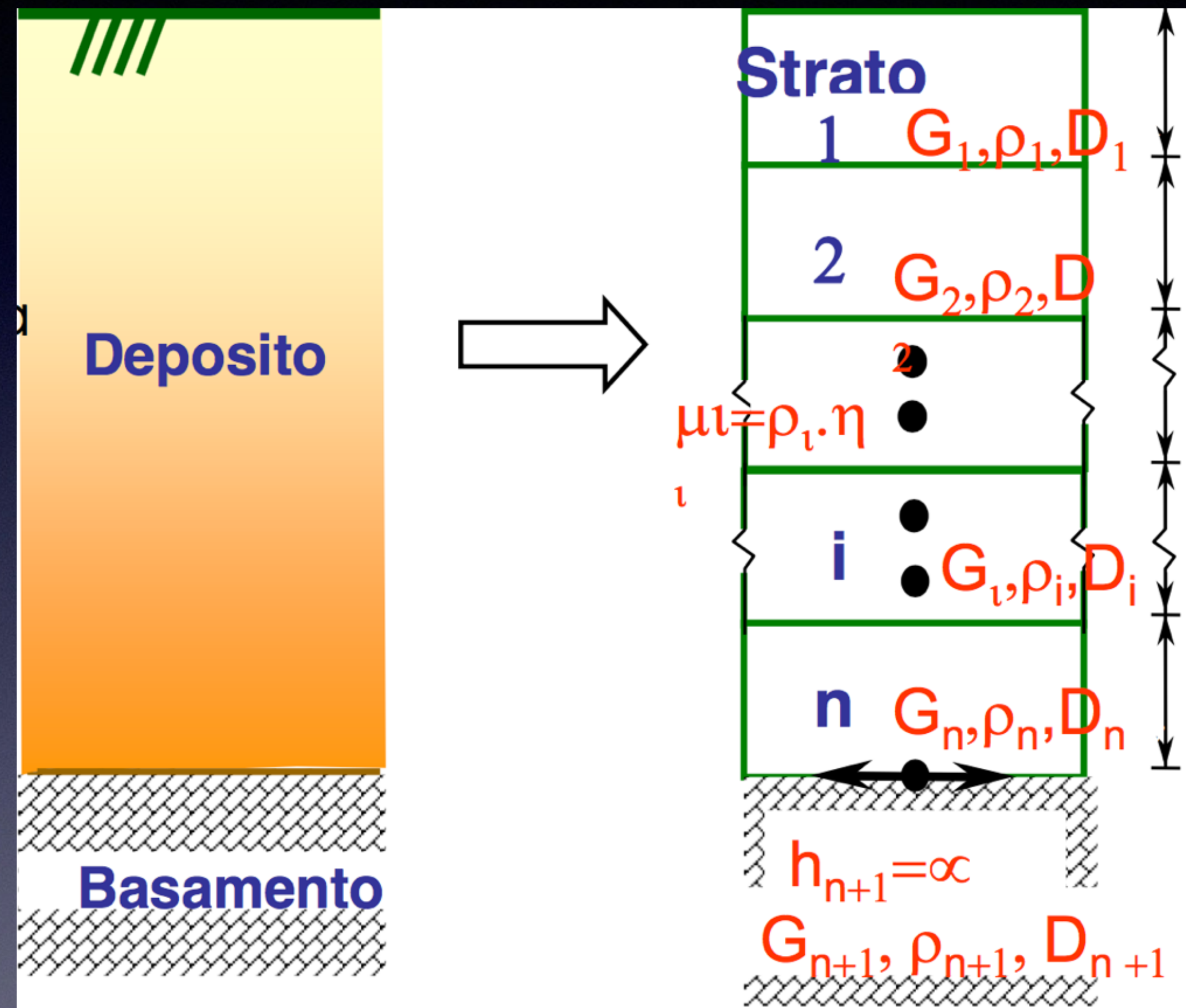
Absorbing Boundaries (2D)

Modelli a trave a taglio continua

I modelli continui schematizzano il terreno come un mezzo continuo multistrato in cui ogni strato è assunto omogeneo a comportamento visco-elastico lineare (e.g. SHAKE)

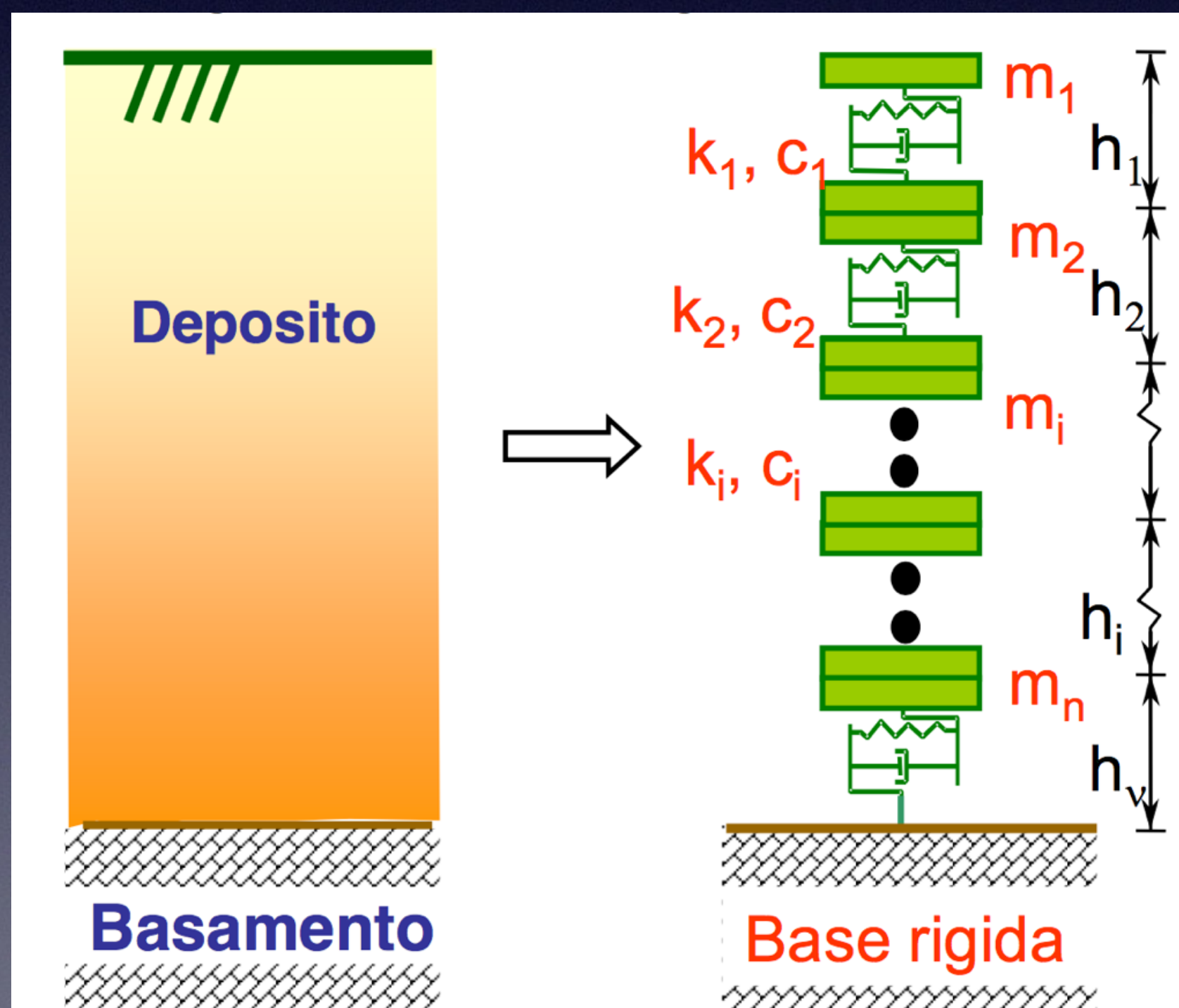
I parametri necessari a caratterizzare ciascun strato sono

lo spessore H_i , la massa ρ , la rigidezza di taglio G , e il coefficiente di smorzamento dello smorzatore D .



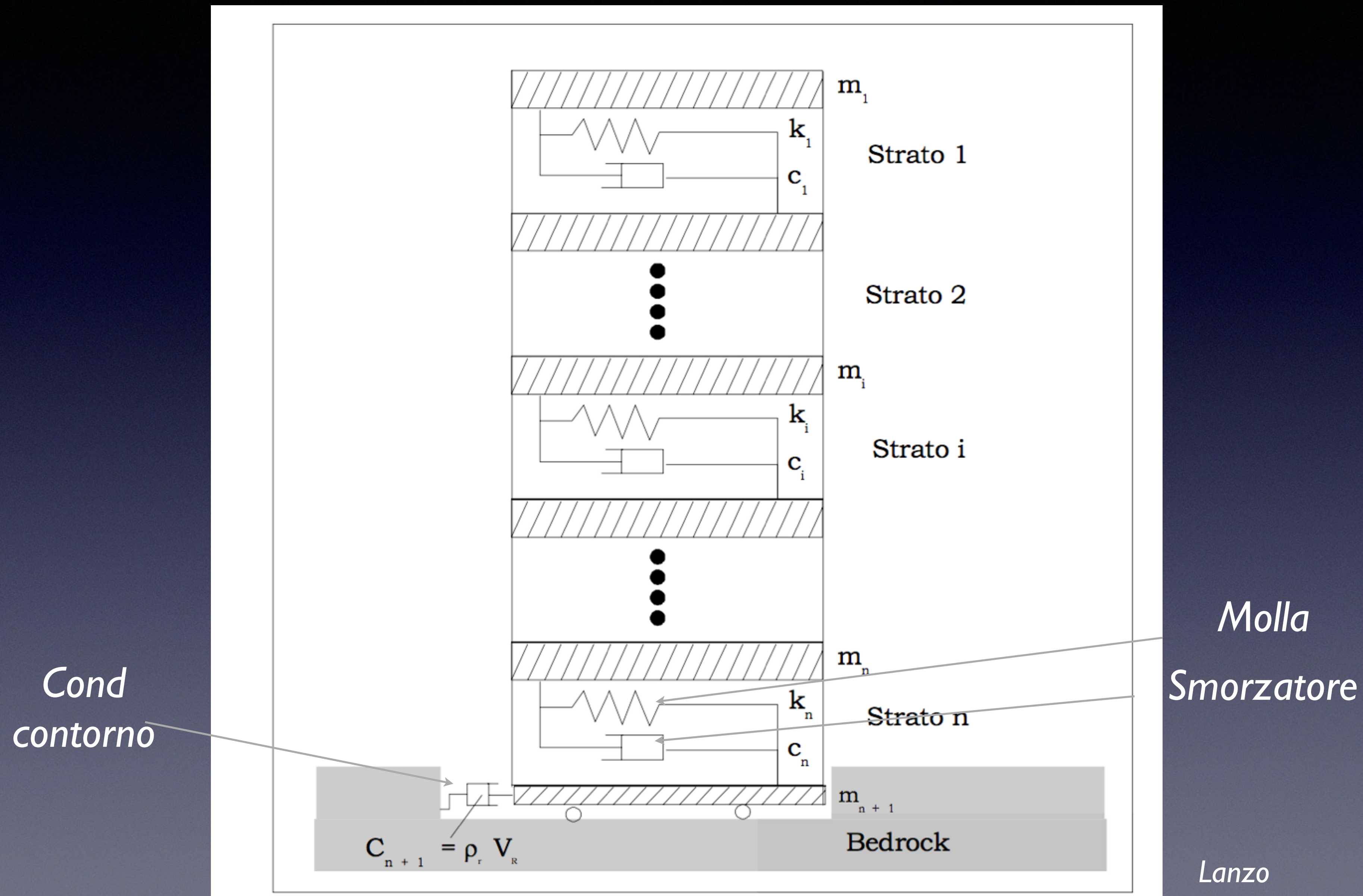
Modelli a trave a taglio continua discretizzata

schematizzano gli strati con una serie di masse concentrate in corrispondenza della superficie di separazione degli strati e collegate tra loro da molle e smorzatori viscosi, che simulano la legge di comportamento sforzi-deformazione, generalmente in modo non lineare.

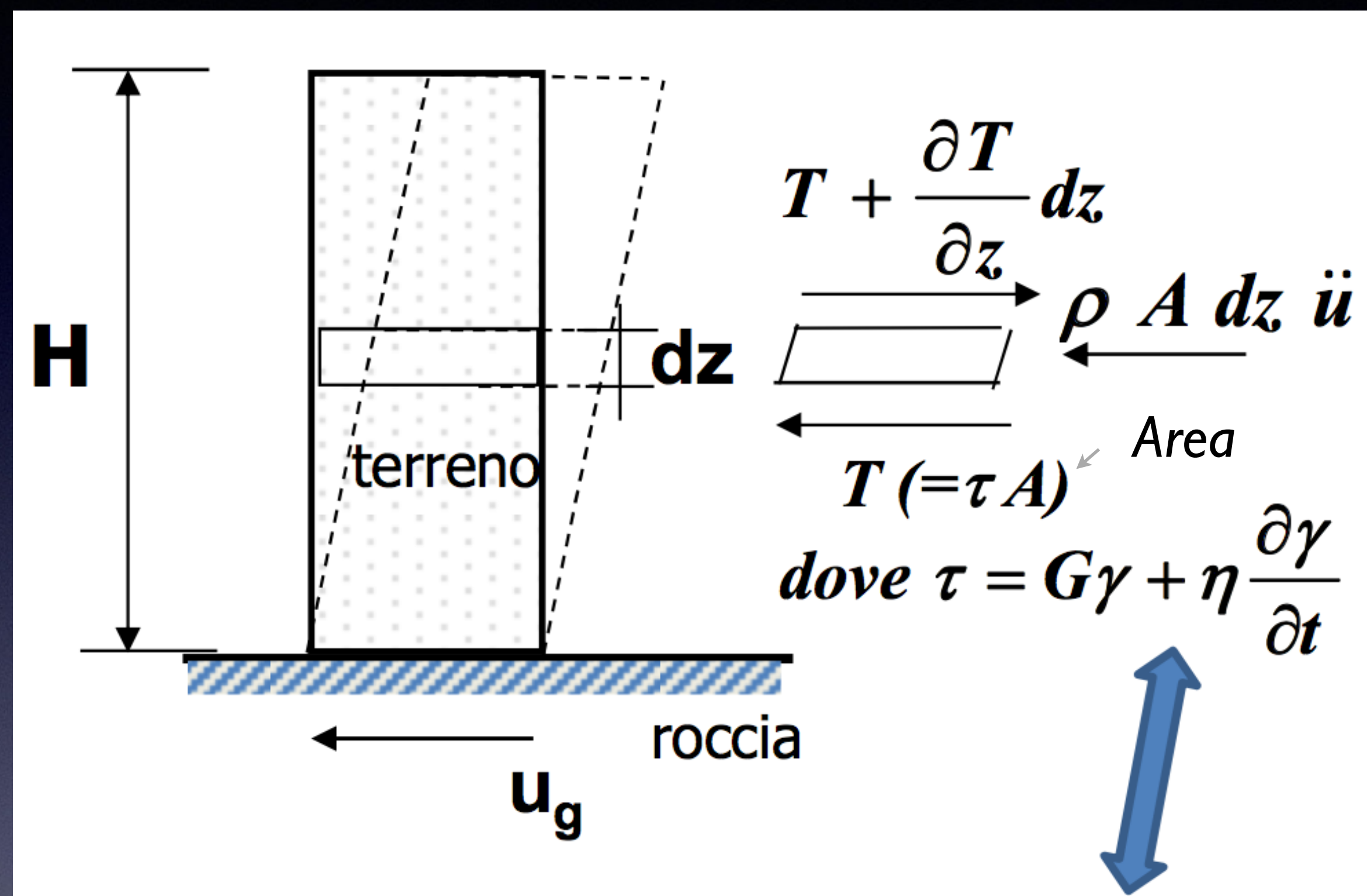


I parametri necessari a caratterizzare ciascun strato sono lo spessore H_i , la massa ρ , la rigidezza della molla K_i (legata al modulo di taglio) e il coefficiente di smorzamento dello smorzatore ε (D).

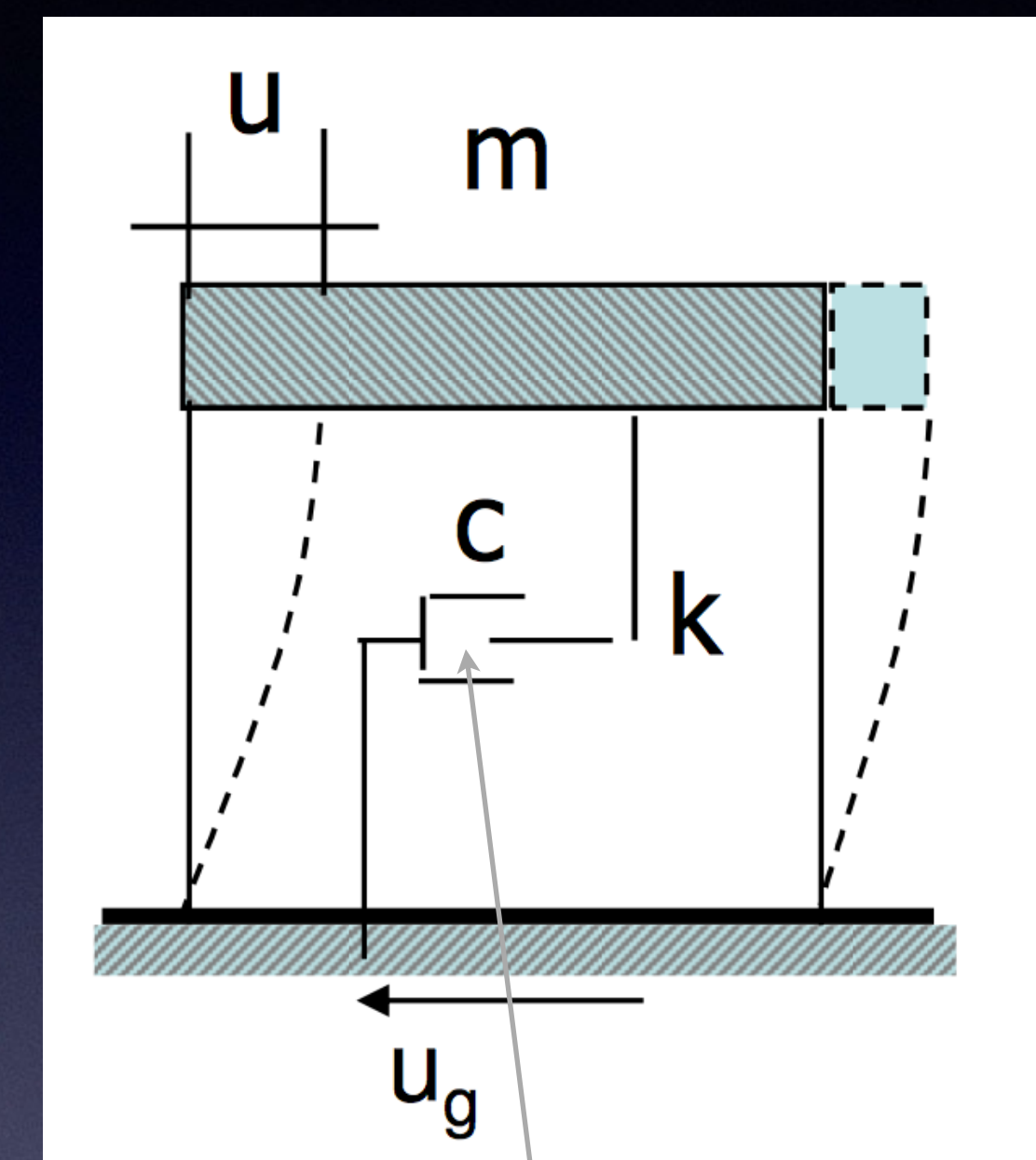
Modelli a trave a taglio continua discretizzata



Modelli a trave a taglio continua discretizzata



Viscosità



Smorzatore

Risoluzione delle equazioni del moto

Livello I = Pianificazione (comunale) . Definizione di zone omogenee dal punto di vista geologico-geomorfologico

Definire le zone omogenee dal punto di vista litologico / topografico per determinare:

- Zone suscettibili di amplificazione
- Zone potenzialmente instabili

cioè definire le

MOPS Microzone Omogenee in Prospettiva Sismica;

Microzonazione Sismica

(Linee Guida Nazionali e Leggi Regionali)

3 Livelli

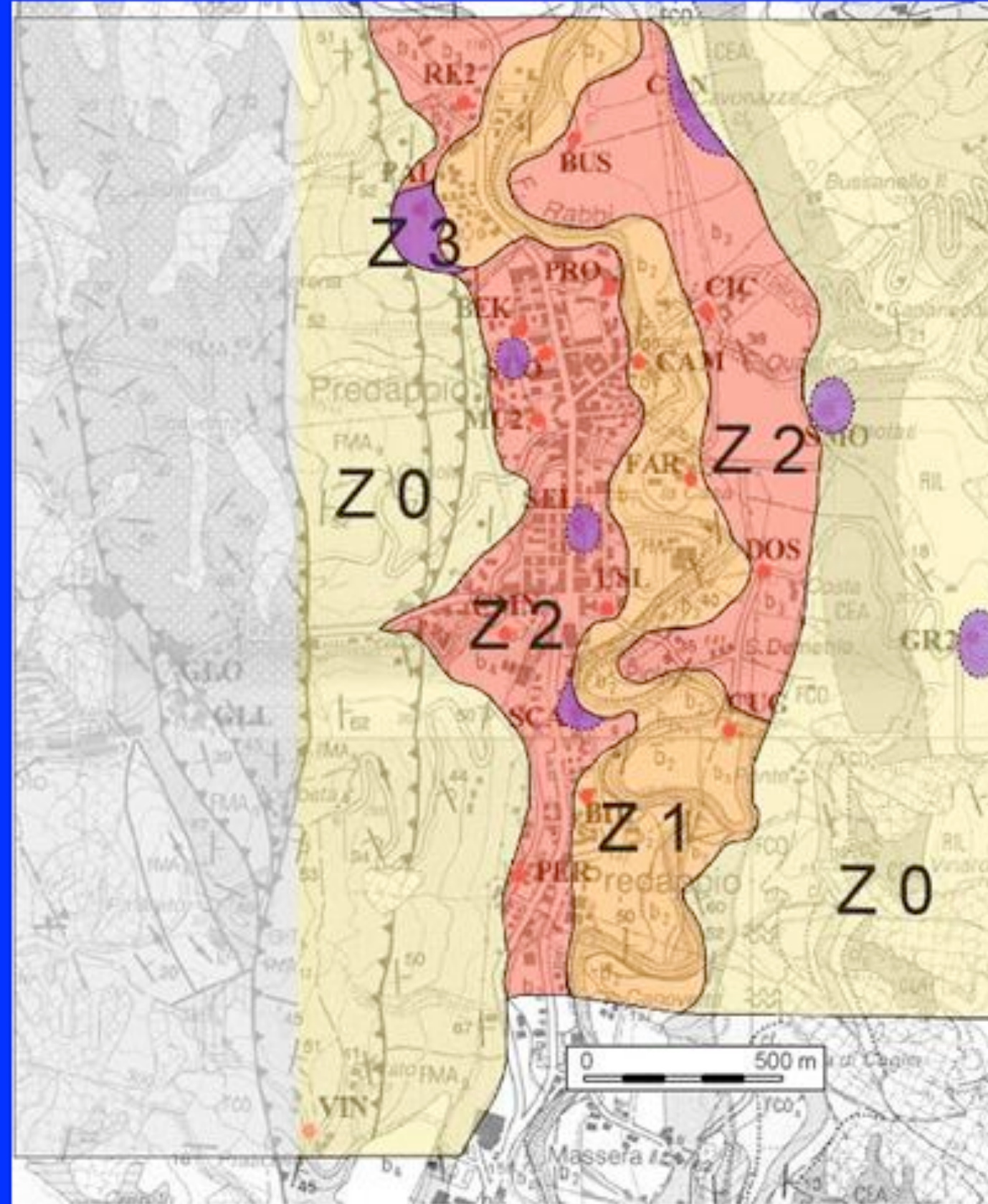
Livello 1 = Pianificazione (comunale) . Definizione di zone omogenee dal punto di vista geologico-geomorfologico

Livello 2 = Pianificazione. Definizione di zone omogenee dal punto di vista sismico basate su misure sperimentali speditive

Livello 3 = Intervento. Definizione della risposta sismica locale per siti specifici di interesse di Piano di Intervento

La mappa di microzonazione

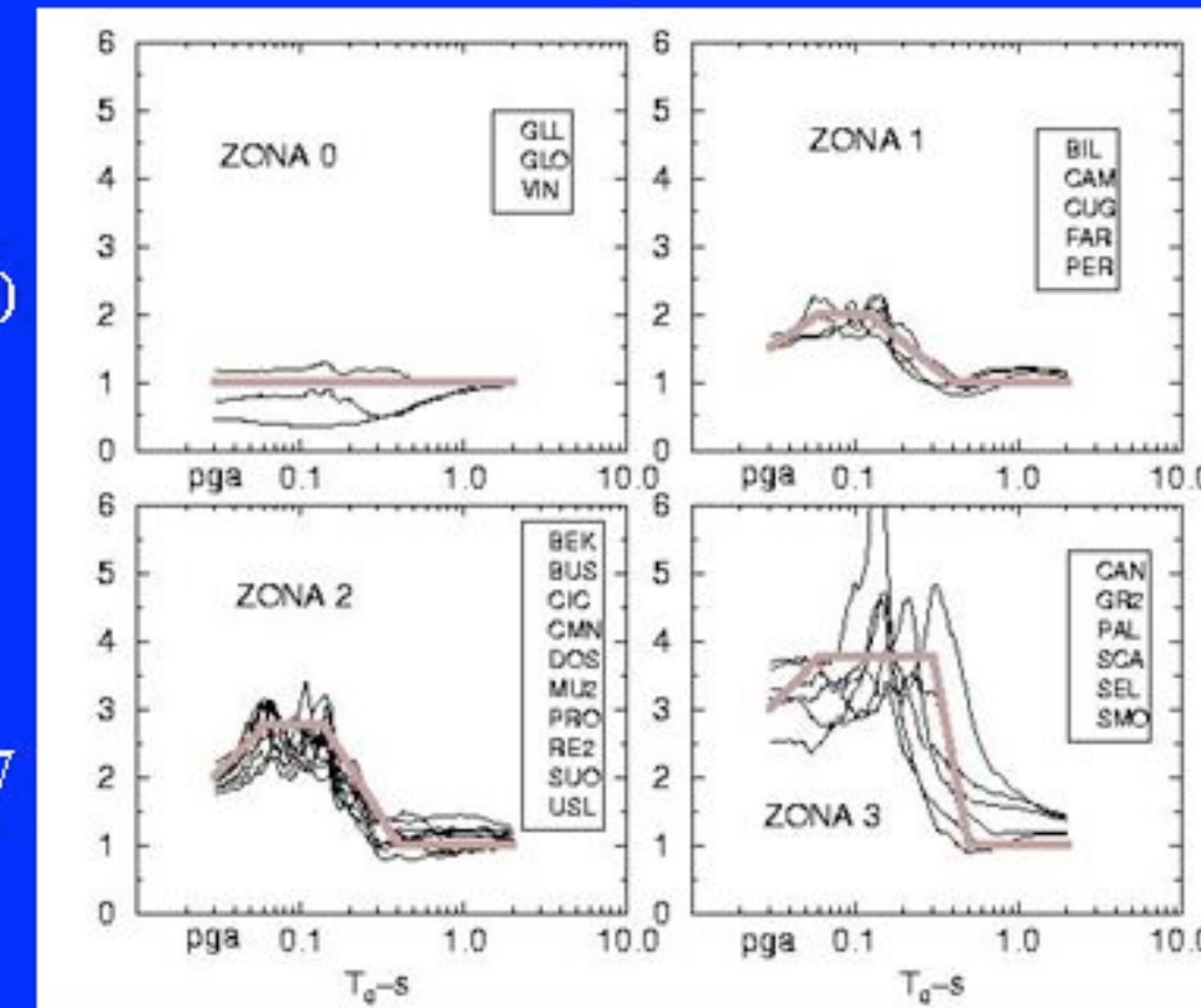
Valutazione sperimentale effetti di sito



$SI_1=1.0$

$SI_1=1.7$

- Z.0: riferimento
- Z.1: depositi alluvionali di spessori limitati (< 6 m)
- Z.2: terrazzi alluvionali piu' antichi
- "Z.3": spessori elevati dei sedimenti, frane quiescenti, alterazioni superficiali, ...



$SI_1=1.4$

$SI_1=3.0$

$Sa_{zona} / Sa_{riferimento}$

La mappa di microzonazione

Attuazione dell'articolo 11 della legge 24 giugno 2009, n.77
MICROZONAZIONE SISMICA - Livello 1
Tavola 5
Carta delle microzone omogenee in prospettiva sismica
 Foglio 1/2 - Nord
 Regione Veneto
 Comune di Schio

Soggetto realizzatore: **TECNOLOGICA srl**
 Viale Comandanti Alleati d'Europa, 9/15
 45100 ROVIGO

Data: 17 Dicembre 2013

MI s.r.l.
 Via Giuseppe Verdi, 1
 45100 ROVIGO

Zone Stabili (Non suscettibili di amplificazione)

Zona 1: Lapideo (pendio < 15°)
 Zona 2: Granulare cementato (pendio < 15°)

Zone stabili suscettibili di amplificazioni locali

Zona 3: Lapideo (pendio > 15°)
 Zona 4: Alternanza di litipi (pendio > 15°)
 Zona 5: Substrato di origine effusiva o metamorfica
 Zona 6: Lapideo, stratificato
 Zona 7: < 10 m
 Zona 8: 10-15 m
 Zona 9: 15-20 m
 Zona 10: 20-30 m
 Zona 11: 30-40 m
 Zona 12: 40-50 m
 Zona 13: 50-200 m
 Zona 14: > 200 m

Zone suscettibili di instabilità

Instabilità di versante: Attiva
 Instabilità di versante: Quiescente
 Instabilità di versante: Inattiva
 Instabilità di versante: Non definita
 Liquefazione
 Aree interessate da deformazioni dovute a faglie attive e capaci
 Cedimenti differenziali
 Sovrapposizione di zone suscettibili di instabilità differenti

Forme di superficie e sepolte

Conoide alluvionale
 Falda detritica
 Area con cavità sepolte/sinkhole
 Orlo di scarpata morfologica (>20m)
 Cresta
 Valle sepolta stretta (C<0.25)
 Valle sepolta larga (C<0.25)
 Picco isolato
 Cavità sepolta/sinkhole

Faglie attive e capaci

Faglia inversa attiva (certa)
 Faglia inversa attiva (presunta)
 Faglia trascorrente/obliqua attiva (certa)
 Faglia trascorrente/obliqua attiva (presunta)

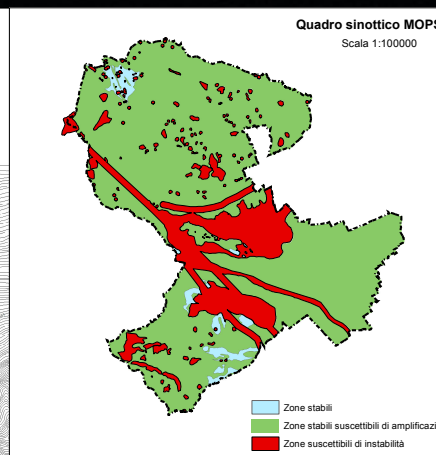
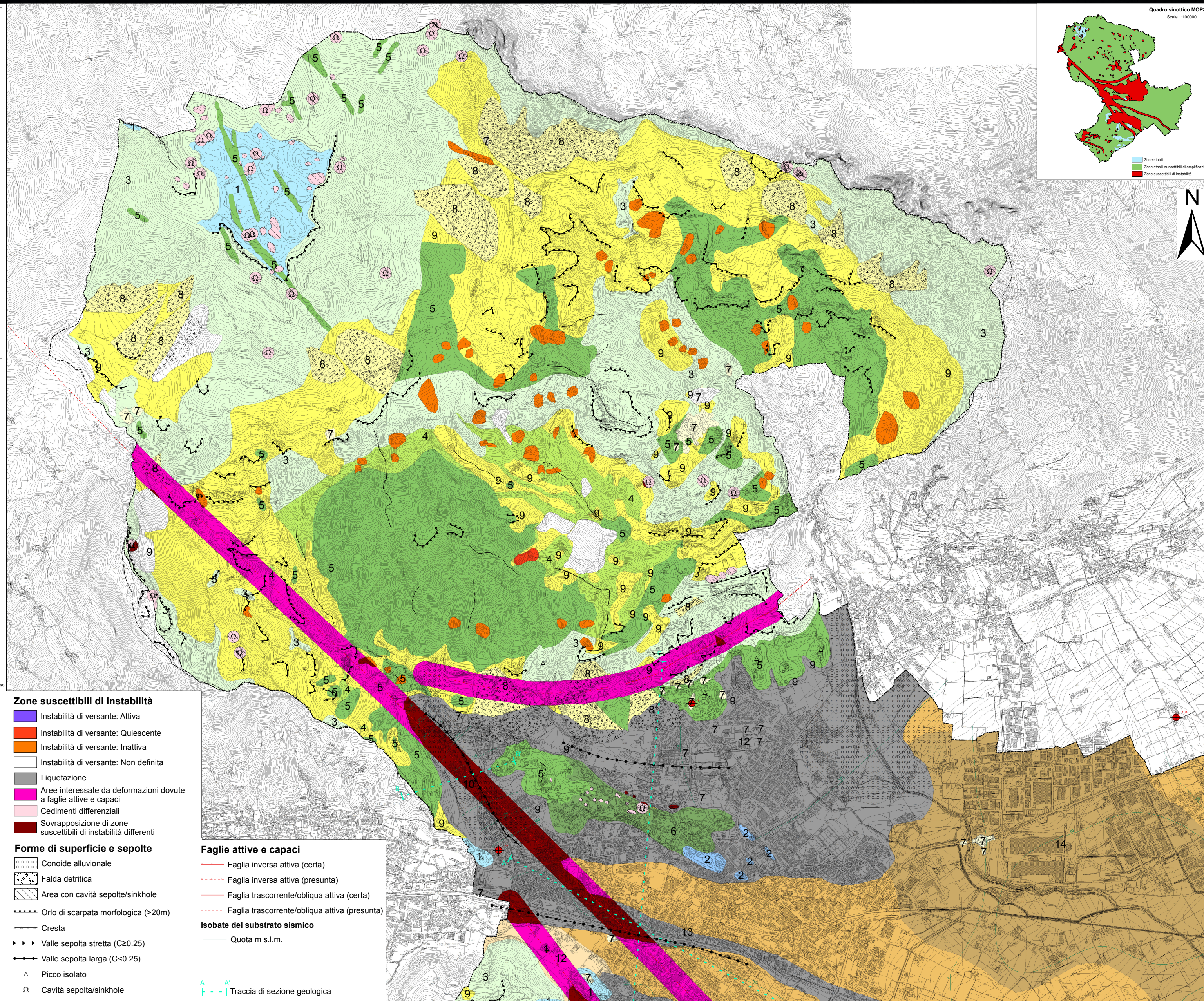
Isobate del substrato sismico

Quota m s.l.m.

Traccia di sezione geologica

Scala 1:10000

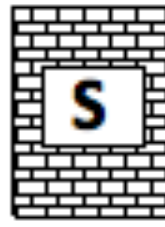
N.B.: Le aree bianche esterne al confine comunale non sono state indagate



La mappa di microzonazione

Zone Stabili (Non suscettibili di amplificazione)

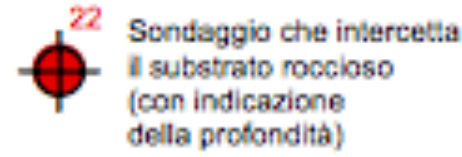
Zona 1 Zona 2



Lapideo
(pendio < 15°)

Granulare
cementato
(pendio < 15°)

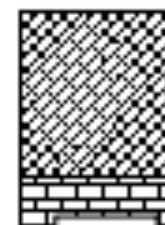
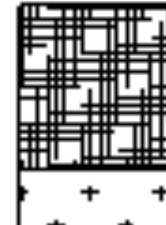
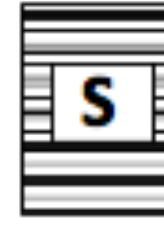
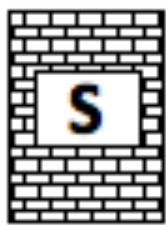
S Stratificato



Sondaggio che intercetta
il substrato roccioso
(con indicazione
della profondità)

Zone stabili suscettibili di amplificazioni locali

Zona 3 Zona 4 Zona 5 Zona 6



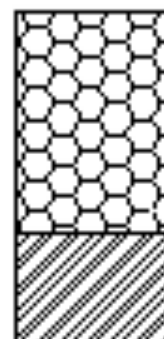
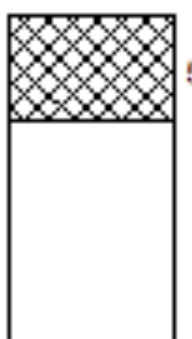
Lapideo
(pendio > 15°)

Alternanza
di litotipi
(pendio > 15°)

10-15 m
Substrato
di origine
effusiva o
metamorfica

10-15 m
Lapideo,
stratificato

Zona 7 Zona 8 Zona 9 Zona 10



5-10 m

15-20 m

15-20 m

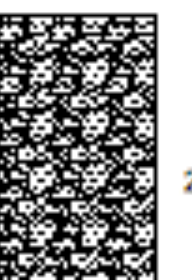
40-50 m

Substrato

Substrato

Materiale roccioso
fortemente
cataclasiato

Zona 11 Zona 12 Zona 13 Zona 14



20-30 m

40-50 m

60-200 m

Zone suscettibili di instabilità

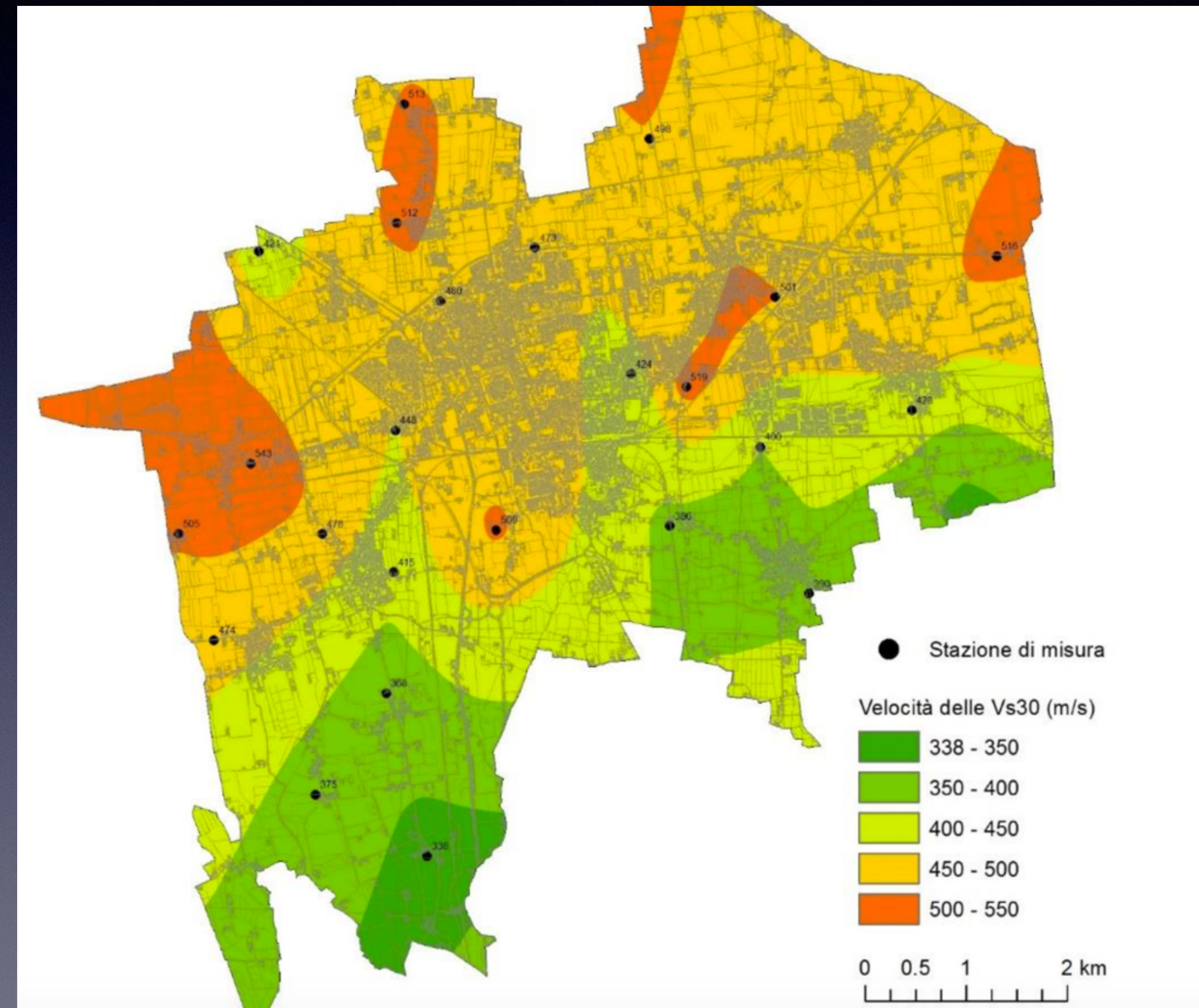
- Instabilità di versante: Attiva
- Instabilità di versante: Quiescente
- Instabilità di versante: Inattiva
- Instabilità di versante: Non definita
- Liquefazione
- Aree interessate da deformazioni dovute a faglie attive e capaci
- Cedimenti differenziali
- Sovrapposizione di zone suscettibili di instabilità differenti

Forme di superficie e sepolte

- Conoide alluvionale
- Falda detritica
- Area con cavità sepolte/sinkhole
- Orlo di scarpata morfologica (>20m)

- Zone suscettibili di amplificazione
- Zone potenzialmente instabili

Livello 2 = Pianificazione. Definizione di zone omogenee dal punto di vista sismico basate su misure sperimentali speditive



Livello 2 = Pianificazione. Definizione di zone omogenee dal punto di vista sismico basate su misure sperimentali speditive

Utilizzo di ABACHI DI AMPLIFICAZIONE

L2 Utilizzo di ABACHI DI AMPLIFICAZIONE

CLAY

Vs30(m/s)	200	250	300
F.A. PGA	1.8	1.7	1.6
F.A. S1	1.5	1.4	1.4
F.A. S2	3.2	2.5	2.4
F.A. S3	5.3	4.3	3.7

SAND

Vs30(m/s)	250	300	350
F.A. PGA	1.5	1.4	1.2
F.A. S1	1.3	1.3	1.2
F.A. S2	2.1	2.1	1.8
F.A. S3	3.8	3.8	3.1

GRAVEL

Vs30(m/s)	400	450	500	550	600
F.A. PGA	1.3	1.2	1.2	1.2	1.2
F.A. S1	1.2	1.2	1.2	1.3	1.1
F.A. S2	1.8	1.8	1.7	1.8	1.6
F.A. S3	3.1	3.1	3.1	3.1	2.8

L2 Utilizzo di ABACHI DI AMPLIFICAZIONE

TABELLE MONTAGNA		ARGILLE		SABBIE		GRAVEL					
		150	200	250	300	350	400	450	500	600	
Fattori di Amplificazione PGA	colonna 1 H (m)	10	2	1.9	1.8	1.9	1.9	1.5	1.4	1.3	1.2
	colonna 2 VsH (m/s)	15	1.9	1.9	1.8	1.8	1.8	1.6	1.4	1.1	1.1
		20	1.9	1.9	1.9	1.7	1.7	1.8	1.6	1.4	1.1
		30		1.8	1.8	1.7	1.7	1.7	1.4	1.3	1.2
		40		1.8	1.8	1.6	1.6	1.7	1.3	1.2	1.2
		50		1.9	2	1.7	1.7	1.6	1.3	1.3	1.2
INTENSITA' DI HOUSNER											
SI (0.1 s < T < 0.5 s)		150	200	250	300	350	400	450	500	600	
	10	1.9	1.8	1.6	1.4	1.3	1	1	1	1	
	15	2.2	2.2	2	1.7	1.3	1.1	1	1	1	
	20	2.3	2.2	2	2	1.7	1.5	1.3	1.3	1.2	
	30		2	2	1.9	1.5	1.4	1.3	1.2	1.2	
	40		2.6	2.6	1.7	1.4	1.4	1.2	1.2	1.1	
	50		2.3	2.2	1.7	1.4	1.3	1.2	1.1	1	
S2 (0.4 s < T < 0.8 s)		150	200	250	300	350	400	450	500	600	
	10	1	1	1	1	1	1	1	1	1	
	15	1.5	1.4	1.3	1.3	1	1	1	1	1	
	20	2.3	1.9	1.5	1.5	1.2	1.1	1	1	1	
	30		2.2	2.2	1.7	1.8	1.3	1.2	1	1	
	40		2.6	2.4	1.5	1.4	1.4	1.3	1.1	1	
	50		2.3	2.3	1.6	1.5	1.5	1.2	1.1	1.1	

L3

Valutazione quantitativo di sito

=

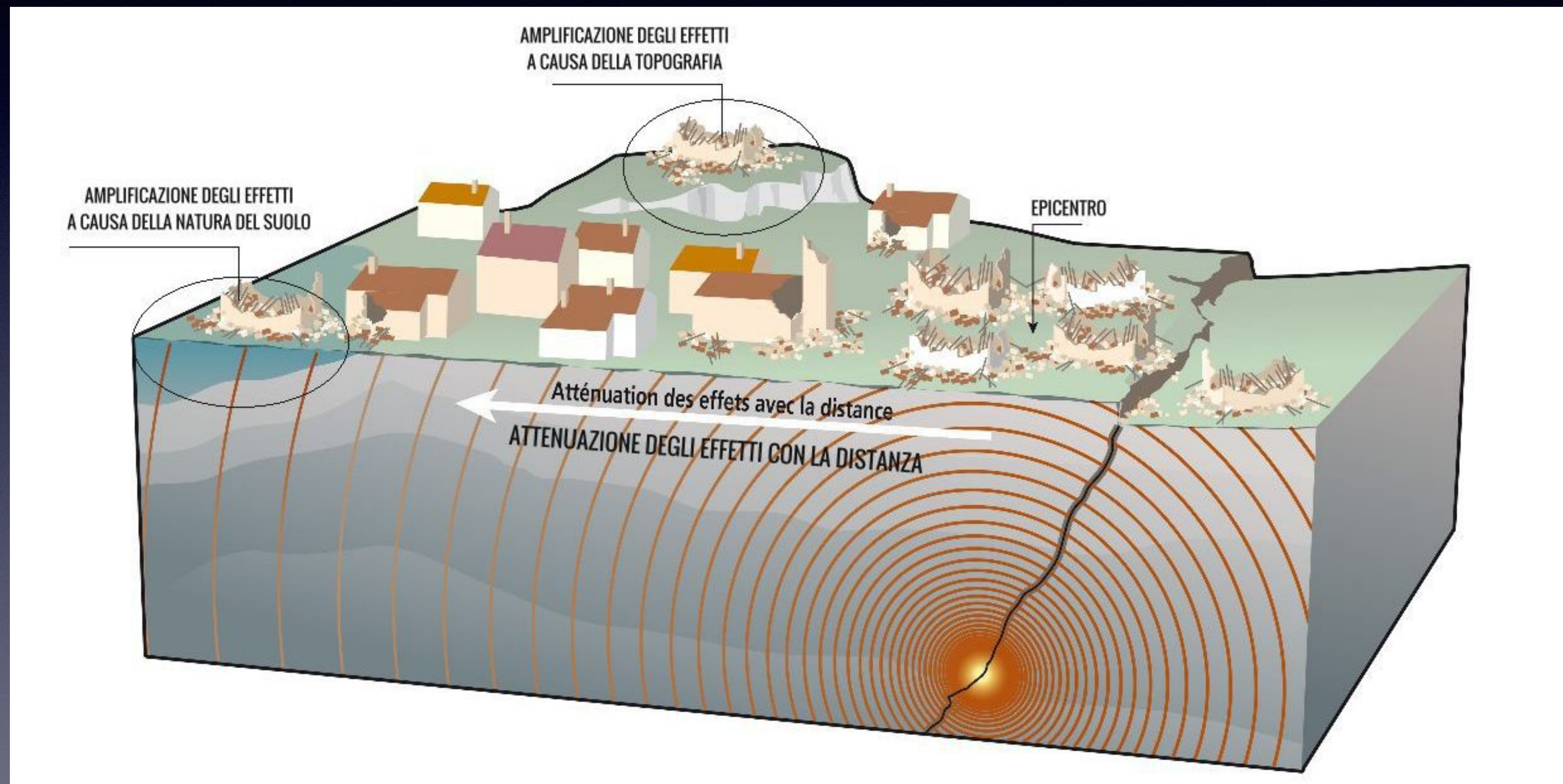
Risposta Sismica Locale

Parte 2

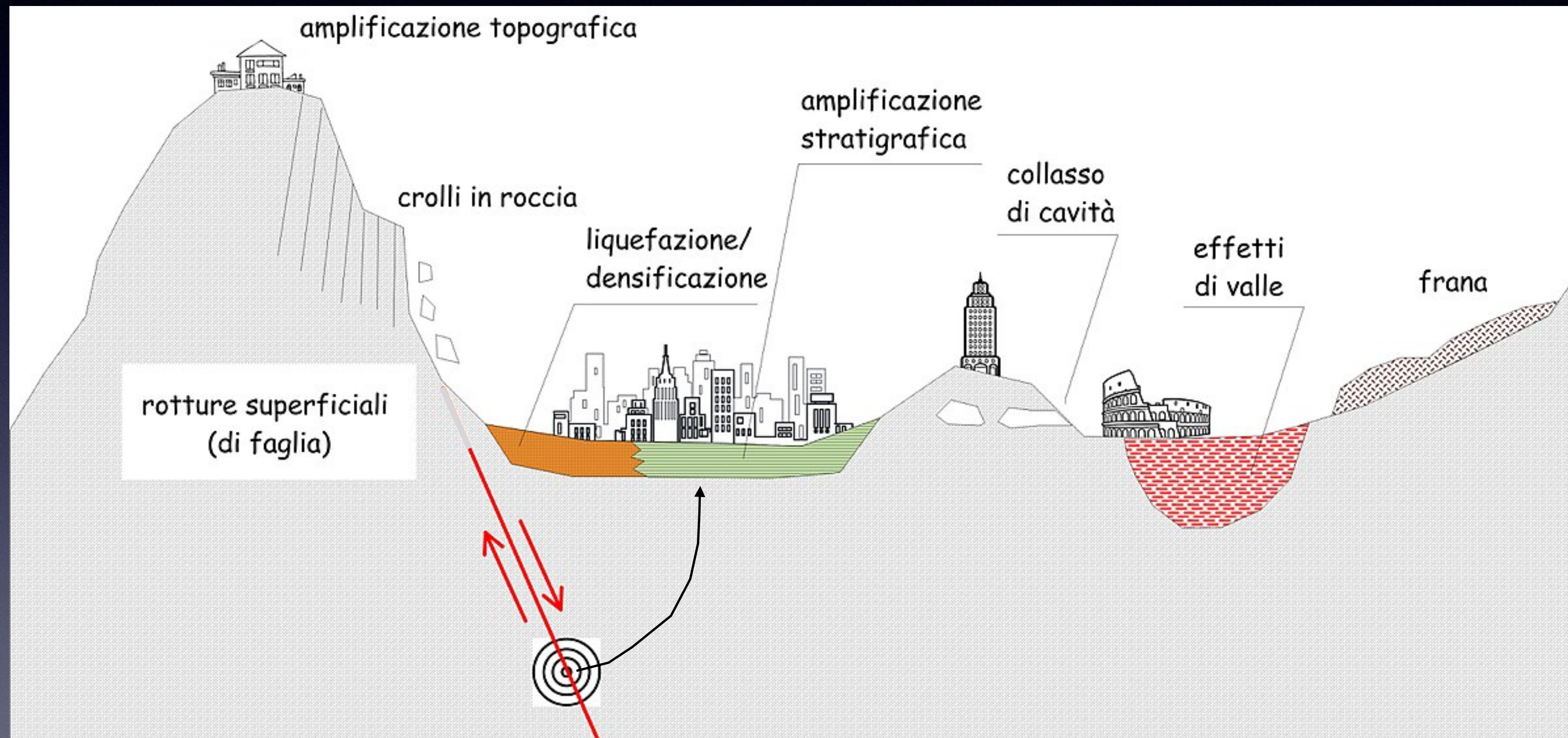
Abbiamo visto la 'risposta sismica',
ma cosa accade localmente?

Microzonazione e RSL
(Risposta Sismica Locale)

- La risposta sismica locale



- La risposta sismica locale



Pagliarioli
mod

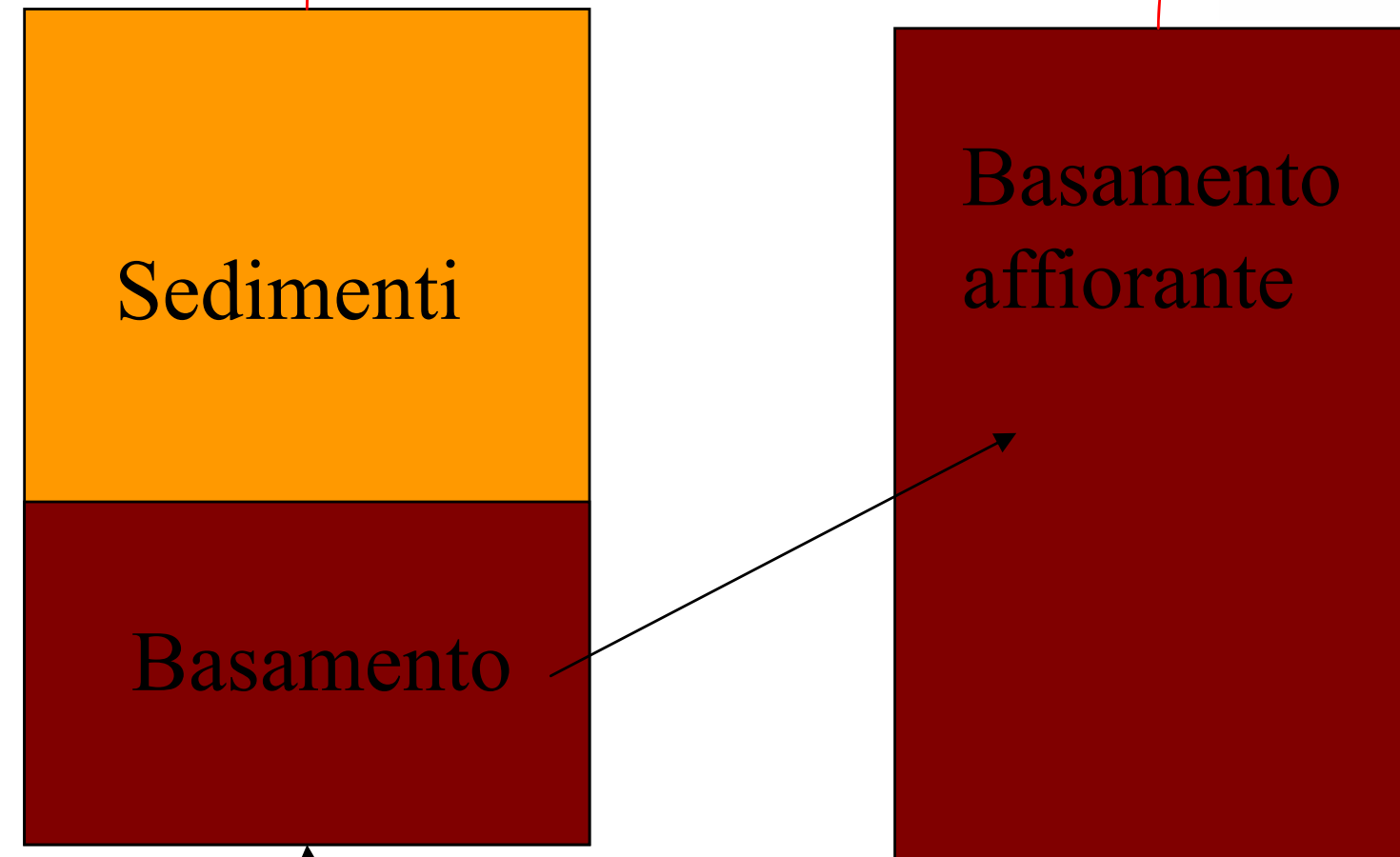
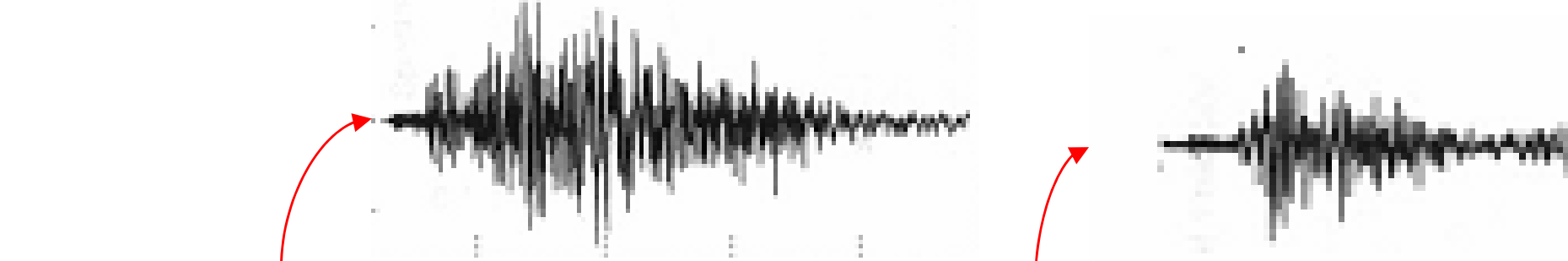
Risposta sismica locale ed effetti indotti

- Modificazioni dello scuotimento del suolo causate da condizioni geologiche-geomorfologiche-geotecniche locali:
 - Vicinanza a faglie sismogenetiche attive (*effetti di campo-vicino*)
 - Amplificazione stratigrafica
 - Amplificazione topografica } **Effetti di sito** (S_T, S, T_B, T_C, T_D)
- Effetti di instabilità indotti dal terremoto causati da condizioni geologiche-geomorfologiche-geotecniche locali:
 - Aperture di faglie e fratture in superficie
 - Instabilità di pendii e versanti (anche sottomarini)
 - Cedimenti del suolo \Rightarrow liquefazione/densificazione
 - Tsunami (maremoti) } **Effetti indotti**

Effetti litologici

Terremoto alla superficie $f(v)$

Moto di riferimento $g(v)$

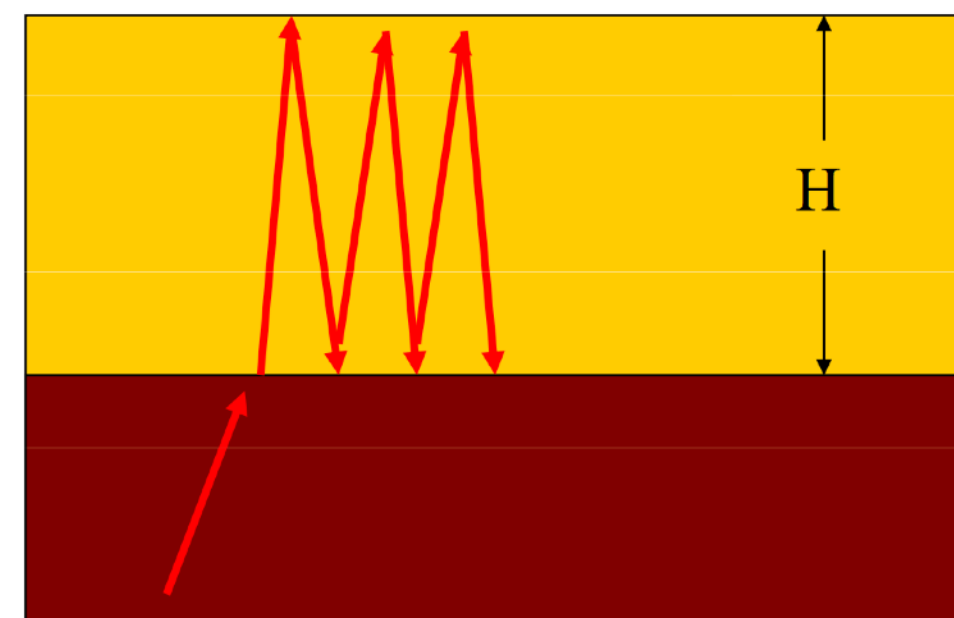


$$F(v) = \frac{f(v)}{g(v)} > 0$$

Funzione di trasferimento



Input sismico



Energia amplificata da strato soffice

Amplificazione Litologica

Effetti topografici

L'interferenza delle onde incidenti è costruttiva in prossimità dei rilievi

Le sommità sono più pericolose dei fondi valle...

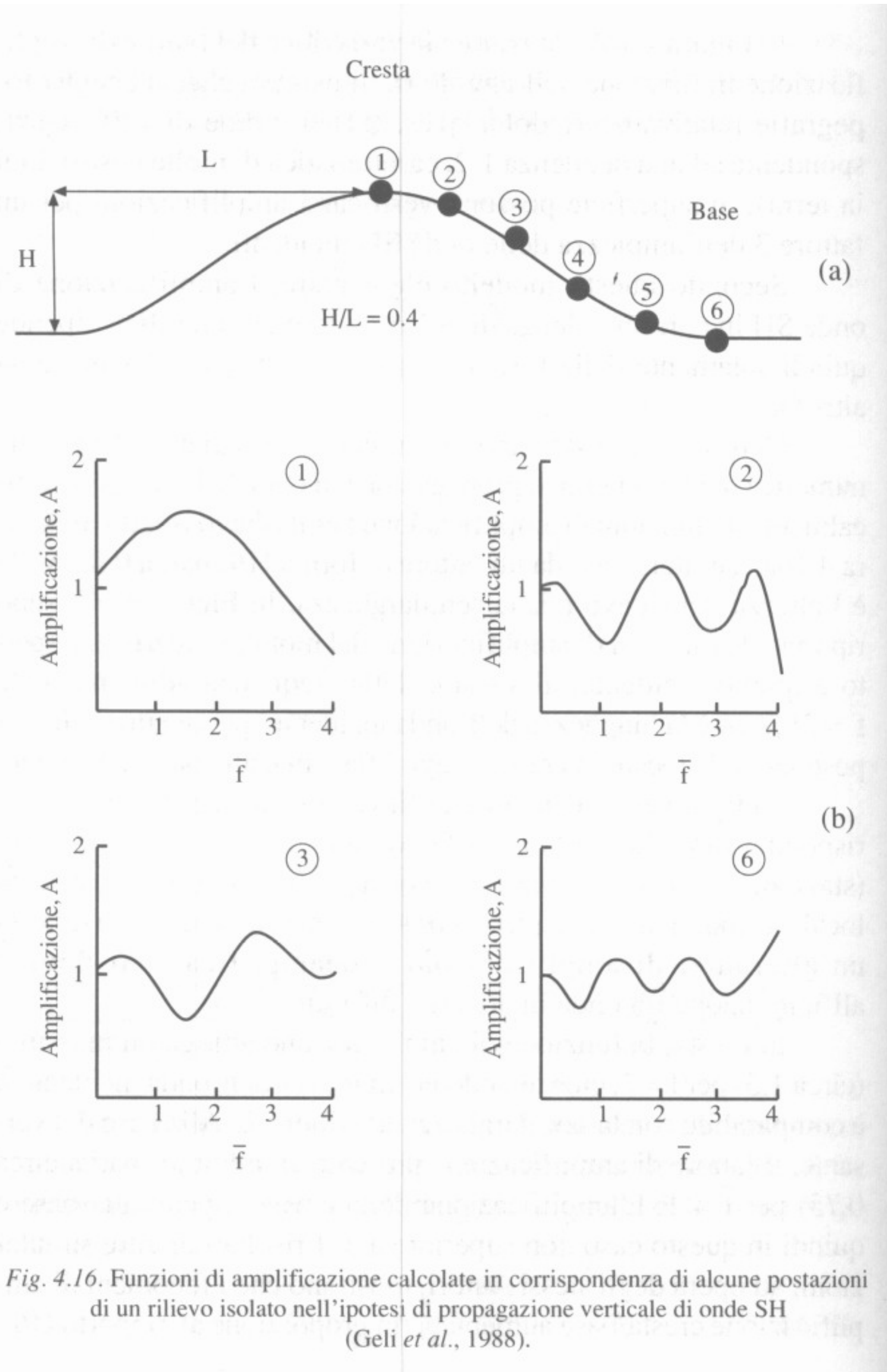
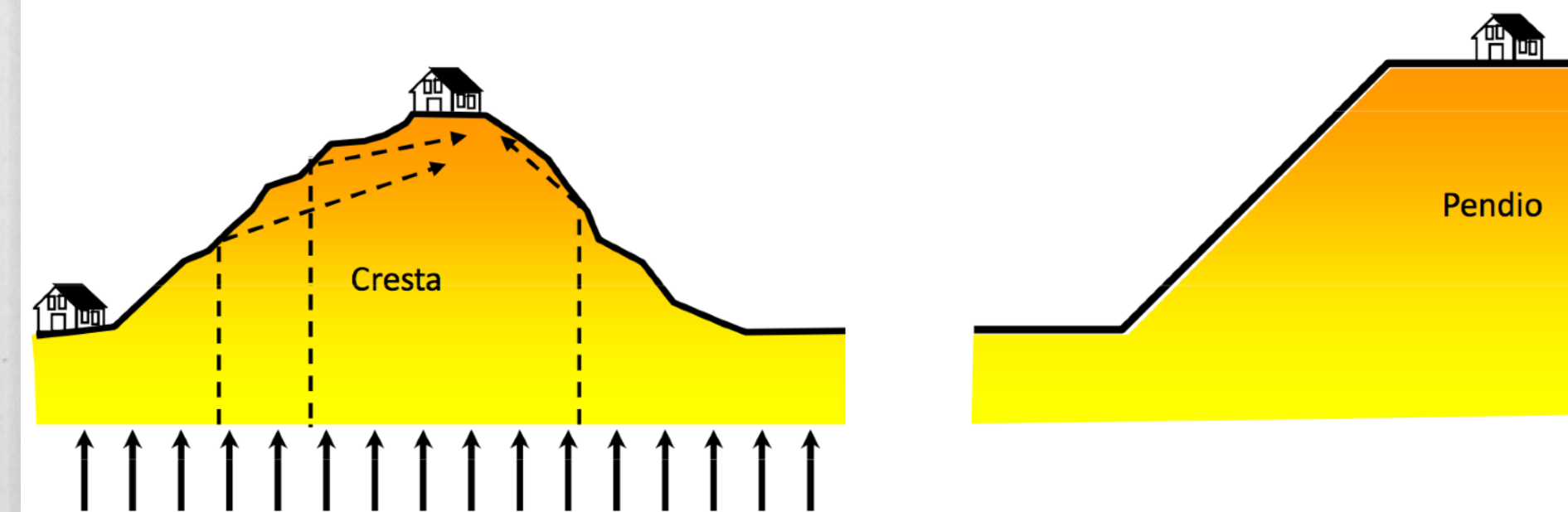


Fig. 4.16. Funzioni di amplificazione calcolate in corrispondenza di alcune postazioni di un rilievo isolato nell'ipotesi di propagazione verticale di onde SH (Geli et al., 1988).



Onde di Volume

(per la geotecnica)

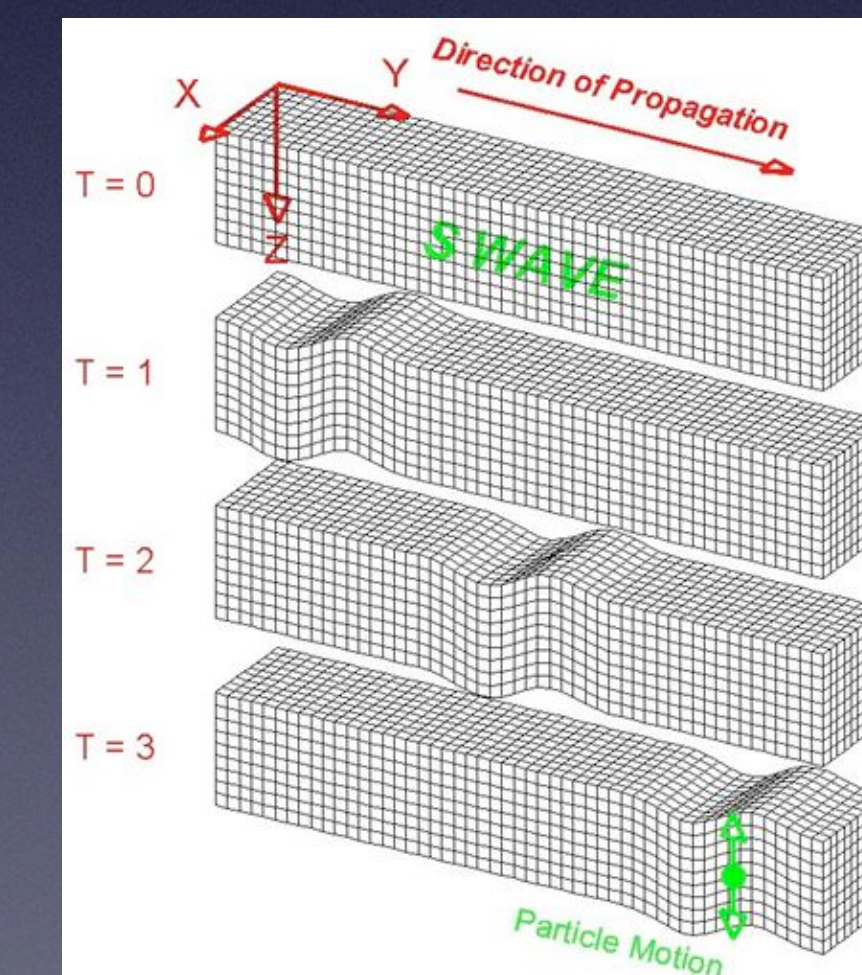
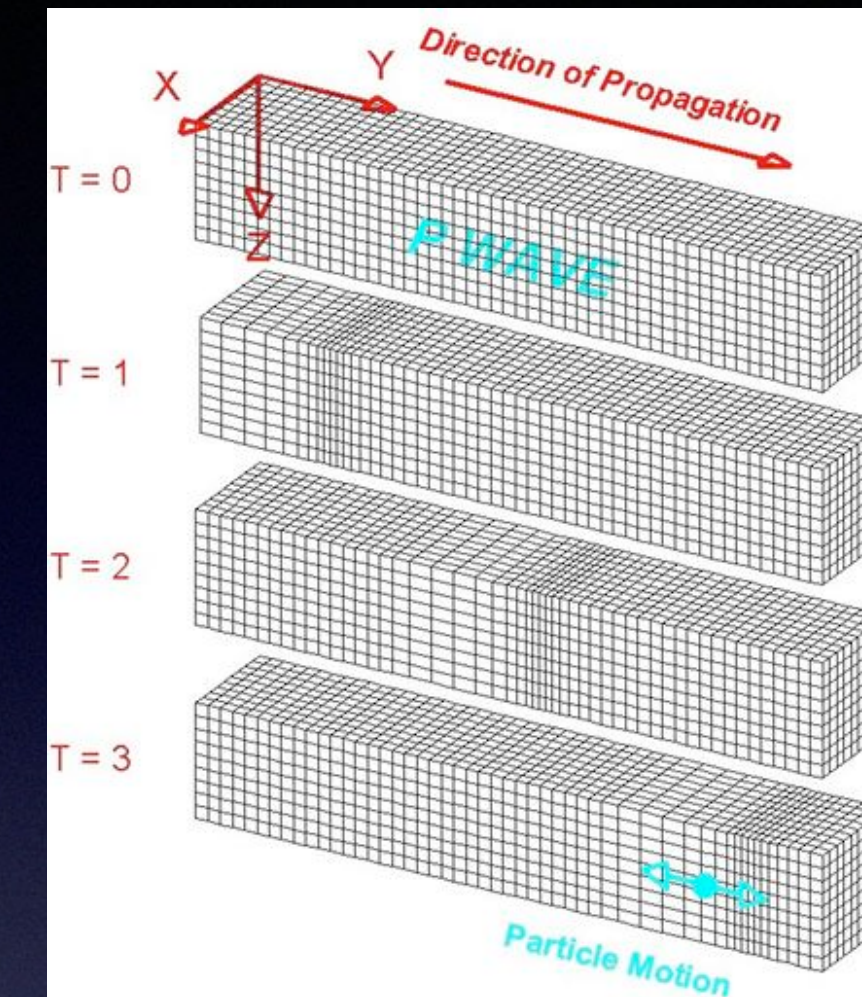
$$V_p = \sqrt{K/\rho}$$

Modulo di Rigidezza a compressione
(Ed in edometria)

densità

$$V_s = \sqrt{G/\rho}$$

Modulo di Rigidezza al taglio

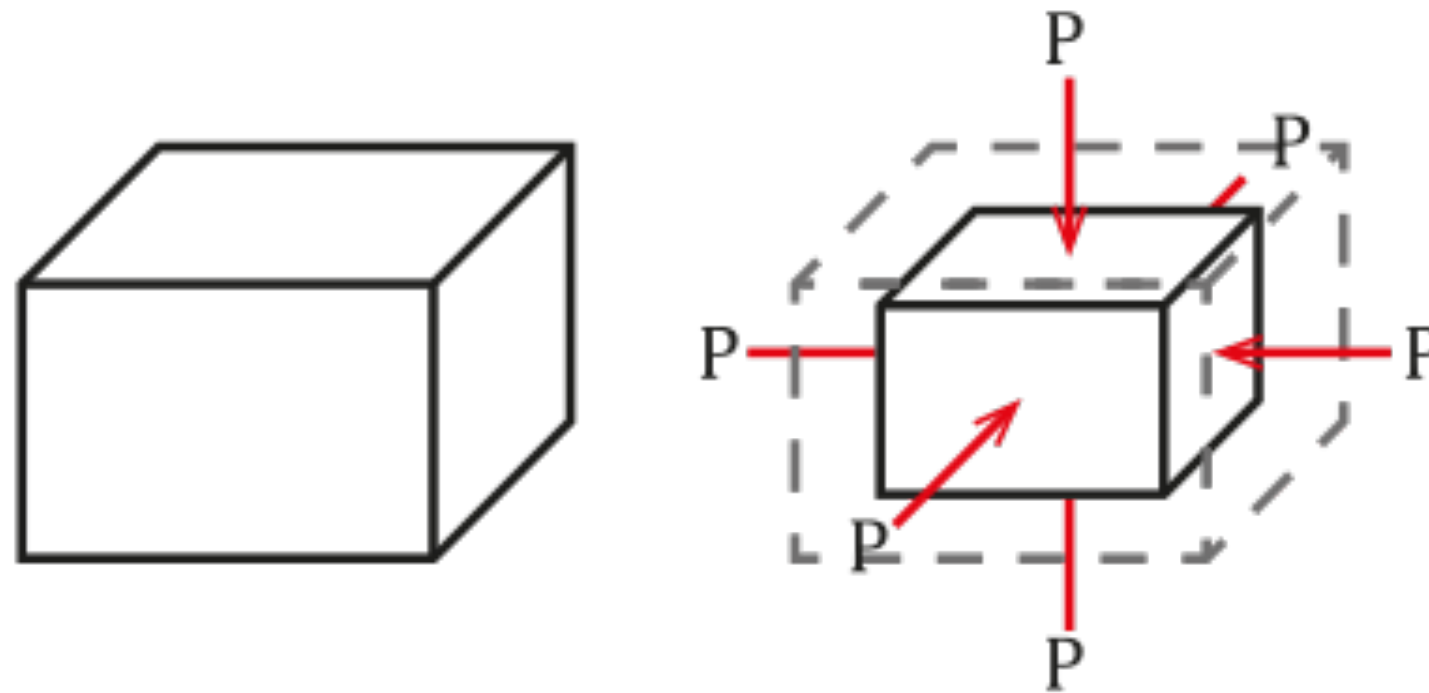


Onde di Volume

(per la geotecnica)

K = modulo di compressibilità

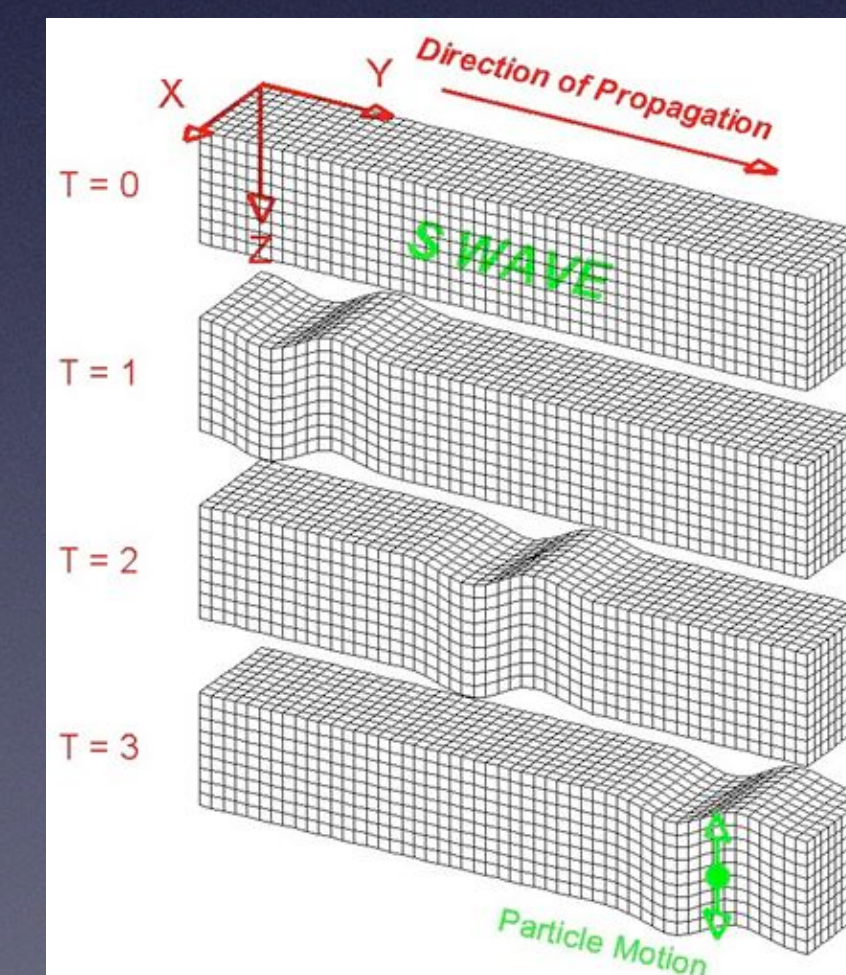
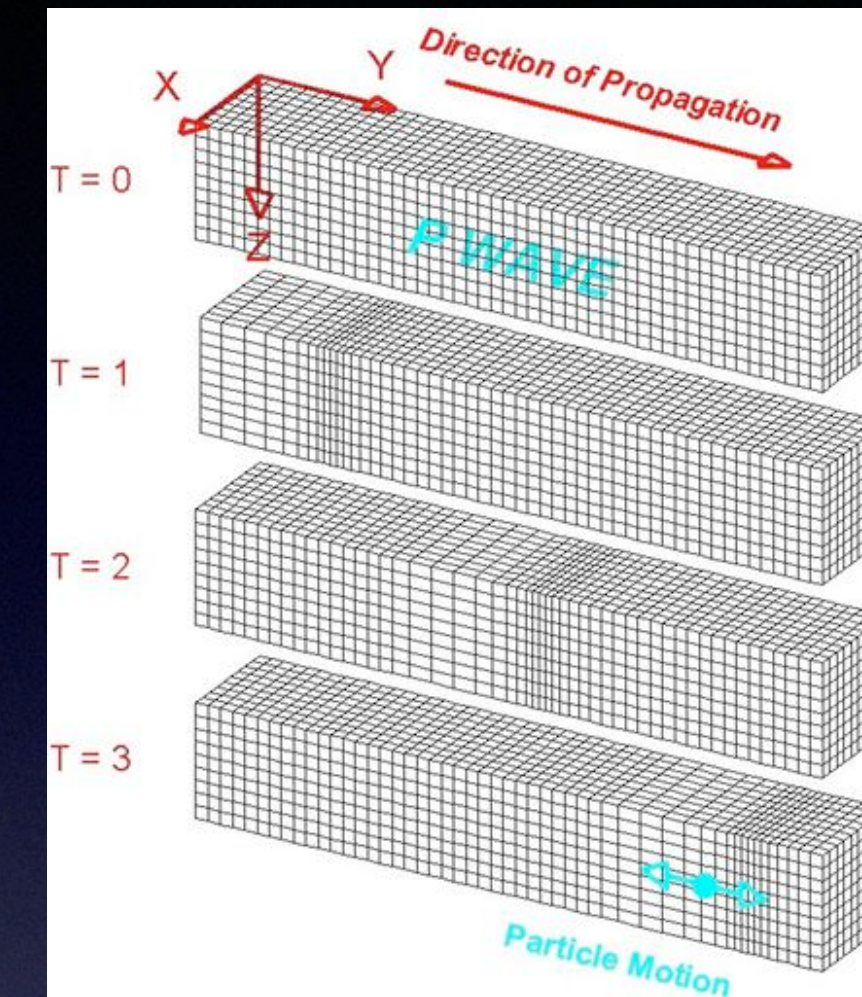
*l'incremento di pressione necessario
a causare un relativo incremento di densità*



Costanti di Lamè

Modulo di taglio

$$K = \lambda + (2 G)$$



Modulo **G**

Modulo
di taglio (μ)

$$G = \rho V_s^2$$

densità ρ *velocità S* V_s

$$G = \frac{(\rho V_p^2) (1-2\gamma)}{2(1-\gamma)}$$

Pwave modulus ρV_p^2 *Poisson* γ

$$G = \frac{E}{2(1+\gamma)}$$

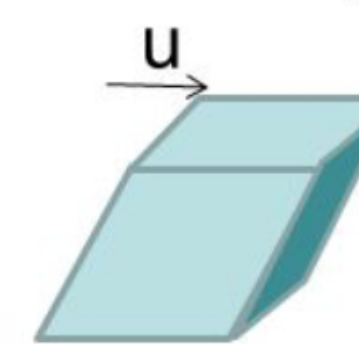
Young modulus E

$$\frac{V_p}{V_s} = \sqrt{\frac{(1-\gamma)}{(0.5-\gamma)}}$$

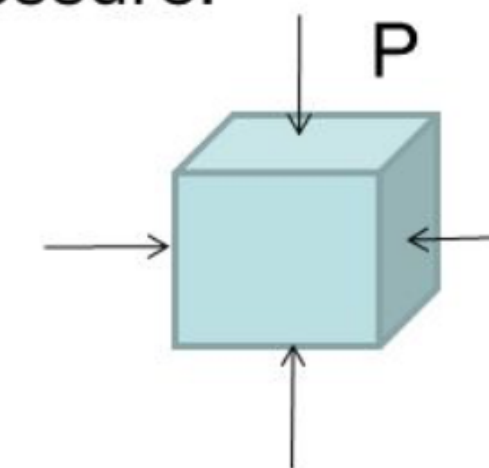
Traction:



Shear:



Hydrostatic Pressure:

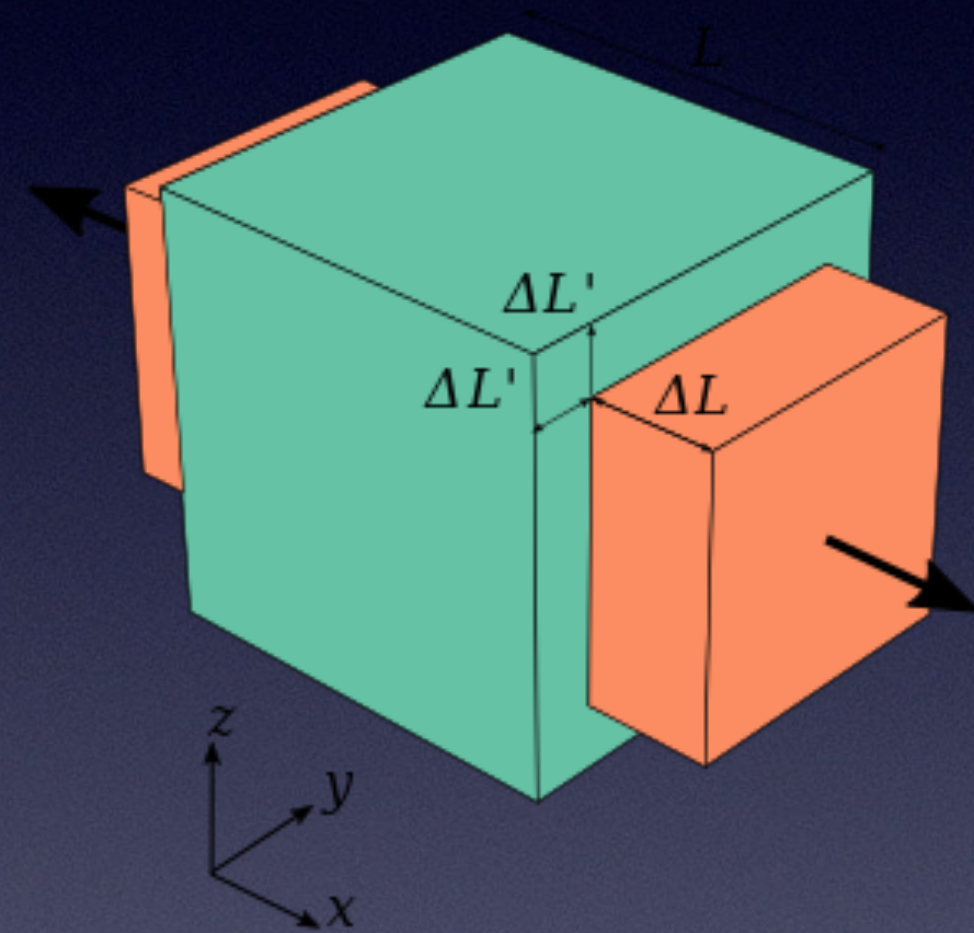


Poisson ratio γ

$$\gamma = - \frac{\epsilon_{m, \text{trav}}}{\epsilon_{m, \text{long}}}$$

Deformazione trasversale

Deformazione longitudinale

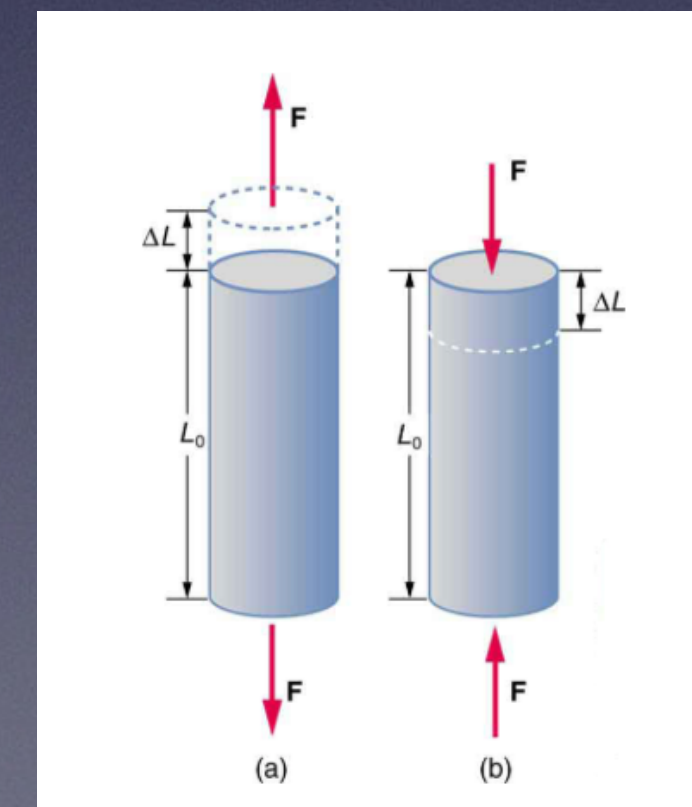


$< 0.5 !$

(gomma)

Modulo di Young E

il rapporto tra lo sforzo σ lungo un asse
e la deformazione conseguente ϵ



Propagazione delle Onde sismiche in un mezzo elastico, omogeneo e isotropo

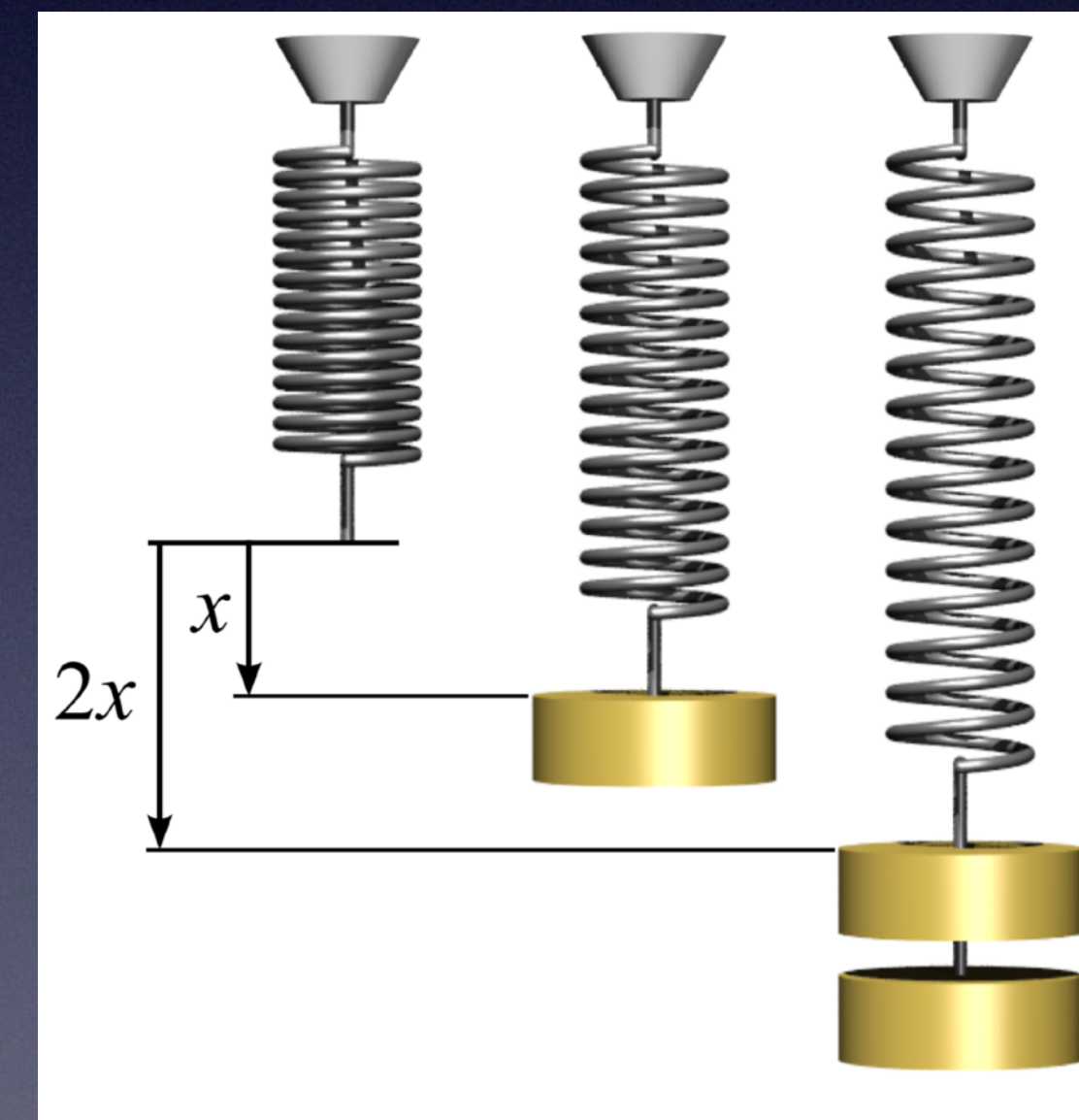
Principi: Il principio della dinamica - legge di Hooke

$$\sigma = E \varepsilon$$

Modulo di Young

Deformazione

Tensione



$$\sigma = k \varepsilon$$

k molla

Propagazione delle Onde sismiche in un mezzo elastico, omogeneo e isotropo

SOLUZIONE dell'Equazione d'onda

P

$$\frac{\partial^2 \bar{\varepsilon}}{\partial t^2} = \frac{\lambda + 2G}{\rho} \nabla^2 \bar{\varepsilon}$$

$$V_P^2$$

$$V_P = \sqrt{\frac{\lambda + 2G}{\rho}}$$

S

$$\frac{\partial^2 \Omega_z}{\partial t^2} = \frac{G}{\rho} \nabla^2 \Omega_z$$

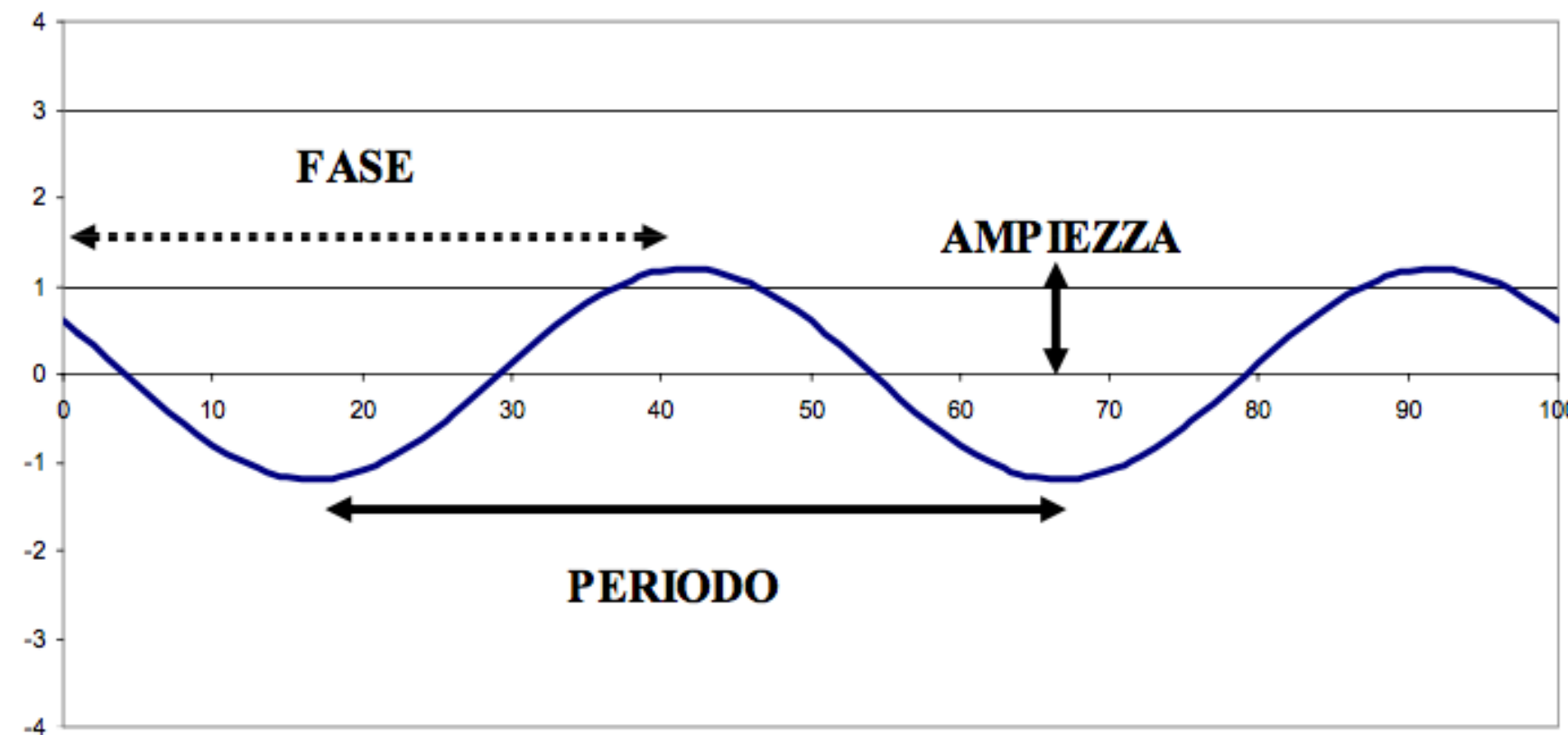
$$V_S^2$$

$$V_S = \sqrt{\frac{G}{\rho}}$$

nei liquidi
G=0
Vs=0

il sottosuolo in prima approssimazione può essere immaginato come un mezzo continuo con equazioni costitutive di tipo lineare (elastiche o visco-elastiche)

In un mezzo di questo tipo, i movimenti del suolo generati da una perturbazione possono essere rappresentati come una combinazione lineare di oscillazioni



$$A(t) = A_{\max} \cos(2\pi ft + \phi)$$

Eq. onda

$$\phi = -2\pi ft_{\max}$$

Fase (quando arriva il massimo?)

$$T = 1/f$$

Periodo (Quanto dura l'oscill.?)

$$f = 1/T$$

Frequenza (Quante oscill.?)

$$\omega = 2\pi f = 2\pi / T$$

Pulsazione

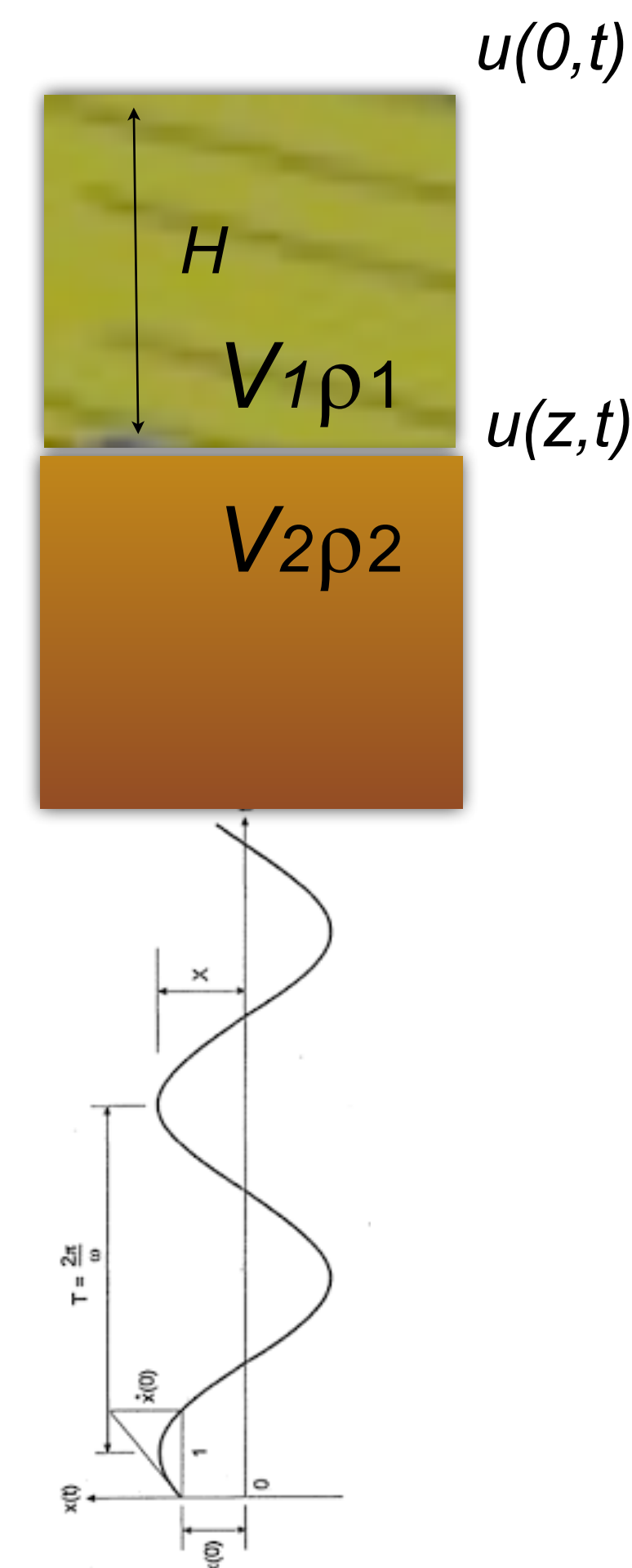
Propagazione delle Onde sismiche in un mezzo elastico, omogeneo e isotropo → sollecitazione armonica

$$u(z,t) = 2A \cos(kz) e^{j\omega t}$$

Funzione di Trasferimento
 $z=H$

$$H(\omega) = \frac{\overset{\text{superficie}}{u_{\max}(0,t)}}{\underset{\text{profondità}}{u_{\max}(z,t)}} = \frac{2Ae^{j\omega t}}{2A\cos(kH)e^{j\omega t}} = \frac{1}{\cos(kH)}$$

Sollecitazione armonica
substrato elastico ideale

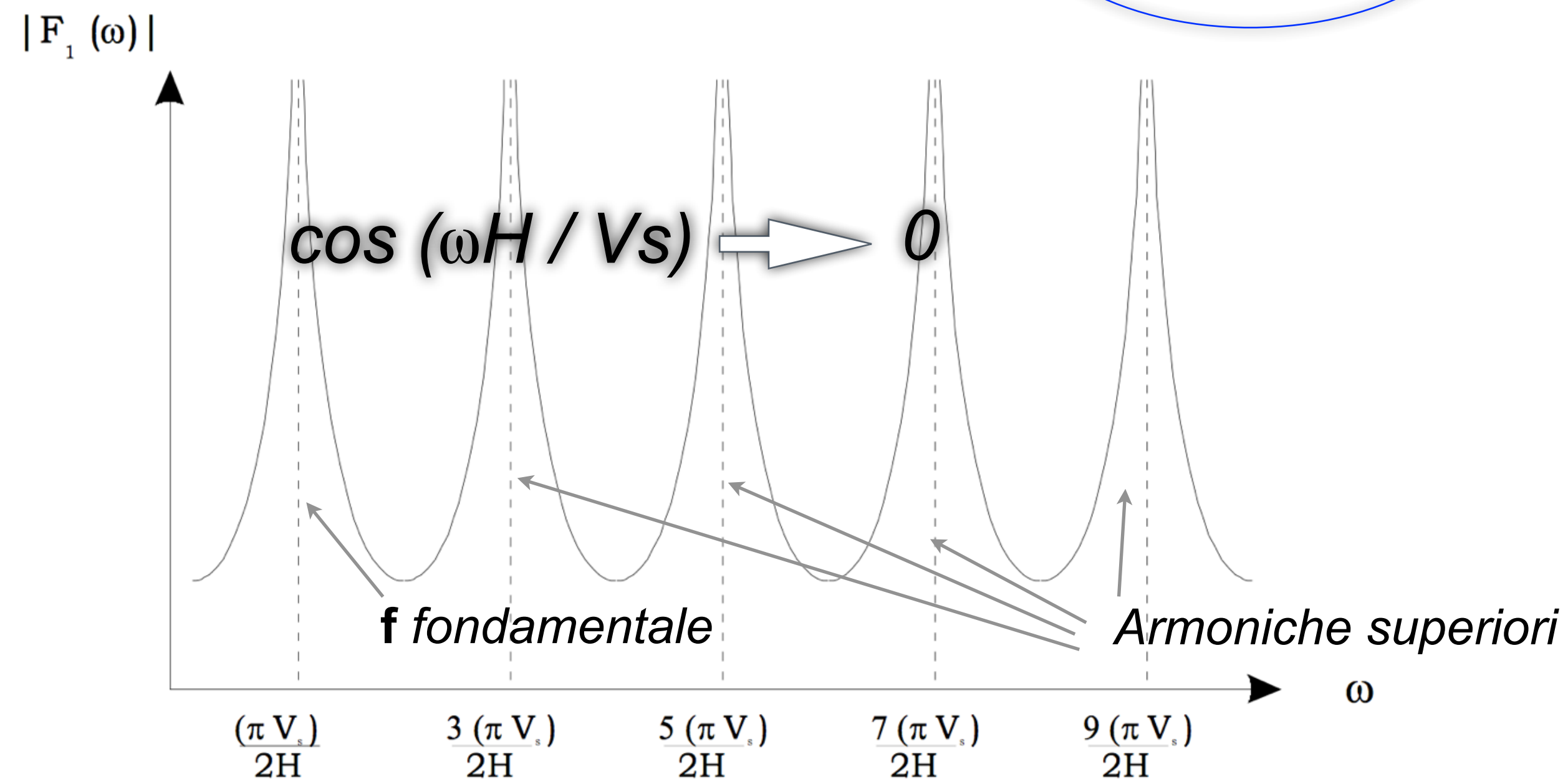


Propagazione delle Onde sismiche in un mezzo elastico, omogeneo e isotropo - sollecitazione armonica

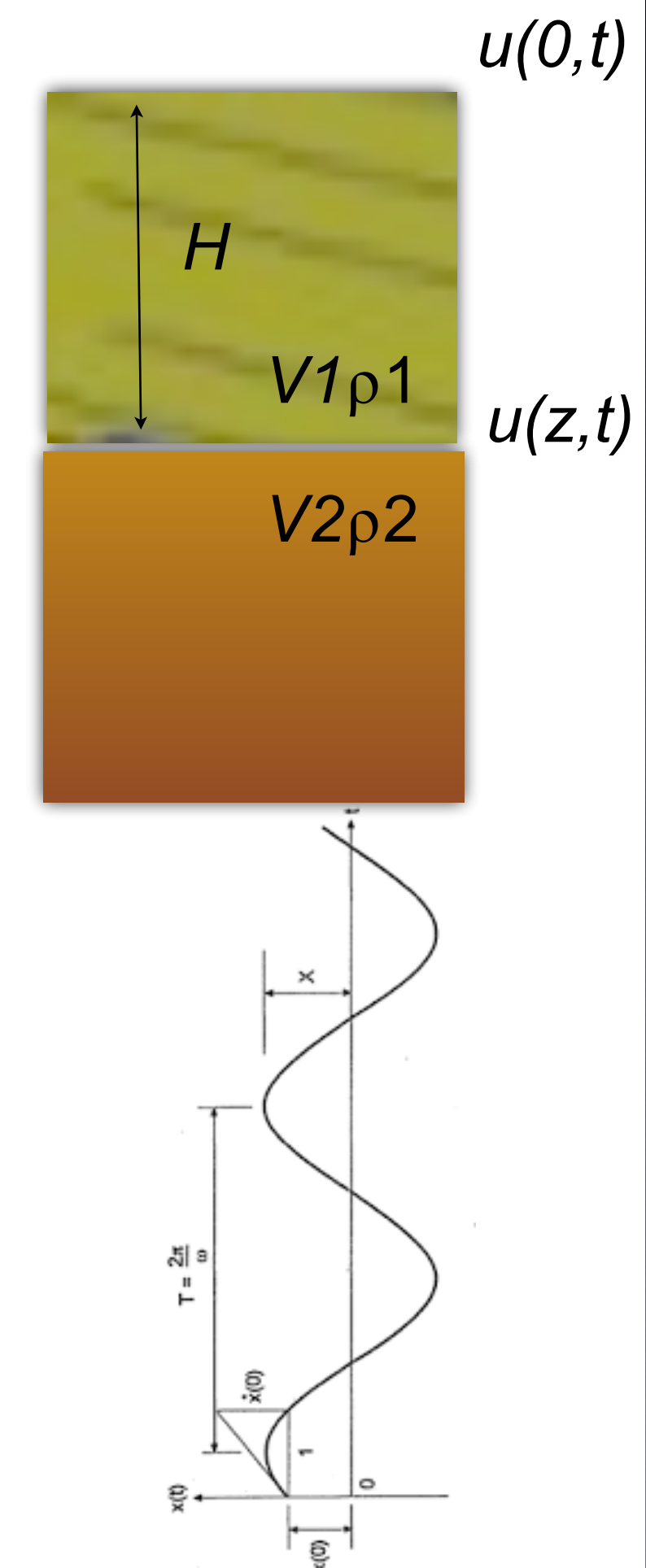
FUNZIONE di AMPLIFICAZIONE A = MODULO Funzione di Trasferimento

$$A(\omega) = |H(\omega)| = \frac{1}{\cos(kH)} = \frac{1}{\cos(\omega H / V_s)}$$

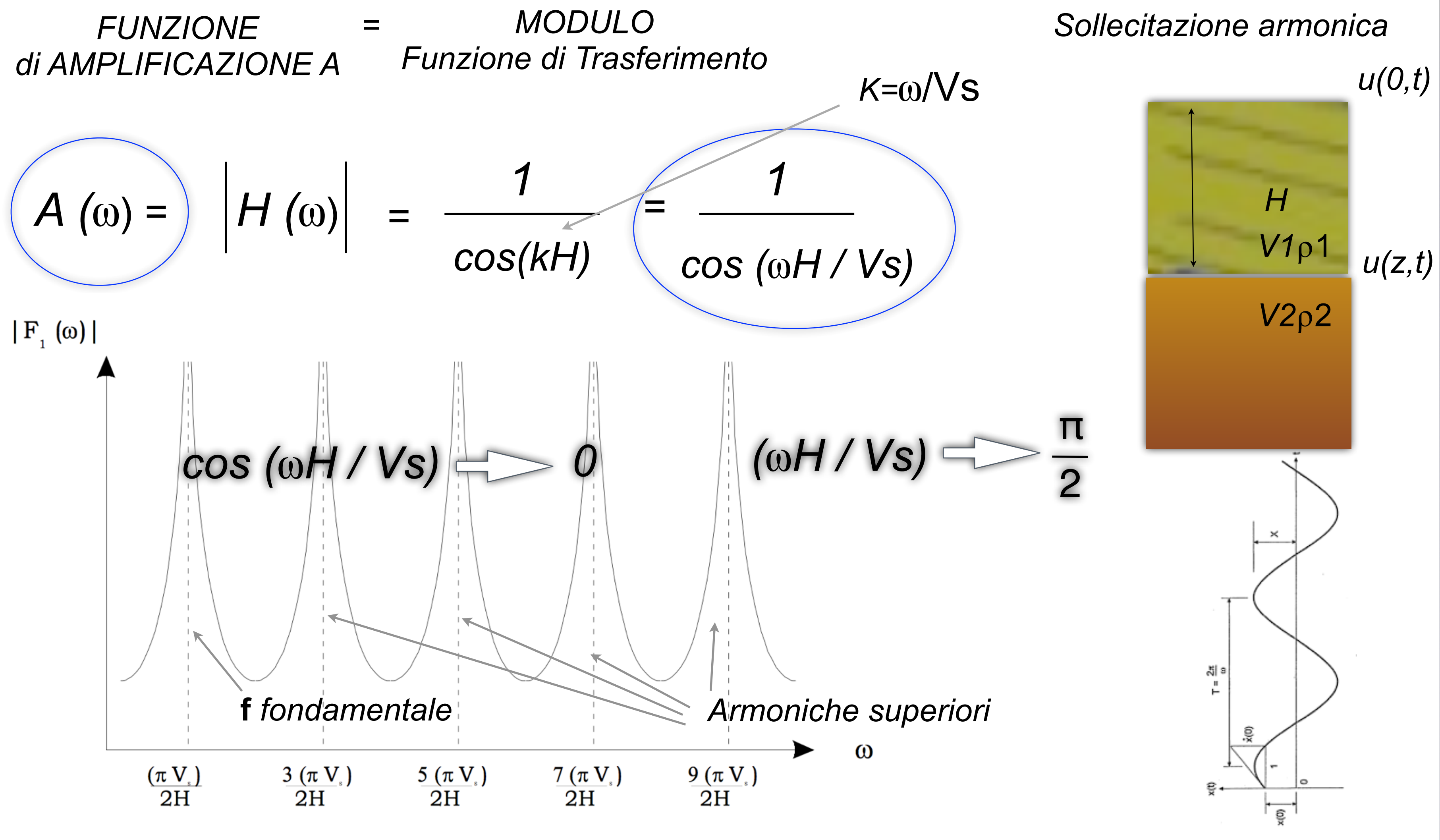
$k = \omega / V_s$



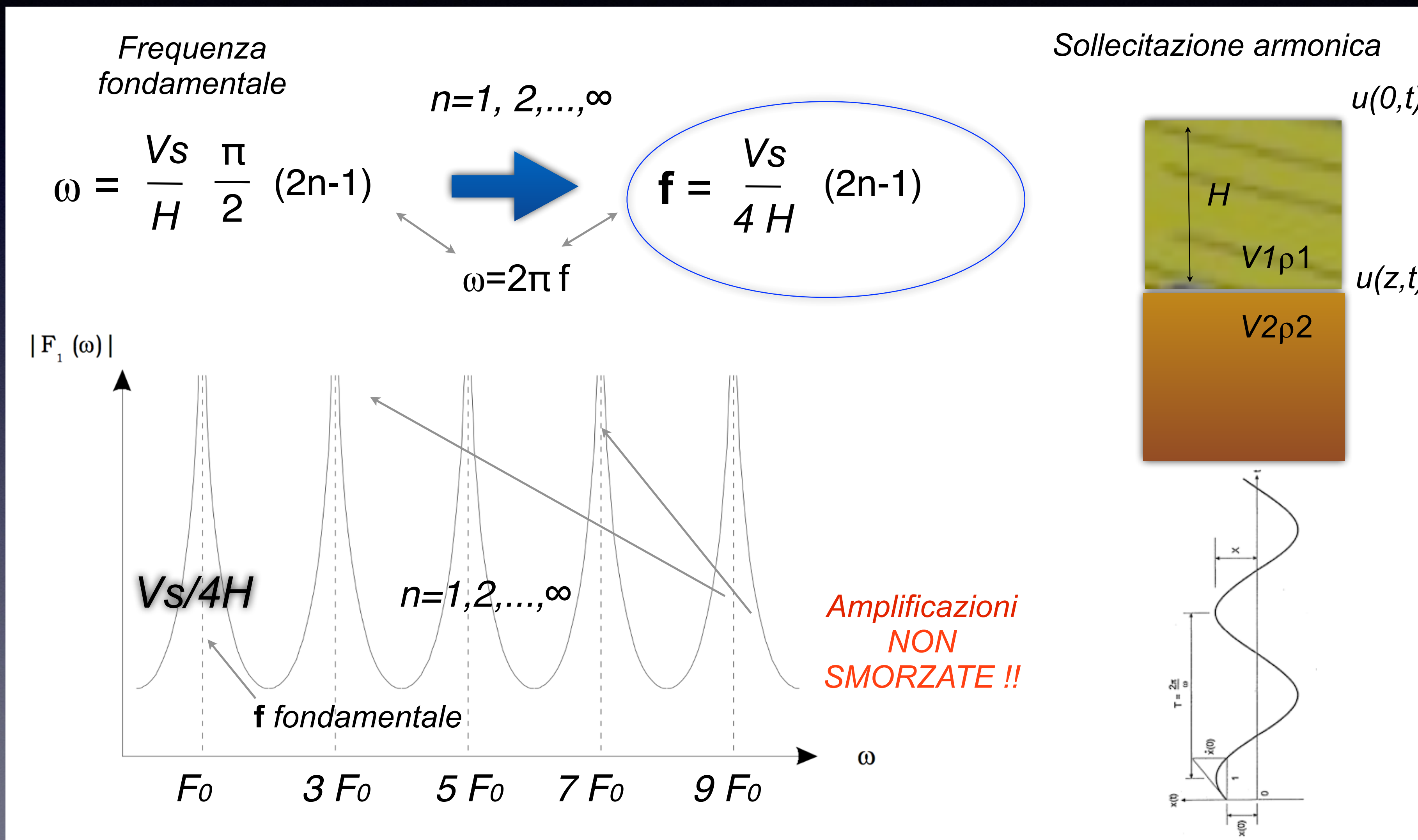
Sollecitazione armonica



Propagazione delle Onde sismiche in un mezzo elastico, omogeneo e isotropo - sollecitazione armonica



Propagazione delle Onde sismiche in un mezzo elastico, omogeneo e isotropo - sollecitazione armonica



Da
Propagazione delle Onde sismiche in un mezzo elastico,
omogeneo e isotropo
ideale



a
Propagazione delle Onde sismiche in un
mezzo reale

Propagazione delle Onde sismiche in un mezzo

parametri delle terre:

-Densità

δ

gr/cm³

-Modulo di rigidezza al taglio

G

N/mm²

-Velocità sismiche S

V_s

m/s

+
-Smorzamento

D

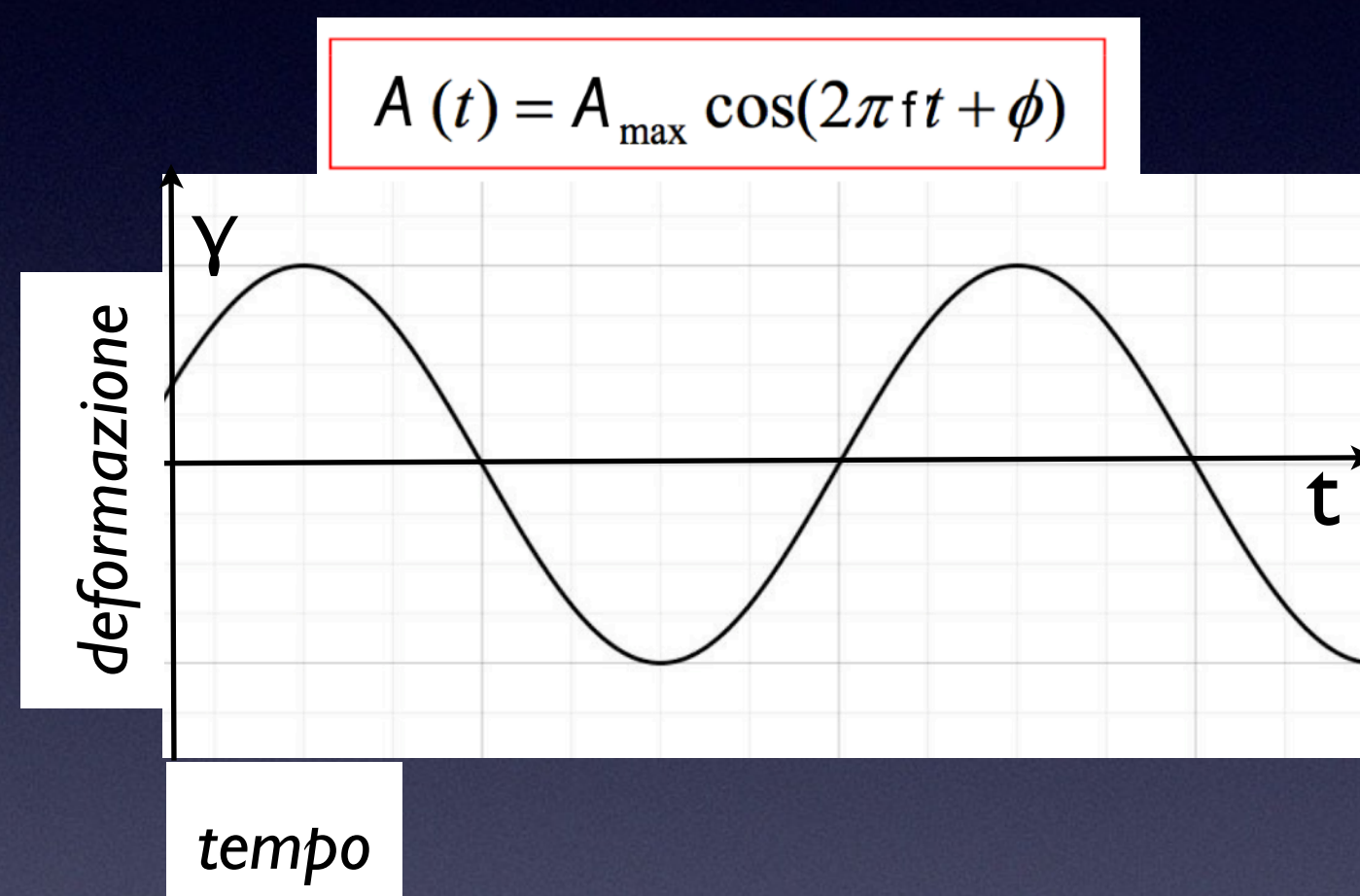
%

ideale

reale

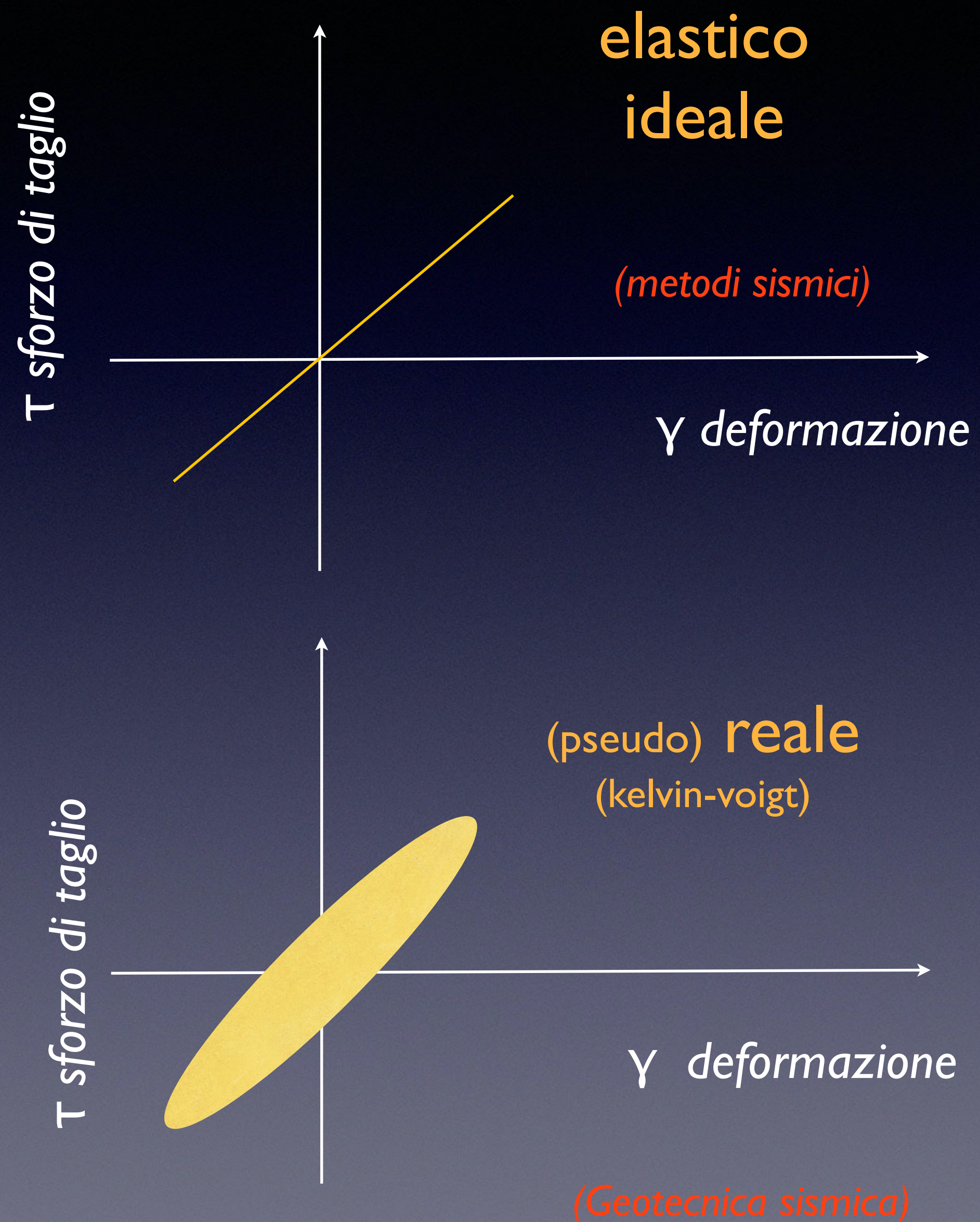
Sforzi (τ) e Deformazioni (γ) a carichi ciclici

*Piccole deformazioni
è lineare elastico*



medie - grandi deformazioni

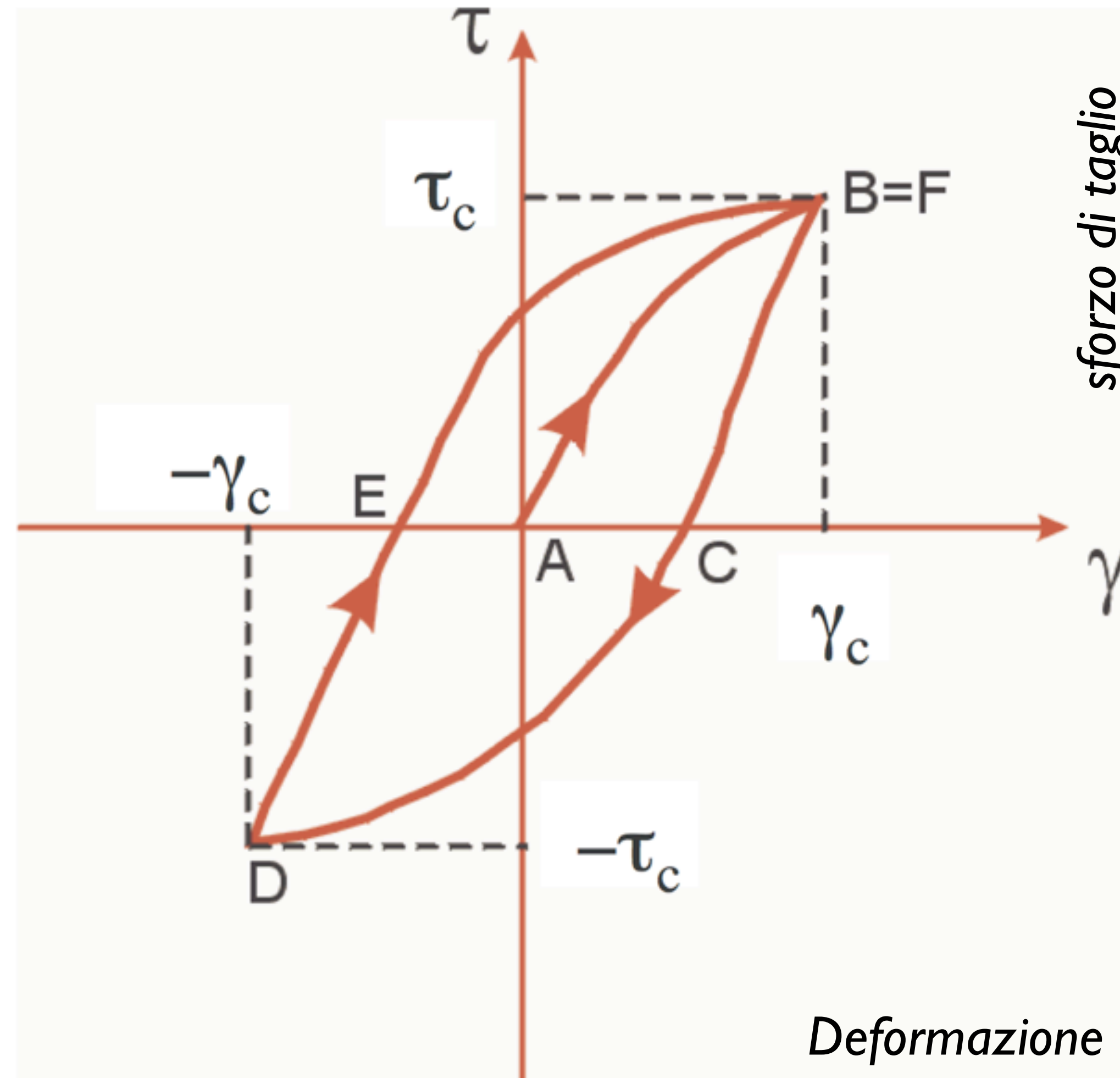
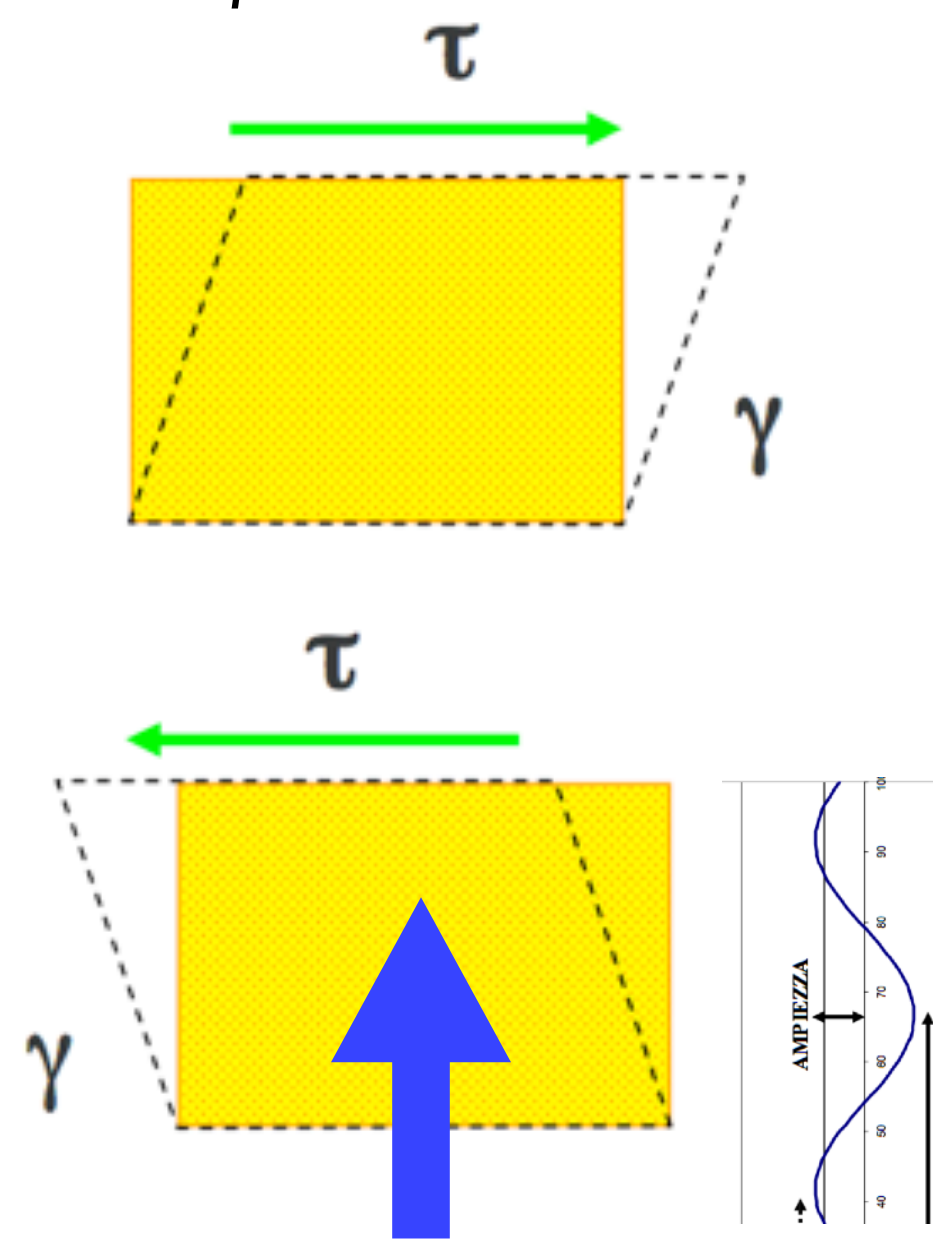
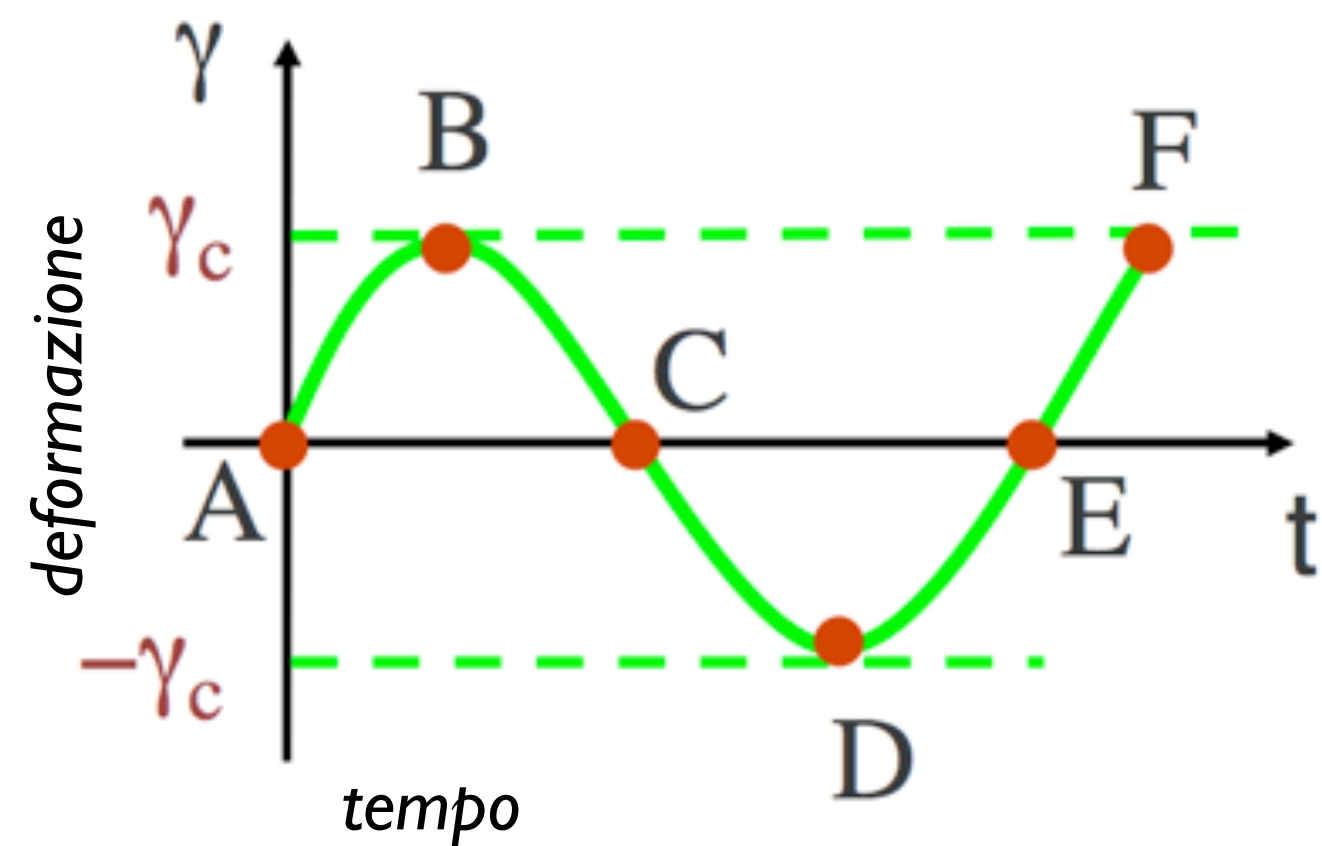
*Terreno è non lineare e dissipativo
(c'è smorzamento)*



I Parametri geotecnici per la modellazione sismica

Risposta di un elemento di terreno soggetto a sollecitazioni cicliche

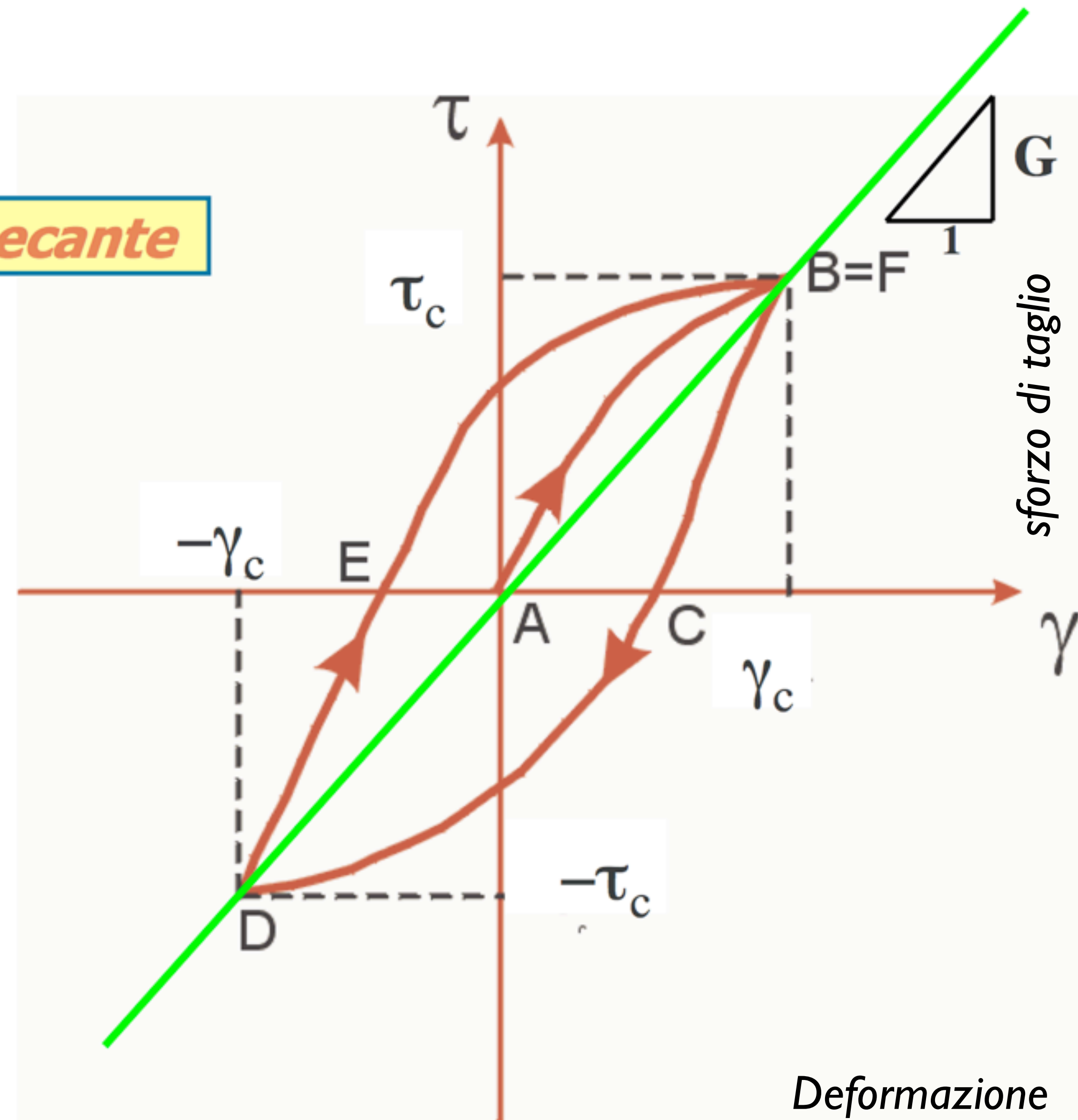
Terreno è non lineare e dissipativo (medie deformazioni)



Parametri geotecnici

Modulo di taglio secante

$$G = \frac{\tau_c}{\gamma_c}$$

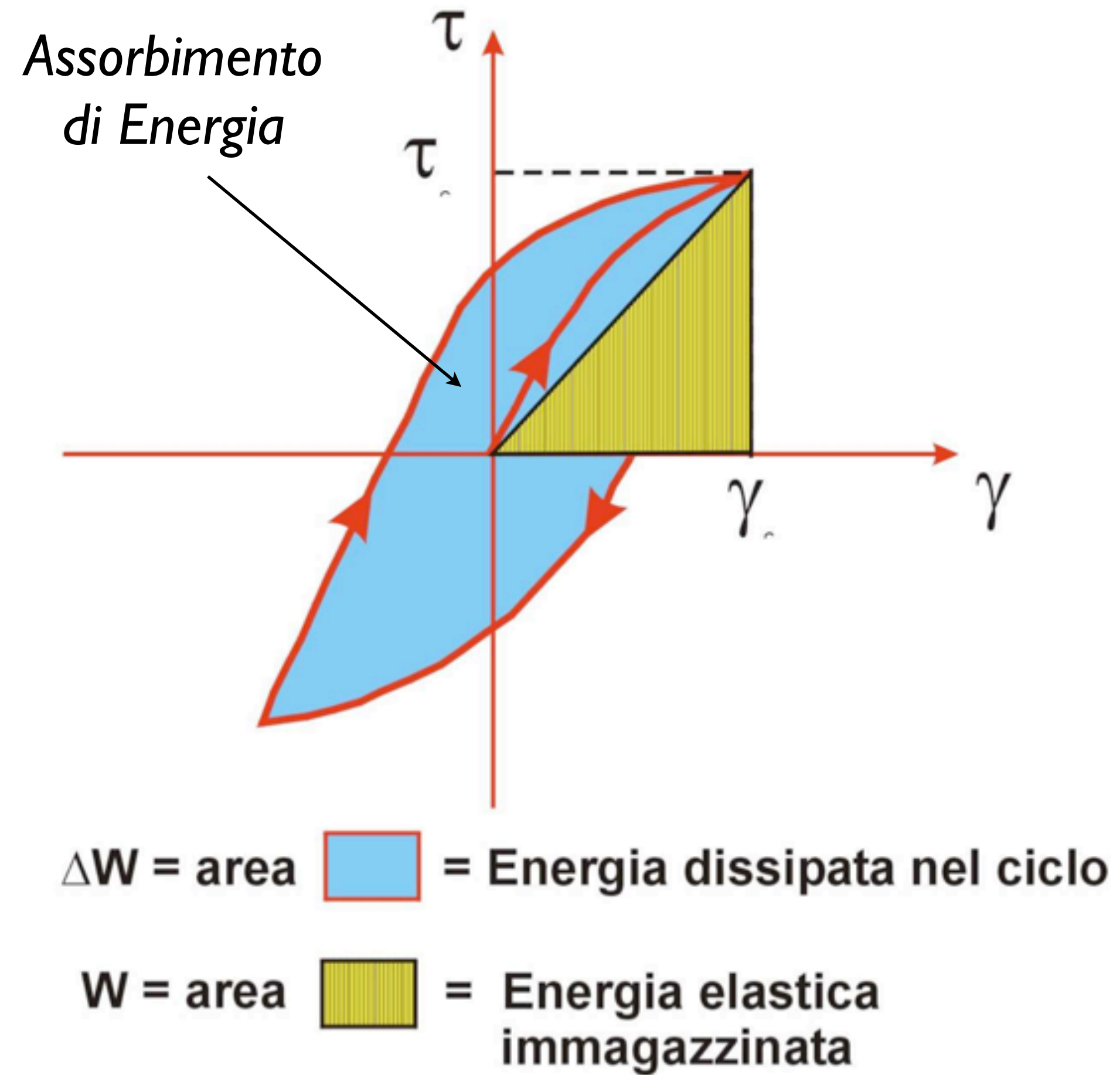


Parametri geotecnici

**Fattore
di smorzamento**

$$D = \frac{1}{4\pi} \frac{\Delta W}{W}$$

$$W = \frac{1}{2} \frac{\tau_c}{\gamma_c}$$

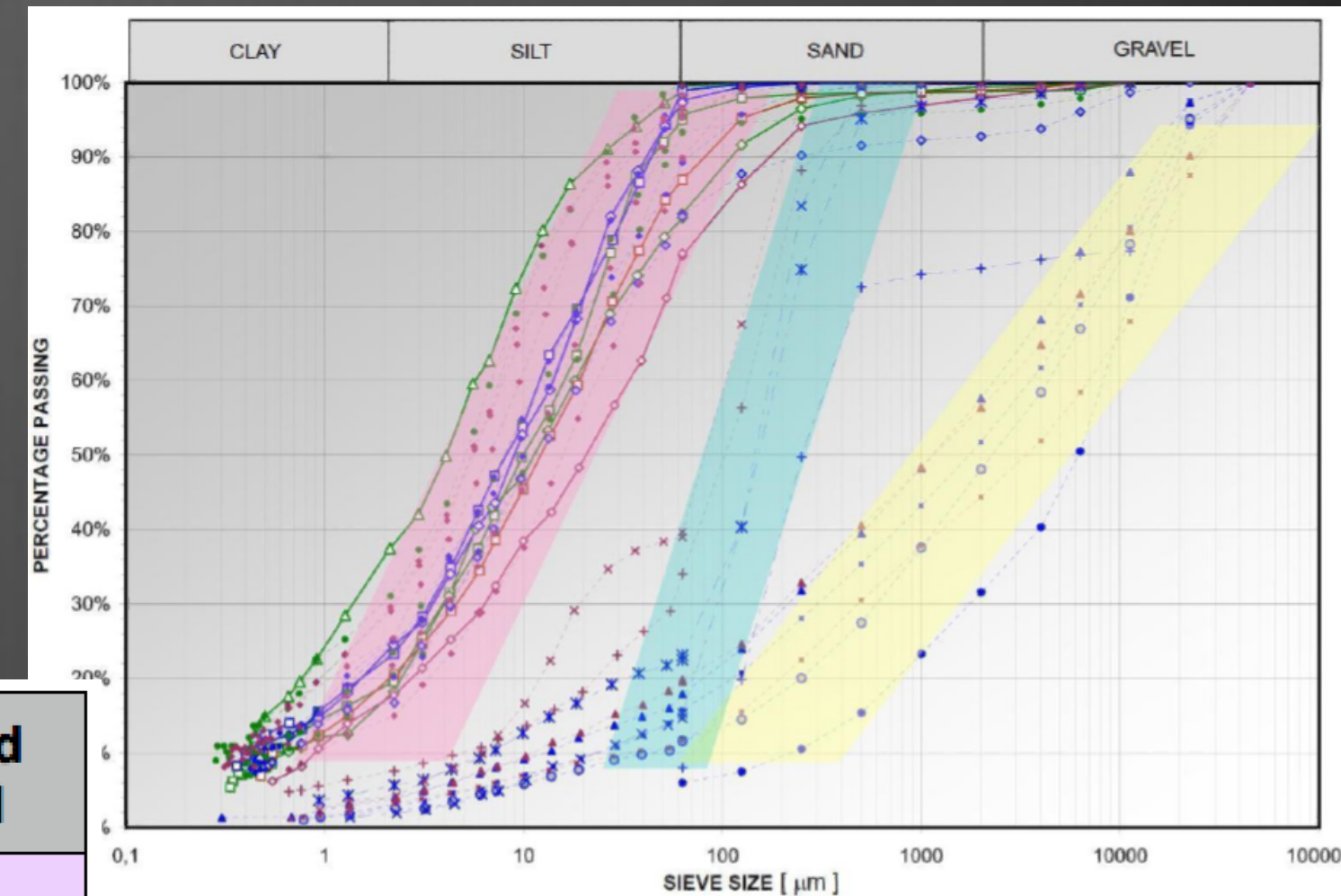




Indagini geofisiche e geotecniche

Indagini sismiche:
risultati ed interpretazioni

Depth (m)	Vs (m/s)	Mean Vs (m/s)	Layer type	Assigned Material
0	258	250	sand	SAND
1	253,3			
2	227,3			
4	191,7	200	silt + clay	CALYCY SILT
6	203,5			
8	251,7			
10	312,1	350	gravel1	GRAVEL
13	365,8			
16	406,7			
21	430,4			
26	443,5	440	gravel2	
31	450,6			



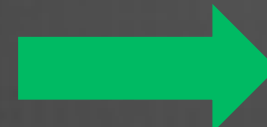
Indagini geotecniche

- caratteristiche fisiche
- proprietà indice
- granulometrie
- limiti di Atterberg
- edometriche
- conducibilità idraulica
- prove triassiali



Indagini geotecniche

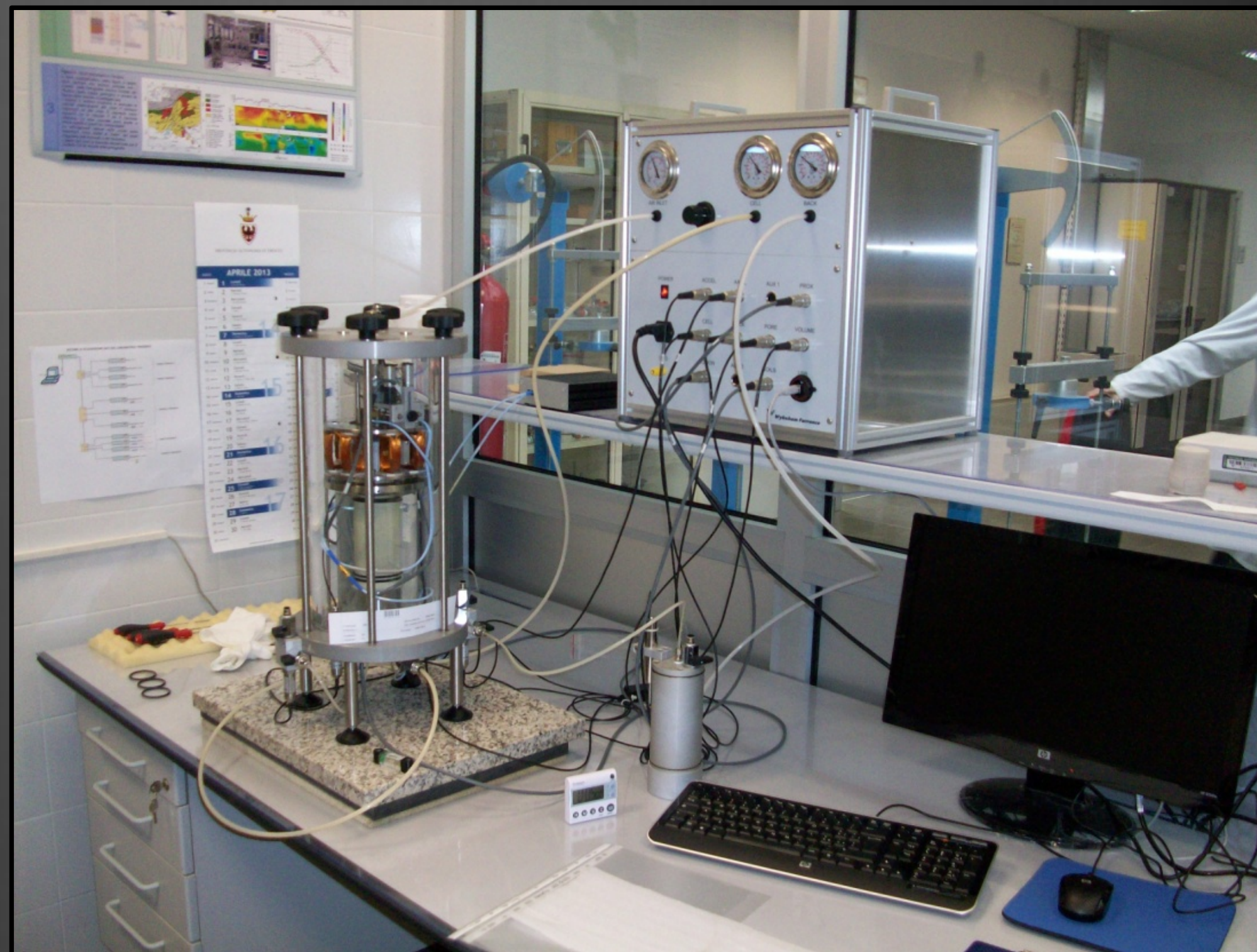
Strumentazione di Colonna Risonante (Lab. di geotecnica P.A.T.)



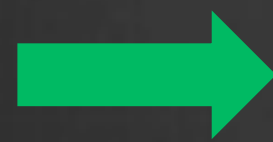
G_0 = modulo di taglio dinamico naturale

G = modulo di taglio dinamico di laboratorio

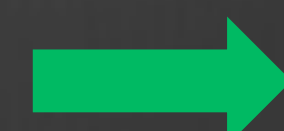
D = smorzamento



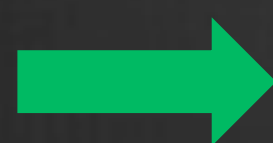
PROVE RC



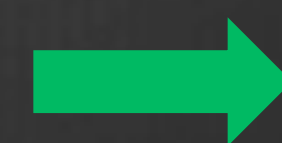
$$\begin{cases} V_s = h \cdot \omega / \beta \\ \omega = 2\pi \cdot Fr \end{cases}$$



$$G = V_s^2 \cdot \rho$$



Amplitude Decay Method



D



S

Resonant Column Tests

fitting of Yokota et al. (1981) model to experimental data obtained on 2 samples: S2-CD L (21.70-22.00 m) and S2-CD M (24.00-24.40 m) at the effective stress of 200 kPa (S2 CD L) and 300 kPa (S2 CD M) normalized using G_0 coming from the hyperbolic relationship of Hardin e Drnevich

α	β	D_{max}	λ
23.3607	0.8887	19.3231	-2.5740

γ (%)	$\frac{G(\gamma)}{G_0} = \frac{1}{1 + \alpha\gamma^\beta}$ (-)	$\frac{D}{D_{max}} = e^{\lambda \frac{\gamma}{G_0}}$ (%)
0.0001	0.994	1.498
0.0002	0.988	1.519
0.0003	0.983	1.539
0.0004	0.978	1.558
0.0005	0.974	1.577
0.001	0.952	1.667
0.002	0.915	1.835
0.004	0.853	2.152
0.01	0.719	3.033
0.02	0.581	4.335
0.03	0.491	5.456
0.04	0.428	6.423
0.05	0.380	7.262
0.1	0.249	10.183
0.2	0.152	13.074
0.3	0.111	14.523

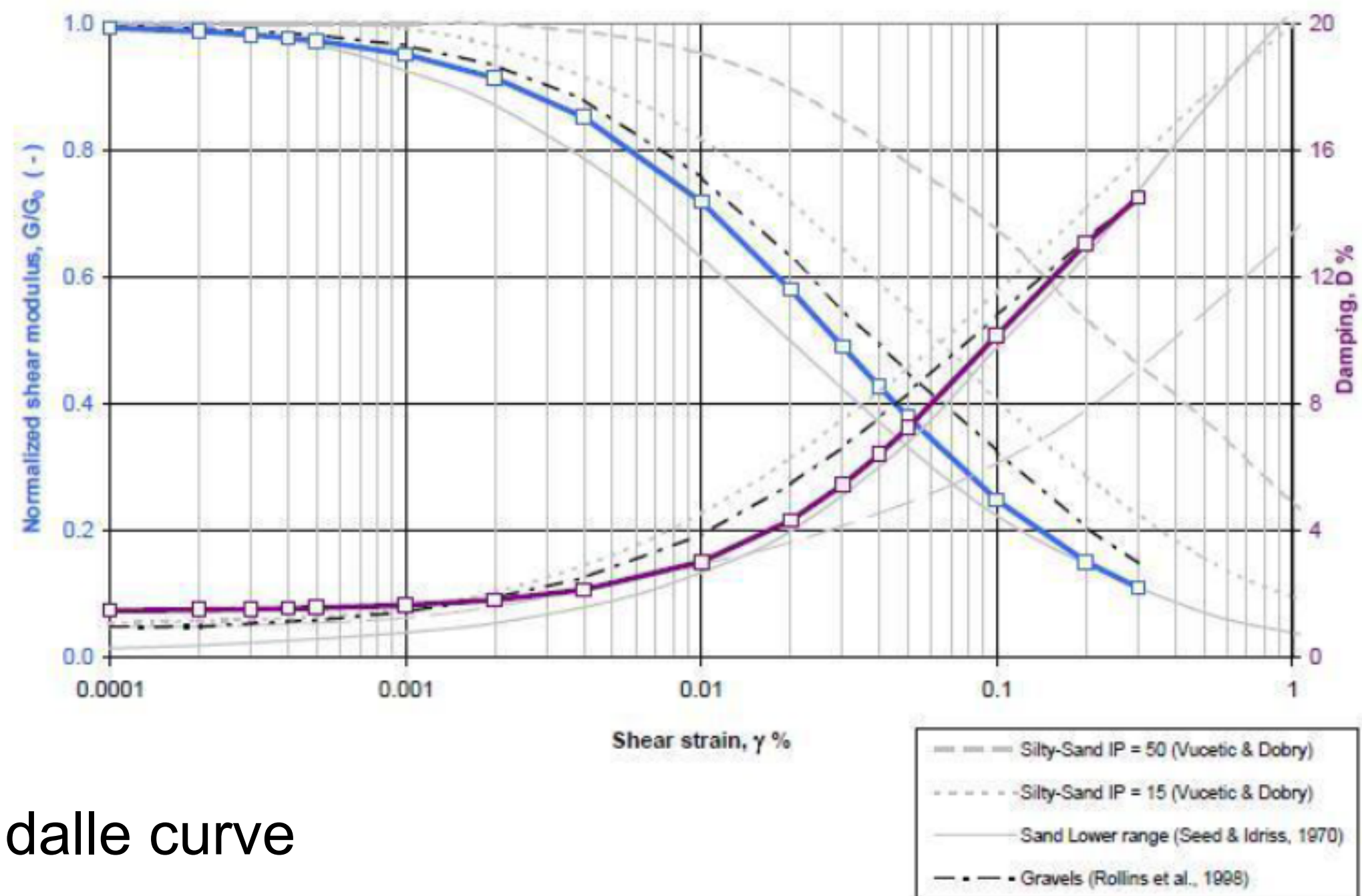
Modello d'interpolazione di Yokota et al., 1981



$$\frac{G}{G_0} = \frac{1}{1 + \alpha\gamma^\beta}$$

$$\frac{D}{D_{max}} = e^{\lambda \frac{\gamma}{G_0}}$$

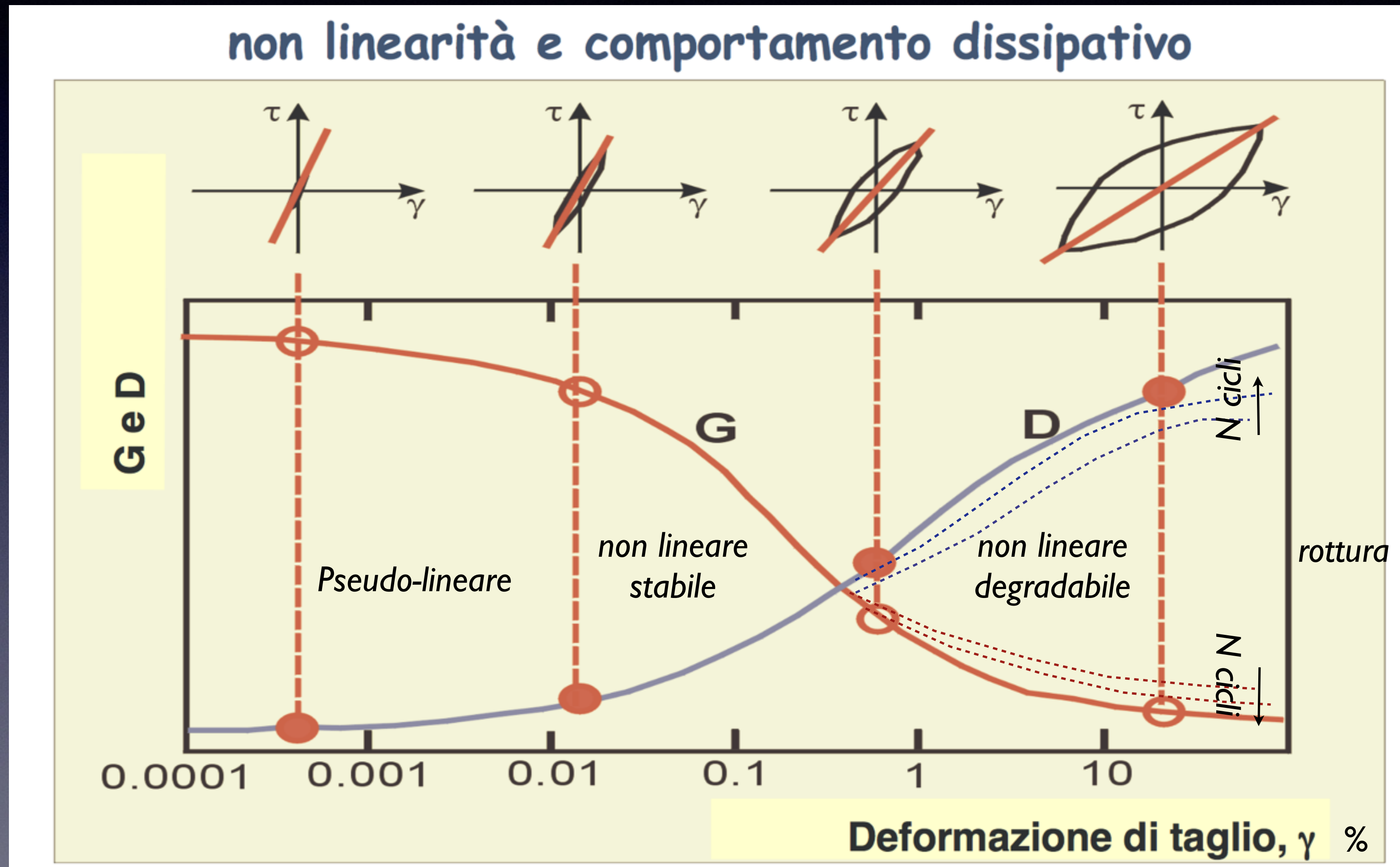
Curve di decadimento per le Sabbie



Valori selezionati dalle curve

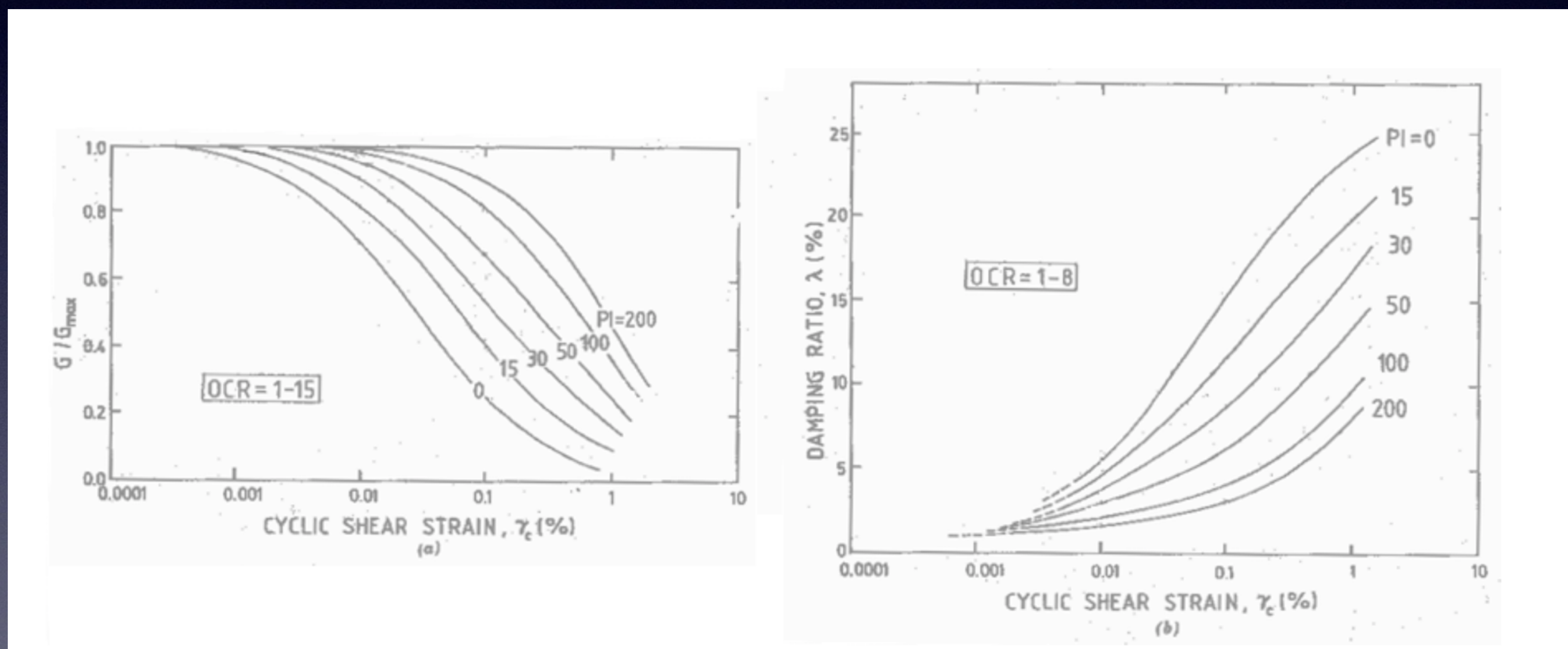
comportamento meccanico dei terreni sottoposti a carichi ciclici

G e D variano in funzione della deformazione γ

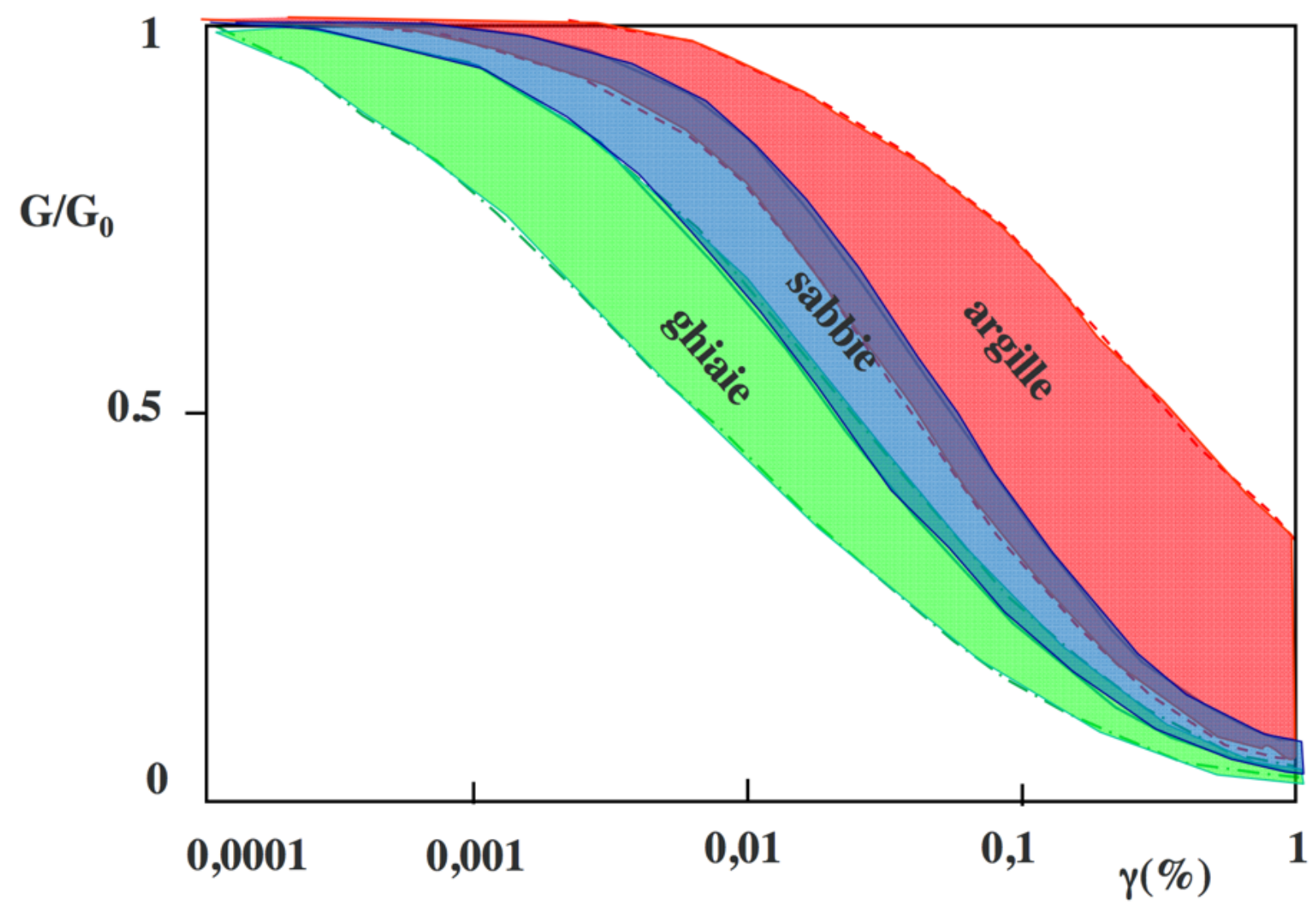


G e D variano in funzione del tipo di suolo

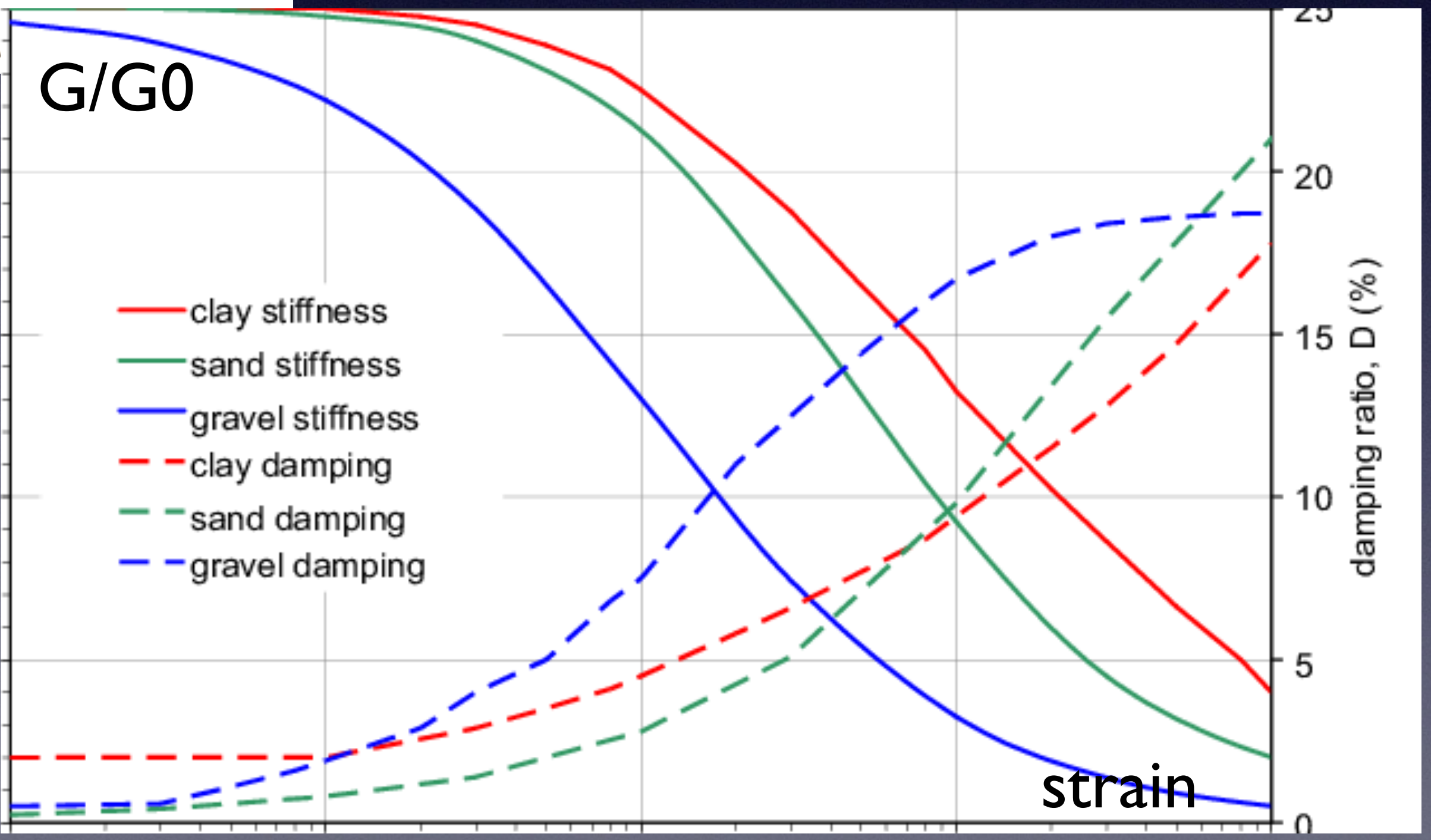
e.g. in base all'indice di plasticità:



Campi di variazione delle curve $G/G_0-\gamma$



(Seed et al., 1986; Dobry & Vucetic)

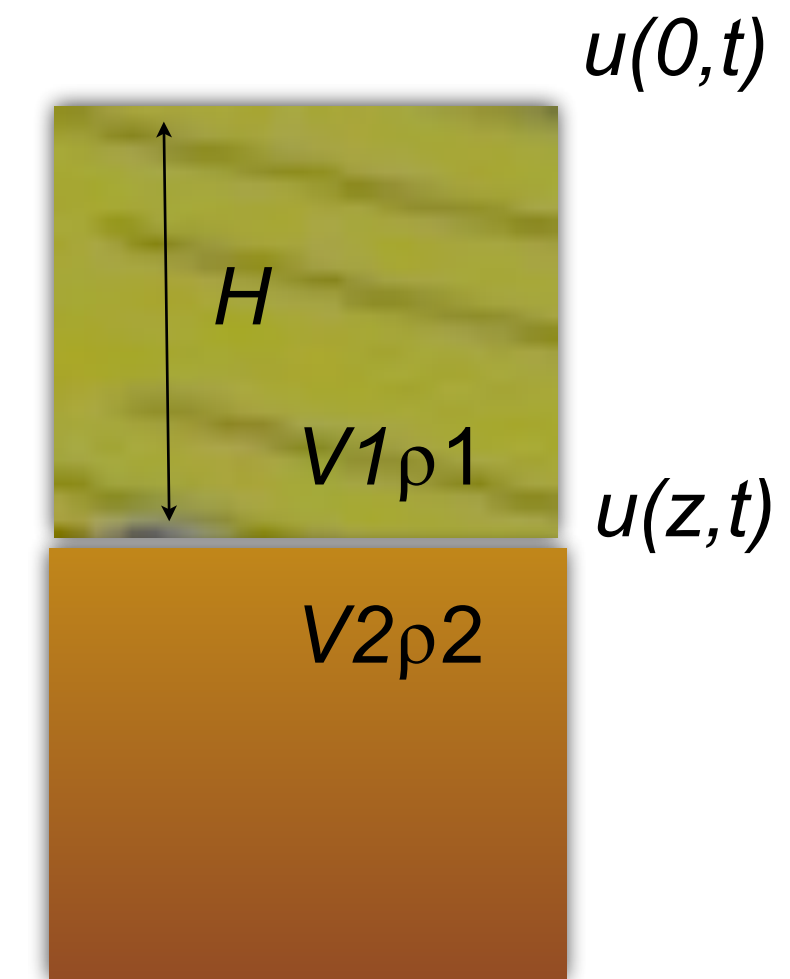


Strato OMOGENEO visco-elastico su subtrato rigido (kelvin-voigt)

EQUAZIONE EQUILIBRIO DINAMICO

$$\rho \frac{du^2}{dt^2} = G \frac{du^2}{dz^2} + \eta \frac{du^3}{dt dz^2}$$

Coefficiente di viscosità



$$\eta = \frac{D (2 G)}{\omega}$$

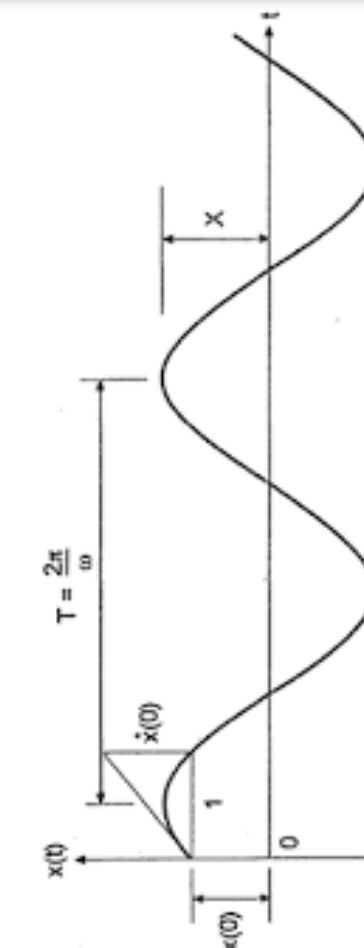
viscosità

frequenza

$$D = \frac{\eta \omega}{2 G}$$

DAMPING

modulo taglio

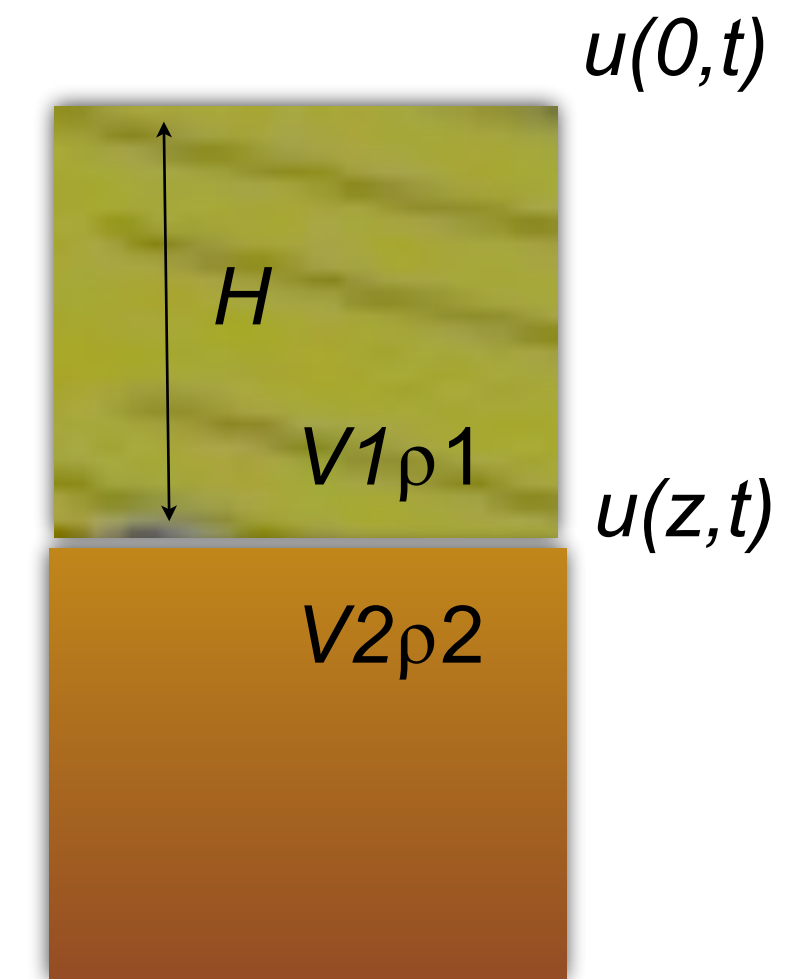


Strato OMOGENEO visco-elastico su subtrato rigido (kelvin-voigt)

EQUAZIONE ONDA S

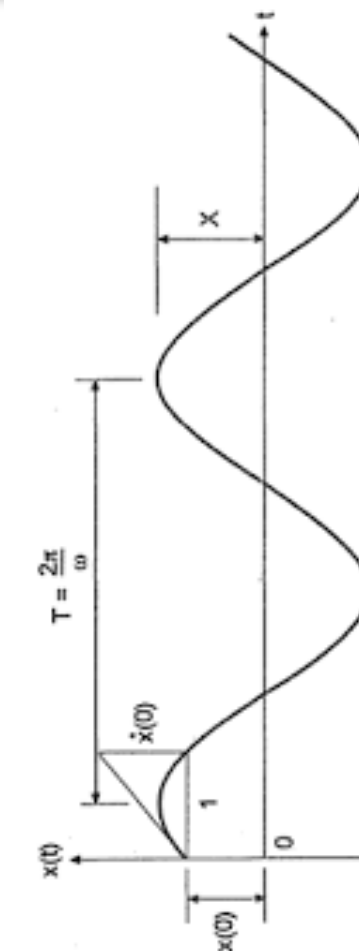
$$\rho \frac{du^2}{dt^2} = G \frac{du^2}{dz^2} + \eta \frac{du^3}{dt dz^2}$$

Coefficiente di viscosità



Soluzione

$$u(z,t) = Ae^{j(kz + \omega t)}$$



Strato OMOGENEO visco-elastico su substrato rigido (kelvin-voigt)

Funzione di trasferimento

$$H(\omega) = \frac{1}{\cos(kH)}$$



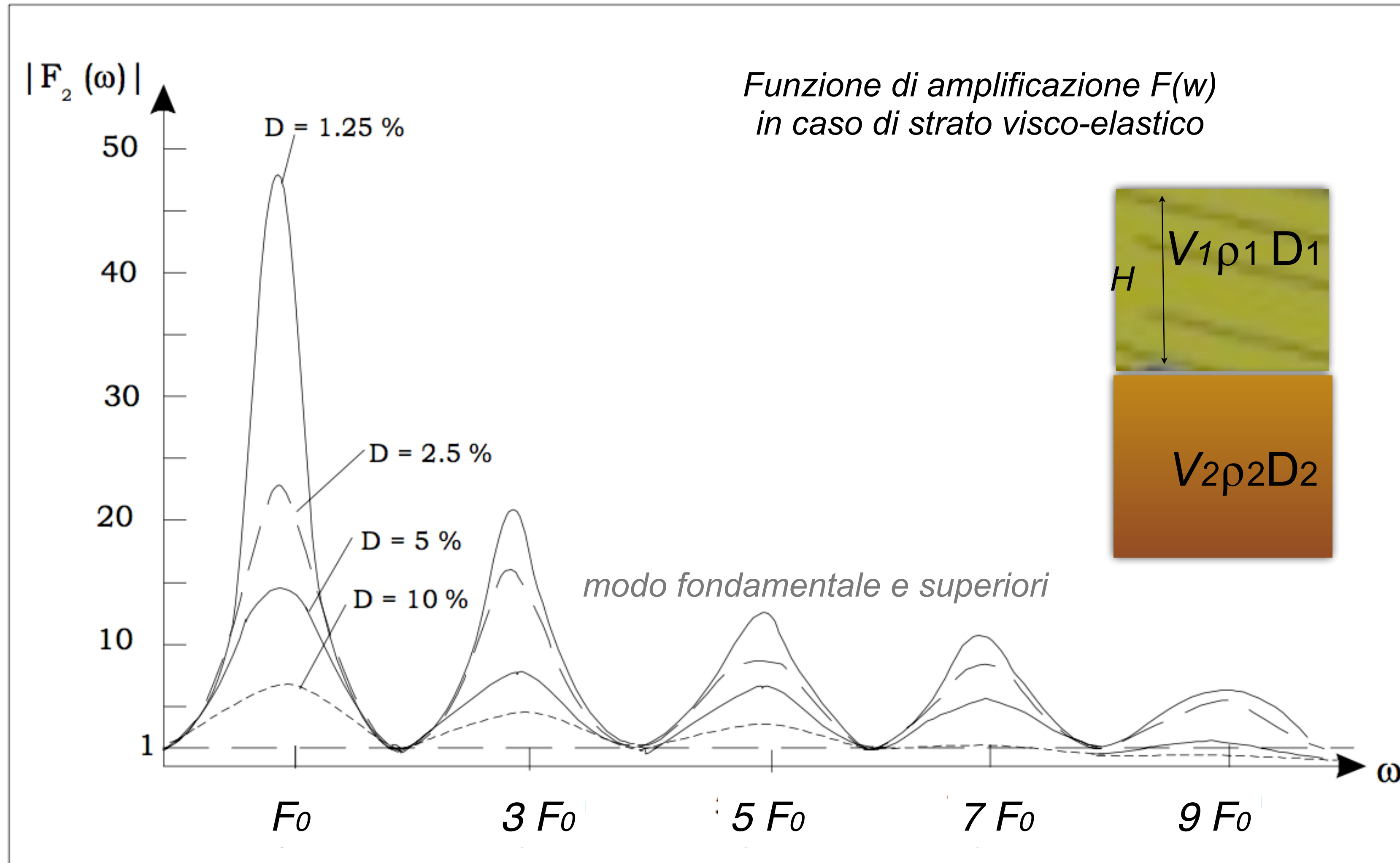
Funzione di amplificazione $F = |H(\omega)|$

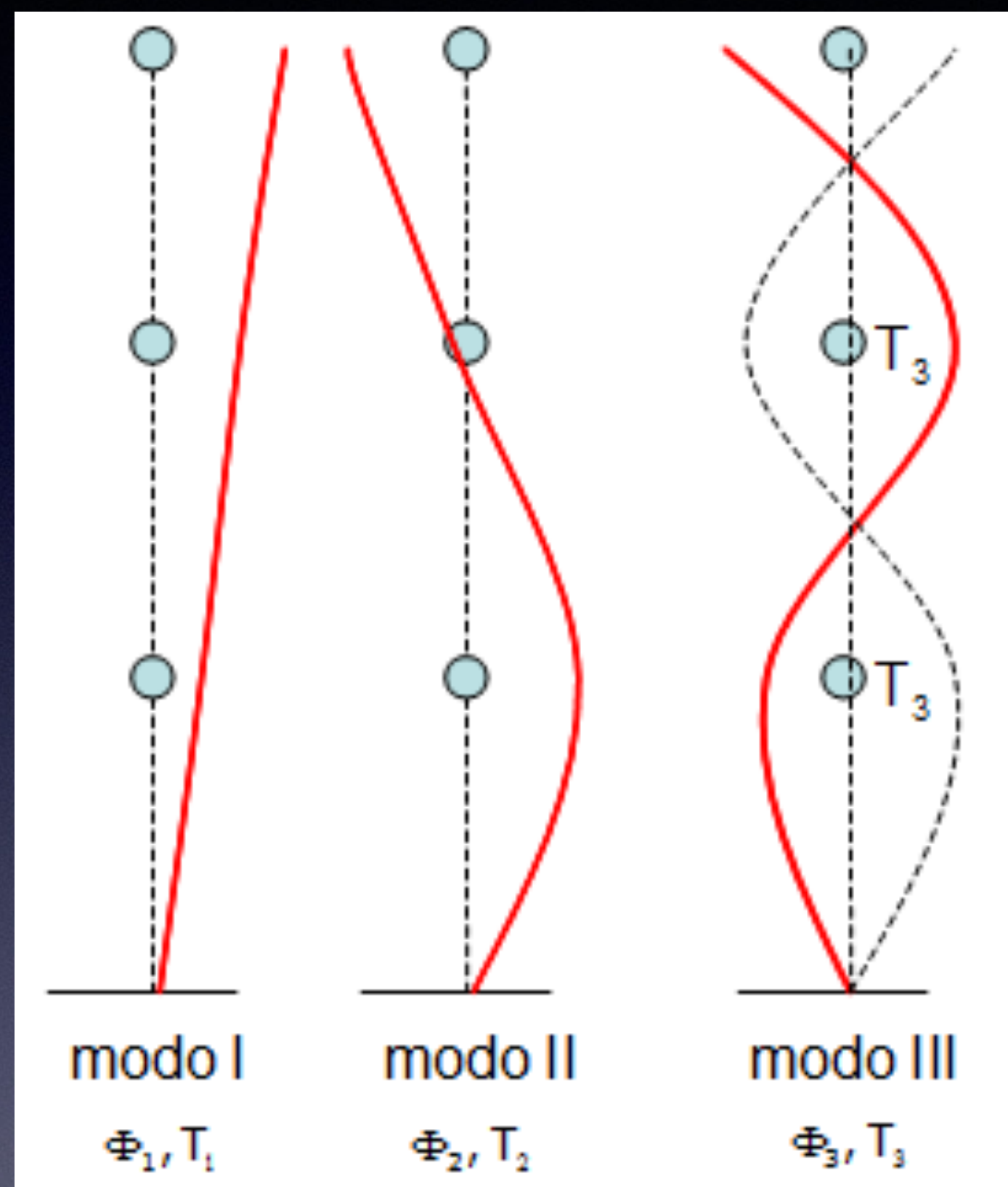
$$F(\omega) = \frac{1}{\sqrt{\cos^2\left(\frac{\omega H}{V_s}\right) + \left(D \frac{\omega H}{V_s}\right)^2}}$$

$$V_s = \sqrt{\frac{G}{\rho}}$$

D

Per moderati campi di deformazione
è considerabile indipendente dalla
frequenza!





Forme modali
(n=1 modo fondamentale)

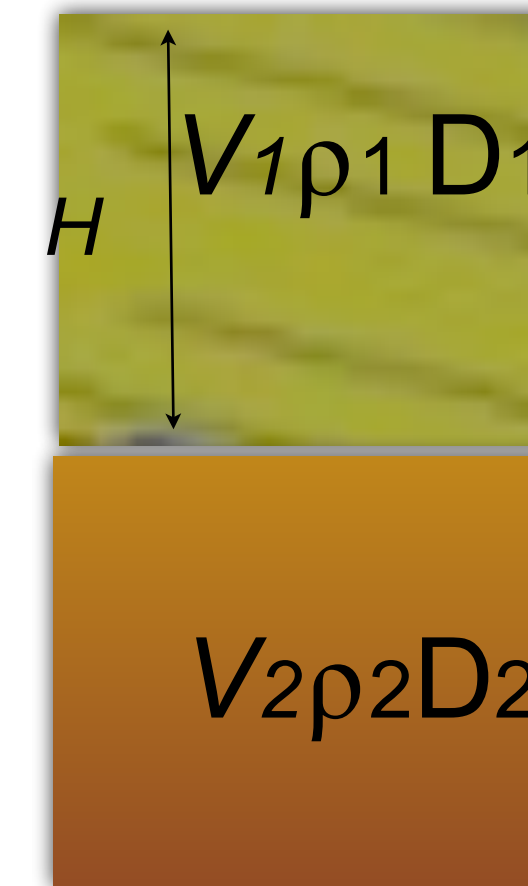
$$u(z,t) = Ae^{j(kz + \omega t)} \quad \text{Soluzione}$$

Strato OMOGENEO visco-elastico su subtrato deformabile (kelvin-voigt)

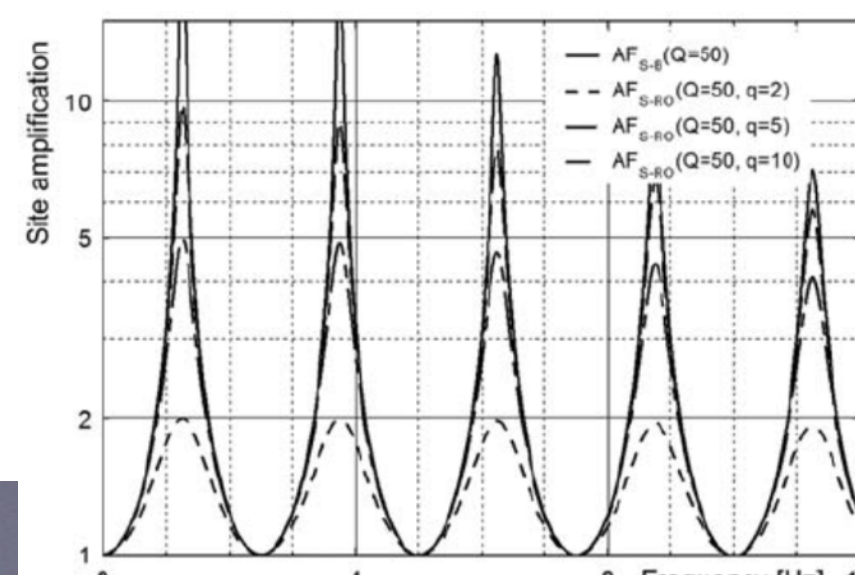
EQUAZIONE EQUILIBRIO DINAMICO

$$\rho \frac{du}{dt}^2 = G \frac{du}{dz}^2 + \eta \frac{du}{dt dz}^2$$

*soluzione non più in forma semplice,
il fattore di Amplificazione in corrispondenza delle
frequenze naturali si approssima (Roesset , 1970)*



$$F_{max} \approx \frac{1}{\frac{1}{i} + (2n-1) \frac{\pi}{2} D}$$



CONTRASTO DI IMPEDENZA

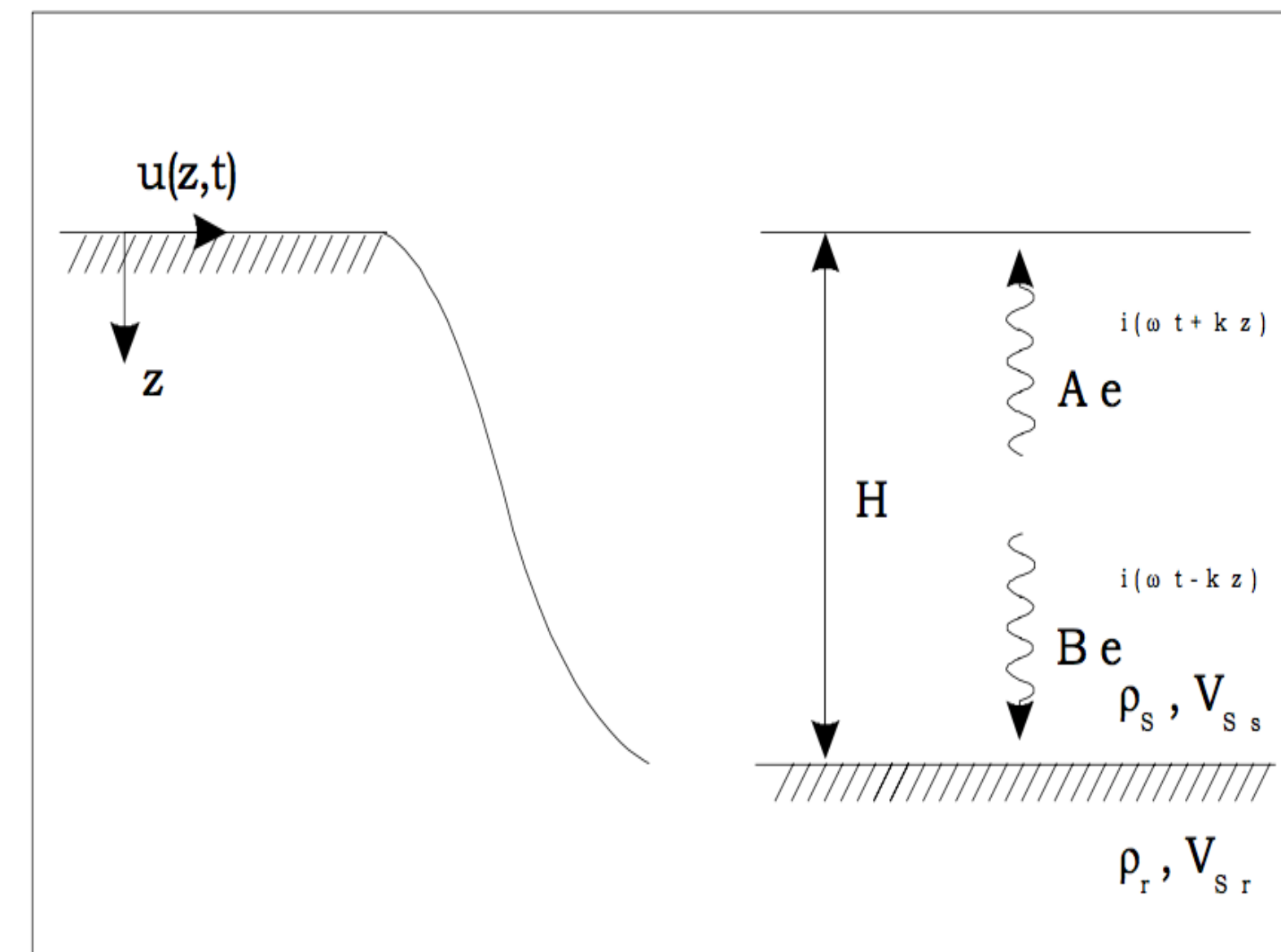
$$i = \frac{v_1 \rho_1}{v_2 \rho_2}$$

Strato OMOGENEO visco-elastico su subtrato deformabile (kelvin-voigt)

EQUAZIONE ONDA S

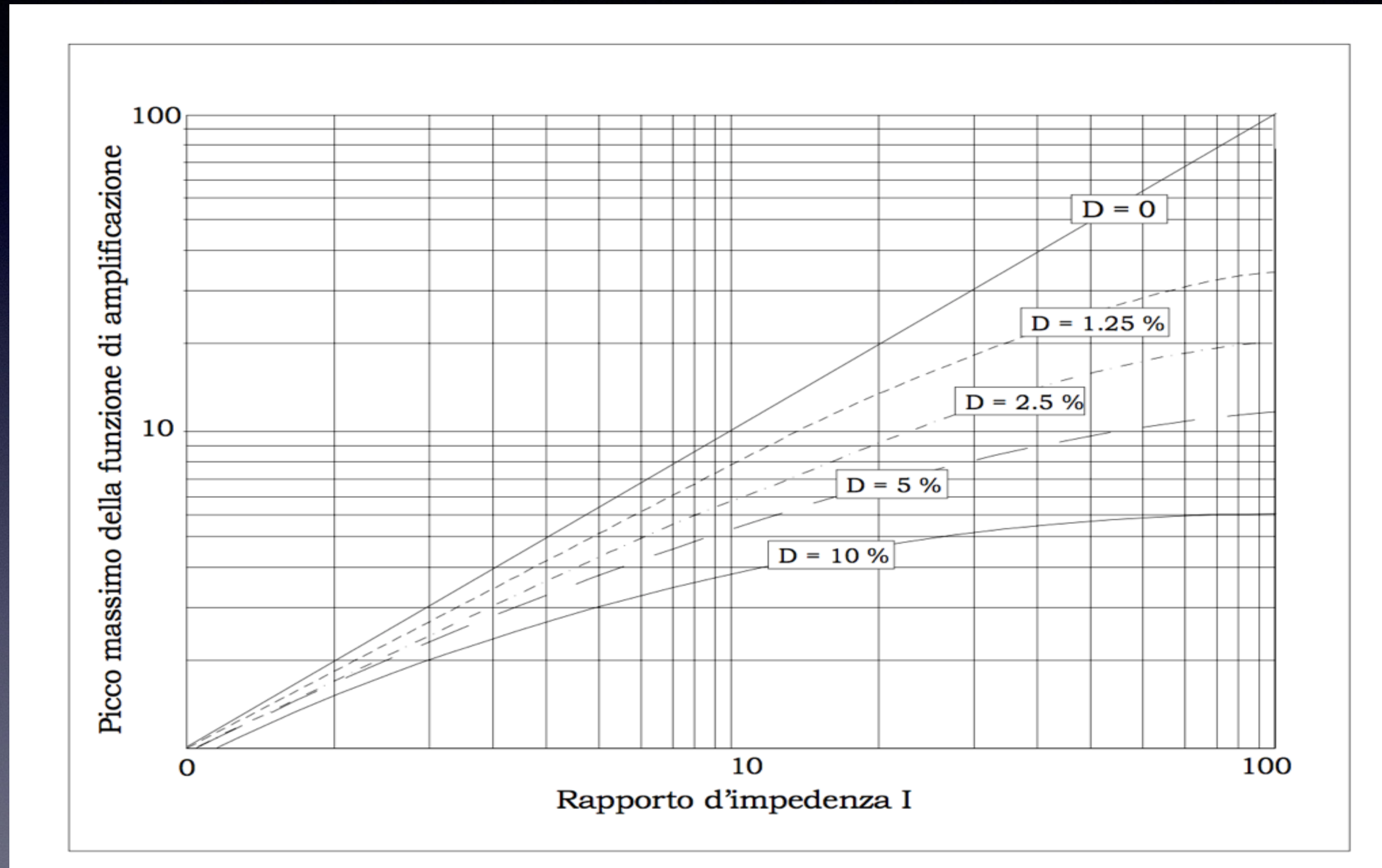
$$\rho \frac{du^2}{dt^2} = G \frac{du^2}{dz^2} + \eta \frac{du^3}{dt dz^2}$$

*Per piccole deformazioni D è
considerato indipendente dalla
frequenza!*



Fattore di Amplificazione onda S incidente

Strato OMOGENEO visco-elastico su subtrato deformabile (kelvin-voigt)

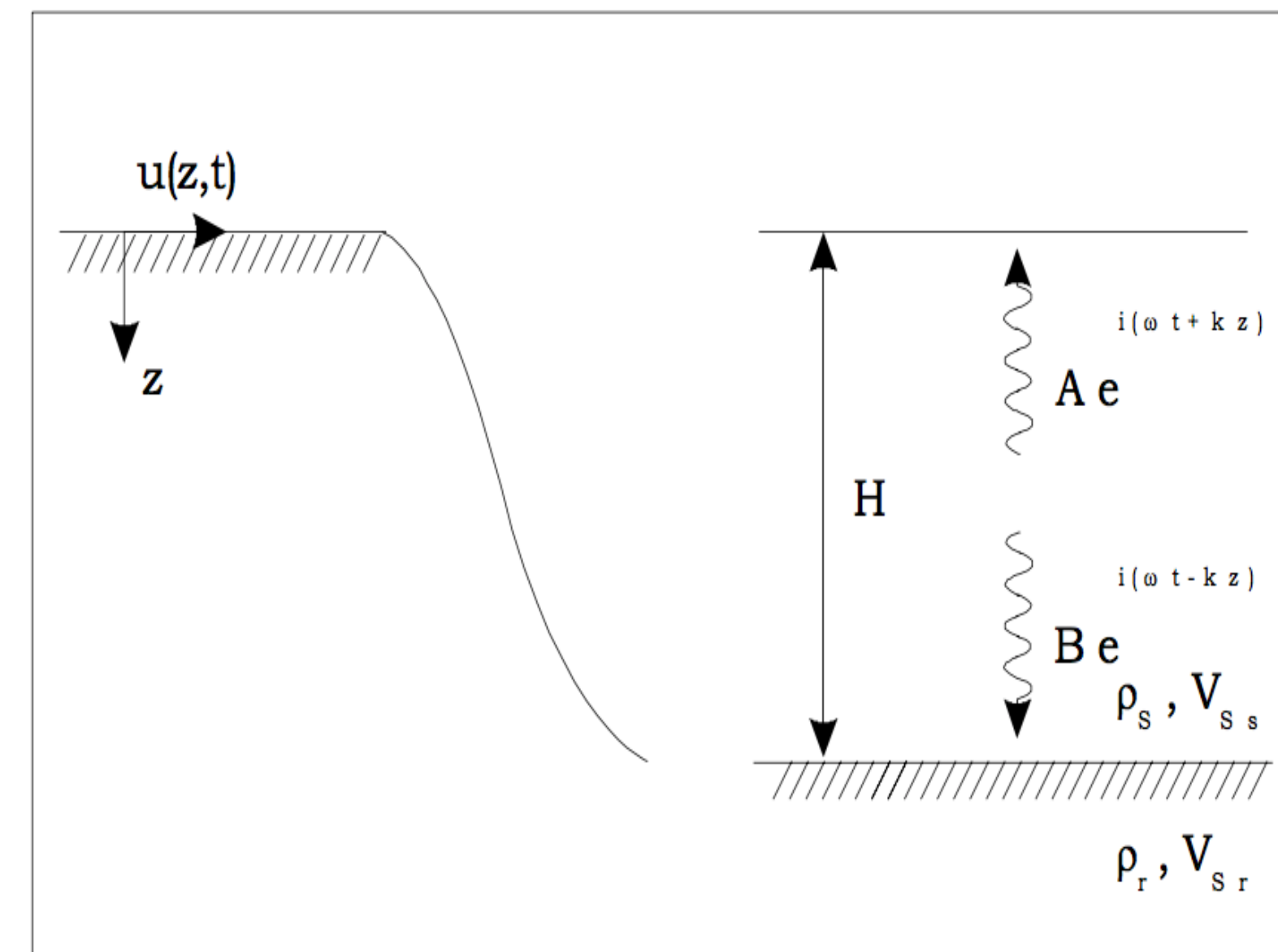


Caso reale: dipende da contrasto di impedenza I e da damping D

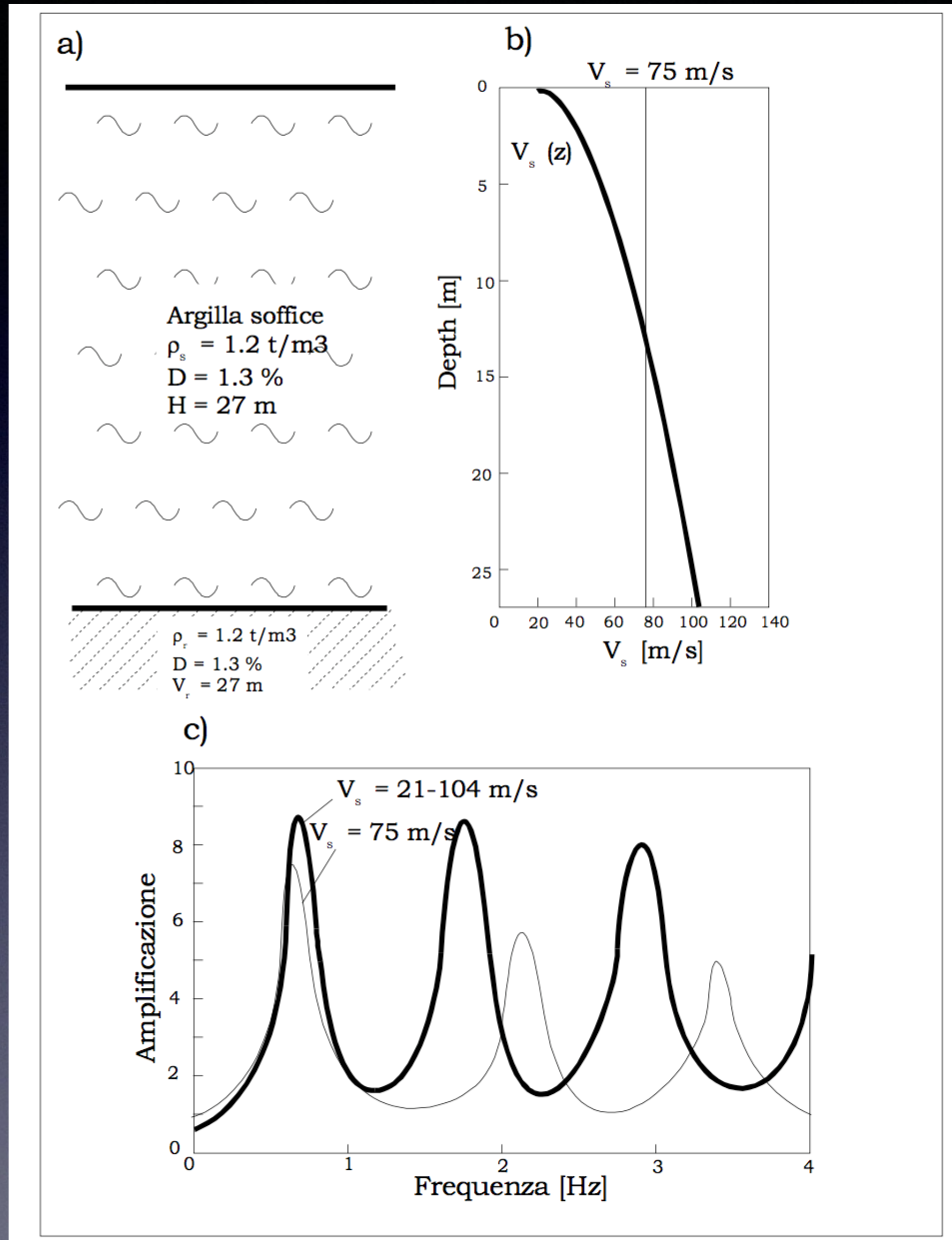
Soluzioni analitiche e numeriche al problema

EQUAZIONE ONDA S

$$\rho \frac{du^2}{dt^2} = G \frac{du^2}{dz^2} + \eta \frac{du^3}{dt dz^2}$$



Fattore di Amplificazione onda S incidente



Loma Prieta

Km di distanza
da epicentro

$F_0 \approx F$ risonanza edifici