International Institute of Seismology and Earthquake Engineering

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Strong Motion Observation - Data Analysis -

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IISEE, BRI

Contents

- Intensity index
- Integration
- Fourier spectrum
- Response spectrum
- Application

Intensity indexes

- Peak ground acceleration (PGA) and peak ground velocity (PGV)
- JMA seismic intensity (I_{JMA}) scale (0 to 7)
- Housner's spectrum intensity, *SI*

$$SI(h) = \int_{0.1}^{2.5} pSv(T, h)\,dT$$

Intensity indexes
Peak values

- Peak ground acceleration (PGA) and peak ground velocity (PGV)

$$PGA = \left| a_X(t) \right|_{\max}$$

$$PGA = \left| \sqrt{a_X{}^2(t) + a_Y{}^2(t)} \right|_{\max}$$

$$PGA = \left| \sqrt{a_X{}^2(t) + a_Y{}^2(t) + a_Z{}^2(t)} \right|_{\max}$$

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Intensity indexes
JMA seismic intensity scale

- JMA seismic intensity (I_{JMA}) scale (0 to 7)
  - Filtering 3-component acceleration
  - Compute vectorial amplitude

$$v(t) = \sqrt{x'^2(t) + y'^2(t) + z'^2(t)}$$

  - Find a_0 satisfies;

$$\int_0^{Td} w(t,a)dt \geq 0.3 \qquad w(t,a) = 0,\ v(t) < a_0$$

$$w(t,a) = 1,\ v(t) \geq a_0$$

  - Compute I_{JMA}

$$I_{\mathrm{JMA}} = 2\log a_0 + 0.94$$

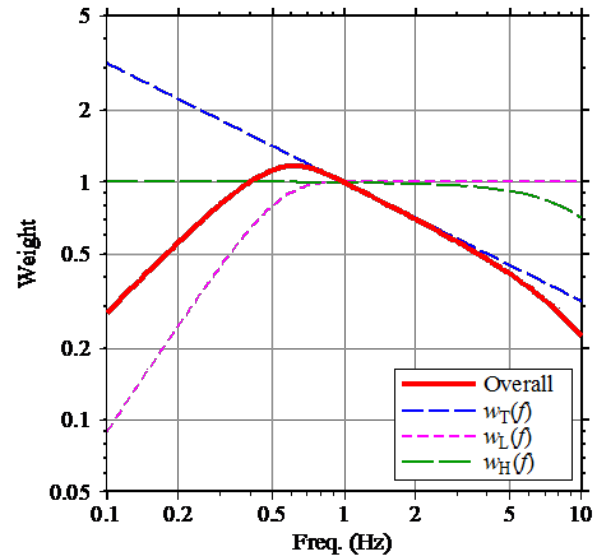
Intensity indexes
JMA seismic intensity scale

- Filters

$$w_T(f) = (1/f)^{1/2}$$

$$w_H(f) = (1 + 0.694y^2 + 0.241y^4 + 0.0557y^6 + 0.009664y^8 + 0.00134y^{10} + 0.000155y^{12})^{-1/2}$$

$$w_L(f) = (1 - \exp(-(f/0.5)^3))^{1/2}$$



Intensity indexes
JMA seismic intensity scale

Scale	Explanation
7	In most buildings, wall tiles and windowpanes are damaged and fall. In some cases, reinforced concrete-block walls collapse.
6+	In many buildings, wall tiles and windowpanes are damaged and fall. Most unreinforced concrete-block walls collapse.
6-	In some buildings, wall tiles and windowpanes are damaged and fall.
5+	In many cases, unreinforced concrete-block walls collapse and tombstones overturn. Many automobiles stop due to difficulty to drive.

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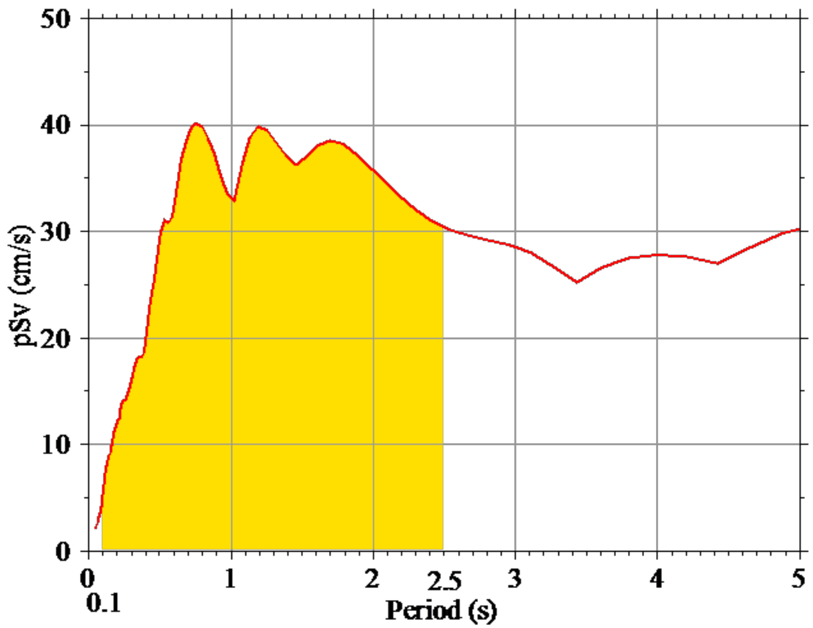
Intensity indexes
JMA seismic intensity scale

Scale	Explanation
5-	Most people try to escape from a danger. Some people find it difficult to move
4	Many people are frightened. Some people try to escape from a danger. Most sleeping people awake.
3	Felt by most people in the building. Some people are frightened.
2	Felt by many people in the building. Some sleeping people awake.
1	Felt by only some people in the building.
0	Imperceptible to people.

Intensity indexes
Housner's spectrum intensity

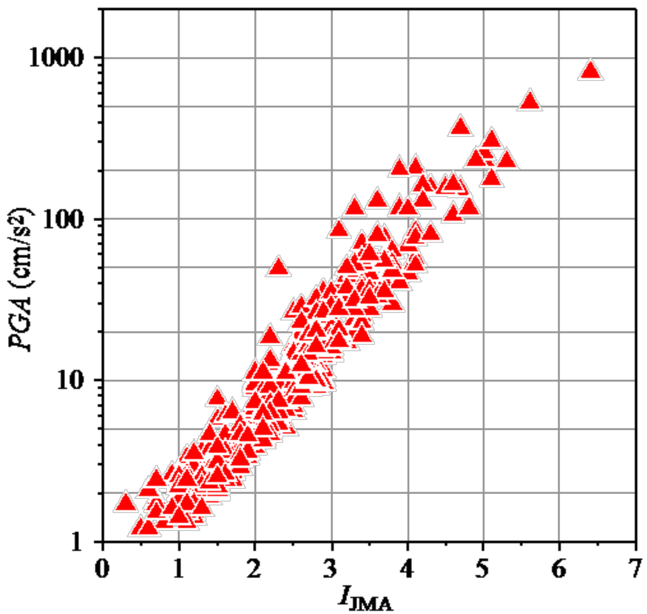
- Housner's spectrum intensity, *SI*

$$SI(h) = \int_{0.1}^{2.5} pSv(T,h)dT$$

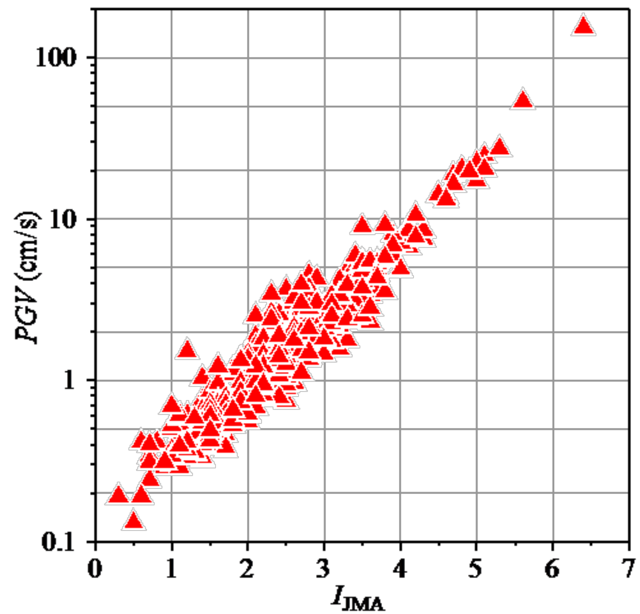


Intensity indexes
Relation among indexes

- 391 records from K-NET during the 2007 Off Chuetsu Earthquake



(a) I_{JMA} vs. *PGA*



(b) I_{JMA} vs. *PGV*

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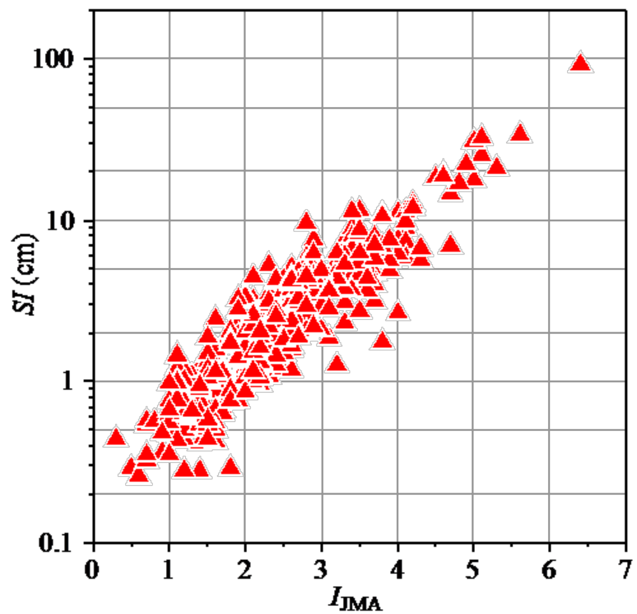
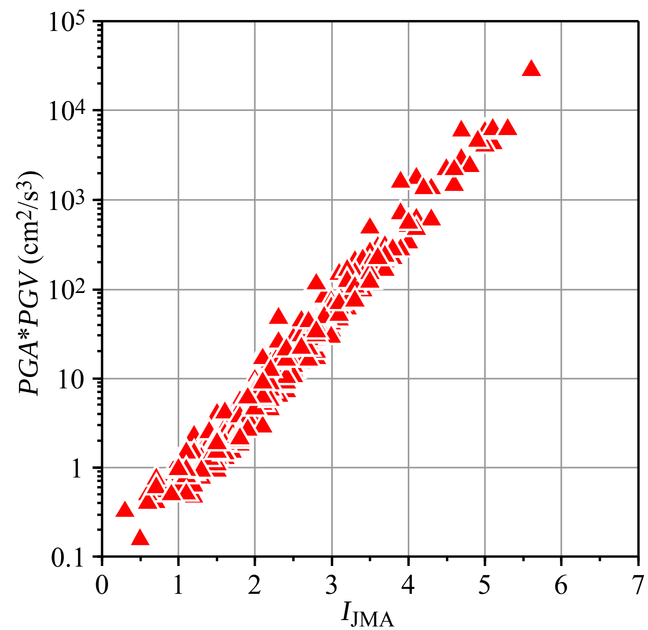
Intensity indexes

Relation among indexes

- 391 records from K-NET during the 2007 Off Chuetsu Earthquake



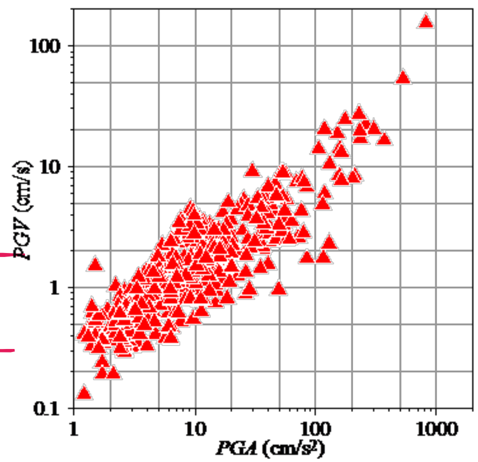
(c) I_{JMA} vs. *SI*



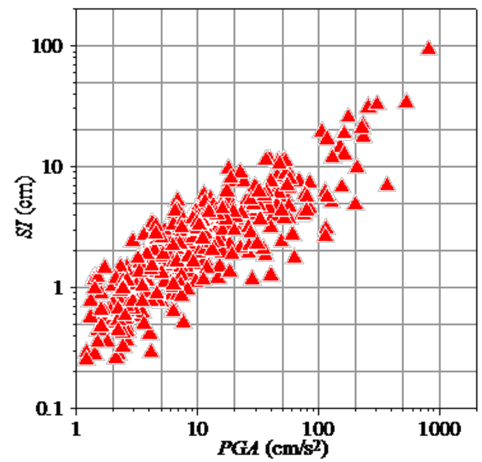
(d) I_{JMA} vs. PGA*PGV

Intensity indexes
Relation among indexes

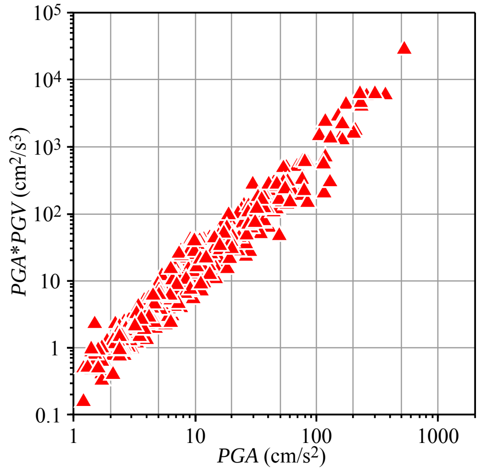
- Relation to *PGA*



(e) *PGA* vs. *PGV*



(f) *PGA* vs. *SI*



(g) *PGA* vs. PGA**PGV*

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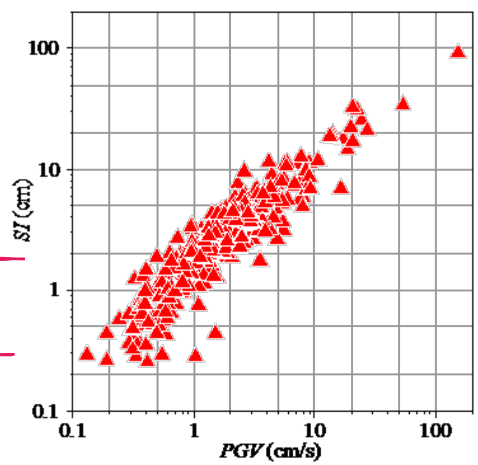
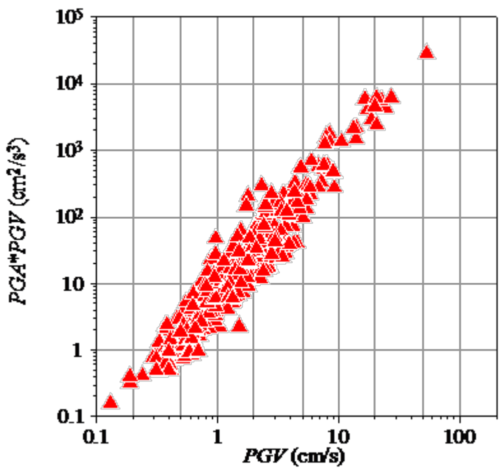
Intensity indexes
Relation among indexes

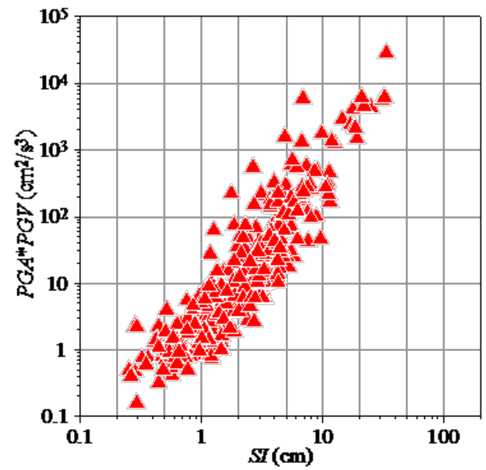
- Relation to *PGA*



(h) *PGV* vs. *SI*



(i) *PGV* vs. *PGA*PGV*



(j) *SI* vs. PGA**PGV*

Integration

- Conversion from acceleration to velocity and displacement
  - Integration in time domain with baseline correction in velocity and/or displacement
  - Integration in frequency domain with high pass filter
  - Simulation of seismograph using a SDOF model (pendulum)

Integration
Time domain

- Trapezoidal method (require baseline correction and/or low-cut filter)

$$v_{j+1} = v_j + (a_j + a_{j+1})\Delta t / 2$$

Integration
Frequency domain

- FFT and invert FFT (with low-cut filter)
  - Fourier transform

$$a(t) \rightarrow A(\omega)$$

  - Integration in frequency domain

$$V(\omega) = A(\omega) / i\omega$$

  - Low-cut filtering

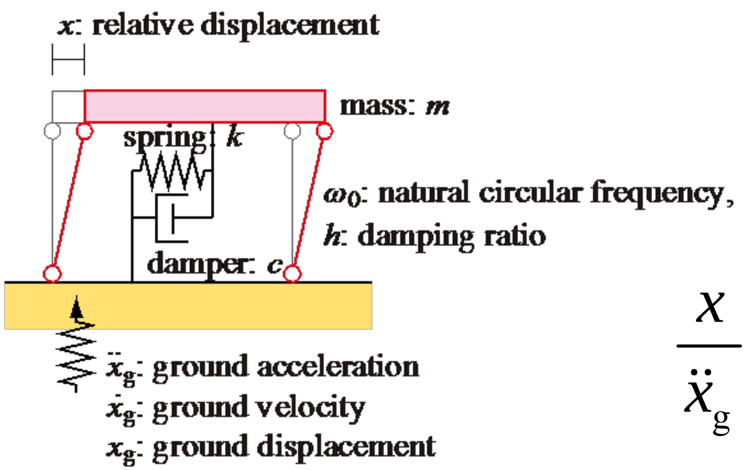
$$V'(\omega) = F_{\mathrm{L}}(\omega) V(\omega)$$

  - Invert Fourier transform

$$V'(\omega) \rightarrow v(t)$$

Integration
Simulation of seismograph

- Simulate simple seismograph



$$\frac{x}{\ddot{x}_{\mathrm{g}}} = -\frac{1}{\omega_0^2 - \omega^2 + 2\mathrm{i}h\omega_0\omega}$$

$$\frac{x}{\dot{x}_{\mathrm{g}}} = -\frac{\mathrm{i}\omega}{\omega_0^2 - \omega^2 + 2\mathrm{i}h\omega_0\omega}$$

$$\frac{x}{x_{\mathrm{g}}} = \frac{\omega^2}{\omega_0^2 - \omega^2 + 2\mathrm{i}h\omega_0\omega}$$

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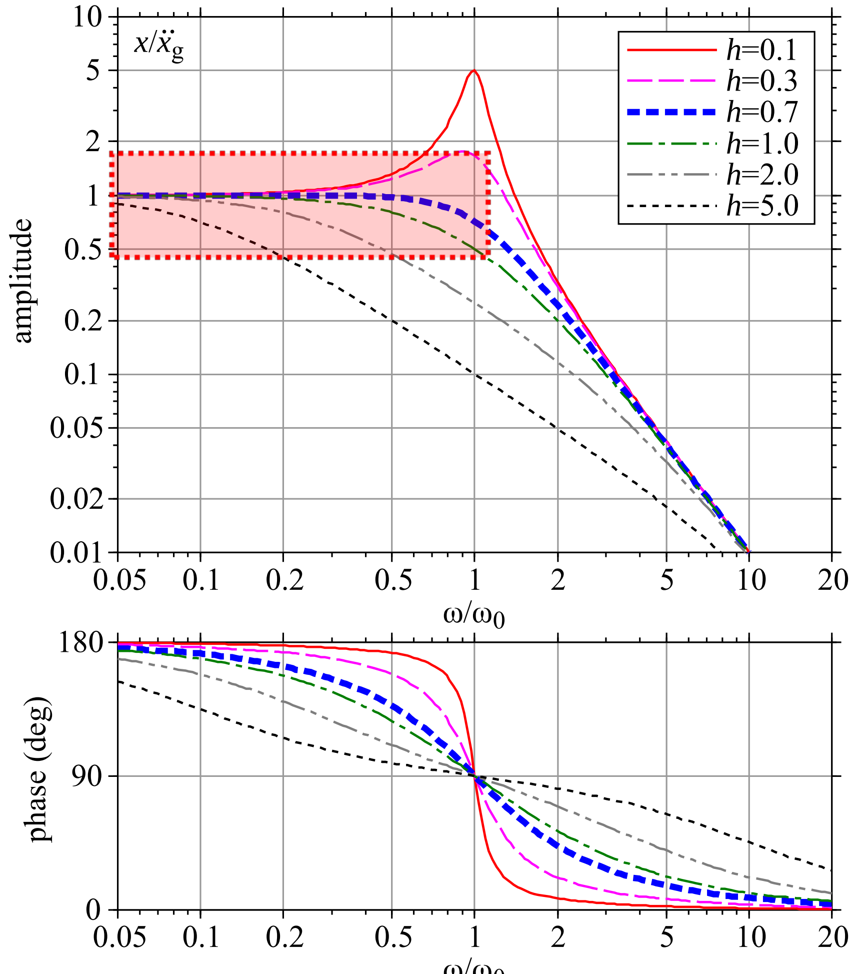
Integration
Simulation of seismograph

- Acceleration

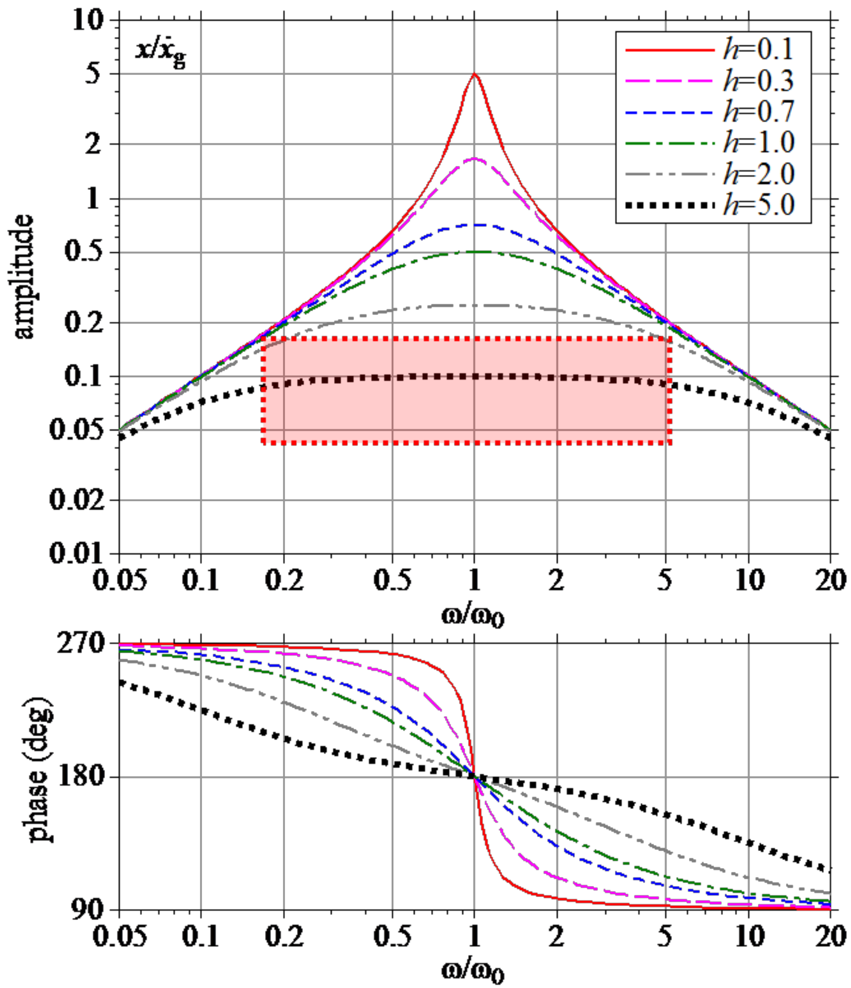
$$x / \ddot{x}_g$$



Integration
Simulation of seismograph

- Velocity

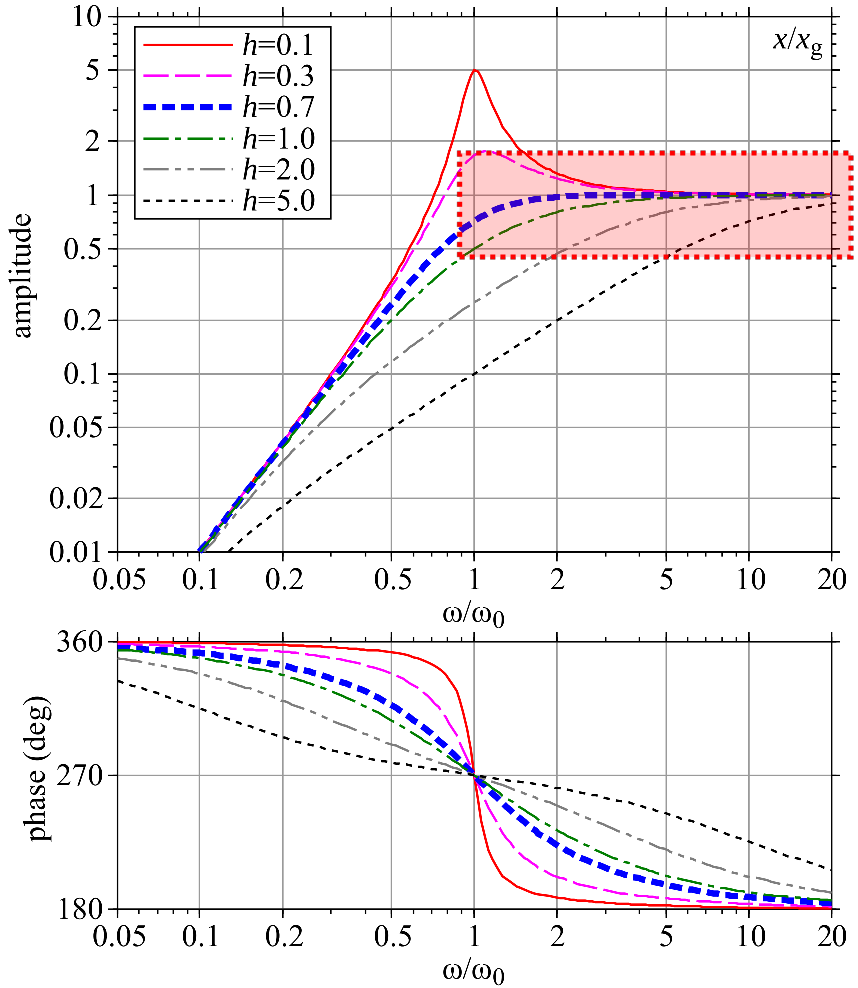
$x/\dot{x}_g$



Integration
Simulation of seismograph

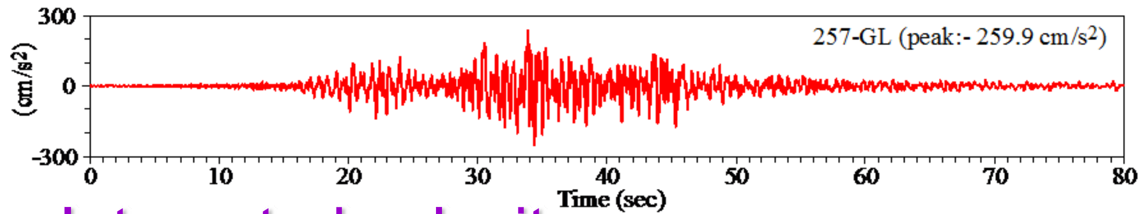
- Displacement

x/x_g

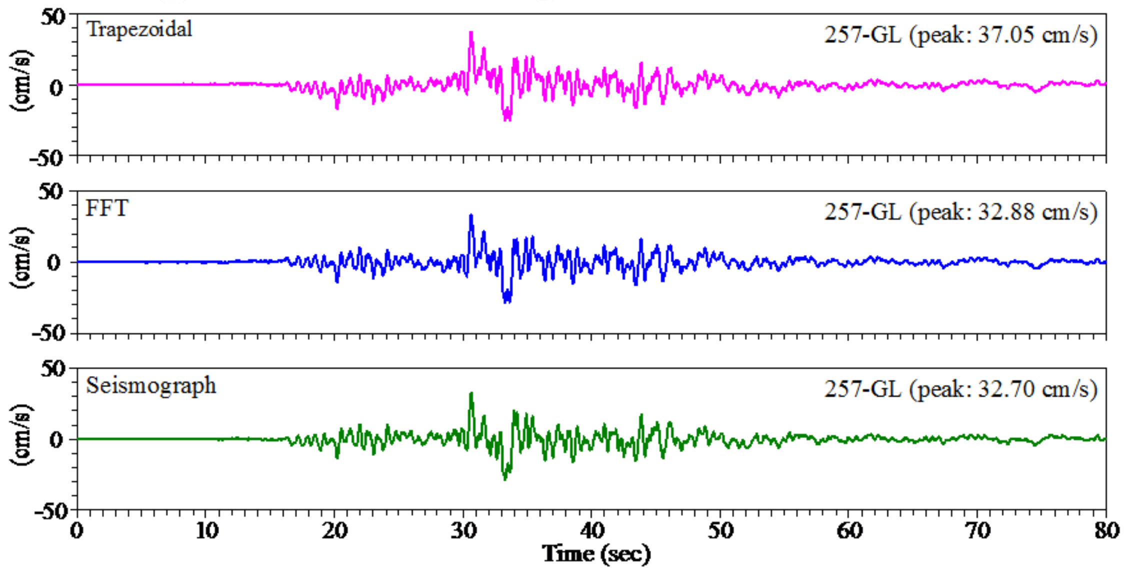


Integration
Comparison among methods

- GL at Kushiro Gov. Office Bldg., 2003
  - Acceleration



  - Integrated velocity



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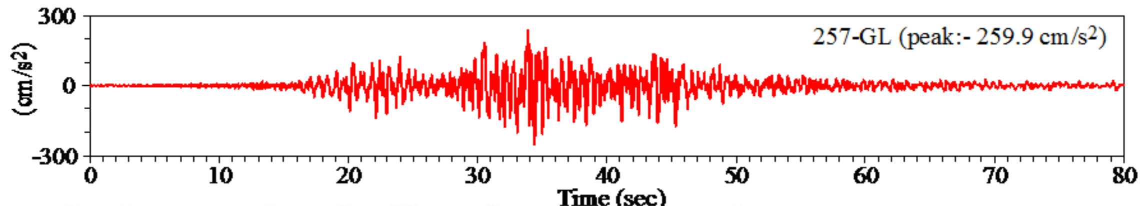
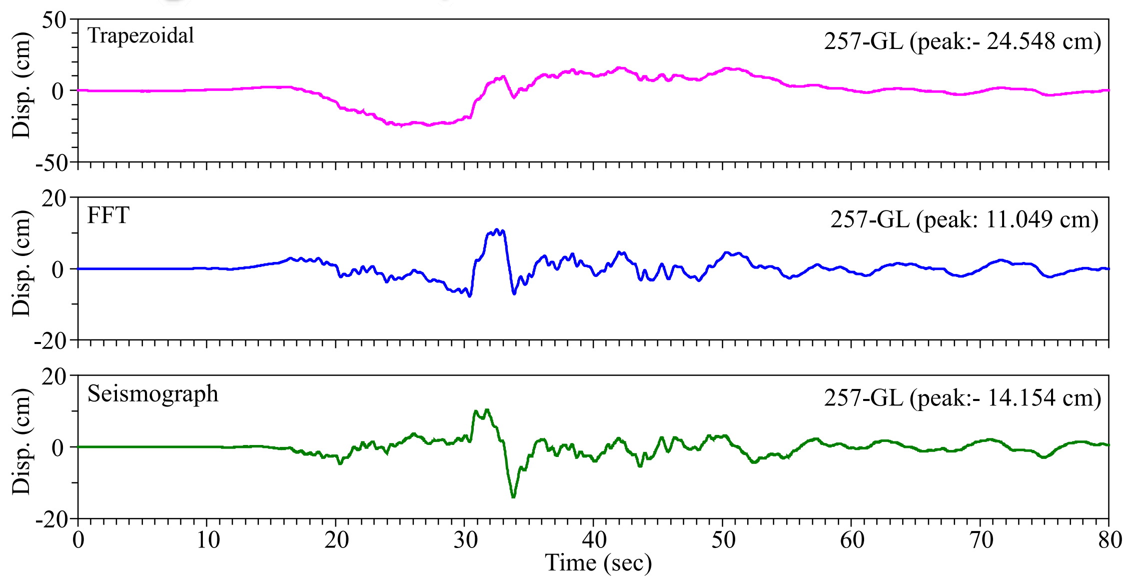
Integration
Comparison among methods

- GL at Kushiro Gov. Office Bldg., 2003
  - Acceleration



  - Integrated displacement



Fourier analysis

- Conversion from the time domain to the frequency domain

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-i(2\pi f t)} dt \qquad X_k = \frac{T}{N} \sum_{m=0}^{N-1} x_m e^{-i(2\pi k m / N)}$$

- Conversion from the frequency domain to the time domain (inverse Fourier transform)

$$x(t) = \int_{-\infty}^{\infty} X(f) e^{i(2\pi f t)} df \qquad x_m = \sum_{k=0}^{N-1} X_k e^{i(2\pi k m / N)}$$

Fourier analysis
Fourier and power spectra

- Fourier (amplitude) spectrum

$$F(f) = \left| X(f) \right|$$

- Power spectrum

$$P_{XX}(f) = \frac{1}{T} E\left[X(f) X^*(f) \right]$$

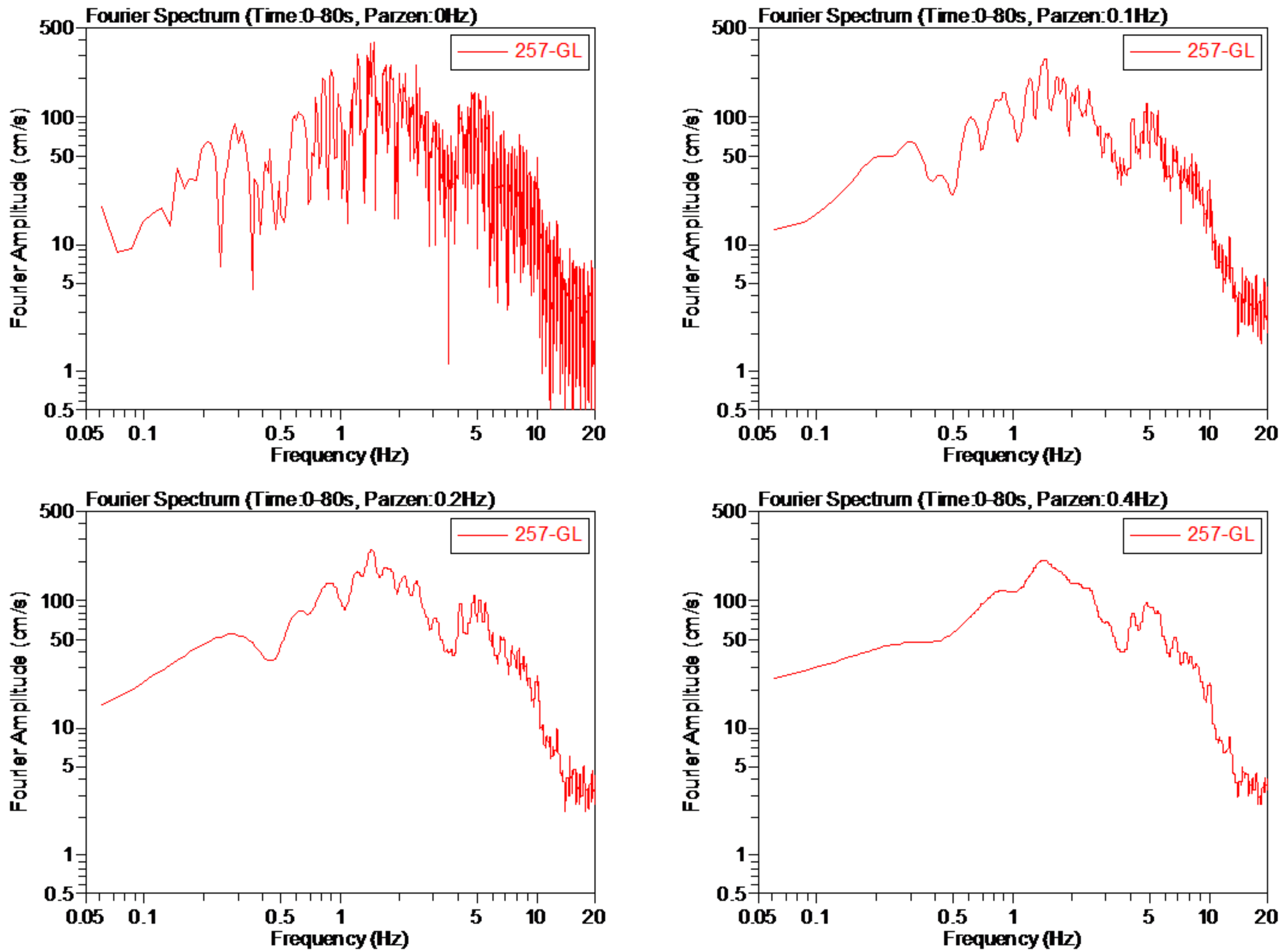
- Smoothing by spectrum window

$$\bar{P}(f) = \int_{-\infty}^{\infty} P(f) W(f-g) dg$$

  - Parzen window

$$W(f) = \frac{3}{4} u \left(\frac{\sin \frac{\pi u f}{2}}{\frac{\pi u f}{2}} \right)^4$$

Fourier analysis
Smoothing effect



Fourier analysis
Transfer function

- Fourier spectral ratio

$$H_0(f) = Y(f) / X(f) \qquad H_0(f) = |Y(f)| / |X(f)|$$

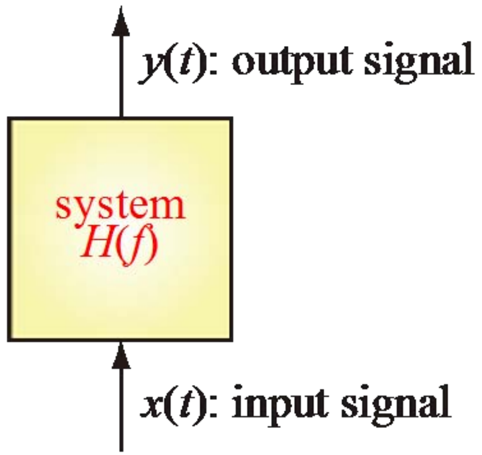
- Cross power spectrum

$$P_{XY}(f) = \frac{1}{T} E\left[X^*(f) Y(f)\right]$$

- Transfer function

$$H_1(f) = P_{XY}(f) / P_{XX}(f)$$

$$H_2(f) = P_{YY}(f) / P_{YX}(f)$$



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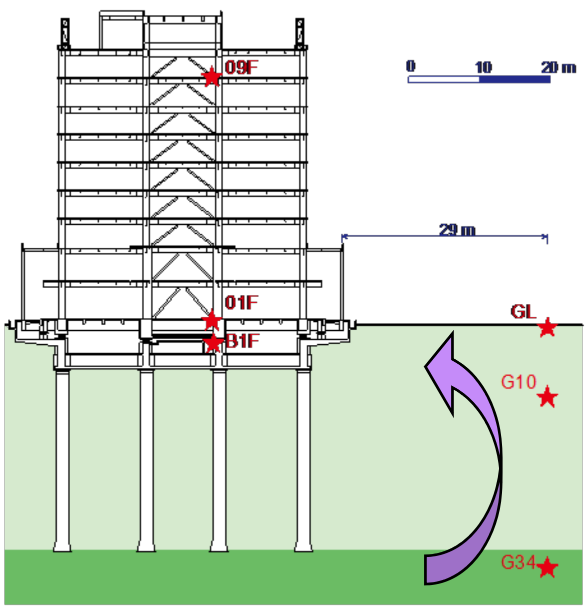
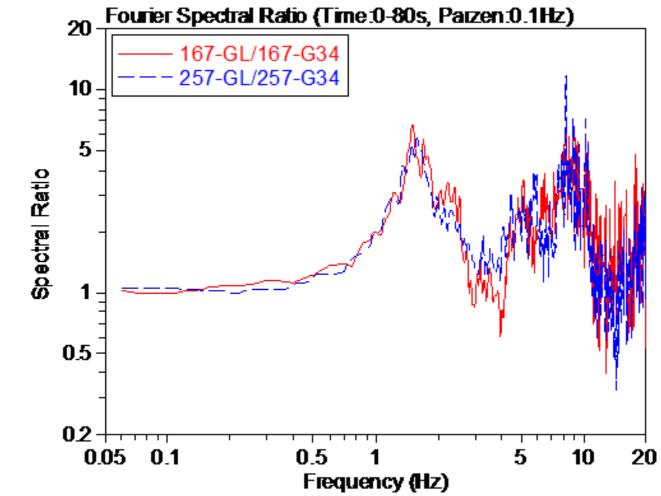
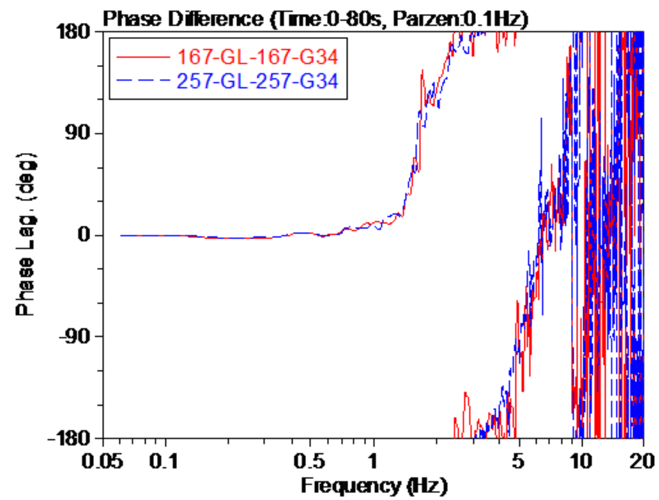
Fourier analysis
Example

- Site effect at Kushiro (GL/GL-34m)







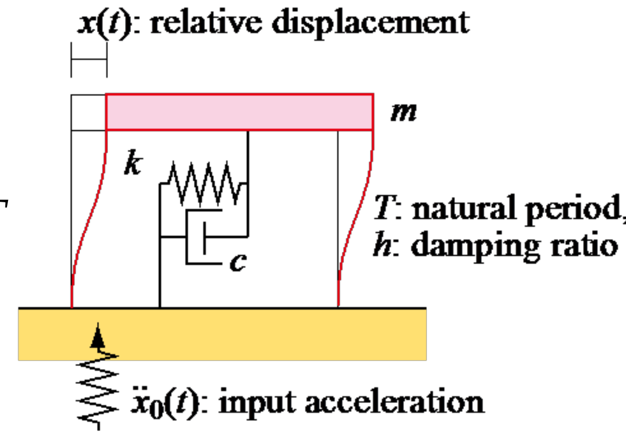
Response spectrum

- Relation between natural period and maximum response of Single-degree-of-freedom (SDOF) system
  - Displacement response spectrum (S_d)
  - Velocity response spectrum (S_v)
  - Acceleration response spectrum (S_a)
  - Pseudo velocity response spectrum ($_pS_v = \omega S_d$ or $_pS_v = S_a/\omega$)

Response spectrum

Definition

$$\omega_d = \sqrt{1-h^2}\,\omega = 2\pi\sqrt{1-h^2}\big/T$$



- Relative displacement

$$x(t) = \frac{1}{\omega_d}\int_0^t \ddot{x}_0(\tau)e^{-h\omega(t-\tau)}\sin\omega_d(t-\tau)d\tau$$

- Relative velocity

$$\dot{x}(t) = \int_0^t \ddot{x}_0(\tau)e^{-h\omega(t-\tau)}\left[\cos\omega_d(t-\tau) - \frac{h}{\sqrt{1-h^2}}\sin\omega_d(t-\tau)\right]d\tau$$

- Absolute acceleration

$$\ddot{x}(t) + \ddot{x}_0(t) = \omega_d\int_0^t \ddot{x}_0(\tau)e^{-h\omega(t-\tau)}\left[\left(1-\frac{h^2}{1-h^2}\right)\sin\omega_d(t-\tau) + \frac{2h}{\sqrt{1-h^2}}\cos\omega_d(t-\tau)\right]d\tau$$

Response spectrum
Definition

- Response spectrum

$$S_\mathrm{d}(T,h)=\left|x(t)\right|_\mathrm{max} \qquad S_\mathrm{v}(T,h)=\left|\dot{x}(t)\right|_\mathrm{max}$$

$$S_\mathrm{a}(T,h)=\left|\ddot{x}(t)+\ddot{x}_0(t)\right|_\mathrm{max}$$

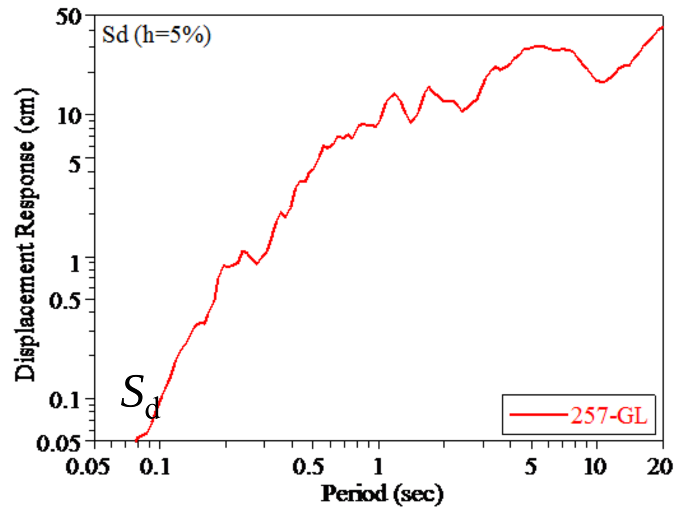
- Relation between T and S_d, S_v or S_a for a certain h

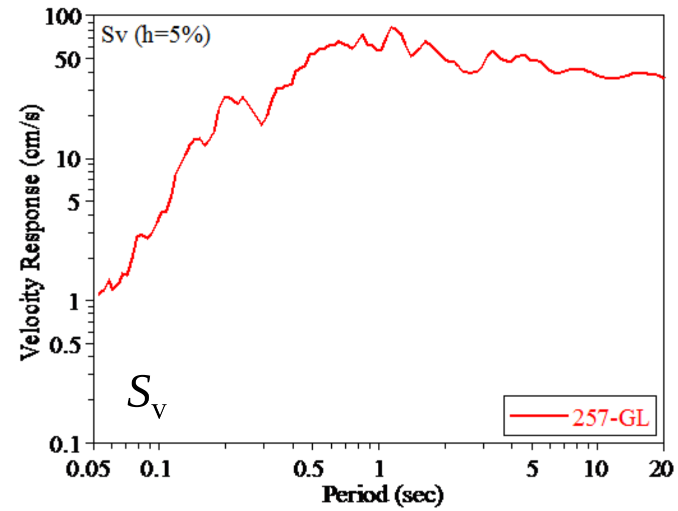
- Pseudo velocity response spectrum

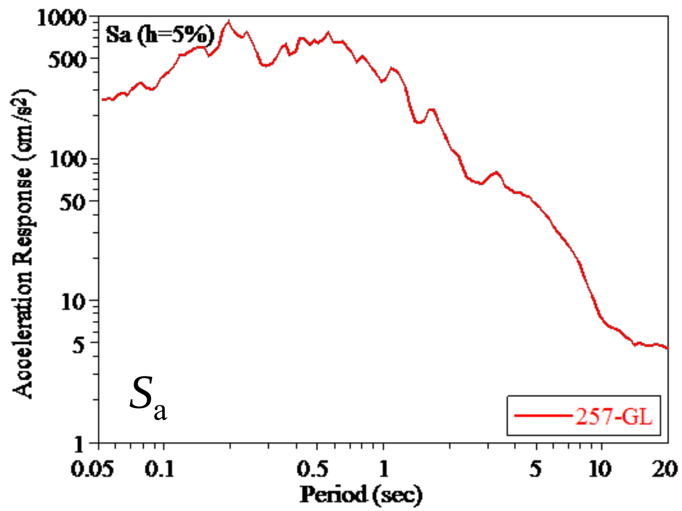
$$S_\mathrm{d}\approx\frac{S_\mathrm{v}}{\omega} \qquad {}_\mathrm{p}S_\mathrm{v}=\omega S_\mathrm{d}$$

$$S_\mathrm{a}\approx\omega S_\mathrm{v} \qquad {}_\mathrm{p}S_\mathrm{v}=\frac{S_\mathrm{a}}{\omega}$$

Response spectrum
Example







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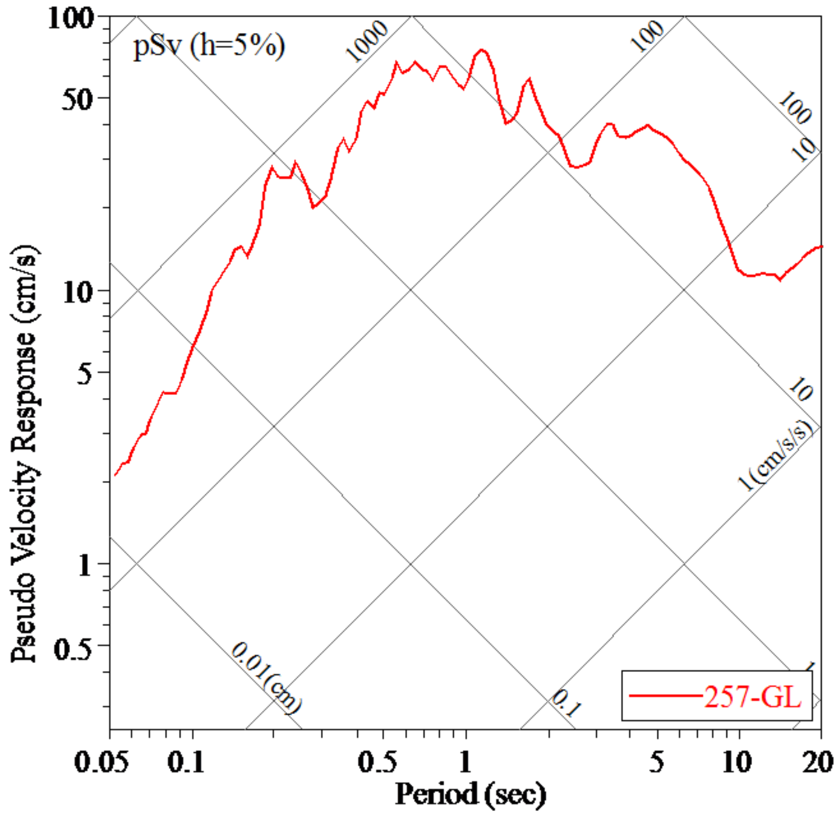
Response spectrum
Tripartite plot

- In full-log coordinates



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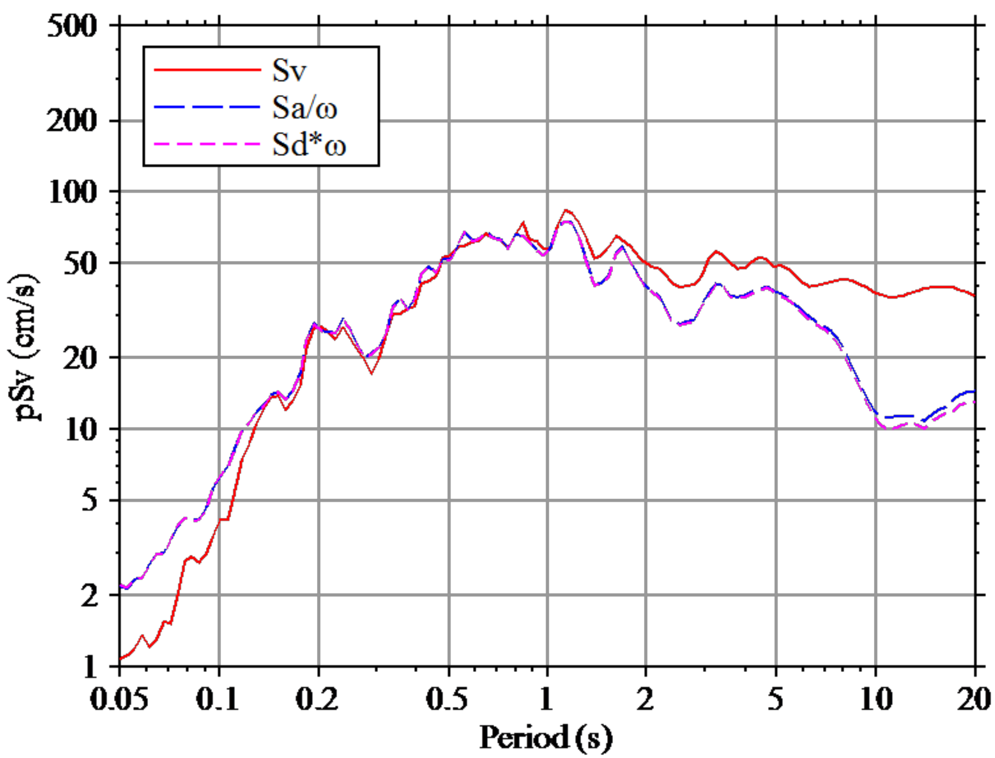
Response spectrum

Relation among Sa, Sv and Sd

- $S_v \sim {}_pS_v = S_a/\omega \sim {}_pS_v = S_d\omega$



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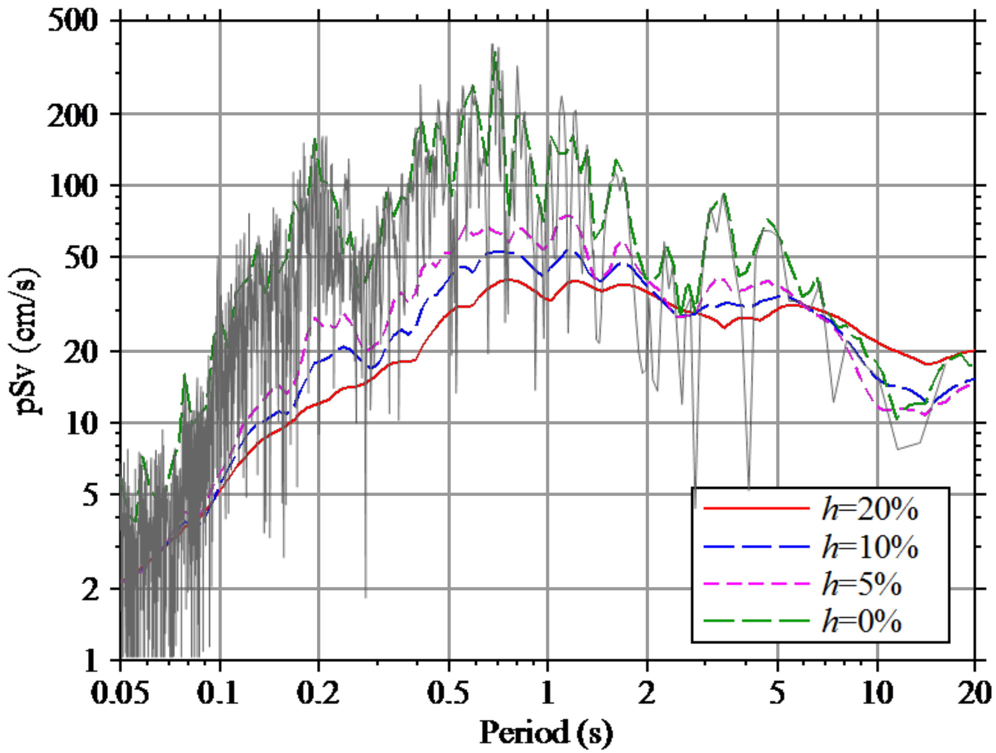
Response spectrum
Difference by damping

- *h*=0%, 5%, 10% and 20%
- Fourier spectrum



Application

- Attenuation formulas of seismic intensity indexes
  - Relation between (PGA, PGV, I_{JMA}, etc) and (M, X, site condition, etc)
- Discussion on effect of surface geology
- Investigation into shallow/deep geological structure
- Estimation of stronger ground motions

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Application

- Warranty for seismic code
- Improvement of seismic code
- Verification of structural design
- Verification of new technology
- Examination of failure mechanism of structure

Application

- Early warning system
  - Estimation seismic intensity before S-wave arrival
- Structural health monitoring system
  - Real-time identification of structural damage