IV

MTiG International Workshop

IMPORTANCE OF DYNAMIC SOIL-STRUCTURE INTERACTION IN THE SEISMIC PERFORMANCE ANALYSIS OF BUILDINGS FOUNDED ON PILES

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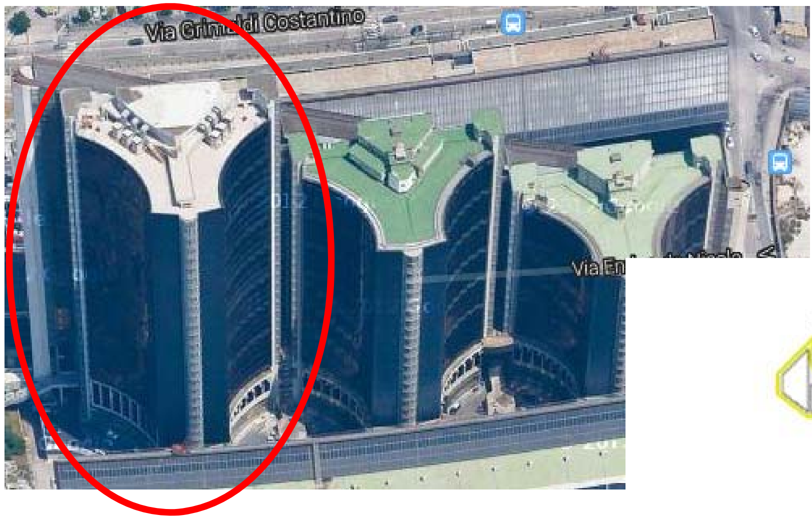
LAYOUT OF PRESENTATION

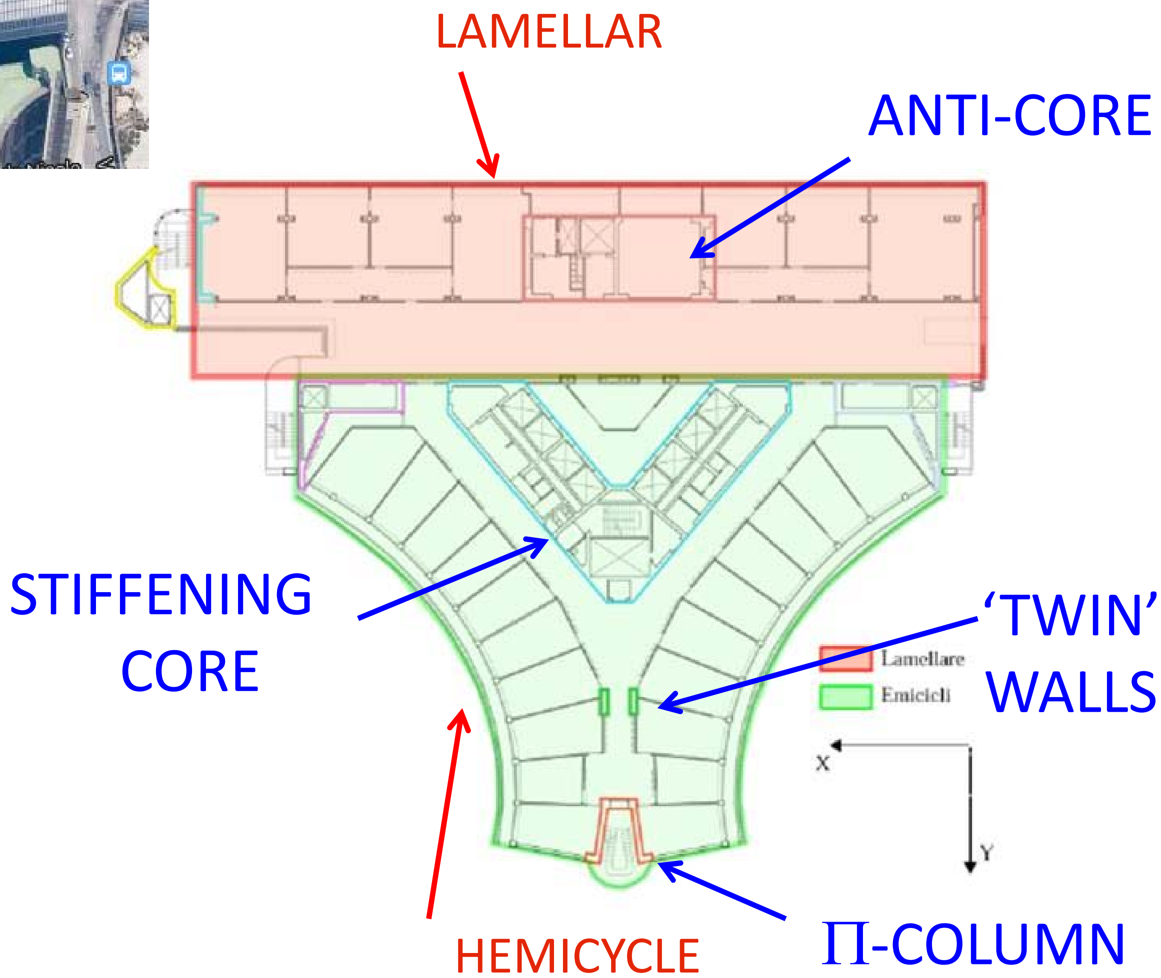
1. Site-effects often evaluated according to Standard Classification;
2. Pile-soil kinematic interaction: Change of the FREE-FIELD MOTION;
3. Inertial interaction Analsyis: FIXED BASE vs. COMPLIANCE BASE MODELS;

   How much is the overall effect of the above geotechnical aspects on the seismic response of a building founded on piles?

4. Case study THE NEW LAW COURT BUILDING IN NAPOLI.

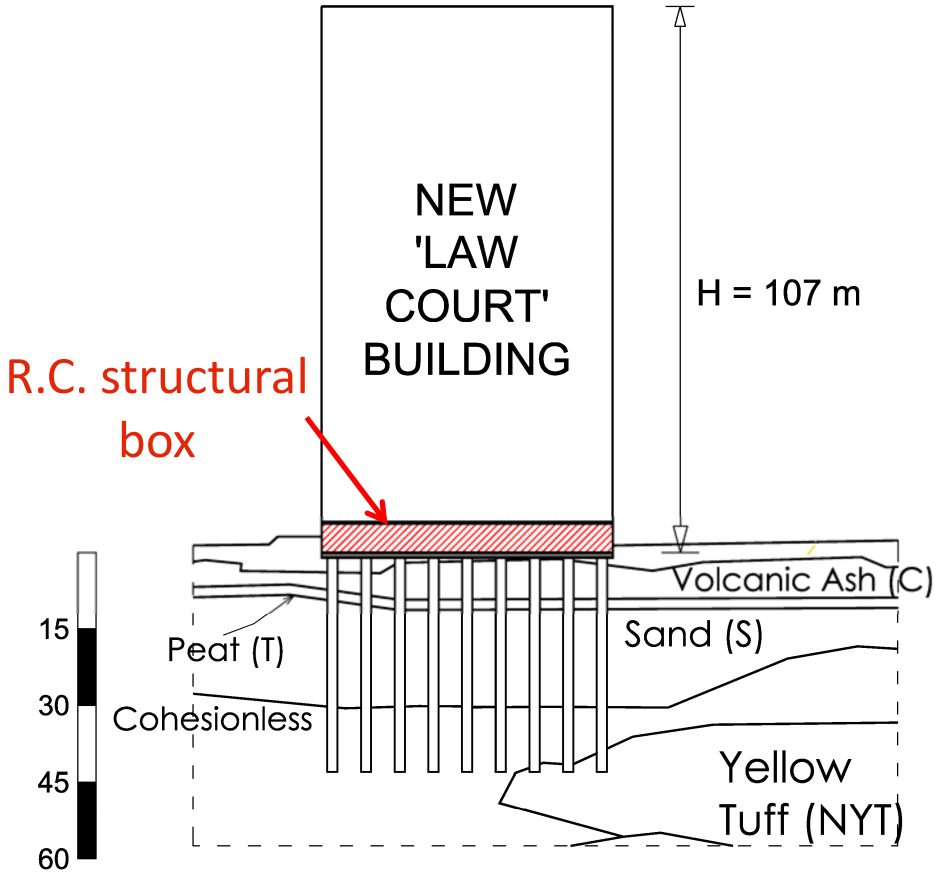
Case Study: THE NEW 'LAW COURT' BUILDING IN NAPOLI

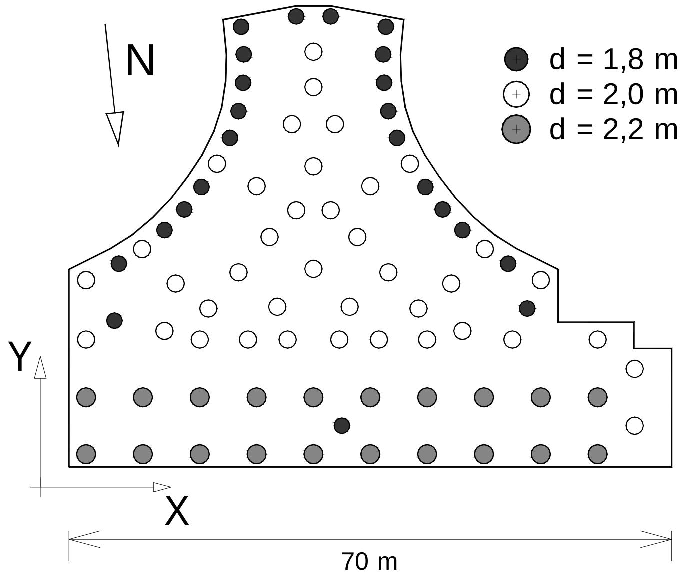




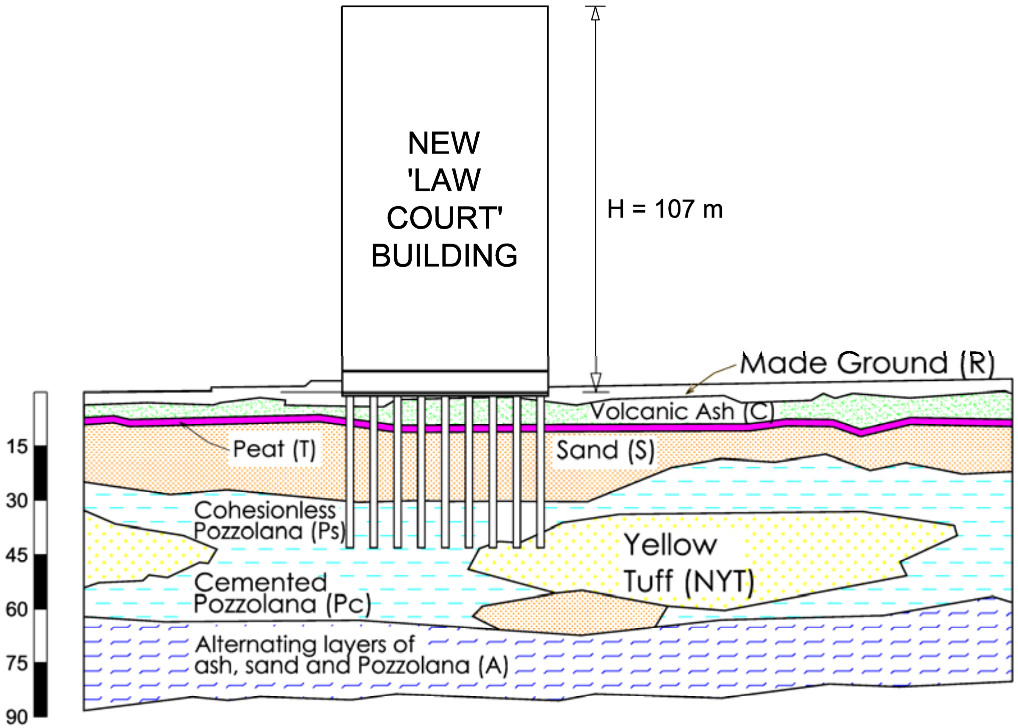
PILED FOUNDATION

1. 82 piles unevenly distributed over an area of 3300 m^2
2. Large diameter bored piles, 42 m long
3. L < B; B > 15m → 'Large' piled raft (Russo & Viggiani 1998)

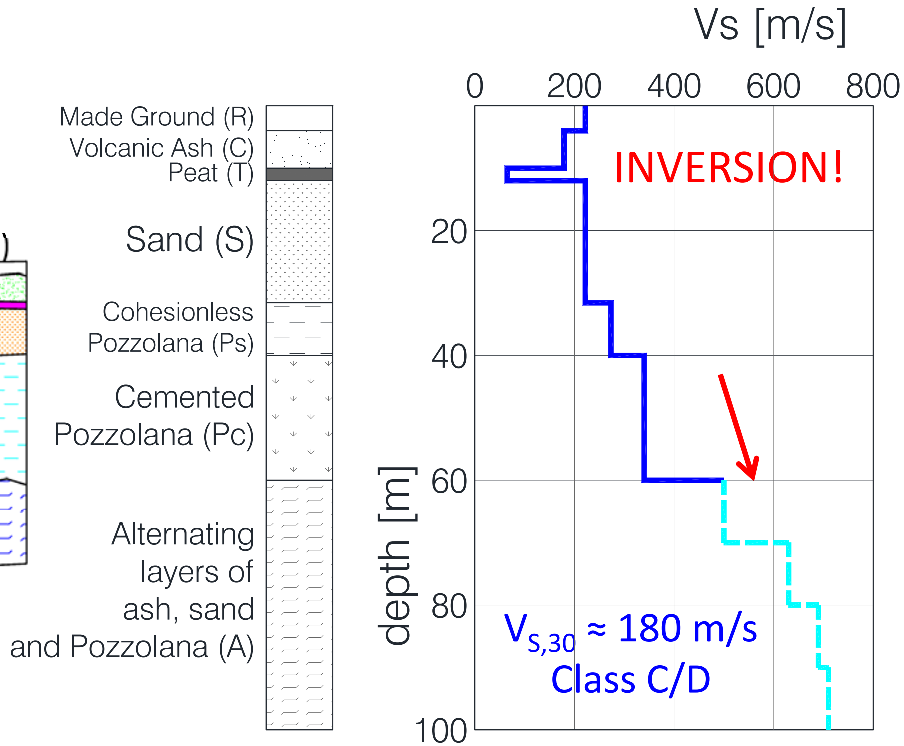




SUBSOIL AND DESIGN CONDITIONS AT THE BUILDING SITE



Shear wave velocity profile
from Cross-Hole and Down-Hole tests
(VINALE, 1988)



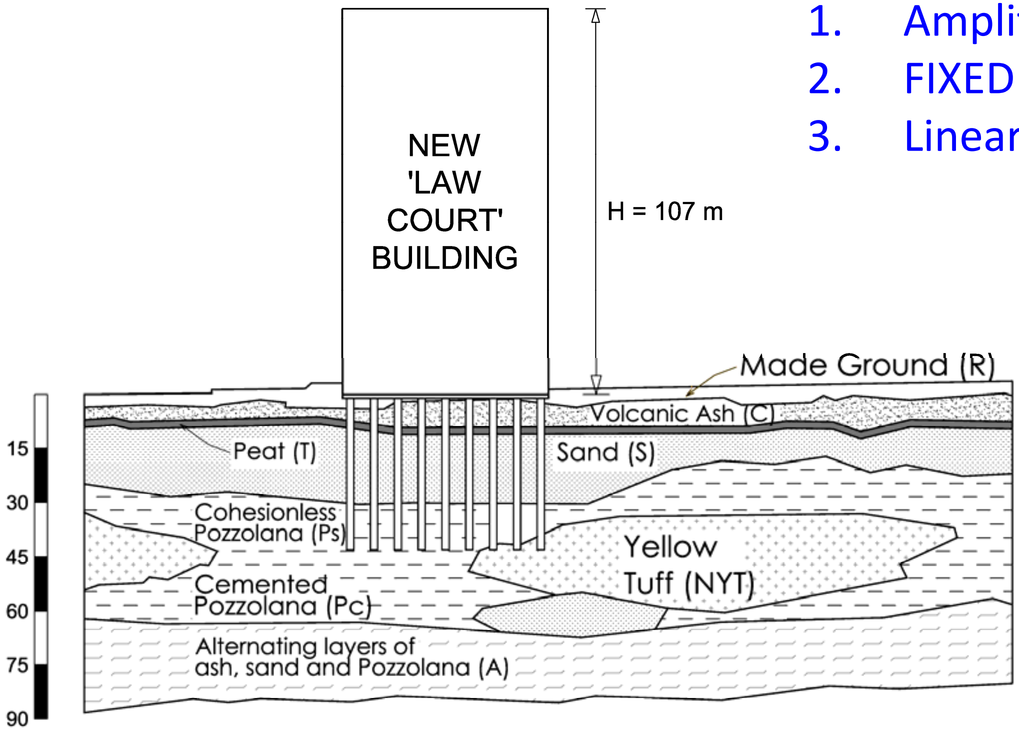
Life-Safety Limit State (SLV)

$V_R = C_u \cdot V_N = 1.5 \cdot 50 = 75$ years

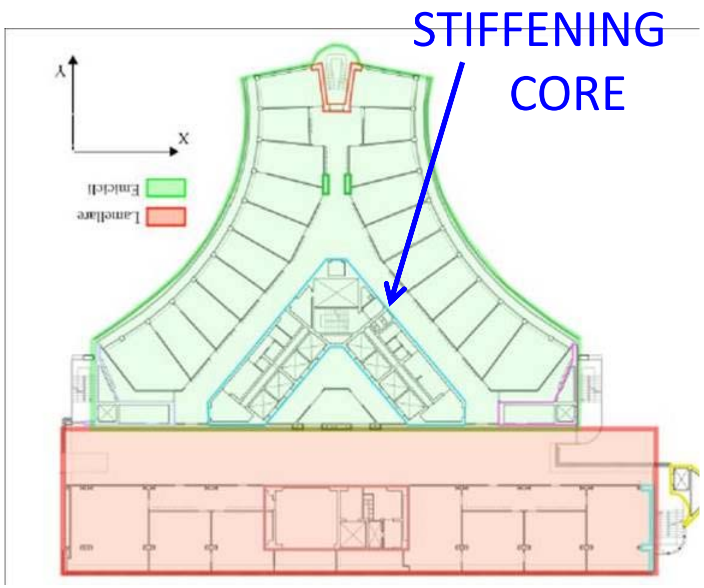
PGA = 0.19 g

T_R = 712 years

SEISMIC PERFORMANCE ACCORDING TO THE CONVENTIONAL APPROACH



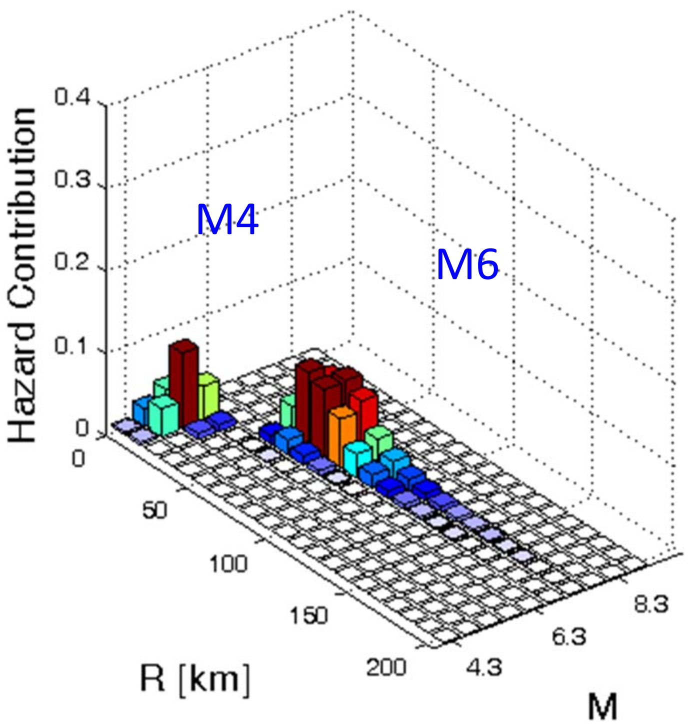
1. Amplification effects based on $V_{s,30}$;
2. FIXED BASE model;
3. Linear pseudo-static FE analysis.



The conventional approach would have led to very expensive measures for seismic retrofitting (Bilotta A. et al., 2013)

INPUT MOTIONS FOR SEISMIC SITE RESPONSE (SSR)

Disaggregation of seismic hazard in terms of PGA

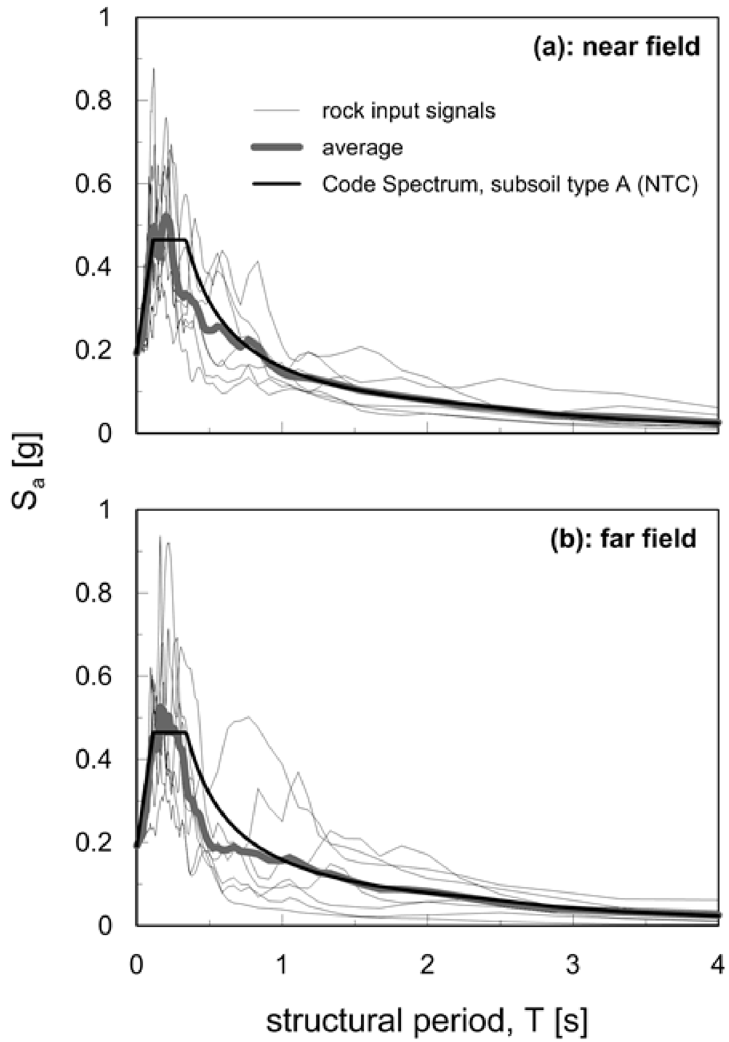


$V_R = C_u \cdot V_N = 1.5 \cdot 50 = 75$ years

PGA = 0.19 g

T_R = 712 years

Selection of acceleration time histories

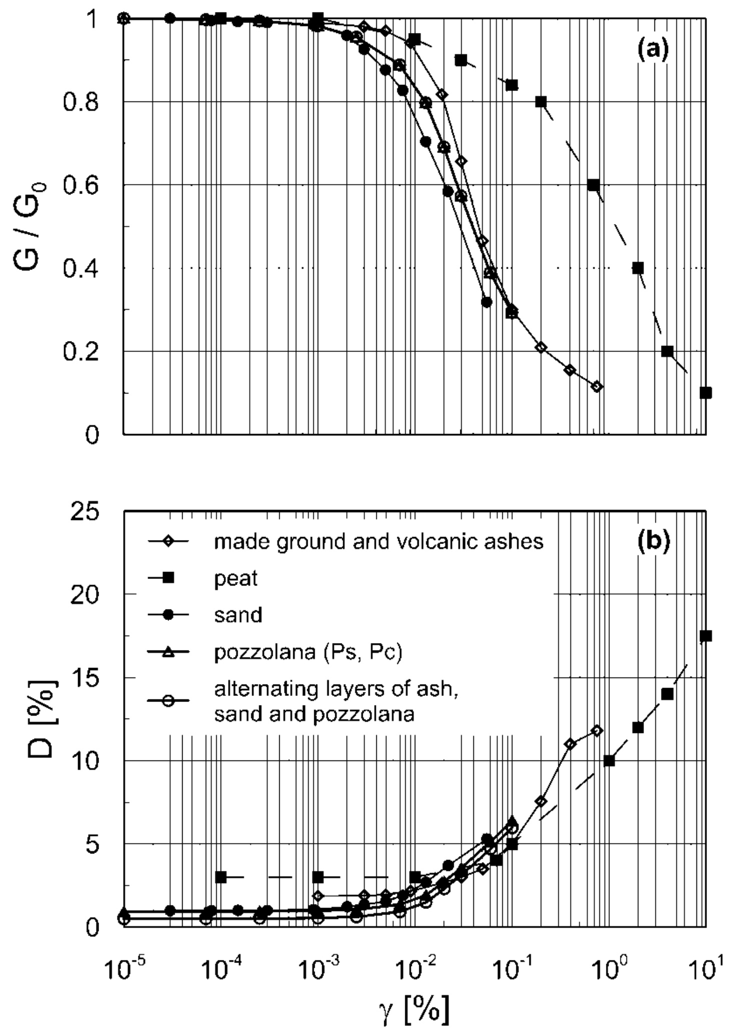


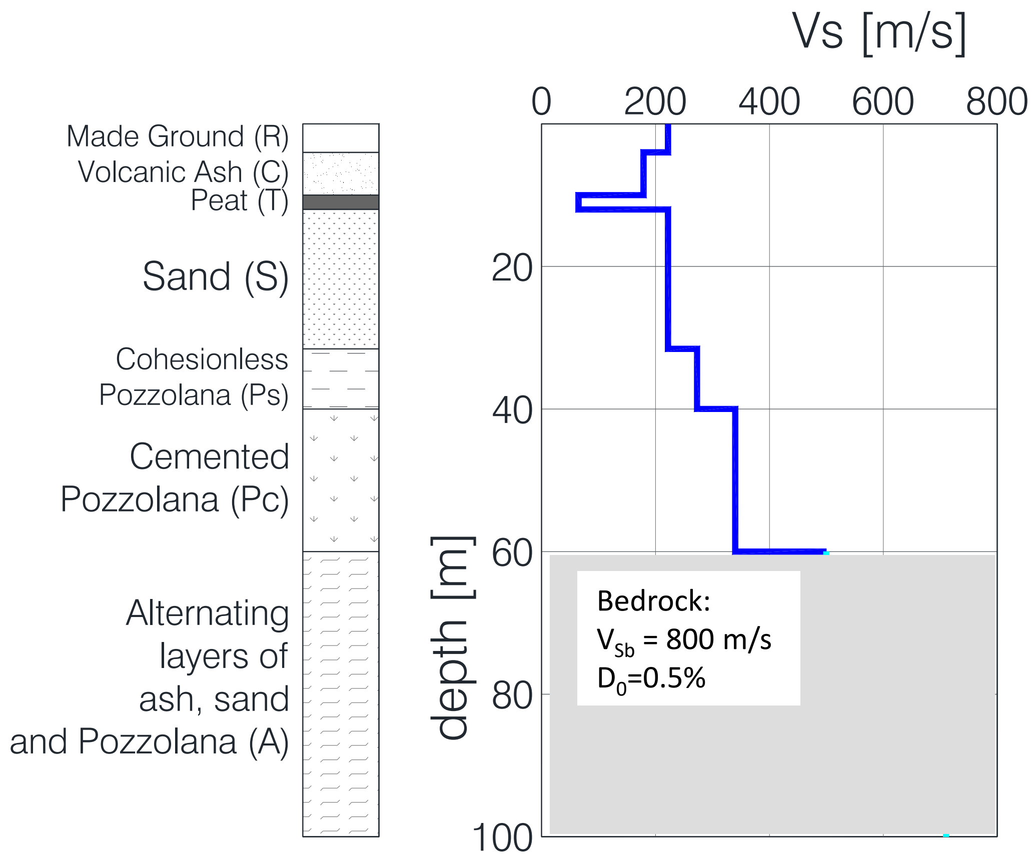
M4 Group
(NEAR FIELD)
4.3 < M < 6.0
0 < R < 20 km

M6 Group
(FAR FIELD)
6.3 < M < 7.3
40 < R < 80 km

ESD
Rexel 3.5
(Iervolino et al. 2009)

SUBSOIL MODEL FOR LINEAR EQUIVALENT SSR ANALYSES



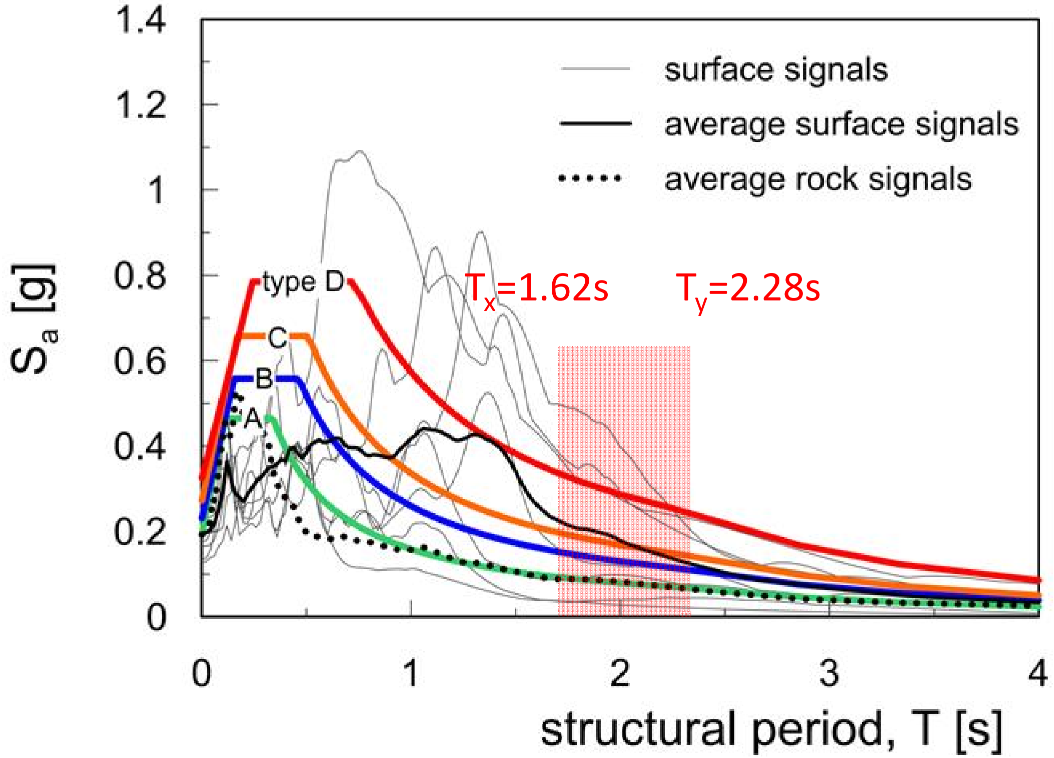


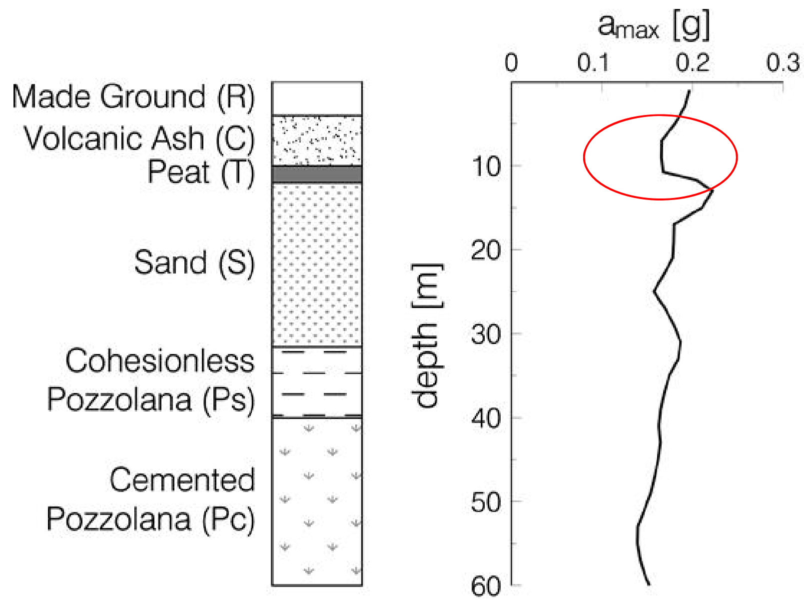
POZZOLANA: Resonant Column test (Vinale, 1988)
PEAT: two extreme behaviours (PEAT 1 and PEAT 2)
(literature curves after Wehling et al., 2003)

RESULTS OF SSR ANALYSES: ACCELERATIONS

Spectral accelerations

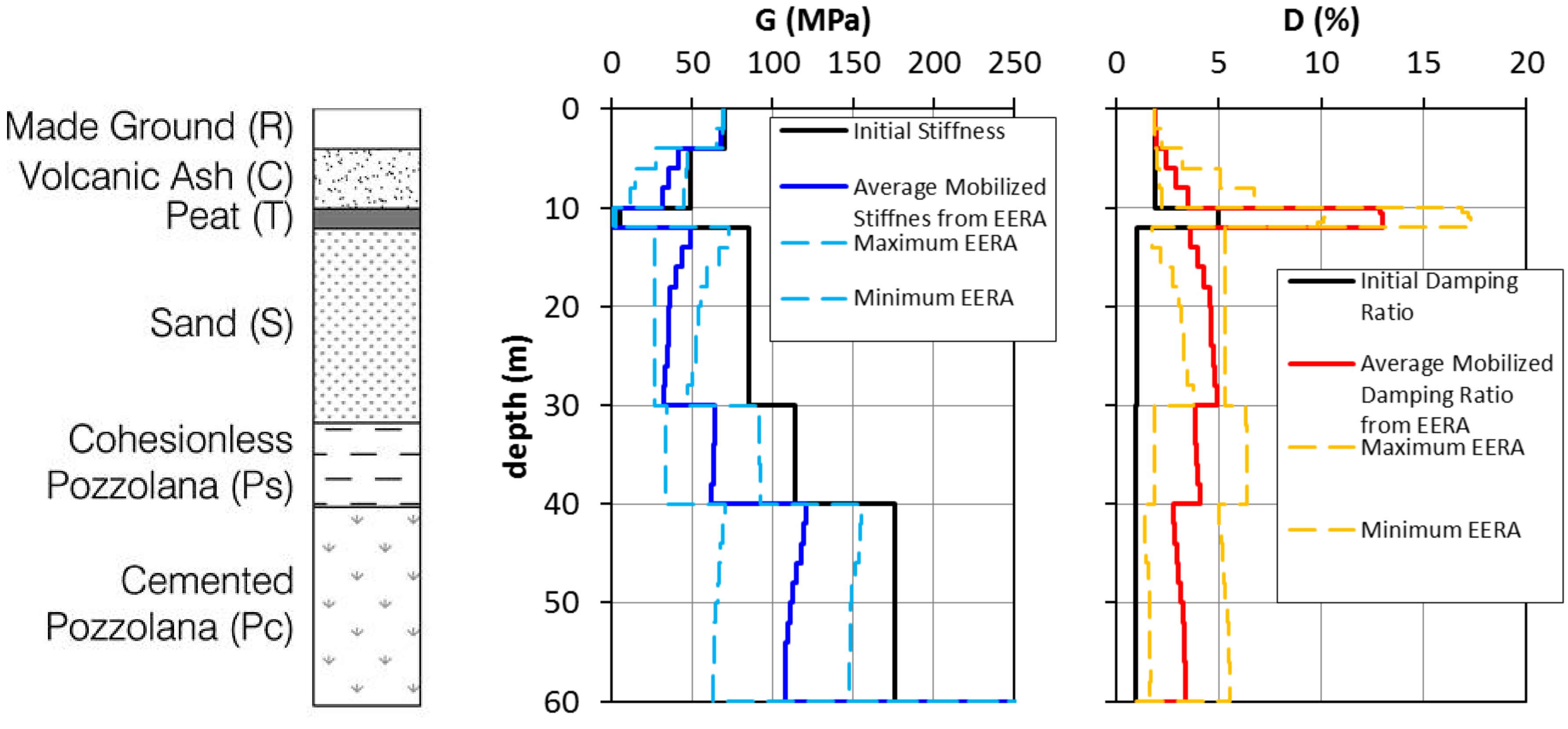
Profile of a_{max}





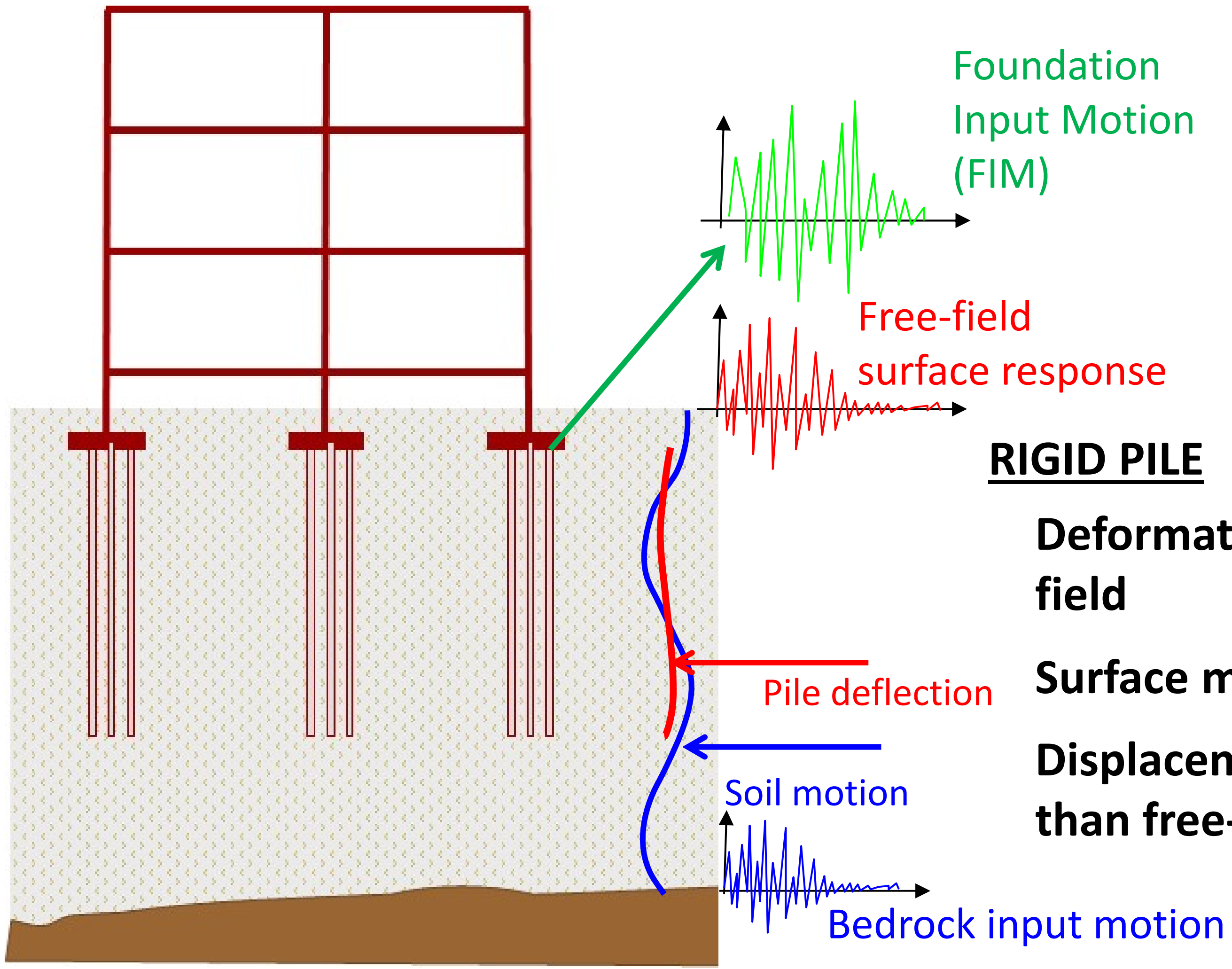
Peat layer acting as a 'natural damper'

RESULTS OF SSR ANALYSES: MOBILIZED STIFFNESS AND DAMPING RATIO



Average profiles used for subsequent interaction analyses (Kausel et al., 1978)

PILE SOIL KINEMATIC INTERACTION



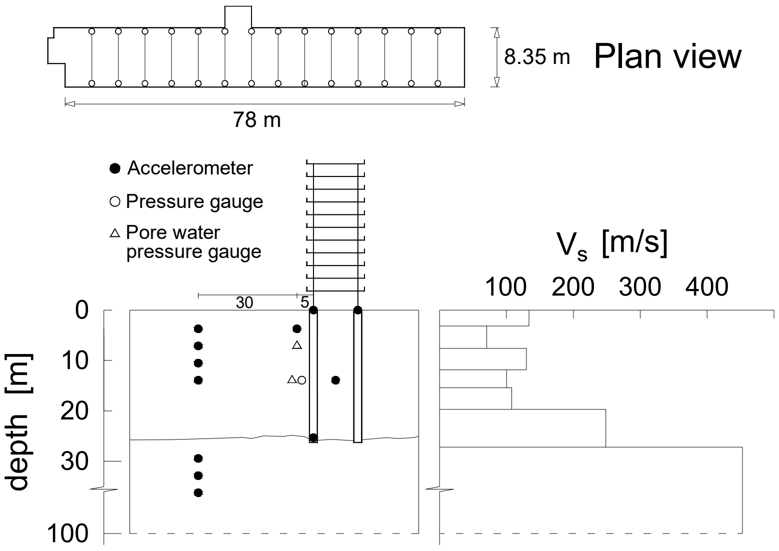
<u>RIGID PILE</u>

Deformation different than free-field

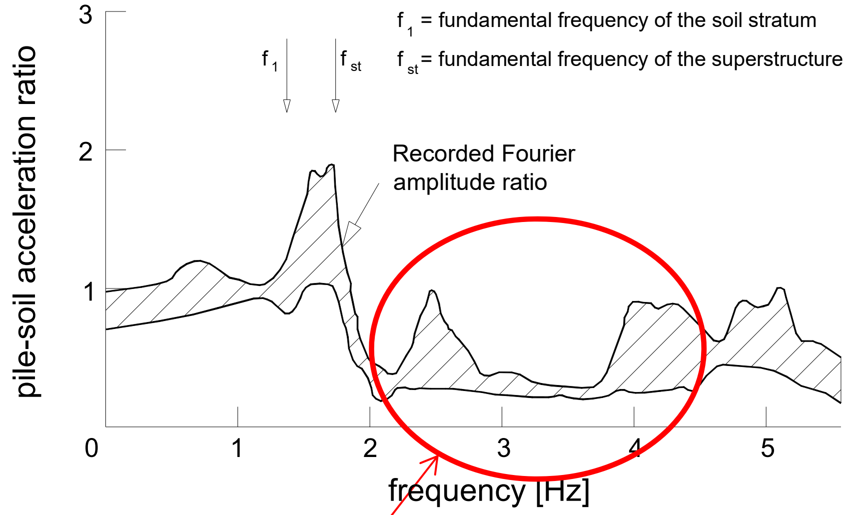
Surface motion ≠ free-field motion

Displacements at pile head other than free-filed and <u>rotations</u>

FILTERING EFFECT – EXPERIMENTAL EVIDENCE



(a)



(b)

HIGH FREQUENCIES, a_P/a_S is less than 1

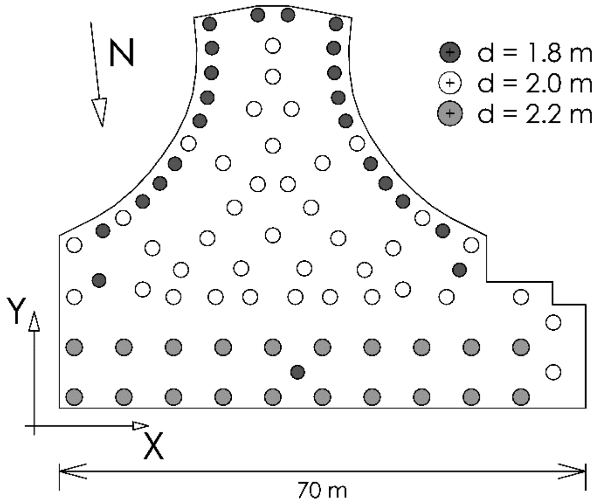
CASE HISTORY

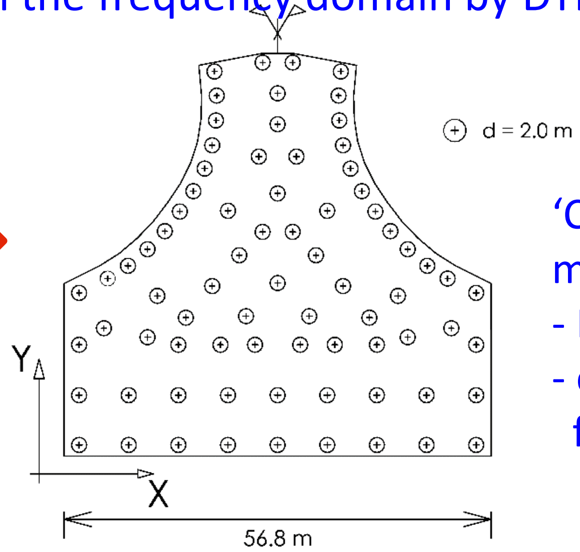
Otha et al., 1980

Gazetas, 1984

KINEMATIC SSI: FOUNDATION INPUT MOTION

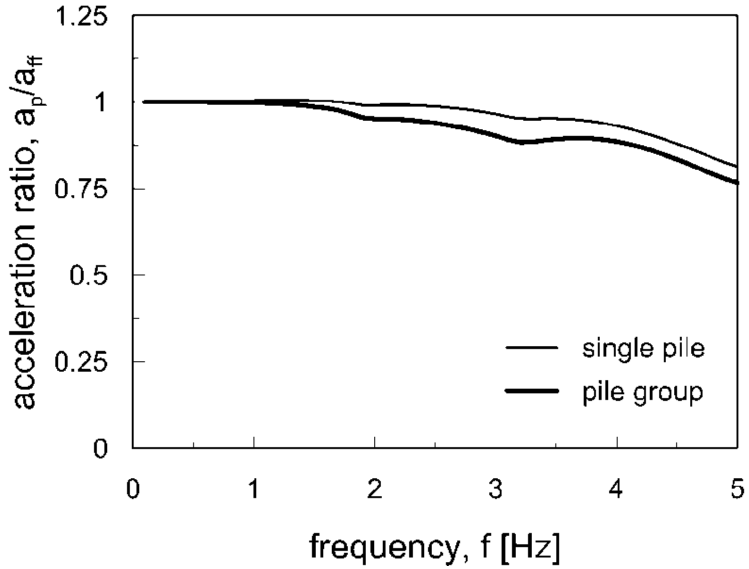
3D dynamic analyses in the frequency domain by DYNAPILE 2.0 (Ensoft 1999)

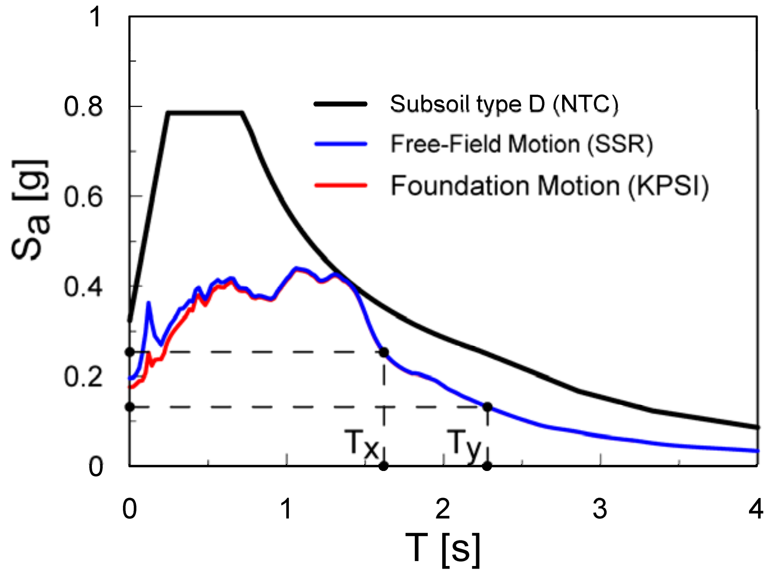




'Consistent Boundary Matrix method' hybrid approach based on:

- FEM for vertical impedance
- closed form equations for horizontal impedance



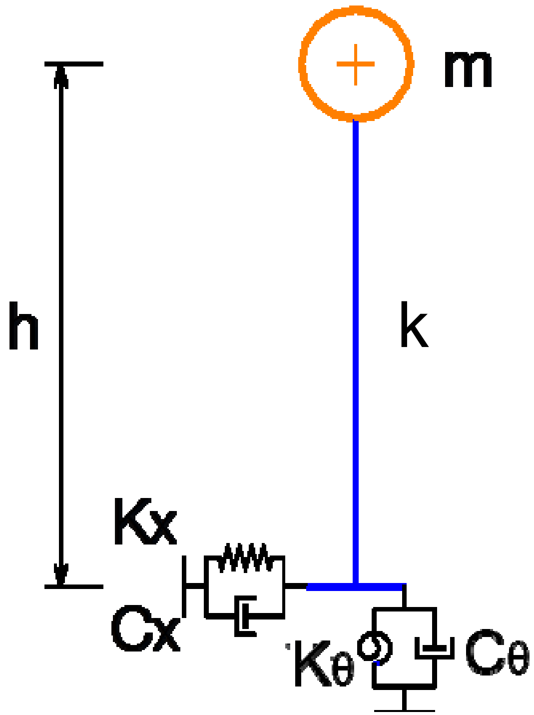


THE FILTERING EFFECT IS NEGLIGIBLE

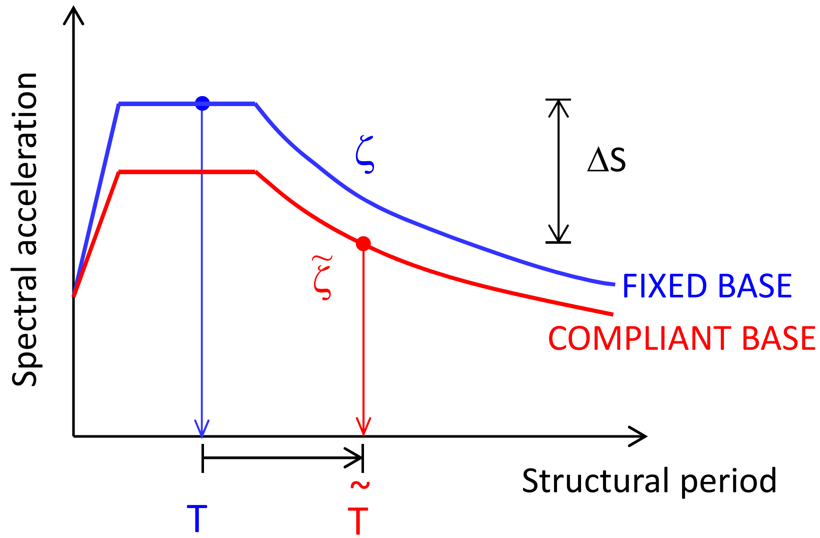
Foundation Input Motion (FIM) assumed equal to the FREE-FIELD conditions

INERTIAL SSI: IMPORTANCE OF FOUNDATION COMPLIANCE

Veletsos & Meek, 1974, Veletsos & Nair, 1975



$$\tilde{\zeta} = \tilde{\zeta}_0 + \left(\frac{\tilde{f}}{f}\right)^3 \zeta$$

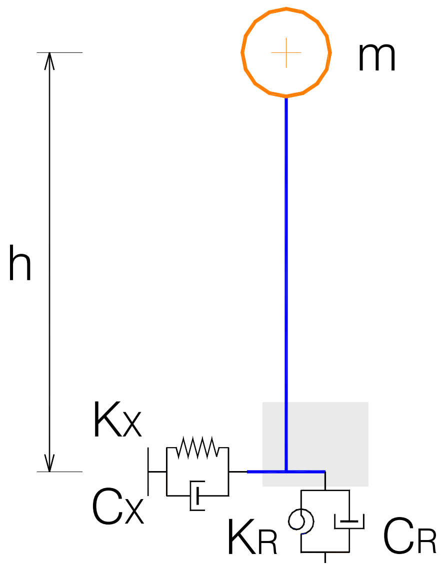


$$\frac{\tilde{f}}{f} = \frac{1}{\sqrt{\left[1 + \frac{k_X}{K_X}\left(1 + \frac{K_X}{K_\theta}\frac{h^2}{r^2}\right)\right]}}$$

INERTIAL SSI: IMPORTANCE OF FOUNDATION COMPLIANCE

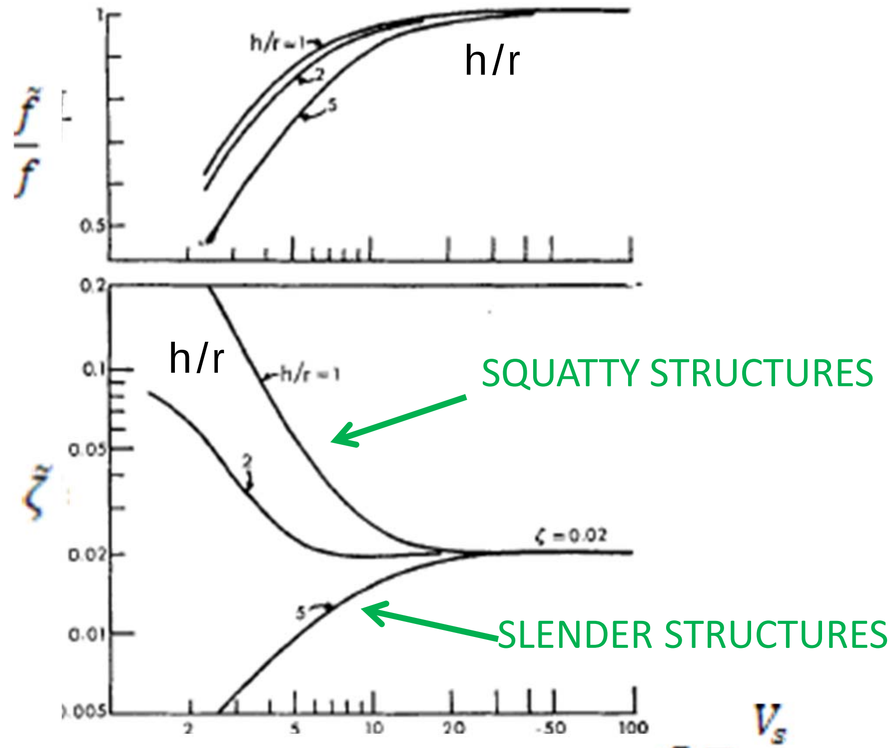
The REPLACEMENT OSCILLATOR METHOD

(Veltsos & Meek, 1974; Veletsos & Nair, 1975)



$$\frac{\tilde{f}}{f} = \frac{1}{\sqrt{\left[1 + \frac{k_X}{K_X}\left(1 + \frac{K_X}{K_\theta}\frac{h^2}{r^2}\right)\right]}}$$

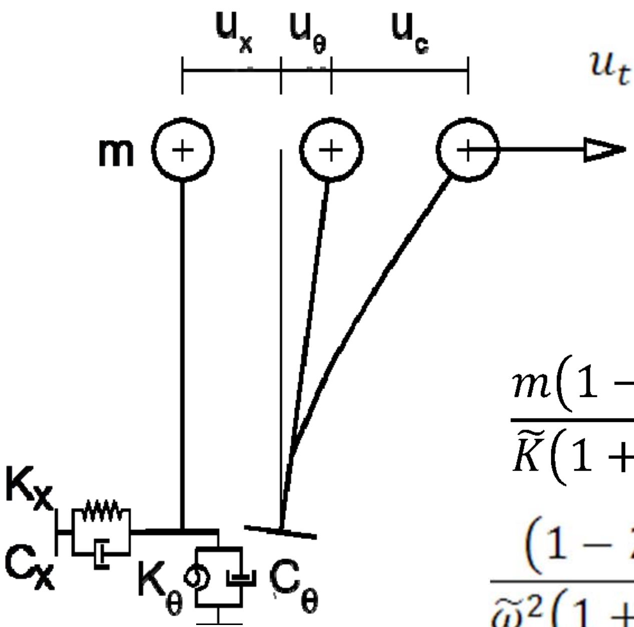
$$\tilde{\zeta} = \tilde{\zeta}_0 + \left(\frac{\tilde{f}}{f}\right)^3 \zeta$$



$$\sigma = \frac{V_s}{fh}$$

$$\sigma = \frac{V_s}{fh} \qquad \delta = \frac{m}{\rho \pi r^2 h}$$

INERTIAL SSI: THE APPROACH BY MARAVAS ET AL. (2014)



$$u_t = u_c + u_x + u_\theta$$

$$\frac{1}{\tilde{k}^*} = \frac{1}{K_x^*} + \frac{h^2}{K_\theta^*} + \frac{1}{k^*}$$

$$K_j^* = K_j(1 + 2i\zeta_j)$$

$$\frac{m(1-2i\tilde{\zeta})}{\tilde{K}(1+4\tilde{\zeta}^2)} = \frac{m(1-2i\zeta_x)}{K_x(1+4\zeta_x^2)} + \frac{mh^2(1-2i\zeta_\theta)}{K_\theta(1+4\zeta_\theta^2)} + \frac{m(1-2i\zeta)}{k(1+4\zeta^2)}$$

$$\frac{(1-2i\tilde{\zeta})}{\tilde{\omega}^2(1+4\tilde{\zeta}^2)} = \frac{(1-2i\zeta_x)}{\omega_x{}^2(1+4\zeta_x^2)} + \frac{(1-2i\zeta_\theta)}{\omega_\theta{}^2(1+4\zeta_\theta^2)} + \frac{(1-2i\zeta)}{\omega_c^2(1+4\zeta^2)}$$

$$\omega_\theta = \sqrt{\frac{K_\theta}{mh^2}}$$

$$\omega_x = \sqrt{\frac{K_x}{m}}$$

$$\omega_c = \sqrt{\frac{k}{m}}$$

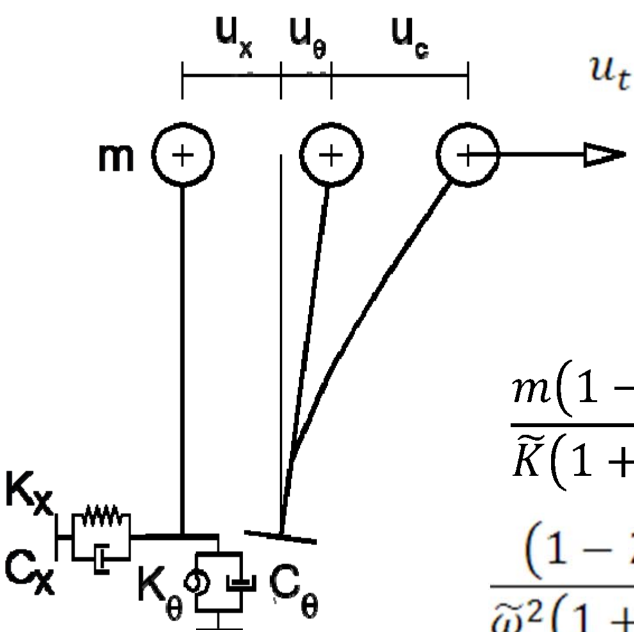
REAL PART

$$\frac{1}{\tilde{\omega}^2(1+4\tilde{\zeta}^2)} = \frac{1}{\omega_x{}^2(1+4\zeta_x^2)} + \frac{1}{\omega_\theta{}^2(1+4\zeta_\theta^2)} + \frac{1}{\omega_c^2(1+4\zeta^2)}$$

IMAGINARY PART

$$\frac{\tilde{\zeta}}{\tilde{\omega}^2(1+4\tilde{\zeta}^2)} = \frac{\zeta_x}{\omega_x{}^2(1+4\zeta_x^2)} + \frac{\zeta_\theta}{\omega_\theta{}^2(1+4\zeta_\theta^2)} + \frac{\zeta}{\omega_c^2(1+4\zeta^2)}$$

INERTIAL SSI: THE APPROACH BY MARAVAS ET AL. (2014)



$$u_t = u_c + u_x + u_\theta$$

$$\frac{1}{\tilde{k}^*} = \frac{1}{K_x^*} + \frac{h^2}{K_\theta^*} + \frac{1}{k^*}$$

$$K_j^* = K_j(1 + 2i\zeta_j)$$

$$\frac{m(1-2i\tilde{\zeta})}{\tilde{K}(1+4\tilde{\zeta}^2)} = \frac{m(1-2i\zeta_x)}{K_x(1+4\zeta_x^2)} + \frac{mh^2(1-2i\zeta_\theta)}{K_\theta(1+4\zeta_\theta^2)} + \frac{m(1-2i\zeta)}{k(1+4\zeta^2)}$$

$$\frac{(1-2i\tilde{\zeta})}{\tilde{\omega}^2(1+4\tilde{\zeta}^2)} = \frac{(1-2i\zeta_x)}{\omega_x{}^2(1+4\zeta_x^2)} + \frac{(1-2i\zeta_\theta)}{\omega_\theta{}^2(1+4\zeta_\theta^2)} + \frac{(1-2i\zeta)}{\omega_c^2(1+4\zeta^2)}$$

$$\omega_\theta = \sqrt{\frac{K_\theta}{mh^2}}$$

$$\omega_x = \sqrt{\frac{K_x}{m}}$$

$$\omega_c = \sqrt{\frac{k}{m}}$$

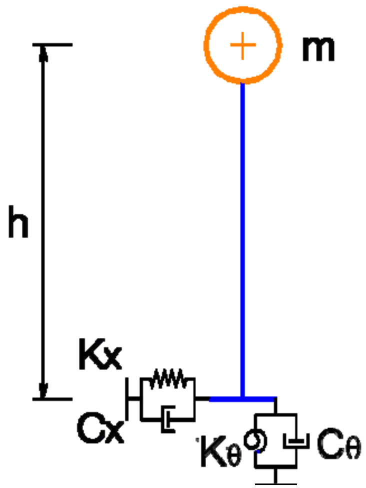
REAL PART

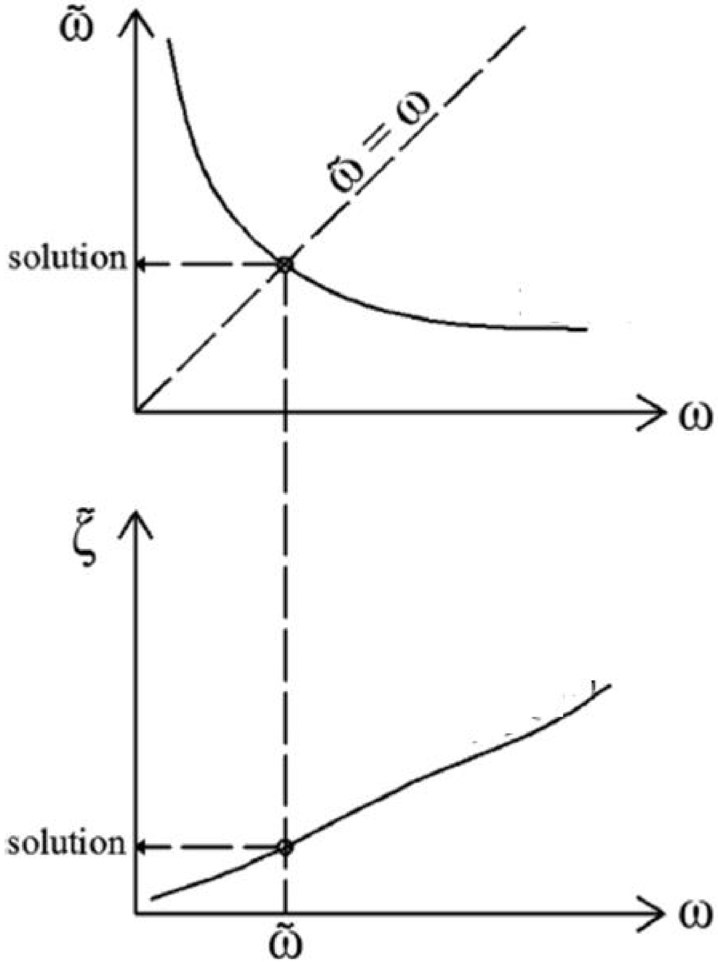
$$\frac{1}{\tilde{\omega}^2} = \left(\frac{1}{\omega_x^2} + \frac{1}{\omega_\theta^2} + \frac{1}{\omega_c^2}\right)$$

IMAGINARY PART

$$\tilde{\zeta} = \left(\frac{\tilde{K}}{K_x}\right)\zeta_x + \left(\frac{\tilde{K}h^2}{K_\theta}\right)\zeta_\theta + \left(\frac{\tilde{K}}{k}\right)\zeta$$

INERTIAL SSI: THE APPROACH BY MARAVAS ET AL. (2014)





REAL PART

$$\frac{1}{\tilde{\omega}^2} = \left(\frac{1}{\omega_x^2} + \frac{1}{\omega_\theta^2} + \frac{1}{\omega_c^2}\right)$$

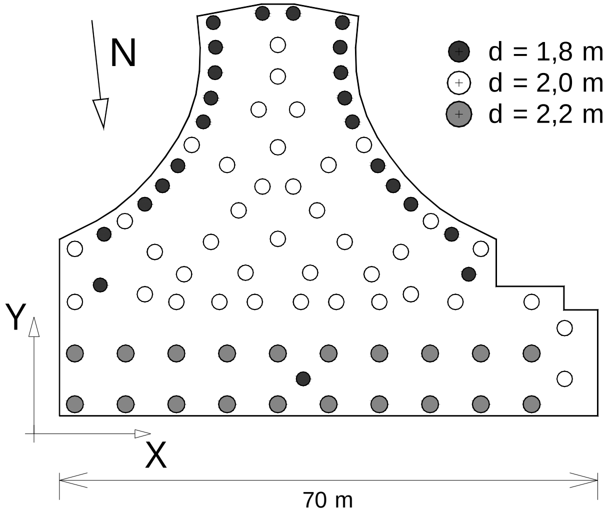
IMAGINARY PART

$$\tilde{\zeta} = \left(\frac{\tilde{K}}{K_x}\right)\zeta_x + \left(\frac{\tilde{K}h^2}{K_\theta}\right)\zeta_\theta + \left(\frac{\tilde{K}}{k}\right)\zeta$$

$$K_j^* = K_j(1 + 2i\zeta_j)$$

IMPEDANCE FUNCTIONS HAVE TO BE PRELIMINARY EVALUATED

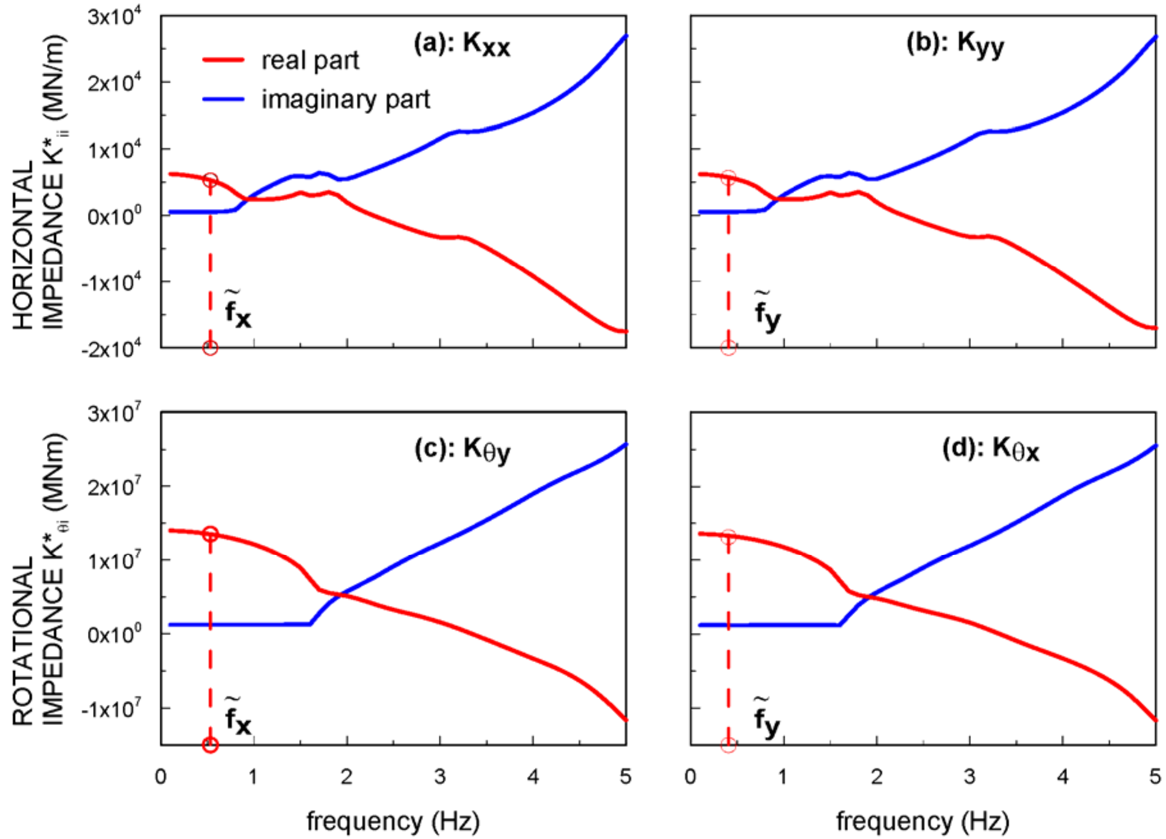
INERTIAL SSI: EVALUATION OF IMPEDANCE FUNCTIONS



REAL PART EQUATION
CONDITIONS OF RESONANCE

$$\tilde{\omega}_x^2 = \left(\frac{1}{\omega_x^2} + \frac{1}{\omega_\theta^2} + \frac{1}{\omega_c^2}\right)^{-1}$$

$$\tilde{K}_x = \left(\frac{1}{K_x} + \frac{h^2}{K_{\theta y}} + \frac{1}{k_x}\right)^{-1}$$

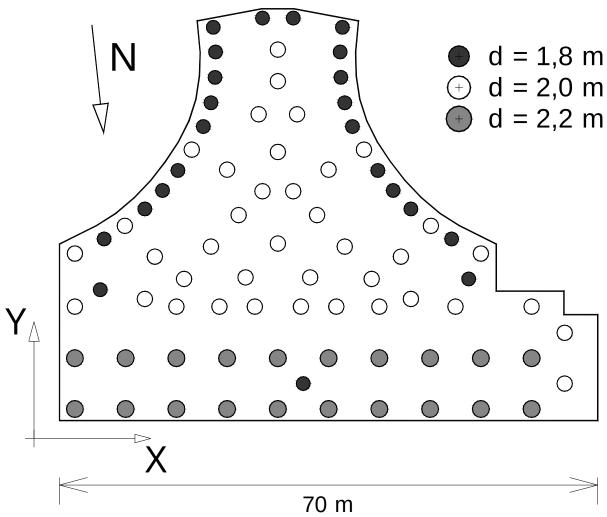


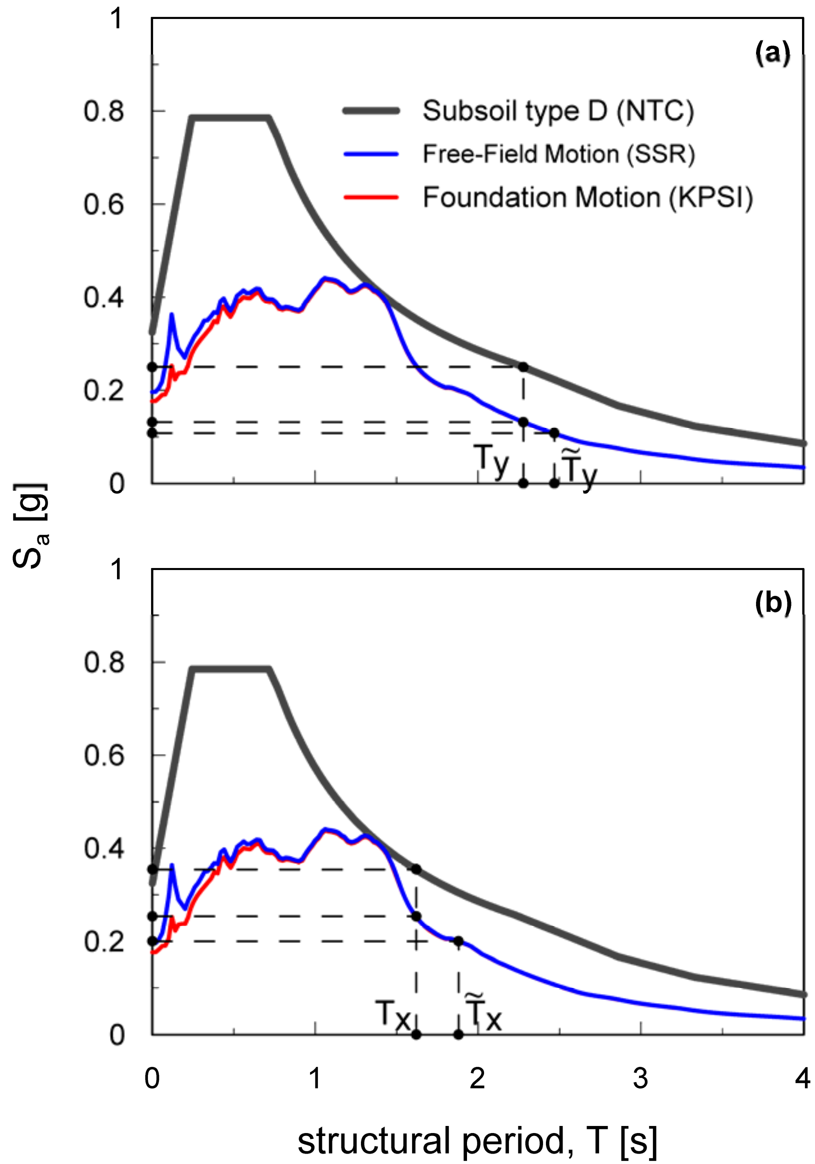
$$\tilde{f}_x = 0.531Hz \qquad \frac{\tilde{T}_x}{T_x} = 1.16$$

$$\tilde{f}_y = 0.405Hz \qquad \frac{\tilde{T}_y}{T_y} = 1.08$$

INCREASE OF STRUCTURAL PERIODS

REPLACEMENT OSCILLATOR: EVALUATION OF THE EQUIVALENT PERIOD





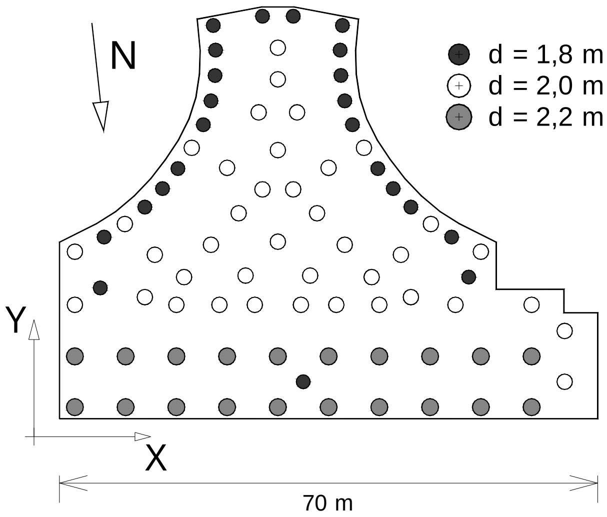
Increment of structural period

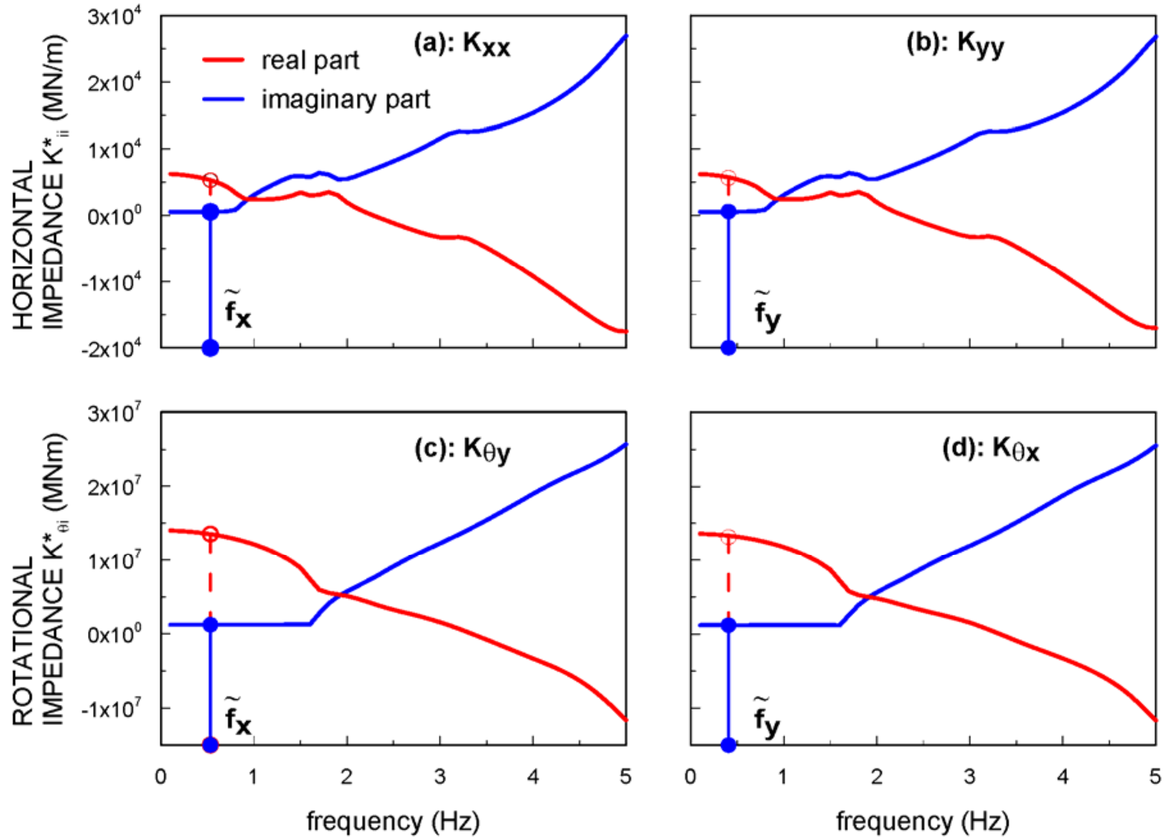
$$\frac{\widetilde{T}_X}{T_X} = 1.16, \quad \frac{\widetilde{T}_Y}{T_Y} = 1.08$$

Overall reduction of spectral acceleration

#	Y-direction (1st mode)	X-direction (2nd mode)
SSR	47.2%	28.3%
SSI	9.5%	15.1%
OVERALL	56.4%	43.4%

INERTIAL SSI: EVALUATION OF IMPEDANCE FUNCTIONS





CONDITIONS OF RESONANCE

$$\tilde{\omega}_x^2 = \left(\frac{1}{\omega_x^2}+\frac{1}{\omega_\theta^2}+\frac{1}{\omega_c^2}\right)^{-1}$$

$$\zeta_j = \frac{Im(K_j^*)}{2Re(K_j^*)}$$

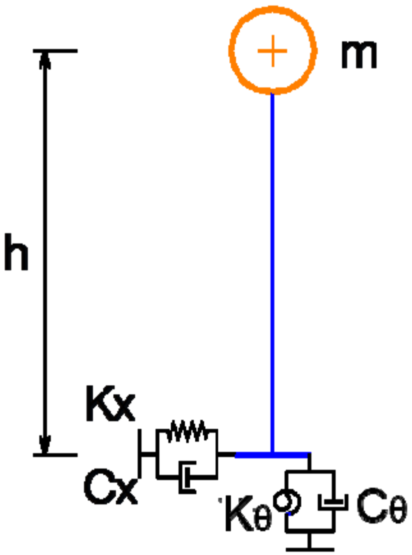
IMAGINARY PART EQUATION

$$\tilde{\zeta} = \left(\frac{\tilde{K}}{K_x}\right)\zeta_x + \left(\frac{\tilde{K}h^2}{K_\theta}\right)\zeta_\theta + \left(\frac{\tilde{K}}{k}\right)\zeta = \alpha_X\zeta_X + \alpha_\theta\zeta_\theta + \alpha\zeta$$

$$\tilde{\zeta} \approx \zeta$$

NO INCREASE OF STRUCTURAL DAMPING

REPLACEMENT OSCILLATOR: EVALUATION OF THE APPARENT DAMPING



$$\tilde{\omega}^2 = \left(\frac{1}{\omega_x^2} + \frac{1}{\omega_\theta^2} + \frac{1}{\omega_c^2}\right) \qquad \frac{1}{\tilde{K}} = \left(\frac{1}{K_X} + \frac{h^2}{K_\theta} + \frac{1}{k}\right)$$

$$\tilde{\zeta} = \left(\frac{\tilde{K}}{K_x}\right)\zeta_x + \left(\frac{\tilde{K}h^2}{K_\theta}\right)\zeta_\theta + \left(\frac{\tilde{K}}{k}\right)\zeta = \alpha_X\zeta_X + \alpha_\theta\zeta_\theta + \alpha\zeta \qquad \alpha_X + \alpha_\theta + \alpha = 1$$

$$\alpha_X = \frac{1}{1 + \frac{K_X h^2}{K_\theta} + \boxed{\frac{K_X}{k}}} \quad \alpha_\theta = \frac{1}{\frac{K_\theta}{K_X h^2} + 1 + \boxed{\frac{K_\theta}{h^2 k}}} \quad \alpha = \frac{1}{\frac{k}{K_X} + \frac{k h^2}{K_\theta} + 1}$$

$$\omega_\theta = \sqrt{\frac{K_\theta r^2}{m h^2}}$$

$$\omega_x = \sqrt{\frac{K_x}{m}}$$

$$\omega_c = \sqrt{\frac{k}{m}}$$

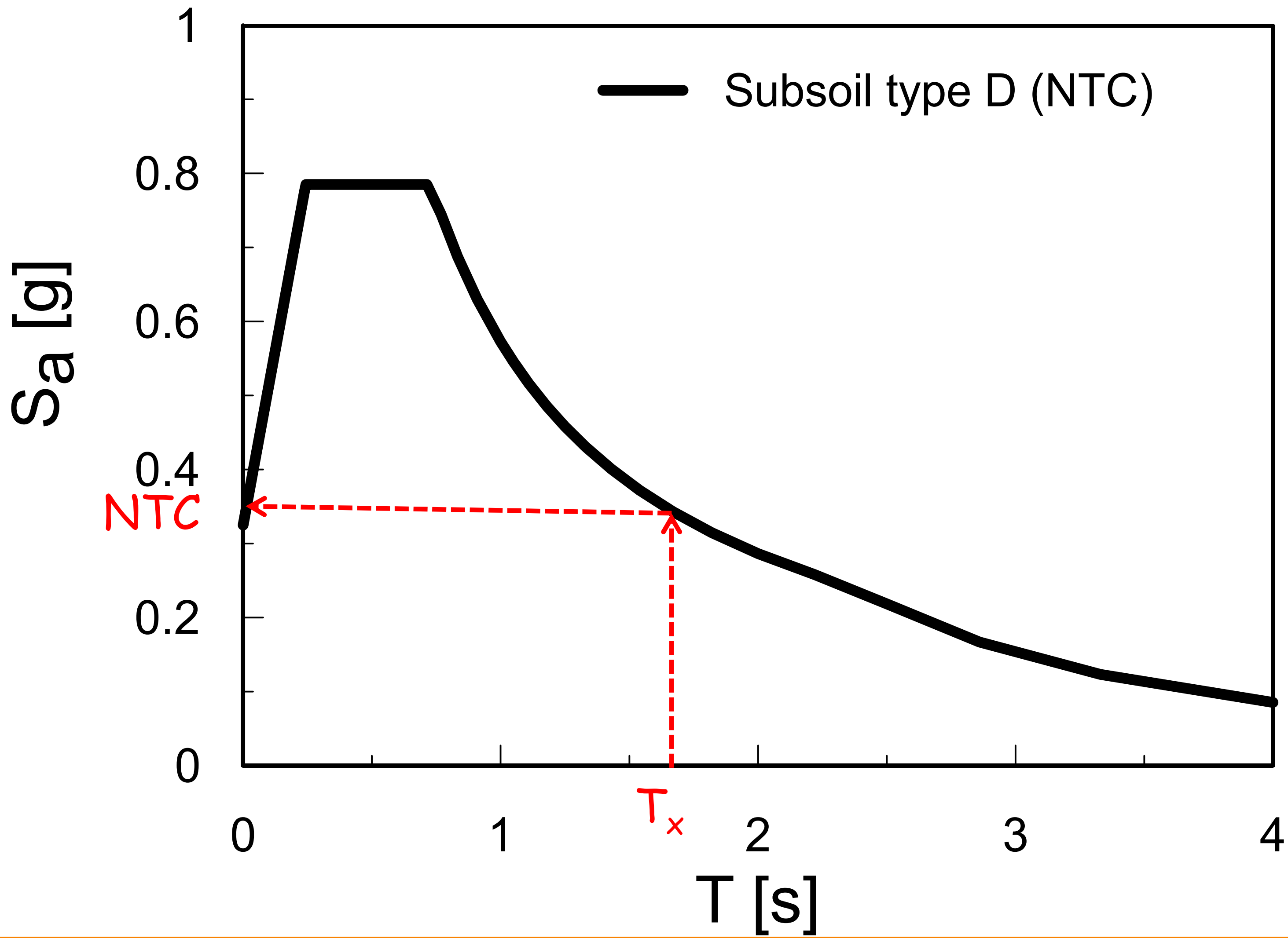
$$\frac{K_x}{k} \gg 1 \rightarrow \alpha_x \ll \alpha$$

$$\frac{K_\theta}{k h^2} \gg 1 \rightarrow \alpha_\theta \ll \alpha$$

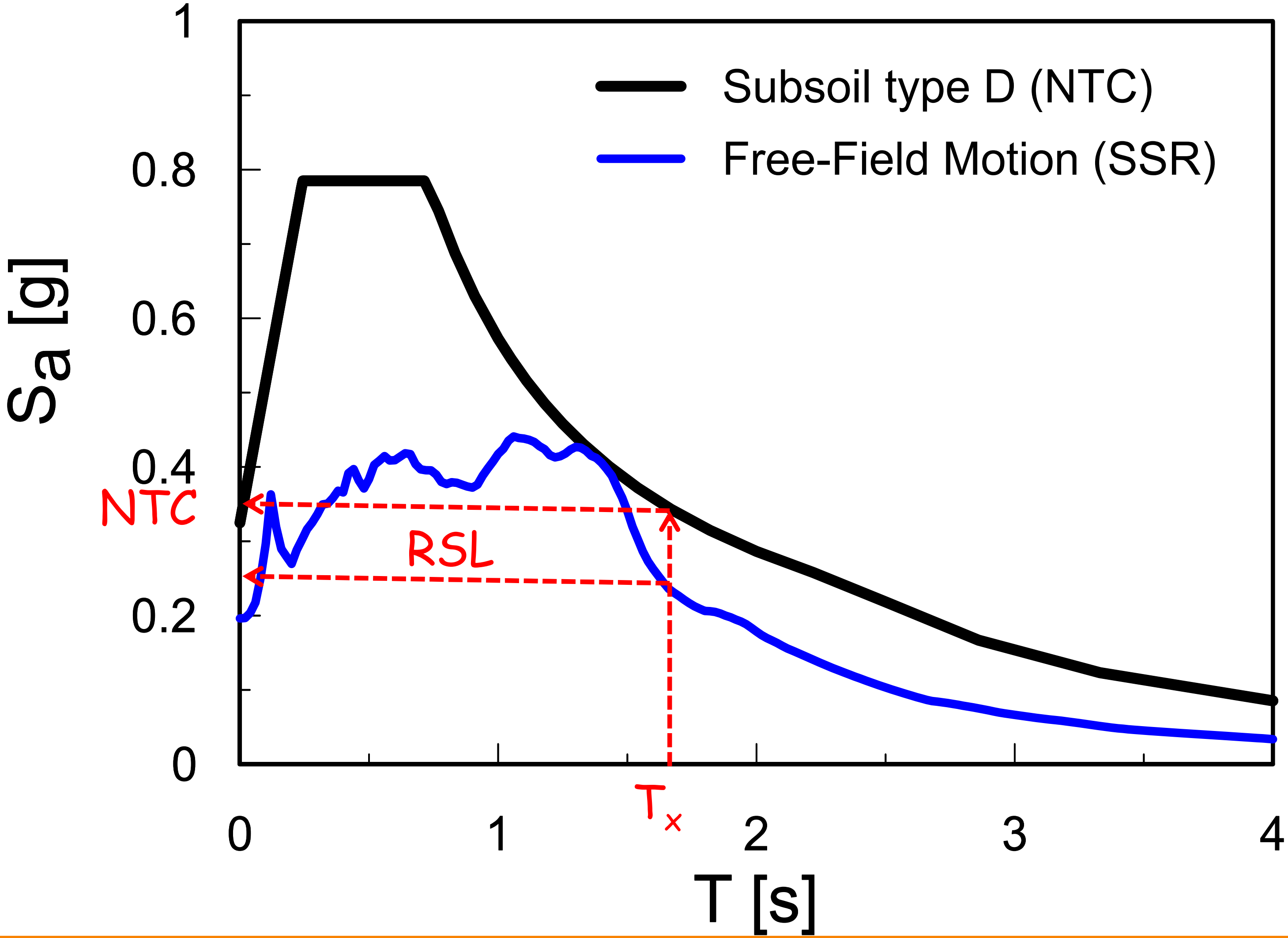
$\rightarrow$ $\tilde{\zeta} \approx \zeta$

NO INCREASE OF STRUCTURAL DAMPING

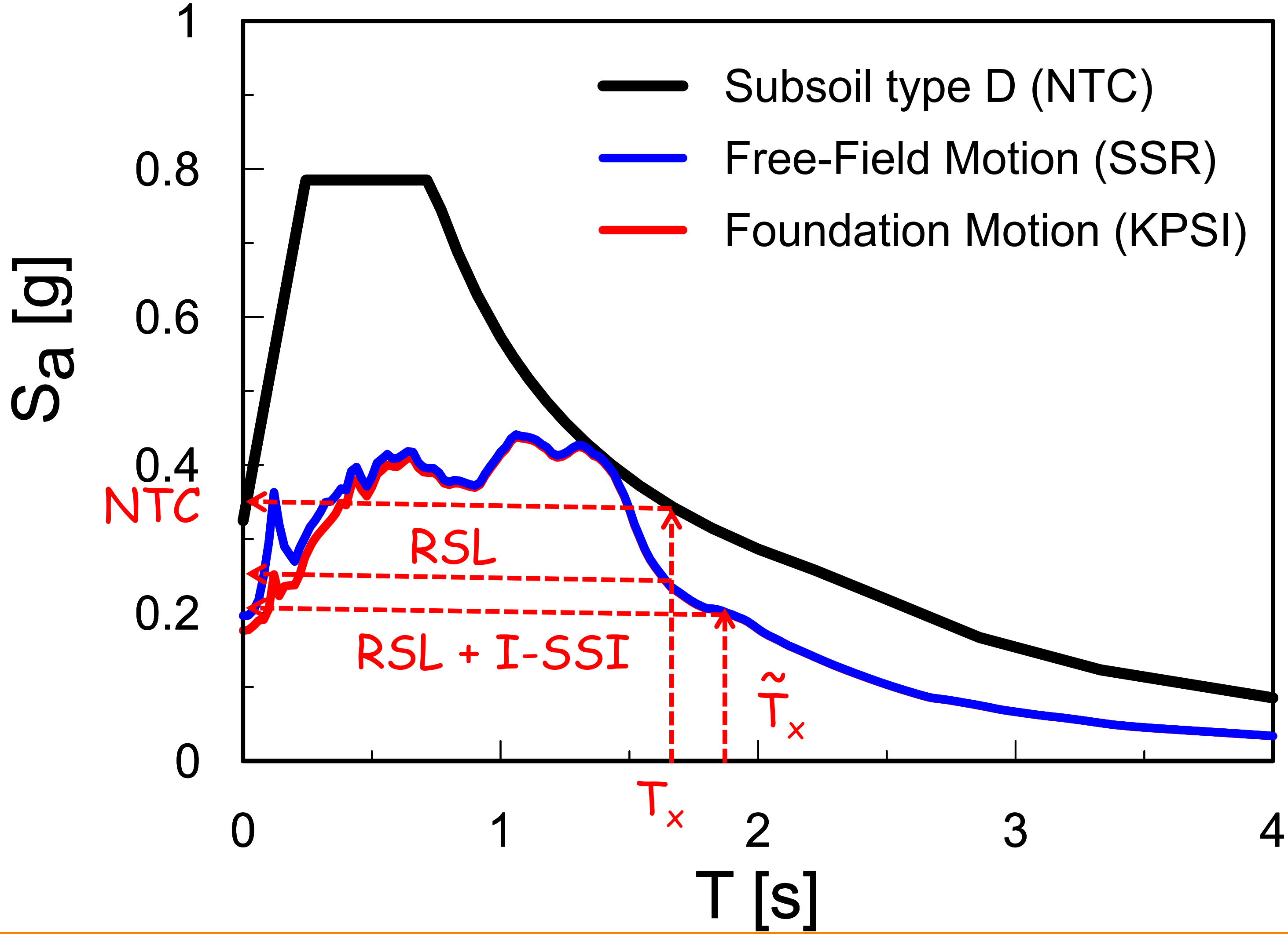
SUMMARY



SUMMARY


1
0.8
0.6
0.4
0.2
0
Sa [g]
Subsoil type D (NTC)
Free-Field Motion (SSR)
NTC
RSL
Tx
0
1
2
3
4
T [s]

SUMMARY


1
0.8
0.6
0.4
0.2
0
Sa [g]
0
1
2
3
4
T [s]
Subsoil type D (NTC)
Free-Field Motion (SSR)
Foundation Motion (KPSI)
NTC
RSL
RSL + I-SSI
Tx
T̃x

Conclusions (PART I)

1. After a preliminary unsatisfactory evaluation based on code-specified spectra, the seismic actions were re-evaluated by a more sophisticated approach, giving credit to SSR and SSI

2. SSR was evaluated by one-dimensional LE analysis, which highlighted the beneficial effects of a peat layer, acting as a natural damper; spectral ordinates reduced by 47% and 28%

3. Pile-soil kinematic interaction was then analysed by Dynapile 2.0 code. The filtering action exerted by piles did not affect the FIM

Conclusions (PART II)

4. Intertial SSI was analysed by the 'replacement oscillator' method, using Maravas et al. (2014)

5. The increase of the structural period due to foundation compliance induced a further reduction of the spectral acceleration

6. The apparent damping did not change significantly

7. The overall reduction of spectral acceleration due to SSR and SSI was 57% and 43% for the first and second vibration modes

8. The assessment of SSR and SSI is 'MANDATORY' for a reliable and sustainable prediction of the sesmic perfomance of tall buildings

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