BOĞAZİÇİ UNIVERSITY
KANDILLI OBSERVATORY AND EARTHQUAKE RESEARCH INSTITUTE

CHANGING NEEDS OF ENGINEERS FOR SEISMIC DESIGN

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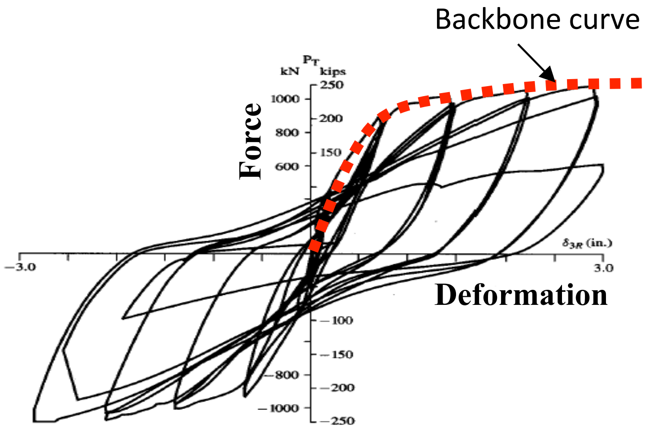
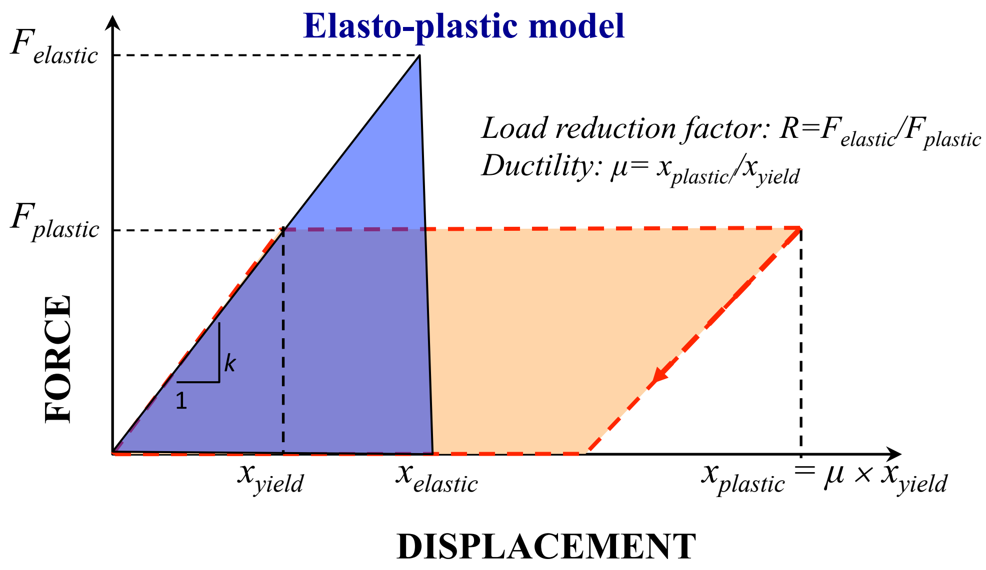
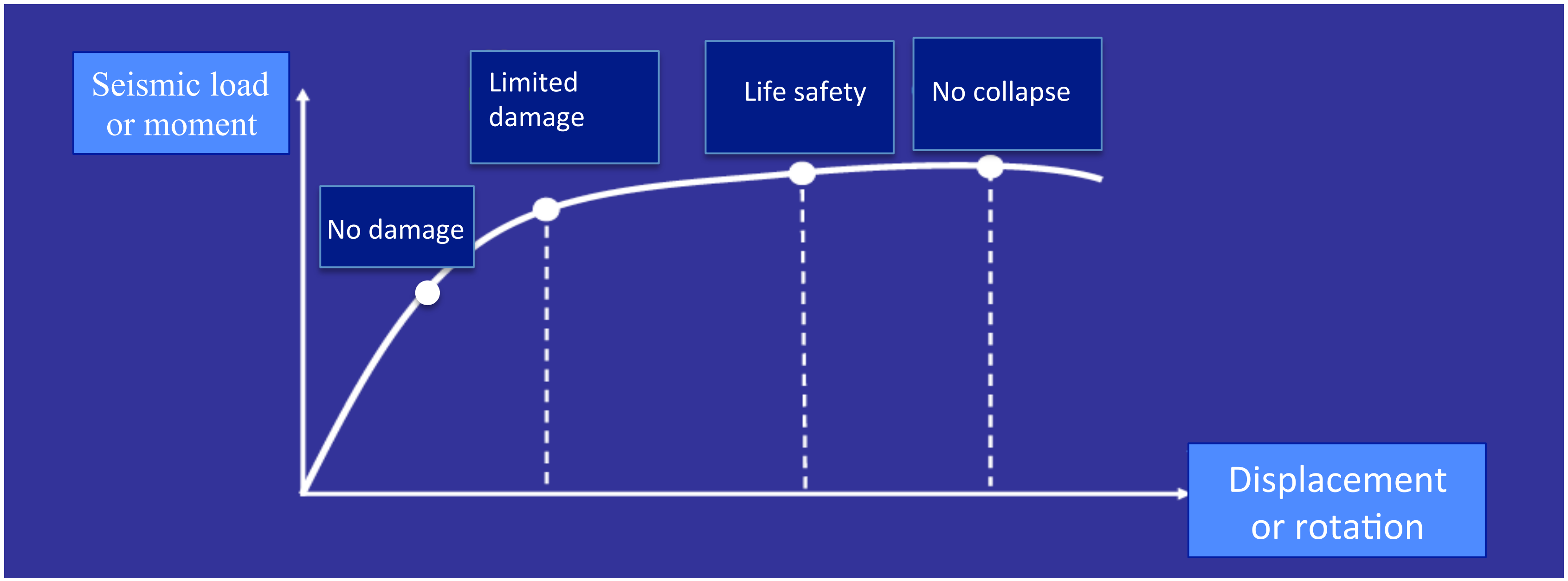
PERFORMANCE-BASED SEISMIC DESIGN OF STRUCTURES

INELASTIC RESPONSE OF STRUCTURES



Dynamic force-deformation hysteresis





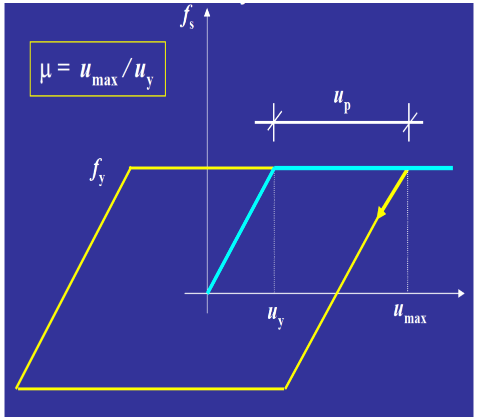
PERFORMANCE-BASED DESIGN

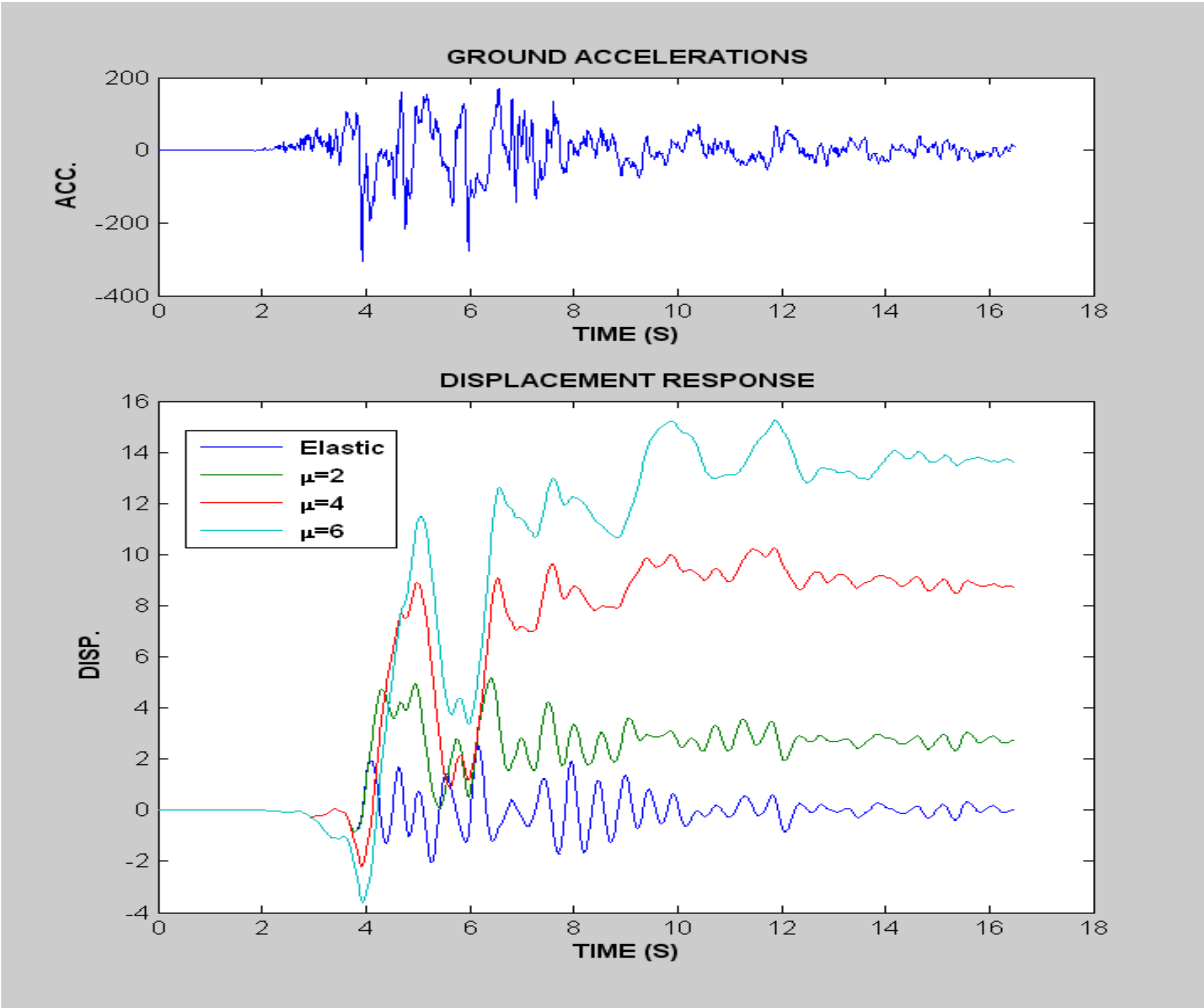
ORDINARY APARTMENT BUILDING		PERFORMANCE LEVEL			
		No damage	Limited Damage	Life safety	No collapse
HAZARD LEVEL	Frequent Eearthquake: 50% in 50 years (Return period=72 years)				
	Infrequent Earthquake: 10% in 50 years Return period = 475 years)				
	Rare Eearthquake: 2% in 50 years (Return period = 2475 years)				

HOSPITAL BUILDING		PERFORMANCE LEVEL			
		No damage	Limited Damage	Life safety	No collapse
HAZARD LEVEL	Frequent Eearthquake: 50% in 50 years (Return period=72 years)				
	Infrequent Earthquake: 10% in 50 years Return period = 475 years)				
	Rare Eearthquake: 2% in 50 years (Return period = 2475 years)				

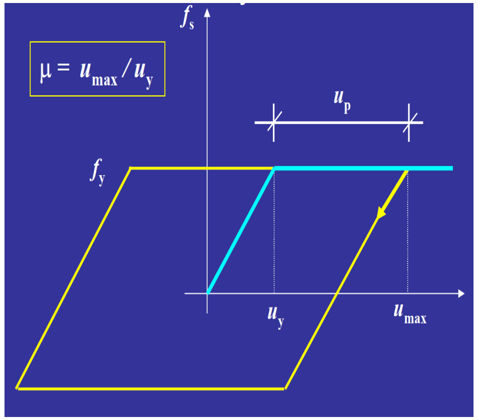
SENSITIVITY OF INELASTIC RESPONSE TO YIELD LEVEL AND YIELD TIME

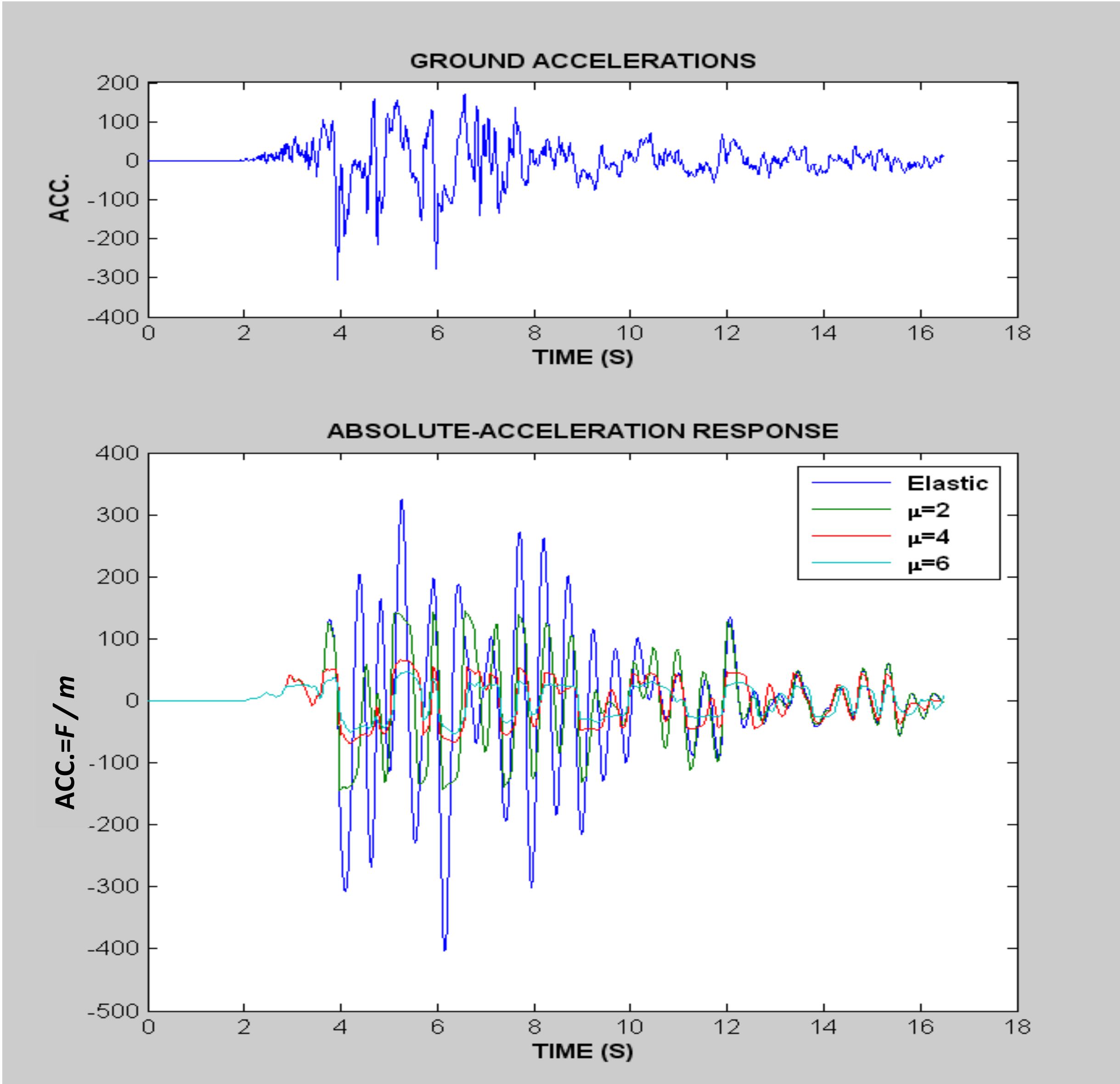
ELASTO-PLASTIC RESPONSE OF A 2.0 Hz SDOF OSCILLATOR





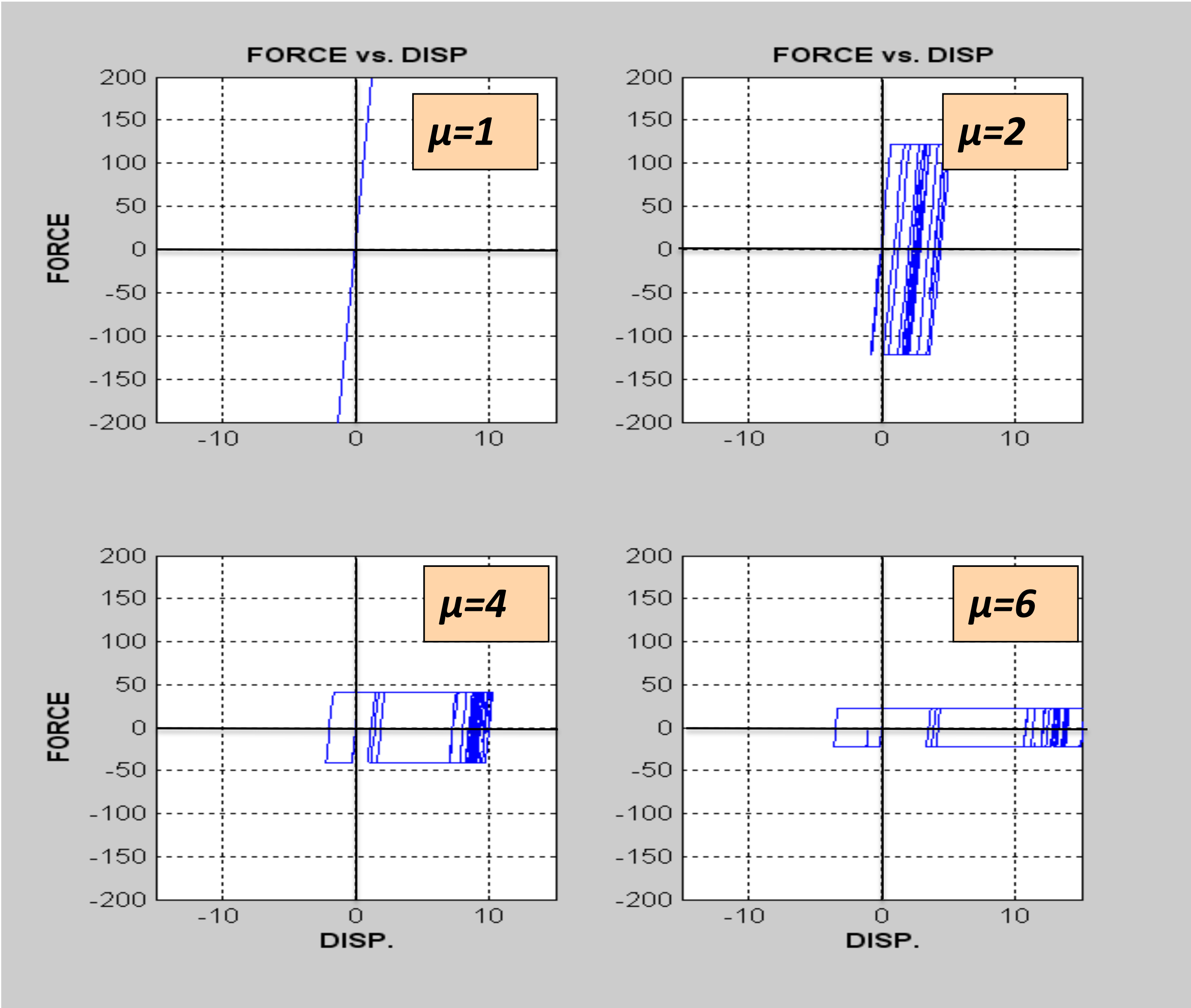
ELASTO-PLASTIC RESPONSE OF A 2.0 Hz SDOF OSCILLATOR



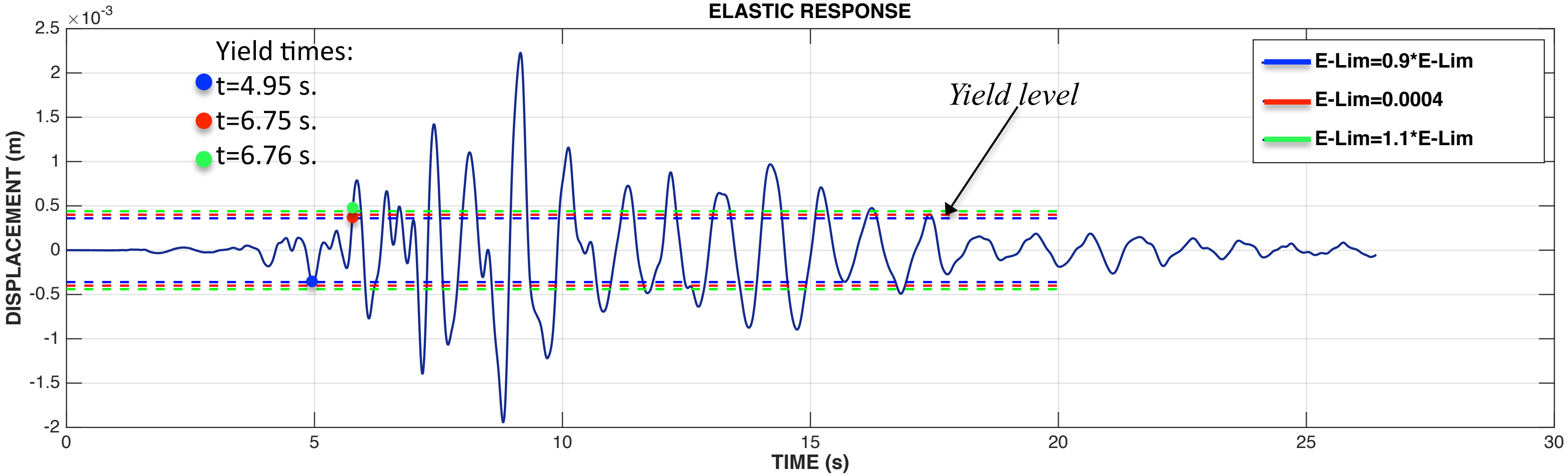


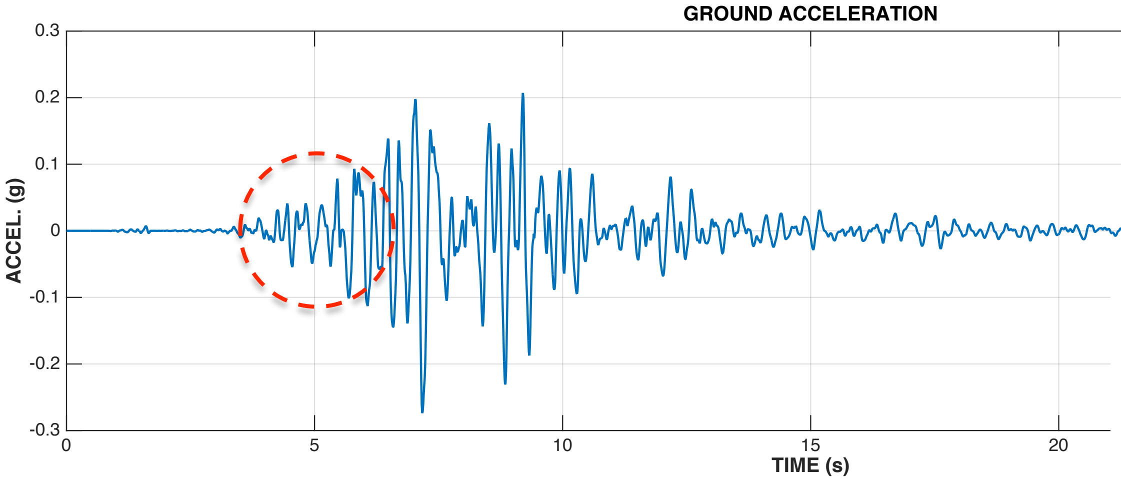
FORCE-DEFORMATION PLOTS OF ELASTO-PLASTIC RESPONSE FOR DIFFERENT DUCTILITY LEVELS

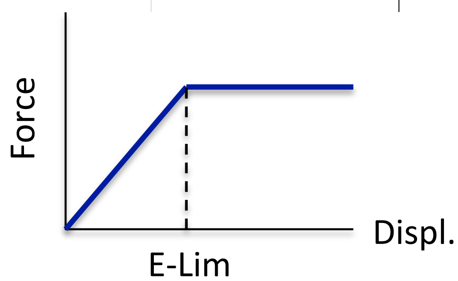
(Note that the plots have the same axis limits)



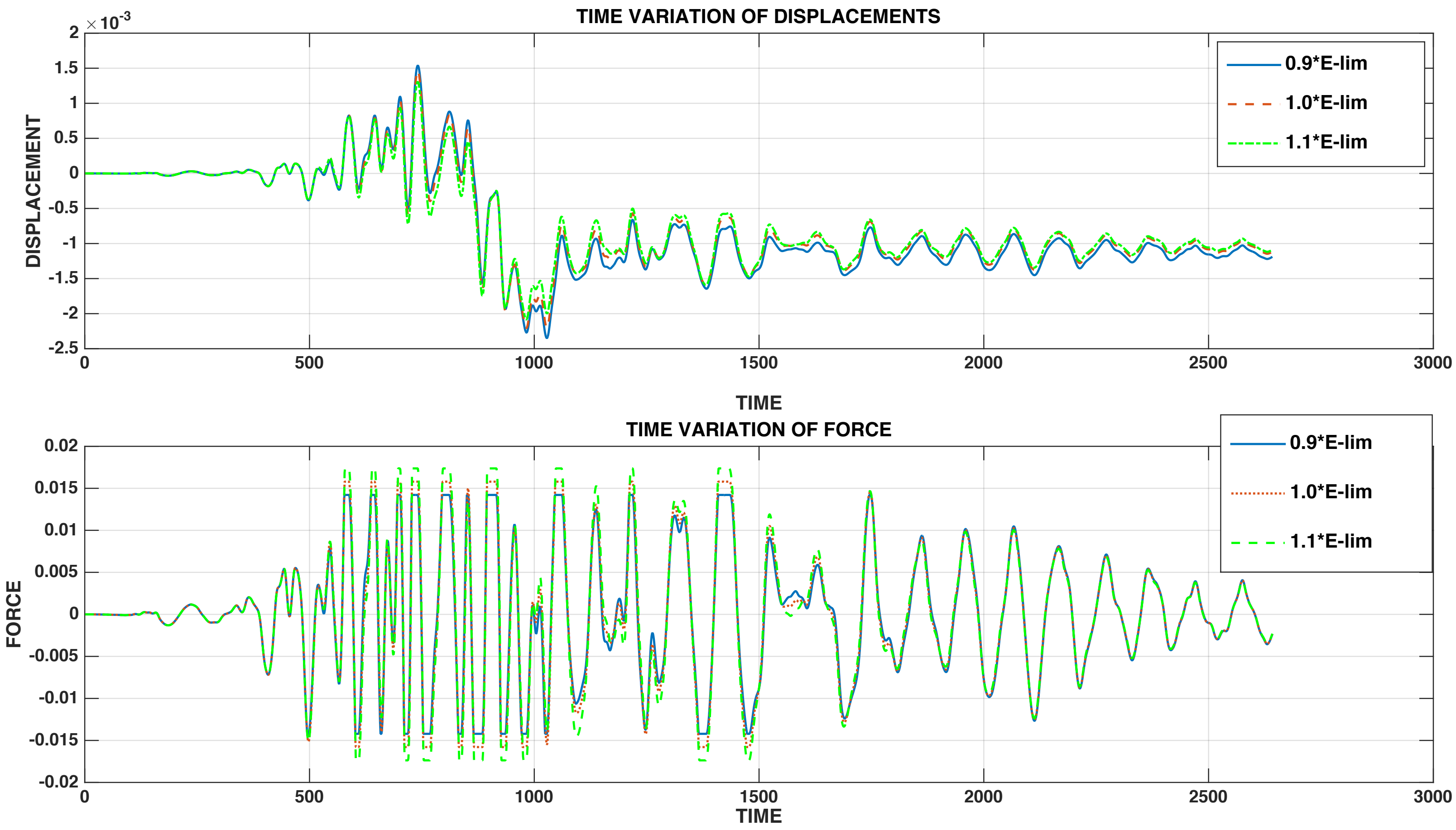
SENSITIVITY OF INELASTIC RESPONSE TO INPUT AND YIELD LEVEL



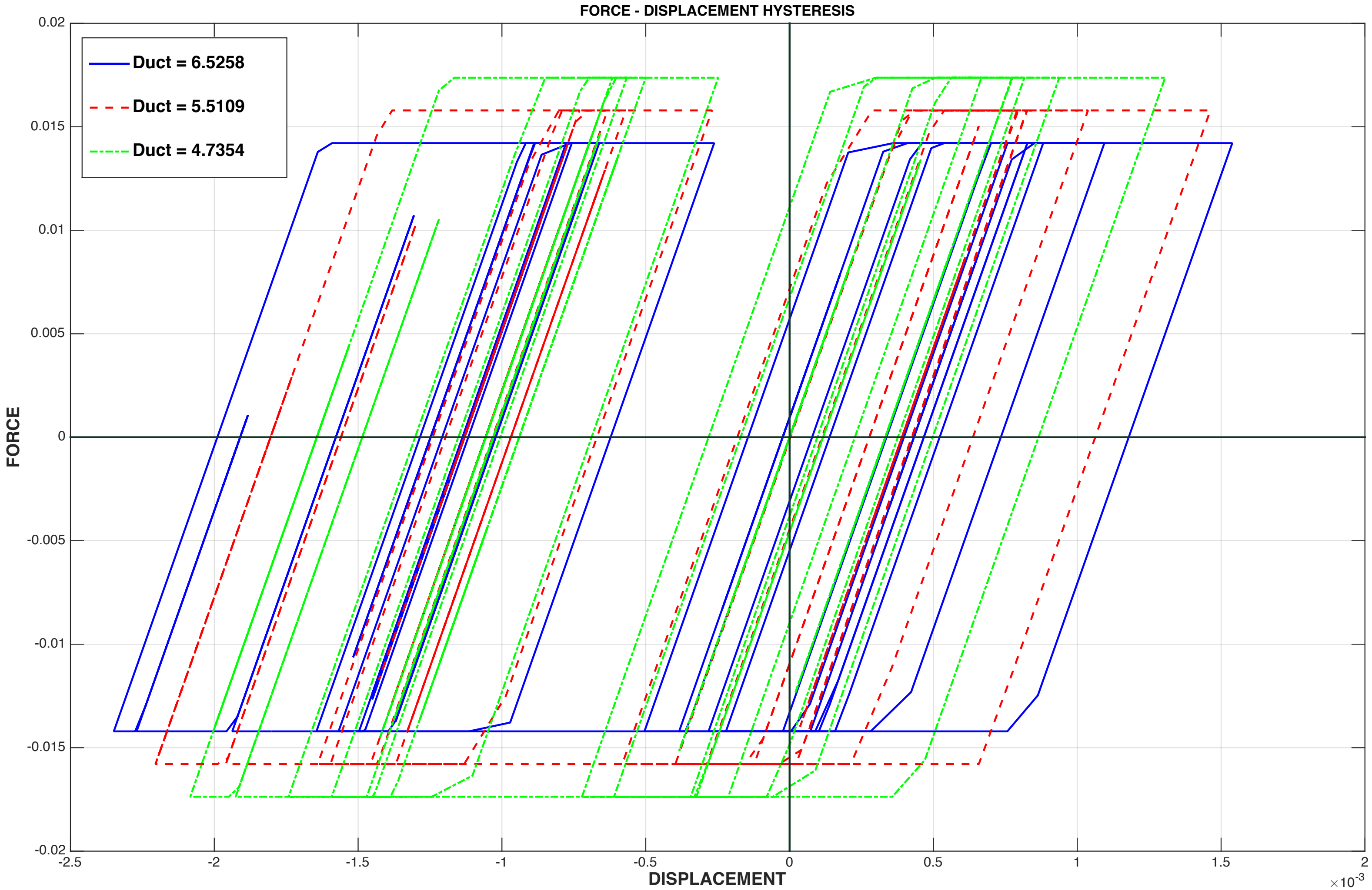




SENSITIVITY OF INELASTIC RESPONSE TO INPUT AND YIELD LEVEL: VARIATION OF FORCE AND DISPLACEMENT

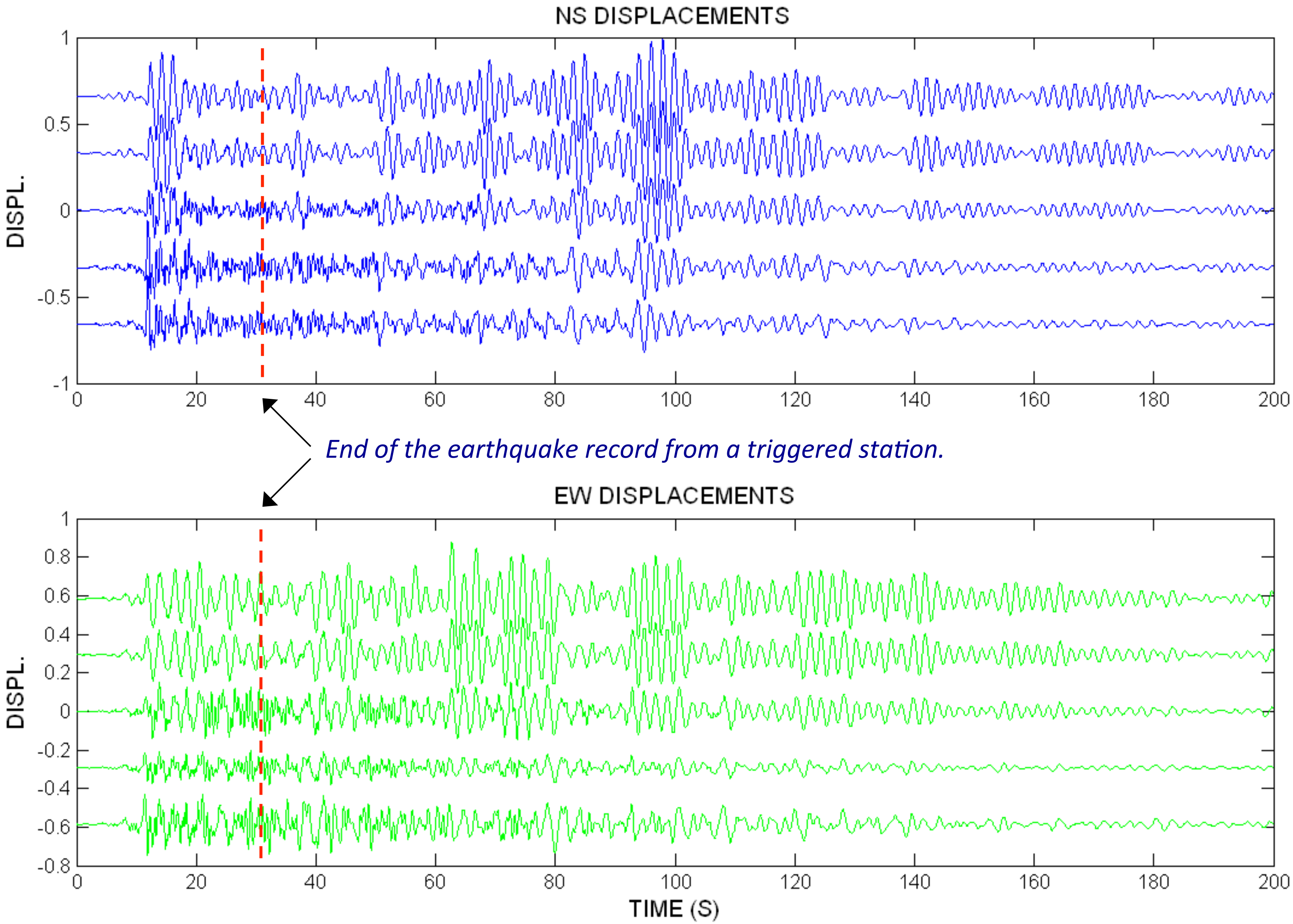


SENSITIVITY OF INELASTIC RESPONSE TO INPUT AND YIELD LEVEL: VARIATION OF FORCE-DISPLACEMENT HYSTERESIS

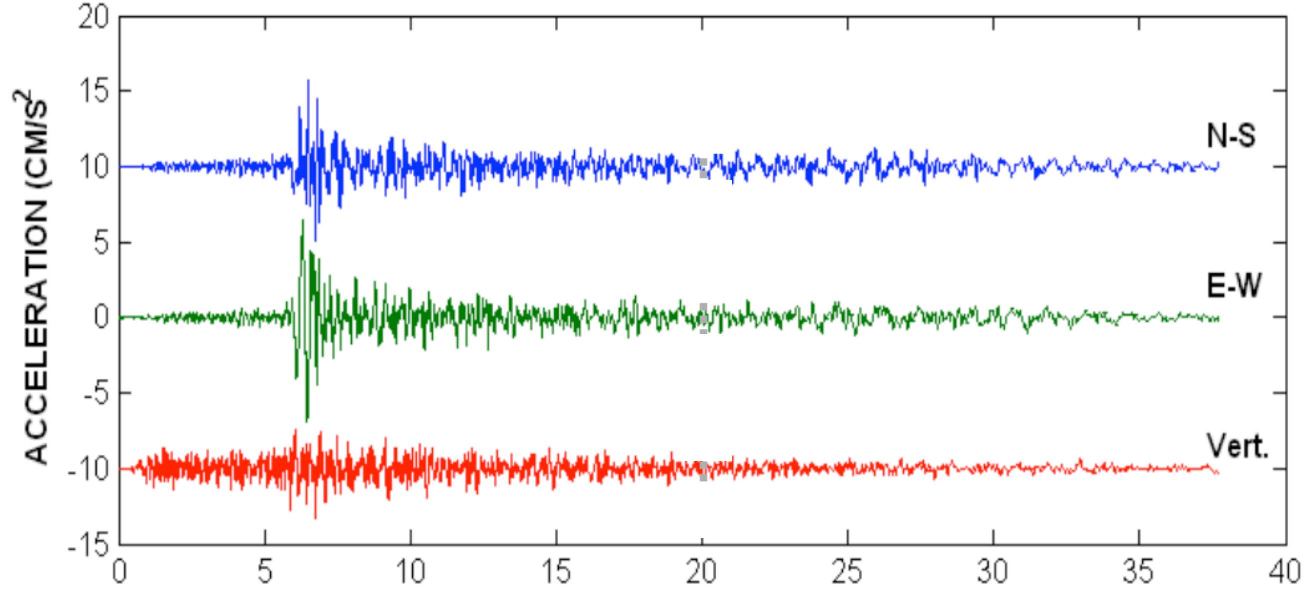


IMPORTANCE OF SURFACE WAVES FOR LONG-PERIOD STRUCTURES

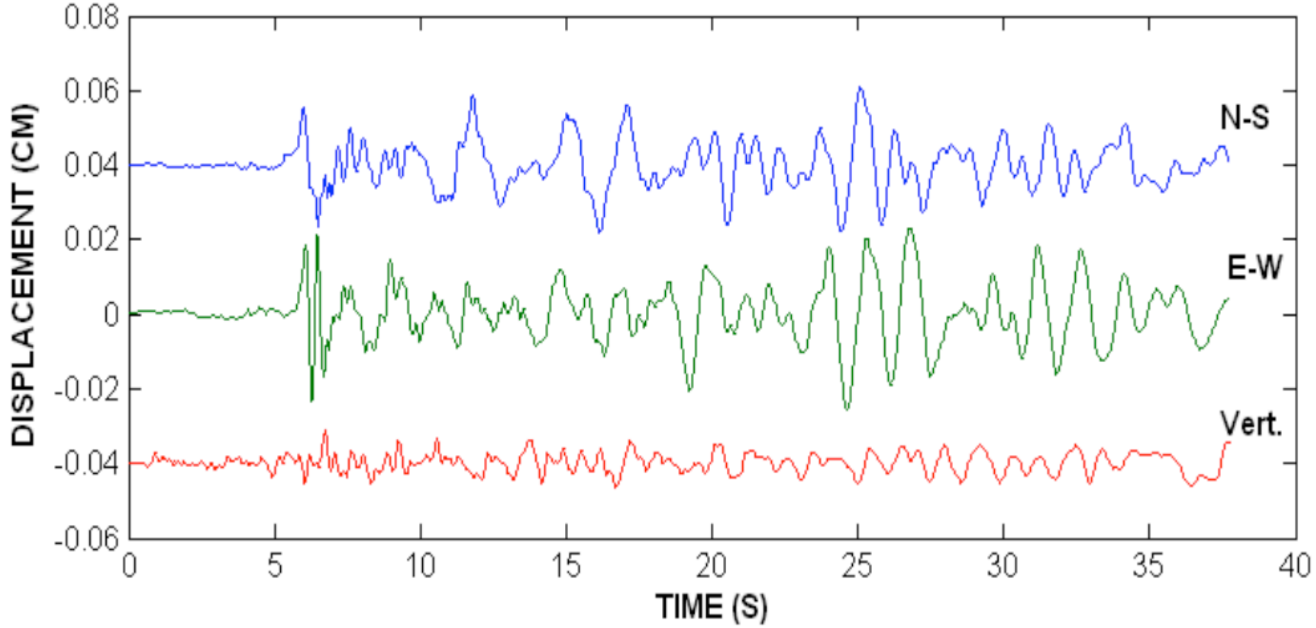
DISPLACEMENTS OF A 17-STORY BUILDING IN LOS ANGELES DURING A M=4.9 EARTHQUAKE



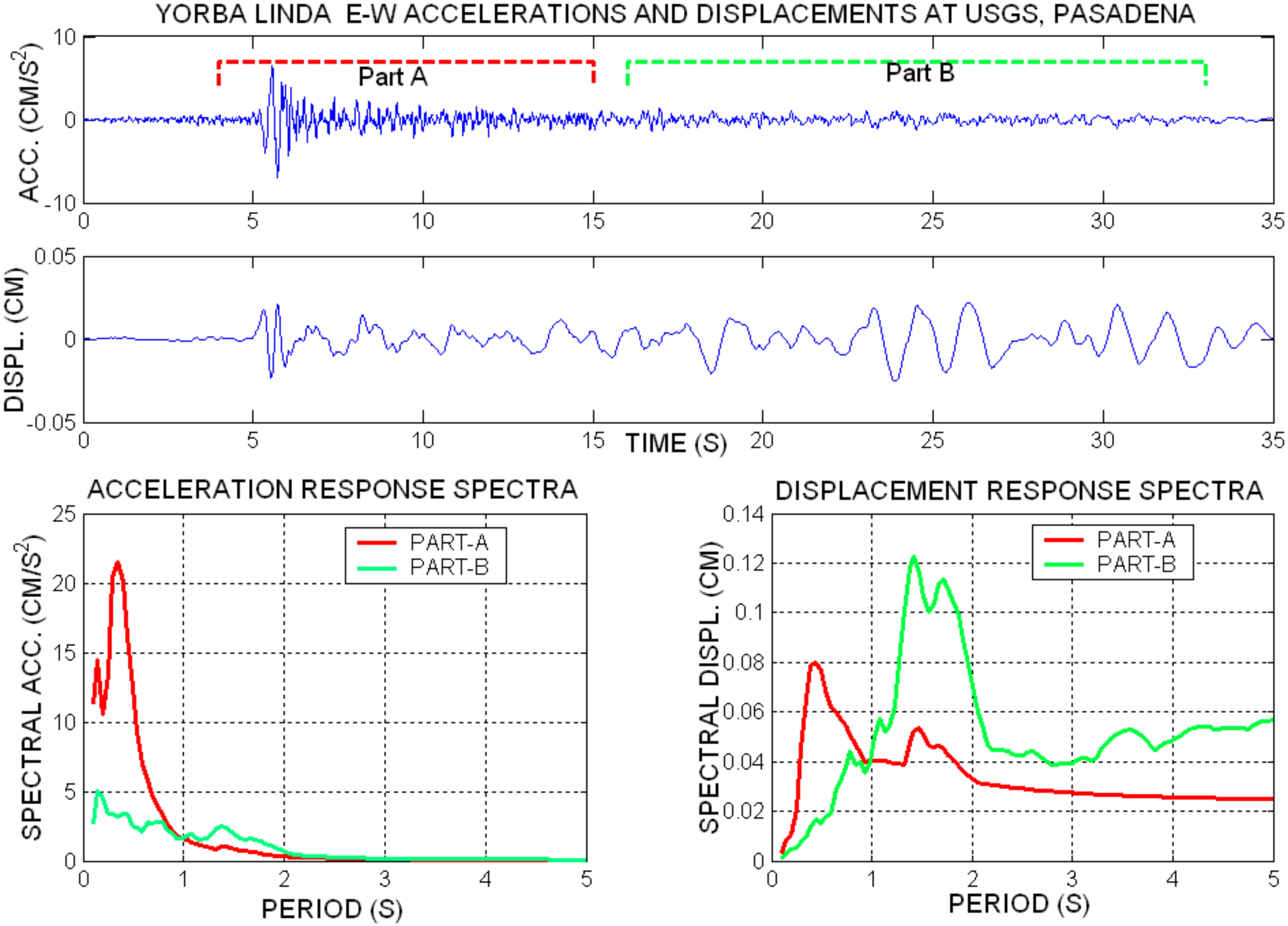
N-S, E-W, AND VERTICAL ACCELERATIONS AT GROUND LEVEL



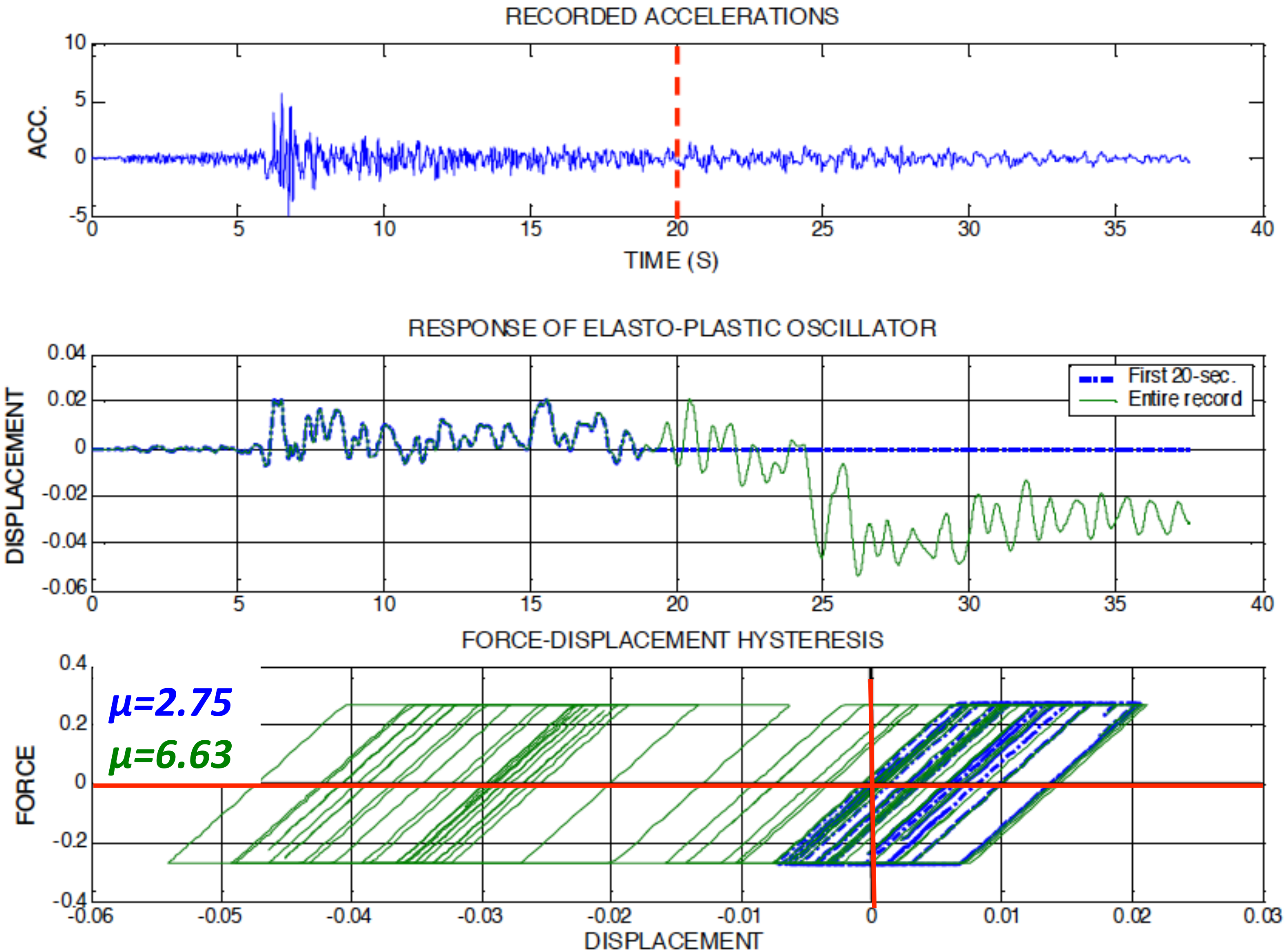
N-S, E-W, AND VERTICAL DISPLACEMENTS AT GROUND LEVEL



EFFECTS OF SURFACE WAVES ON BUILDING RESPONSE

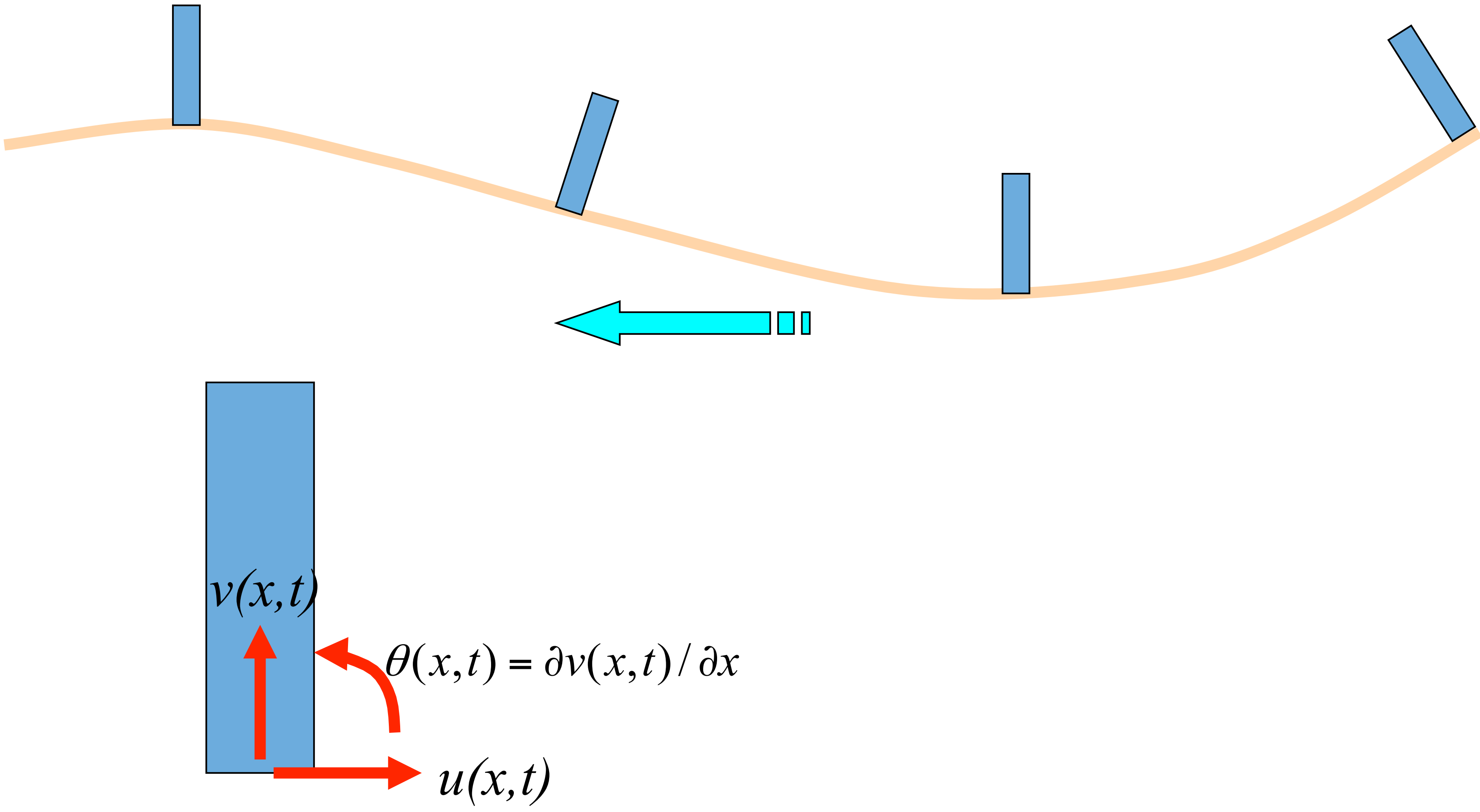


EFFECTS OF SURFACE WAVES ON BUILDING RESPONSE



ROTATIONAL EXCITATION DUE TO SURFACE WAVES

FORCES ON A TALL BUILDING SUBJECTED TO SURFACE WAVES



RAYLEIGH WAVES ON THE SURFACE OF UNIFORM HALF SPACE

$$u(x,t) = A\left(-ik + \frac{2iqsk}{s^2 + k^2}\right) \cdot e^{i(\omega t - kx)}$$

$$v(x,t) = A\left(\frac{2qk^2}{s^2 + k^2} - q\right) \cdot e^{i(\omega t - kx)}$$

with

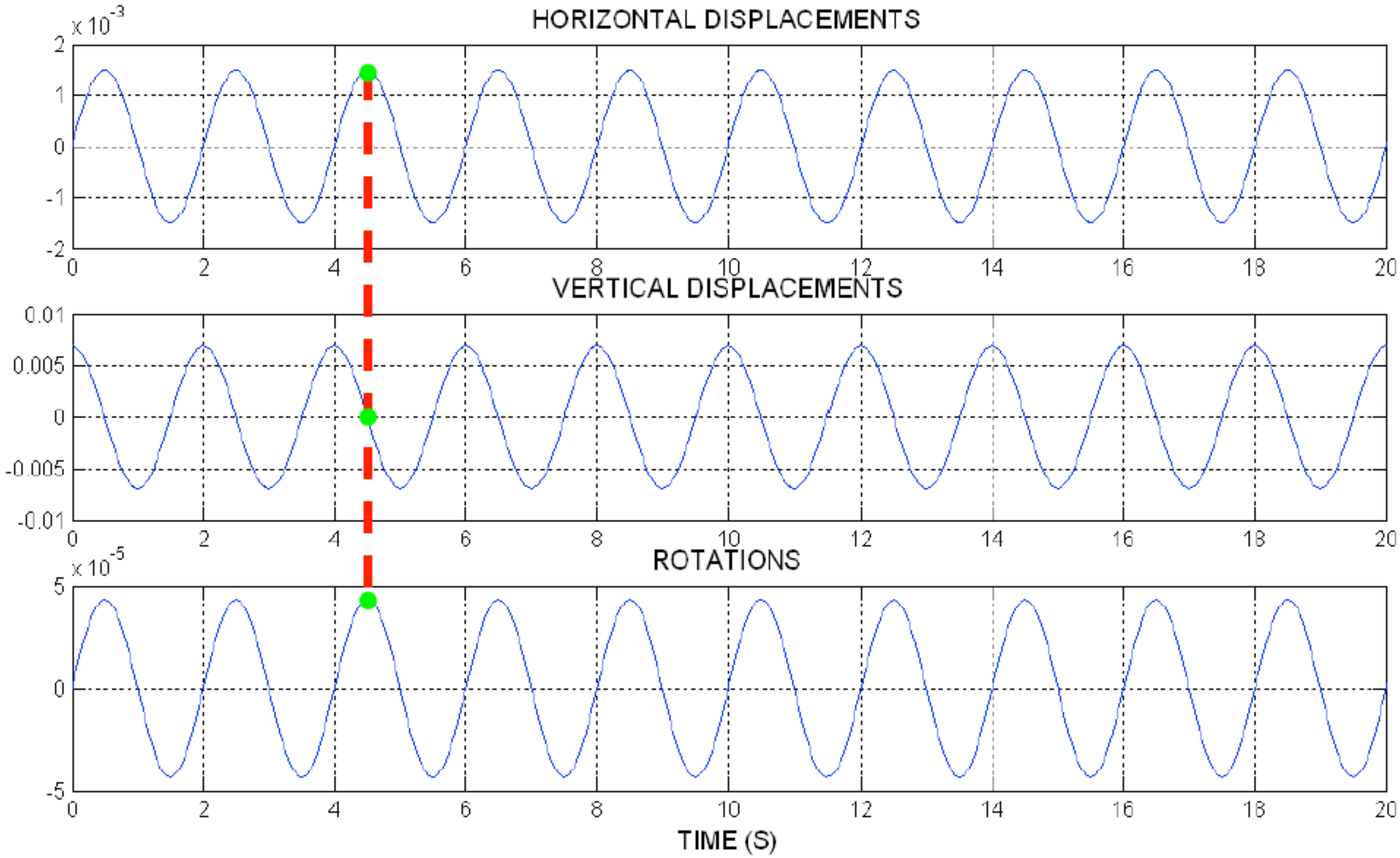
$$k = \frac{\omega}{V}, \quad q = k^2 - \frac{\omega^2}{V^2}, \quad s = k^2 - \frac{\omega^2}{V^2}$$

$$\theta(x,t) = \frac{\partial v(x,t)}{\partial x} = -ik \cdot v(x,t)$$

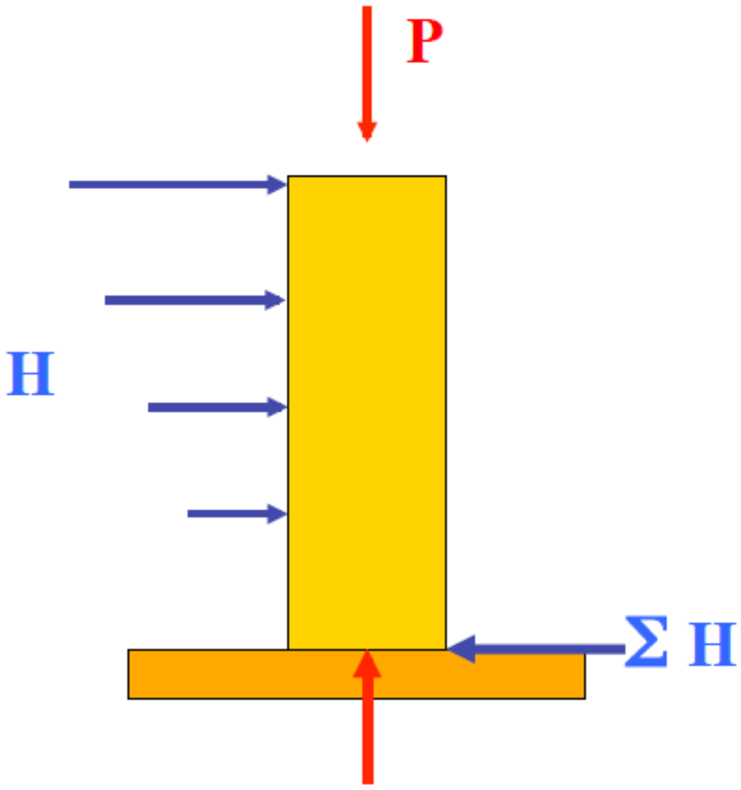
HORIZONTAL AND VERTICAL DISPLACEMENTS AND ROTATIONS DUE TO RAYLEIGH WAVES

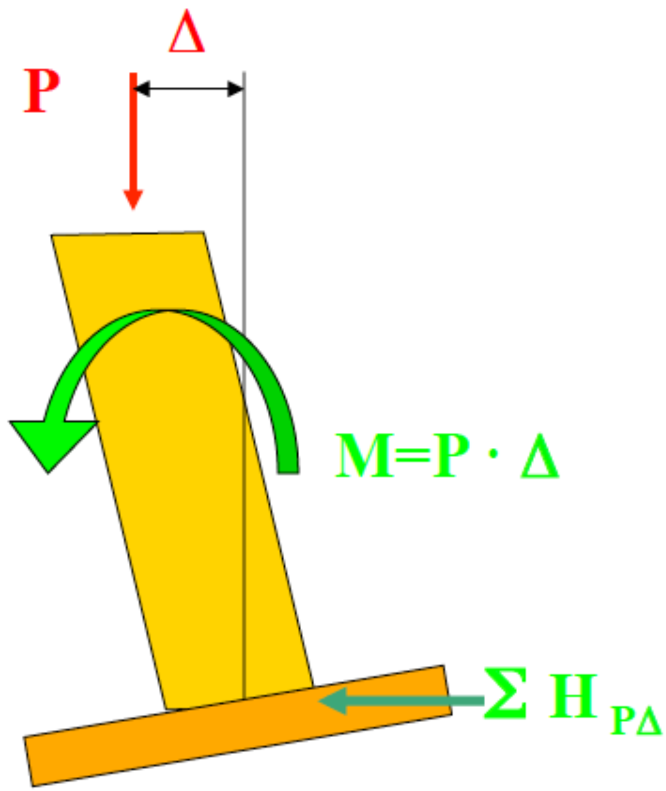
(Note that horizontal and rotational motions are in phase**)**

Uniform half space with $f = 0.5Hz$, $V_r = 500m/s$, $\upsilon = 0.25$, $V_s = V_r / 0.92$, $V_p = \sqrt{3}\, V_s$



P-Δ EFFECTS DUE TO BASE ROTATION

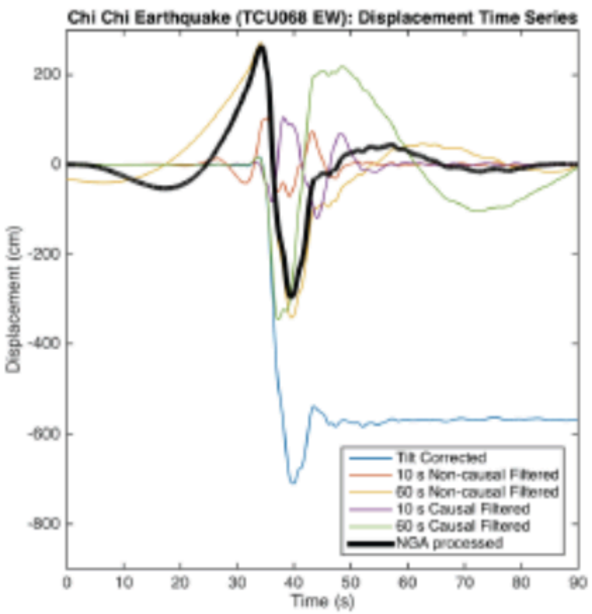




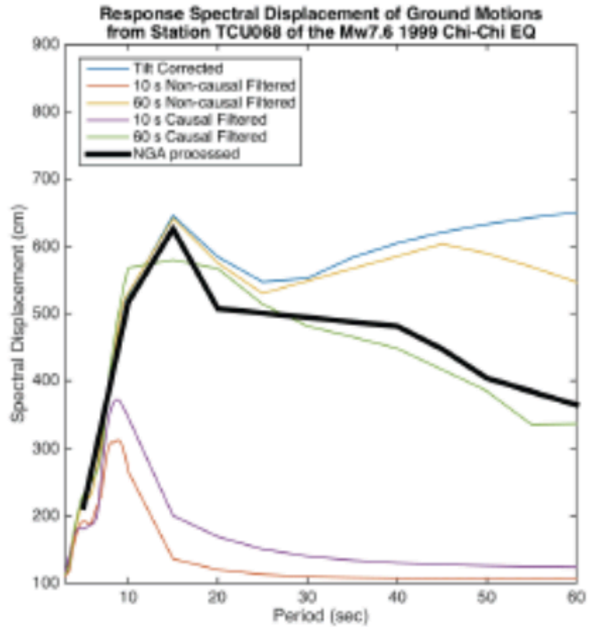
P-Δ Effects

IMPORTANCE OF HIGH-PASS FILTER CORNER ON LONG-PERIOD STRUCTURAL RESPONSE

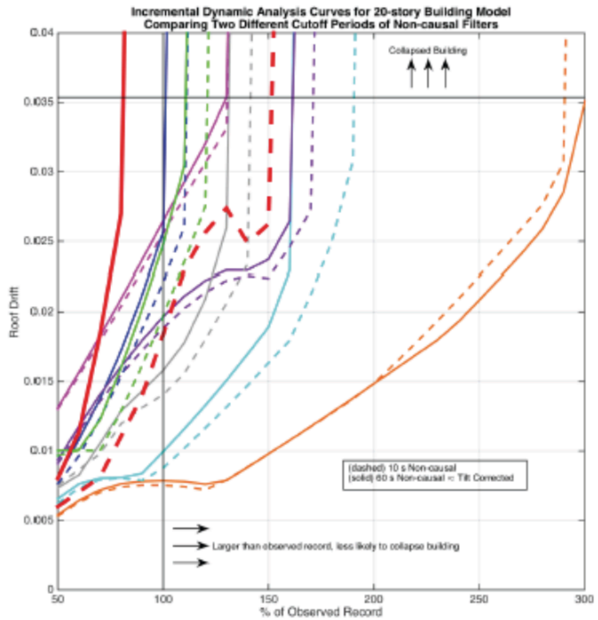
(From: *Becky, R., K. Buyco, and T. Heaton (2017). Filtered data is less likely to introduce collapse in tall buildings than raw records*,
SSA Annual Meeting in Denver, CO, 18-20 April 2017)



Ground Displacement



Displacement response spectra



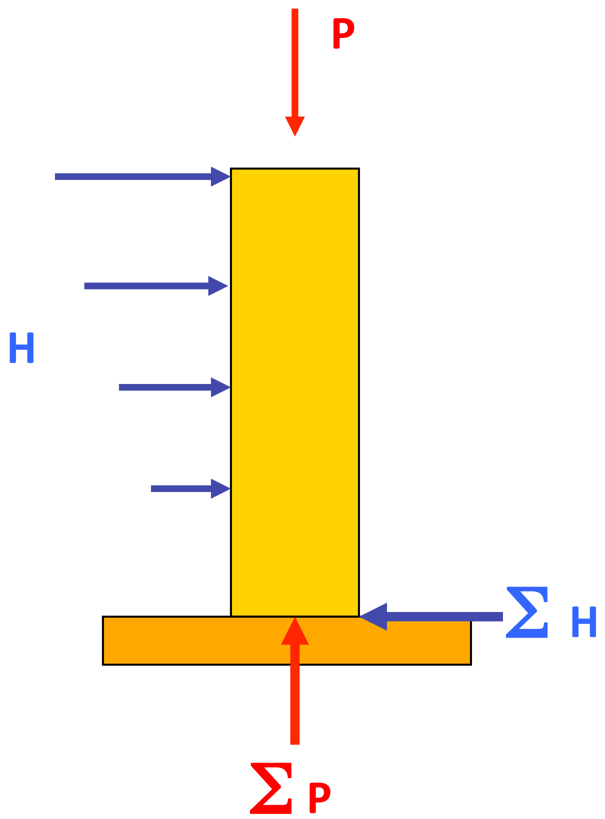
Inter-story drifts in a 20-story building

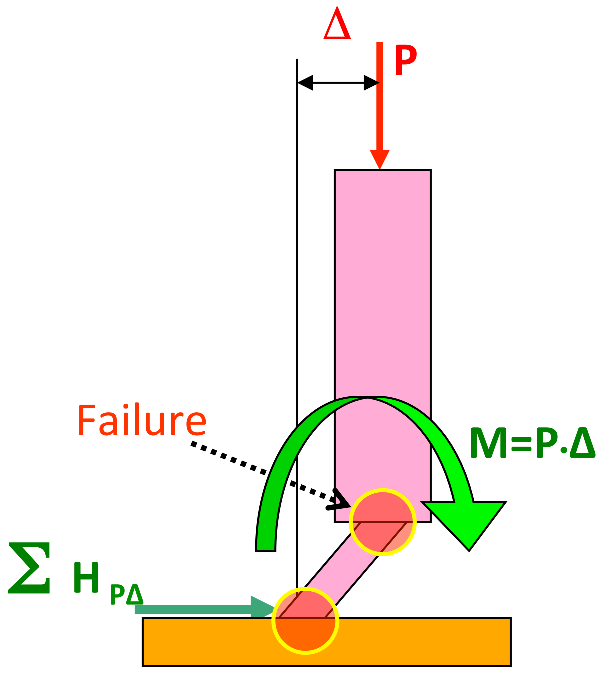
"*The data processing method used in NGA database (i.e., 10 sec. non-causal, zero-phase Butterworth filter) removes the tilt effects from the record and may cause under-estimation of P-Δ effects and collapse probability in long-period structures*".

SOFT-FIRST-STORY BUILDINGS AND P-Δ RESPONSE SPECTRA

DAMAGE TO A TYPICAL APARTMENT BUILDING WITH SOFT FIRST STORY
DURING THE M=7.4, 1999 KOCAELI, TURKEY EARTHQUAKE

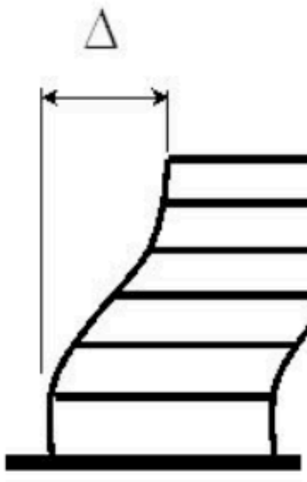
P-Δ EFFECTS ON SOFT-FIRST-STORY BUILDINGS



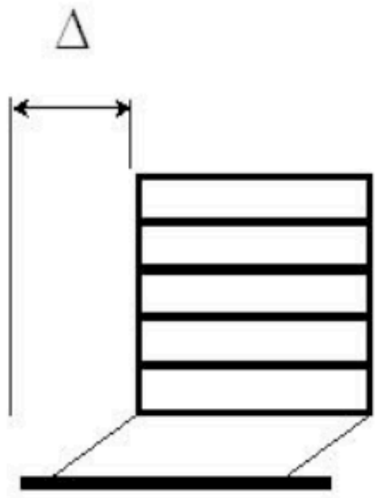


P-Δ Effects due to soft 1st story

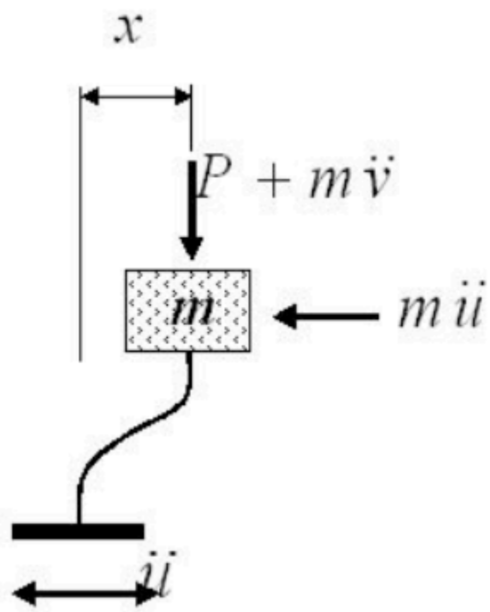
RESPONSE SPECTRA WITH P-Δ EFFECTS



No soft story



Soft story



SDOF model
for P-Δ effects

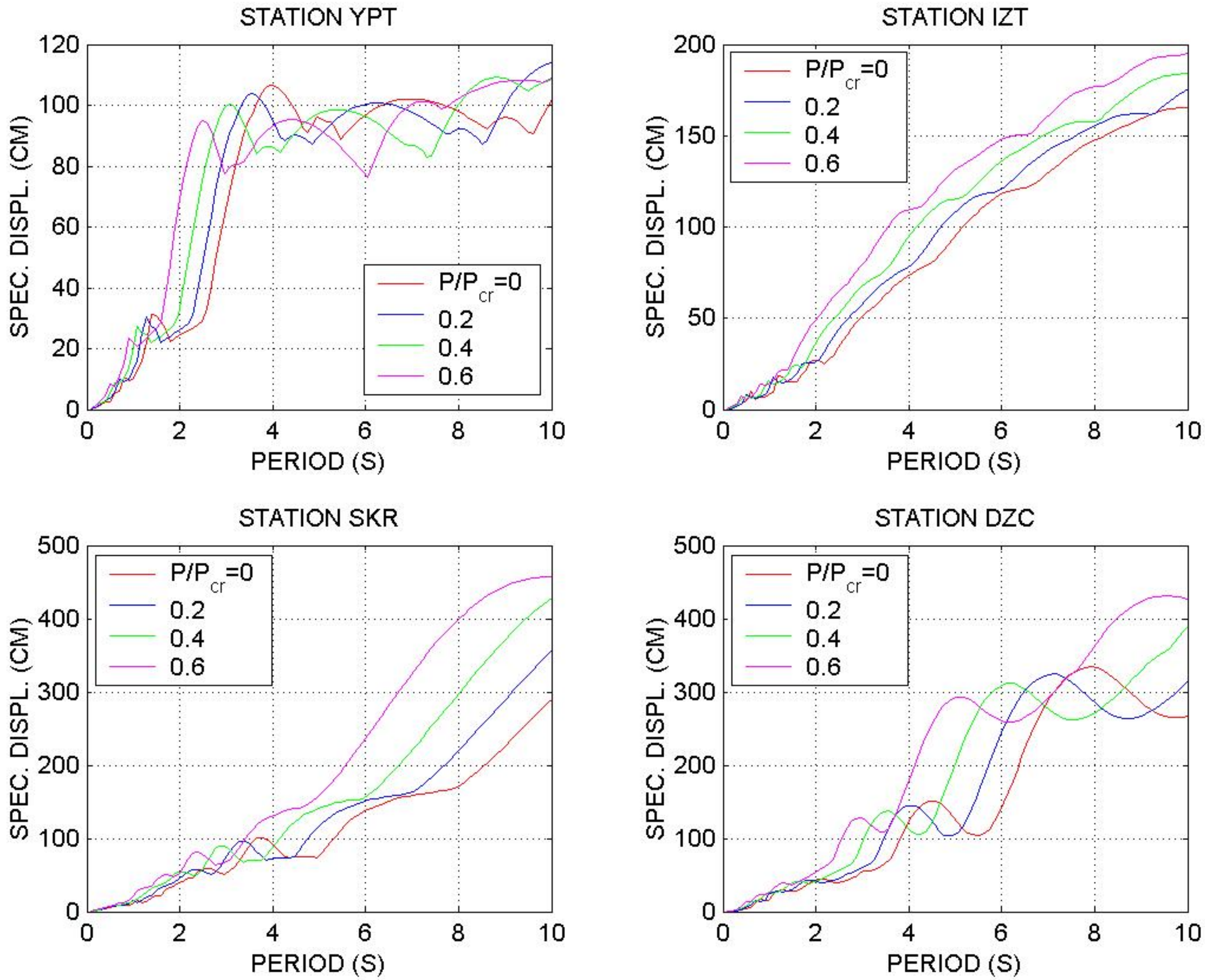
REDUCTION OF NATURAL FREQUENCY DUE TO P-Δ EFFECTS

$$\ddot{x}(t) + 2\xi_0\omega_0 \cdot \dot{x}(t) + \omega_0^2 \cdot \left[1 - \frac{P}{P_{cr}}\left(1 - \frac{\ddot{v}(t)}{g}\right)\right] \cdot x(t) = -\ddot{y}(t)$$

$$\omega_{eff} = \omega_0 \cdot \left[1 - \frac{P}{P_{cr}}\left(1 - \frac{\ddot{v}(t)}{g}\right)\right]^{1/2}$$

Additional parameters needed for response spectra: P/P_{cr} and vertical accelerations.

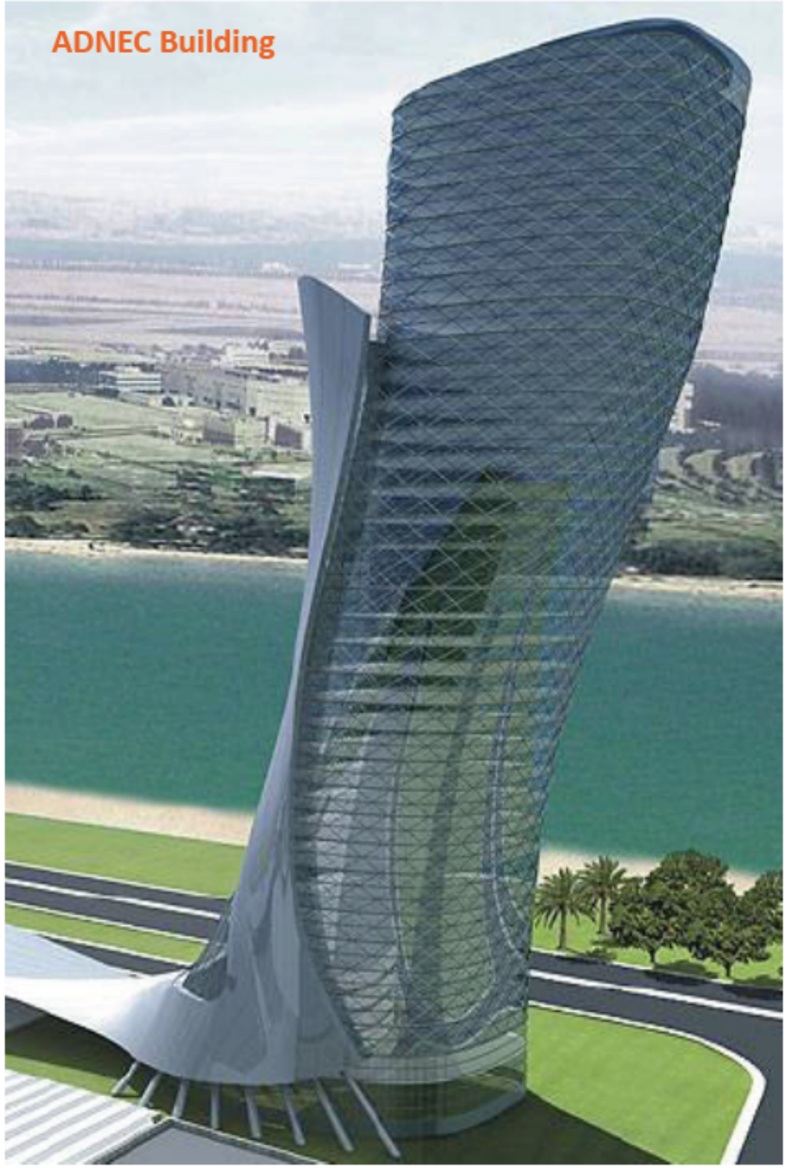
DISPLACEMENT RESPONSE SPECTRA WITH P-Δ EFFECTS



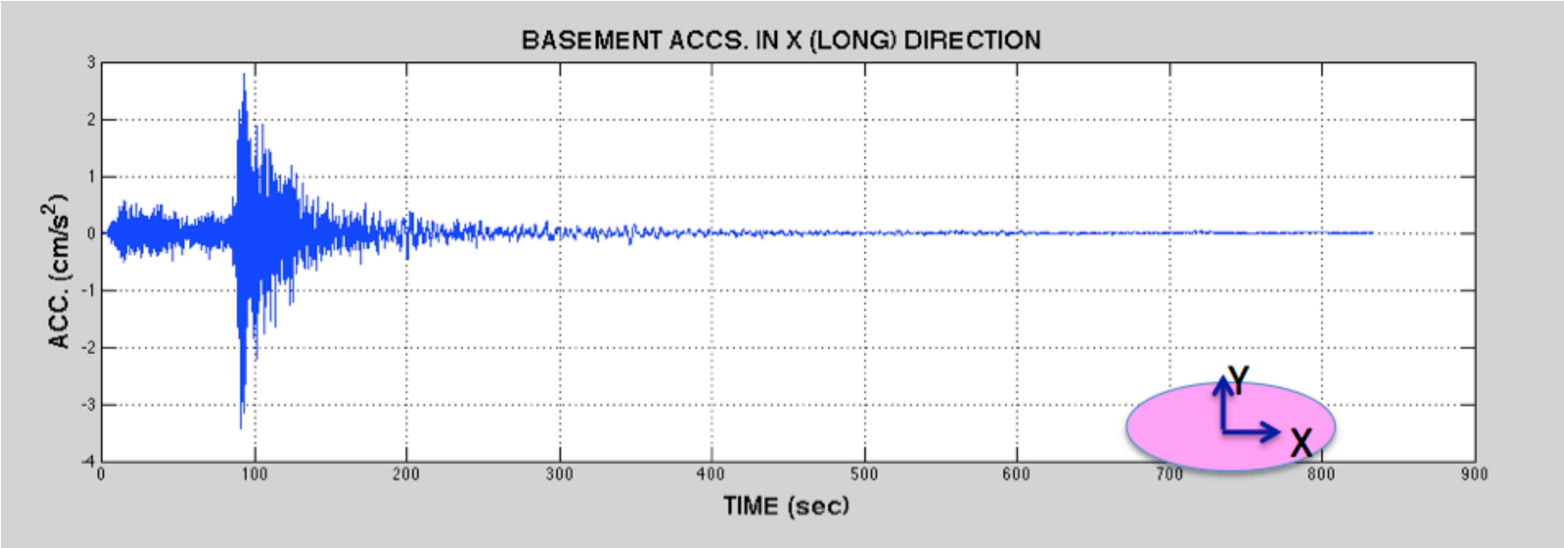
TALL BUILDING RESPONSE TO LARGE DISTANT EARTHQUAKES

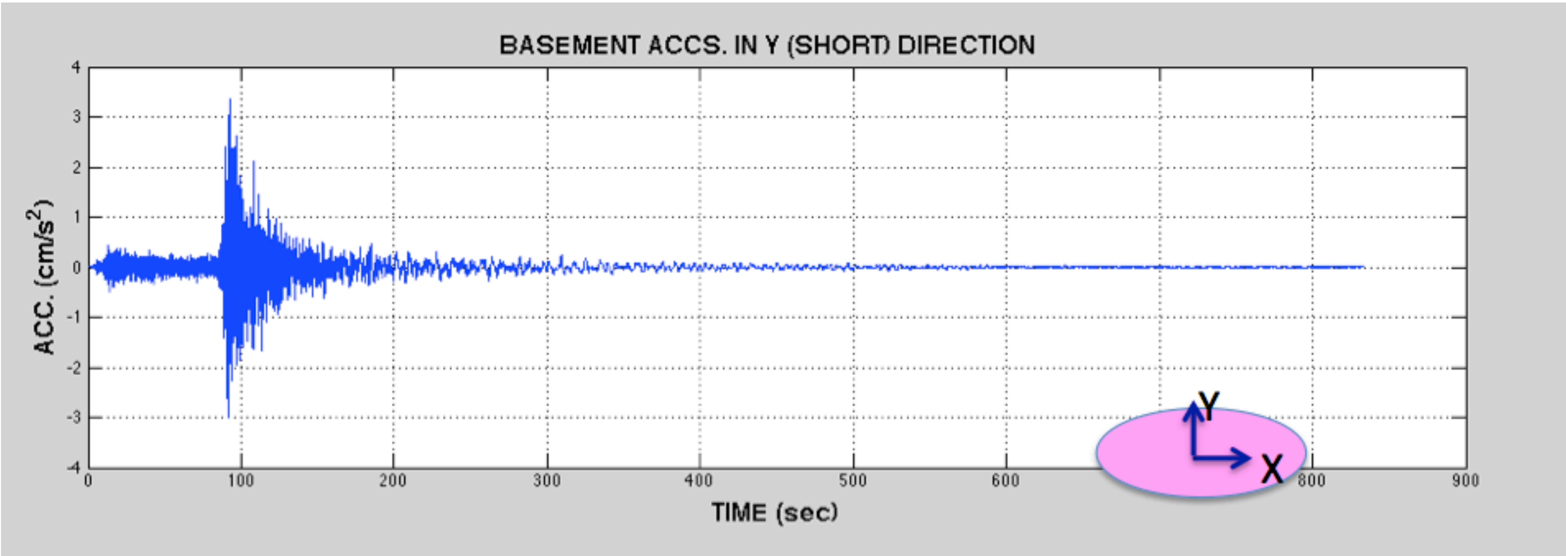
M=7.8; 16 April 2013
≈900 km
Gulf of Oman
United Arab Emirates
Abu Dhabi
Dubai
Muscat
Bandar Abbās
Zahedan
Saravan
Khāsh
Chābahār
Gwadar

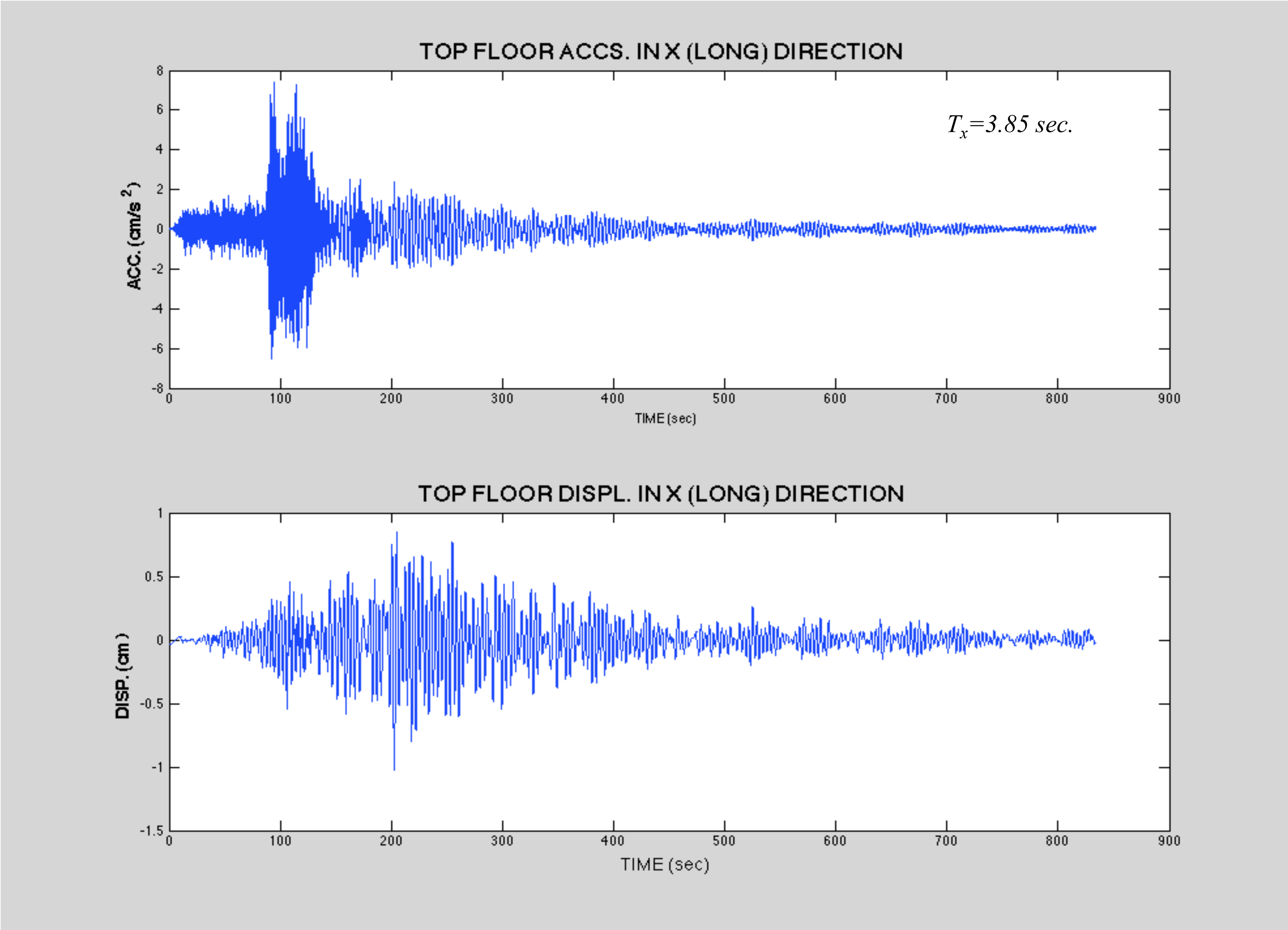
SOME OF THE BUILDINGS WITH STRUCTURAL HEALTH MONITORING SYSTEMS IN ABU DHABI



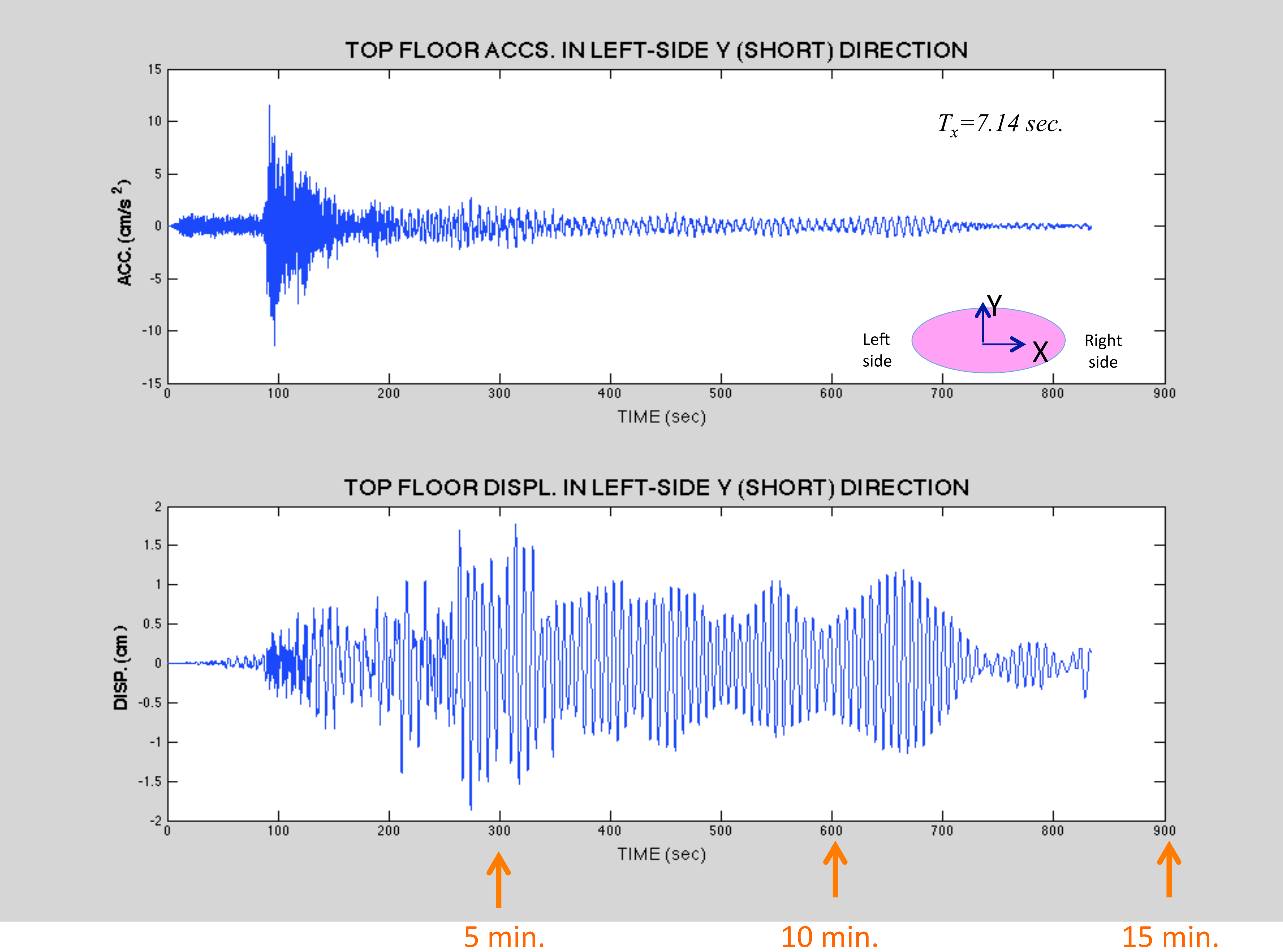
RECORDED GROUND ACCELERATIONS



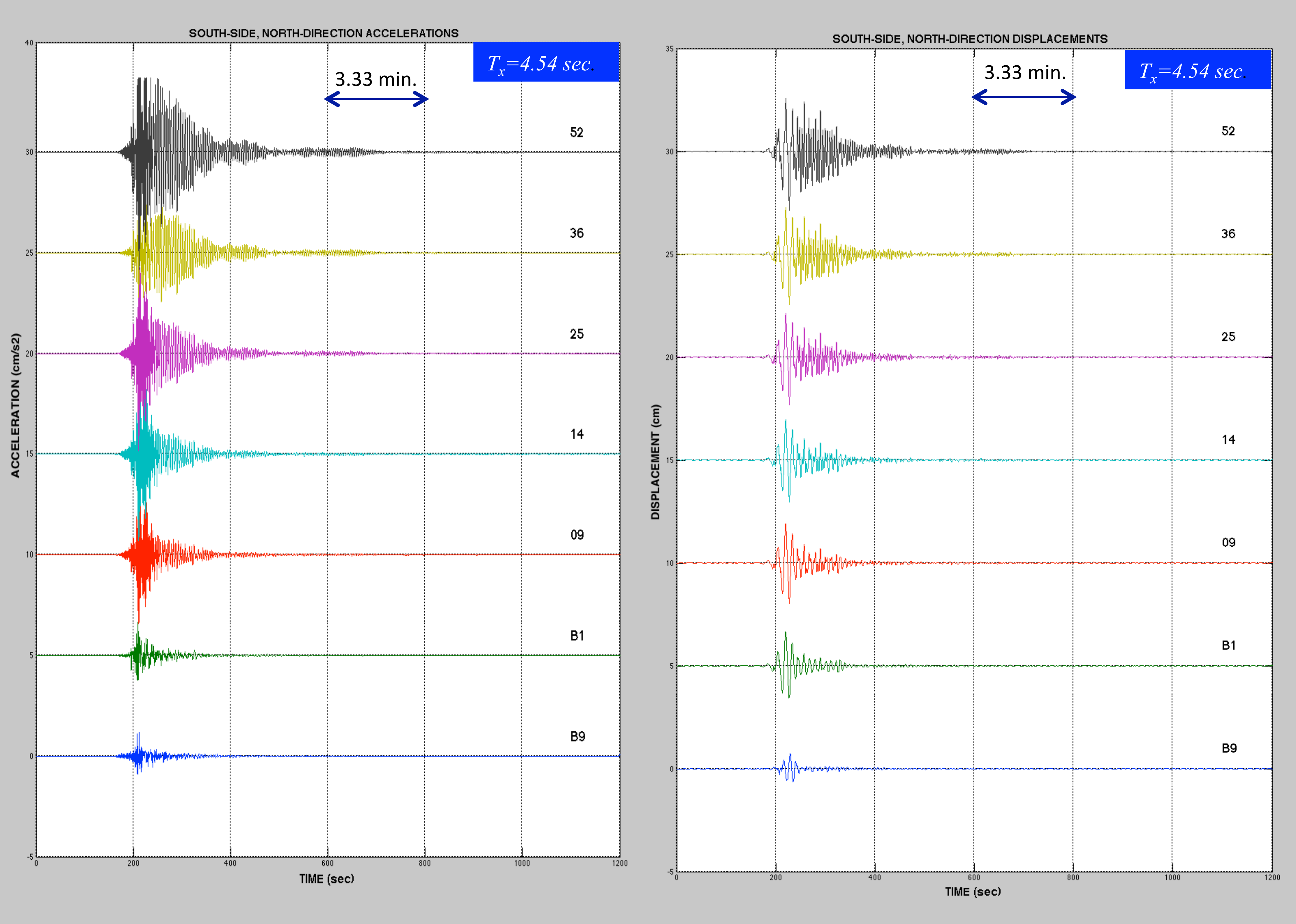




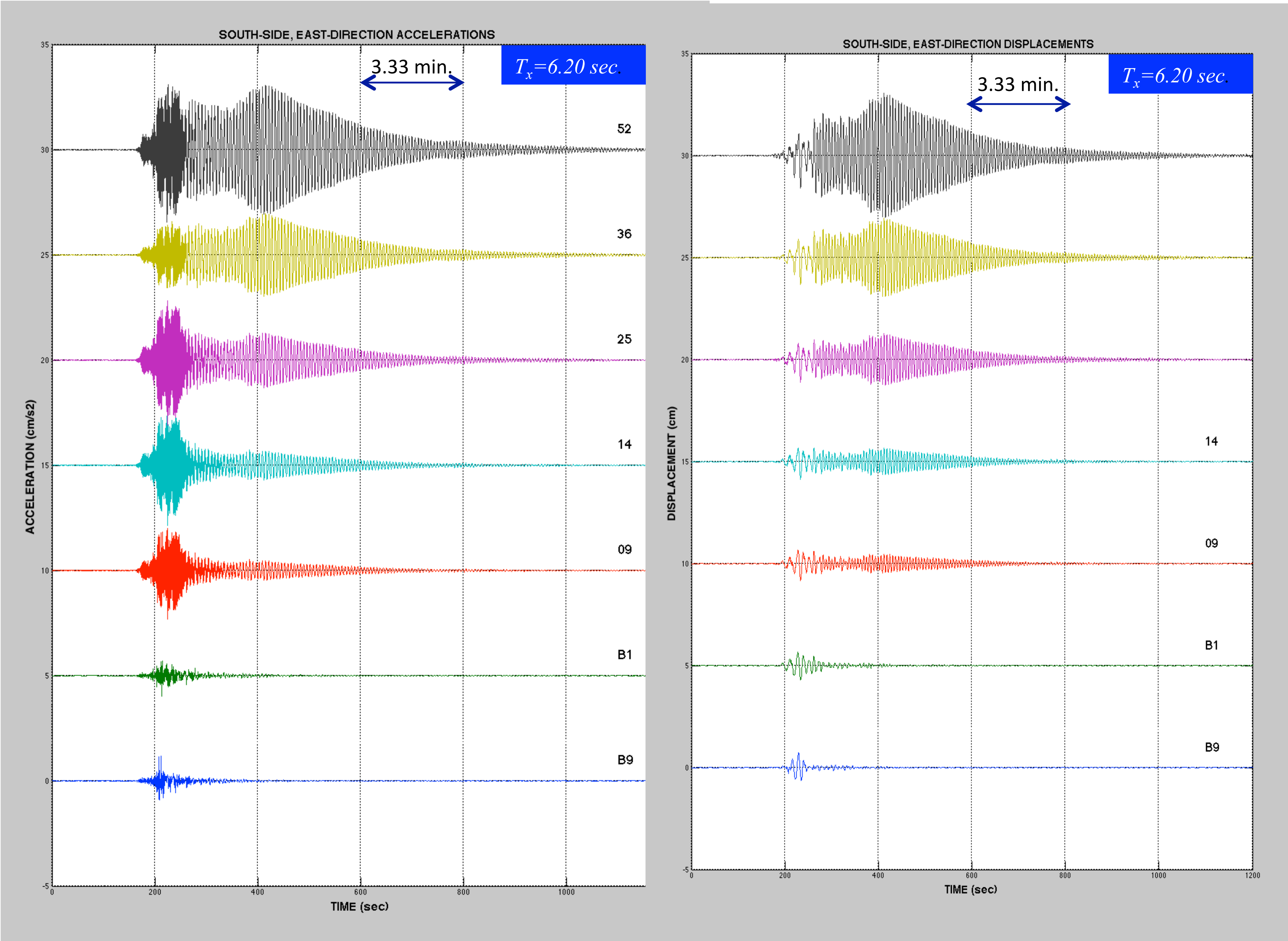
5 min. 10 min. 15 min.


TOP FLOOR ACCS. IN LEFT-SIDE Y (SHORT) DIRECTION
ACC. (cm/s 2)
TIME (sec)
Tx=7.14 sec.
Left side
Right side
Y
X
TOP FLOOR DISPL. IN LEFT-SIDE Y (SHORT) DIRECTION
DISP. (cm)
TIME (sec)
5 min.
10 min.
15 min.

62-story Sapphire Tower
The tallest building in Istanbul

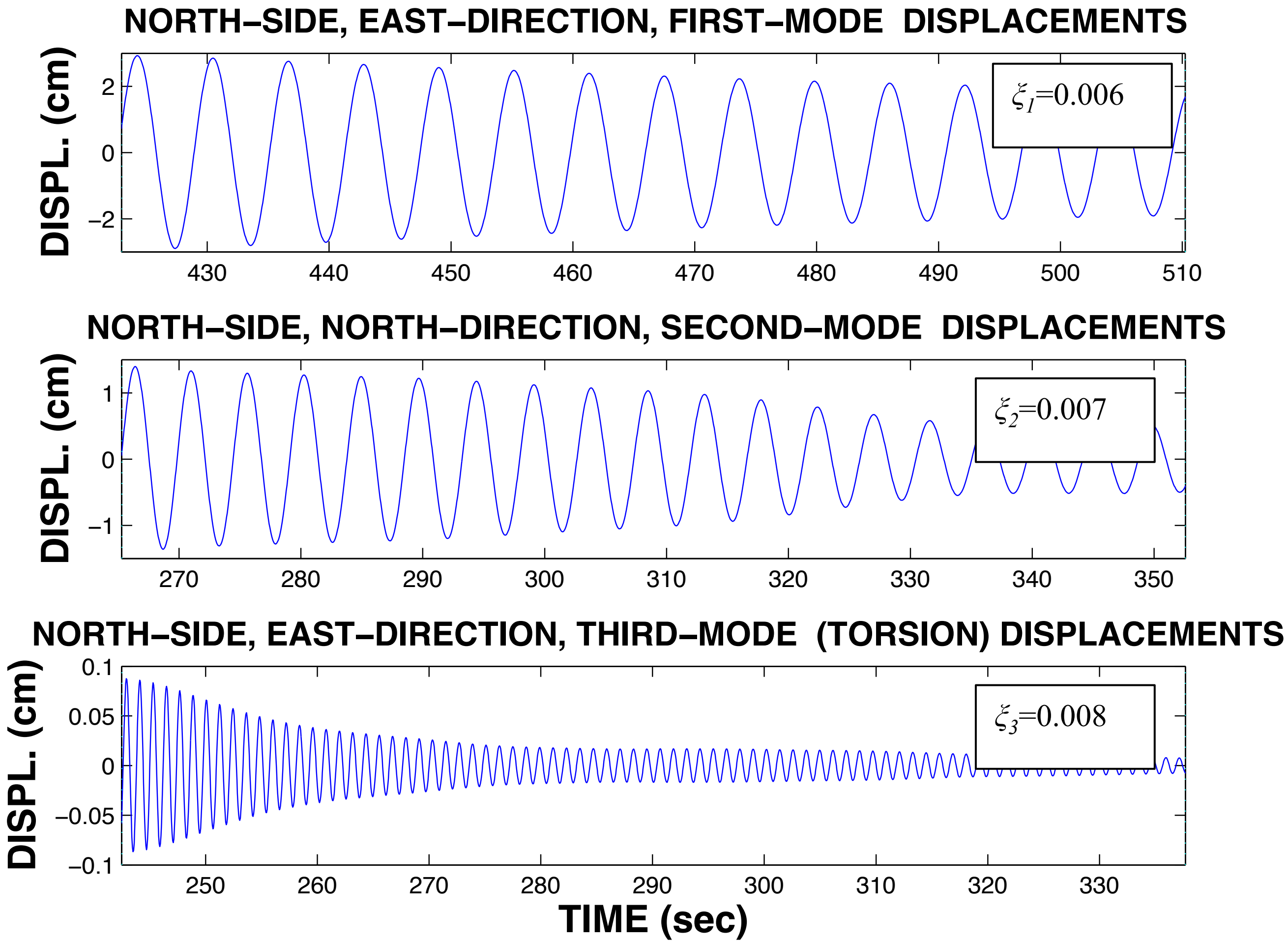


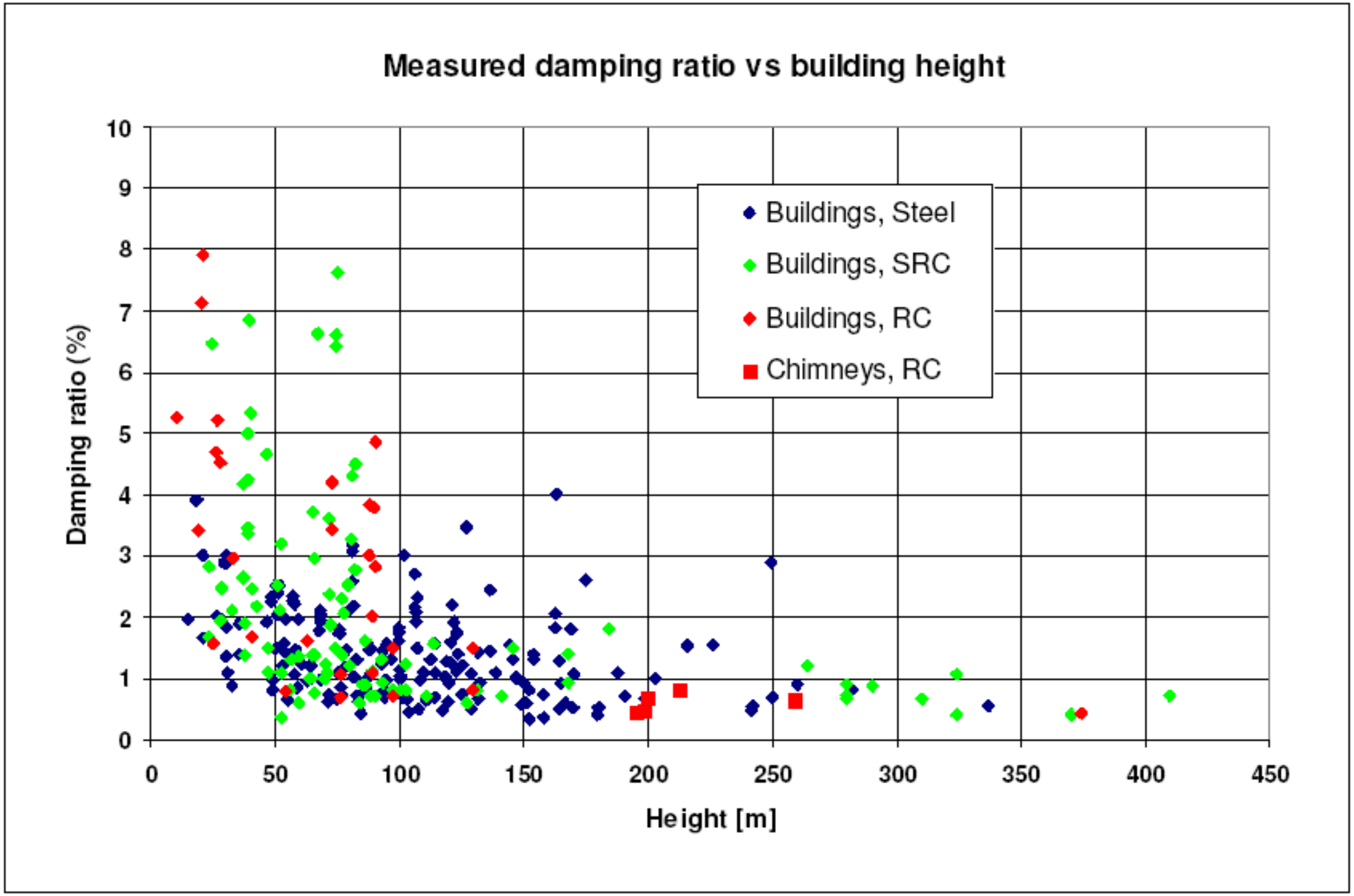
SOUTH-SIDE, NORTH-DIRECTION ACCELERATIONS
T_x=4.54 sec.
3.33 min.
52
36
25
14
09
B1
B9
ACCELERATION (cm/s2)
TIME (sec)
SOUTH-SIDE, NORTH-DIRECTION DISPLACEMENTS
3.33 min.
T_x=4.54 sec.
52
36
25
14
09
B1
B9
DISPLACEMENT (cm)
TIME (sec)



SOUTH-SIDE, EAST-DIRECTION ACCELERATIONS
3.33 min.
T_x=6.20 sec.
52
36
25
14
09
B1
B9
ACCELERATION (cm/s2)
TIME (sec)
SOUTH-SIDE, EAST-DIRECTION DISPLACEMENTS
3.33 min.
T_x=6.20 sec.
14
09
B1
B9
DISPLACEMENT (cm)
TIME (sec)

CALCULATED DAMPING RATIOS





From Satake at.al, 2003

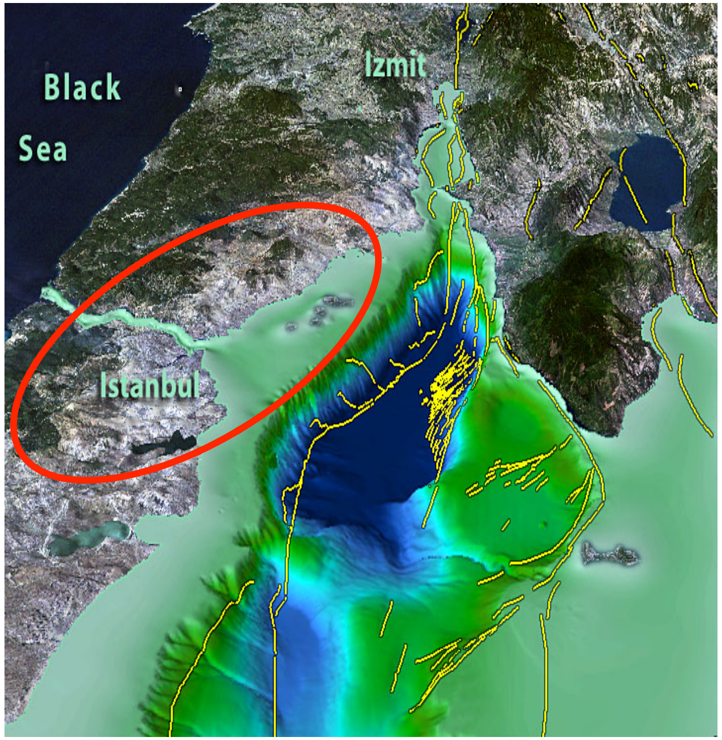
SOME SUGGESTIONS FOR NEW APPROACHES:

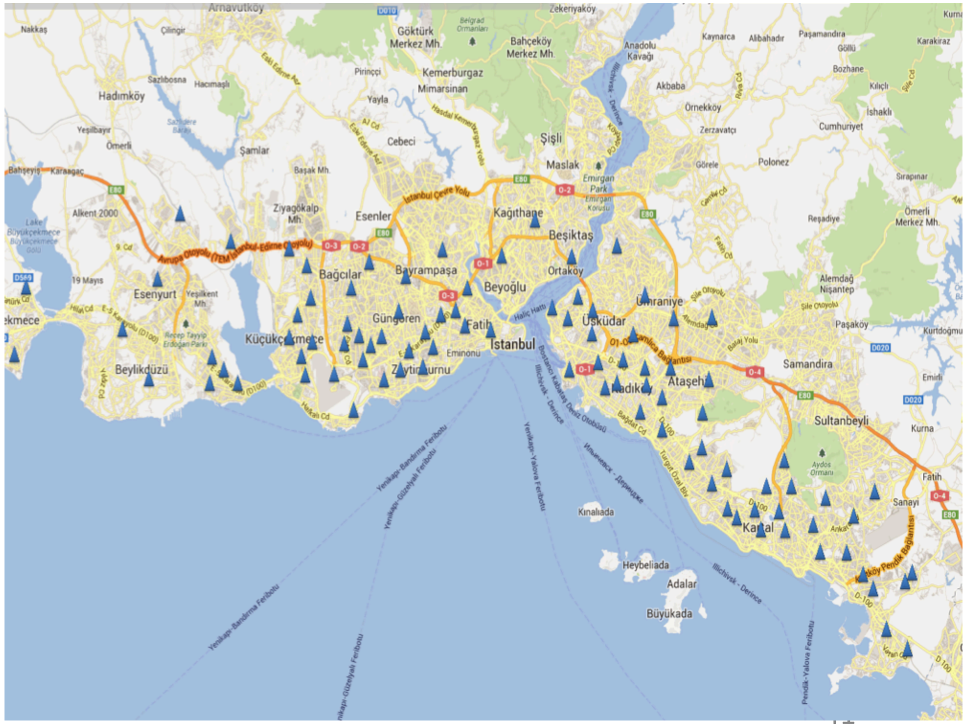
- Utilize data from dense urban networks to supplement GMPEs
- Use a probabilistic approach to calculate response spectra
- Use energy and energy flux for ground motion description and structural response

CAN WE UTILIZE DATA FROM DENSE URBAN NETWORKS TO LOCALIZE GMPEs ?

Example: Istanbul

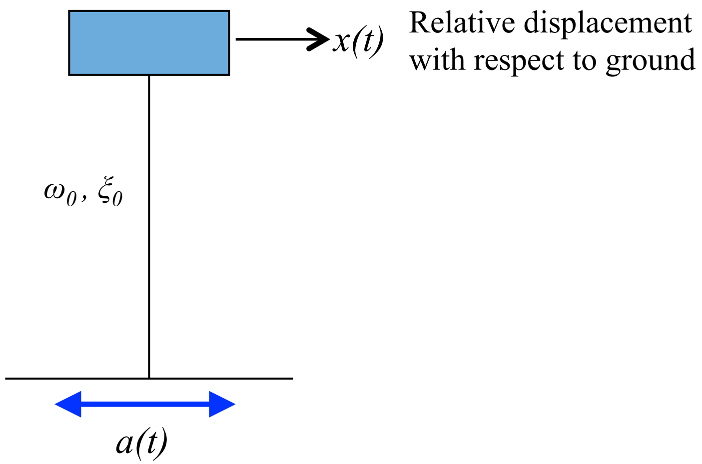
- 100+ real-time strong-motion stations (700 more are currently being installed)
- Over 7,000 records from M>3.00 earthquakes
- Well known fault path
- Topography seems to be important in shaking distribution
- Can a calibrated 3D seismic model be an alternative to GMPEs?

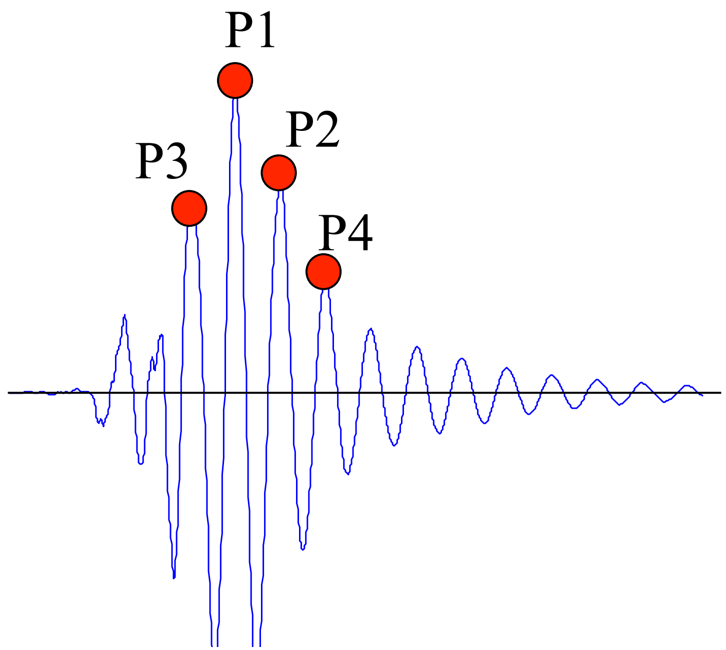


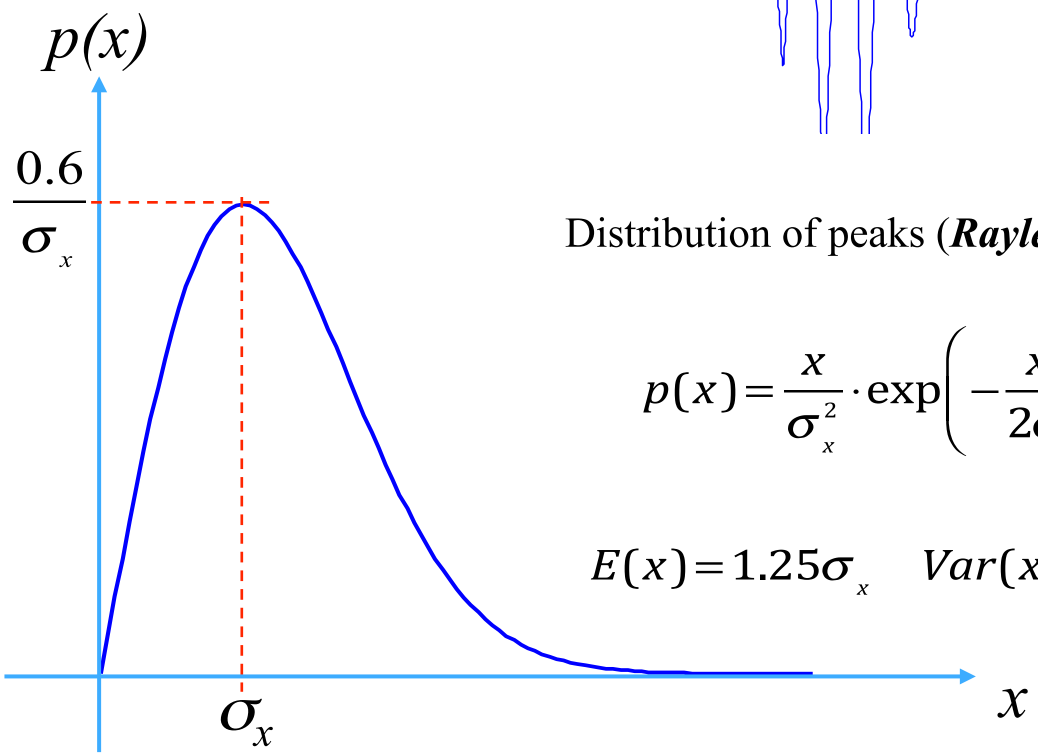


PROBABILISTIC APPROACH TO CALCULATE RESPONSE SPECTRA:

DISTRIBUTION OF PEAKS OF A SDOF OSCILLATOR



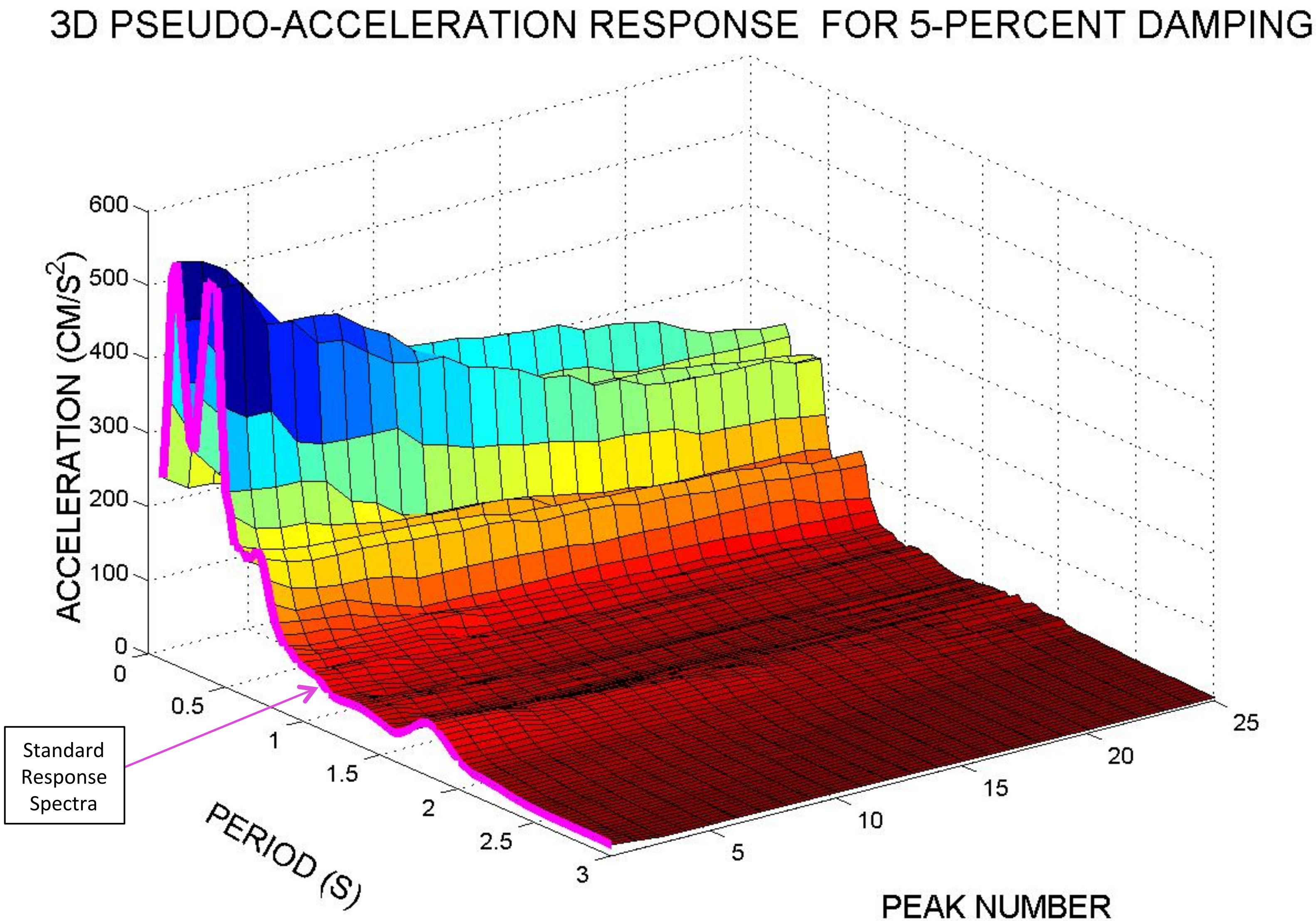




Distribution of peaks (***Rayleigh distribution***)

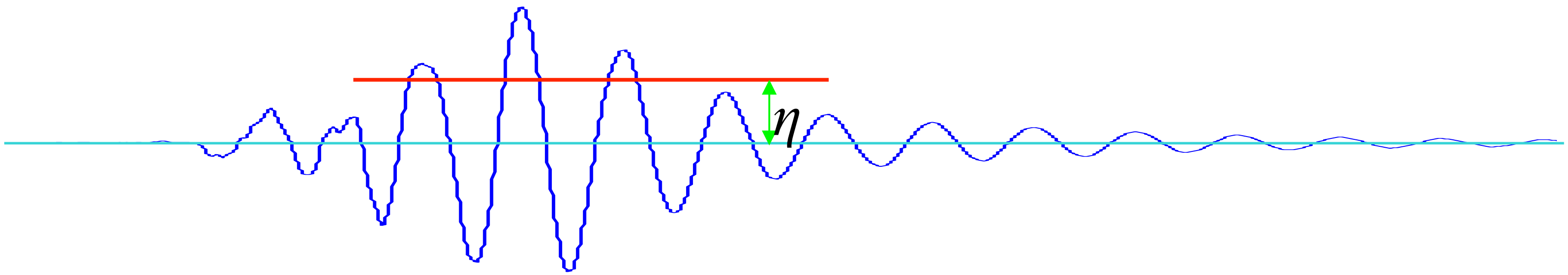
$$p(x) = \frac{x}{\sigma_x^2} \cdot \exp\left(-\frac{x^2}{2\sigma_x^2}\right)$$

$$E(x) = 1.25\sigma_x \qquad Var(x) = 0.43\sigma_x^2$$



The rate of decay of amplitudes with increasing peak number gives a measure of duration.

INFORMATION THAT CAN BE EXTRACTED FROM PROBABILISTIC RESPONSE SPECTRA

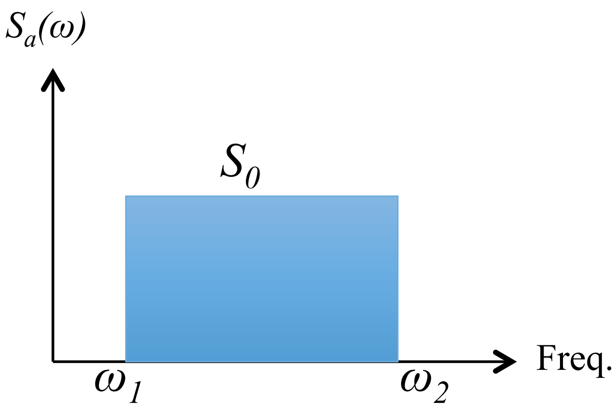


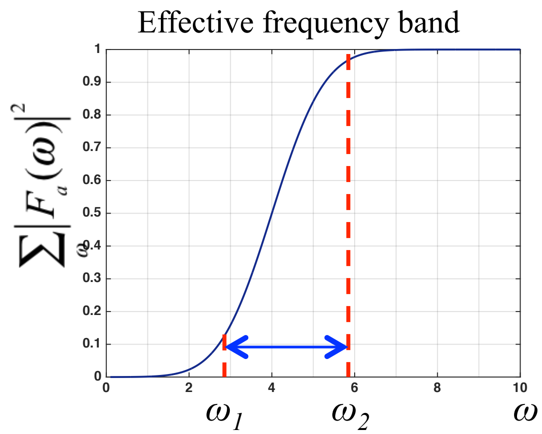
Given: Distribution of peak displacements relative to base.

- Number of crossings of level η per unit time: $N(\eta) = 2f \cdot \exp\left(-\frac{\eta^2}{2\sigma_y^2}\right)$
- Number of cycles (i.e., zero crossings) per unit time: $N(0) = 2f$
- Probability of exceeding a specified displacement level η: $\mathrm{F}(\eta) = \int_0^\eta p(\eta) \cdot d\eta$
- Displacement level corresponding to a specified probability of exceedance: $\eta = \mathrm{inv}\left[\int_0^\eta p(\eta) \cdot d\eta\right]$

RANDOM VIBRATION APPROACH TO STRUCTURAL RESPONSE

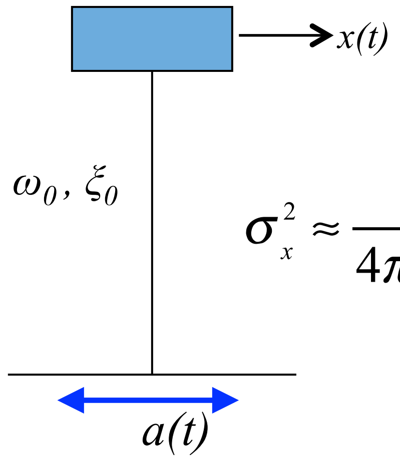
Power Spectral Density of ground accelerations: $S_a(\omega) = \lim_{T\to\infty} \frac{\pi}{T} \cdot E\left[\left|F_a(\omega)\right|^2\right]$ where $\int_{-\infty}^{\infty} S_a(\omega)\cdot d\omega = \sigma_a^2$





$$\sigma_a^2 = \int_\omega S_a(\omega)\cdot d\omega = S_0\cdot(\omega_2 - \omega_1)$$

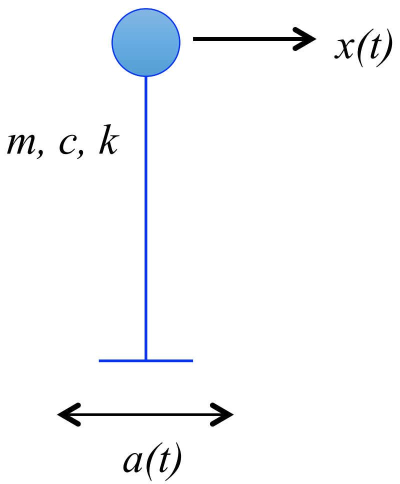
$$\Rightarrow \quad S_0 = \frac{\sigma_a^2}{\omega_2 - \omega_1}$$



$$\sigma_x^2 \approx \frac{S_0}{4\pi^2 \xi_0 \omega_0^3}$$

S_0 is the best single parameter to characterize ground shaking for engineering purposes.

ENERGY-BASED FORMULATION OF RESPONSE



$$m\cdot\ddot{x}(t)+c\cdot\dot{x}(t)+k\cdot x(t)=-m\cdot a(t)$$

Dividing by m and denoting: $k/m=\omega_0^2$ and $c/m=2\xi_0\omega_0$:

$$\ddot{x}(t)+2\xi_0\omega_0\cdot\dot{x}(t)+\omega_0^2\cdot x(t)=-a(t)$$

(ξ_0 and ω_0 vary with x and t if nonlinear)

By integrating over the relative displacement with respect to base:

$$\underbrace{\int_x \ddot{x}(t)\cdot dx}_{E_k=\text{Kinetic Energy}}+\underbrace{\int_x 2\xi_0\omega_0.\dot{x}(t)\cdot dx}_{E_D=\text{Damping Energy}}+\underbrace{\int_x \omega_0^2\cdot x(t)\cdot dx}_{E_A=\text{Absorbed Energy}}=\underbrace{-\int_x a(t)\cdot dx}_{E_I=\text{Input Energy}}$$

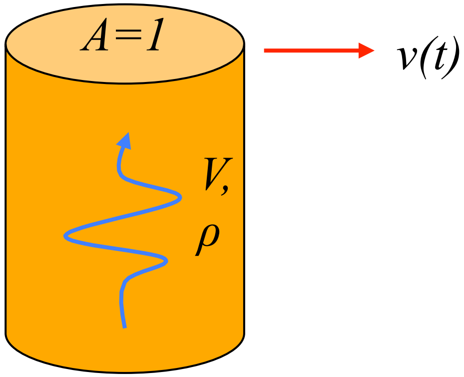
$$E_K+E_D+E_A=E_I \quad \text{(all for per unit mass)}$$

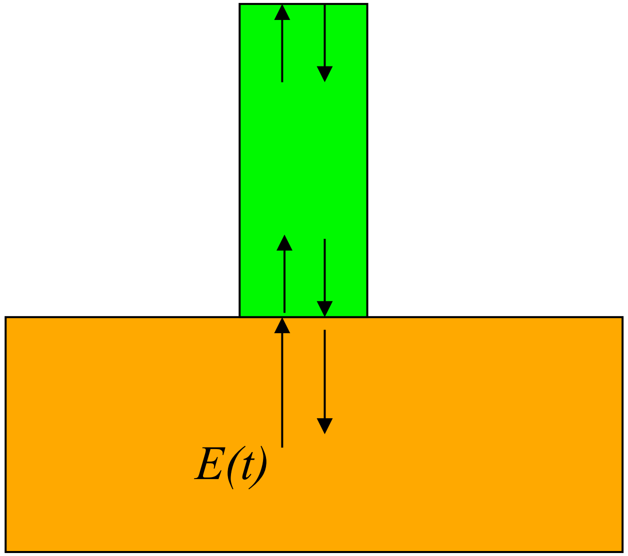
where E_D, E_A includes energies absorbed due to elastic and inelastic behaviors.

Energy response spectrum is the plot of $(E_I)_{\max}$ against $T_0=2\pi/\omega_0$ for given $a(t)$ and ξ_0.

ENERGY FLUX

"Amount of energy transmitted through a cross section per unit time."

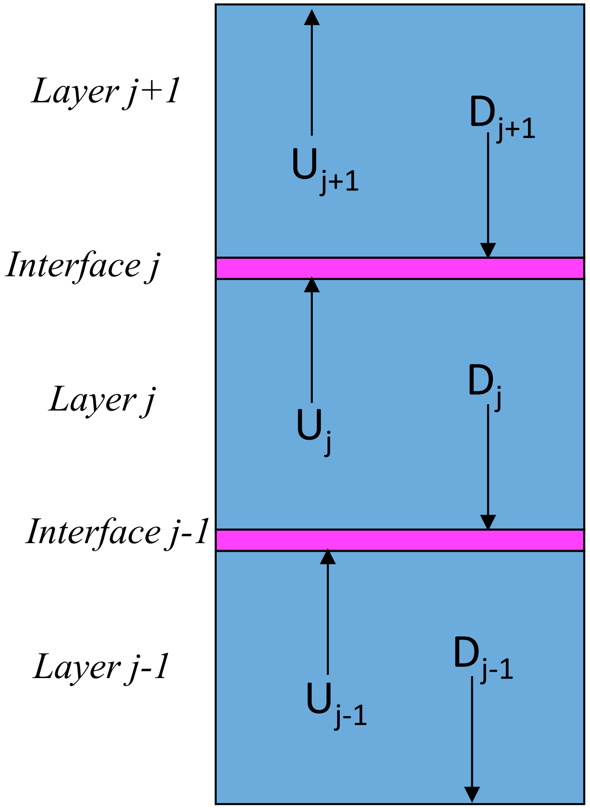




$$Energy\ Flux = \frac{1}{2} \times (mass\ density) \times (ground\ velocity)^2 \times (wave\ propagation\ velocity)$$

$$E(t) = \frac{1}{2} \cdot \rho \cdot [v(t)]^2 \cdot V$$

PROPAGATION OF ENERGY FLUX IN A MULTI-STORY BUILDING



$$U_j(t) = A_j^2(f) \cdot [\alpha_{j-1}(f) \cdot D_j(t-\tau_j) + \beta_{j-1}(f) \cdot U_{j-1}(t-\tau_j)]$$

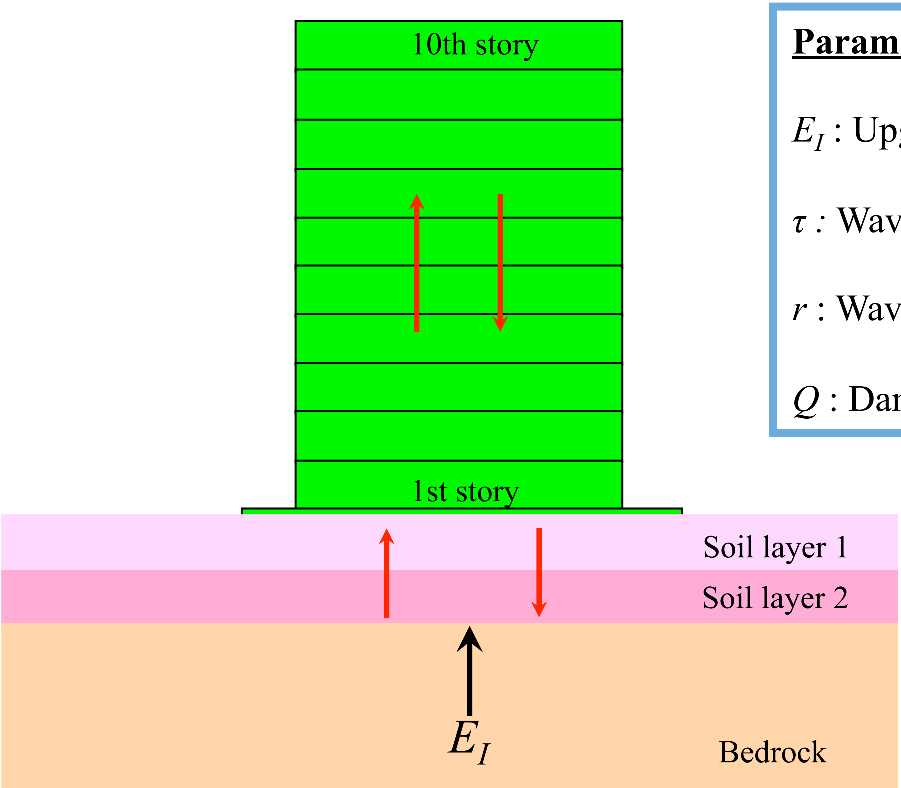
$$D_j(t) = A_j^2(f) \cdot [\alpha_j(f) \cdot U_j(t-\tau_j) + \beta_j(f) \cdot D_{j+1}(t-\tau_j)]$$

$\alpha, \beta =$ Energy reflection and transmission coefficients

$\tau =$ Wave travel time in the layer

$A(f) = \exp\left(-\frac{\pi \tau f}{Q}\right)$ - Energy loss due to damping

EXAMPLE: Energy flux in a 10-story building on two-layer soil media



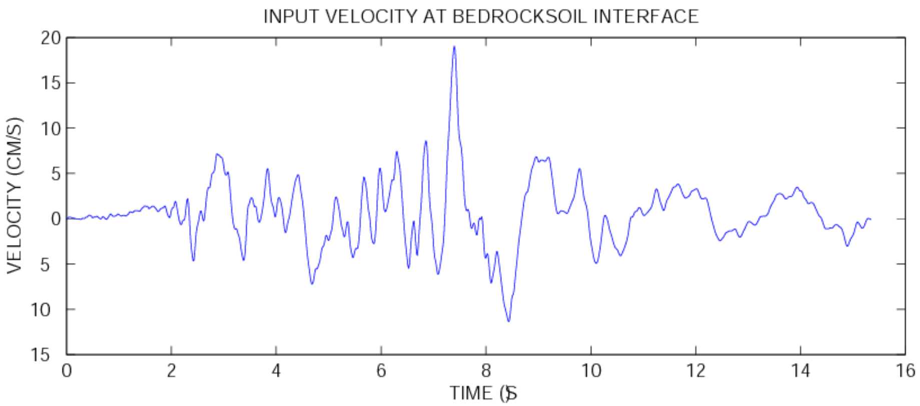
Parameters required:

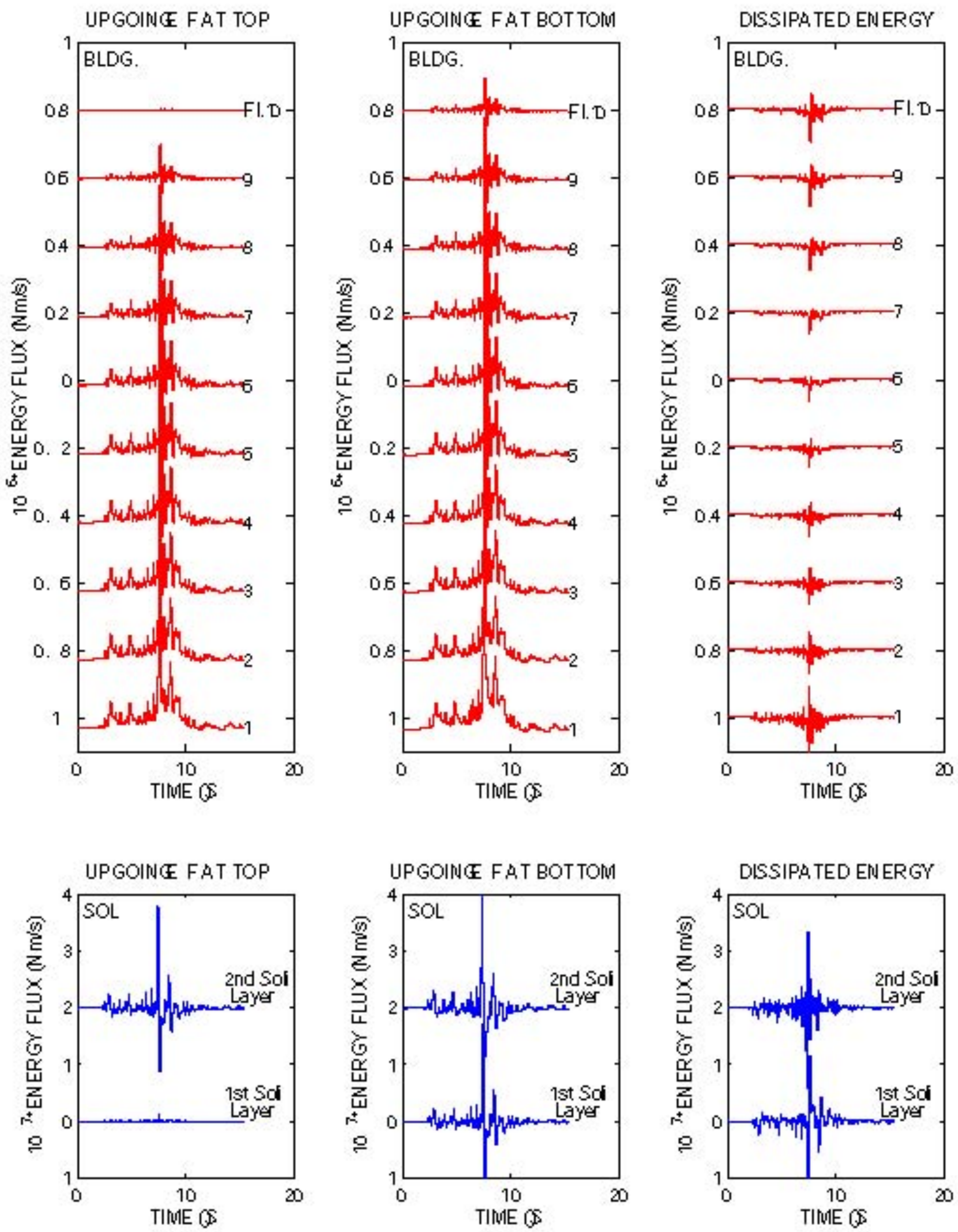
E_I : Upgoing input energy (or velocity) from ground

τ : Wave travel times in layers.

r : Wave reflection coefficients at layer interfaces.

Q : Damping in each layer.




UPGOINGE FAT TOP
UPGOINGE FAT BOTTOM
DISSIPATED ENERGY
BLDG.
FLD
10 6* ENERGY FLUX (Nm/s)
TIME (S)
SOL
2nd Soil Layer
1st Soil Layer
10 7* ENERGY FLUX (Nm/s)

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SOME CONCLUSIONS:

- Performance-based design requires the control of inelastic deformations, which are very sensitive to the initial build-up of ground accelerations and the yield point of the structure.

- Surface waves from distant large earthquakes can be critical for long-period structures because of rotational excitations and P-Δ effects.

- Duration of vibration of a structure is related to its natural frequency and damping, and does not always correlate with the duration of earthquake.

- Collapse of soft-first-story structures is also controlled by P-Δ effects and vertical ground accelerations.

- Damping in tall buildings decrease with increasing height, and can be as low as 1%.

- Probabilistic response spectra provide much more information than standard response spectra.

- Energy-based representation of ground shaking and structural response can be a powerful alternative to current seismic design methods.