A NEW STRUCTURAL HEALTH MONITORING SYSTEM FOR REAL-TIME EVALUATION OF BUILDING DAMAGE

Koichi Kusunoki

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Back to 2006, 2007…

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What is structural health monitoring?

- Structural health monitoring should have functions to
  - Sense
  - Judge
  - Indicate
- With what data?
  - Ambient vibration –Not Event-driven
  - Strong Motion – Event-driven
  - Acceleration, Velocity, Strain, displacement….

Quick Inspection

- After an earthquake…

Residual seismic capacity should be evaluated

Without adequate residual seismic capacity

To reduce enormous harm due to an aftershock

With adequate residual seismic capacity

To reduce the number of refugees

Present situation of the quick Inspection

- Investigated by visual observation by engineers…

It needs many days to investigate

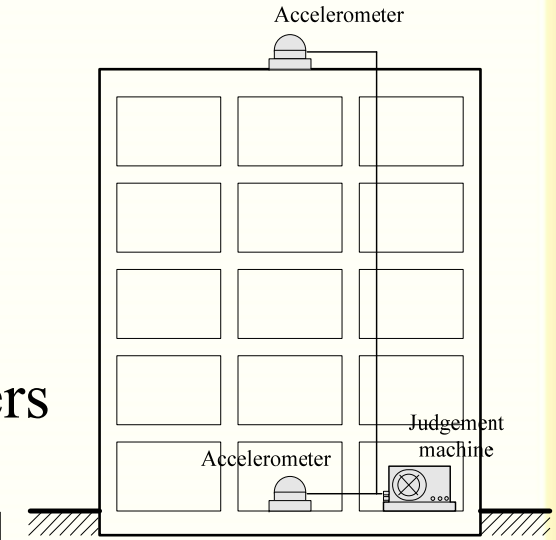
19 days for 46,000 buildings with 5,068 engineers

Many “Limited Entry” judgment

The judgment can vary
according to engineers’ experiences

Proposed System

Performance and demand curves are measured



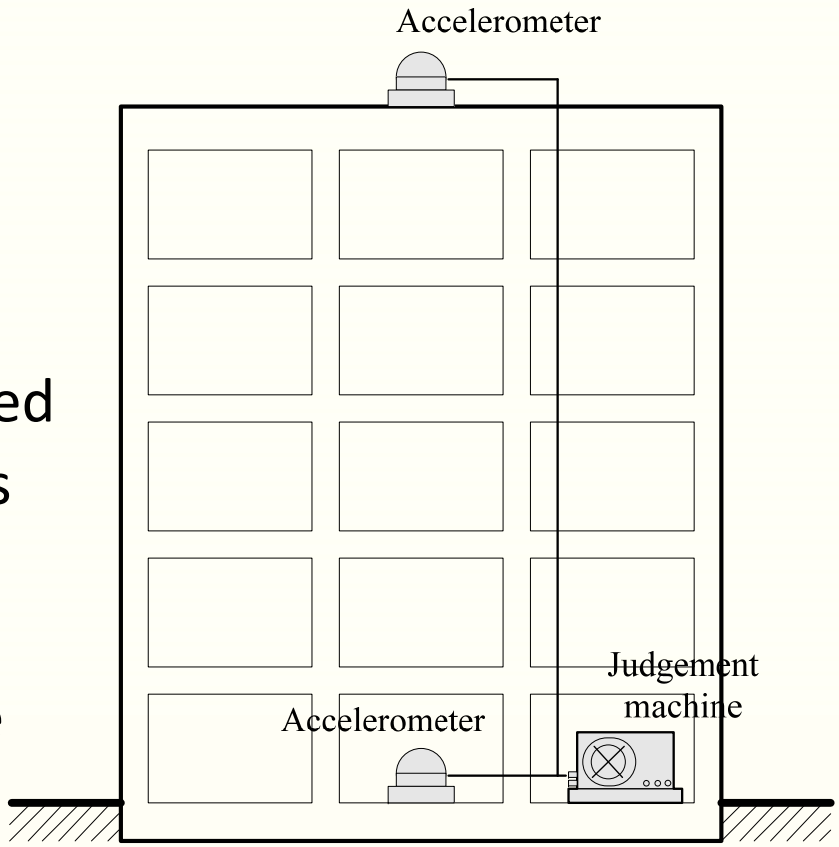
Place few inexpensive accelerometers

Derive displacement from measured acceleration

Evaluate by comparing these curves

Proposed System

- Simplified SHM
  - Few sensors
  - Easy to install
  - Inexpensive system
  - No engineer may be required
  - No need to model buildings in a computer
  - Damage location cannot be identified



Simplified SHM

It is worth to apply

- For example, concern of the high-rise building owner is “business continuity”.
  - “Elastic or non-elastic” evaluation is the most important for owners
  - If it is evaluated as damaged, the damage level somehow does not interest them.

- Shelter needs to be evaluated its safety quickly.

Kumamoto Earthquake

- April 14 Mw = 6.2
- April 16 Mw = 7.0
- Casualties 49

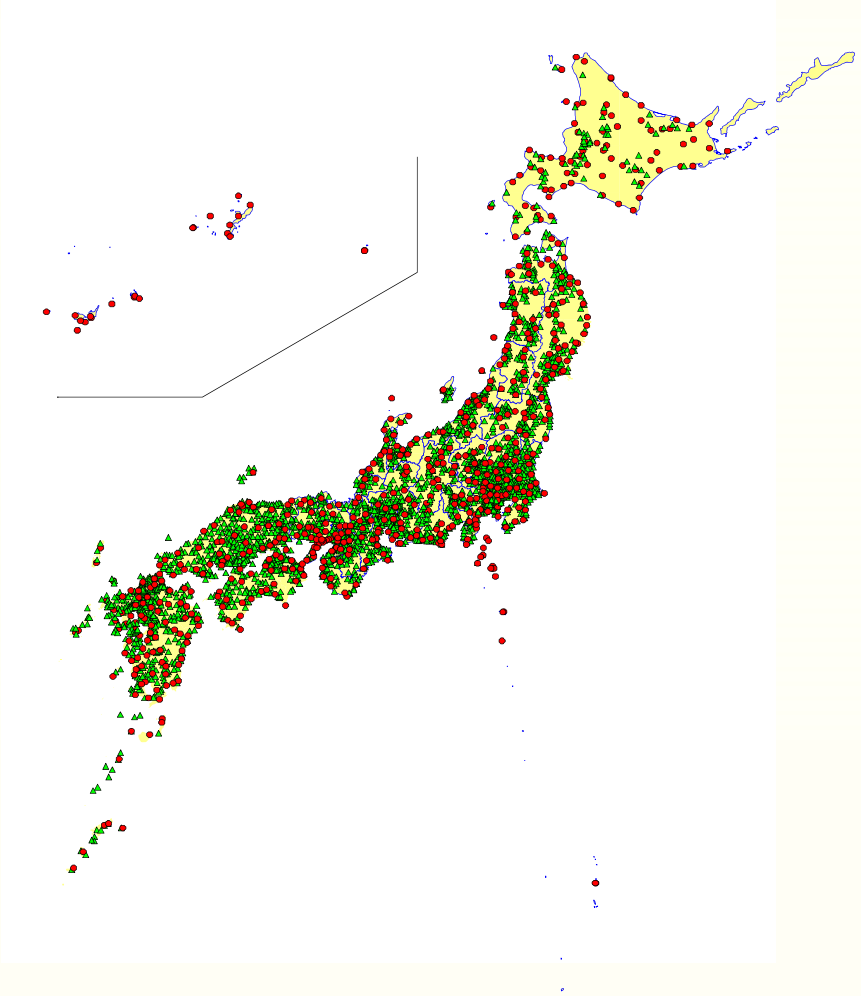
Hidden background of this research

- Large PGAs were measured.
- However, most of them did not cause severe damages to many buildings.

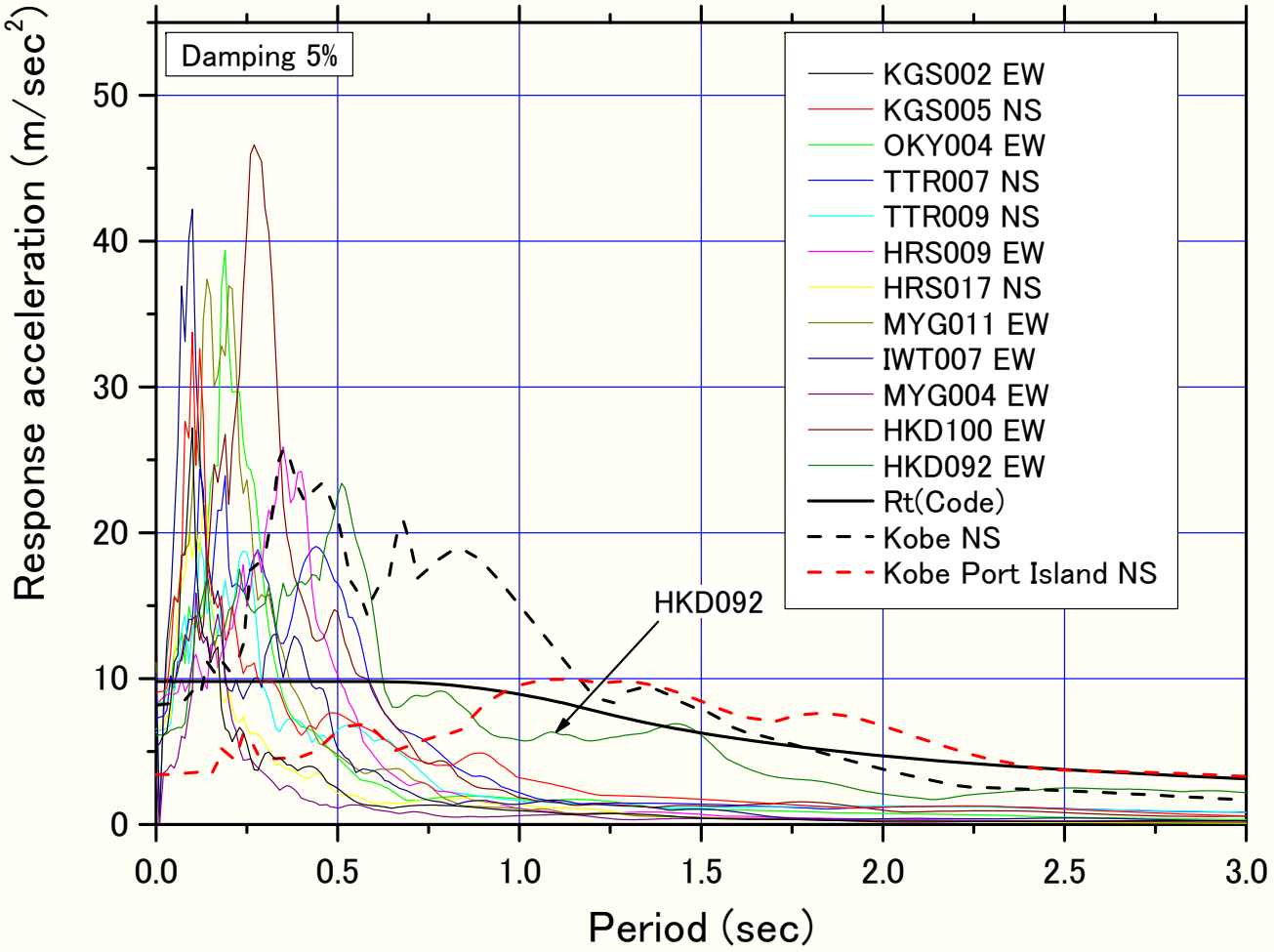
Seismic Intensity Observation Point

JMA: 600 points, Local Gov. 3,800
(Before Kobe Earthquake 150 points)
As of July, 2002

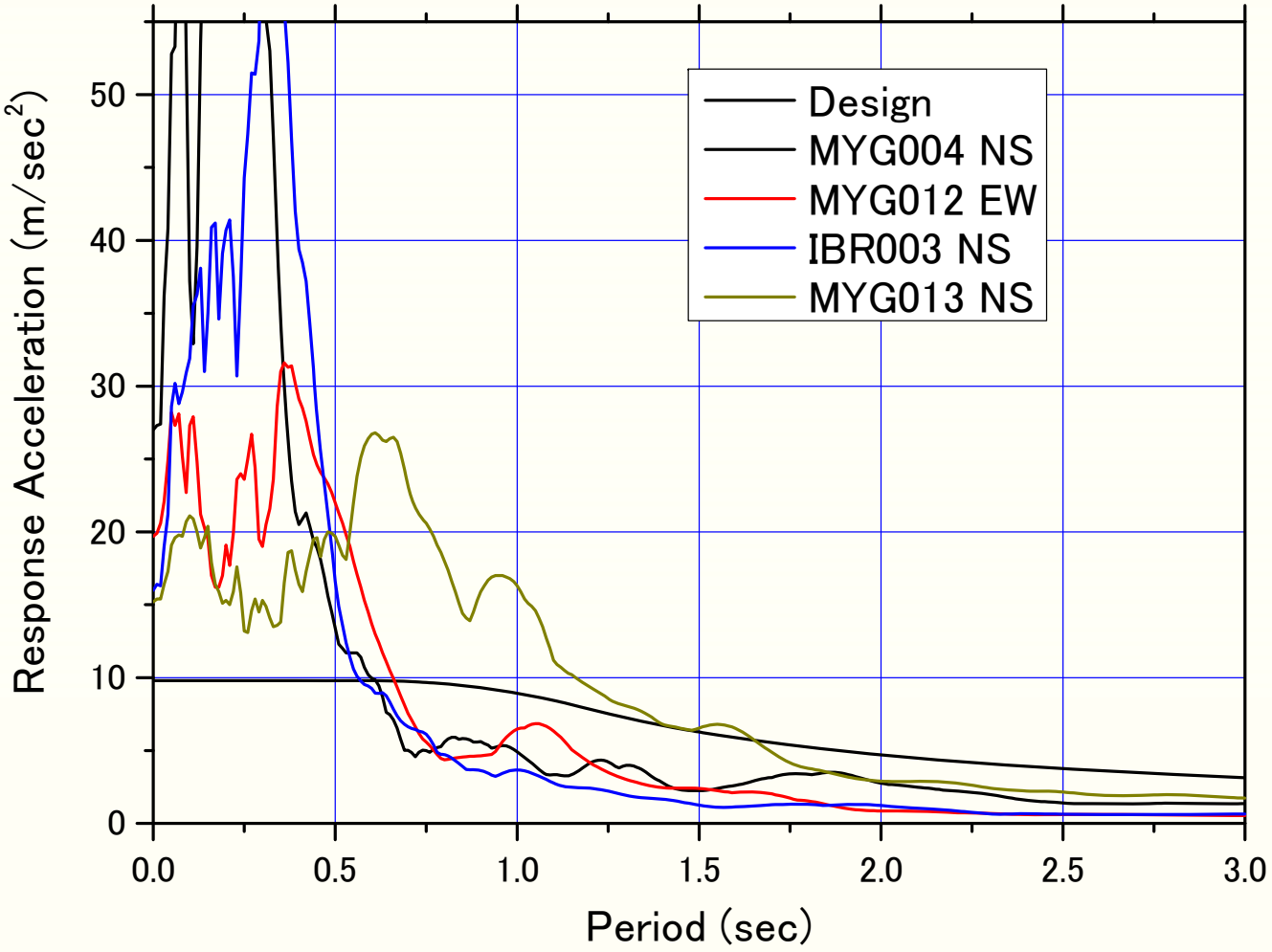
K-NET (NIED) about 1,000 Points



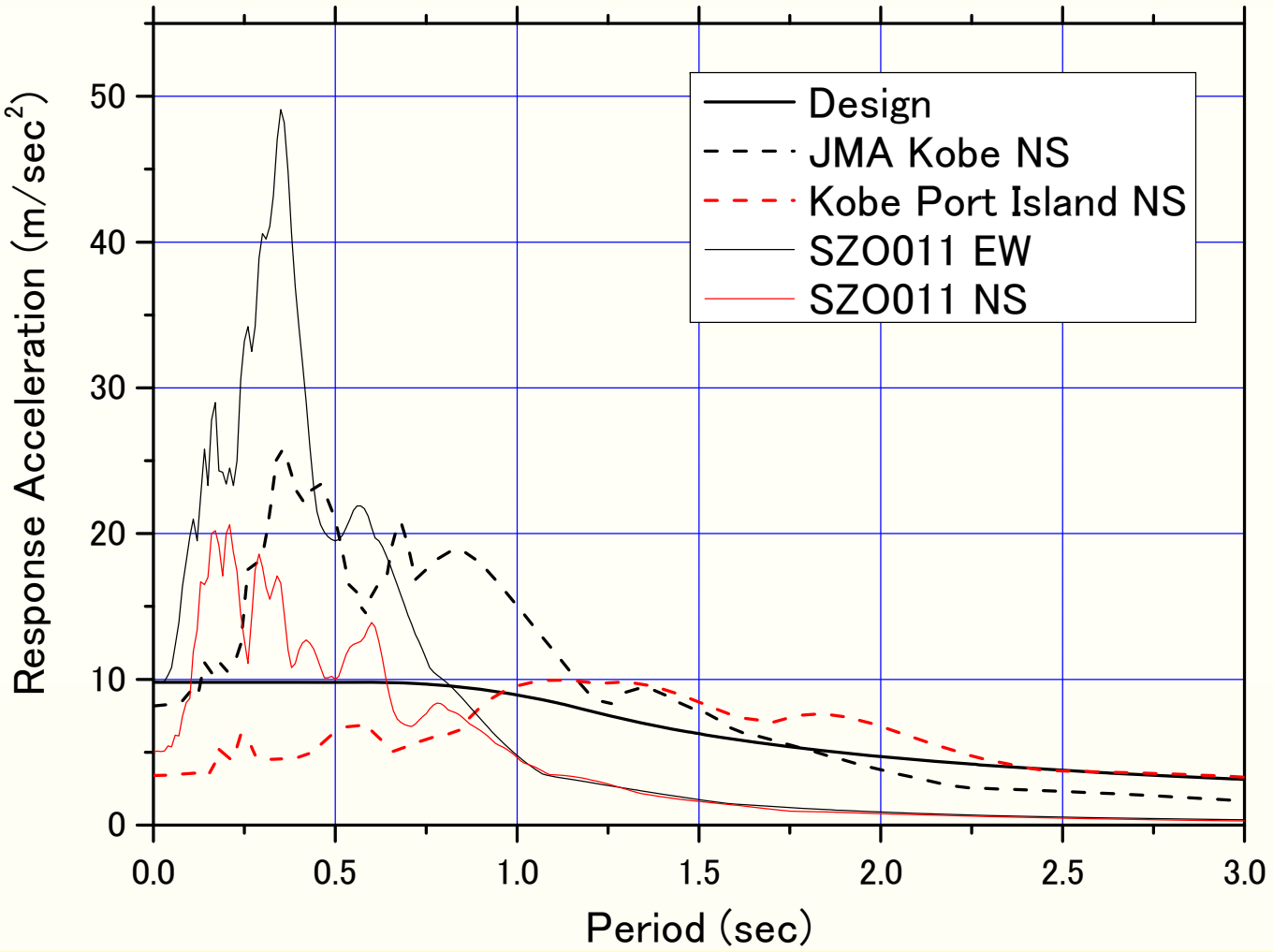
Response Spectra



Tohoku EQ


Response Acceleration (m/sec^2)
Period (sec)
Design
MYG004 NS
MYG012 EW
IBR003 NS
MYG013 NS
0
10
20
30
40
50
0.0
0.5
1.0
1.5
2.0
2.5
3.0

2011 Shizuoka EQ



RC apartment building (10story, 2004)

Cracks in non-structural walls

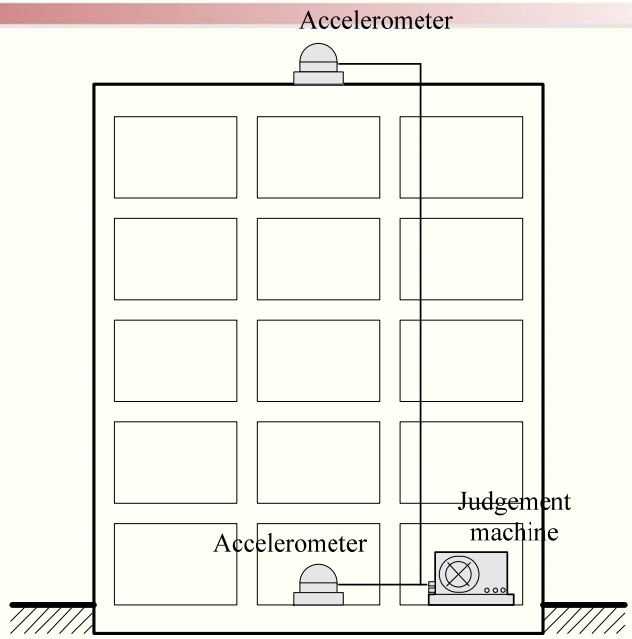
From NIT, Nagoya Univ.

Hidden background of this research

- Large PGAs were measured.
- However, most of them did not cause severe damages to buildings.
- Analysis says they must be damaged
  (Prof. Iervoliono)
- **Why…..?**
- Actual strength is different from Analysis?
  (Prof. Dubina)
- Actual input is different from free field?
- It is difficult to figure out the reason BECAUSE building response was not measured.

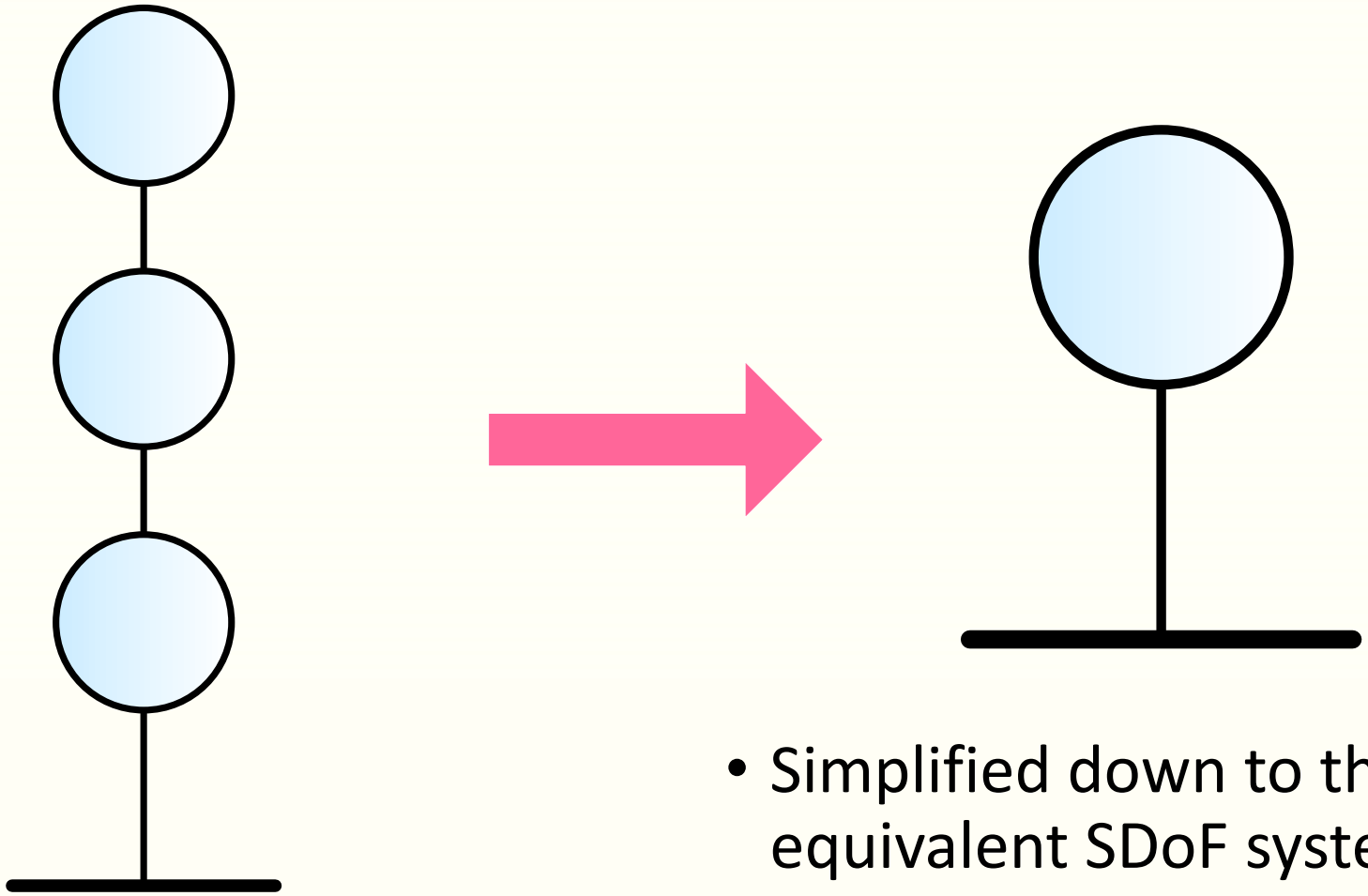
Simplified SHM W/ PBD

- At MOST one sensor for each floor.
- Apply the Performance-based design procedure (Capacity design method).
- Compare performance curve to demand curve.
- Both curves are calculated only from the measured acceleration.



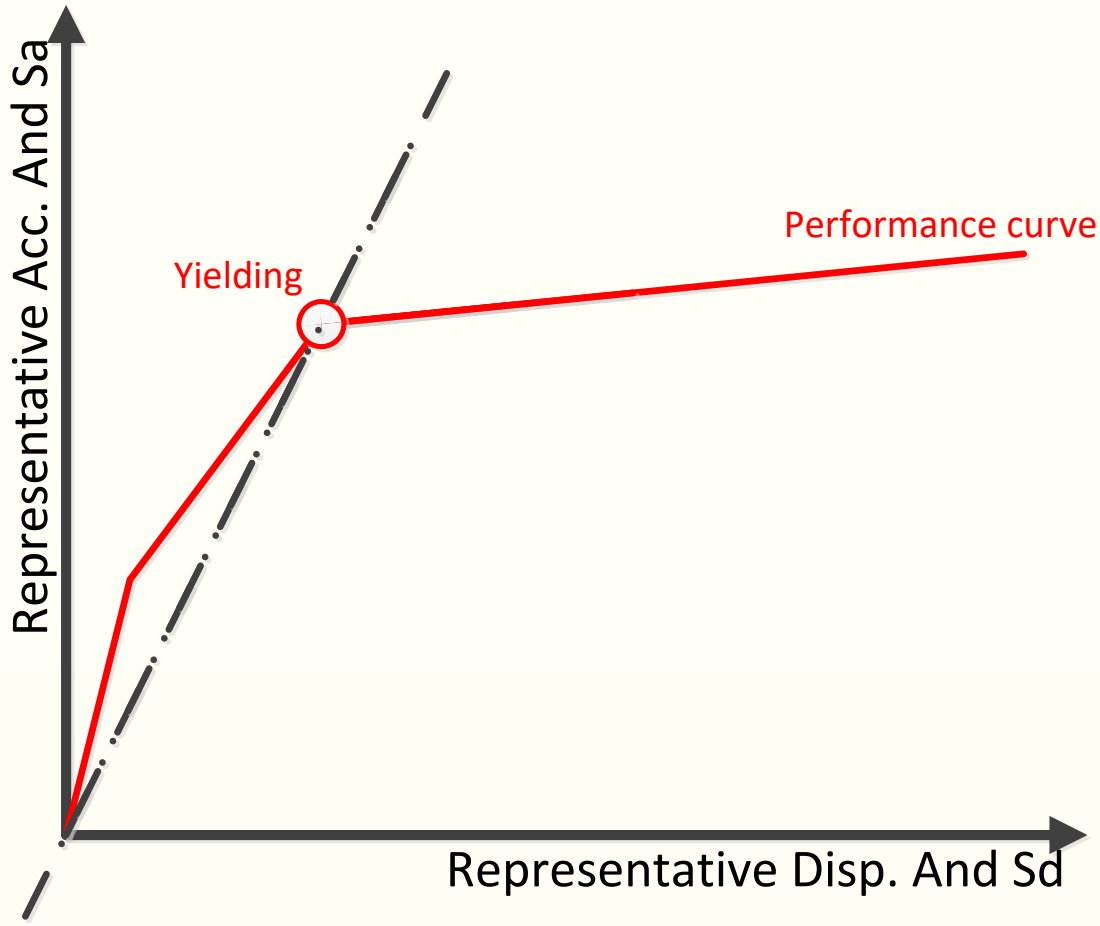
ITK sensor

Damage evaluation

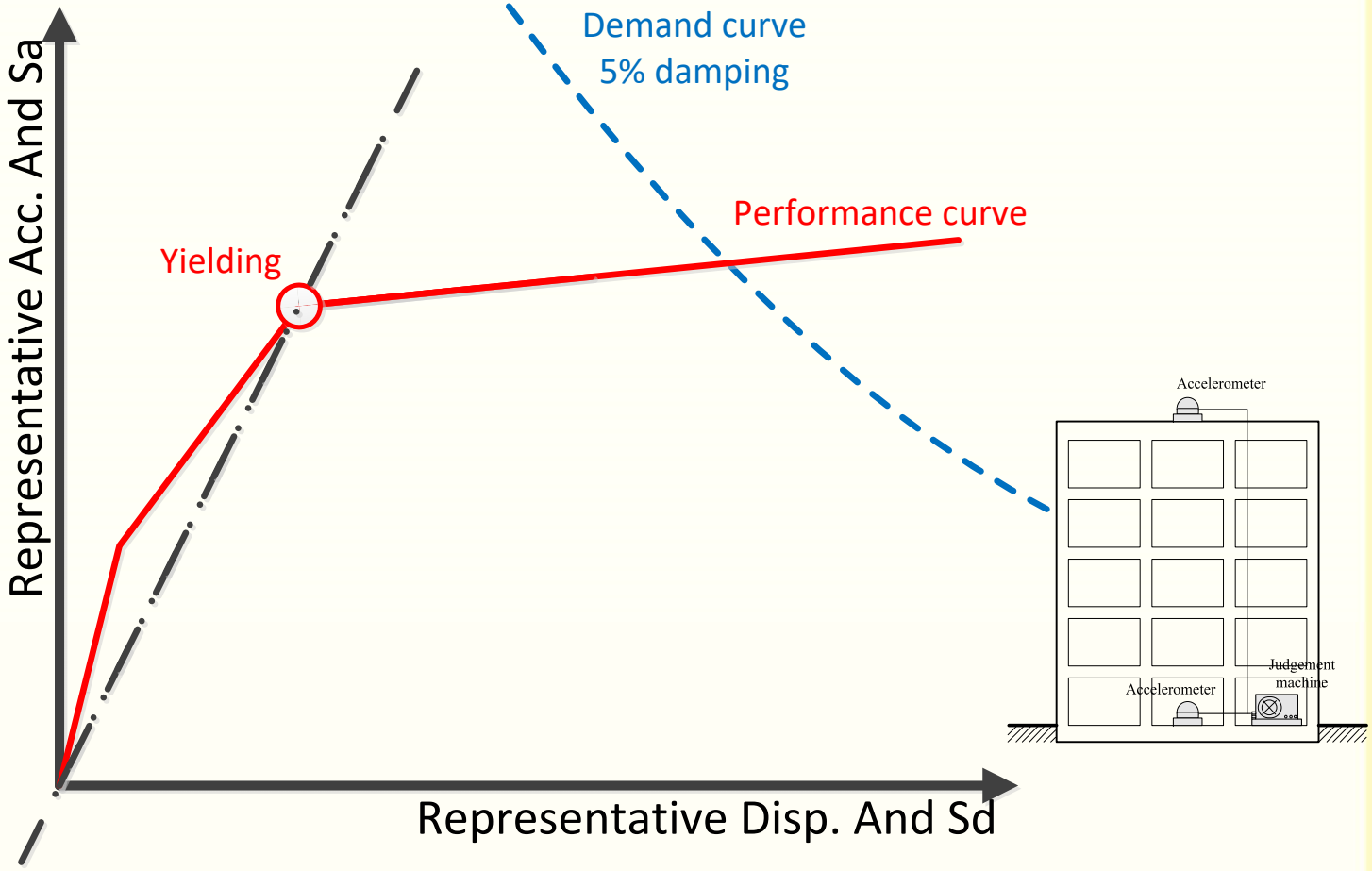


- Simplified down to the equivalent SDoF system

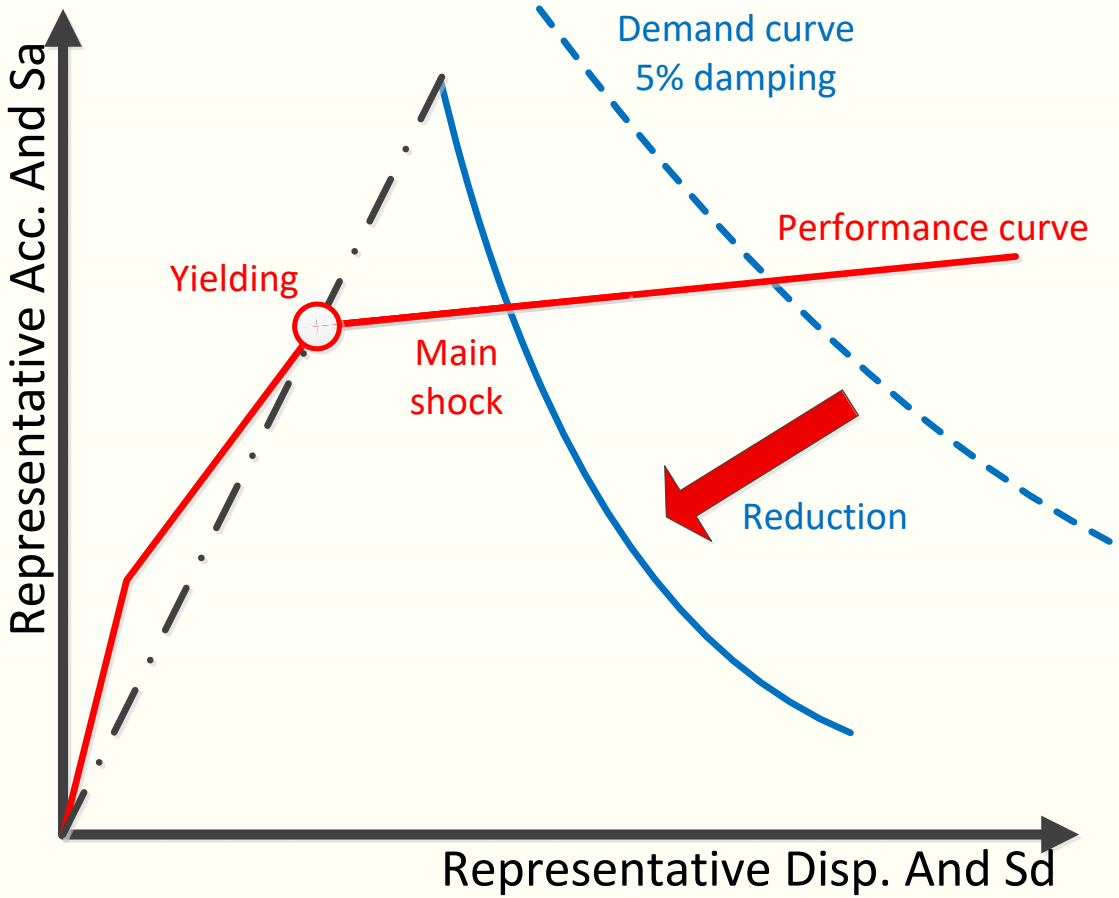
Evaluation method based on PBD



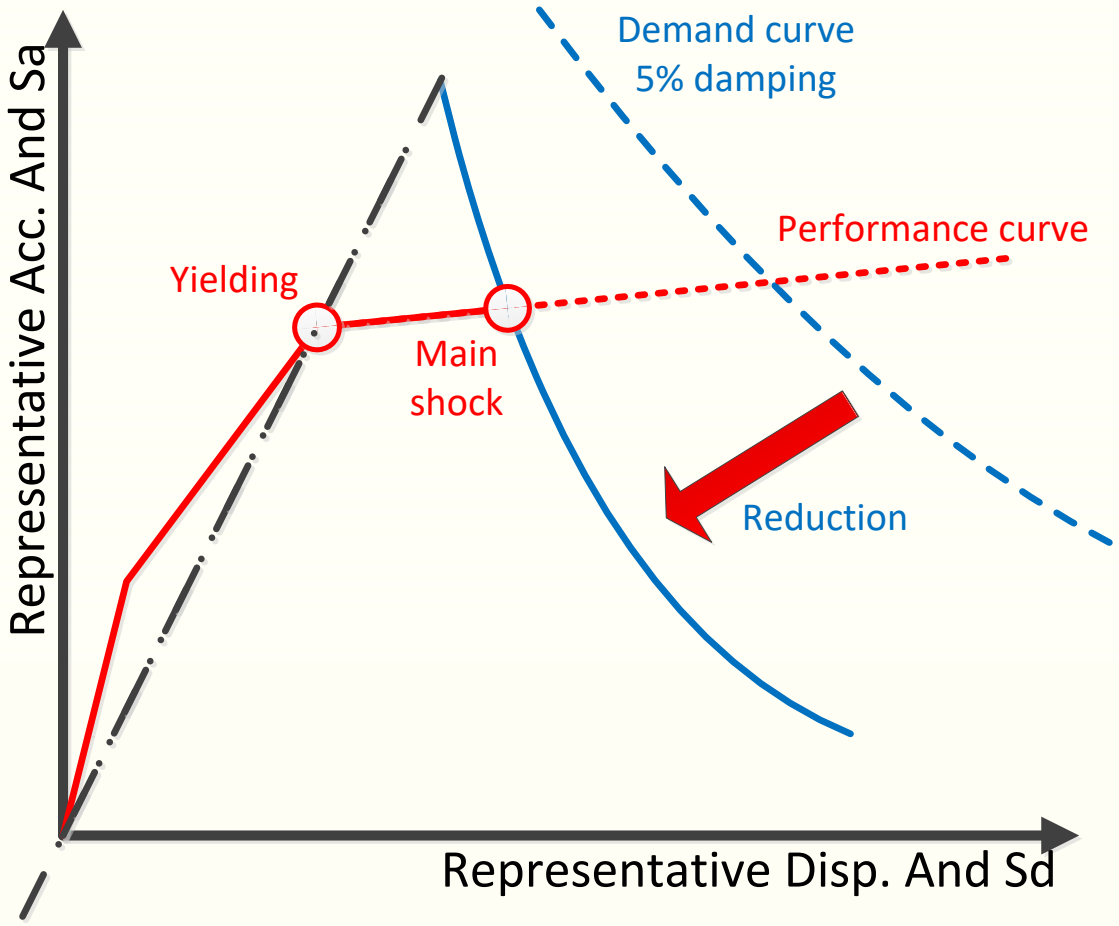
Evaluation method based on PBD



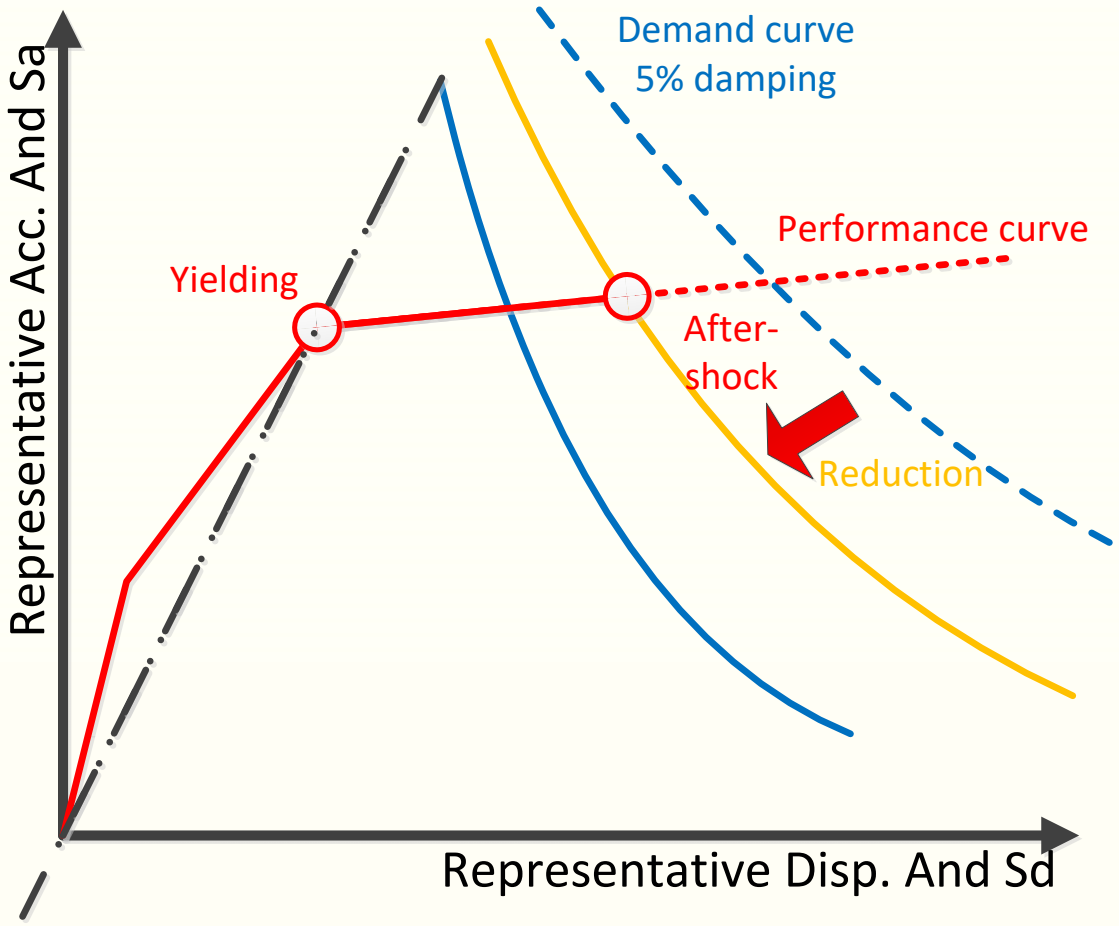
Evaluation method based on PBD



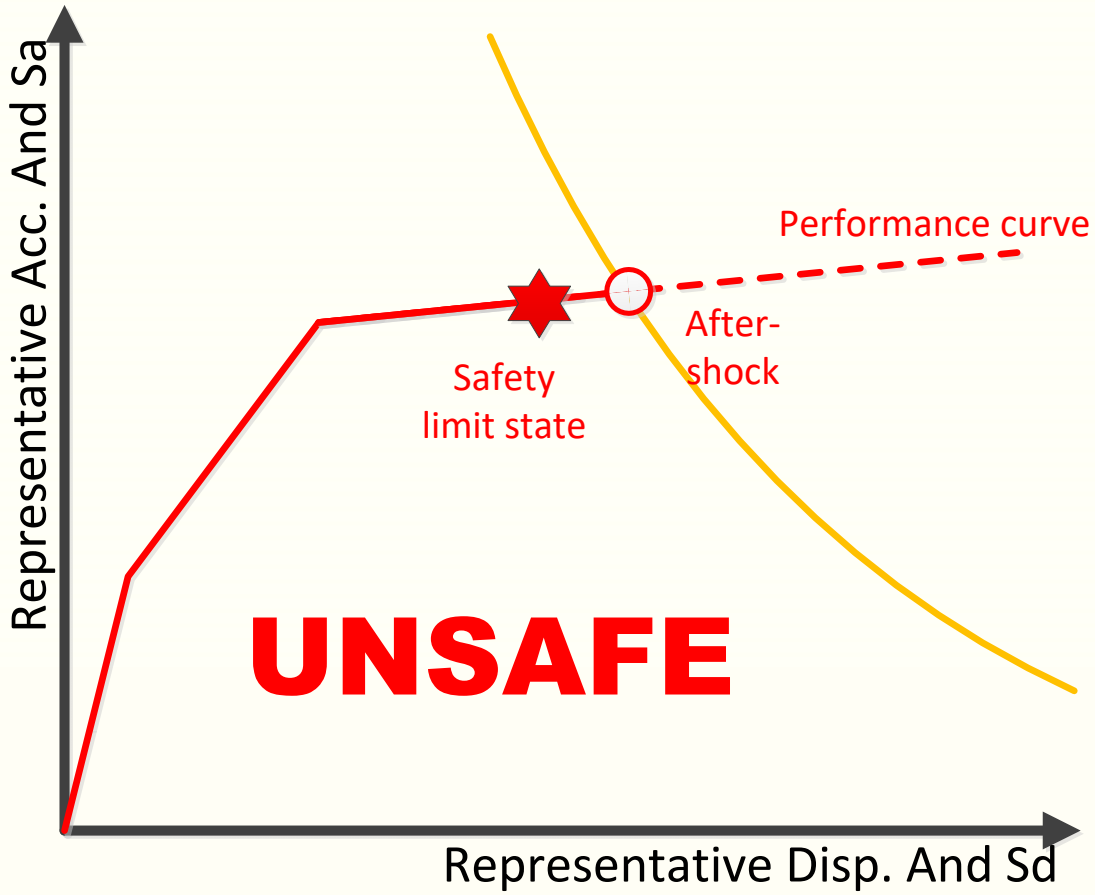
Evaluation method based on PBD



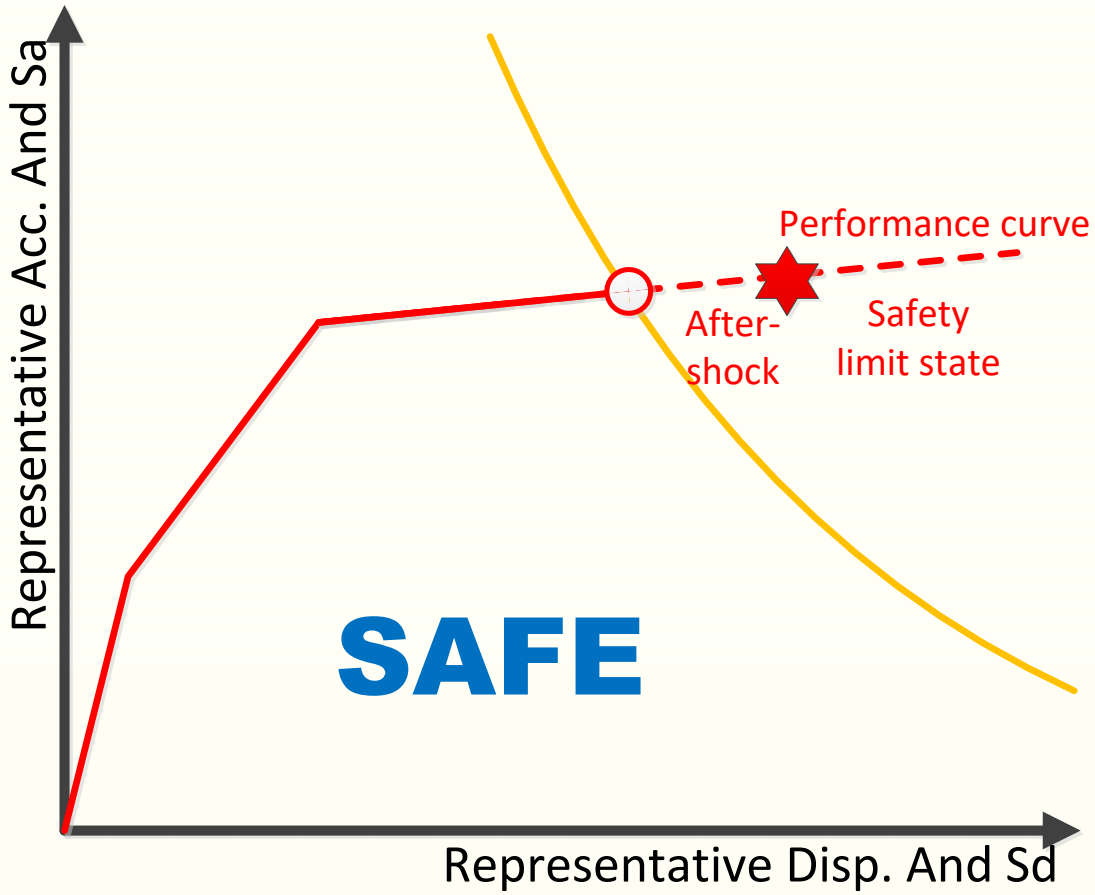
Evaluation method based on PBD



Evaluation method based on PBD

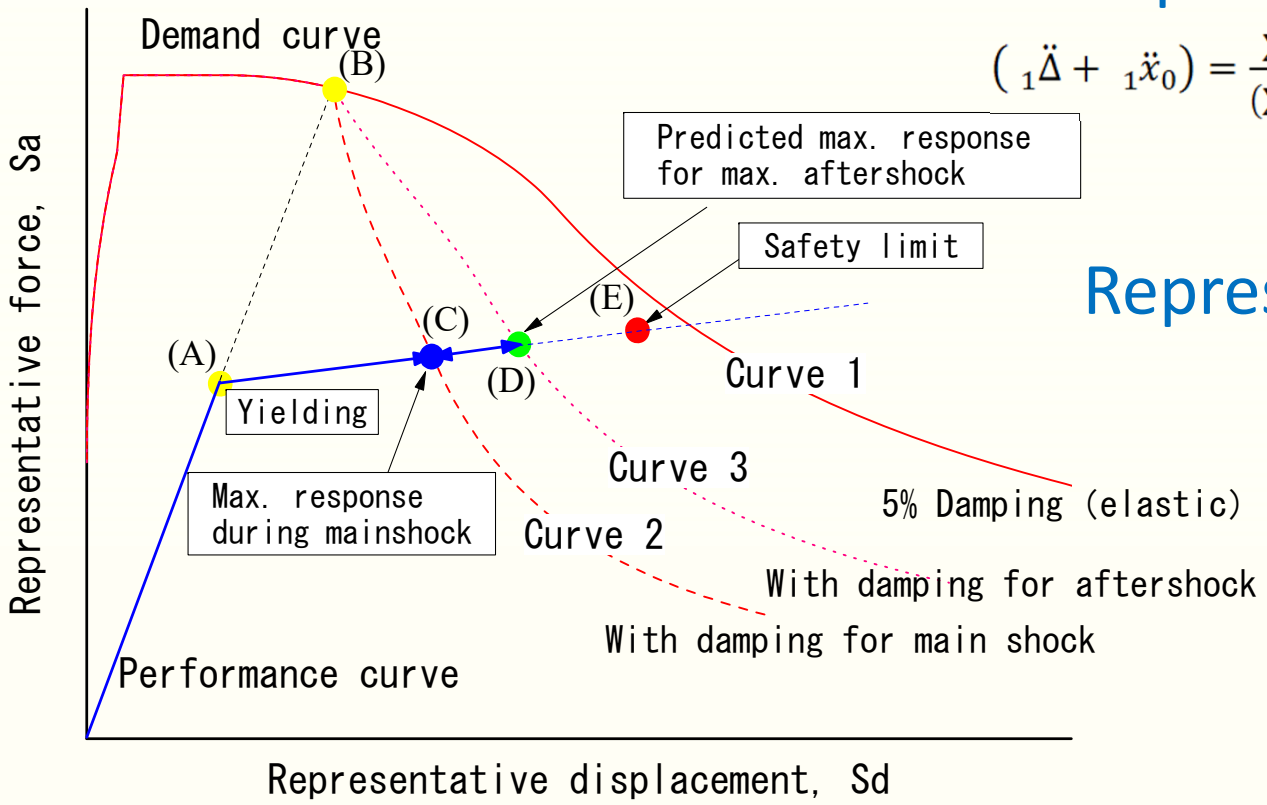


Evaluation method based on PBD



Damage evaluation

- Based on Capacity Spectrum Method



Representative force

$$\left({}_1\ddot{\Delta} + {}_1\ddot{x}_0\right) = \frac{\sum m_i \cdot {}_1x_i^{\,2}}{\left(\sum m_i \cdot {}_1x_i\right)^2} \sum_{i=1}^{N} m_i \cdot {}_1\ddot{x}_i + {}_1\ddot{x}_0$$

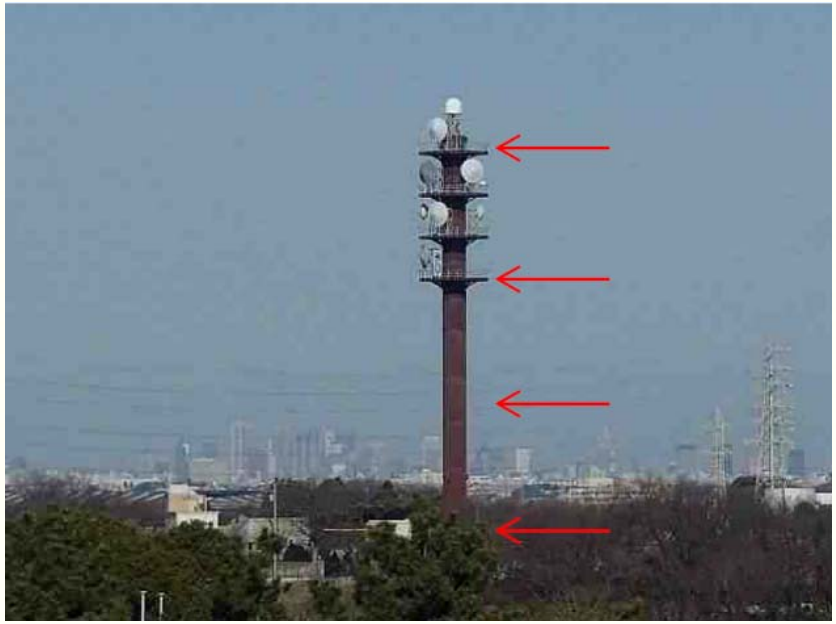
Representative disp.

$${}_1\Delta = \frac{\sum m_i \cdot {}_1x_i^{\,2}}{\sum m_i \cdot {}_1x_i}$$

Introduction about steel towers

- Two steel towers for microwave telecommunications with height of about 60m were instrumented in Y2014.
- Two relatively large earthquakes occurred and their responses were successfully stored.
- The damage evaluation results and design parameters such as the predominant period and the required performance will be discussed

Instrumented towers



- Hazawa Tower
  (H=58m)

- Higashi Oshima Tower
  (H=63m)

Accelerometers

- ITK-002

Max. 2,450 cm/s^2

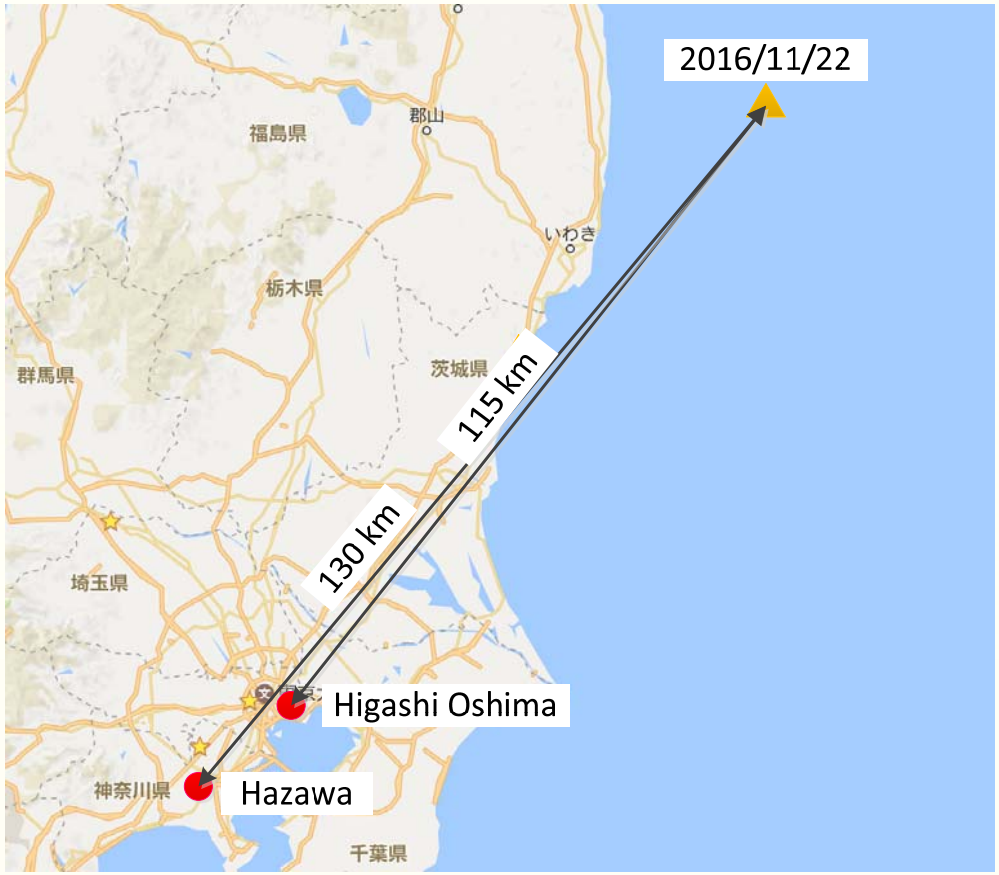
Err. 0.1 gal/s

- IoLAM

Max. 3,430 cm/s^2

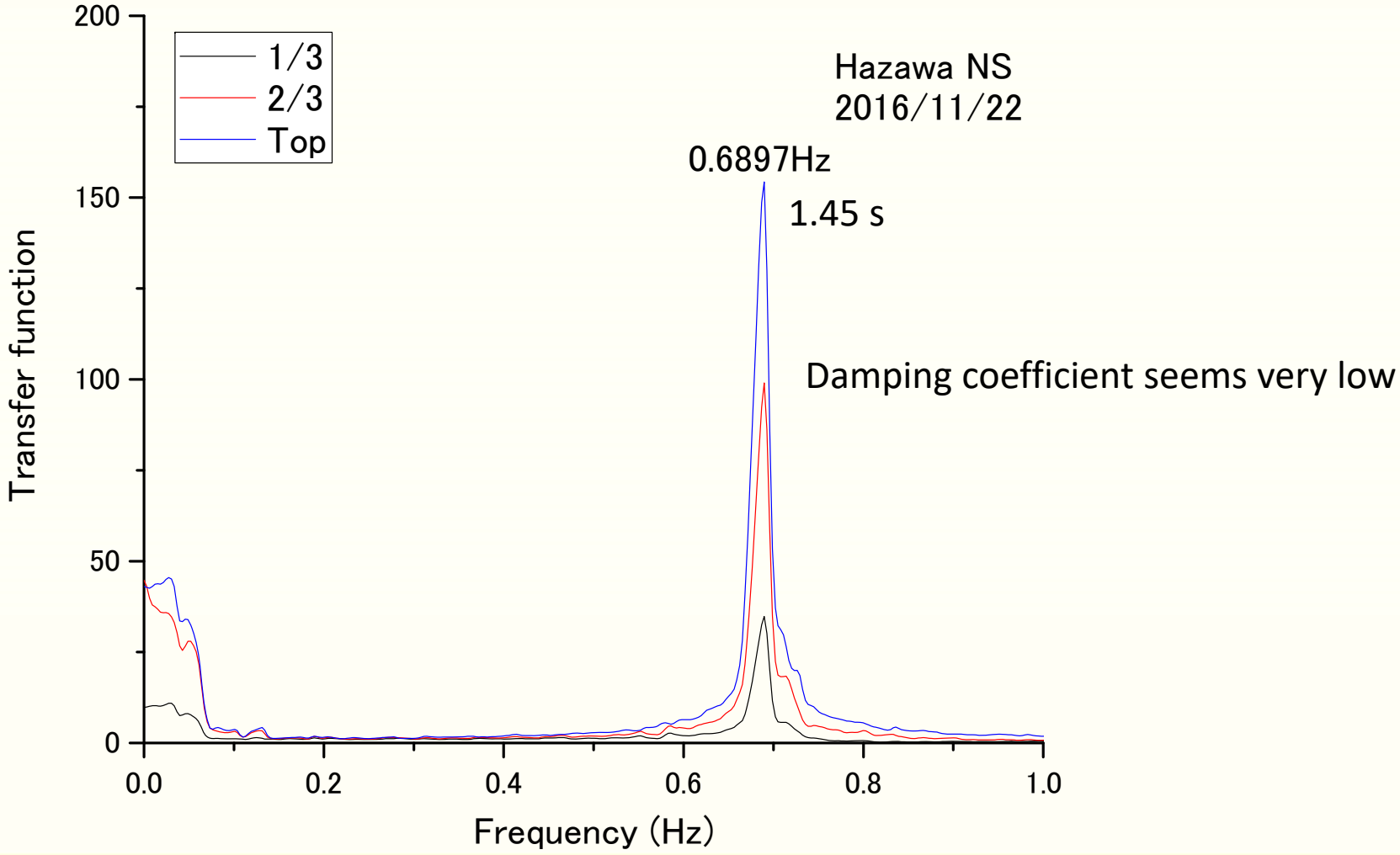
Err. 0.1 gal/s

Fukushima Ken Oki EQ (Nov/22/'16)

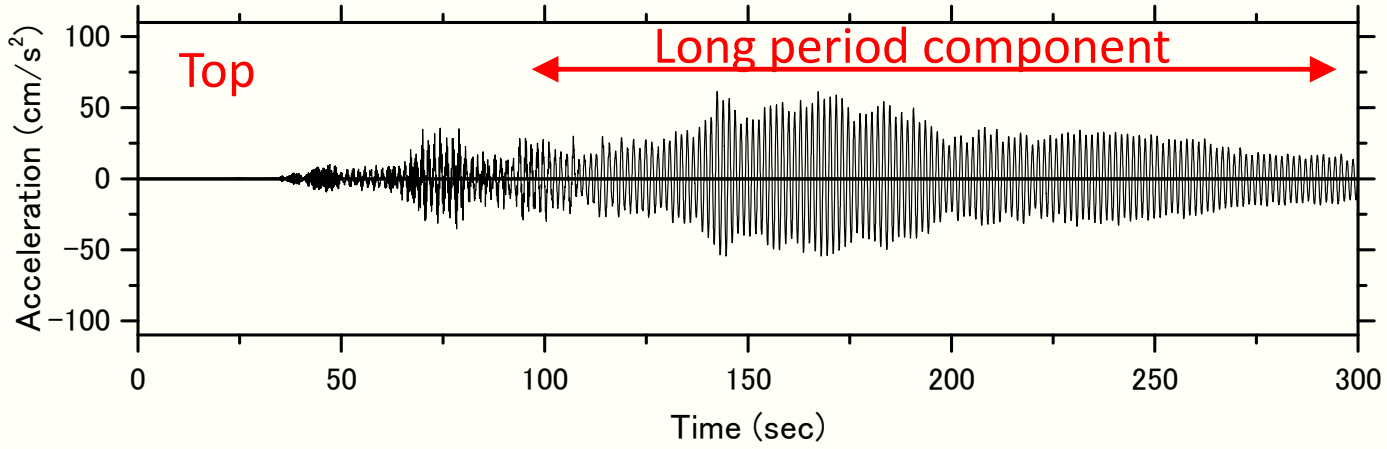


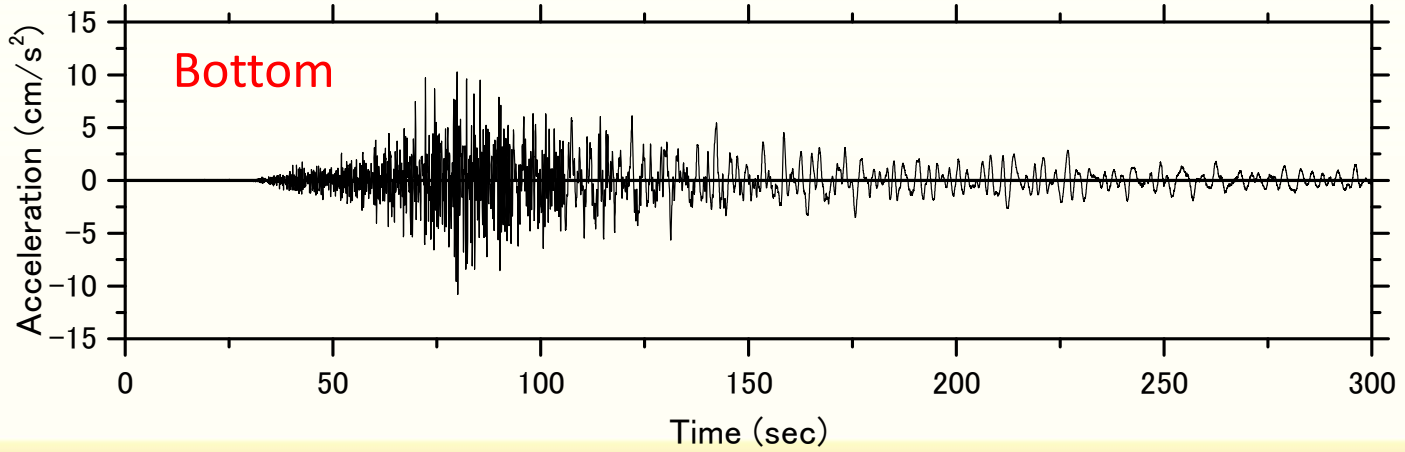
- M=7.4
- Seismic Intensities
  =III
- Epicentral Distance
  ≒120km

Transfer function (NS) of Hazawa



Waveforms (NS) of Hazawa

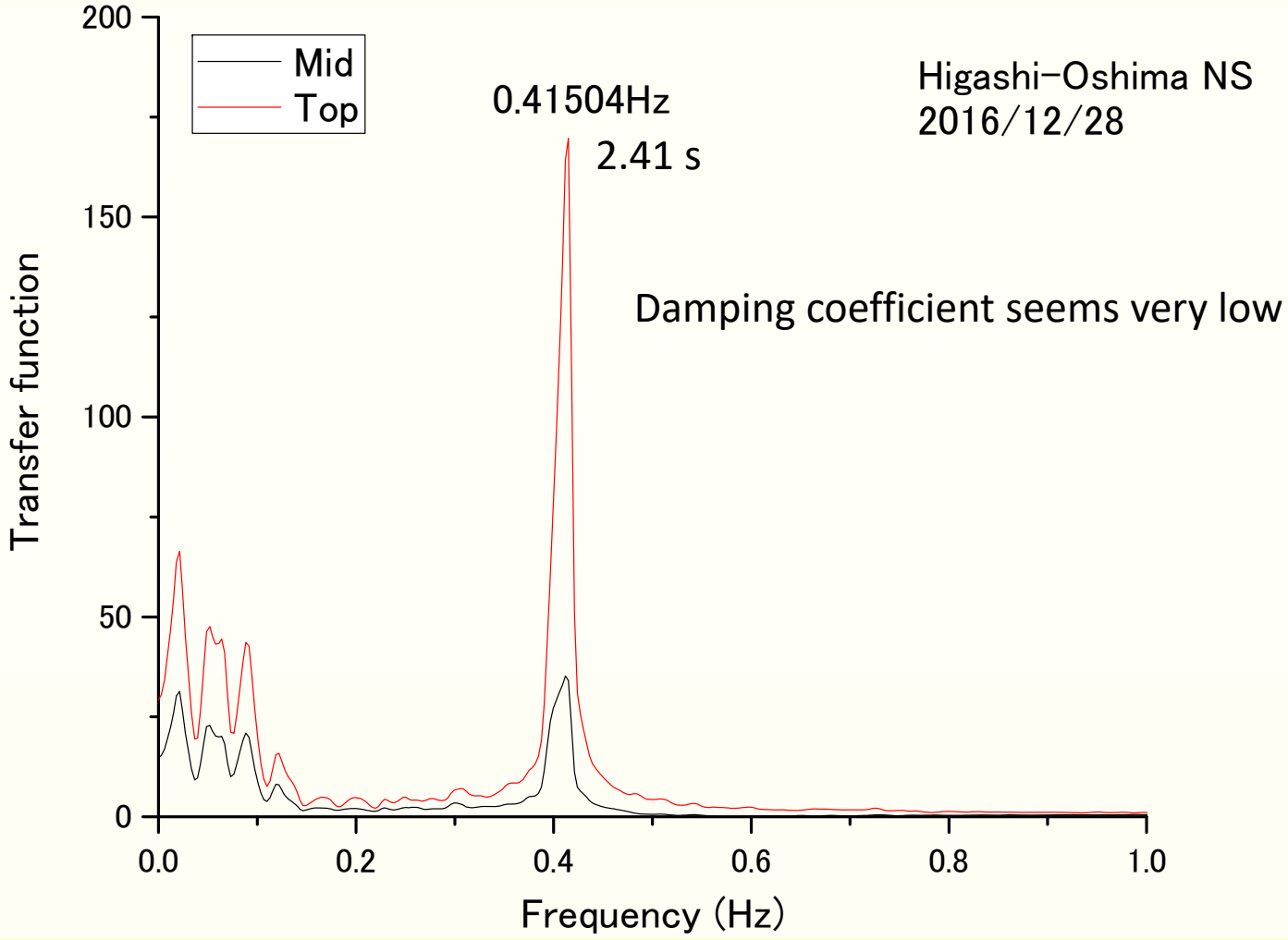




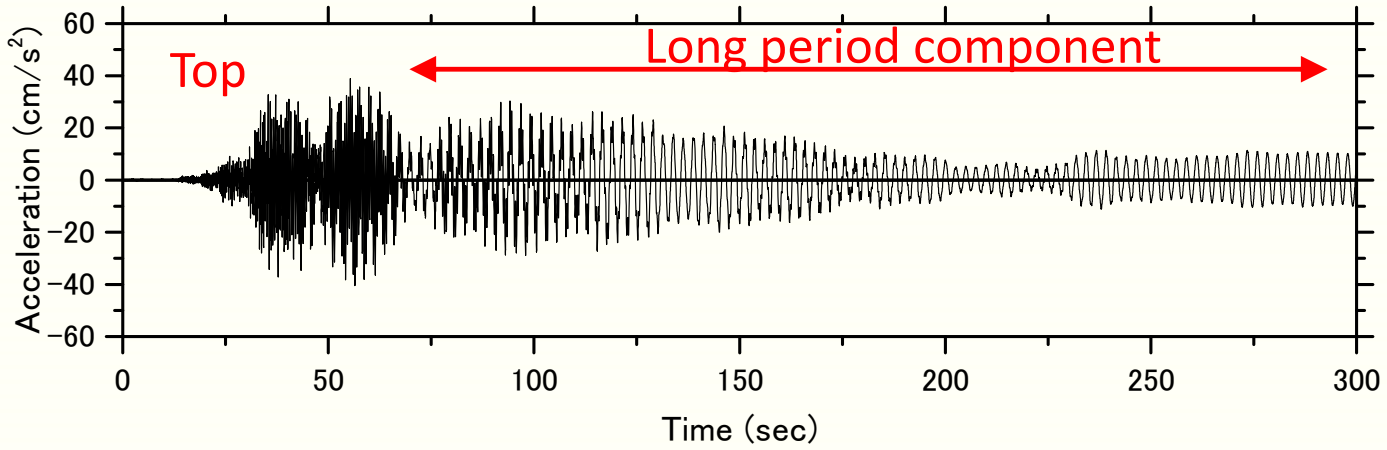
Ibaraki Ken North EQ(Dec/28/'16)

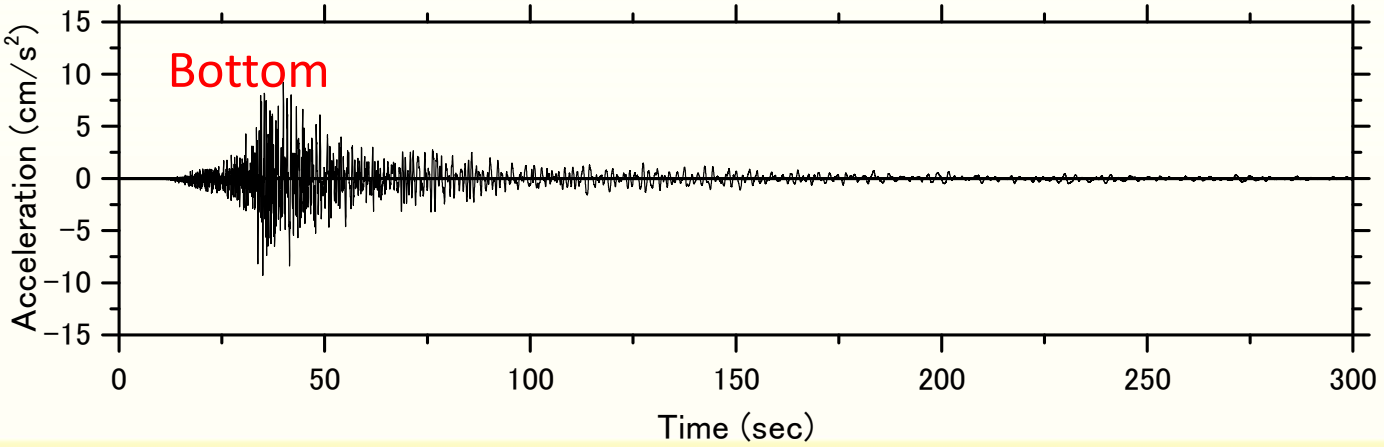
- M=6.3
- Seismic Intensities
  =III
- Epicentral Distance
  ≒80km

Transfer function (NS) of Higashi-Oshima

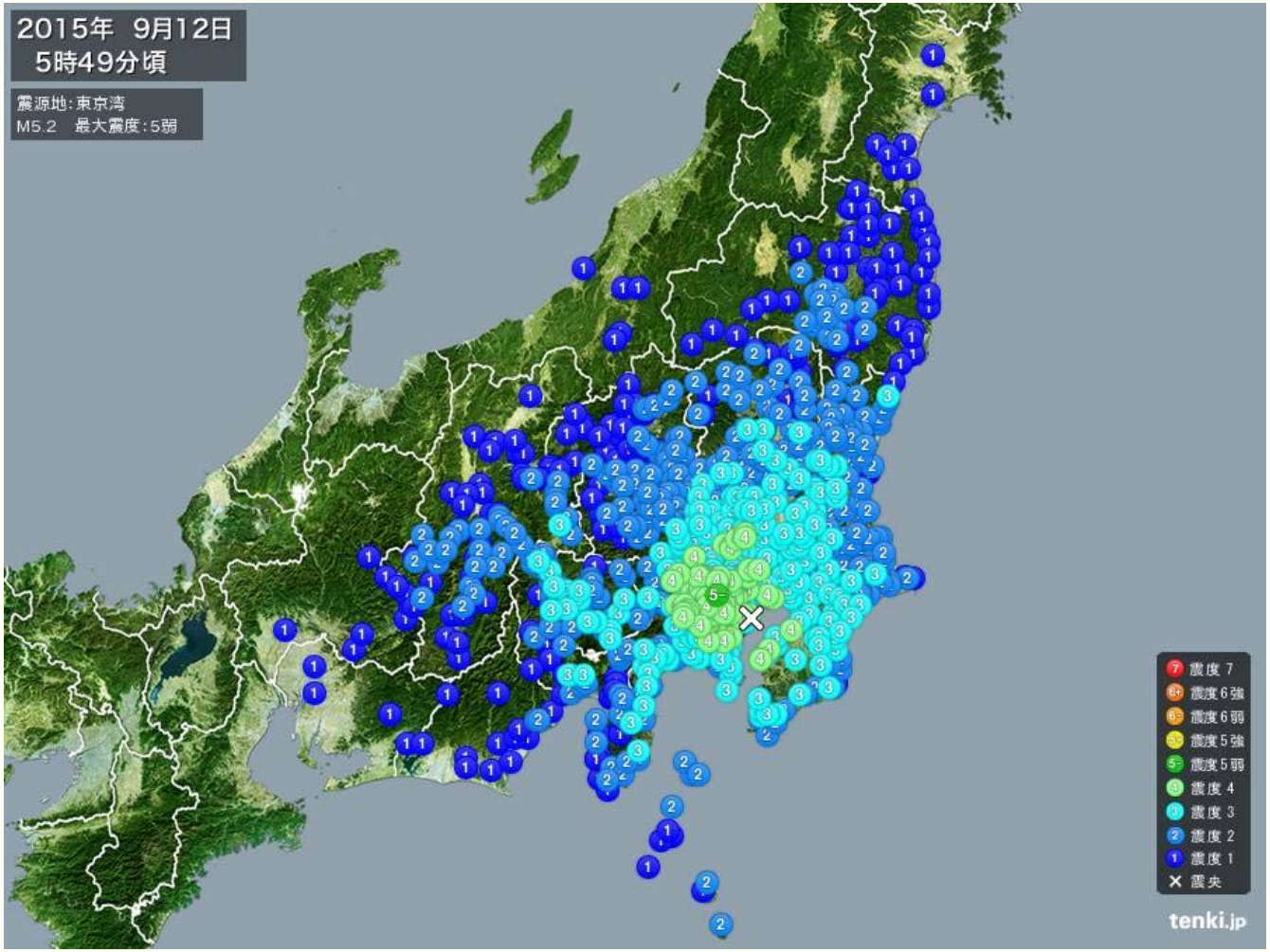


Waveforms (NS) of Higashi-Oshima

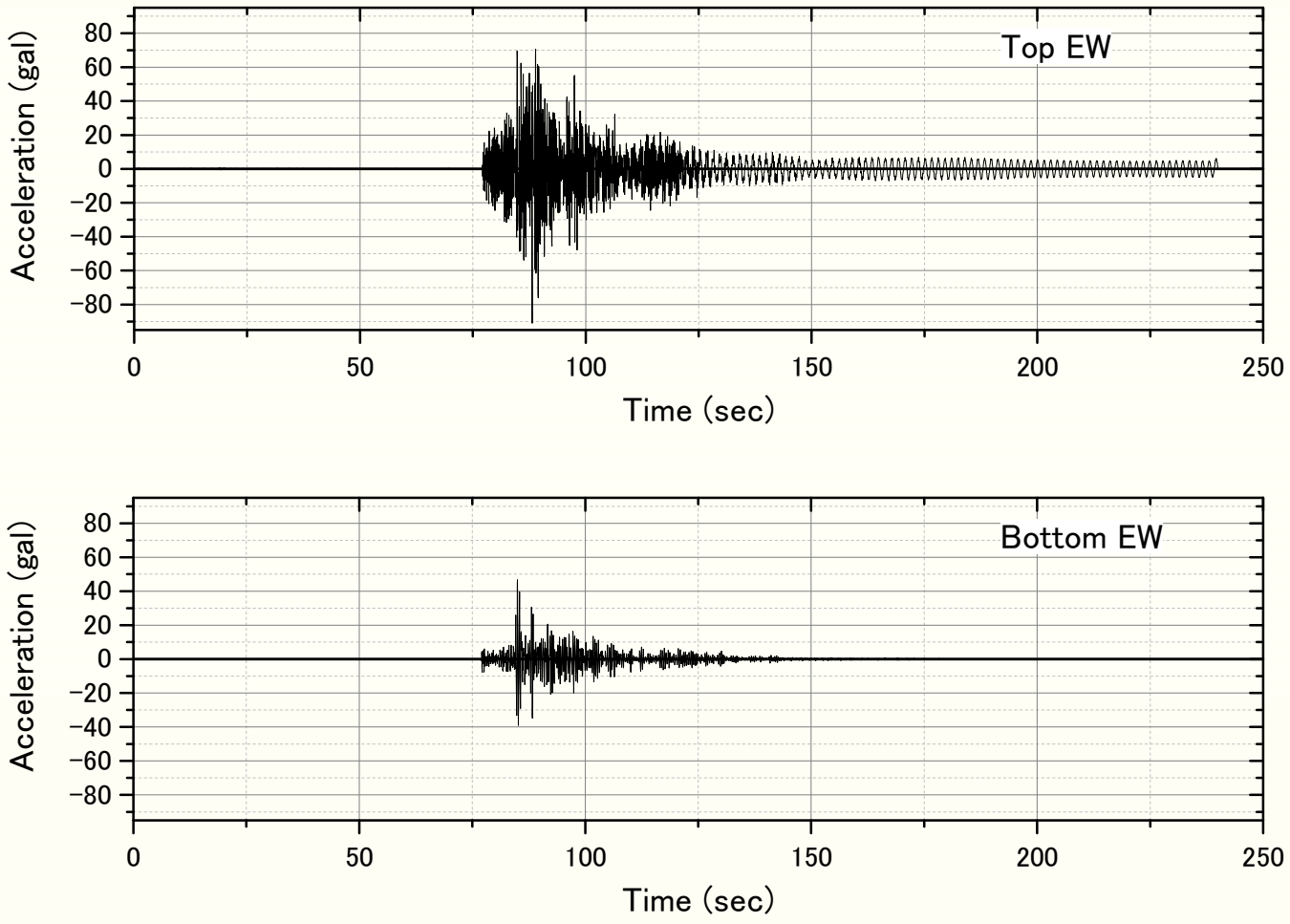




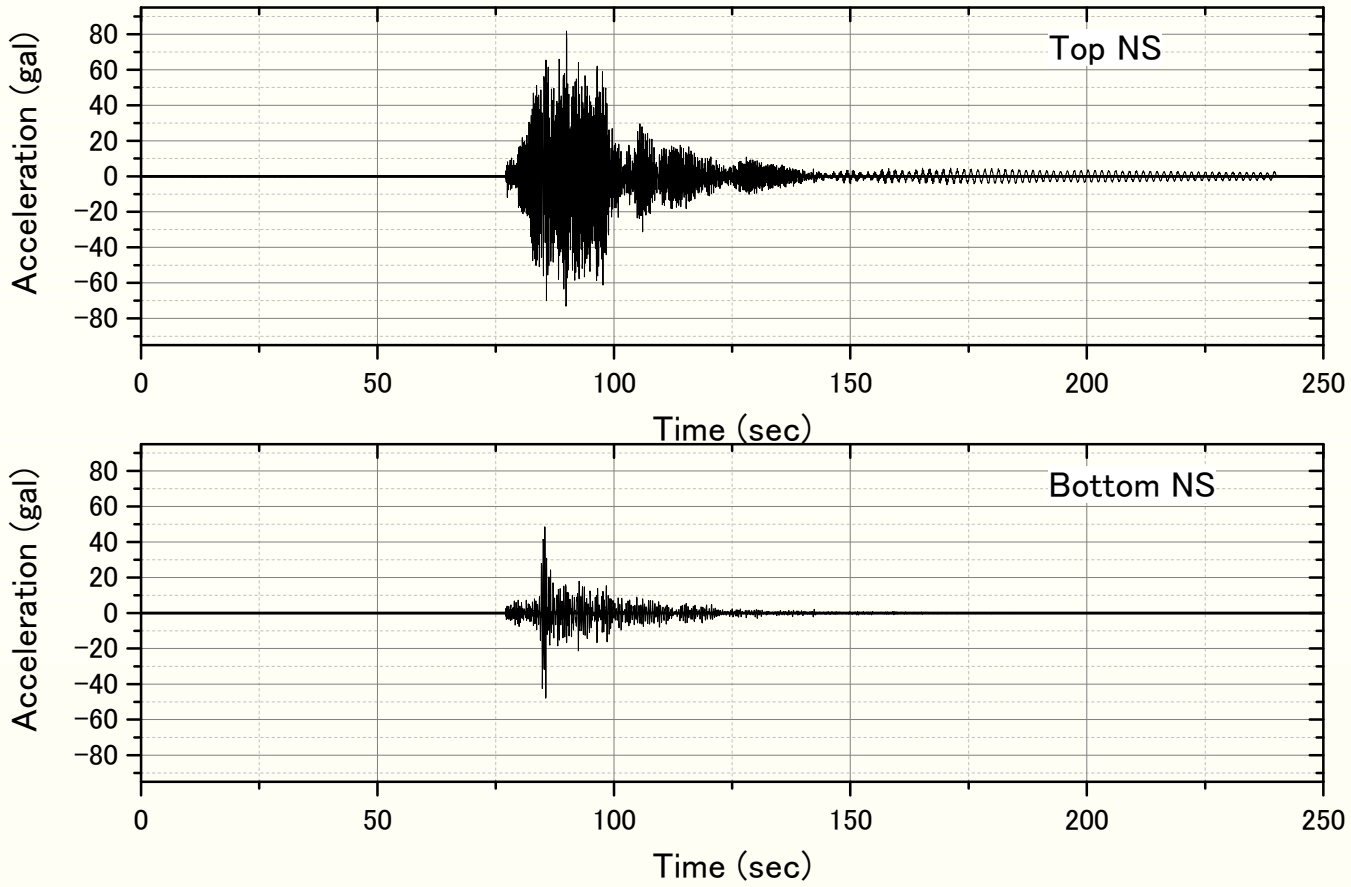
Tokyo Bay EQ (2015/9/12)



Hazawa Tower EW

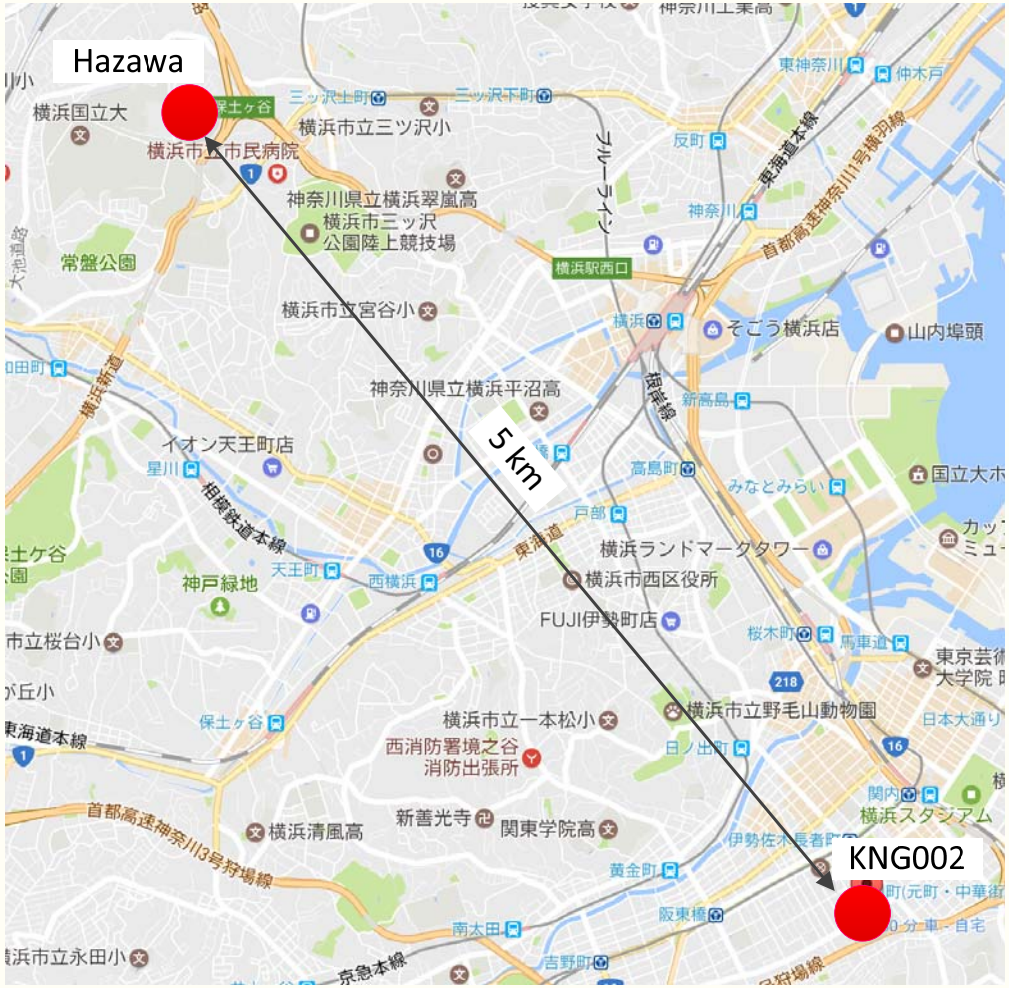


Hazawa Tower NS

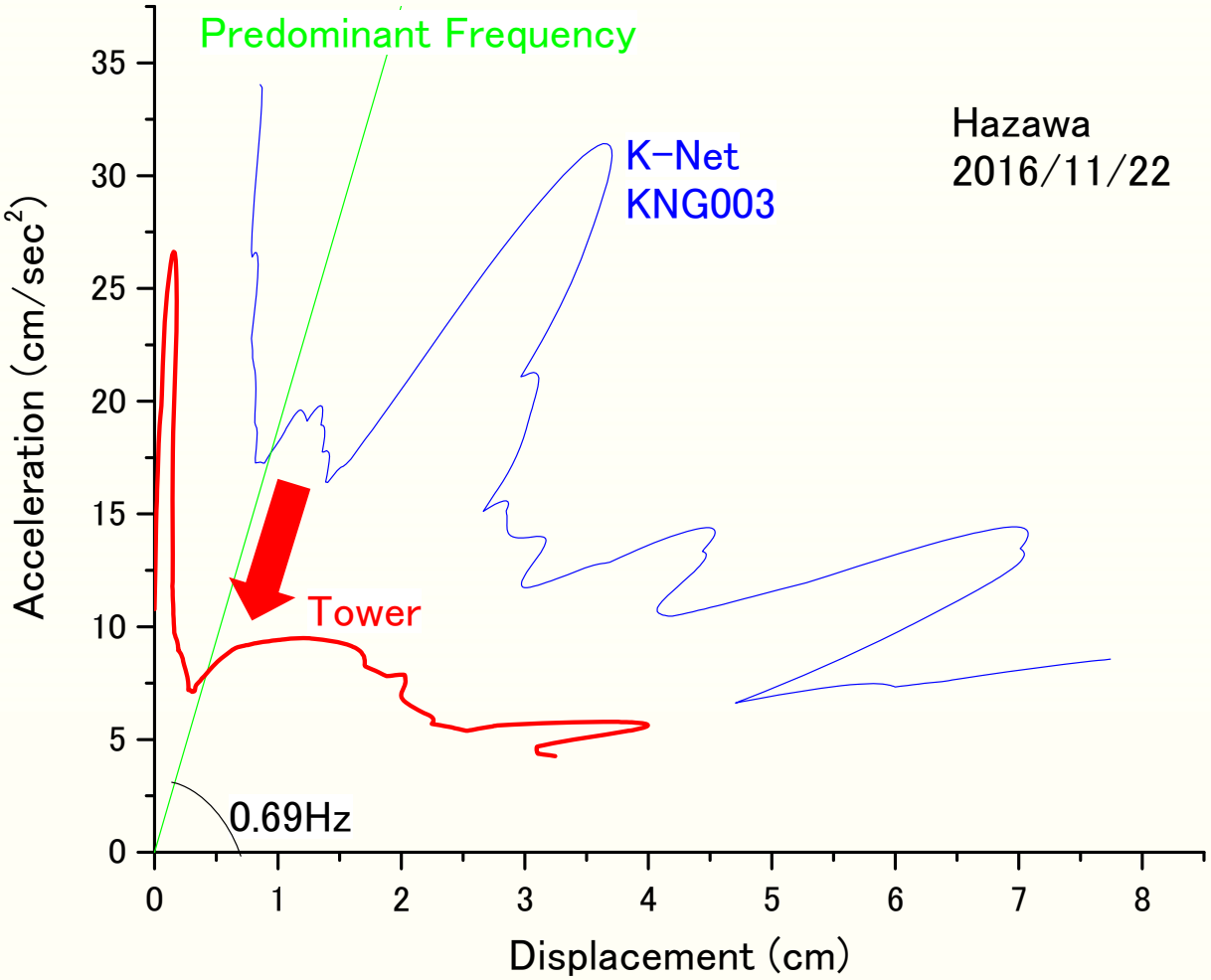


Health Monitoring

Hazawa Tower and KNG002 station

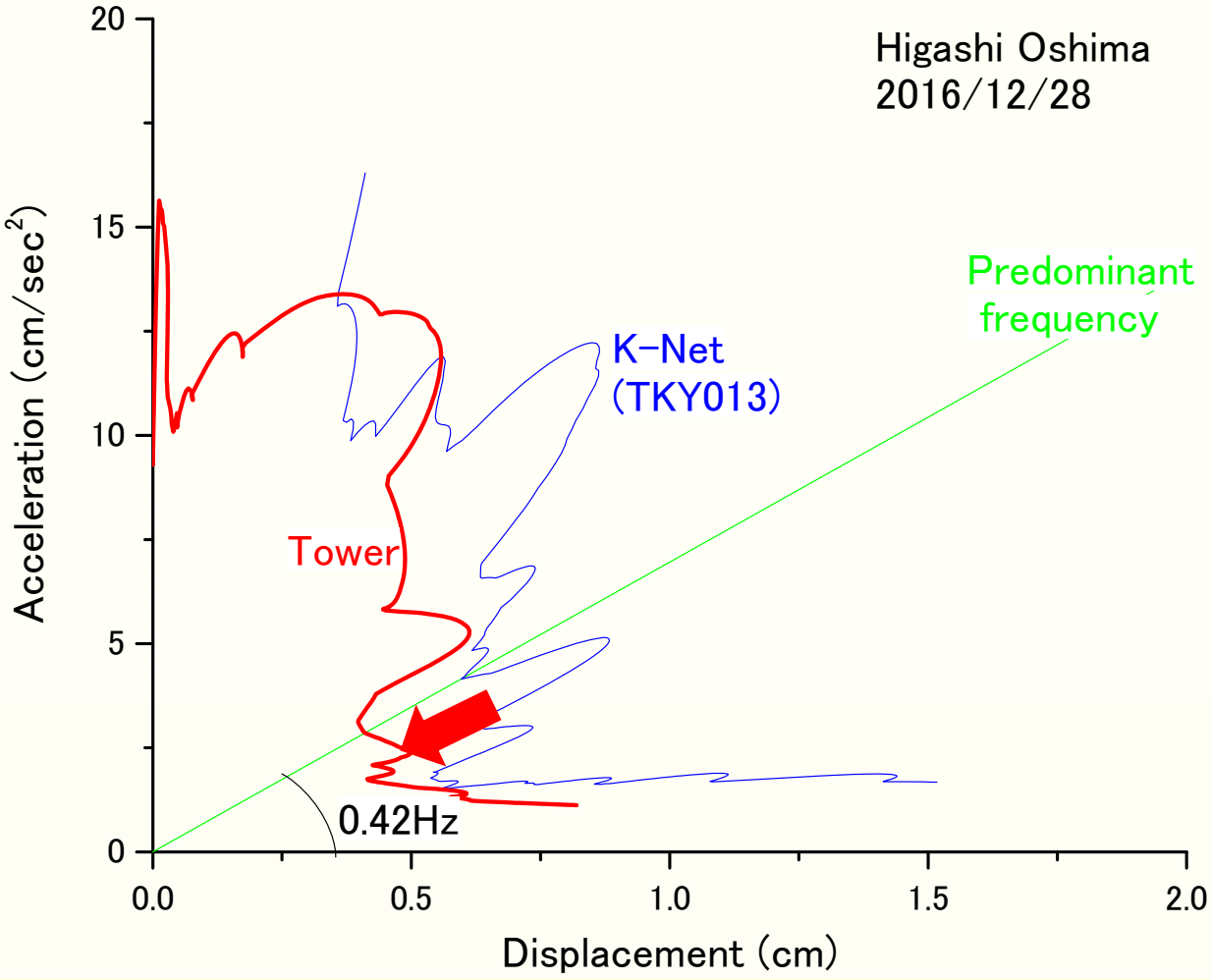


Demand curves (Hazawa &KNG002)



Higashi-Oshima & TKY013 station

Demand curves
Shigashi-Oshima & TKY013

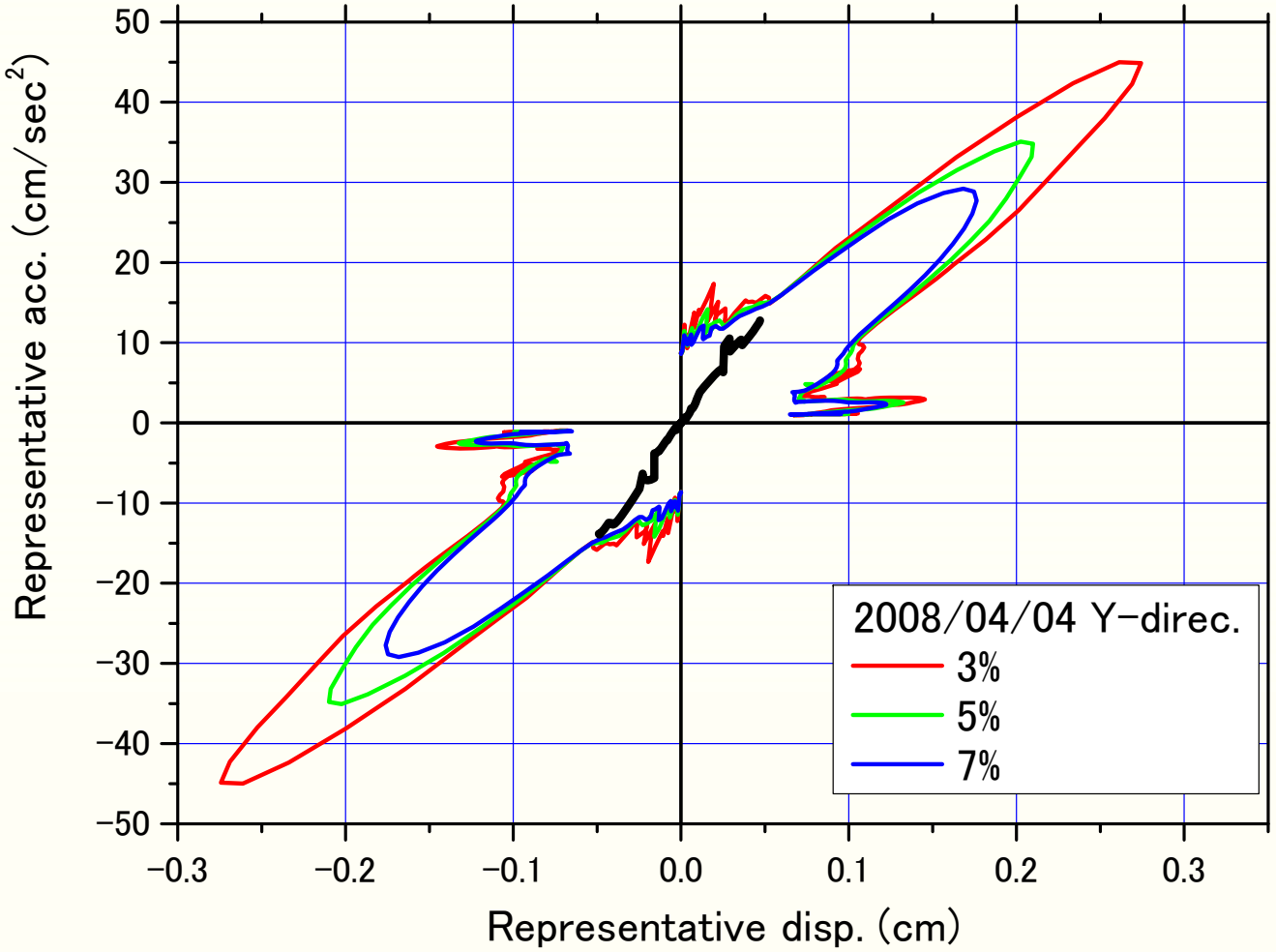


Building Example
Yokohama National Univ.

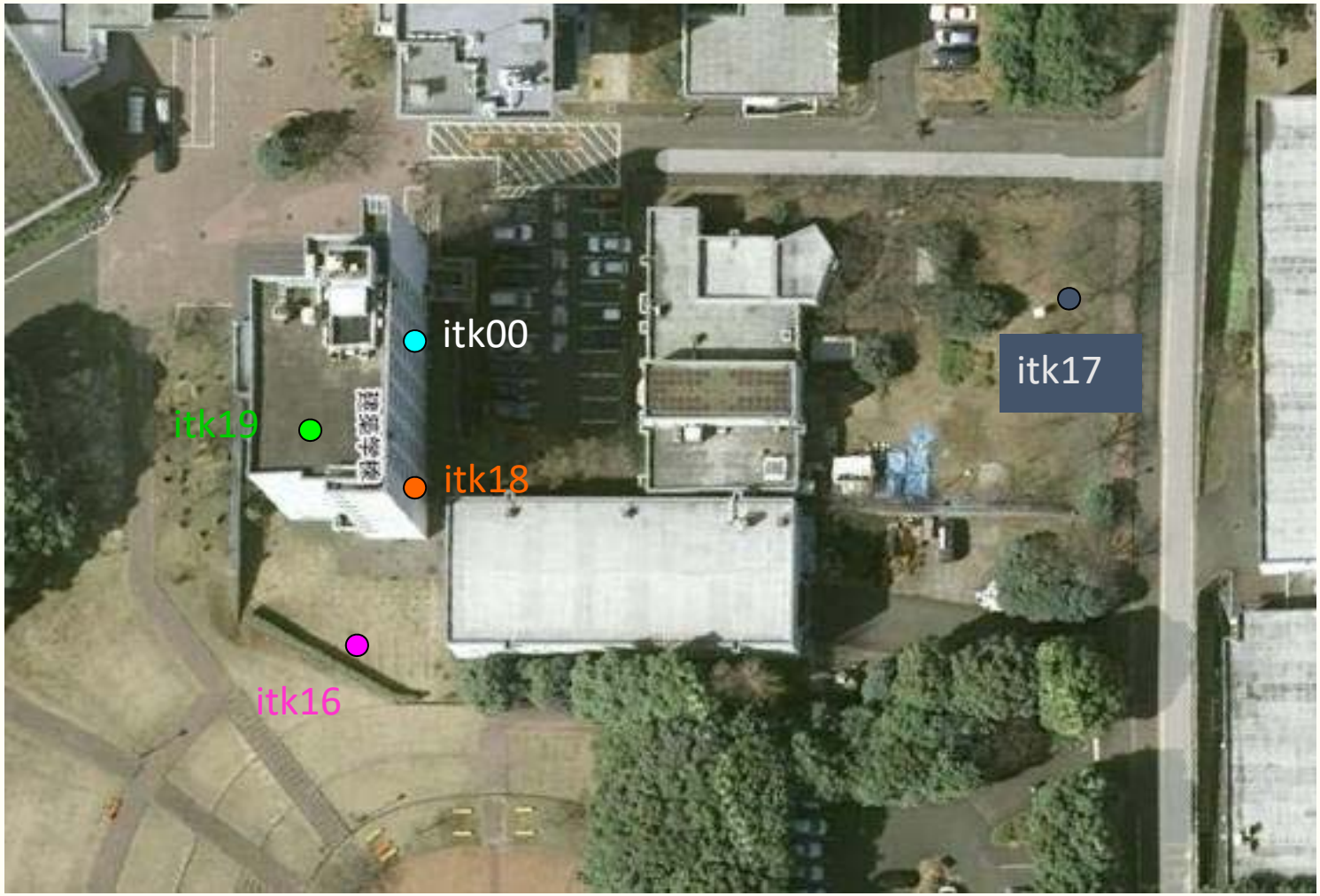
- Department of architecture

- SRC structure
- H= 30.8 m
- 8-story + 1 BF
- Retrofitted before
  Tohoku EQ

Performance & Demand Curves



Locations of sensors

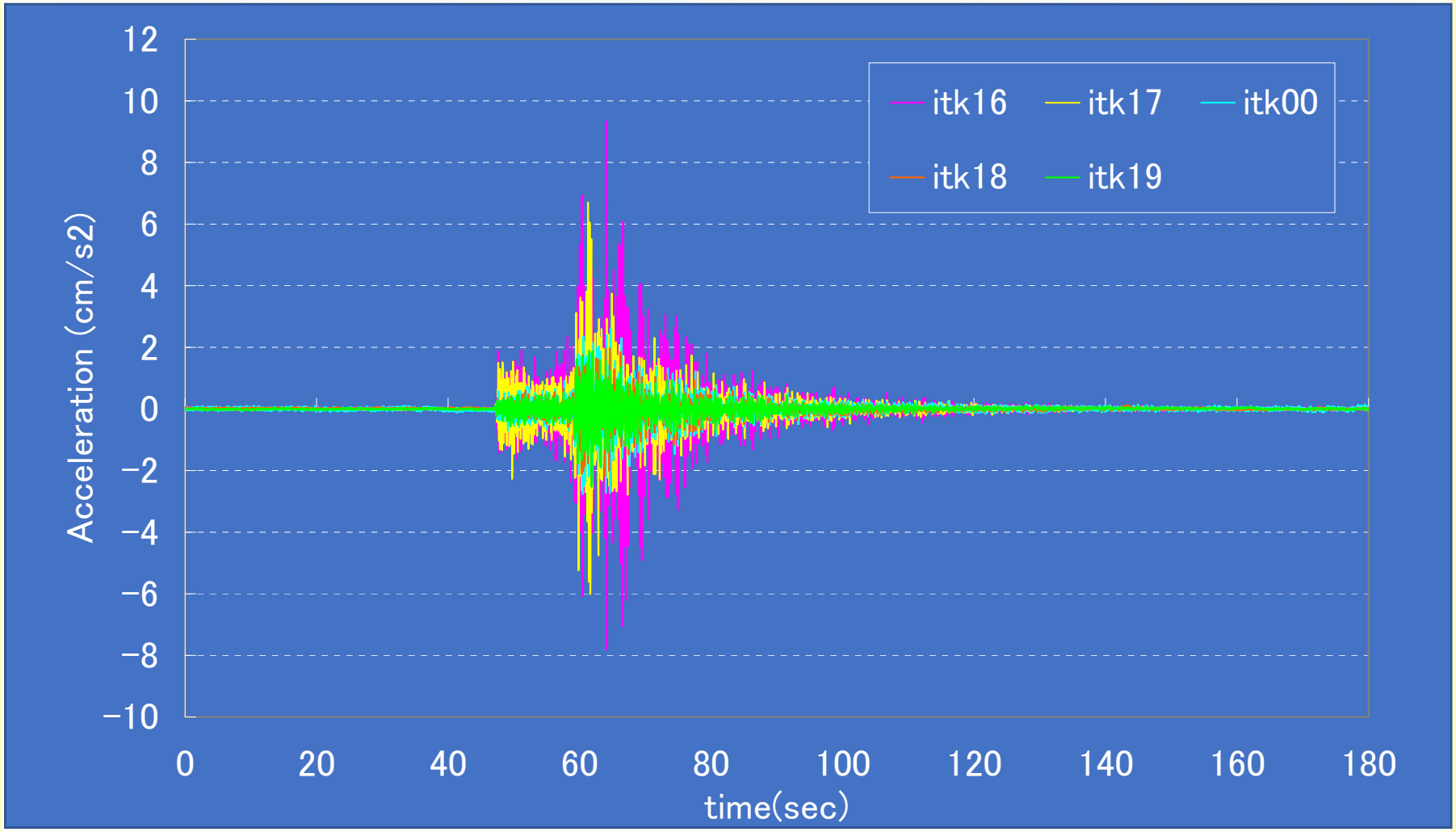


Installation

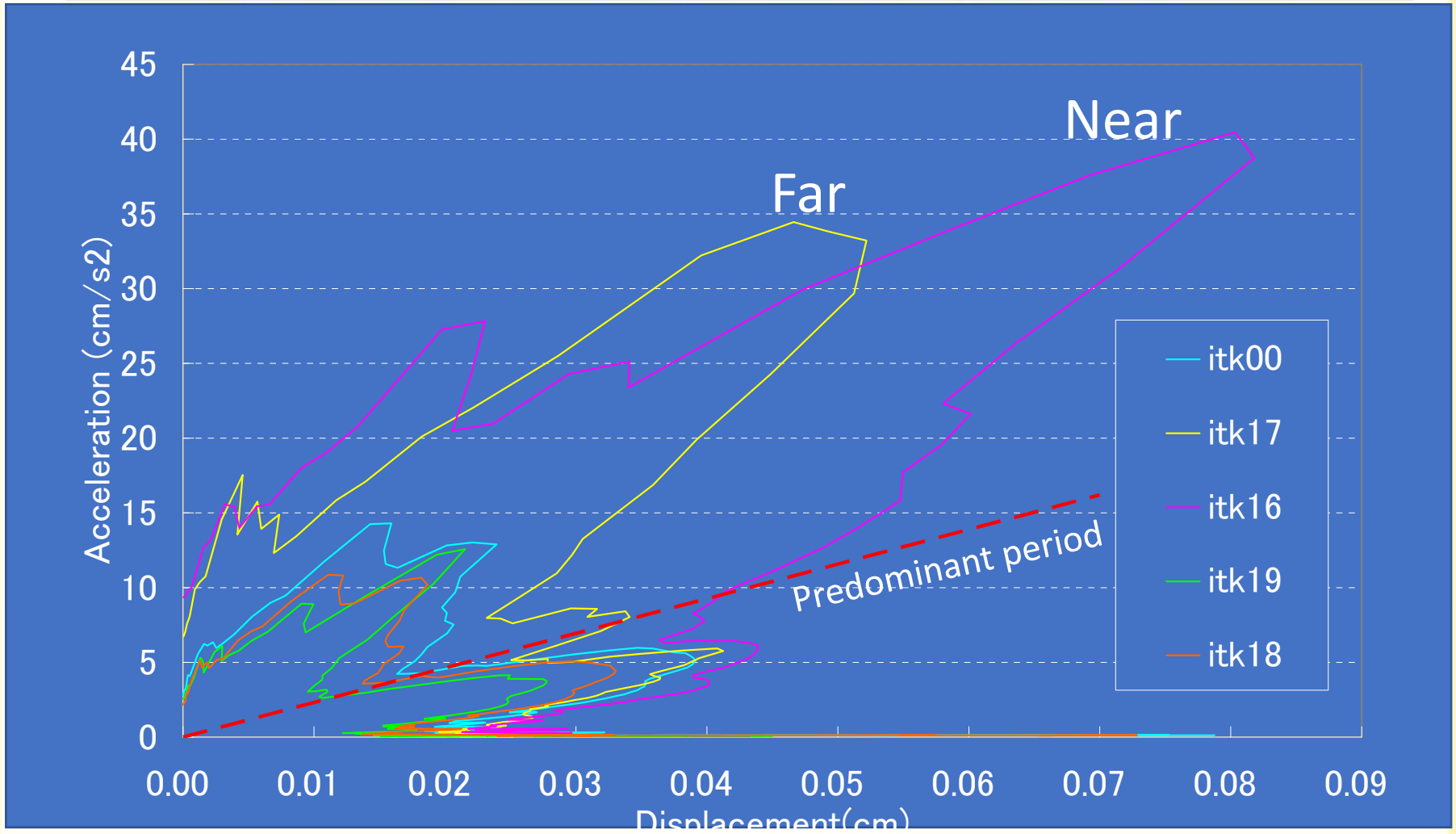
Soaked….

New treatment

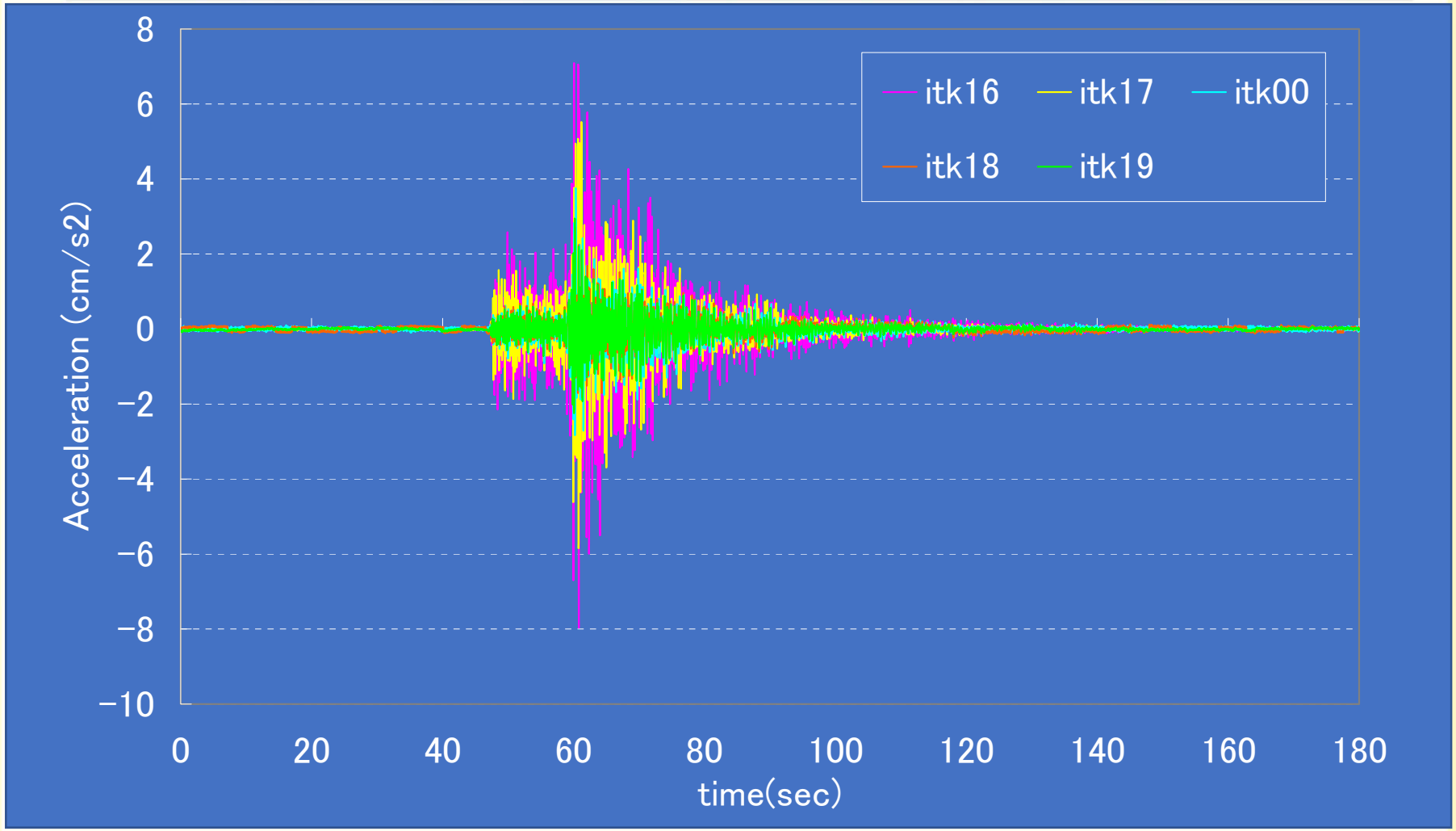
Recorded accelerations (X Direction)



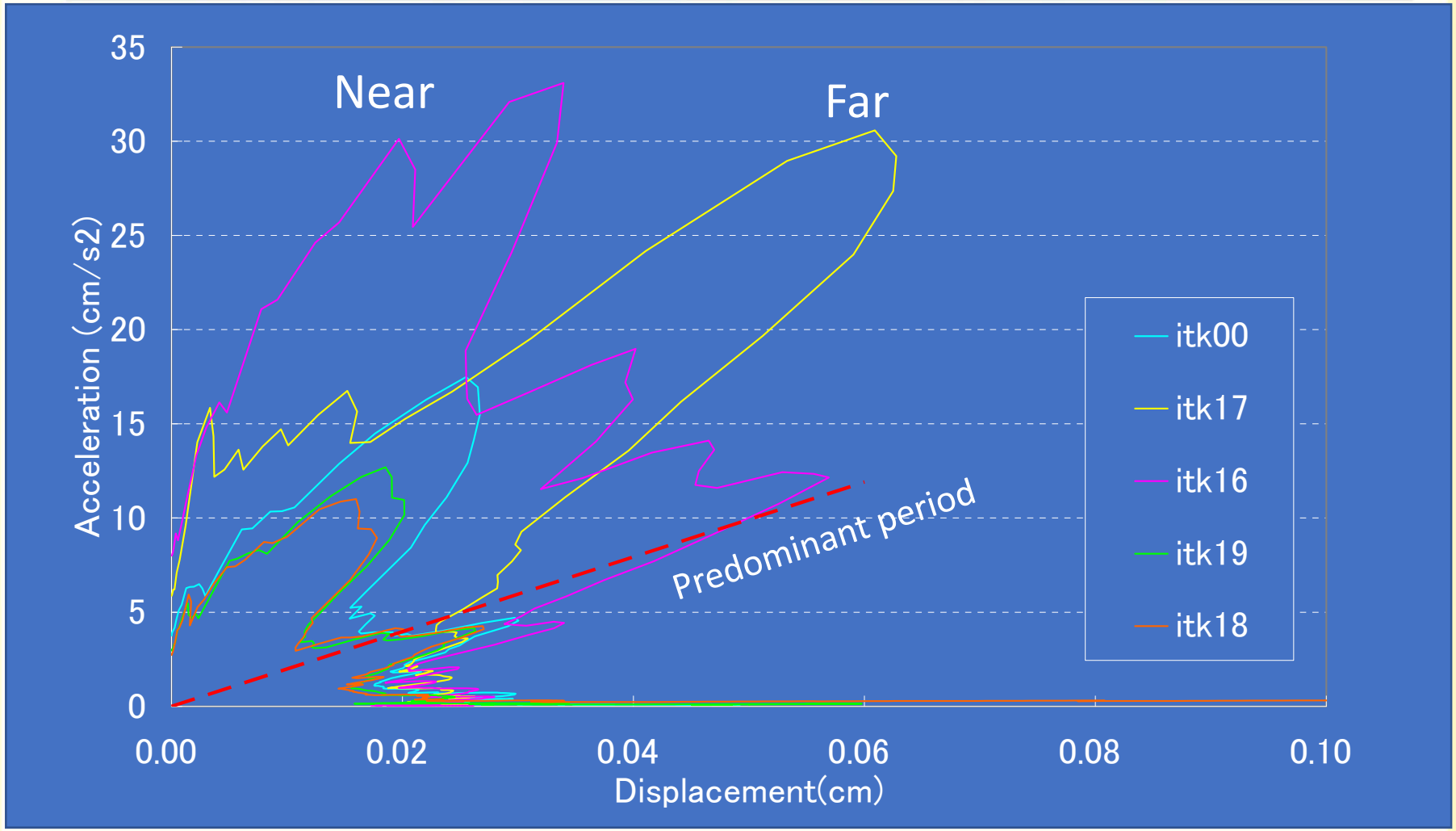
Demand curve (X Direction)



Recorded accelerations (Y Direction)



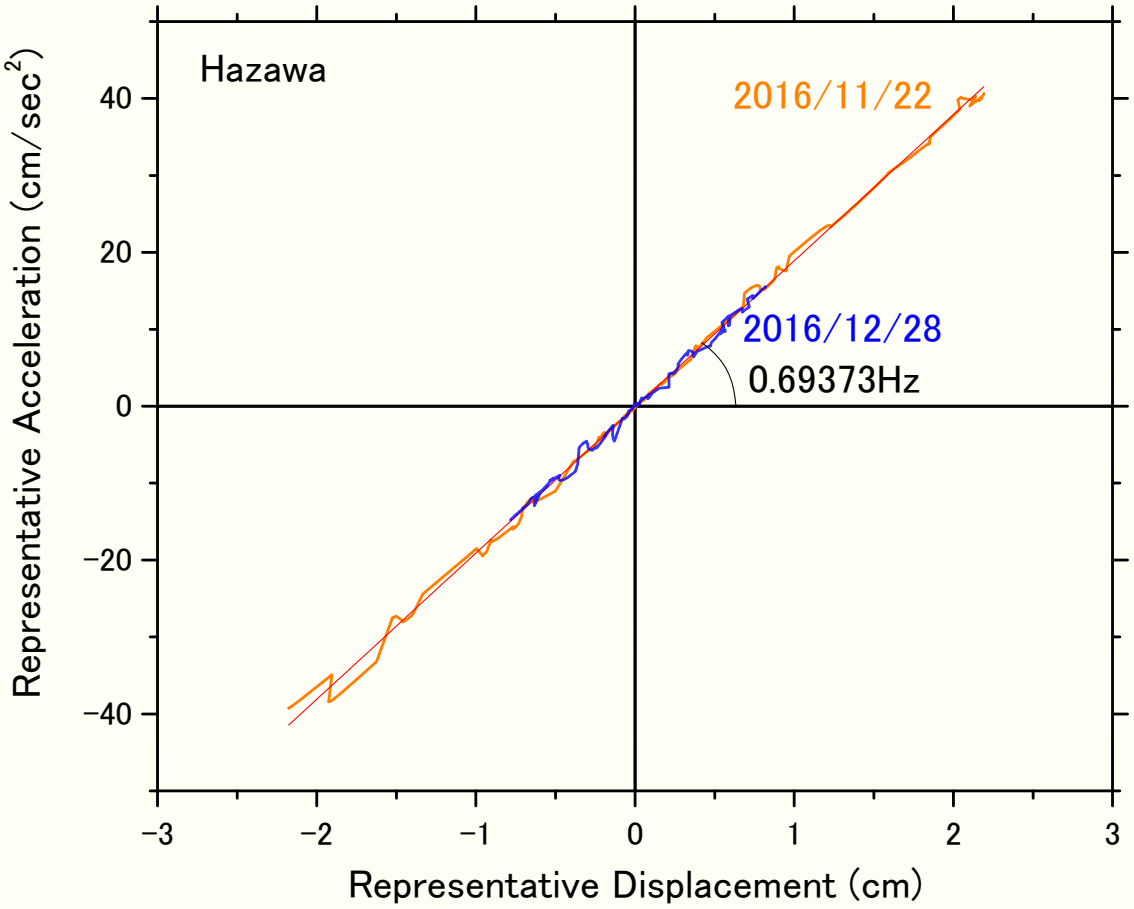
Demand curves (Y Direction)



Input motion

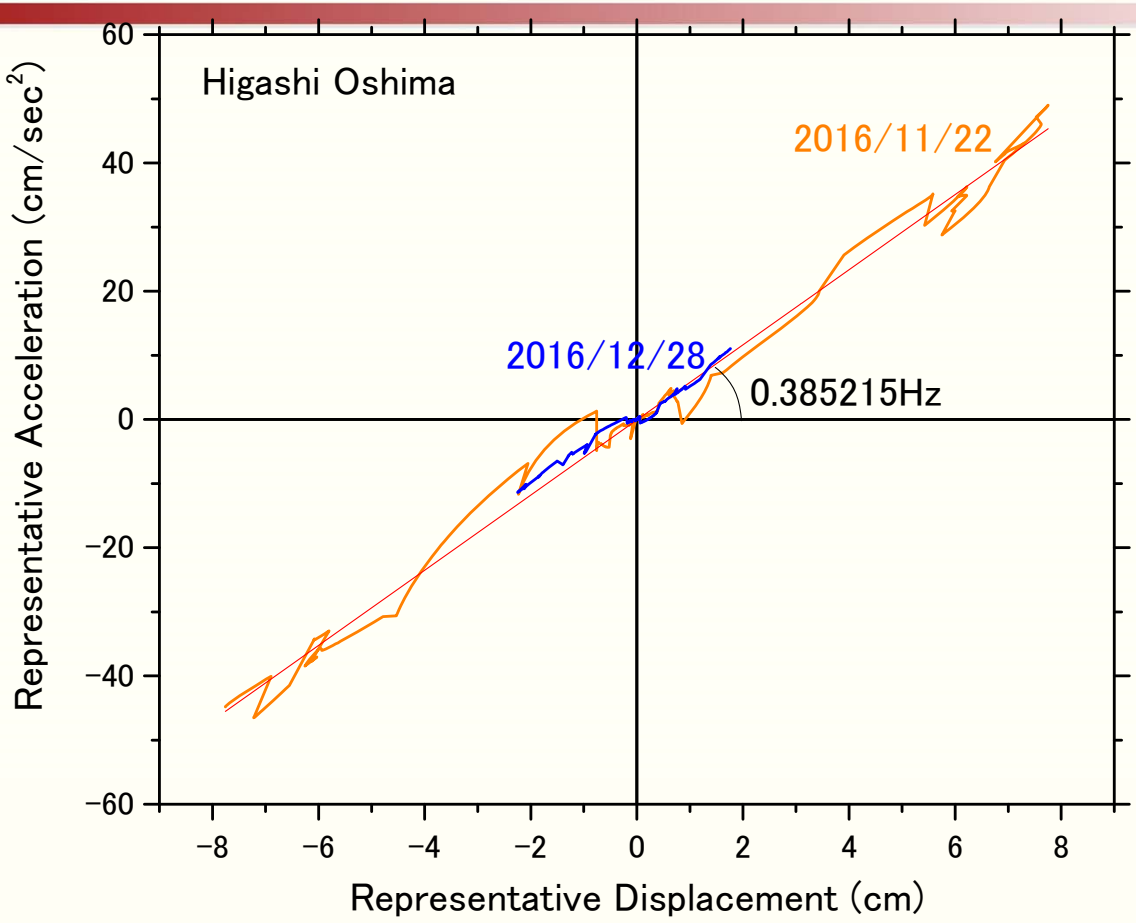
- The actual input motion is probably quite different from the waveform measured on the free field.

Performance curve (Hazawa)



- The accuracy with three sensors looks acceptable.

Performance curve (Higashi-Oshima)



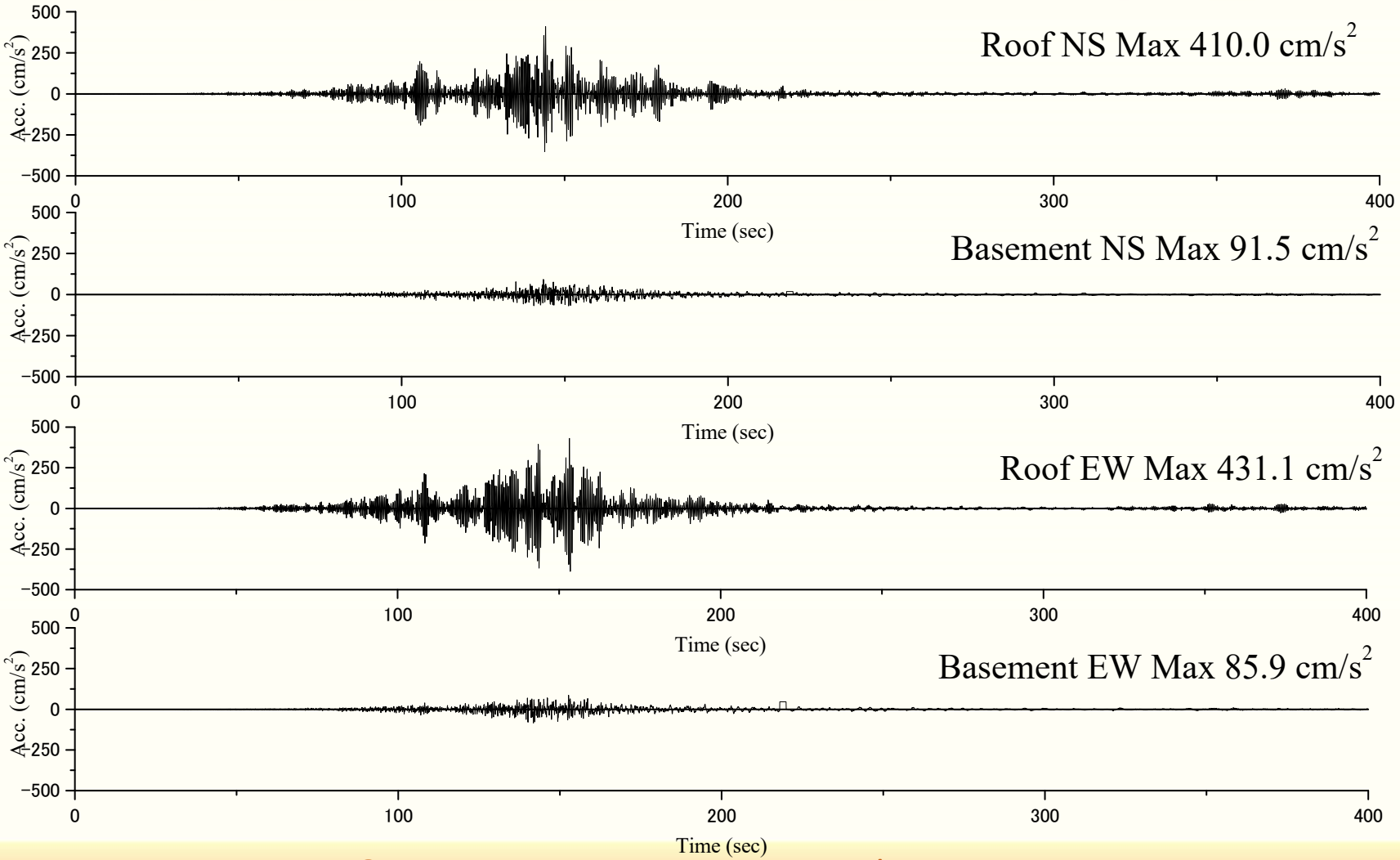
- Since there are only two sensors, the accuracy is relatively low.

Building Example
Yokohama National Univ.

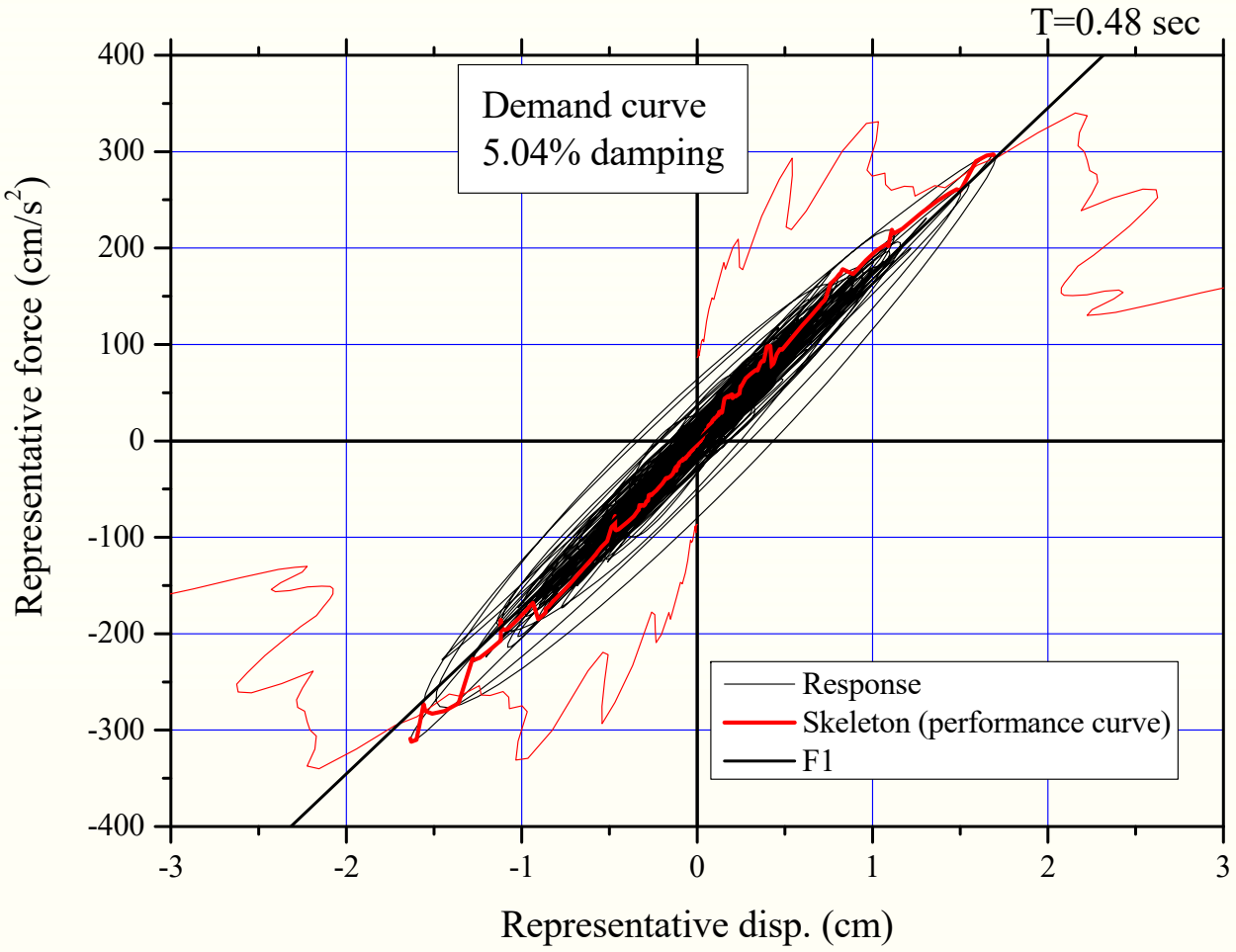
- Department of architecture

- SRC structure
- H= 30.8 m
- 8-story + 1 BF
- Retrofitted before
  Tohoku EQ

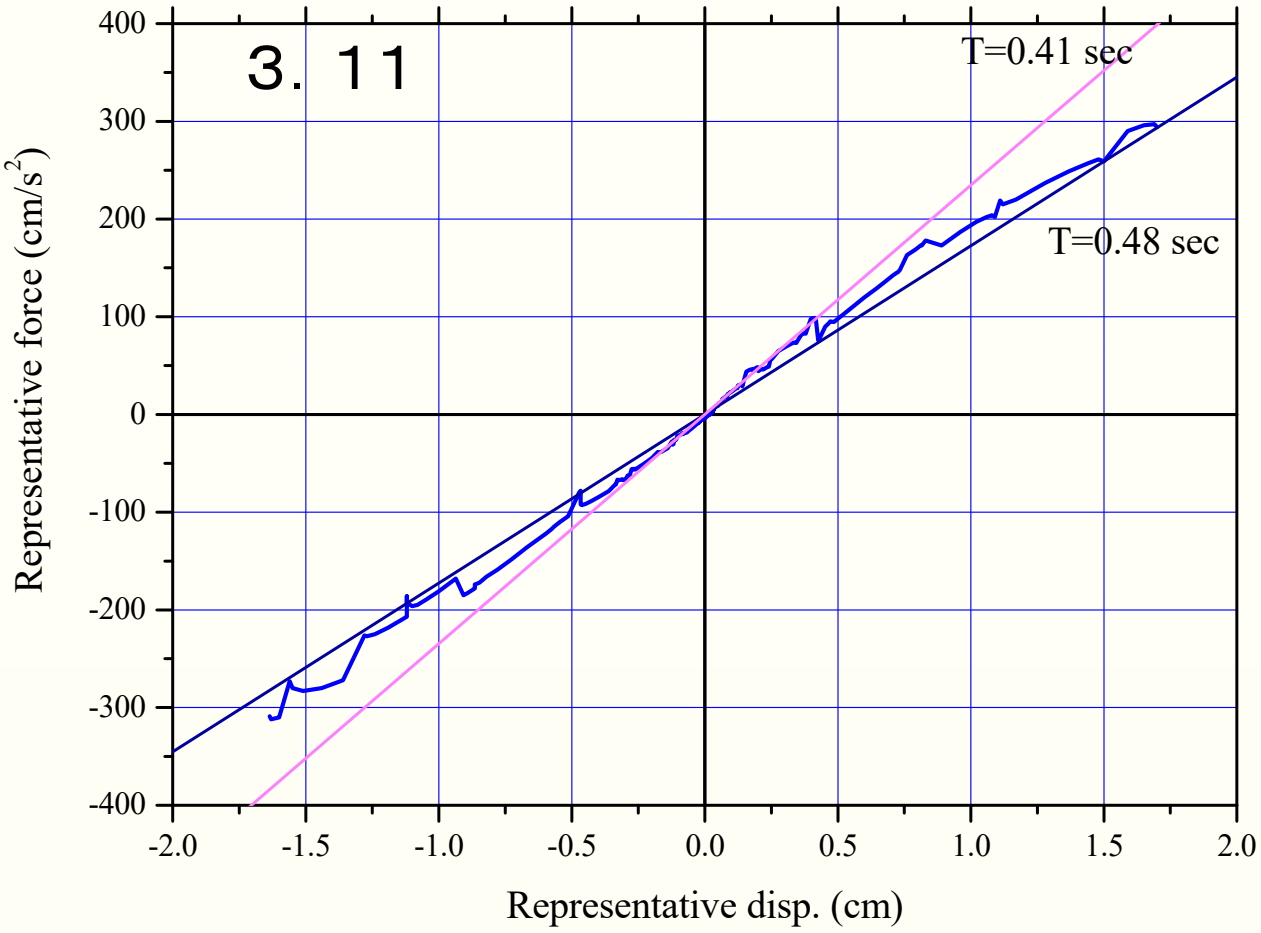
Tohoku EQ


Roof NS Max 410.0 cm/s2
Basement NS Max 91.5 cm/s2
Roof EW Max 431.1 cm/s2
Basement EW Max 85.9 cm/s2
Acc. (cm/s2)
Time (sec)
500
250
0
-250
-500
0
100
200
300
400

Performance and demand curves

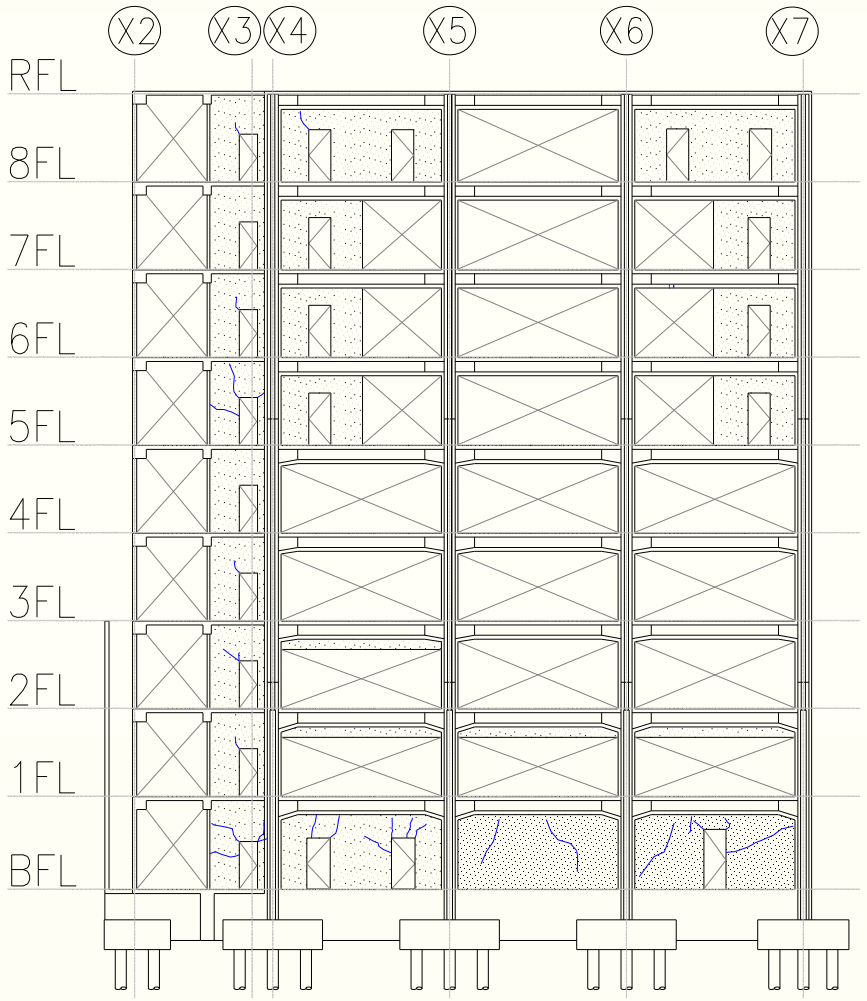


Performance and demand curves



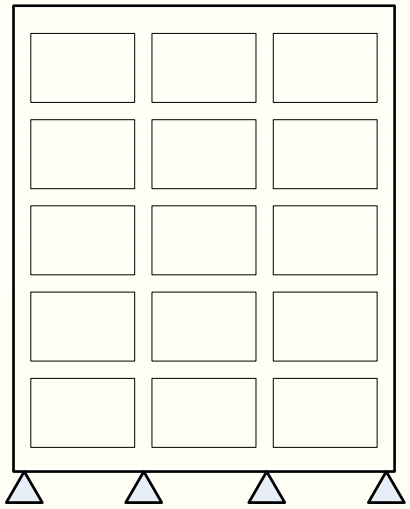
Damage evaluation

- Flexural cracks were observed at the bottom of walls
- Detected damage level coincide the observed level
- The system worked well
- The result was informed to all staffs.

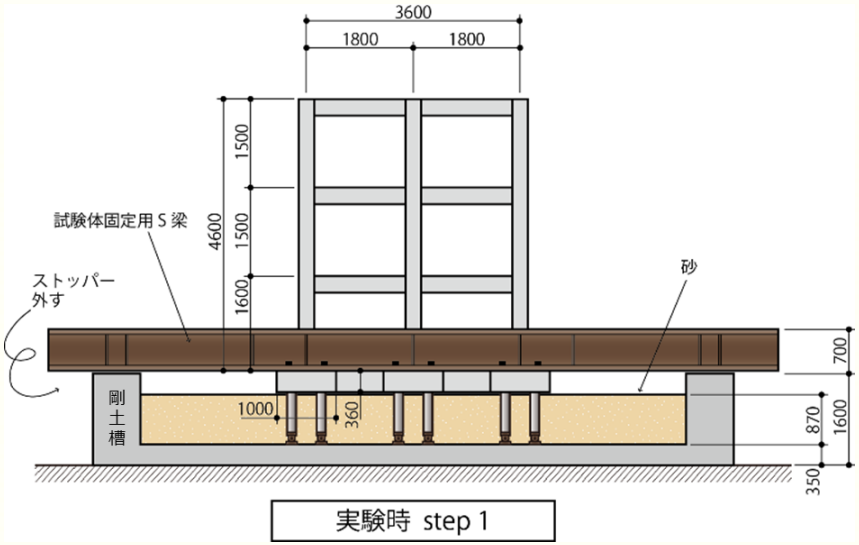


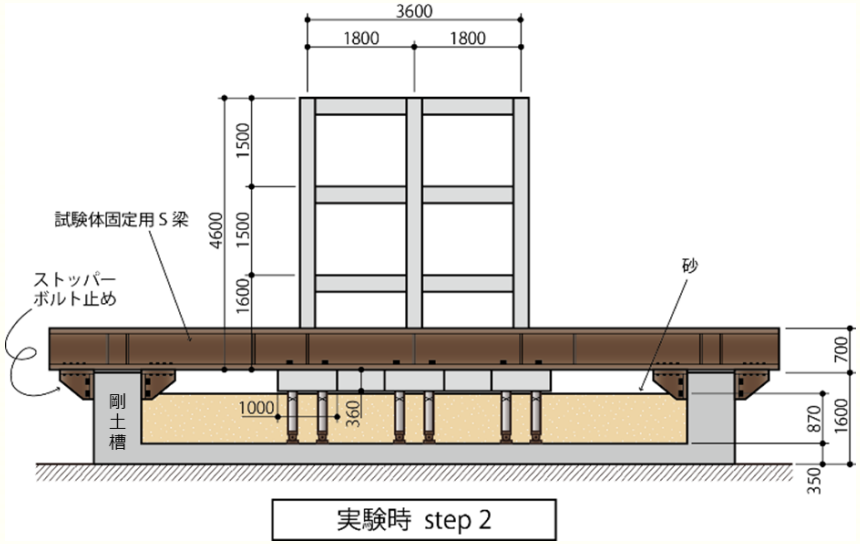
Another question

- Does analysis with fixed-base boundary condition give a reasonable prediction?



E-Defense test with pile system





- 3-story R/C structure
  - Vibrated with pile system
  - Fixed to the table and vibrated with the same imput motion

Concluding Remarks

- **Structural monitoring is indispensable to achieve a breakthrough for the seismic design methodology.**

- The measurement systems worked successfully.
- Because of a long-period component in each earthquake, both towers continued to oscillate even after the ground shaking had diminished or even ceased.
- The demand curves associated with the base of each tower were smaller than those of the free field (K-Net).
- The performance curves of the towers were derived successfully from the measured accelerations, which showed that the towers remained elastic.
- It is recommended that more accelerometers be placed in Higashi Oshima Tower.

Acknowledgement

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