Respuesta de Sitio en Suelos

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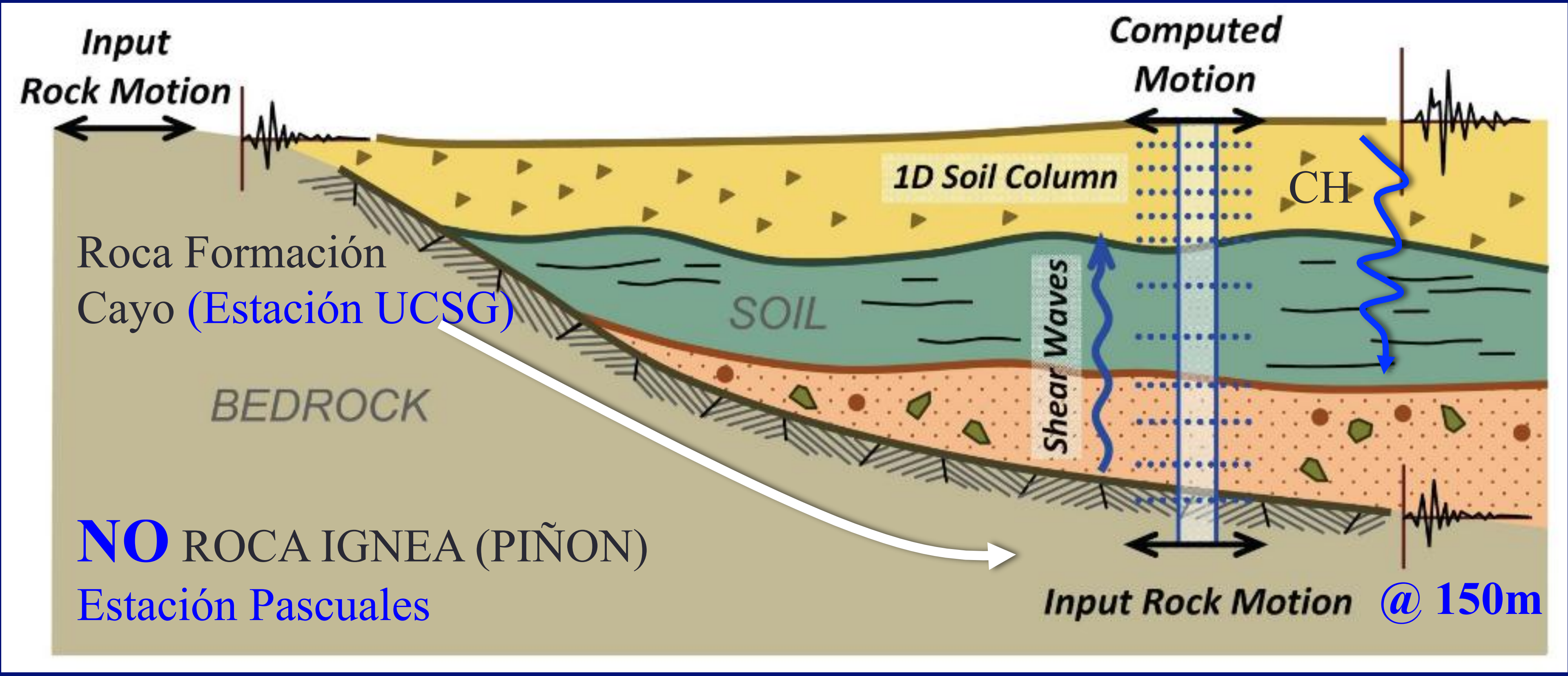
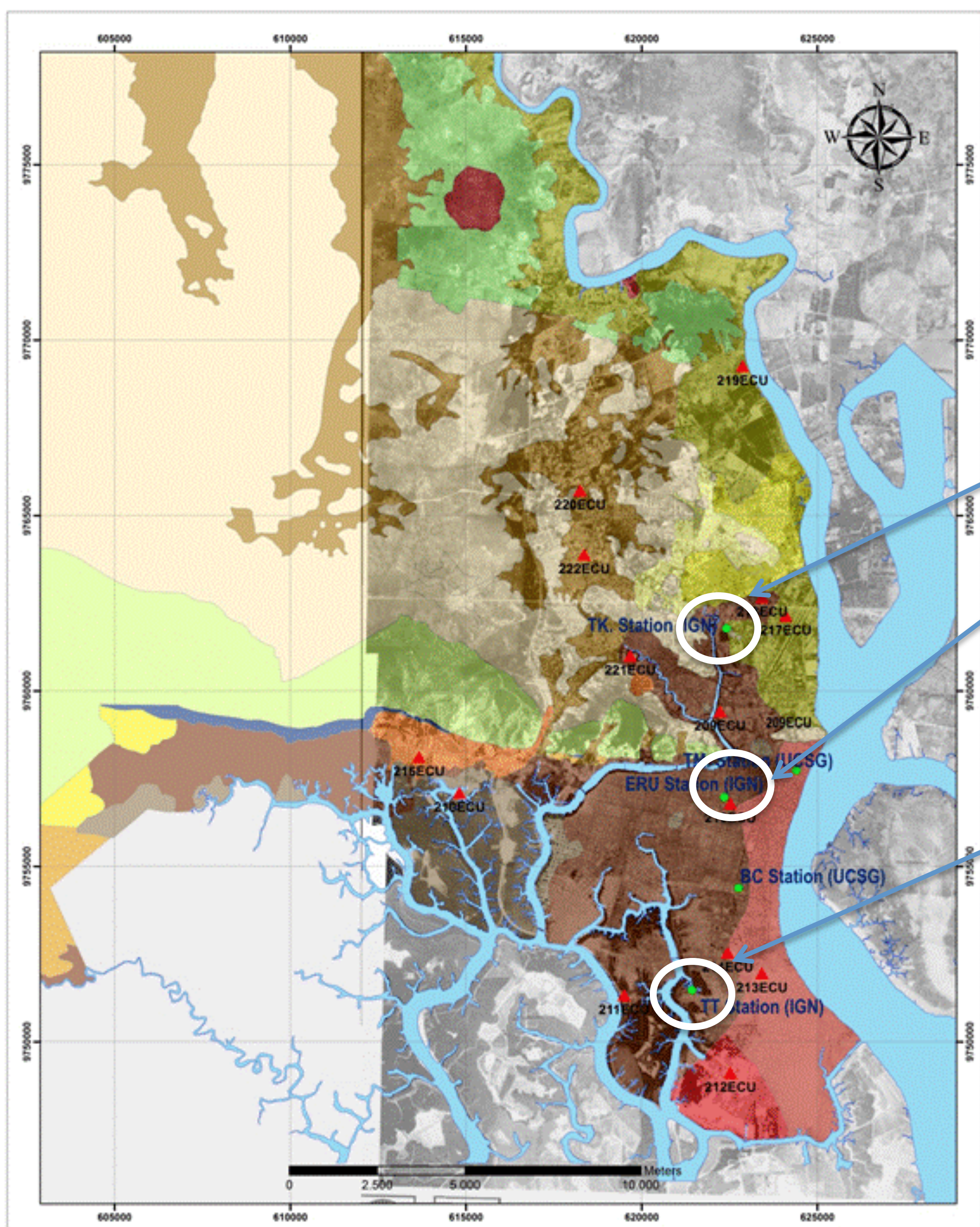


Input
Rock Motion
Computed
Motion
1D Soil Column
CH
Roca Formación
Cayo (Estación UCSG)
SOIL
Shear Waves
BEDROCK
NO ROCA IGNEA (PIÑON)
Estación Pascuales
Input Rock Motion
@ 150m

Principales factores que influyen en los efectos locales del sitio (Romo et al., 2000)

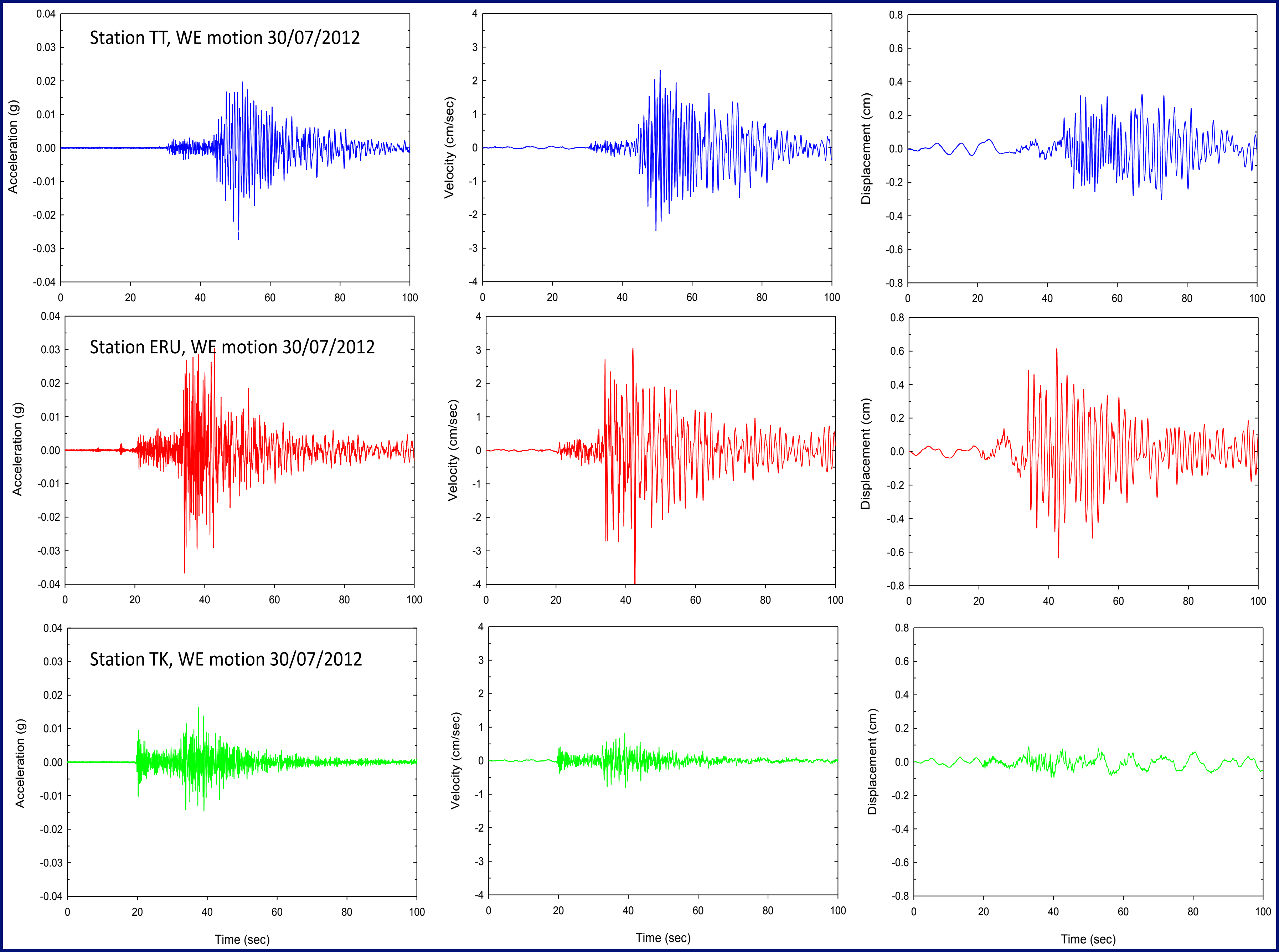
Sismológicos	• Intensidad y contenido de frecuencias de los movimientos sísmicos de roca basal • Duración de los movimientos en roca basal
Geológicos	• Estructuras geológicas locales • Tipo de roca subyacente • Características estratigráficas: espesor de los depósitos y tipos de suelos
Geotécnicos	• Características de vibración elástica de los depósitos de suelo • Comportamiento no lineal del suelo • Impedancia relativa entre la roca basal y los depósitos de suelo sobreyacientes
Geométricos	• Depósitos de suelo estratificados no horizontales • Topografía de la interfaz suelo-roca basal • Configuración de la cuenca

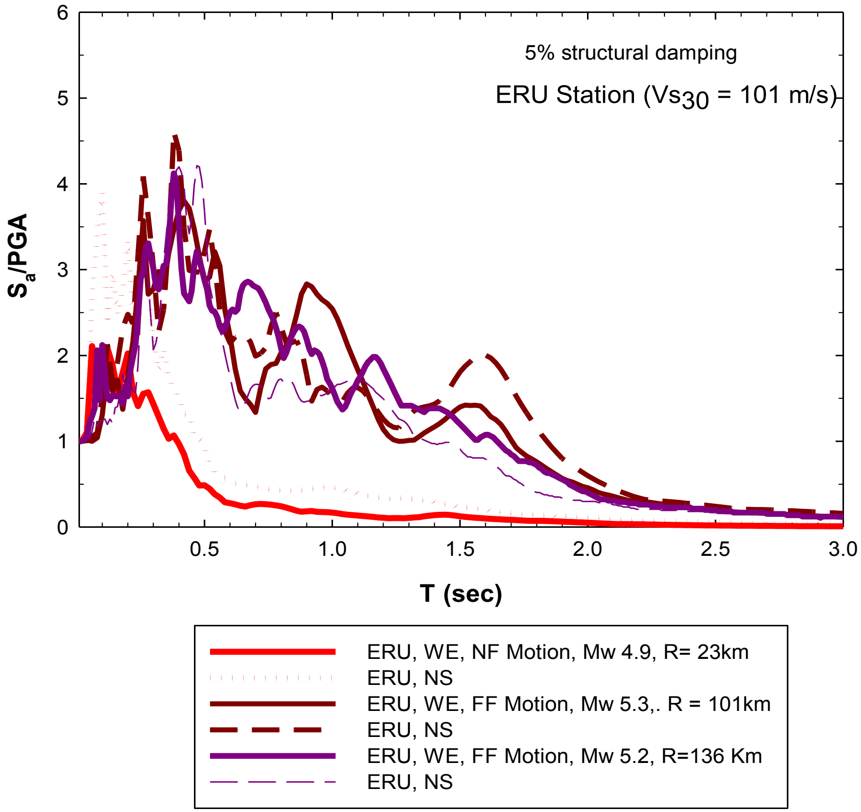


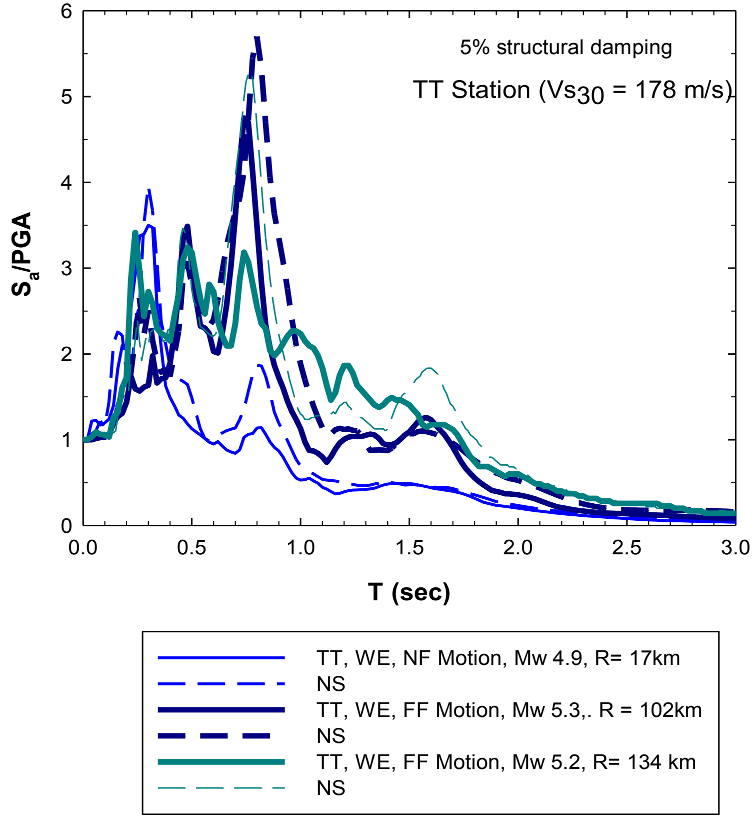
Tk station Vs_{30}= 800 m/s
Suelo tipo B (NEC-15)

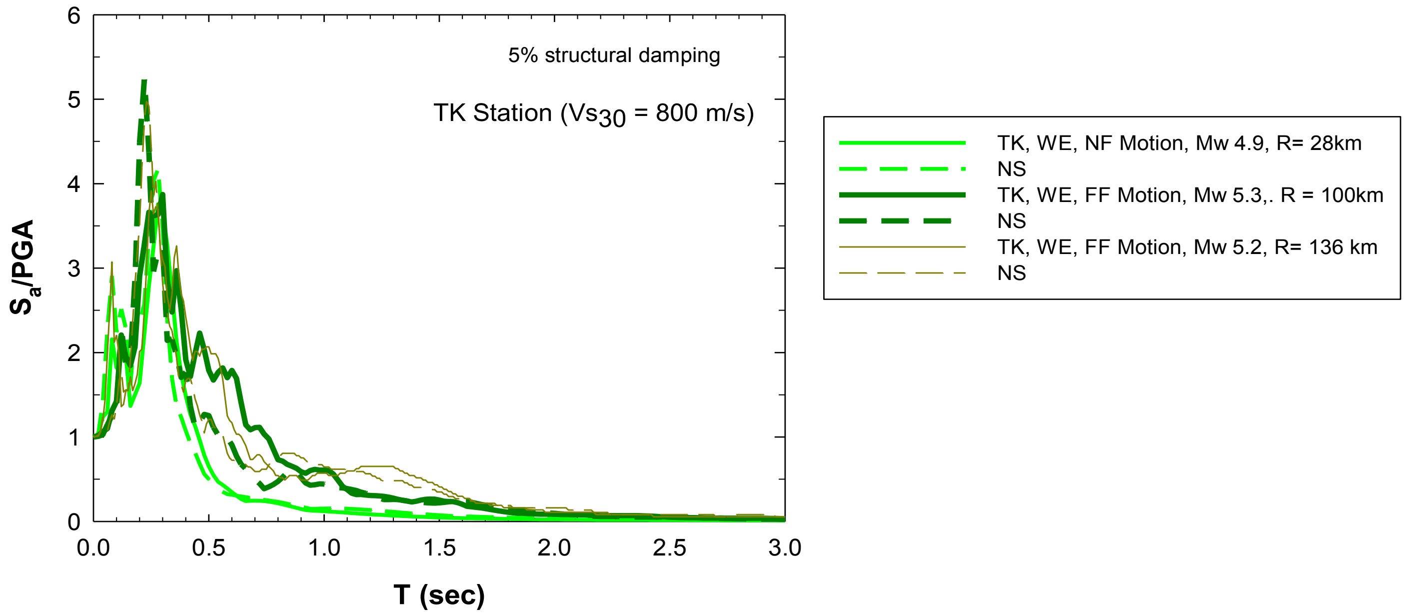
ERU station Vs_{30}= 101 m/s
Suelo tipo F (NEC-15)

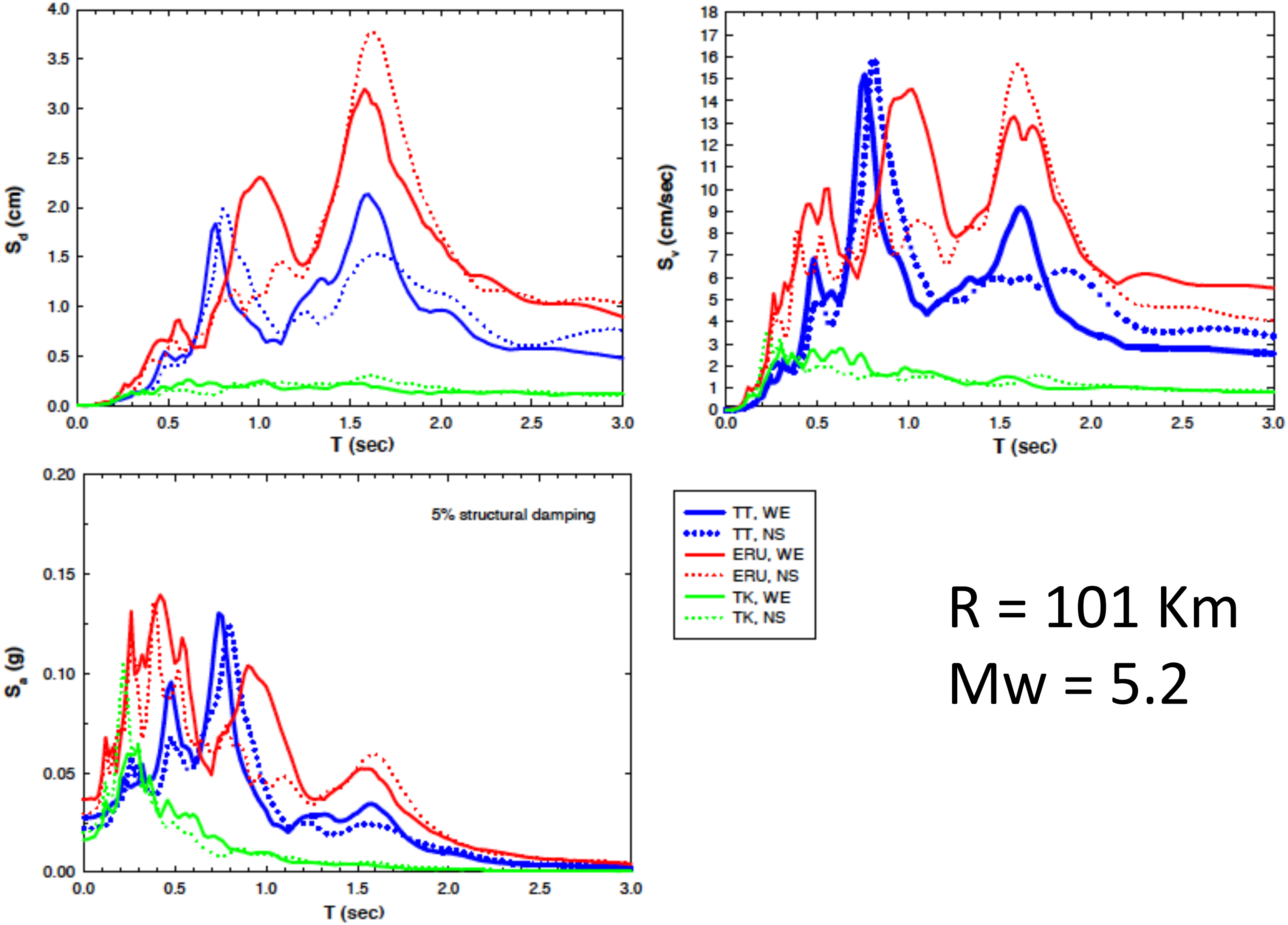
TT station Vs30= 178 m/s
Suelo tipo F (NEC-15)


Station TT, WE motion 30/07/2012
Station ERU, WE motion 30/07/2012
Station TK, WE motion 30/07/2012
Acceleration (g)
Velocity (cm/sec)
Displacement (cm)
Time (sec)


5% structural damping
ERU Station (Vs_{30} = 101 m/s)
S_a/PGA
T (sec)
0
1
2
3
4
5
6
0.5
1.0
1.5
2.0
2.5
3.0
ERU, WE, NF Motion, Mw 4.9, R= 23km
ERU, NS
ERU, WE, FF Motion, Mw 5.3,. R = 101km
ERU, NS
ERU, WE, FF Motion, Mw 5.2, R=136 Km
ERU, NS


5% structural damping
TT Station (Vs_{30} = 178 m/s)
S_a/PGA
T (sec)
0
1
2
3
4
5
6
0.0
0.5
1.0
1.5
2.0
2.5
3.0
TT, WE, NF Motion, Mw 4.9, R= 17km
NS
TT, WE, FF Motion, Mw 5.3,. R = 102km
NS
TT, WE, FF Motion, Mw 5.2, R= 134 km
NS

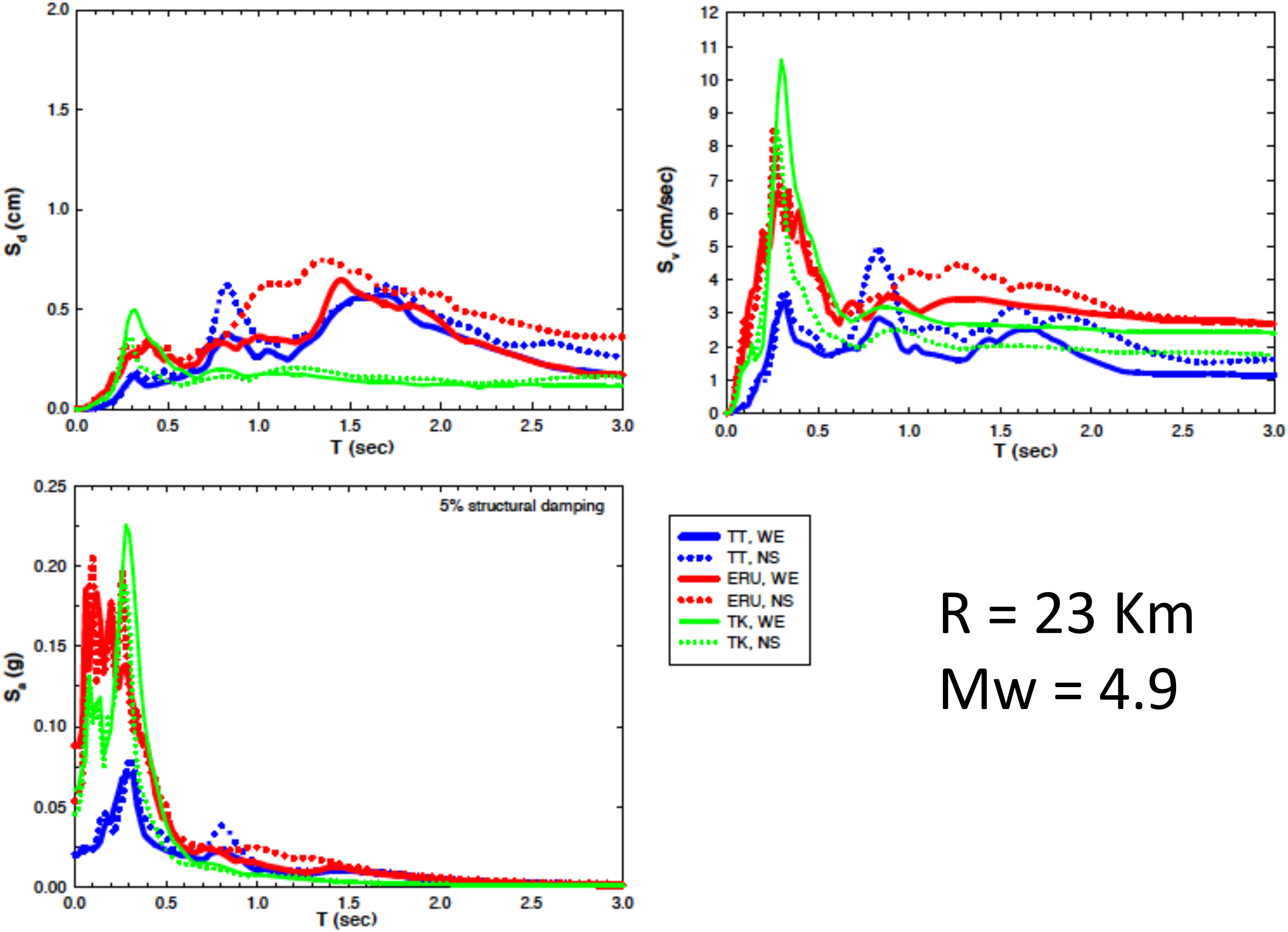

5% structural damping
TK Station (Vs_{30} = 800 m/s)
S_a/PGA
T (sec)
0
1
2
3
4
5
6
0.0
0.5
1.0
1.5
2.0
2.5
3.0
TK, WE, NF Motion, Mw 4.9, R= 28km
NS
TK, WE, FF Motion, Mw 5.3,. R = 100km
NS
TK, WE, FF Motion, Mw 5.2, R= 136 km
NS



R = 101 Km

Mw = 5.2

Figure 4.25 Acceleration, velocity and displacement response spectra for recorded subduction ground motion event (FF) from July 30, 2012, at IGN's stations; TT, ERU and TK

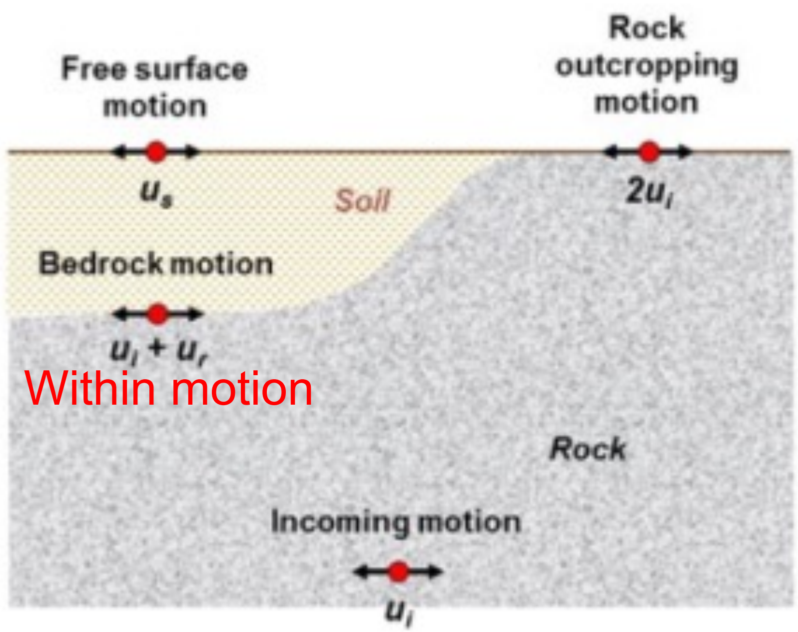


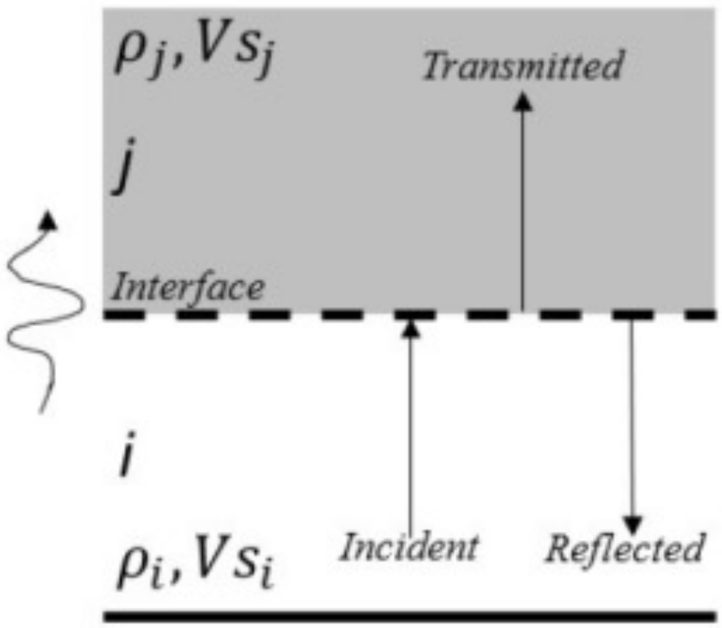
R = 23 Km

Mw = 4.9

Figure 4.26 Acceleration, velocity and displacement response spectra for recorded crustal ground motion event (NF) from October 28, 2012, at IGN's stations; TT, ERU and TK

Relación de impedancia y deconvolución

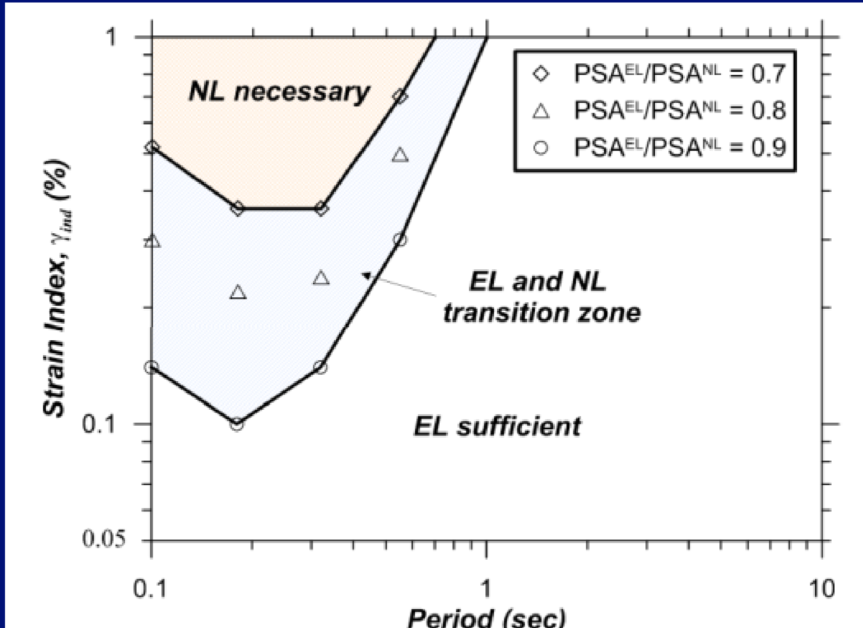




Within motion (rock) = f (αz, Msuelo, Tsuelo)

$$\alpha_z = \frac{\rho_j \ v_{s_j}}{\rho_i \ v_{s_i}}$$

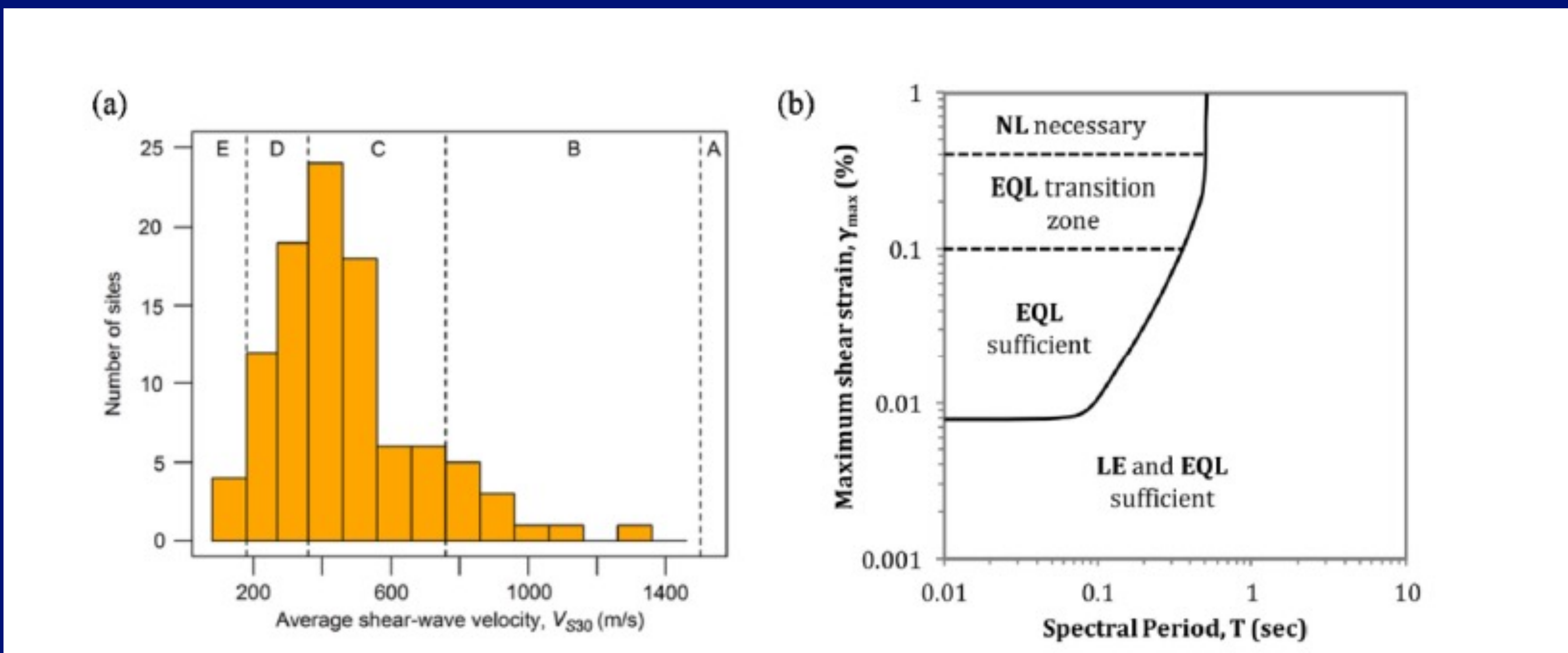
Cuando usar análisis Lineales Equivalentes Vs Nolineales



Kim et al (2013)

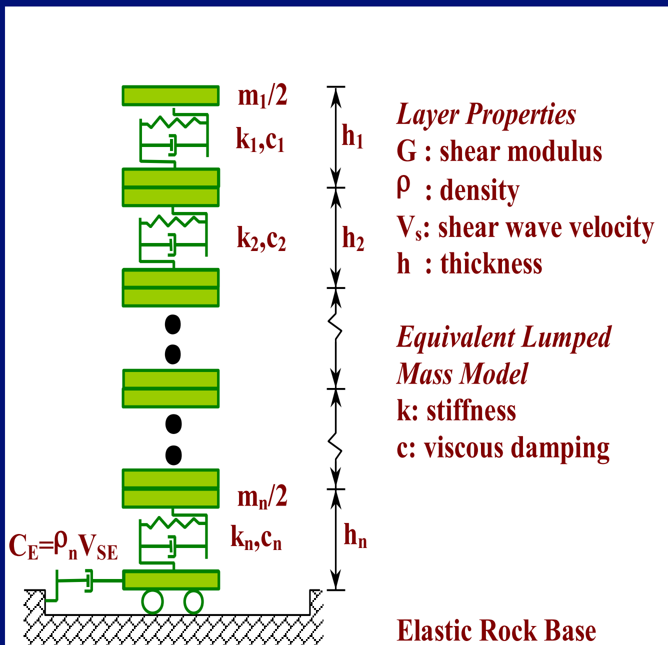
$$\gamma_{ind} = \frac{PGV^{r}}{V_{S30}}$$

Kaklamanos et al (2013)



Métodos de análisis de respuesta de sitio 1D-vertical

Modelo de masas distribuidas, NL

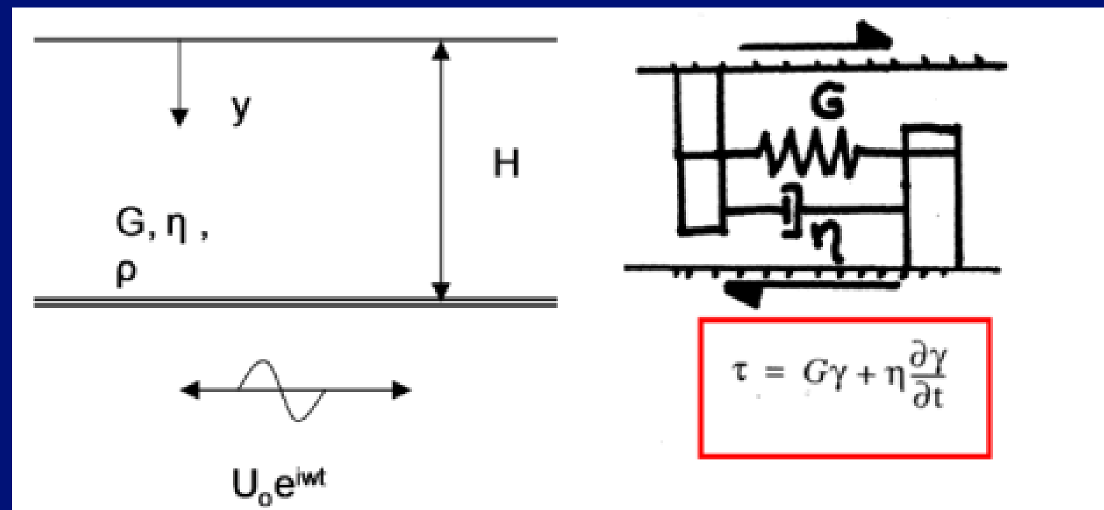


Multi-degree of freedom lumped parameter model

$$[M]\{\ddot{u}\}+[K]\{u\}+[C]\{\dot{u}\}=-[M]\{I\}\ddot{u}_g$$

$$[C]=\alpha_R[M]+\beta_R[K]$$

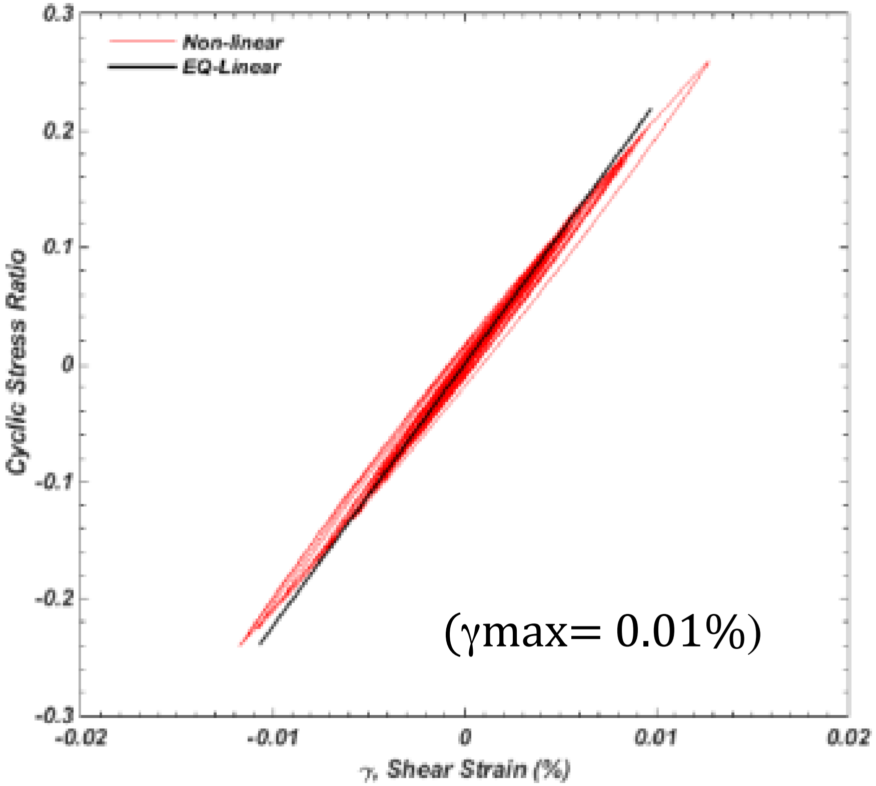
Modelo de propagación de ondas, LE

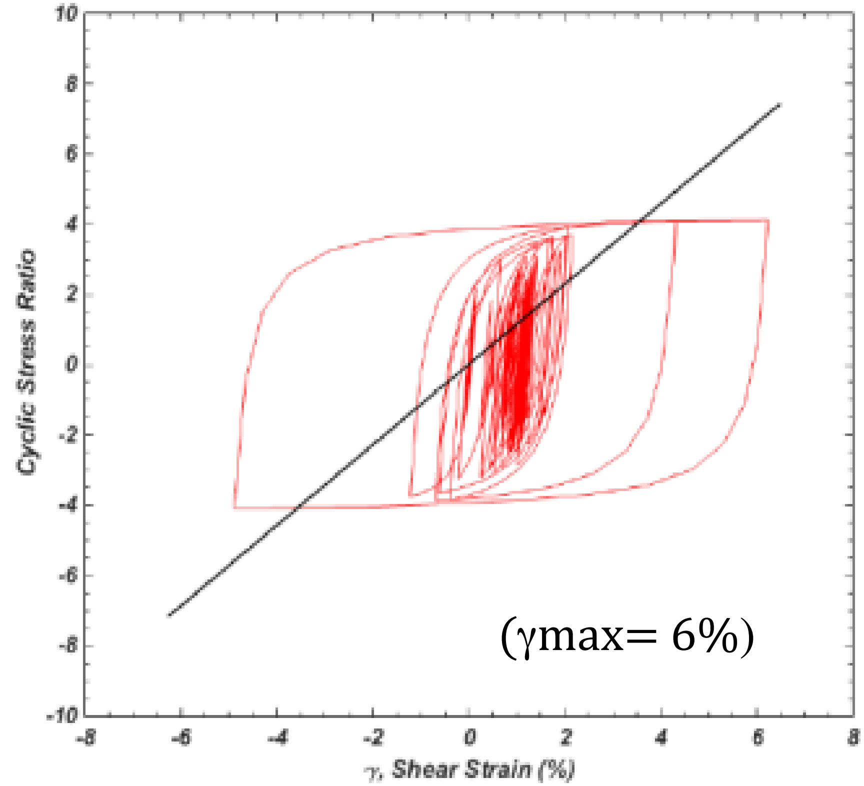


Mov. Armonico Est. Estable

$$\rho\frac{\partial^2 u}{\partial t^2}=G\frac{\partial^2 u}{\partial z^2}+\eta\frac{\partial^3 u}{\partial z^2\partial t}$$

$$f_{max,i}=\frac{V_{s,i}}{4H_i}\ ; \qquad T_{min}=\frac{1}{f_{max}}$$





2004 M_w 6.0 Parkfield Earthquake (PGA = 0.07g)

Igual sismo pero escalado para PGA = 1.0g

(Hutabarat, 2016)

Respuesta de un Perfil de Suelo a Ondas Sísmicas: Modelo Matemático

- Tres factores modifican ondas sísmicas propagándose de roca basal a la superficie:
  - Resonancia
  - Conservación de energía
    - Al pasar de un material más rígido a uno menos rígido la amplitud de onda aumenta
  - Amortiguamiento del suelo atenúa las ondas sísmicas
    - Amortiguamiento en suelos es mucho mayor al amortiguamiento en rocas

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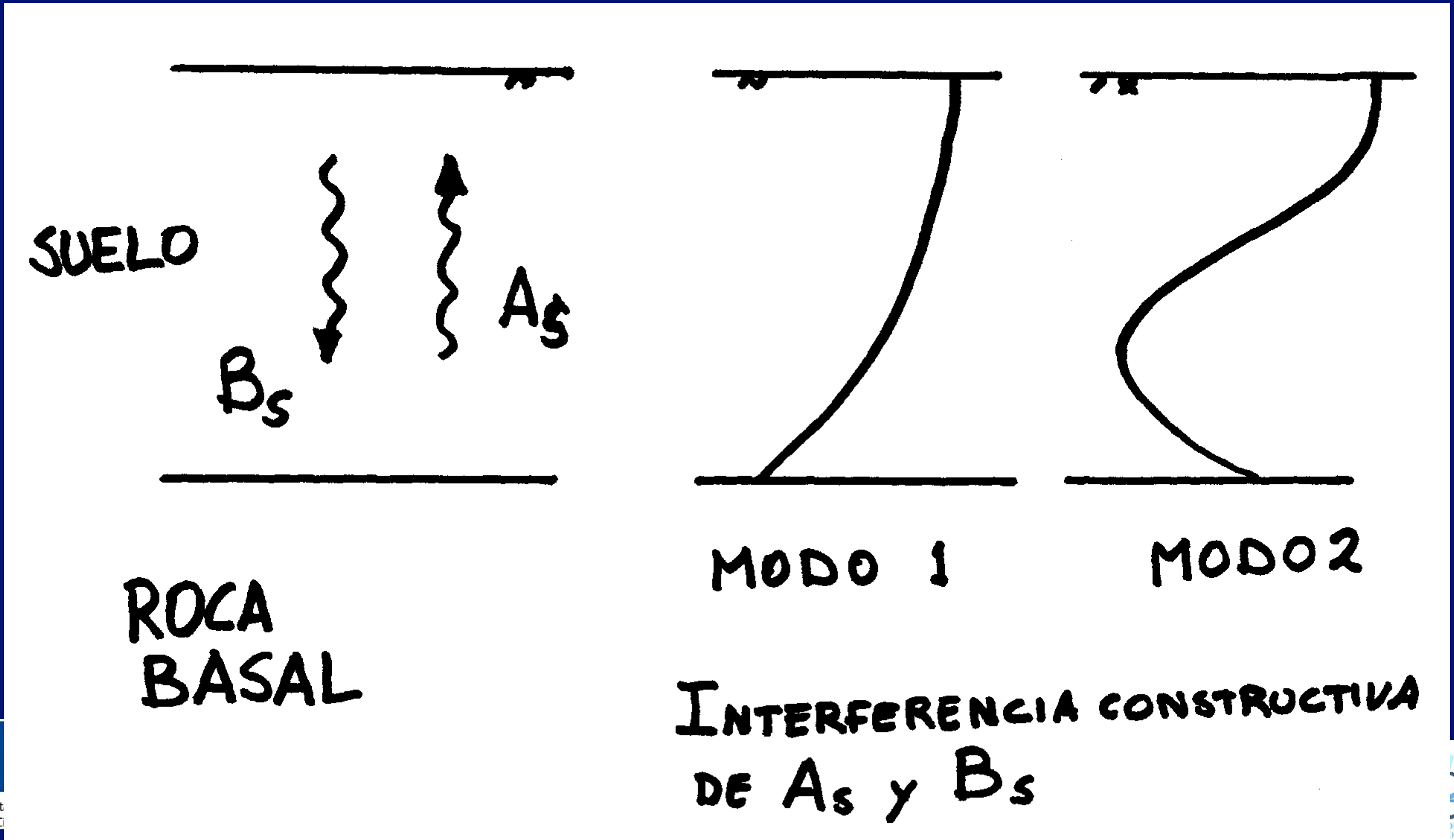
Respuesta de un Perfil de Suelo a Ondas Sísmicas: Resonancia

- ¿Por qué hay amplificación?



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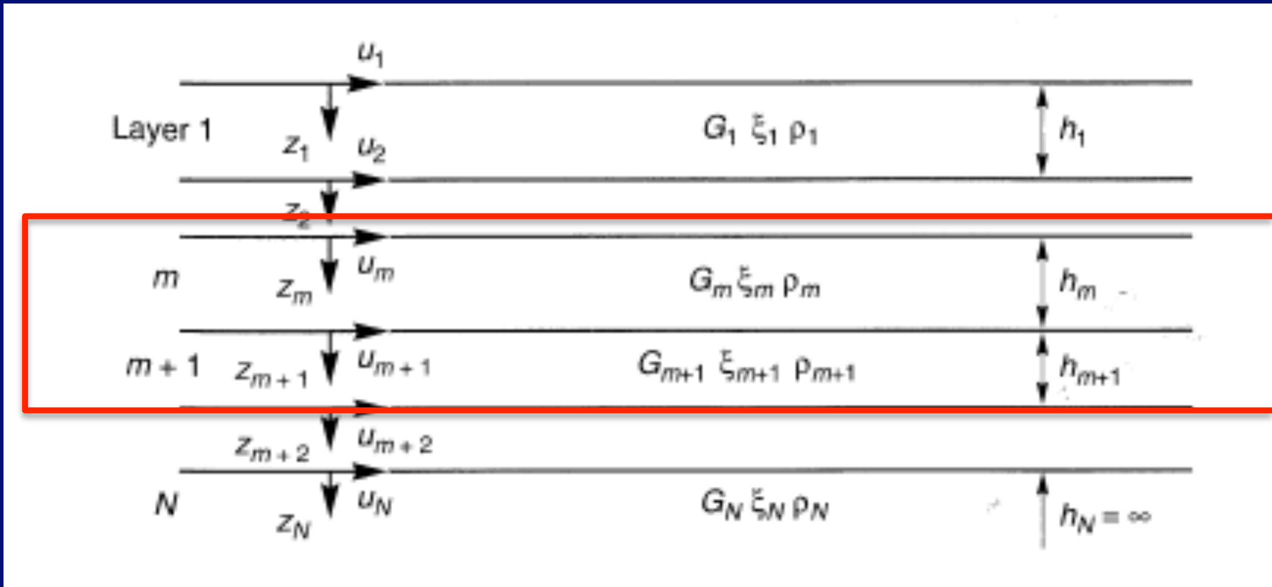
Anàlisis LINEAL EQUIVALENTE – SHAKE 2000

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial z^2} + \eta \frac{\partial^3 u}{\partial z^2 \partial t}$$

$$G^* = G + i\omega\eta$$

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



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

Desplaz. horizontal

$$u_m(Z_m = h_m, t) = (A_m e^{ik_m^* h_m} + B_m e^{-ik_m^* h_m})\, e^{i\omega t}$$

Amplitud de ondas en capa m

$$v_s^* = \sqrt{\frac{G^*}{\rho}} = \sqrt{\frac{G(1+i2\xi)}{\rho}} \approx \sqrt{\frac{G}{\rho}}(1+i\xi)$$

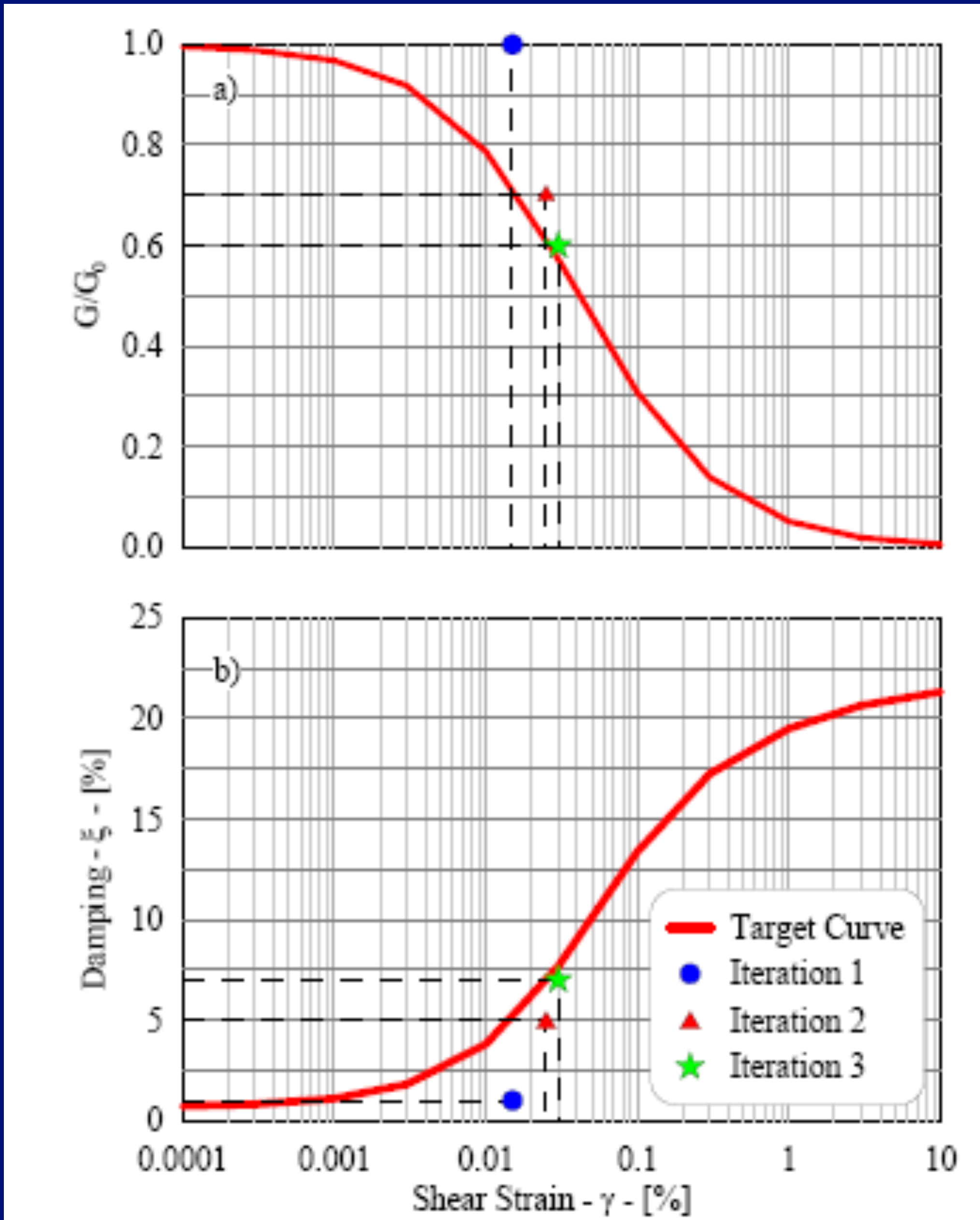
$$A_{m+1} = \tfrac{1}{2}A_m(1+\alpha_m^*)e^{ik_m^* h_m} + \tfrac{1}{2}B_m(1-\alpha_m^*)e^{-ik_m^* h_m}$$

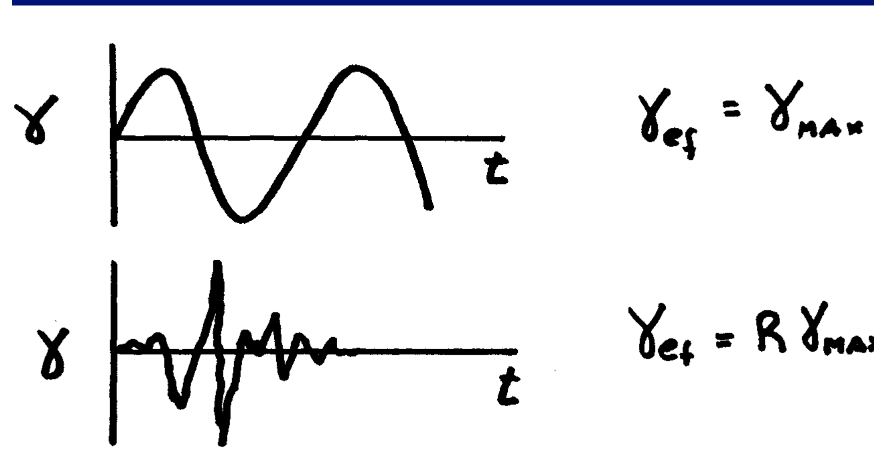
$$B_{m+1} = \tfrac{1}{2}A_m(1-\alpha_m^*)e^{ik_m^* h_m} + \tfrac{1}{2}B_m(1+\alpha_m^*)e^{-ik_m^* h_m}$$

La propagación de la energía de la Onda de una capa m a m+1 es controlada por la relación impedancia Compleja:

$$\alpha_m^* = \frac{k_m^* G_m^*}{k_{m+1}^* G_{m+1}^*} = \frac{\rho_m (v_s^*)_m}{\rho_{m+1} (v_s^*)_{m+1}}$$

Amplitud de ondas en capa m+1


1.0
0.8
0.6
0.4
0.2
0.0
a)
G/G0
25
20
15
10
5
0
b)
Damping - ξ - [%]
Target Curve
Iteration 1
Iteration 2
Iteration 3
0.0001
0.001
0.01
0.1
1
10
Shear Strain - γ - [%]


γ
t
γef = γMAX
γ
t
γef = R γMAX

Respuesta de un Perfil de Suelo a Ondas Sísmicas: Metodología

Aceleraciones en roca en el dominio del tiempo

$a_R(t)$

↓ Transformada de Fourier

Aceleraciones en roca en el dominio de la frecuencia

$A_R(f)$

↓

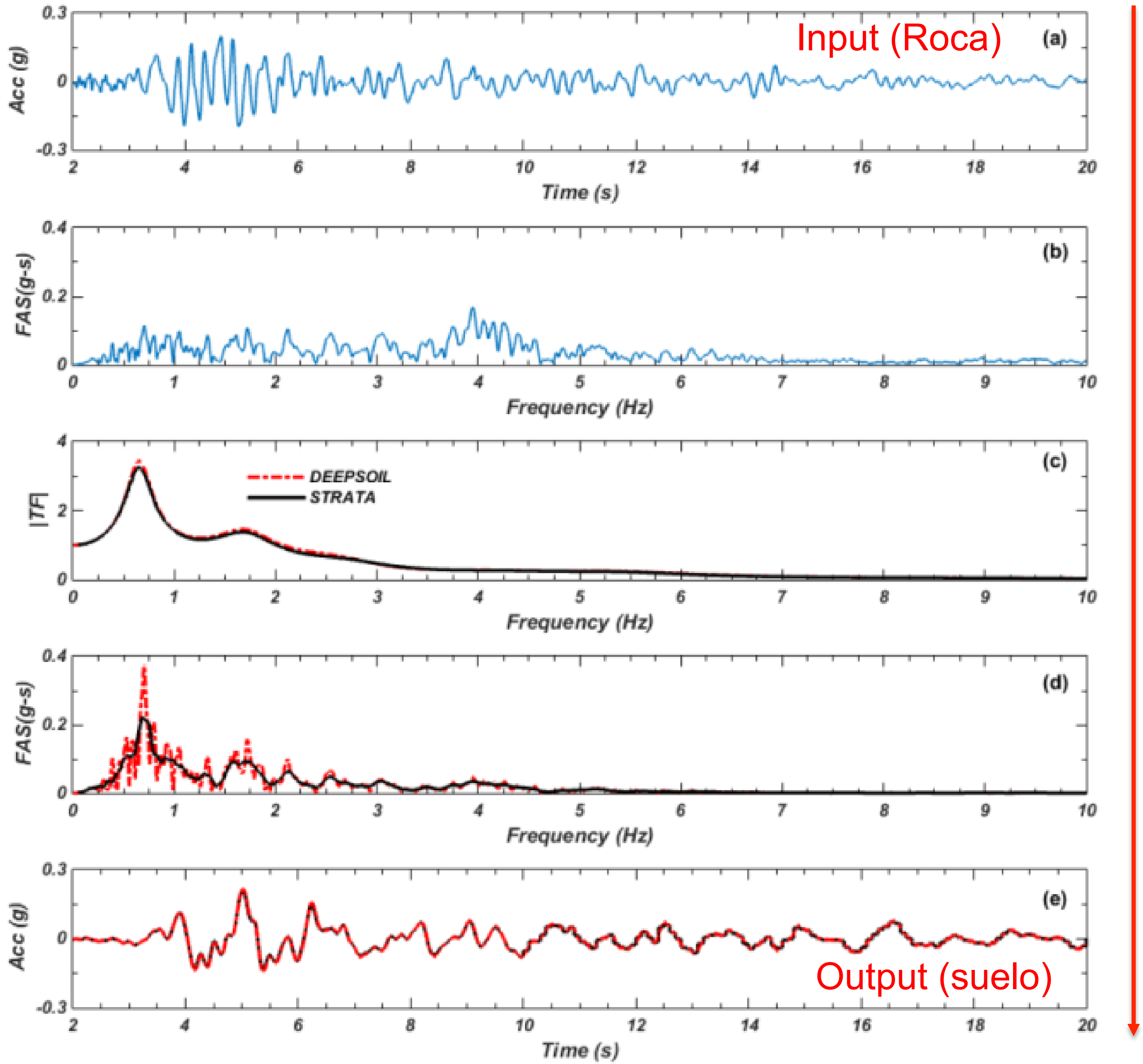
Obtener una función de transferencia $|F|$ (Función de las propiedades del perfil de suelos)

↓ $A_s(f) = |F| A_R(f)$

Aceletraciones en suelo en el dominio de la frecuencia $A_s(f)$

↓ Transformada inversa de Fourier

Aceleración en suelo en el dominio del tiempo $a_s(t)$



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Respuesta de un Perfil de Suelo a Ondas Sísmicas

- Ejemplo 1:

  Suelo elástico sobre roca rígida (no amortiguamiento)

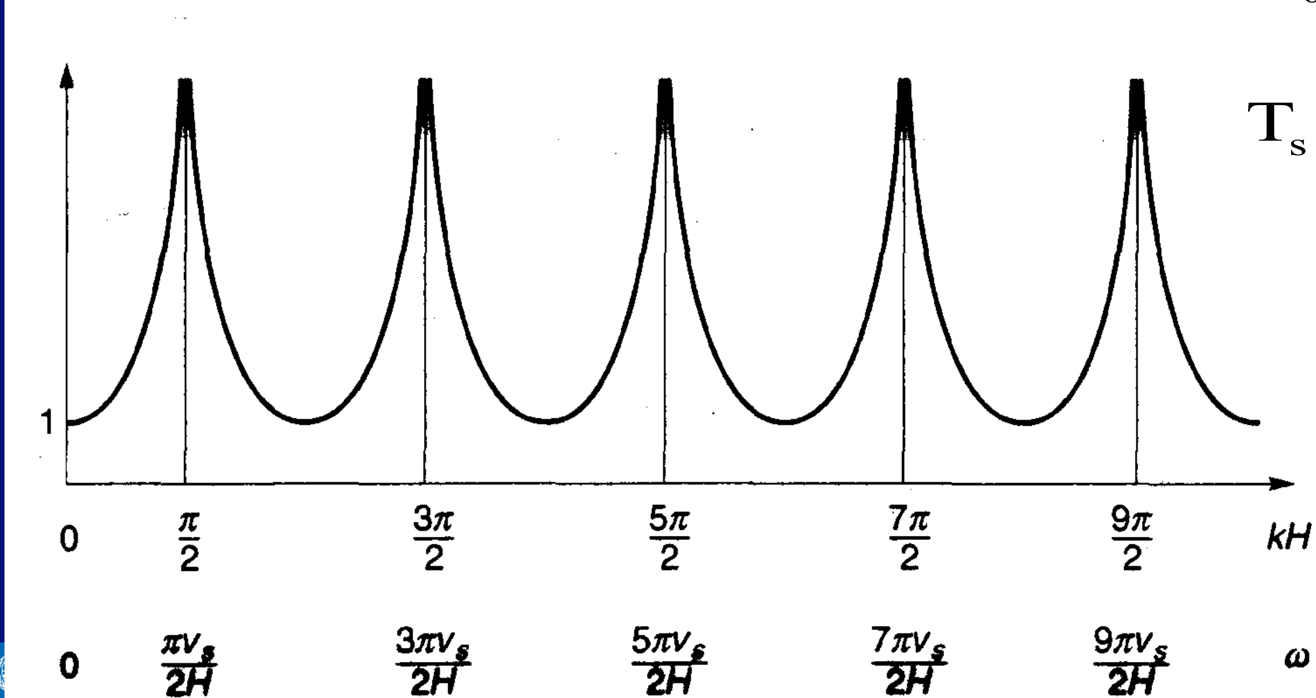
$$\left|F(\omega)\right| = \frac{1}{\cos \omega \frac{H}{V_s}}$$

$$\frac{\omega_0 H}{V_s} = \frac{\pi}{2}$$

$$\omega_0 = \frac{\pi V_s}{2H}$$

$$T_s = \frac{2\pi}{\omega_0} = \frac{4H}{V_s}$$

$F_1(\omega)$



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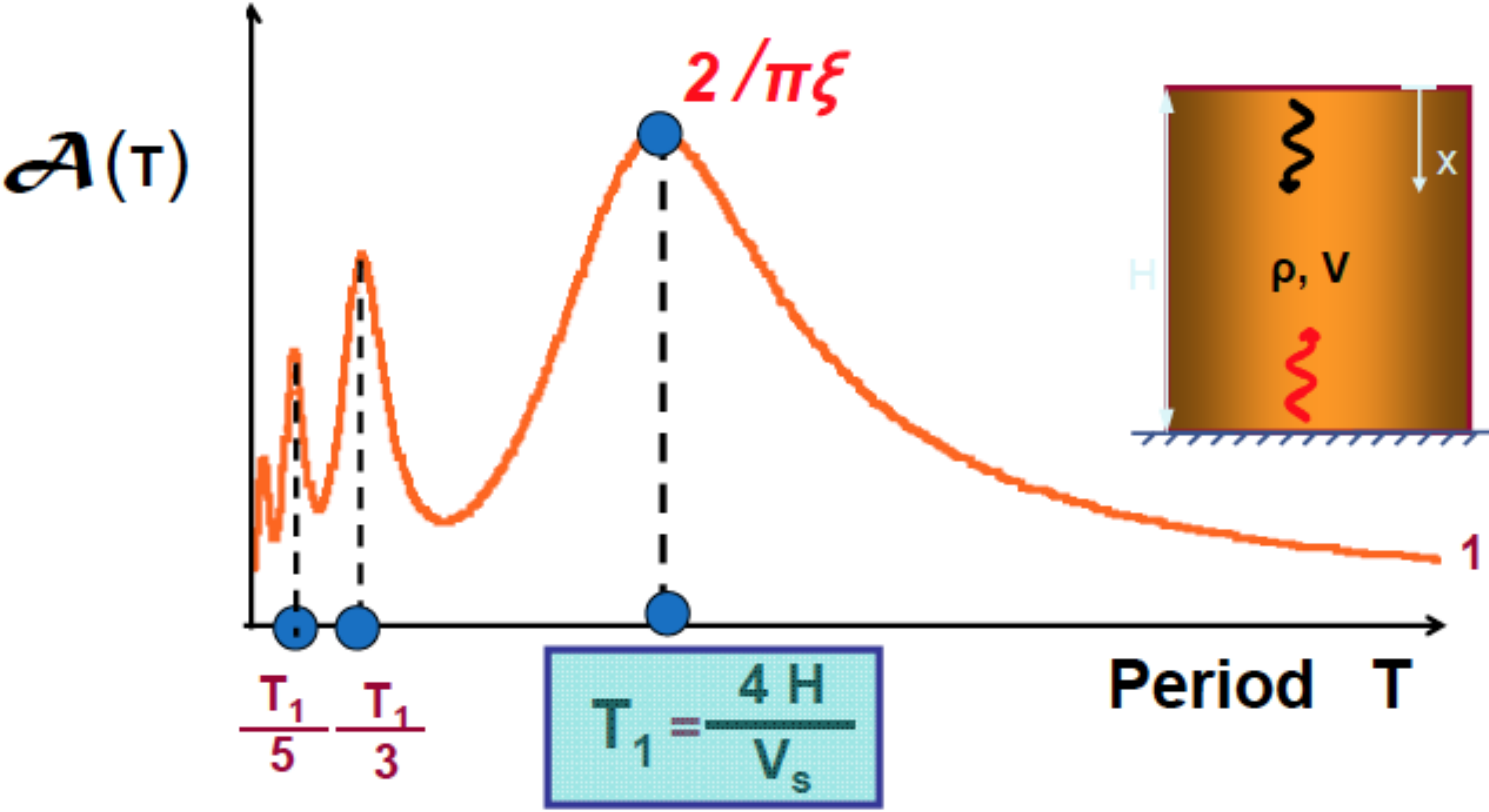
"SOIL AMPLIFICATION"

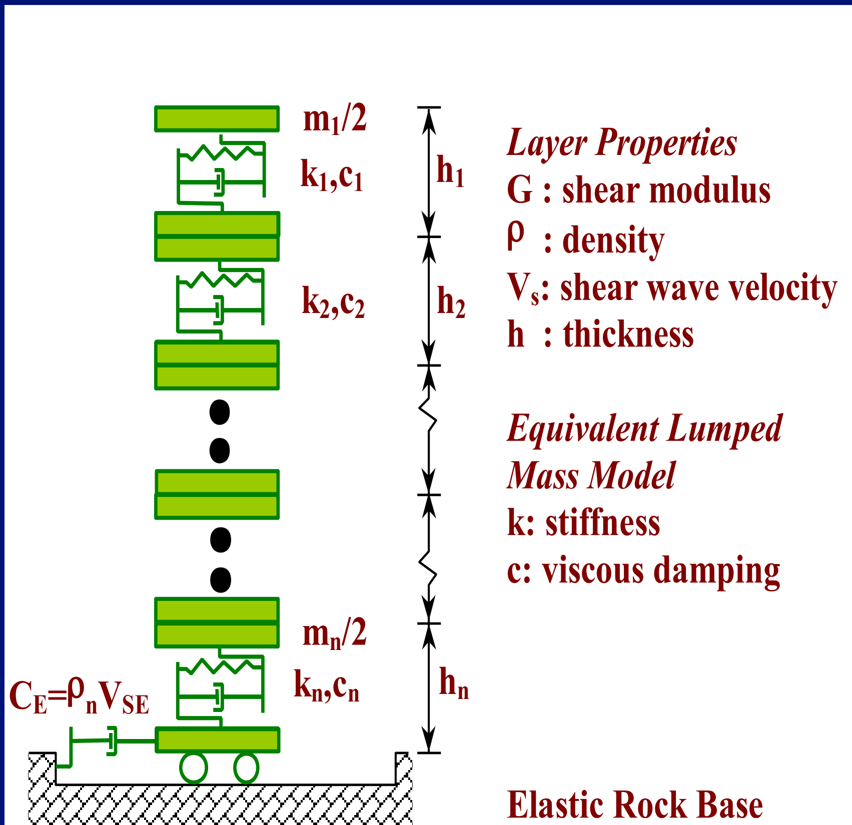
Harmonic Excitation

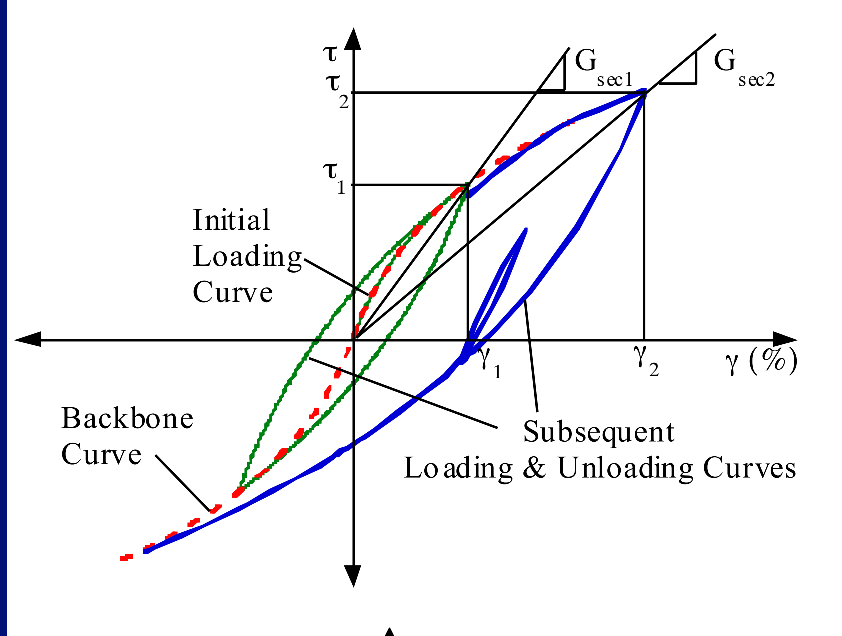


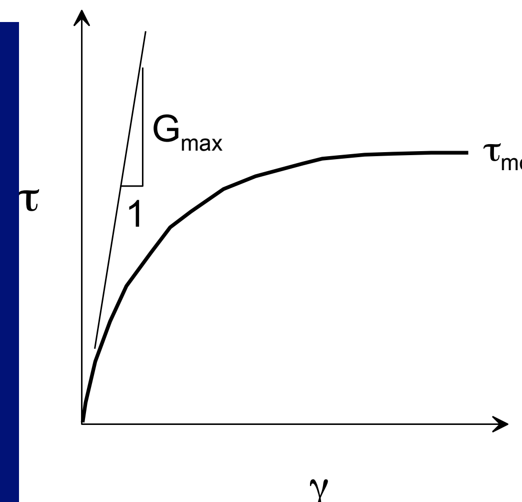
Modelos numéricos de respuesta Nolineal

Codes	*ID*	*Computational Method*	*Viscous Damping Matric, [C]*	*Nonlinear Soil Model*		*Reference for Soil Model*	*Reference for Computer Code*
				Backbone Curve	Hysteretic Damping		
D-MOD2000	DMOD2000	1D time integration (Newmark β) solving dynamic equation (Lumped Mass system)	Full Rayleigh Damping[1]	Modified Kondner & Zelasko (MKZ)	Extended Masing Rules (Vucetic, 1990)	Kondner & Zelasko (1963); Matasovic & Vucetic (1993)	Matasovic & Ordonez (2011)
DEEPSOIL	DS-MKZ		Frequency Independent (Hashash, 2009)	Extended MKZ	Non Masing Rules (MRDF) – Phillips & Hashash (2009)	Park & Hashash (2001)	Hashash et al (2015)
	DS-GQ/H			GQ/H		Groholski et al (2016)	
NERA	NERA	1D forward Finite Difference (FD) solving stress wave propagation using Central Difference algorithm.	N/A	IM Soil Model	Follow the behavior of unloading-reloading behavior similar to Masing (1926) rules.	Iwan (1967) ; Mroz (1967)	Bardet & Tobita (2001)
FLAC	FLAC	2D forward FD solving full dynamic equation. (Distributed Mass)	Full Rayleigh Damping	Sigmoidal (Sig3)		Itasca, 2011	Itasca, 2011
OPENSEES	OPENSEES	2D Finite Element Method (FEM) solving full dynamic equation. (Distributed Mass)		Pressure Independent Multi Yield surface (PIMY)		Yang (2000); Yang & Elgamal (2000)	McKenna & Fenves (2006)
FLIP	FLIP	2D Finite Element Method (FEM) solving full dynamic equation. (Distributed Mass)		Multi-Spring Model	Generalized Masing Rules (Ishihara et al. 1985)	Towhata & Ishihara (1985), Iai et al (1990), Iai et al (2011)	FLIP Consortium (2011)

Anàlisis NO LINEAL – DMOD 2000







$\gamma_r = \tau_{mo} / G_{max}$

Multi-degree of freedom lumped parameter model

$$[M]\{\ddot{u}\} + [K]\{u\} + [C]\{\dot{u}\} = -[M]\{I\}\ddot{u}_g$$

$$[C] = \alpha_R [M] + \beta_R [K]$$

$$\tau = \frac{G_{mo}\gamma}{1 + \beta\left(\frac{G_{mo}}{\tau_{mo}}\gamma\right)^s} = \frac{G_{mo}\gamma}{1 + \beta\left(\frac{\gamma}{\gamma_r}\right)^s}$$

Calibración modelo MKZ arcilla de GYE

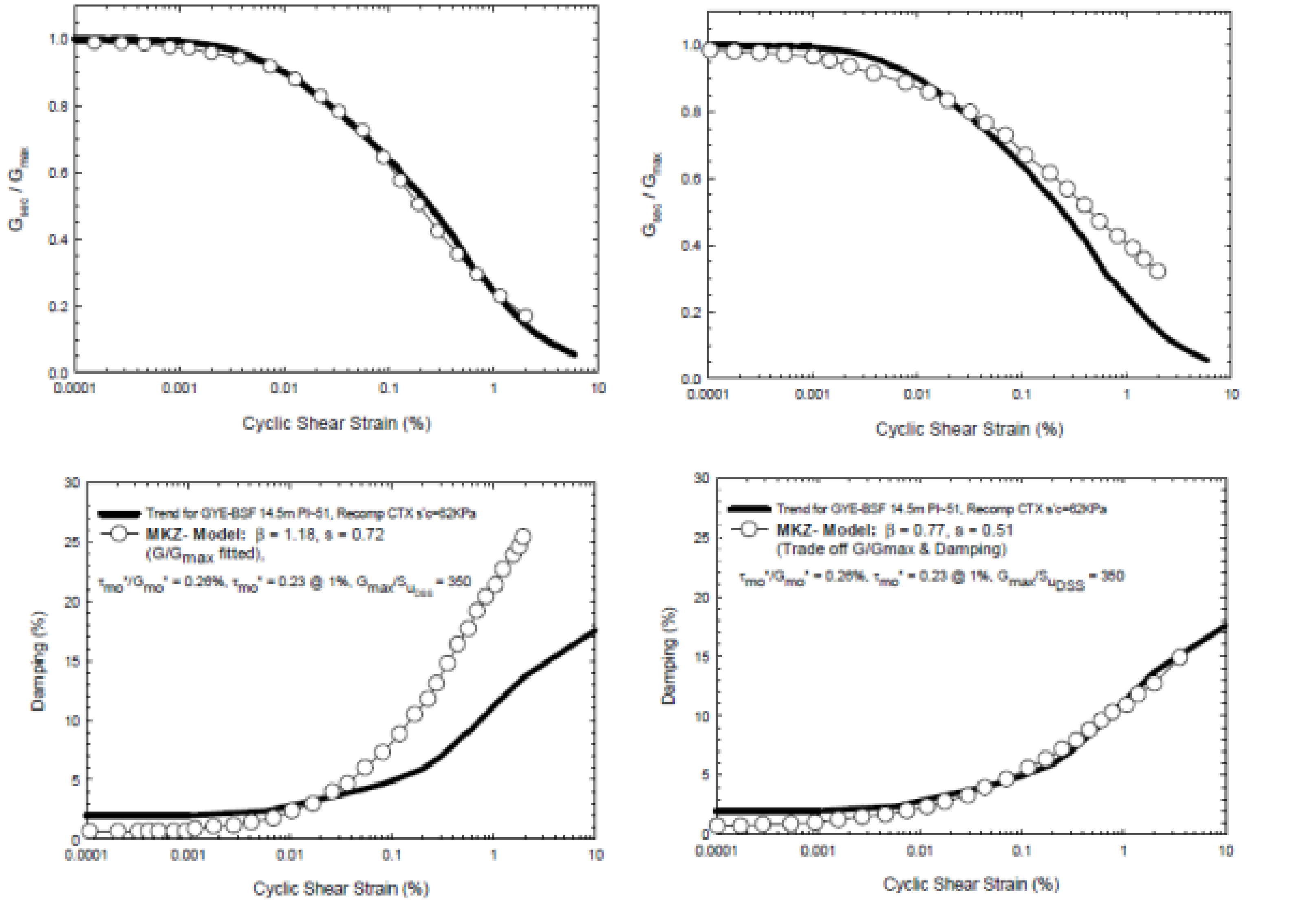
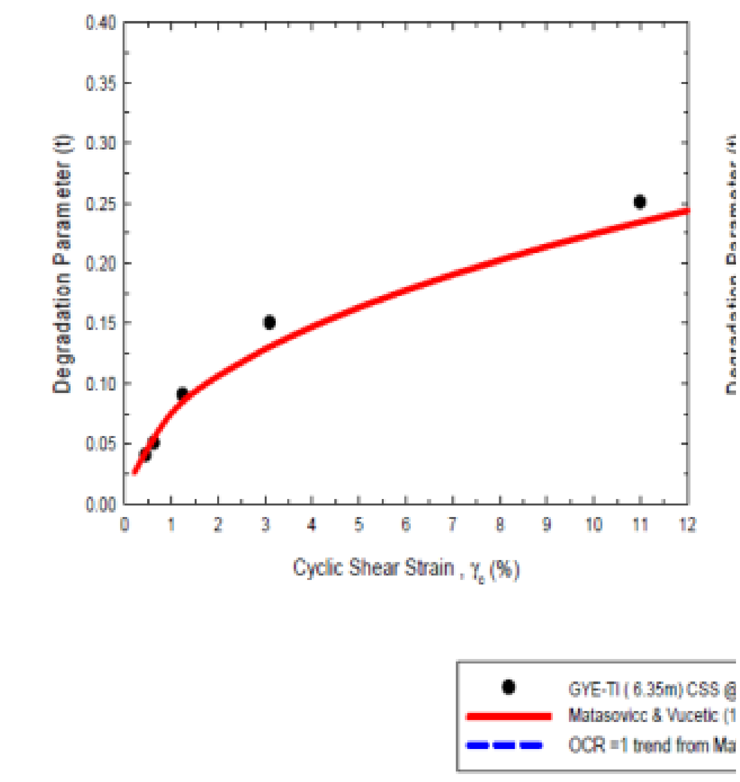


Figure 3.93 Calibration of the MKZ model with the modulus reduction and damping curve from cyclic test data



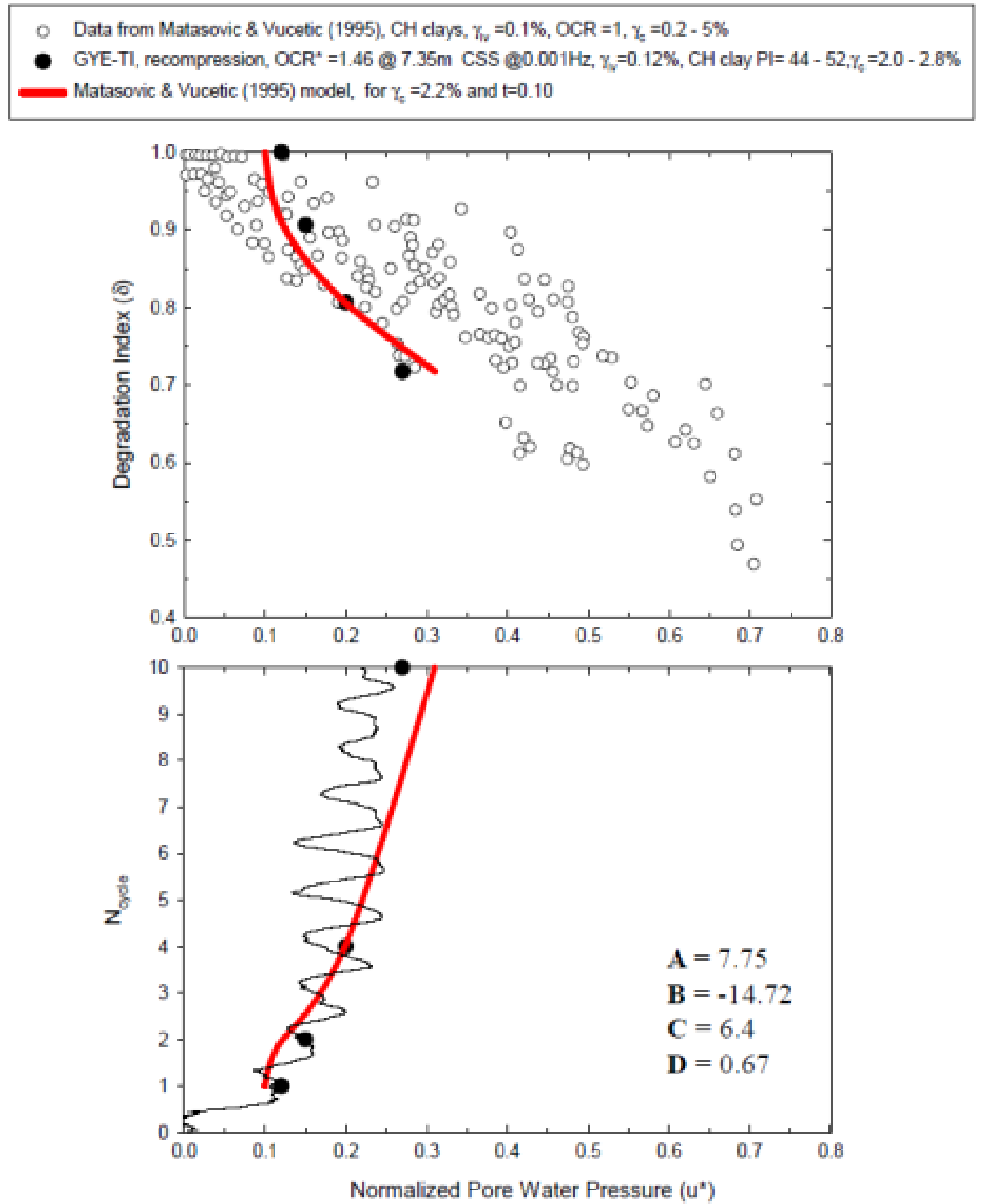


Figure 3.91 Calibration of pore-water pressure generation model constants for MKZ model for GYE-TI clay with a volumetric cyclic threshold shear strain of 0.12%

Modelo general quadrático/hiperbolico (GQ/H)

- El modelo GQ/H (Groholski et al., 2015) permite definir la resistencia al corte del suelo al momento de la falla permitiendo representar la no linealidad del suelo en bajos niveles de deformación
- El comportamiento no lineal se controla mediante una función de ajuste de curva dependiente de la deformación unitaria de corte
- Implementado en el software Deepsoil (Hashash et al., 2016)

- Formulación:

$$\frac{\tau}{\tau_{max}} = \frac{2(\gamma/\gamma_r)}{1 + (\gamma/\gamma_r) + \sqrt{\{1 + (\gamma/\gamma_r)\}^2 - 4\theta_\tau(\gamma/\gamma_r)}}$$

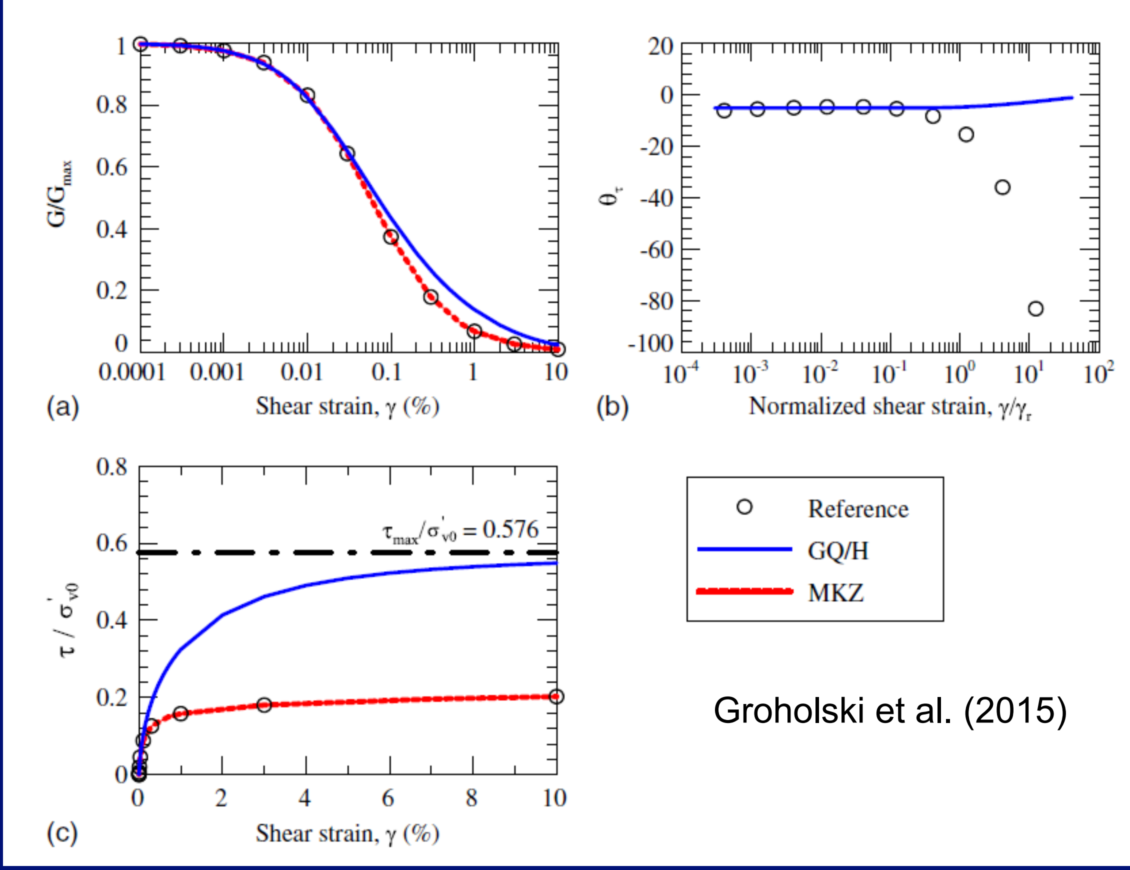
Donde τ es el esfuerzo al corte, τ_{max} es la resistencia al momento de la falla, γ es la deformación unitaria al corte, γ_r es la deformación al corte de referencia, y θ_t es el parámetros de ajuste de curvatura.

- Parámetros de ajuste de curvatura:

$$\theta_\tau = \theta_1 + \frac{\theta_2 \cdot \left(\frac{\gamma}{\gamma_r}\right)}{\theta_3 + \left(\frac{\gamma}{\gamma_r}\right)} \leq 1$$

Modelo general quadrático/hiperbolico (GQ/H)

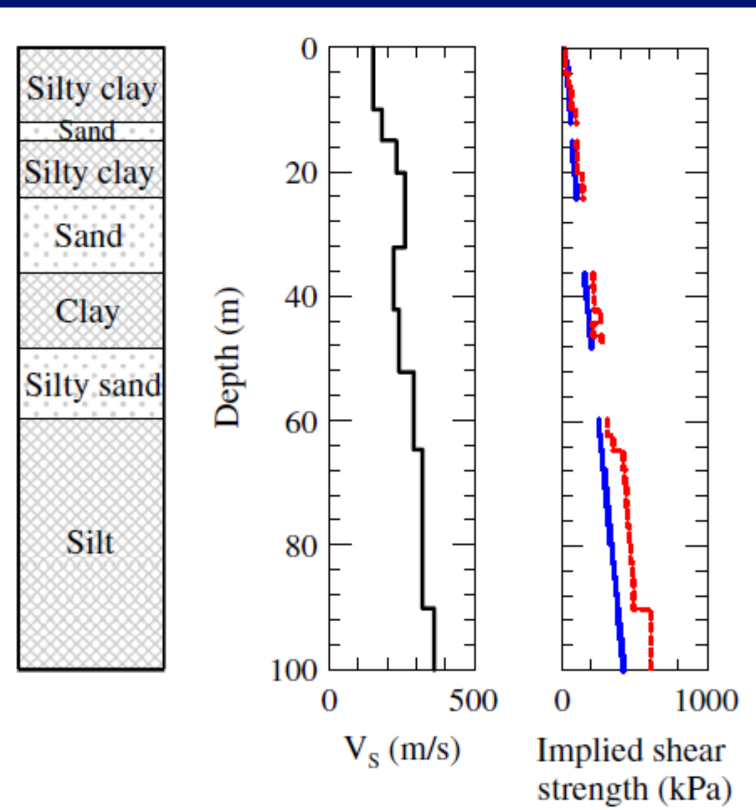
- Curvas de degradación
  - Se define un valor del esfuerzo de corte (τ) a altas deformaciones
  - Mejora el control de la curva de reducción del módulo, reduce la amplificación o degradación al tener un nivel de resistencia real

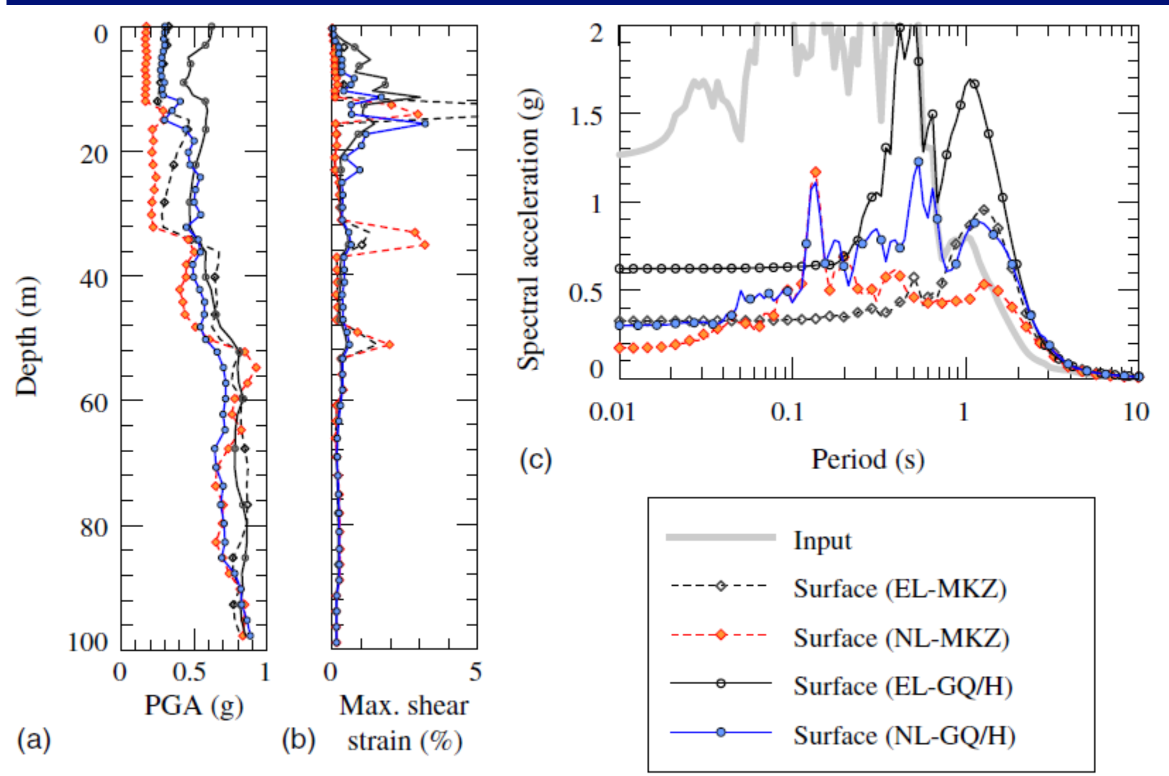


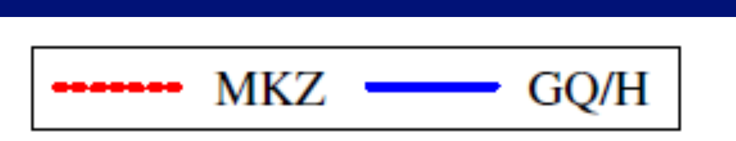
Groholski et al. (2015)

Modelo general quadrático/hiperbolico (GQ/H)

- Influencia en los análisis de respuesta de sitio – Groholski et al. (2015)

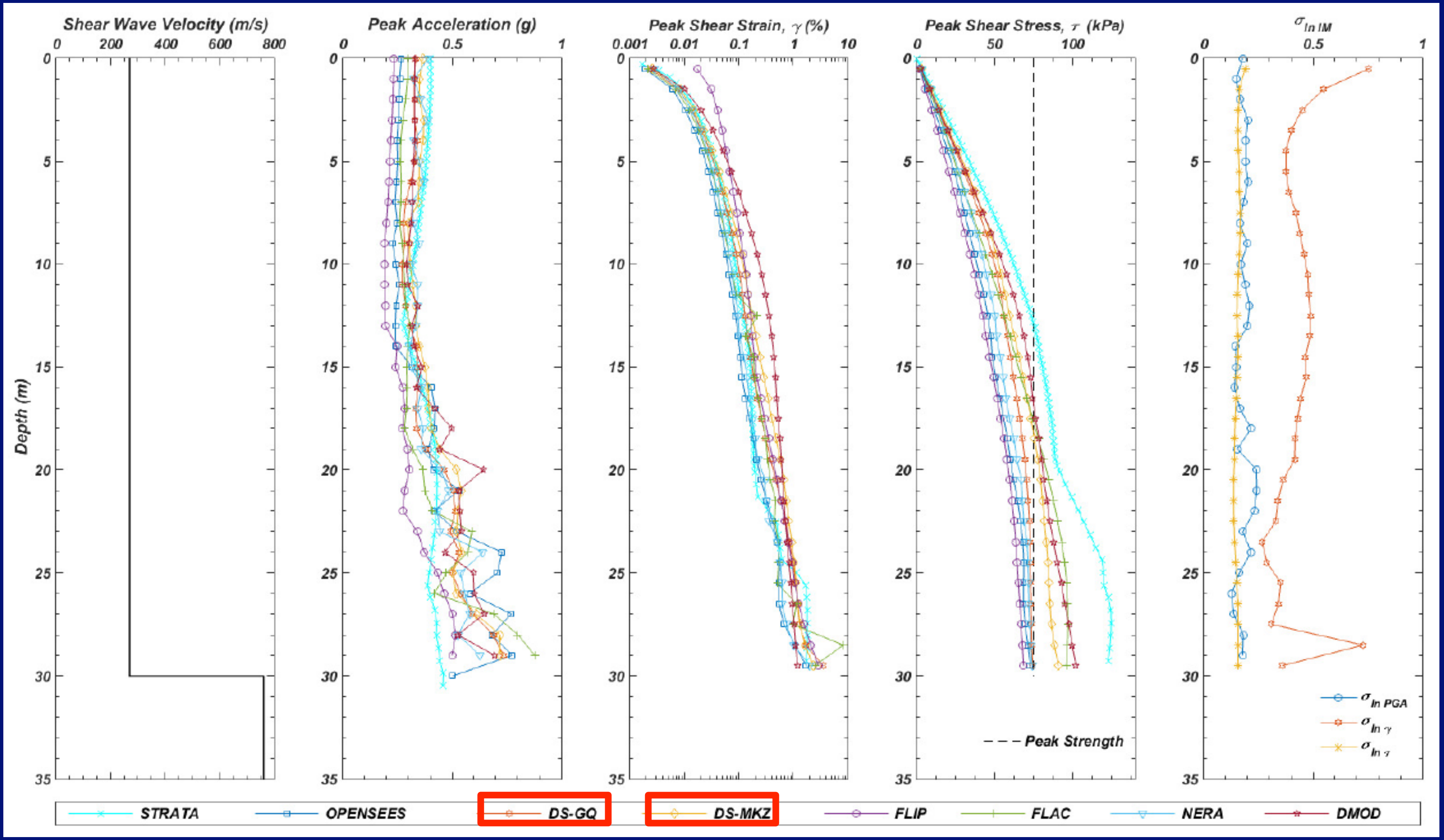






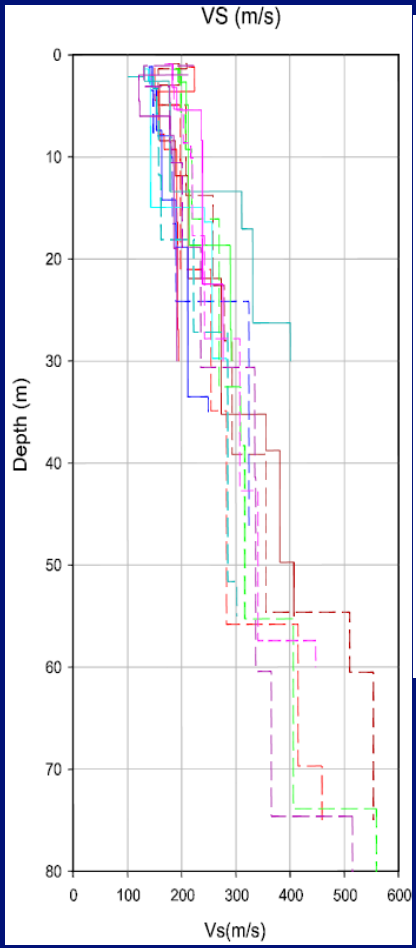
Modelo general quadrático/hiperbolico (GQ/H)

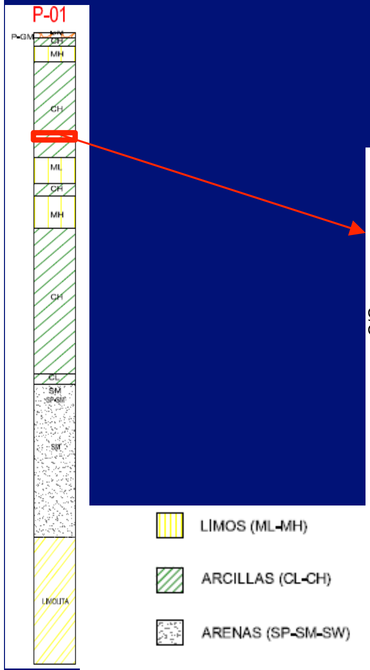
- Influencia en los análisis de respuesta de sitio – Hutabarat (2016)

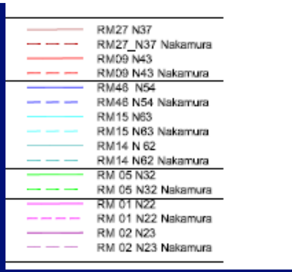


Modelo general quadrático/hiperbolico (GQ/H)

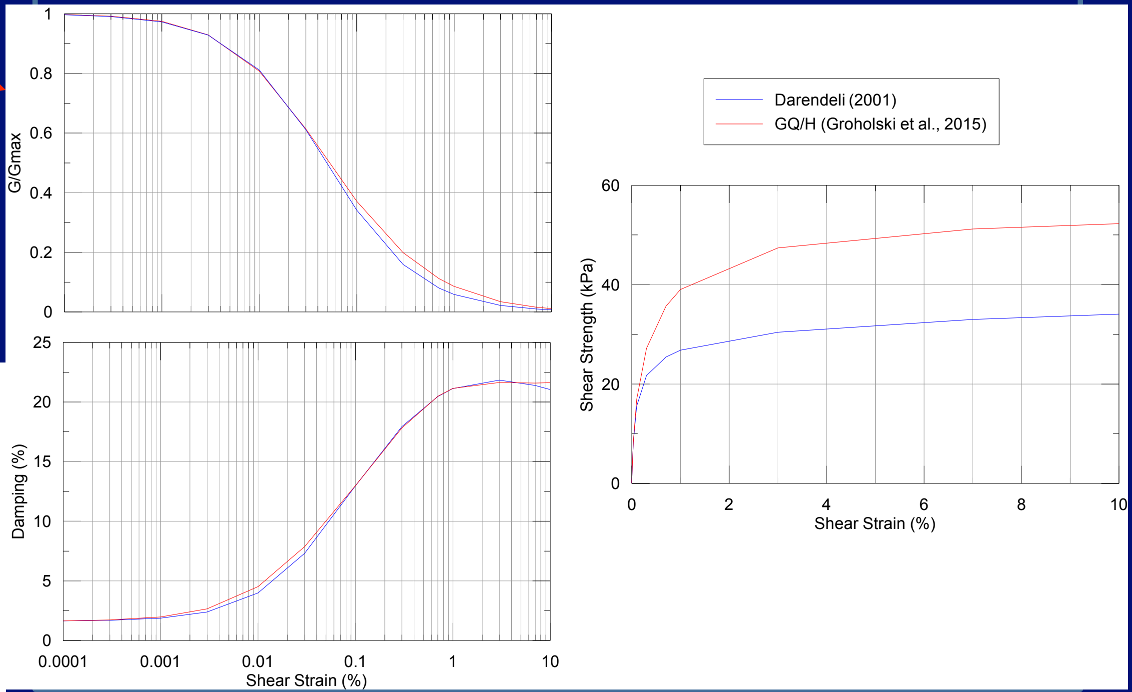
- Influencia en los análisis de respuesta de sitio – Proyecto Microzonificación Sísmica de Esmeraldas







- Ajuste curva de degradación y amortiguamiento para materiales finos:



Parámetros dinámicos de suelos

- ✓ Perfil de Vs en campo.

  $G_{max} = \rho (V_s)^2 , \rho = \gamma_t /g$

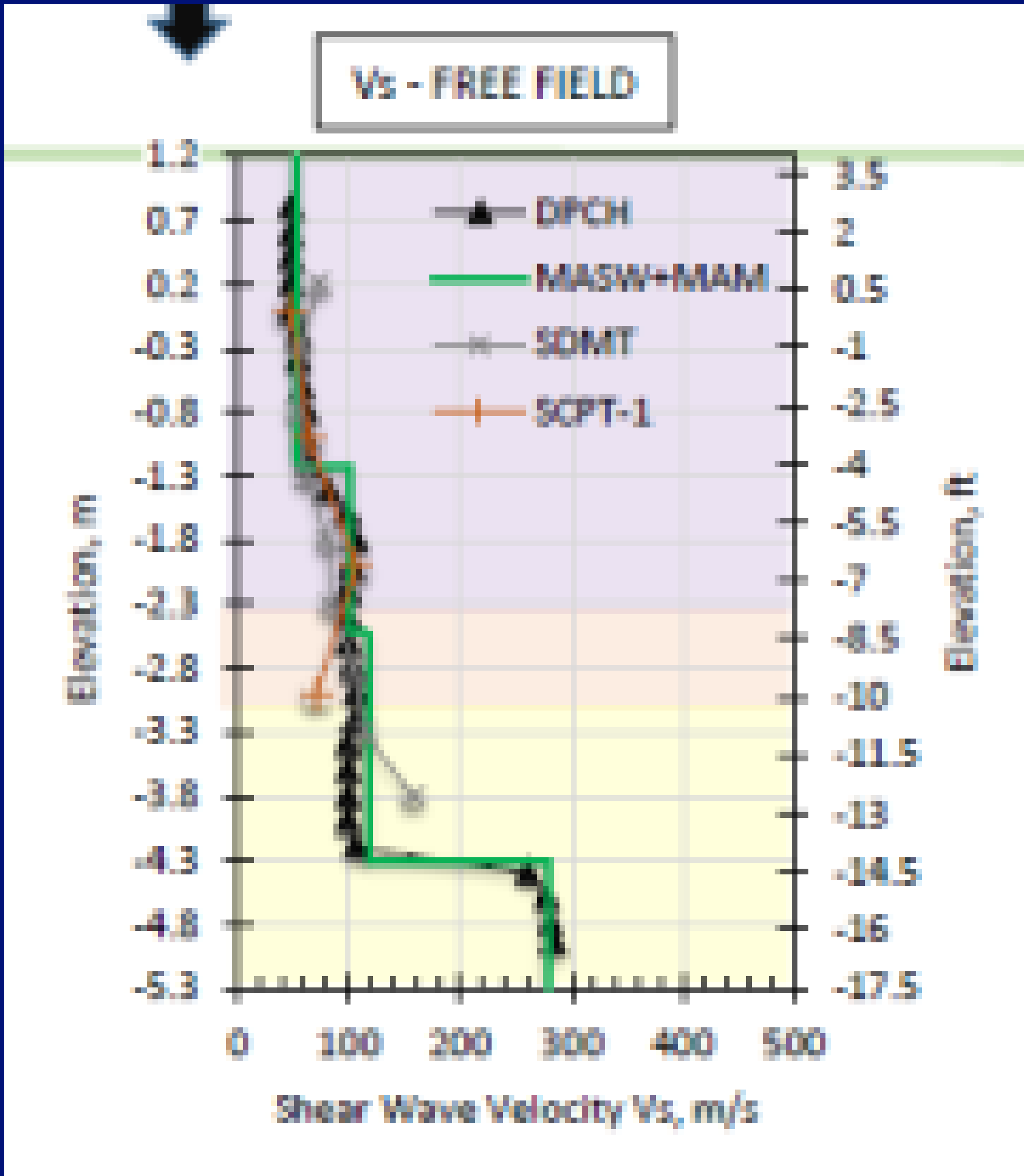
- ✓ Curva, dependiente de la deformación, de reducción del modulo de corte normalizado (G/G_{max} vs. γ)

- ✓ Curva, dependiente de la deformación, del amortiguamiento del material (λ vs. γ)

- ✓ Resistencia al corte (Su or $\tan\phi'$)

Ref: Arroyo, J (2017)

Sitio donde se observó licuación, Terrappen Briceño



DPCH (Crosshole, 2 scptu, Dr. Cox (UT AUSTIN)

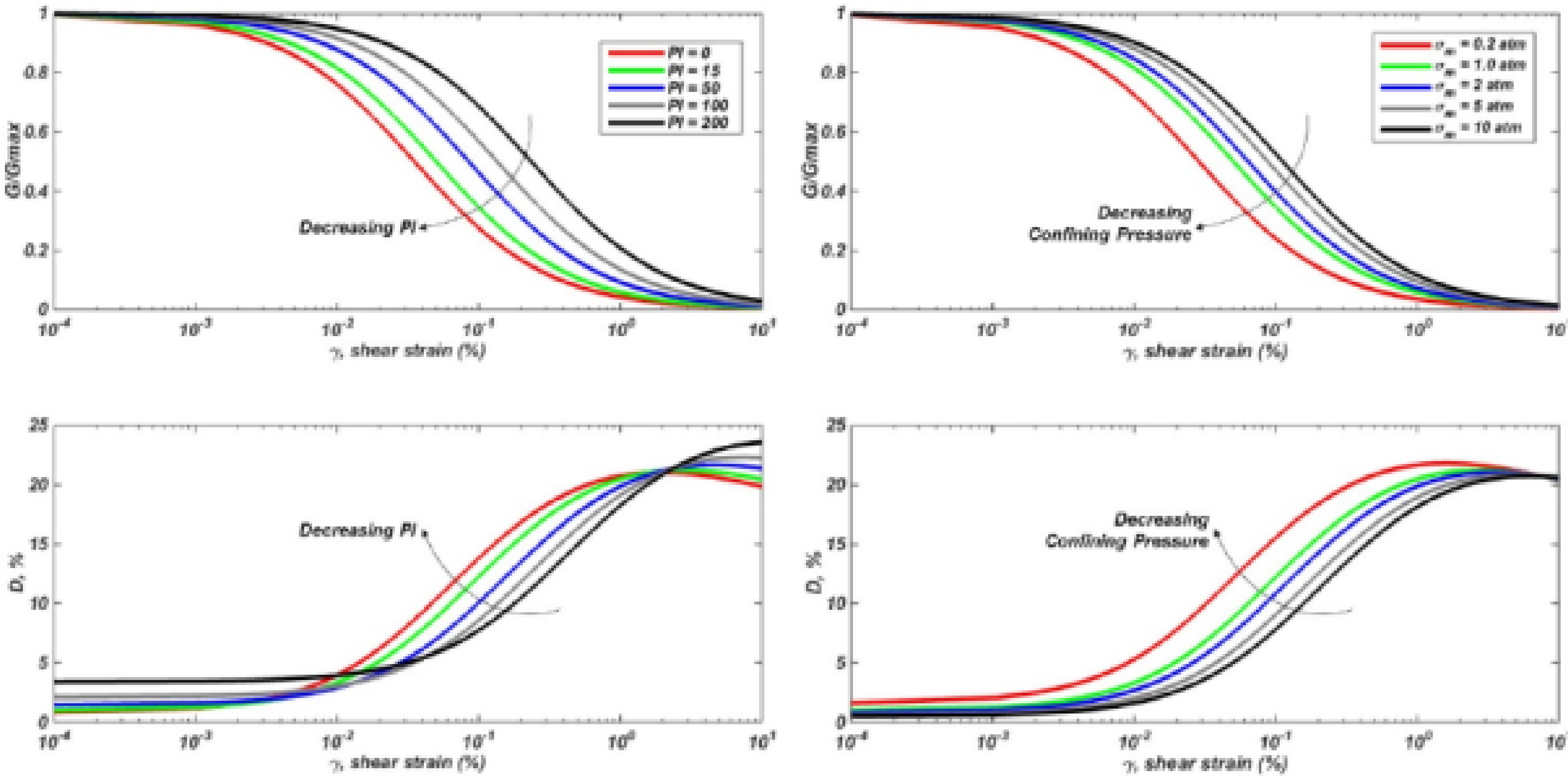
MASW + MAM
Geoestudios, Nestor

SDMT (Dilatometro dinamico)
Dr. Amoroso

SCPT (Downhole)
SUBTERRA, Ing. Illingworth

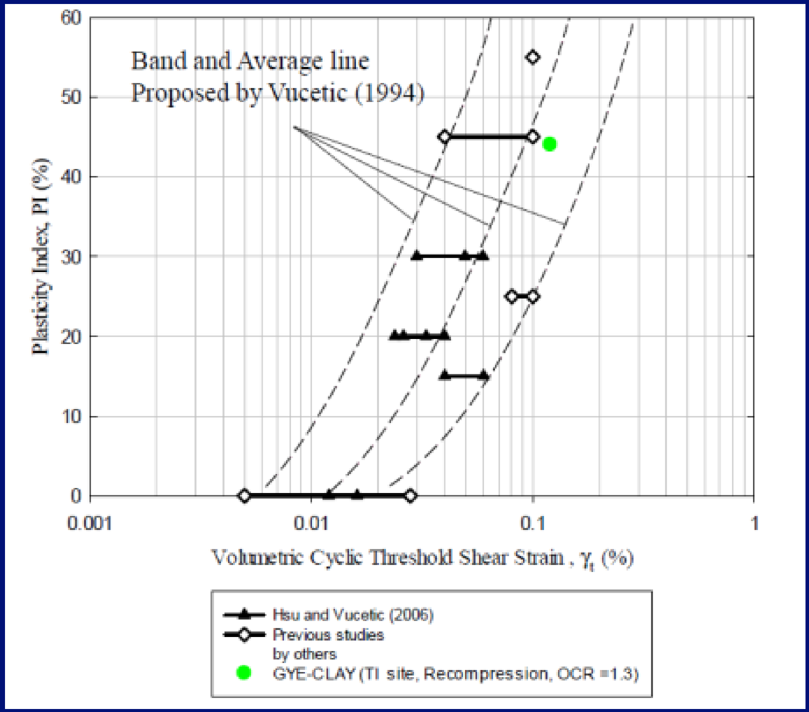
Esfuerzo confinante
constante

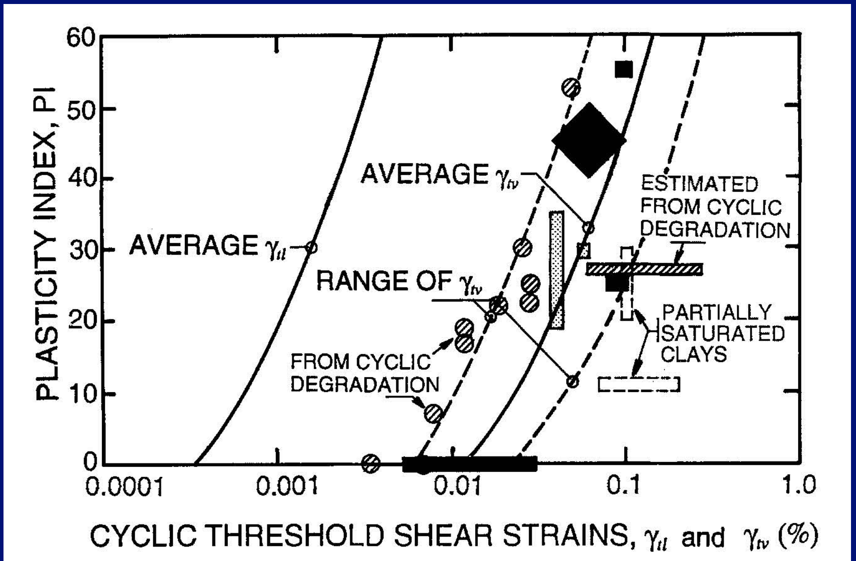
PI constante



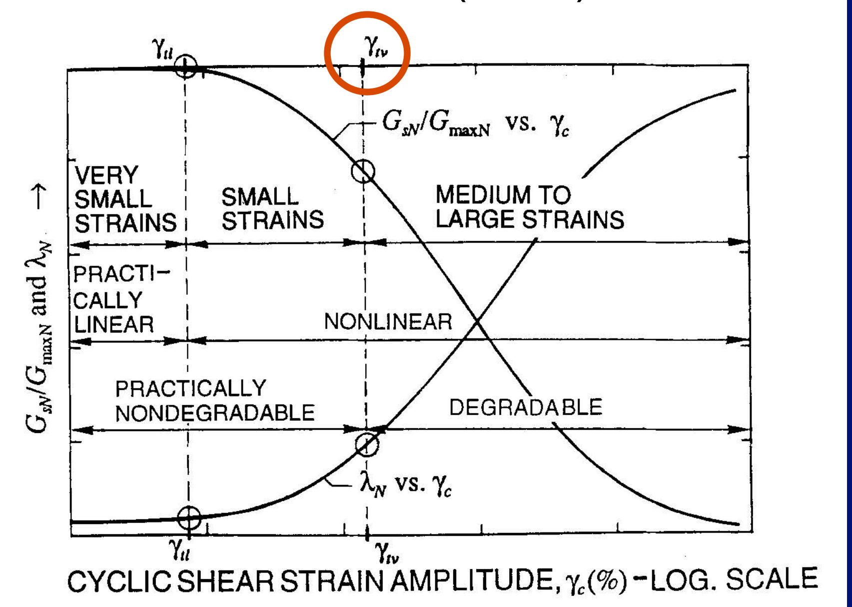
Darendeli (2001)

Volumetric Threshold Strain

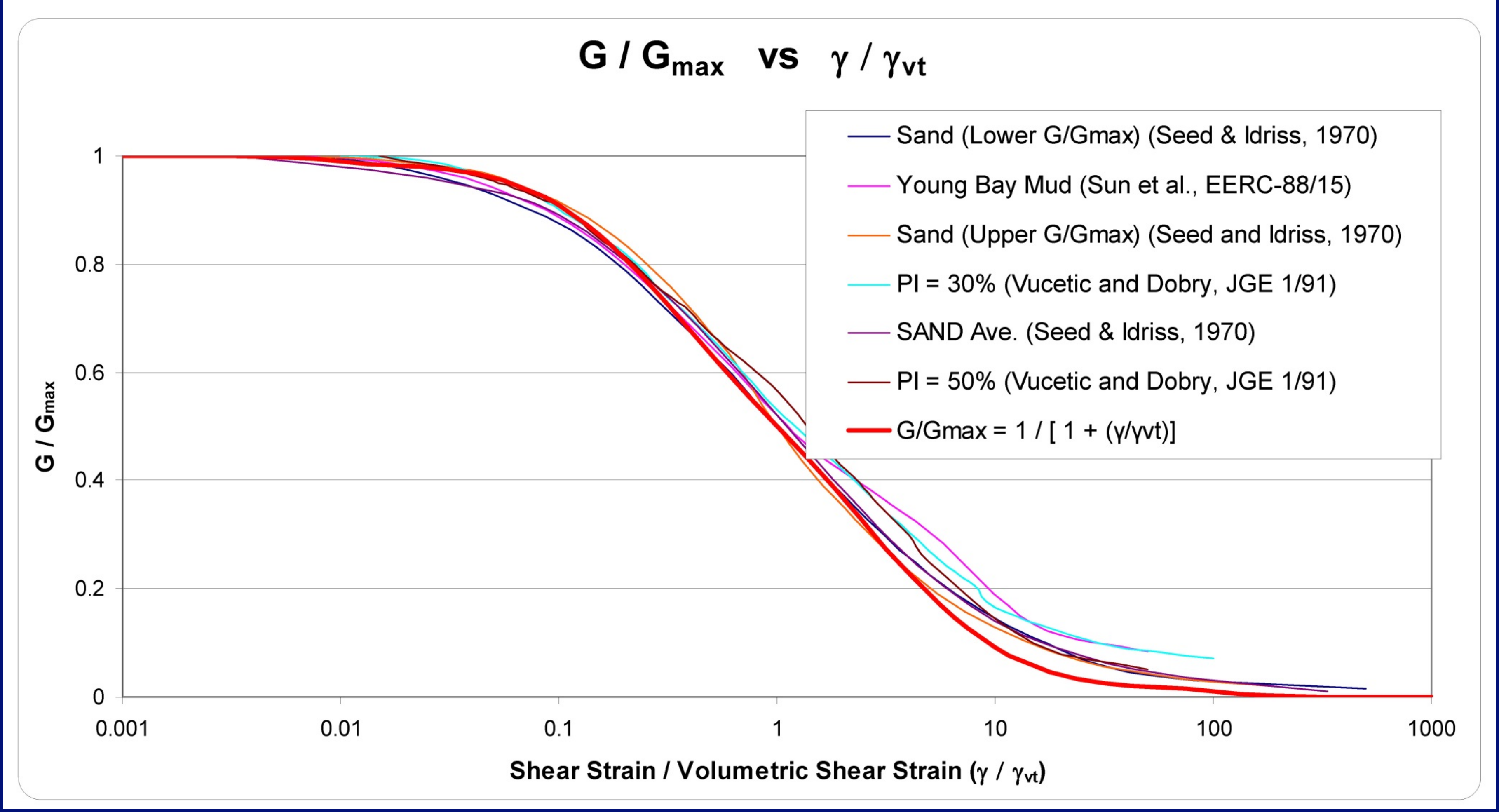




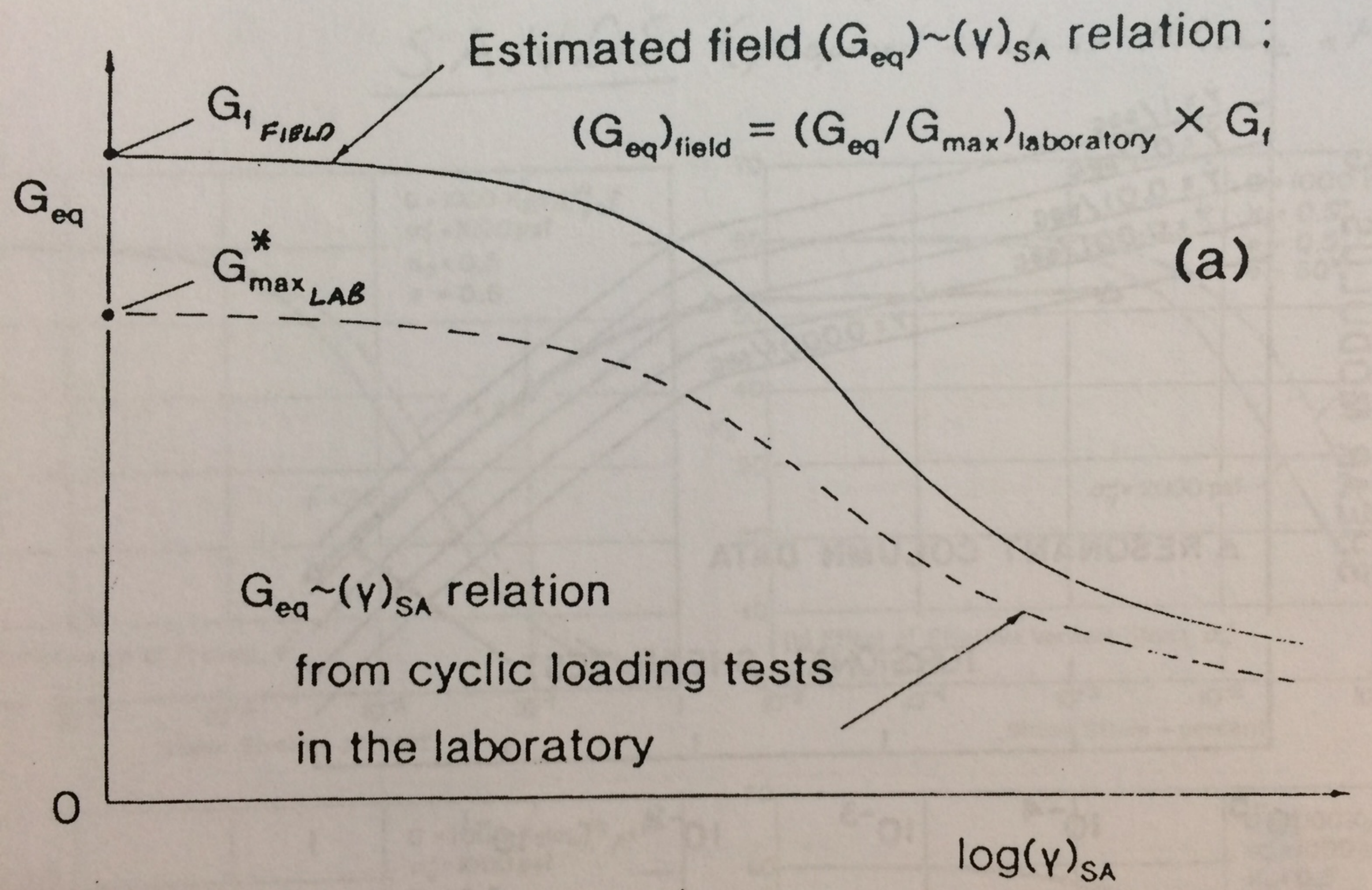
Vucetic (1994)



Normalized Response



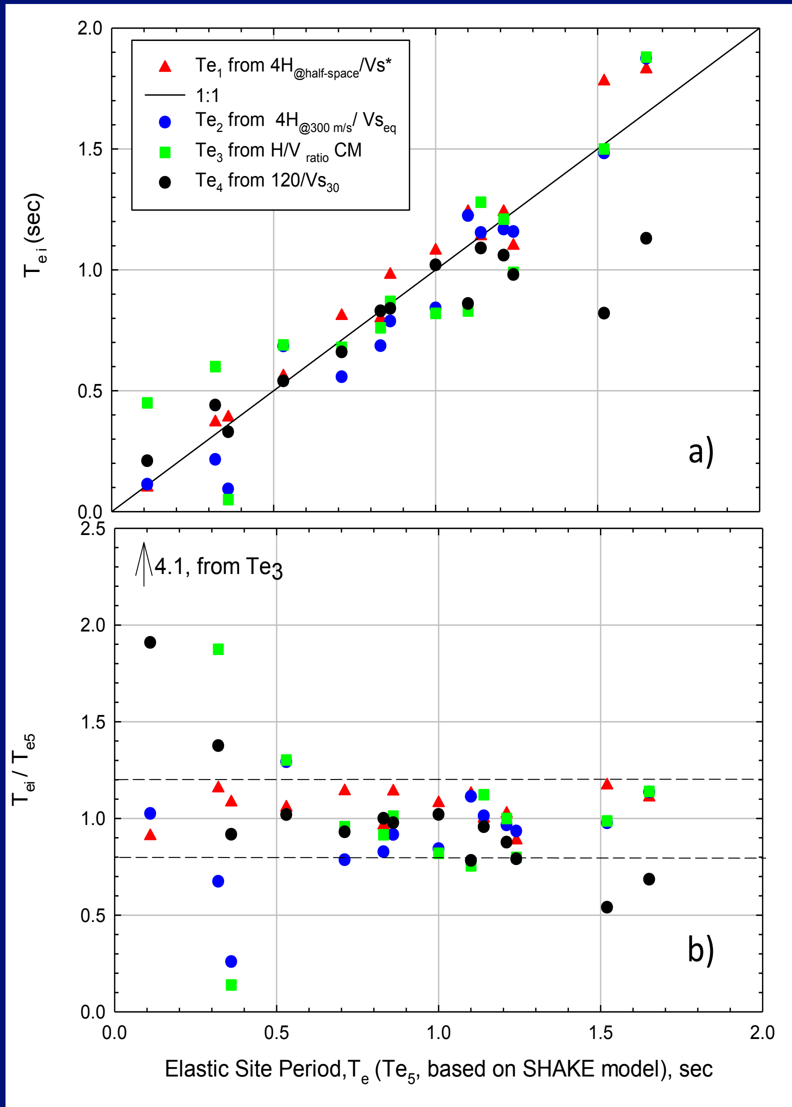
Field Strain-Dependent Shear Modulus Reduction Curve

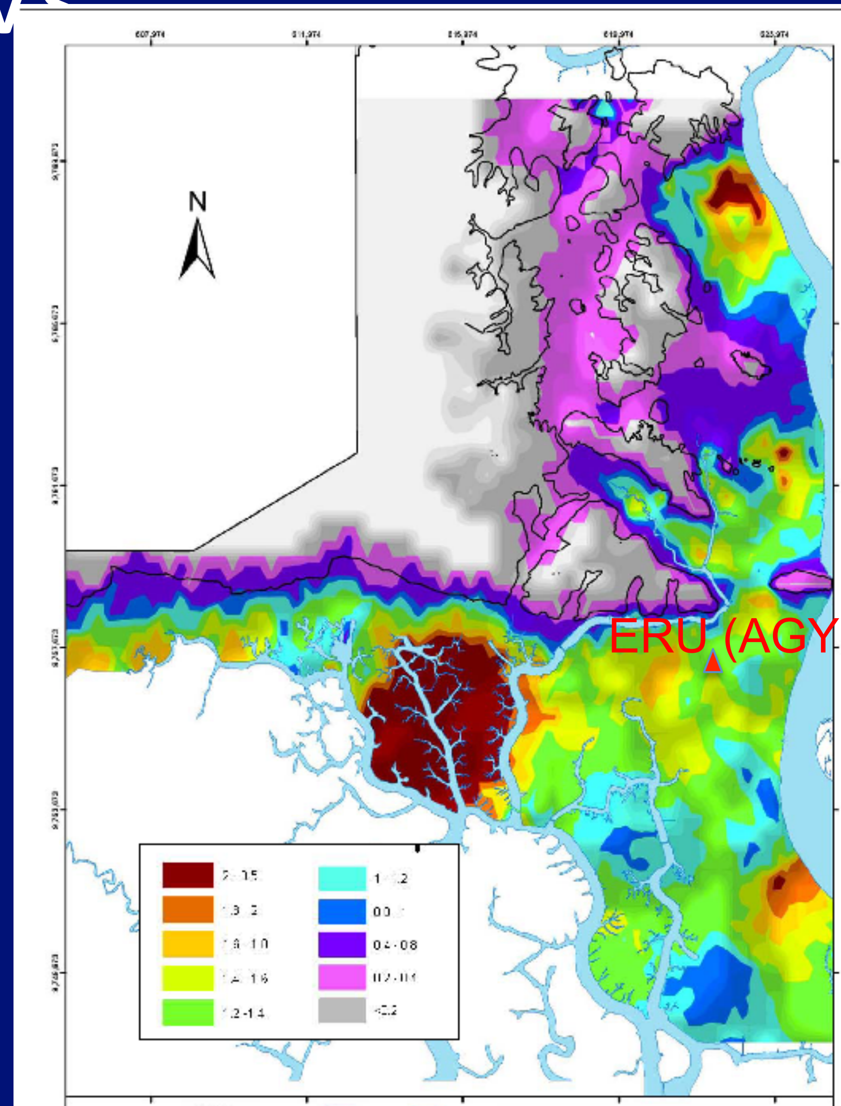


(after Tatsuoka et al. 1995)

$Vs^* = (\sum Vsi.Hi)/Htotal$, $Te_1 = 4H_{total}/Vs^*$

Vs

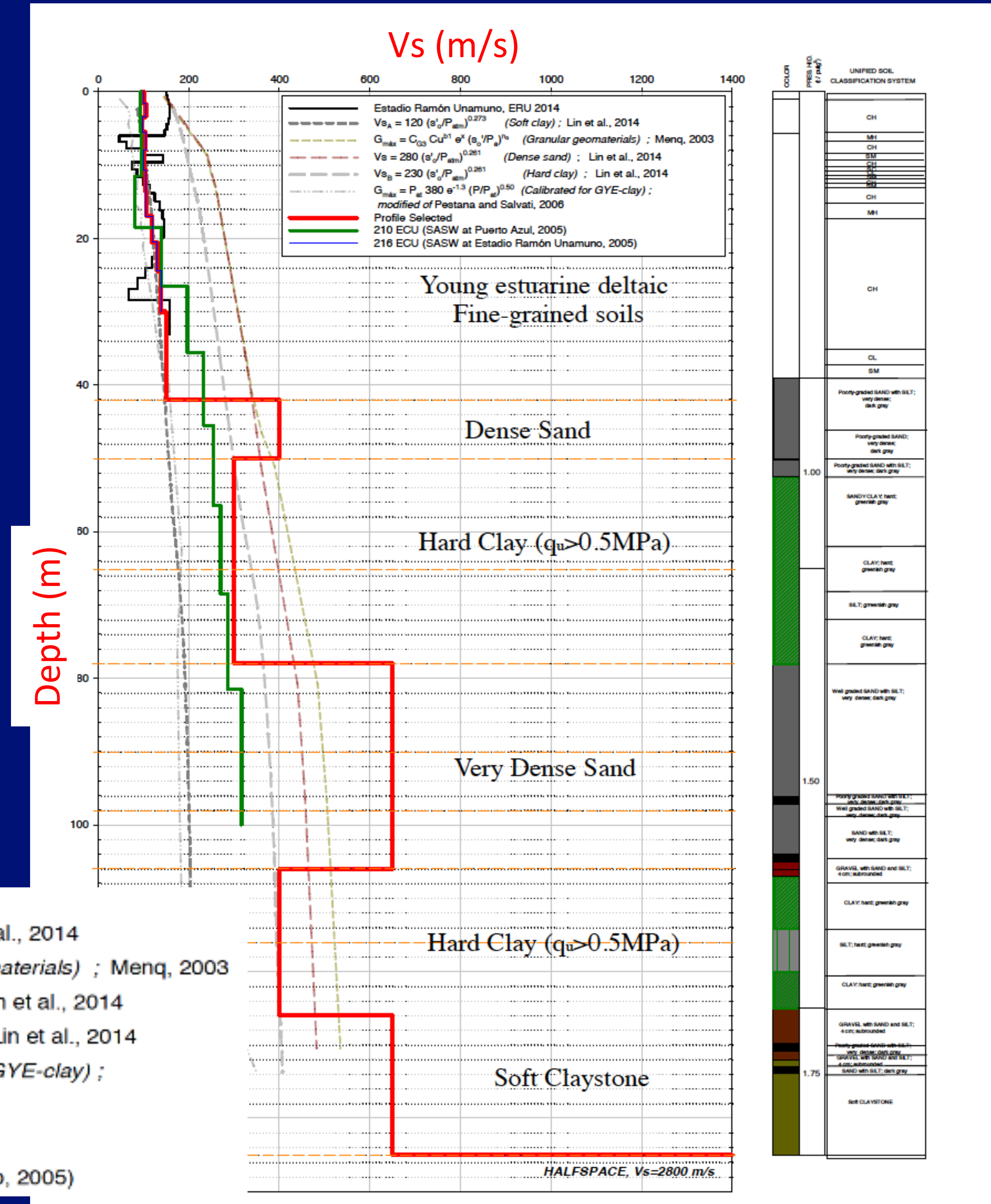


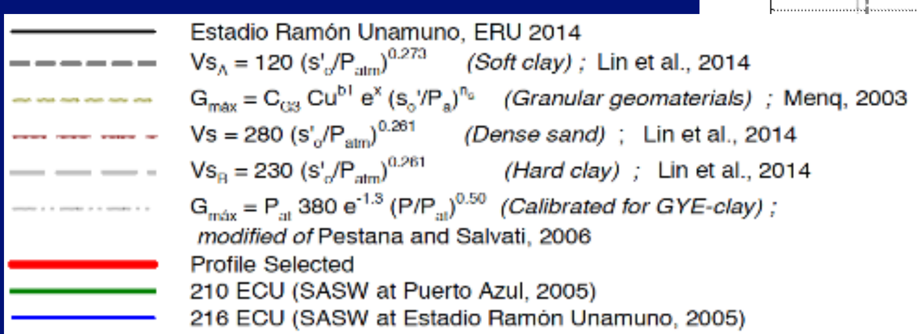


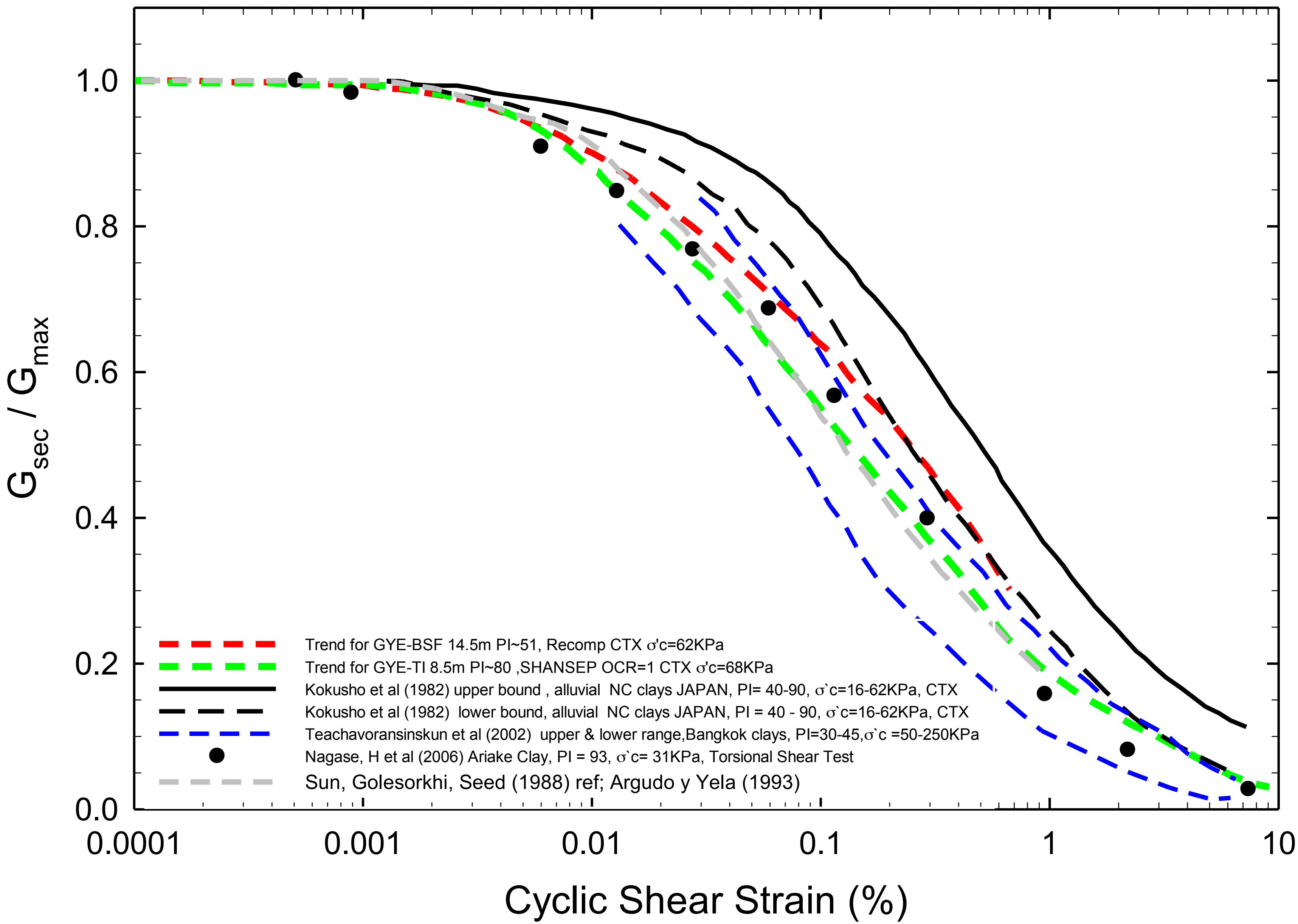
Seismic calibration

Te =1.55s

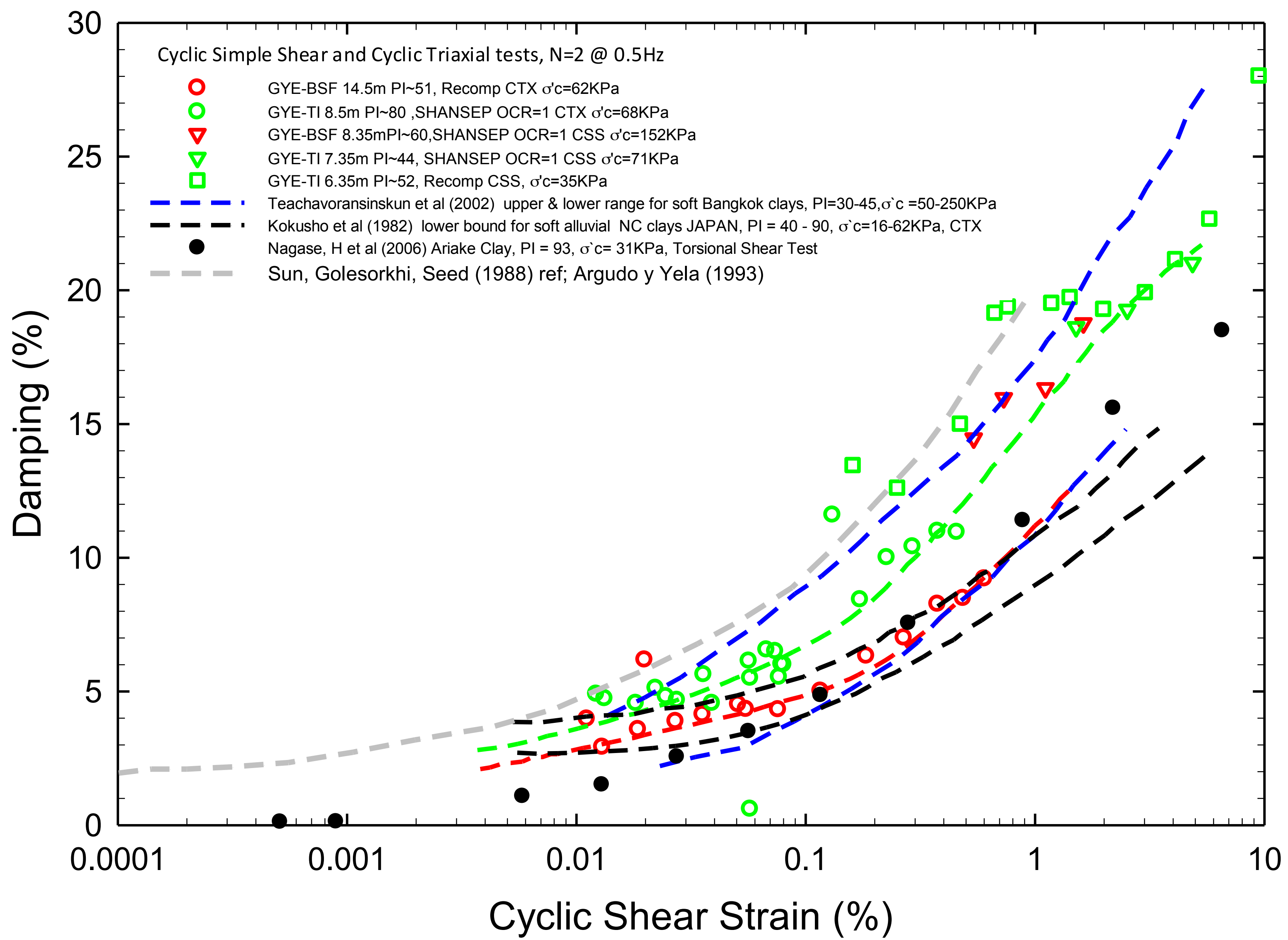
Site ERU





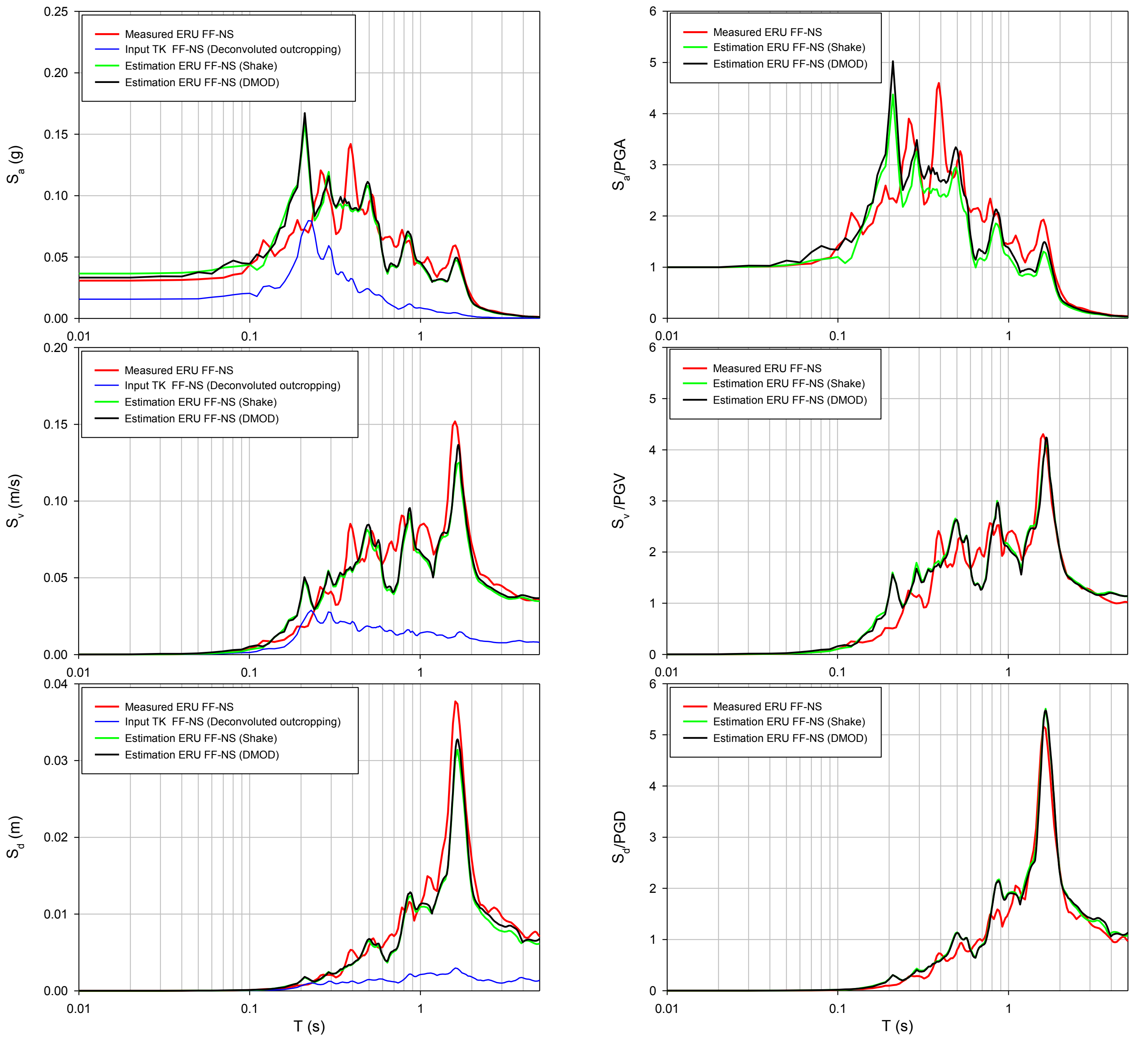


1.0
0.8
0.6
0.4
0.2
0.0
G_{sec} / G_{max}
0.0001
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
Trend for GYE-BSF 14.5m PI~51, Recomp CTX σ'c=62KPa
Trend for GYE-TI 8.5m PI~80 ,SHANSEP OCR=1 CTX σ'c=68KPa
Kokusho et al (1982) upper bound , alluvial NC clays JAPAN, PI= 40-90, σ`c=16-62KPa, CTX
Kokusho et al (1982) lower bound, alluvial NC clays JAPAN, PI = 40 - 90, σ`c=16-62KPa, CTX
Teachavoransinskun et al (2002) upper & lower range,Bangkok clays, PI=30-45,σ`c =50-250KPa
Nagase, H et al (2006) Ariake Clay, PI = 93, σ`c= 31KPa, Torsional Shear Test
Sun, Golesorkhi, Seed (1988) ref; Argudo y Yela (1993)

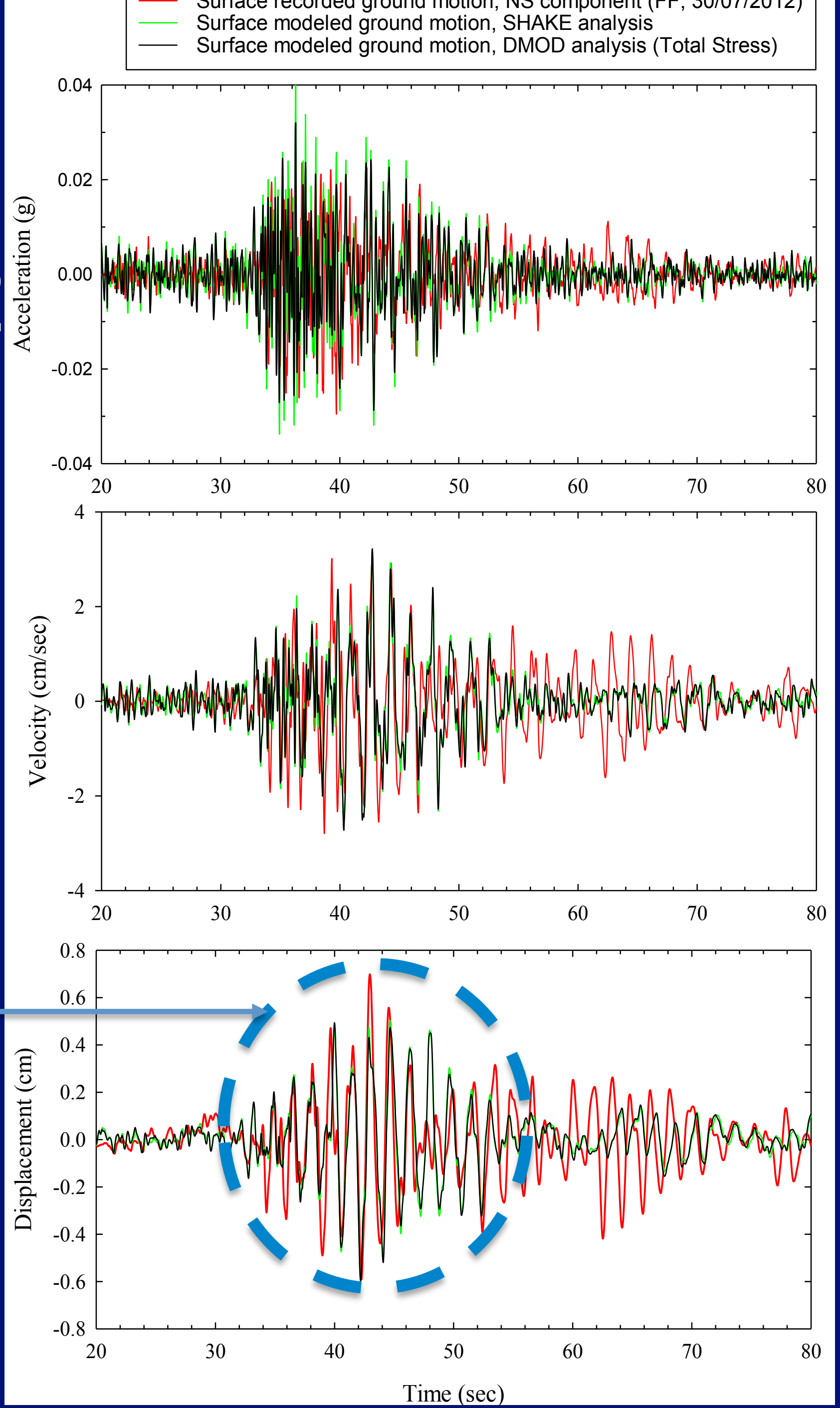

Cyclic Simple Shear and Cyclic Triaxial tests, N=2 @ 0.5Hz
GYE-BSF 14.5m PI~51, Recomp CTX σ'c=62KPa
GYE-TI 8.5m PI~80 ,SHANSEP OCR=1 CTX σ'c=68KPa
GYE-BSF 8.35mPI~60,SHANSEP OCR=1 CSS σ'c=152KPa
GYE-TI 7.35m PI~44, SHANSEP OCR=1 CSS σ'c=71KPa
GYE-TI 6.35m PI~52, Recomp CSS, σ'c=35KPa
Teachavoransinskun et al (2002) upper & lower range for soft Bangkok clays, PI=30-45,σ`c =50-250KPa
Kokusho et al (1982) lower bound for soft alluvial NC clays JAPAN, PI = 40 - 90, σ'c=16-62KPa, CTX
Nagase, H et al (2006) Ariake Clay, PI = 93, σ`c= 31KPa, Torsional Shear Test
Sun, Golesorkhi, Seed (1988) ref; Argudo y Yela (1993)
Damping (%)
0
5
10
15
20
25
30
0.0001
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)

Sismo 30 /7/2012

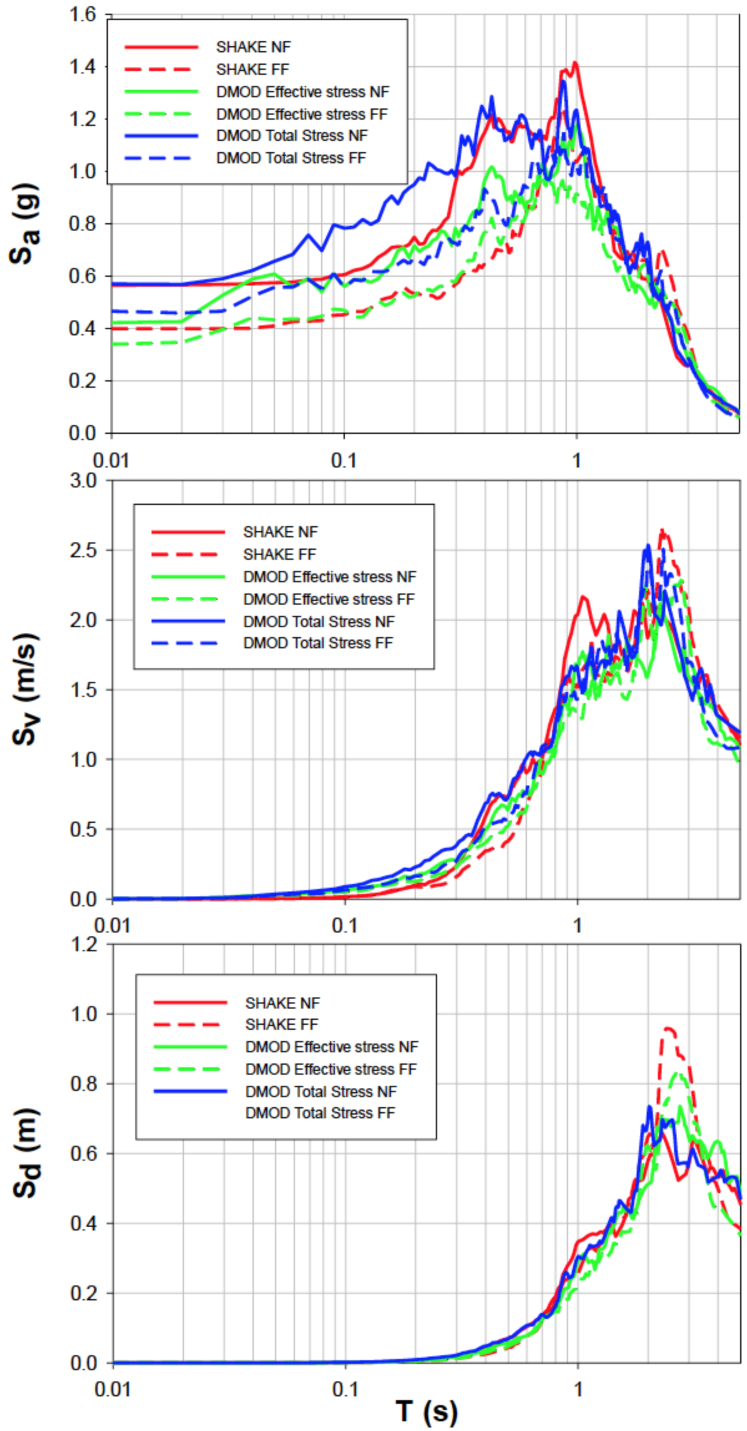
R =101 km
Subduction event
Mw = 5.3



Sismo 30 /7/2012

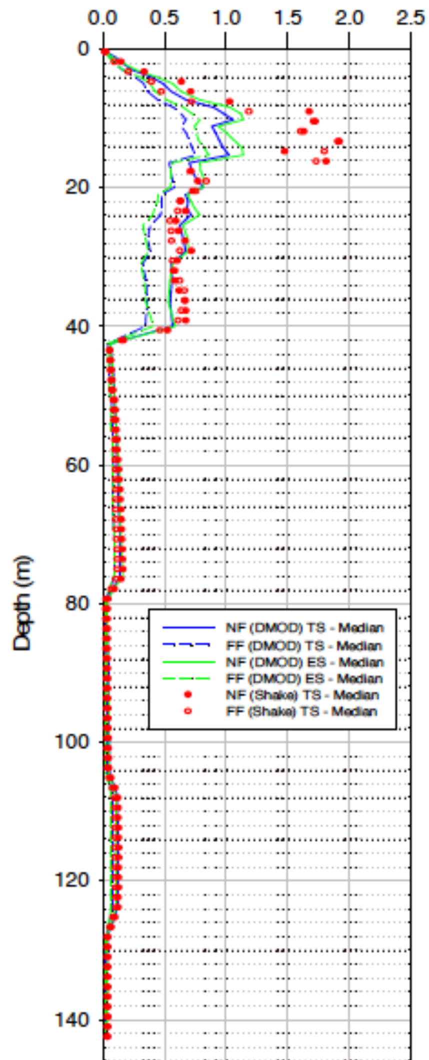


Ondas de corte

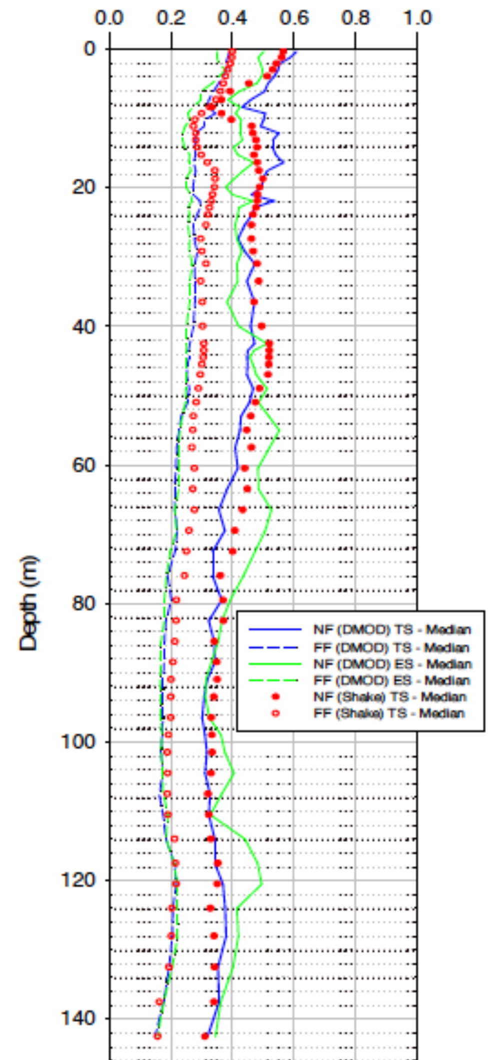


Análisis de sismos de diseño para sitio ERU, Tr = 475 años

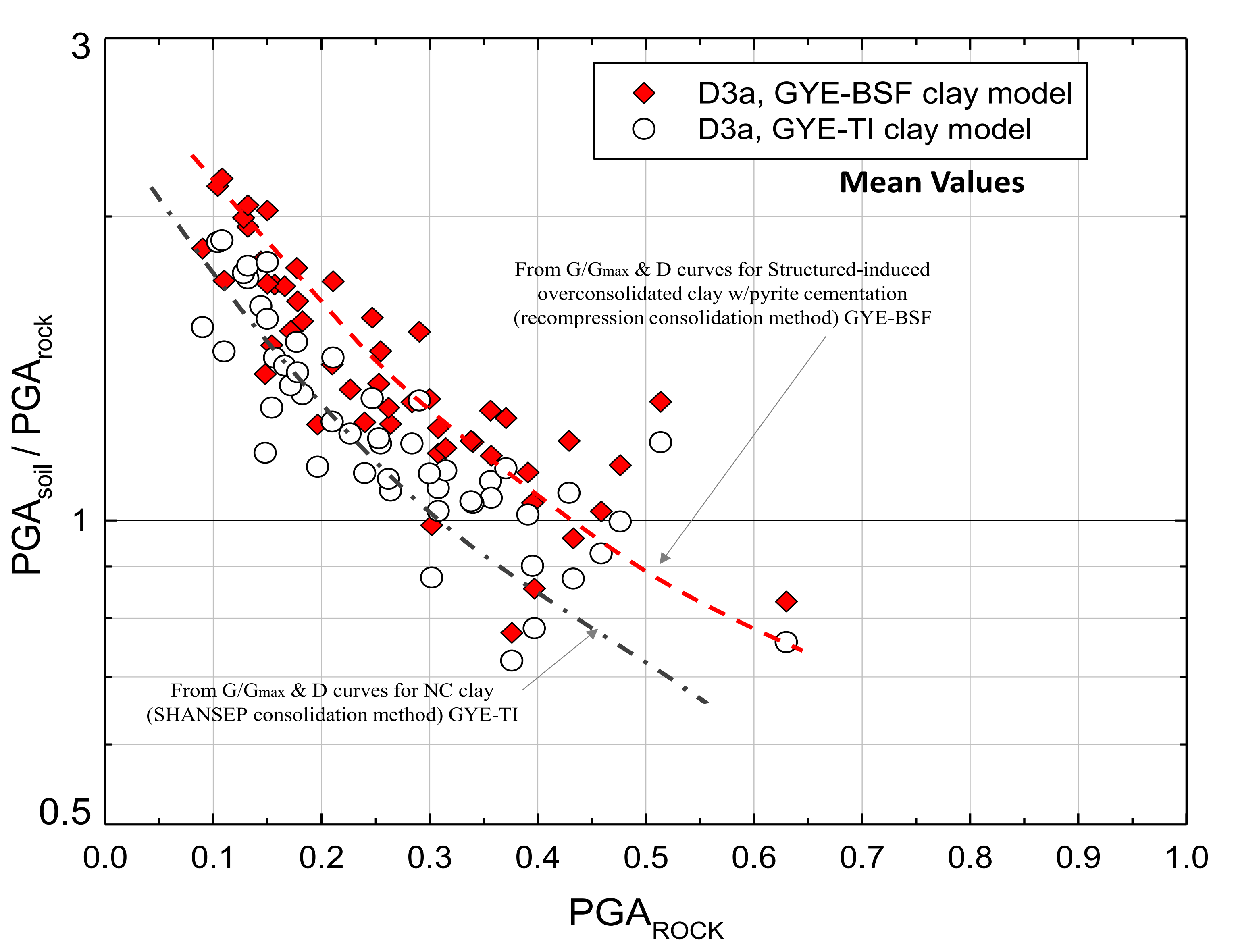
γ_{max} (%)

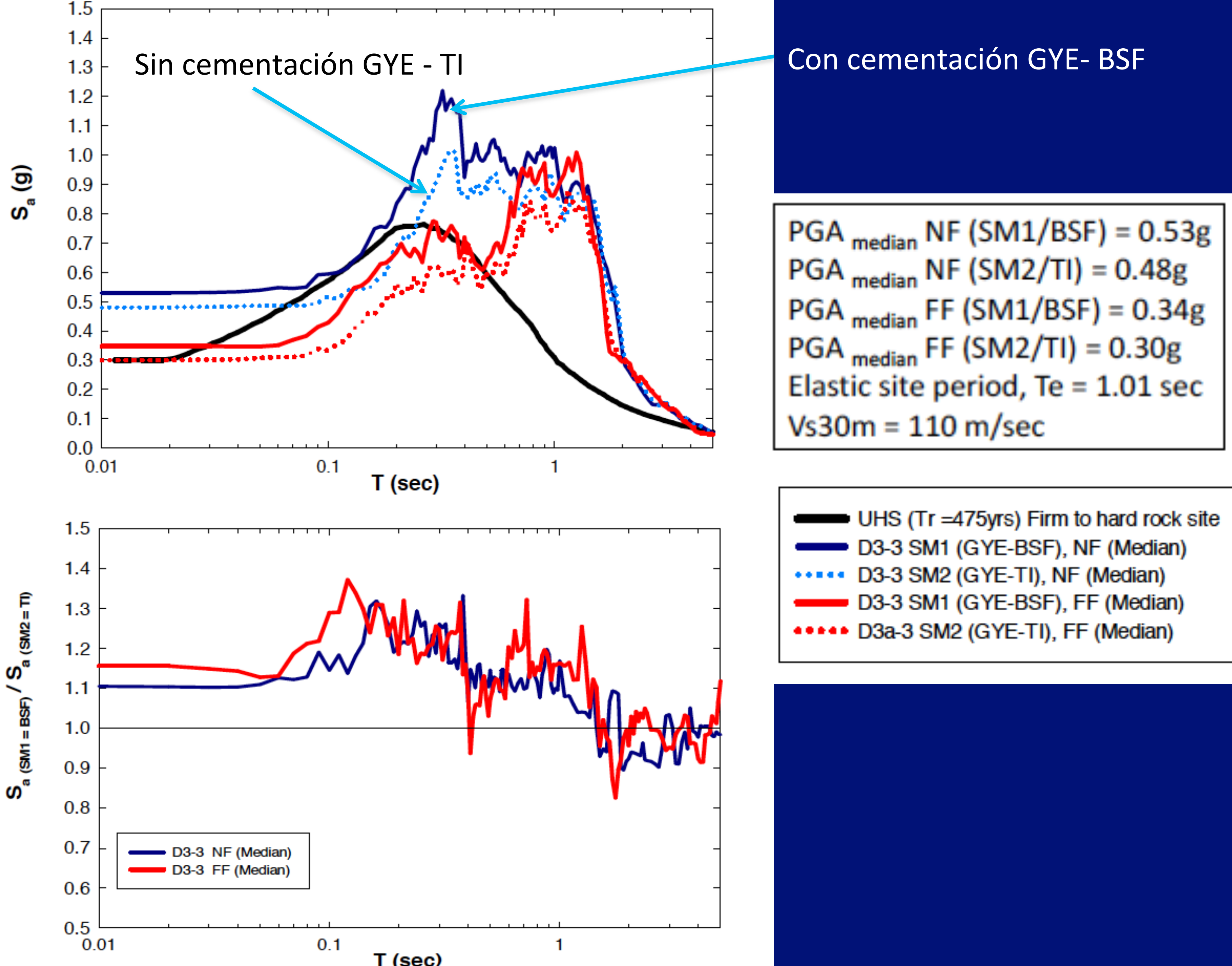


PGA (g)

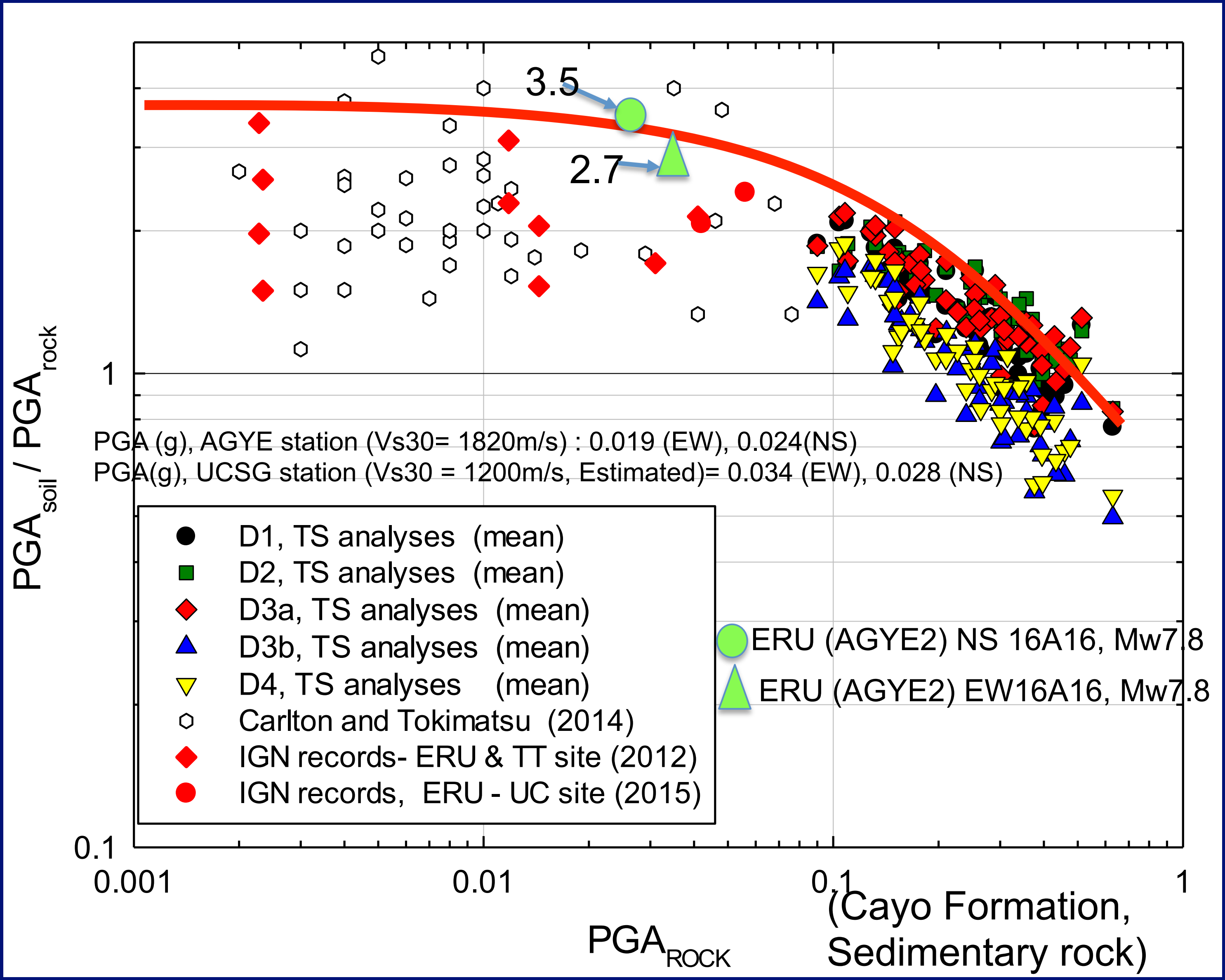


Efecto de cementación de las arcillas GYE





PGA_{median} NF (SM1/BSF) = 0.53g
PGA_{median} NF (SM2/TI) = 0.48g
PGA_{median} FF (SM1/BSF) = 0.34g
PGA_{median} FF (SM2/TI) = 0.30g
Elastic site period, Te = 1.01 sec
Vs30m = 110 m/sec

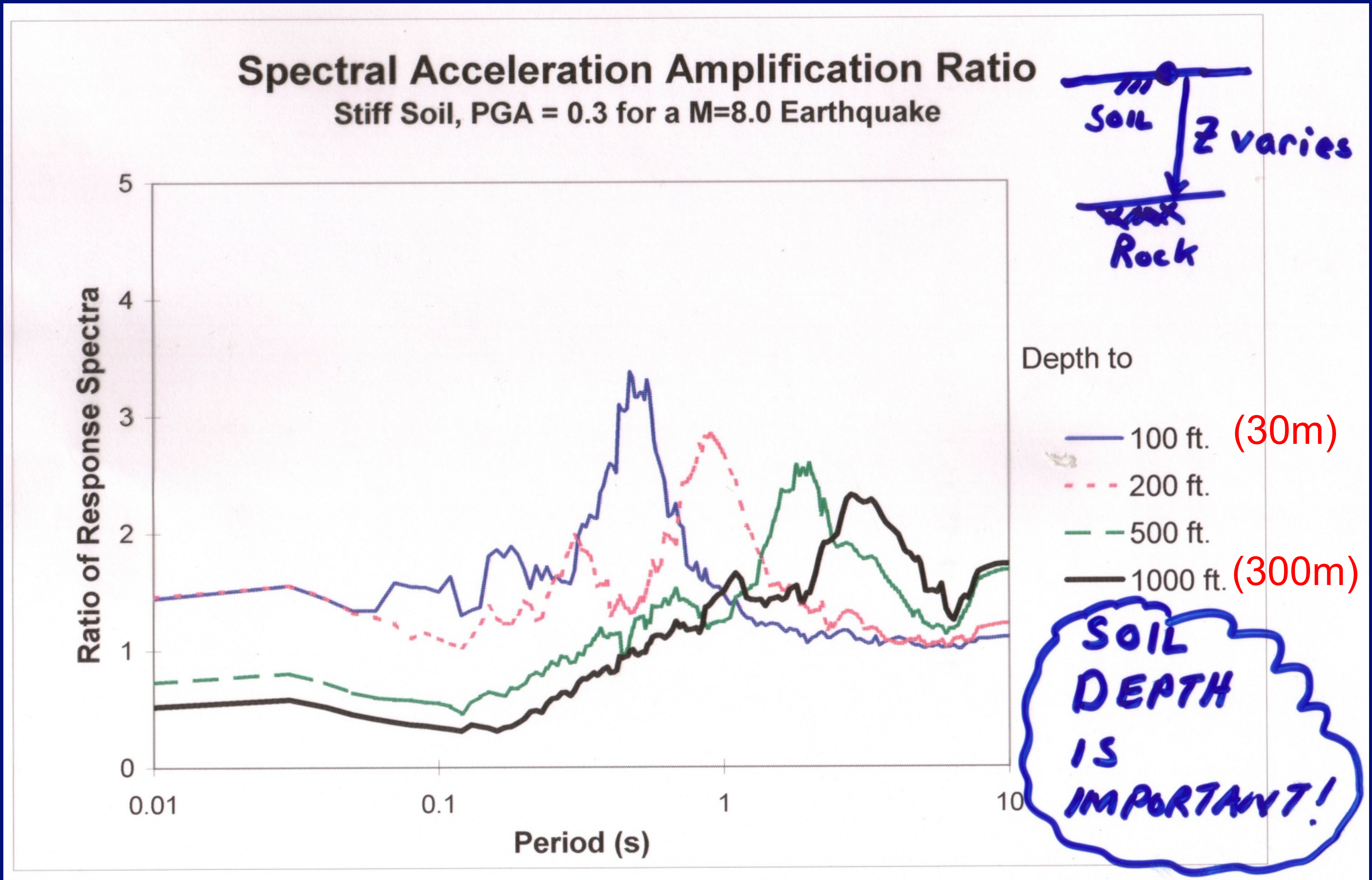


3.5
2.7
PGA (g), AGYE station (Vs30= 1820m/s) : 0.019 (EW), 0.024(NS)
PGA(g), UCSG station (Vs30 = 1200m/s, Estimated)= 0.034 (EW), 0.028 (NS)
D1, TS analyses (mean)
D2, TS analyses (mean)
D3a, TS analyses (mean)
D3b, TS analyses (mean)
D4, TS analyses (mean)
Carlton and Tokimatsu (2014)
IGN records- ERU & TT site (2012)
IGN records, ERU - UC site (2015)
ERU (AGYE2) NS 16A16, Mw7.8
ERU (AGYE2) EW16A16, Mw7.8
1
0.1
0.001
0.01
0.1
1
PGA_{soil} / PGA_{rock}
PGA_{ROCK}
(Cayo Formation, Sedimentary rock)

SITE EFFCTS

Effects of Depth to Bedrock

(Bray, 2017)



(30m)

(300m)

SITE EFFCTS

Effects of Soft Soil

(Bray, 2017)