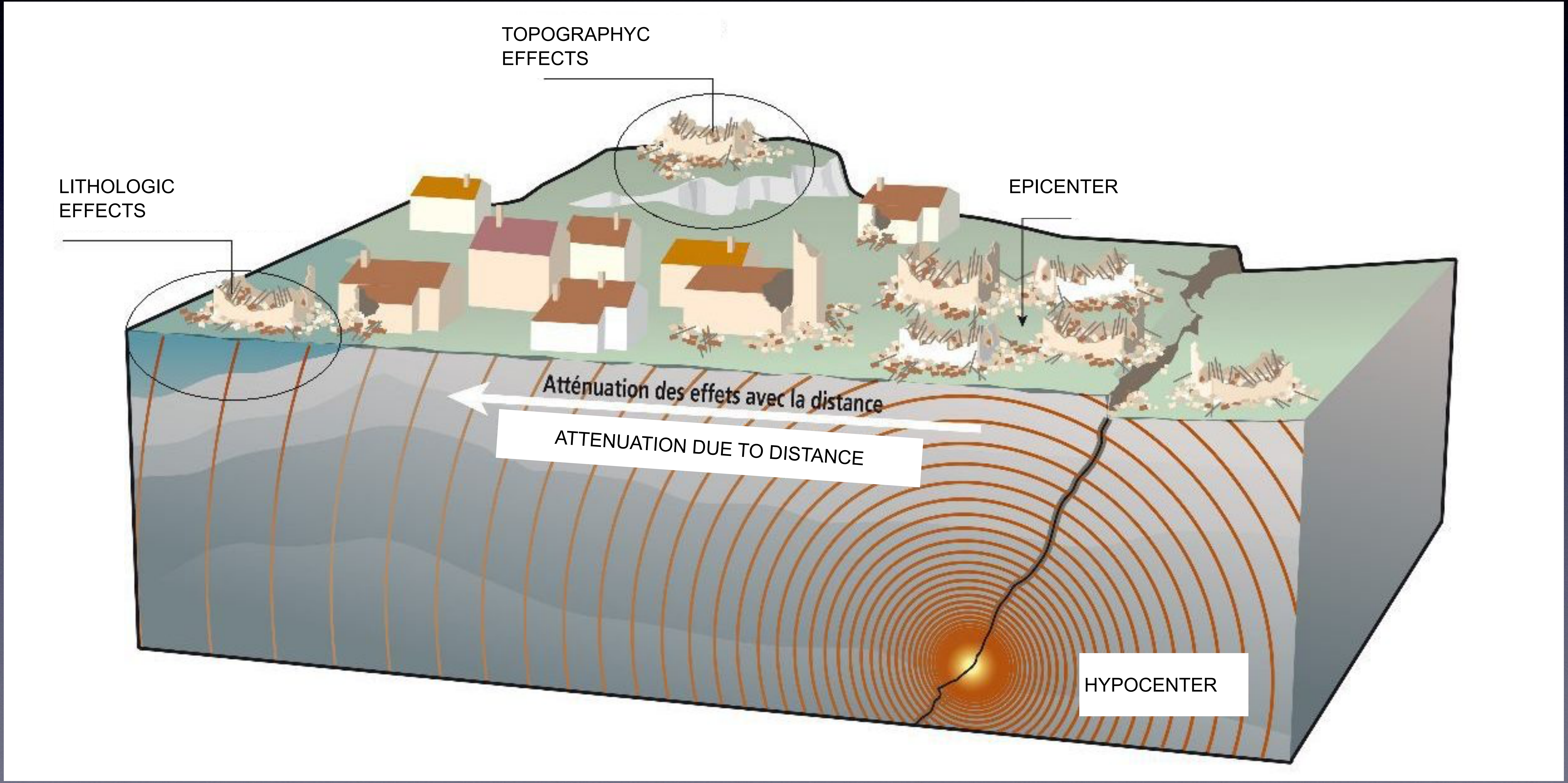
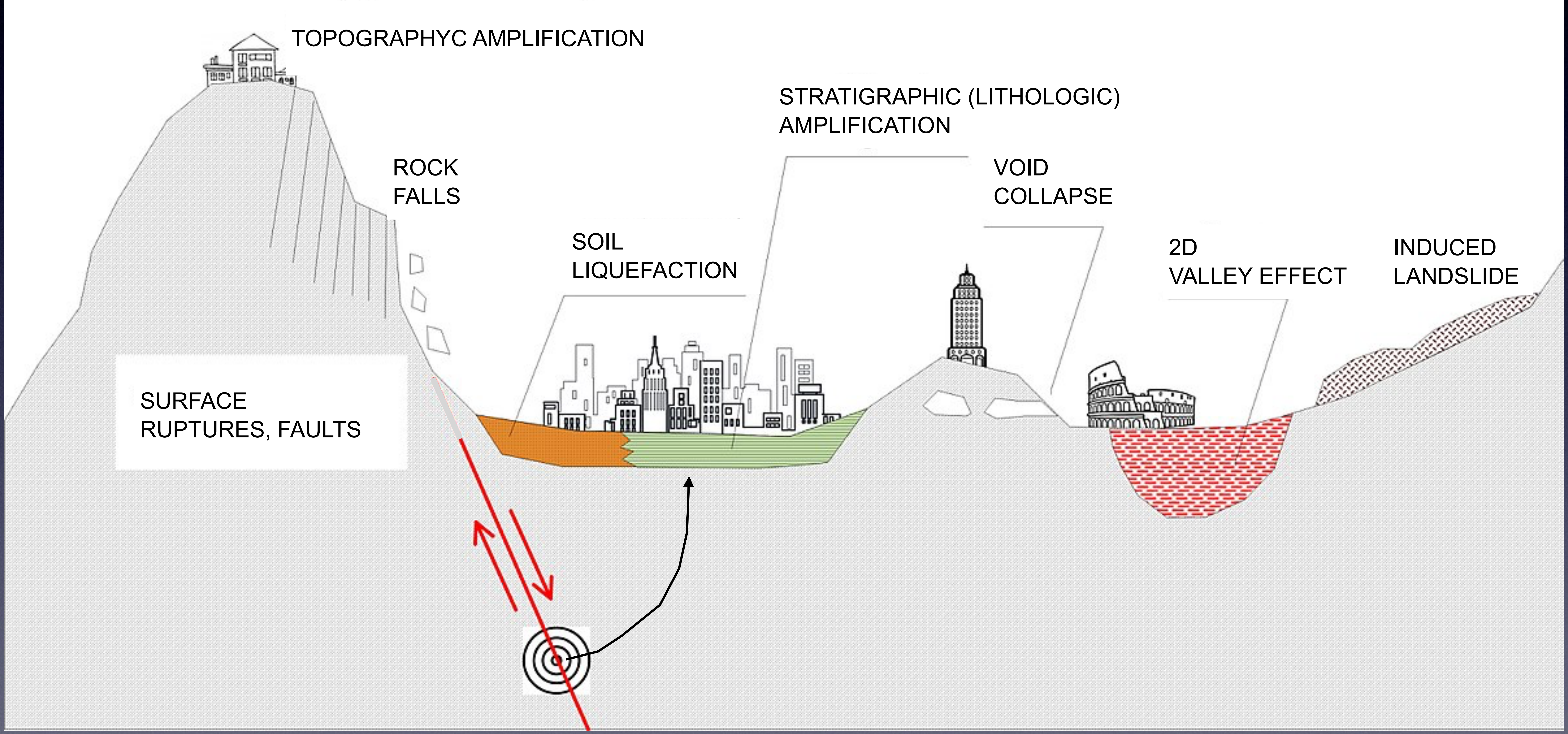
We have seen the seismic problem
but what happen locally?

Microzonation and Seismic Local Response (RSL)

-The seismic local response



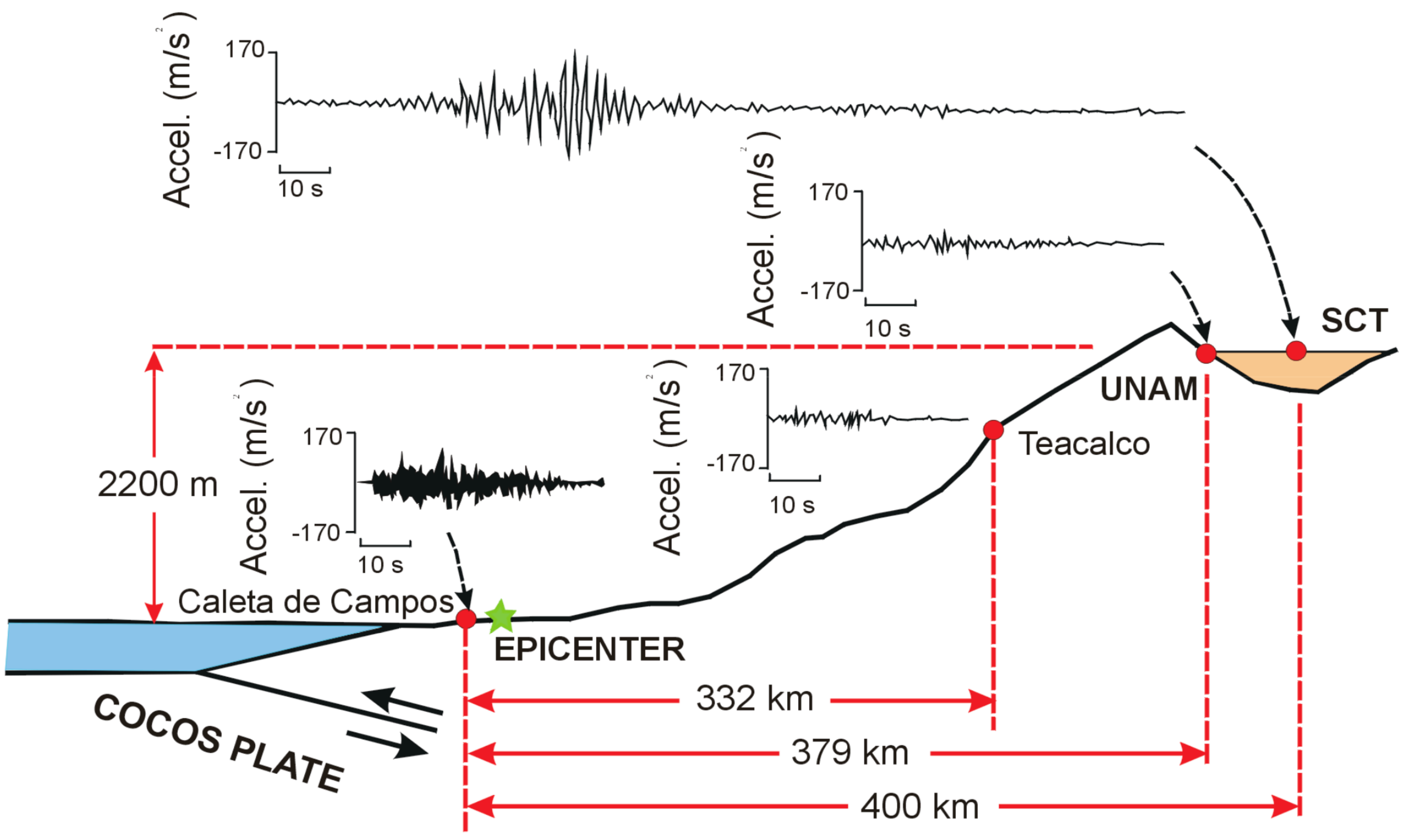
-The seismic local response : + induced effects



Pagliaroli mod

LOCAL CONDITIONS MODIFY THE EARTHQUAKE EFFECTS

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

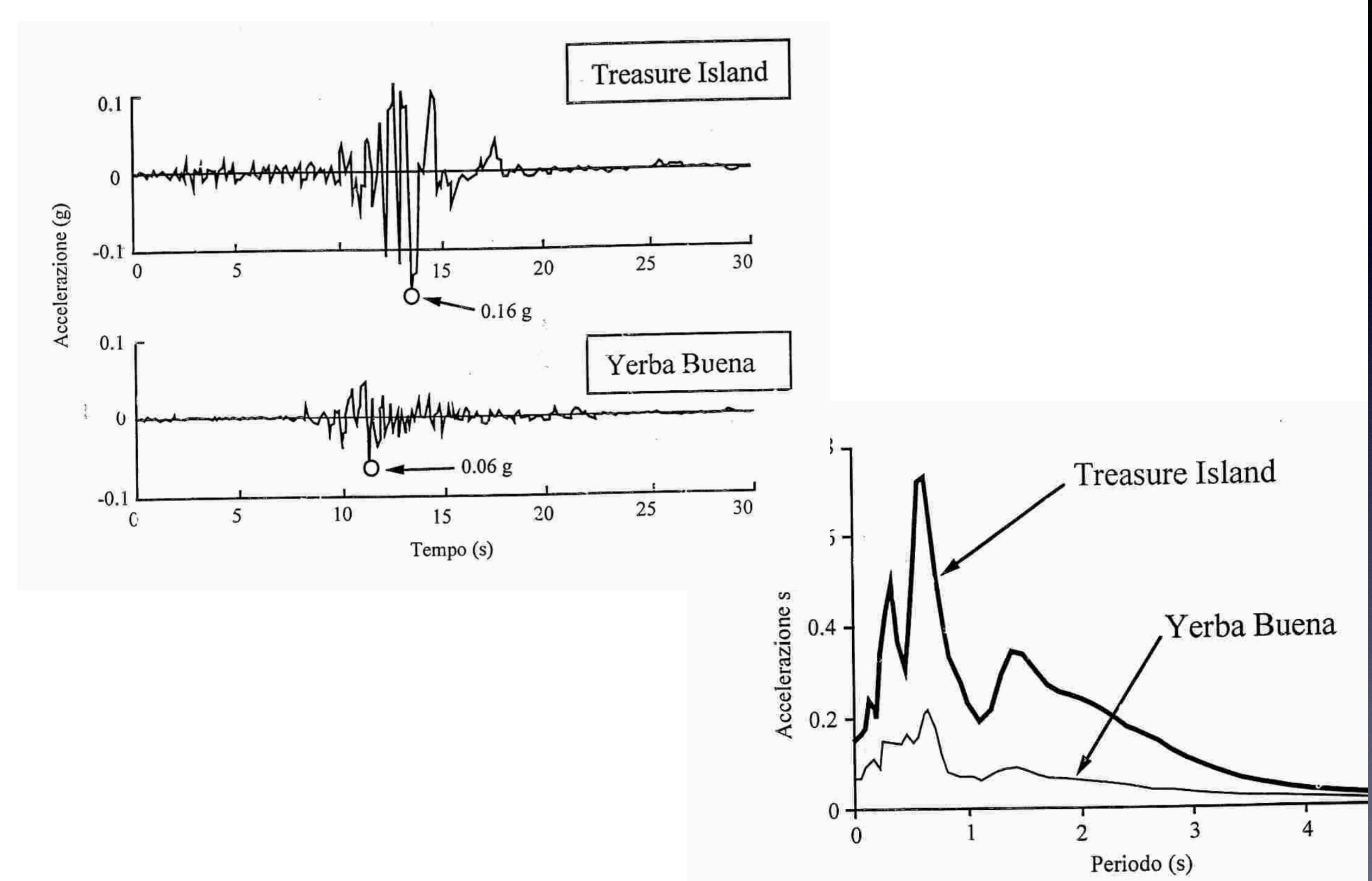


Loma Prieta earthquake 17/1/1989 (M=7.1)

Loma Prieta - San Fransisco bay (USA)

PGA 0.16 g

PGA 0.06 g



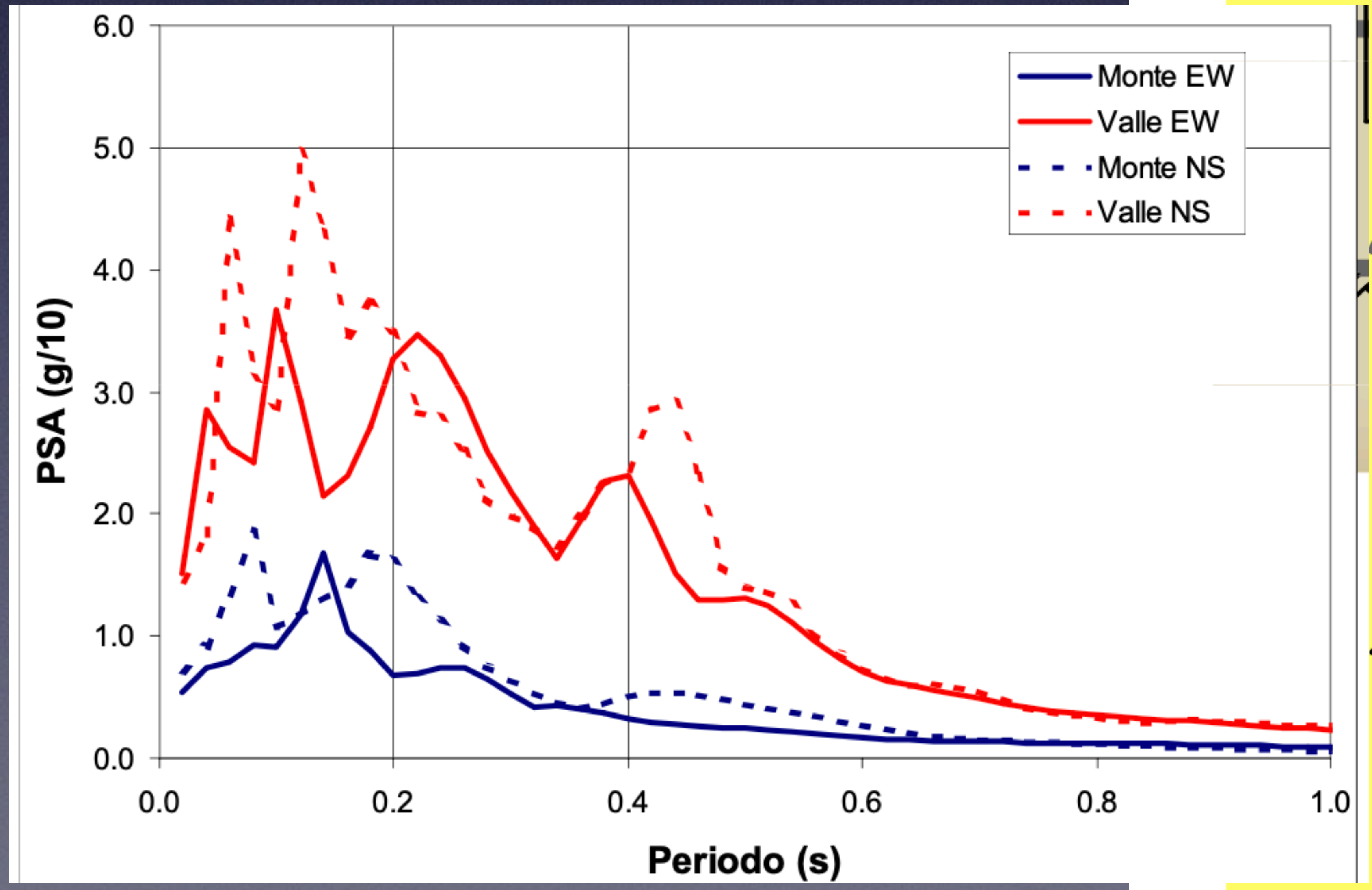
Sequenza sismica Umbria- Marche del 1997: il caso di Cesi

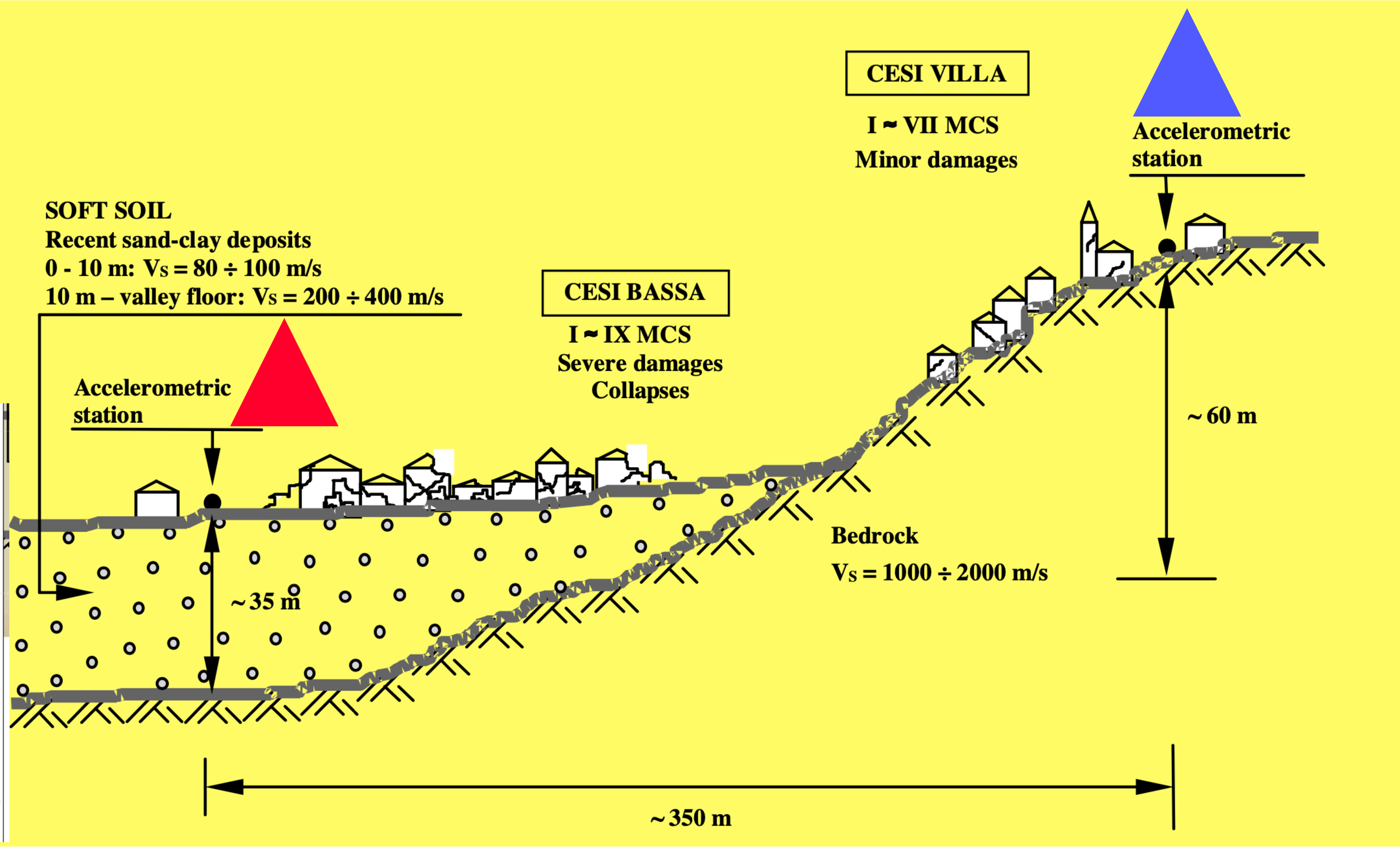
Cesi Bassa - IX MCS

Cesi Villa - VII MCS

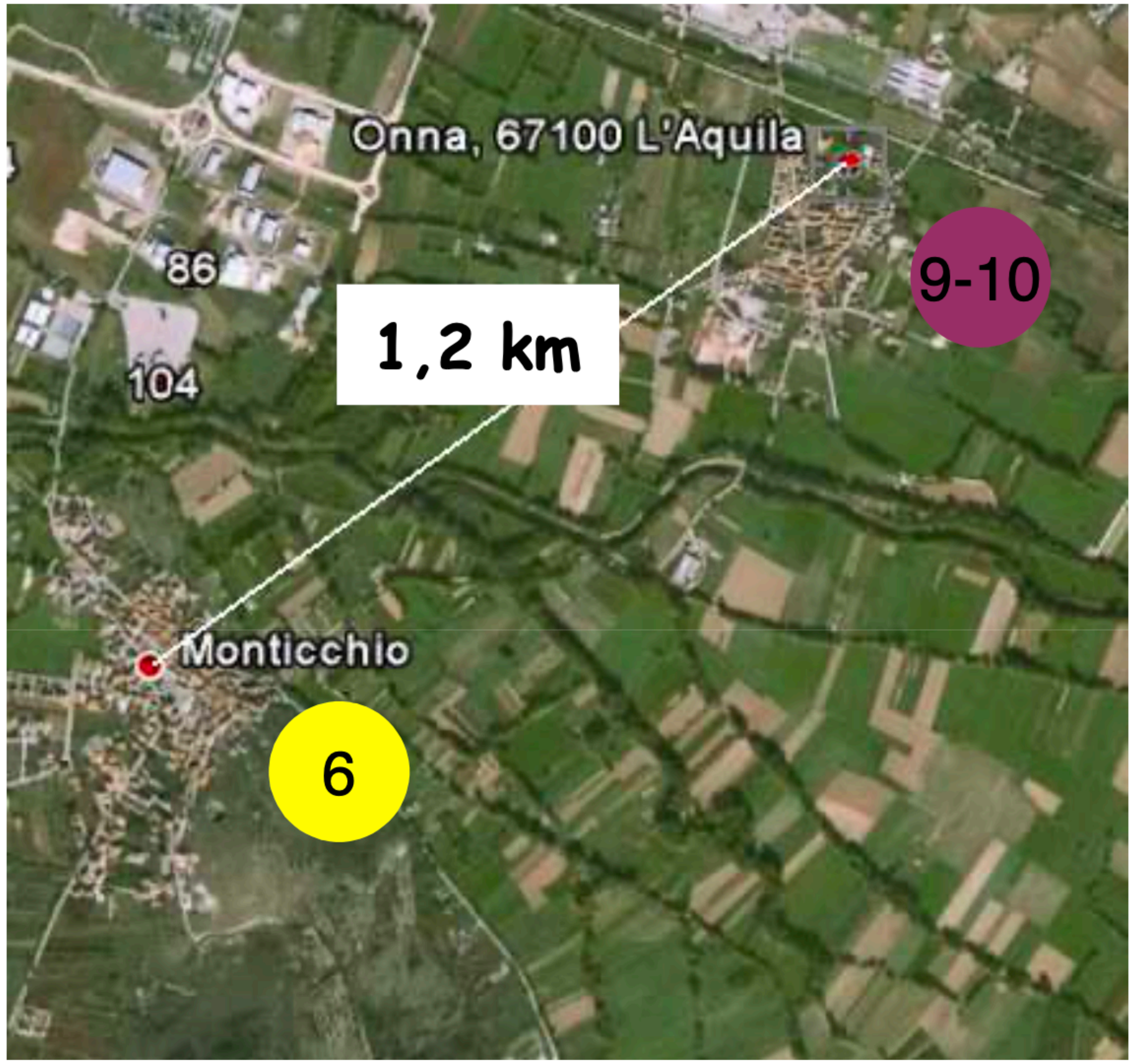
A **Cesi Bassa** i danneggiamenti corrispondono al IX grado MCS, mentre a **Cesi Villa** si hanno danni corrispondenti al VII grado MCS. La distanza tra le due aree è di poche centinaia di metri e le costruzioni non presentano differenze di vulnerabilità tali da spiegare le differenze di intensità macrosismica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

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



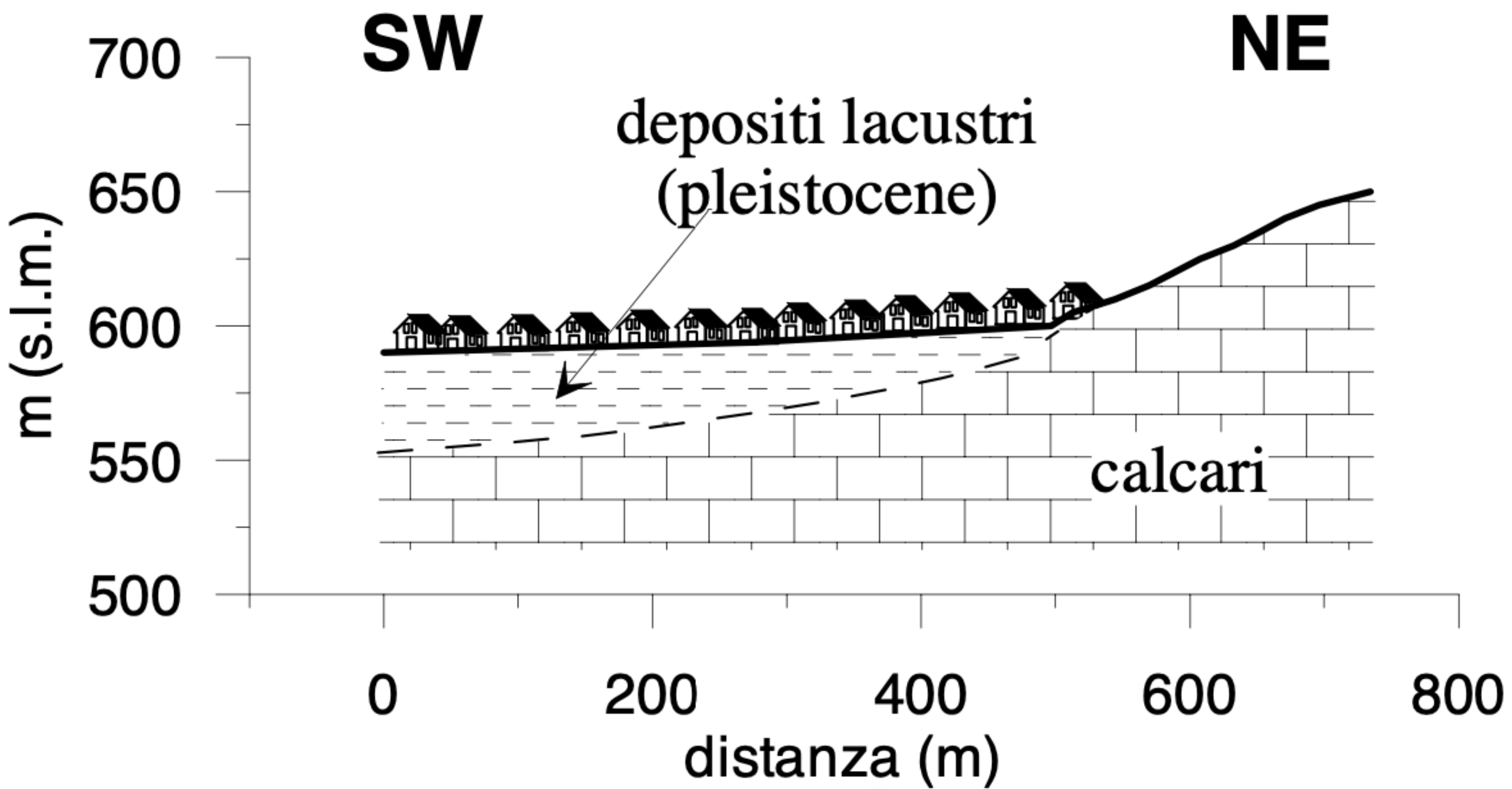


Il terremoto de L'Aquila del 06/04/2009 (M=6.3)

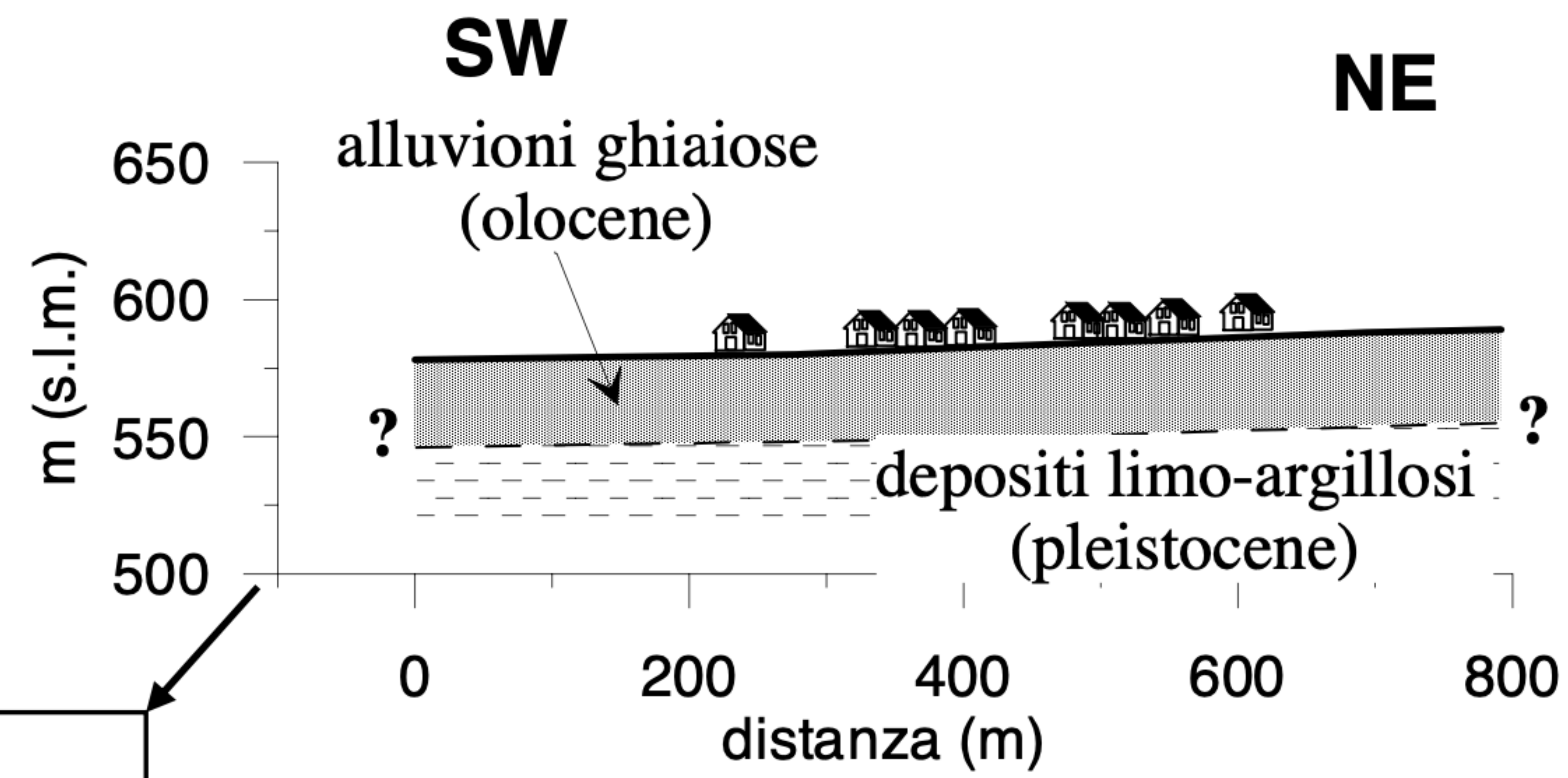


Distanza epicentrale ≅ 12 km

Monticchio



Onna



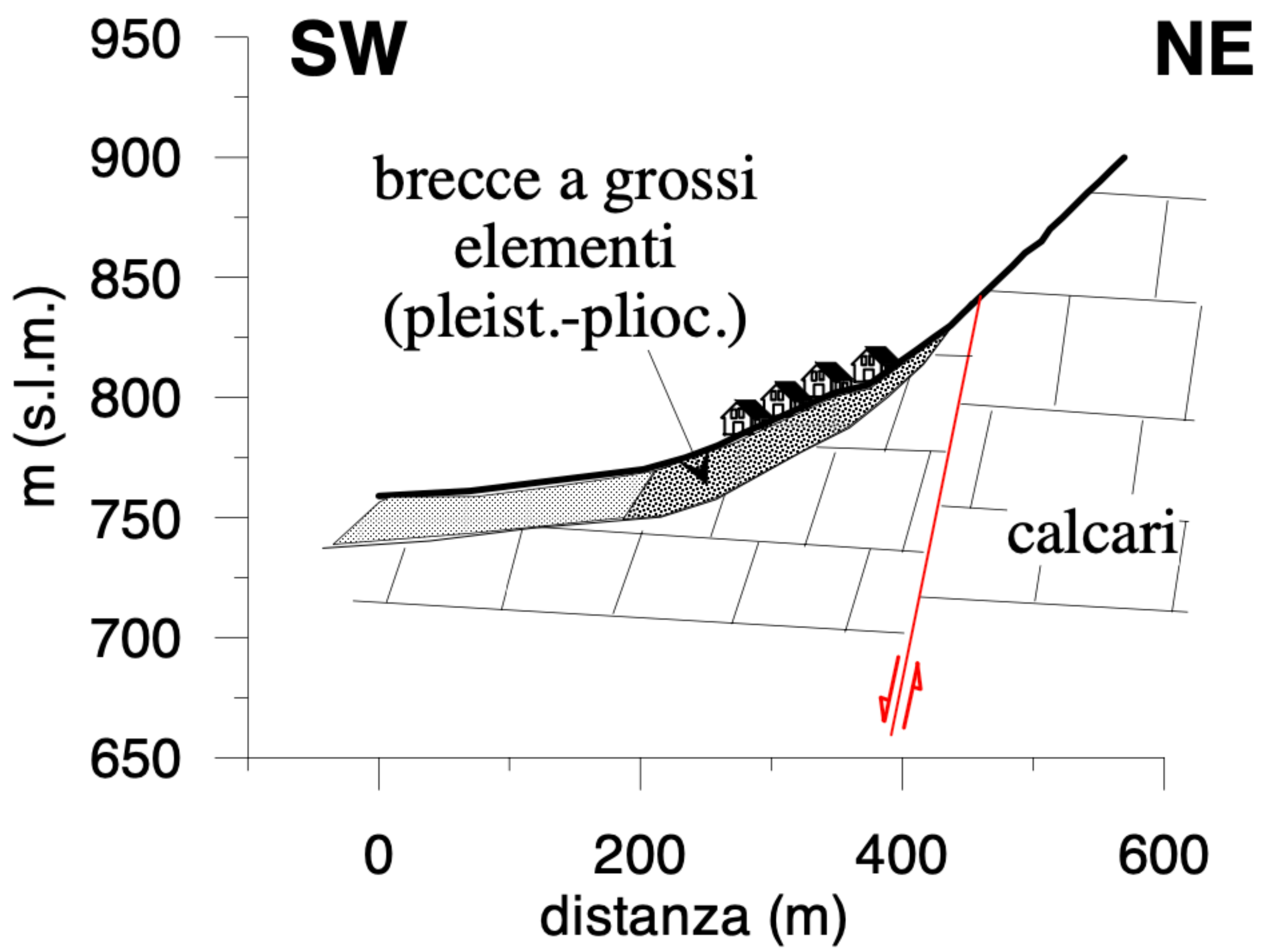
Terremoto del 1461
Onna completamente distrutta

(cortesia Dott. Di Capua, INGV)

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

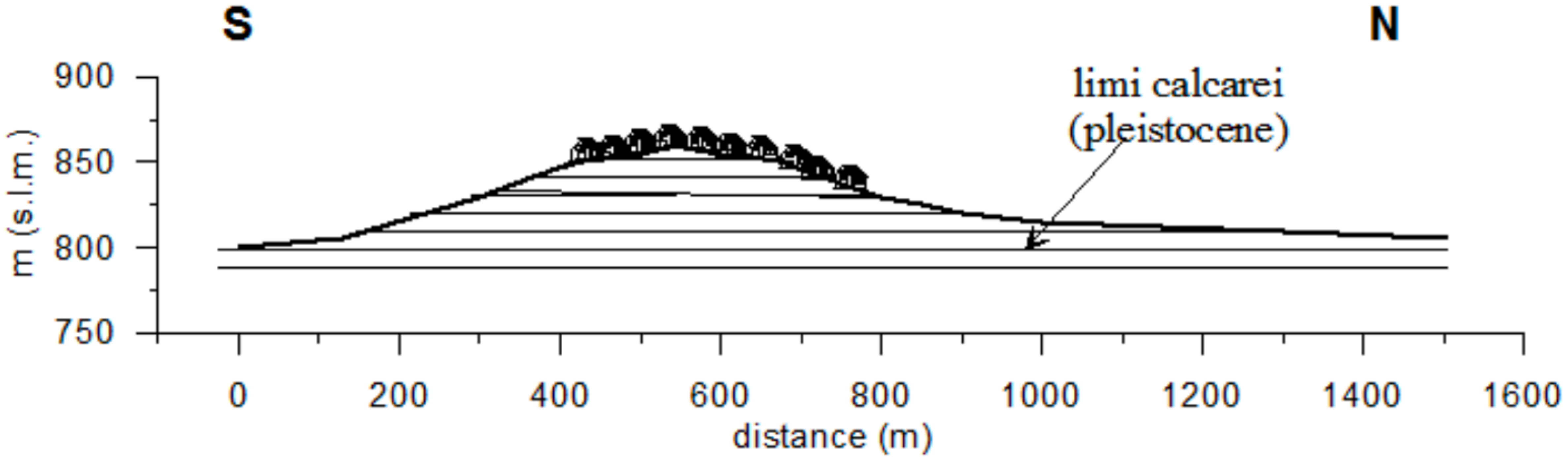
Distanza epicentrale ≅ 25 km

San Pio delle Camere



Castelnuovo

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



(a)

Terremoti del 1461, 1703, 1762
Castelnuovo completamente distrutta

(cortesia Dott. Di Capua, INGV)

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

Ground motion modification due to:

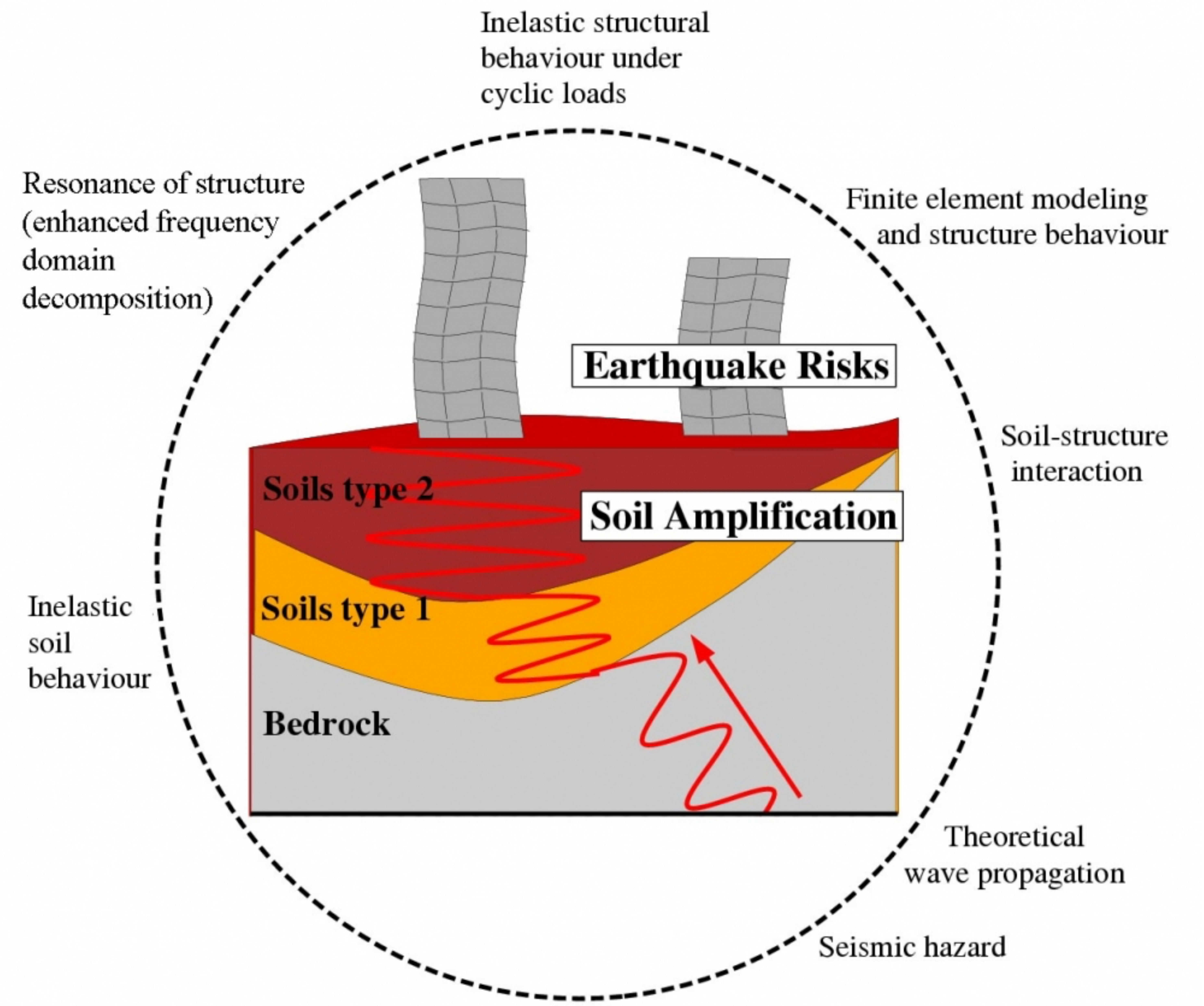
1. Lithological conditions = ‘the site effect’ (1D and 2D/3D)
2. Morphological conditions = ‘the topographic effect’

Effects of seismic induced instabilities:

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

The seismic response

Soil act as a FILTER, can modify and amplify the seismic motion coming from the inner earth faults.



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

ν= *frequency*

1. Lithological conditions

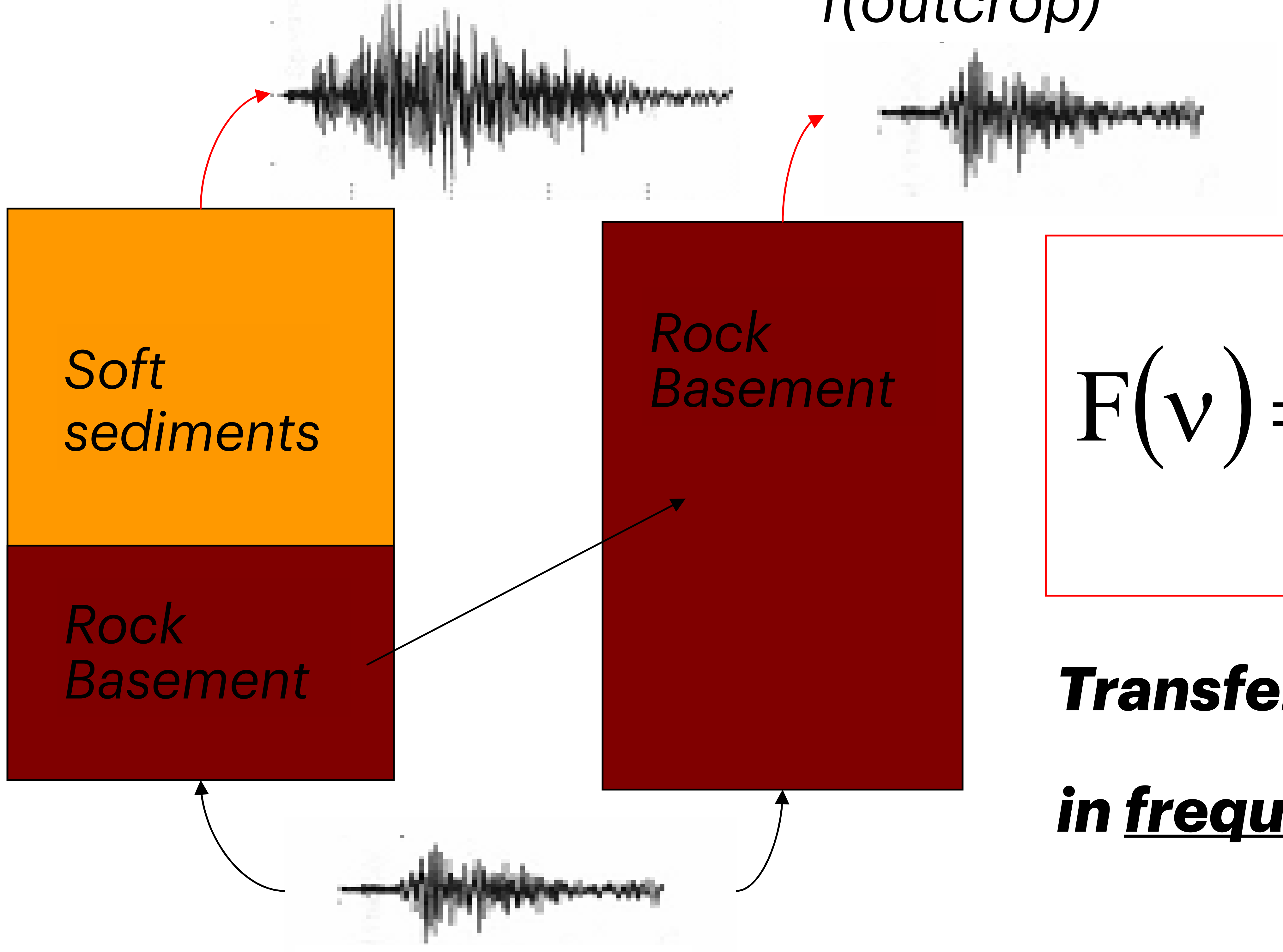
Soft soils can modify the energy propagation:

a relative estimation

The

TRANSFER FUNCTION

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



Motion at the surface g(ν)

Reference motion in hard rock f(ν)
f(outcrop)

Soft sediments

Rock Basement

Rock Basement

Seismic input

$$F(\nu)=\frac{g(\nu)}{f(\nu)}$$

Transfer Function

in <u>frequency domain</u>

g(ν) > f(ν) = <u>amplification</u>

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

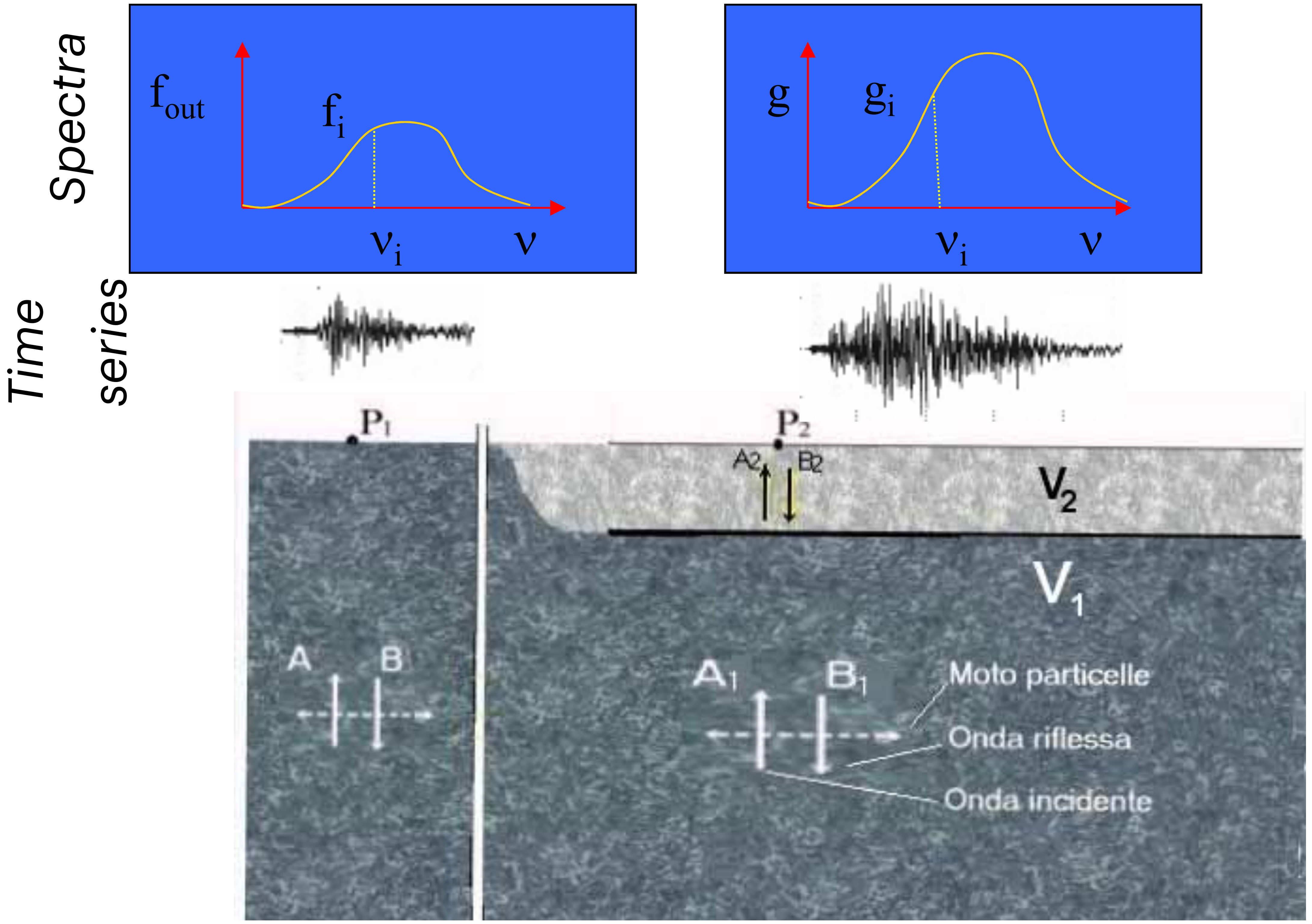
1. Lithological conditions

Practically the amplification function is used and assumed as the <u>modulus</u> of the transfer function

Amplification factor = $|F(\nu)|$

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

Amplification Function Ft(v)



Amplification Function

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

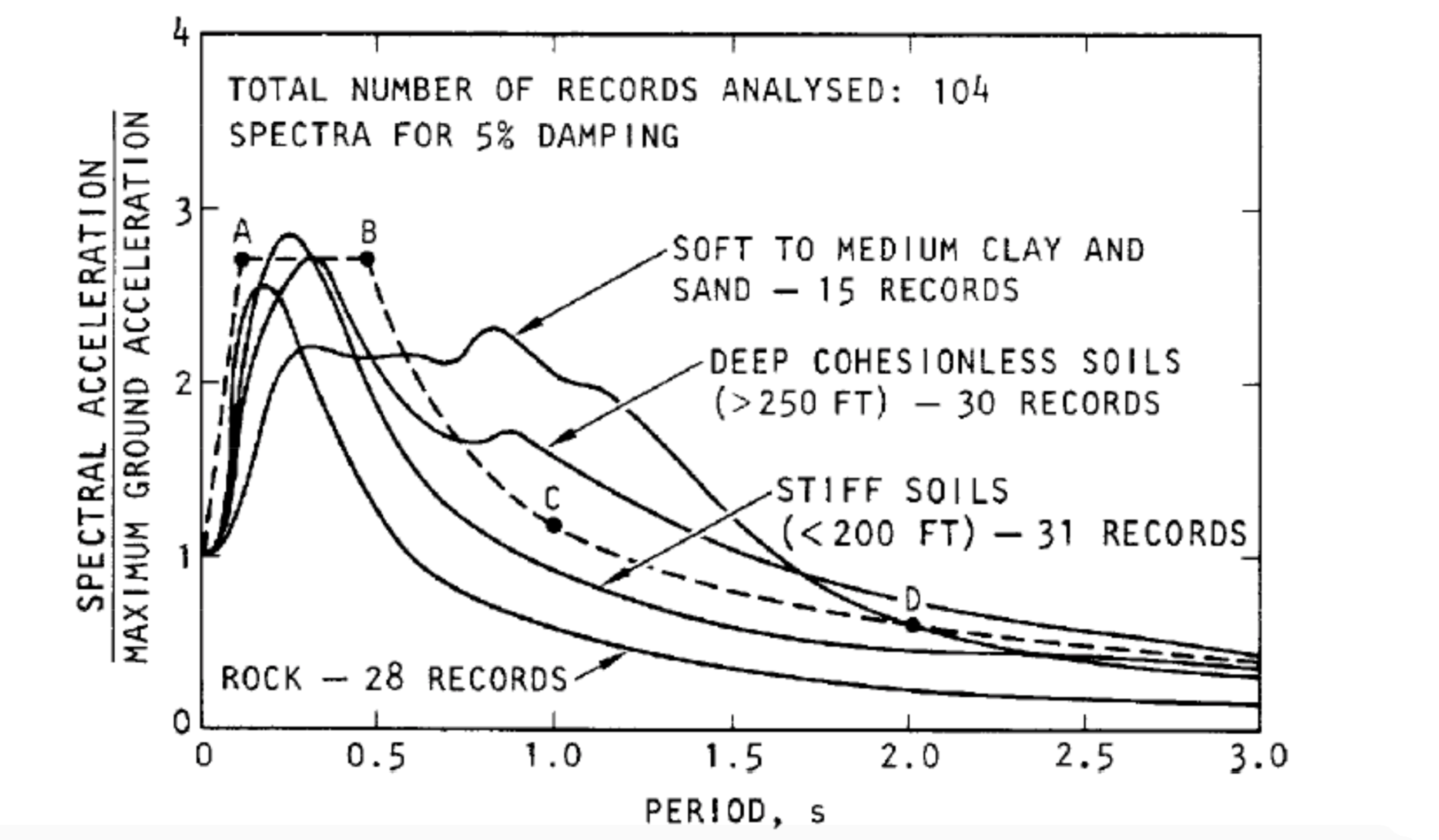
Amp. funct. ≠ Transfer funct.

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)

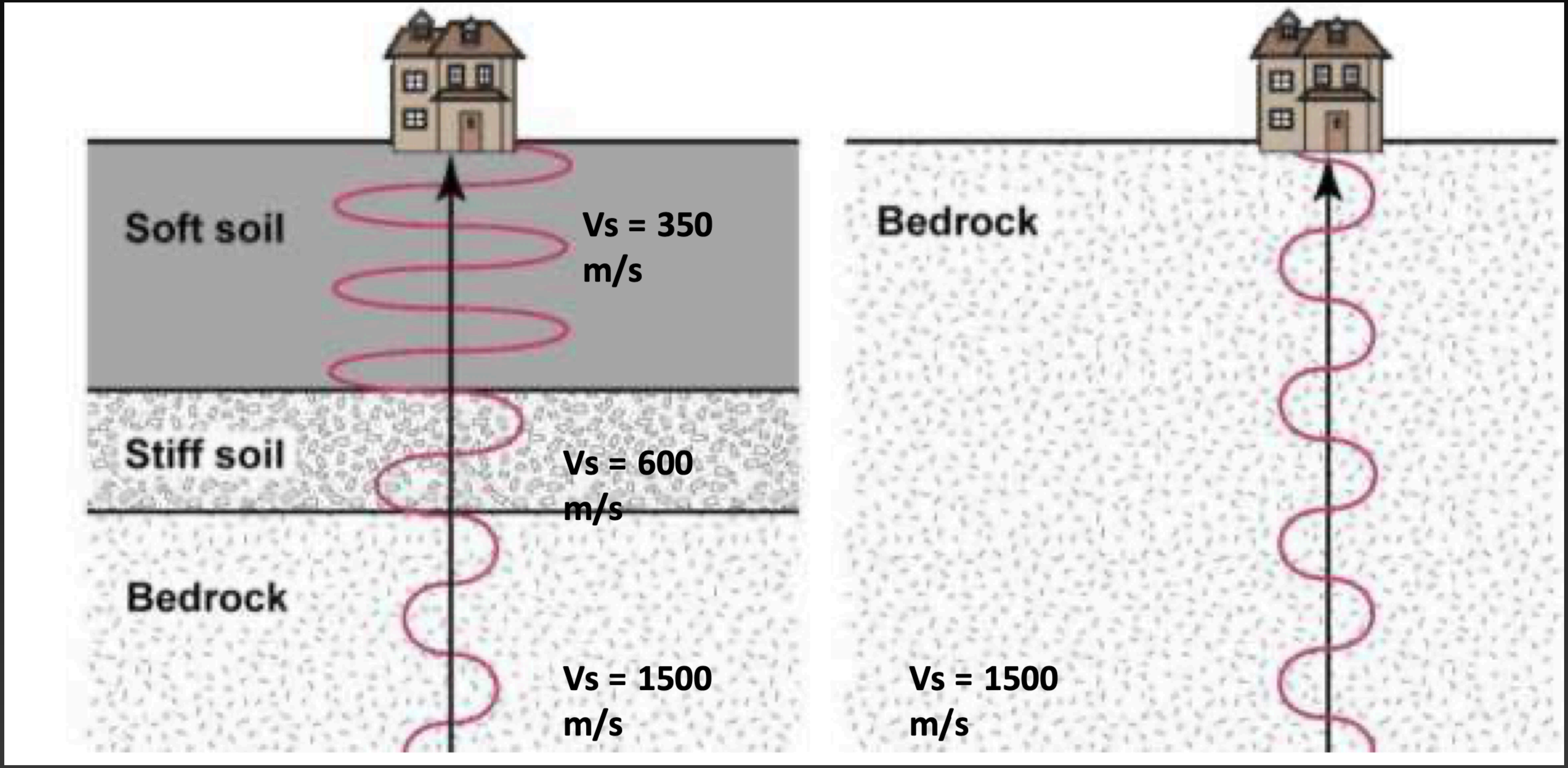


Local geological conditions can modify the seismic motion (local amplifications)

Due to conservation of energy,

slower soils can improve the

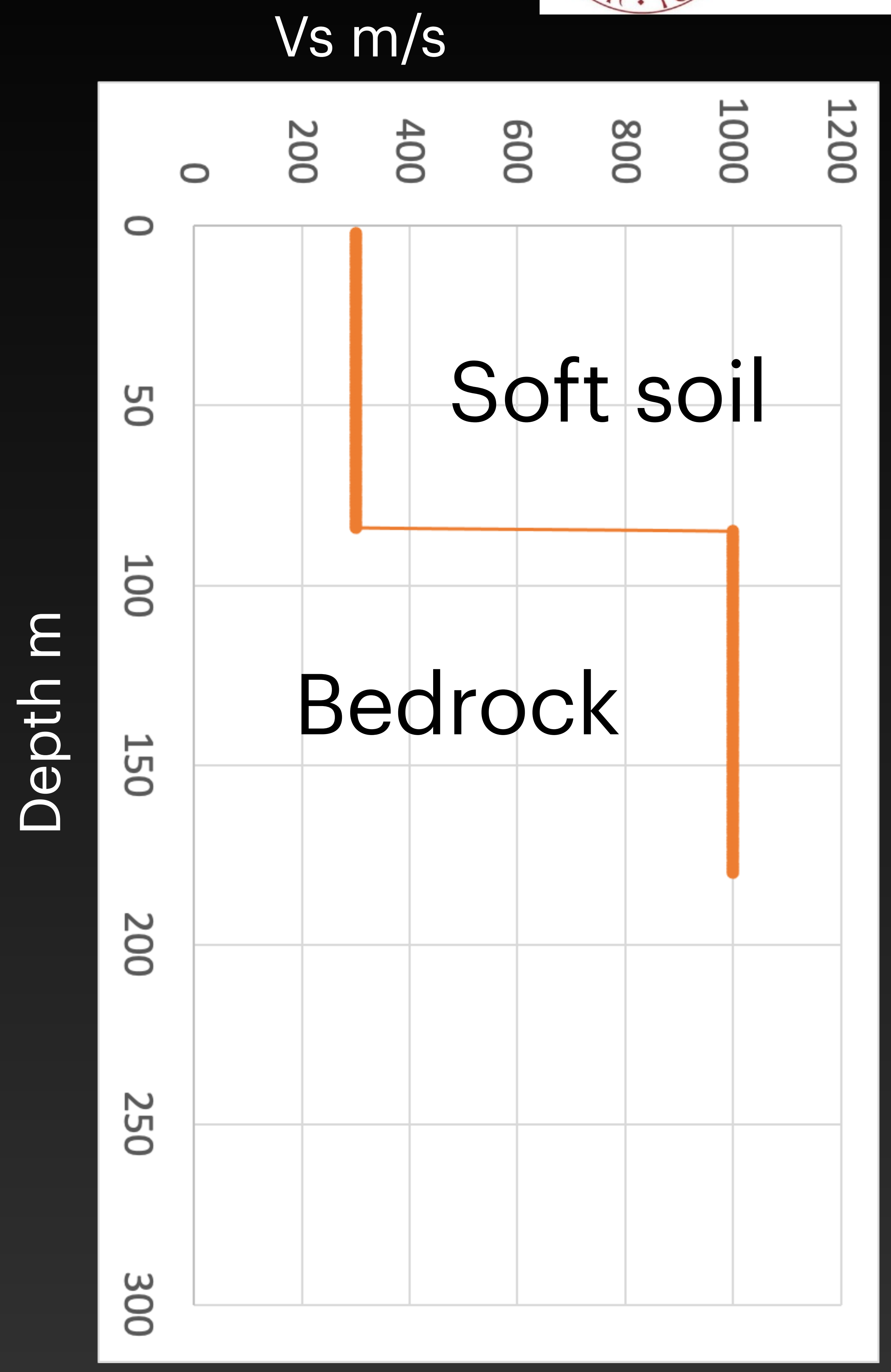
seismic motion !



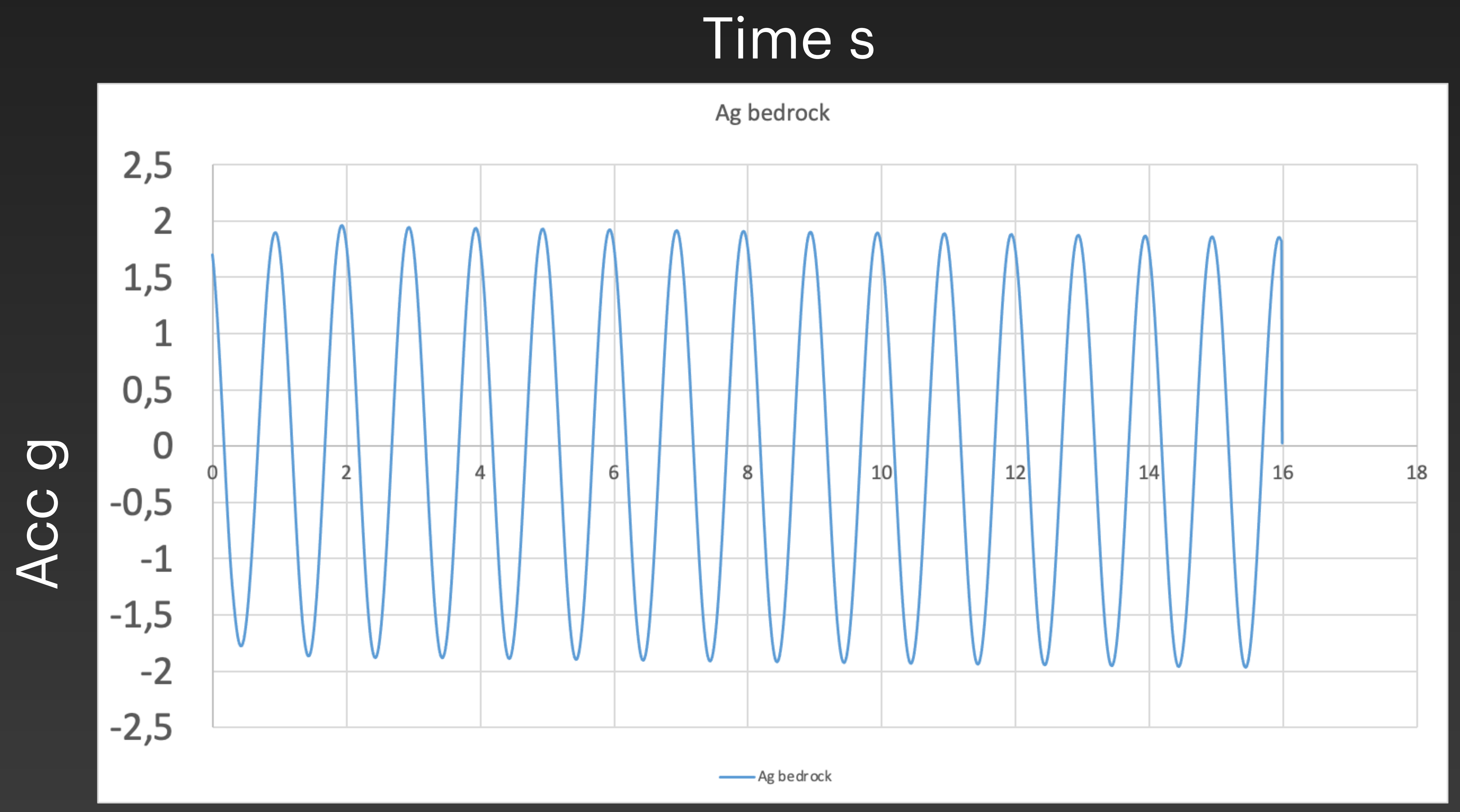
Soft soil effect

Synth example

80 m o soft soil over an hard soil model



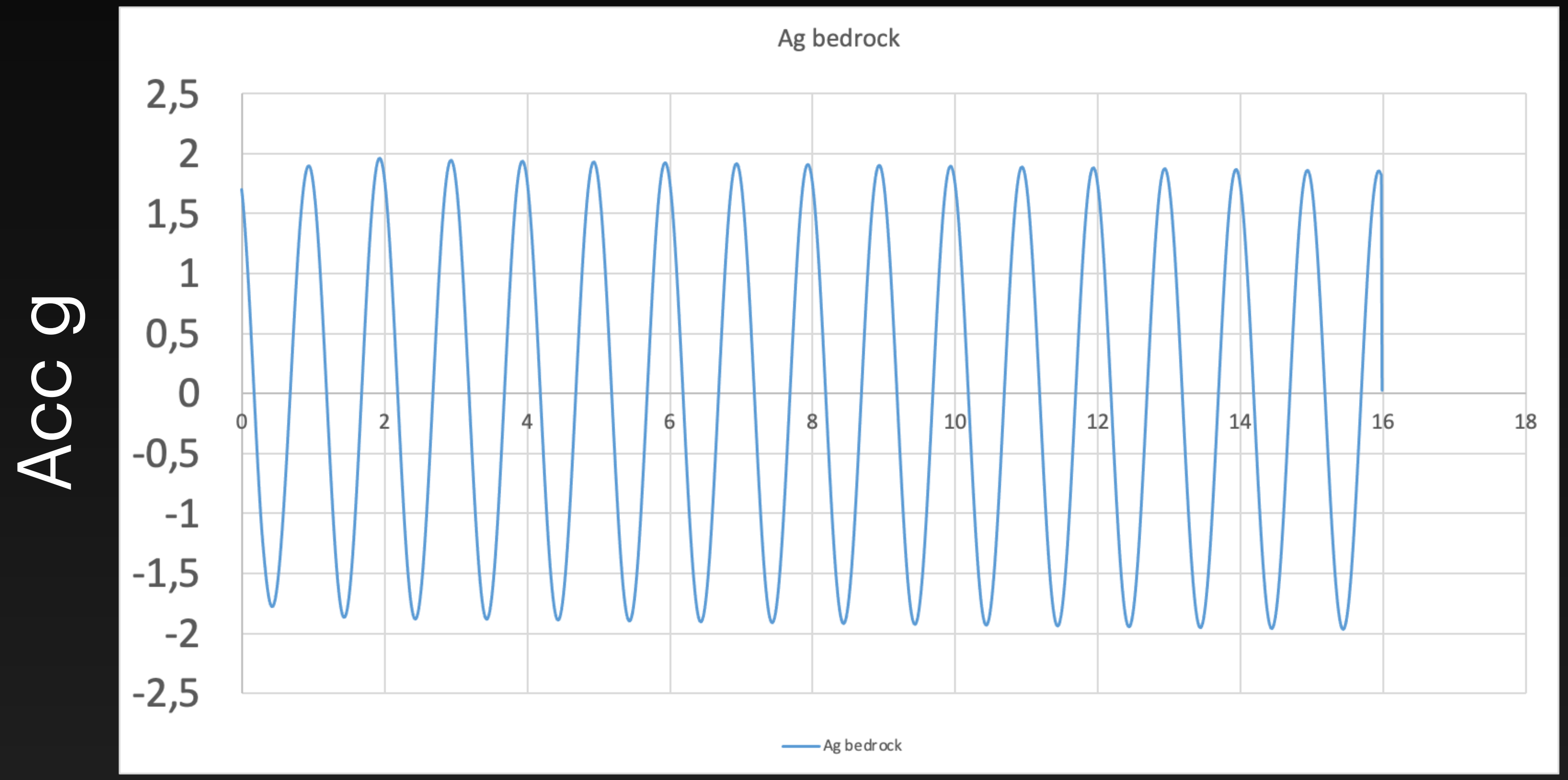
Input: cosine 2g wave at 1 Hz frequency



Soft soil effect

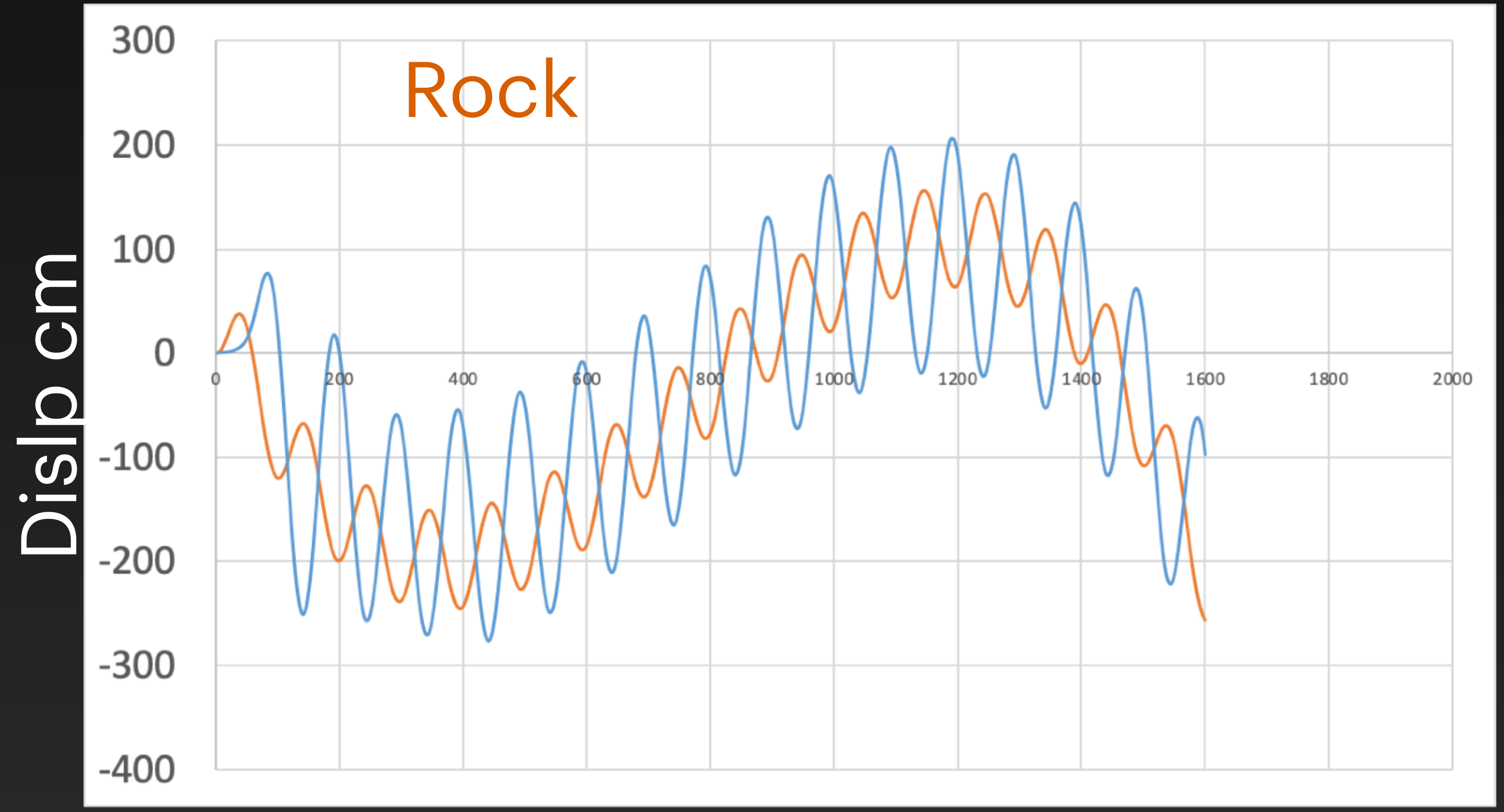
Time s

INPUT

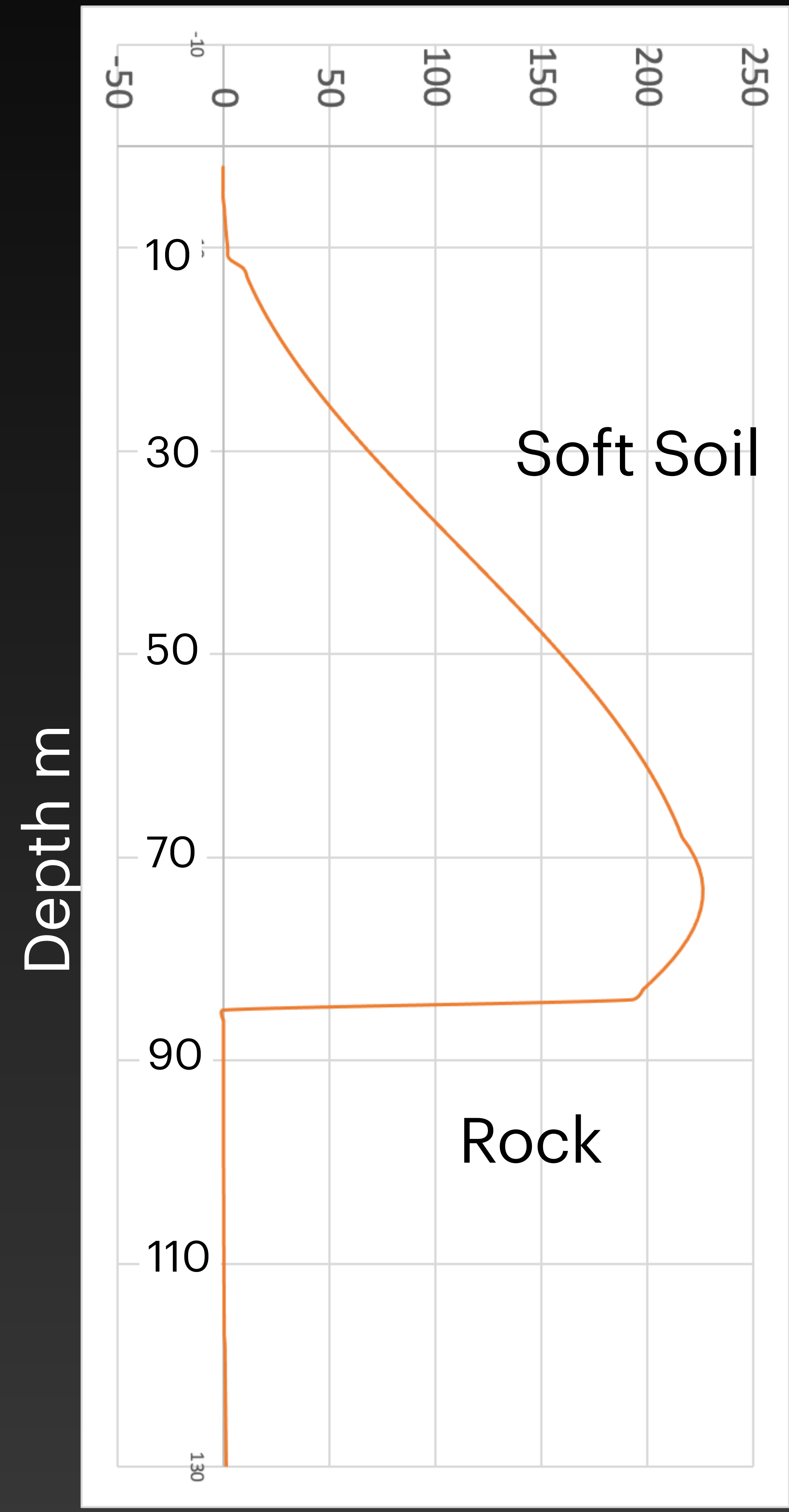


2 g Acceleration

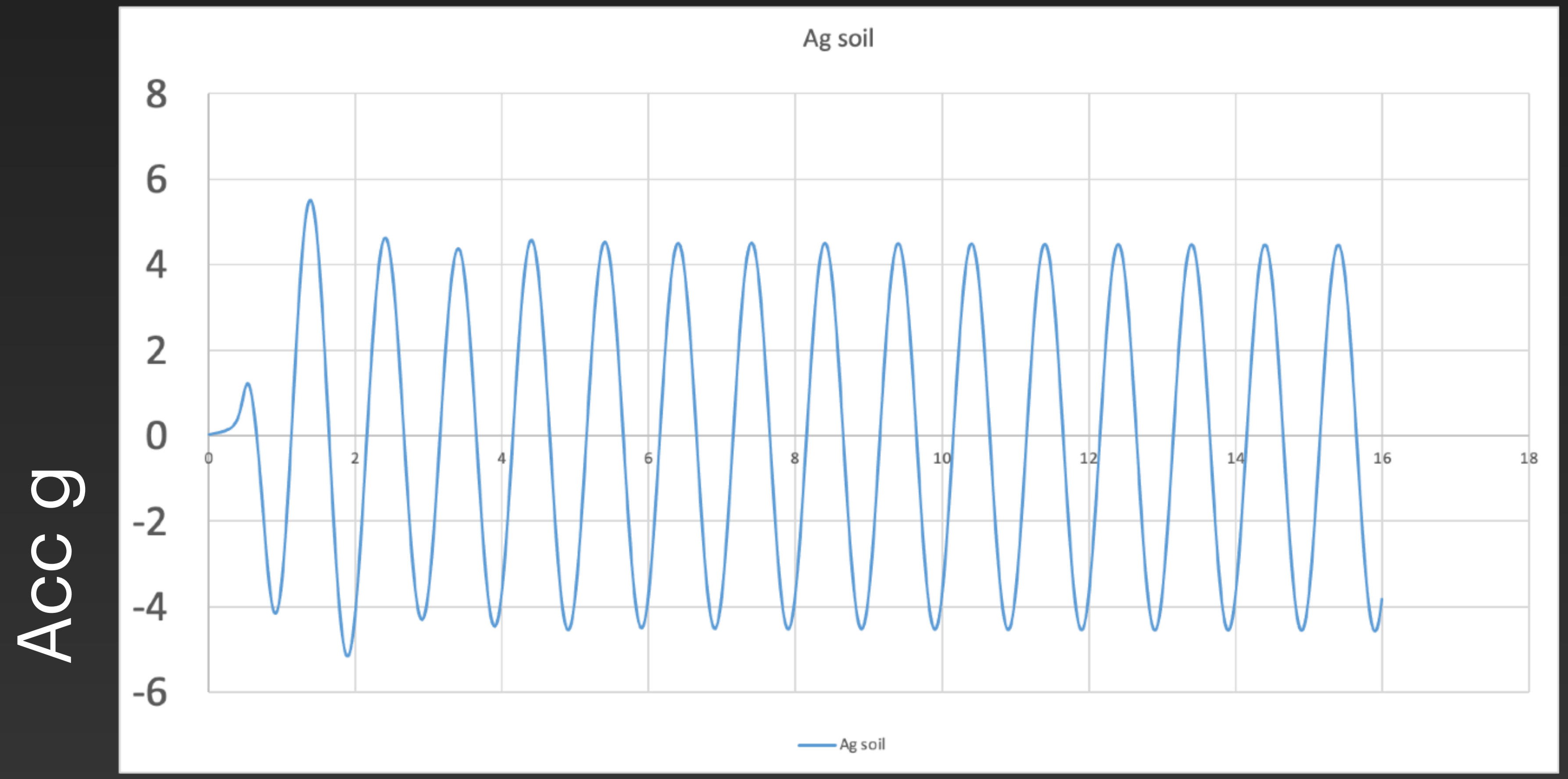
Input



Dissipated Energy



OUTPUT



5g Acceleration

At surface!

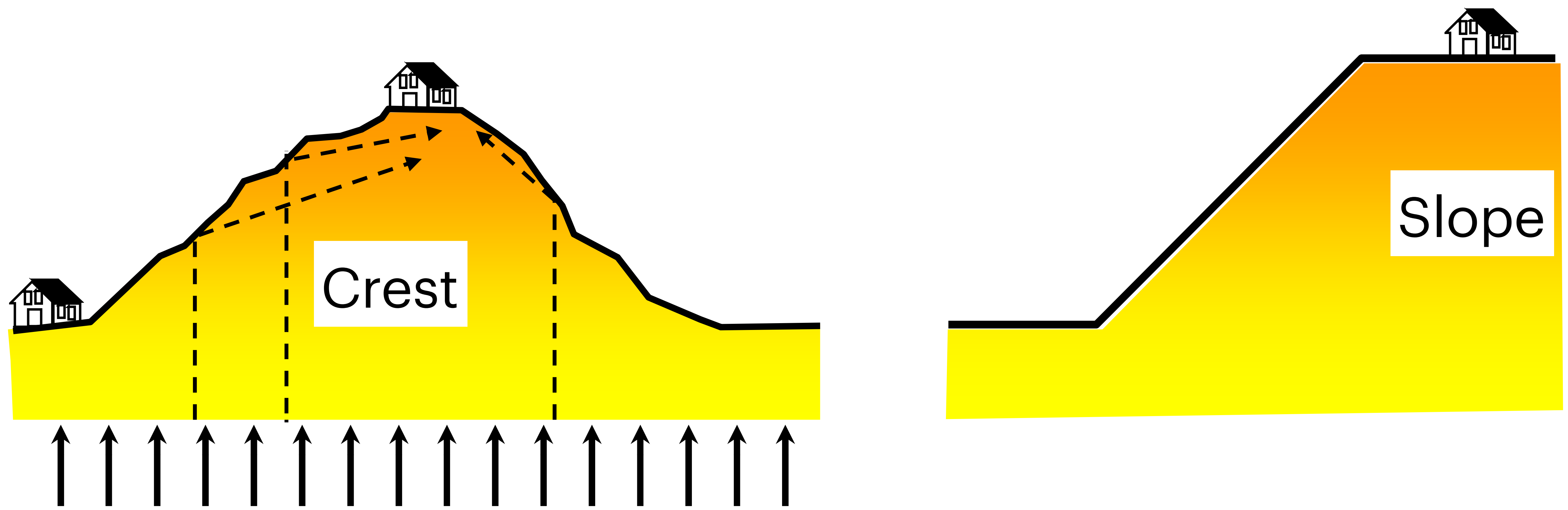
Local geological conditions can modify the seismic motion (local amplifications)

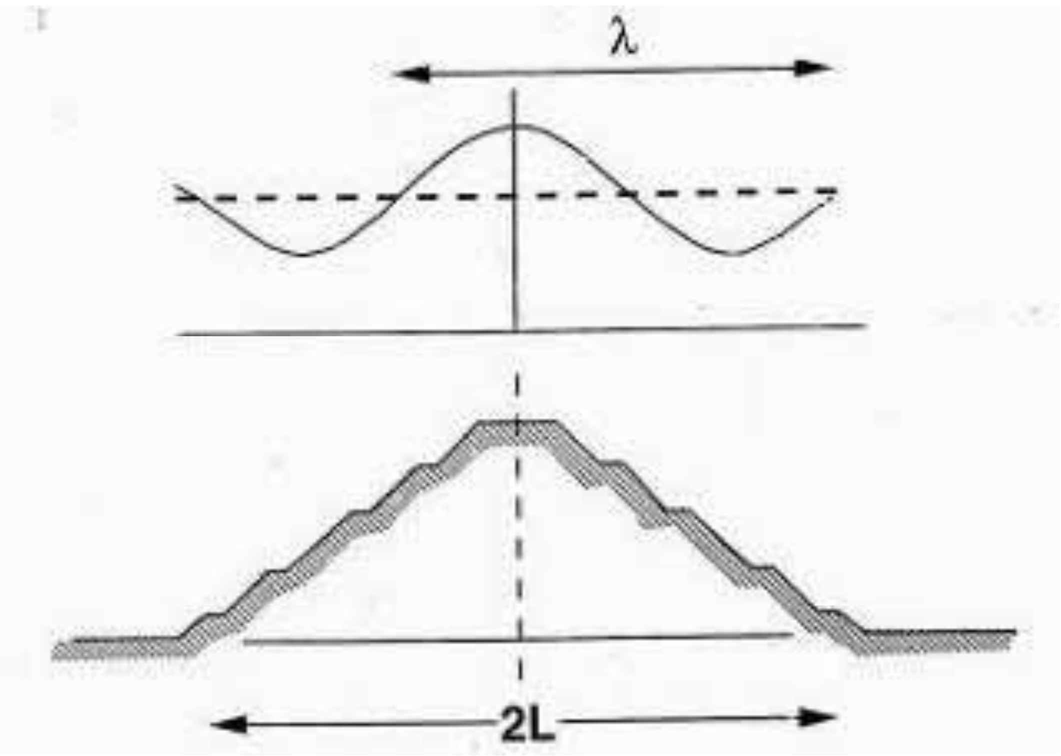
2. Topographic conditions

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 ≈λ

>> slope >> amplification

L = hill semi-length

λ = wavelength

2. Topographic conditions

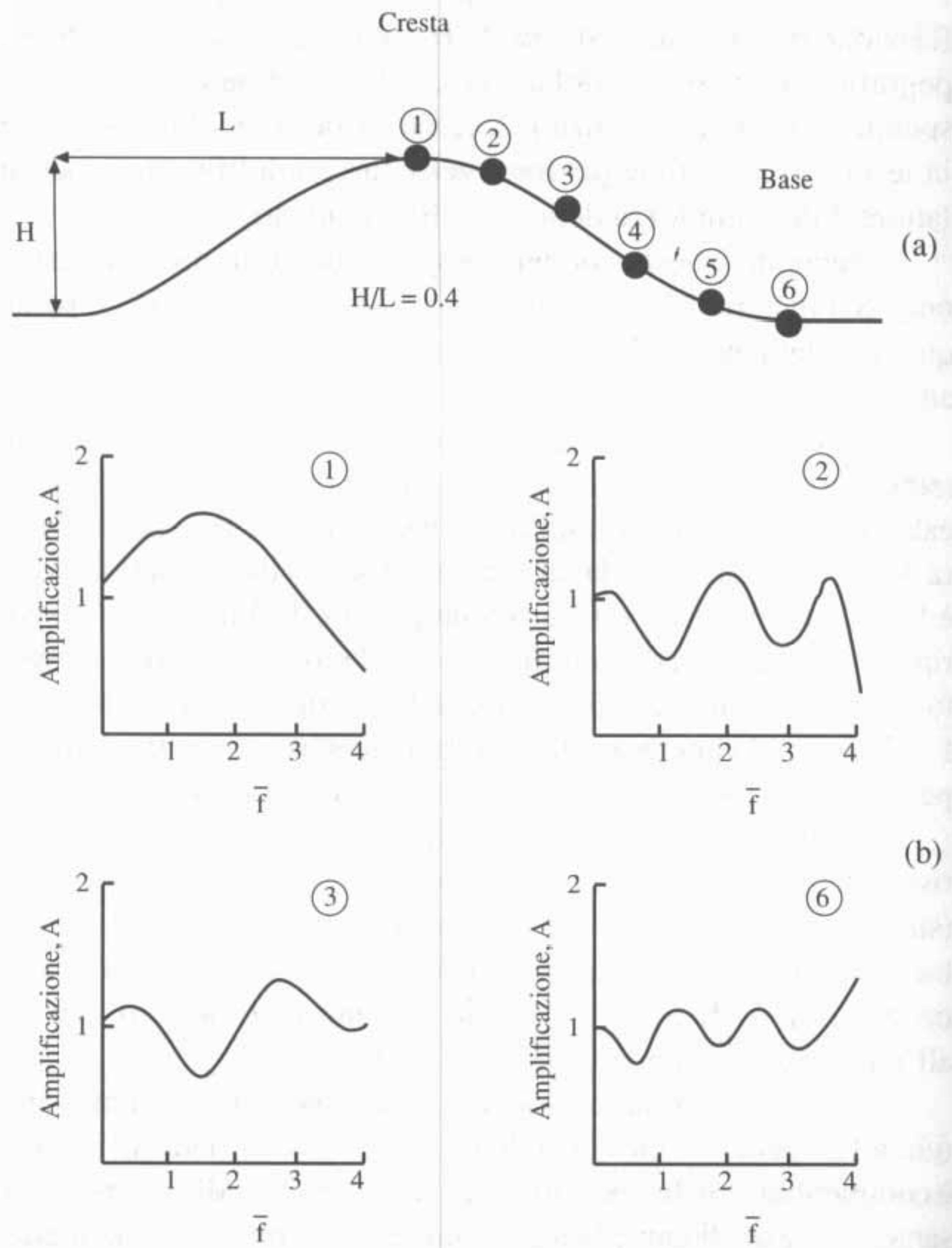


Fig. 4.16. Funzioni di amplificazione calcolate in corrispondenza di alcune postazioni di un rilievo isolato nell'ipotesi di propagazione verticale di onde SH (Geli *et al.*, 1988).

Effects depends on waves direction and slope geometry.

The key parameter is β=2L/λ, being

L = half width of the mountain

and

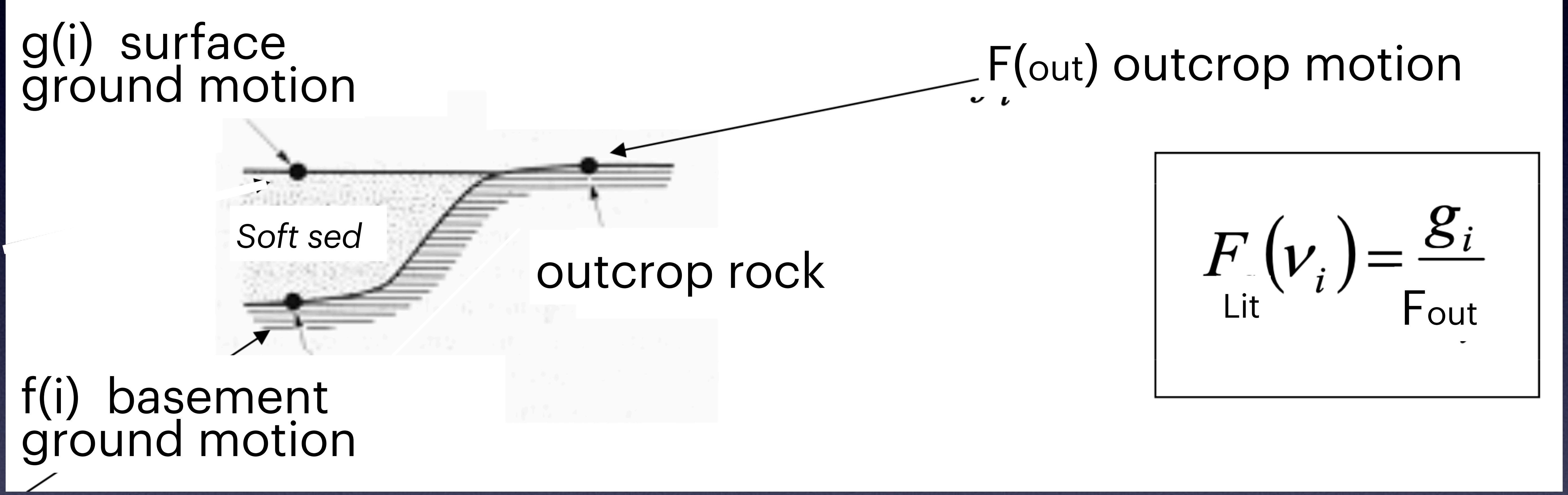
λ = seismic wavelength

(λ =velocity/frequency = c/f)

The maximum effect is for β=1 , 2L=λ

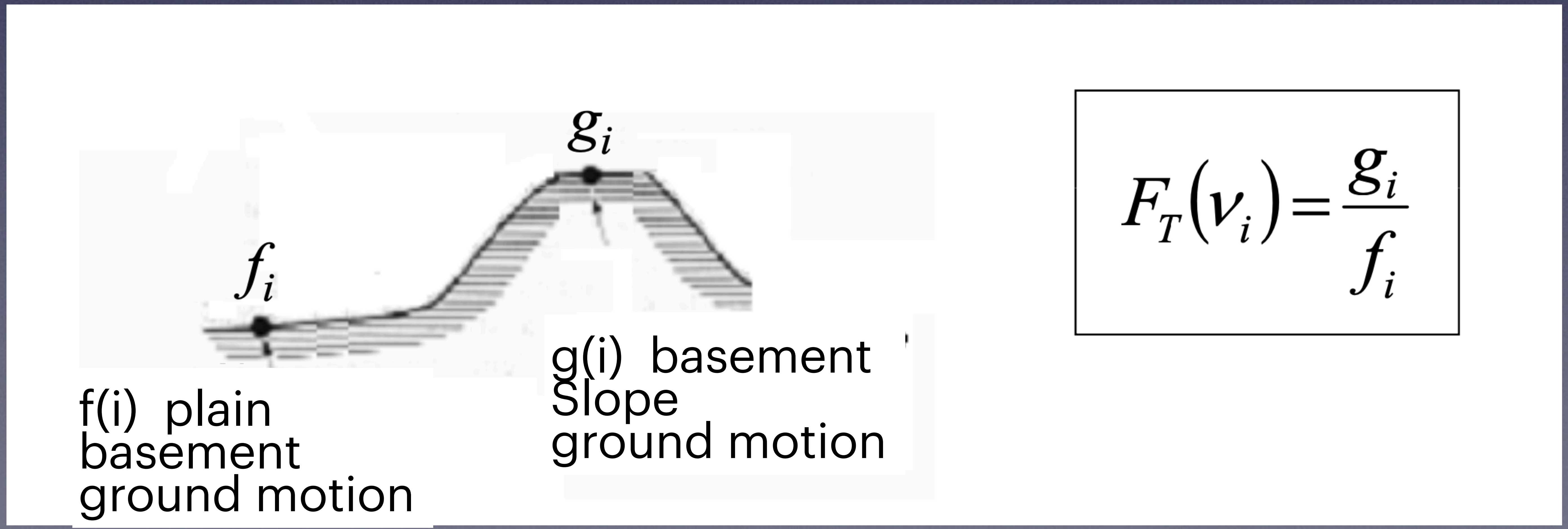
Local geological conditions can modify the seismic motion (local amplifications)

1. Lithological conditions



$$F_{Lit}(\nu_i) = \frac{g_i}{F_{out}}$$

2. Topographic conditions



$$F_T(\nu_i) = \frac{g_i}{f_i}$$

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,

$\lambda = c/f$ = velocity / frequency

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

$\lambda = 300/3 = 100$ 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

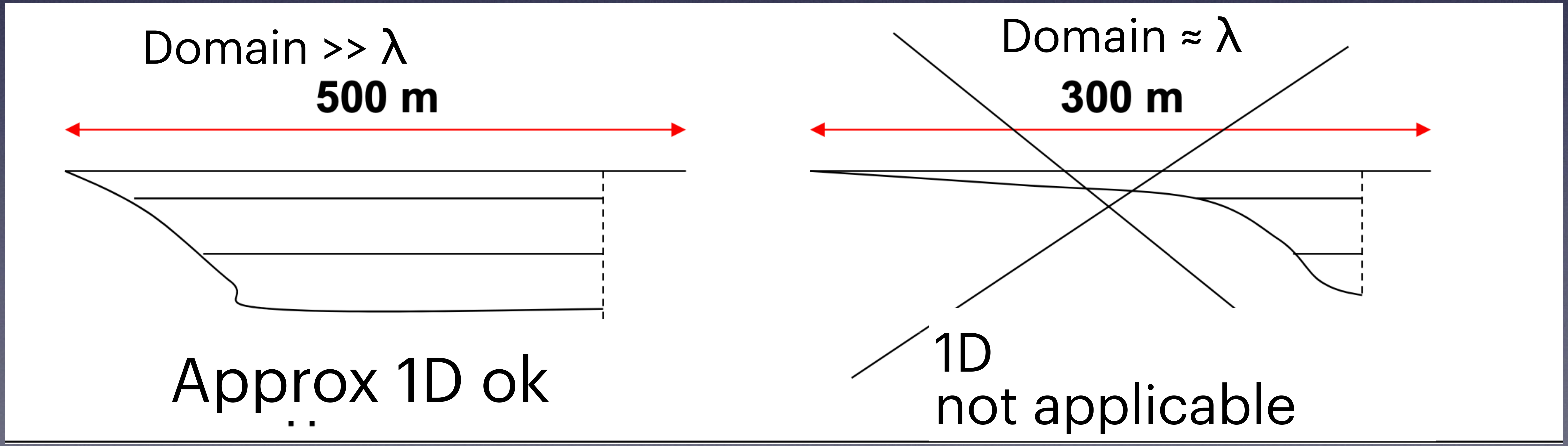
If the site can be considered as horizontal flat layered for the λ of interest = 1D, otherwise it must be considered 2D

Es

Vs = 500 m/s

f= 2 Hz

λ = 250 m



Domain >> λ

500 m

Approx 1D ok

Domain ≈ λ

300 m

1D
not applicable

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

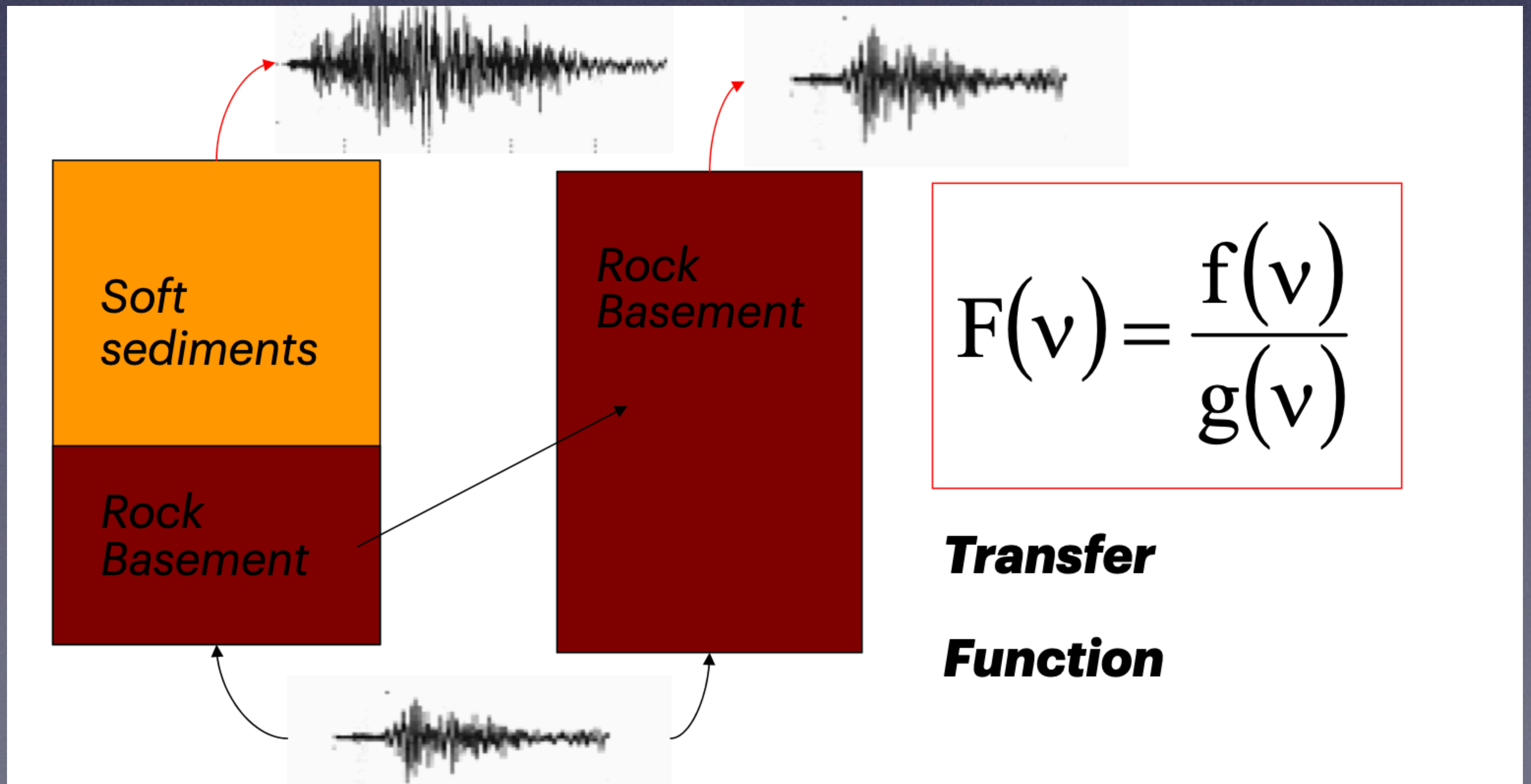
What it means 1D, 2D (3D)?

The assuming dimensions of the problem

Some geological features are strictly multi-dimensional,

cannot be adopted 1D simplified assumptions…

1D world

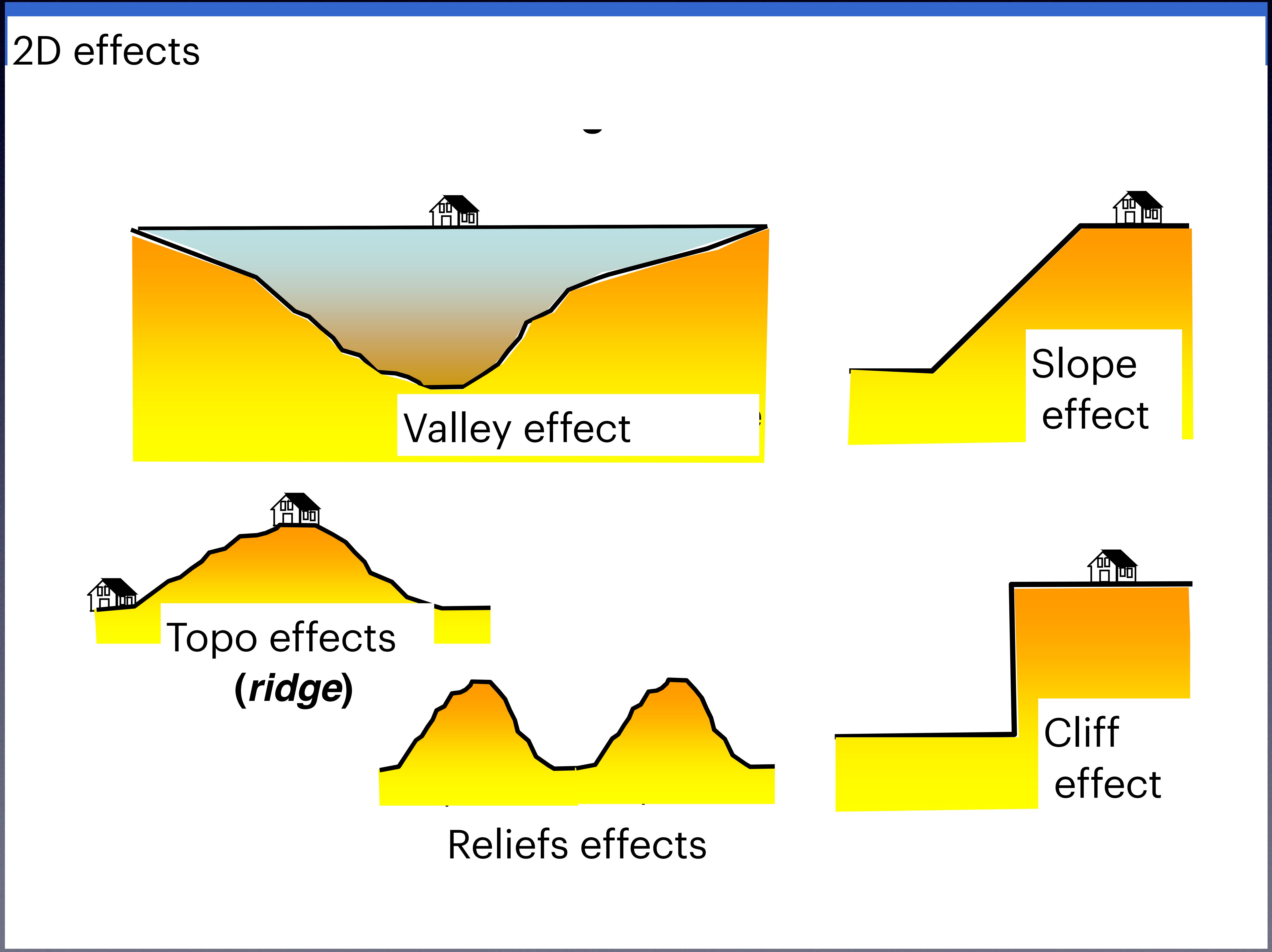


$$F(\nu)=\frac{f(\nu)}{g(\nu)}$$

Transfer Function

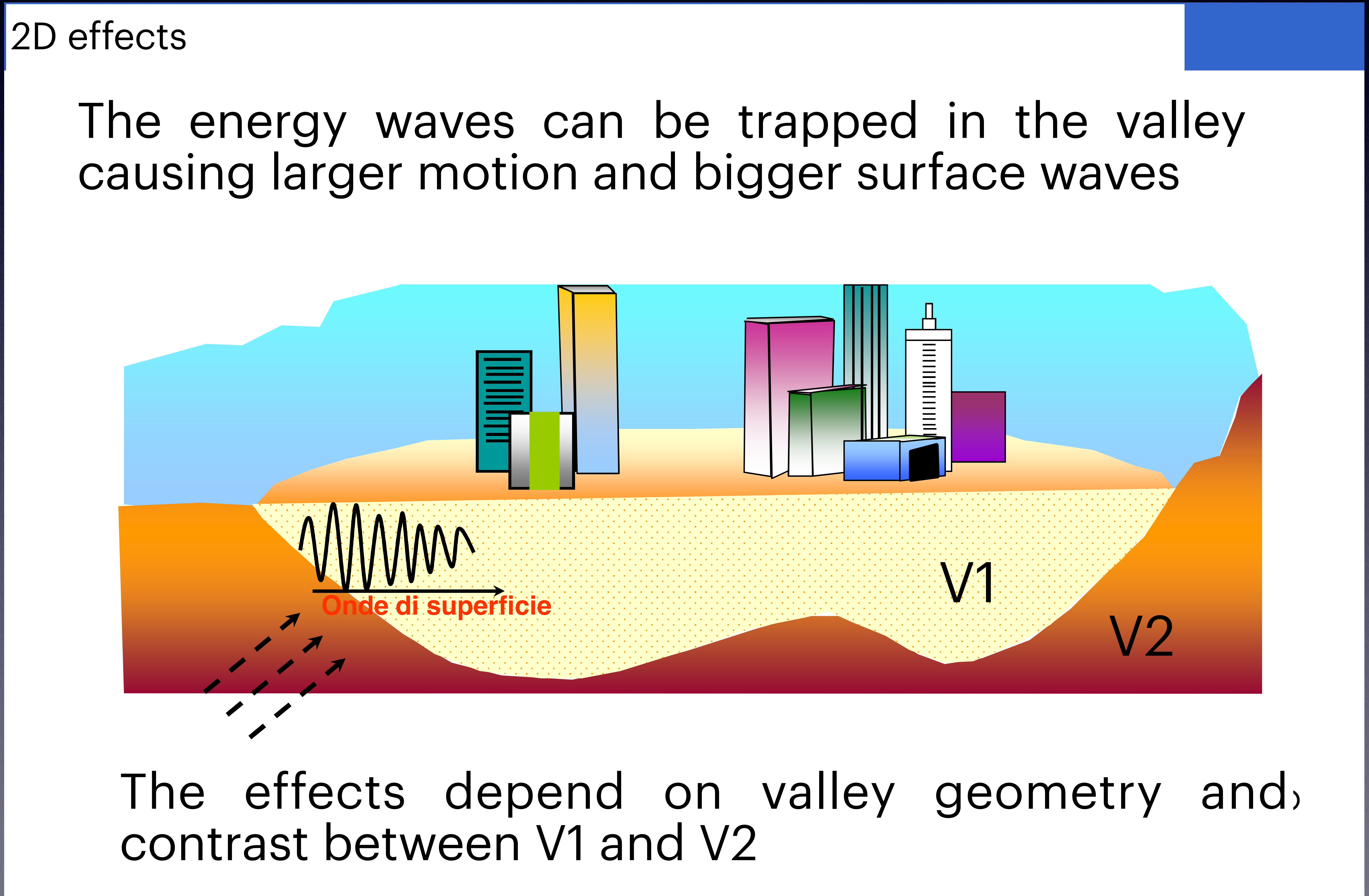
Local geological conditions can modify the seismic motion (local amplifications)

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

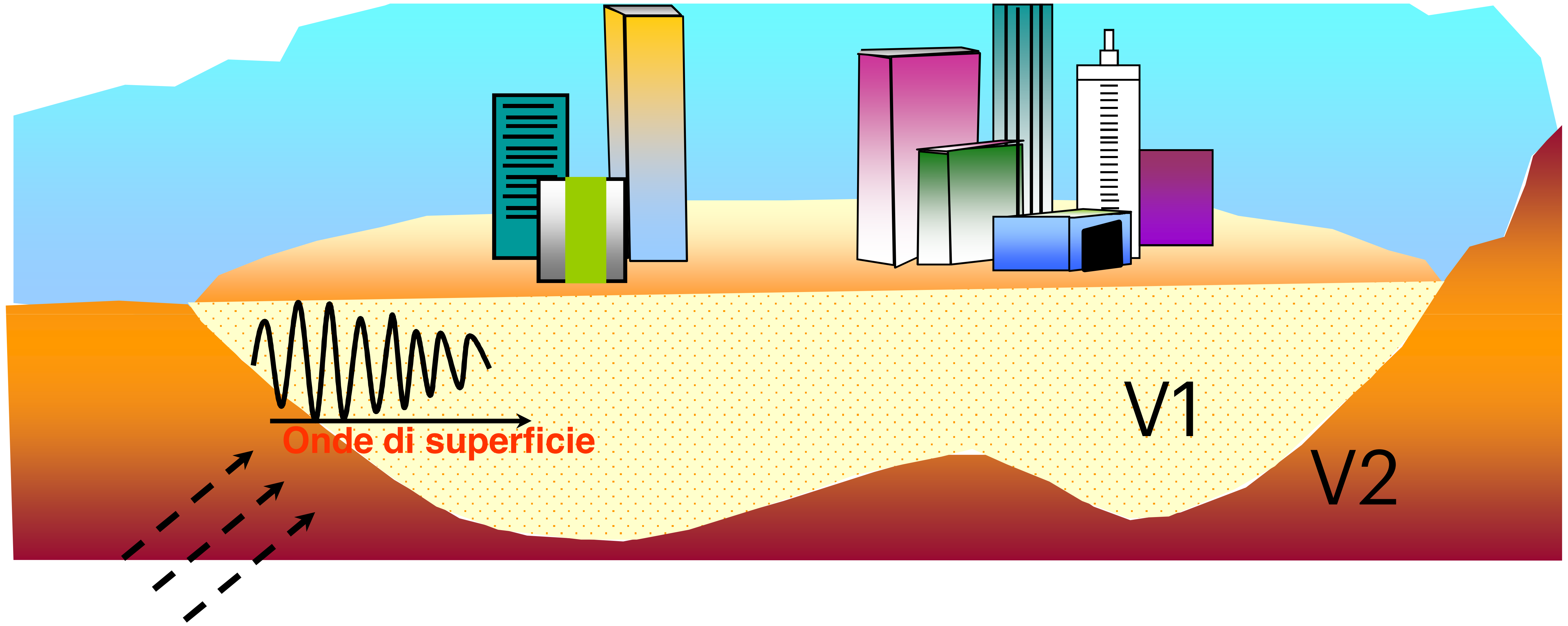
The effects depend on valley geometry and contrast between V1 and V2

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



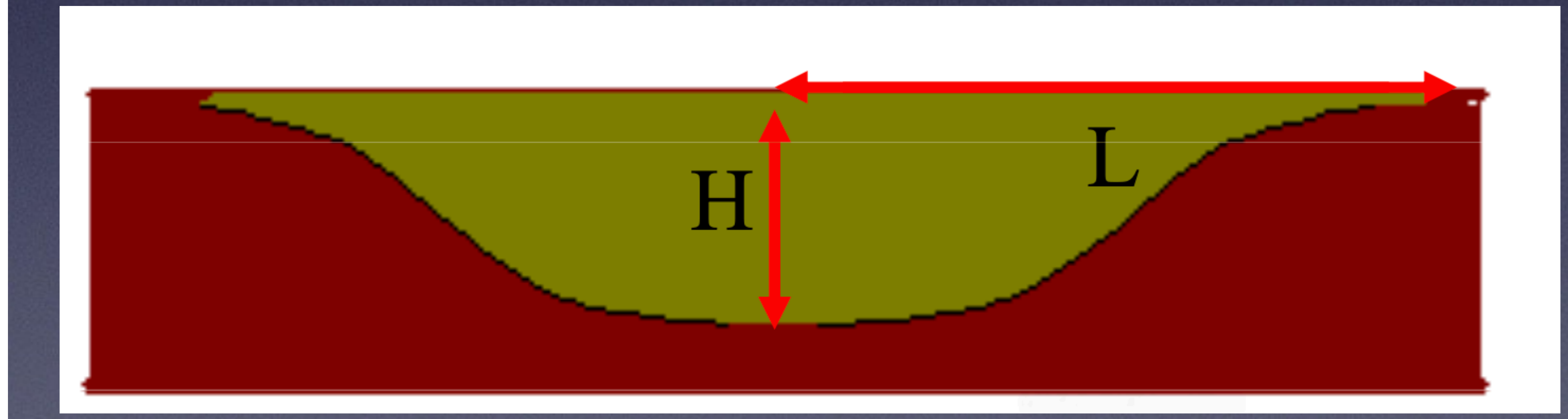
The effects depend on valley geometry and contrast between V1 and V2

SHAPE RATIO

H/L

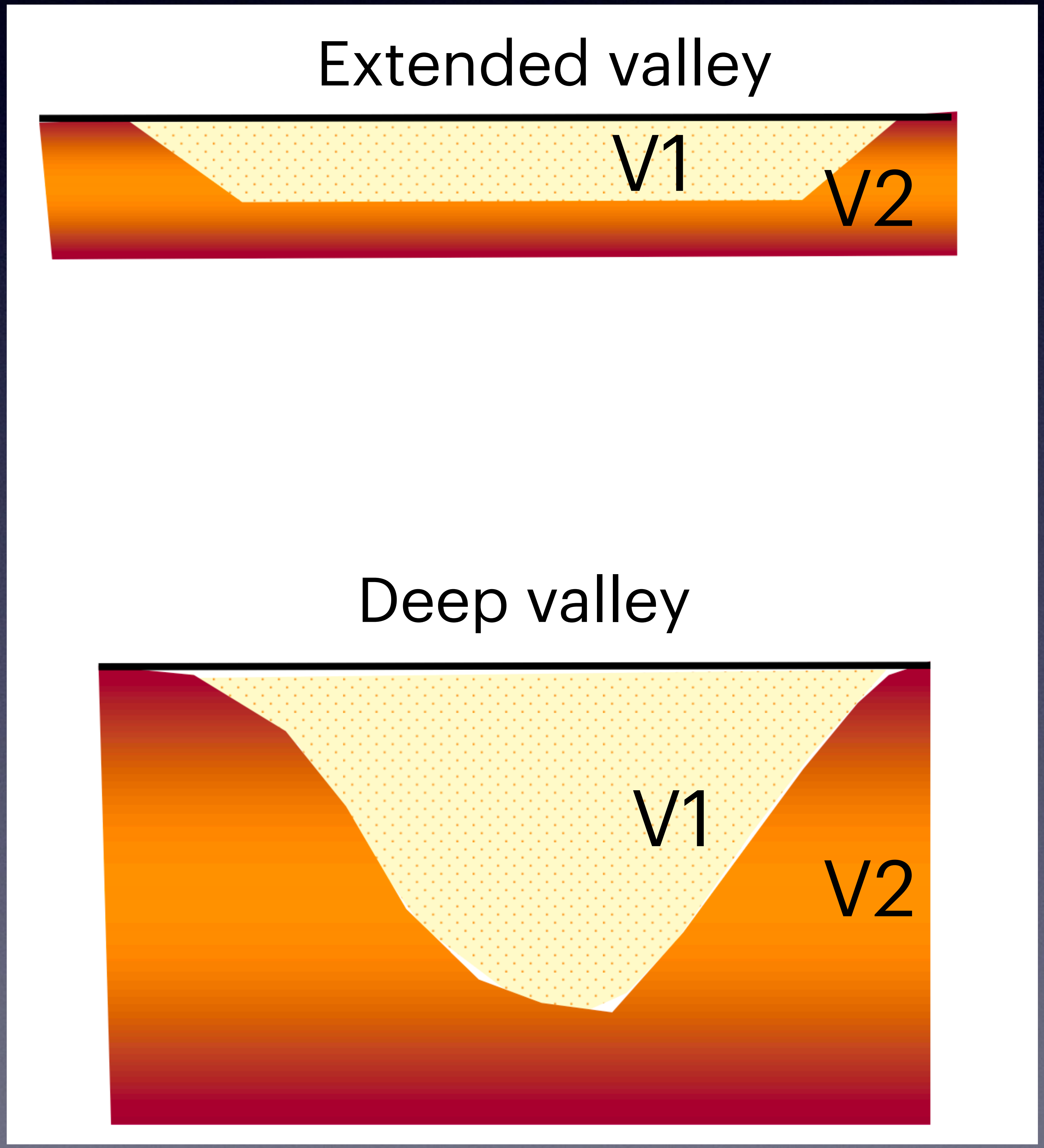
H= thickness

L =halfwidth



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

The 'valley' 2D effects



<< SHAPE RATIO

H/L

H= thickness

L =halfwidth

>> SHAPE RATIO

H/L

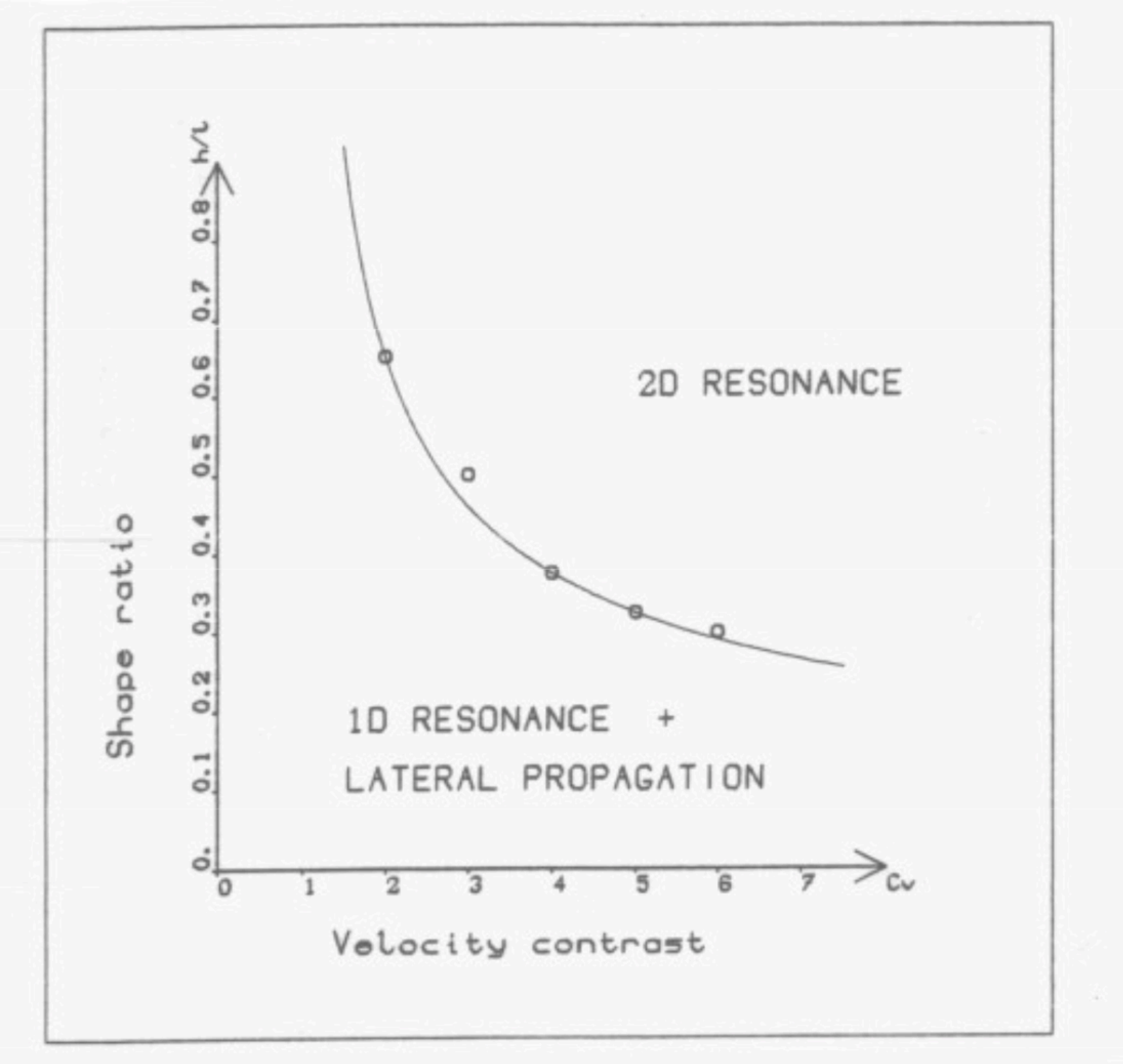
H= thickness

L =halfwidth

>> shape ratio

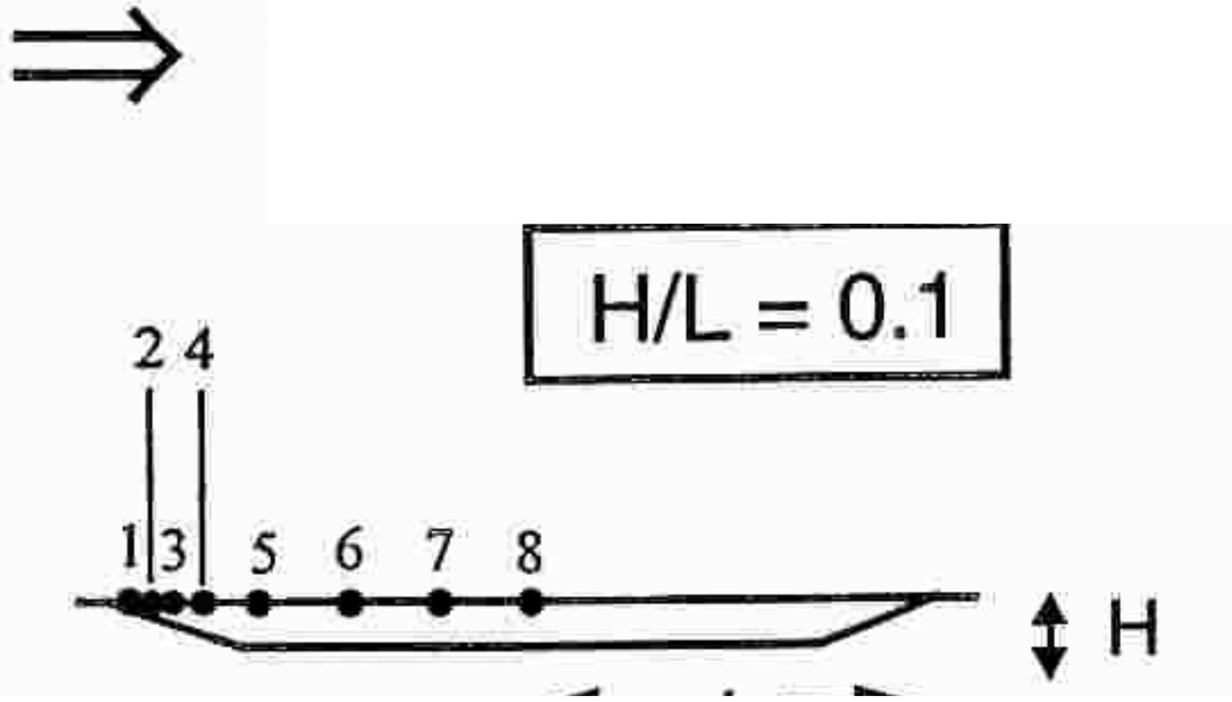
>> velocity contrast

= greater amplification!



The ‘valley’ 2D effects

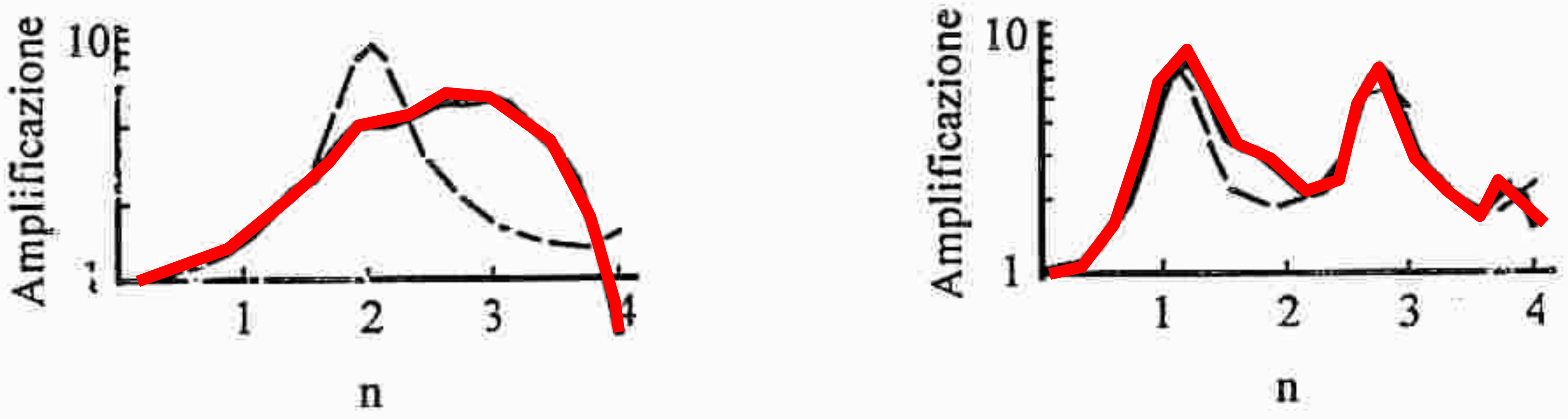
Surface valley H/L < 0.25



2D simulation

1D simulation

Analytic simulation


Border

Center

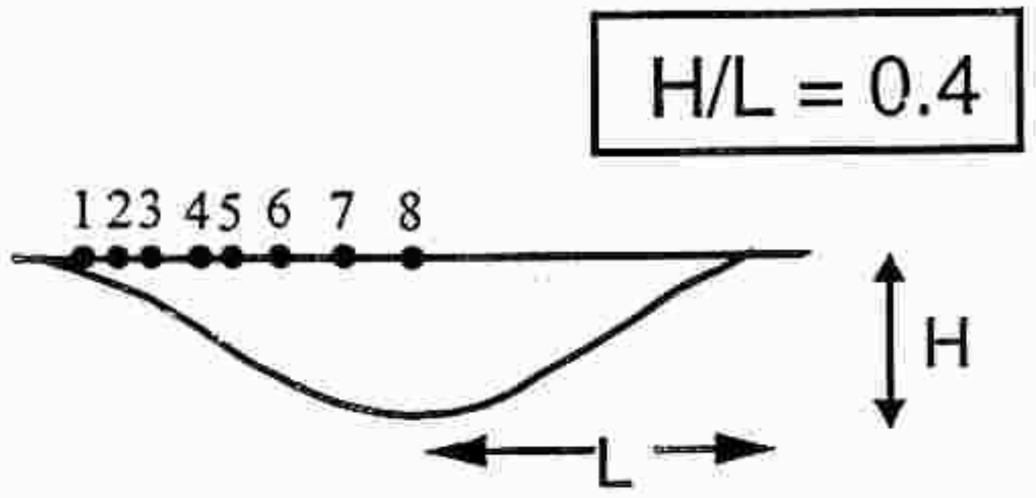
1D approx. ok for the center of the valley

(Bard & Gariel, 1986)

The ‘valley’ 2D effects

Deep valley H/L > 0.25

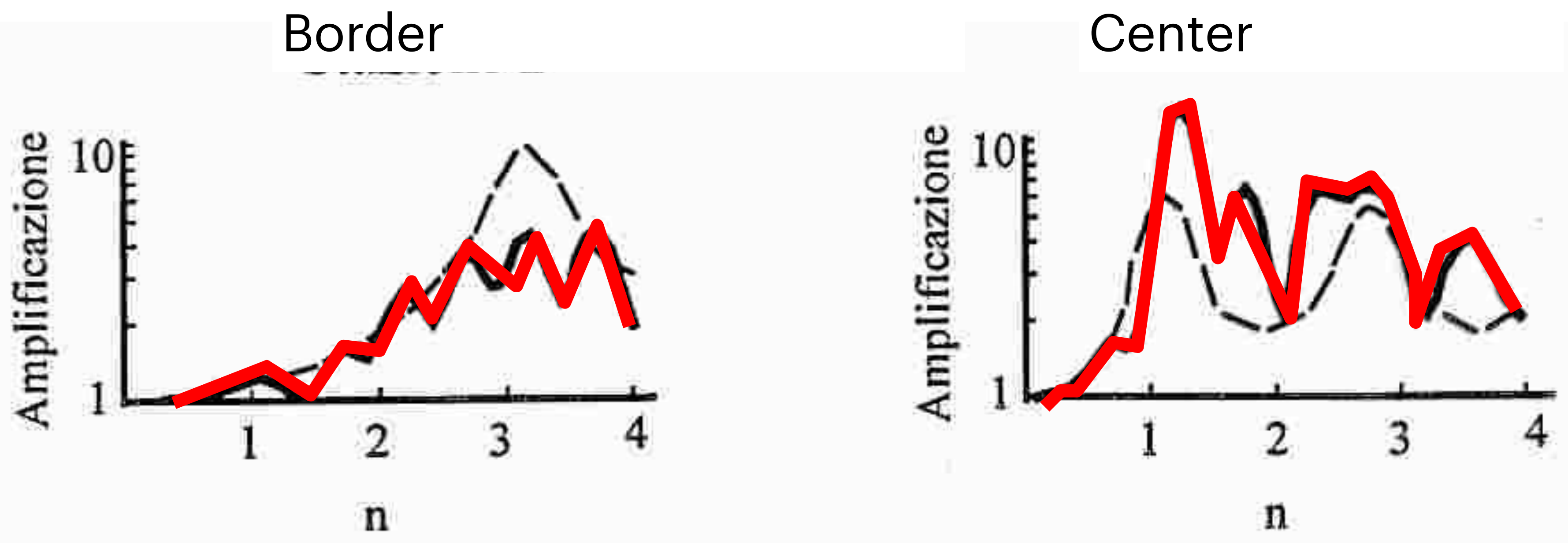
⇒



🟥 2D simulation

-----1D simulation

Analytic simulation



- 1D approximation not usable

e

(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 = quantitive **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

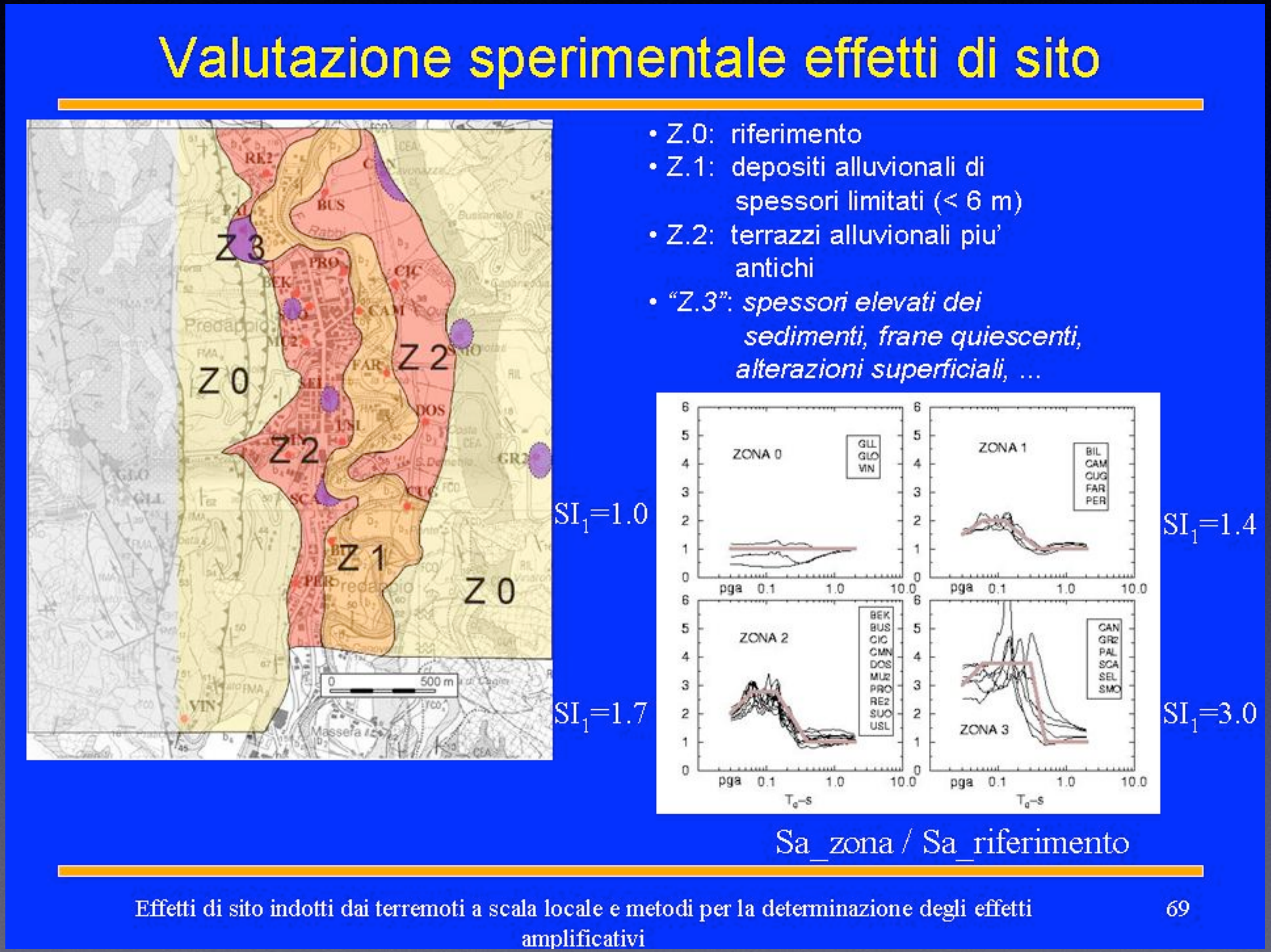
Level 1 = Urban Planning level, mandatory for all the municipalities,
Defining zones homogenous form the geological/geomorphological points of view

(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, ...*

SI_1=1.0

SI_1=1.4

SI_1=1.7

SI_1=3.0

Sa_zona / Sa_riferimento

Effetti di sito indotti dai terremoti a scala locale e metodi per la determinazione degli effetti amplificativi 69

Starting from a geologic map:

Identify all the zones with the same deposits

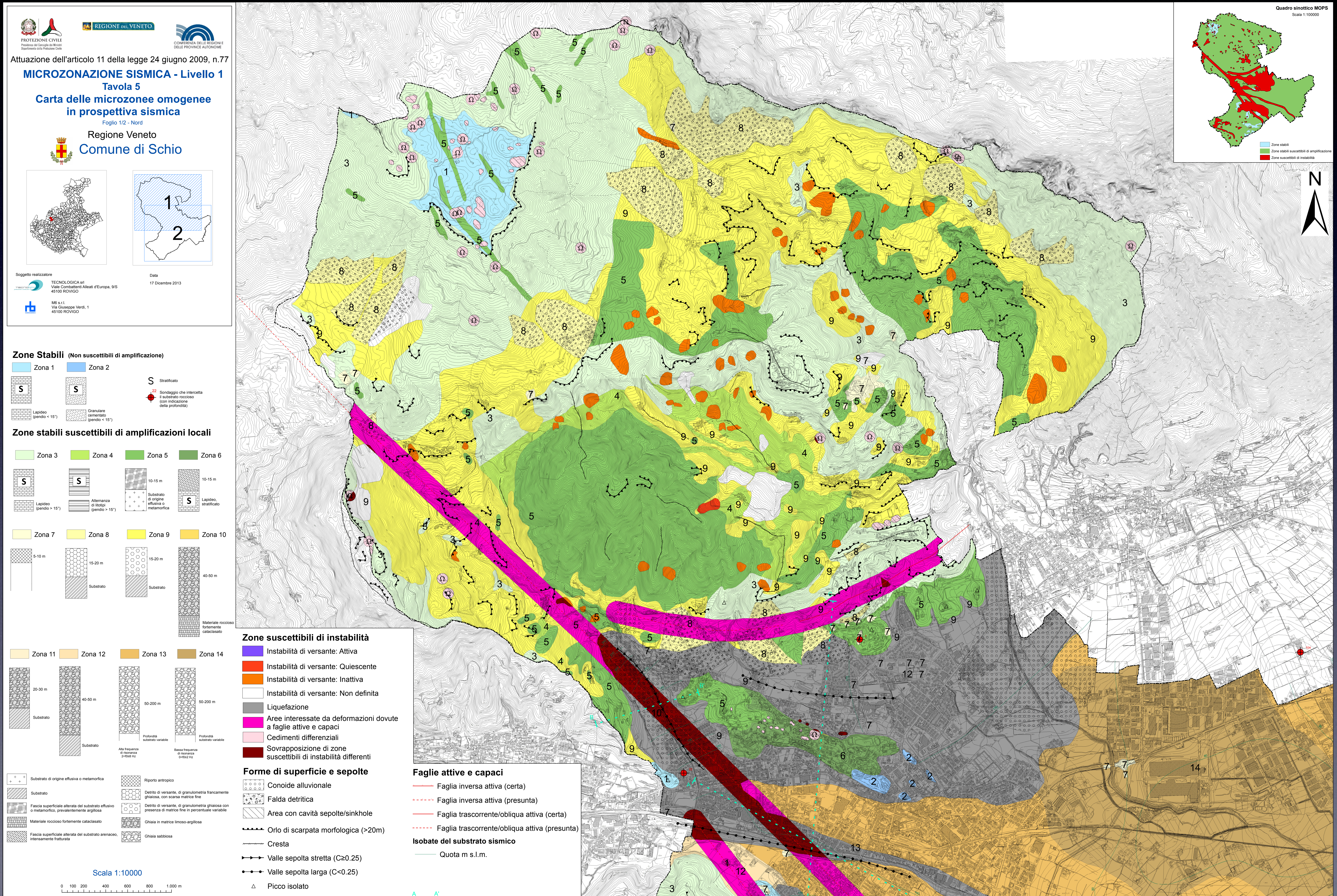
Starting from a geomorphological map:

Identify all the zones with instabilities such:

Active and quiescent landslides,

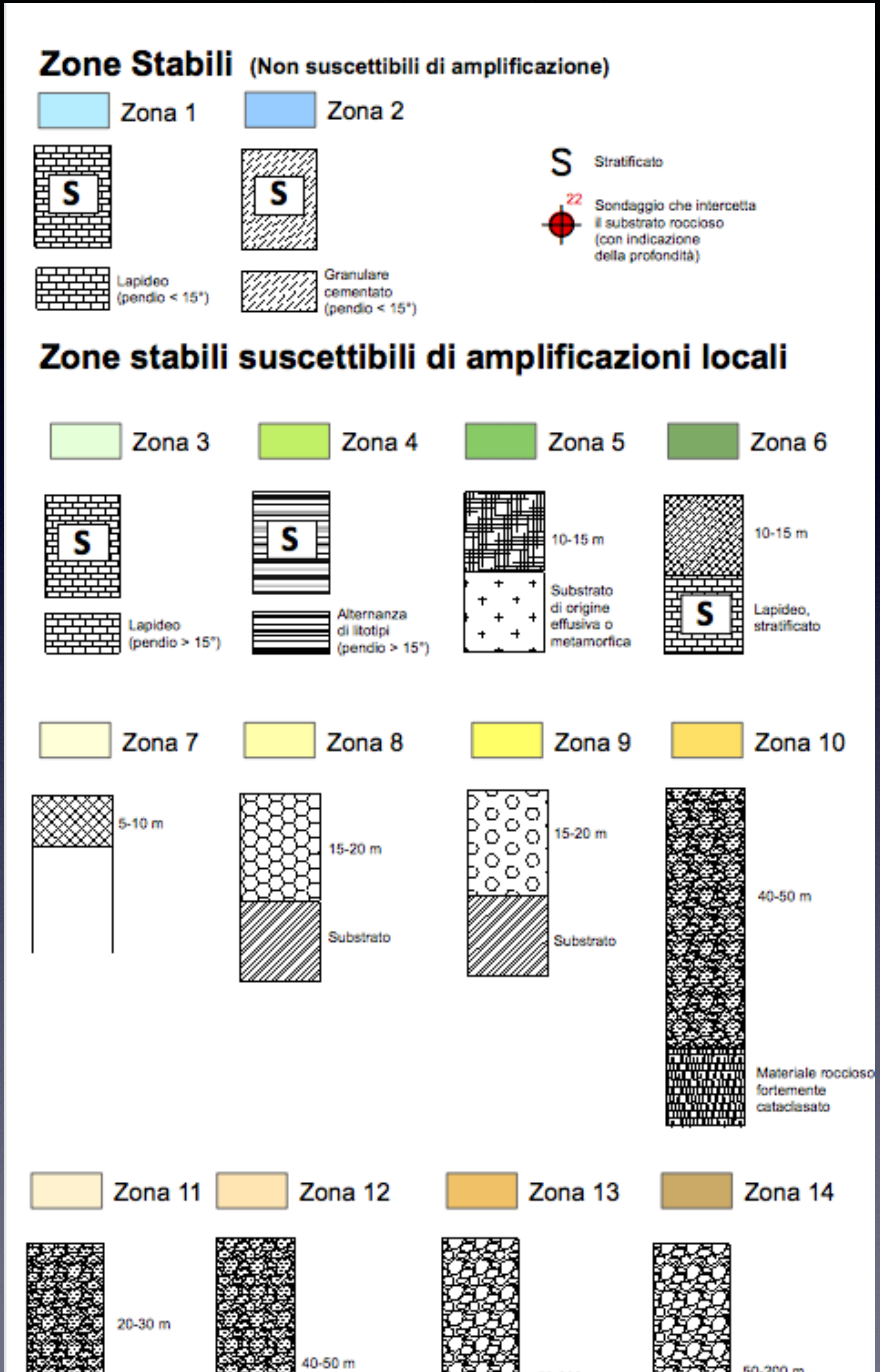
karst voids, etc.

The Seismic MICROZONATION



The MICROZONATION

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



Zone Stabili (Non suscettibili di amplificazione)

Zona 1
Zona 2

S Stratificato

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

Lapideo (pendio < 15°)
Granulare cementato (pendio < 15°)

Zone stabili suscettibili di amplificazioni locali

Zona 3
Zona 4
Zona 5
Zona 6

Lapideo (pendio > 15°)
Alternanza di litotipi (pendio > 15°)
Substrato di origine effusiva o metamorfica
Lapideo, stratificato

Zona 7
Zona 8
Zona 9
Zona 10

Substrato
Substrato
Materiale roccioso fortemente cataclasato

Zona 11
Zona 12
Zona 13
Zona 14

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

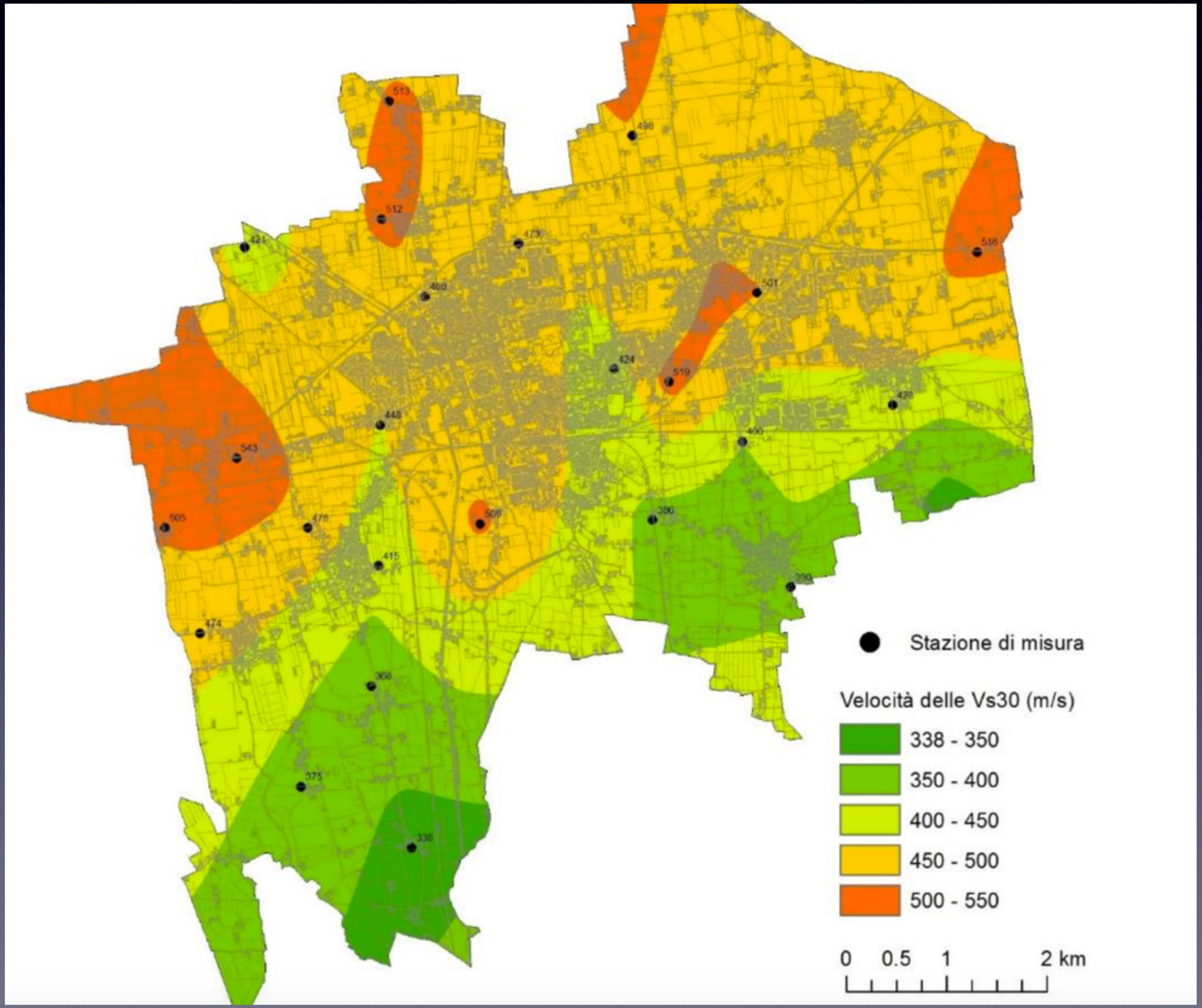
Forme di superficie e sepolte

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

The Seismic MICROZONATION

Level 2 = Planning.
Define homogeneous zones
Basing on experimental simplified procedures.

E.g. Vs simplified measurements, etc

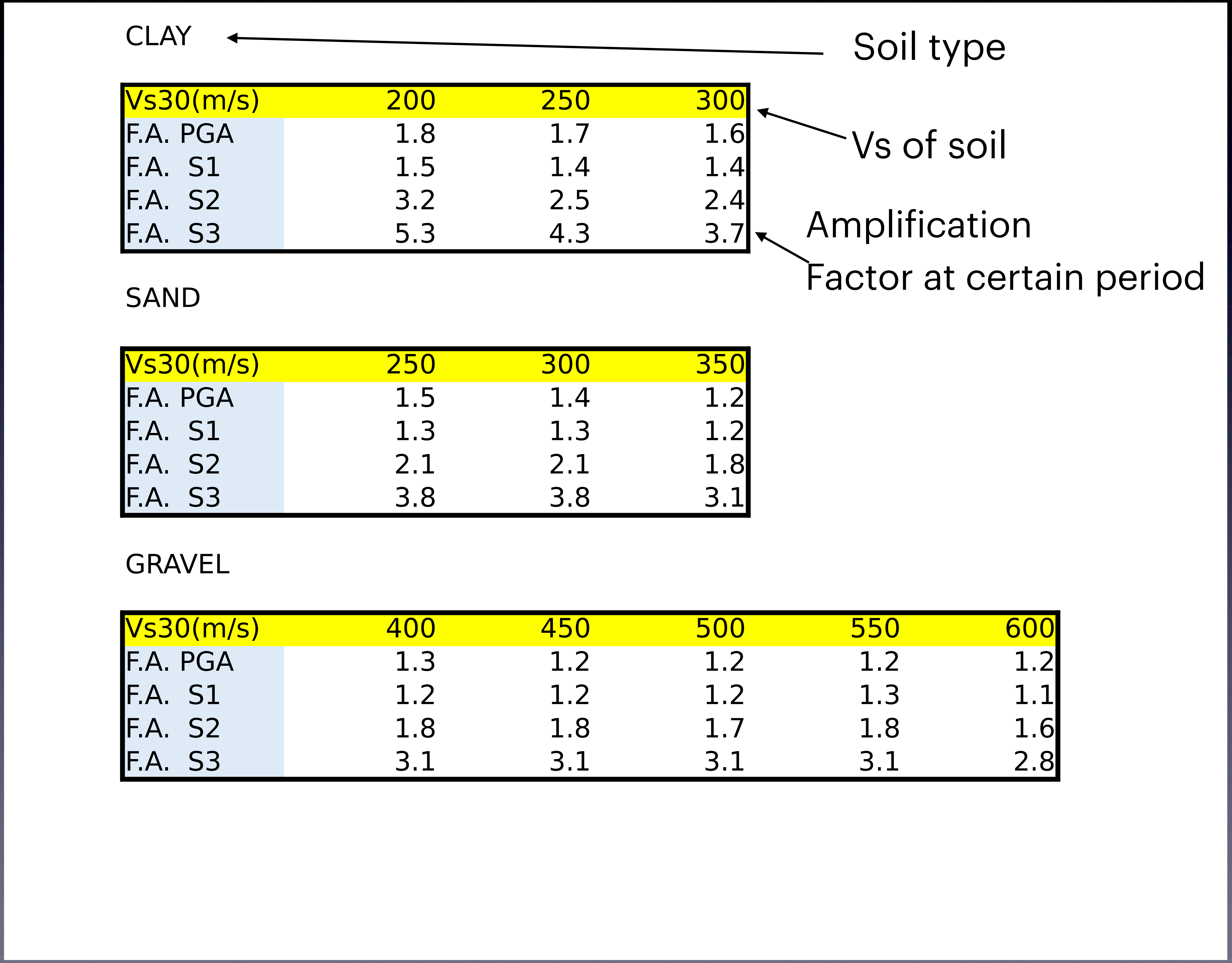


The Seismic MICROZONATION

ABACHI PIANURA

LEVEL 2

Using
AMPLIFICATION ABAQUS



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
The Seismic MICROZONATION

LEVEL 2

Using AMPLIFICATION ABAQUS

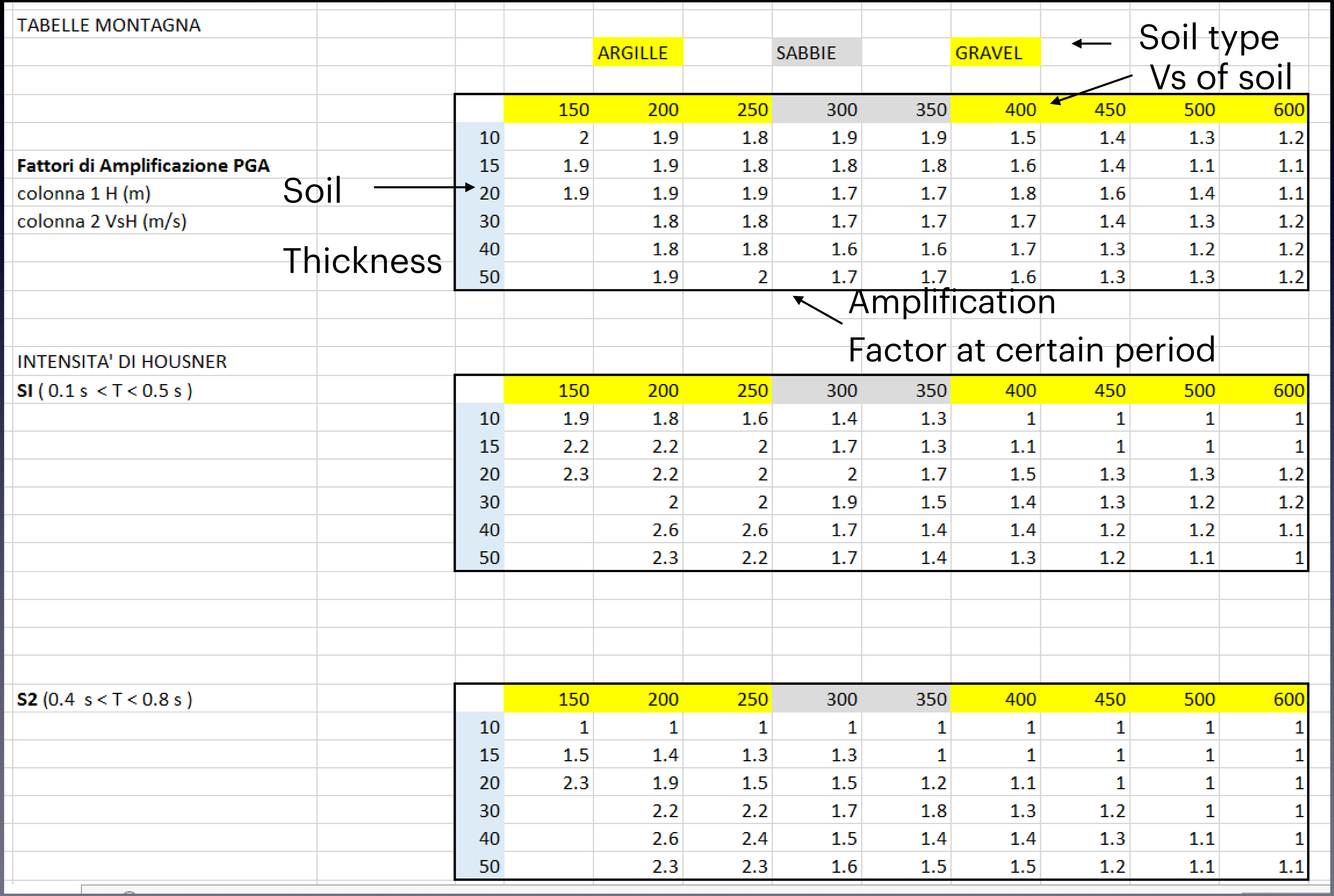


TABELLE MONTAGNA

Soil type

Vs of soil

		ARGILLE		SABBIE		GRAVEL			
	150	200	250	300	350	400	450	500	600
10	2	1.9	1.8	1.9	1.9	1.5	1.4	1.3	1.2
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

Fattori di Amplificazione PGA
colonna 1 H (m)
colonna 2 VsH (m/s)

Soil

Thickness

Amplification

Factor at certain period

INTENSITA' DI HOUSNER

SI (0.1 s < T < 0.5 s)

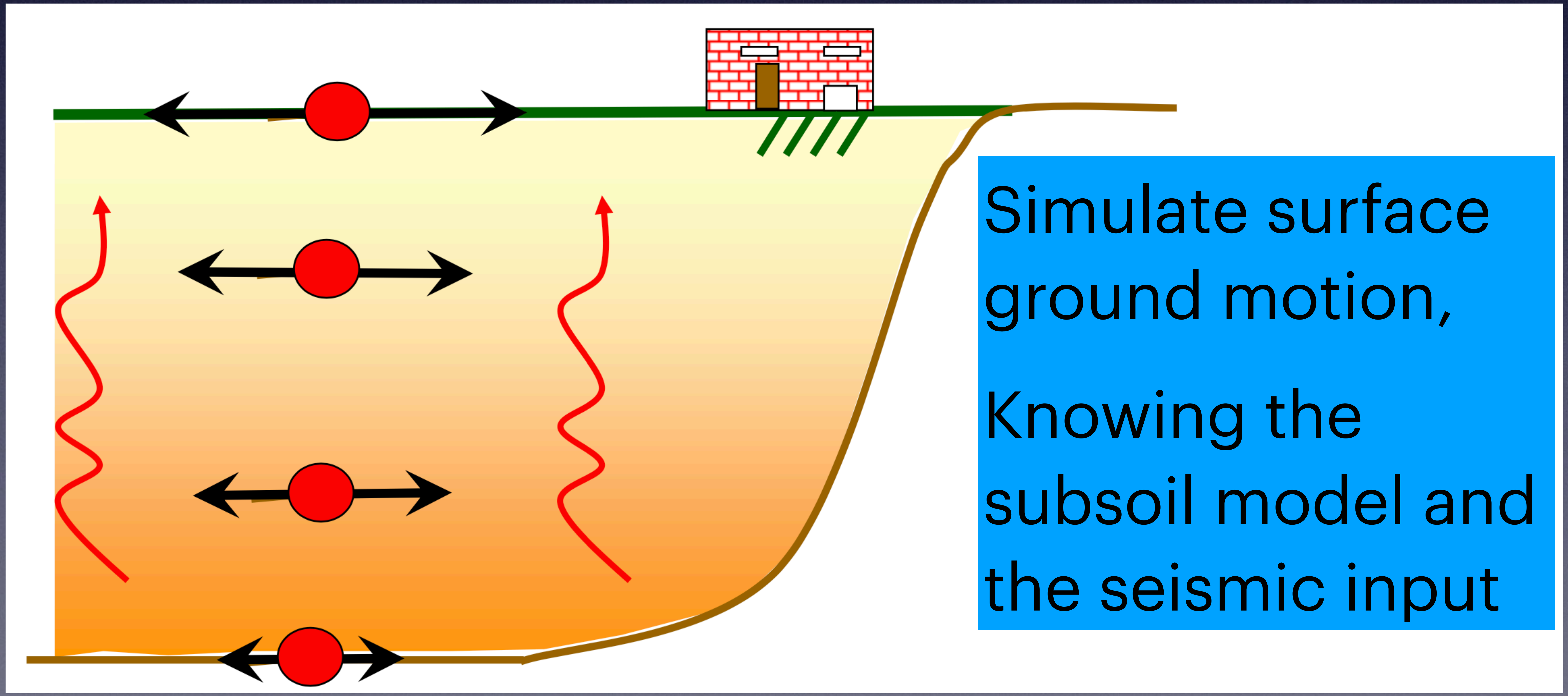
	150	200	250	300	350	400	450	500	600
10	1.9	1.8	1.6	1.4	1.3	1	1	1	1
15	2.2	2.2	2	1.7	1.3	1.1	1	1	1
20	2.3	2.2	2	2	1.7	1.5	1.3	1.3	1.2
30		2	2	1.9	1.5	1.4	1.3	1.2	1.2
40		2.6	2.6	1.7	1.4	1.4	1.2	1.2	1.1
50		2.3	2.2	1.7	1.4	1.3	1.2	1.1	1

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

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

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



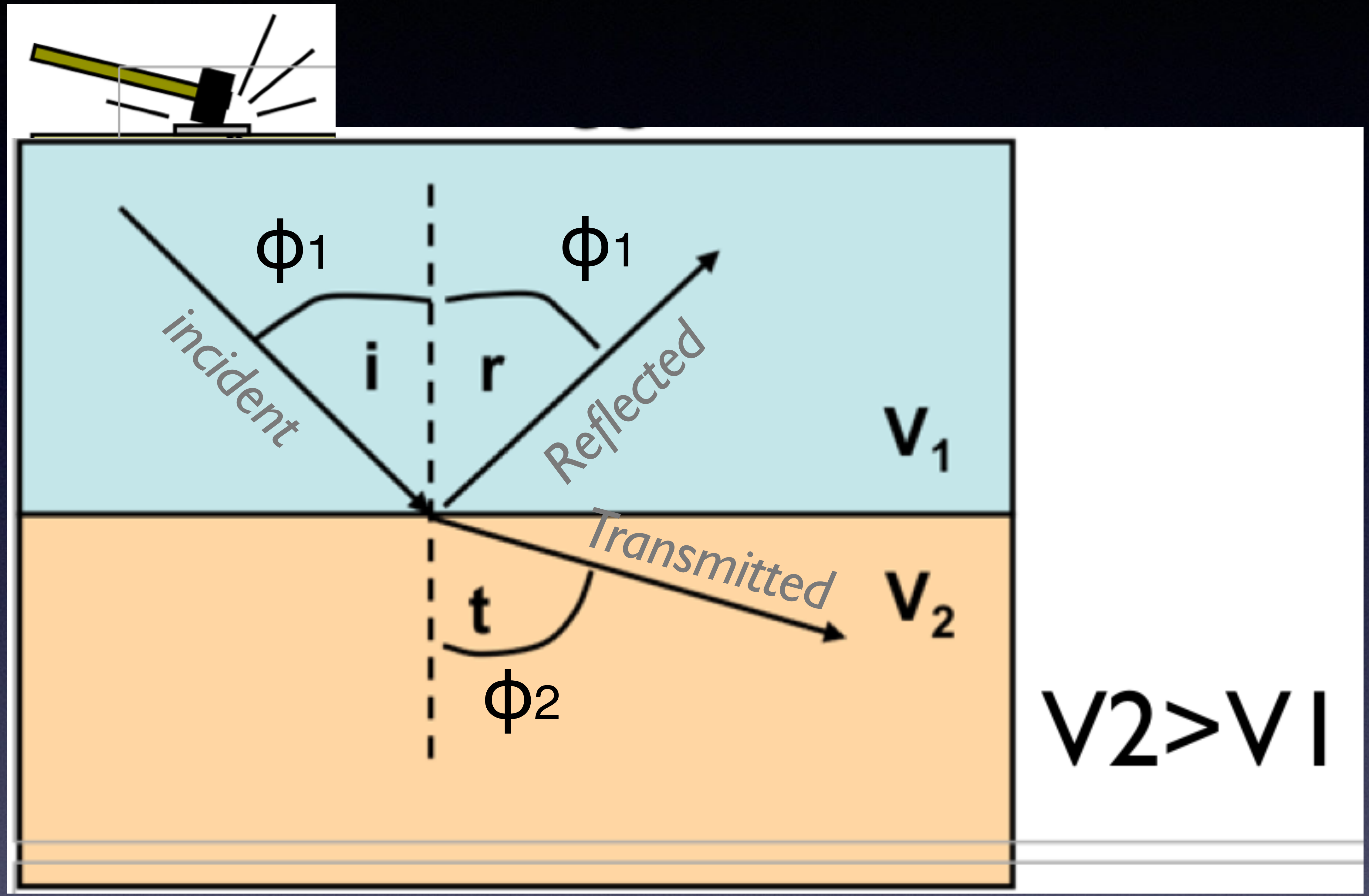
Simulate surface ground motion,

Knowing the subsoil model and the seismic input

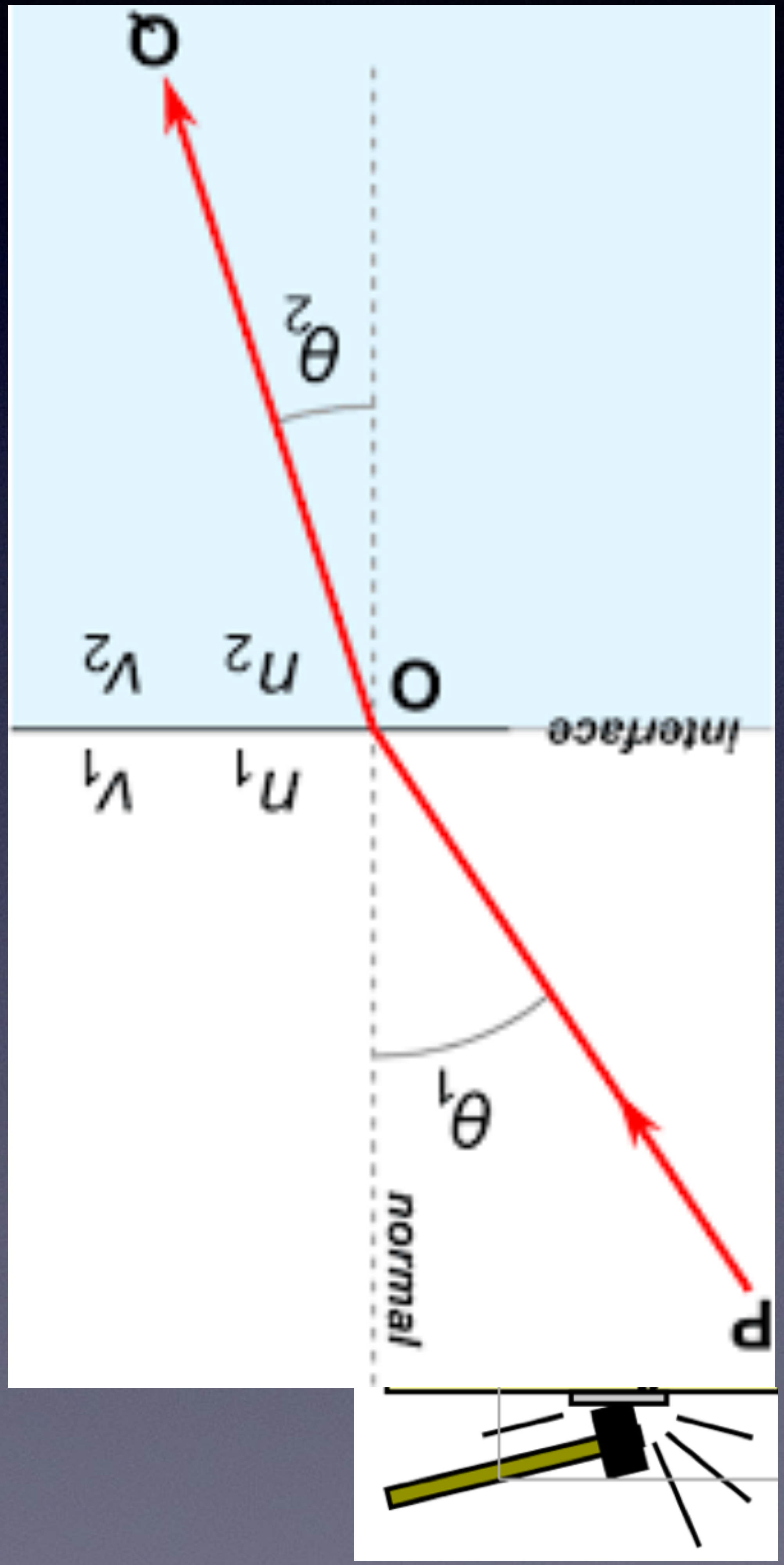
e.g.
the deterministic
Approach

Seismic Response Analysis

Snell Law



$\phi_2 < \phi_1$



EARTHQUAKE

Impedance Contrast $= \dfrac{\rho_2 V_2}{\rho_1 V_1} > 1 \rightarrow t\ \phi_2 > i°\ \phi_i$

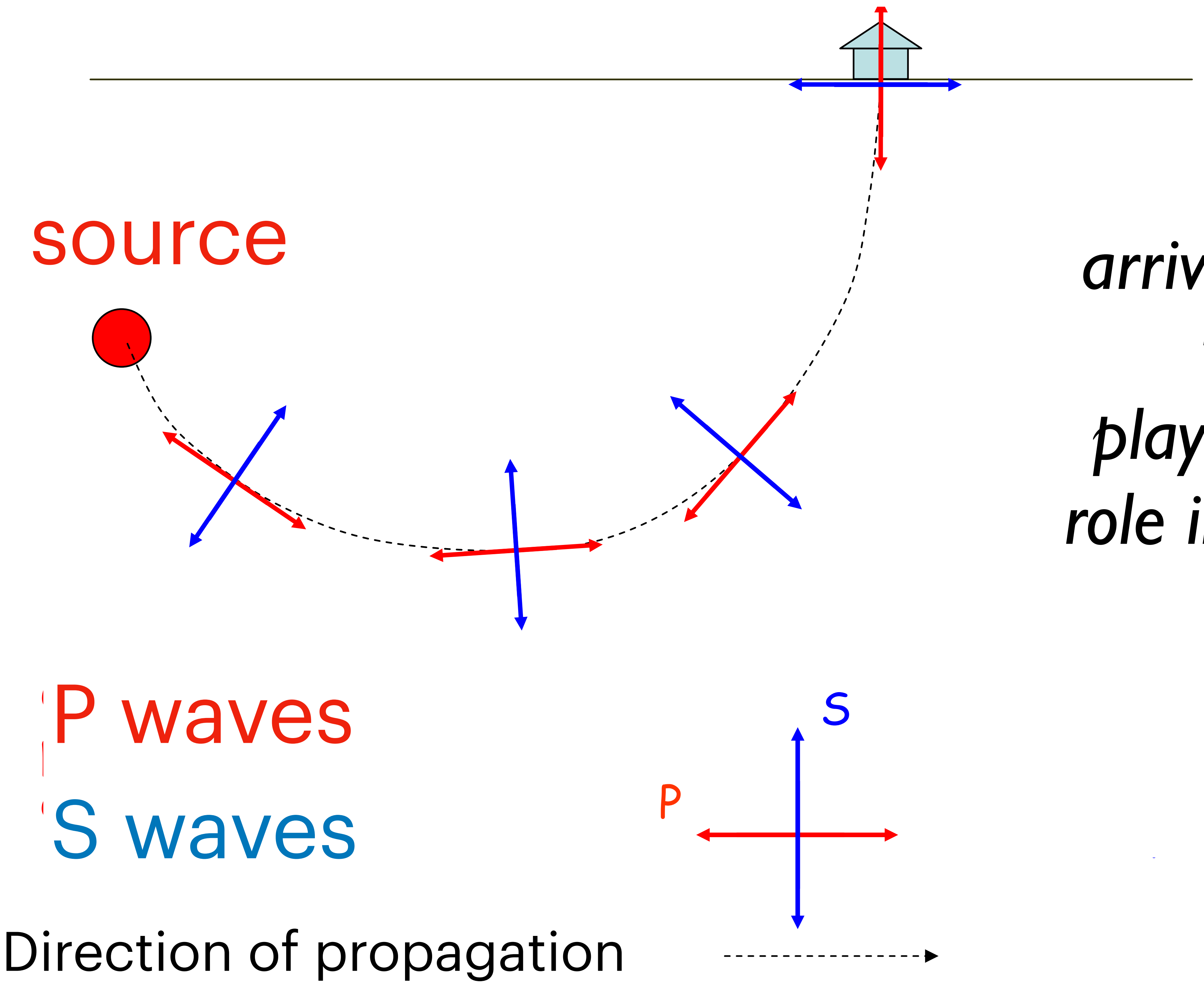
density *Velocity*

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)



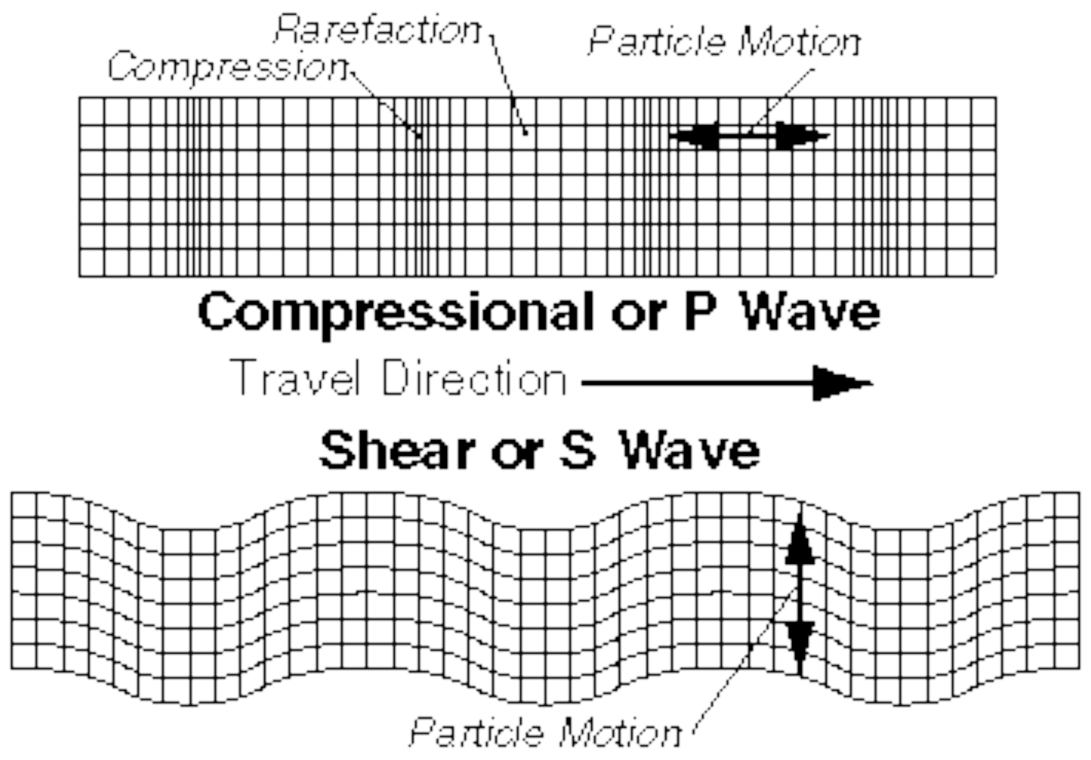
source

P waves

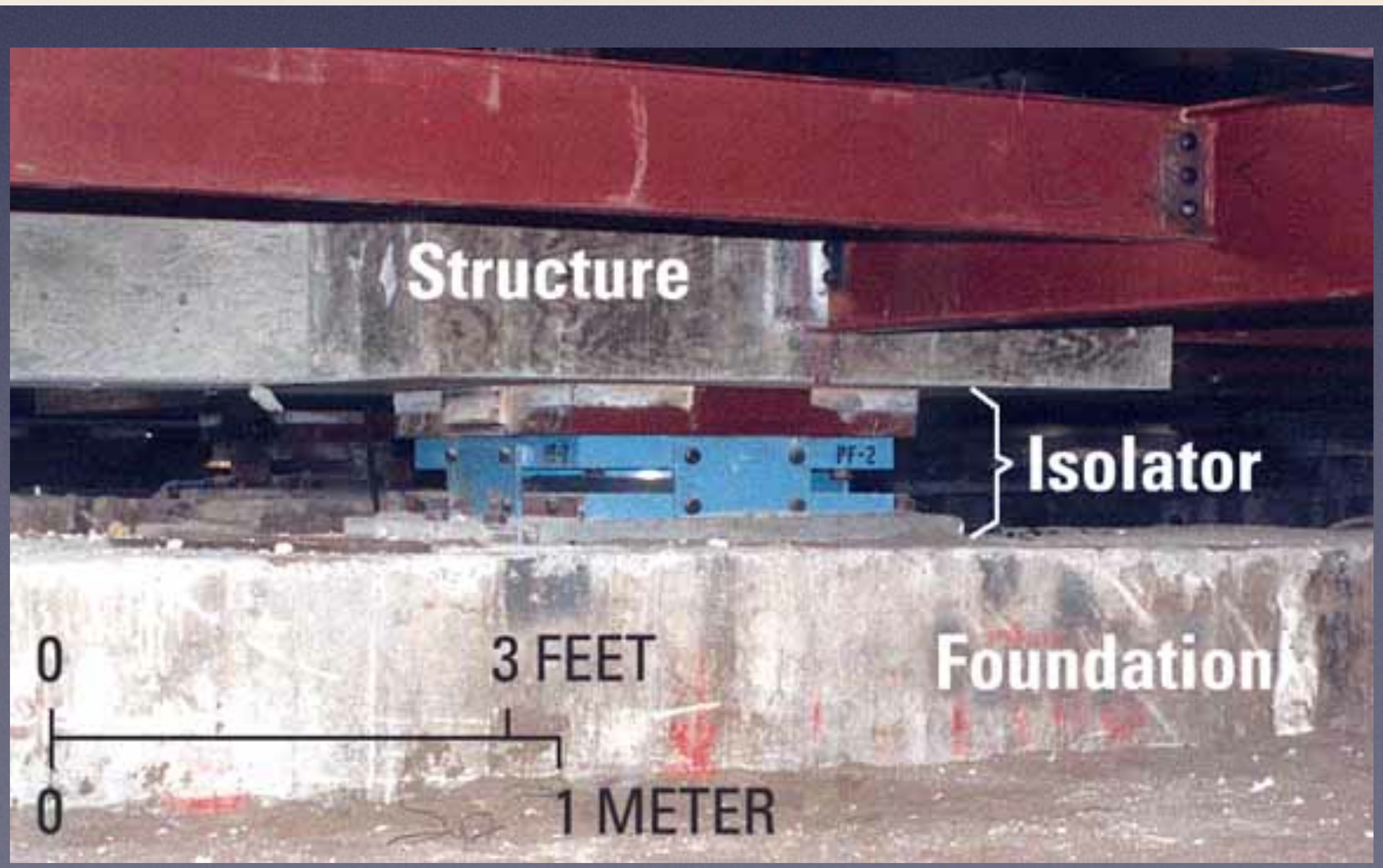
S waves

Direction of propagation

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



Seismic Response Analysis



Seismic Response Analysis

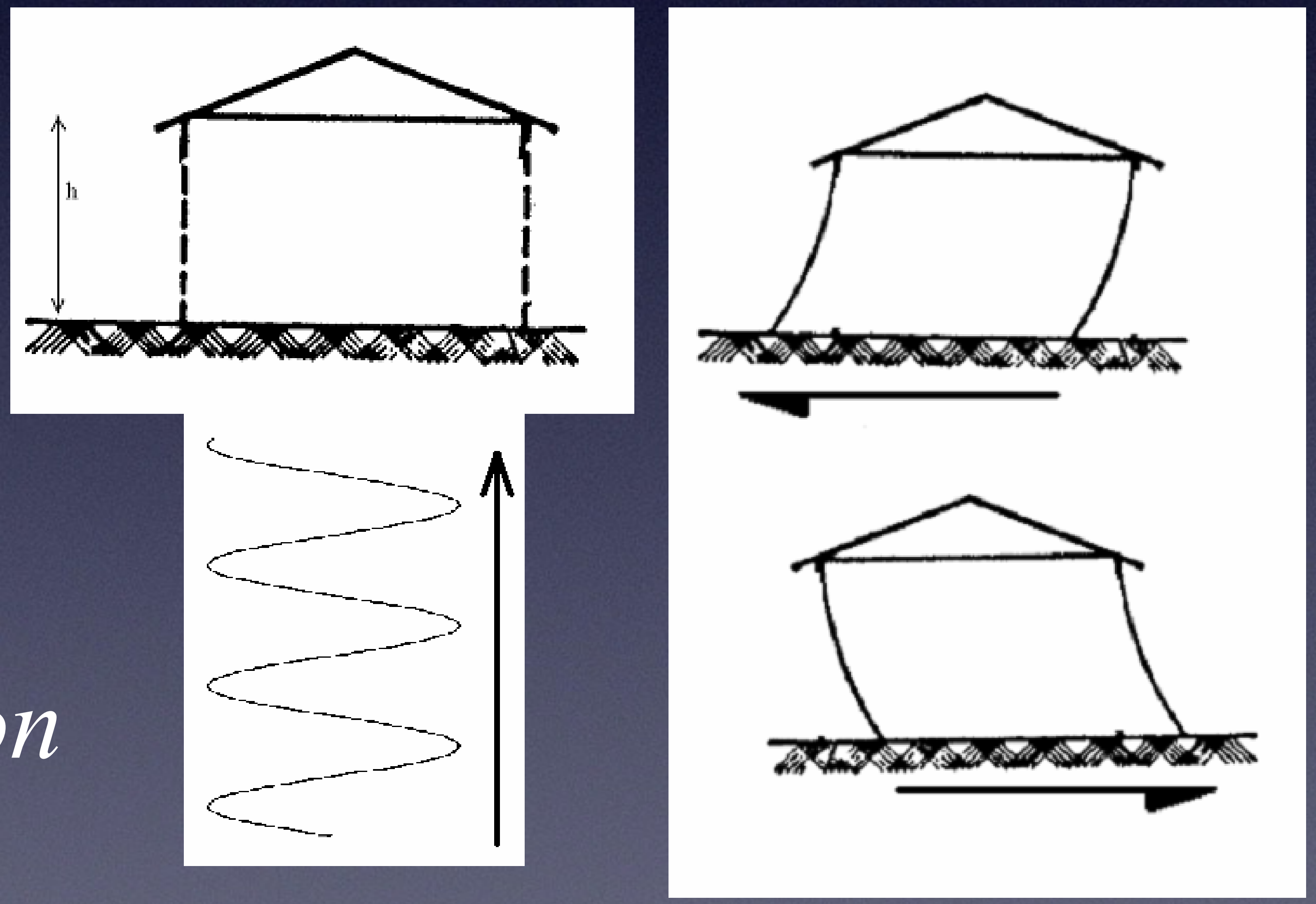
The damages is due to the relative motion between the Building parts (e.g. roof/floor)

The motion depend on the period of the structure

n= floor number

$$T \approx n/10 \ (\text{seconds})$$

T = proper period of the construction

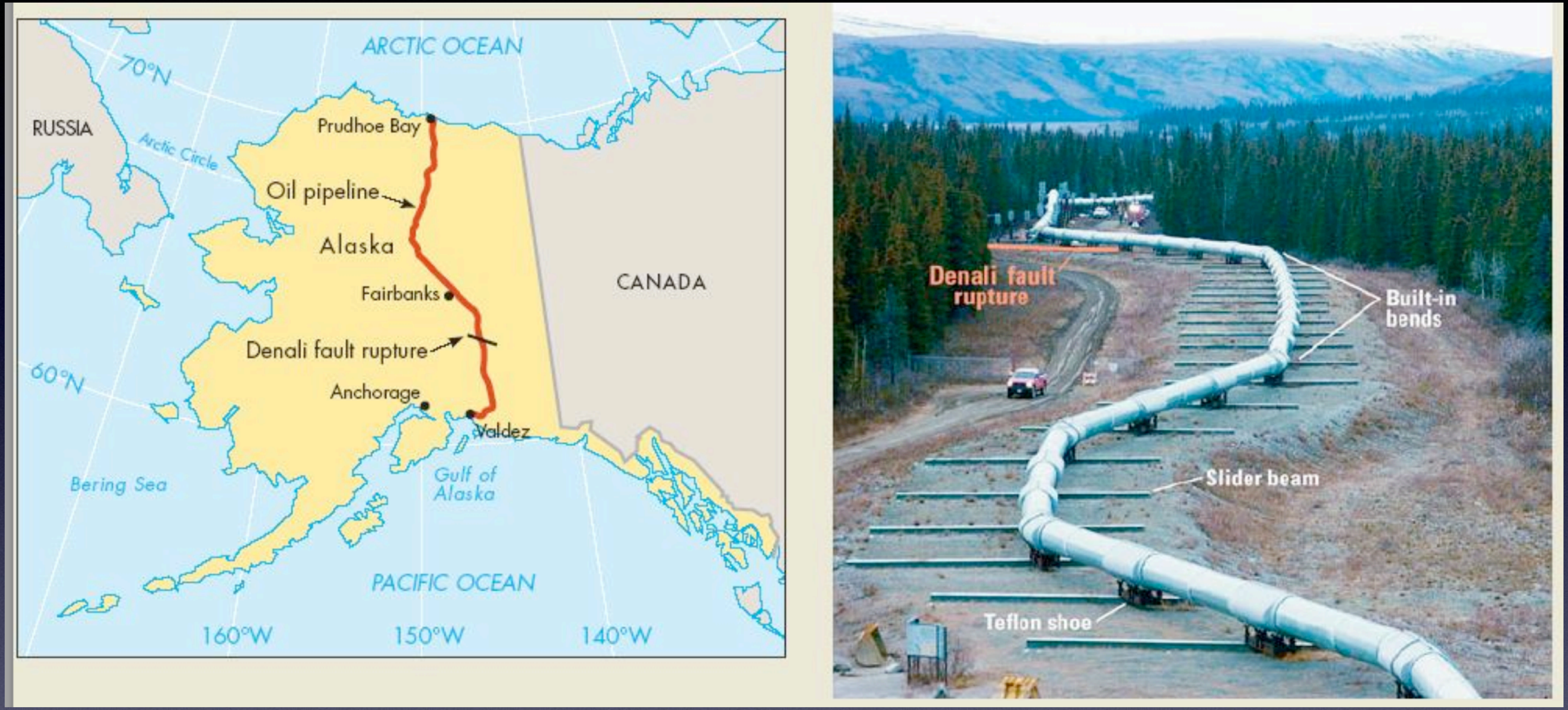


Dip. di Scienze della Terra– Università di Siena

S waves

S waves

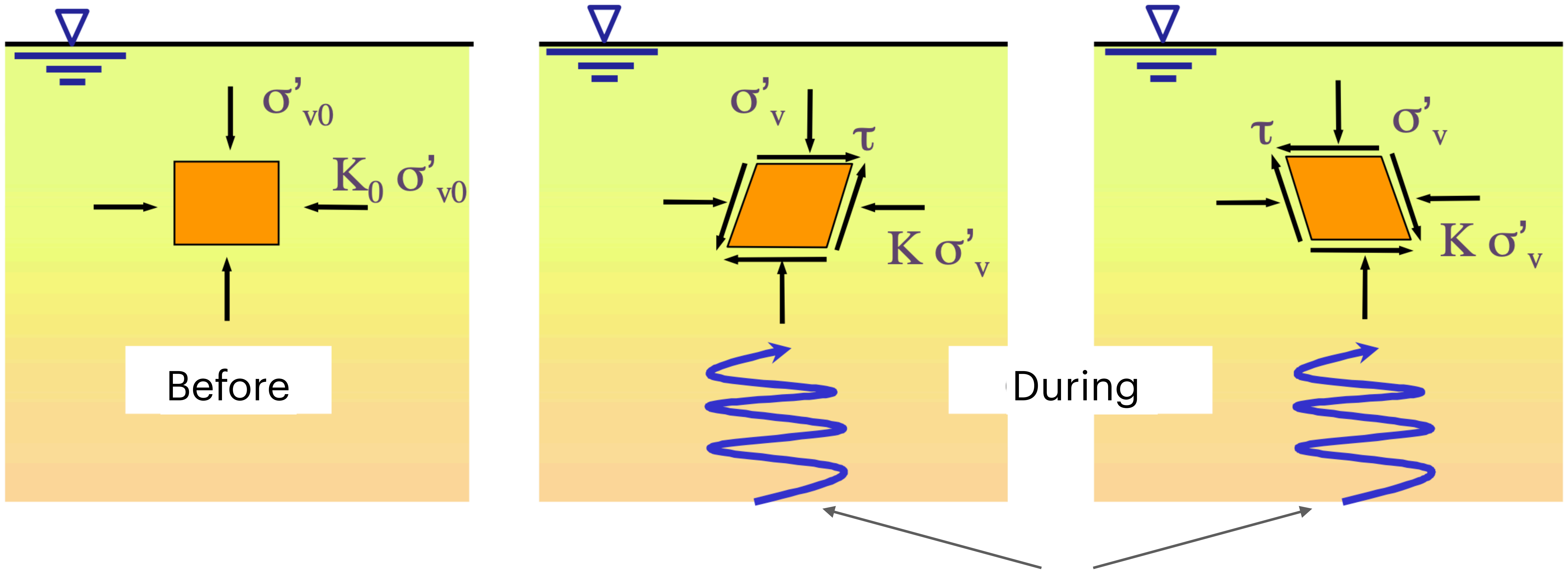
Alaska oil-pipes mounted on teflon slider system



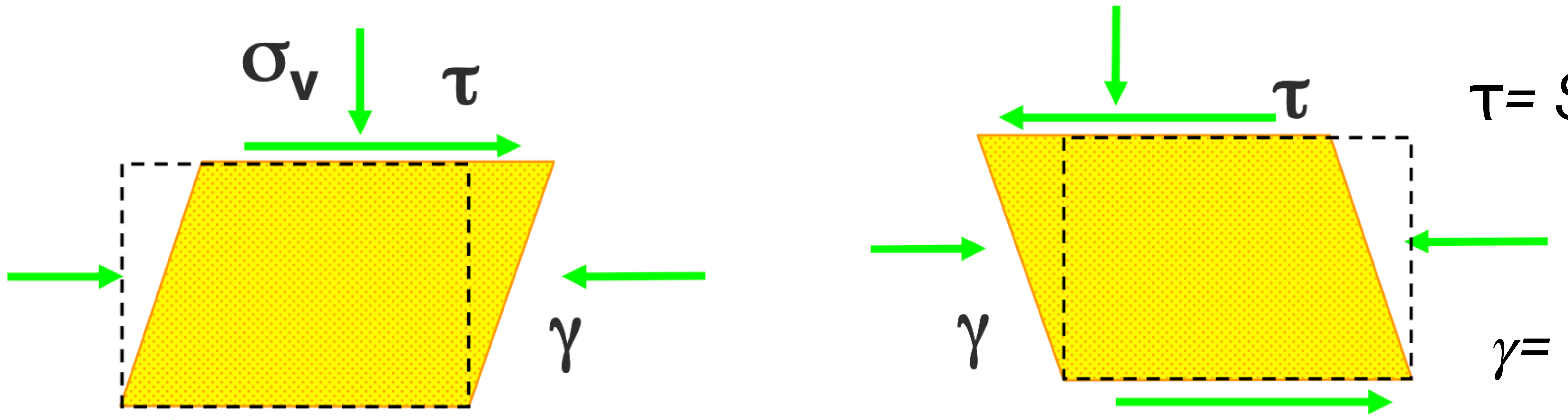
Seismic Response Analysis

Terrain element under earthquake stress conditions

σ= *pressure*



S waves coming from the inner crust



τ= *Shear stress*

γ= Shear strain

(Undrained Conditions)

Define Soil Deformability

The (earthquakes) seismic waves

Body waves

(in geotechnics)

Compression modulus
(Ed in odometry)

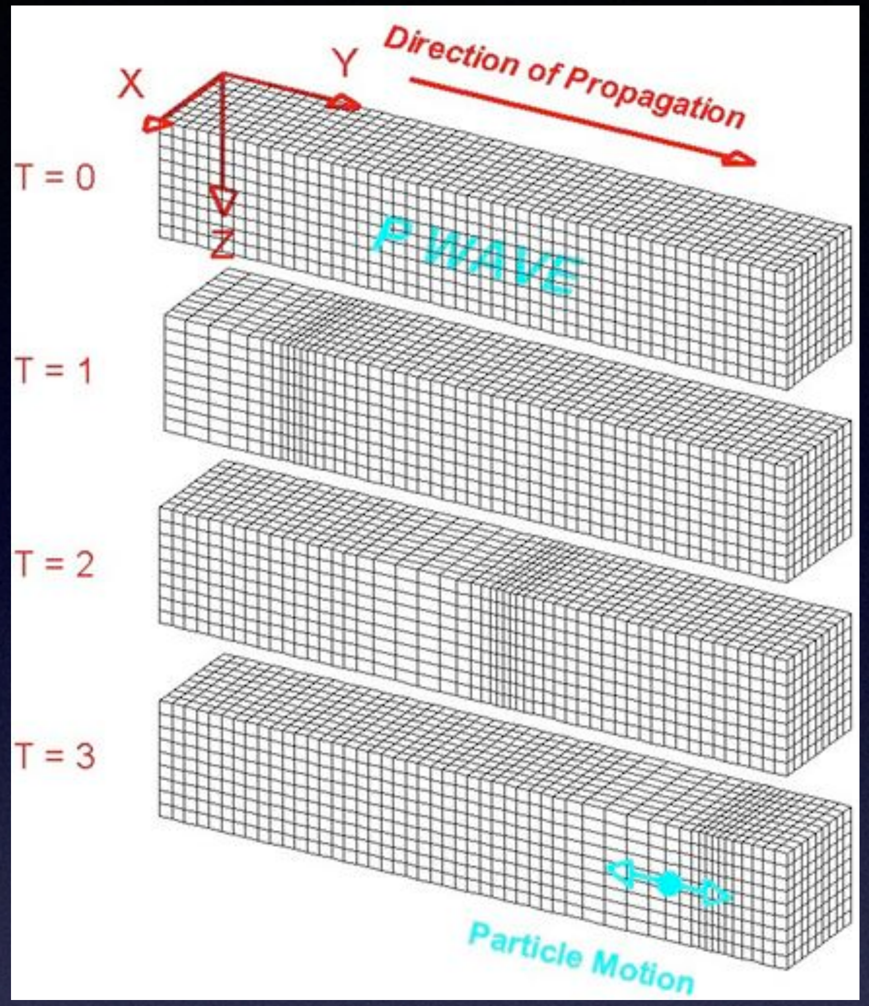
$$V_p = \sqrt{K + 4/3\mu/\rho}$$

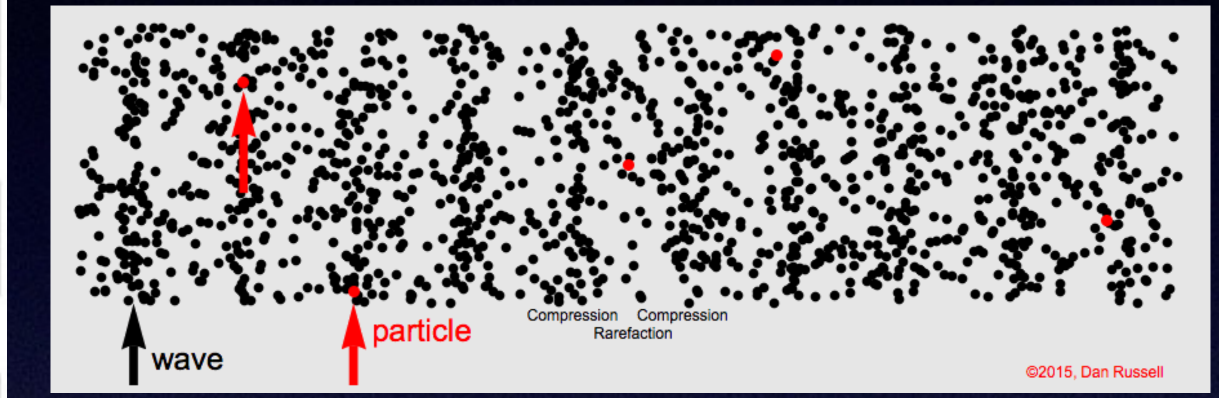
Density

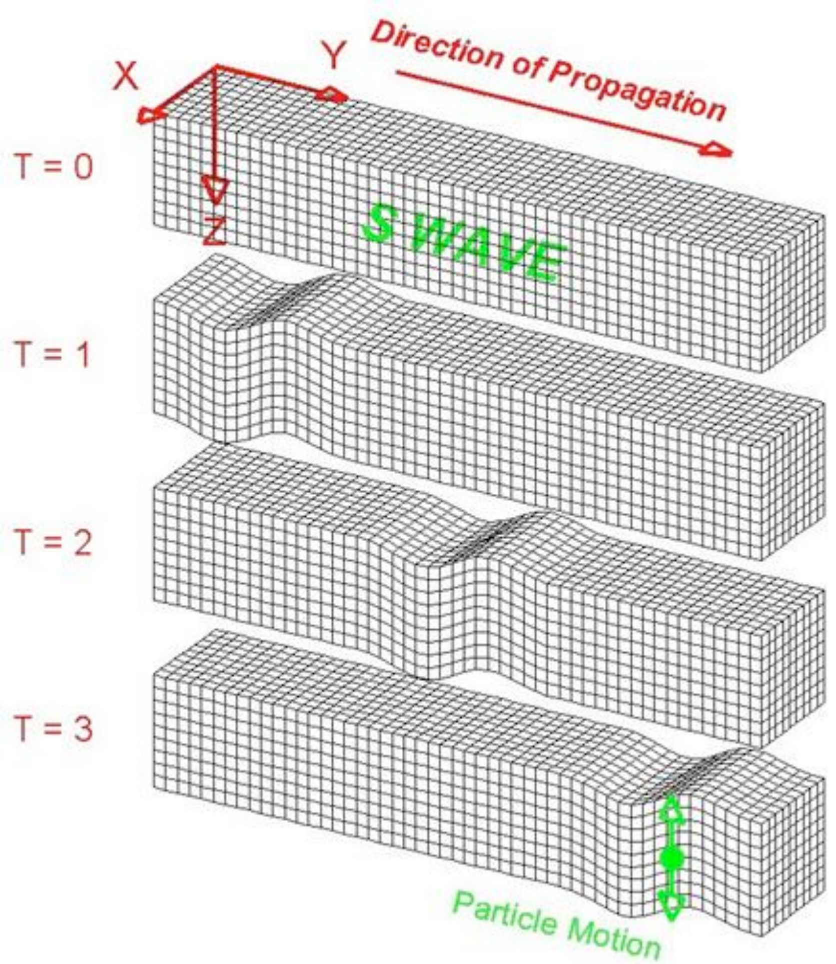
$$V_s = \sqrt{G/\rho}$$

Shear modulus

?







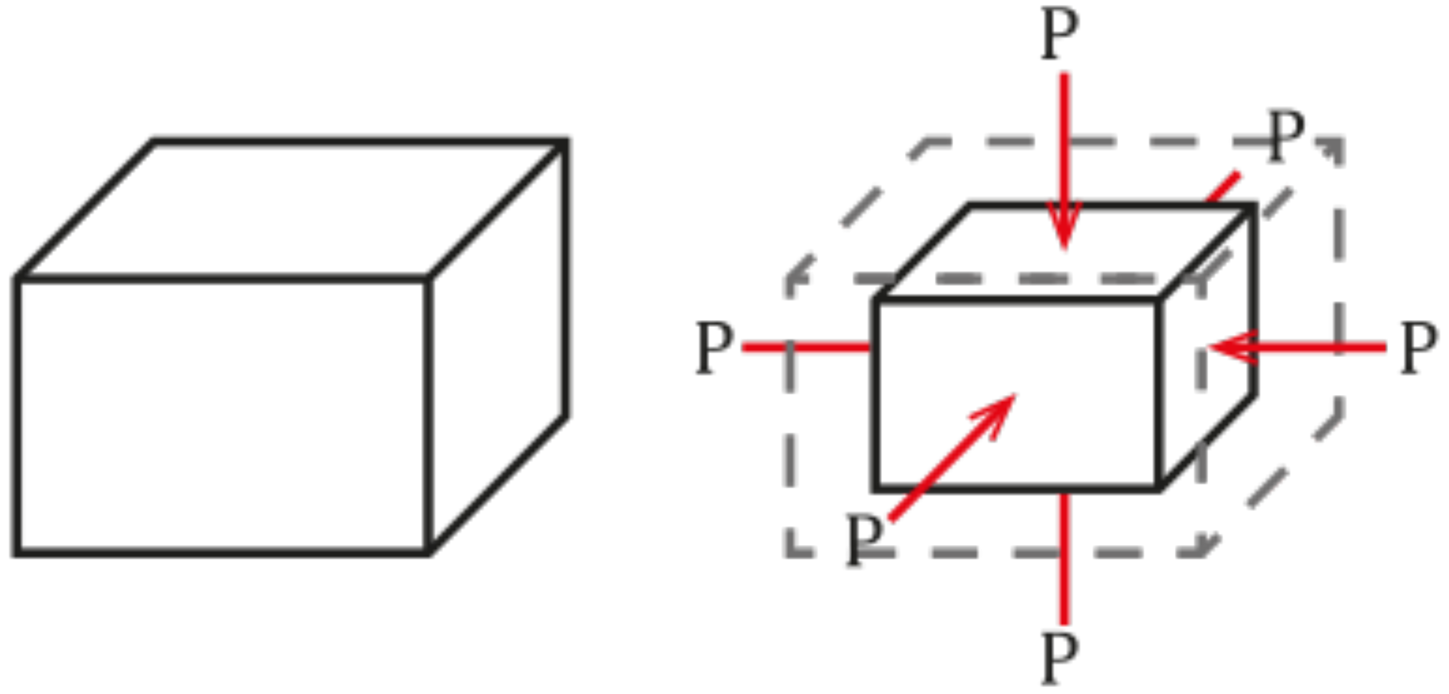
elastic moduli

Body waves

(in geotechnics)

K = compression modulus

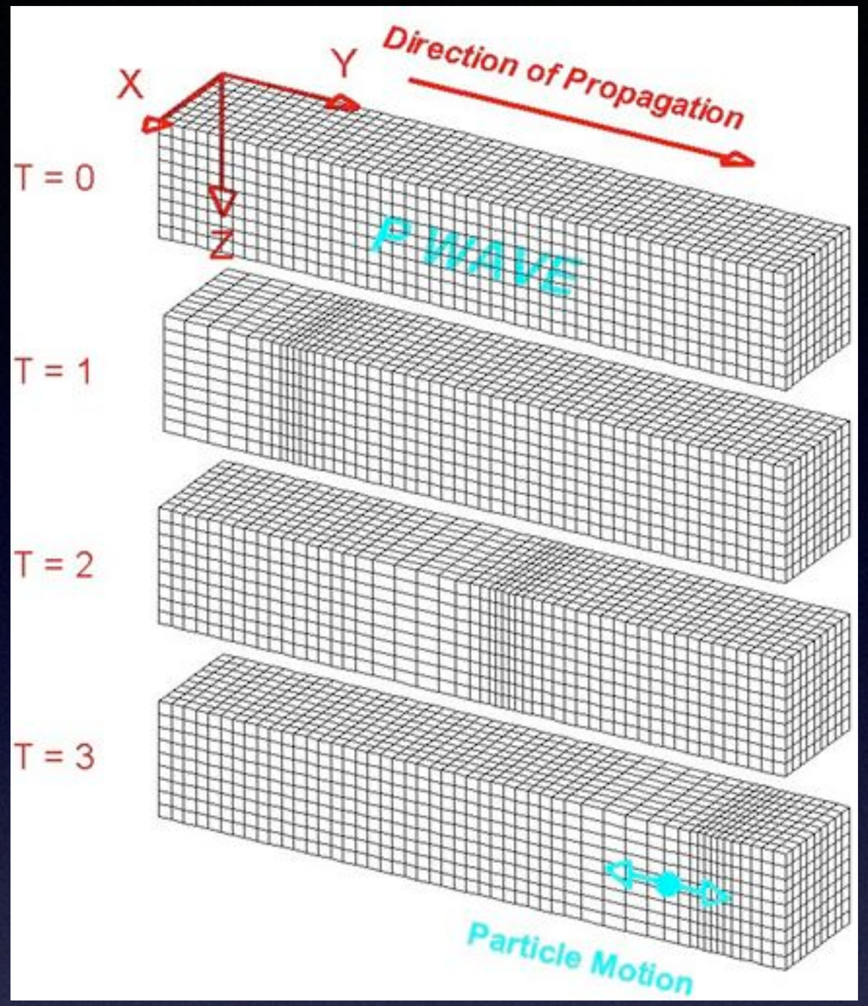
The pressure increment necessary to induce a density change

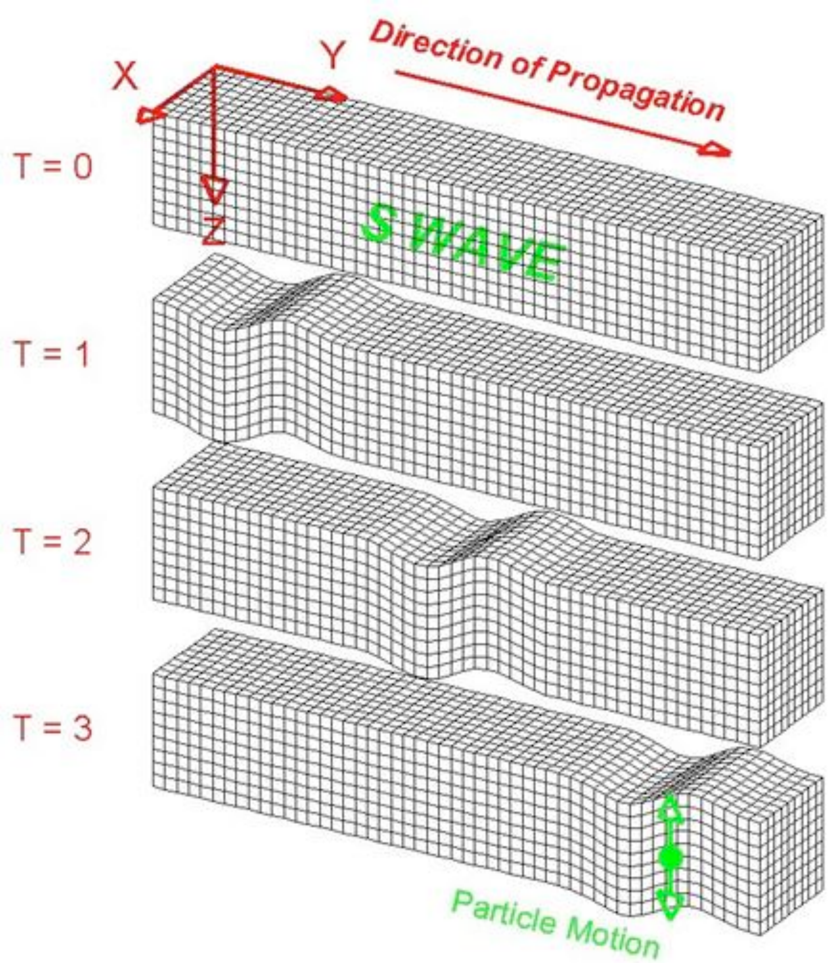


Lamè constant

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

Shear Modulus





elastic moduli

G shear Modulus

Density *S waves velocity*

$$G = \rho\ Vs^2$$

P wave velocity

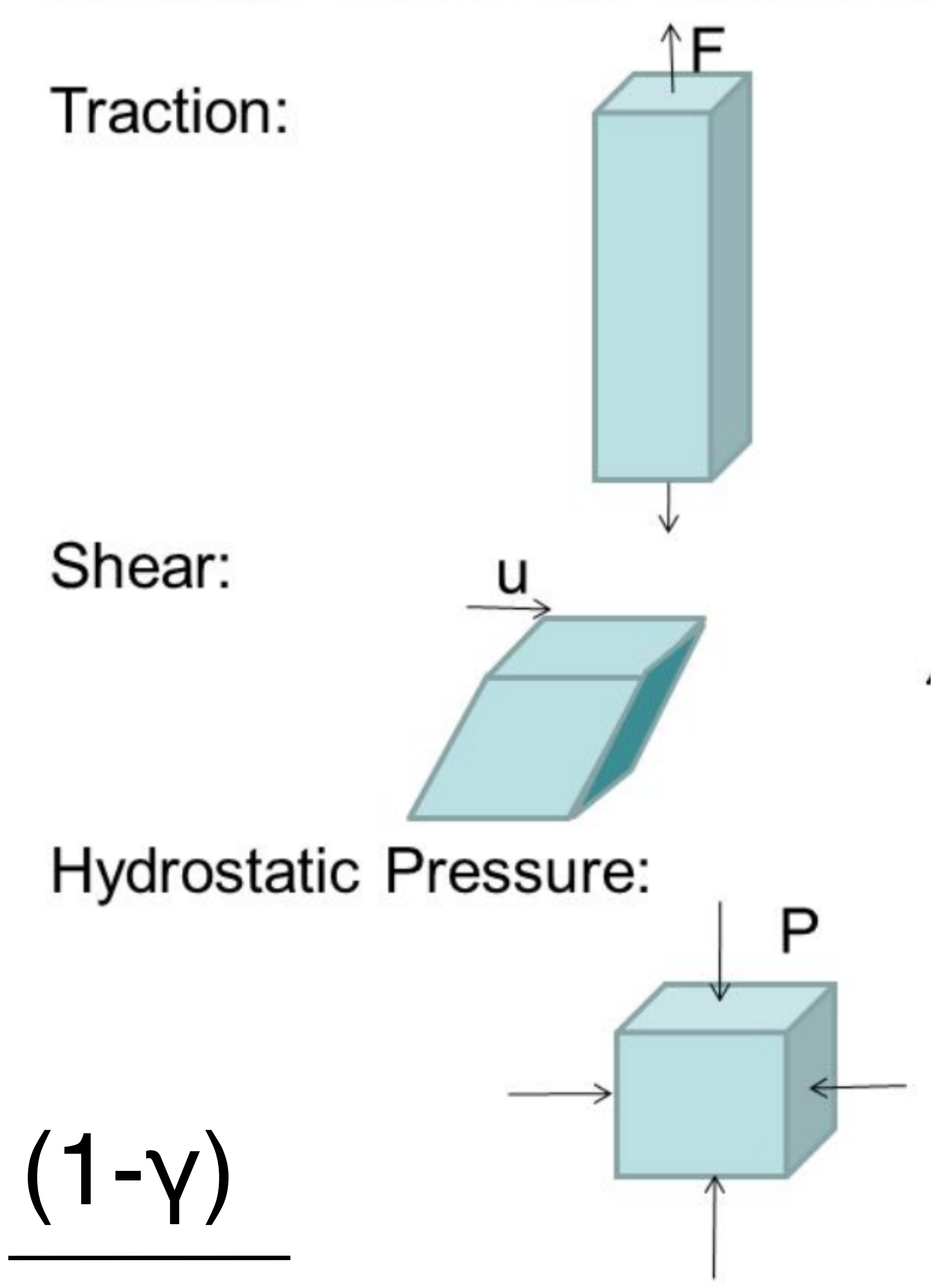
Poisson

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

Young modulus

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

$$\frac{Vp}{Vs} = \sqrt{\frac{(1\text{-}\gamma)}{(0.5\text{-}\gamma)}}$$

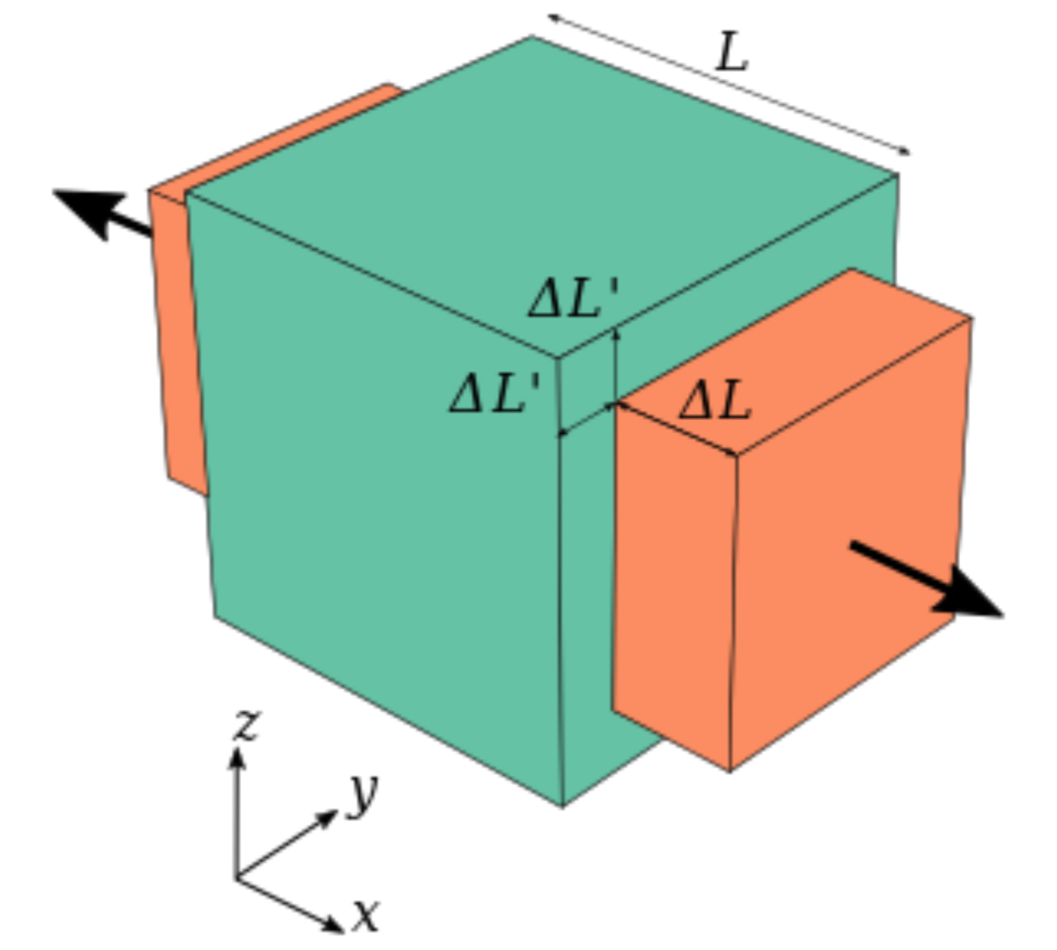


elastic moduli

Poisson ratio γ

Ratio between the transverse strain and longitudinal deformation

$$\frac{\textit{Transverse strain}}{\textit{Longitudinal strain}}$$

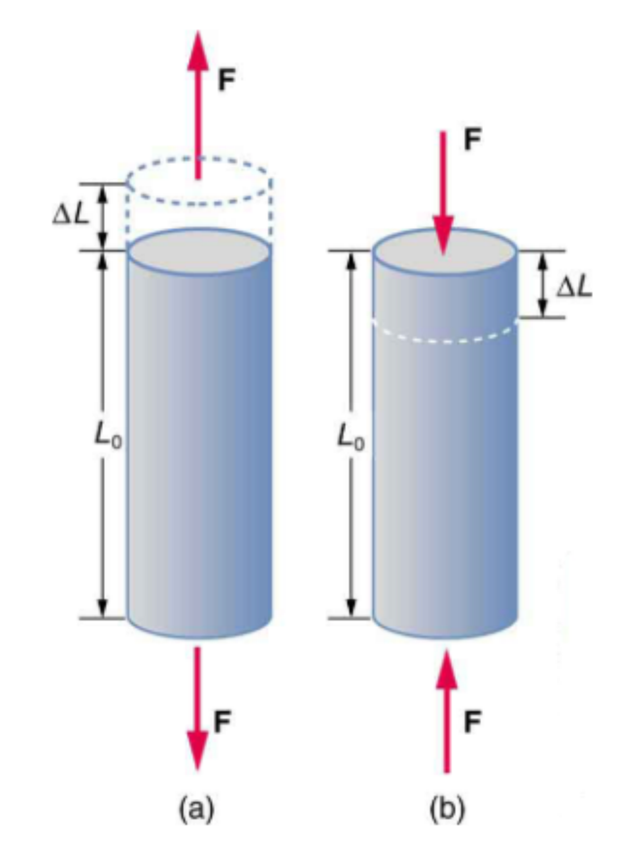


$\gamma < 0.5$! (0.5 rubber)

Young modulus E

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

$$\frac{\textit{Applied tension } \boldsymbol{\sigma}}{\textit{Deformation } \varepsilon}$$



Elastic waves propagating

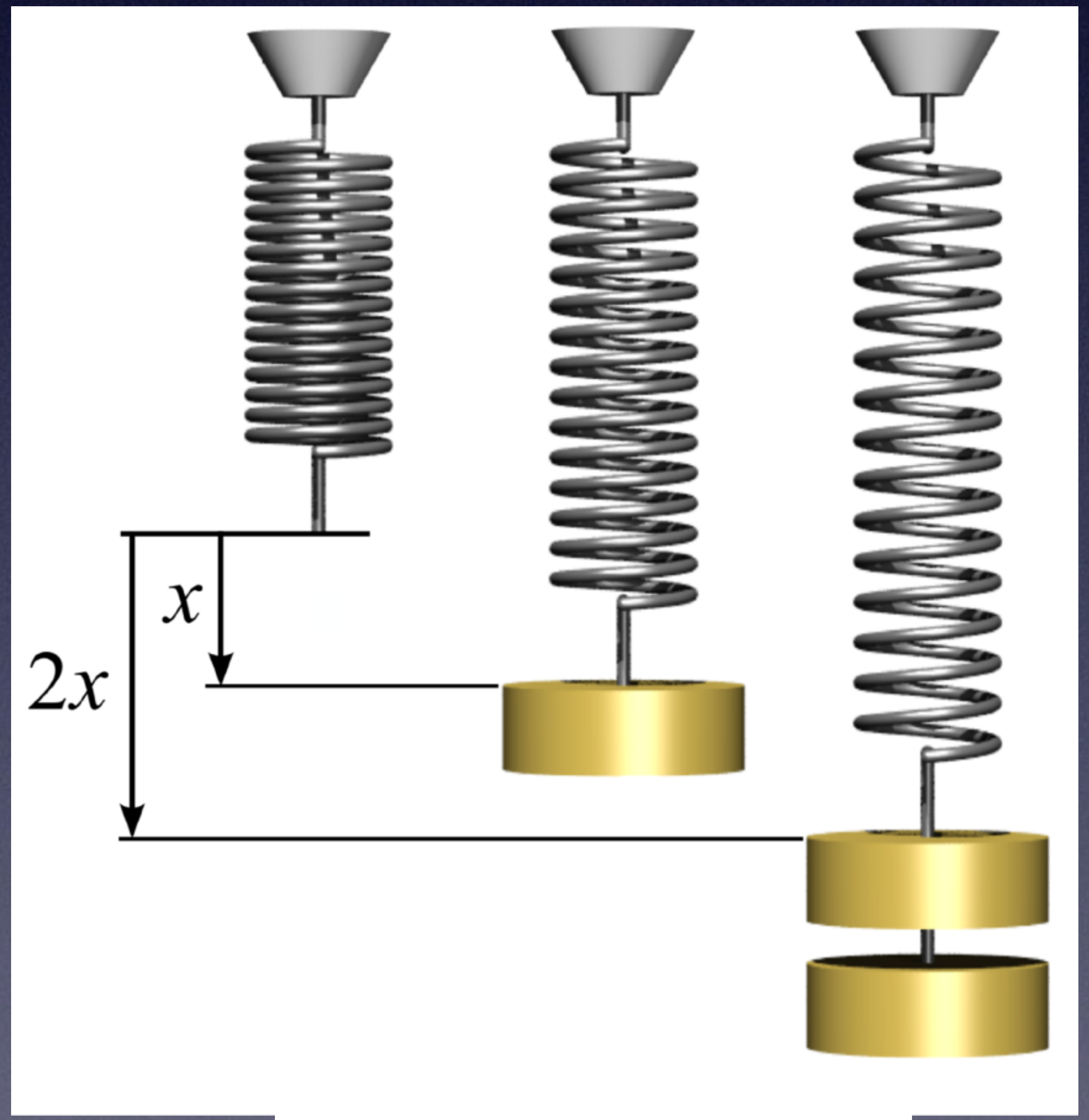
Dynamic principles - Hooke law

$$\sigma = E\varepsilon$$

Young modulus

Deformation ε

Tension



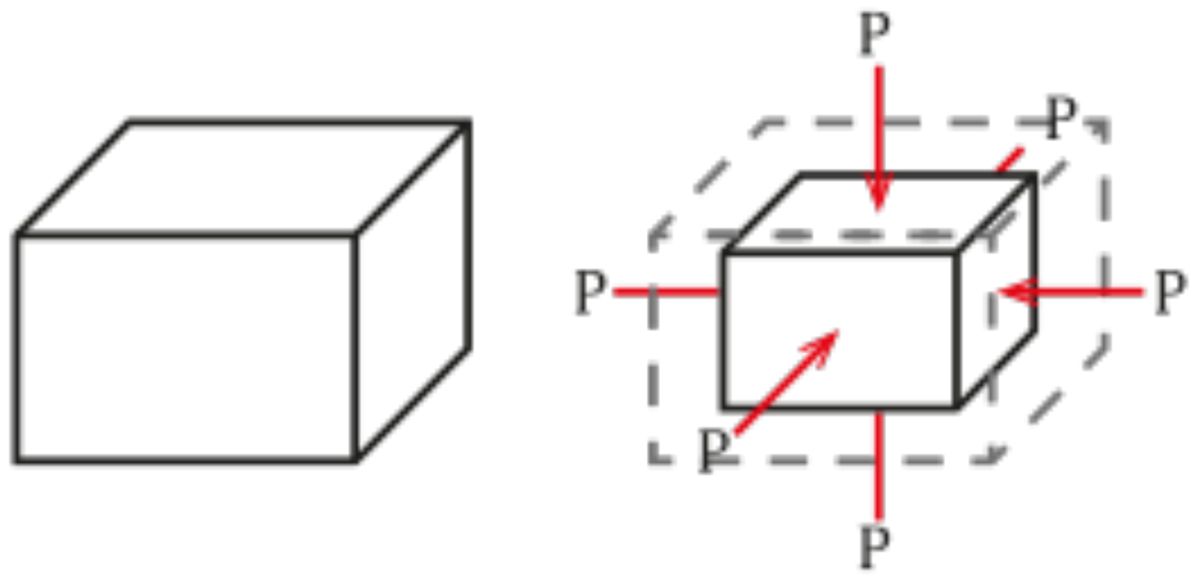
$$\sigma = K\,\varepsilon$$

k spring

wave motion - Wave Equation

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

Stress-strain



strain (ε) tensor

$\varepsilon_{xx} = du/dx$

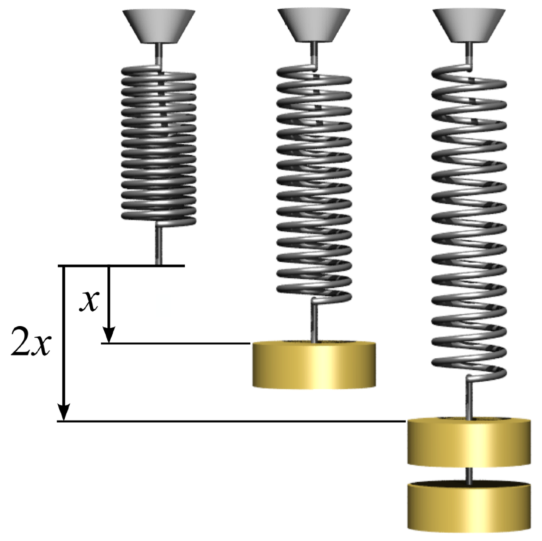
$\varepsilon_{yy} = dv/dy$

$\varepsilon_{zz} = dw/dz$

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

Dilatation → $\Delta = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$

Hooke law (isotropic media)



Normal stress $\sigma_{ii} = \lambda\,\Delta + 2\,\mu\varepsilon_{ii}$ *for i= x,y,z*

shear stress $\sigma_{ij} = \mu\varepsilon_{ij}$ *for i ≠ j*

elastic constant of lamè

λ μ

compress. *Shear*

wave motion - Wave Equation

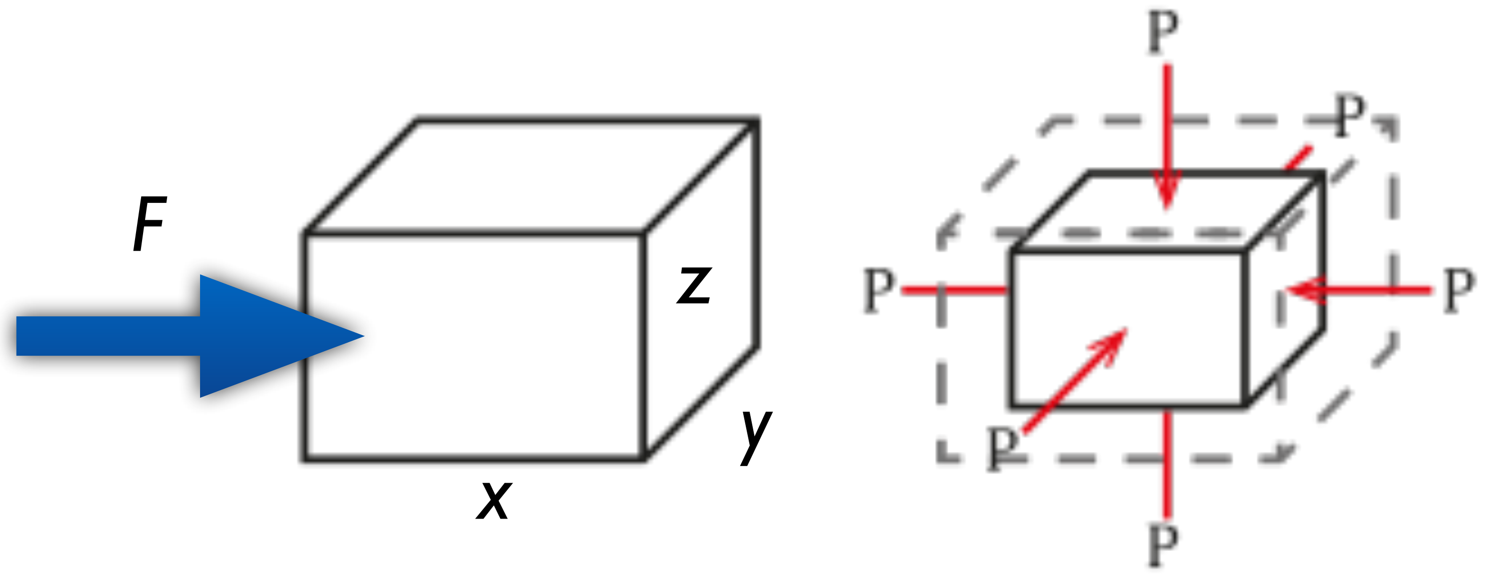
density

Mass of the cube dm= ρ dxdydz

Newton Law $F = m\,a$

stress

$$\rho \frac{d^2 u}{d t^2} = \frac{d\sigma_{xx}}{d x} + \frac{d\sigma_{xy}}{d y} + \frac{d\sigma_{xz}}{d z}$$



Hooke law

Normal stress

dilatation

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

diff for x, y, z

Dilatation

laplacian

$$\rho \frac{d^2 \Delta}{d t^2} = (\lambda + 2\mu) \nabla^2 \Delta$$

Wave Equation !

Lame parameters

Elastic waves in homogeneous and isotropic media

Body waves

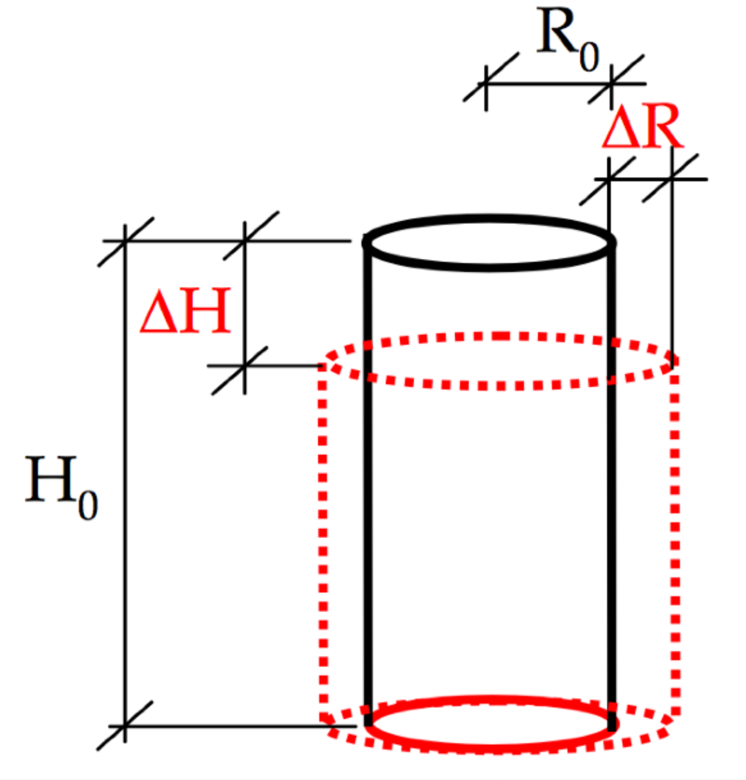
Solution eq. diff. (Equazione d’onda)

Volumetric deformation

P

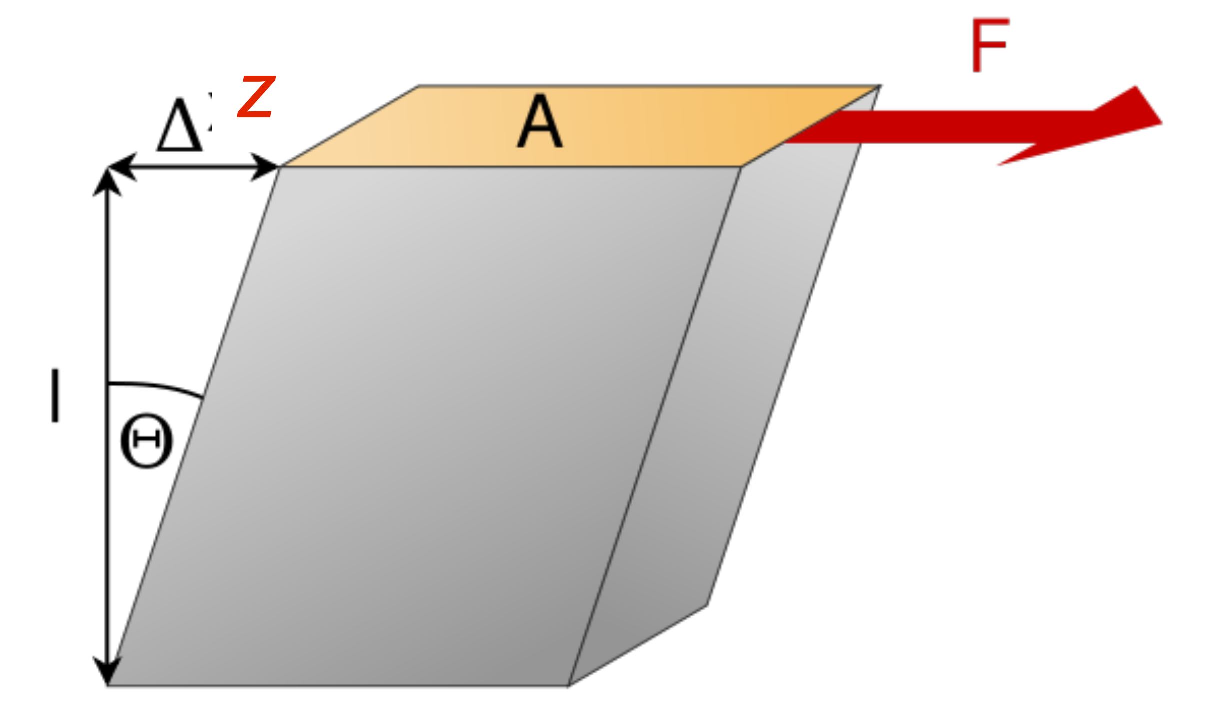
$$\frac{\partial^2 \overline{\varepsilon}}{\partial t^2} = \frac{\lambda + 2G}{\rho} \nabla^2 \overline{\varepsilon}$$

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



S

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



Rotational copmponents (x, y, z)

Elastic waves in homogeneous and isotropic media

Solution of waves equations

P

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

S

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

V_P^2

V_S^2

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

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

In fluids
G= 0
Vs=0

Elastic waves in elastic homogeneous and isotropic media

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

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

in x, y e z

HOOKE LAW in z

u = dispalcement

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

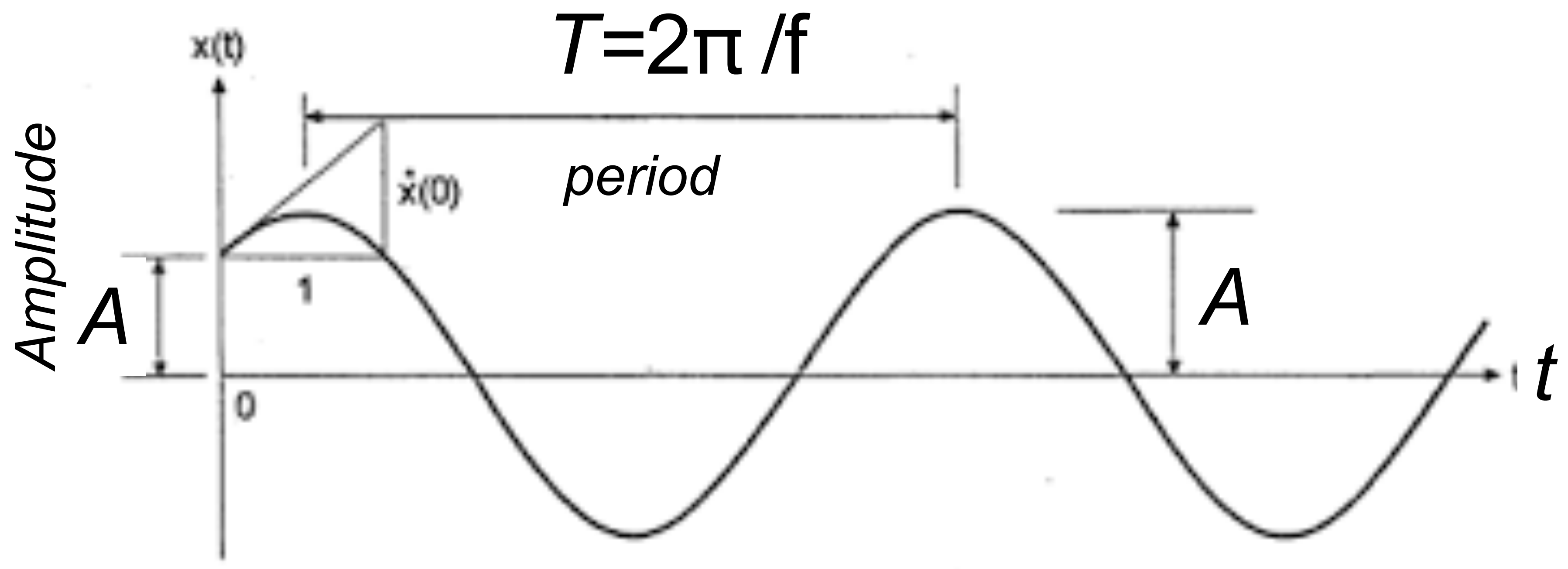
ELASTIC
WAVE
EQUATION (S)

Elastic waves in homogeneous and isotropic media

S waves equation

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

harmonic sinusoidal wave



Solution (eulerian)

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

depth

time

displ.

Amp.

Pulsation $\omega=2\pi\, f$

Wavenumber $K=\omega/Vs$

Frequency

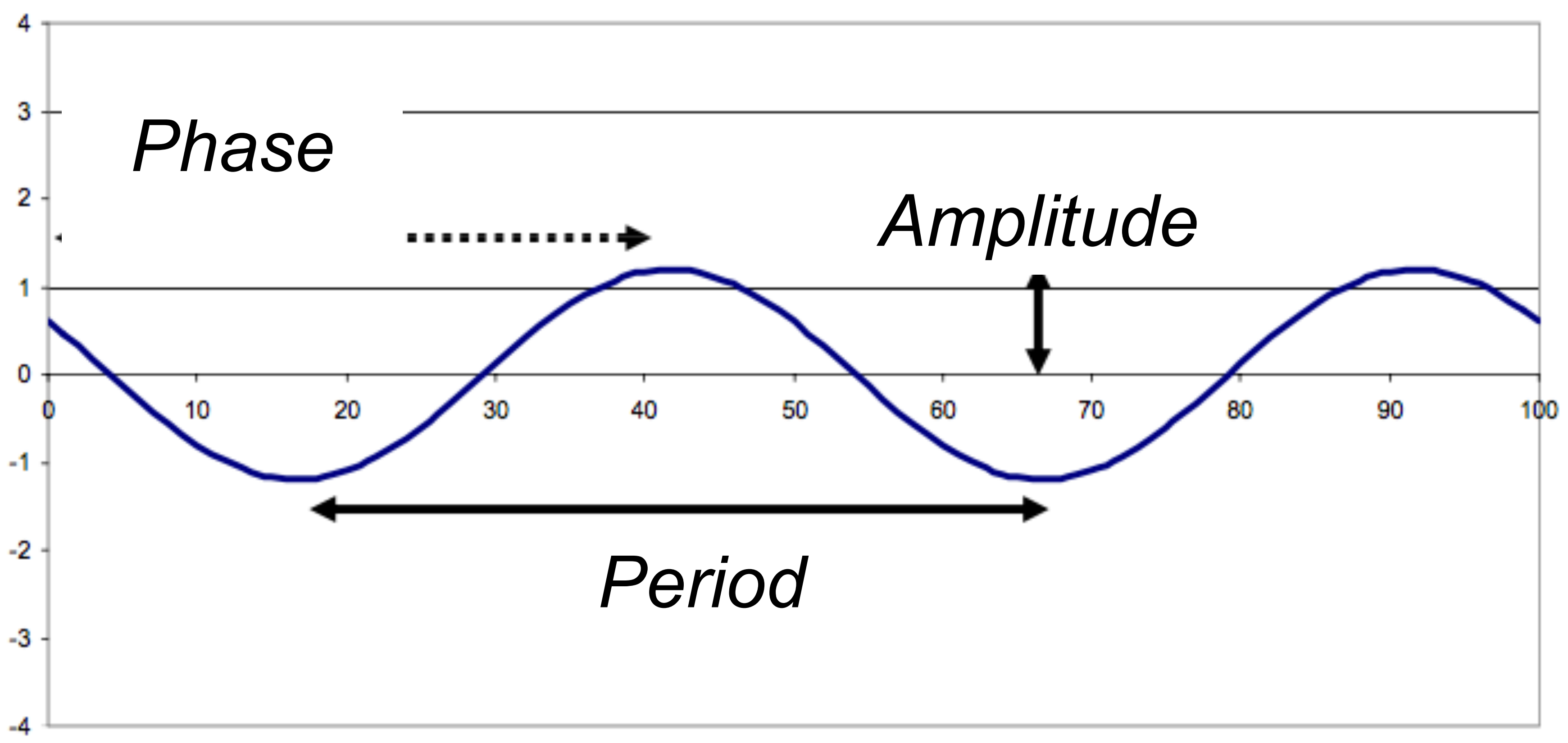
Bound. Conditions
halfspace
G=0 z=0

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

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



$$\boxed{A\,(t) = A_{\max}\cos(2\pi\, f\, t + \phi)}$$ *Eq. Wave*

$\phi = -2\pi\, f t_{\max}$	phase (when arrive the maximum?)
$T = 1/\ \mathrm{f}$	Period (how much last the motion?)
$\mathrm{f}\ = 1/T$	Frequency (how much oscillation?)
$\omega = 2\pi\ \mathrm{f} = 2\pi\,/\,T$	Pulsation

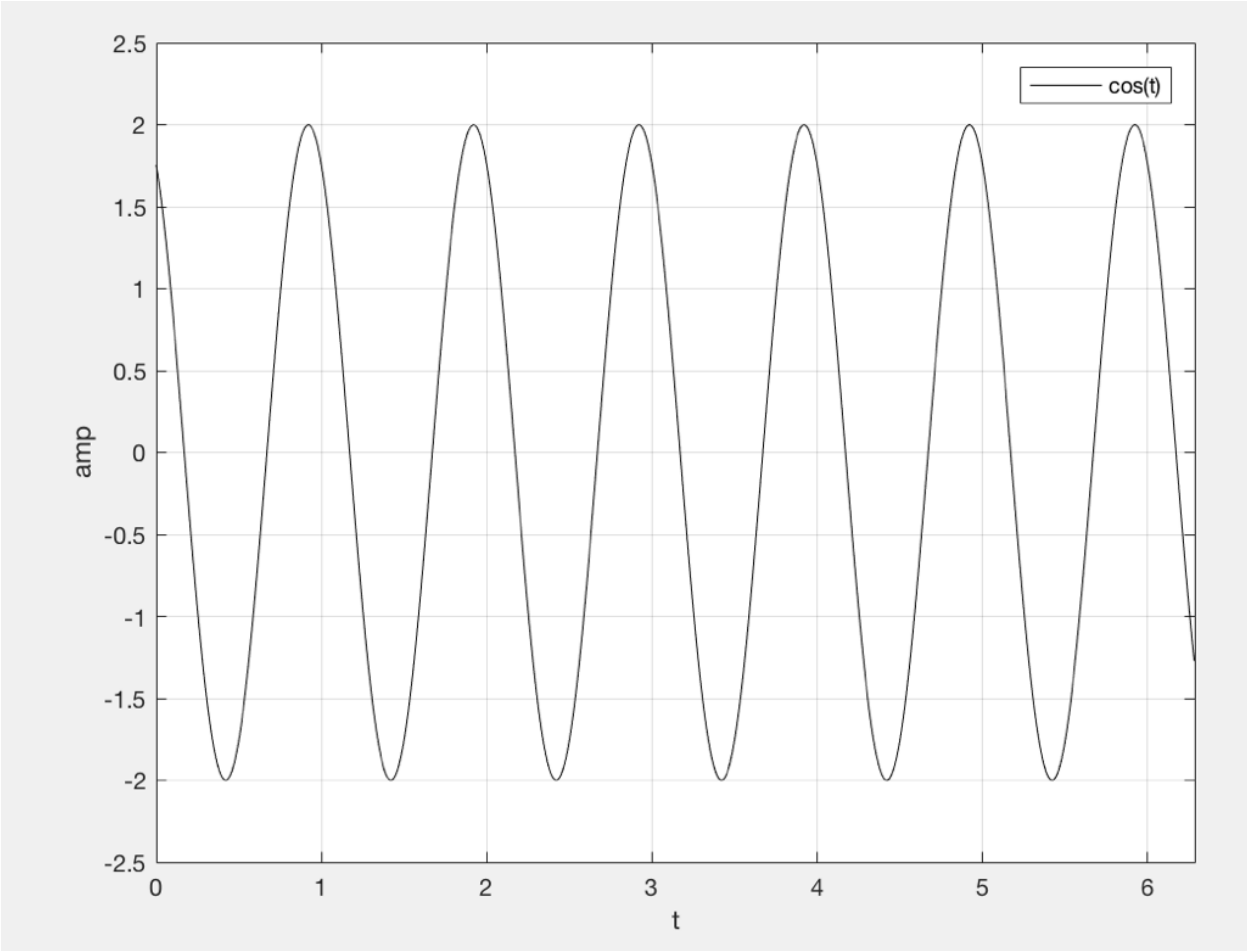
$$A(t) = A_{\max}\cos(2\pi\, f\, t + \phi)$$

Displacement

Frequency

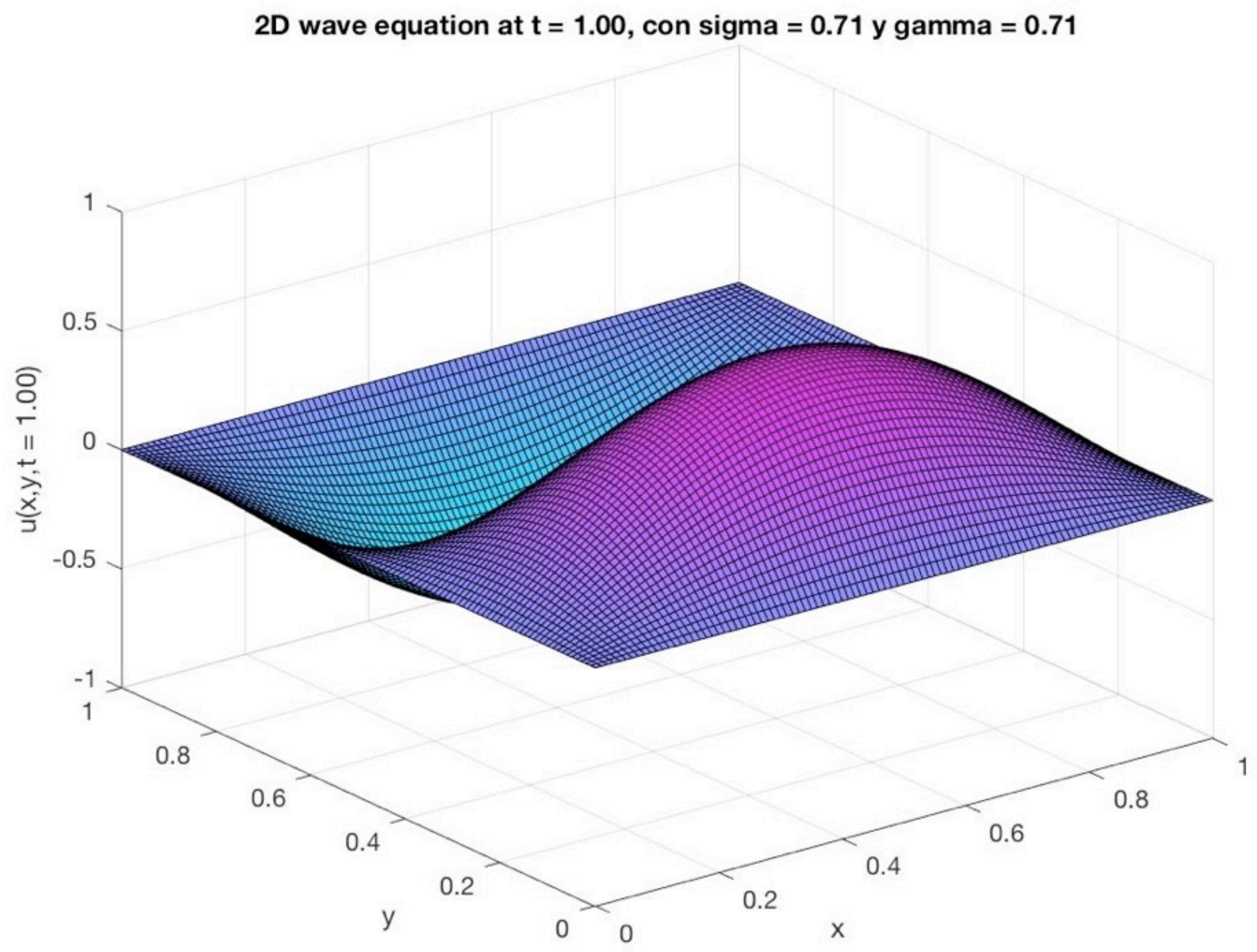
Phase

```
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
```



2D wave eq solution

```
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
```

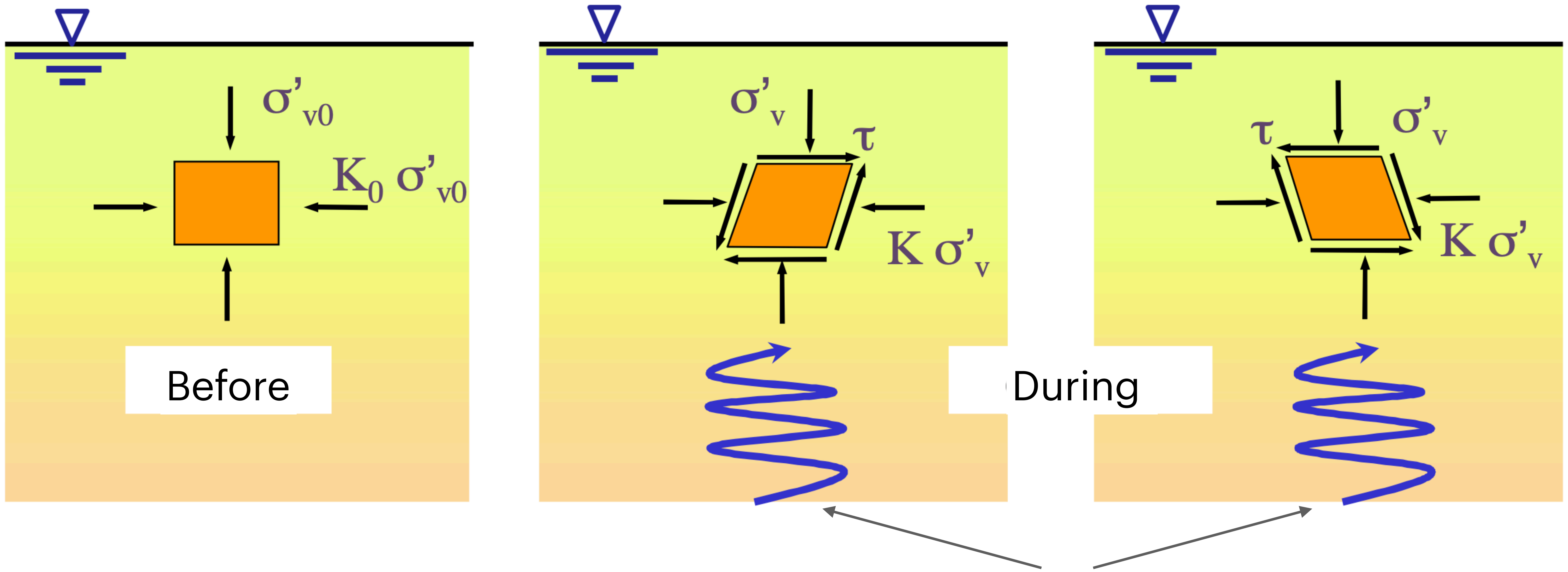


Seismic Response Analysis

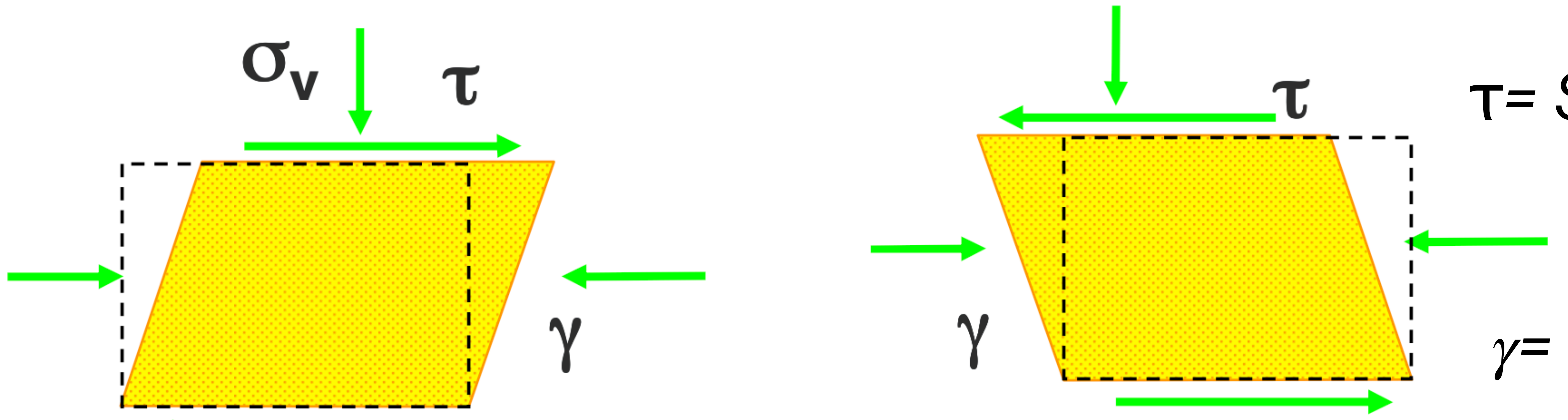
Terrain element under earthquake stress

σ= *pressure*

Conditions



S waves coming from the inner crust



τ= *Shear stress*

γ= Shear strain

(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 $z=H$

Surface

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

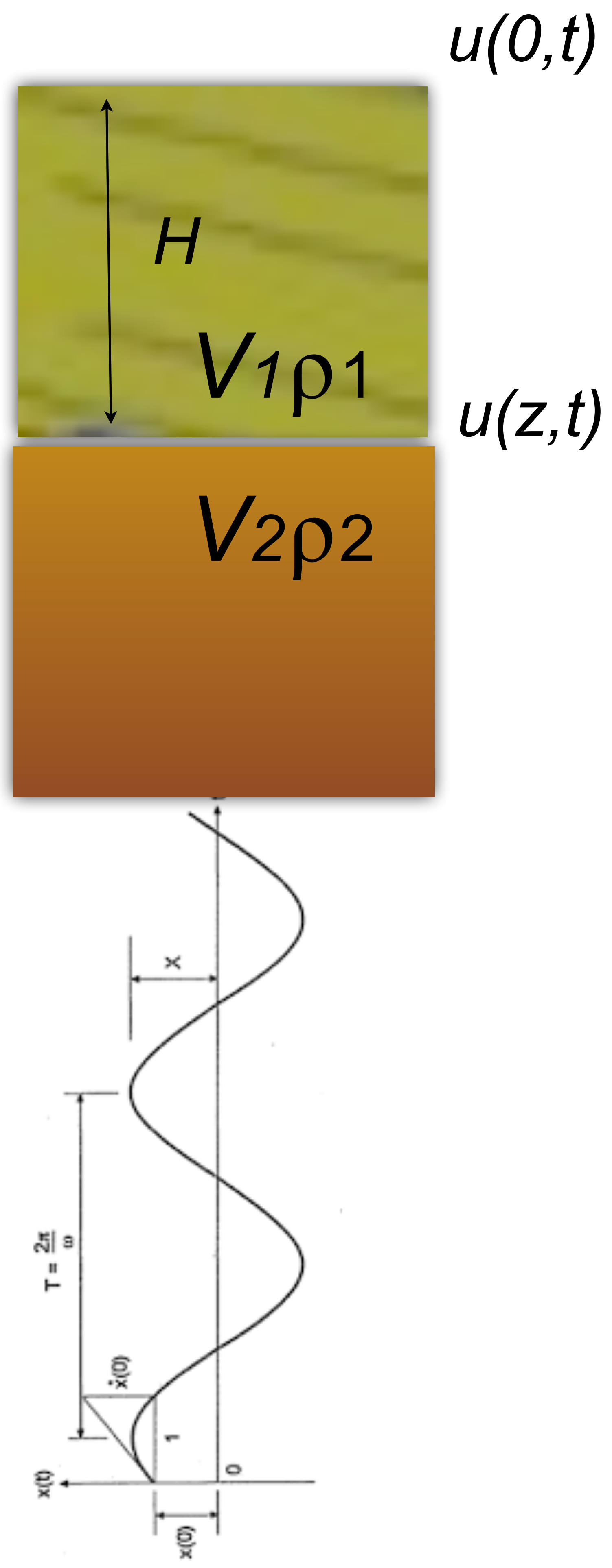
Depth

Wavenumber Thickness

$k=2\pi/\lambda$ $\lambda = c/f$

λ= wavelength c= velocity; f= frequency

Ideal harmonic
Motion



Seismic waves in esalti media, isotropic and homogeneous

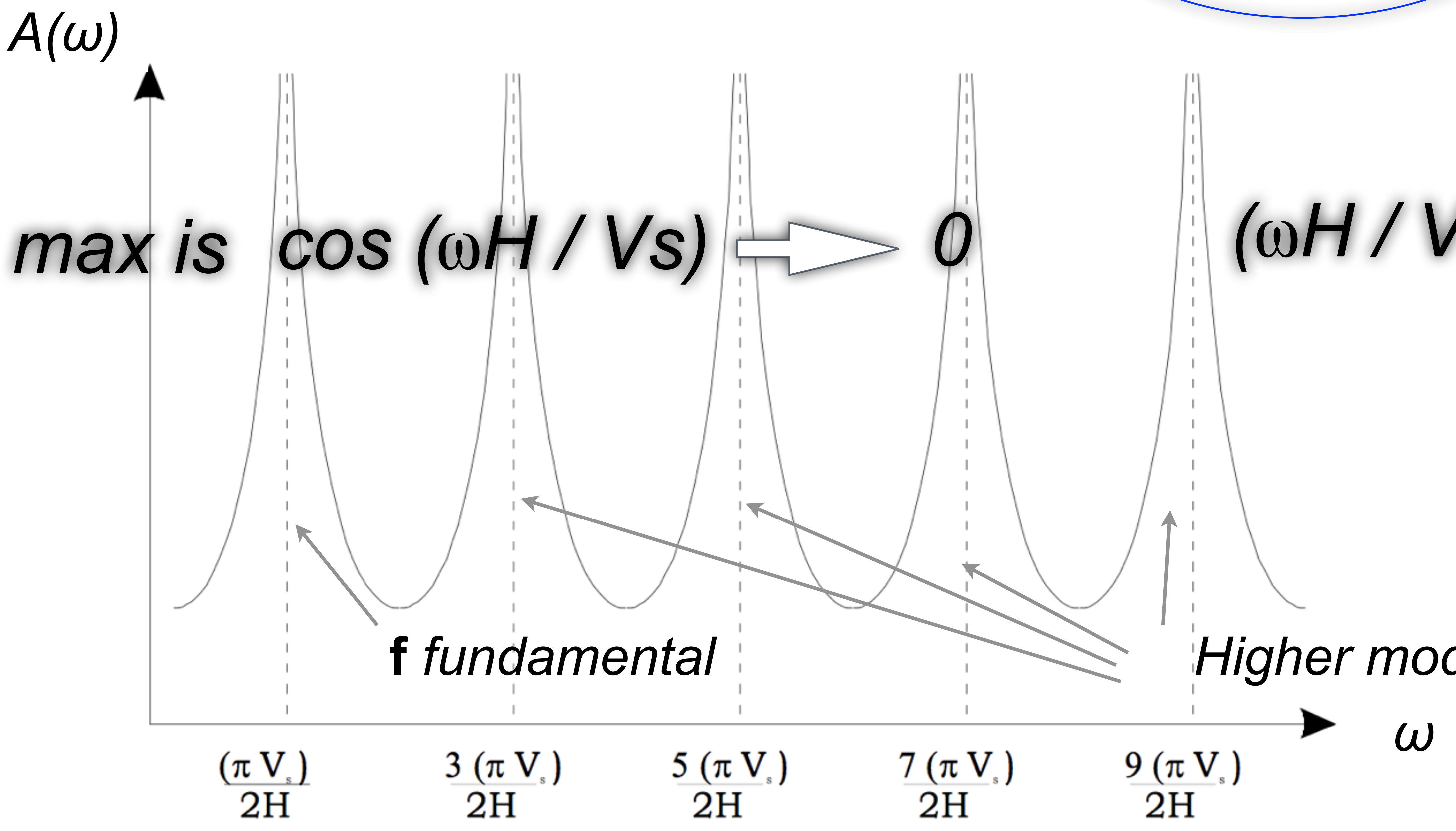
→ harmonic motion

AMPLIFICATION FUNCTION = Modulus of Transfer function

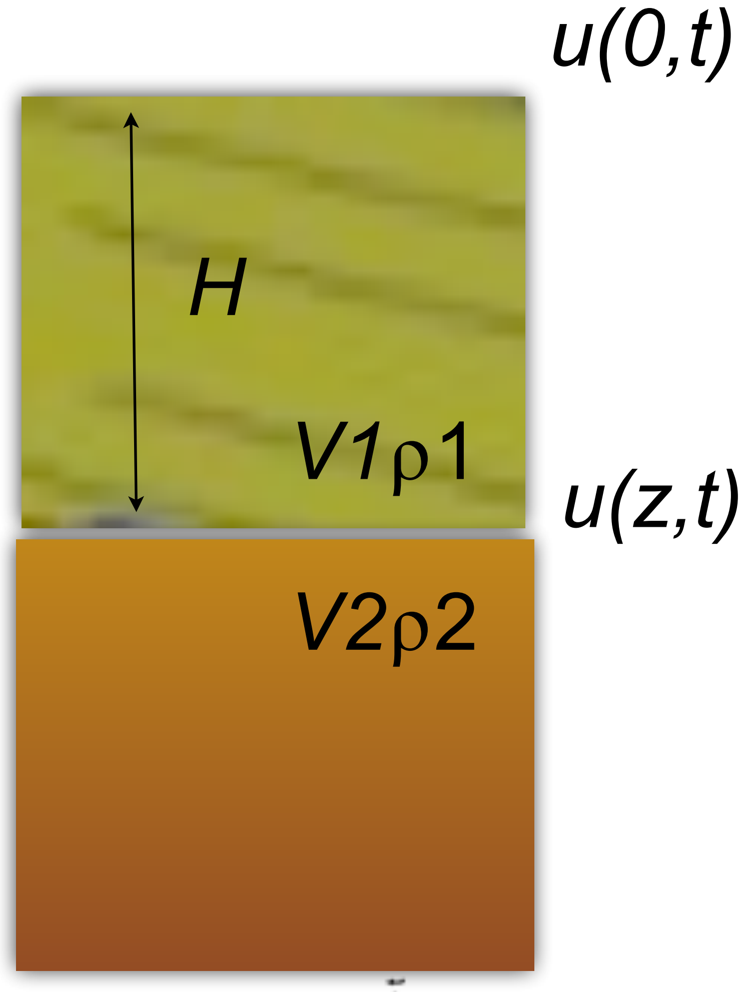
Harmonic motion

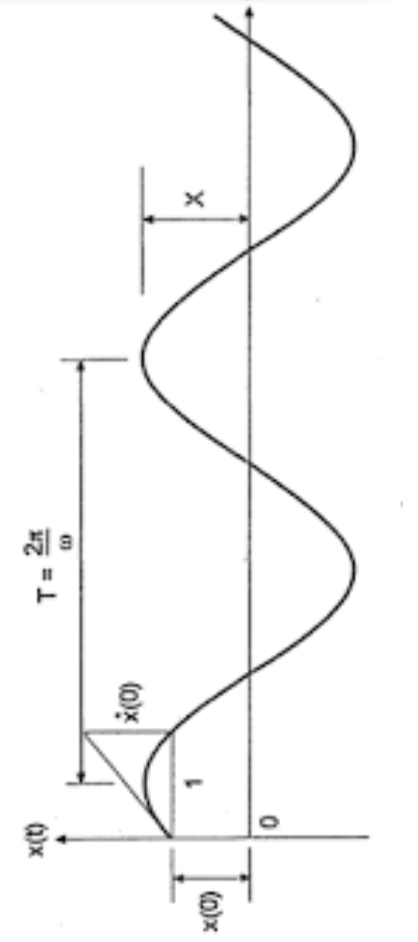
$K=\omega/Vs$

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



max is $\cos(\omega H / Vs) \Rightarrow 0$ $\quad (\omega H / Vs) \Rightarrow \frac{\pi}{2}$





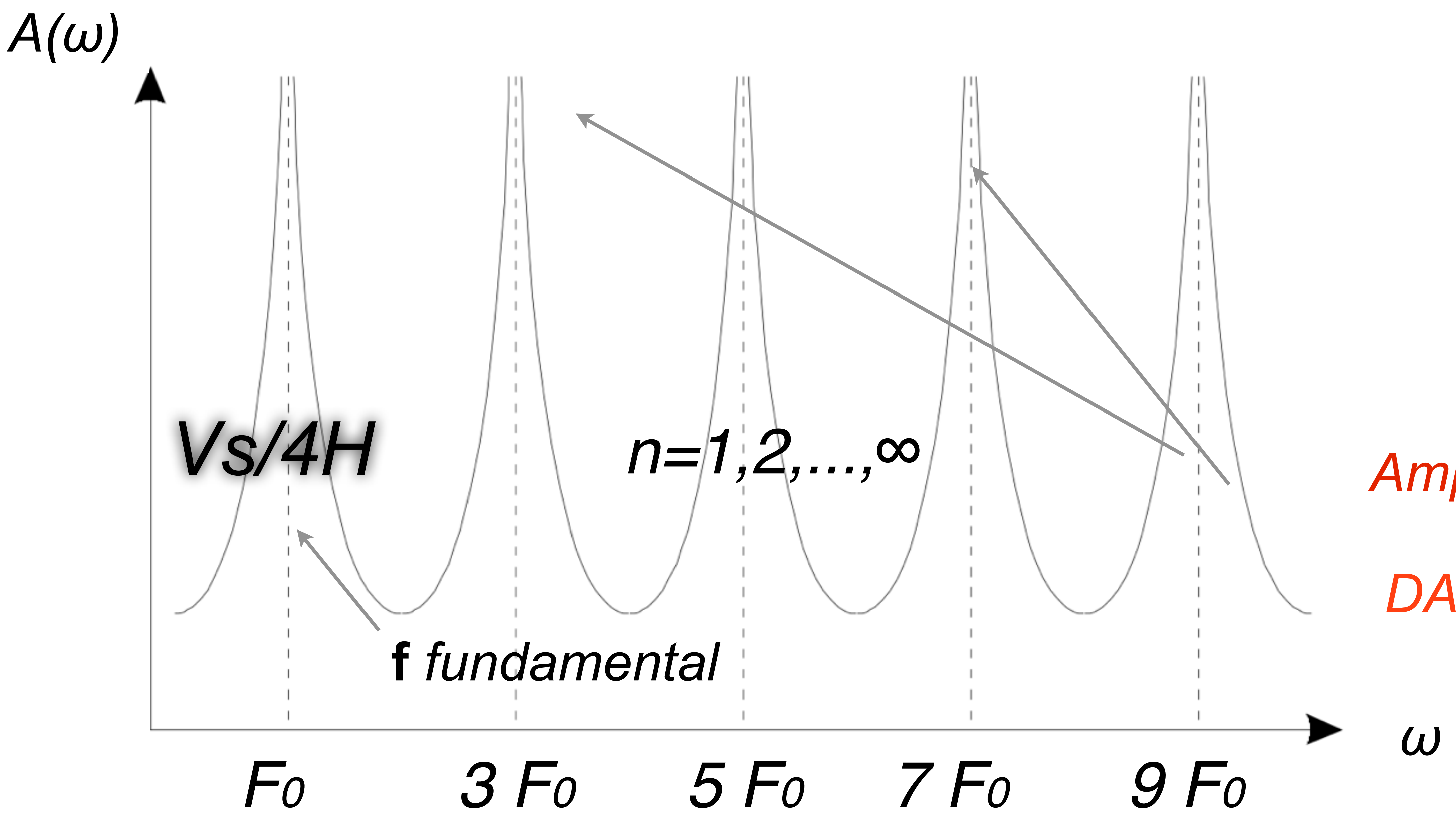
Seismic waves in esalti media, isotropic and homogeneous → harmonic motion

fundamental Frequency

n=1, 2,...,∞

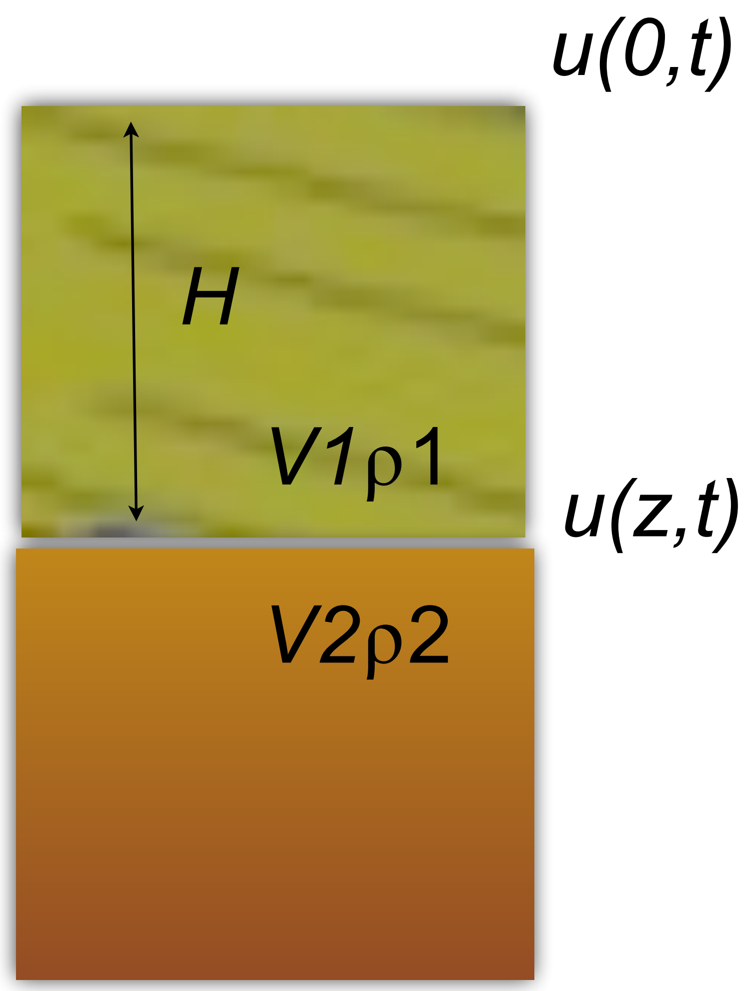
$$\omega = \frac{Vs}{H}\,\frac{\pi}{2}\,(2n\text{-}1) \quad\Rightarrow\quad \mathbf{f} = \frac{Vs}{4\,H}\,(2n\text{-}1)$$

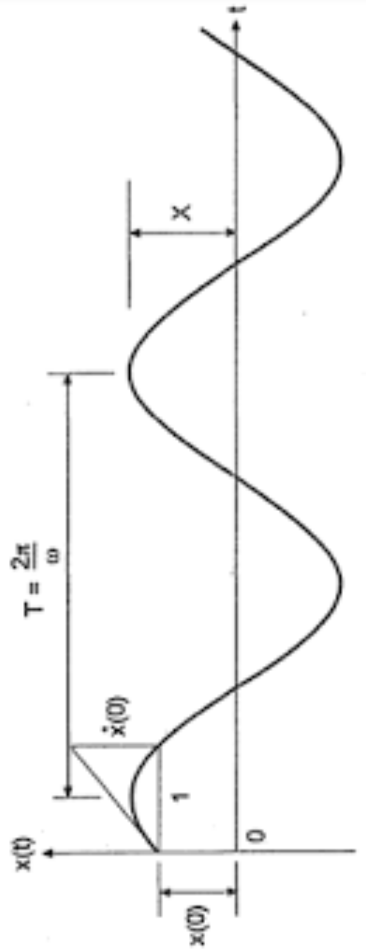
$\omega = 2\pi\, f$



Amplification NOT DAMPED !!

Harmonic motion





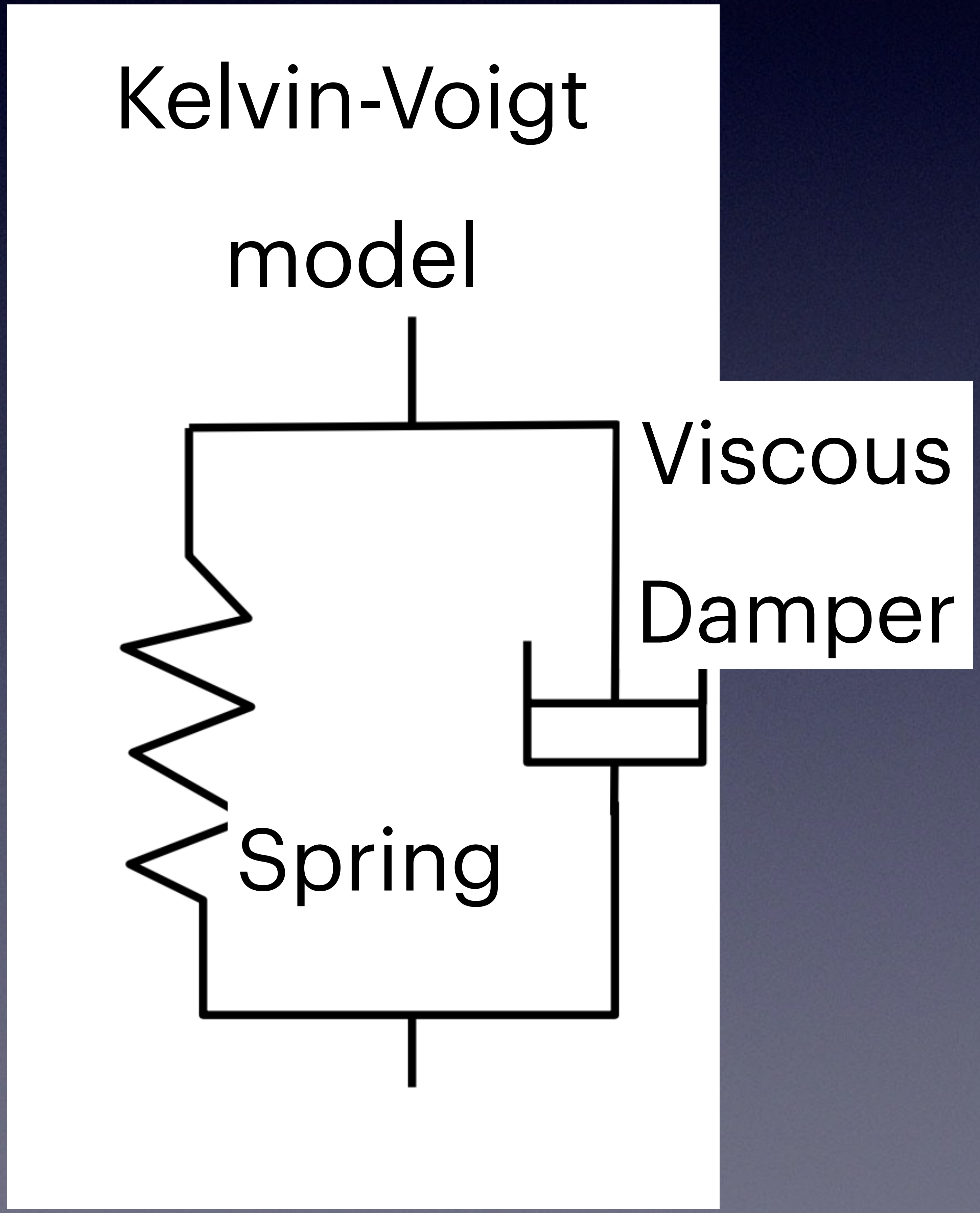
From the waves in ideal elastic homogeneous isotropic media

↓

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)



Kelvin-Voigt model

Viscous Damper

Spring

DIPARTIMENTO DI GEOSCIENZE

UNIVERSITÀ DEGLI STUDI DI PADOVA

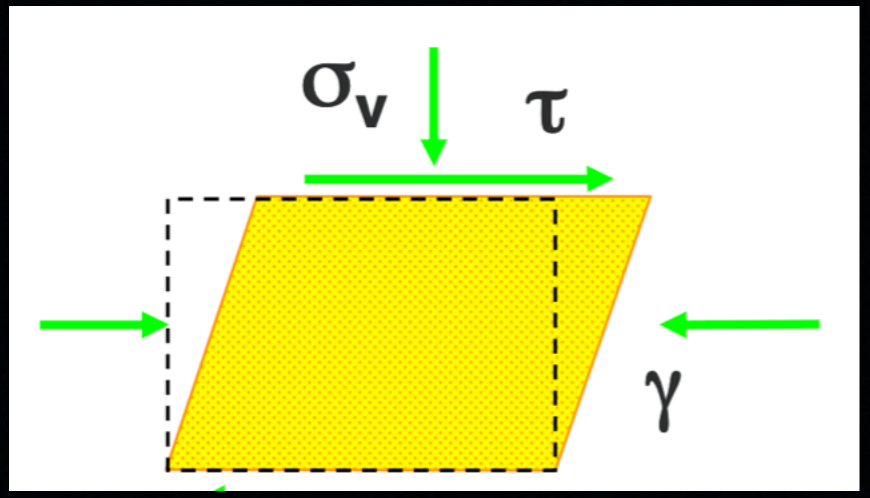
Waves propagation in the real soil

Soil parameters for seismic response analysis

$G = \rho Vs^2$

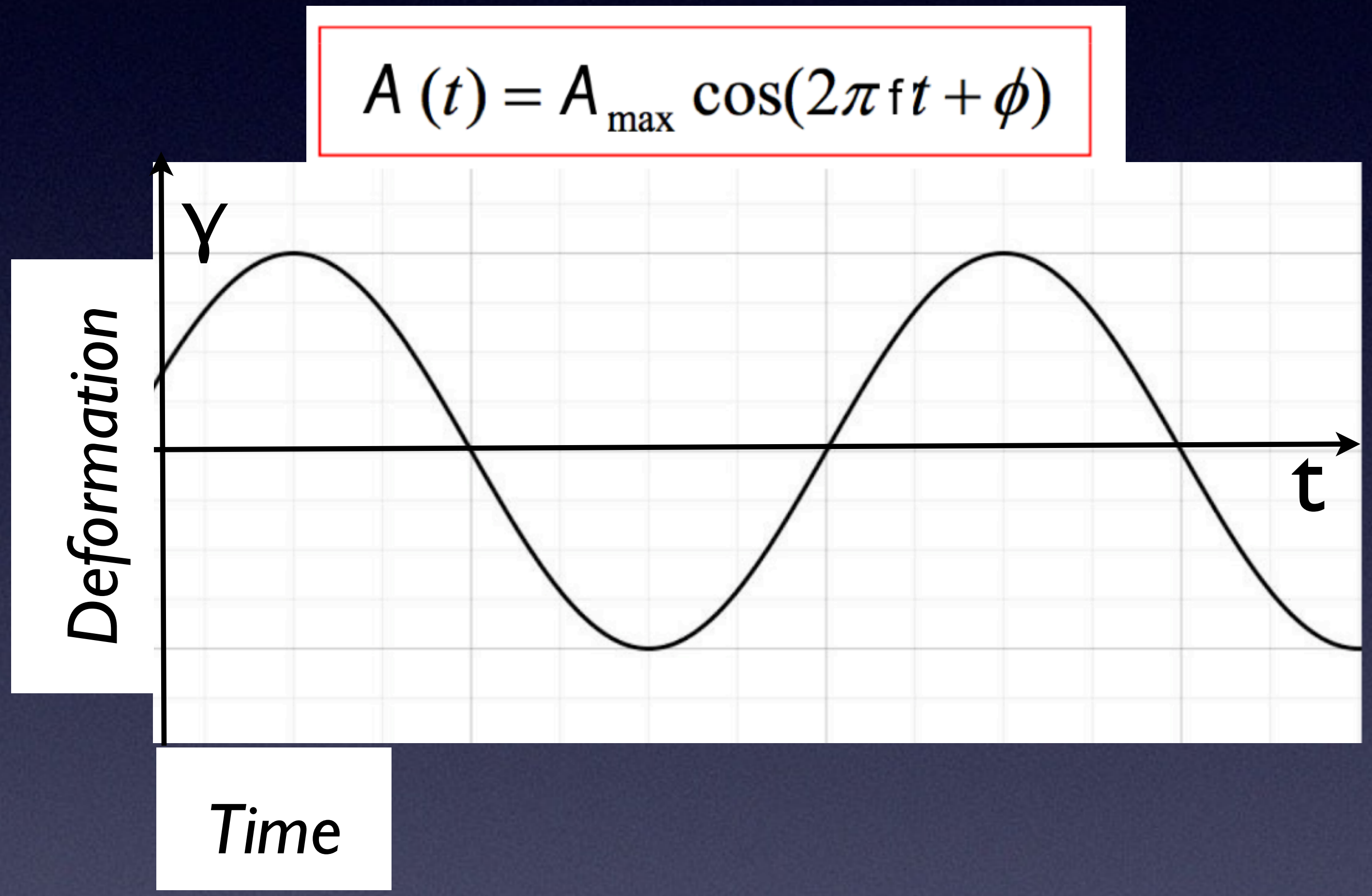
-Density	δ	gr/cm3	Ideal
-Shear modulus	G	N/mm2	
-Seismic Shear velocity	Vs	m/s	
+			
-Damping	D	%	real

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



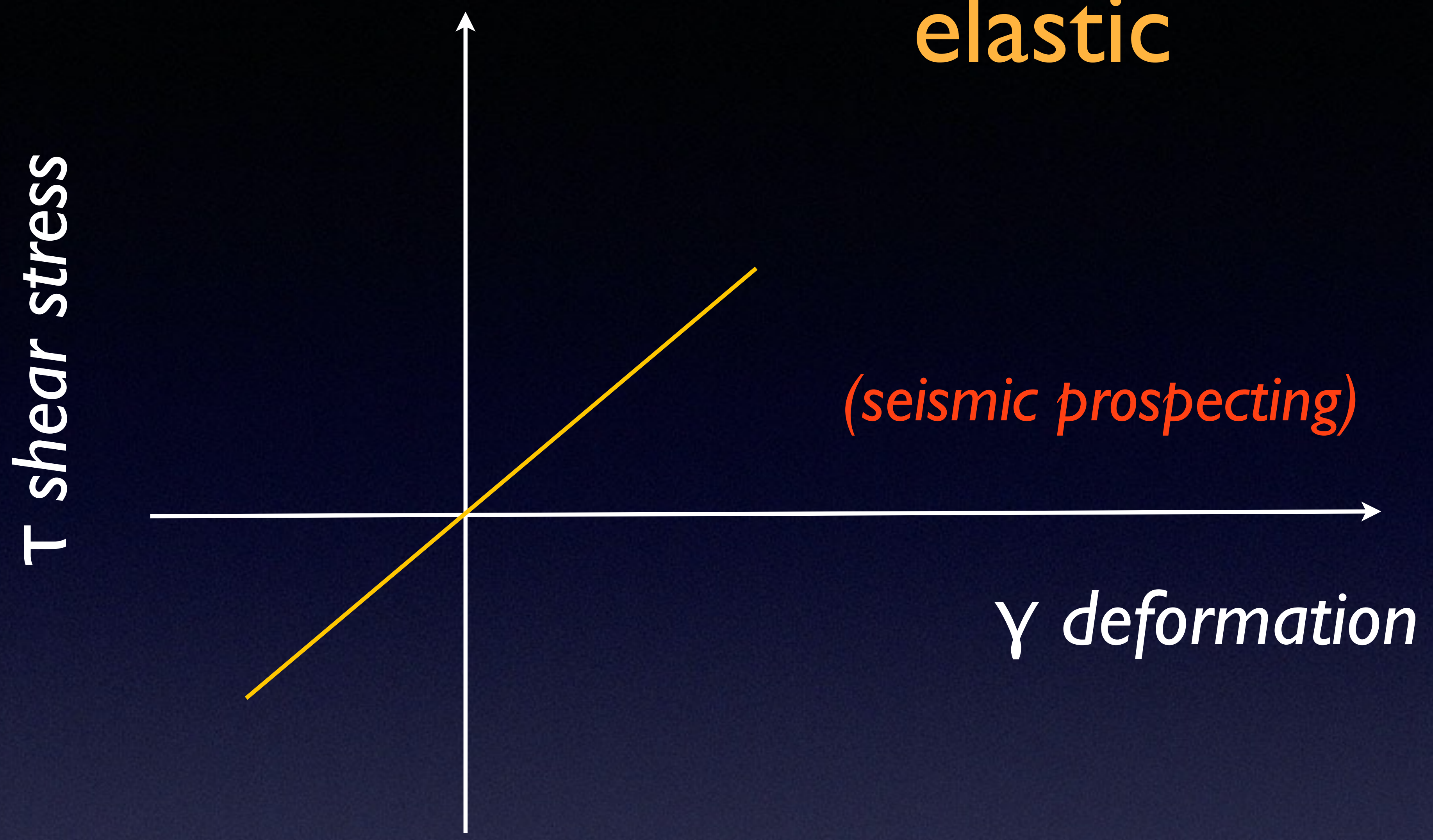
Small deformation

Soil is linear elastic (seismic prospecting)



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

elastic



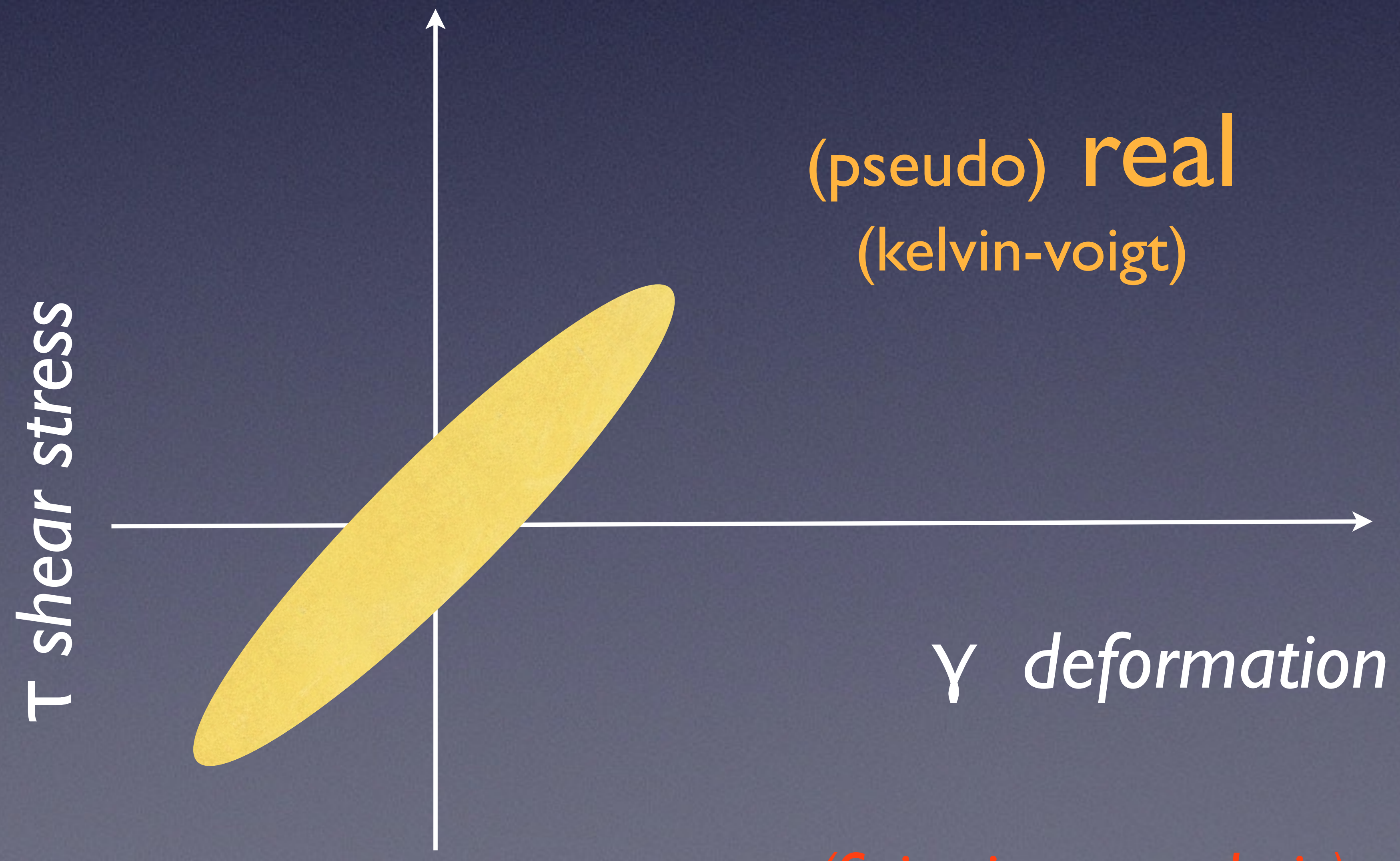
(seismic prospecting)

Medium to big deformation

Soil is not linear and dissipative (damped)

(pseudo) **real**

(kelvin-voigt)

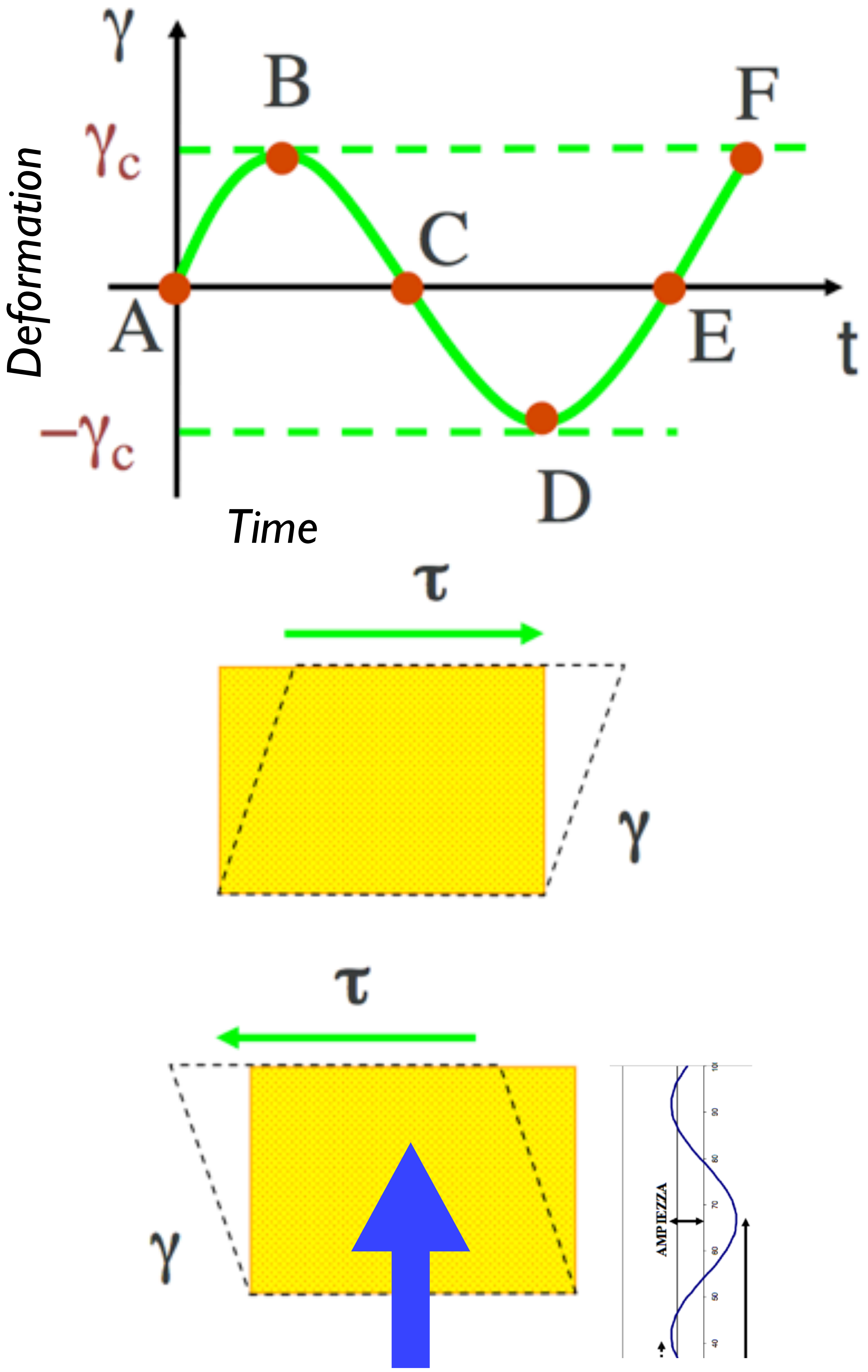


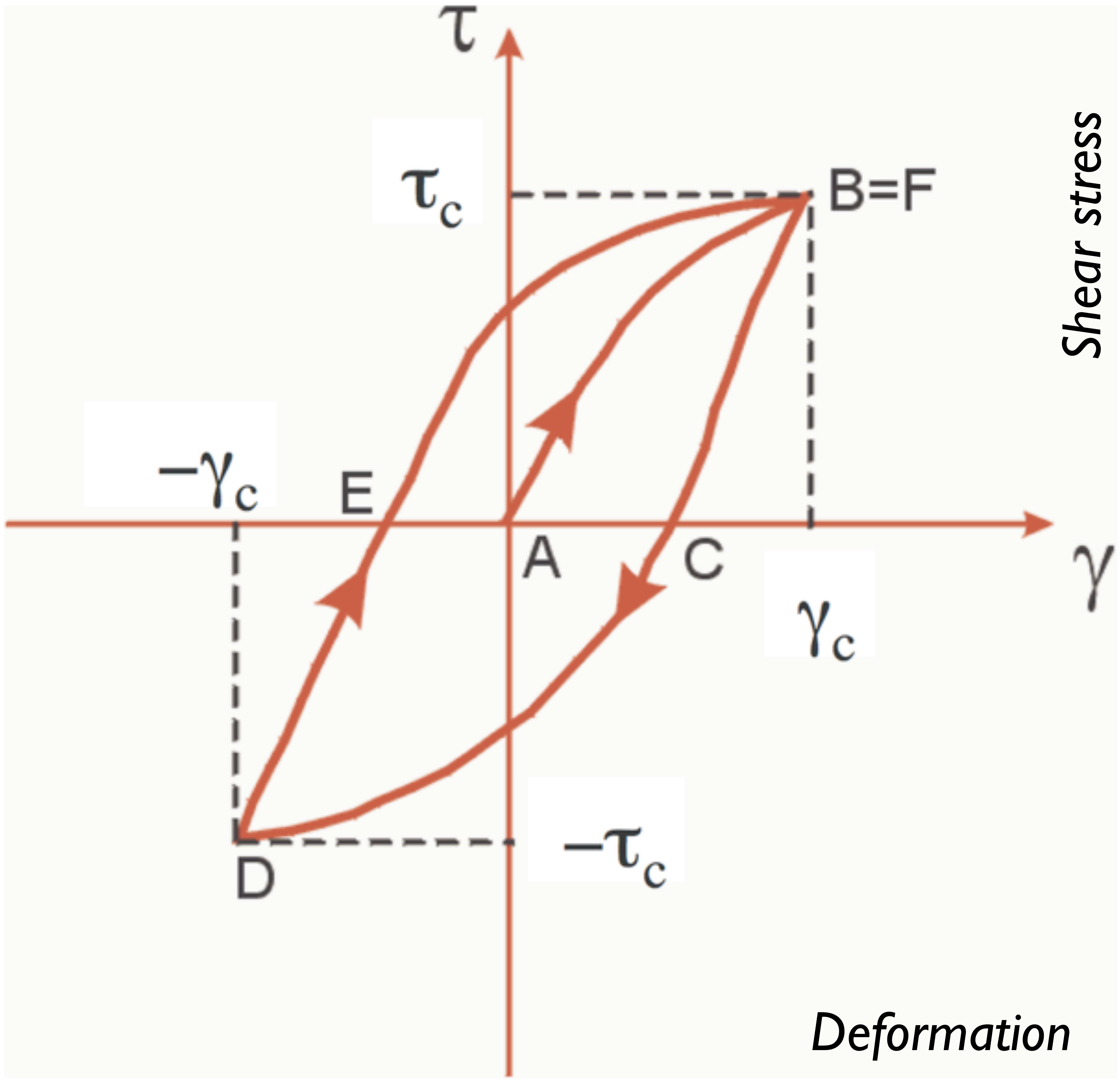
(Seismic geotechnic)

Geotechnical parameters in seismic motion

Response of soil to cyclic loads

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

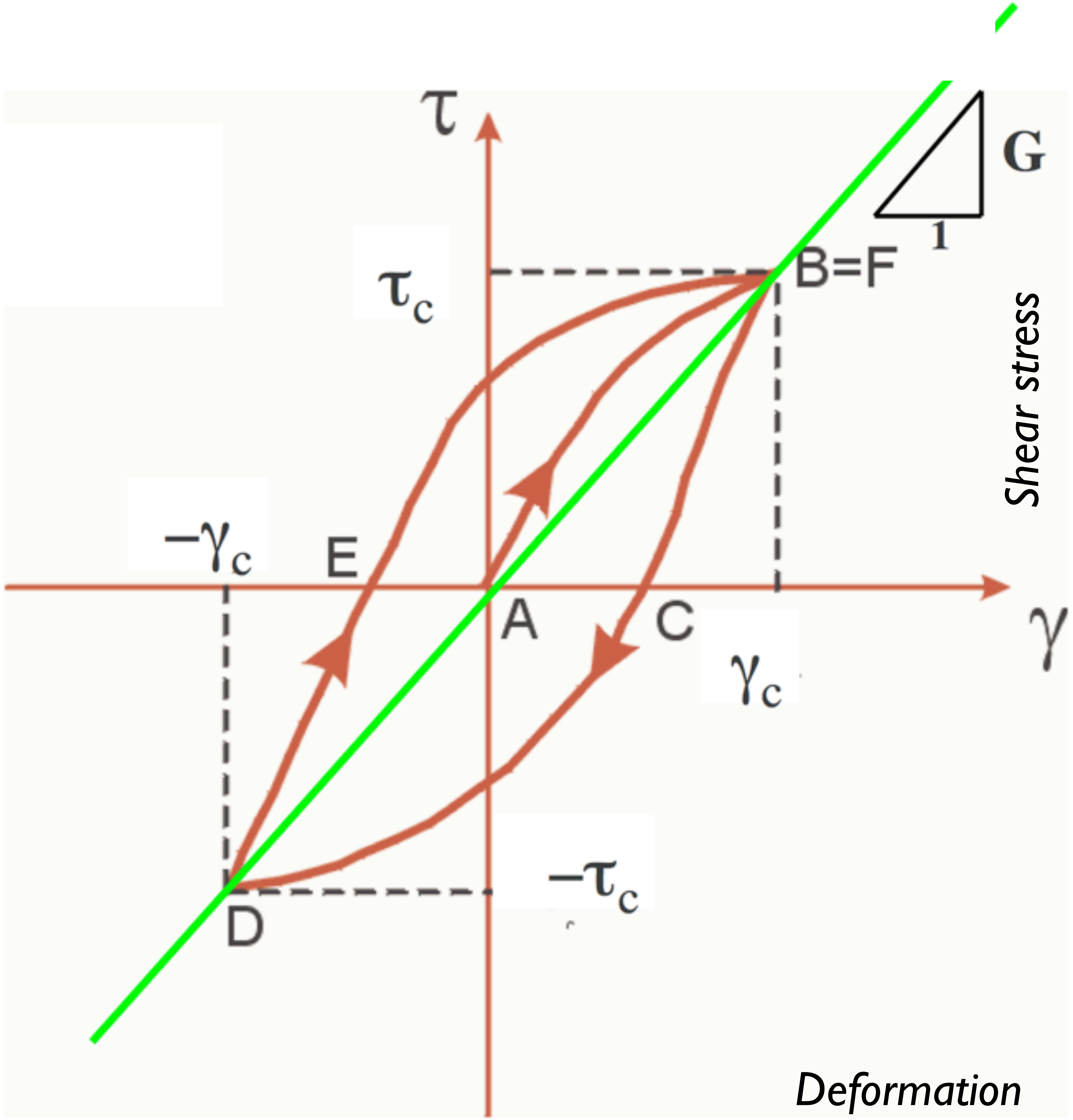




Geotechnical parameters

G modulus

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



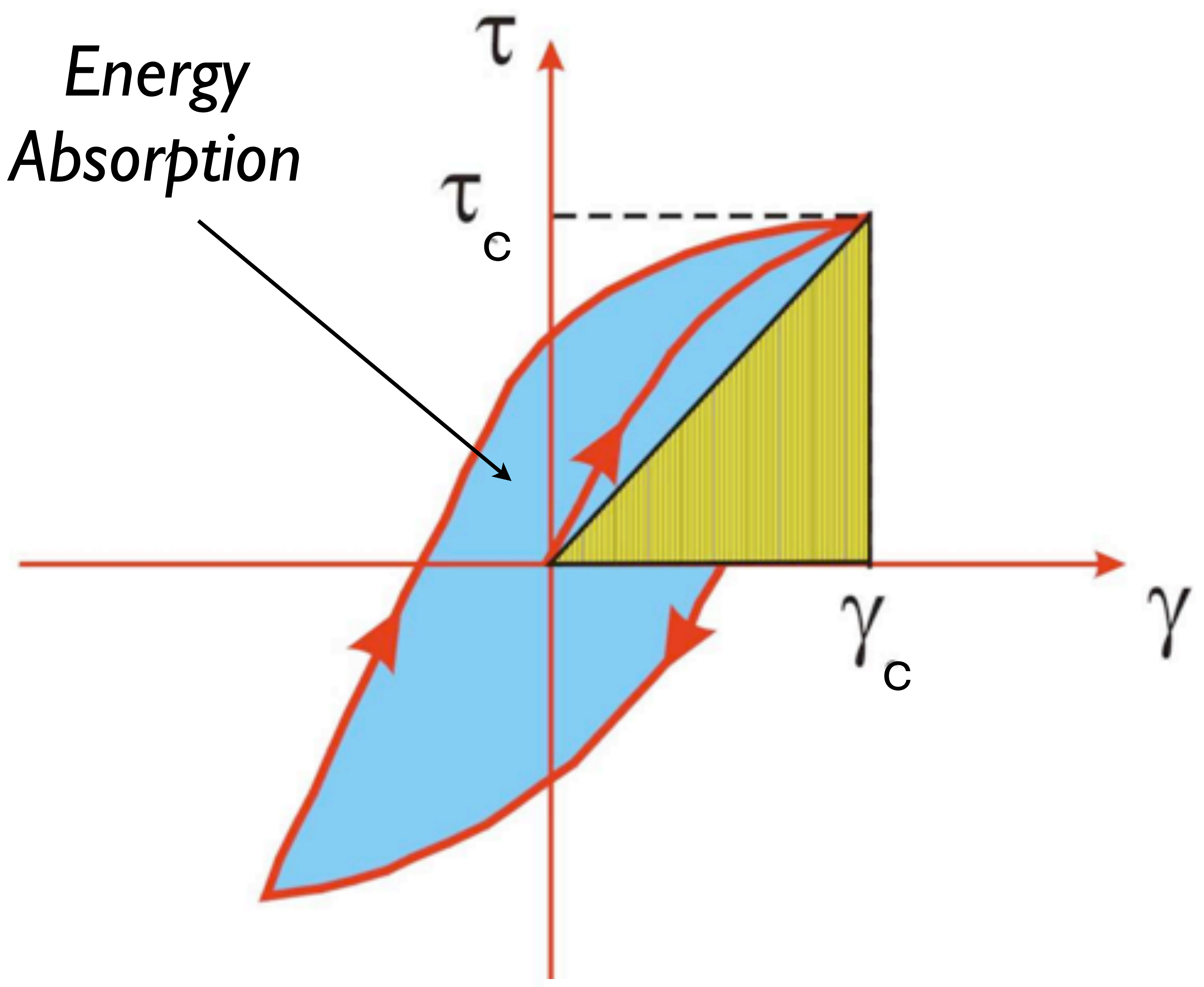
Secant of τ-γ

Geotechnical parameters

D Damping

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

Ratio between the dissipated energy and the elastic energy stored



ΔW = area 🟦 = *Energy dissipated in the cycle*

W = area 🟨 = *Energy stored*

Lab DAMPING with resonant column test

Geotechnical

tests

RESONANT

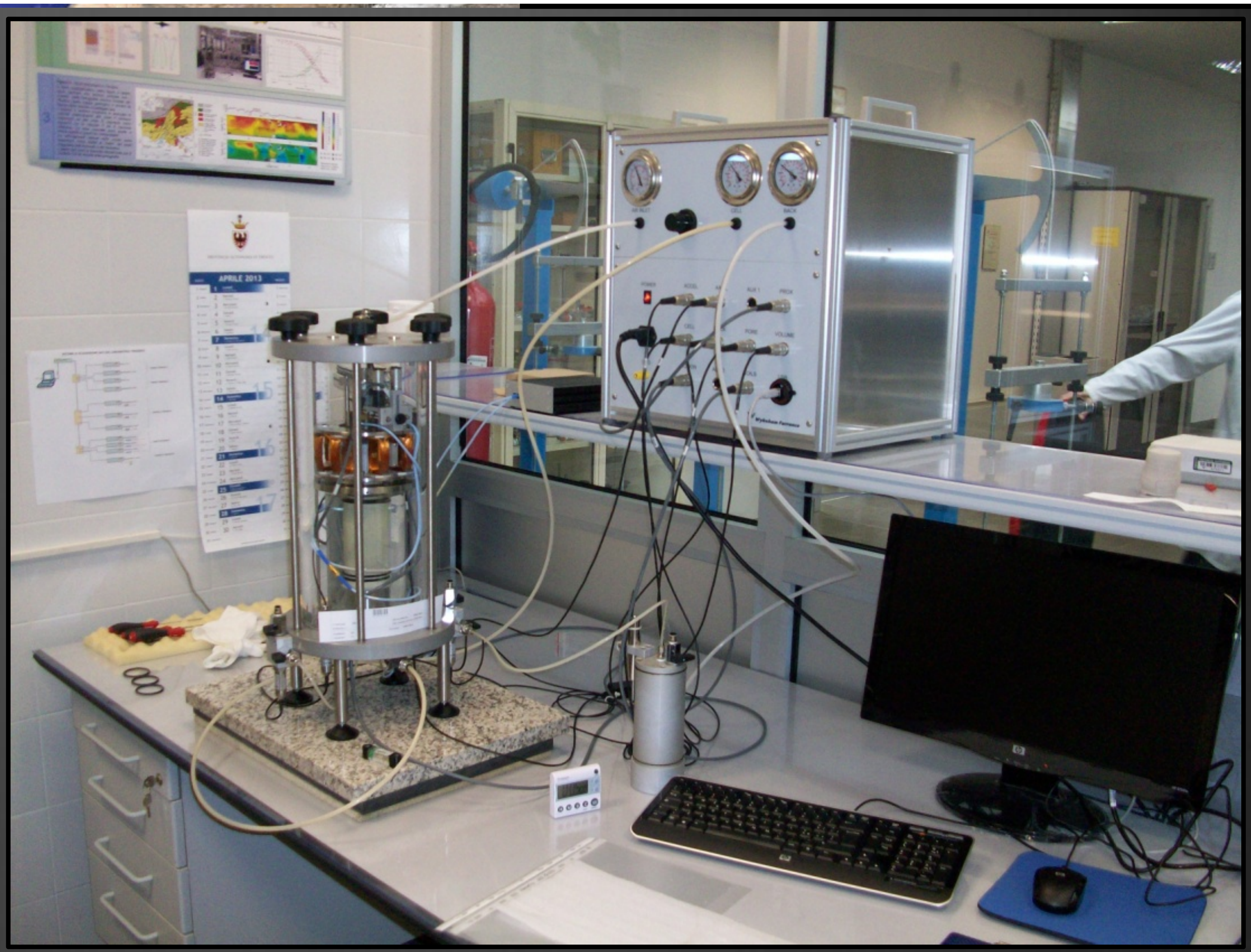
COLUMN

To get

G shear modulus

And

D damping



RC

TEST

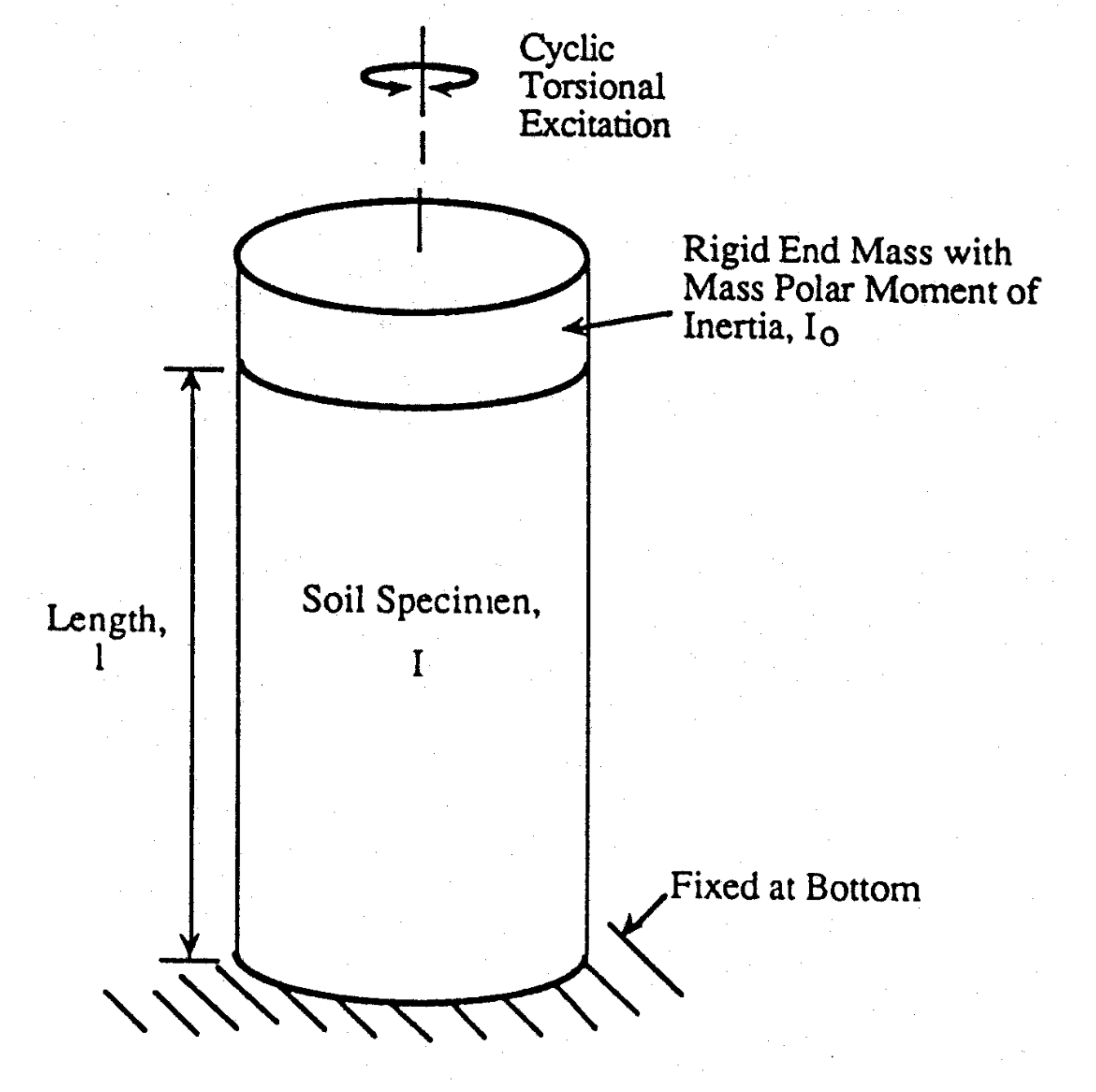
$$\begin{cases} V_s = h \cdot \omega / \beta \\ \omega = 2\pi \cdot F_r \end{cases} \rightarrow G = V_s^2 \cdot \rho$$

Amplitude Decay Method → D

Extra Material

Lab DAMPING with resonant column test

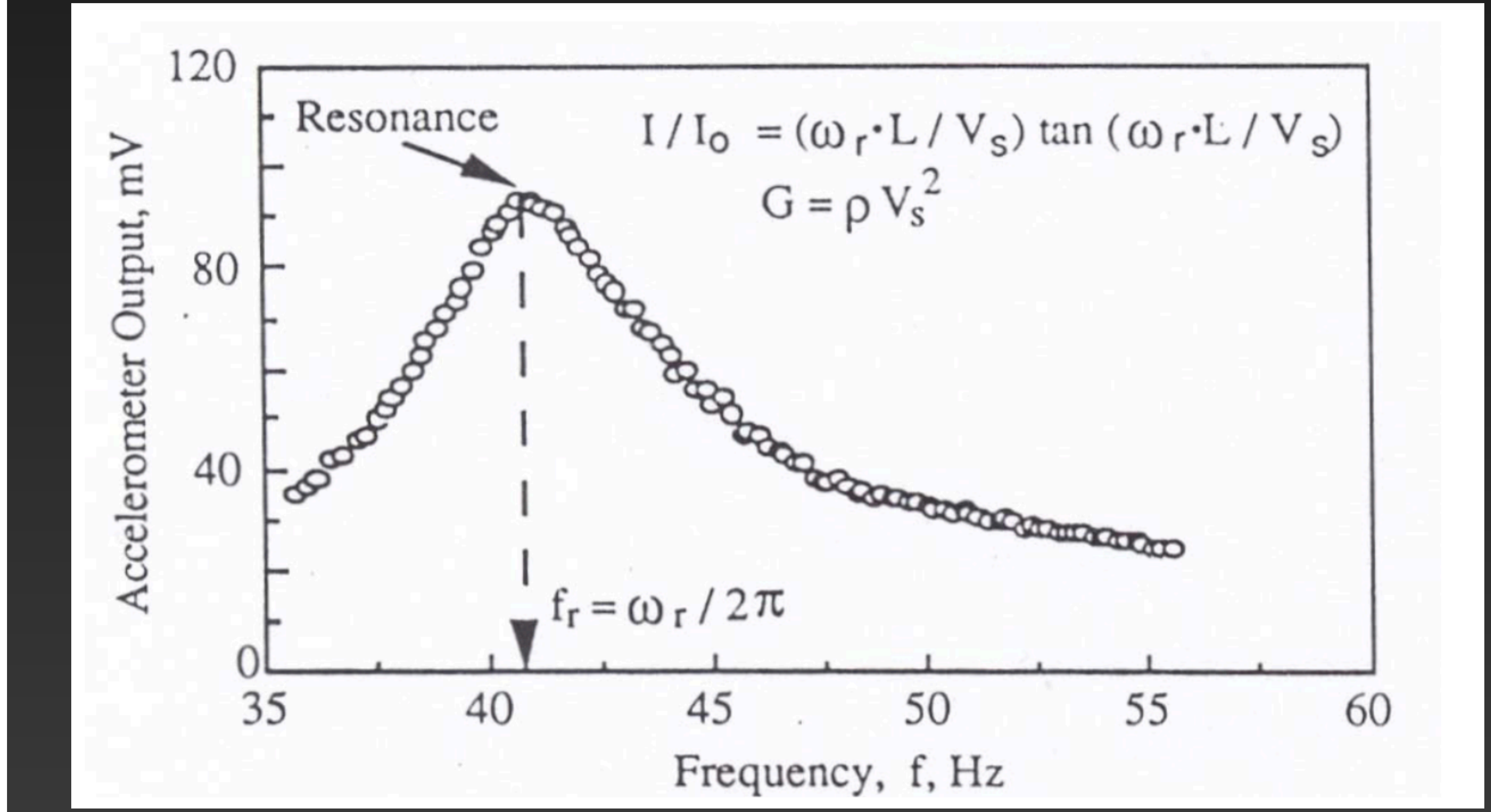
Determining the dynamic deformation properties (shear modulus G and damping ratio D) of soils.



i) prepare the specimen (density)

ii) Apply harmonic torsional excitation to the specimen with varying frequency.

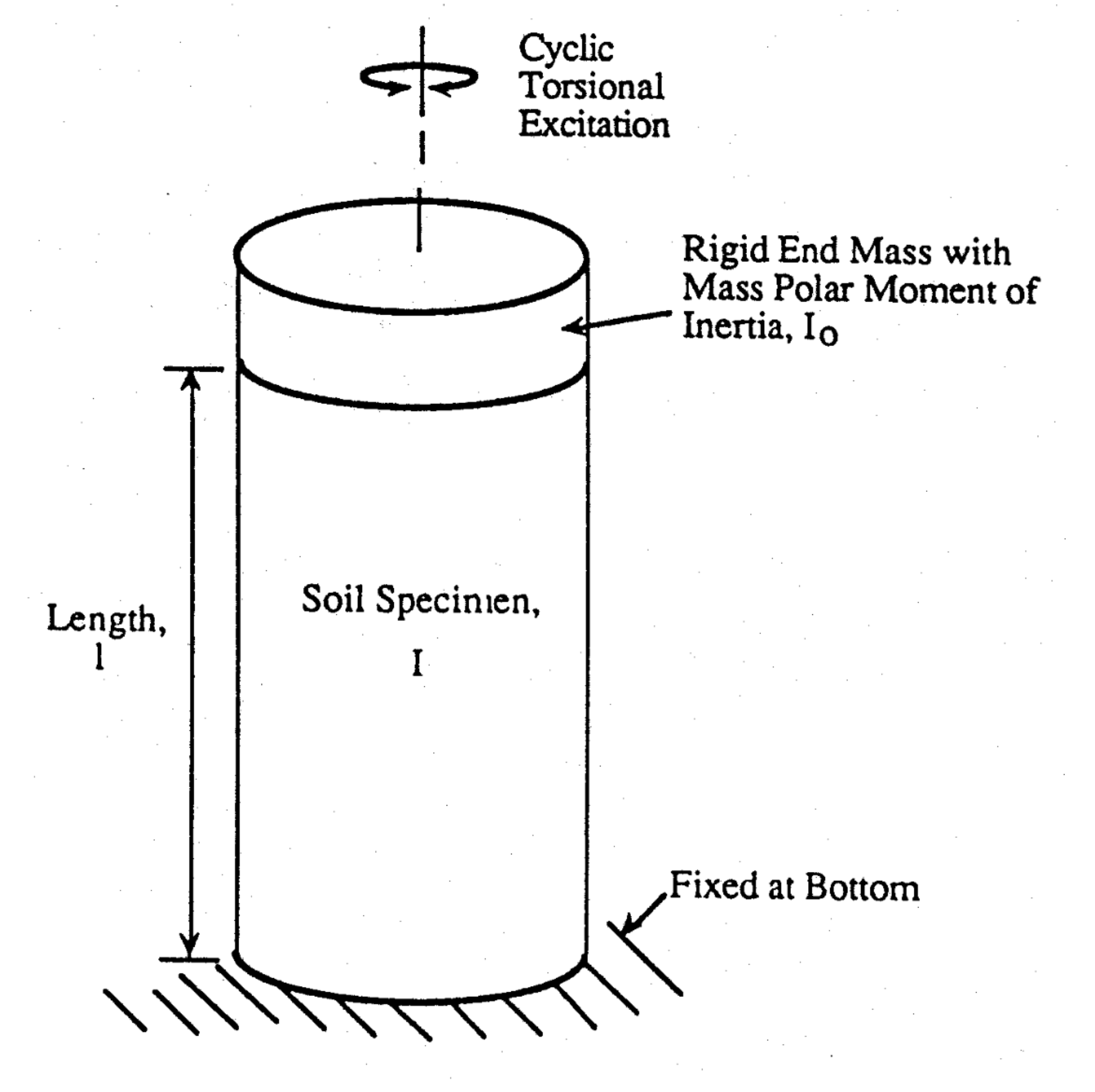
iii) Obtain the response of the acceleration amplitude with varying frequency and find the first-mode resonance where output voltage of accelerometer is maximised.



Extra Material

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.

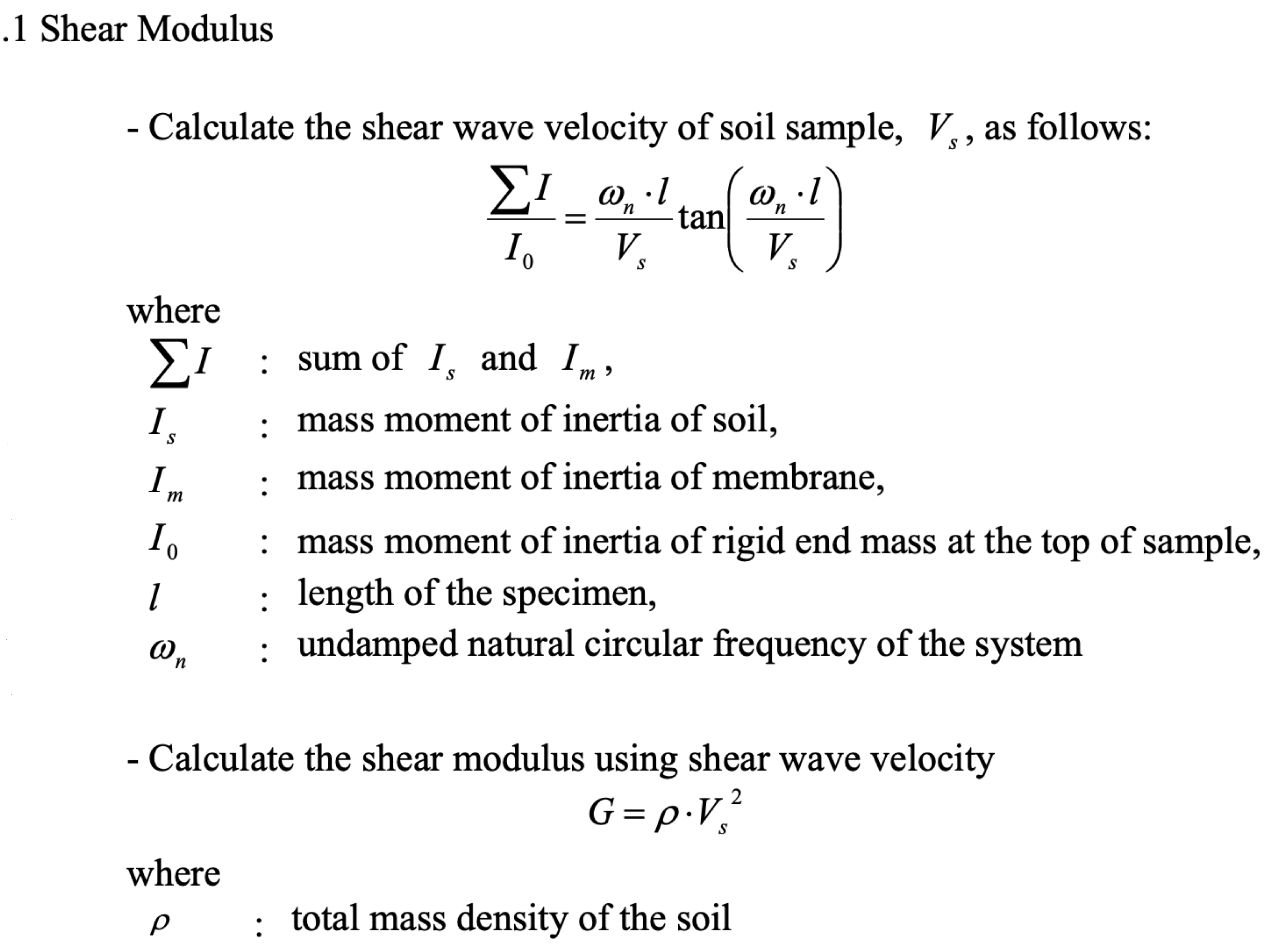
v) Obtain the free-vibration decay curve (using an oscilloscope) by shutting off the driving force while the specimen is vibrating at the resonant frequency. (*or find the frequencies where the amplitude of vibration is 0.707 times of first-mode resonance*.)

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

Extra Material

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

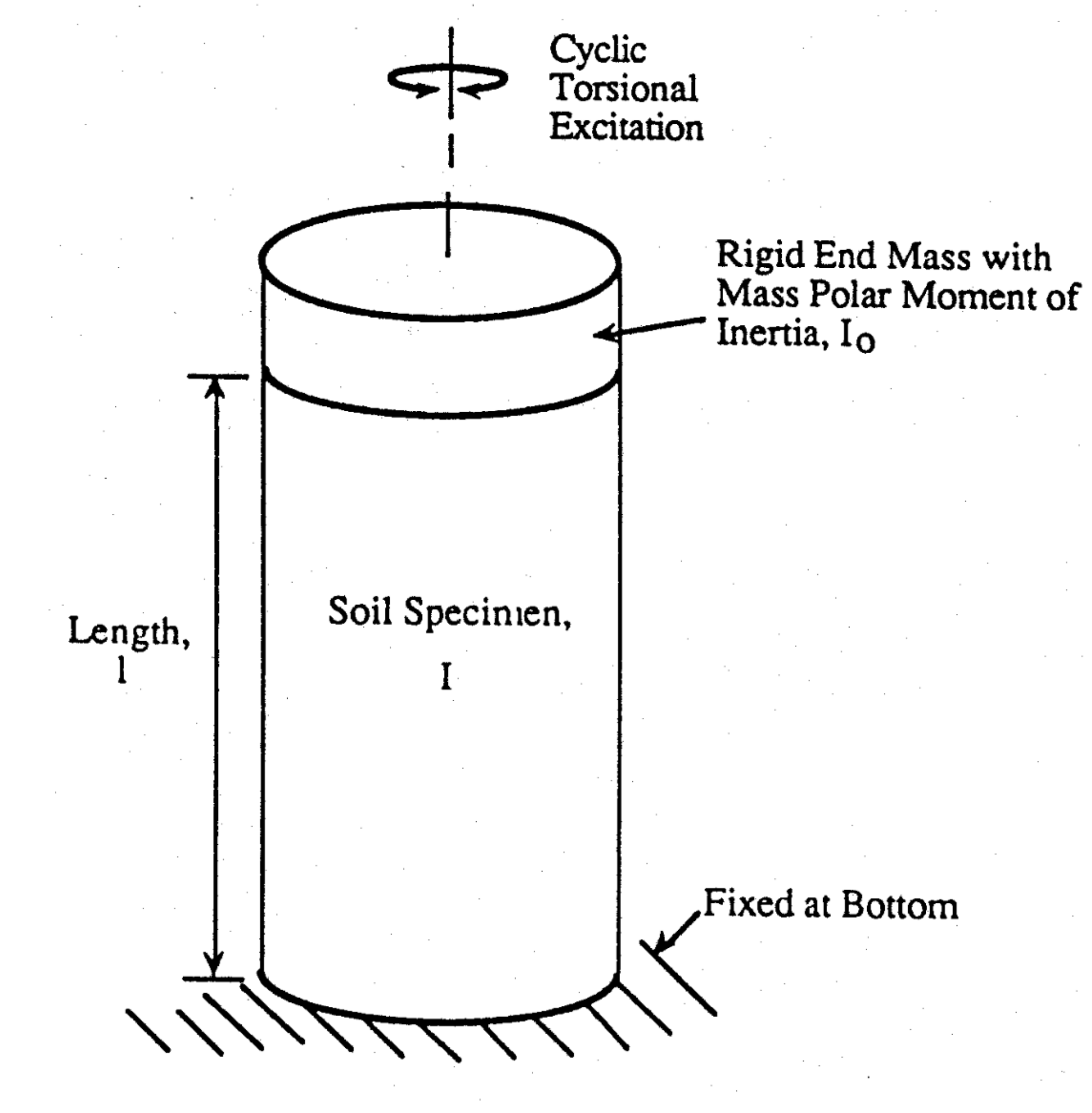
$\sum I$: sum of I_s and I_m,
I_s : mass moment of inertia of soil,
I_m : mass moment of inertia of membrane,
I_0 : mass moment of inertia of rigid end mass at the top of sample,
l : length of the specimen,
ω_n : undamped natural circular frequency of the system

- Calculate the shear modulus using shear wave velocity

$$G = \rho \cdot V_s^{\,2}$$

where

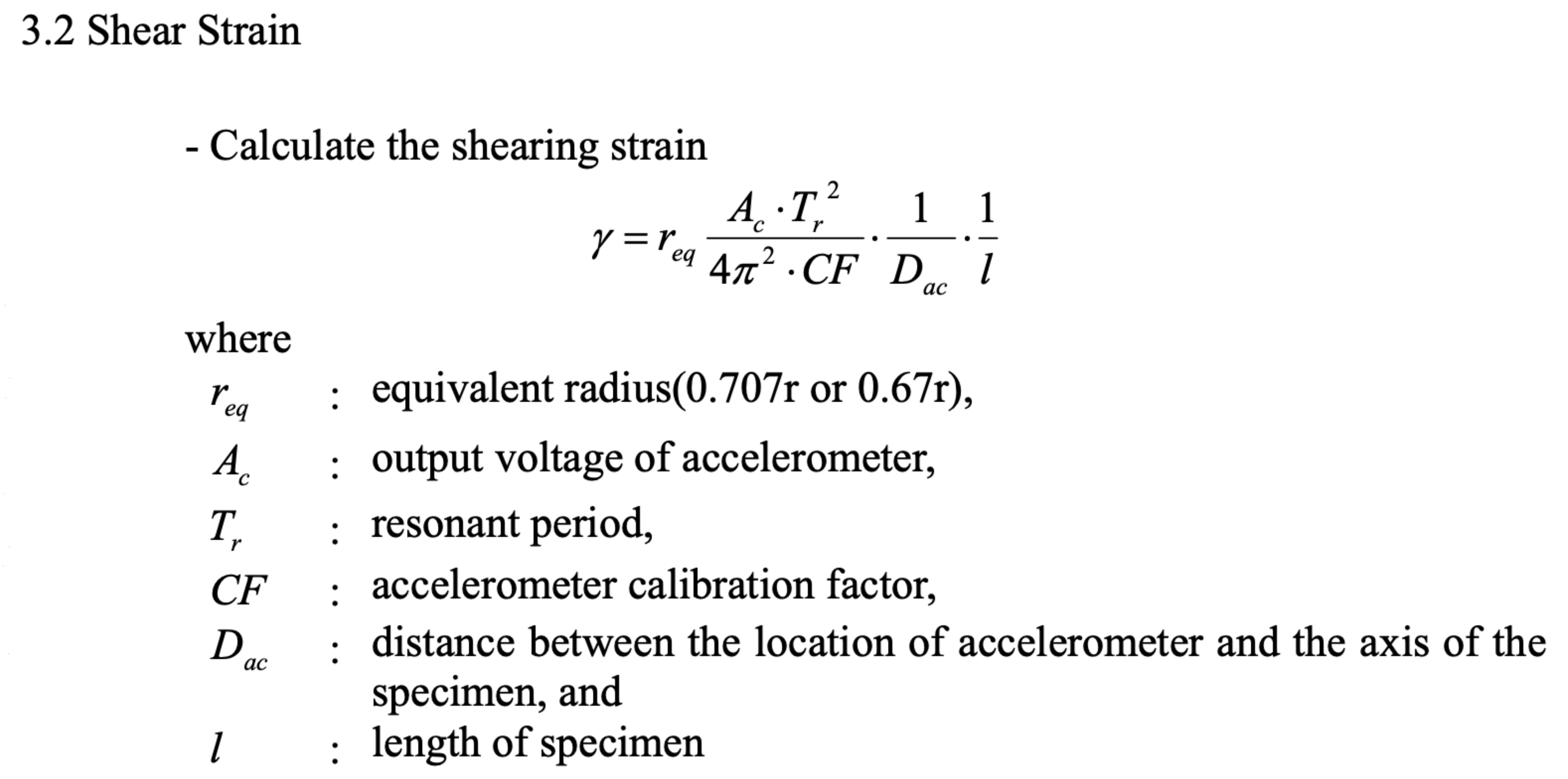
ρ : total mass density of the soil



Extra Material

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),

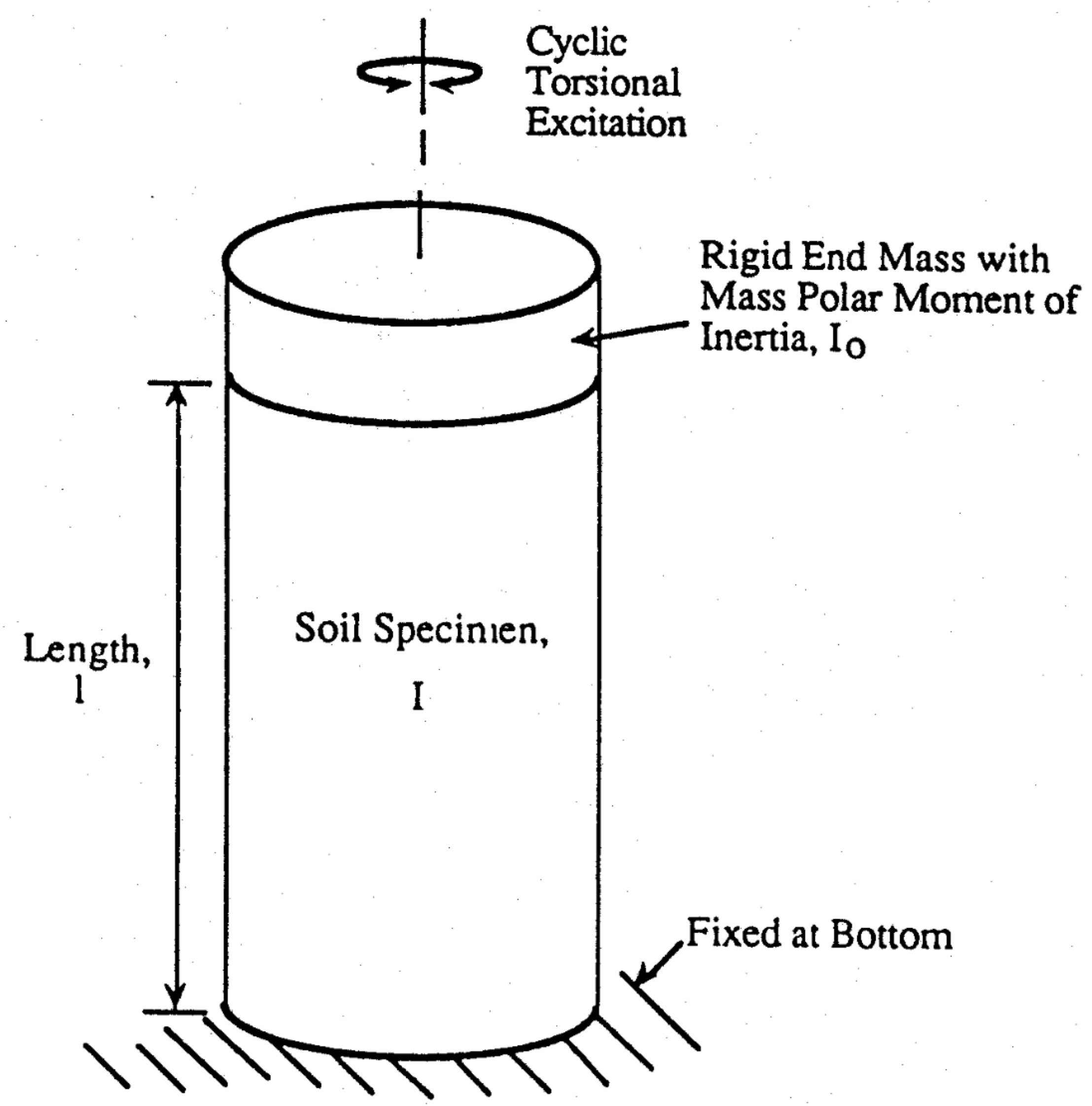
A_c : output voltage of accelerometer,

T_r : resonant period,

CF : accelerometer calibration factor,

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

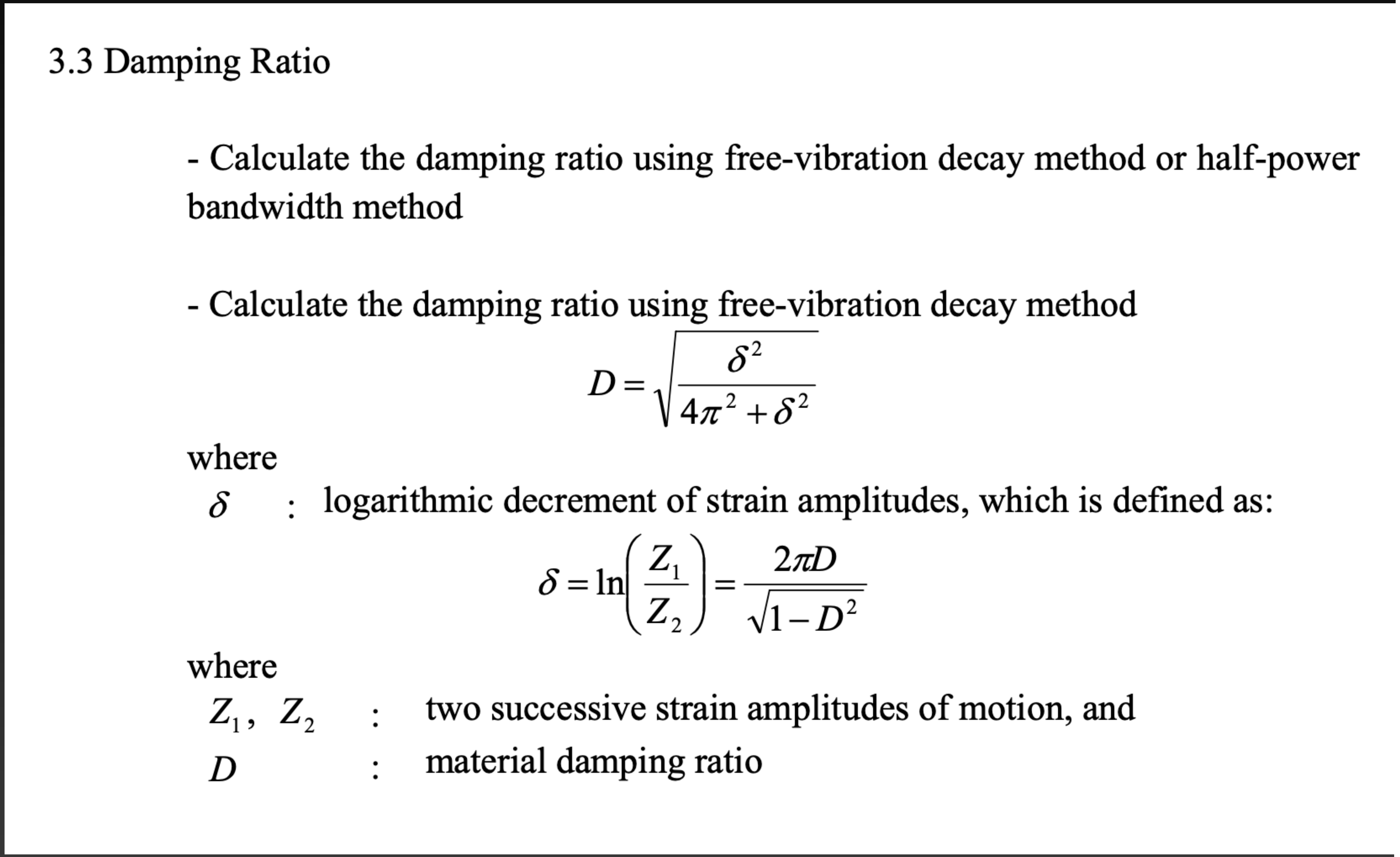
l : length of specimen



Extra Material

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

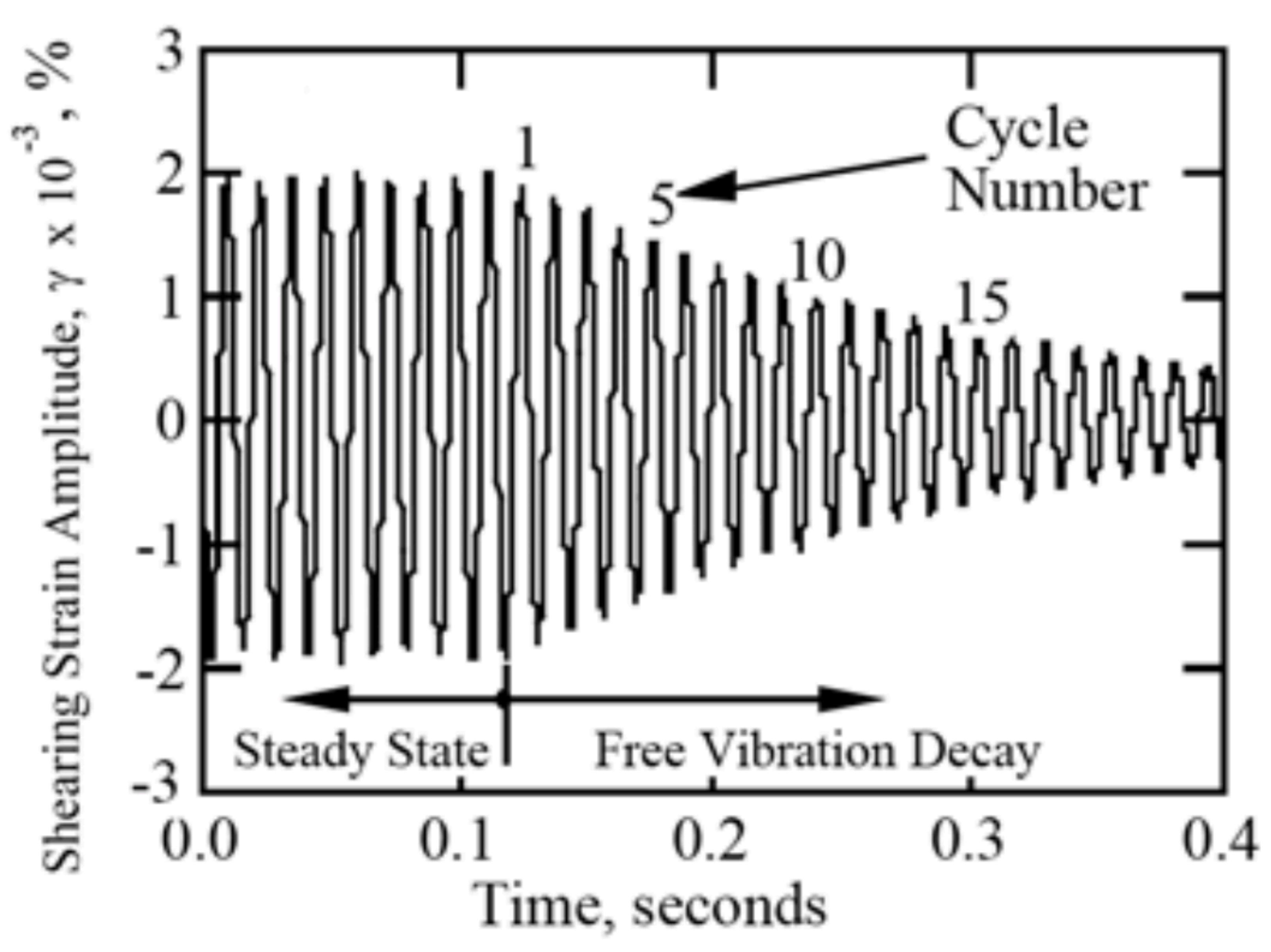
δ : logarithmic decrement of strain amplitudes, which is defined as:

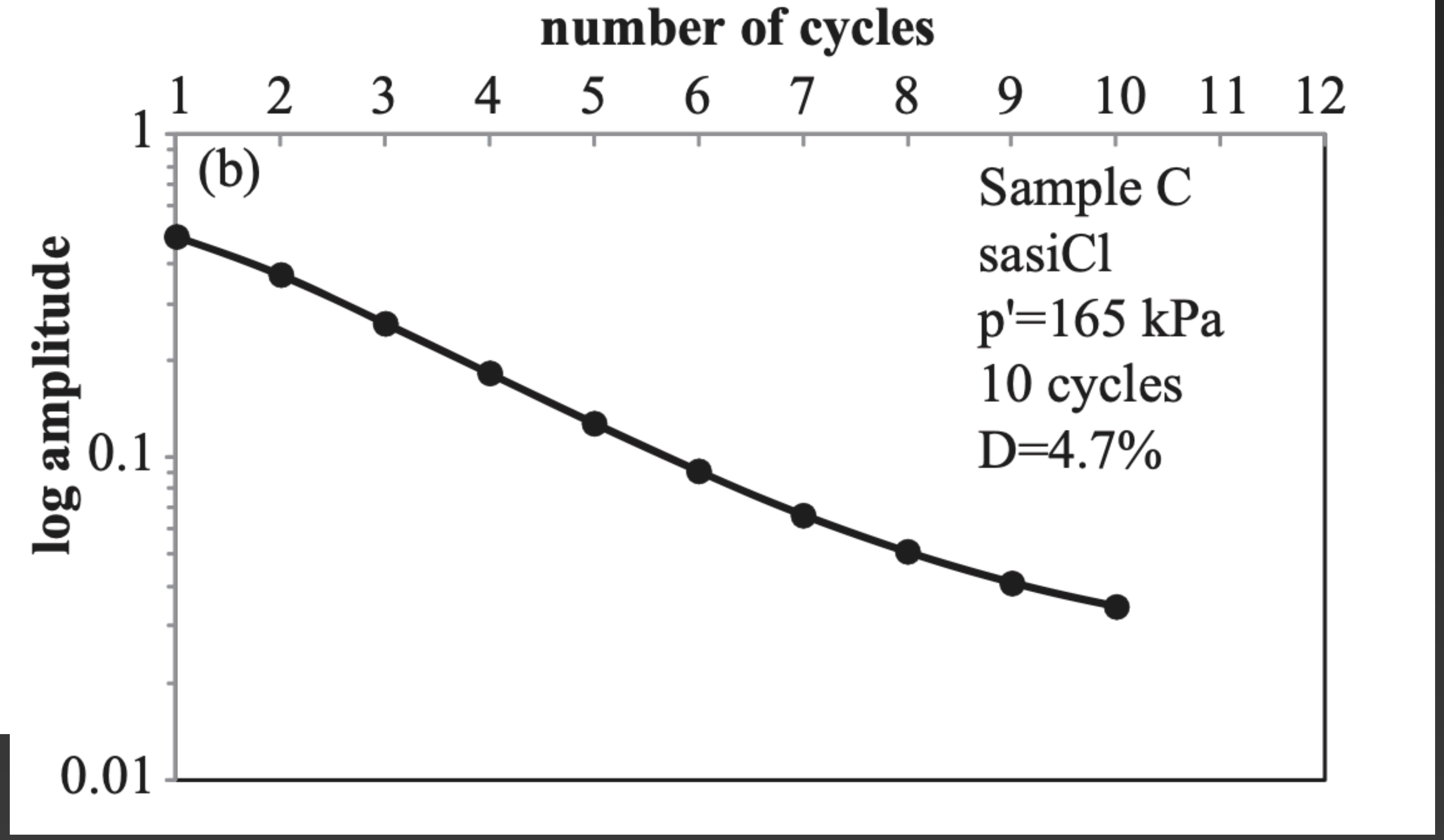
$$\delta = \ln\left(\frac{Z_1}{Z_2}\right) = \frac{2\pi D}{\sqrt{1 - D^2}}$$

where

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

D : material damping ratio

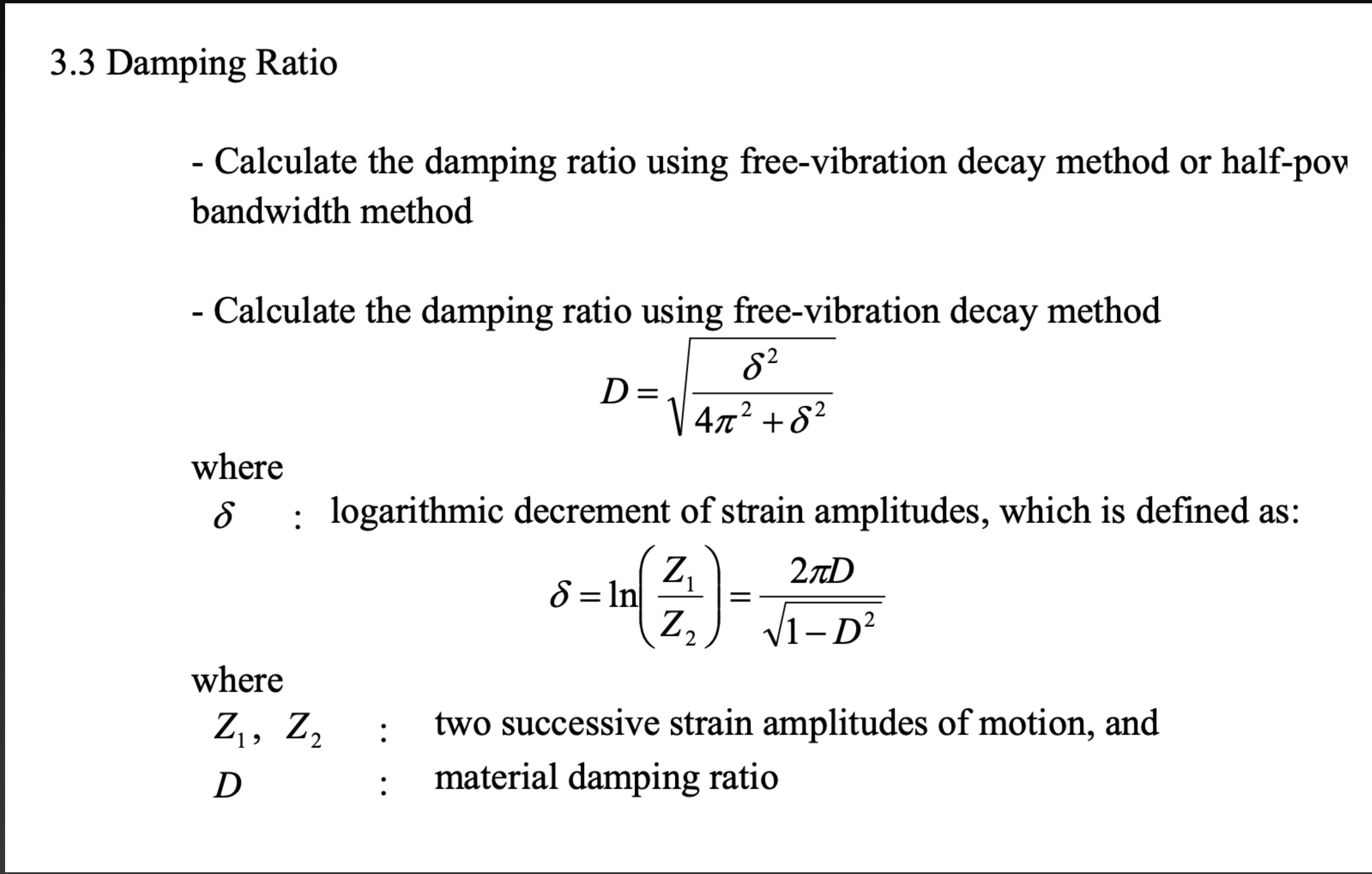




Extra Material

Lab DAMPING with resonant column test

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



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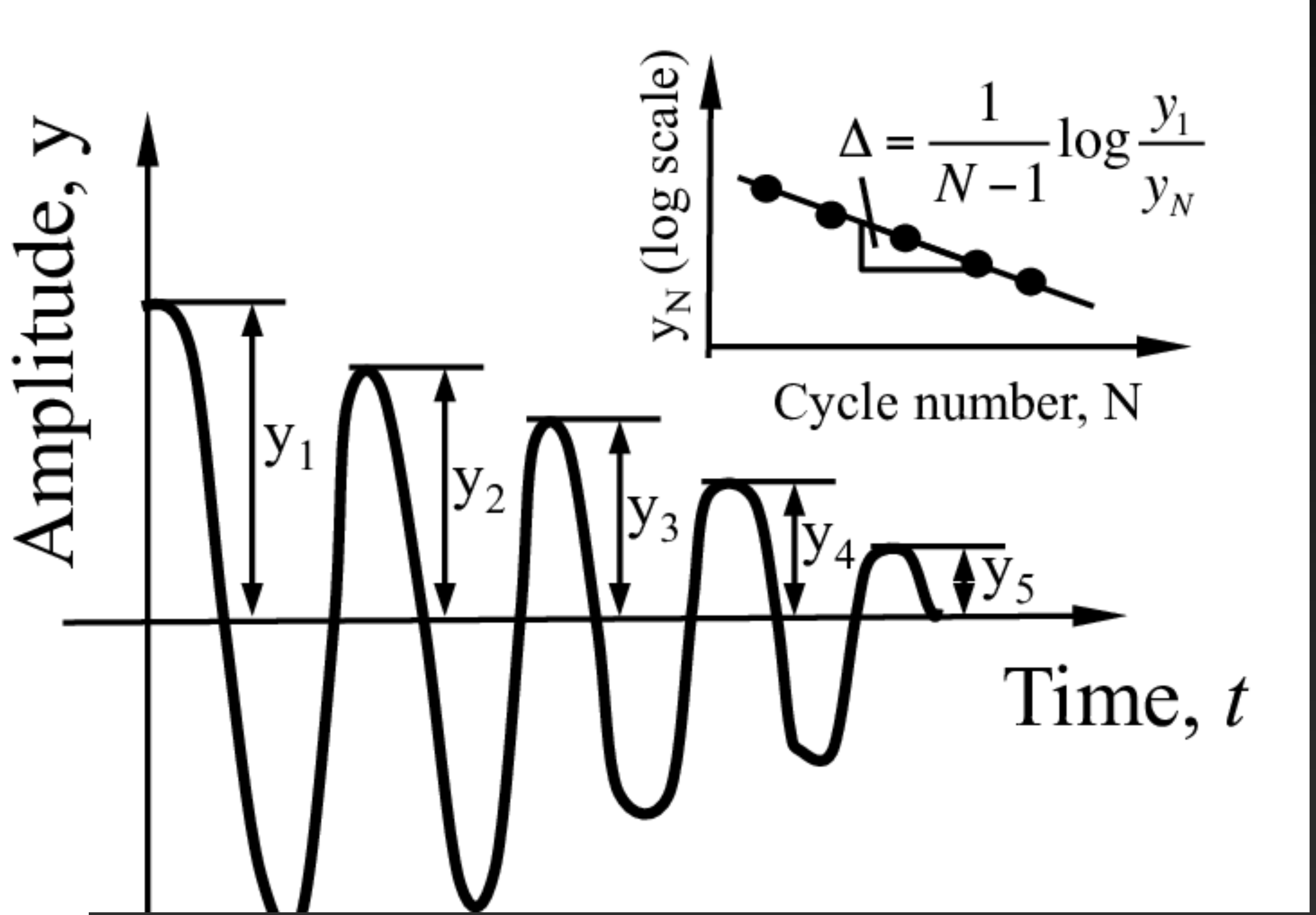
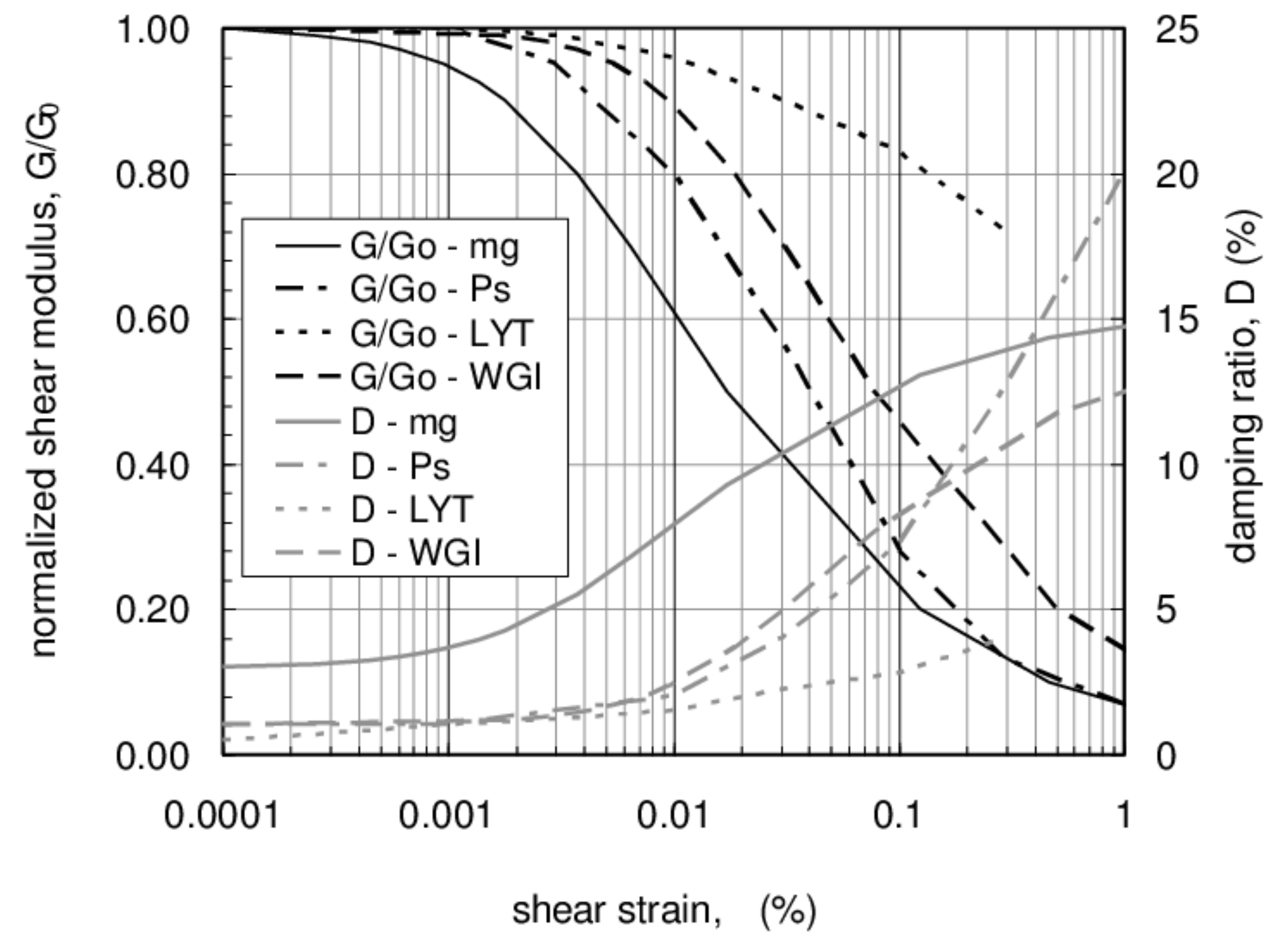


For moderate deformation
D can be assumed as
Independent from frequency !

Extra Material

Lab DAMPING with resonant column test



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

Expressed in function of the

shear strain γ (%)

>> γ >> D (%)

>> γ << G (G/G0)

G0 = Gmax = 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

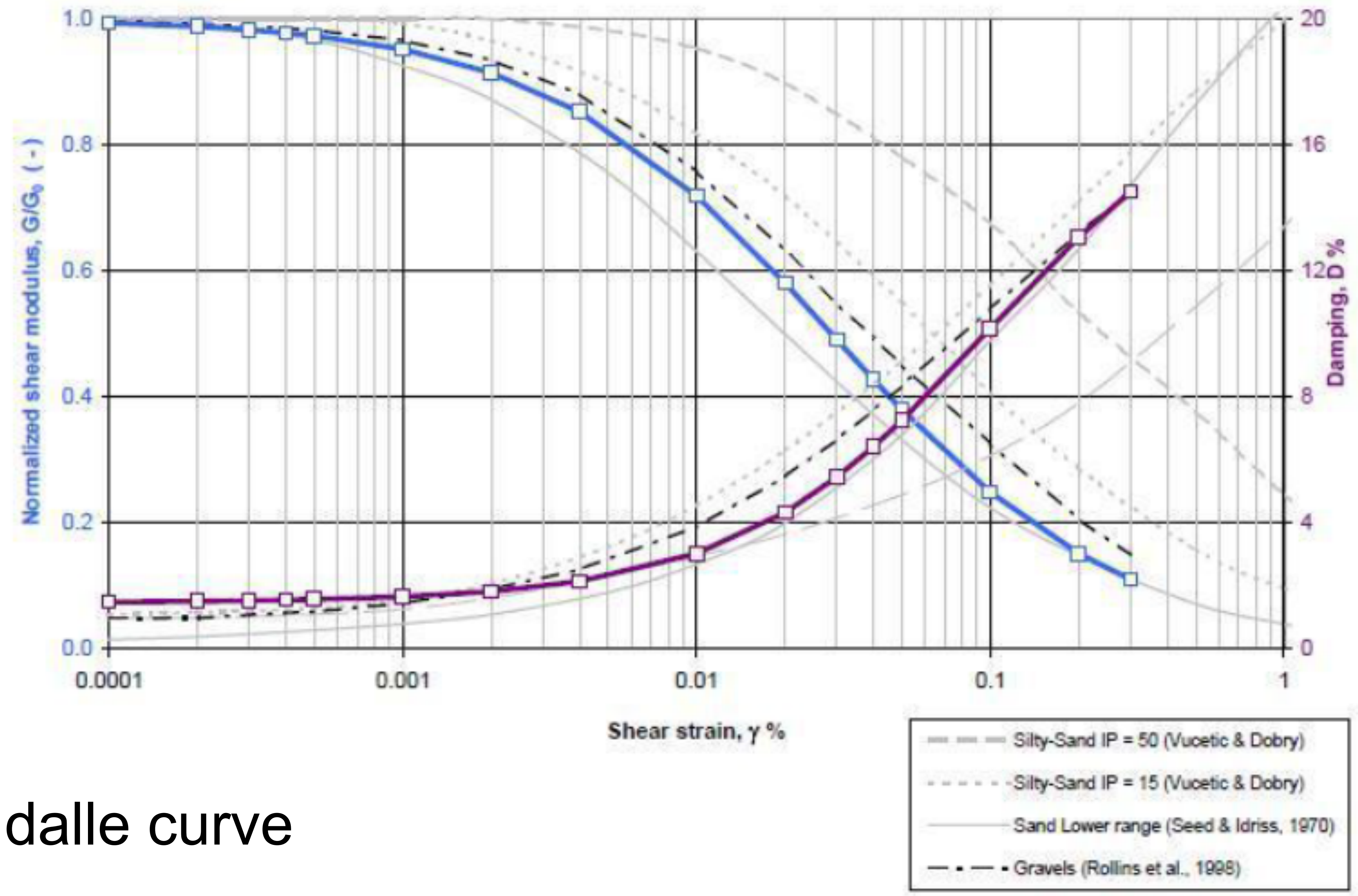
coming from the hyperbolic relationship of *Hardin e Drnevich*

Example for sand

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

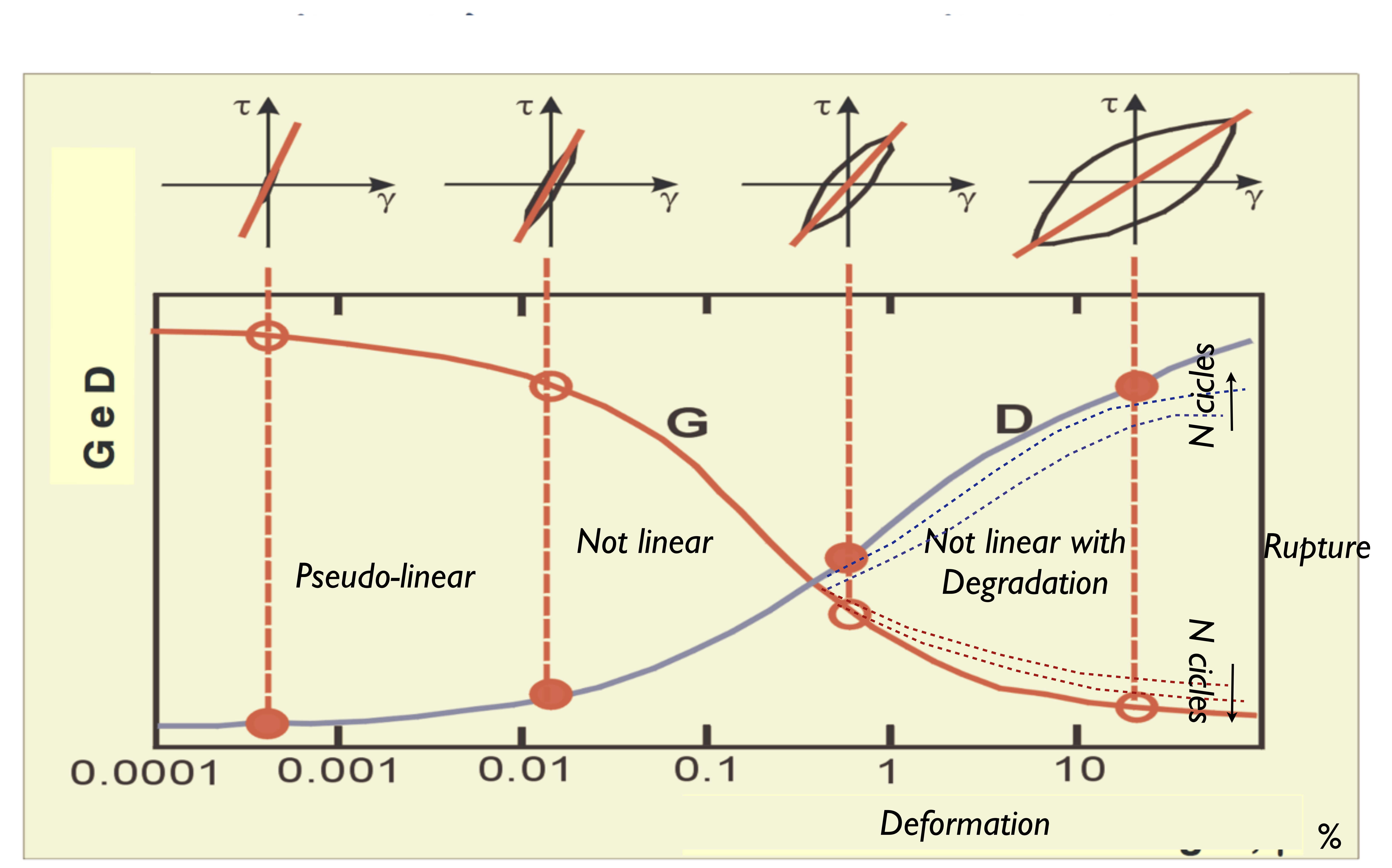
	$\frac{G(\gamma)}{G_0} = \frac{1}{1+\alpha\gamma(\%)^\beta}$	$\frac{D}{D_{max}} = e^{\lambda\frac{G}{G_0}}$
γ (%)	G / G_0 (-)	D (%)
0.0001	0.994	1.498
0.0002	0.988	1.519
0.0003	0.983	1.539
0.0004	0.978	1.558
0.0005	0.974	1.577
0.001	0.952	1.667
0.002	0.915	1.835
0.004	0.853	2.152
0.01	0.719	3.033
0.02	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

Valori selezionati dalle curve



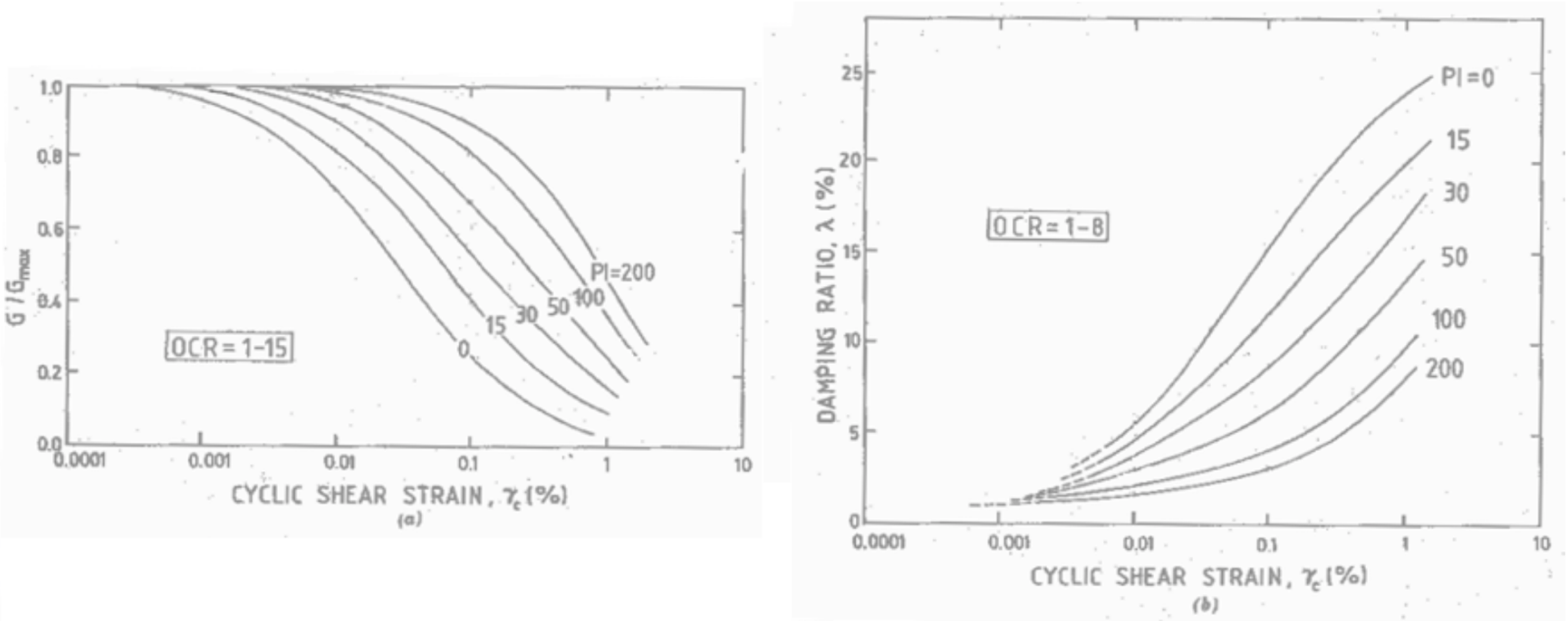
Soil under cyclic loads

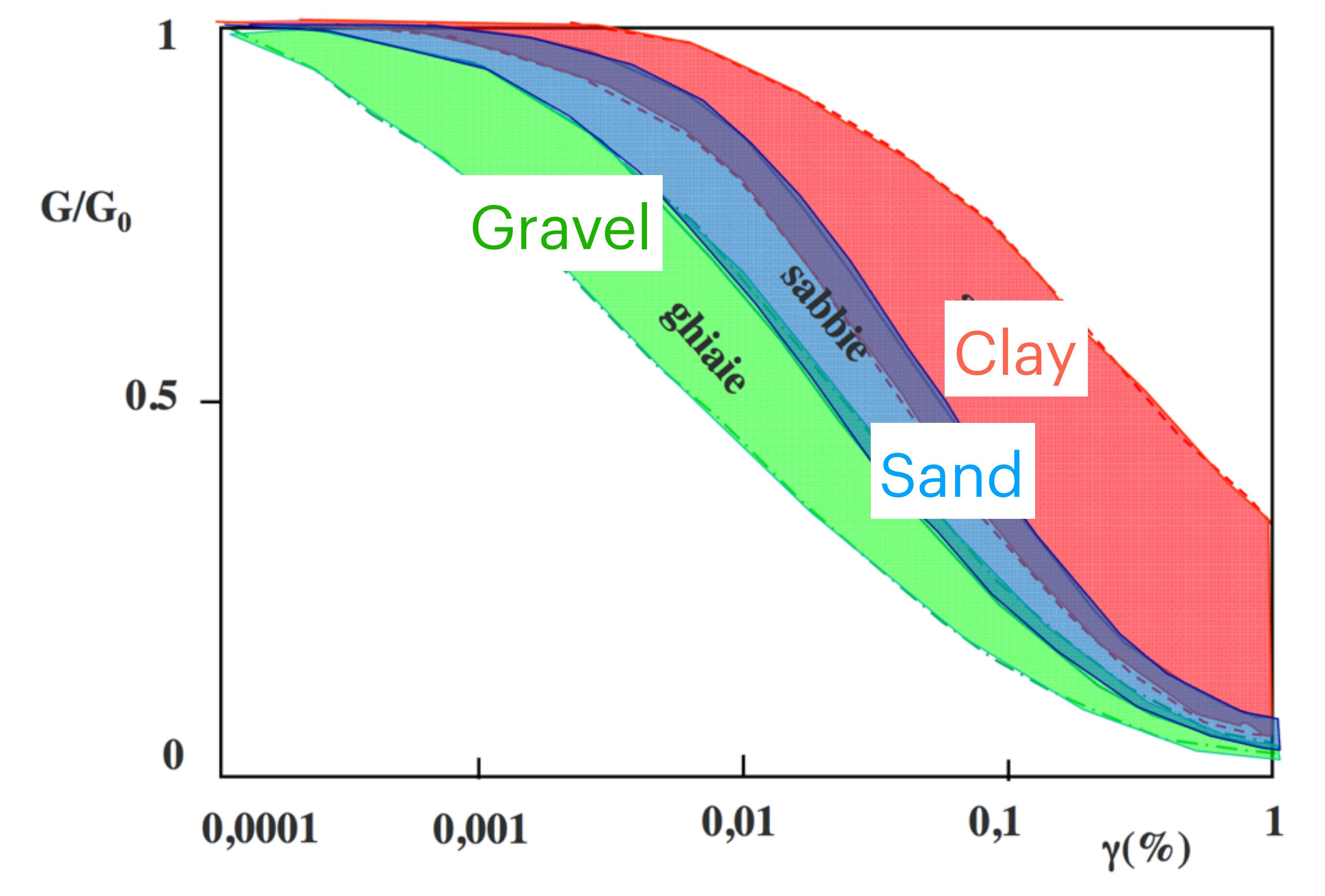
G e D vary in function of deformation ɣ NOT LINEAR!



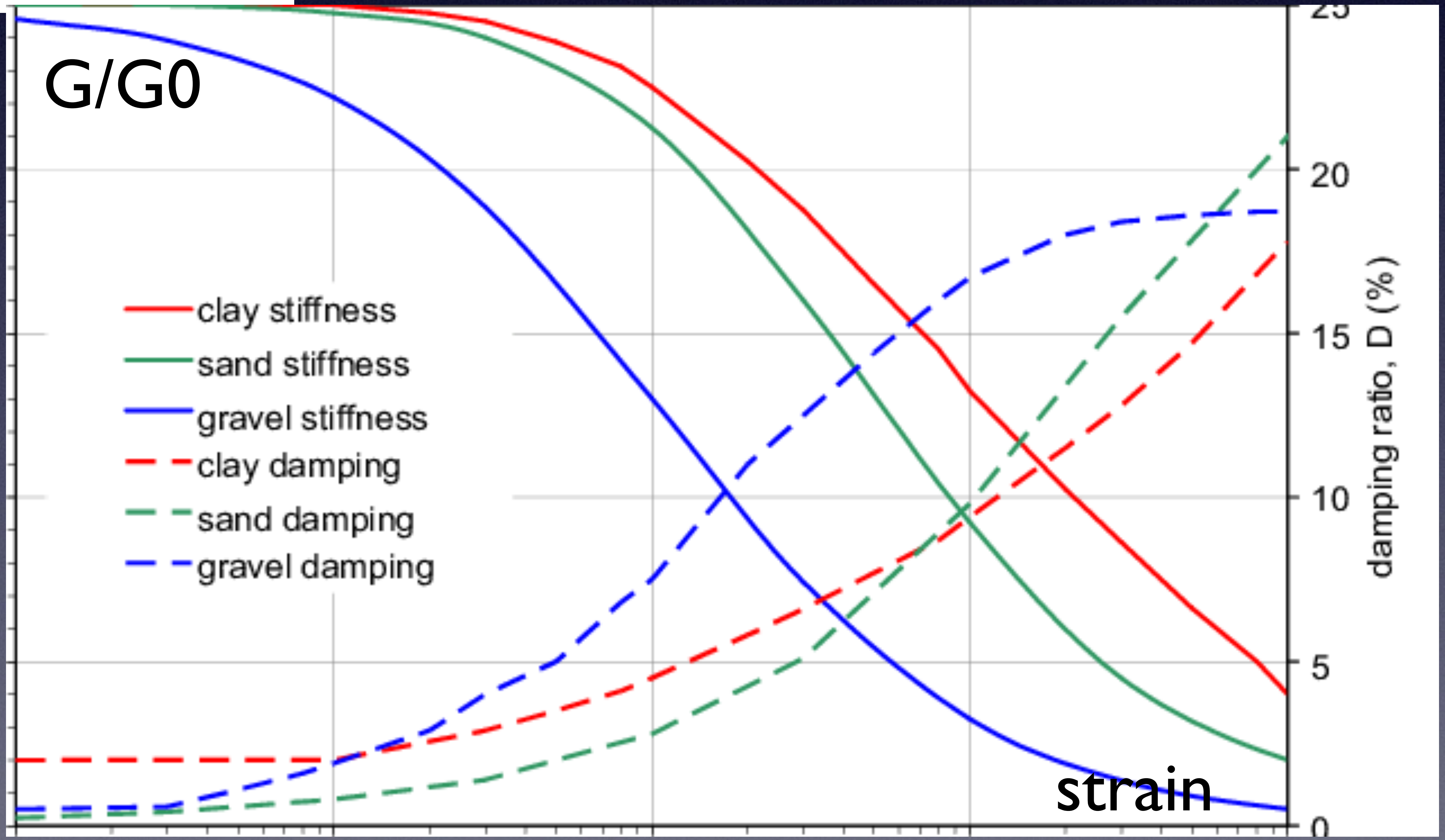
G e D curves in function of soil type

e.g. clay, sand, gravel…





(Seed et al., 1986; Dobry & Vucetic, 1987)

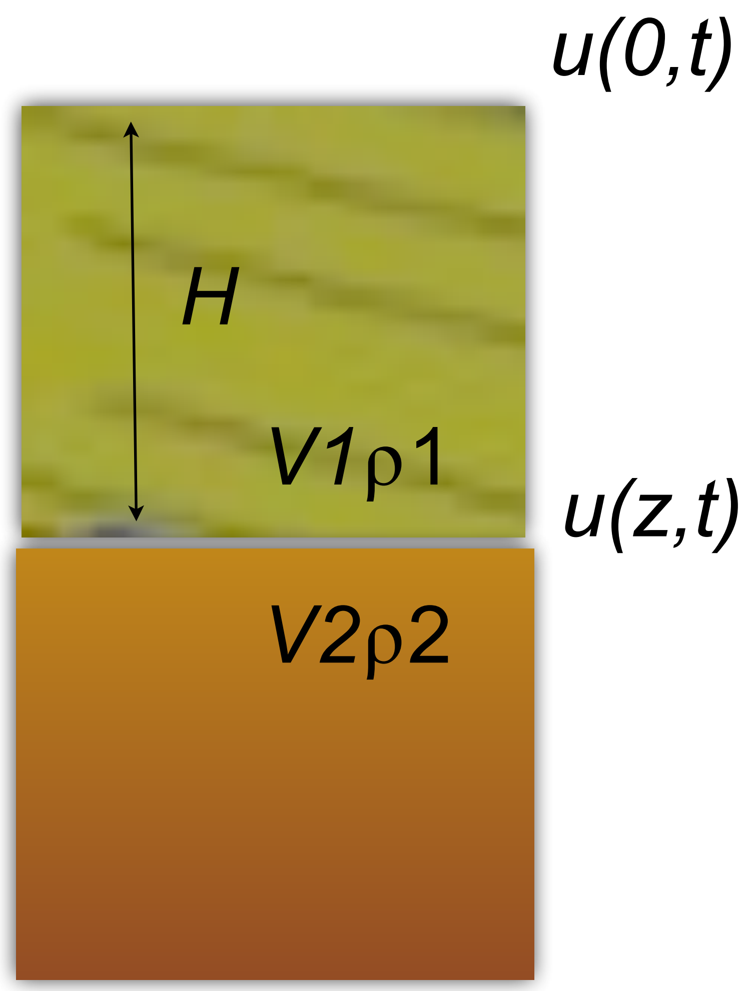


Soil visco-elastic homogeneous on rigid plate (kelvin-voigt)

Dynamic equilibrium equation

Viscosity Coefficient

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



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

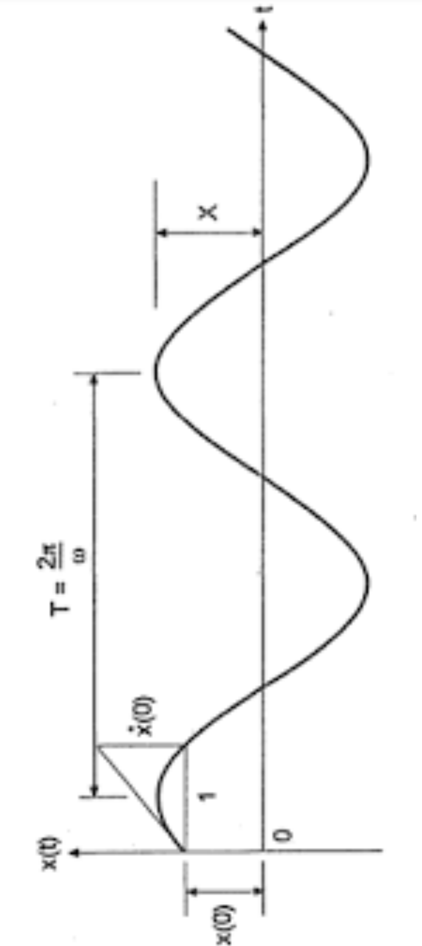
Viscosity

Frequency

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

DAMPING

G modulus



Soil visco-elastic homogeneous (kelvin-voigt)

Transfer Function

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

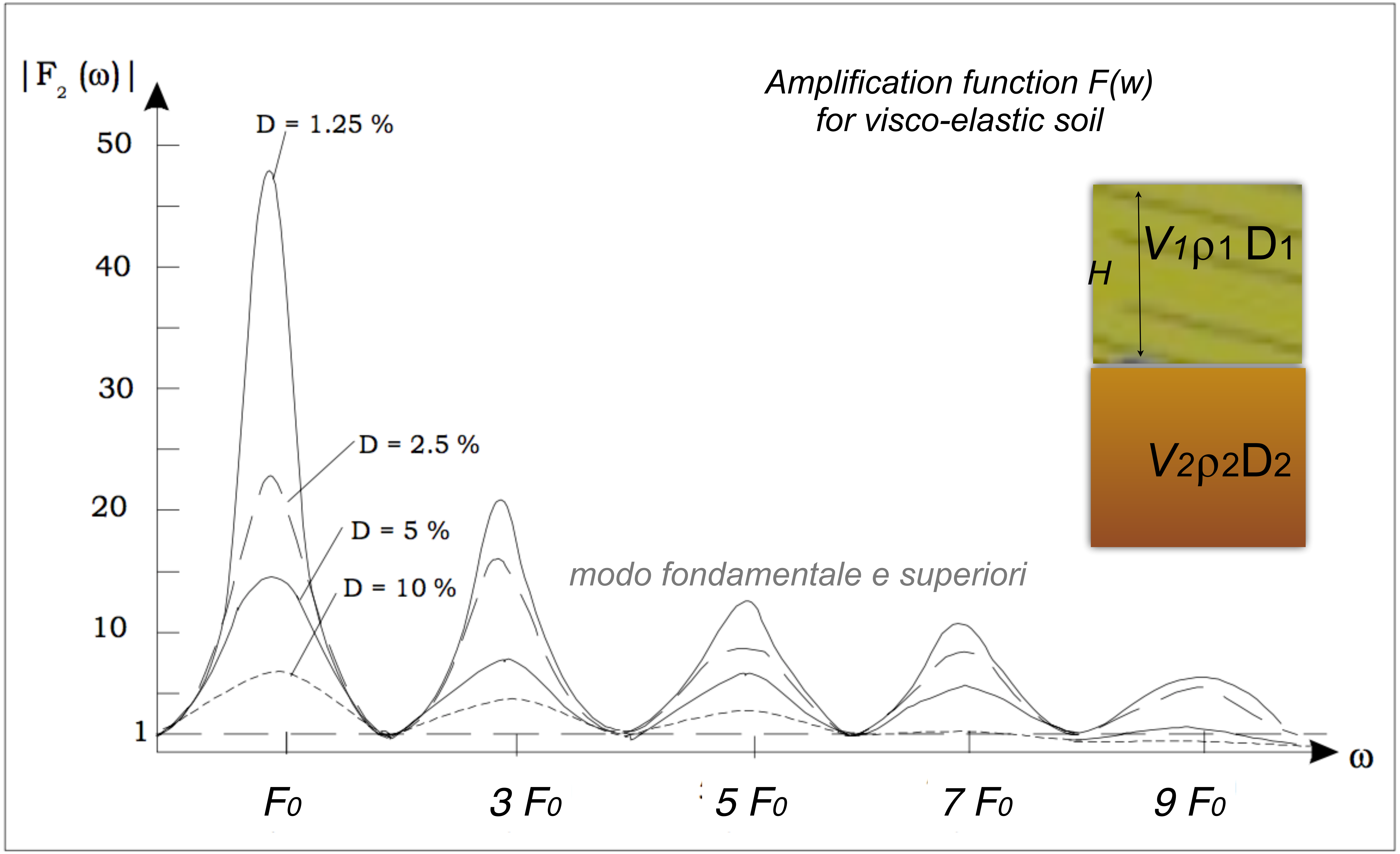
$$Vs = \sqrt{\frac{G}{\rho}}$$

Amplification Function = $\left|H\,(\omega)\right|$

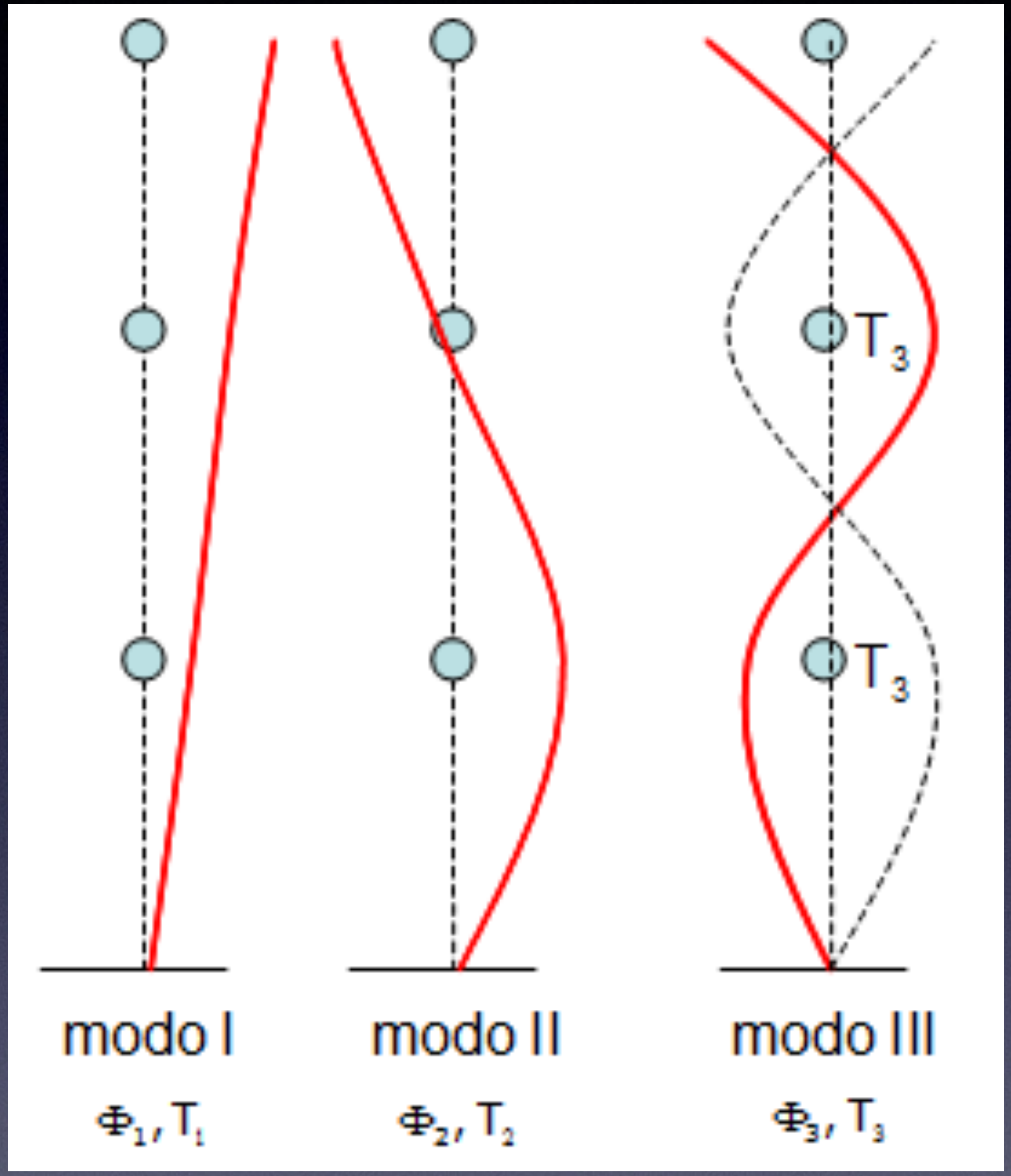
$$F\,(\omega) = \frac{1}{\sqrt{\cos^{2}\left(\frac{\omega\,H}{Vs}\right) + \left(D\frac{\omega\,H}{Vs}\right)}}$$

D

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



Amplification function F(w)
for visco-elastic soil



Modes

(n=1 fundamental mode)

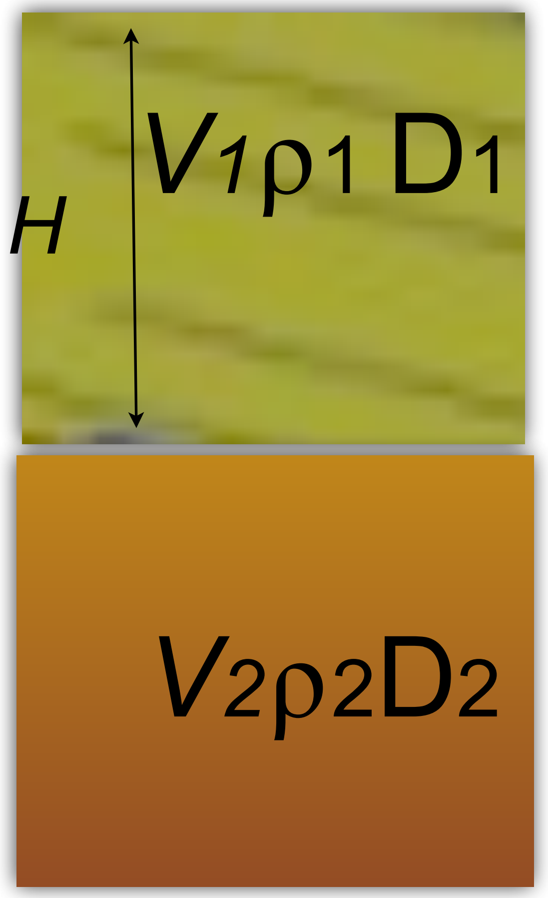
$$u(z,t) = Ae^{j(k z+ \omega t)}$$

Solution

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

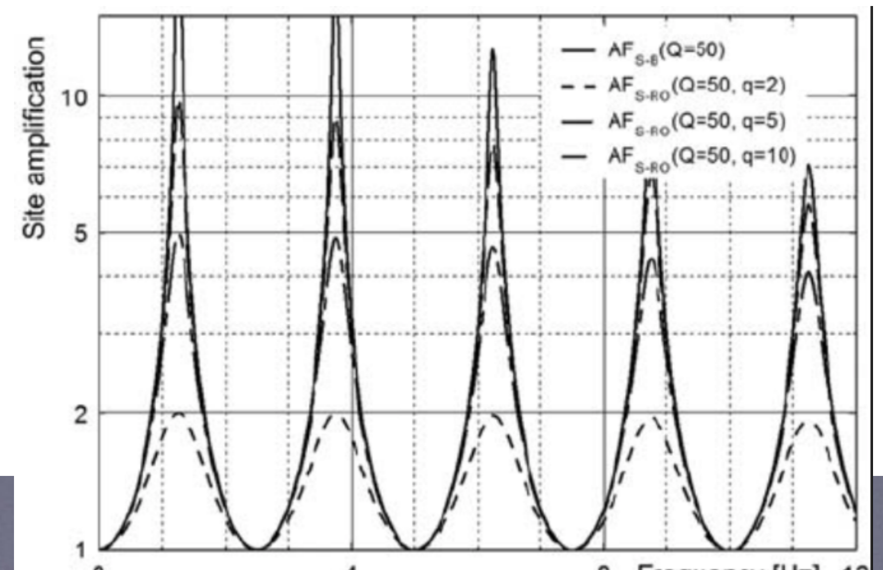
EQUAZIONE EQUILIBRIO DINAMICO

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



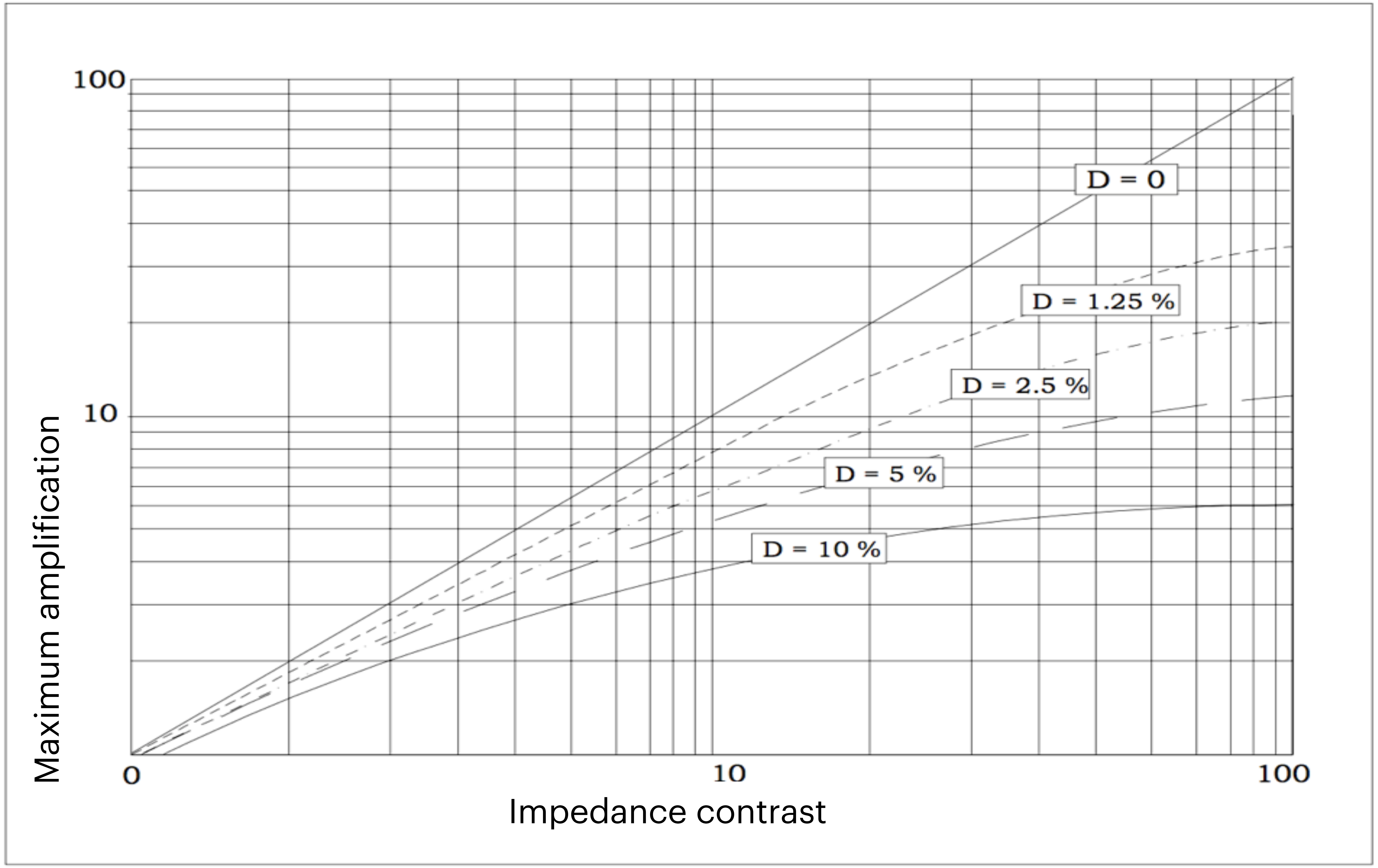
Solution no more in simple formulation
Amplification factor must be approximated (Roesset , 1970)

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



IMPEDANCE CONTRAST

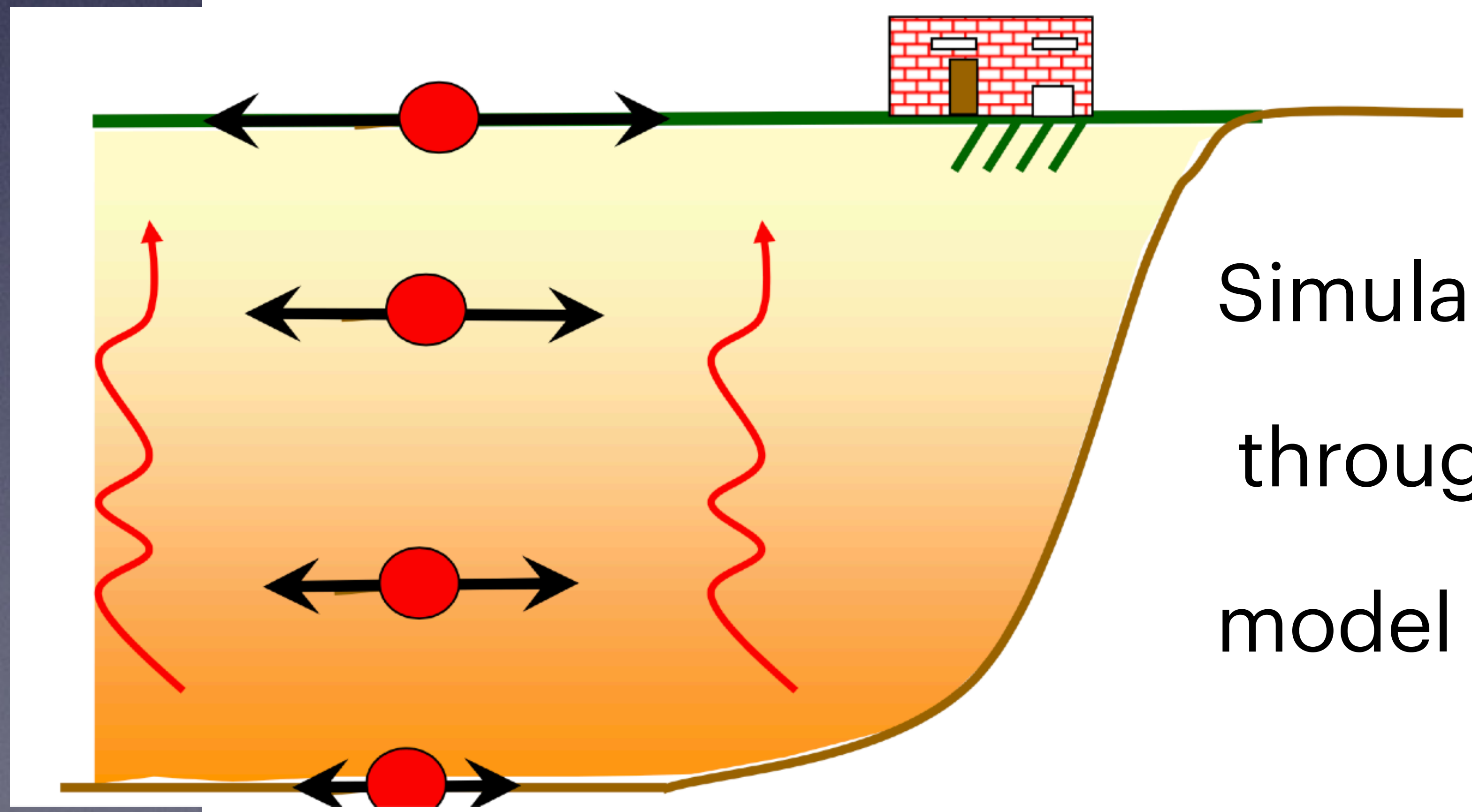
$$i = \frac{V1\,\rho 1}{V2\,\rho 2}$$



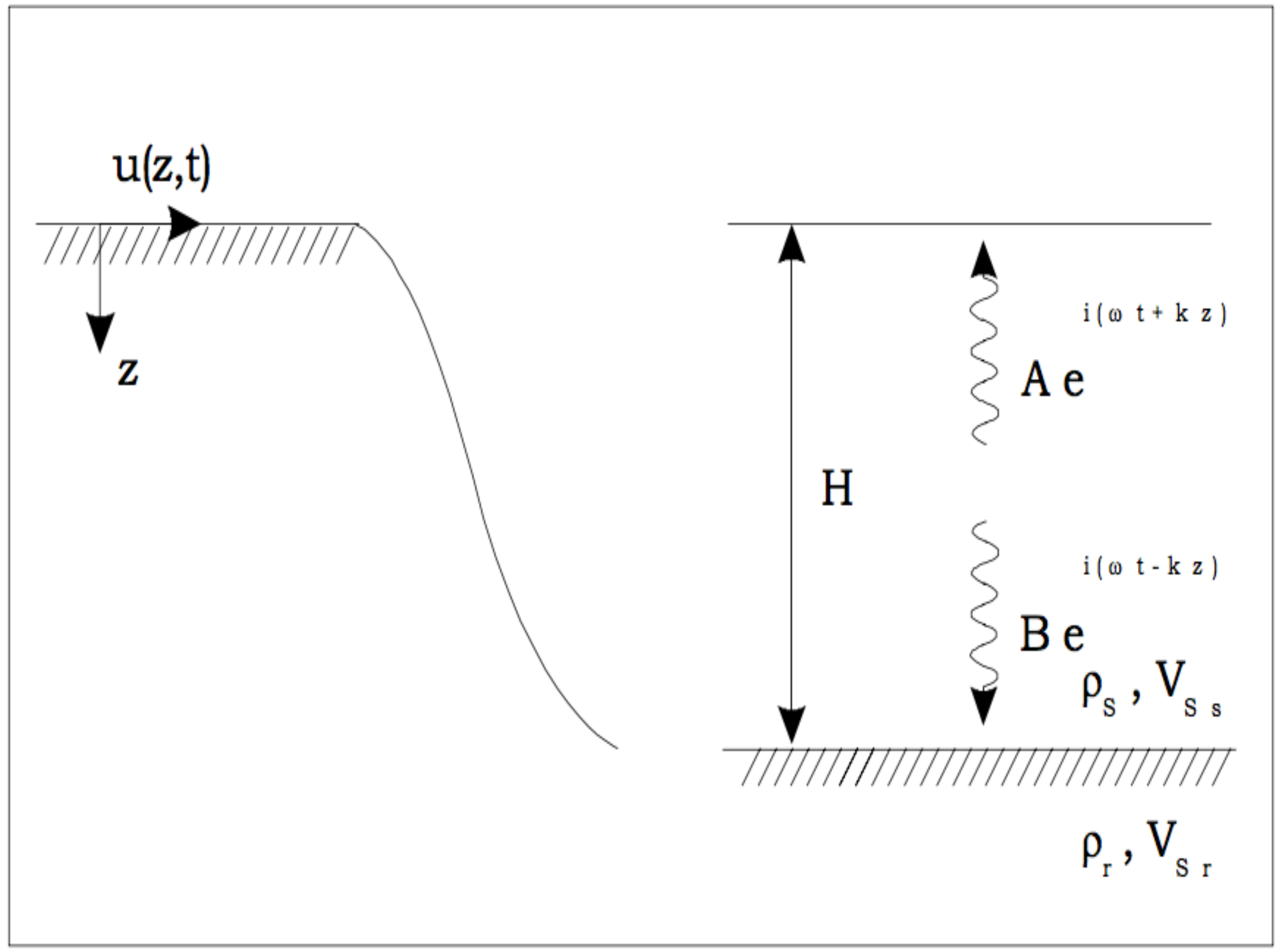
Response depends on impedance contrast and damping D

Numerical methods for Seismic response analysis

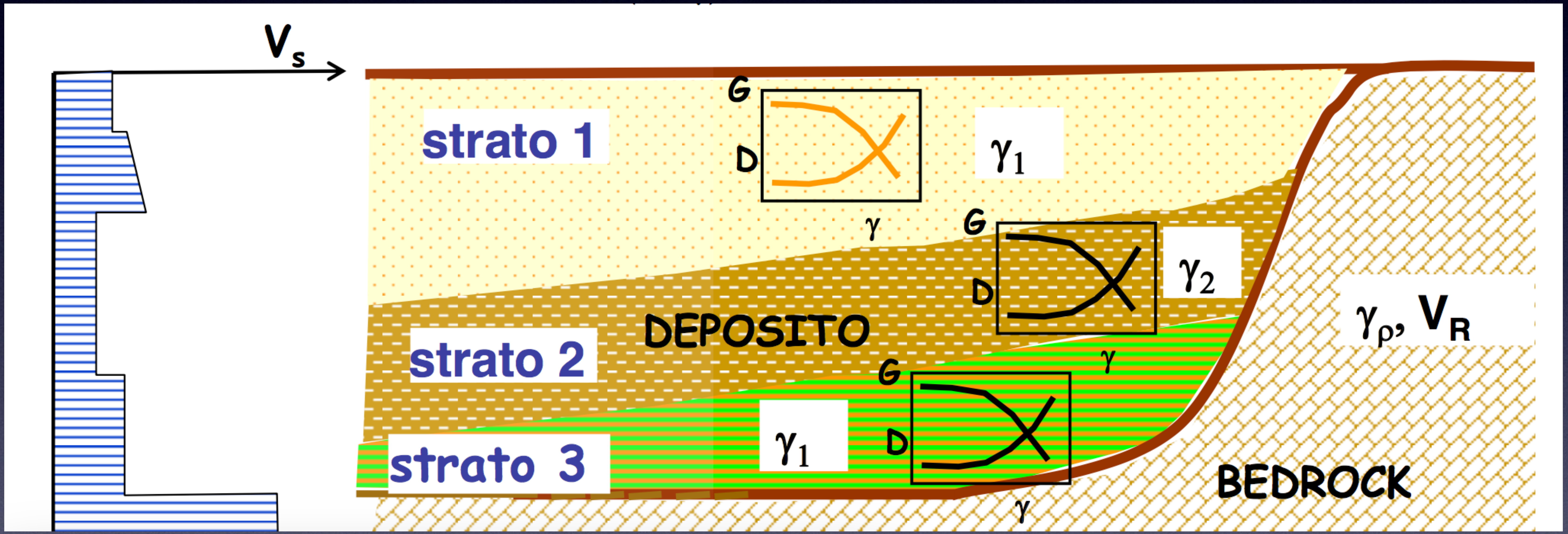
$$\rho \frac{du^{2}}{dt^{2}} = G \frac{du^{2}}{dz^{2}} + \eta \frac{du^{3}}{dt\, dz^{2}}$$



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)

Codes for the RSL

Frequency domain
Shake, EERA, Strata,...

Time domain
DESRA, FLAC, QUAD4, ...

1D, 2D, etc.

Continuous models

Codes for the RSL

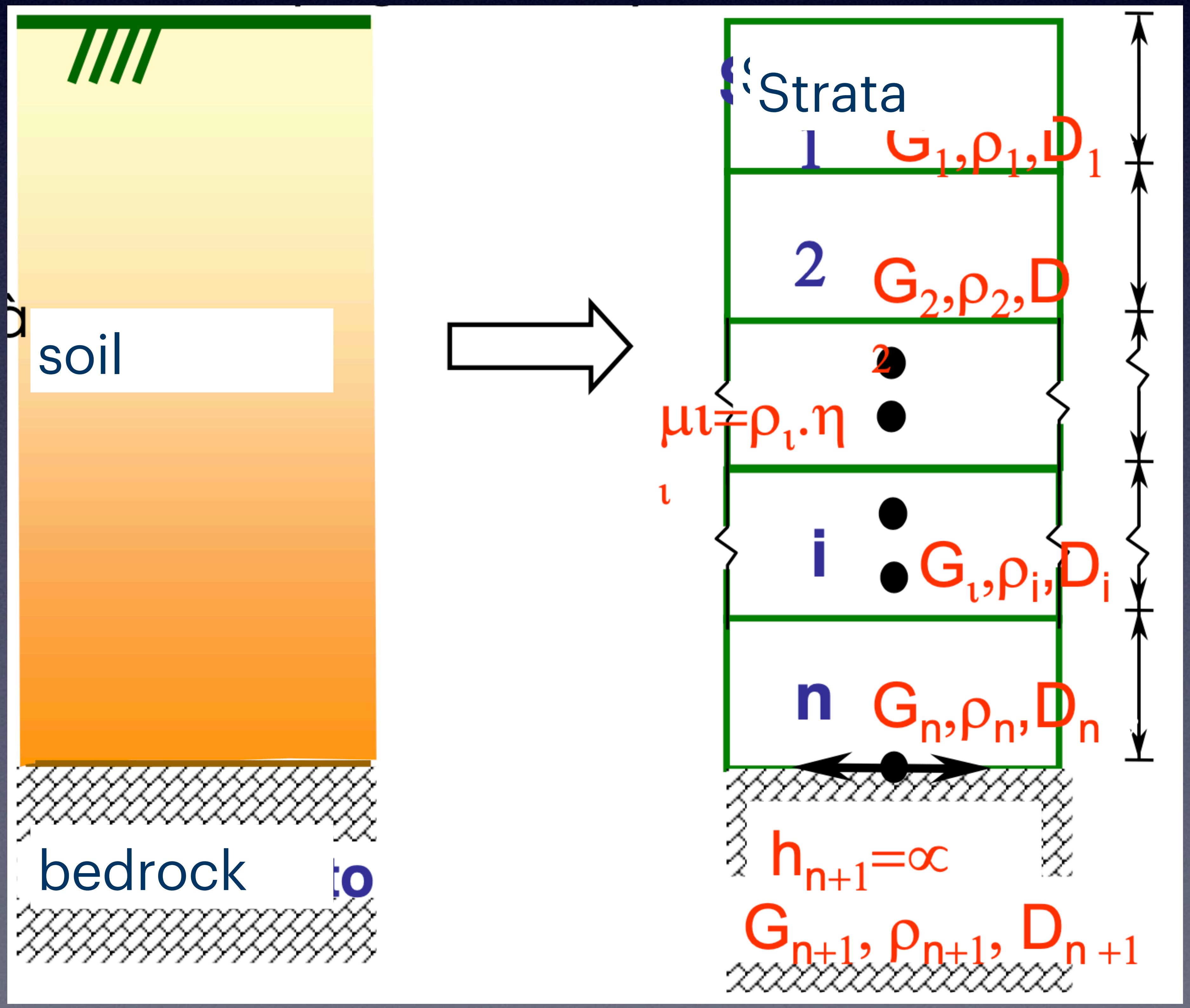
Discrete models

1D, 2D, etc.

Seismic Response Analysis

Linear-equivalent methods

e.g. Shake, Strata, Pro Strata (the most used code in engineering)



We need:

1. Vs (G), thickness and Damping for each soil layer

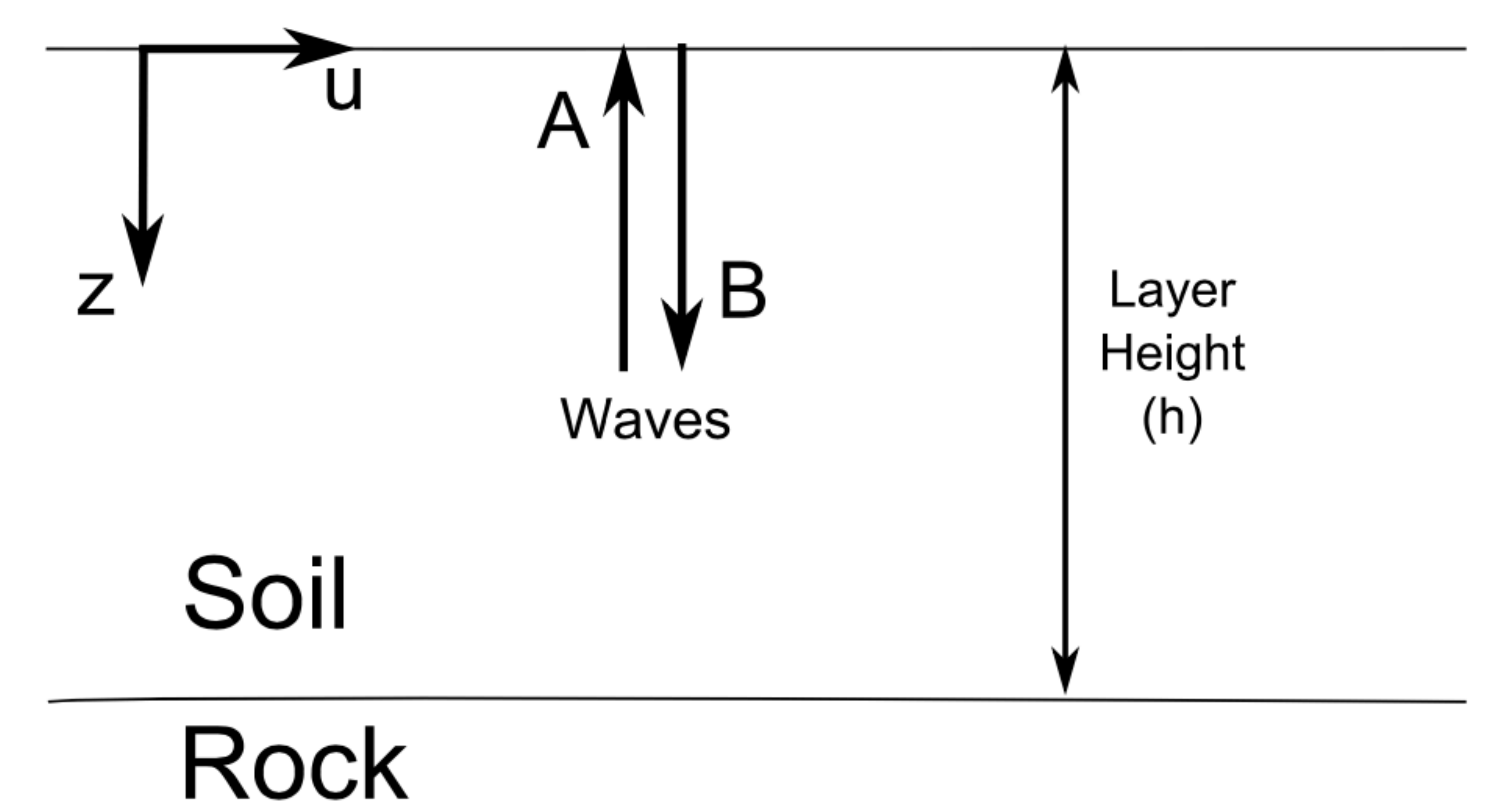
2. An earthquake as input

Seismic Response Analysis

Linear-equivalent methods

Iteratively consider non linearity in the response

u= displacement, t= time, k=wavenumber, z=depth, w = angular frequency

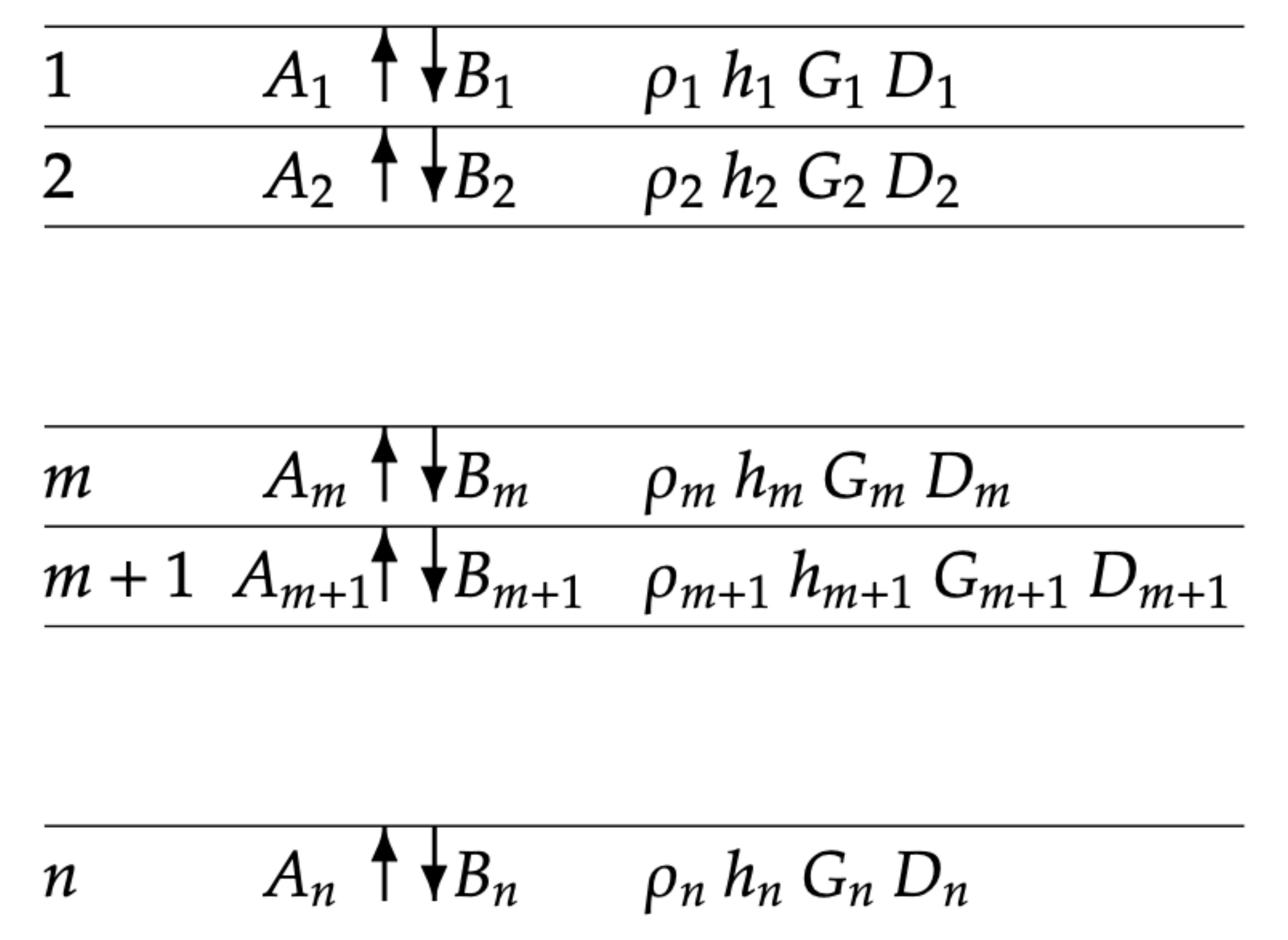


$$u(z,t) = A\exp\left[i\left(\omega t + k^{*}z\right)\right] + B\exp\left[i\left(\omega t - k^{*}z\right)\right]$$

A and B wave amplitudes

A direct waves

B reflected waves



Multi-layers models

Seismic Response Analysis

Linear-equivalent methods

Iteratively consider non linearity in the response

u= displacement, t= time, k=wavenumber, z=depth, w = angular frequency

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

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

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

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

We need

the strain in each layer

(that is function of G and D)

Vs = shear velocity, G = shear modulus, D = damping ; ρ = density

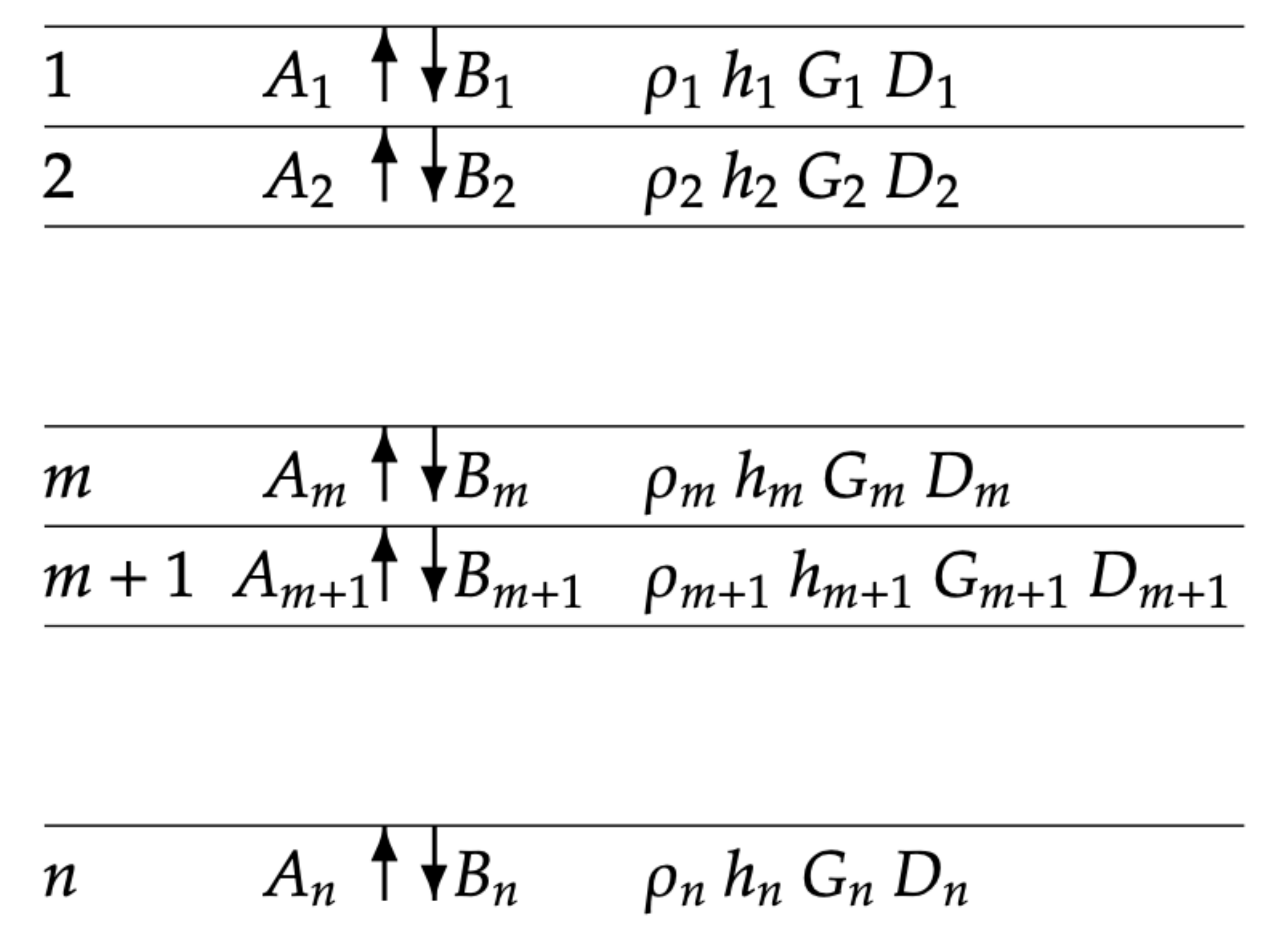
Seismic Response Analysis

Linear-equivalent methods

Iteratively consider non linearity in the response

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

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



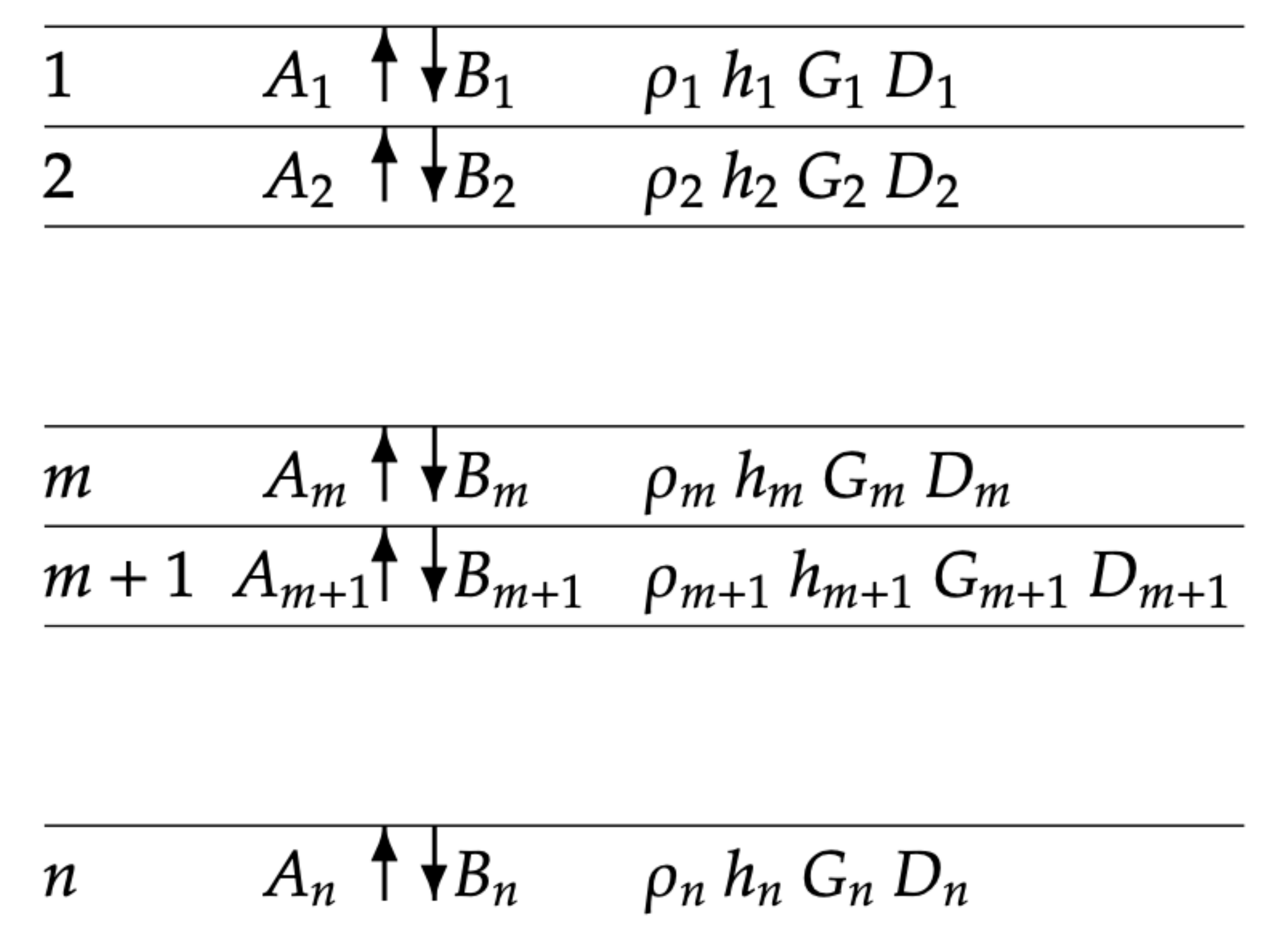
The codes compute the strain transfer Function between the layers m, m+n, (generally at the middle of the layer Hm/2)

Seismic Response Analysis

Linear-equivalent methods

Iteratively consider non linearity in the response

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



As starting condition it uses the initial values:

$G=G_o= Gmax$

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

$D= D_o =Dmin$

Seismic Response Analysis

Linear-equivalent methods

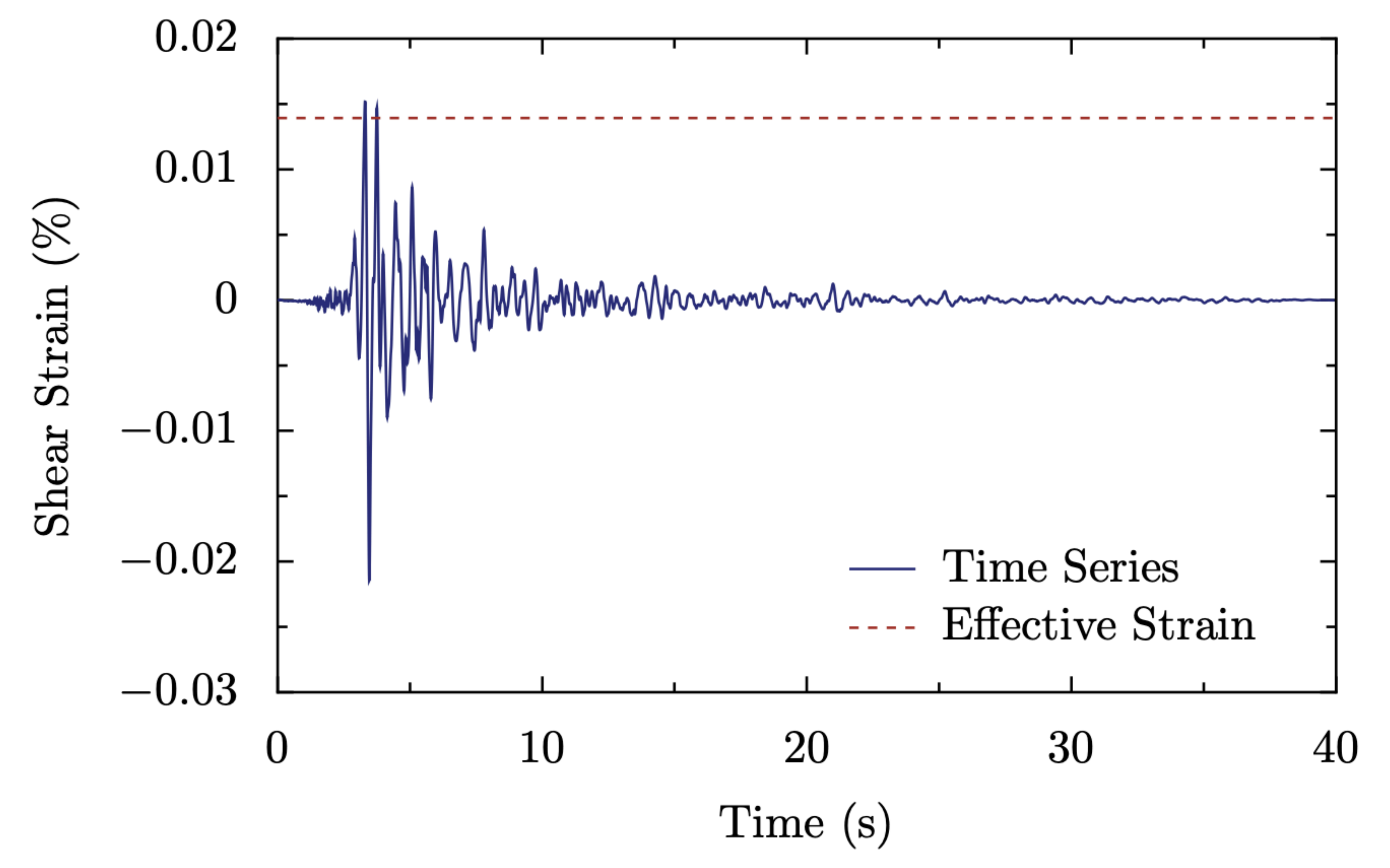
Since the maximum strain γ for Gmax refers to a very short moment,

A more realistic effective strain is preferred

usually γeff=65% of γmax

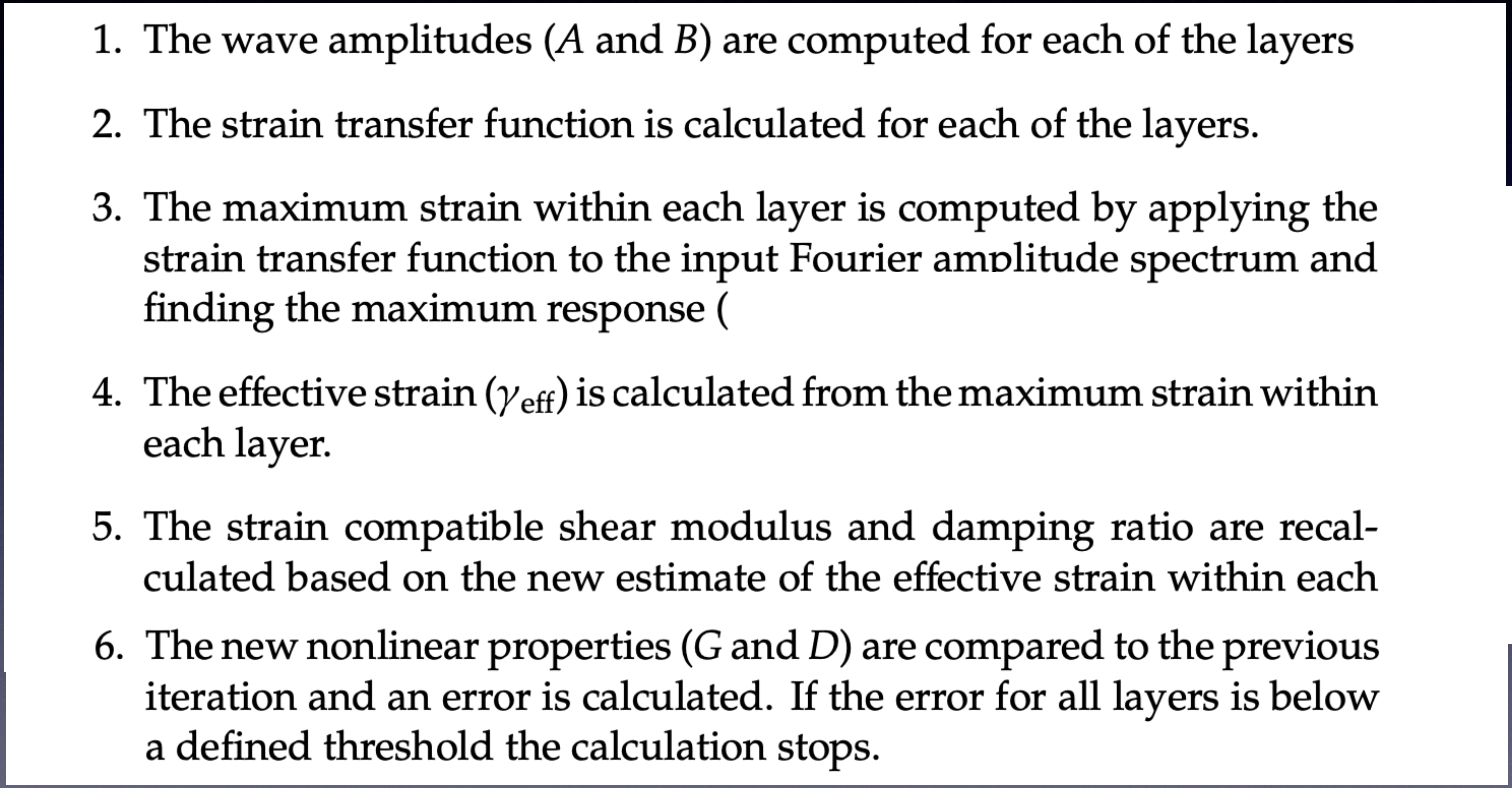
γeff = β γmax

β = 0.65 - 0.7 range

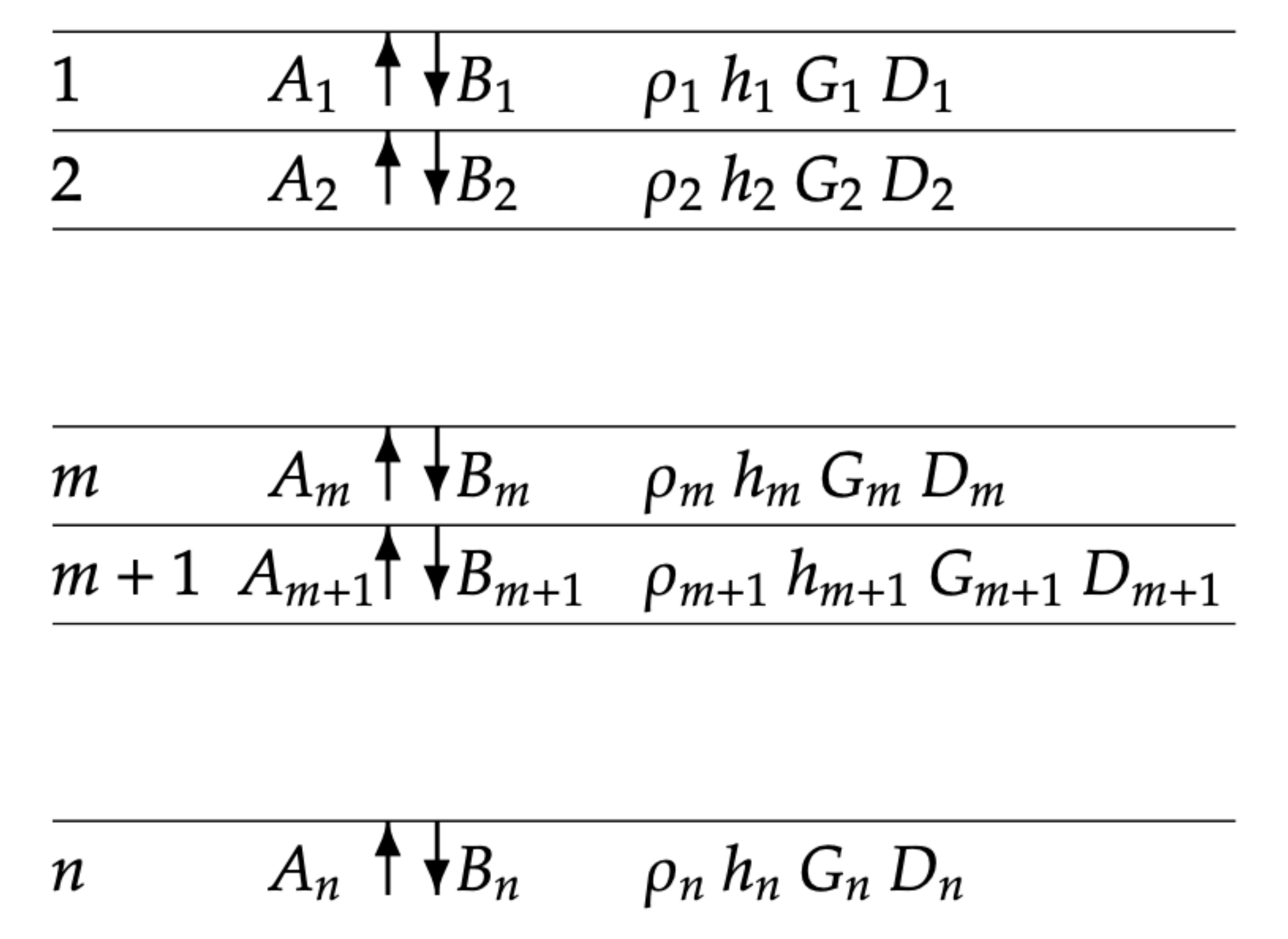


Seismic Response Analysis

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.



Seismic Response Analysis

In practice:

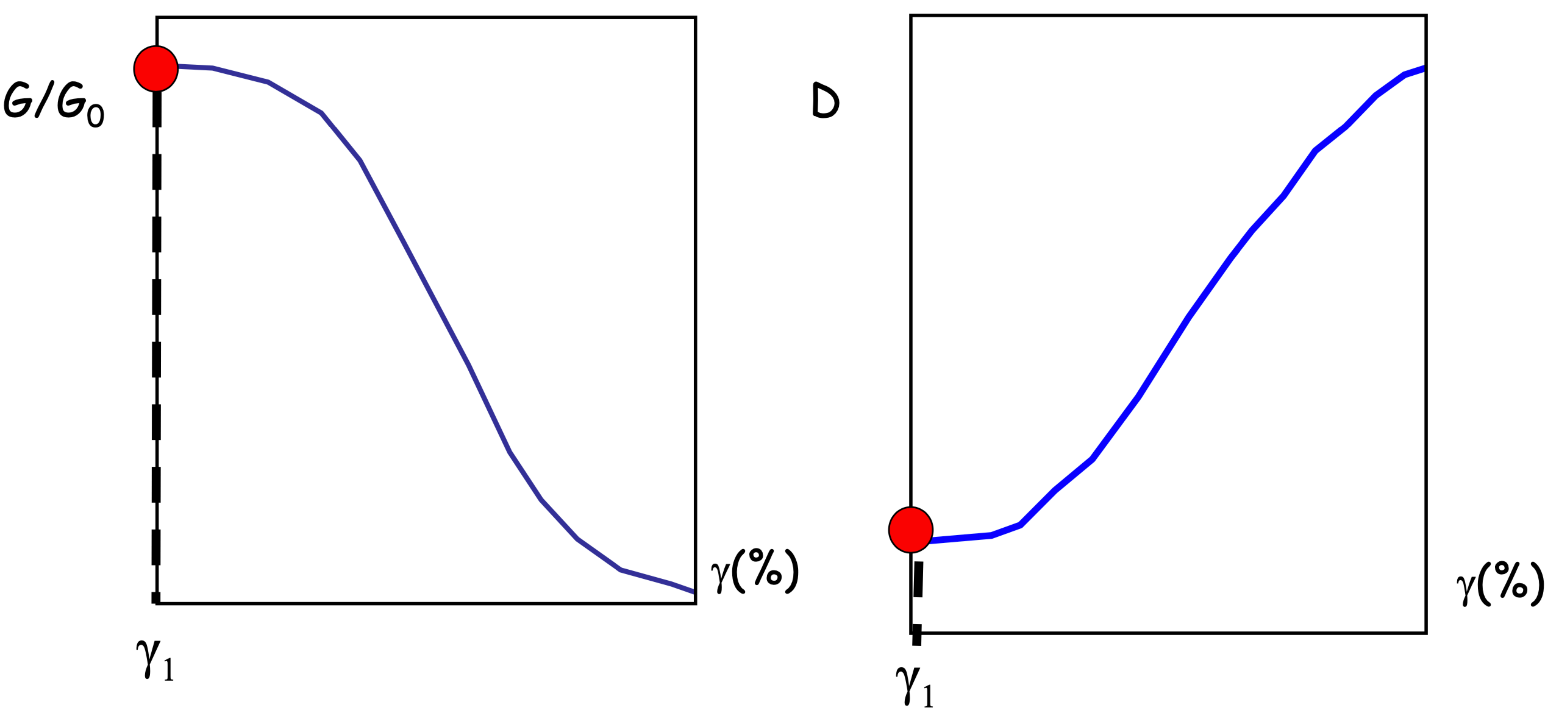
We compute for each layer

the strain γ by the

Transfer Function

starting

from Gmax and Do



G/Go = 1

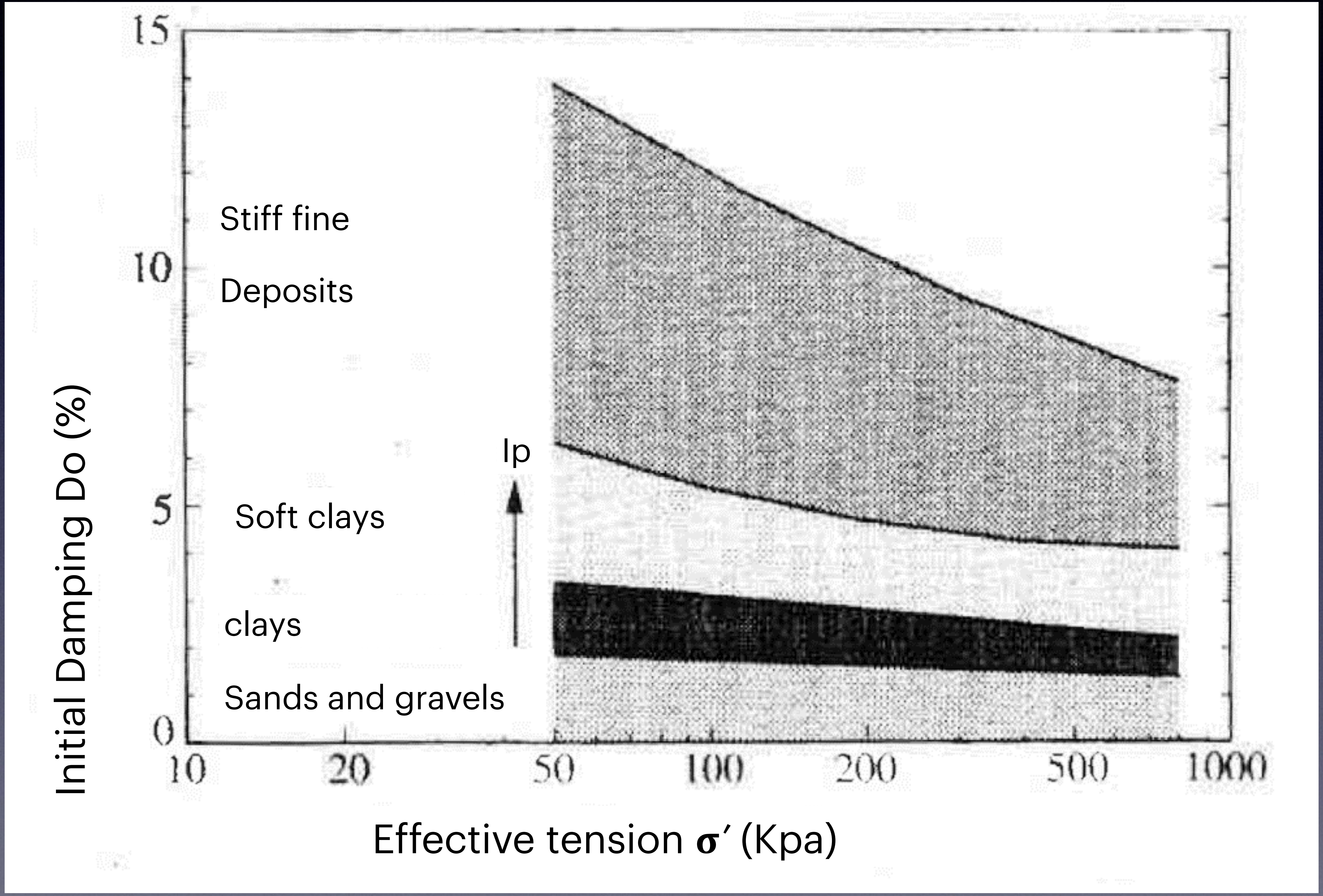
Gmax= G0 (from Vs)

Seismic Response Analysis

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

Do is considered ≈ 1% for gravel and sands, for finer deposit it depends on effective tension **σ**′

(literature values are commonly used)

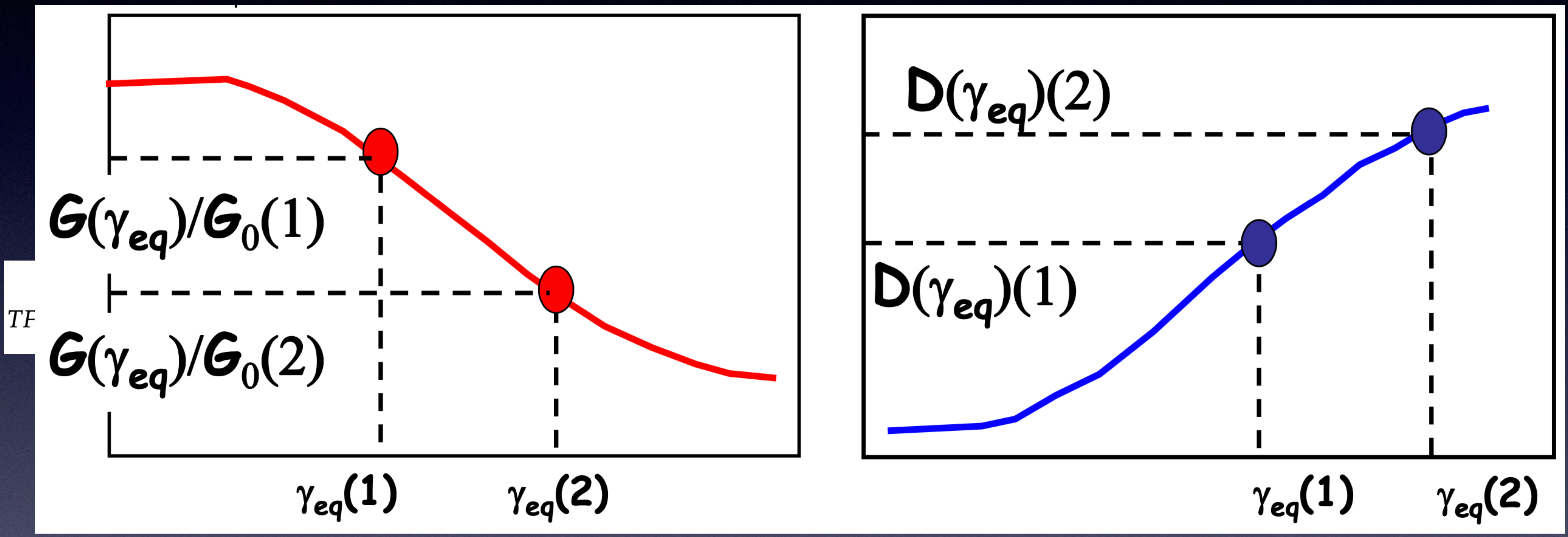


Seismic Response Analysis

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 ε

(G decay is not significant) →solution converges

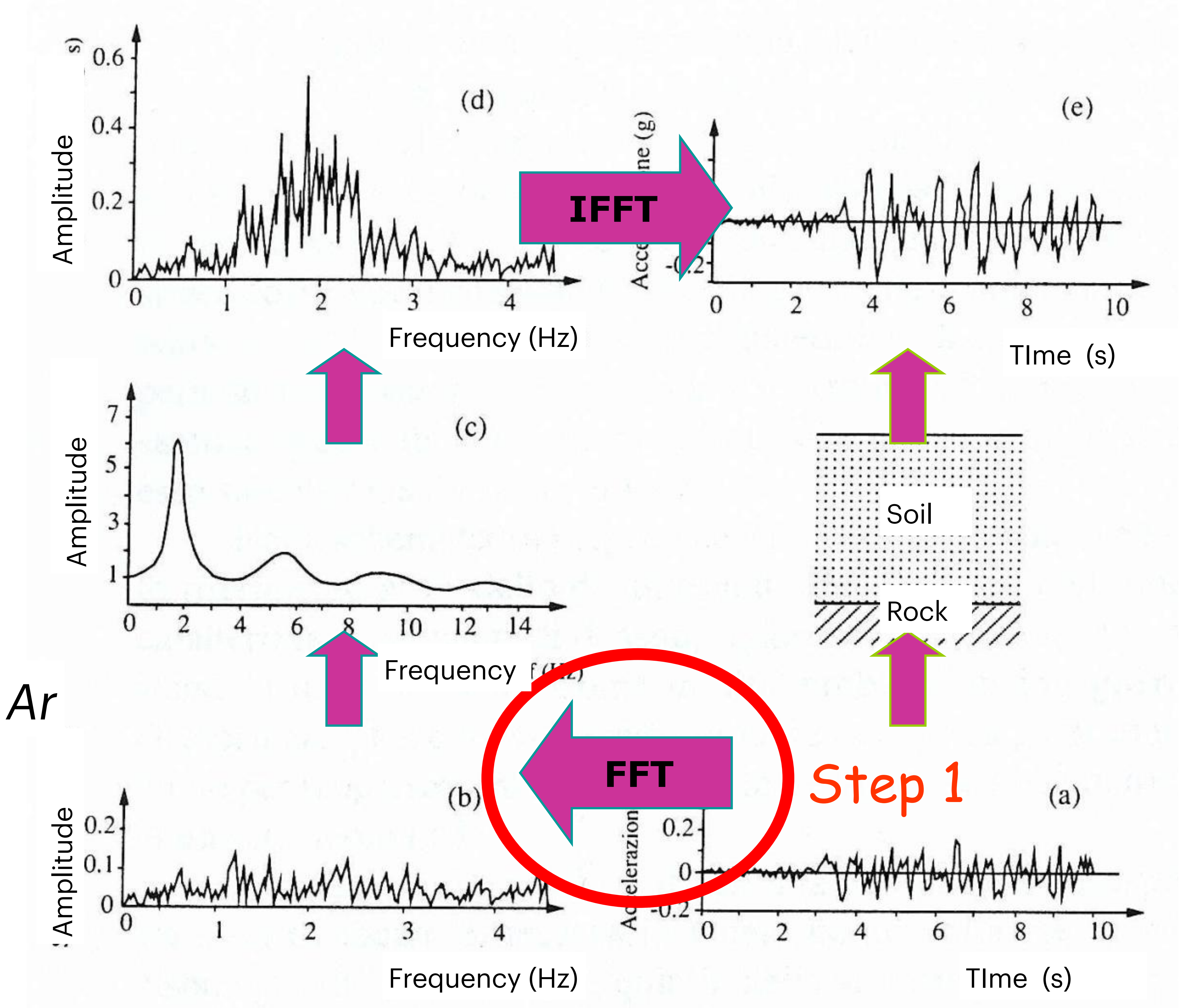
Shake/strata/EERA codes

Response Analysis via transfer function computation

(in frequency domain)

Step 1

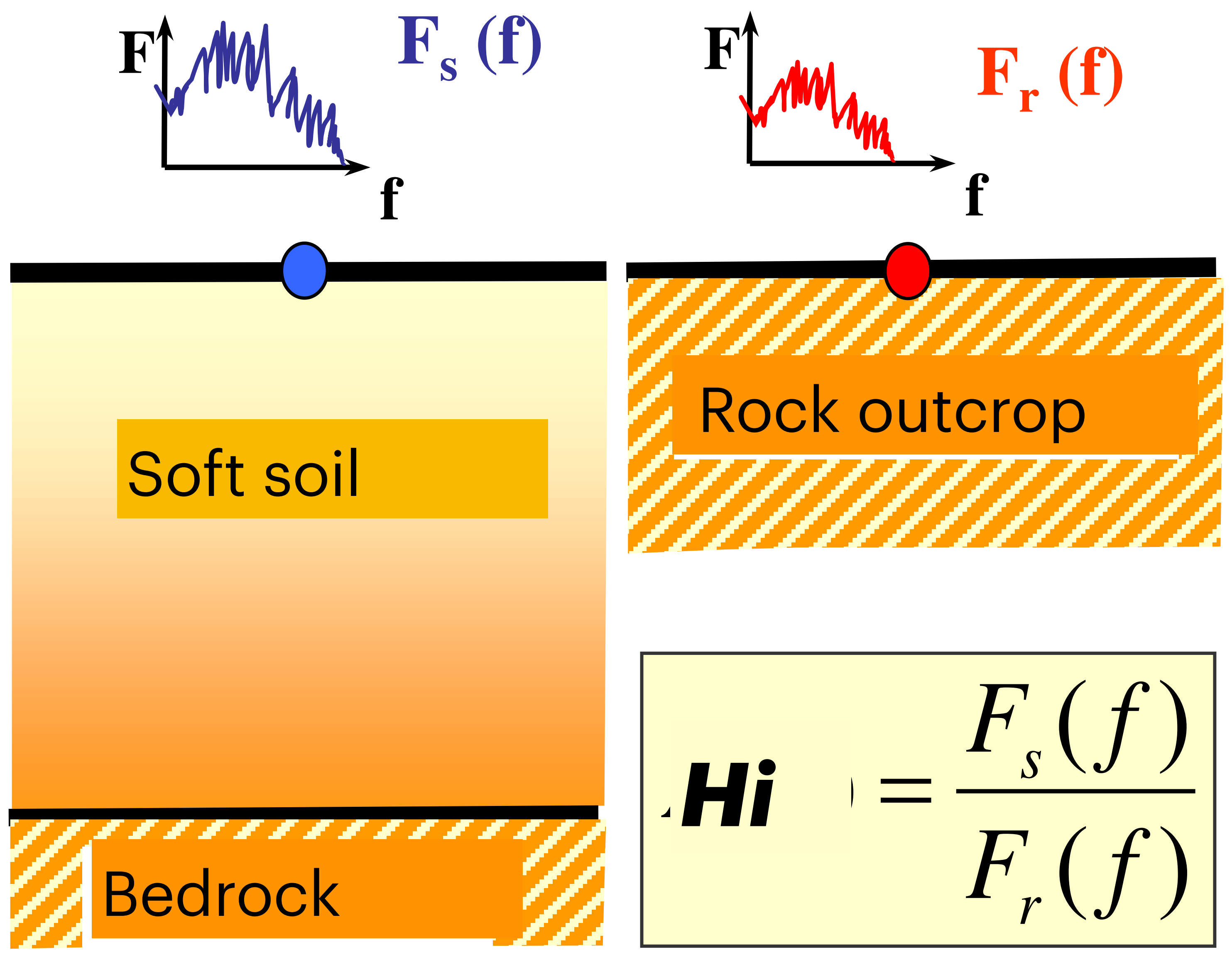
Compute the Fourier transform FFT of the input accelerogram at the base of the soil column **Ar** (i.e. a sum of simple harmonics)



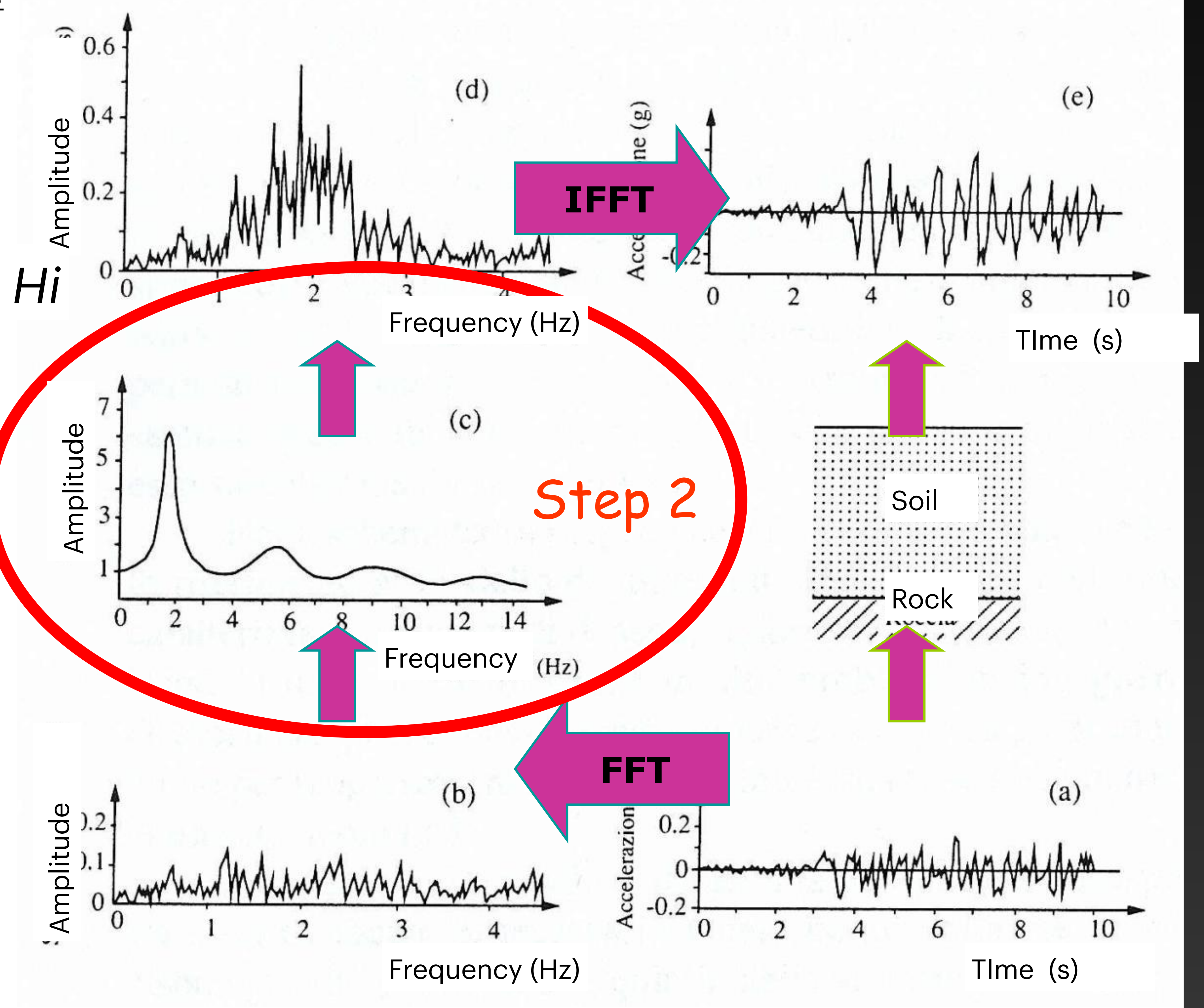
Shake/strata/EERA codes

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

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



$$\boldsymbol{Hi} = \frac{F_s(f)}{F_r(f)}$$



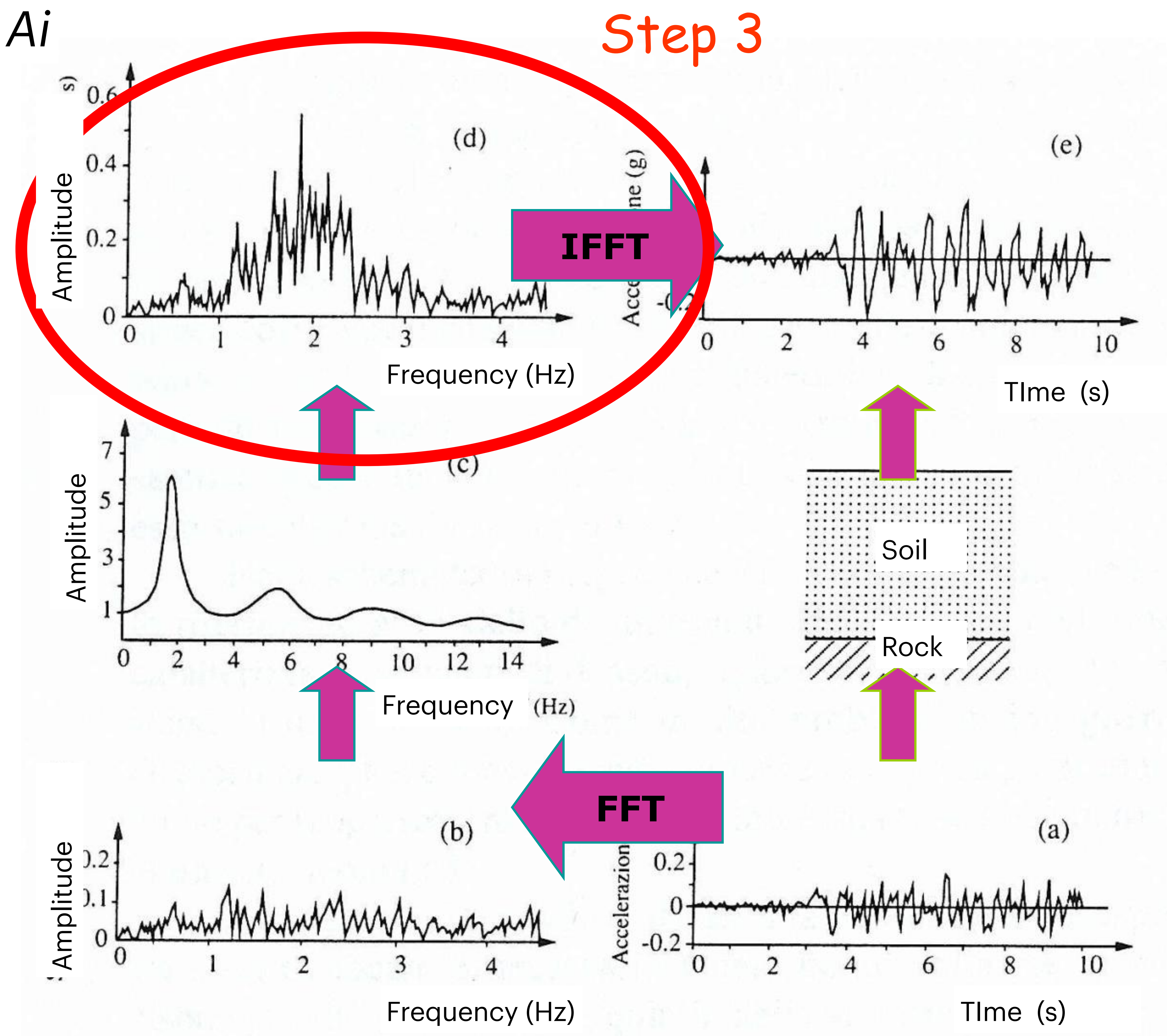
Shake/strata/EERA codes

Step 3

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

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

(In time domain would be the more complex convolution)

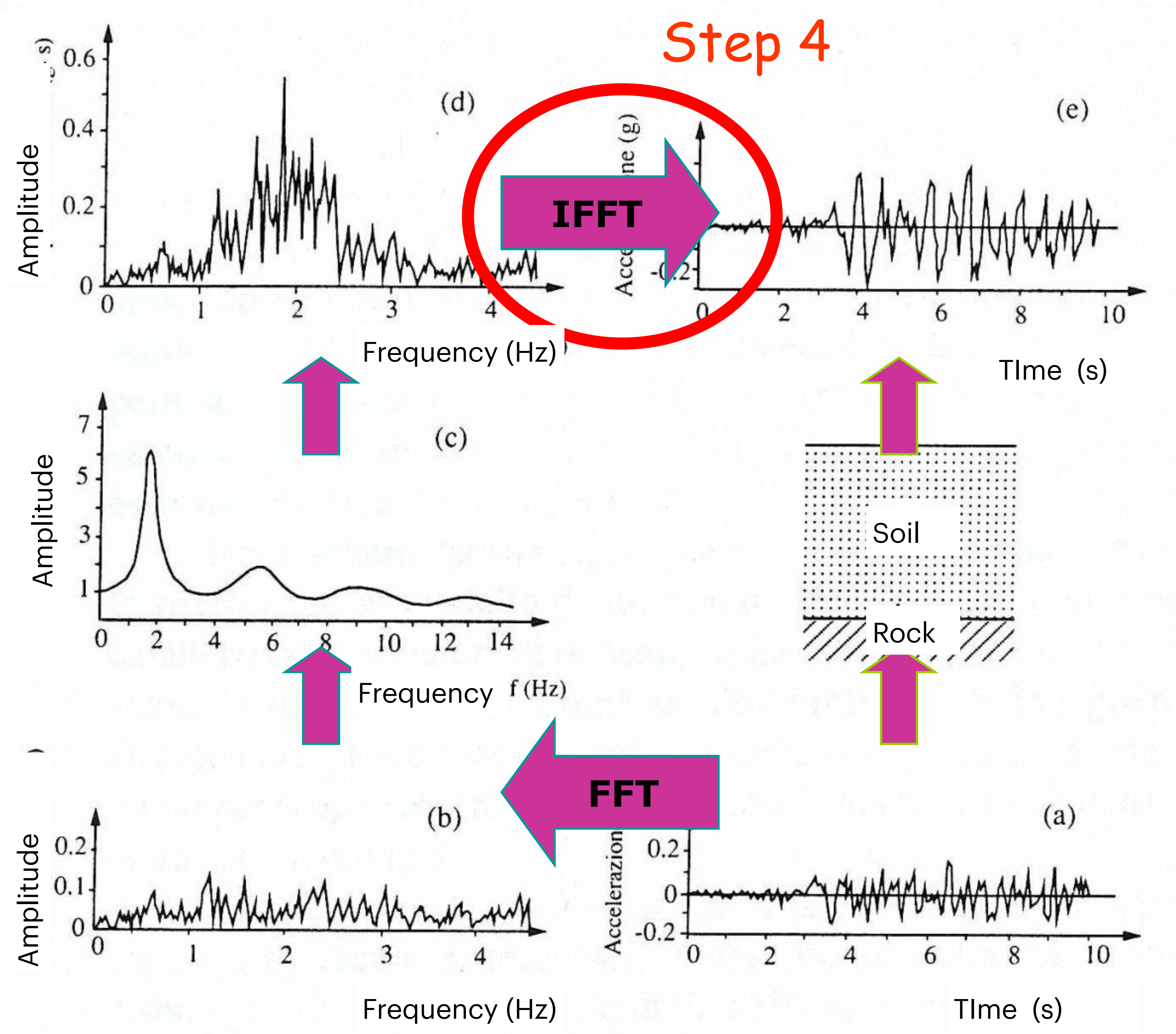


Shake/strata/EERA codes

Step 4

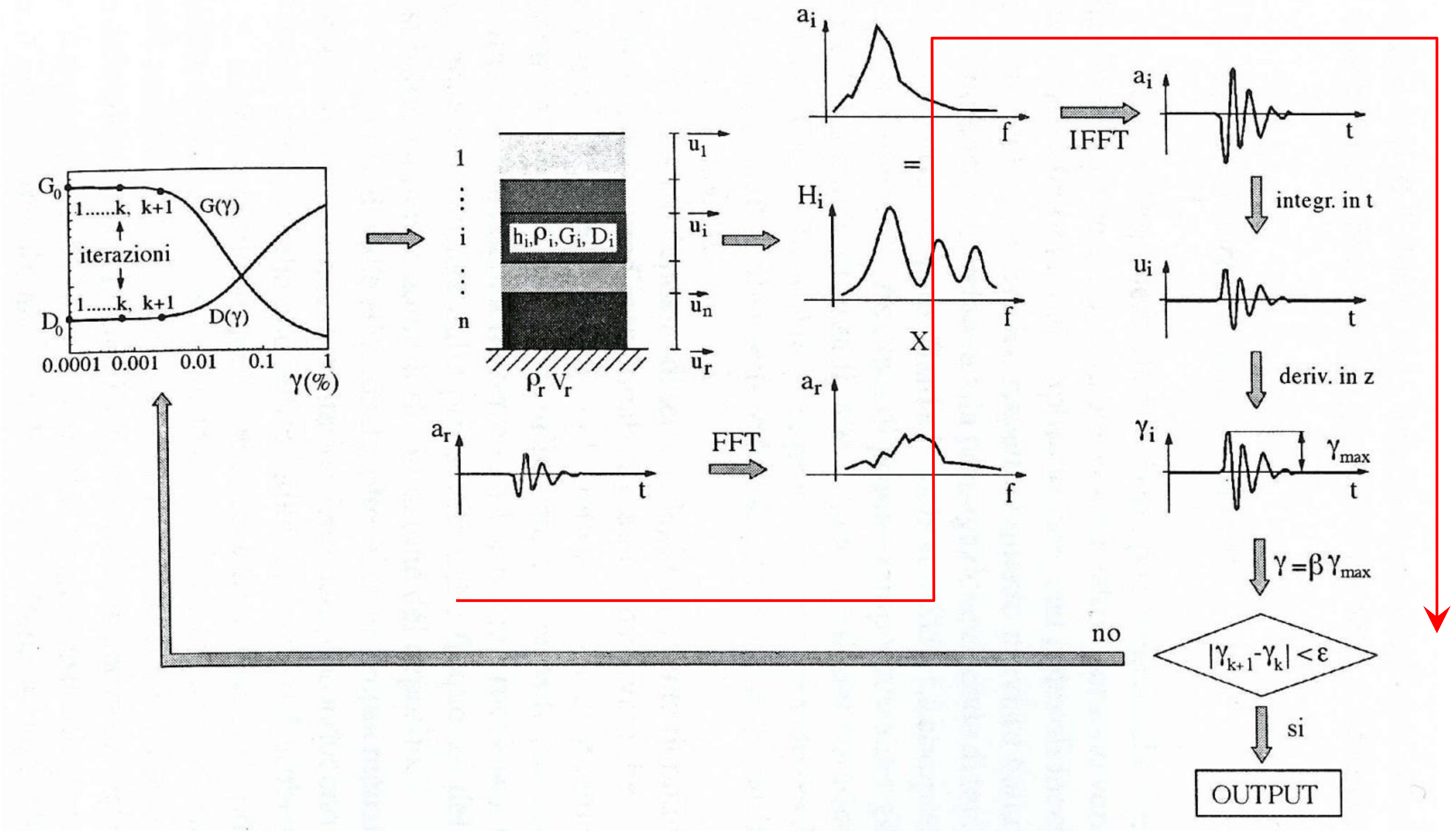
Compute the Anti Fourier transform I FFT of the response at the surface:

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

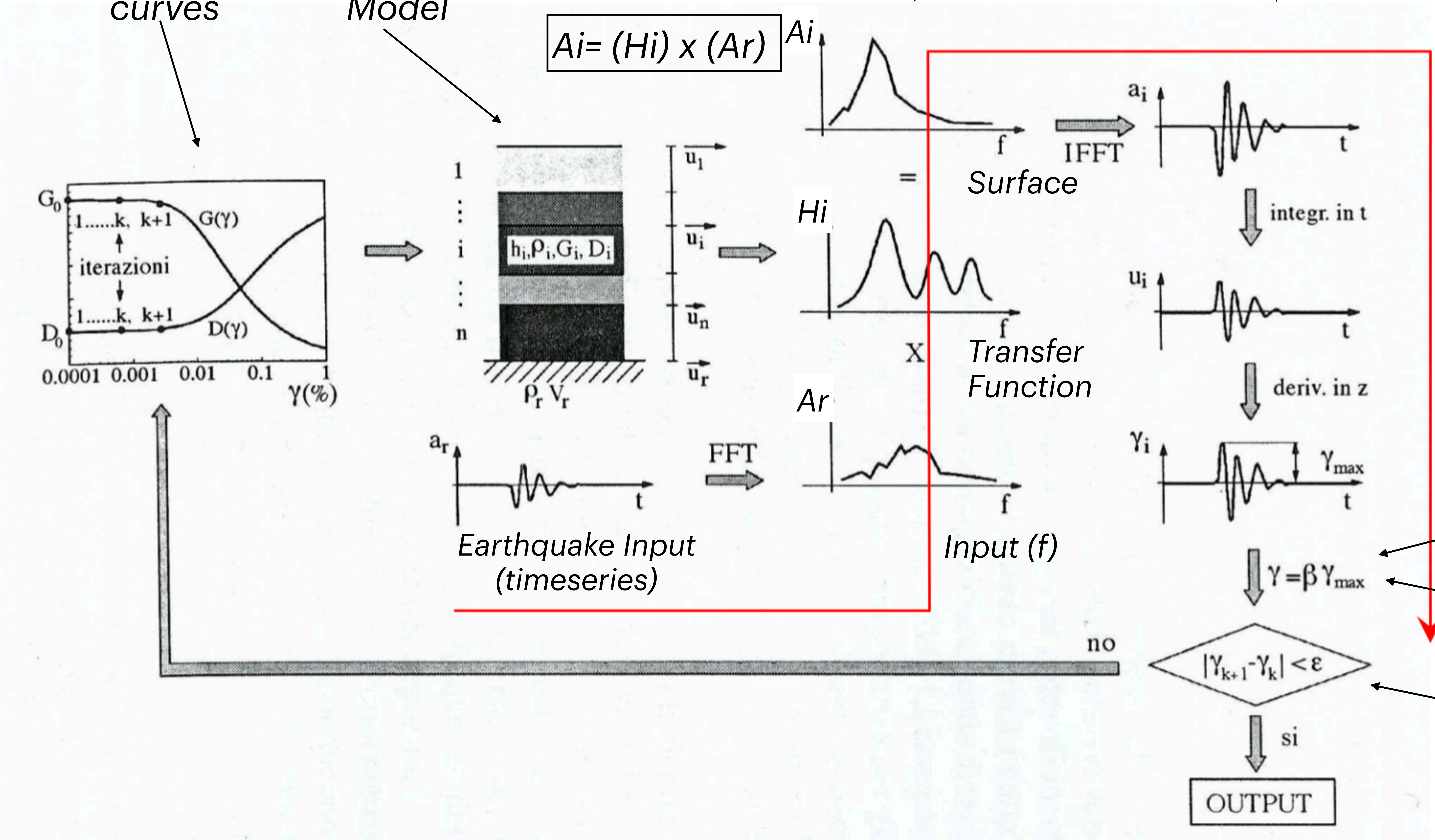


Shake/strata/EERA codes

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



Starting data:



G and D curves

H and Vs Model

Ai= (Hi) x (Ar)

Frequency domain

Time domain

Ai

Surface

Hi

Transfer Function

Ar

Input (f)

Earthquake Input (timeseries)

Acc.

Displ.

Deformation

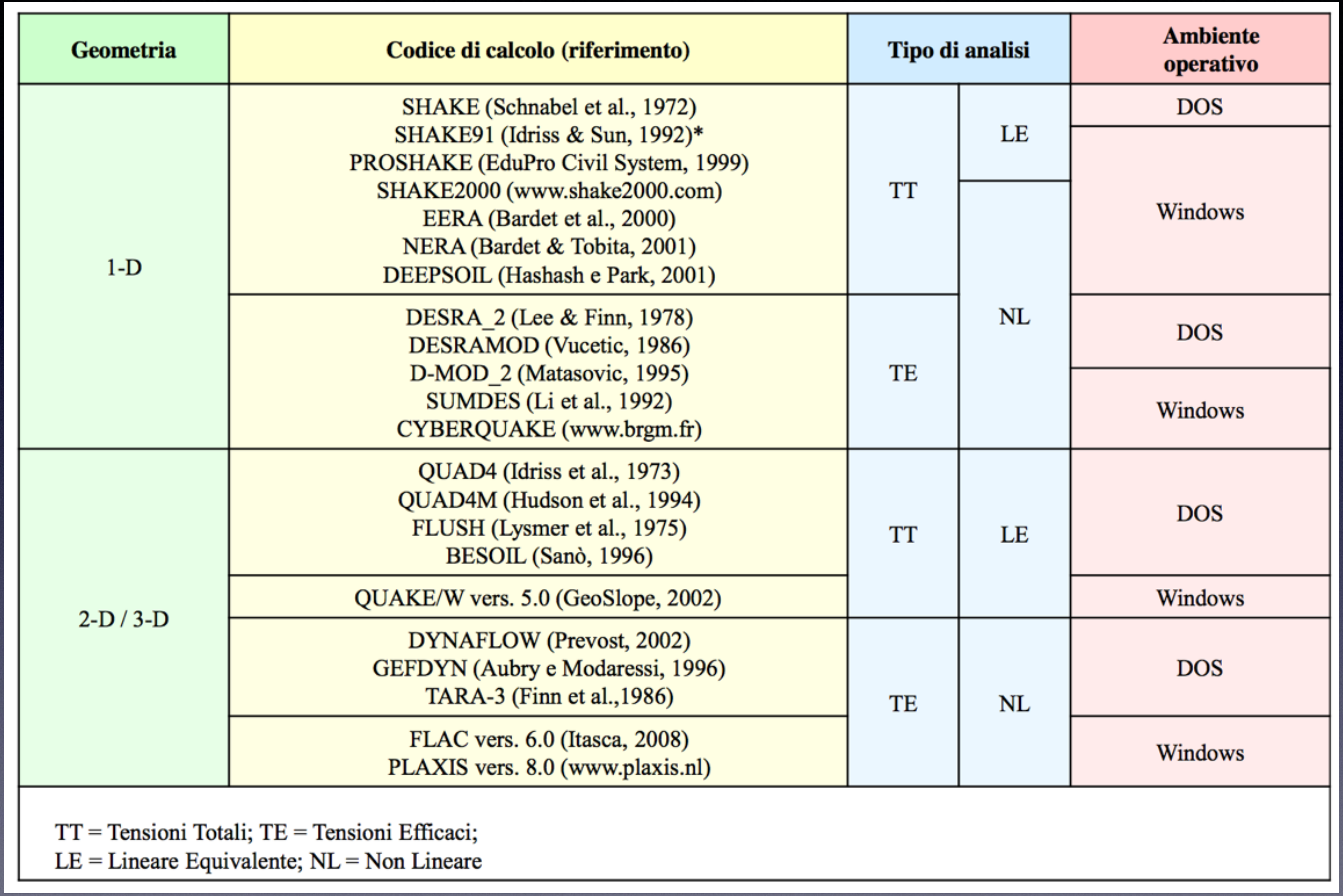
Real Def.

β = 0.65

ε= established error

No significant changes in G, D = solution converges

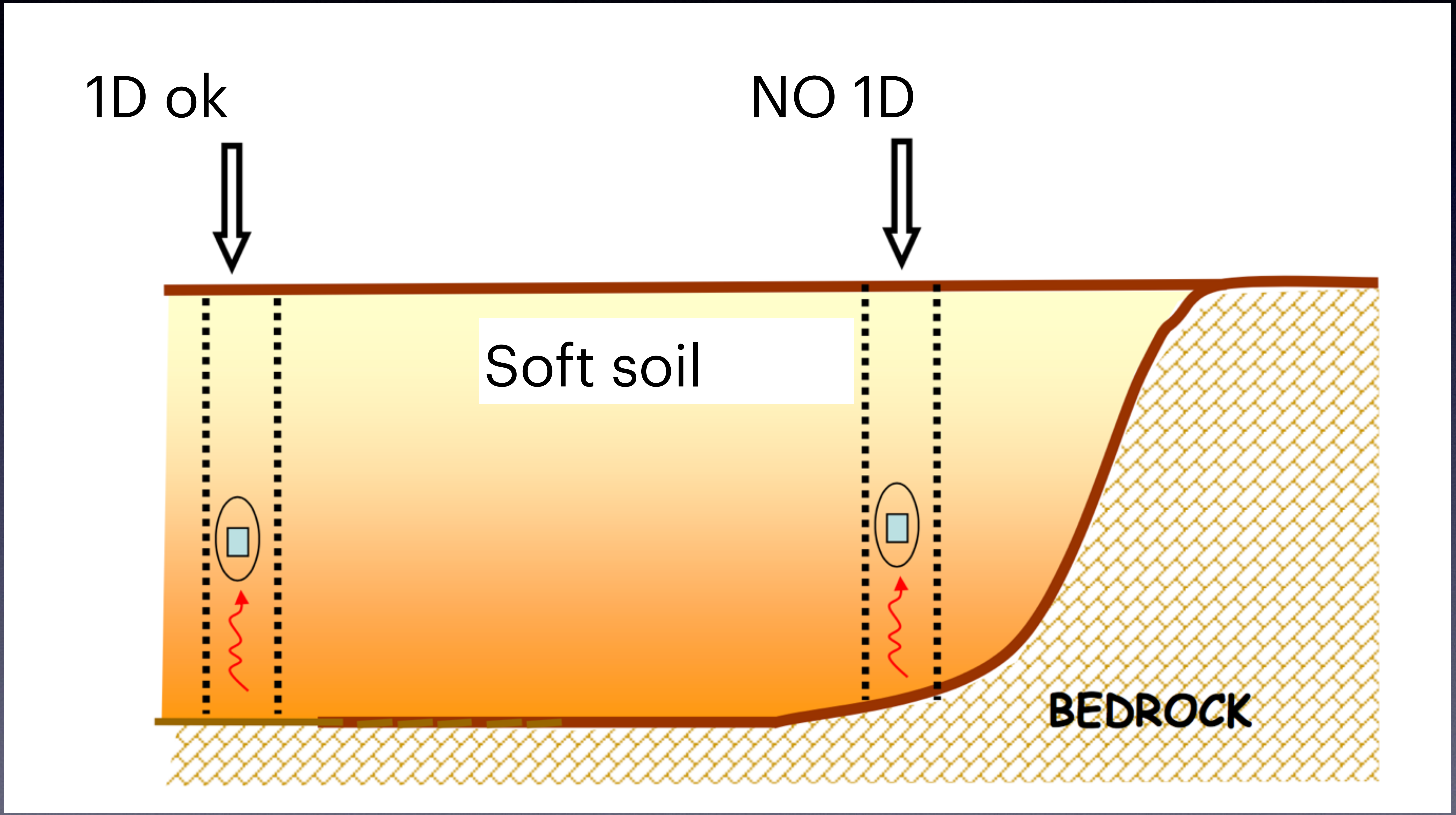
Codes for LSR



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

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

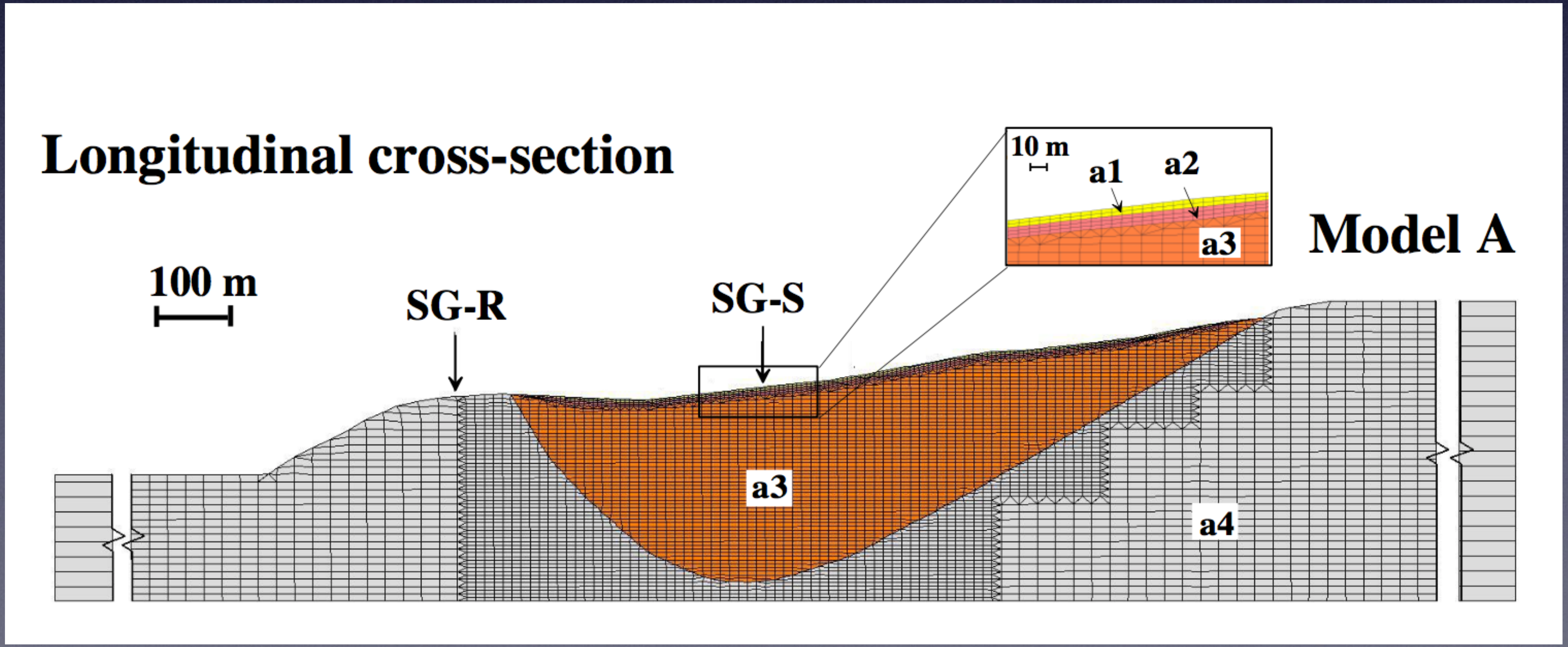
And in 2 dimensions ?



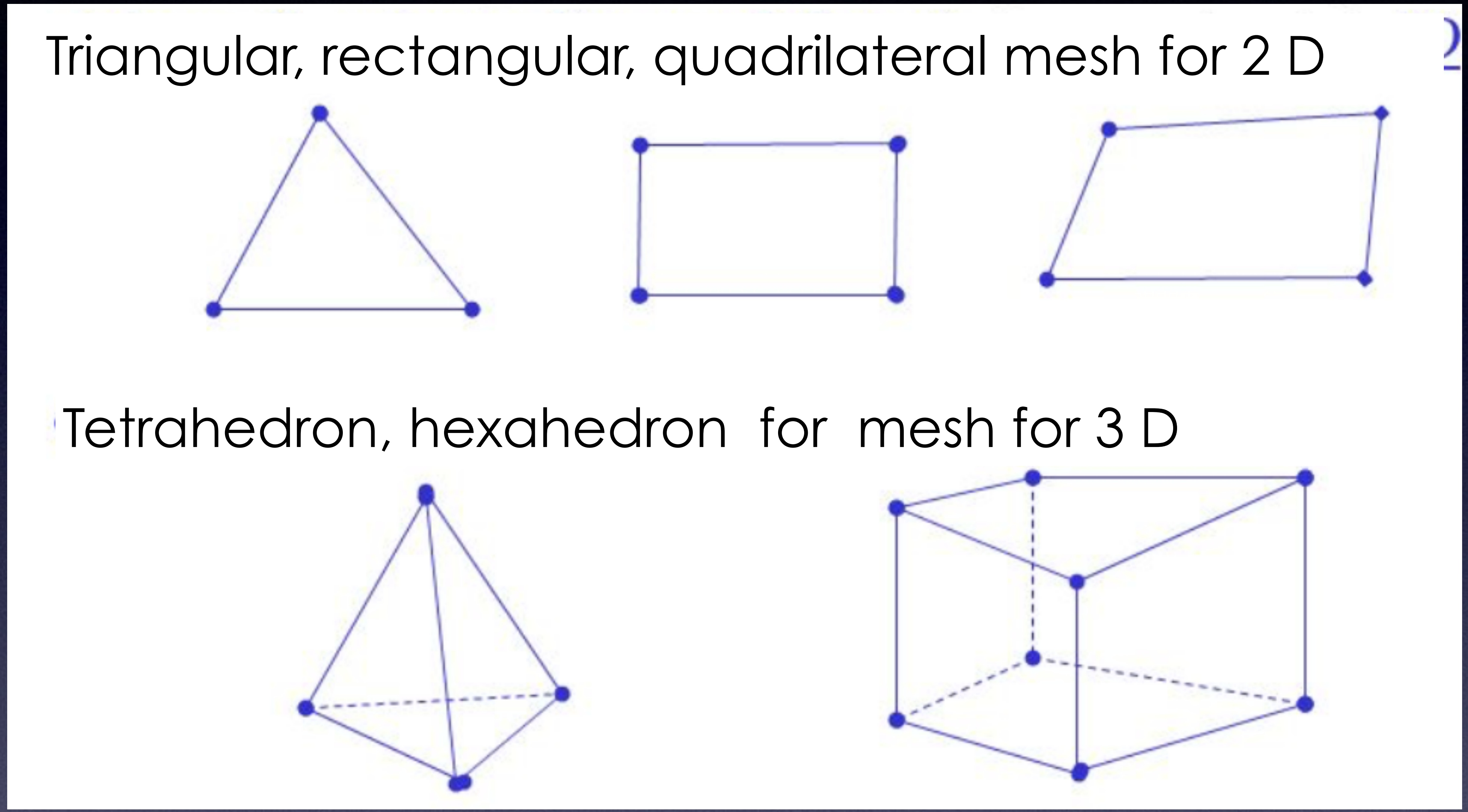
2D numeric solution
For seismic response analysis

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

2D



2D numeric solution
For seismic response analysis

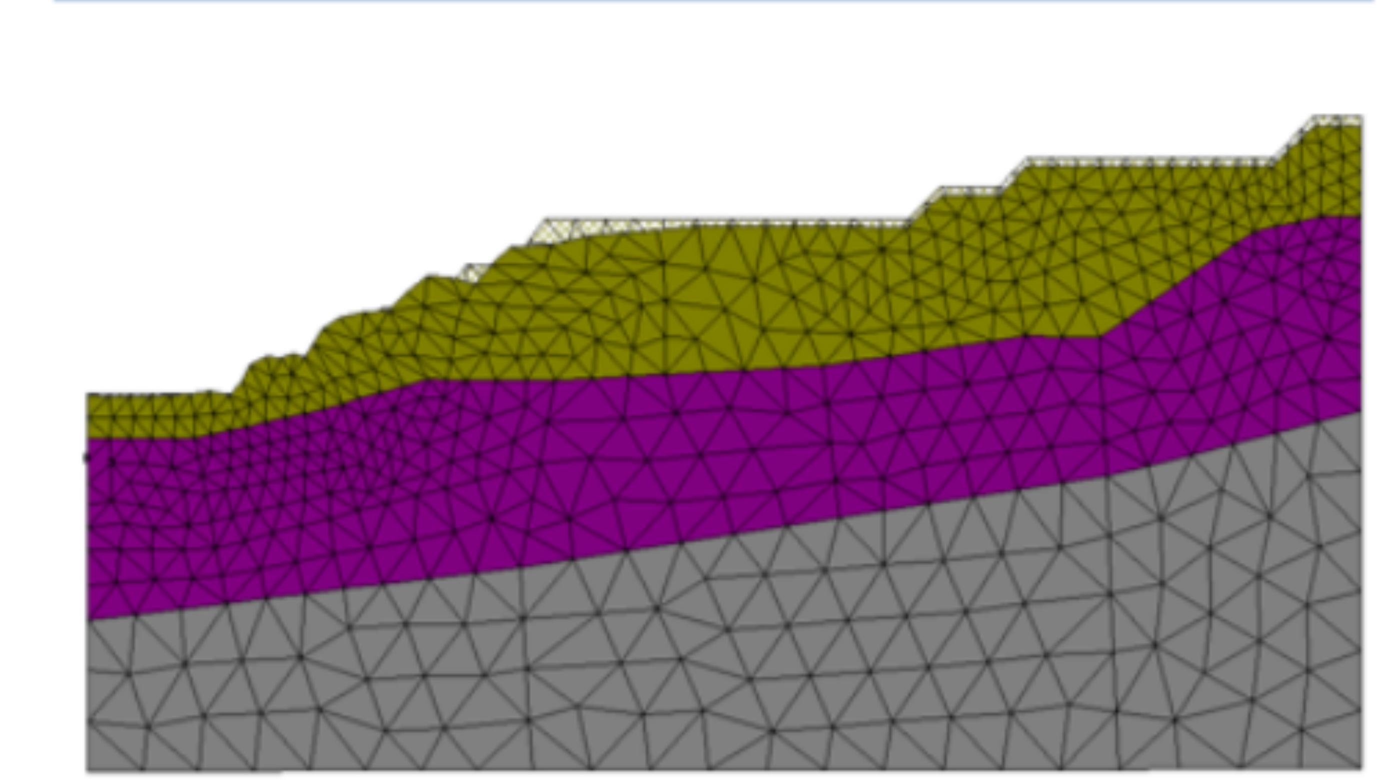


Triangular, rectangular, quadrilateral mesh for 2 D

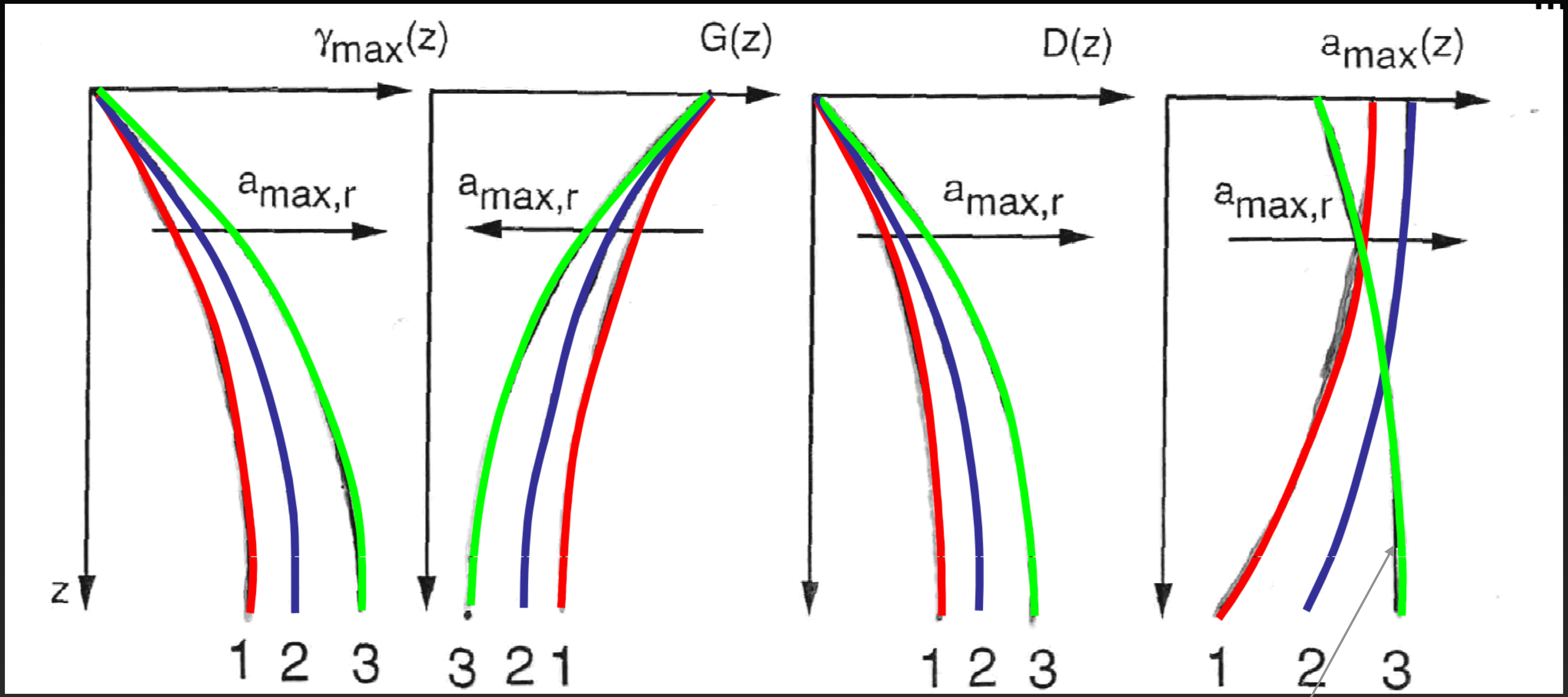
Tetrahedron, hexahedron for mesh for 3 D

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

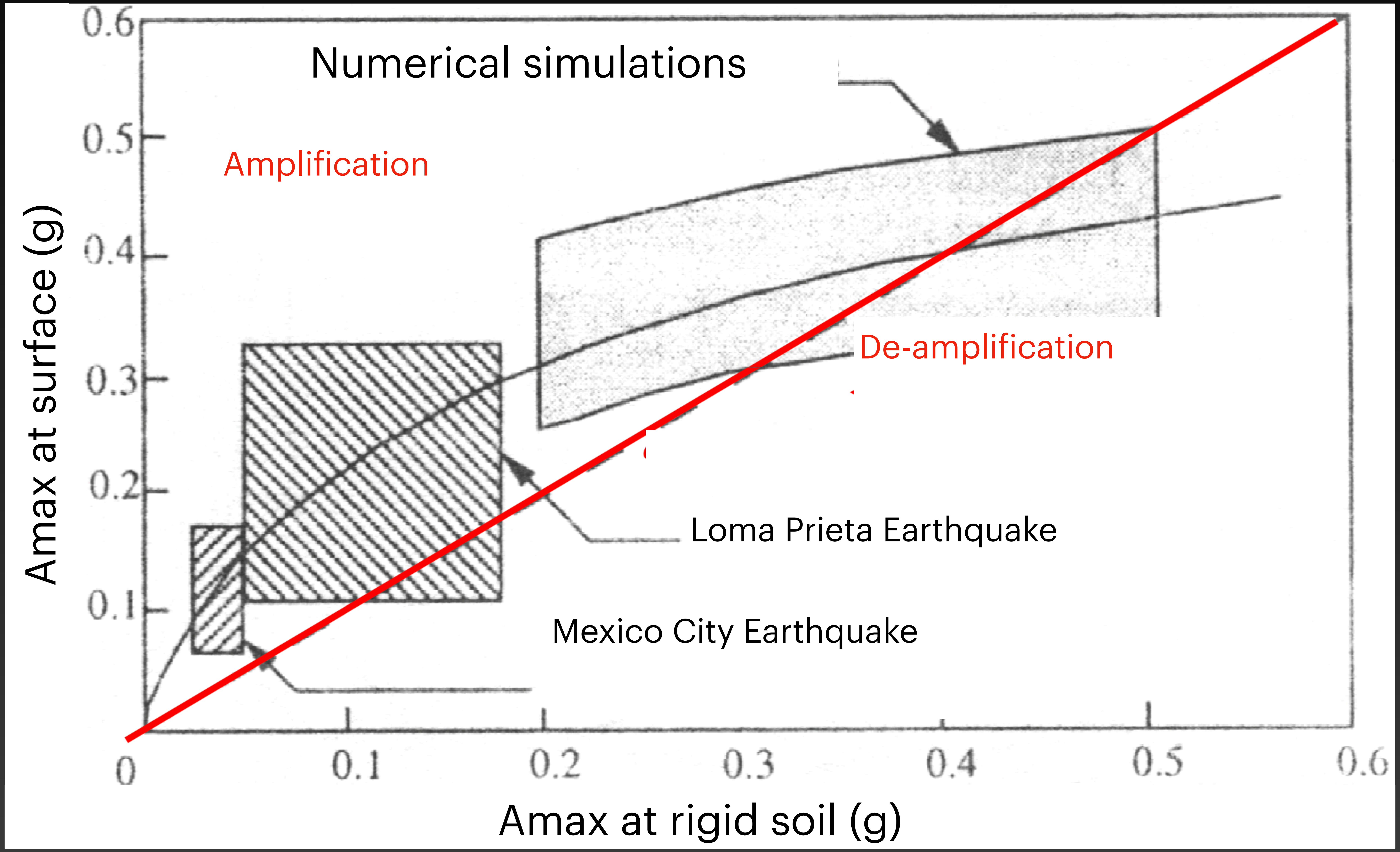


- >> Acc >> deformation γ
- >> Acc >> damming D
- >> Acc << shear rigidity G

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

The effect of non linearity

Example in soft soil



In case of very strong

acceleration non linearity

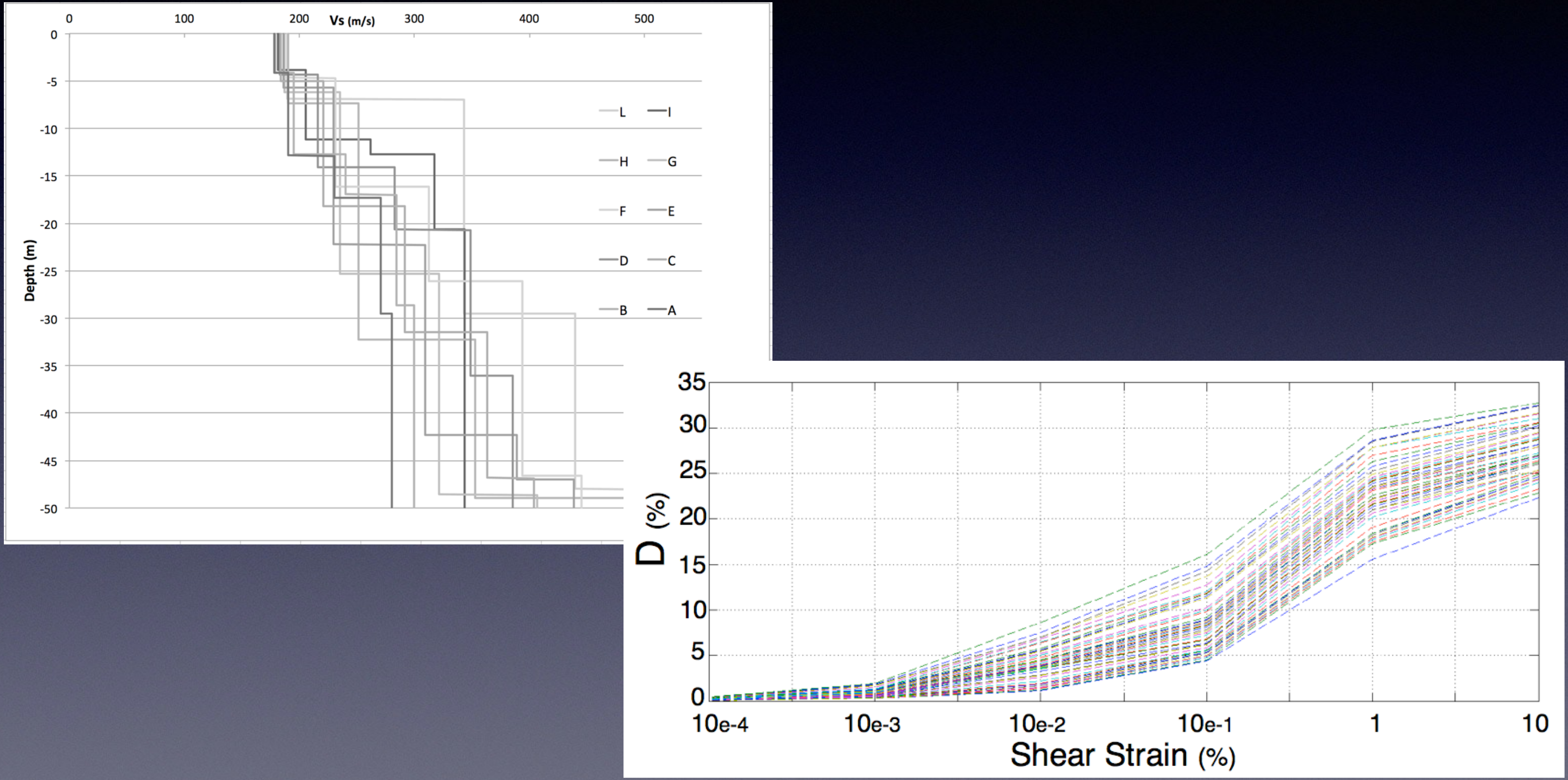
Can even de-amplify the motion

(attenuation prevails)

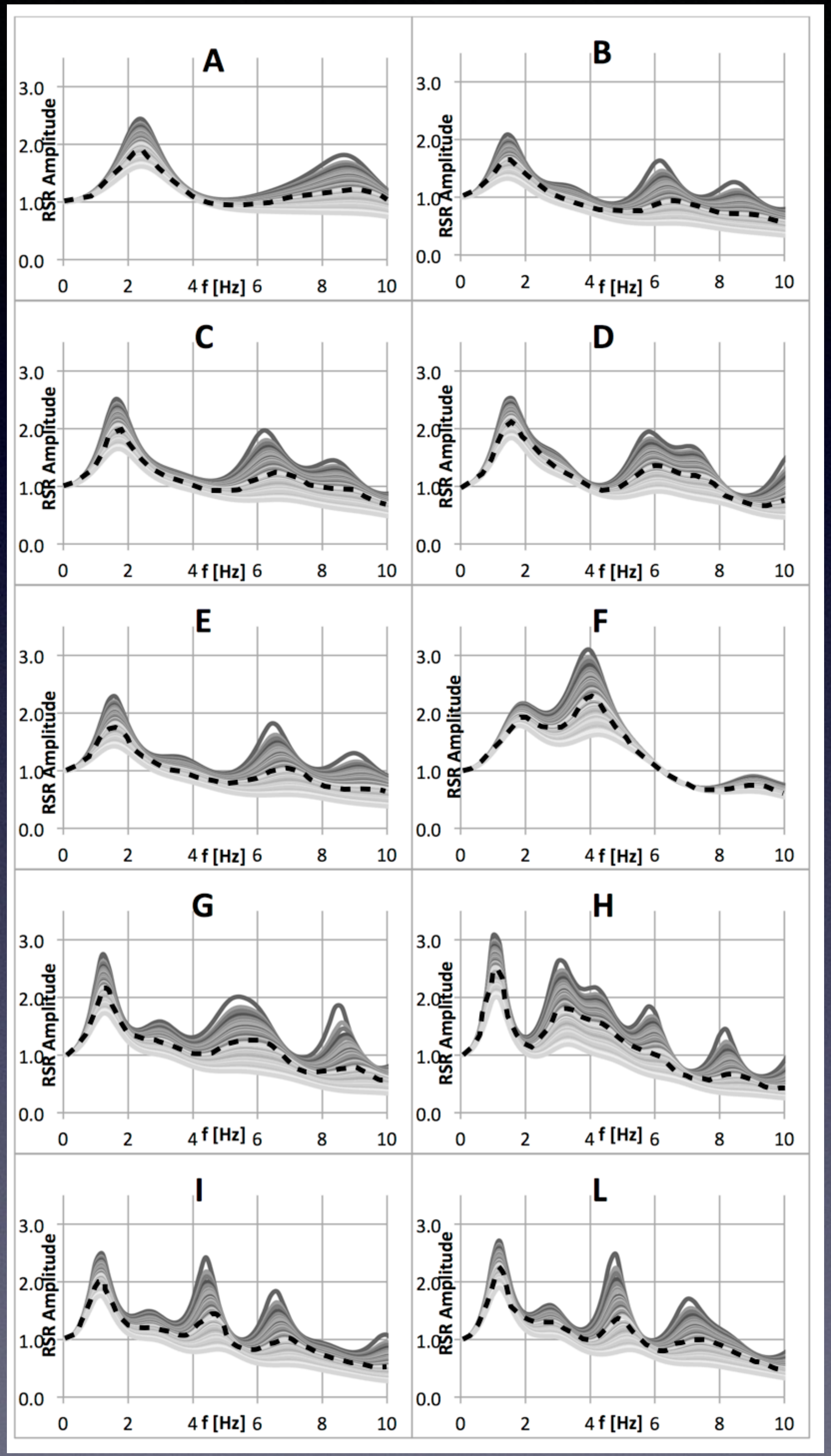
The sensitivity of G (Vs) and D

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 PeakGroundAcc
+/- 20%

Small
Impedance

+/- 60%

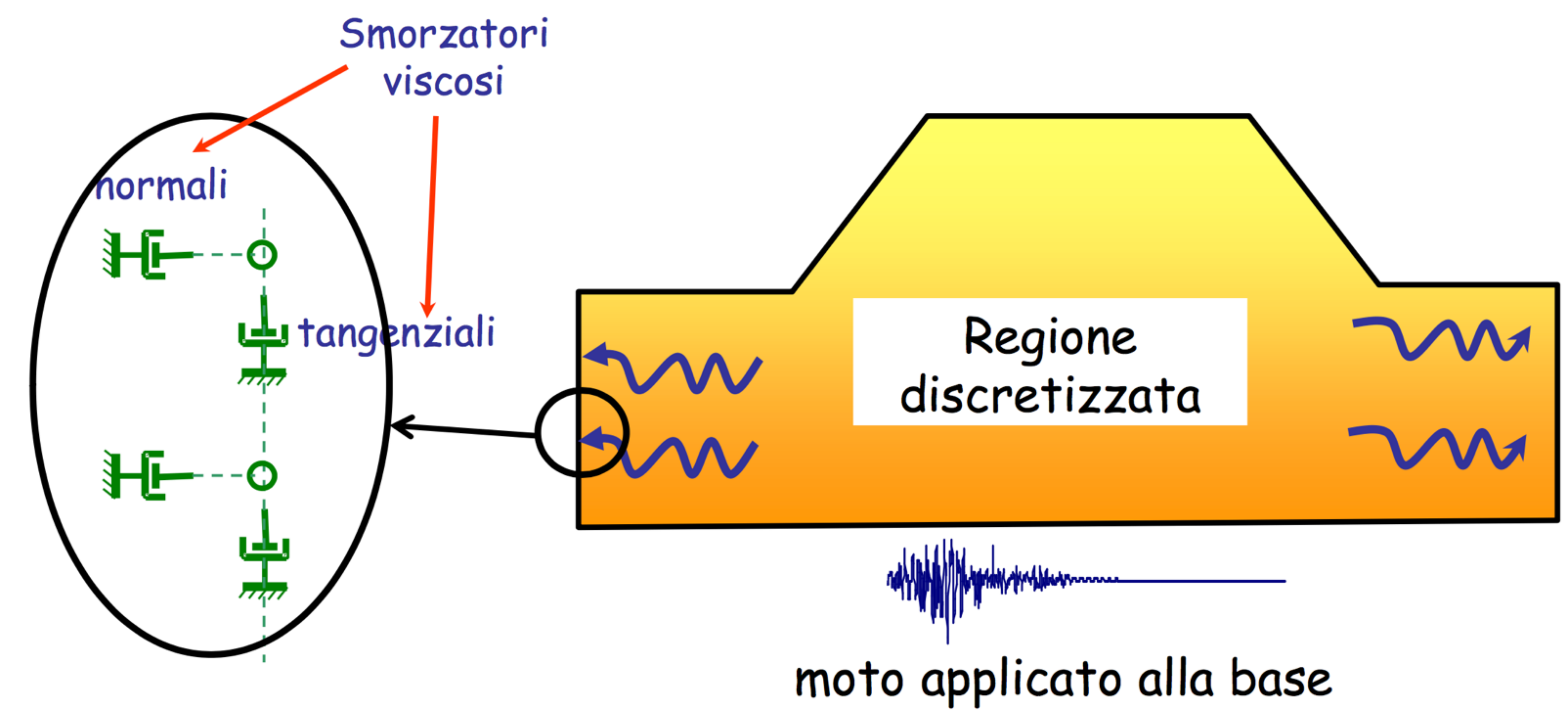
High
Impedance

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

Extra materials

Condizioni al contorno

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



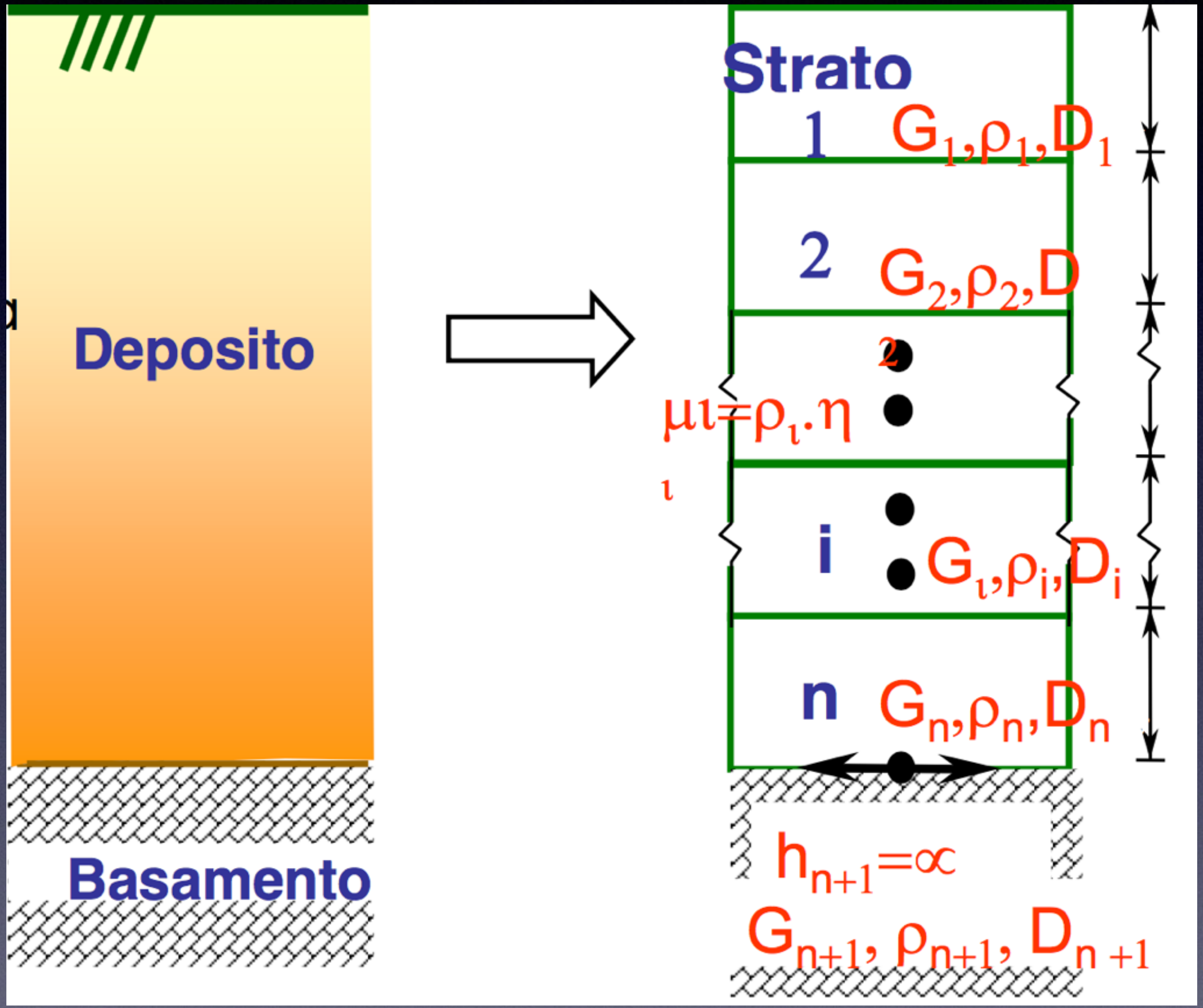
Absorbing Boundaries (2D)

Soluzioni numeriche

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

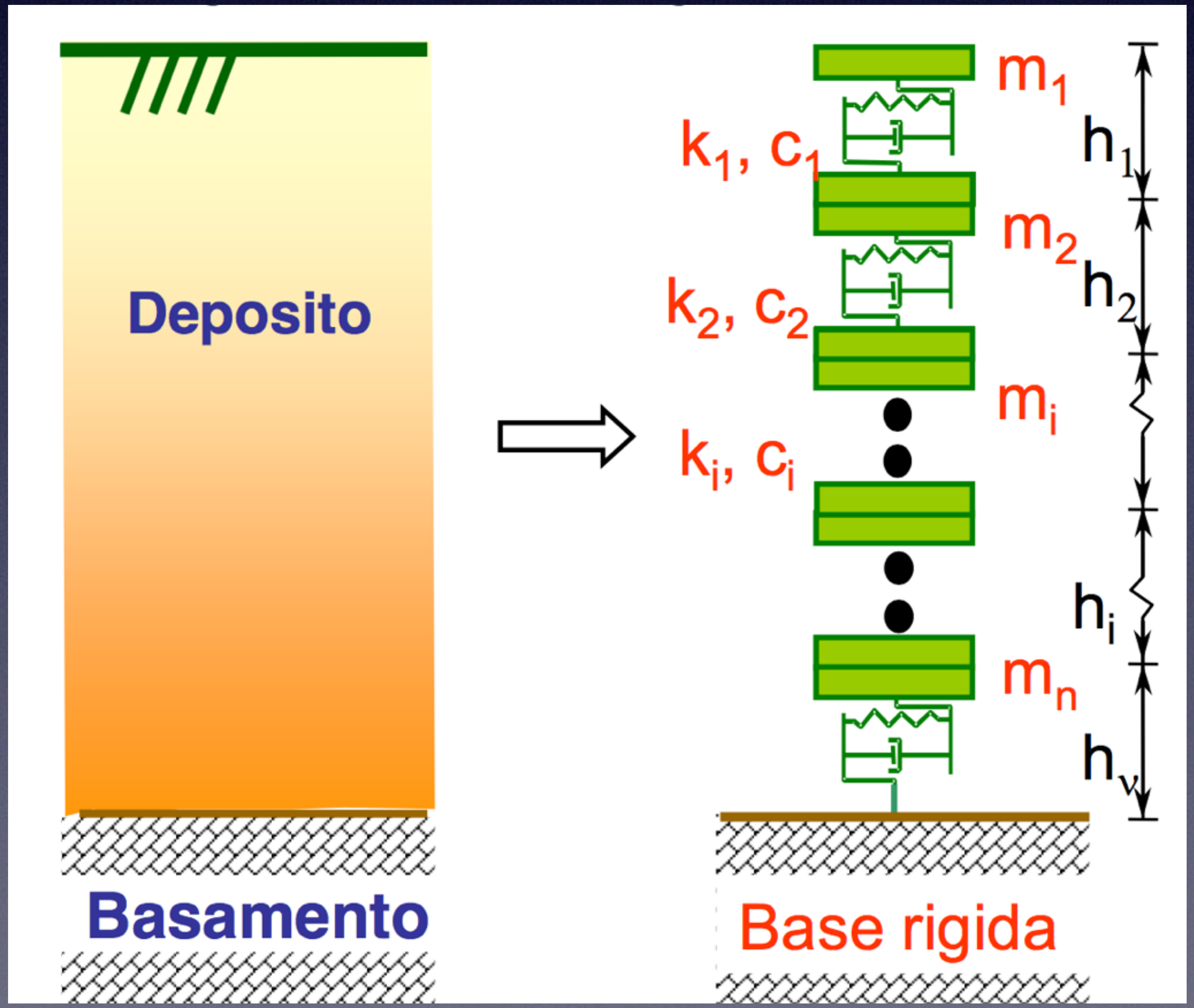
lo spessore Hi, la massa ρ, la rigidezza di taglio G,
e il coefficiente di smorzamento dello smorzatore D.



Soluzioni numeriche

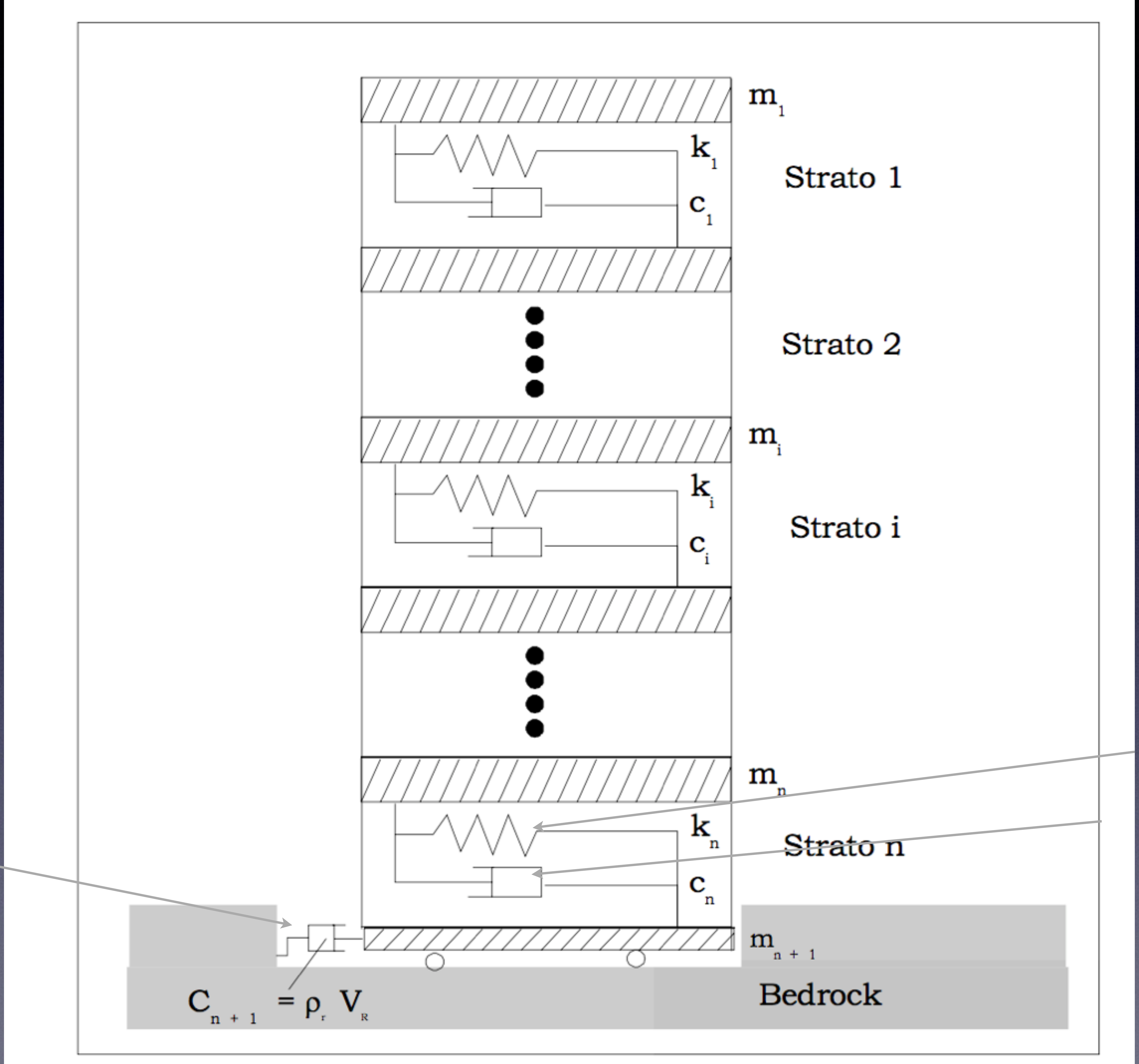
Modelli a trave a taglio continua discretizzata

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 Hi, la massa ρ, la rigidezza della molla Ki (legata al modulo di taglio) e il coefficiente di smorzamento dello smorzatore ε (D).

Modelli a trave a taglio continua discretizzata



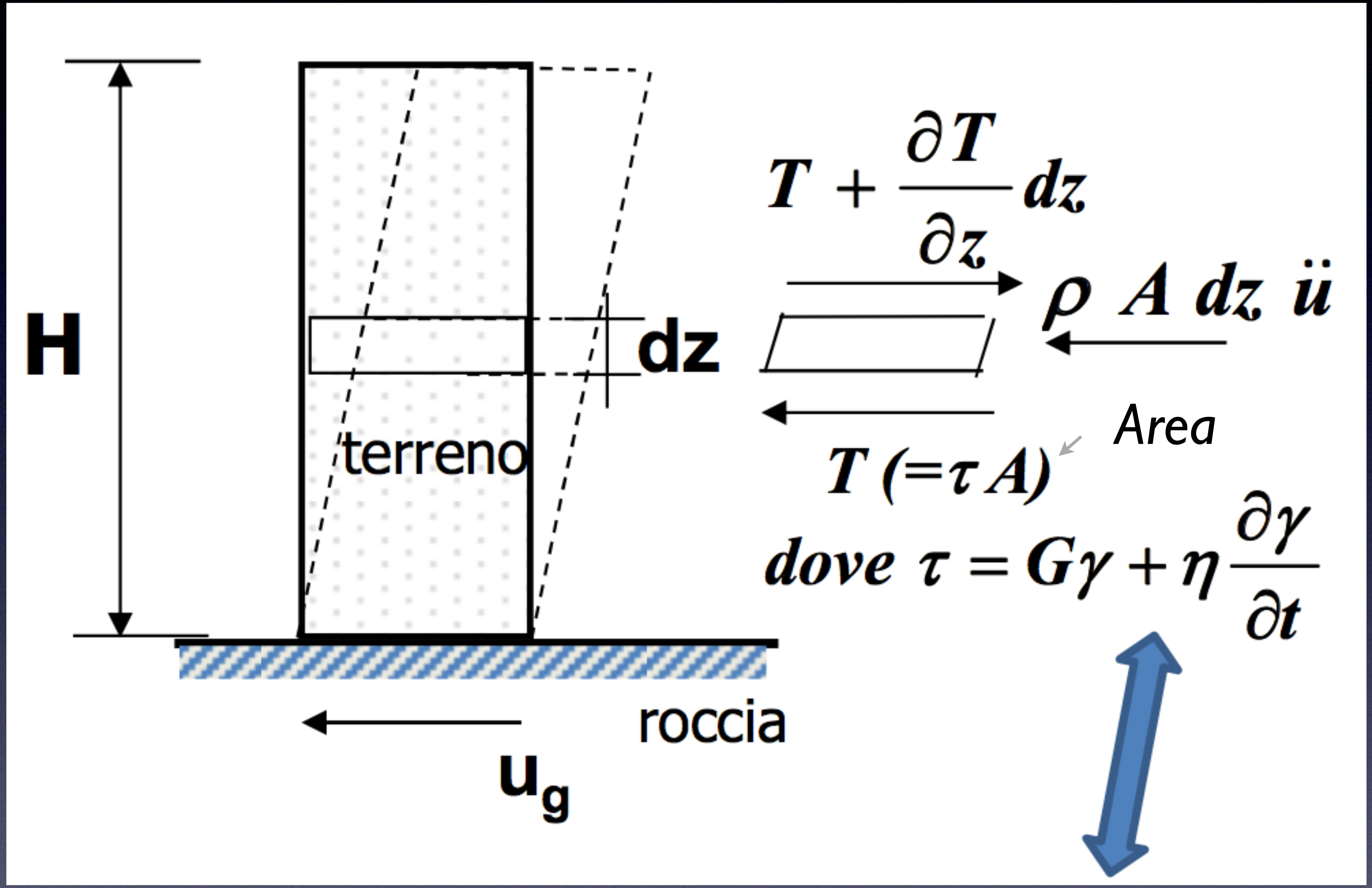
Molla

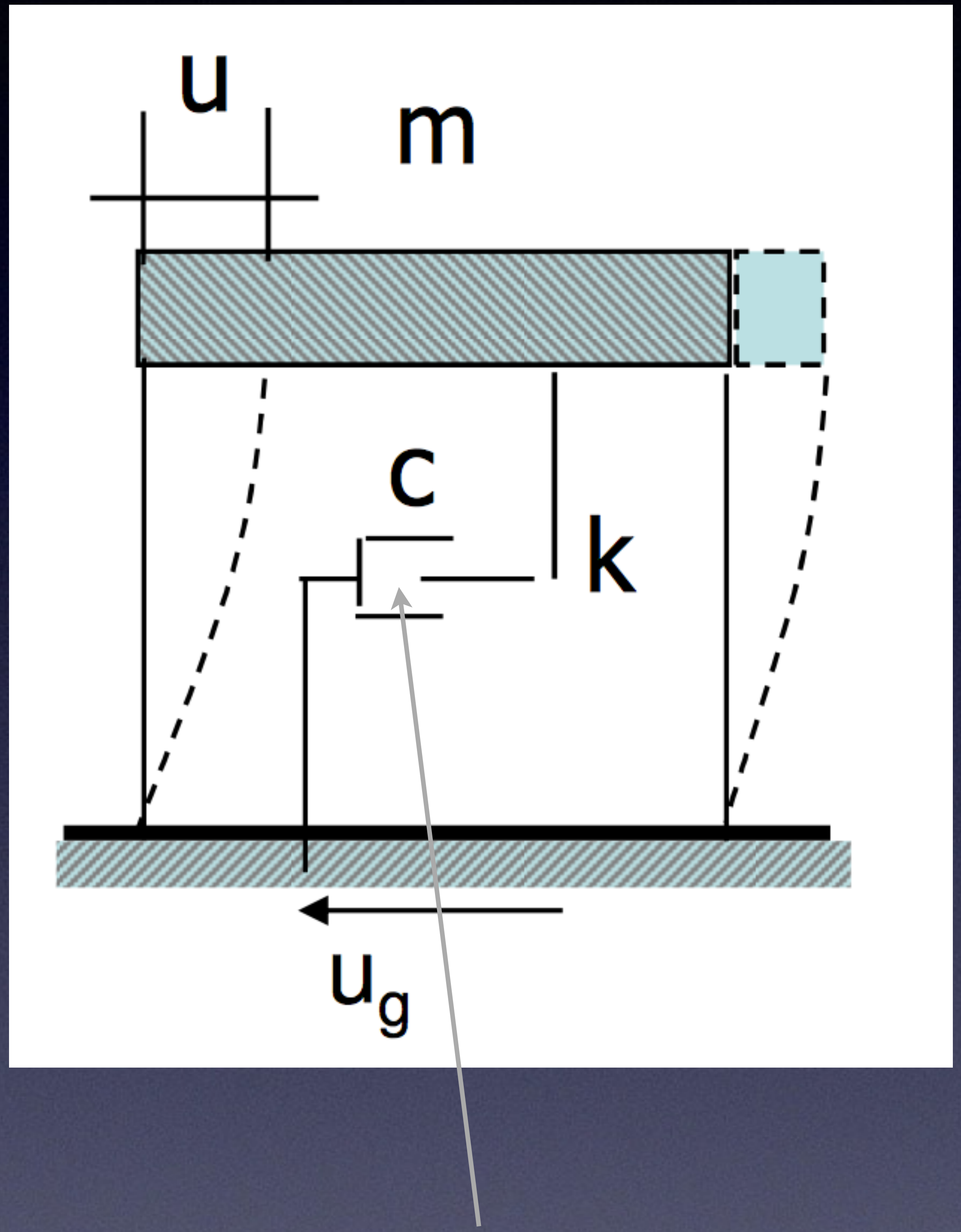
Smorzatore

Cond contorno

Lanzo

Modelli a trave a taglio continua discretizzata





Viscosità

Smorzatore

Risoluzione delle equazioni del moto

Livello 1 = 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)

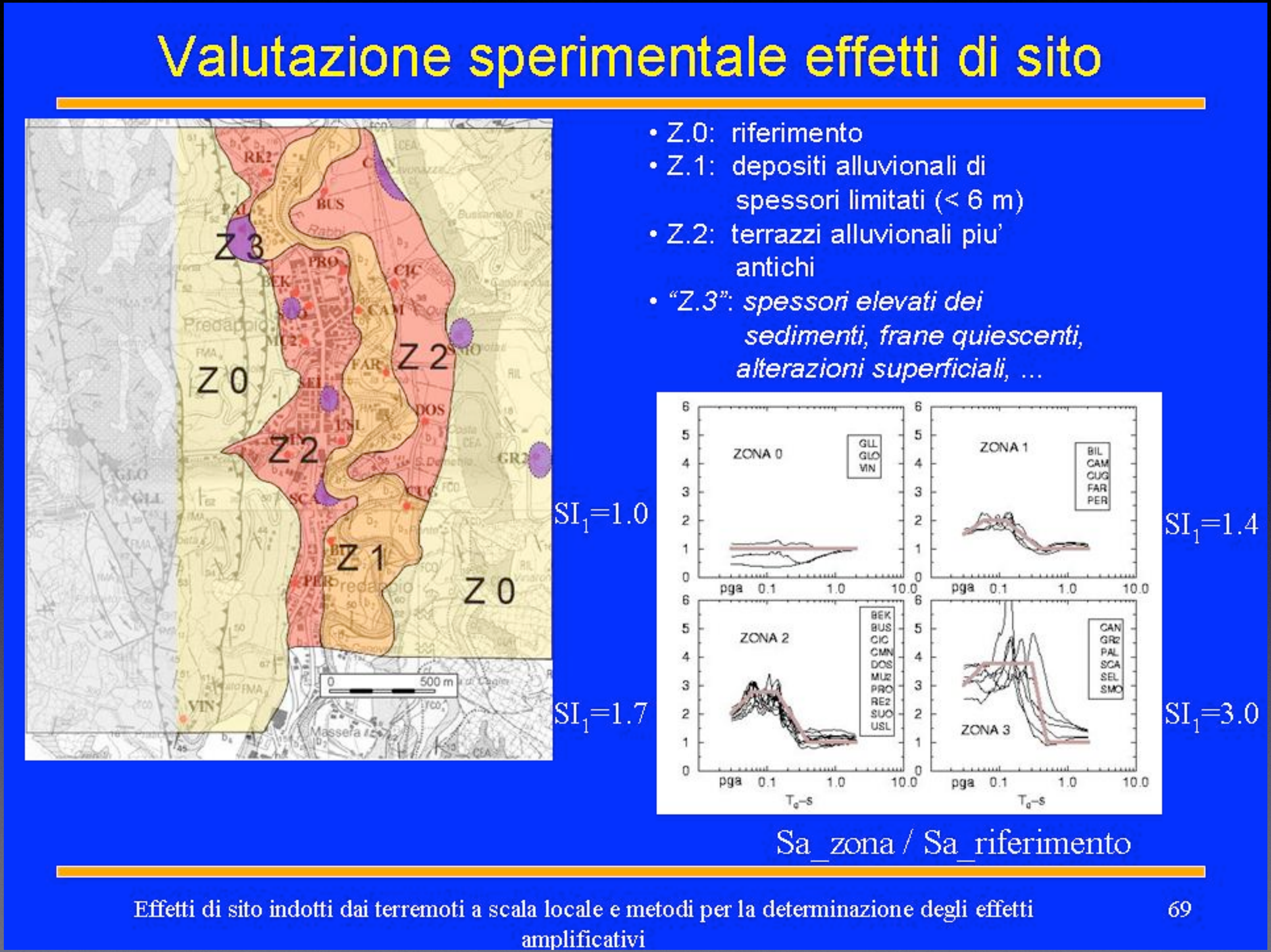
3 Livelli

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

L1 mappa di microzonazione



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, ...*

$SI_1=1.0$

$SI_1=1.4$

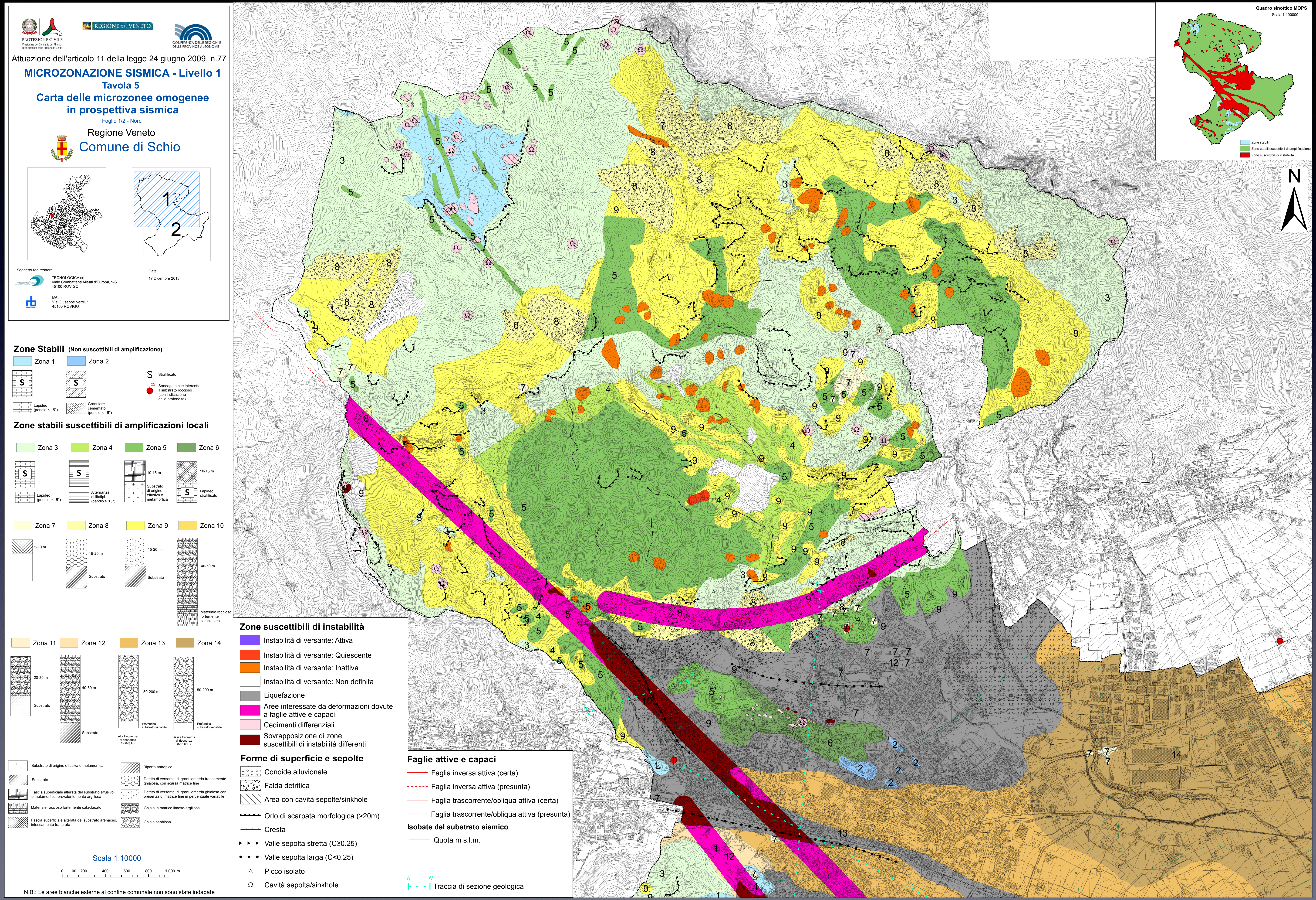
$SI_1=1.7$

$SI_1=3.0$

Sa_zona / Sa_riferimento

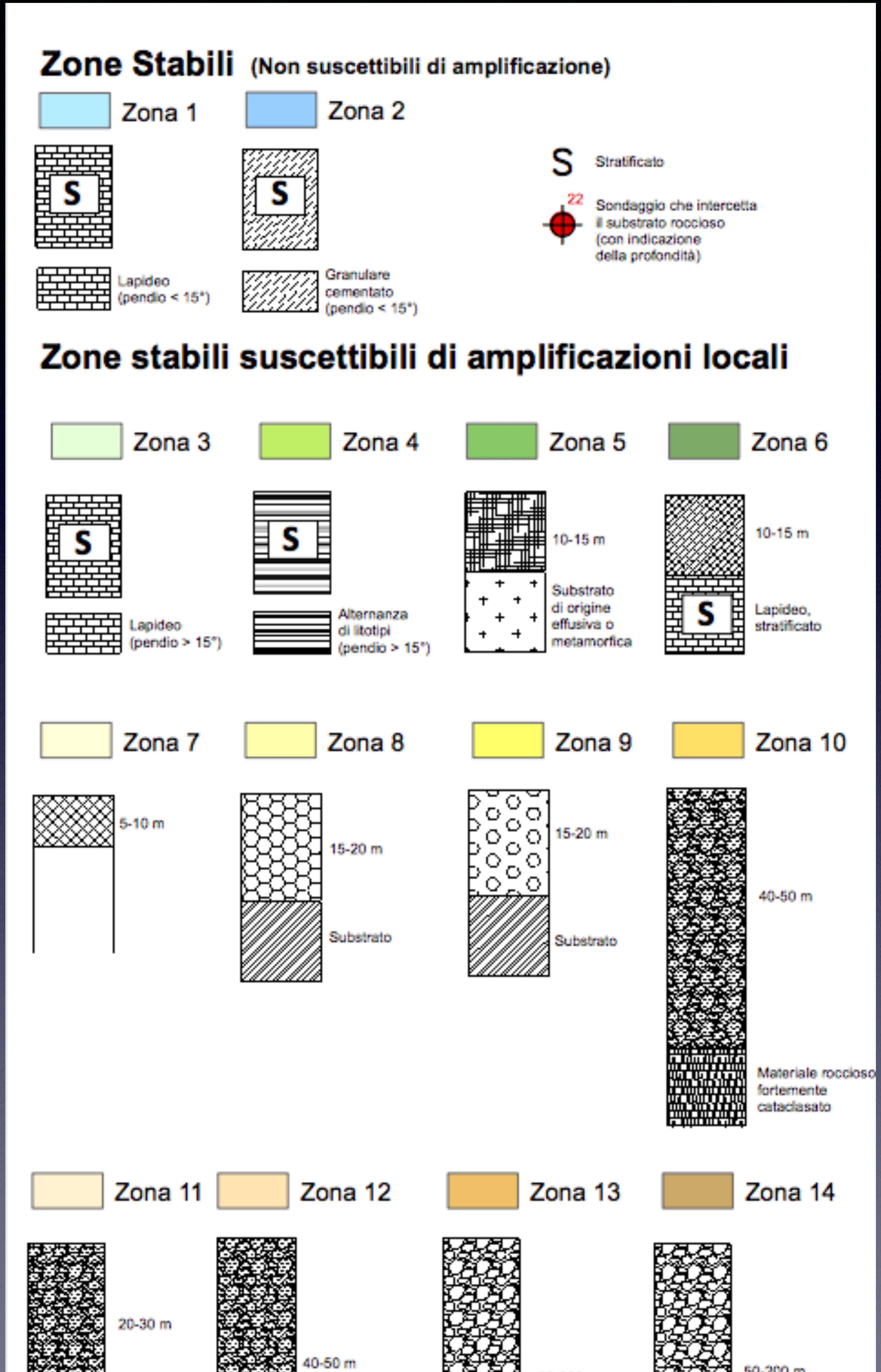
Effetti di sito indotti dai terremoti a scala locale e metodi per la determinazione degli effetti amplificativi 69

L1 mappa di microzonazione



L1 mappa di microzonazione

- Zone suscettibili di amplificazione
- Zone potenzialmente instabili



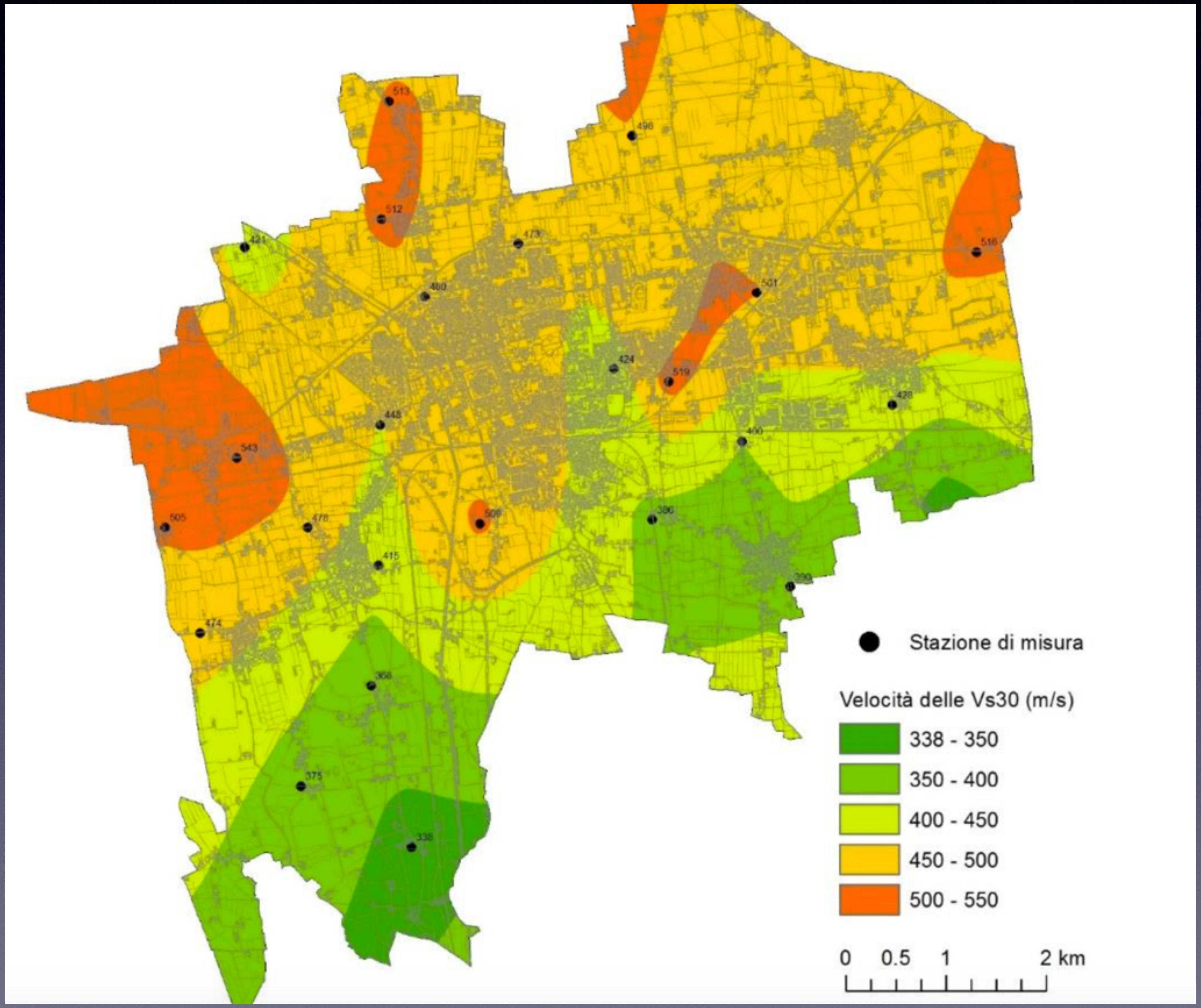
Zone suscettibili di instabilità

- 🟪 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)

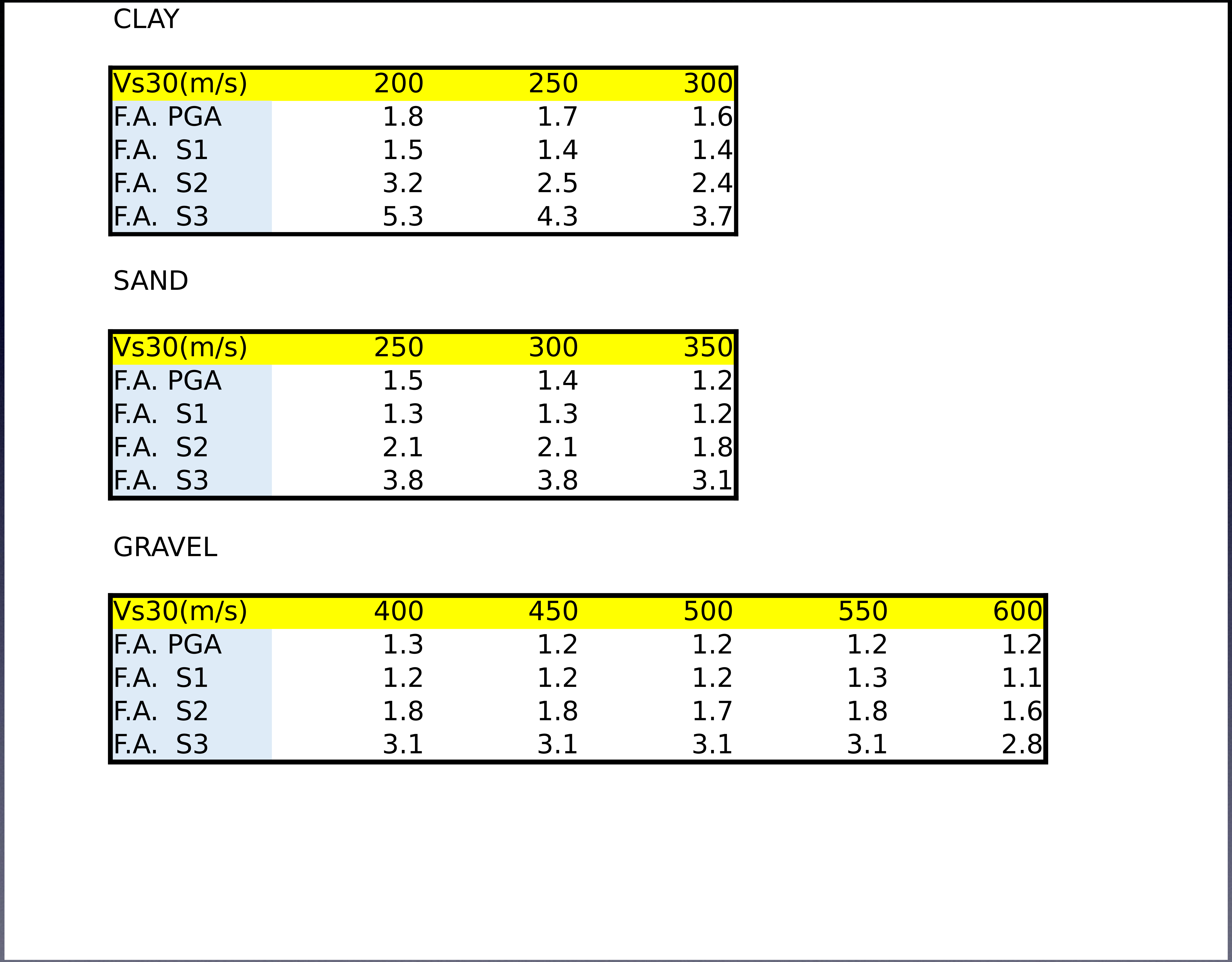
Livello 2 = Pianificazione. Definizione di zone omogenee dal punto di vista sismico basate su misure sperimentali speditive



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

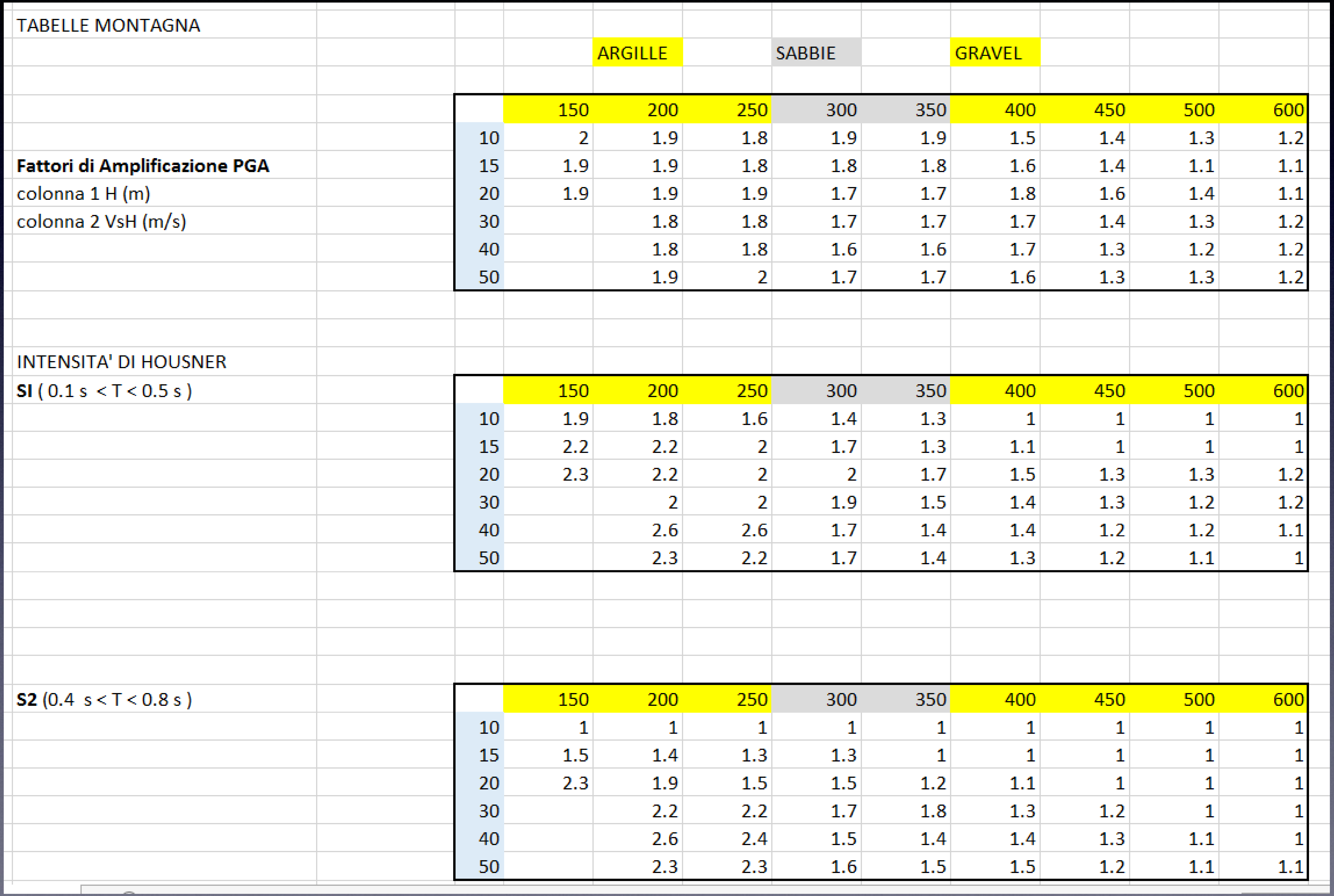


TABELLE MONTAGNA

ARGILLE SABBIE GRAVEL

Fattori di Amplificazione PGA
colonna 1 H (m)
colonna 2 VsH (m/s)

	150	200	250	300	350	400	450	500	600
10	2	1.9	1.8	1.9	1.9	1.5	1.4	1.3	1.2
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

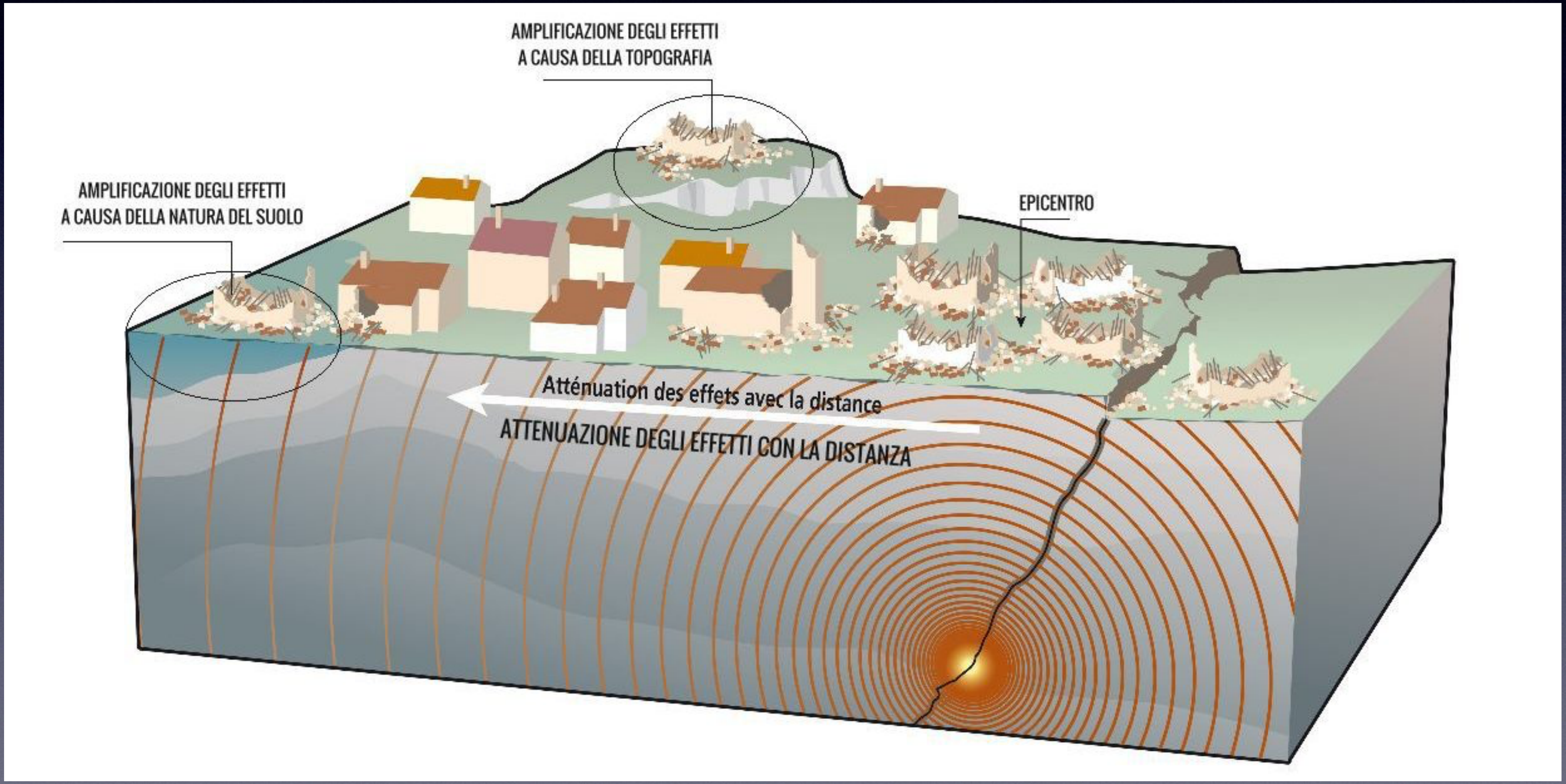
L3
Valutazione quantitativo di sito
=
Risposta Sismica Locale

Parte 2

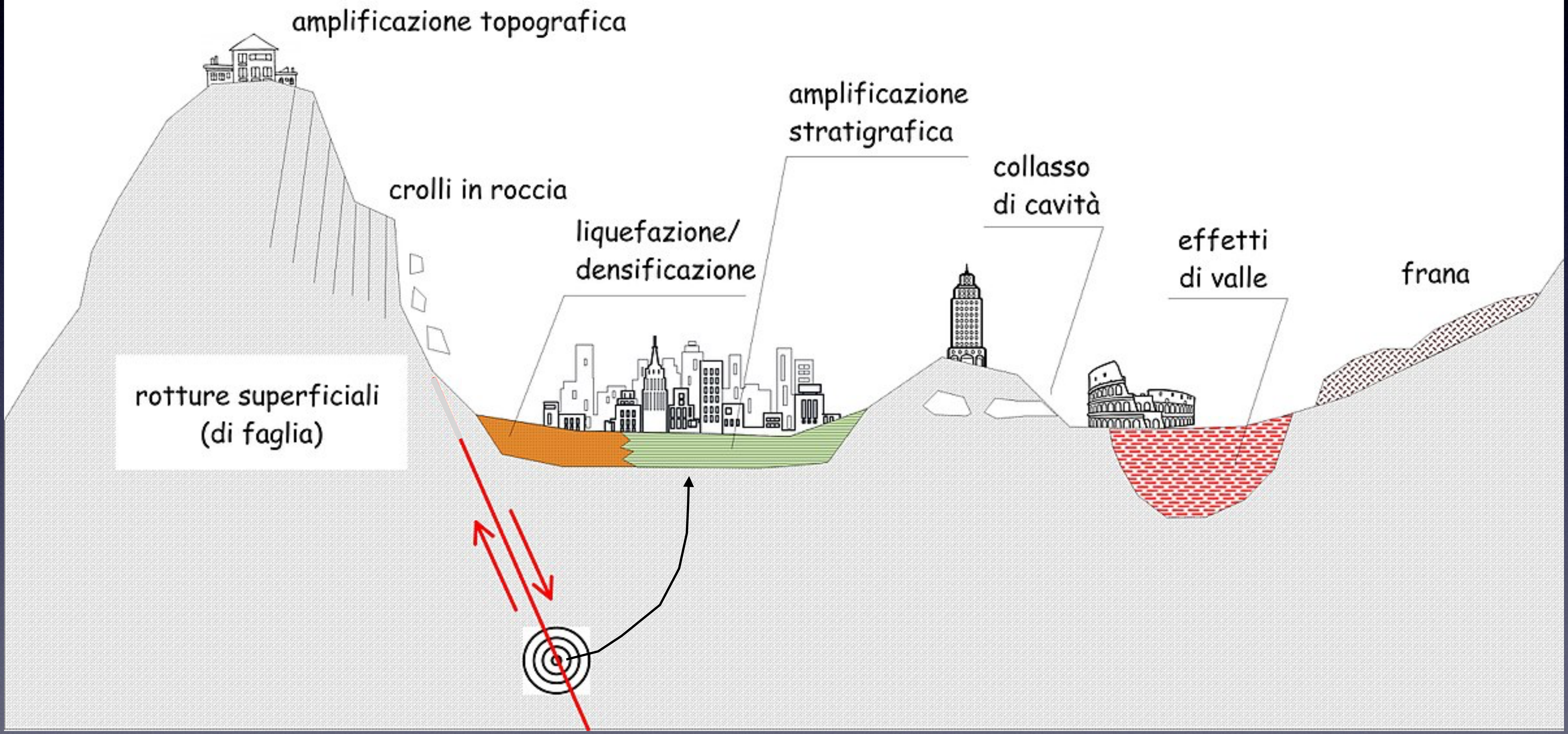
Abbiamo visto la ‘risposta sismica’,
ma cosa accade localmente?

Microzonazione e RSL
(Risposta Sismica Locale)

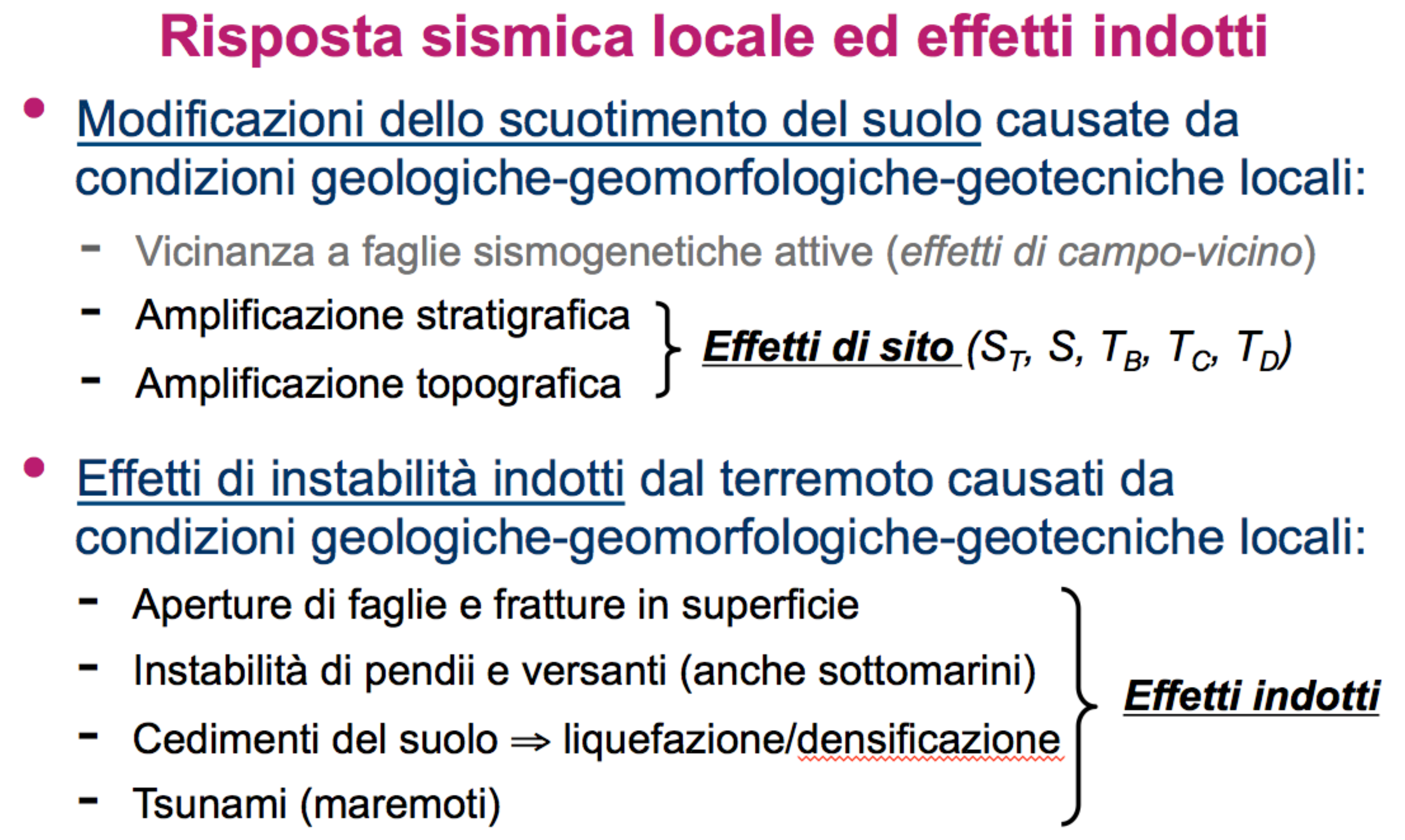
- La risposta sismica locale



- La risposta sismica locale



Pagliaroli mod



Risposta sismica locale ed effetti indotti

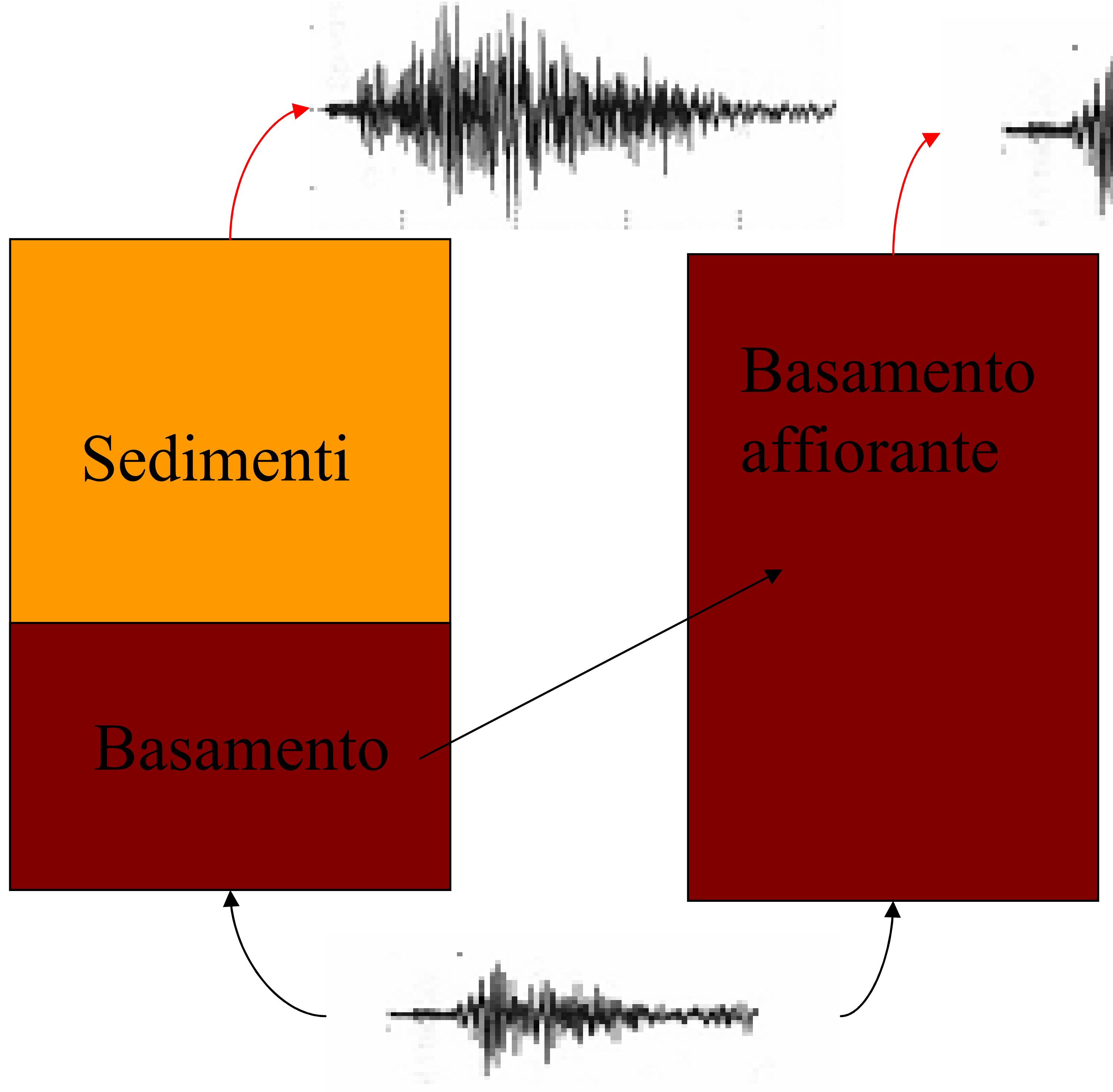
- Modificazioni dello scuotimento del suolo causate da condizioni geologiche-geomorfologiche-geotecniche locali:
  - Vicinanza a faglie sismogenetiche attive (*effetti di campo-vicino*)
  - Amplificazione stratigrafica
  - Amplificazione topografica

  } ***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 ⇒ liquefazione/densificazione
  - Tsunami (maremoti)

  } ***Effetti indotti***

Effetti litologici



Terremoto alla superficie f(ν)

Moto di riferimento g(ν)

Sedimenti

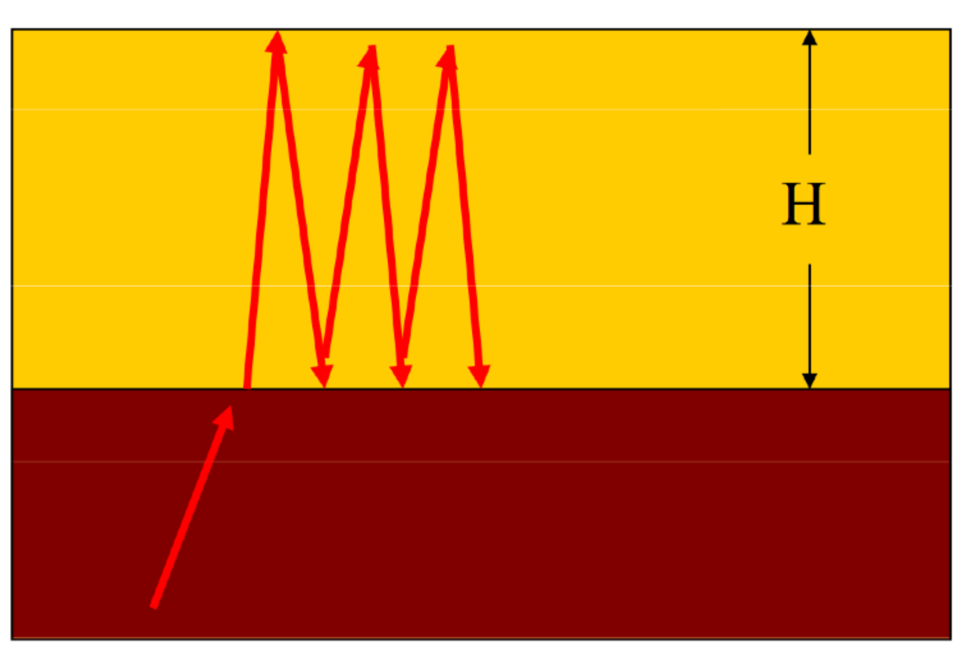
Basamento

Basamento affiorante

Input sismico

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

Funzione di trasferimento



Energia amplificata da strato soffice

Amplificazione Litologica

Effetti topografici

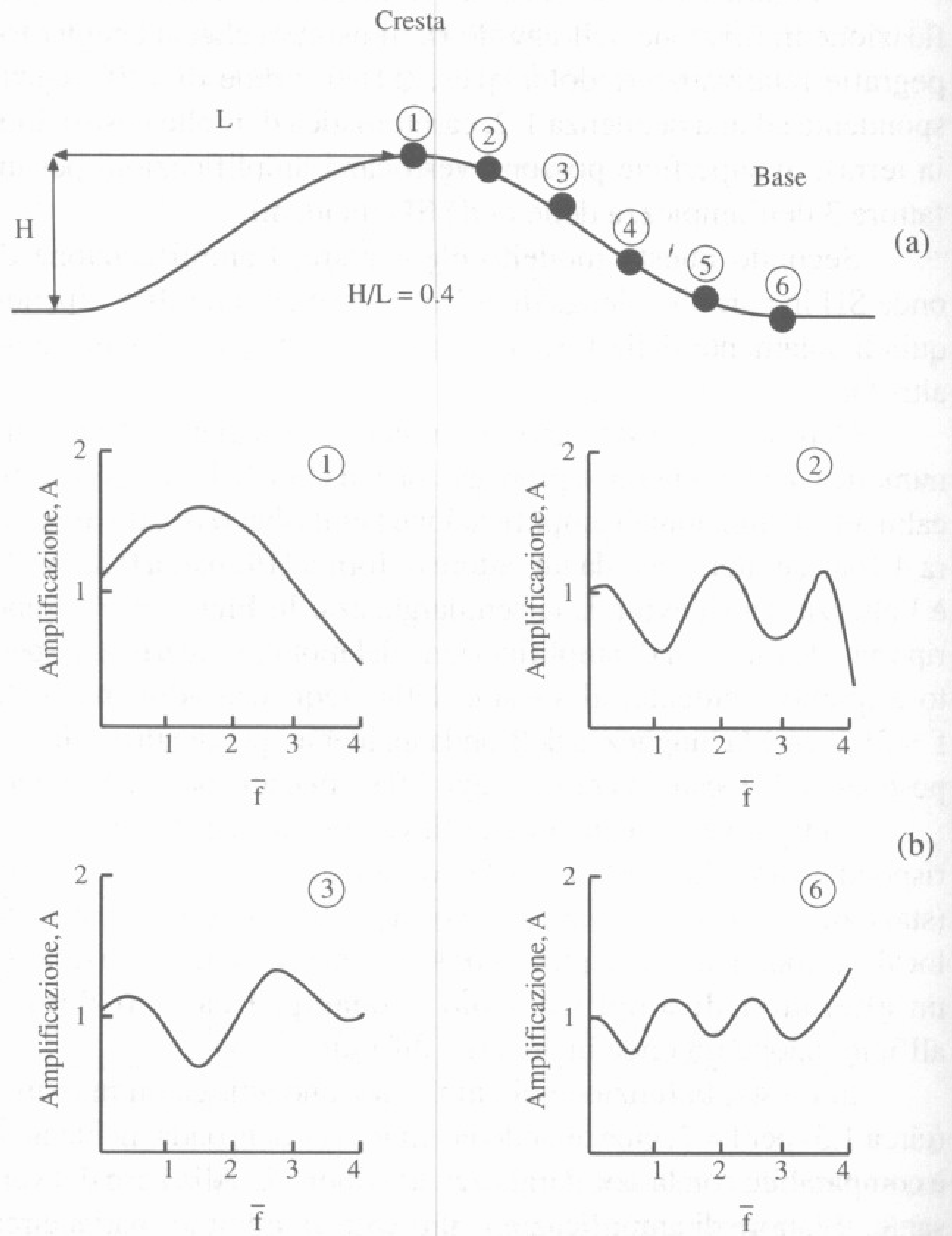
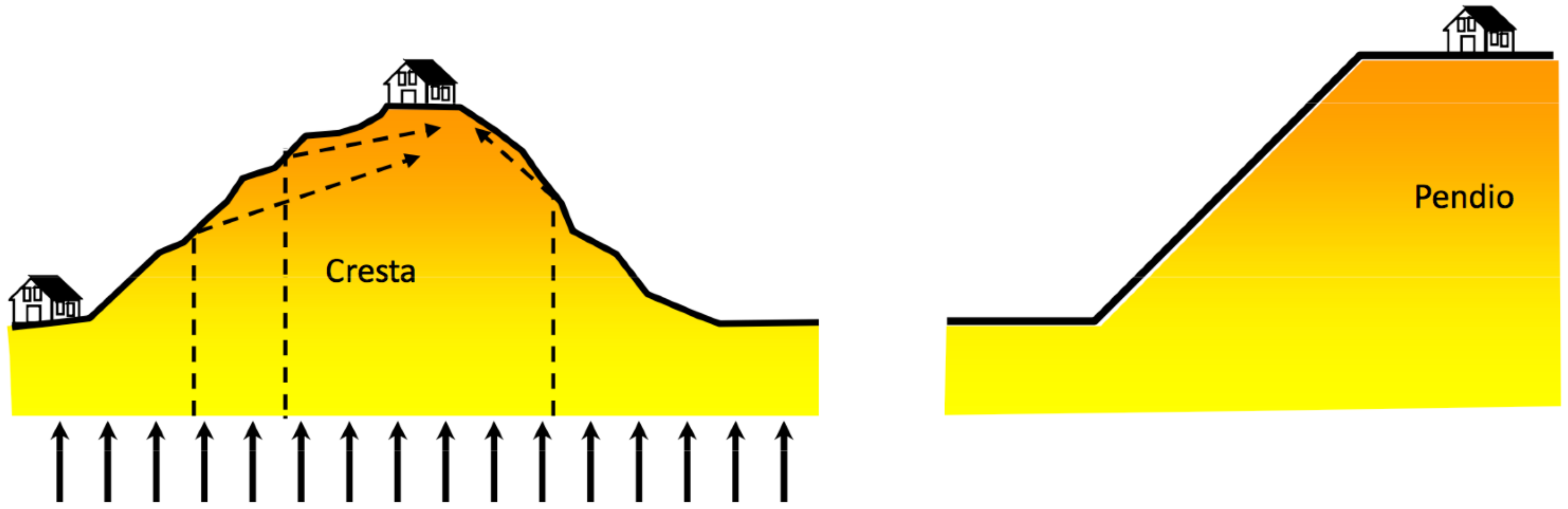


Fig. 4.16. Funzioni di amplificazione calcolate in corrispondenza di alcune postazioni di un rilievo isolato nell'ipotesi di propagazione verticale di onde SH (Geli *et al.*, 1988).

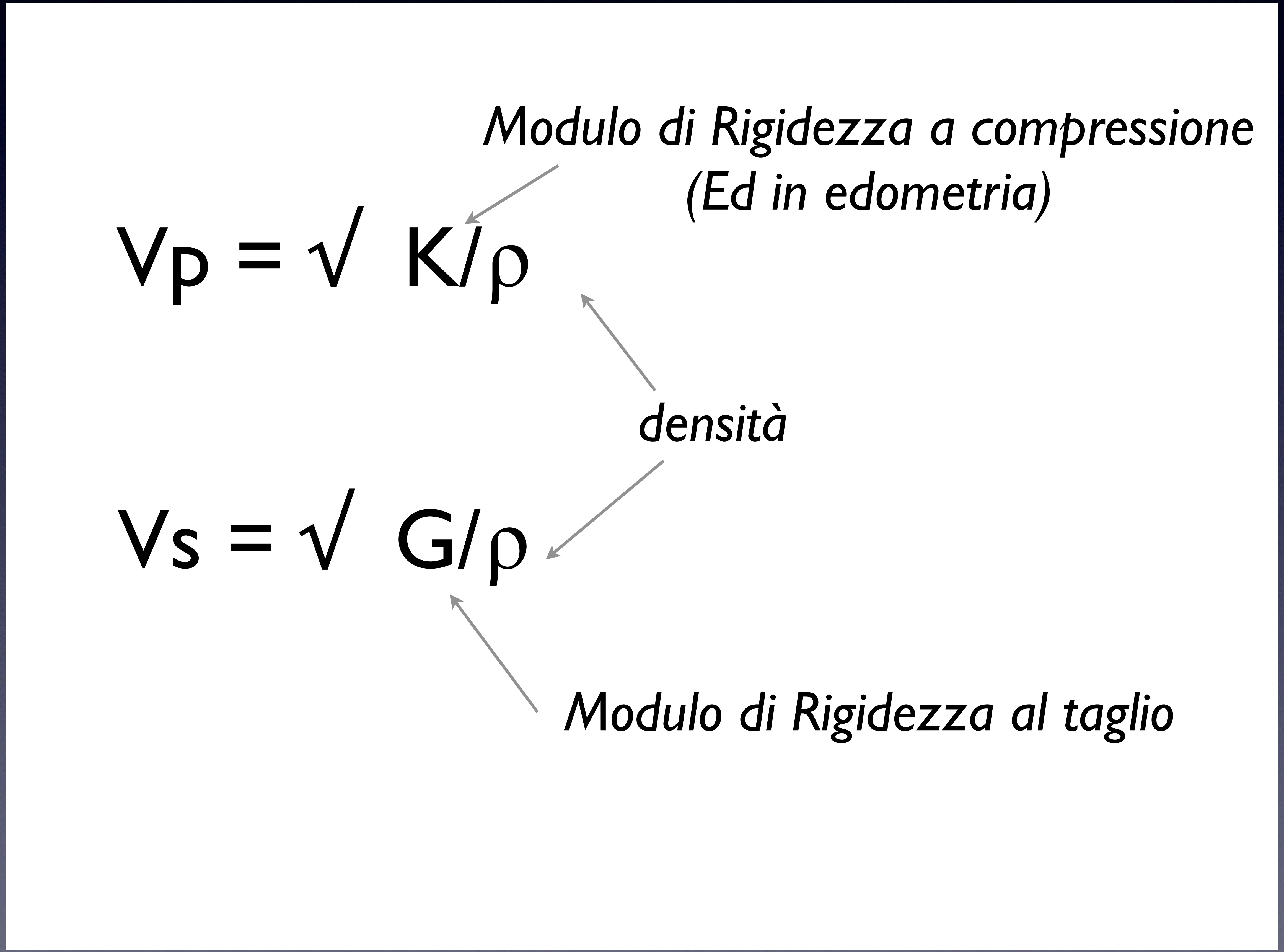
L'inteferenze delle onde incidenti è costruttiva in prossimità dei rilievi

Le sommità sono più pericolose dei fondi valle...



Onde di Volume

(per la geotecnica)



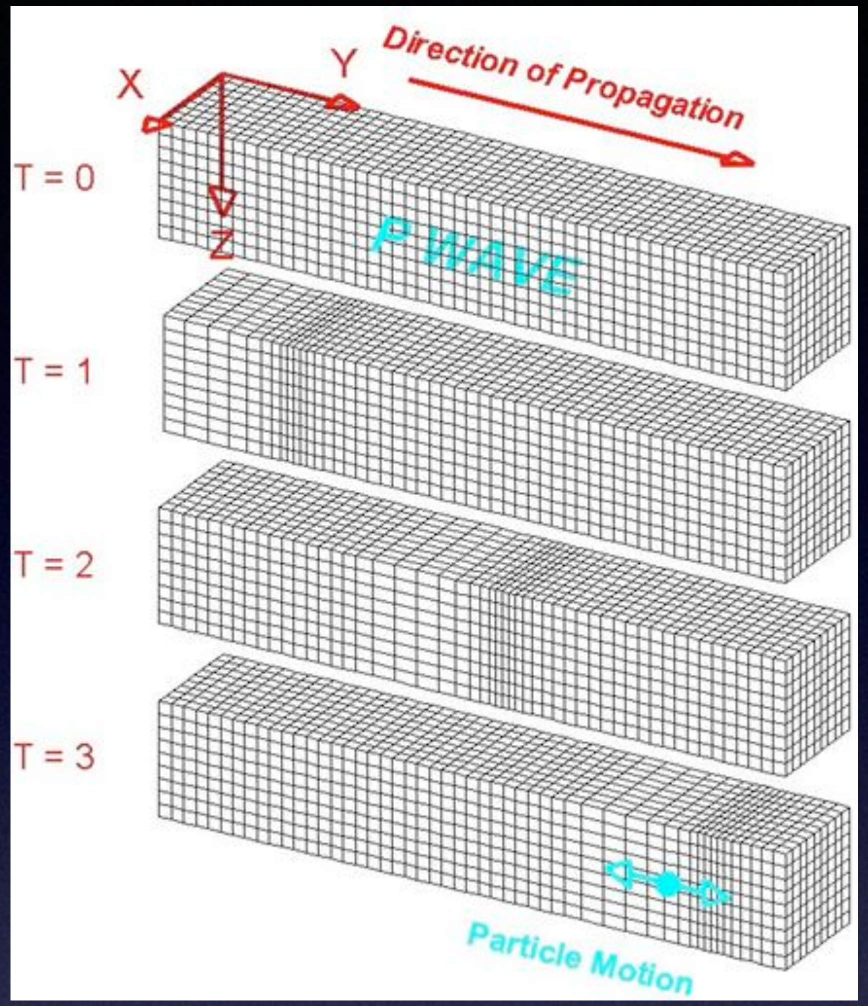
Modulo di Rigidezza a compressione (Ed in edometria)

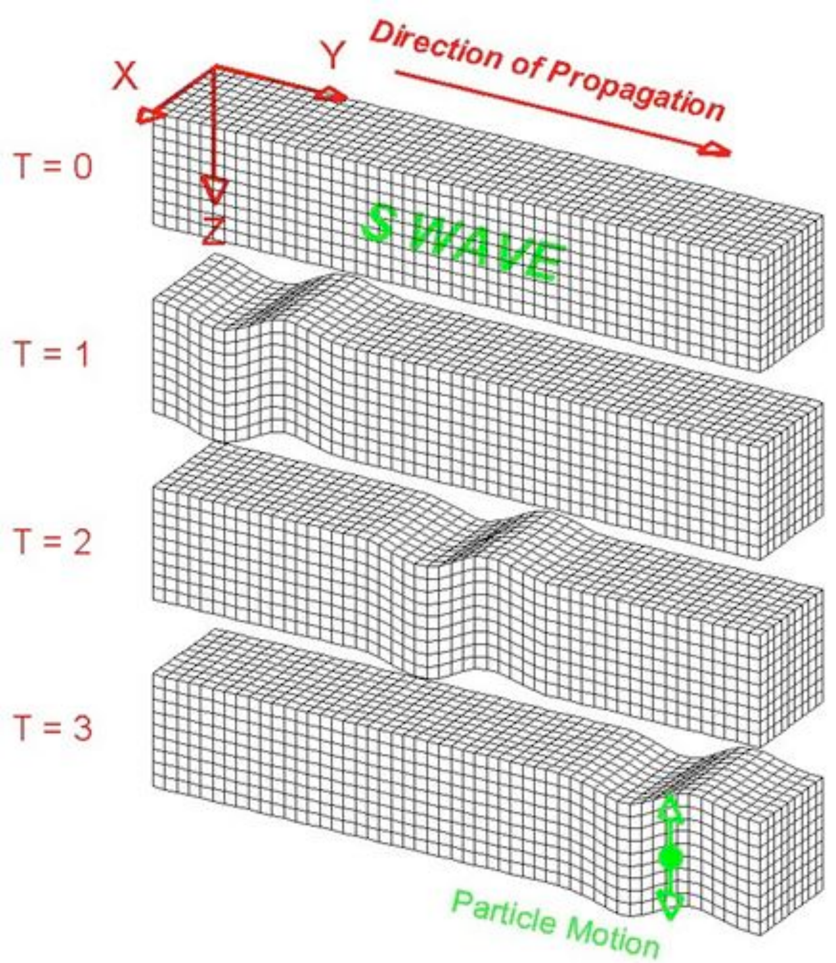
$$V_p = \sqrt{K/\rho}$$

densità

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

Modulo di Rigidezza al taglio



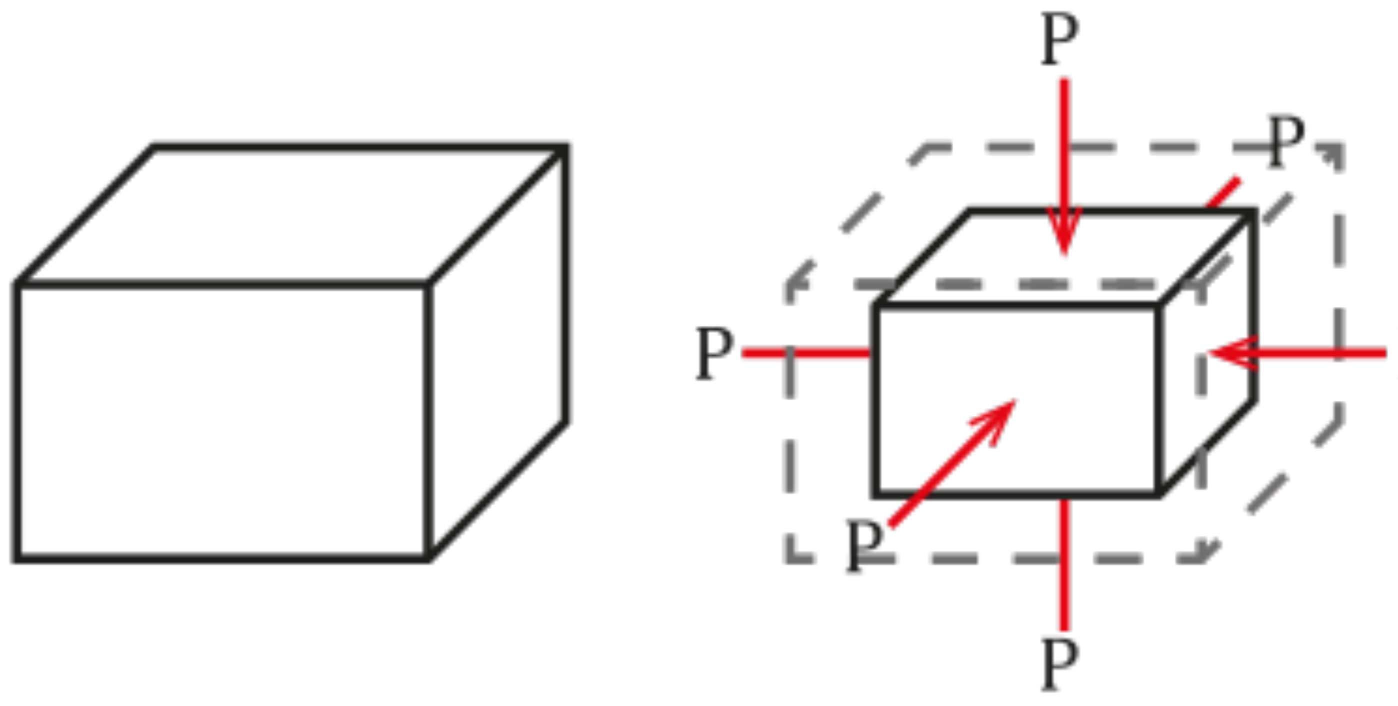


Onde di Volume

(per la geotecnica)

K = modulo di compressibilità

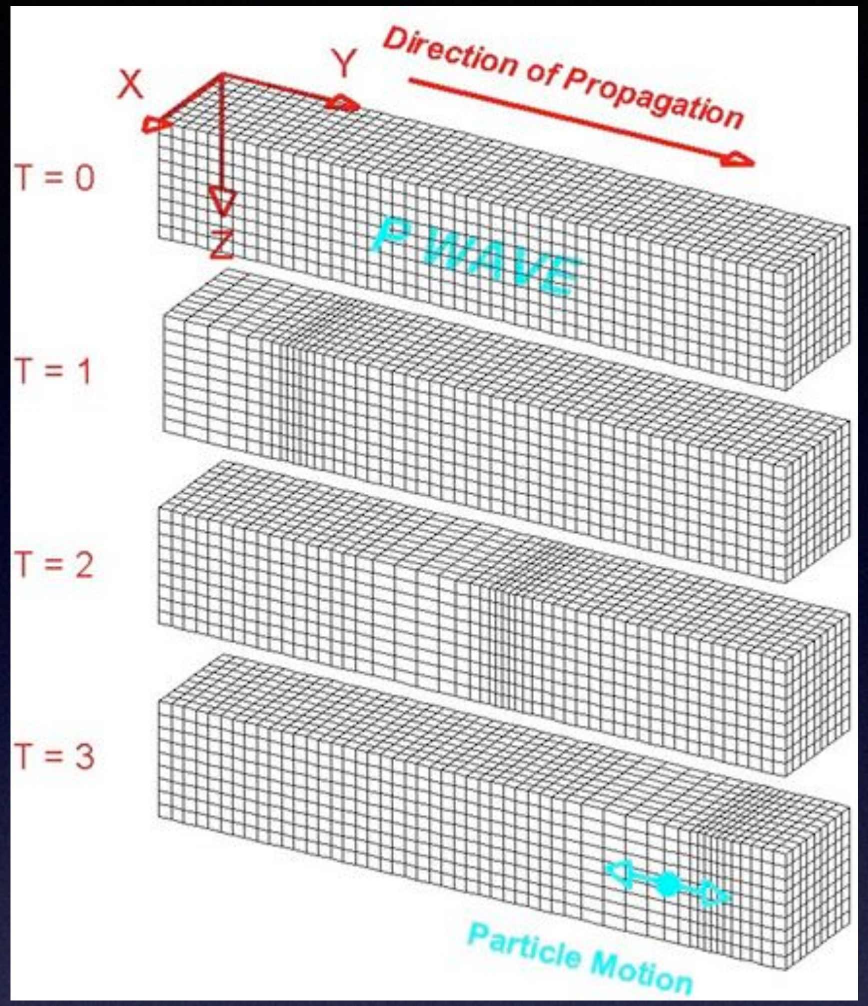
l'incremento di pressione necessario
a causare un relativo incremento di densità

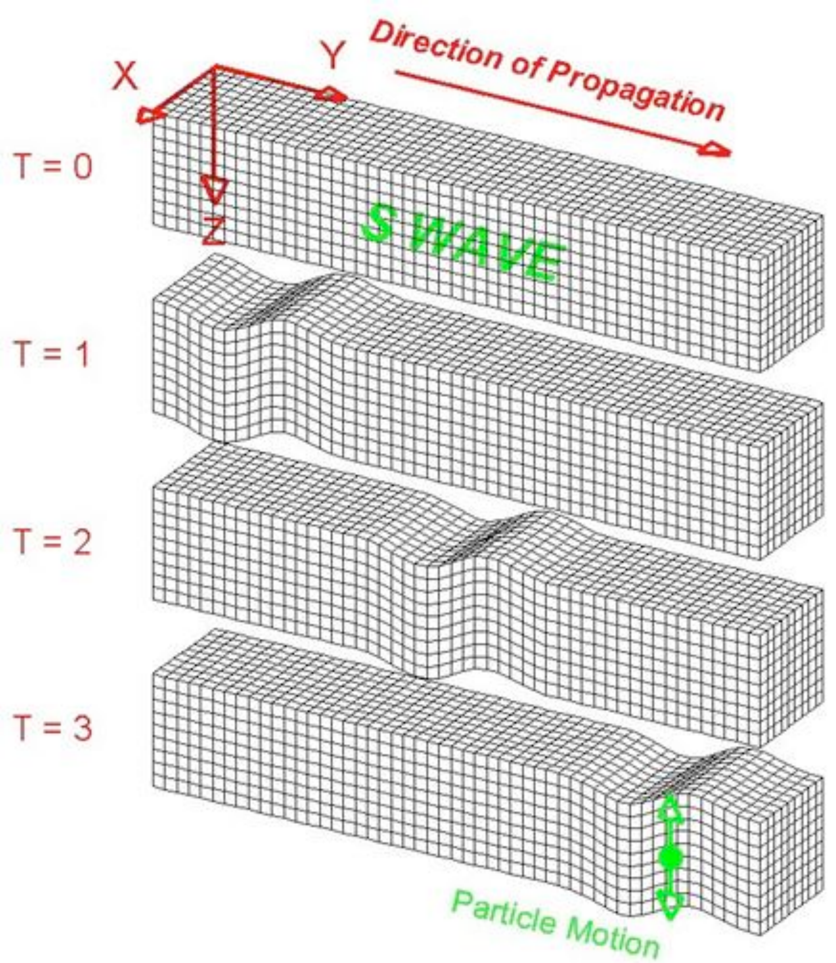


Costanti di Lamè

Modulo di taglio

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





Moduli elastici

Modulo G

Modulo di taglio (μ)

densità

velocità S

$$G = \rho\ Vs^2$$

Pwave modulus

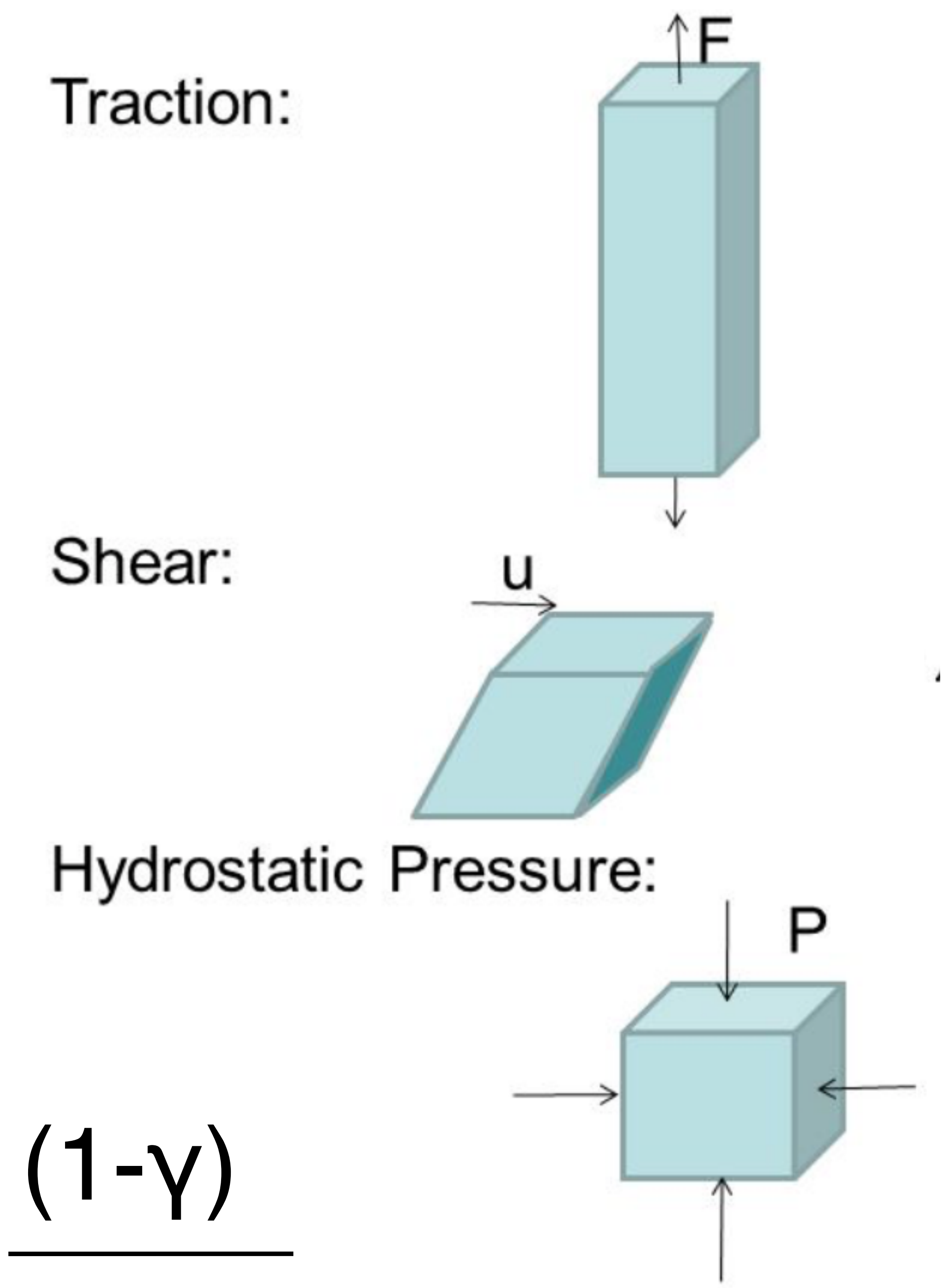
Poisson

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

Young modulus

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

$$\frac{Vp}{Vs} = \sqrt{\frac{(1-\gamma)}{(0.5-\gamma)}}$$

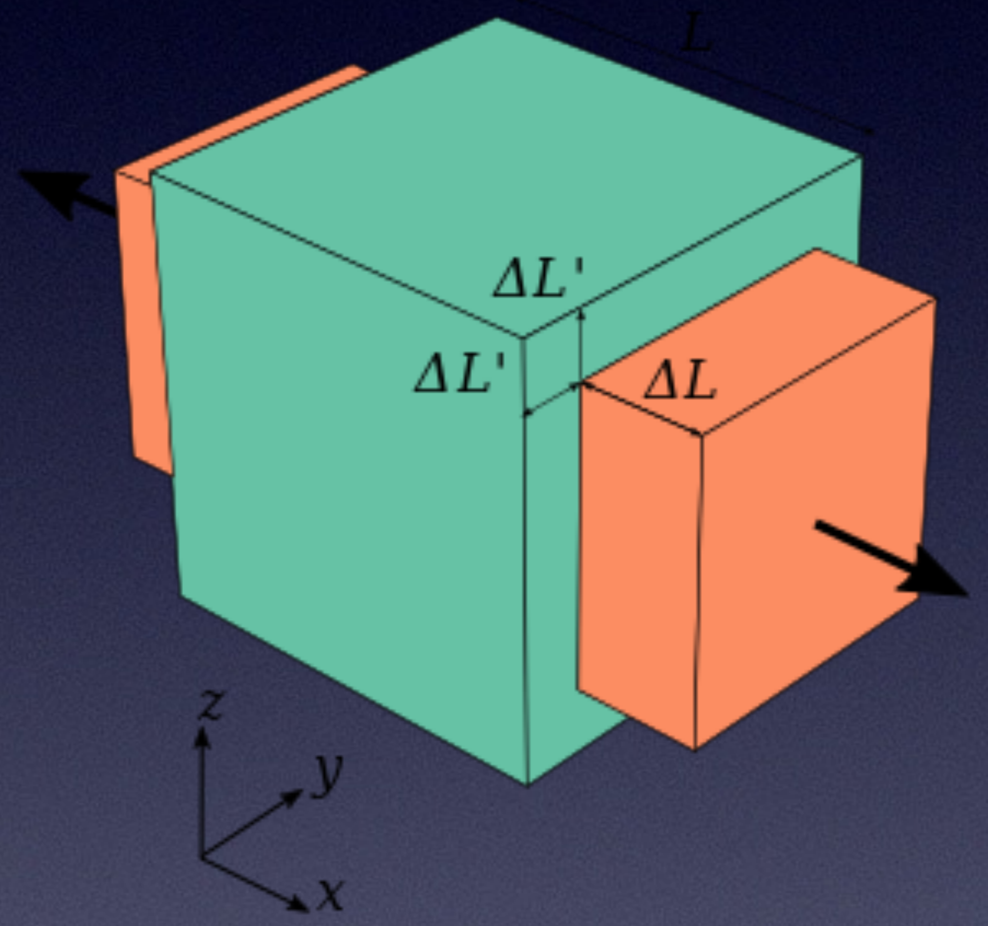


Moduli elastici

Poisson ratio γ

$$\gamma = -\frac{\varepsilon_{\text{m, trasv}}}{\varepsilon_{\text{m, long}}}$$

$$\frac{\textit{Deformazione trasversale}}{\textit{Deformazione longitudinale}}$$

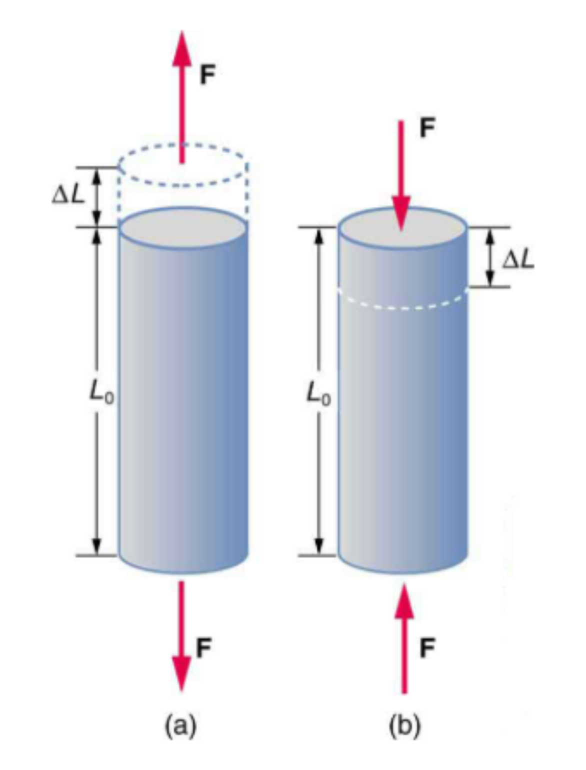


$<$ 0.5 !

(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

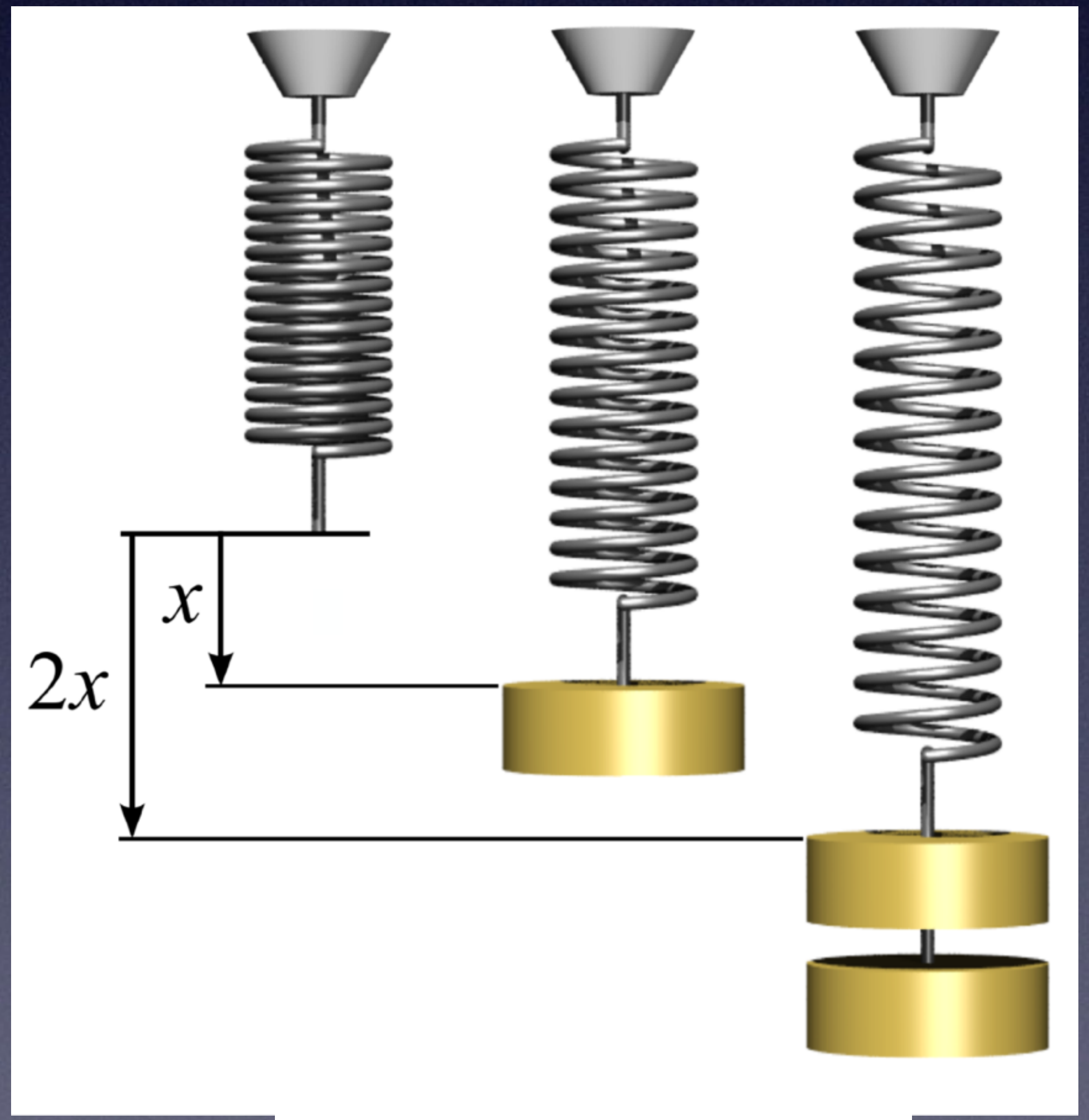
Principi: II principio della dinamica - legge di Hooke

$$\sigma = E\varepsilon$$

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

$$\frac{\partial^2 \overline{\varepsilon}}{\partial t^2} = \underbrace{\frac{\lambda + 2G}{\rho}}_{Vp^2} \nabla^2 \overline{\varepsilon}$$

S

$$\frac{\partial^2 \Omega_z}{\partial t^2} = \underbrace{\frac{G}{\rho}}_{Vs^2} \cdot \nabla^2 \Omega_z$$

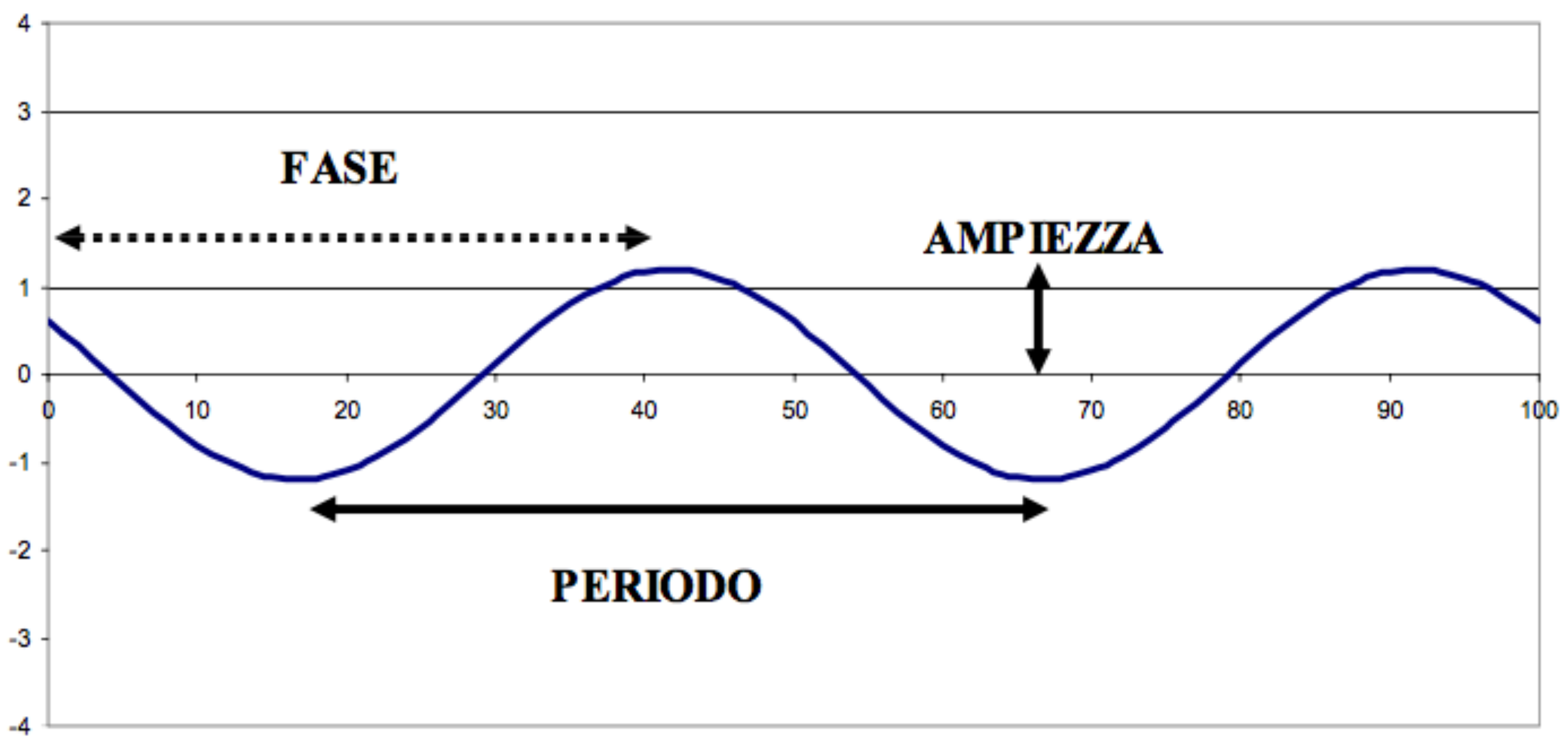
$$\boxed{V_P = \sqrt{\frac{\lambda + 2G}{\rho}}}$$

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

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



$\boxed{A(t) = A_{\max}\cos(2\pi f t + \phi)}$	Eq. onda
$\phi = -2\pi f t_{\max}$	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

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

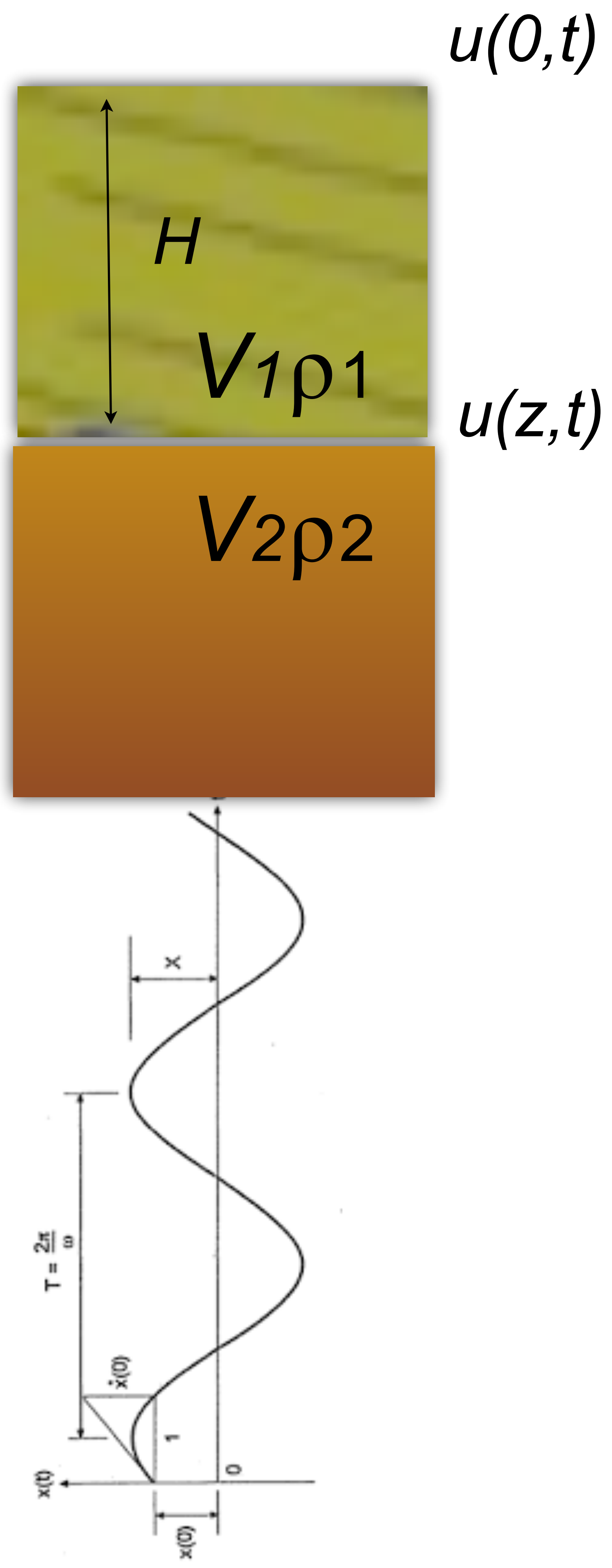
Funzione di Trasferimento
z=H

superficie

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

profondità

Sollecitazione armonica
substrato elastico ideale

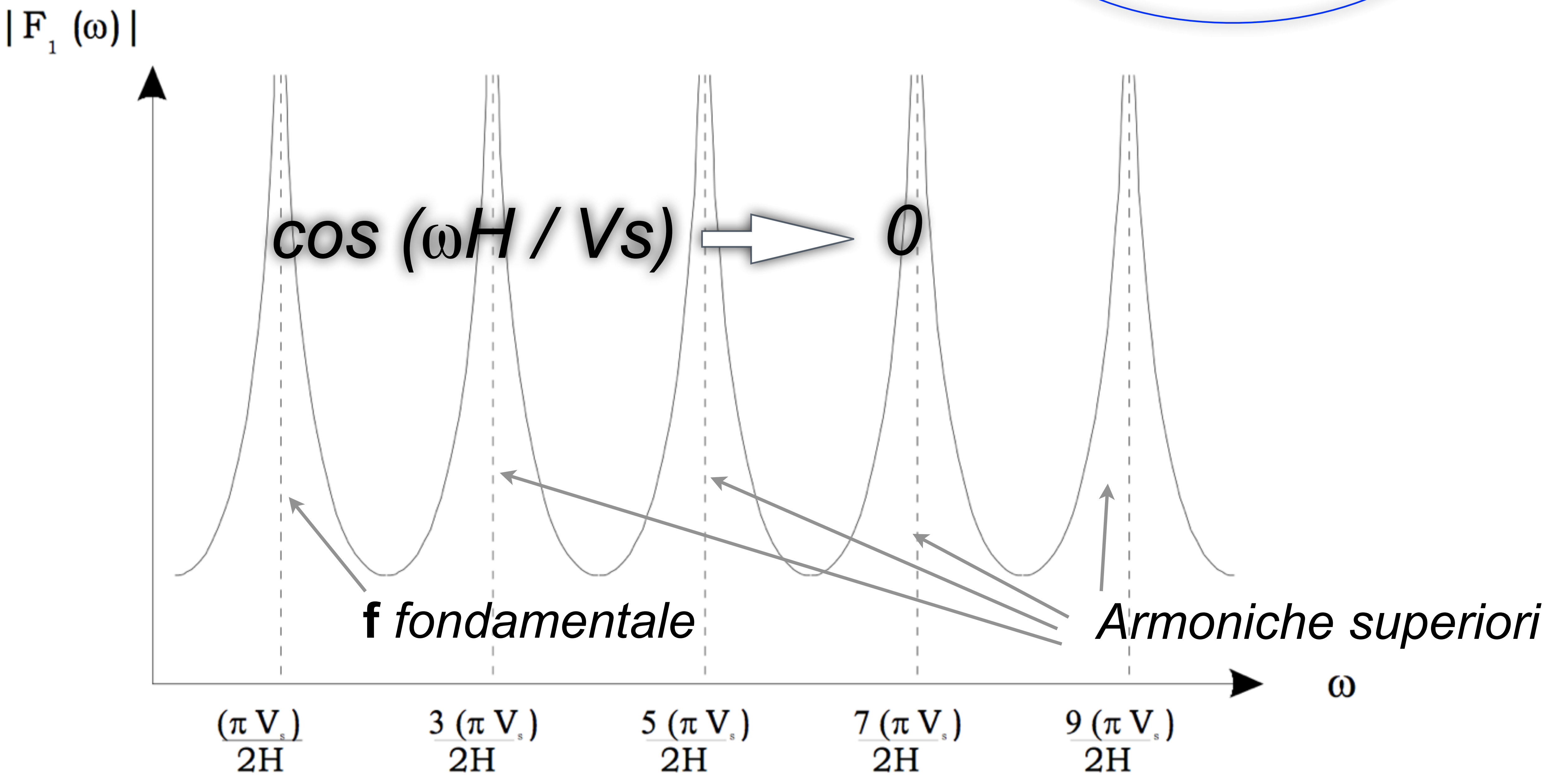


Propagazione delle Onde sismiche in un mezzo elastico, omogeneo e isotropo - sollecitazione armonica

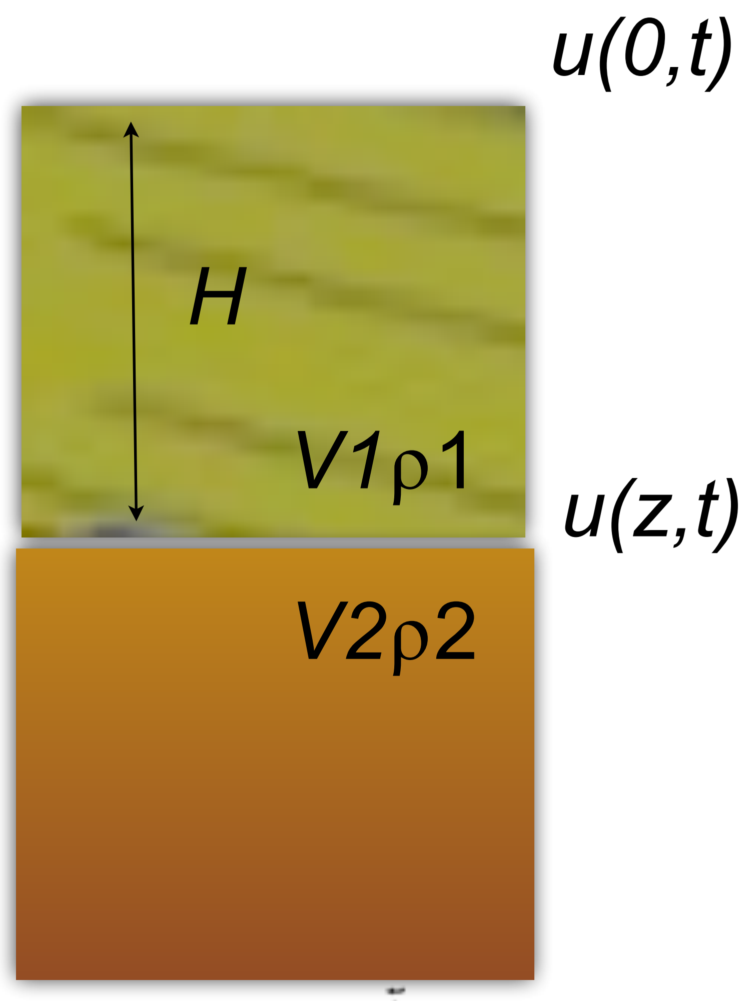
FUNZIONE di AMPLIFICAZIONE A = *MODULO Funzione di Trasferimento*

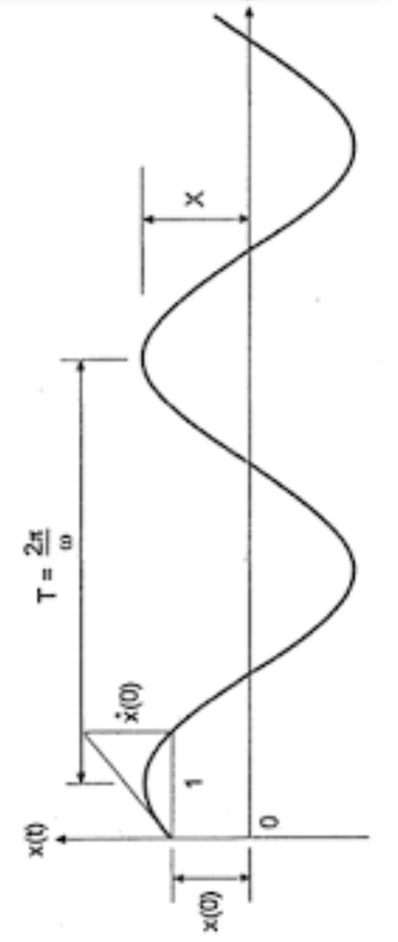
K=ω/Vs

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



Sollecitazione armonica





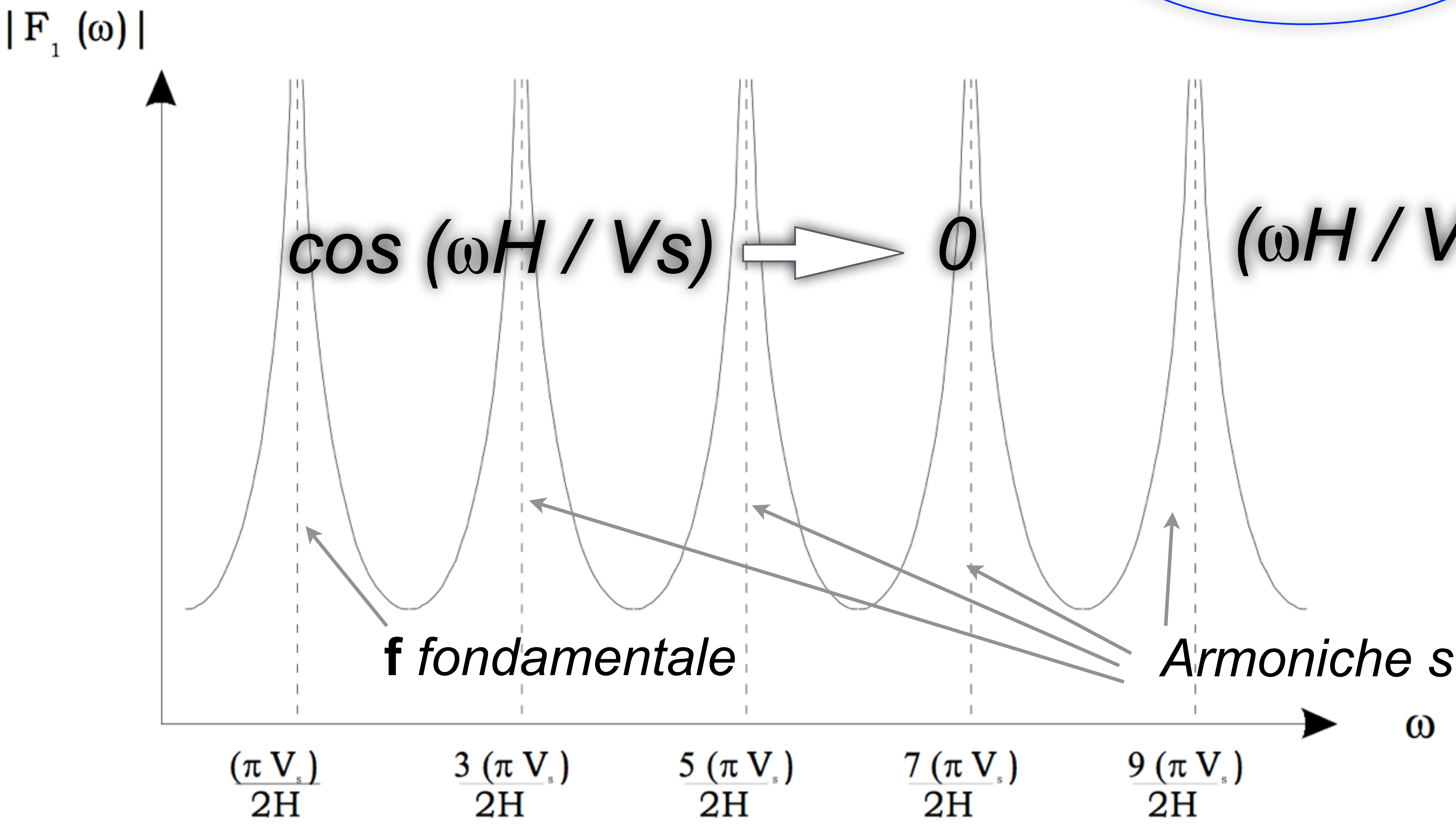
Propagazione delle Onde sismiche in un mezzo elastico, omogeneo e isotropo - sollecitazione armonica

FUNZIONE di AMPLIFICAZIONE A = *MODULO Funzione di Trasferimento*

Sollecitazione armonica

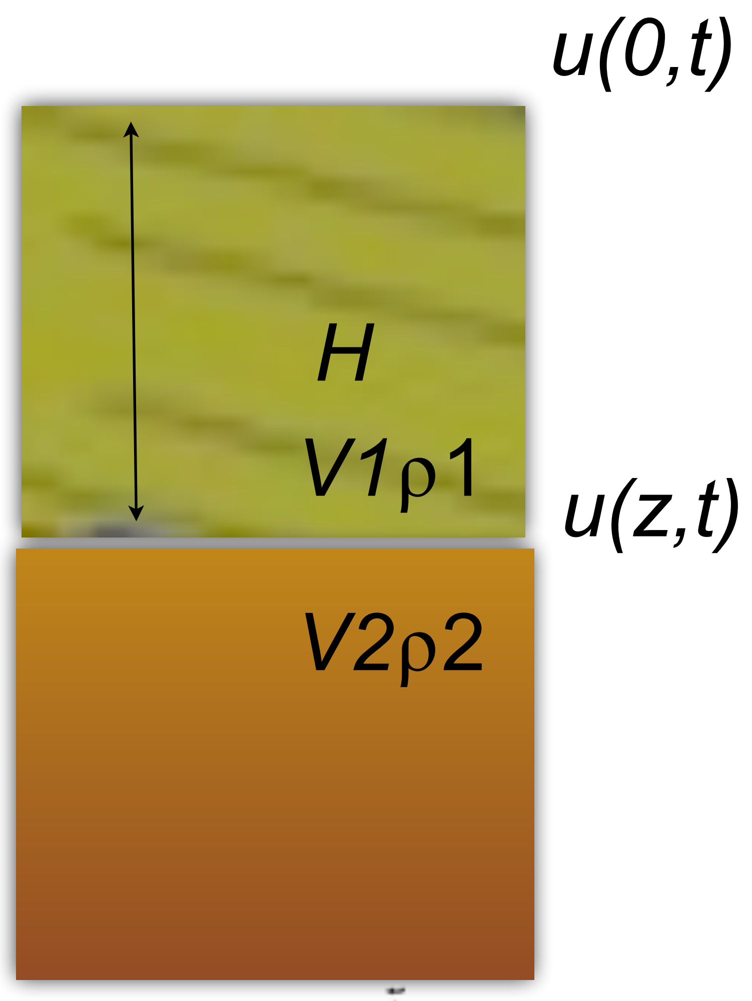
$K=\omega/Vs$

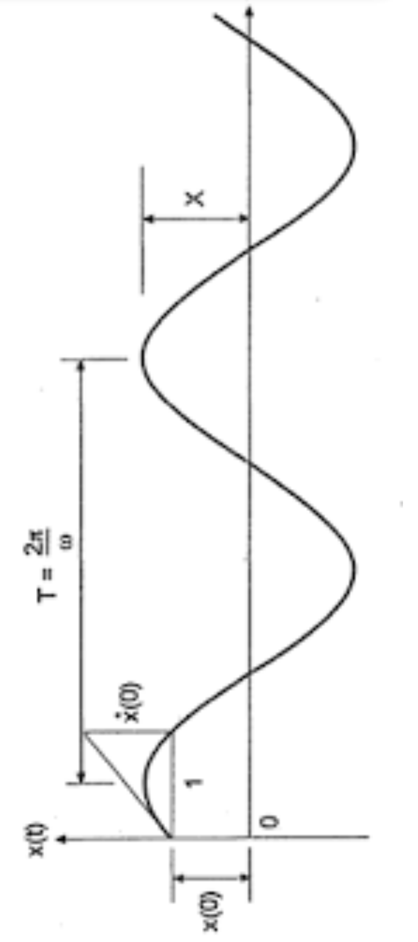
$$A(\omega) = \left|H(\omega)\right| = \frac{1}{\cos(kH)} = \frac{1}{\cos(\omega H / Vs)}$$



$$\cos(\omega H / Vs) \Rightarrow 0$$

$$(\omega H / Vs) \Rightarrow \frac{\pi}{2}$$





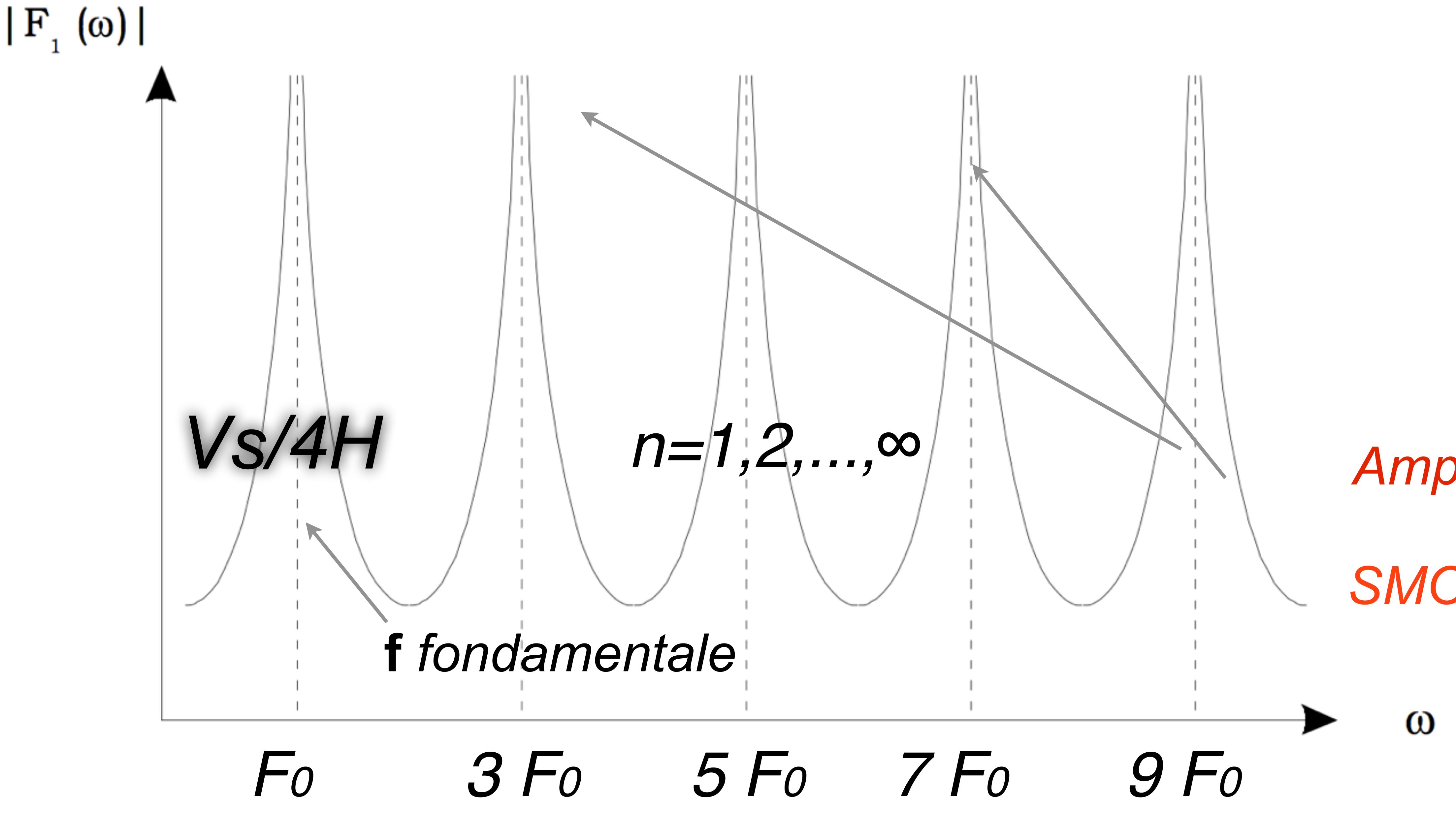
Propagazione delle Onde sismiche in un mezzo elastico, omogeneo e isotropo - <u>sollecitazione armonica</u>

Frequenza fondamentale

n=1, 2,...,∞

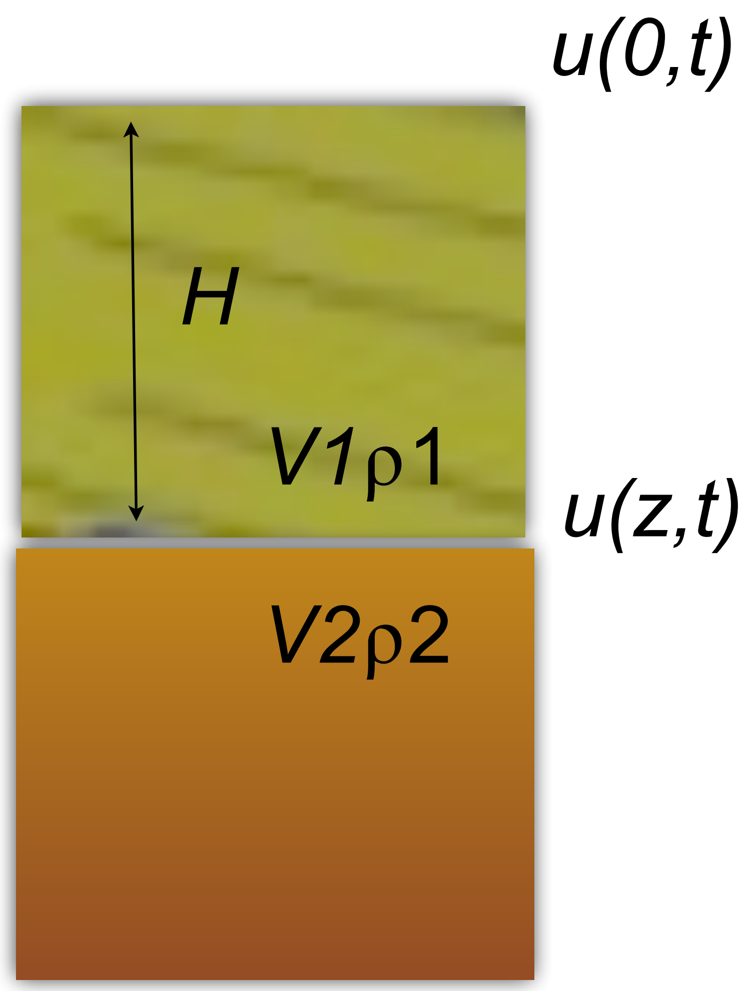
$$\omega = \frac{Vs}{H}\,\frac{\pi}{2}\,(2n-1) \quad \Rightarrow \quad \mathbf{f} = \frac{Vs}{4\,H}\,(2n-1)$$

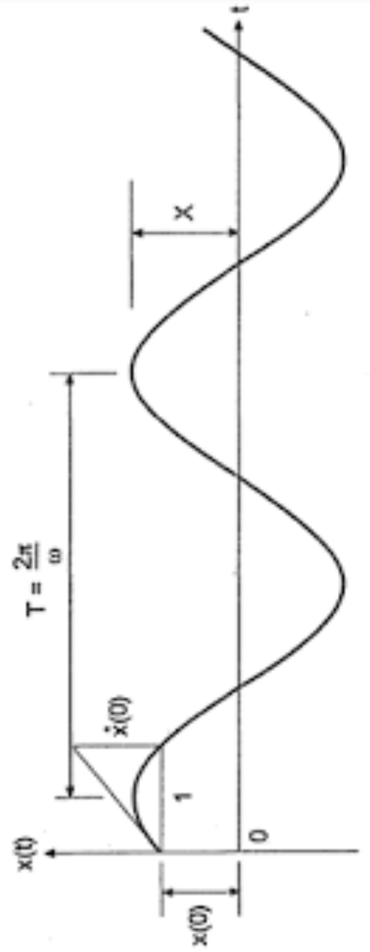
$$\omega = 2\pi\, f$$



Amplificazioni NON SMORZATE !!

Sollecitazione armonica





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

↓

a
Propagazione delle Onde sismiche in un mezzo reale

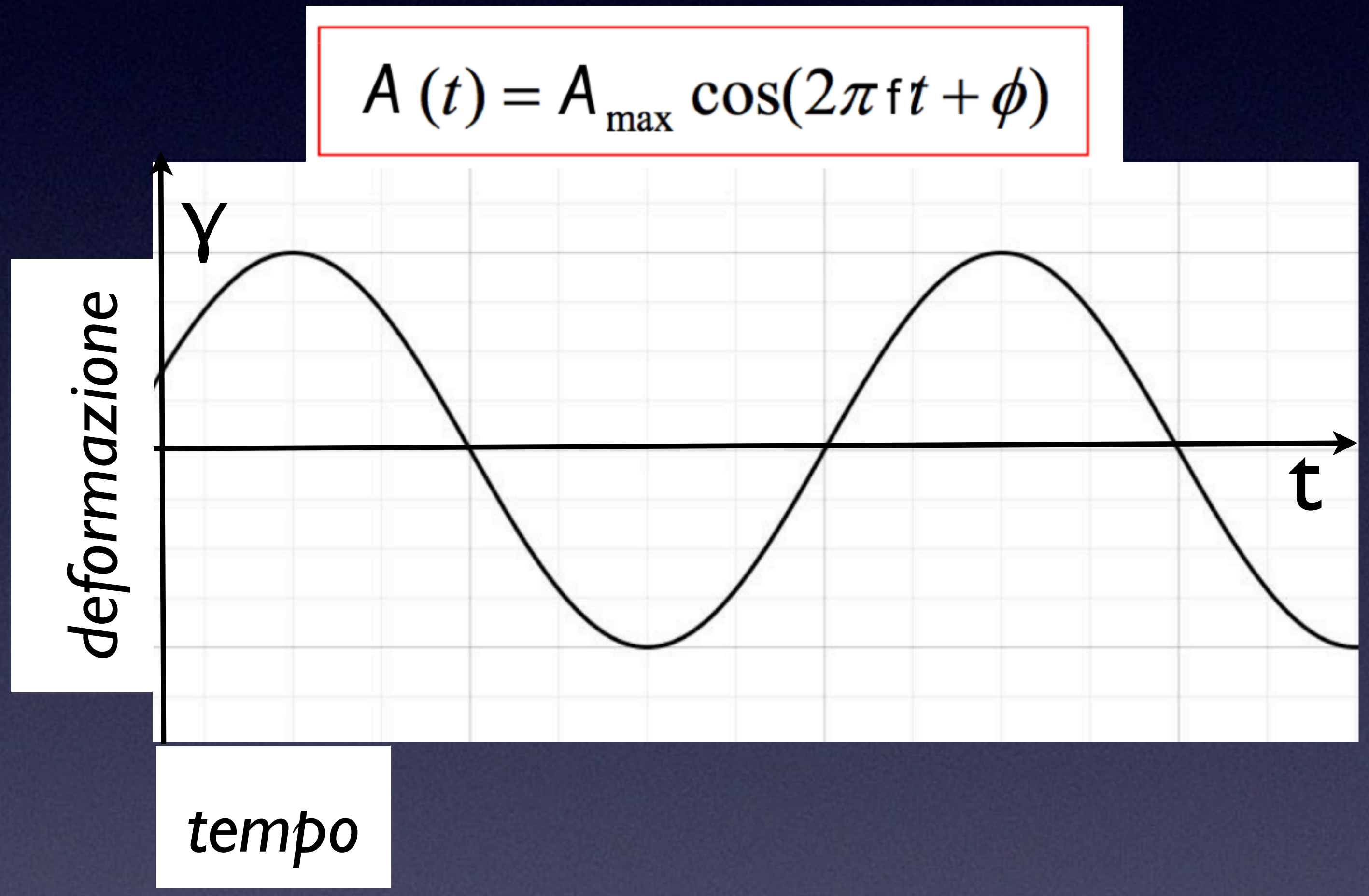
Propagazione delle Onde sismiche in un mezzo

parametri delle terre:

-Densità	δ	gr/cm3	ideale
-Modulo di rigidezza al taglio	G	N/mm2	
-Velocità sismiche S	Vs	m/s	
+			
-Smorzamento	D	%	reale

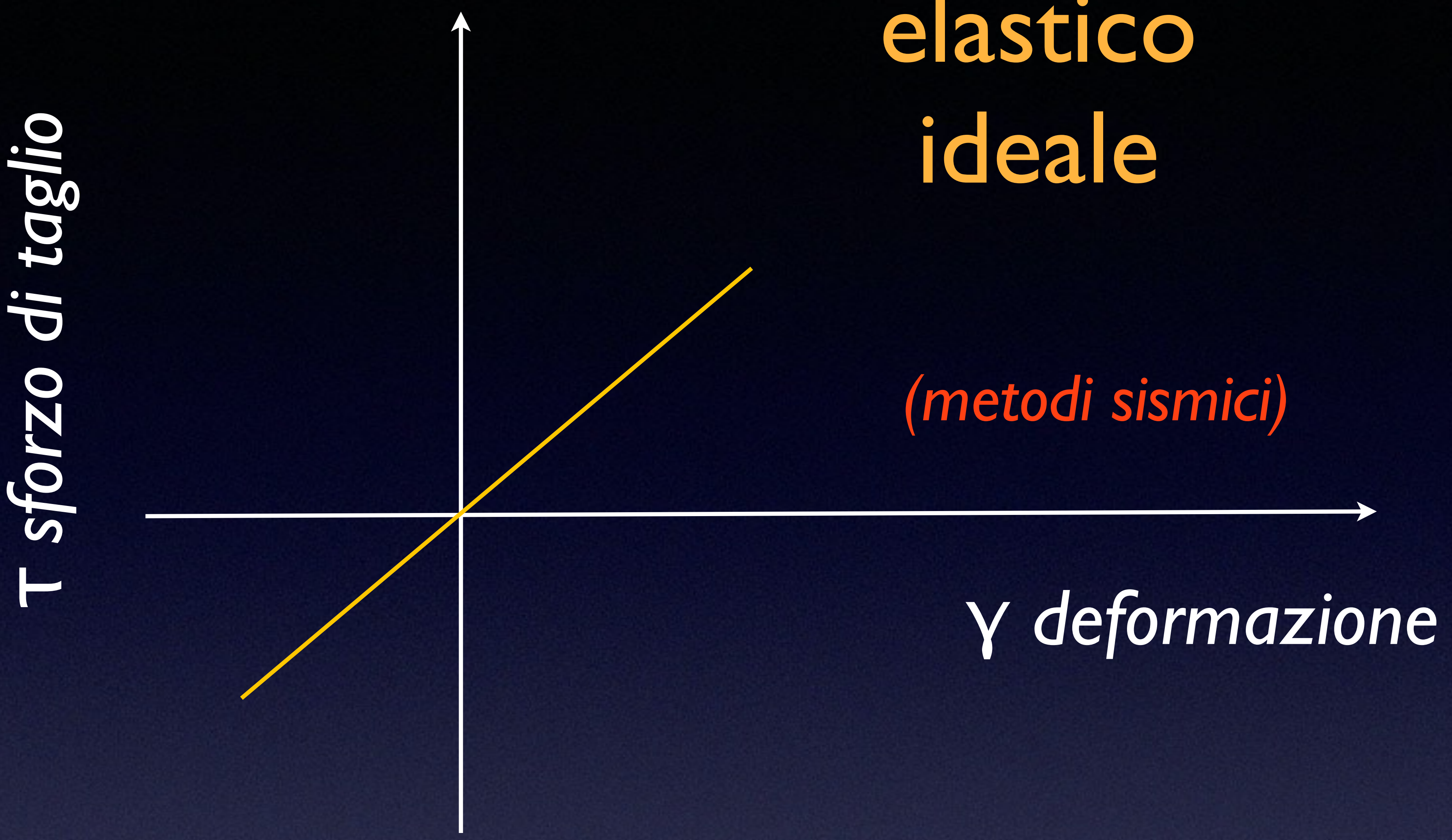
Sforzi (τ) e Deformazioni (γ) a carichi ciclici

Piccole deformazioni
è lineare elastico



medie - grandi deformazioni

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



elastico
ideale

(metodi sismici)

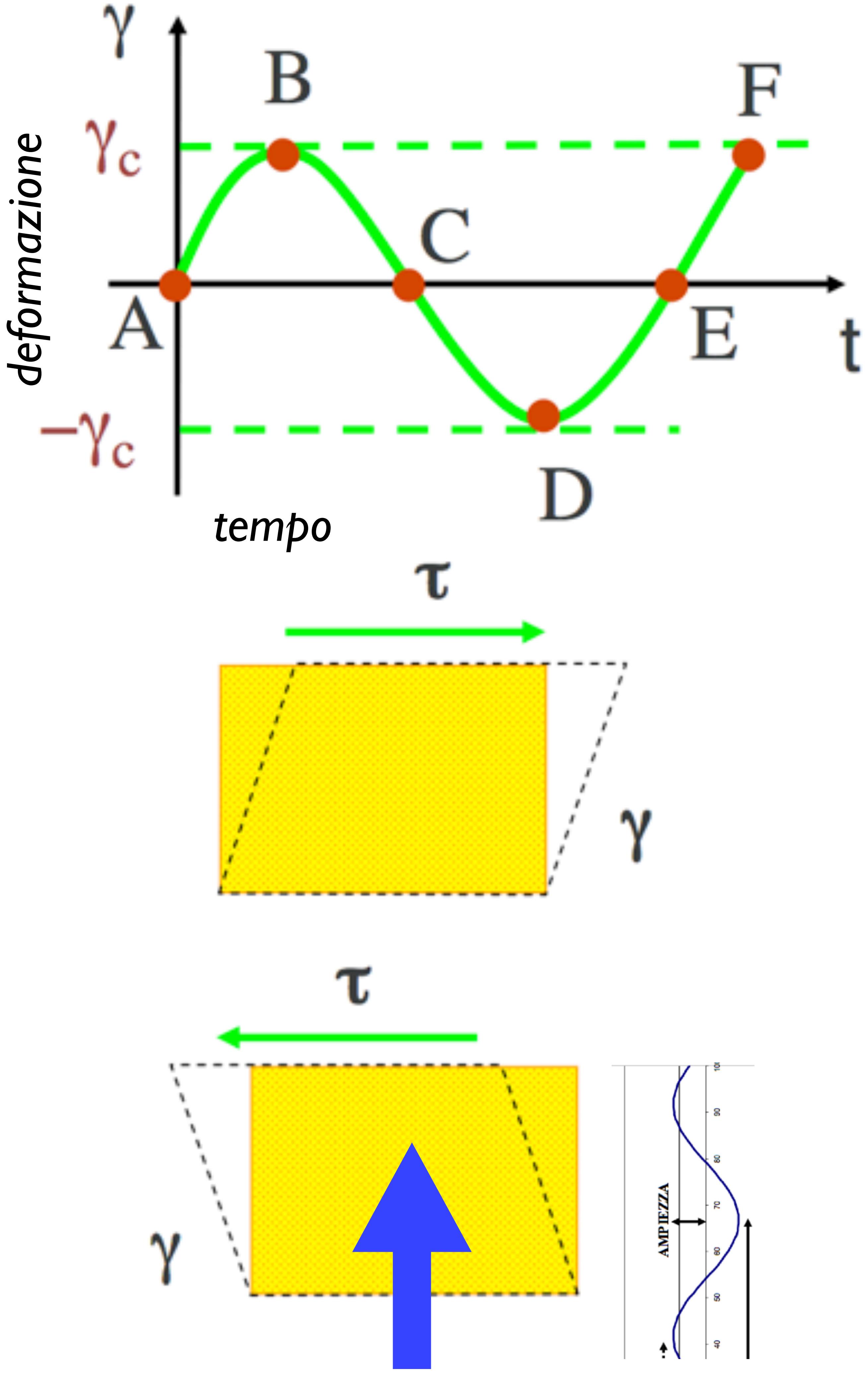
(pseudo) **reale**
(kelvin-voigt)

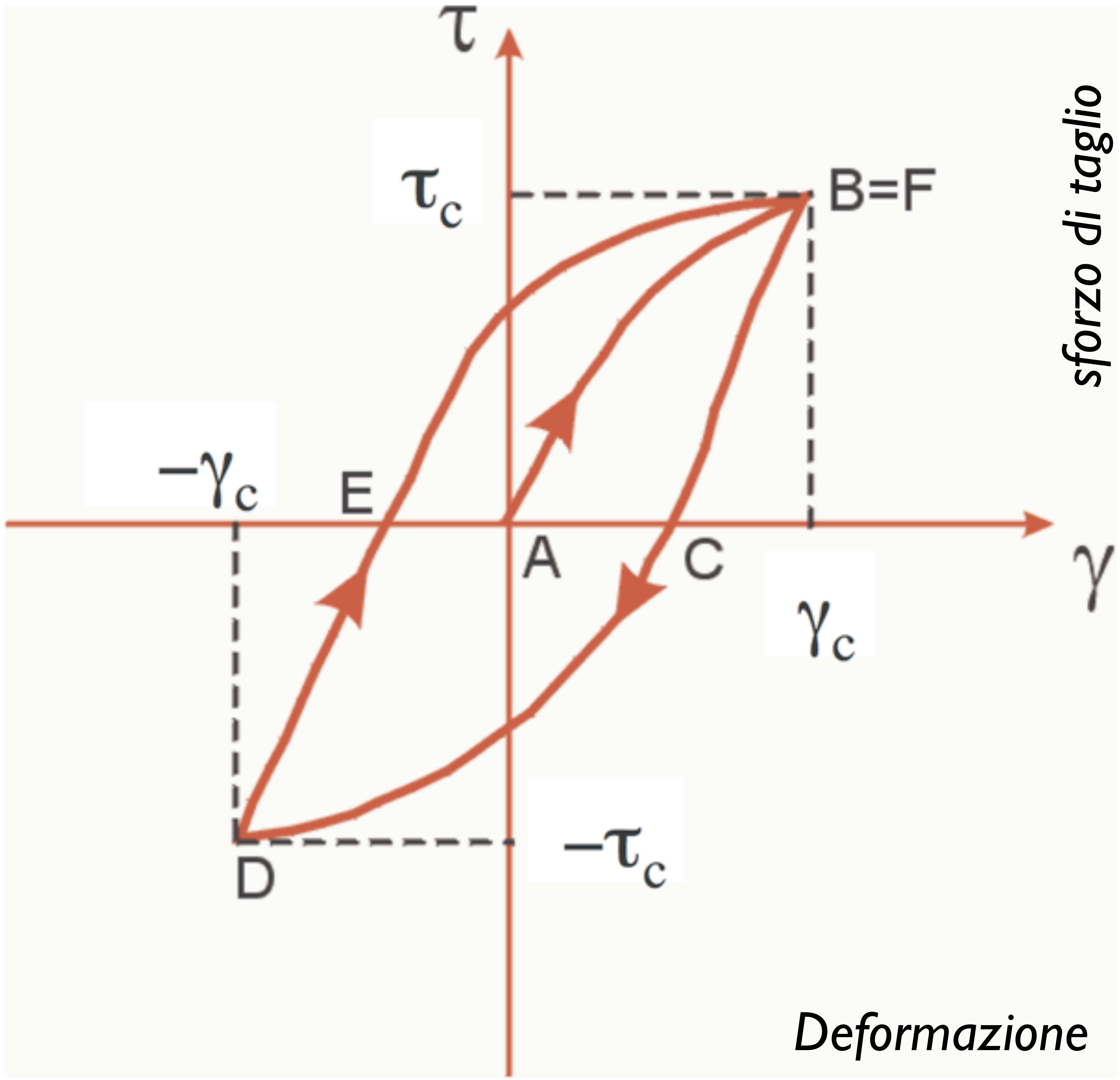
(Geotecnica sismica)

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)

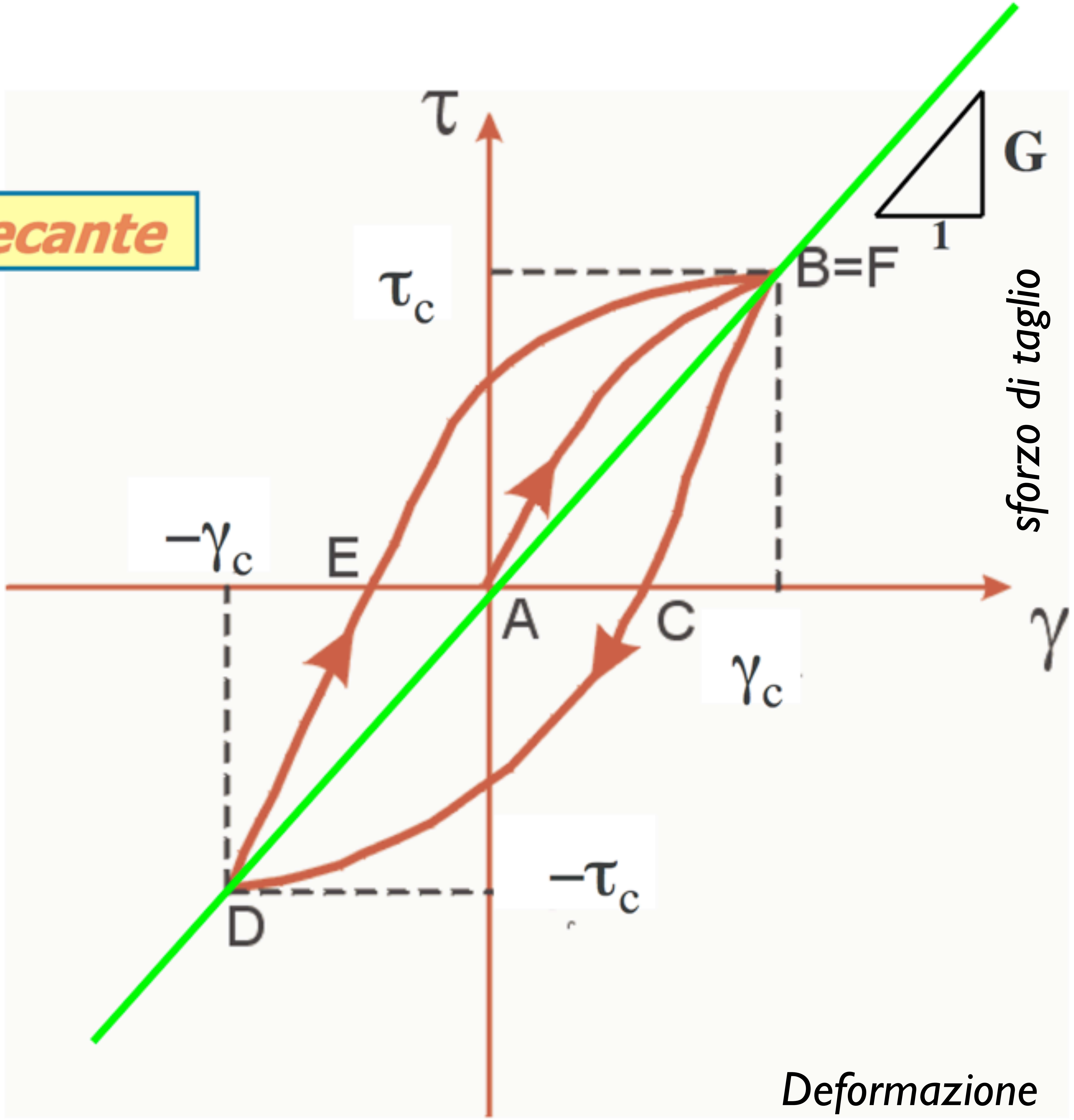




Parametri geotecnici

Modulo di taglio secante

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

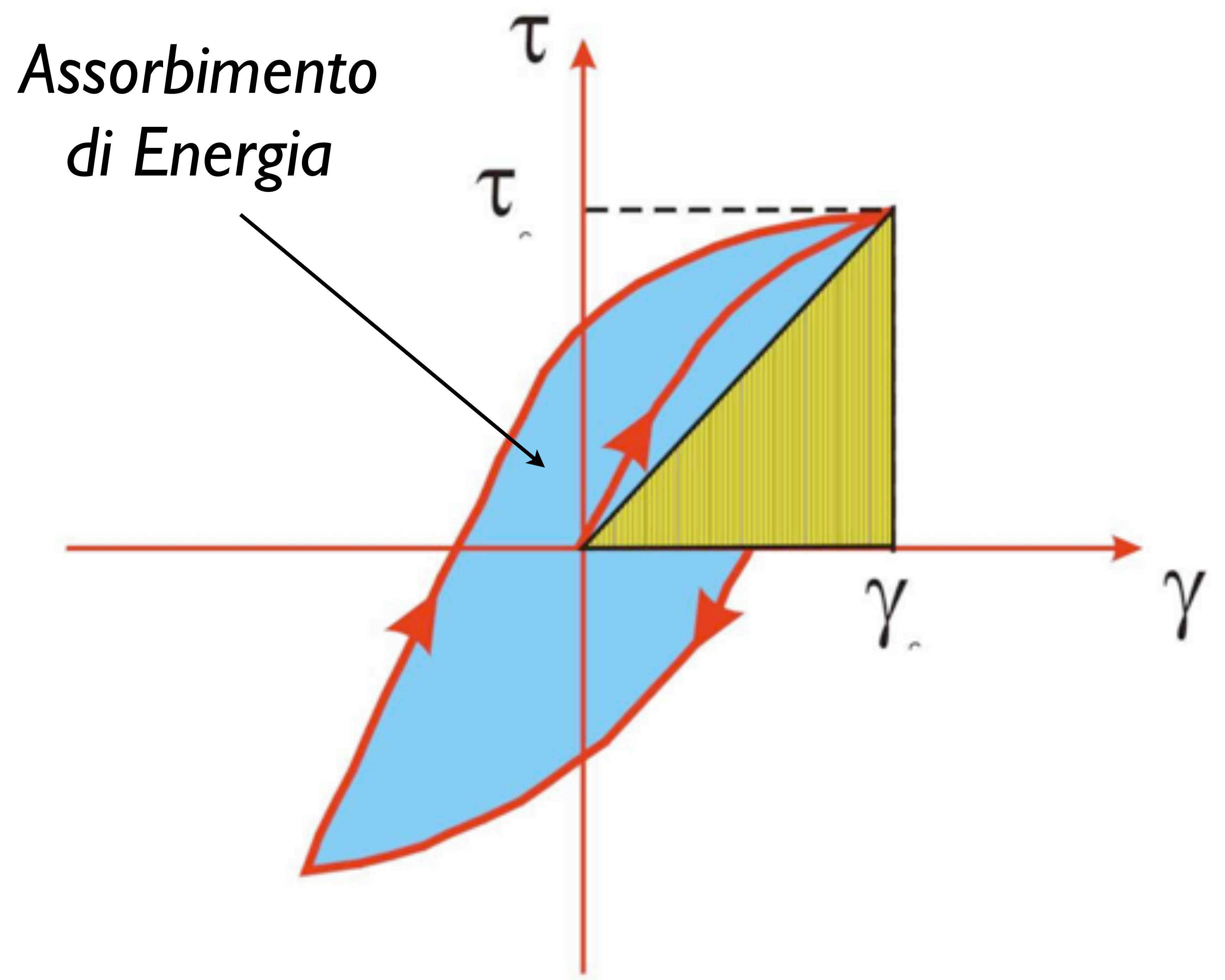


Parametri geotecnici

Fattore di smorzamento

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

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



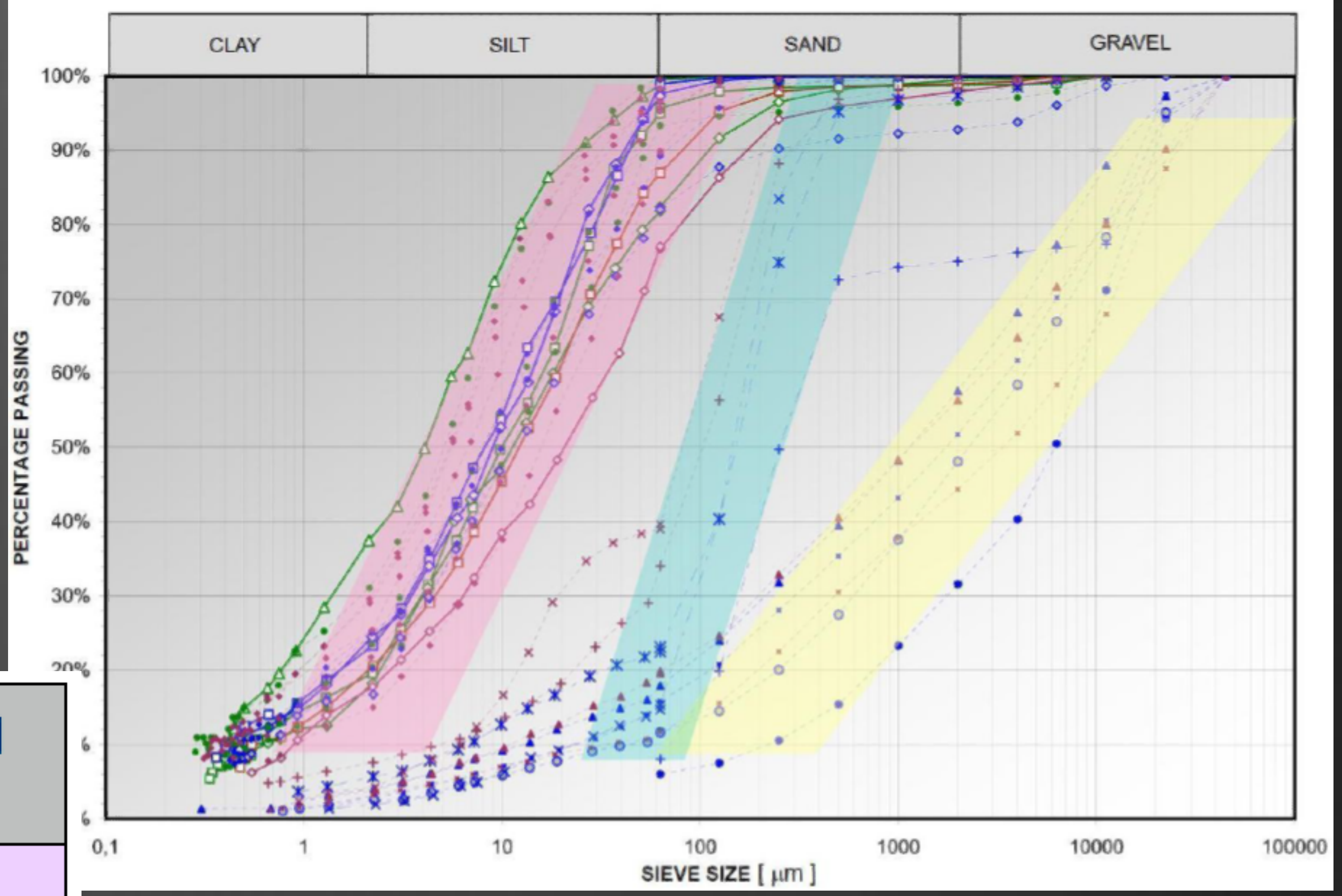
Assorbimento di Energia

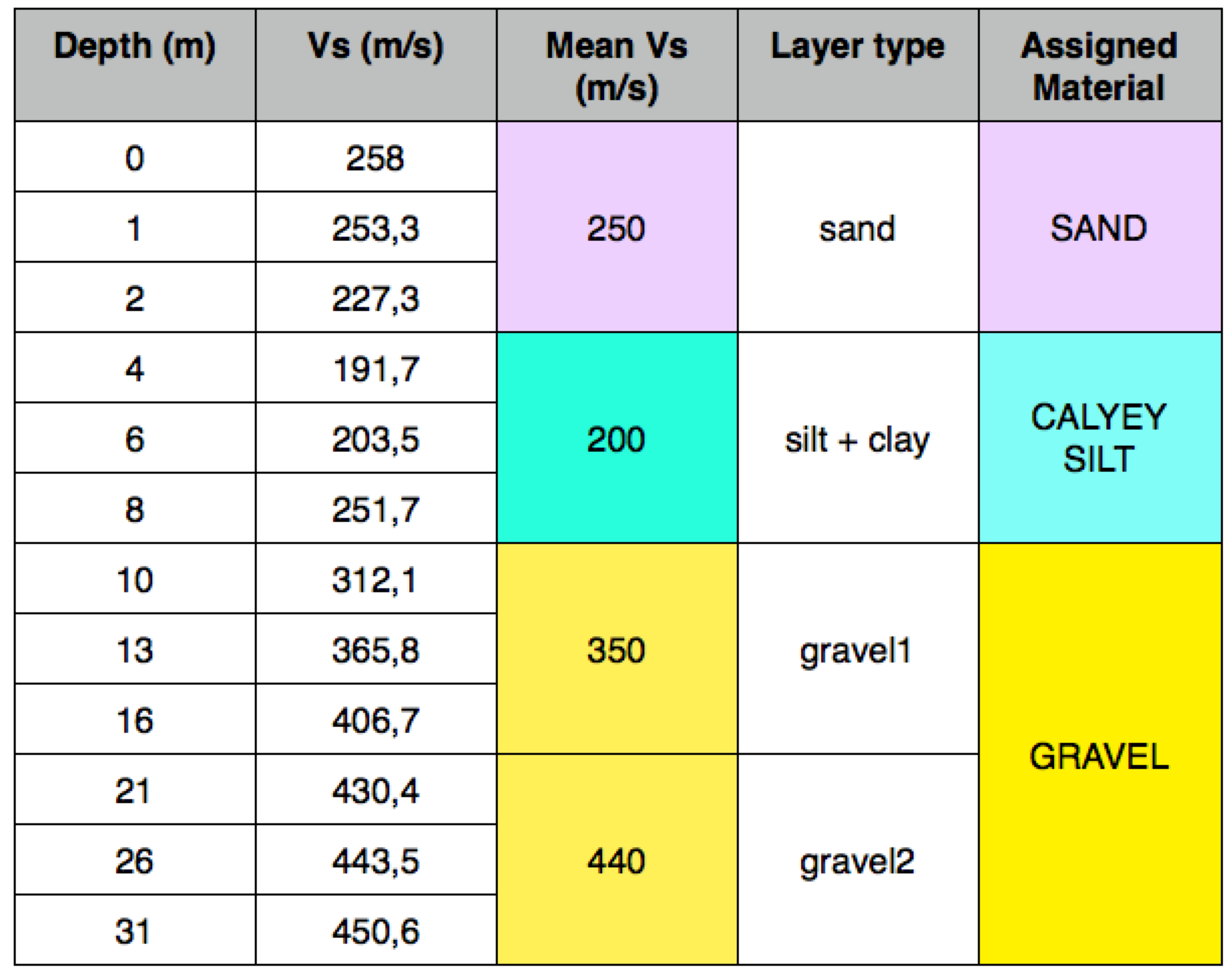
ΔW = area 🟦 = Energia dissipata nel ciclo

W = area 🟨 = Energia elastica immagazzinata

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	CALYEY 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

Indagini geotecniche

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

G_o = modulo di taglio dinamico naturale

G = modulo di taglio dinamico di laboratorio

D = smorzamento

PROVE RC

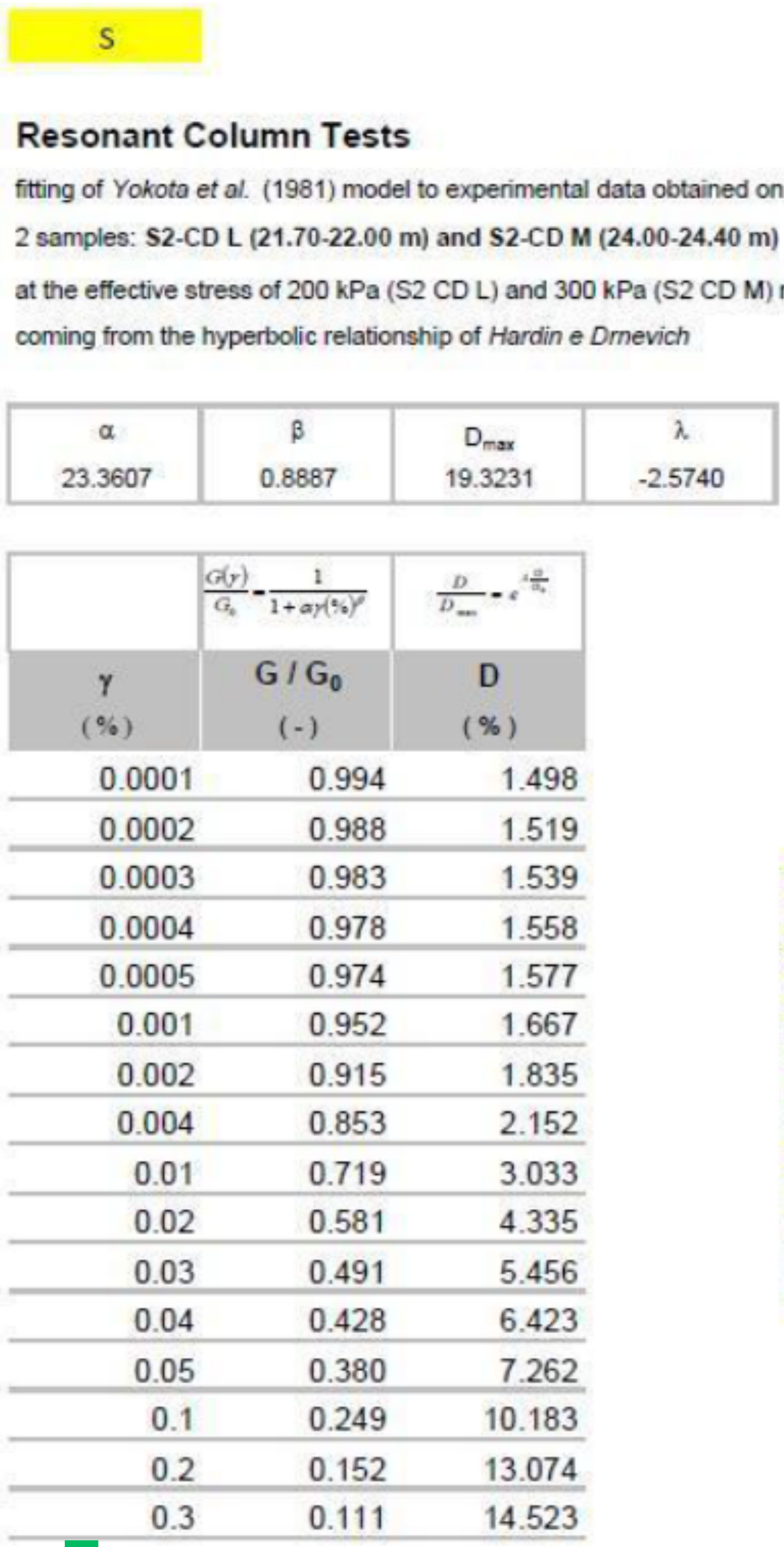
$$\begin{cases} Vs = h \cdot \omega / \beta \\ \omega = 2\pi \cdot Fr \end{cases} \rightarrow G = Vs^2 \cdot \rho$$

Amplitude Decay Method → D

Modello d'interpolazione di Yokota et al., 1981

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

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



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)**

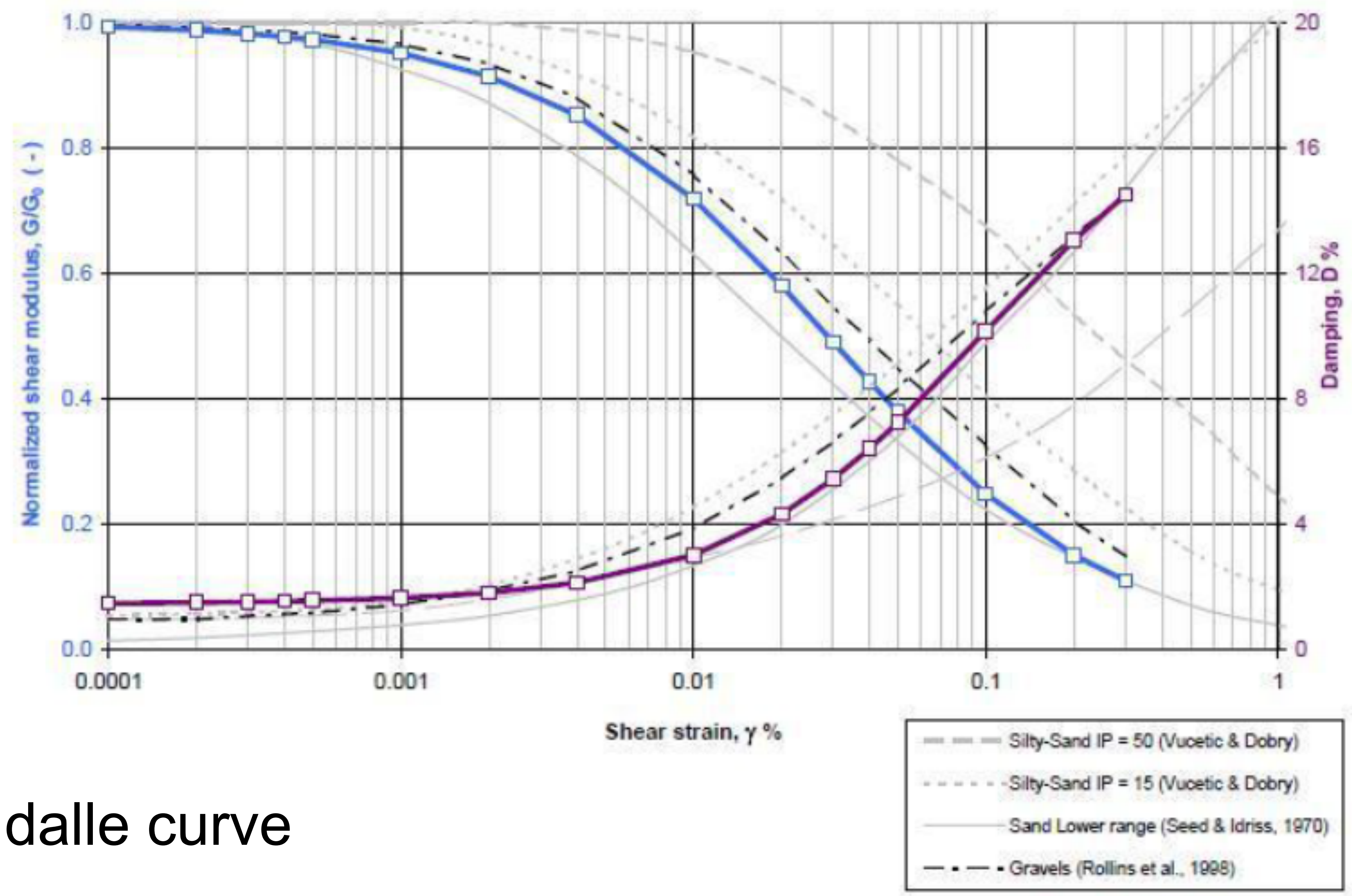
at the effective stress of 200 kPa (S2 CD L) and 300 kPa (S2 CD M) normalized using G_0

coming from the hyperbolic relationship of *Hardin e Drnevich*

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

	$\frac{G(\gamma)}{G_0} = \frac{1}{1+\alpha\gamma(\%)^{\beta}}$	$\frac{D}{D_{max}} = e^{\lambda\frac{G}{G_0}}$
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

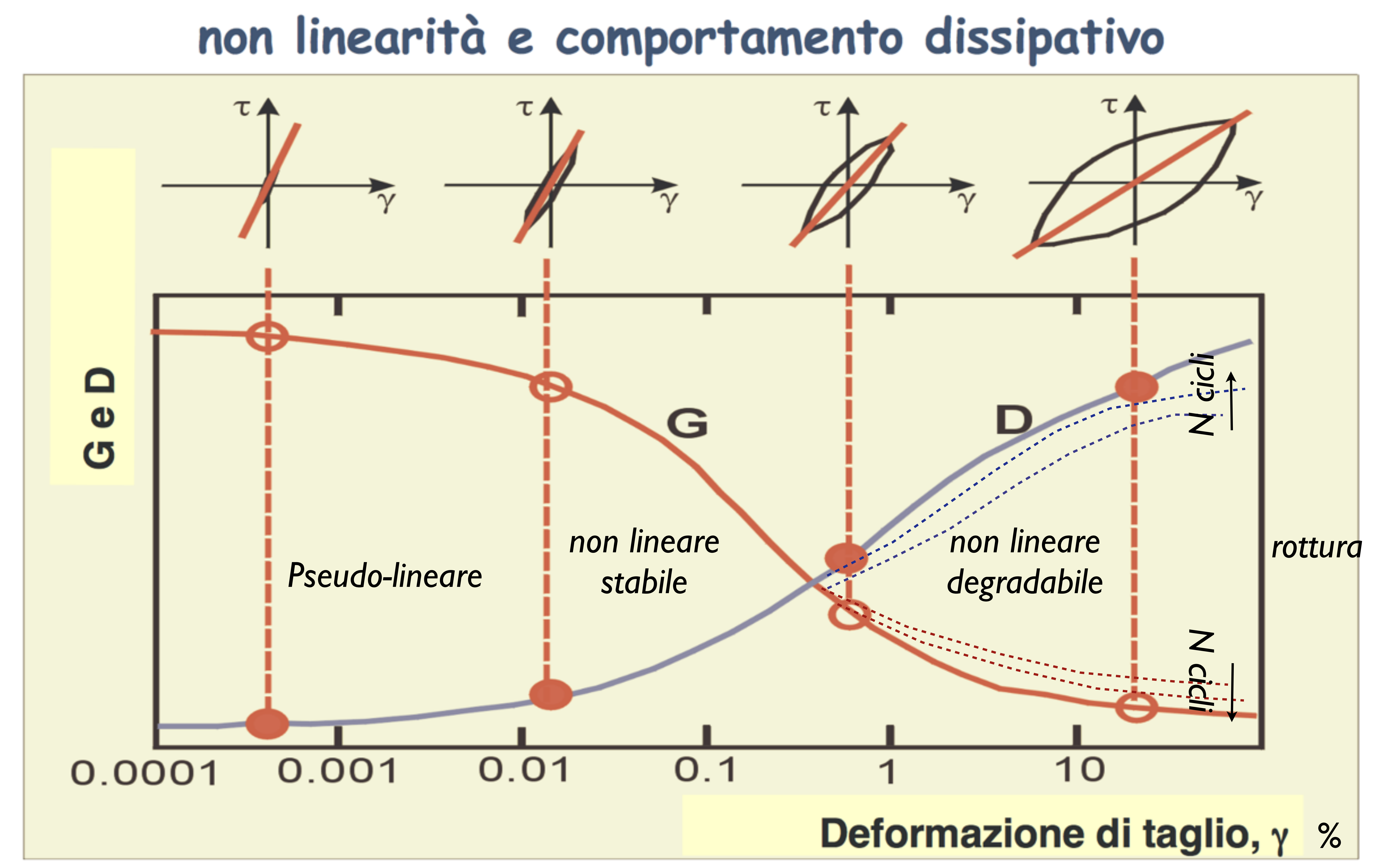
Curve di decadimento per le Sabbie



Valori selezionati dalle curve

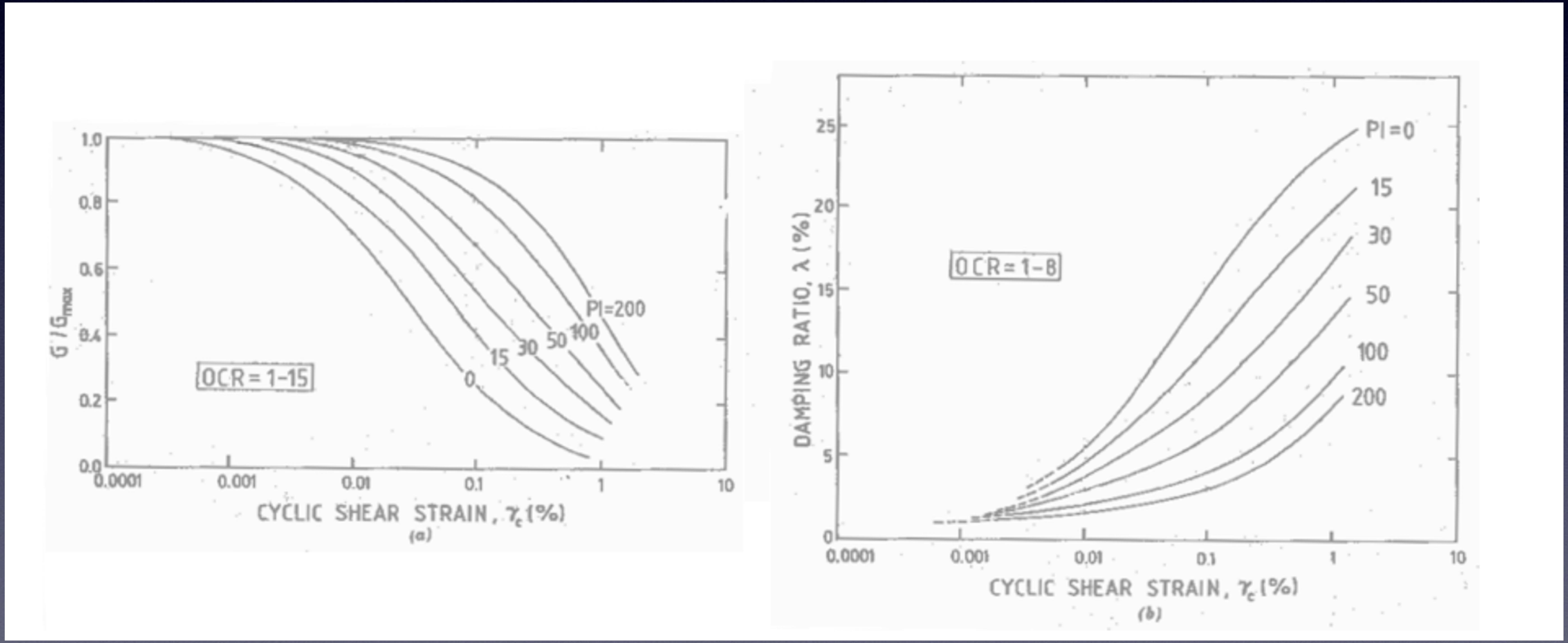
comportamento meccanico dei terreni sottoposti a carichi ciclici

G e D variano in funzione della deformazione ɣ

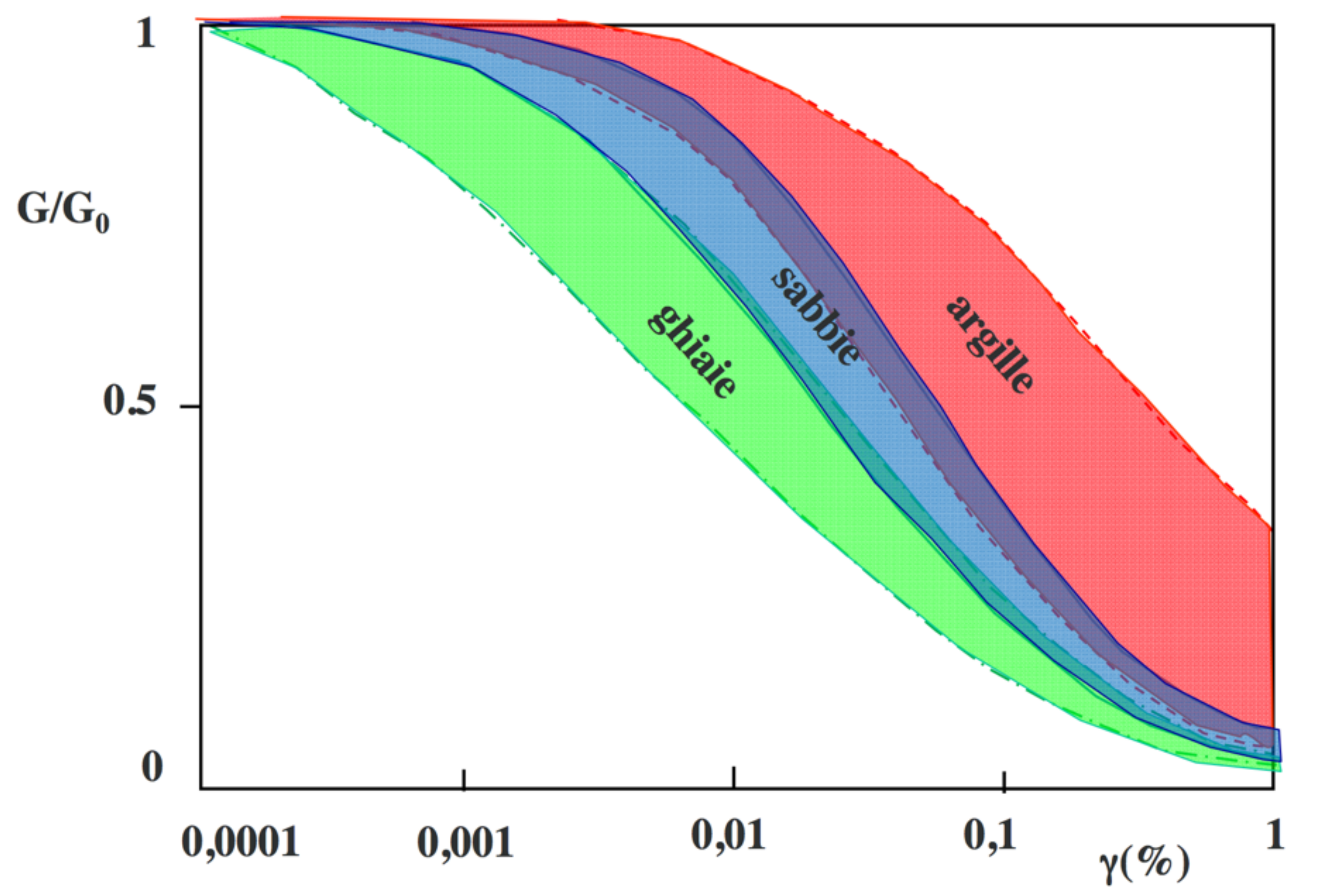


G e D variano in funzione del tipo di suolo

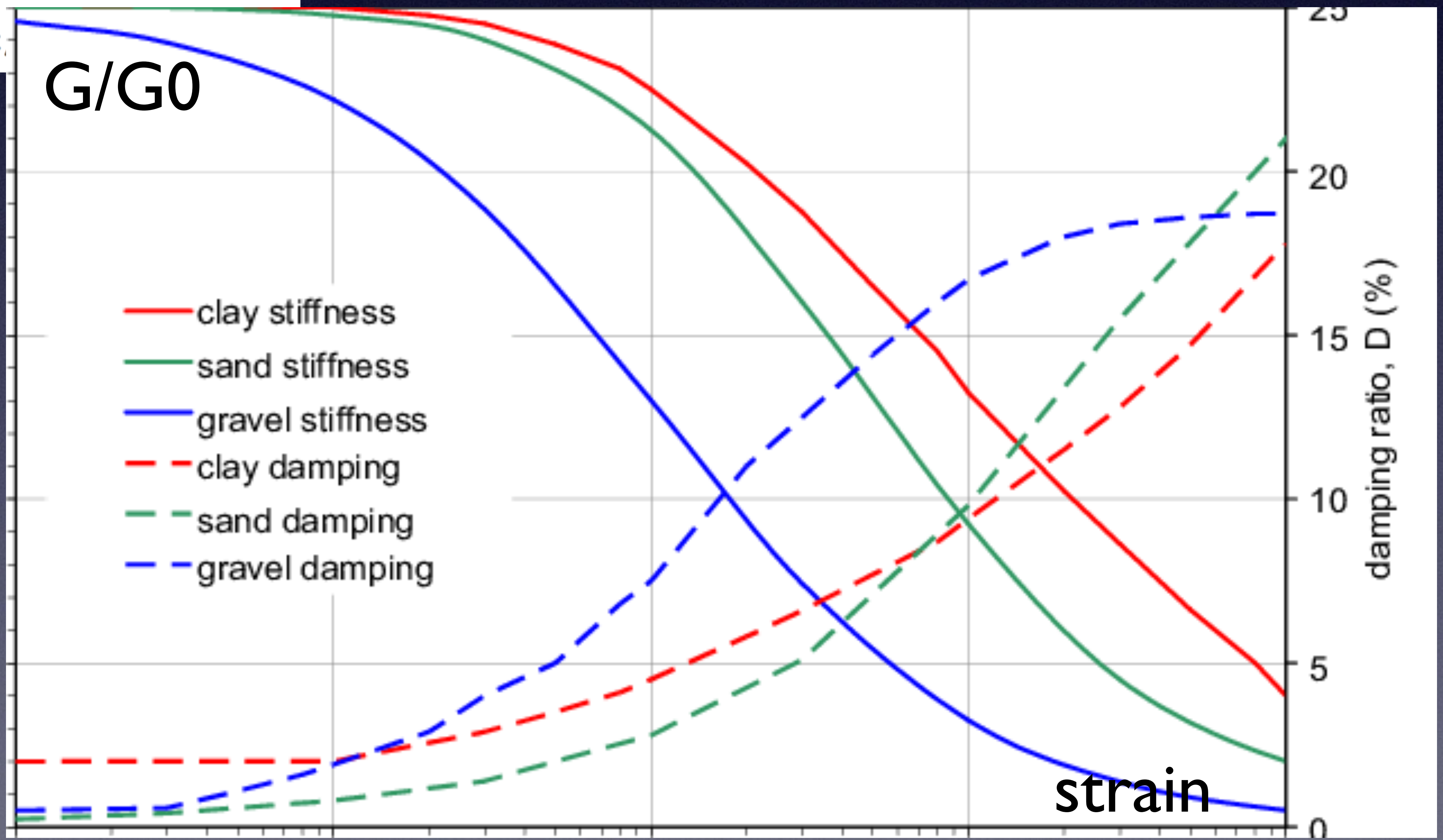
e.g. in base all'indice di plasticità:



Campi di variazione delle curve G/G_0-γ



(Seed et al., 1986; Dobry & Vucetic

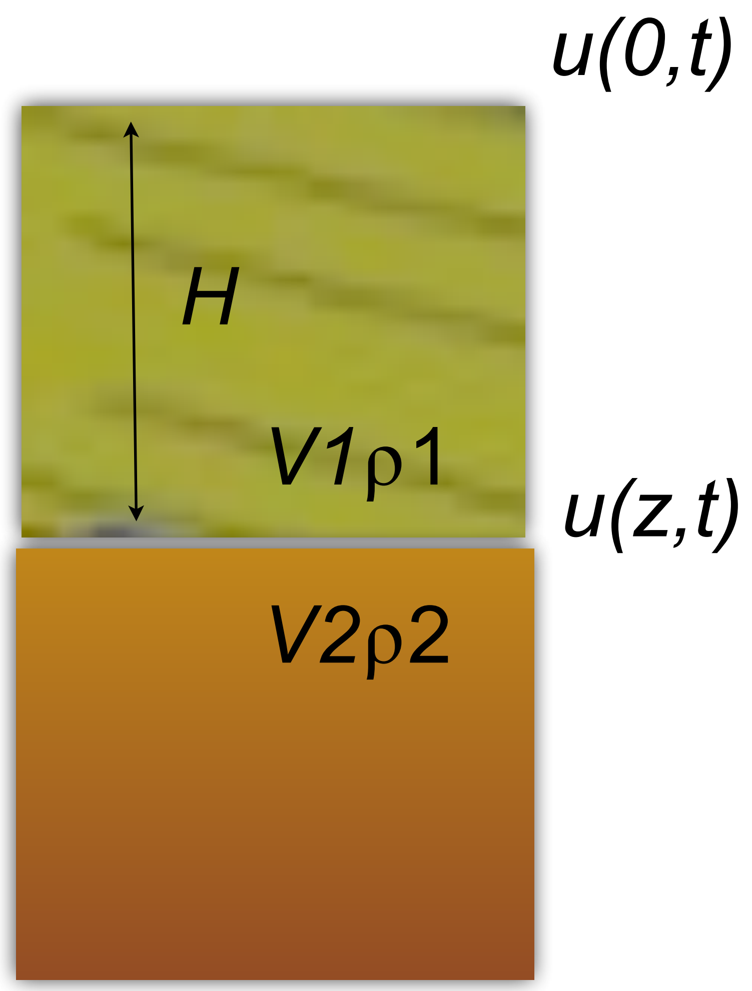


Strato OMOGENEO visco-elastico su subtrato rigido (kelvin-voigt)

EQUAZIONE EQUILIBRIO DINAMICO

Coefficiente di viscosità

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



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

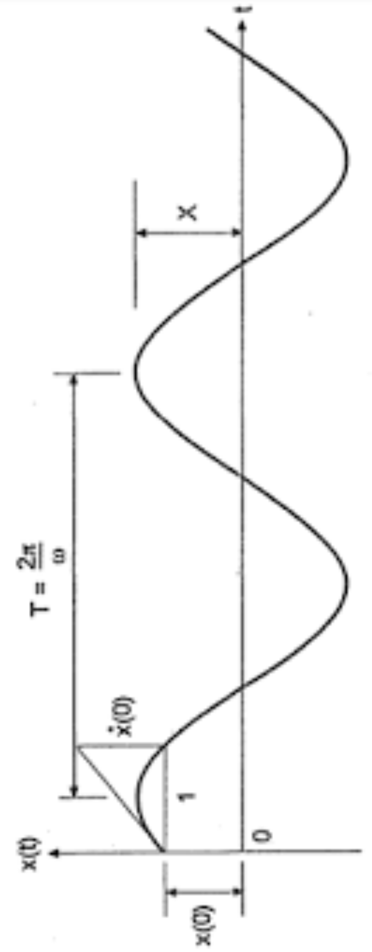
viscosità

frequenza

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

DAMPING

modulo taglio

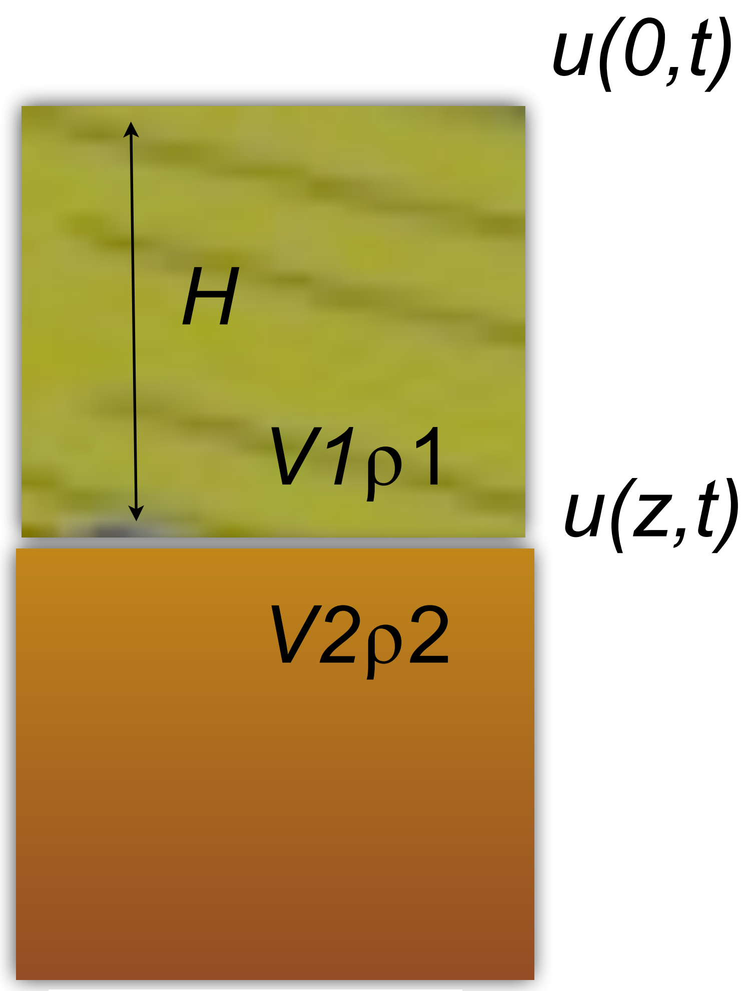


Strato OMOGENEO visco-elastico su subtrato rigido (kelvin-voigt)

EQUAZIONE ONDA S

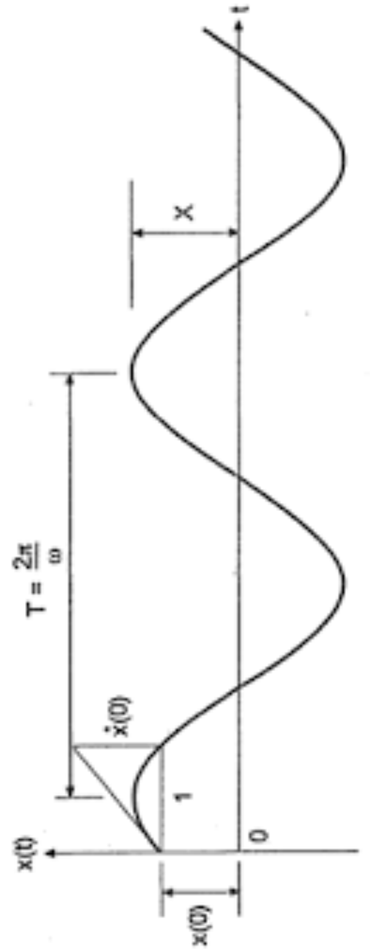
Coefficiente di viscosità

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



Soluzione

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



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

Funzione di trasferimento

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

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

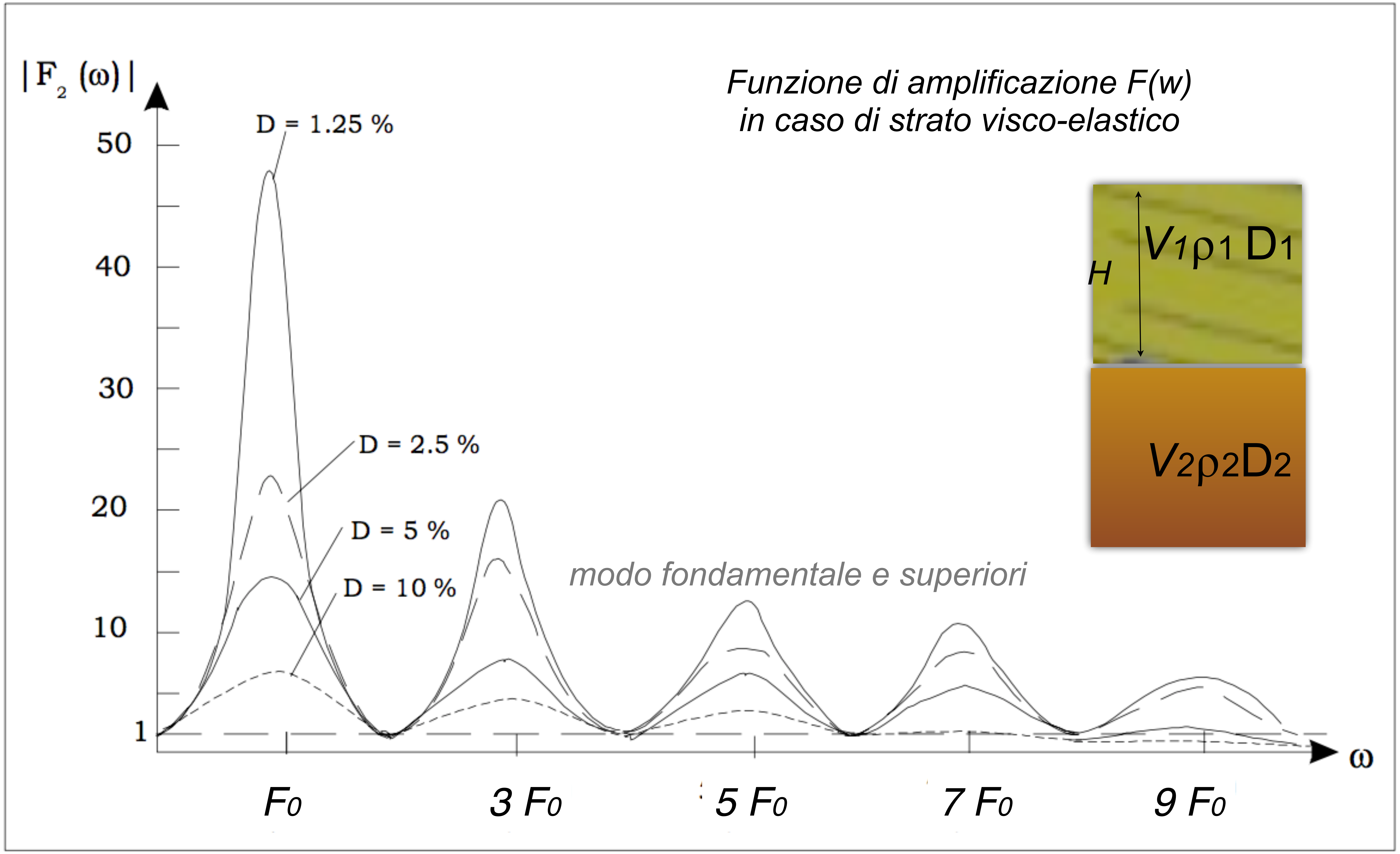
$$F\,(\omega) = \frac{1}{\sqrt{\cos^2\left(\frac{\omega\,H}{Vs}\right) + \left(D\frac{\omega\,H}{Vs}\right)}}$$

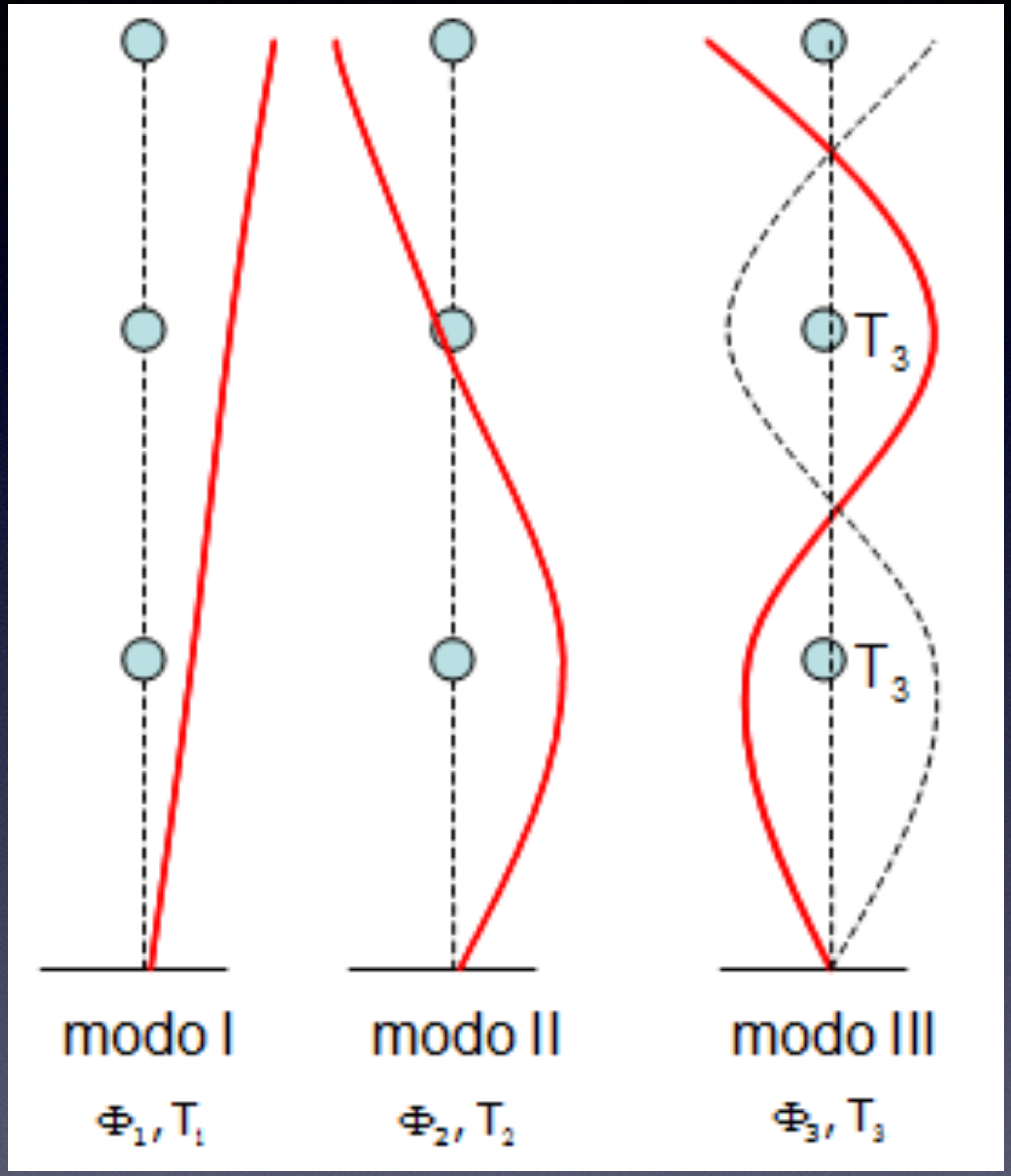
$$Vs = \sqrt{\frac{G}{\rho}}$$

D

Per moderati campi di deformazione è considerabile indipendente dalla frequenza!

Funzione di amplificazione F(w) in caso di strato visco-elastico





Forme modali (n=1 modo fondamentale)

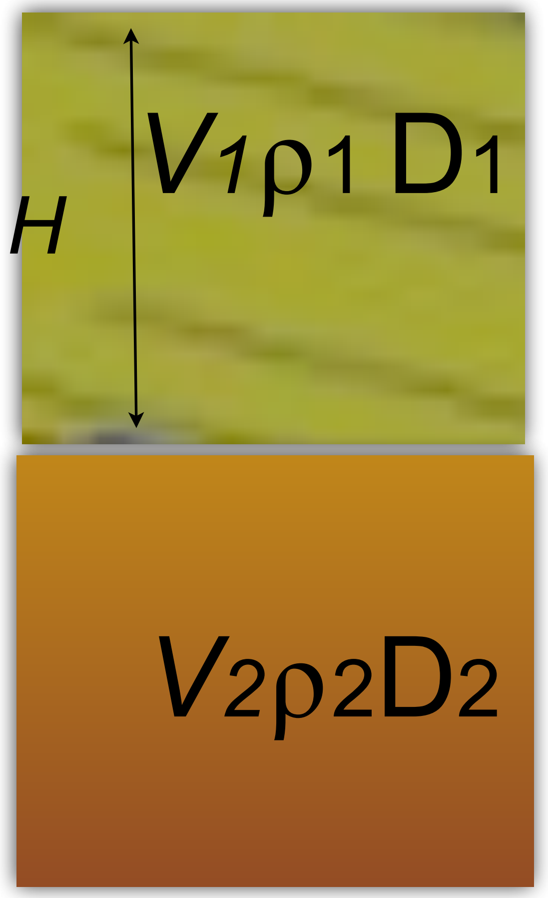
$$u(z,t) = Ae^{j(k\,z+\,\omega\,t)}$$

Soluzione

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

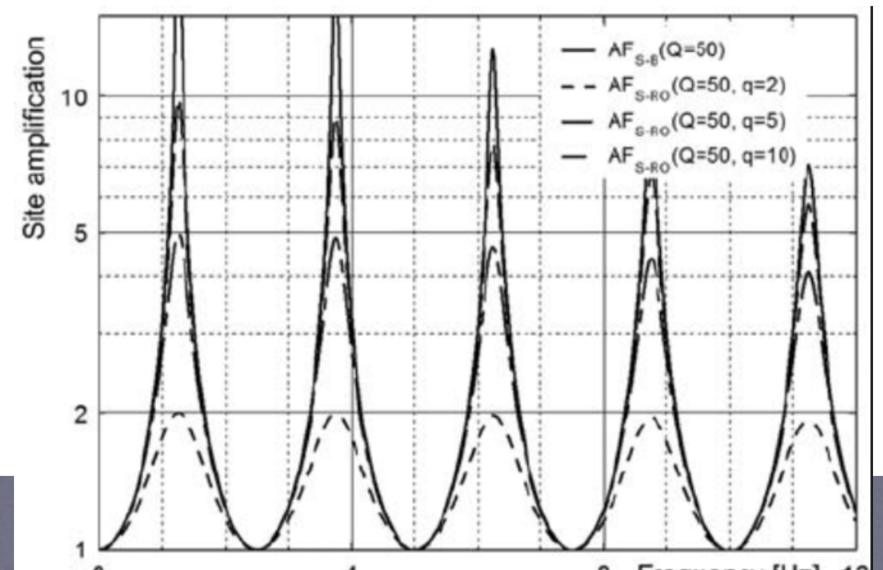
EQUAZIONE EQUILIBRIO DINAMICO

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



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

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



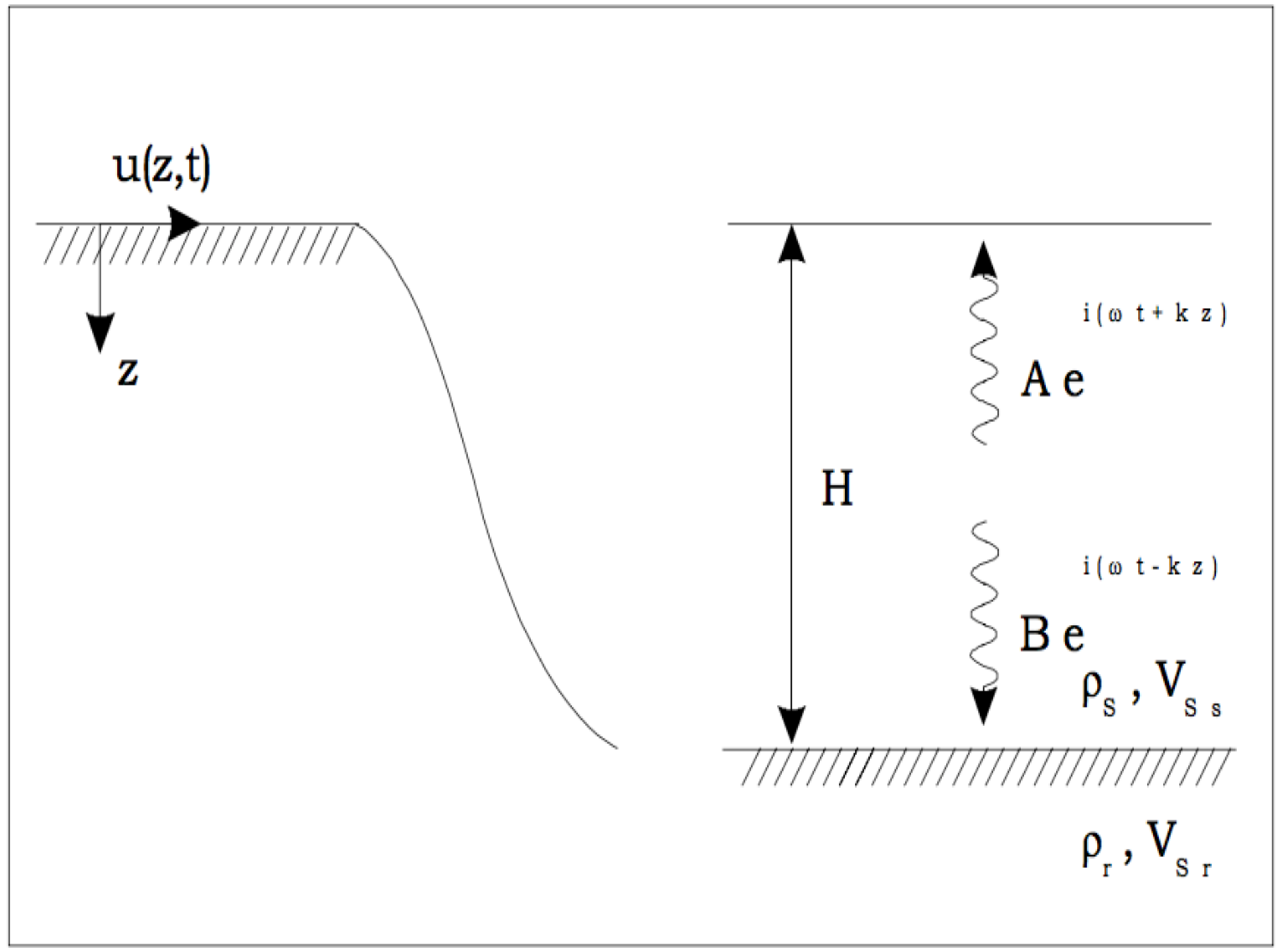
CONTRASTO DI IMPEDENZA

$$i = \frac{V1\,\rho 1}{V2\,\rho 2}$$

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

EQUAZIONE ONDA S

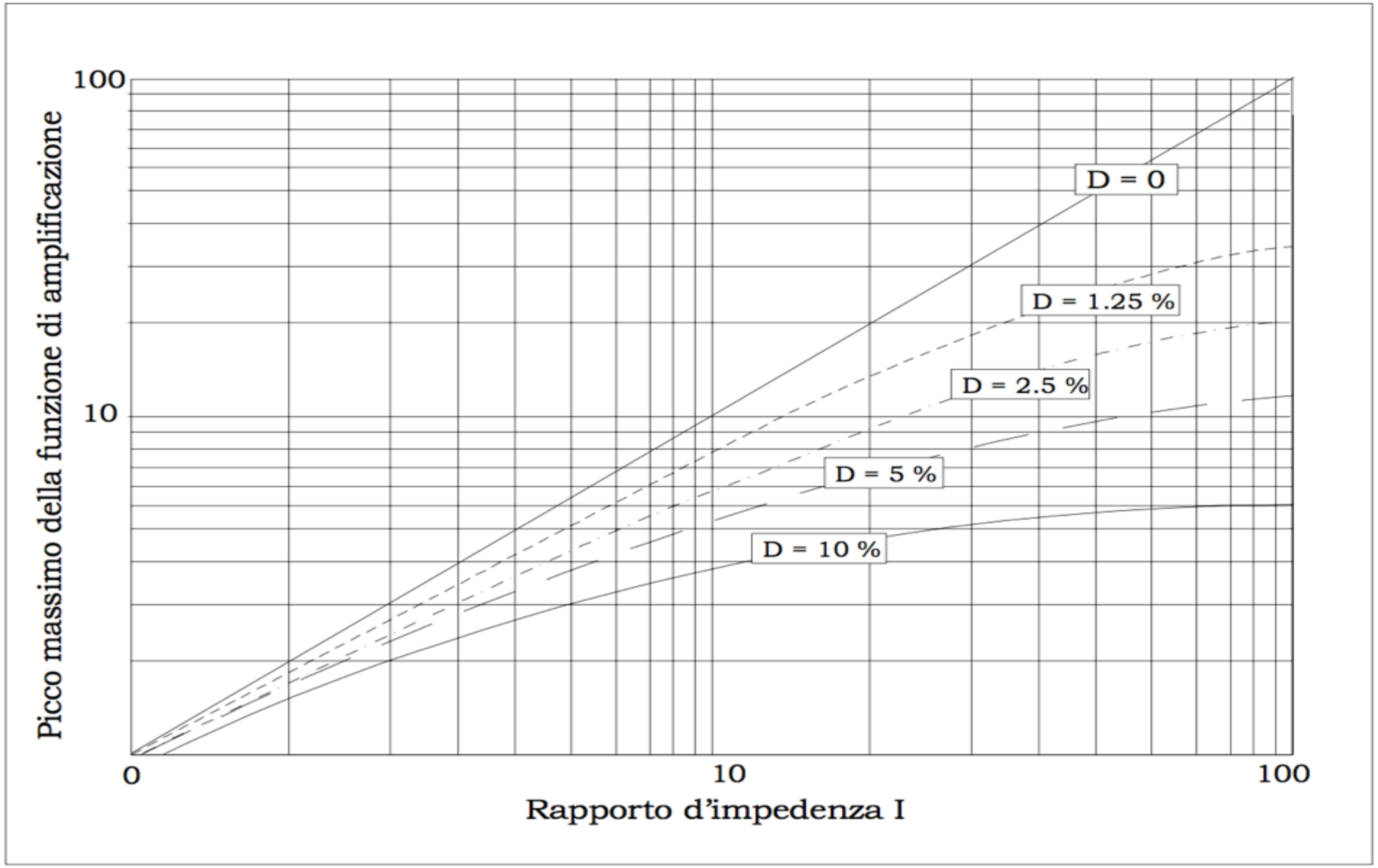
$$\rho \frac{du^{2}}{dt^{2}} = G \frac{du^{2}}{dz^{2}} + \eta \frac{du^{3}}{dt\,dz^{2}}$$



Per piccole deformazioni D è considerato indipendente dalla frequenza!

Fattore di Amplificazione onda S incidente

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

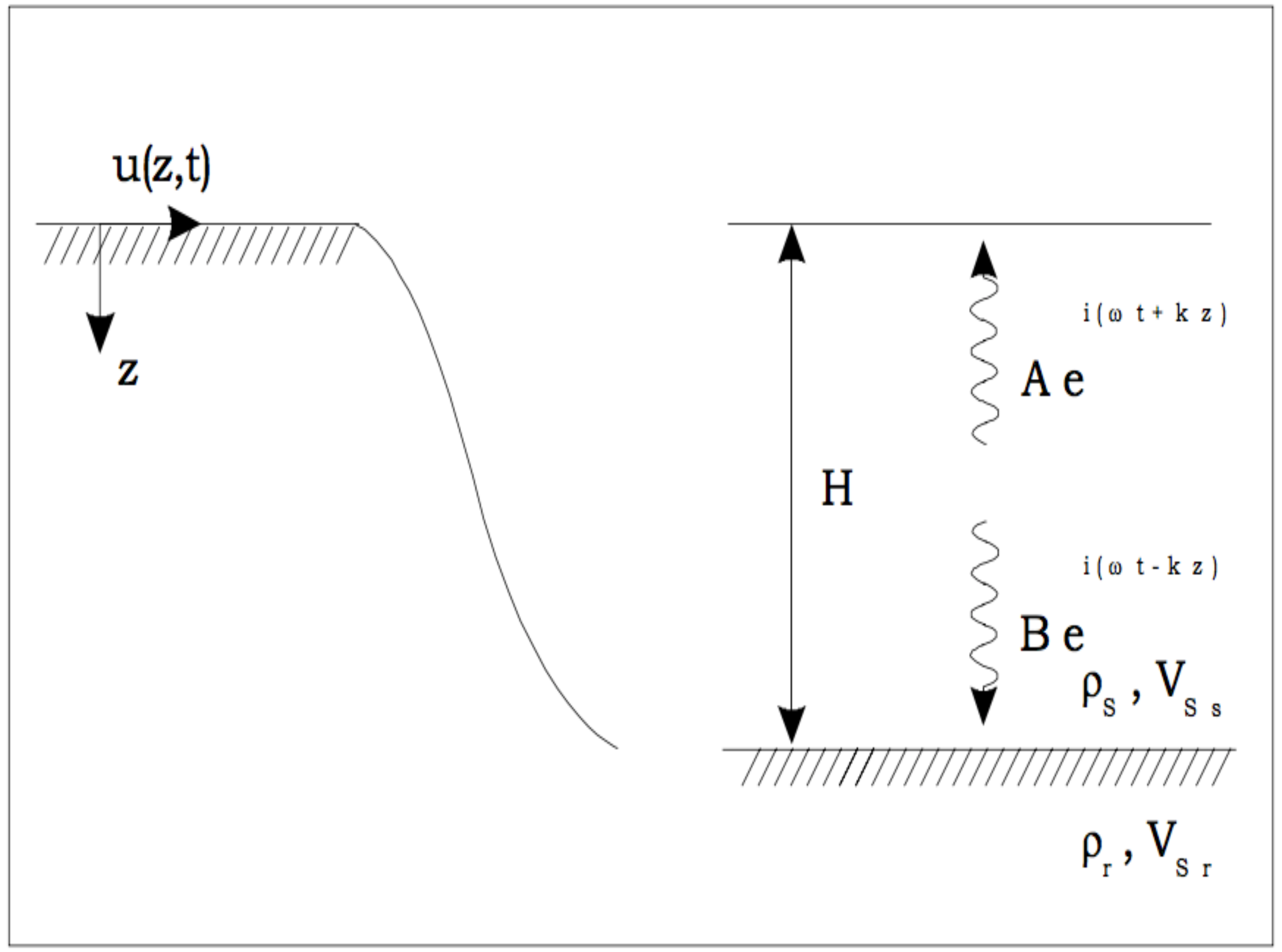


Caso reale: dipende da contrasto di impedenza I e da damping D

Soluzioni analitiche e numeriche al problema

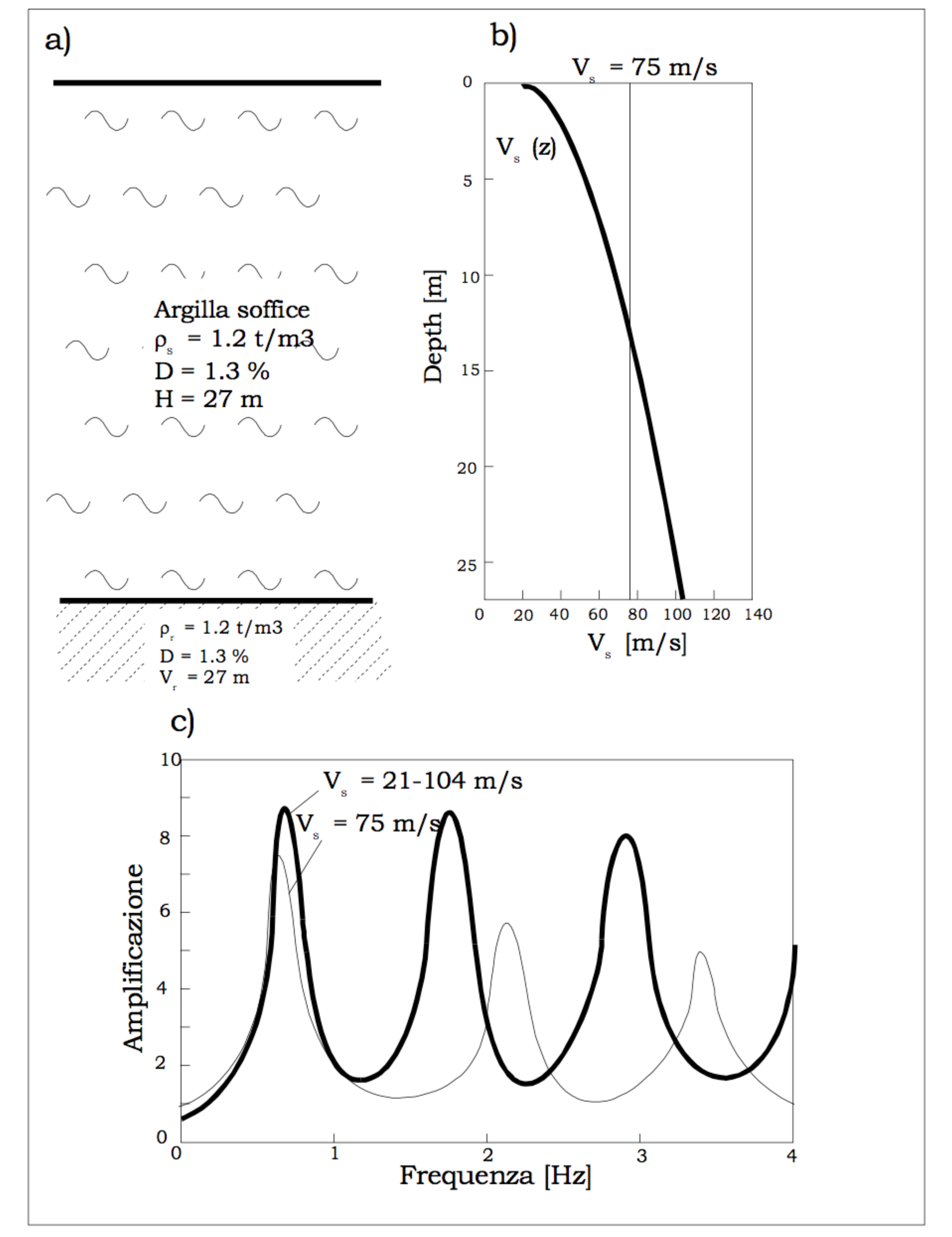
EQUAZIONE ONDA S

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



Fattore di Amplificazione onda S incidente

Es Soluzioni analitiche Città del Messico



Loma Prieta

Km di distanza
da epicentro

F0 ≈ F risonanza edifici