Ambient Noise Imaging and Monitoring,

Cargese (Corsica), on April 22nd-27th, 2013

Wave Methods for Structural System Identification and Health Monitoring of Buildings

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http://www.usc.edu/dept/civil_eng/Earthquake_eng/

Outline

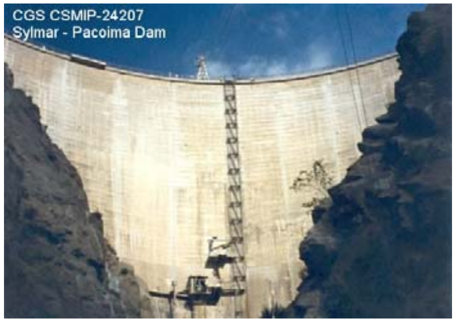
- The problem
- Similarities and differences with the similar problem in geophysics
- Examples using earthquake excitation
- What is being done and can be done with noise?

The Problem

- Determine if a structure has been damaged, **during** or **soon after** the earthquake, before physical inspection is possible.
- Such information is useful for **timely** decision making on **evacuation**; and also **emergency response** (help will be sent where most needed).
- Benefits to society: **prevent loss of life and injuries** caused by potential collapse of the weakened structure during shaking from aftershocks/ **avoid needless** evacuation (San Francisco Occupancy Redemption Program).
- What is needed: sensors, data communication network, and **methodology for damage detection** (what physical parameter should be monitored, what change means damage, etc.).

The Structures

- Bridges
- Dams
- **Buildings**



Height:

h = 4m/floor; H=10–300 m

Shear wave velocity:

Vs = 100 – 400 m/s

Fundamental period of vib.:

T ~ n/10 (roughly)

Data:

0.02 – 25 Hz (50 Hz)

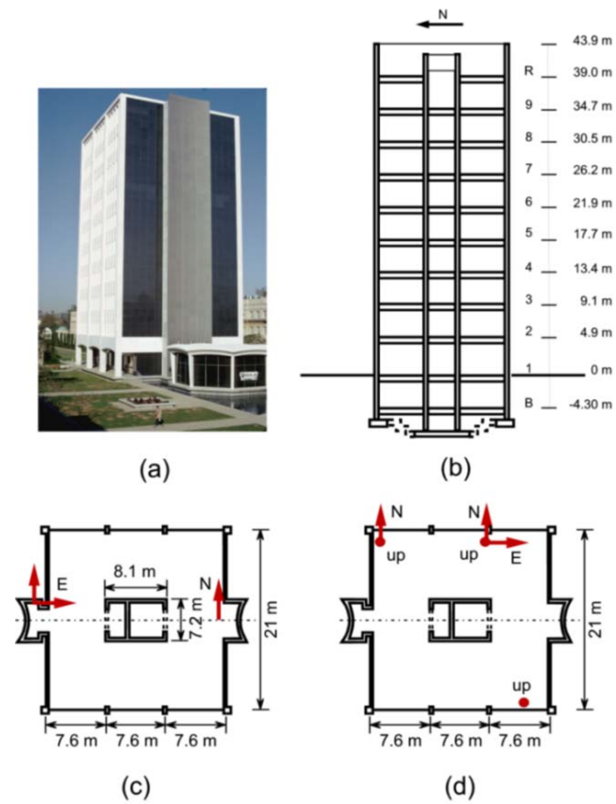
Buildings

Materials:

Reinforced concrete: nonlinear elastic behavior
Steel: much more linear behavior.

Lateral force resisting system:

Moment resisting frame, Shear walls, bracing.



Type of deformation:

The elements (beams and columns) -
deform more in bending (dispersive w.p.)
Building as a whole -
deforms more like a **shear beam** (nondispersive w.p.).
Evidence:
ratios of modes of vibration (1:3:5:7…. vs. 1:6.27:17.5…)

Structural Health Monitoring

Definition: tracking the state of health of a structure based on some instrumental data

Vibrational methods:

- NDT – local; determine the location of damage (within an element); excitation – actuator; not practical for buildings (need access to the element; expensive).
- Seismic – use earthquake excitation, ambient noise or shaker.

  Modal - frequencies of vibration or mode shapes - global

  Wave - velocities of wave propagation through the structure – intermediate scale (?)

Historical Perspective – ambient noise tests

- Review article by Ivanovic, Trifunac and Todorovska, ISET 2000.

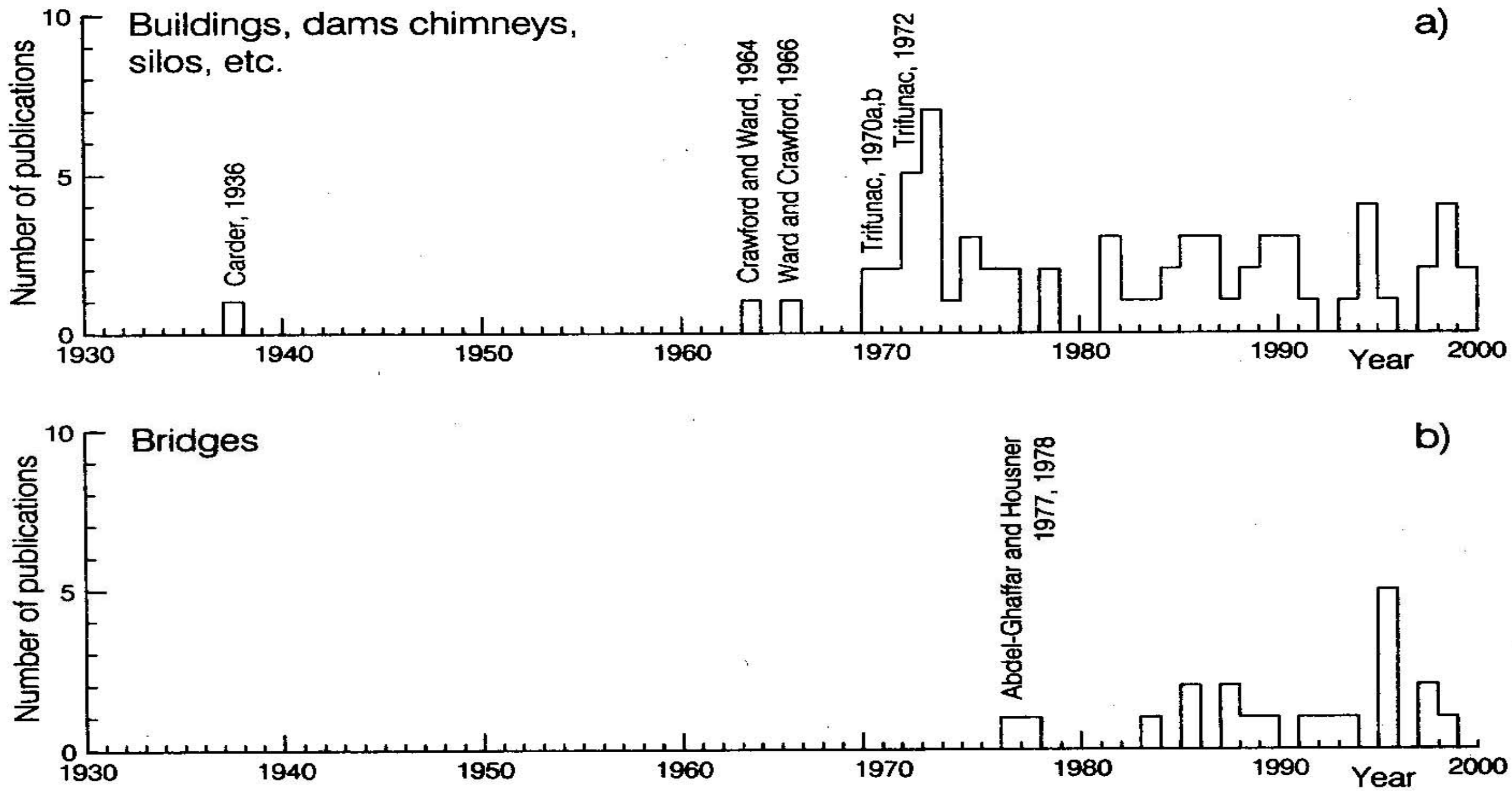


Fig. 1 Frequency of occurrence of published contributions to the subject of ambient vibration testing of full-scale structures: (a) buildings, dams, chimneys, silos,... (b) bridges

Historical Perspective – earthquake records

Some Milestones in Earthquake Engineering (Trifunac et al., 2001):

- 1906: San Francisco earthquake, California.
- 1923: Great Kanto earthquake, Japan.
- 1924: ERI is established in Japan.
- 1932: Suyehiro gives lectures in the U.S. In his lectures he mentions ambient vibration studies of ERI building etc.
- 1933: Long Beach earthquake, California (M=5.4).
- 1940: Imperial Valley earthquake, California.
- 1948: EERI established in U.S.
- 1956: 1WCEE held in San Francisco (every 4 years since then)
- 1971: San Fernando earthquake, California. Many records in structures
- 1994: Northridge earthquake, California. Many records in structures.

Earthquake Records in Structures

Hollywood Storage Building:

Longest history of recording in U.S. – 80 years.

First record in 1933 (So. California earthquake).

Intrumentation Programs:

National Strong Motion Program (USGS)

California Strong Motion Instrumentation Program (CGS)

Buildings ~ 225 (1-62 stories high); bridges: 76; dams: 28

Ground: > 800 stations; 30 geotechnical (downhole) arrays; etc.

Code Buildings: instrumented by owner

Structural Health Monitoring

- Assessment must be **reliable** and **accurate** to be useful:
  - **No failures** to detect significant damage.
  - **No false alarms** – imagine e.g. needless evacuation of a hospital.
- Method must be
  - **Robust**
  - **Sensitive** to damage and **Not sensitive** to other factors (SSI, weather, etc.)
  - **Accurate**
- Robust Methods:
  - Parameter estimation – can track changes
  - Performance based – check id design forces have been exceeded; check for correlation of damage with interstory drift. – cannot track changes
  - Damage probability matrices - rough, good for large stock prediction.

Wave Propagation Method

- Damage sensitive parameter – **velocity of wave propagation**
- Uses information on **phase** rather than amplitudes
- **Shear** and **Torsional** wave velocities identified
- Physical basis:

$$V = \sqrt{\mu / \rho}; \quad \mu = \text{shear modulus}; \quad \rho = \text{mass density}$$

$$V = h / \tau; \quad \tau = \text{travel time}; \quad h\text{=distance travelled}$$

- **Data: vibrationalal (e.g. accelerations)**
- **Moving window analysis** – to detect changes

Wave Propagation Method

- Advantages of the method:
  - **Robust** when applied to **actual buildings** and **large amplitude response data**
  - **Local in nature - more sensitive to local damage** than the modal methods
  - **Not sensitive** to foundation rocking and **SSI**, the weakness of the natural frequencies of vibration
  - Does not require prior measurement

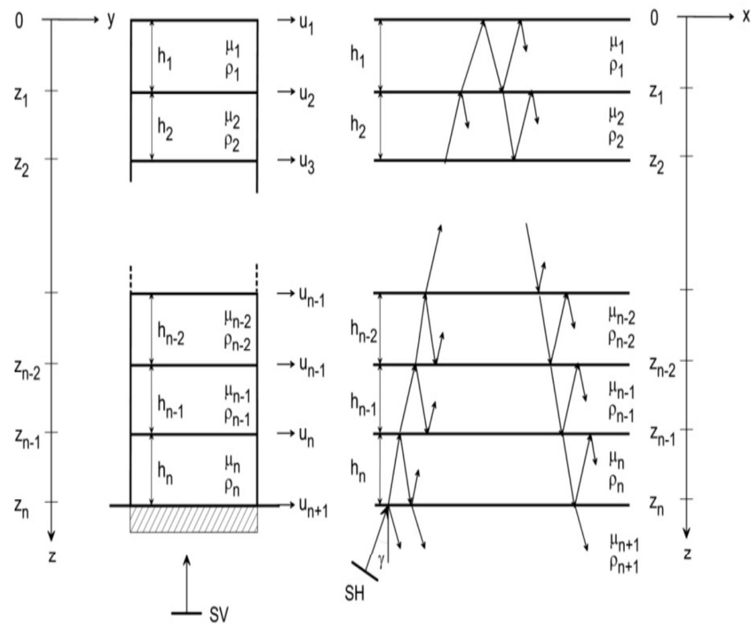
Wave Propagation Method

- Historical perspective:
  - Kanai and Yoshizawa, 1963; Kanai, 1965:   Shows the equivalence of representation of response as sum of modes and sum of bouncing waves.
  - Safak, 1999: Proposes use of travel time for damage detection. Argues it is more local than freq. of vibration.
  - Kawakami and Oyunchimeg, 2003; Oyunchimeg and Kawakami, 2003: NIOM method, damaged and undamaged buildings.
  - Ivanovic et al. 2006: Cross-correlation, Van Nuys damaged building.
  - Snieder and Safak, 2006: Impulse response functions, Millikan library small response.
  - Kohler et al., 2007: Impulse response functions, Factor bldg.
  - Todorovska and Trifunac, SDEE 2008; SCHM 2008: Impulse response functions, damage detection in two severely damaged buildings (ICS, Van Nuys).
  - Todorovska, BSSA 2009a,b: demonstrates insensitivity to SSI on a model; explains wondering of frequency of Millikan library.
  - Todorovska and Rahmani, SCHM 2013; Rahmani and Todorovska 2013a,b,c: waveform inversion……

Model

How to measure travel time:

- **Impulse response functions =** normalized cross-correlations= Green's functions for modified boundary conditions (Snieder and Safak, 2006)
- Layered shear beam model - **analytic TF and IRFs adopted from geophysics** (propagator matrix approach; Trampert et al., 1993; Todorovska and Rahmani, SCHM 2012).
- Building is NOT a borehole; specific issues .

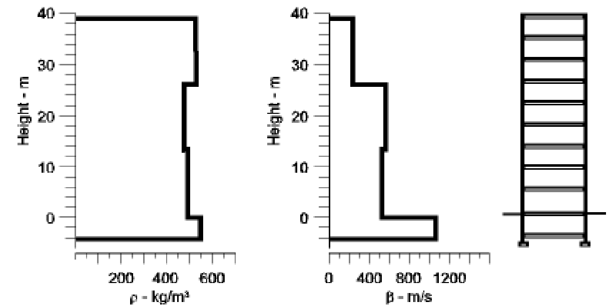


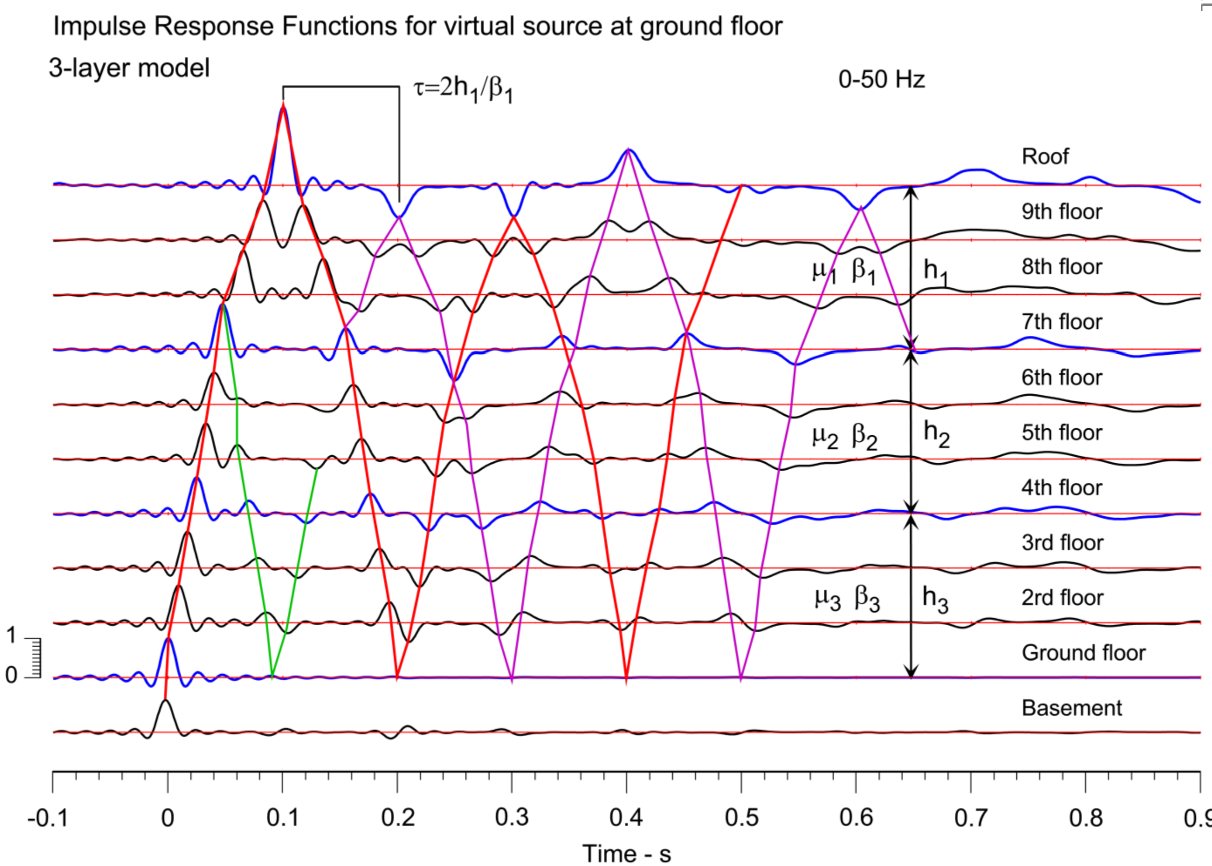
$$TF \equiv \hat{h}_i(\omega) = FT\left\{\frac{\hat{u}_i(\omega)}{\hat{u}_{\text{ref}}(\omega)}\right\}$$

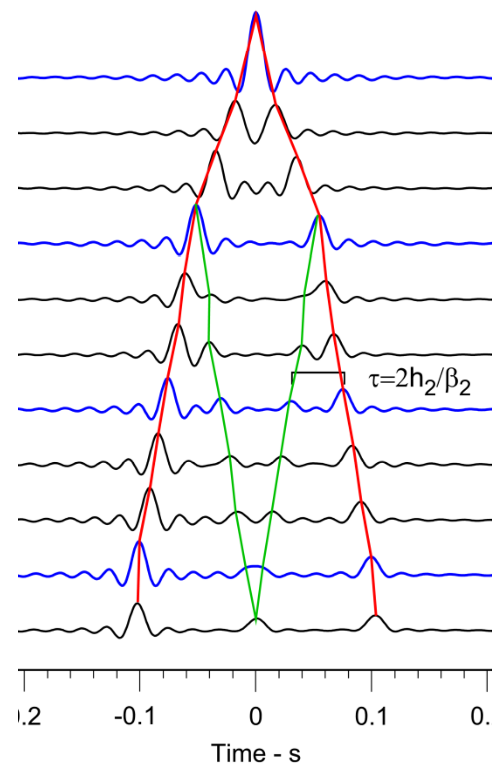
$$IRF \equiv h_i(t) = FT^{-1}\left\{\hat{h}_i(\omega)\right\}$$

$$\text{Regularized}\ \ IRF = FT^{-1}\left\{\frac{\hat{u}_i(\omega)\overline{\hat{u}}_{\text{ref}}(\omega)}{\left|\hat{u}_{\text{ref}}(\omega)\right|^2+\varepsilon}\right\},\quad |\omega| \le \omega_{\max}$$

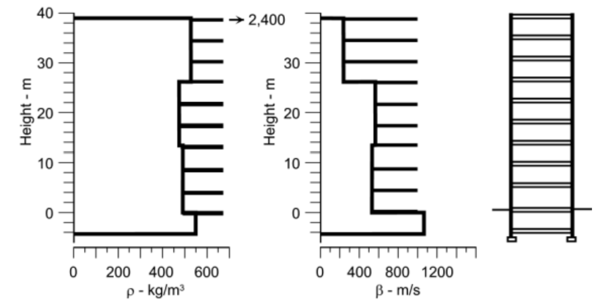
Layered Model IRFs: (Millikan NS)



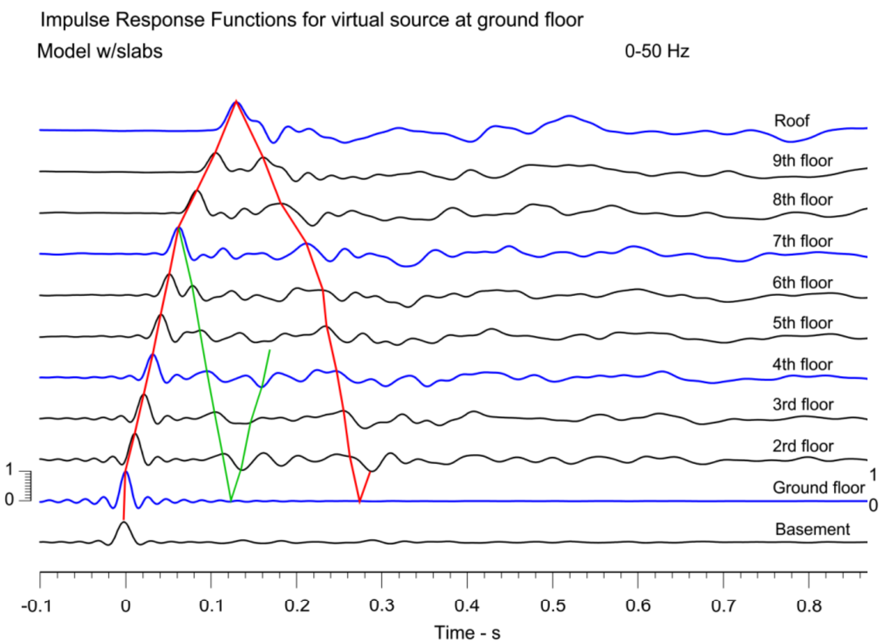


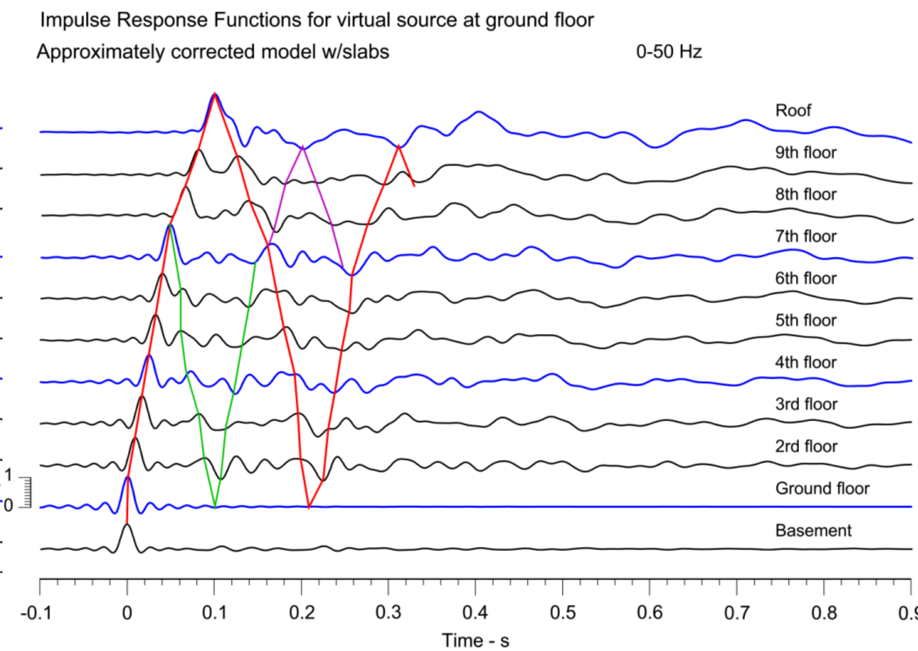


Layered Model IRFs: slabs



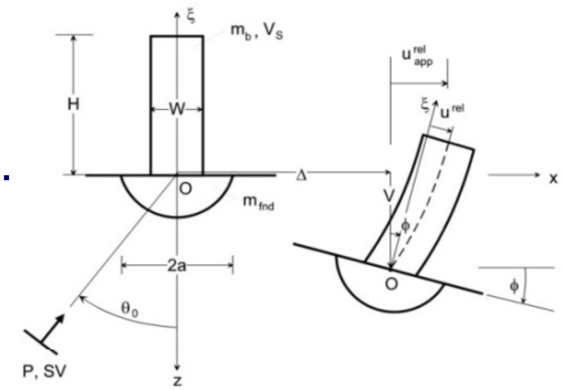
- Additional phase delay due scattering from the slabs – ray theory does not work for this case.



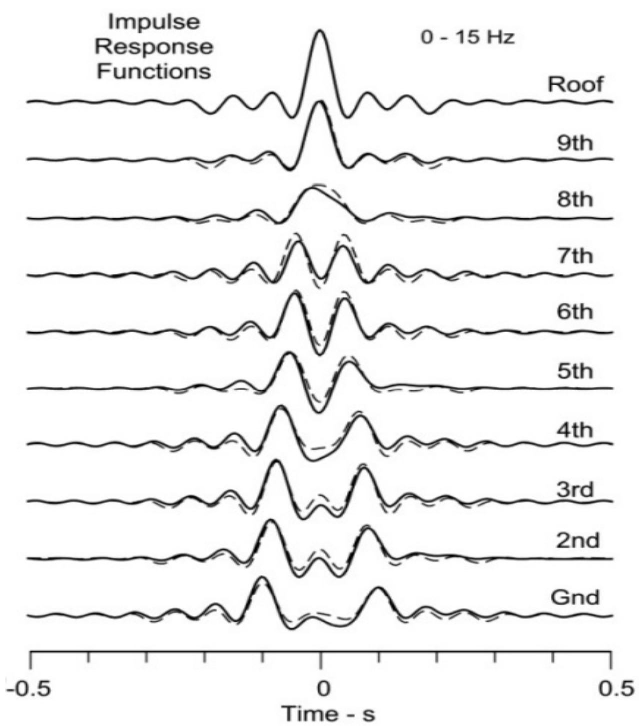


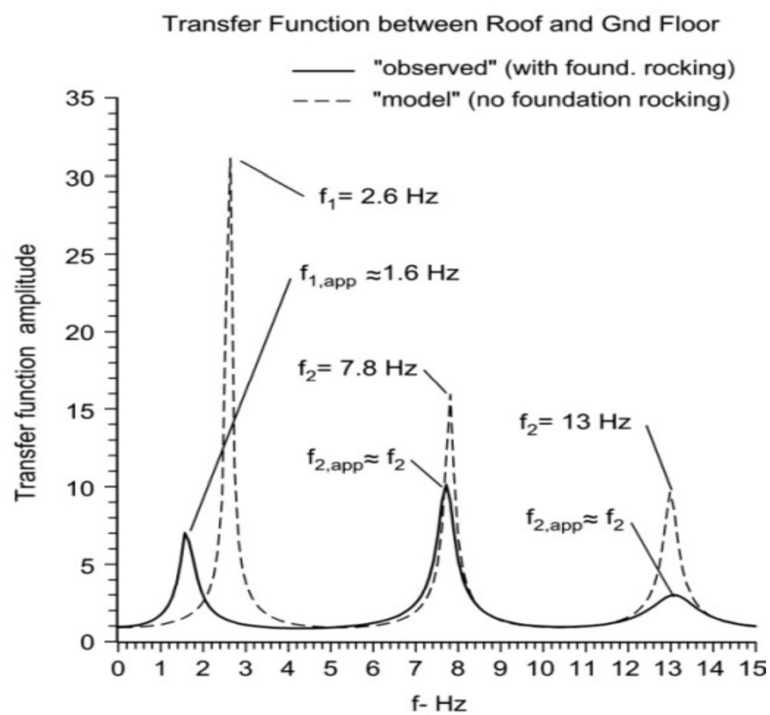
SSI Model IRFs and TF

SSI Model of Millikan library NS response – uniform s.b. (Todorovska, BSSA 2009a,b)



$$\frac{1}{f_{1,sys}^{\;2}} \approx \frac{1}{f_H^{\;2}} + \frac{1}{f_R^{\;2}} + \frac{1}{f_1^{\;2}} \qquad \frac{1}{f_{1,app}^{\;2}} = \frac{1}{f_1^{\;2}} + \frac{1}{f_R^{\;2}}$$

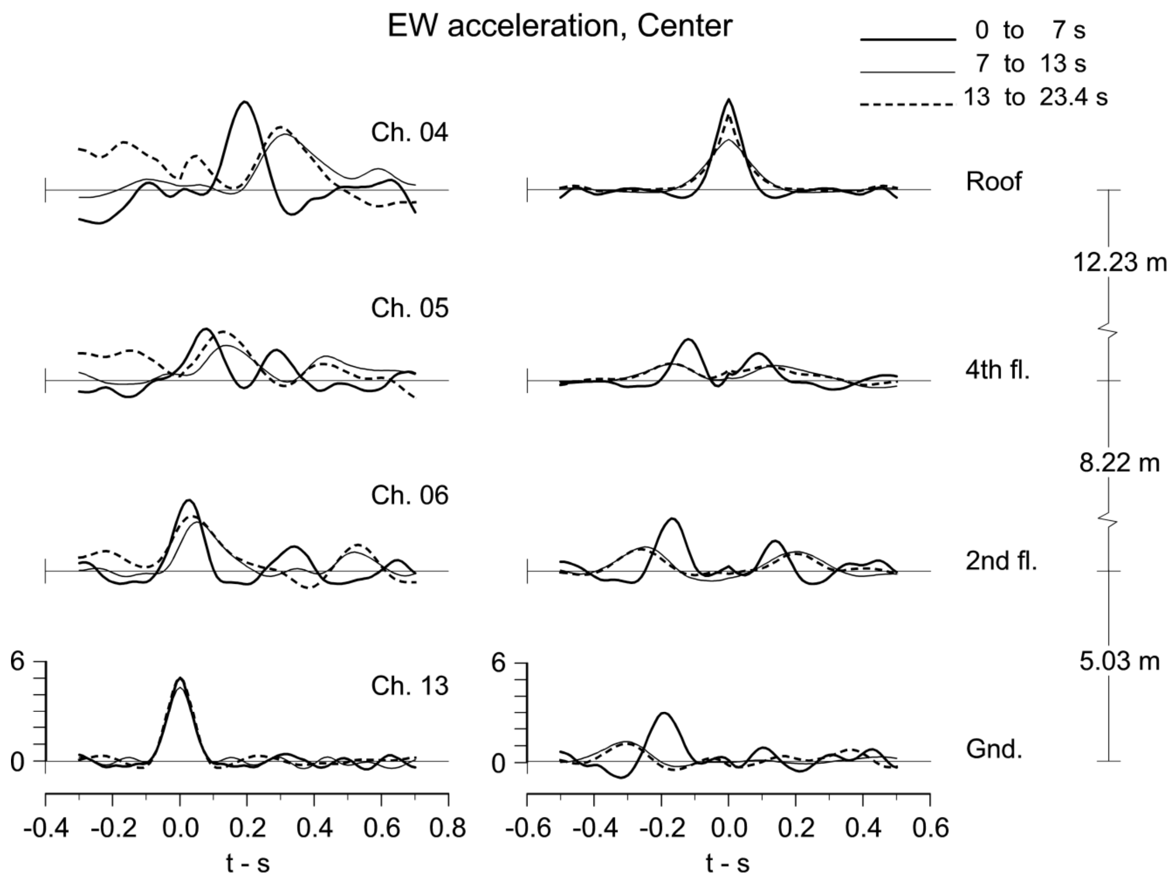




Proof of Concept Studies

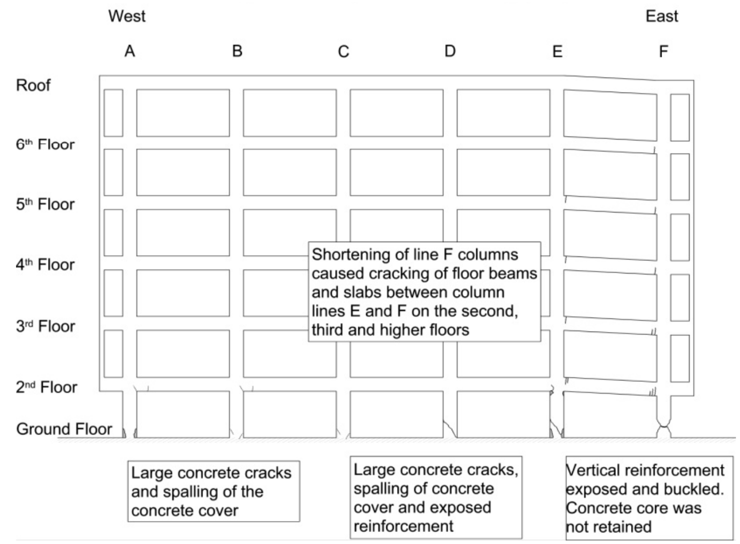
- Two severely damaged buildings (ISC and Van Nuys bldgs; Todorovska and Trifunac, 2008ab)
- **Direct algorithm**: based on ray theory interpretation of IRFs

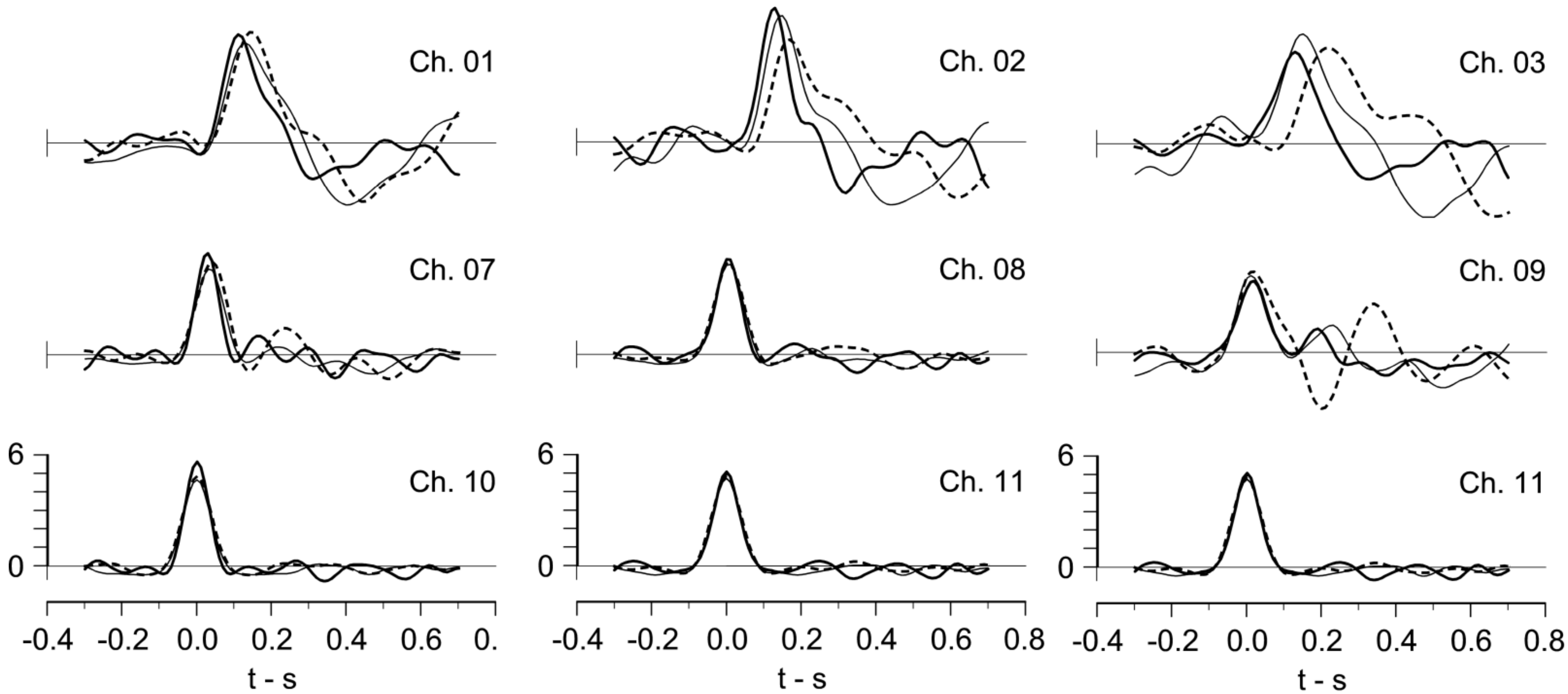
$$V = h / \tau$$



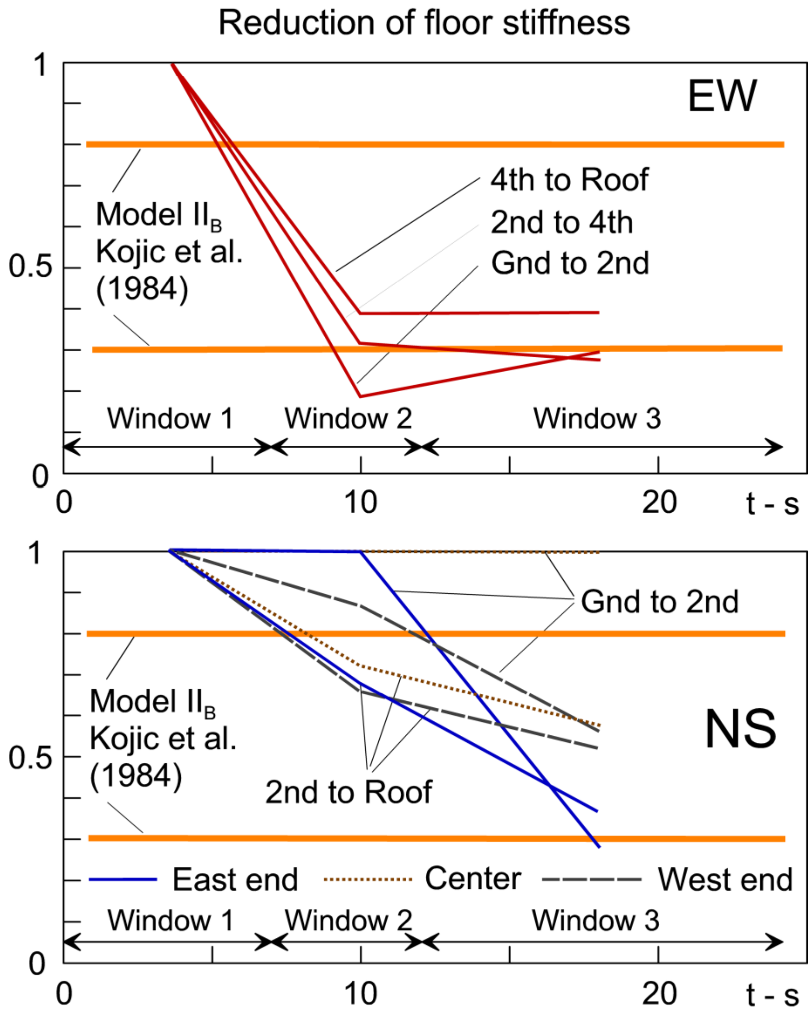
ICS building

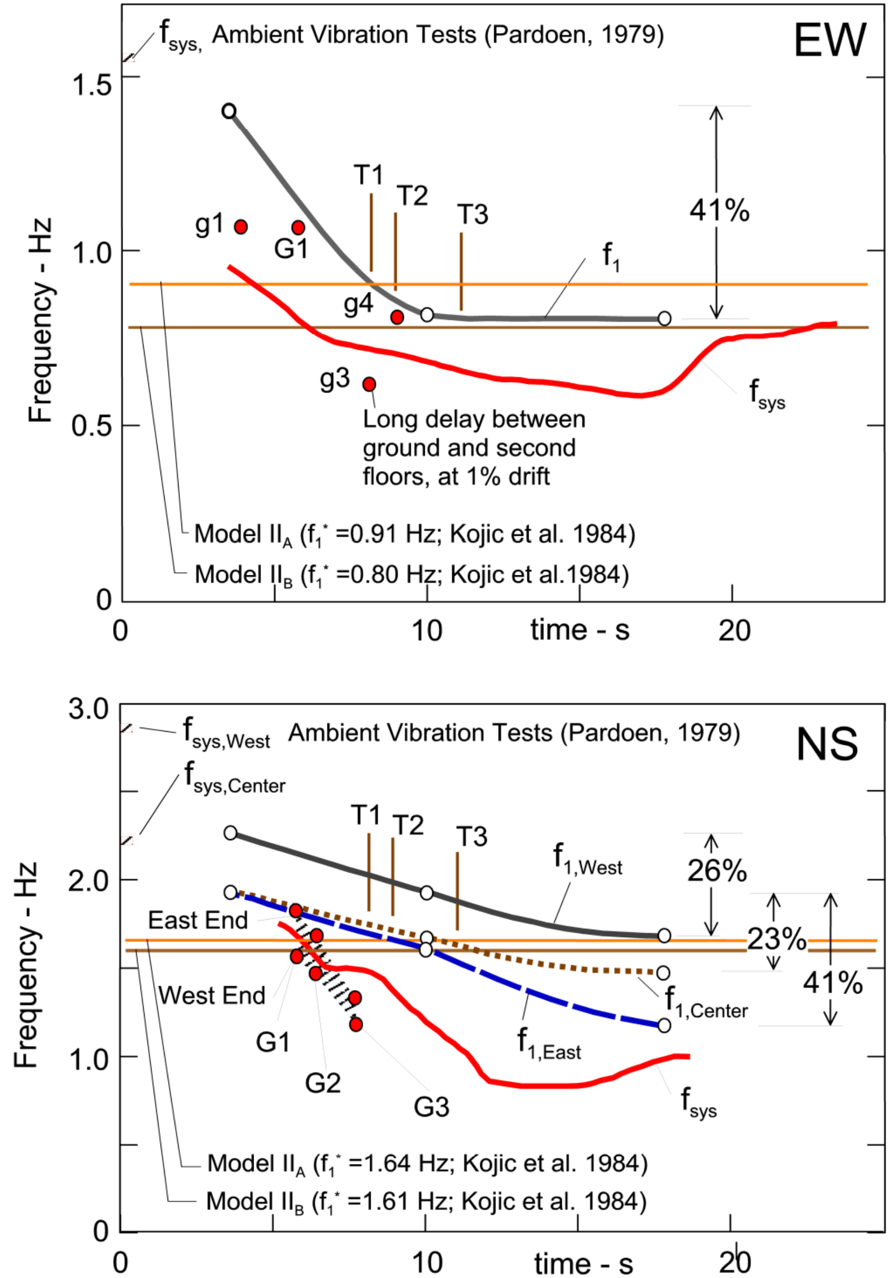
Change in travel time consistent with spatial distribution and degree of damage



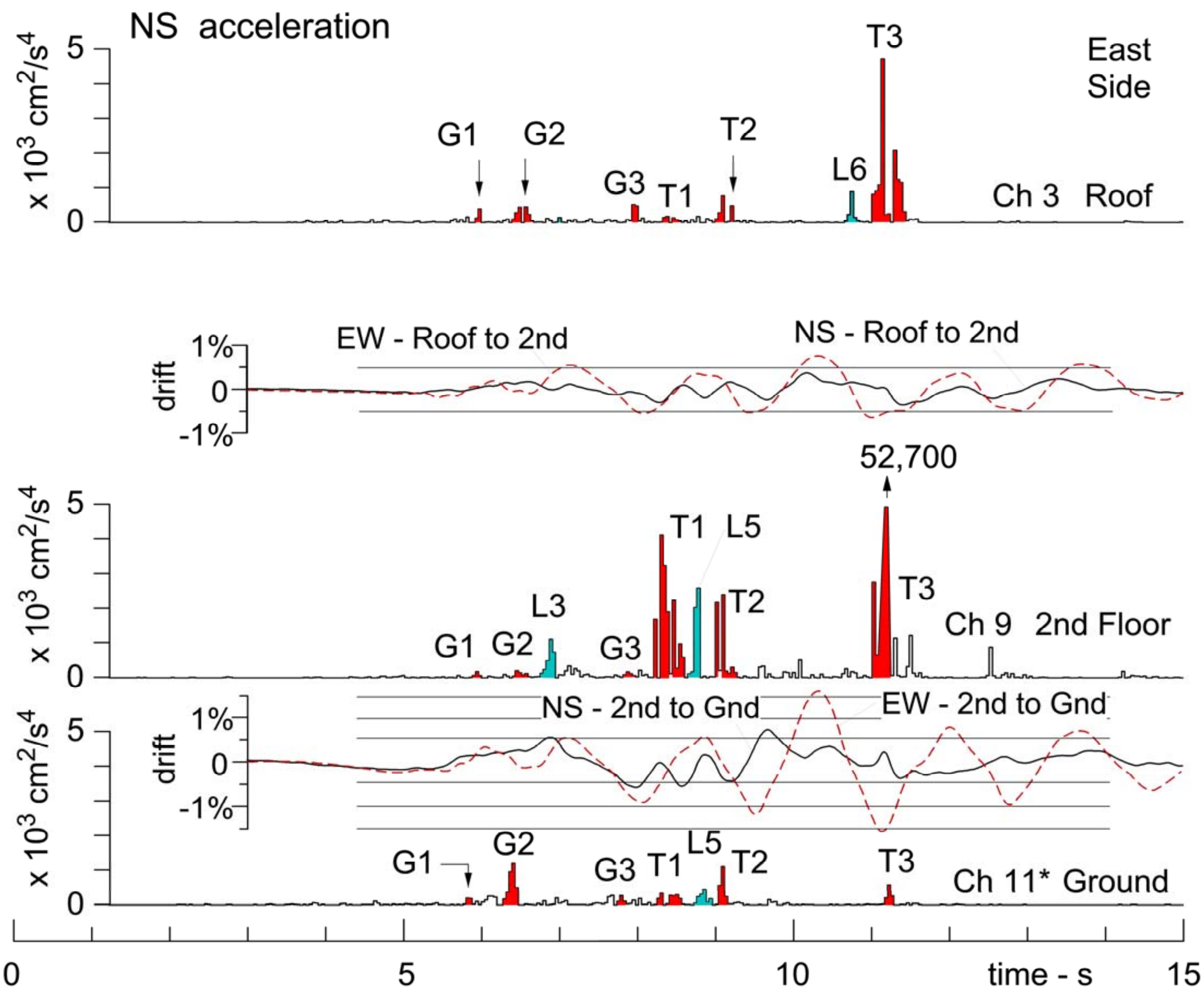


ICS building

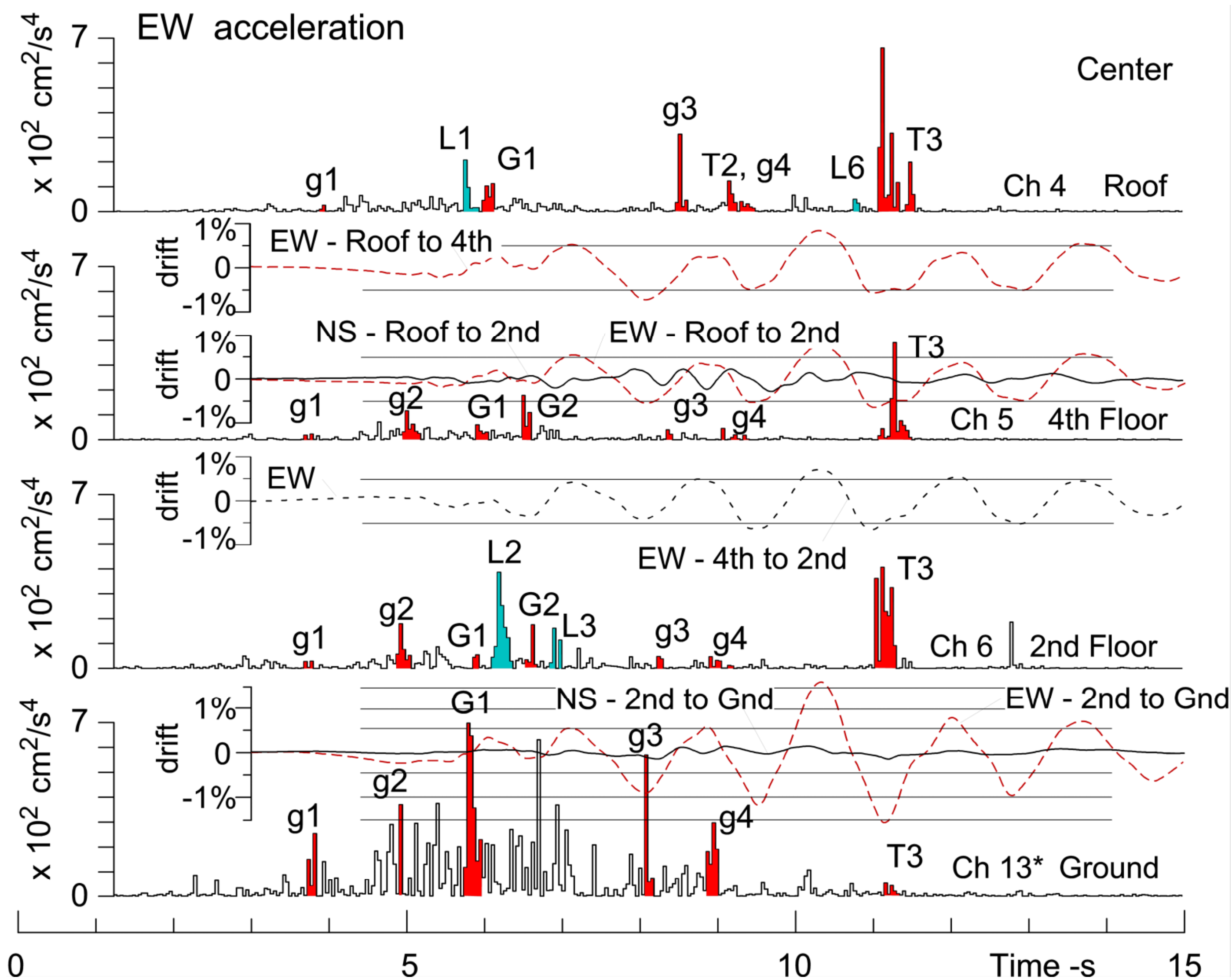




ICS building - Novelties Analysis

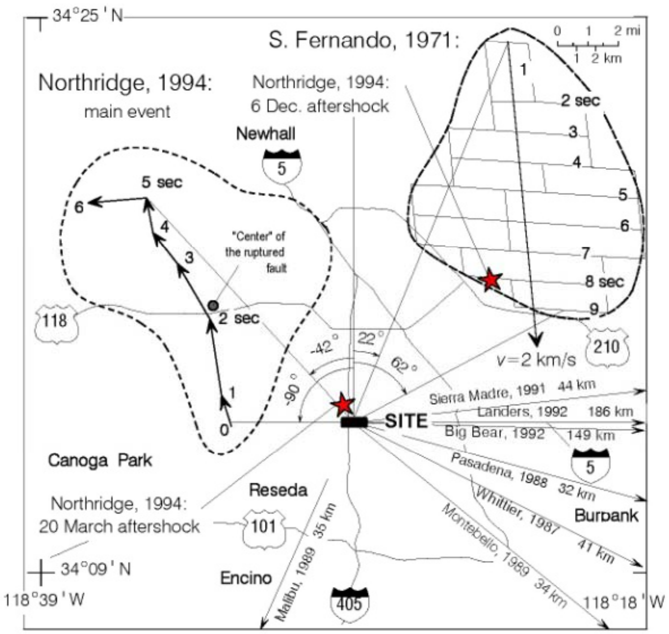


ICS building - Noveltics Analysis



Van Nuys building

7-story, RC, **EW**, **11** earthquakes and 5 ambient vibration tests in **24 years**)



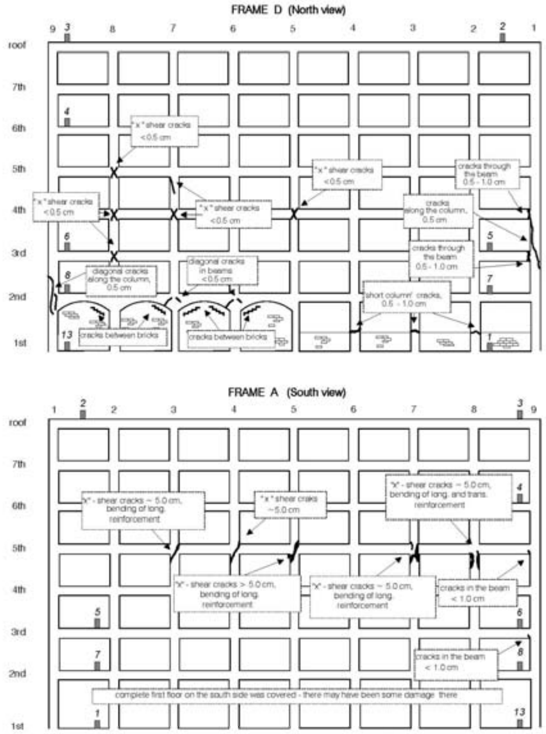
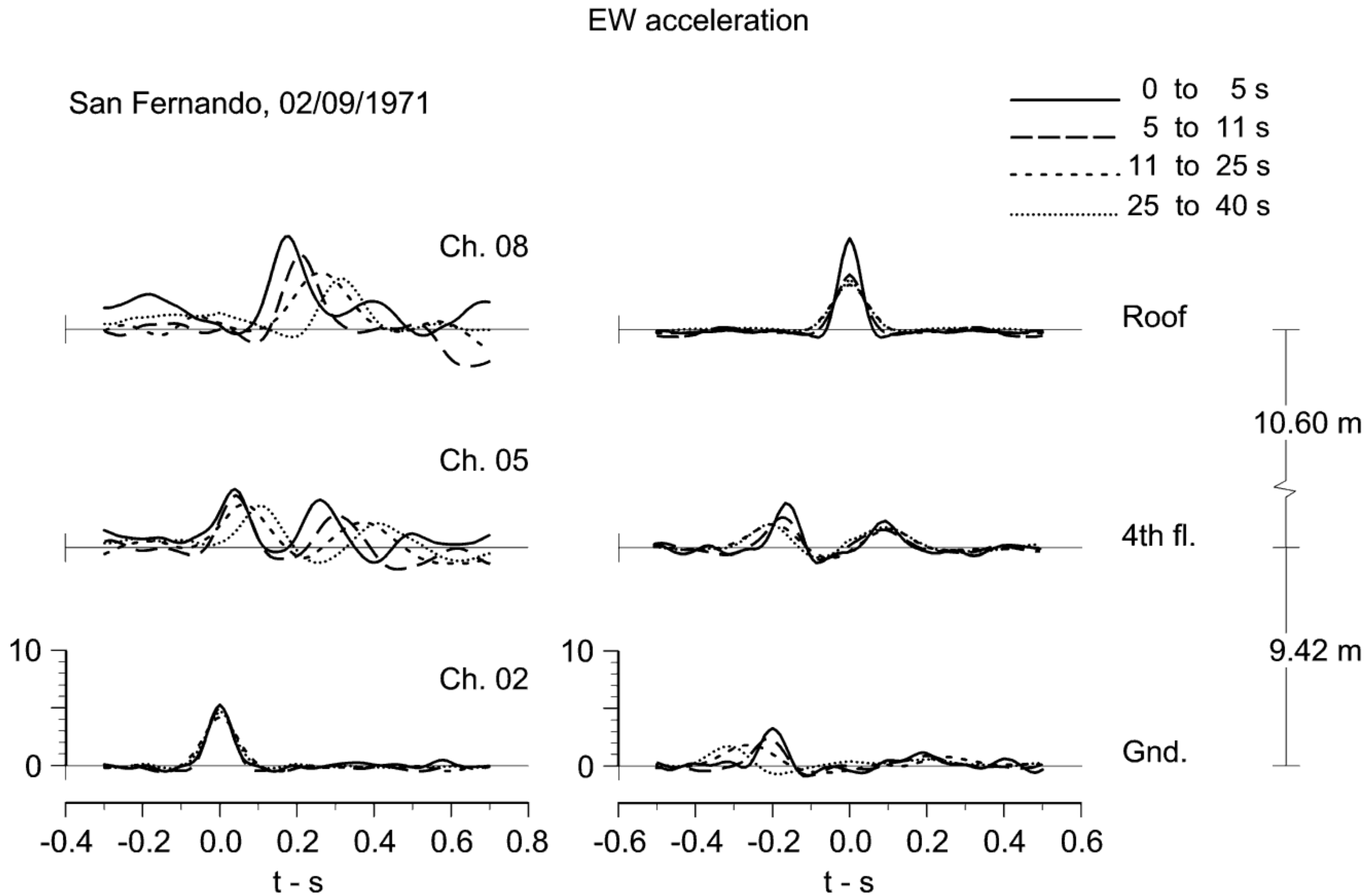


Fig. 3 Schematic representation of the damage: (top) frame D–North view, and (bottom) frame A–south view. The sensor locations for channels 1–8 and 13 (oriented towards North), are also shown.

USC Report No. CE 01-05, Trifunac and Hao, 2001

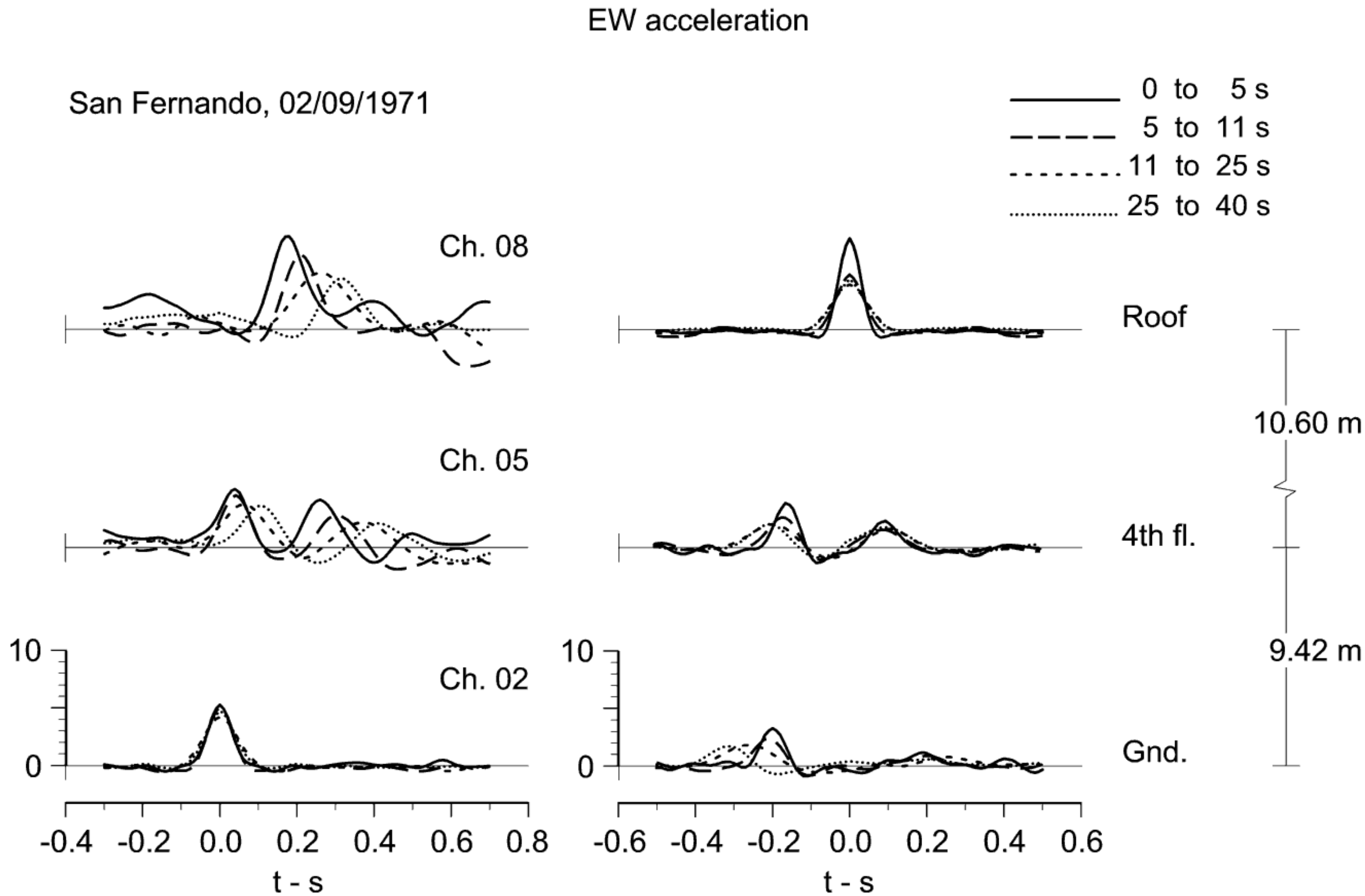
http://www.usc.edu/dept/civil_eng/Earthquake_eng/CE_Reports/01_05/index01_05.html

Van Nuys building

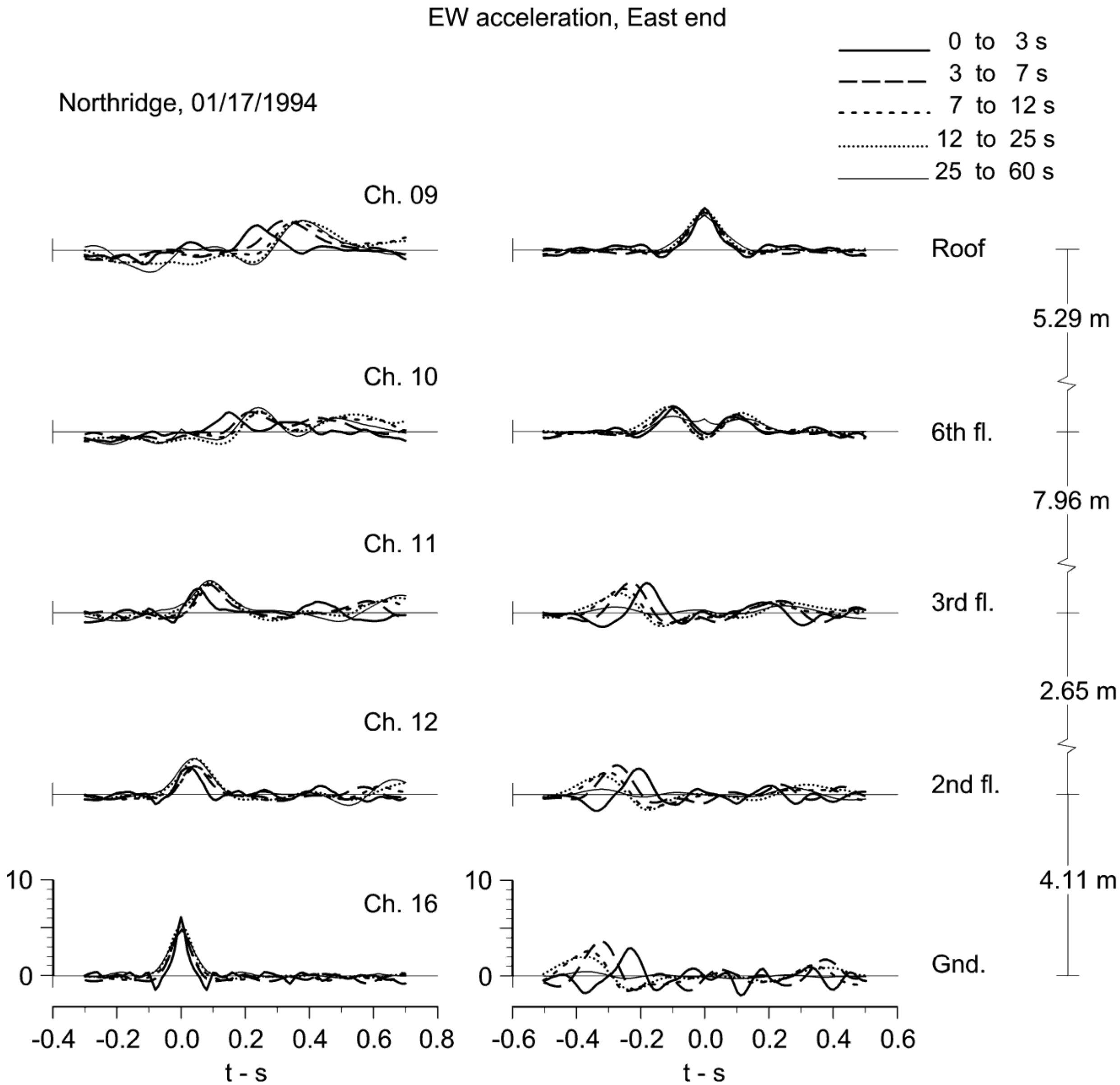


Todorovska and Trifunac, SCHM, 2008

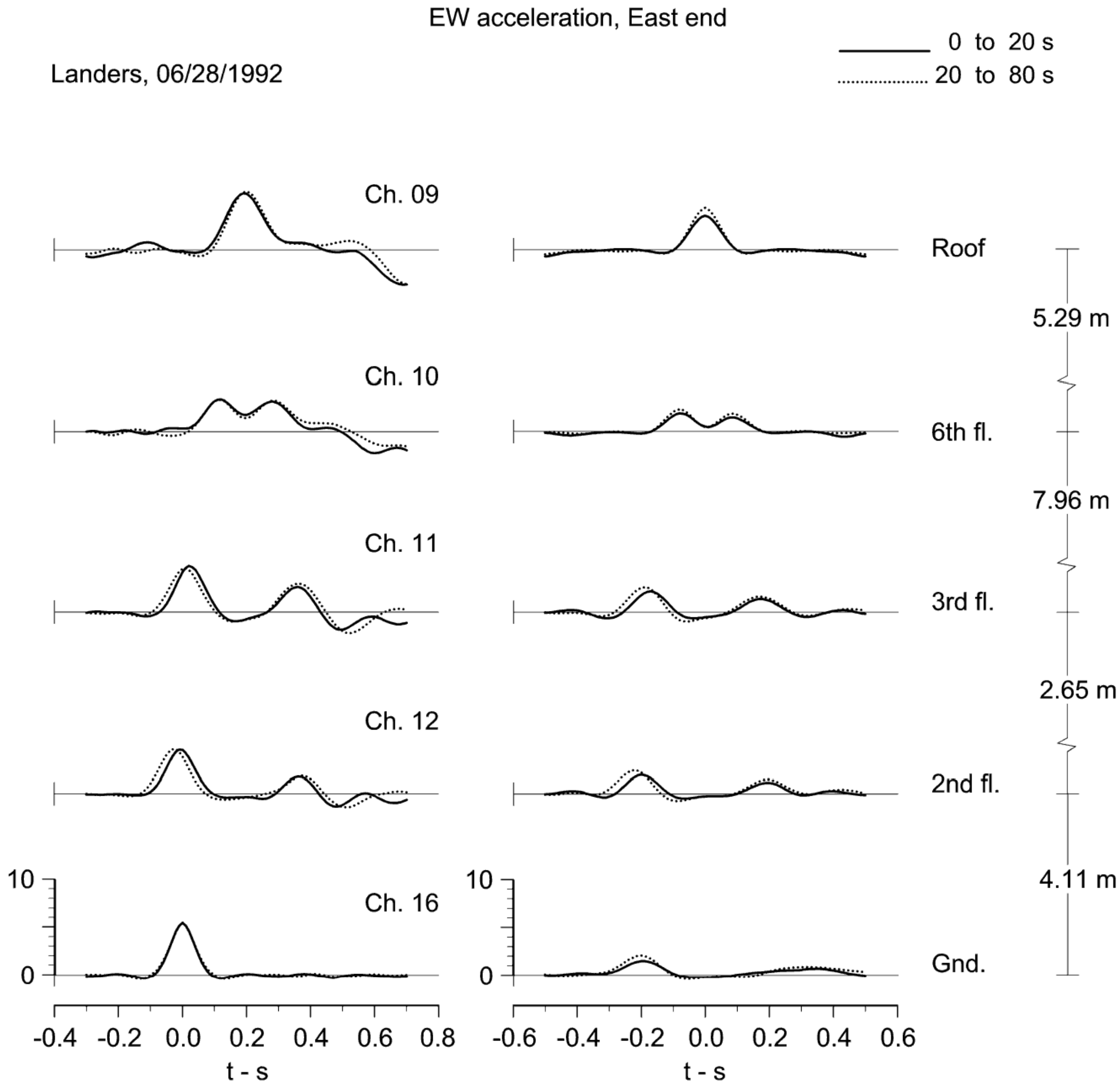
Van Nuys building



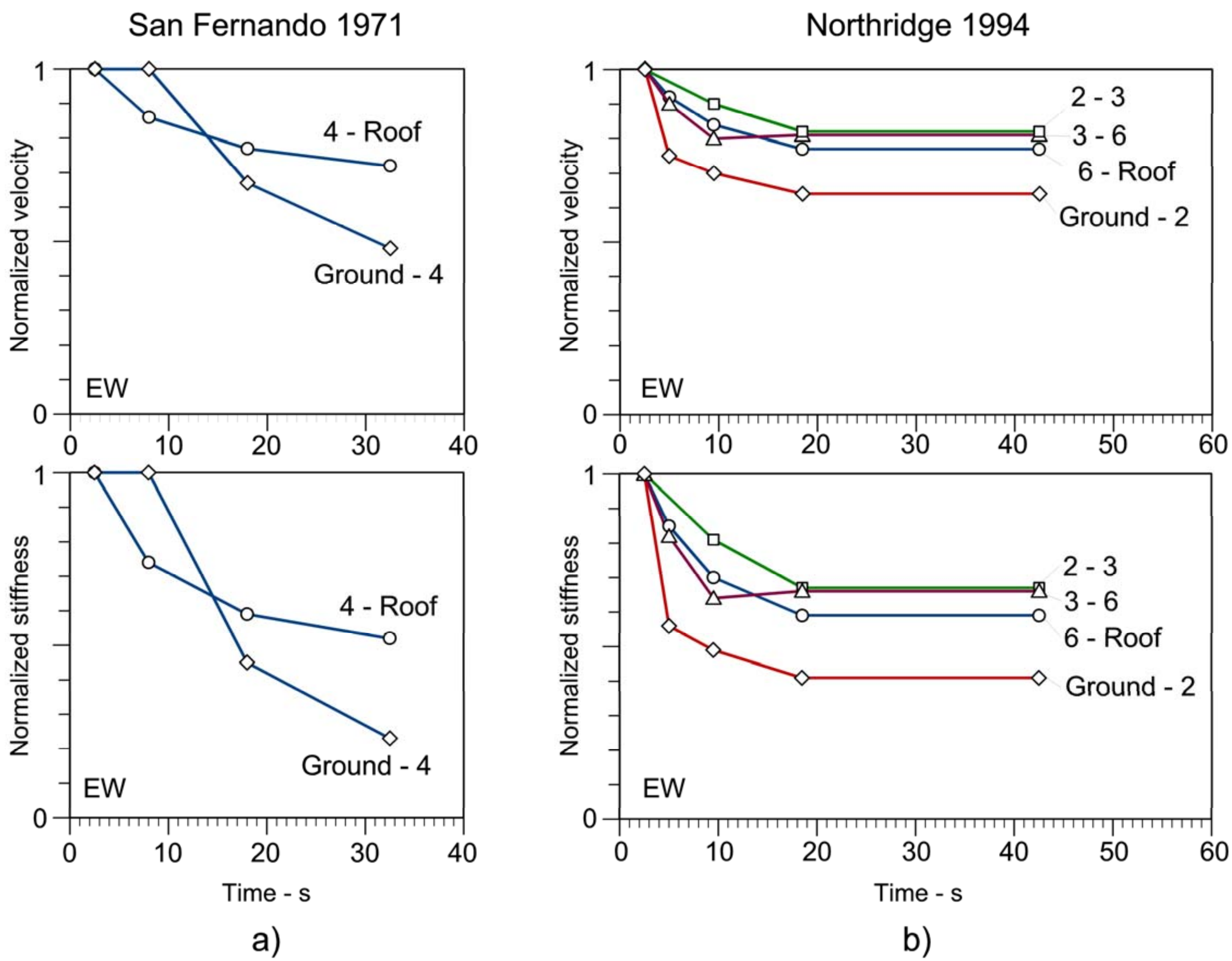
Van Nuys building



Van Nuys building

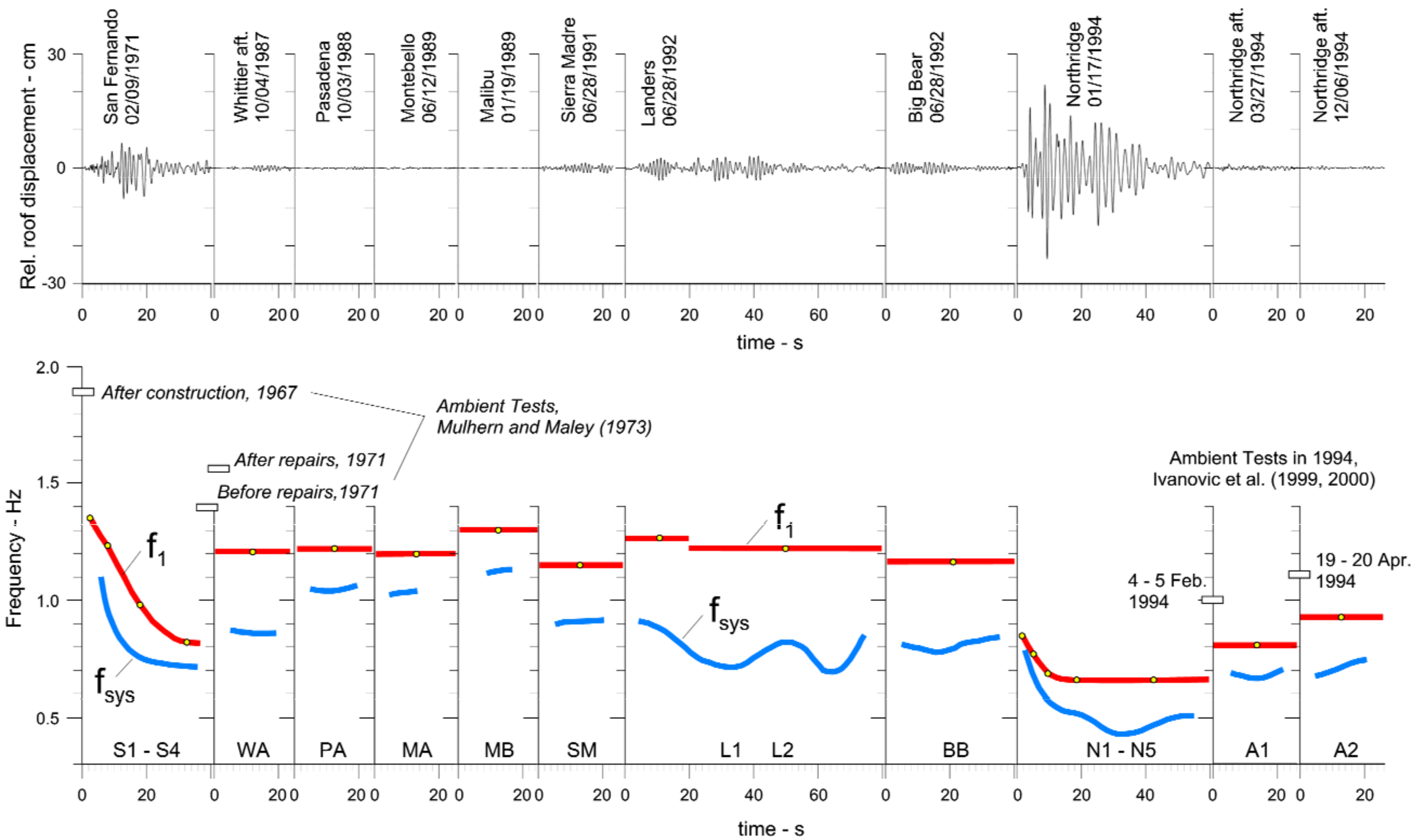


Van Nuys building

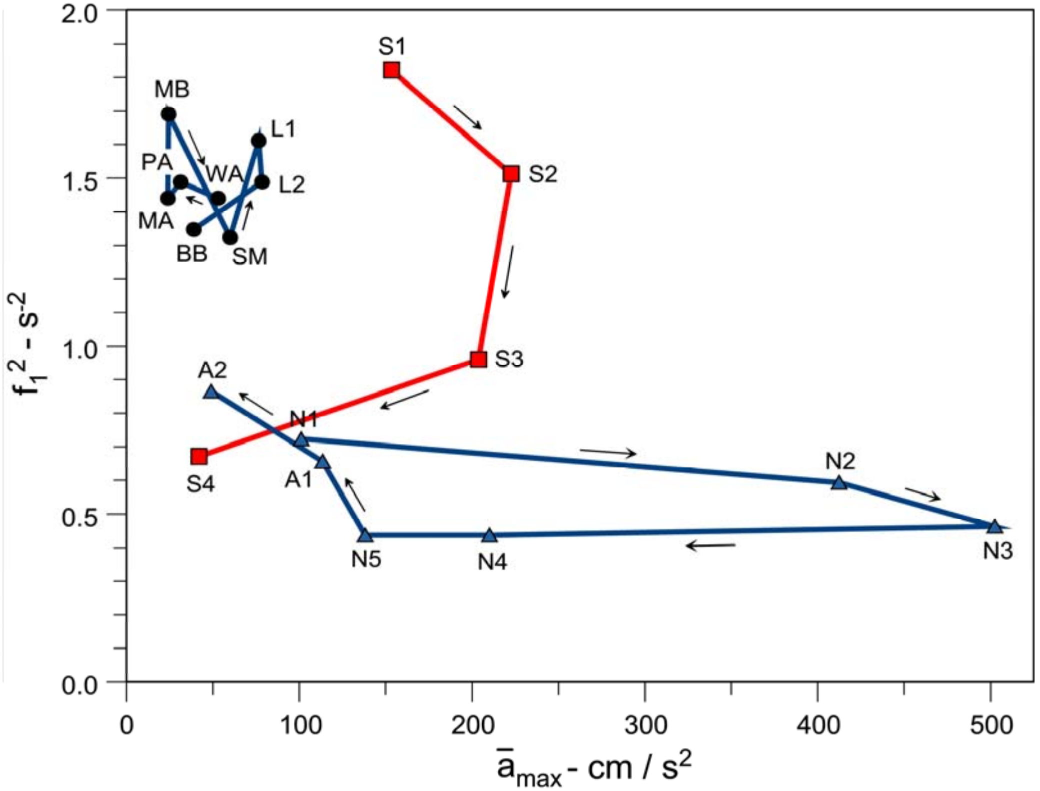


Van Nuys building

f_{sys} – form time-freq. energy distribution, **f_1** – from wave travel times.
f_1 decrease: 1971 San Fernando - by **~40%**. 1994 Northridge - by **~22%**.
Difference between f_1 and f_{sys} is not constant (see Landers and Big Bear).



Van Nuys building



Estimation Error of the Direct Algorithm

- Infinite bandwidth:

$$\hat{h}(\omega)=1 \quad \Leftrightarrow \quad h(t)=\delta(t)= \text{ Dirac Delta-function}$$

- Finite bandwidth:

$$\hat{h}(\omega)=1, \quad |\omega|\leq \omega_{\text{max}} \quad \Leftrightarrow \quad h(t)=\frac{\sin \omega_{\text{max}} t}{\pi t} = \text{ sinc function}$$

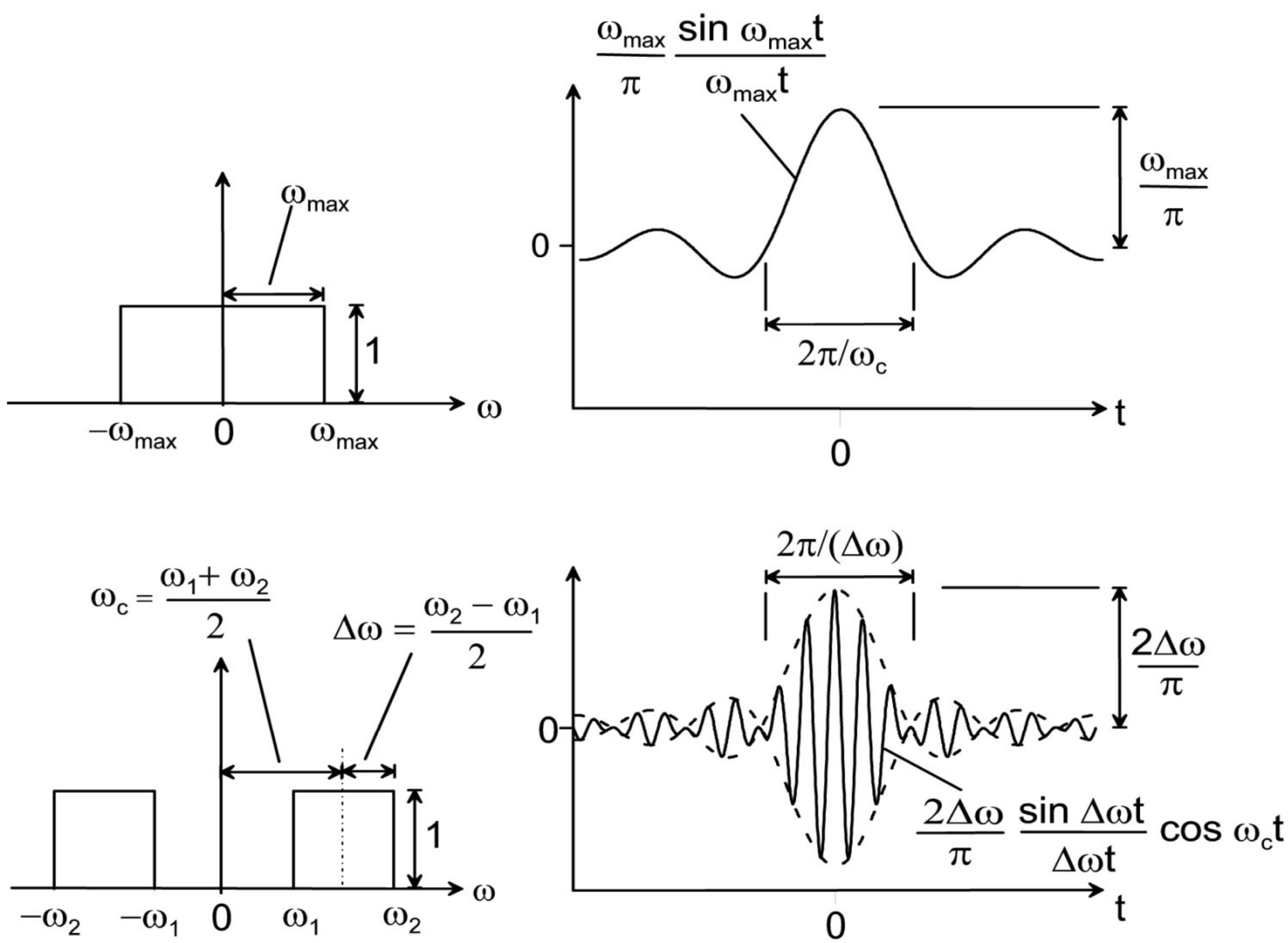
- Spread in time:

$$\text{Pulse half-width} = \Delta t = \pi / \omega_{\text{max}} = 1/(2 f_{\text{max}})$$

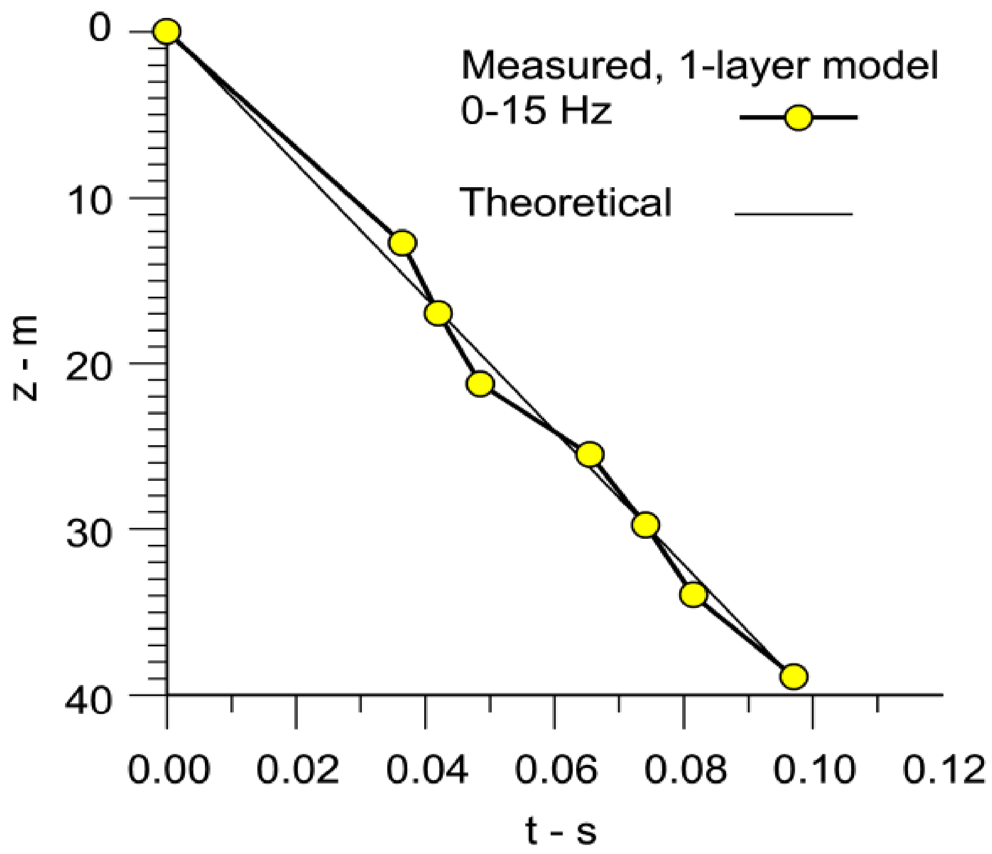
- Heisenberg-Gabor uncertainty principle implies:

$$\text{Relative error} = \frac{\Delta\beta}{\beta} = \frac{\Delta t}{\tau}$$

Estimation Error of the Direct Algorithm



Example: Uniform Shear Beam



Waveform Inversion Algorithm

- We fit by **waveform inversion** of IRFs
- Nonlinear LSQ fit: Levenberg-Marquardt Method; Simulated annealing
- **Much more accurate** estimation
- **Not limited by ray theory assumptions**
- **Uses information on pulse amplitude**, which is primarily governed by the impedance contrast - additional information
- **Frequency band – key parameter for the fit**
  (It controls the pulse width)
- **Resolution**

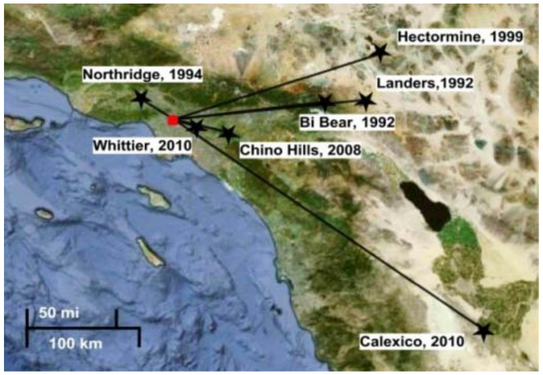
$$h_{min} = \lambda_{\min} / 4 = 1 / (4 f_{\max})$$

Results

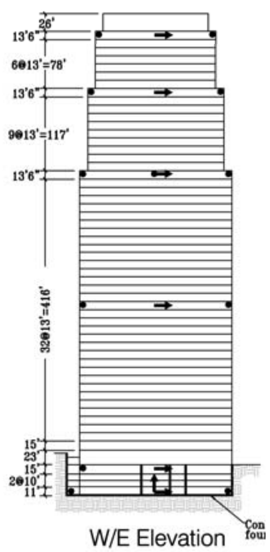
- Three buildings chosen for detailed analysis:
  - **54-story steel frame**. Is layered shear beam appropriate for such a building? What is the variability of the identified wave velocities during 5 events, none of which caused damage?
  - **9-story RC** with shear walls (NS) and central core (EW), densely instrumented. Resolution and dispersion analyzed
  - **12 story RC, lightly damaged**. Is the method sensitive to light damage?

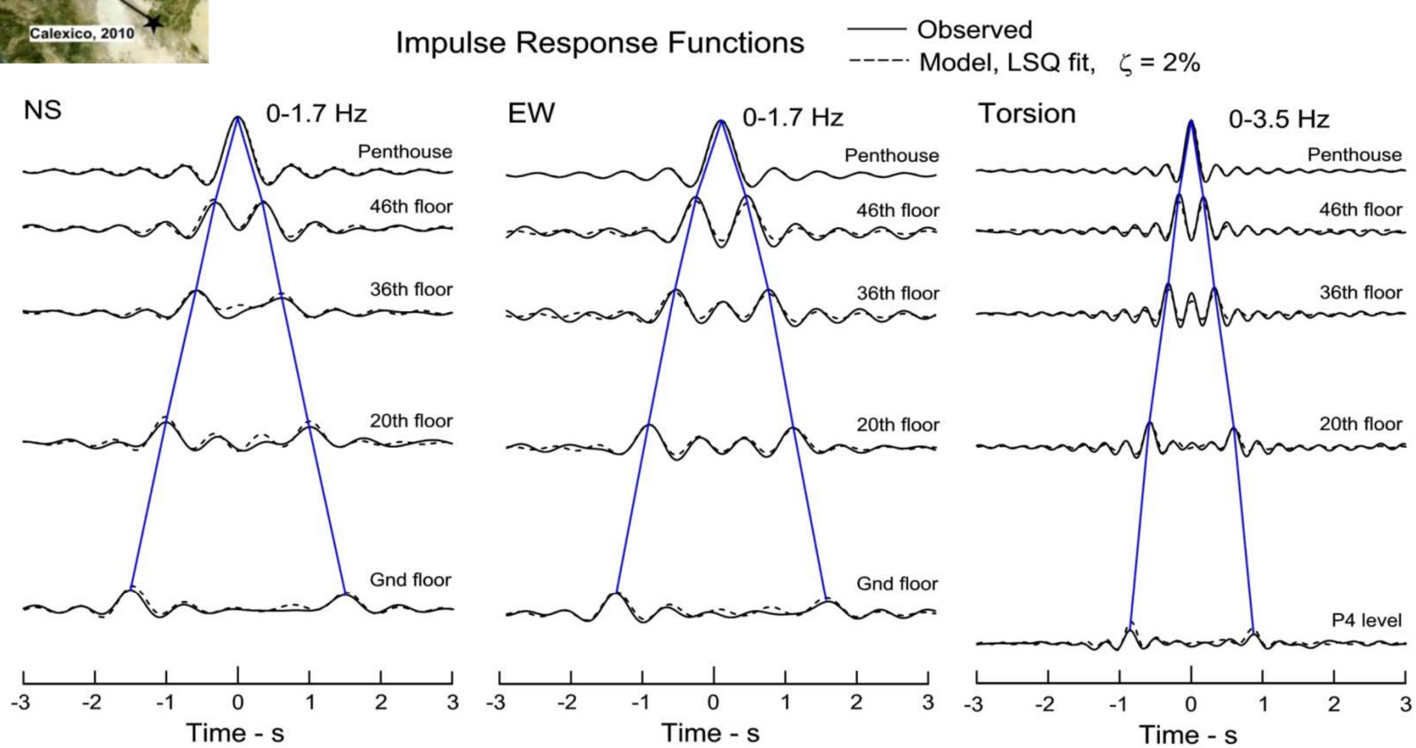
LA 54-story office building

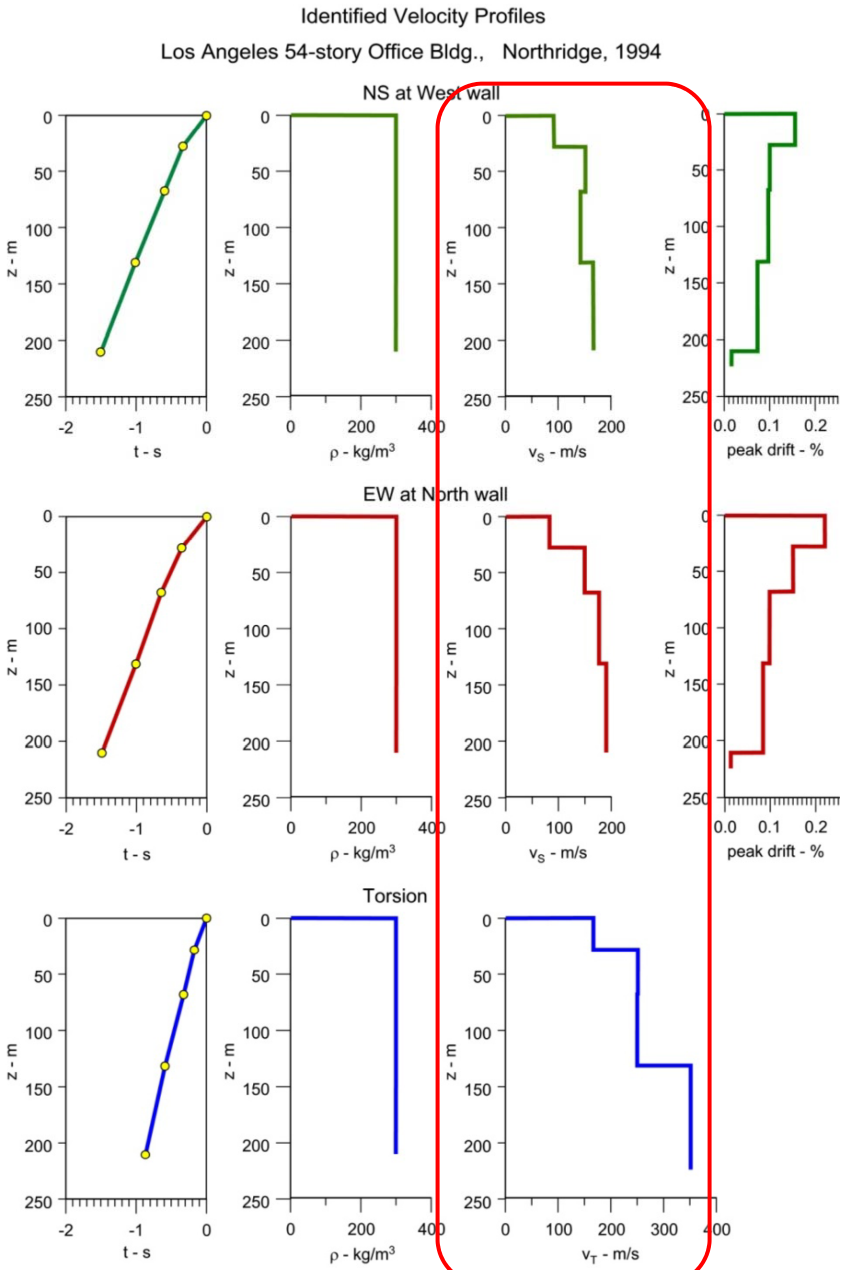
54-story, moment resisting **perimeter steel frame**, on concrete mat foundation; alluvium over sedimentary rock

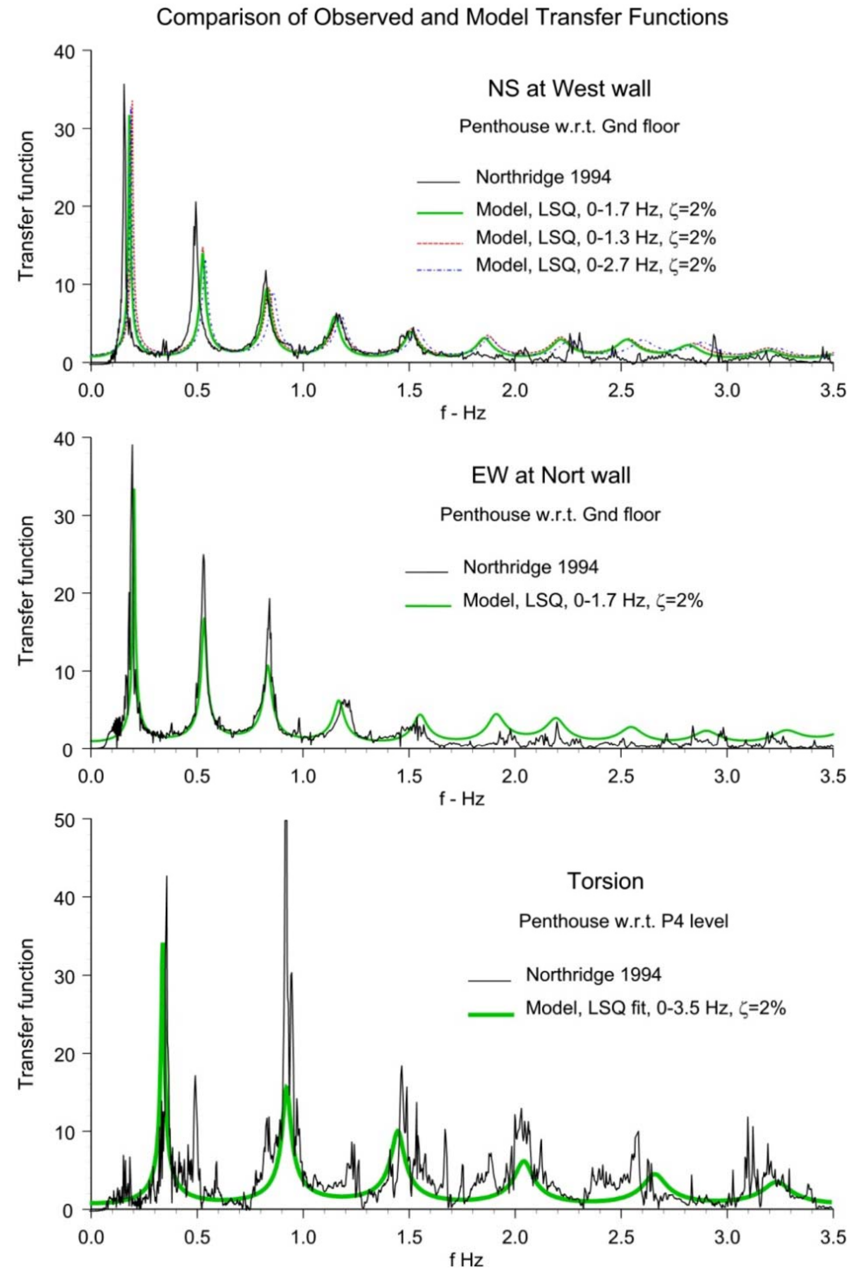


CSMIP Station 24629

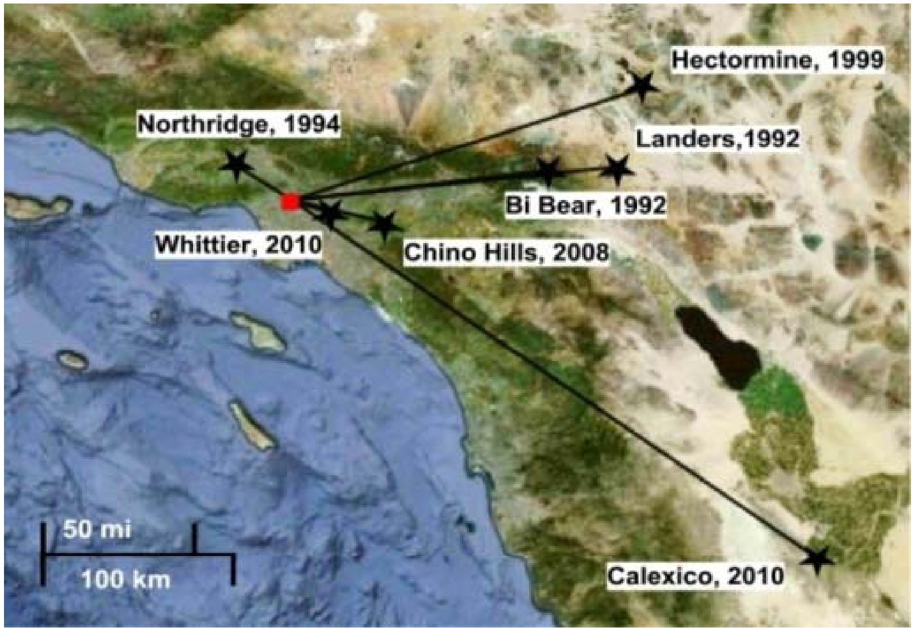





Identified Velocity Profiles
Los Angeles 54-story Office Bldg., Northridge, 1994
NS at West wall
EW at North wall
Torsion
z - m
t - s
ρ - kg/m³
v_S - m/s
v_T - m/s
peak drift - %

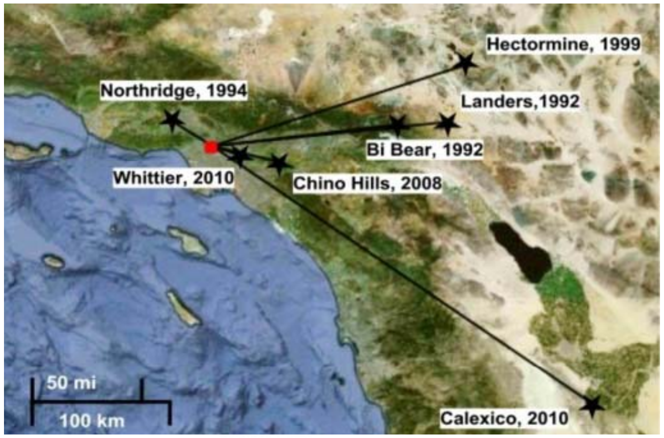

Comparison of Observed and Model Transfer Functions
NS at West wall
Penthouse w.r.t. Gnd floor
Northridge 1994
Model, LSQ, 0-1.7 Hz, ζ=2%
Model, LSQ, 0-1.3 Hz, ζ=2%
Model, LSQ, 0-2.7 Hz, ζ=2%
EW at Nort wall
Penthouse w.r.t. Gnd floor
Northridge 1994
Model, LSQ, 0-1.7 Hz, ζ=2%
Torsion
Penthouse w.r.t. P4 level
Northridge 1994
Model, LSQ fit, 0-3.5 Hz, ζ=2%
Transfer function
f - Hz
f Hz

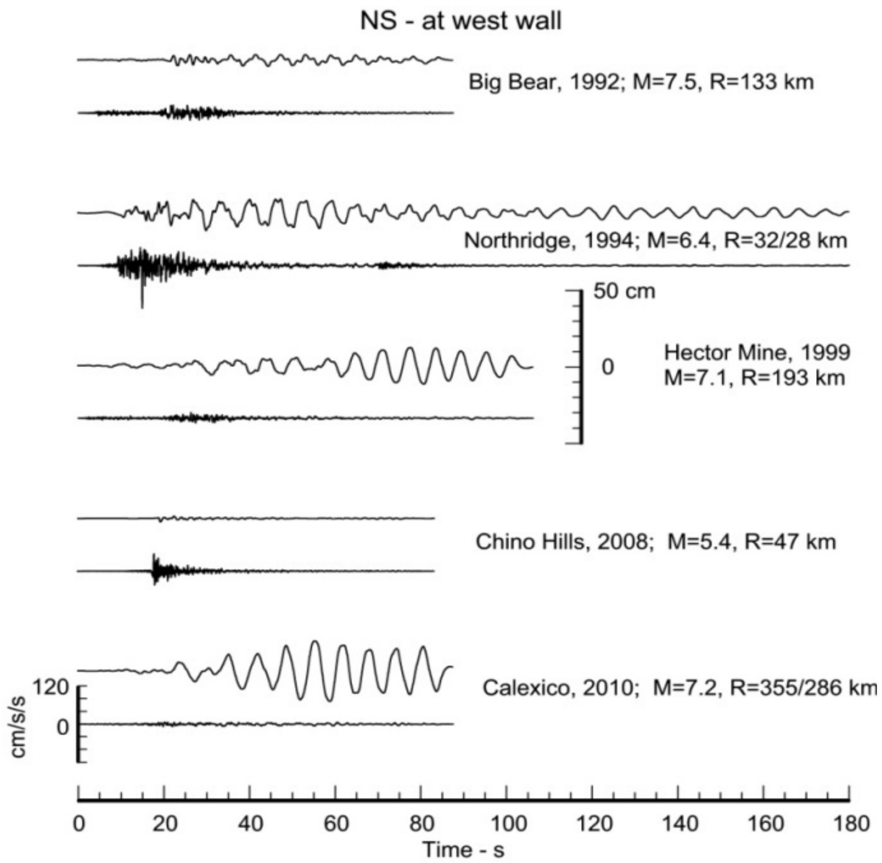
Recorded Earthquakes 1992-2010

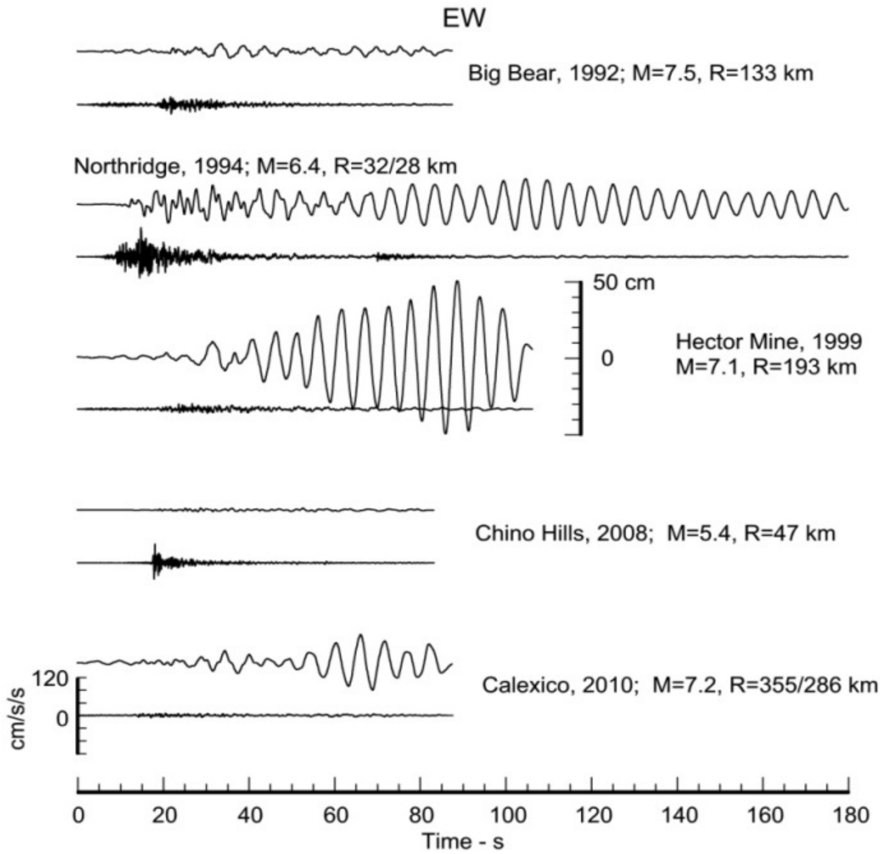


No.	Event name	Date	ML	H - km	Epic/Fault dist - km	Gnd amax - g	Struct. amax - g	Data avail.
1	Landers	06/28/1992	7.3	1	170/158	0.040	0.130	no
2	Big Bear	06/28/1992	6.5	10	133	0.030	0.067	yes
3	Northridge	01/17/1994	6.4	19	32/28	0.140	0.190	yes
4	Hector Mine	10/16/1999	7.1	6	193	0.019	0.082	yes
5	Chino Hills	07/29/2008	5.4	14	47	0.063	0.086	yes
6	Whittier Narrows	03/16/2010	4.4	18	18	0.020	0.022	no
7	Calexico	04/04/2010	7.2	32	355/286	0.009	0.038	yes

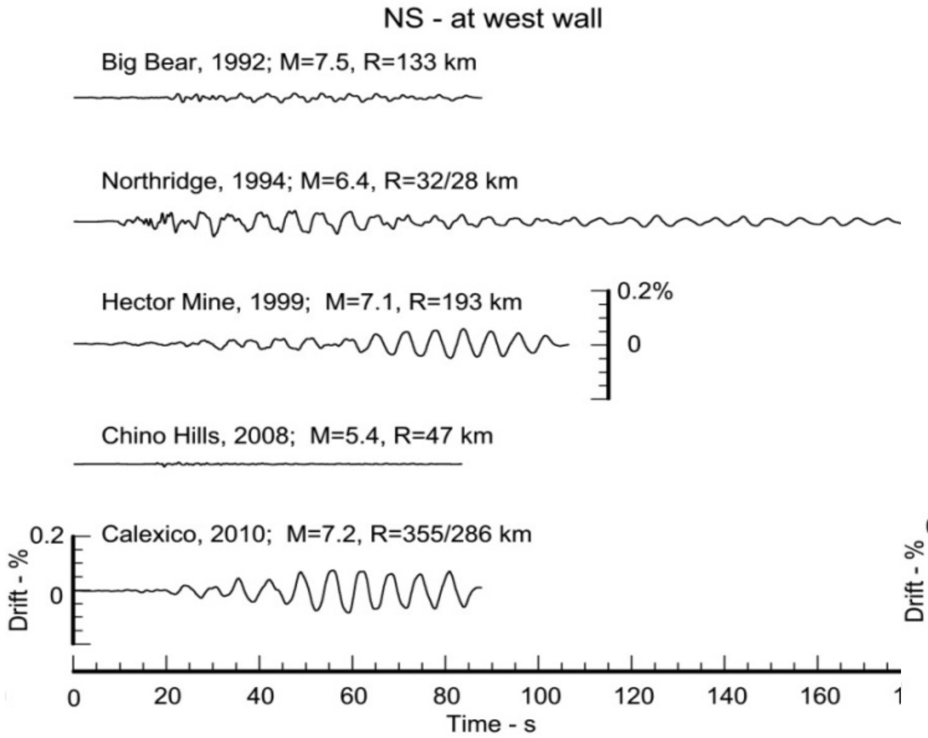
Base acceleration (bottom)
and
Roof displ. (bottom)

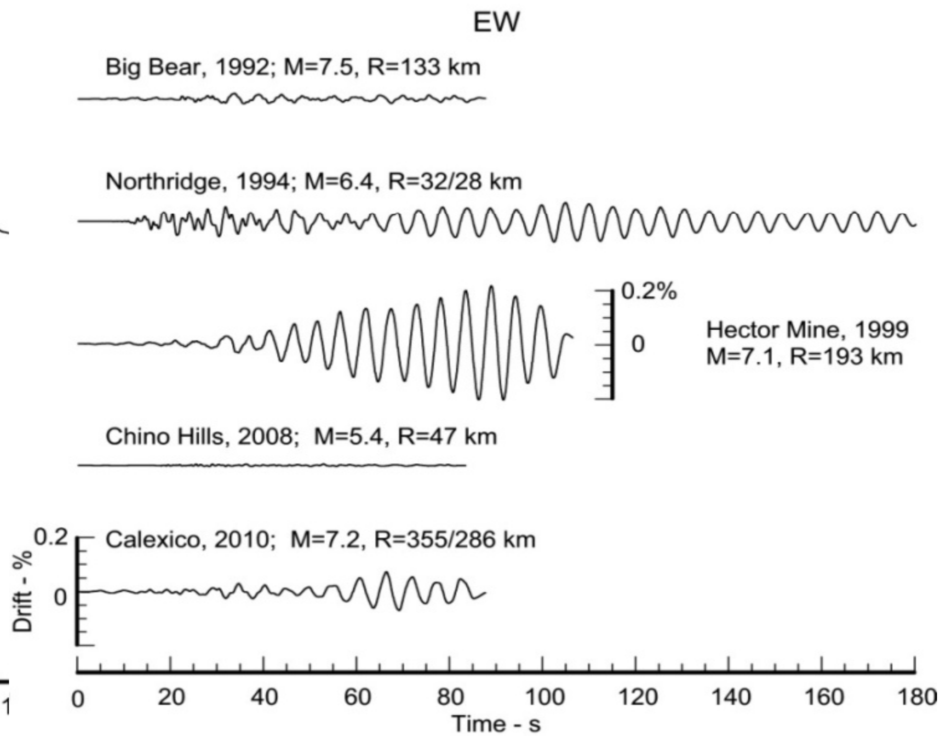




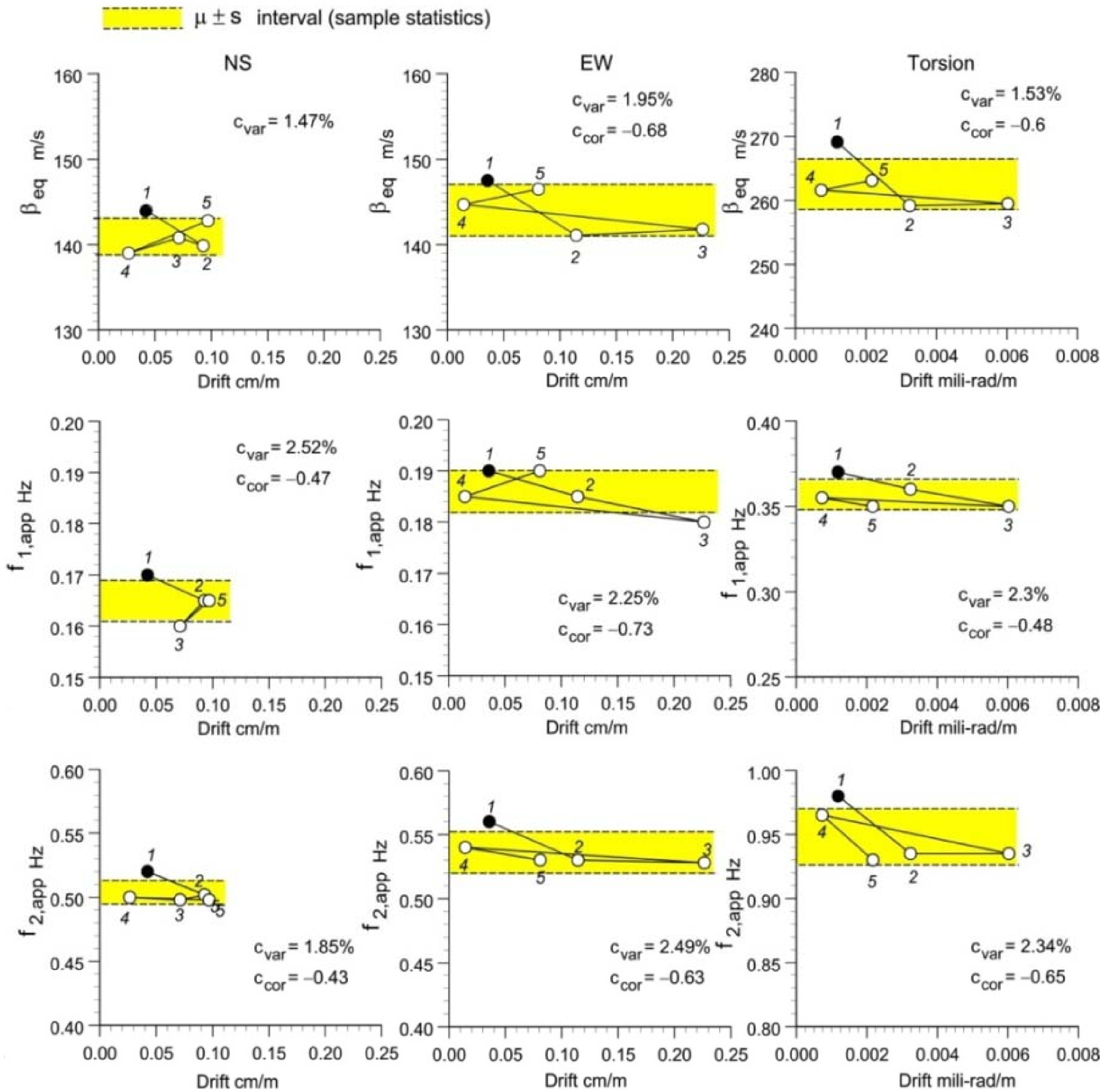


Interstory Drift

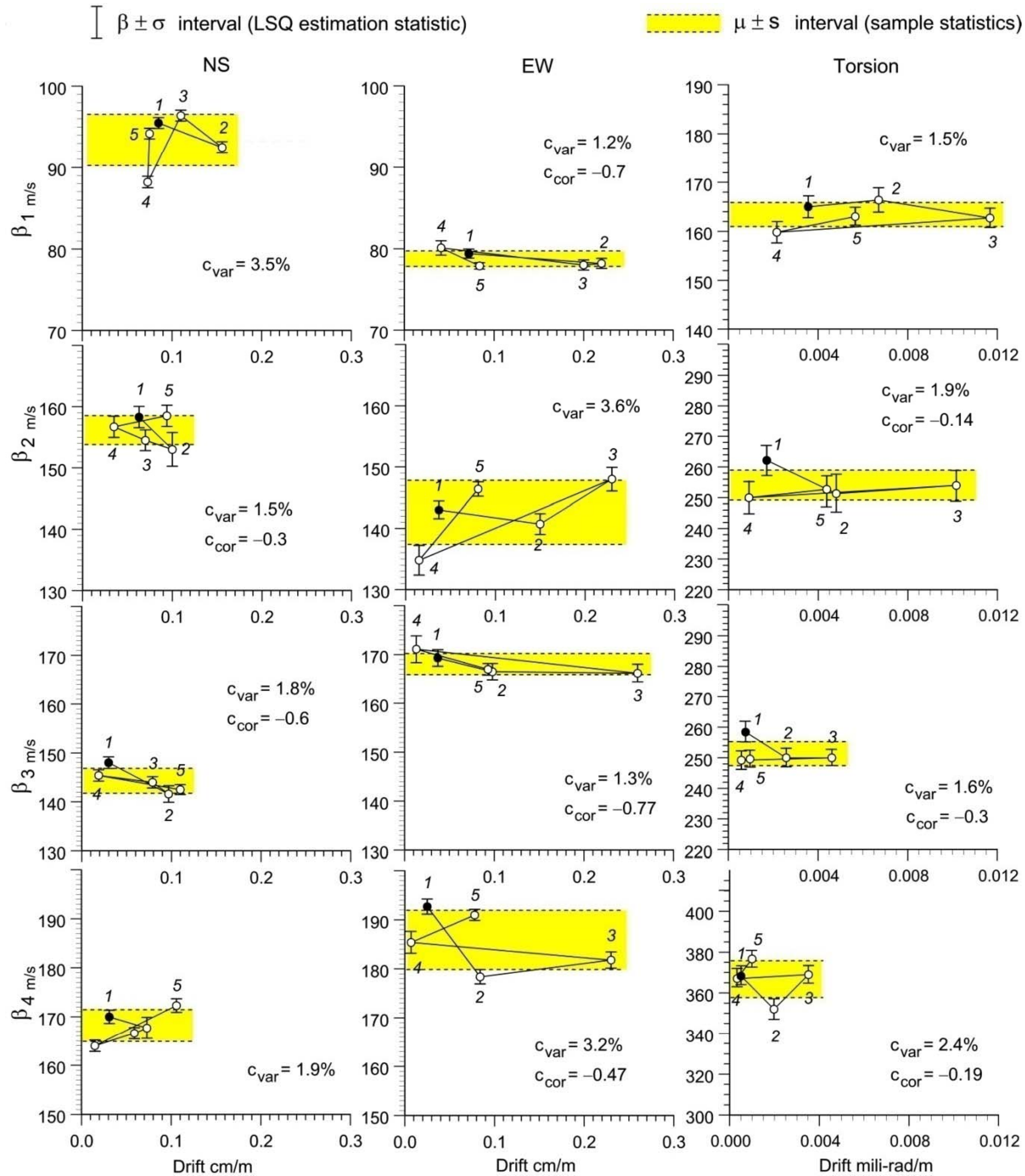




Change in global parameters

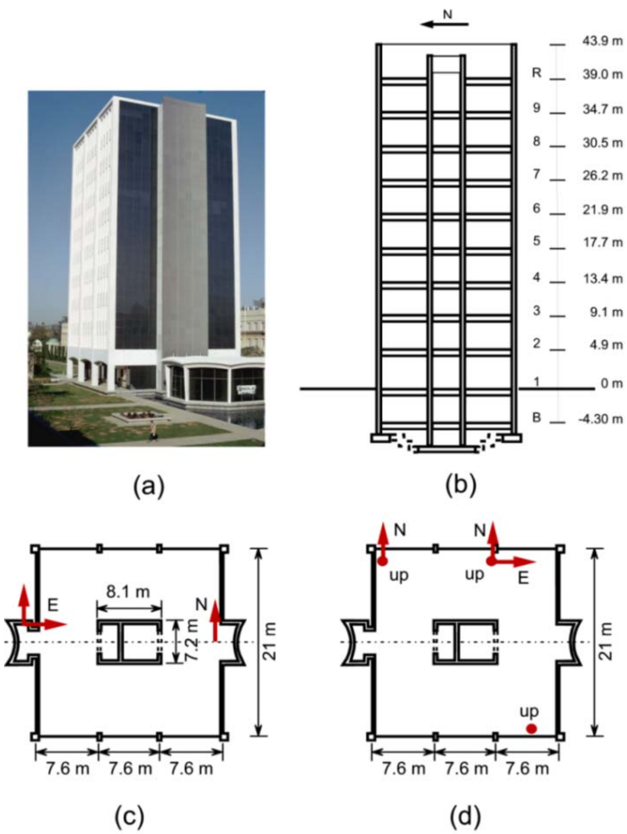


Change in local (layers) parameters

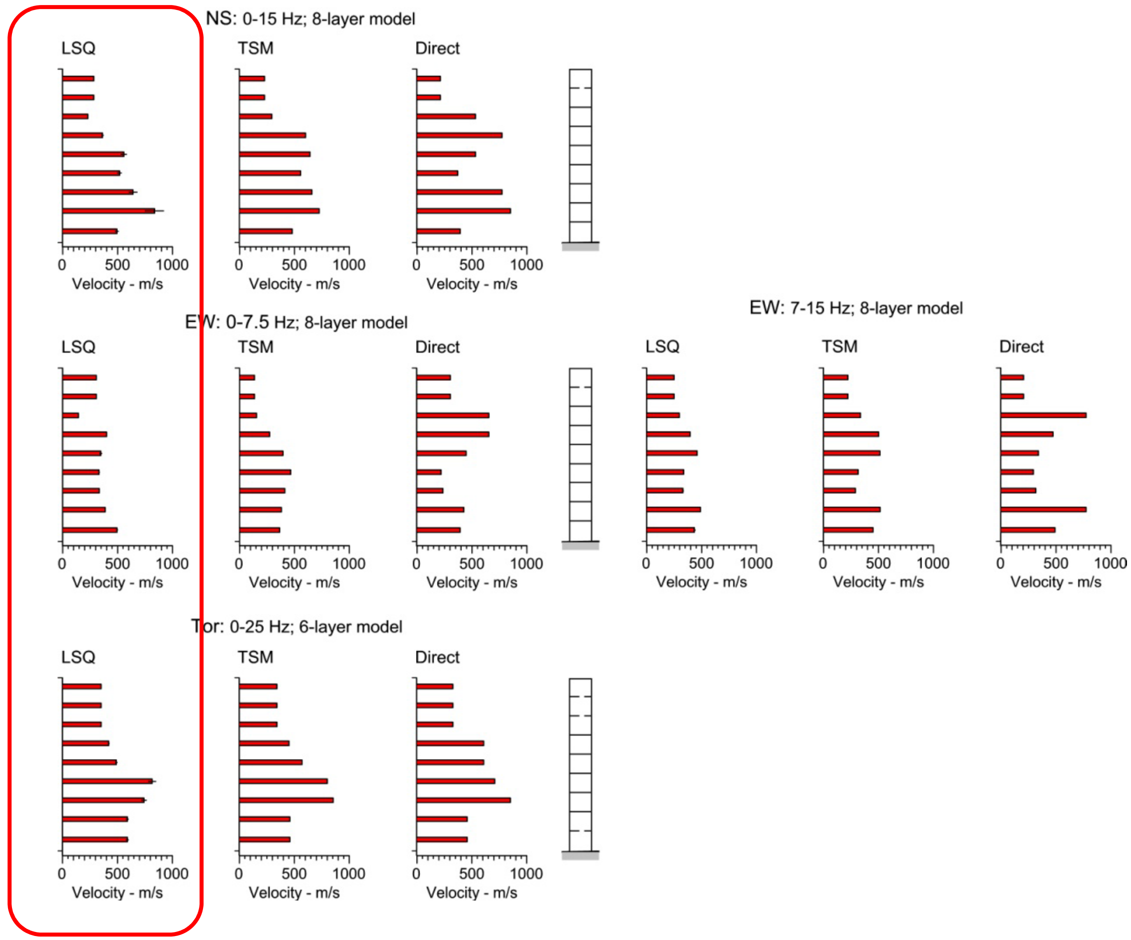


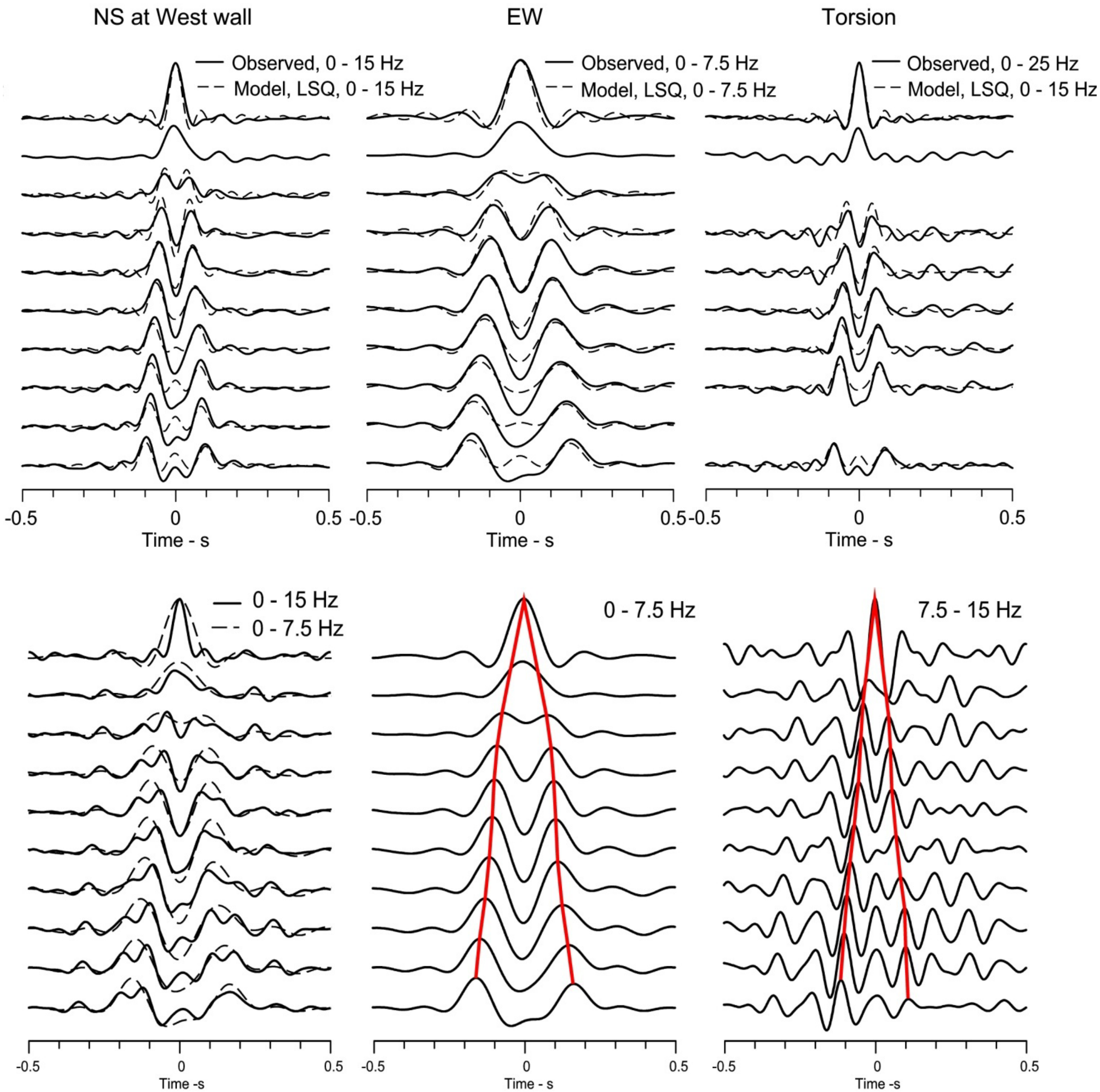
Millikan Library

9-story, RC structure
NSMIP Station 5407



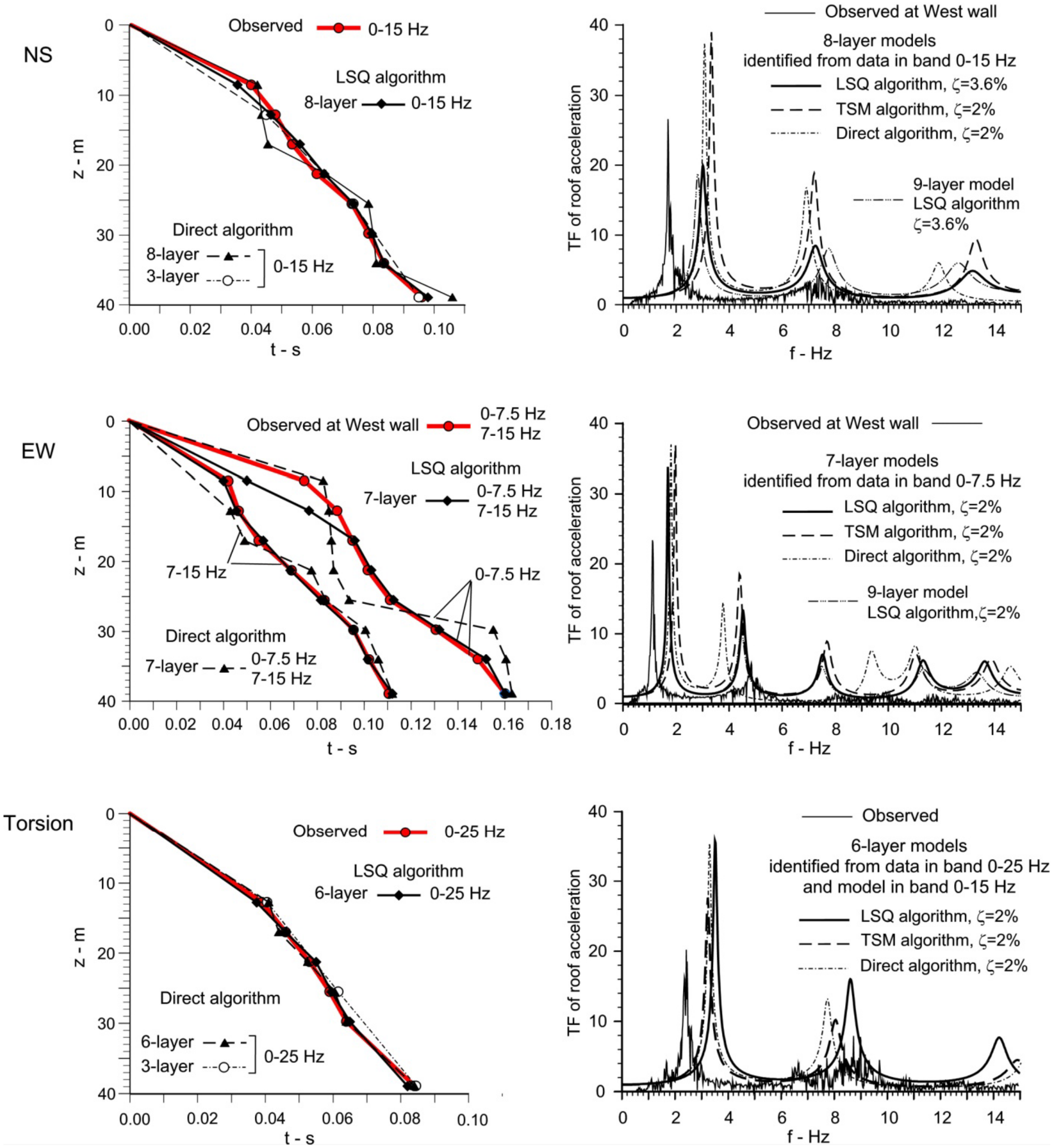
Comparison of different fitting algorithms





Agreement of IRFs: NS, EW and Tor

Evidence of dispersion in EW response

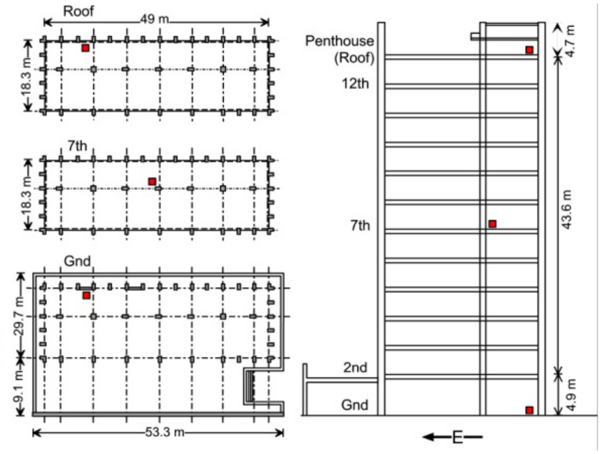


Agreement of Pulse Arrival Times and TFs

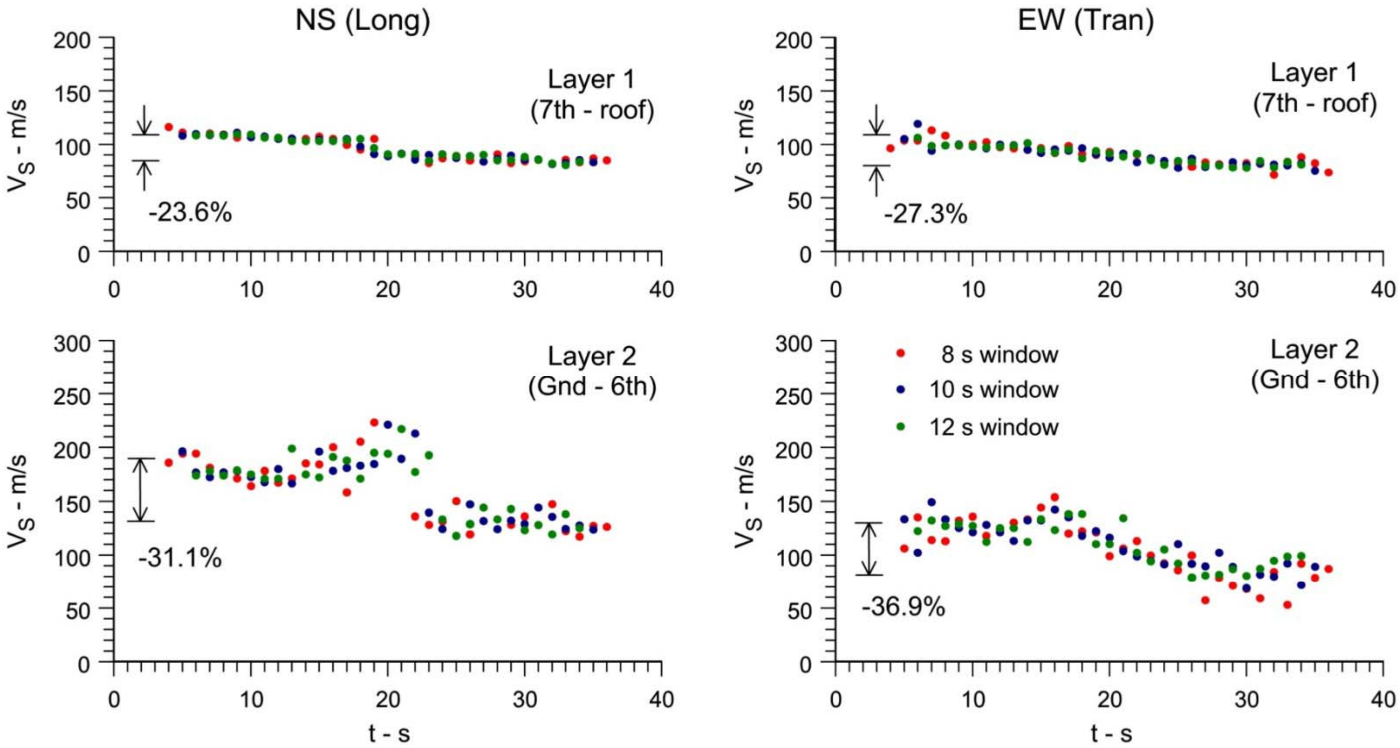
Sherman Oaks
12-story, RC bldg

NSMIP 0466

Lightly damaged in 1971

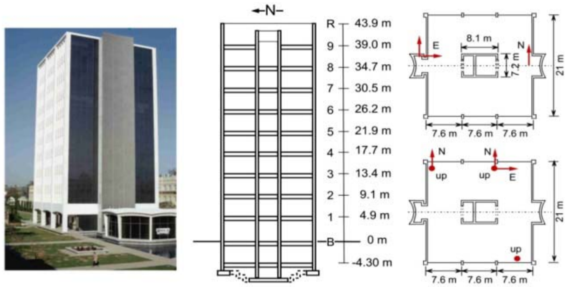


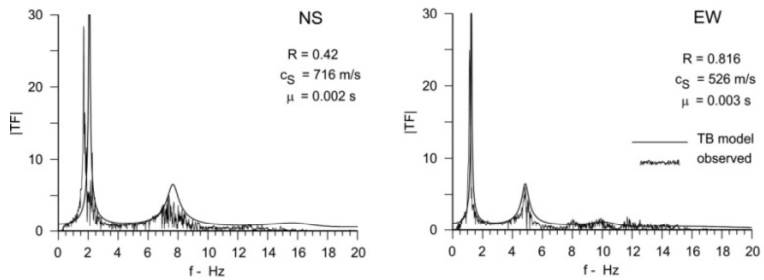
Moving window waveform inversion (Levenberg-Marquardt)

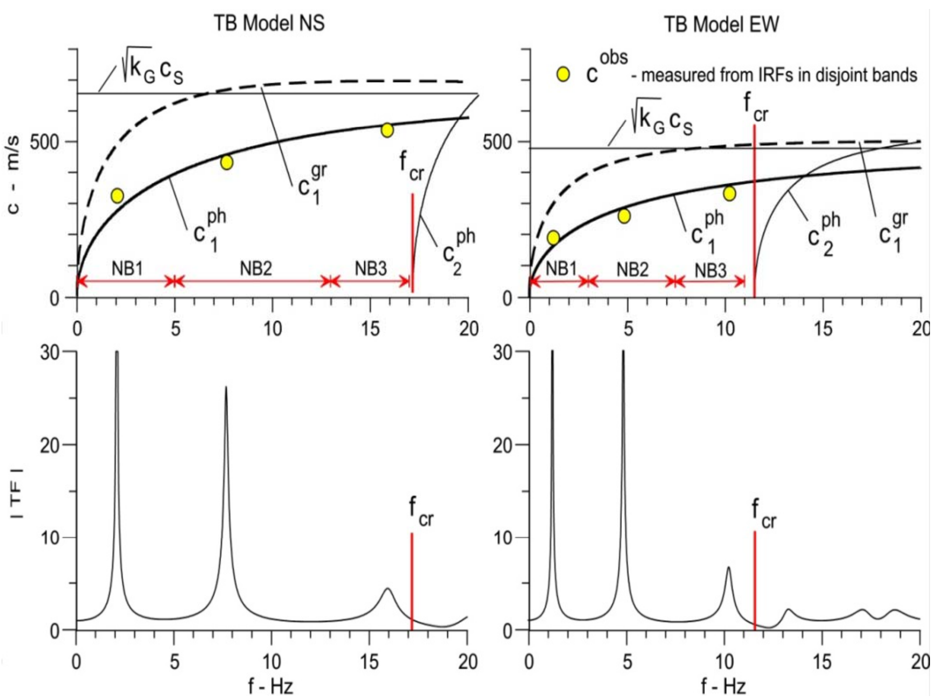


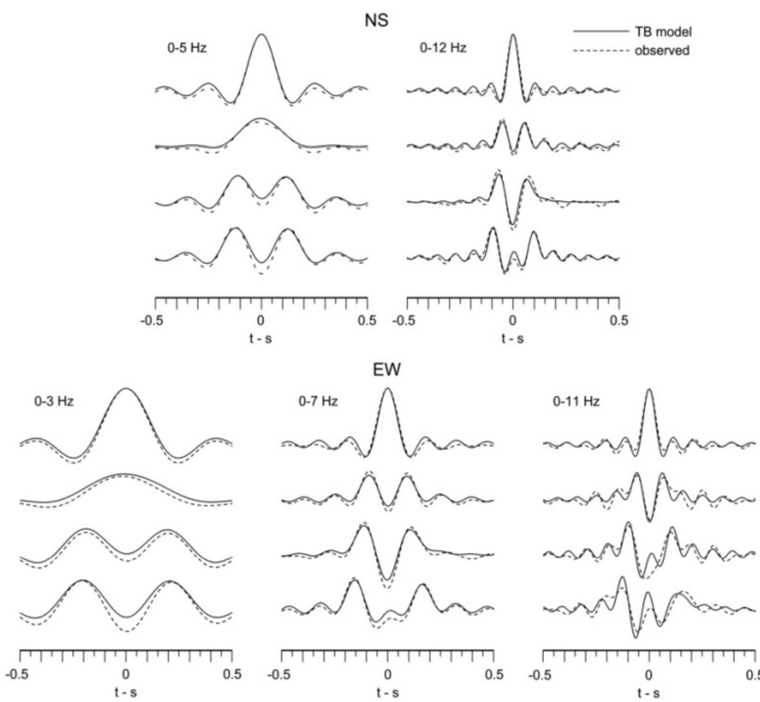
Dispersion due to Bending

- Timoshenko beam model of Millikan library : shear, bending, rotatory intertia; (Timoshenko, 1921; Ebrahimian and Todorovska, 2013a,b)



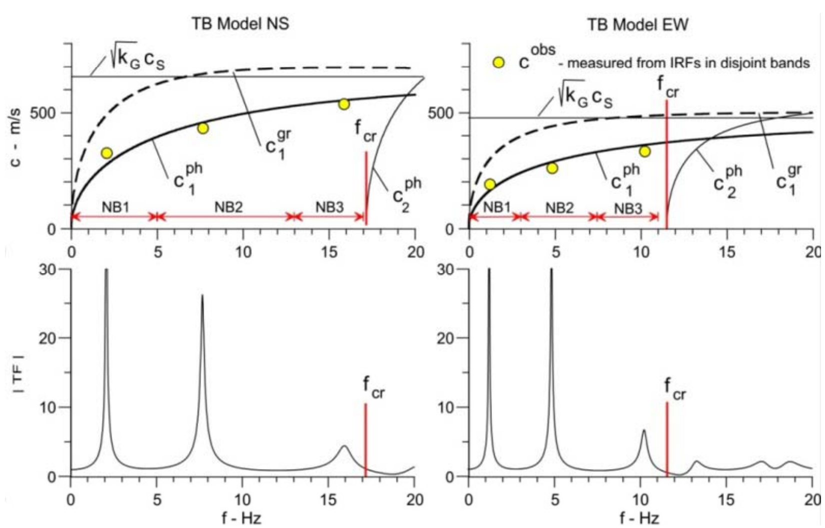


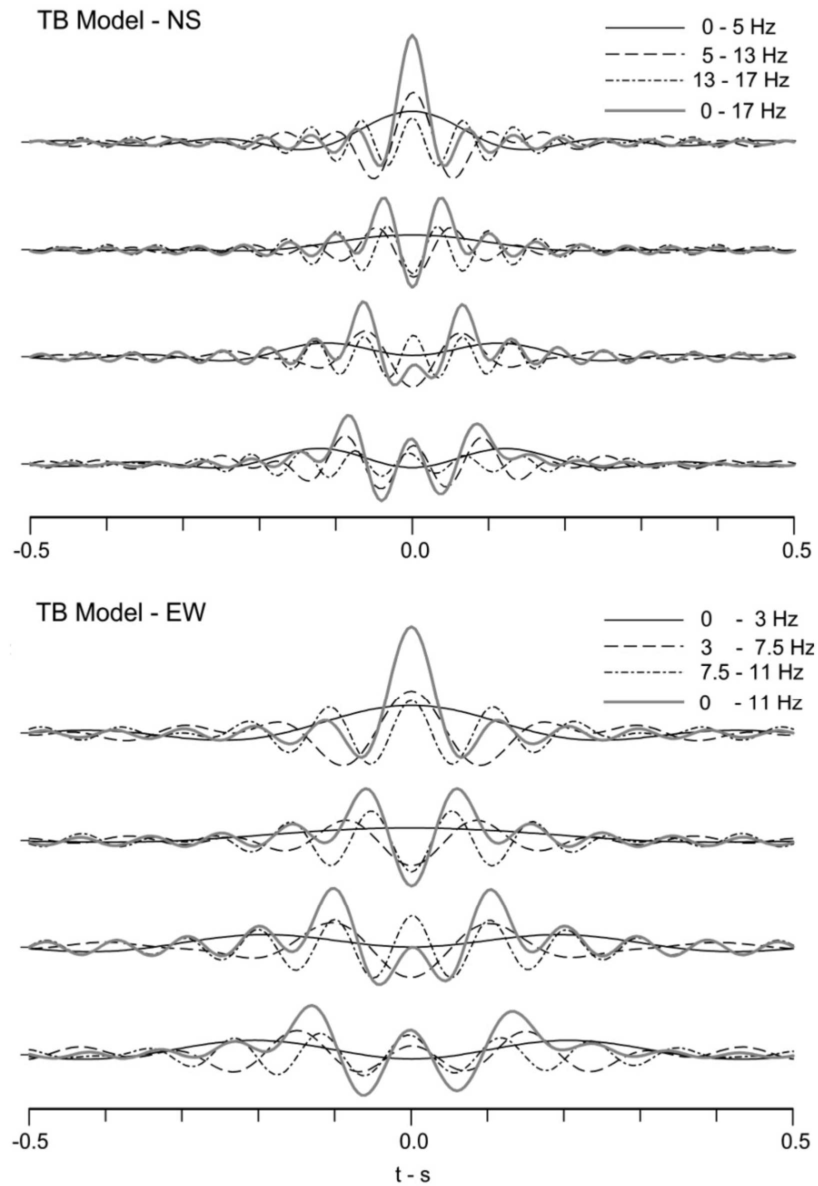




Dispersion due to Bending

- Timoshenko beam model of Millikan library: superposition of IRFs;
- Why estimate is not sensitive to SSI?
- What velocty does broad band inversion give?

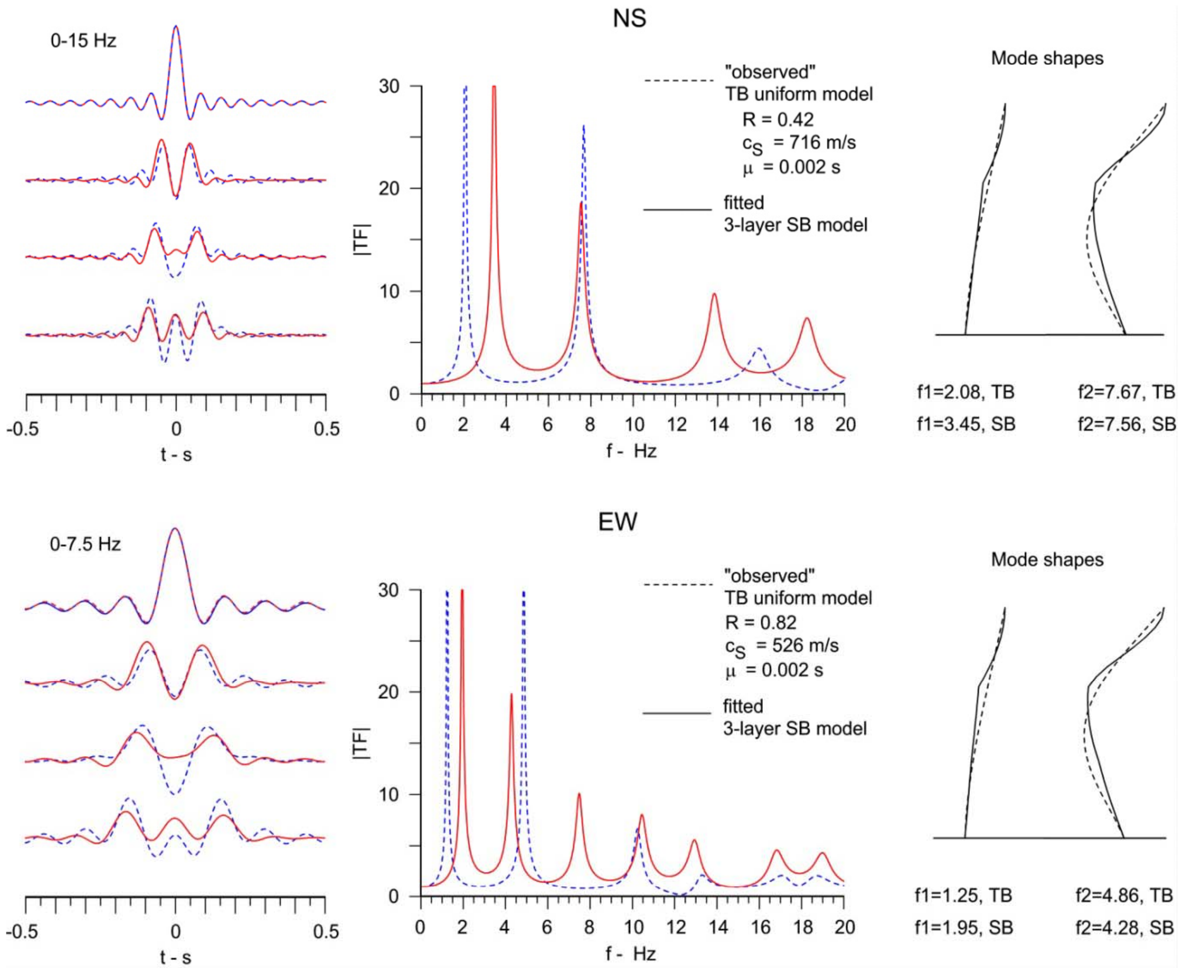




(Ebrahimian et al., 2013)

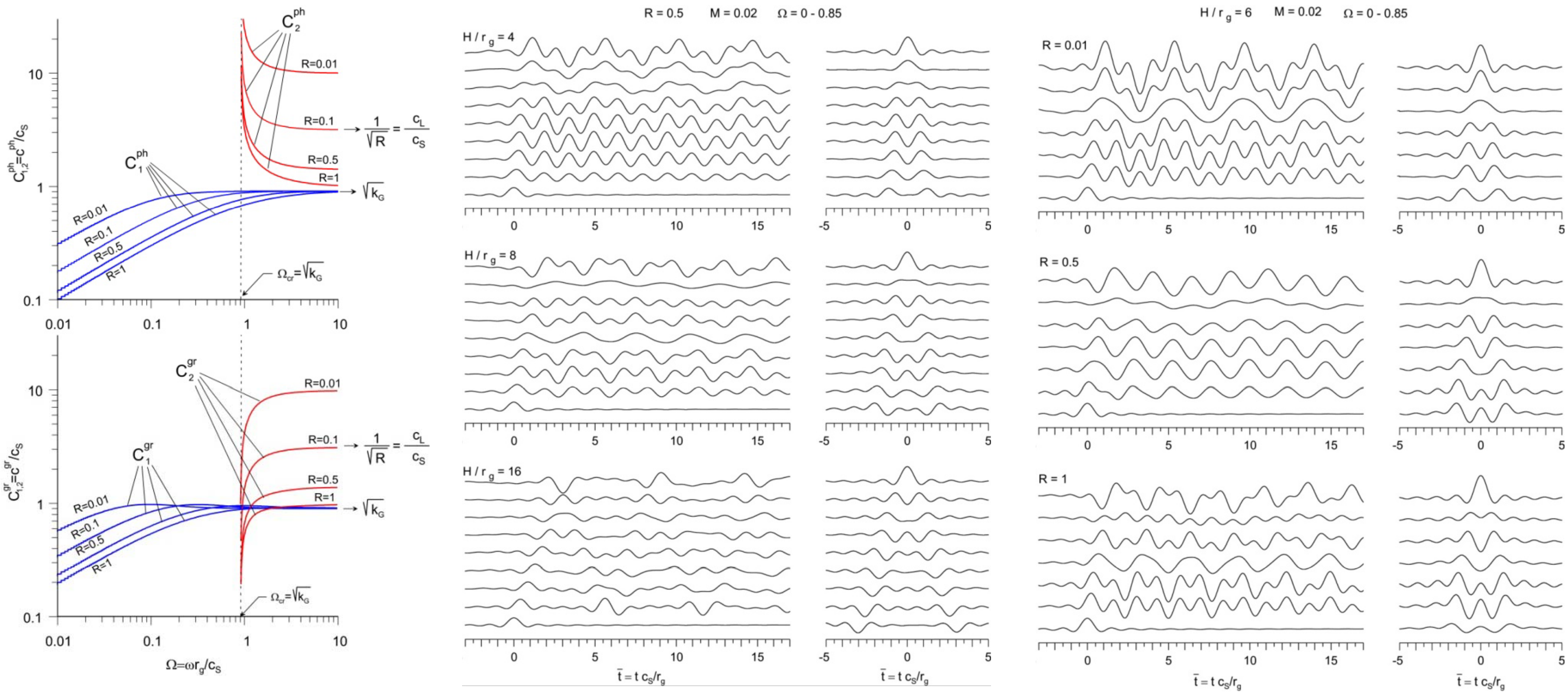
Dispersion due to Bending

- 3-layer shear beam fit in Timoshenko beam response: artifacts due to ignoring dispersion.



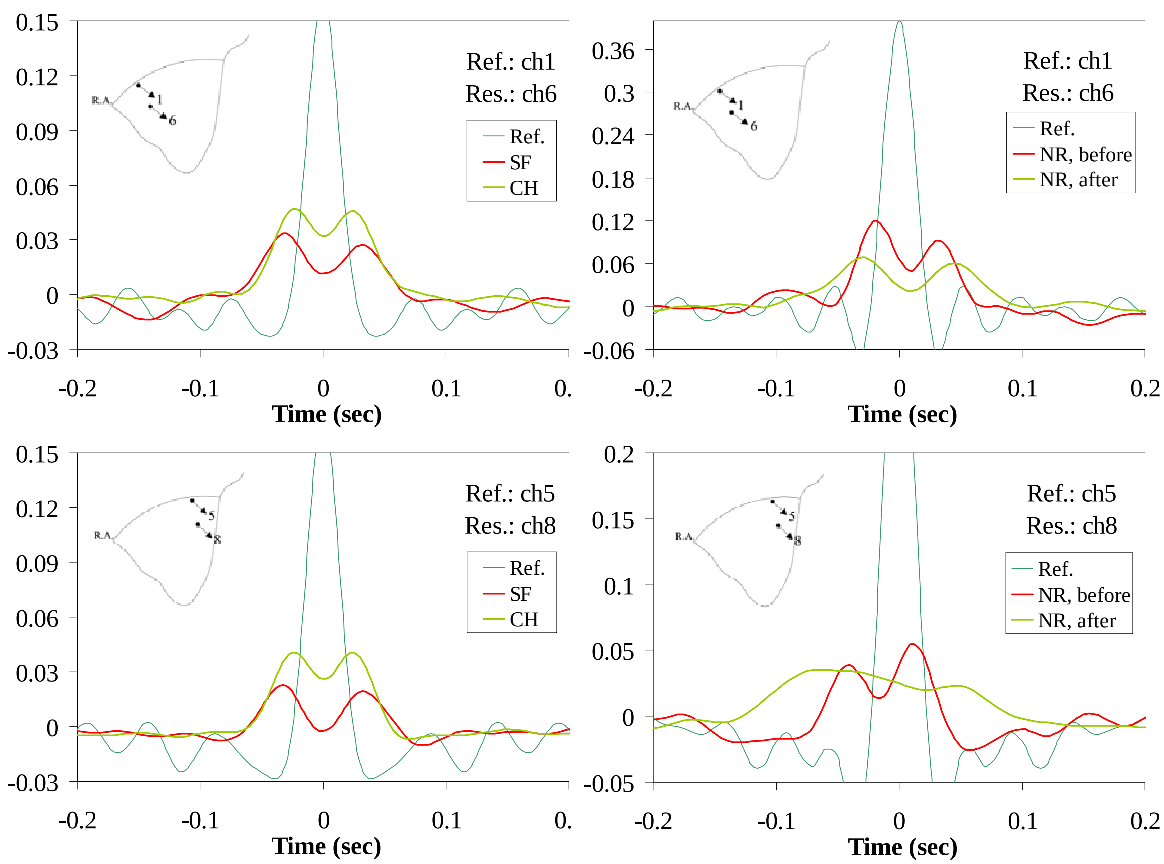
(Ebrahimian et al., 2013)

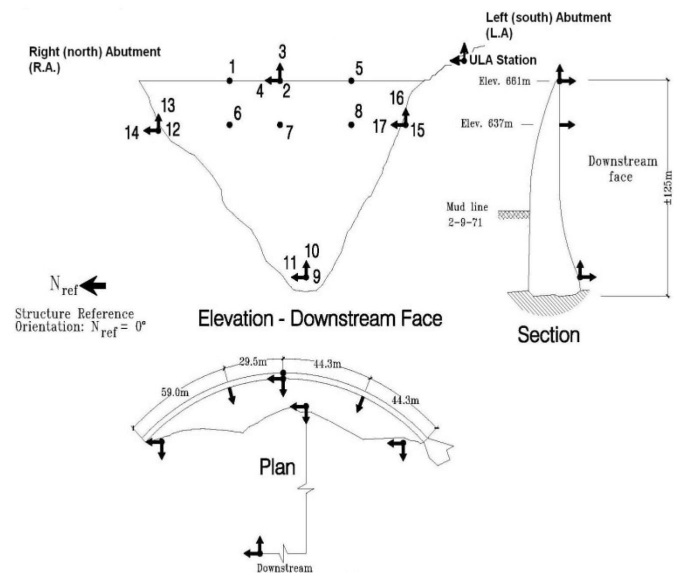
More Timoshenko Beam IRFs

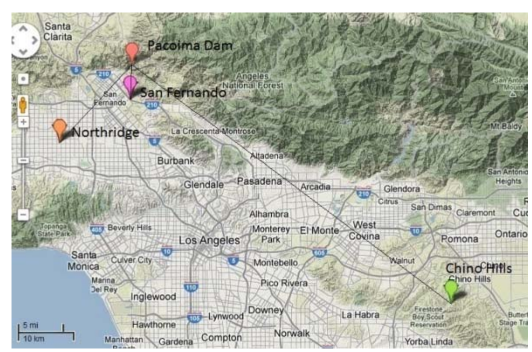


(Ebrahimian and Todorovska, 2013)

Pacoima Dam-Concrete Arch Dam

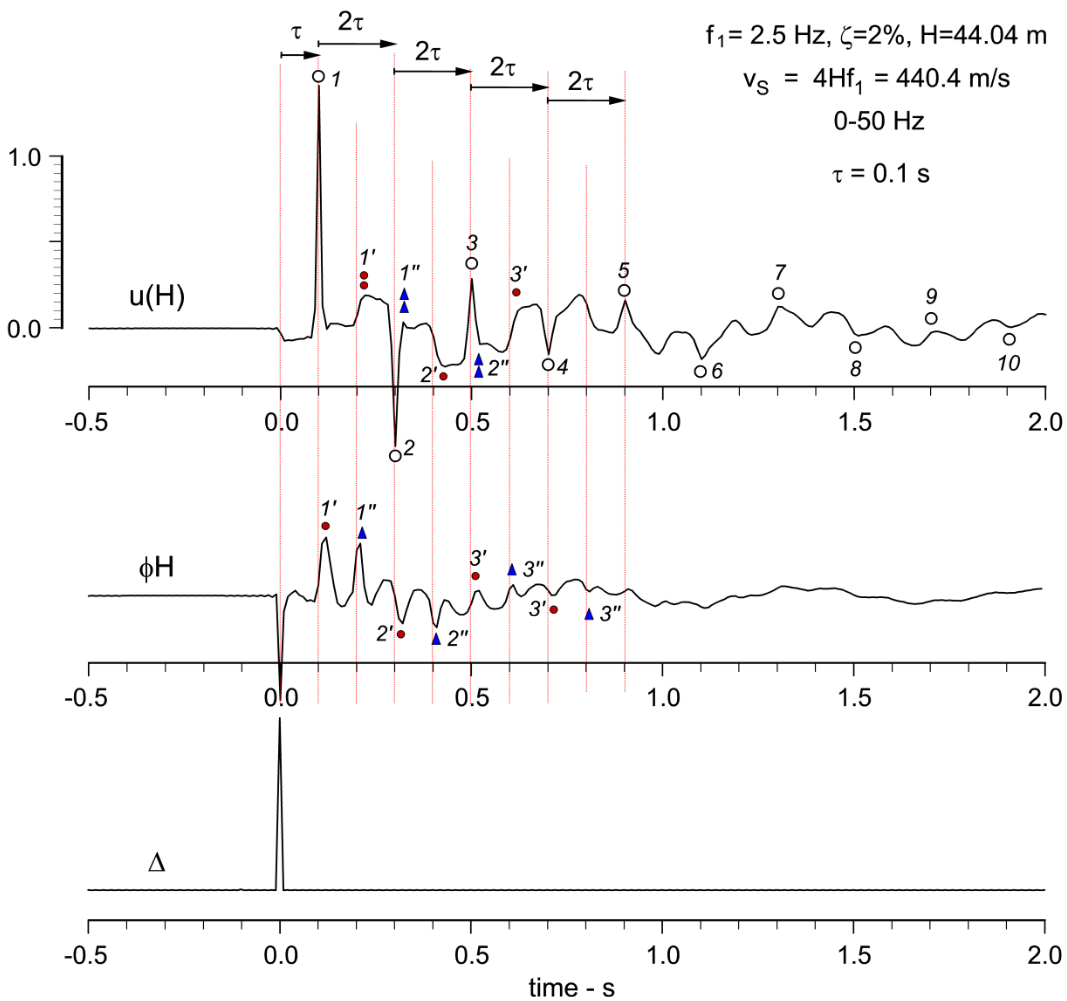


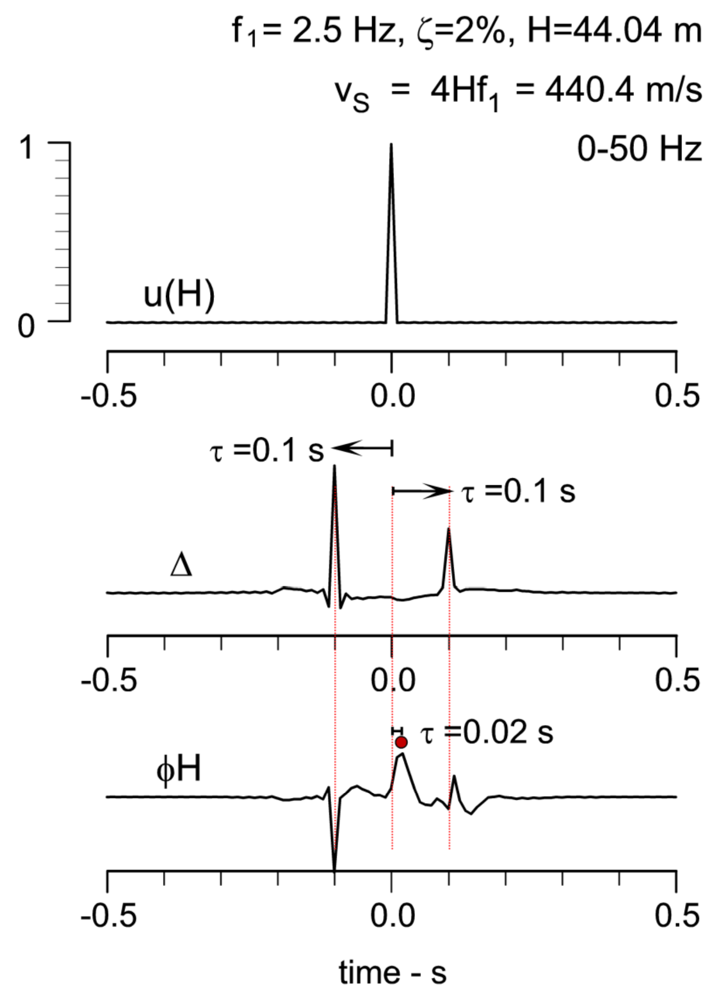




M. Alembagheri et al., 2013

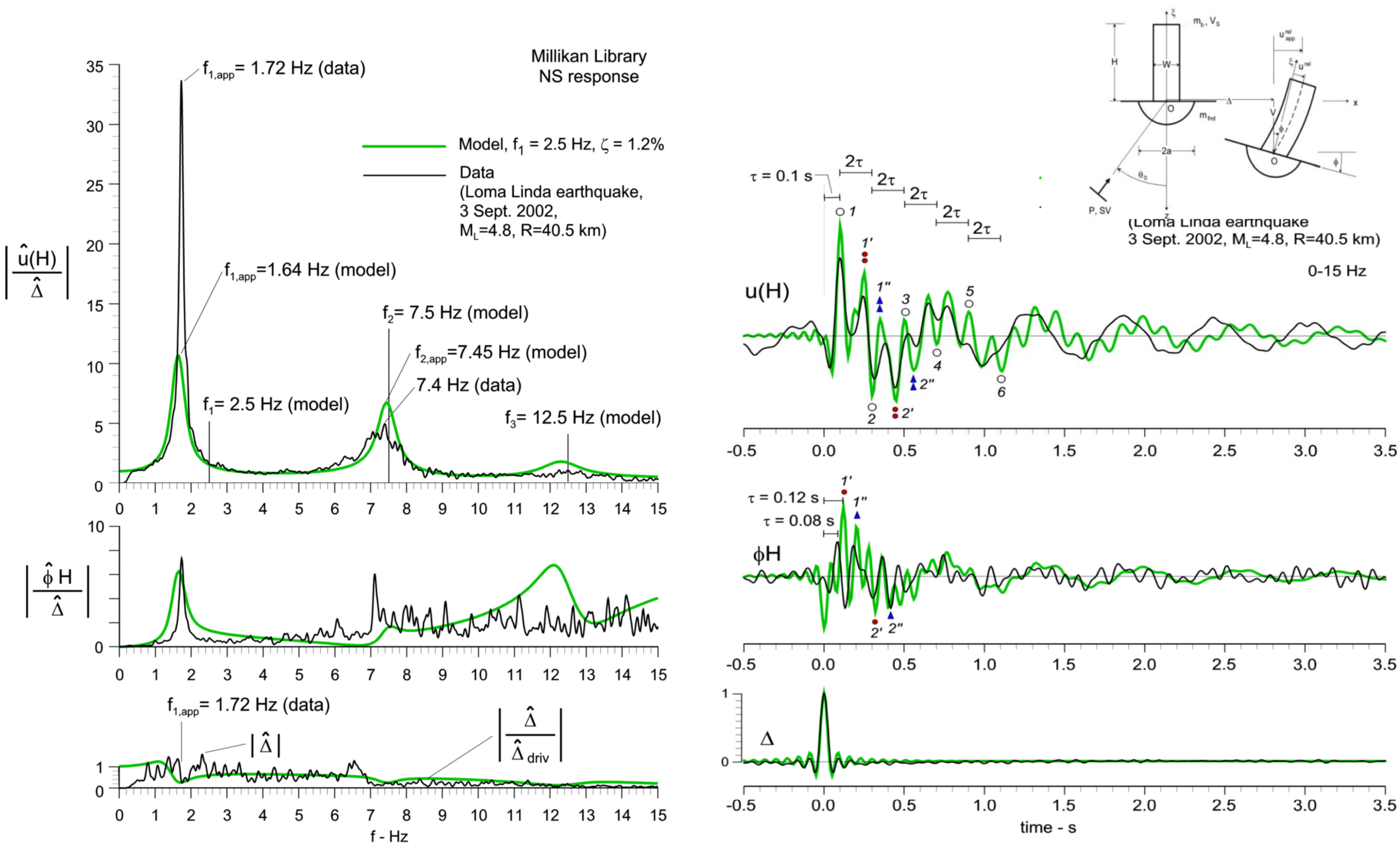
Impulse Responses of SSI Model of Millikan





Todorovska, BSSA 2009a

Cause of Millikan Frequency Wondering – Solved!

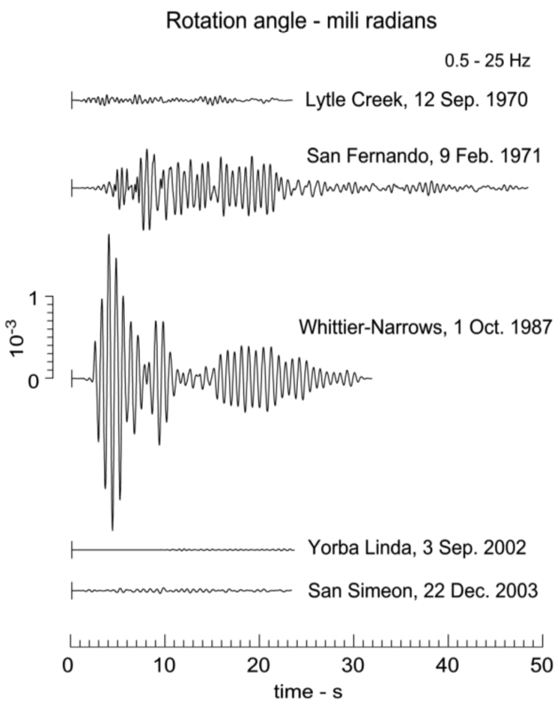


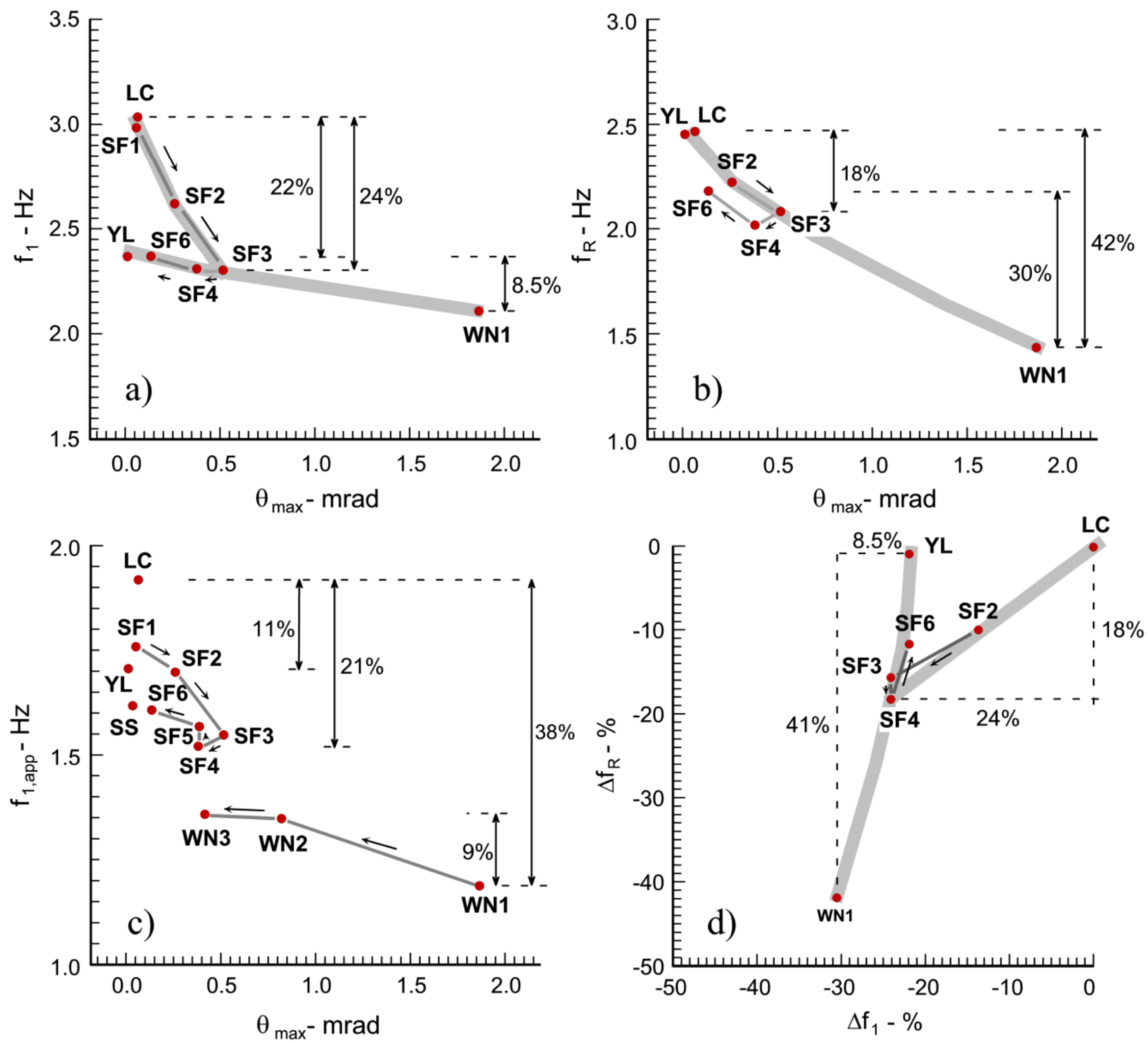
Todorovska, BSSA 2009b

What cause Wondering of Millikan Frequency

$$\frac{1}{f_{1,sys}^{2}} \approx \frac{1}{f_{H}^{2}} + \frac{1}{f_{R}^{2}} + \frac{1}{f_{1}^{2}}$$

$$\frac{1}{f_{1,app}^{2}} = \frac{1}{f_{1}^{2}} + \frac{1}{f_{R}^{2}}$$





Todorovska, BSSA 2009b

Conclusions

- The wave method is promising.
- It is robust, not sensitive to SSI effects, sensitive to damage.
- May be appropriate for many buildings, within carefully chosen frequency bands, specific for the building.

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- Todorovska MI, Rahmani M (2013). System identification of buildings by wave travel time analysis and layered shear beam models - spatial resolution and accuracy, *Struct. Control Health Monit.*, DOI: 10.1002/stc.1484, preview published online 6 March 2012, in press.
- Rahmani M, Todorovska MI (2013). 1D system identification of buildings from earthquake response by seismic interferometry with waveform inversion of impulse responses – method and application to Millikan Library, *Soil Dyn. and Earthqu. Engrg*, Jose Roësset Special Issue, E. Kausel and J. E. Luco, Guest Editors, 47, 157-174, DOI: 10.1016/j.soildyn.2012.09.014.
- Rahmani M, Todorovska MI (2013). 1D system identification of a 54-story steel frame building by seismic interferometry, *Earthquake Eng. and Struct. Dynamics*, conditionally accepted for publication.
- Rahmani M, Todorovska MI (2013). Structural health monitoring of a 54-story steel frame building - wave and vibrational characteristics during five earthquakes, *Earthquake Spectra*, conditionally accepted for publication.
- Rahmani M, Dehaghani ME, Todorovska MI. (2012). Comparative earthquake damage detection in a full scale 12-story RC building using wave travel time, time-frequency and novelties analyses, in preparation
- Ebrahimian M, Todorovska MI (2013). Wave propagation in a Timoshenko beam building model, *J. Eng. Mech.*, ASCE, submitted for publication.
- Alembagheri M, Todorovska MI, Trifunac MD, Ghaemian M (2013). Structural system identification and health monitoring of a concrete arch dam using strong motion records, in preparation.

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- Todorovska MI (2009). Seismic interferometry of a soil-structure interaction model with coupled horizontal and rocking response, Bull. Seism. Soc. Am., 99(2A), 611-625, doi: 10.1785/0120080191.
- Todorovska MI (2009). Soil-structure system identification of Millikan Library North-South response during four earthquakes (1970-2002): what caused the observed wandering of the system frequencies?, Bull. Seism. Soc. Am., 99(2A), 626-635, doi: 10.1785/0120080333.
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- Todorovska MI, Trifunac MD (2008). Impulse response analysis of the Van Nuys 7-story hotel during 11 earthquakes and earthquake damage detection, Structural Control and Health Monitoring, 15(1), 90-116; DOI: 10.1002/stc.208.
- Trifunac MD, Todorovska MI, Manić MI, Bulajić BĐ (2010). Variability of the fixed-base and soil-structure system frequencies of a building – the case of Borik-2 building, Structural Control and Health Monitoring, 17(2), 2010, 120–151, published online 2008, DOI: 10.1002/stc.277.
- Ivanovic SS, Trifunac MD, Todorovska MI (2001). On identification of damage in structures via wave travel times, in M. Erdik, M. Celebi, V. Mihailov, and N. Apaydin (Eds.), Proc. NATO Advanced Research Workshop on Strong-Motion Instrumentation for Civil Engineering Structures, June 2-5, 1999, Istanbul, Turkey, Kluwer Academic Publishers, 2001, pp. 21.

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- Ivanovic SS, Trifunac MD, Todorovska MI (2000). Ambient vibration tests of structures - a review, Bull. Indian Soc. Earthquake Tech., 37(4), 165-197.
- Trifunac MD, Todorovska MI, Hao TY (2001). Full-scale experimental studies of soil-structure interaction - a review, Proc. 2nd U.S.-Japan Workshop on Soil-Structure Interaction, March 6-8, 2001, Tsukuba City, Japan, pp. 52.

Some publications downloadable from:

Project web site:

www.usc.edu/dept/civil_eng/Earthquake_eng/Earthquake_damage_detection_NSF_2008/

Strong Motion Research Group web site:

www.usc.edu/dept/civil_eng/Earthquake_eng/

Acknowledgements

- Some of this work was supported by a grant from the U.S. National Science Foundation (CMMI-0800399).
- Strong motion data for Los Angeles 54-story building was obtained from Engineering Centre for Strong Motion Data (www.strongmotioncenter.org/); for Millikan Library, from the U.S. Geological Survey Strong Motion Instrumentation Project (http://nsmp.wr.usgs.gov/); and for Sherman Oaks 12-story building, from M. Trifunac.

Thank You!