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Site specific ground motion characteristics and building damage in Sendai area during the 2011 Tohoku earthquake

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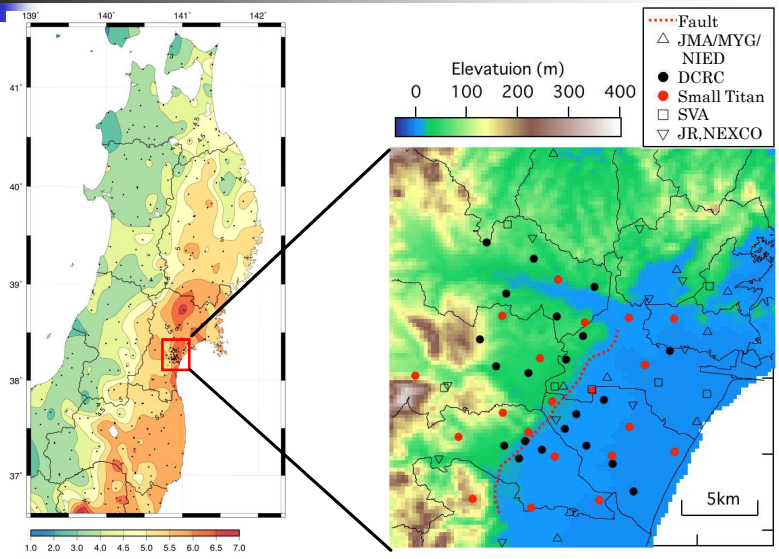
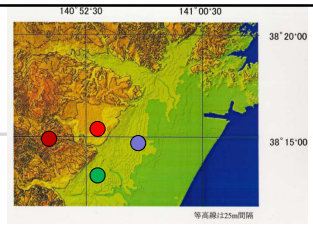
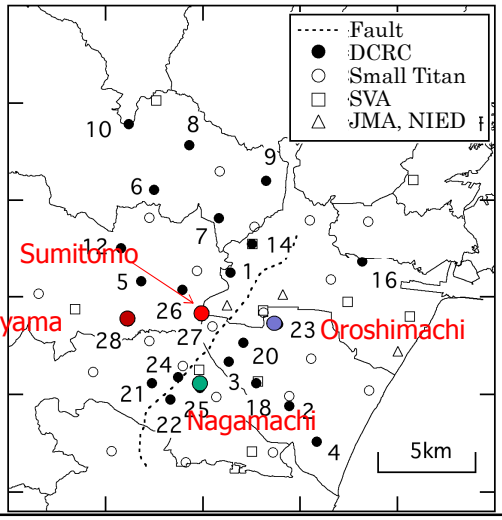
Necessity of 'holistic' earthquake counter measures

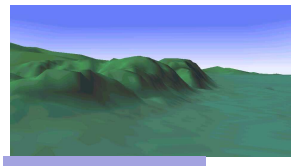
Location of strong motion observation sites

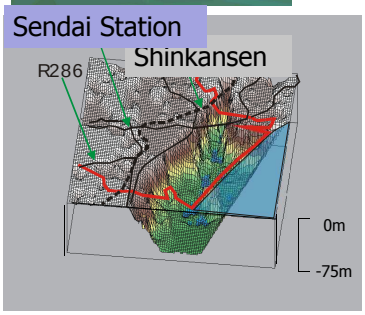


Surface geology and obs. pts. of DCRC, Tohoku Univ.



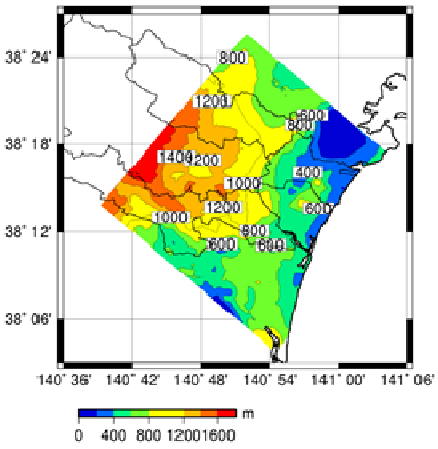




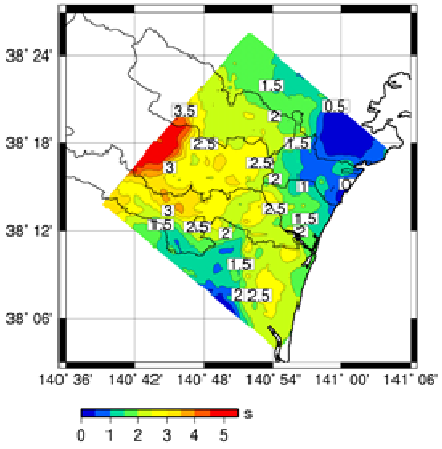


Deep Underground Structure in Sendai Area

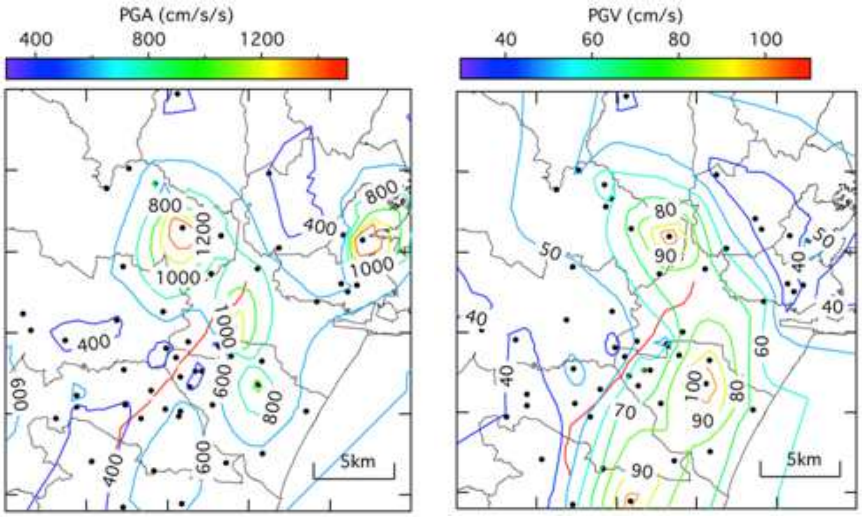
Bedrock depth



Dominant period



PGA and PGV distribution



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PGA & PGV of Observation data ～ DCRC, Tohoku University network

- Max. Acc.(PGA)

300cm/s/s～800cm/s/s

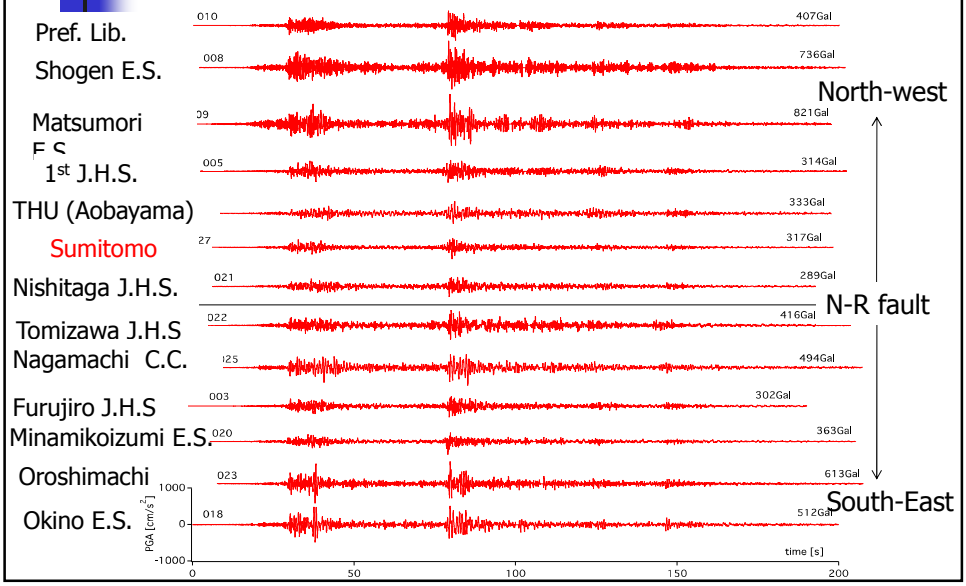
- Max. Vel.(PGV)

30cm/s～80cm/s

(Ohno and Motosaka, 2011)

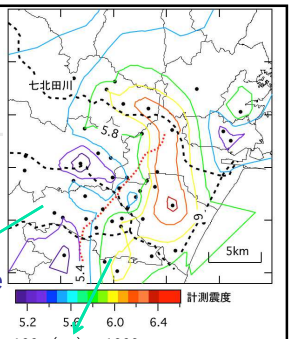
			2011/4/7			2011/3/11			2011/3/9		
No	地震計	地点名	PGA (cm/s^2)	PGV* (cm/s)	計測震度	PGA (cm/s^2)	PGV* (cm/s)	計測震度	PGA (cm/s^2)	PGV* (cm/s)	計測震度
2	ETNA	六郷小	311	42.1	5.7	欠測			欠測		
3	ETNA	古城小	251	22.4	5.1	320	61.3	5.6	24	3.1	3.2
4	ETNA	東六郷小	撤去			613	74.2	5.9	29	3.4	3.4
5	QDR	第一中	230	19.3	5.1	383	41.5	5.6	28	2.9	3.4
8	QDR	将監中央小	534	25.3	5.5	840	64.2	6.0	30	2.2	3.2
9	QDR	松森小	767	75.5	6.2	822	88.2	6.4	46	4.2	3.6
10	QDR	宮城県立図書館1F	279	18.0	4.9	407	65.0	5.5	20	2.4	3.1
11	QDR	宮城県立図書館3F	欠測			欠測			34	3.1	3.5
12	QDR	仙台青陵中等教育学校1F	欠測			欠測			19	3.5	3.3
14	QDR	鶴谷小学校1F	432	30.6	5.6	欠測			20	1.9	3.0
16	QDR	中野小学校1F	欠測			欠測			40	3.2	3.5
18	QDR	沖野小学校1F	360	31.8	5.5	512	79.4	6.1	37	3.5	3.5
20	QDR	南小泉小	220	25.7	5.2	381	63.7	5.5	19	2.4	3.1
21	QDR	西多賀中	186	16.4	5.0	400	47.3	5.5	23	3.0	3.4
22	QDR	富沢中	232	21.1	5.1	416	57.9	5.7	29	3.2	3.3
23	QDR	東配水管理事務所	472	37.3	5.7	613	77.0	6.1	30	2.6	3.2
24	QDR	滝沢寺	撤去			欠測			欠測		
25	QDR	長町南コミュニティセンター	264	29.5	5.5	494	68.3	5.9	59	6.0	4.0
26	QDR	青葉区役所	318	21.9	5.1	欠測			24	3.2	3.2
27	SSA-1	住友生命ビル	167	14.0	4.9	318	30.0	5.3	15	2.2	3.1
28	SMAC-MD	東北大学1F	欠測			333	59.8	5.6	35	4.4	3.6
			*カットオフ周期10秒			*カットオフ周期50秒					

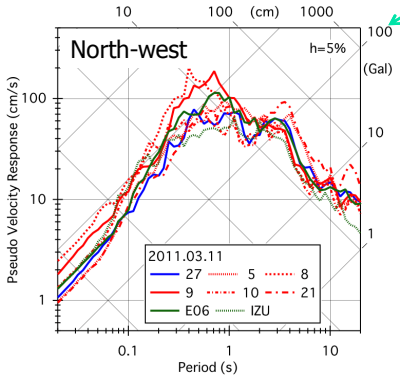
Acceleration waveform（NS-comp.）

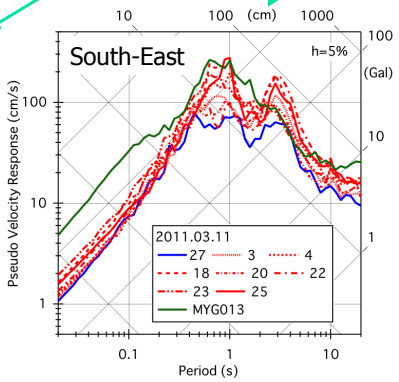


Spectral distribution in Sendai City

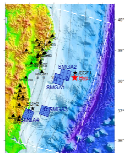
- Sendai station (blue)is hard to shake (Engineering bedrock
- West-north of the fault: short period dominance due to surface geology
- East-south of the fault: 3s period content dominance due to deep underground structure）

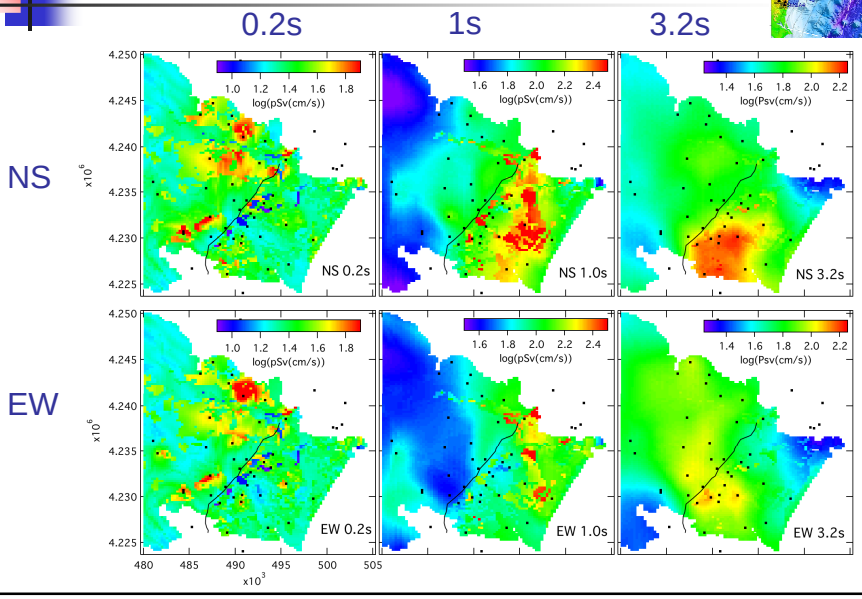




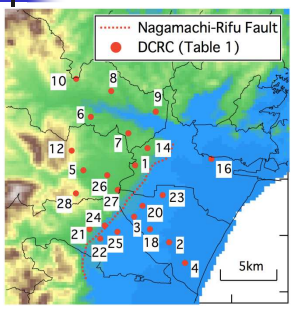


Spectral distribution due to the 2011 Tohoku earthquake (Mw9.0)

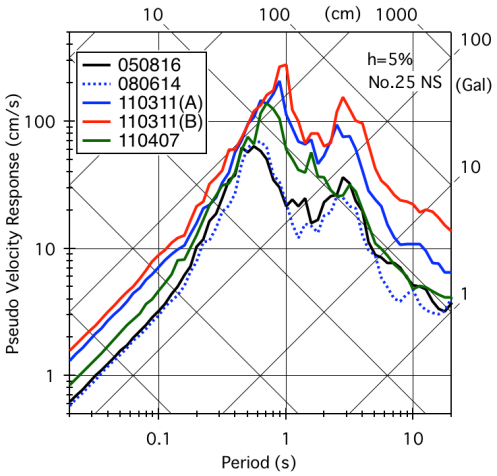




Amplitude dependent dominant period



- Peak due to deep underground structure (period:3s)
- Amplitude dependent dominant period peak due to surface geology (period: 0.5-1.0s)



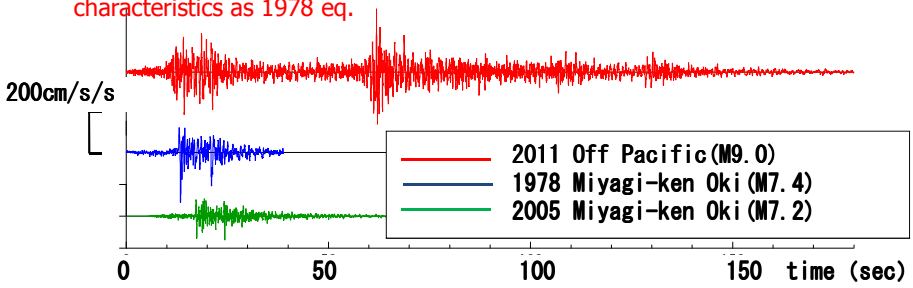
No.025（Nagamachi）

Observed waveforms compared to 1978 &2005 Miyagi-ken Oki earthquakes at Sumitomo Building (near Sendai Station)

Earthquake		NS-comp. S25E	EW-comp S65W	UD-comp.	Seismometer
yr/m/d	M				
2011/3/11	9.0	317.7	234.1	160.3	SSA-1
1978/6/12	7.4	250.9	240.9	90.8	SMAC-Q
2005/8/16	7.2	120.8	78.0	56.4	SSA-1

unit:cm/s/s

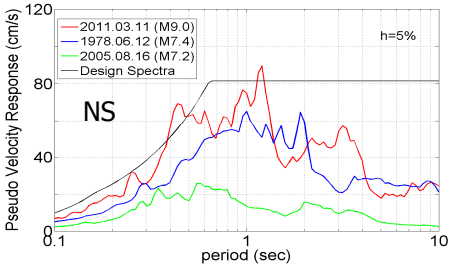
- Long duration(about 3 minutes)
- Ground shaking of 2st wave group is almost the same spectral characteristics as 1978 eq.

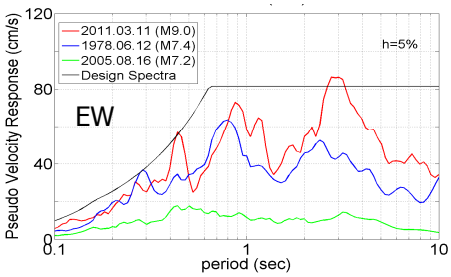


Spectral characteristics

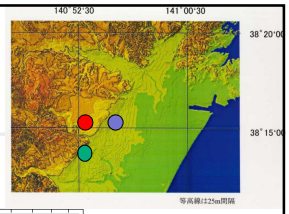
- Period contents less than 1.5s are larger than those of 1978 eq. 1s period contents are 20% larger, around 0.5s contents are 2 times larger.
- Period content around 3s is two times larger compared to 1978 eq.
- Shorter period contents than 1.5s is lager in the NS comp. and Longer period than 1.5s is lager in EW comp.

(Motosaka, Ohono & Mitsuji, 2011)

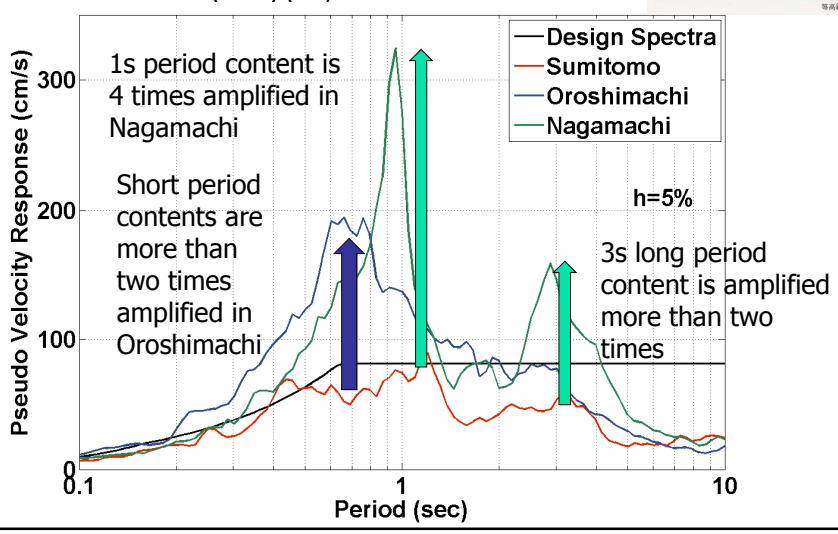




Difference of spectral amplification due to soil conditions

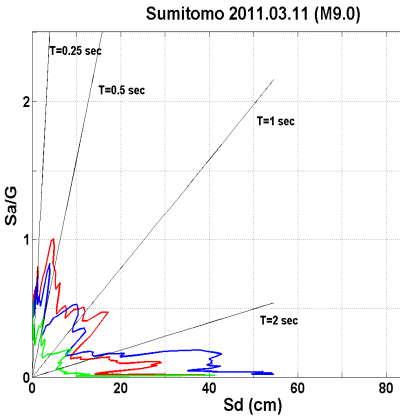


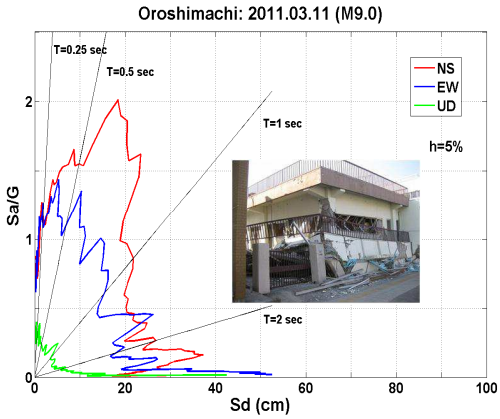
2011.03.11 (M9.0) (NS)



Different Ground Motion Characteristics at Sendai Station (Diluvium) and Damage of Old building on Alluvium site

Sa-Sd Spectra

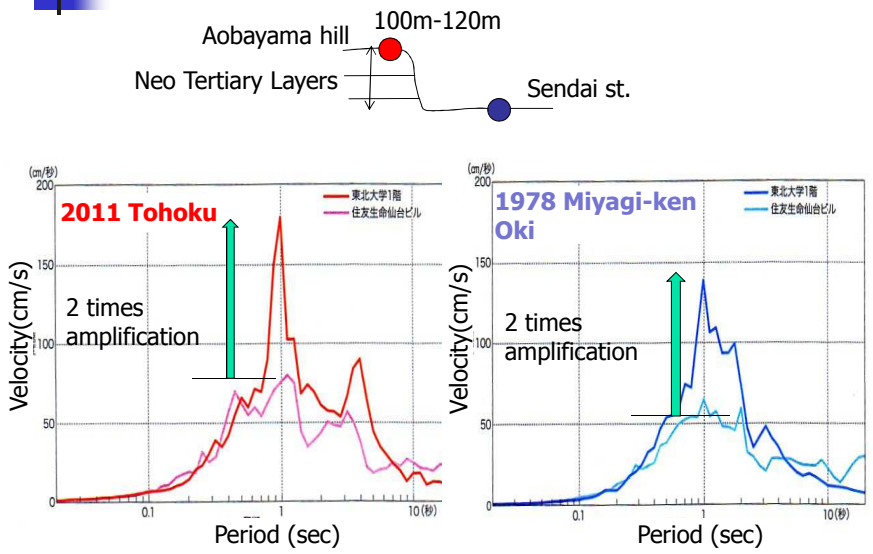




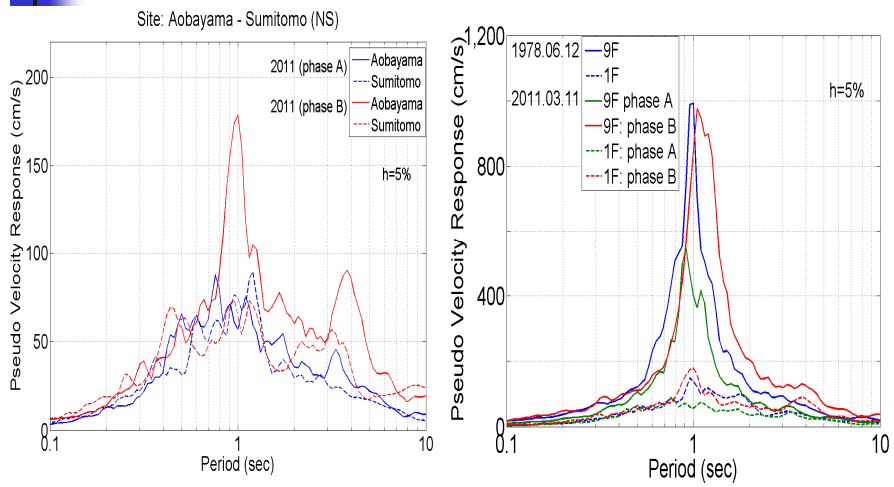
Sendai Station

Oroshimachi

8 and 9 story buildings' damage due to resonance to the amplified ground motion at around 1s period content



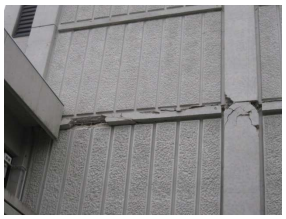
Different spectral amplification for the two phases and resonance of 9-story building at Aobayama hill (NS direction)

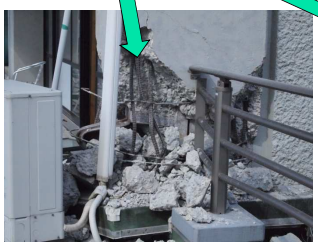


Amplification is two times in the 2nd phase, but not amplified in the 1st phase.

Damage to 9 story SRC building at Aobayama campus, Tohoku Univ. (THU Building)

Research Building of Department of C.E & A-B.S Eng.





4 corner external columns are damaged heavily at their bottom

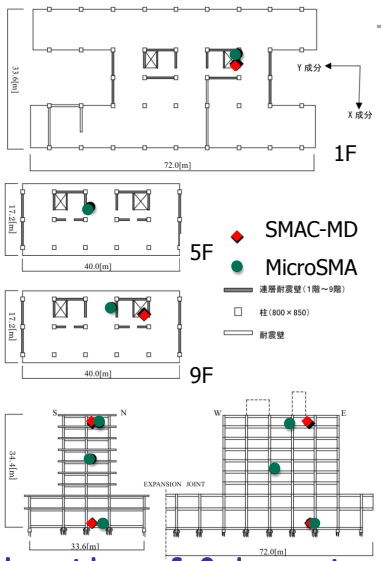
1969 Completion
1978 Earthquake
2000 retrofit
2005 Earthquake
2008 Earthquake

Ground motion at around 1s period content is amplified two times

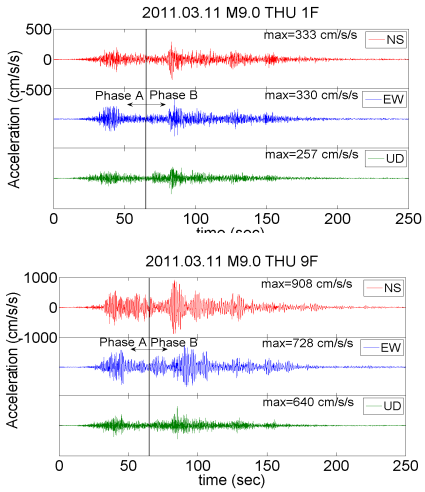
Strong motion records shows:

Max Acc. of NS-comp.
1F: 333cm/s/s
9F: 908cm/s/s

Earthquake Observations at THU Building

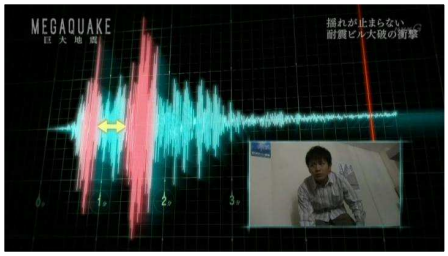


Location of Seismometers in plan and section



Observed Acc. Waveforms (SMAC-MD)

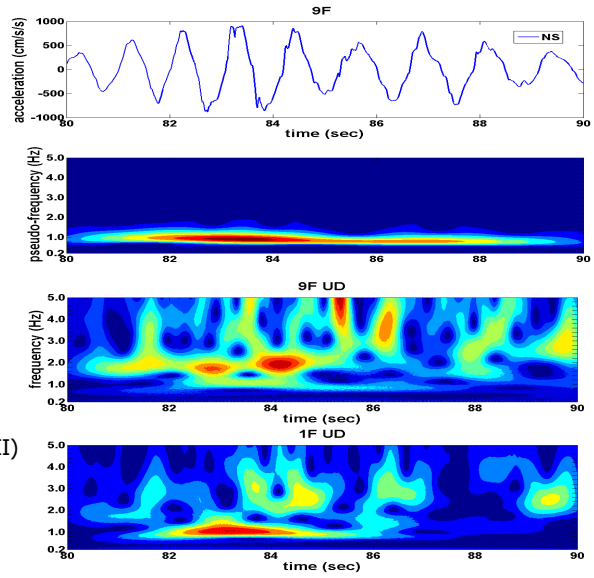
Reproduction of the shaking at 9th fl. by 3D shaking table



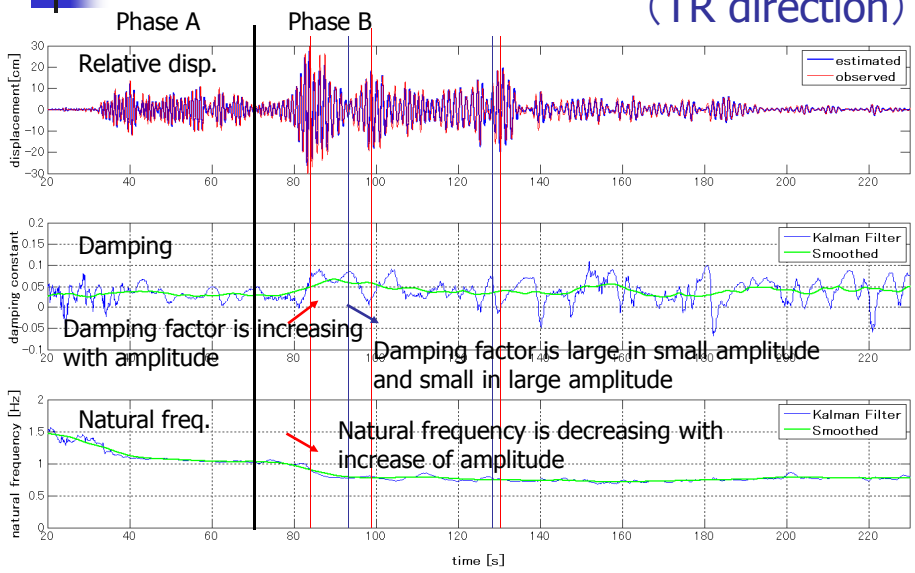
Investigation of dynamic behavior ～Occurrence of Partial uplifting

Explanation of partial uplifting (from NHK-Special MEGAQUAKE III)

Confirmation of higher harmonics by wavelet analysis



System identification of time dependent dynamic characteristics using Kalman Filter (TR direction)



Research building for Department of Information and Intelligent Systems 8-story SRC building

Damage of Pent House

Drop of elevator cargo

Damage of experimental equipments

Damage of research building and equipments,
but no injured person! Drop of elevator!
Earthquake Early Warning! + property of shaking?

Specific Building Damage

- Pile foundation damage
- Ceiling board drop damage
- Housing land damage

Damage of pile-foundation building condominium building in Takasago

Inclination angle:1/100

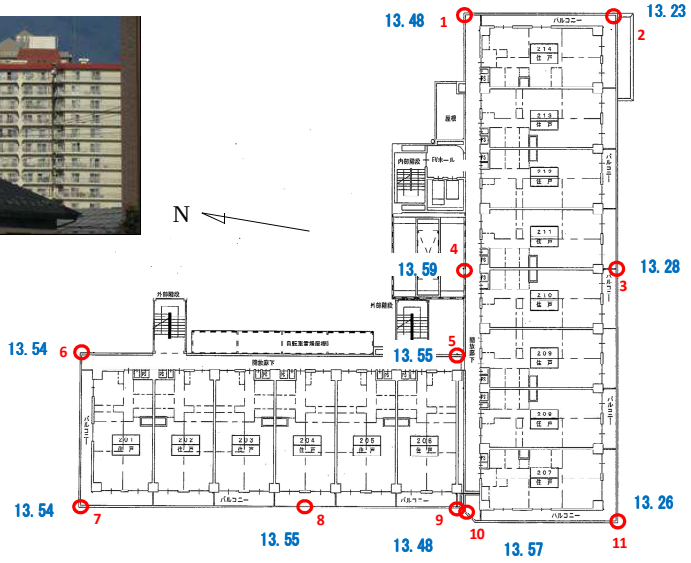
Inclined 14 story SRC building

Completion: 1976
Damaged building during 1978 eq.
Pile length: 24m

Inclination angle:1/56

Increased to 1/45 due to after shock

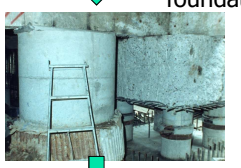
Measurement of subsidence of the damaged building

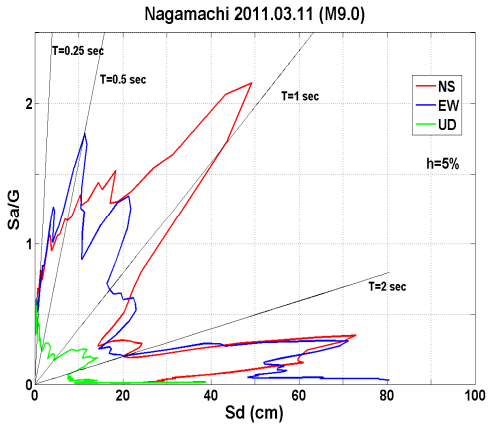


The Reinforced Building was not damaged even if severe shaking

(Sa-Sd Spectra)

Reinforcement of foundation





Ground Motion characteristics in Nagamachi

Reinforcement leads to no structural damage against very strong ground motion with 1s period content !

Inclined RC building in Oroshimachi Damage of piles

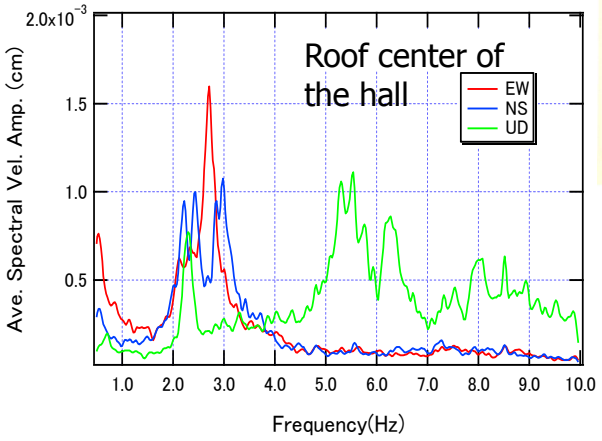
Construction year: 1983
Pile length:26m

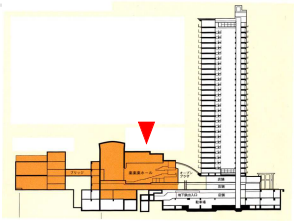
Fall of suspension type ceiling board of large span building

Multi-purpose hall in Sendai
Suspension type ceiling board; 60% during main shock and the remaining 40% during after shock

Hall of Taihaku-ku Culture Center, Sendai

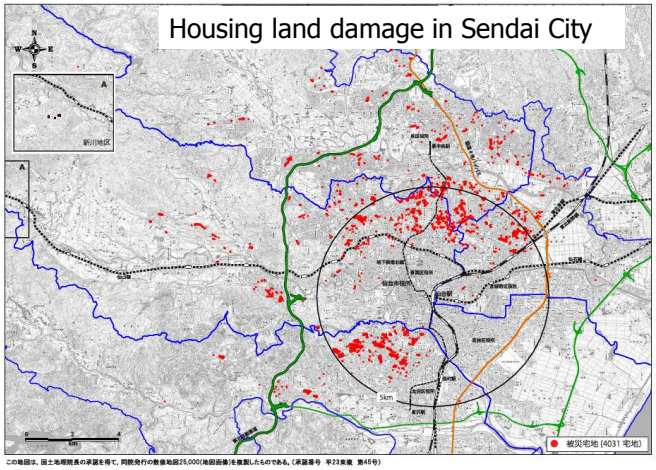
Microtremor measurement at the building with ceiling board damage





* Vertical motion is largely induced.
* Building stiffness is relatively high and is escaped from resonance to 1s period content

Damage of Housing Lands in Sendai City（5,000 points at 9 housing lands)



Common points:

- Valley-filled housing land
- High water level
- Long-duration ground motion

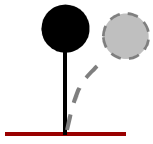
Housing damage by filled soil failure

Nishi-Seikaen, Aoba-ku, Sendai

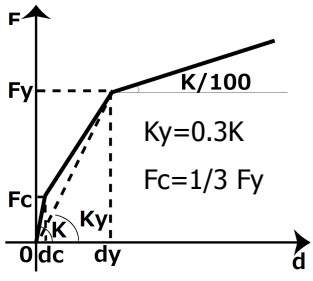
Oritate, Aoba-ku, Sendai

Impact of geological structure on non-linear response of building structures

Building model



Non-linear SDOF system

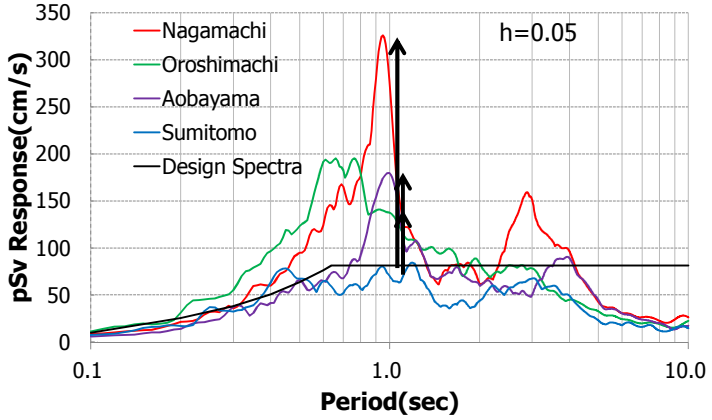


Hysteresis model: Takeda model

- ✓Objective 4 sites
- ✓Objective buildings: 6-, 9-,15-, and 20-story standard RC building with 3.4m story height
- ✓Fundamental period T1(s)
  T1=0.02H H：Building height(m)

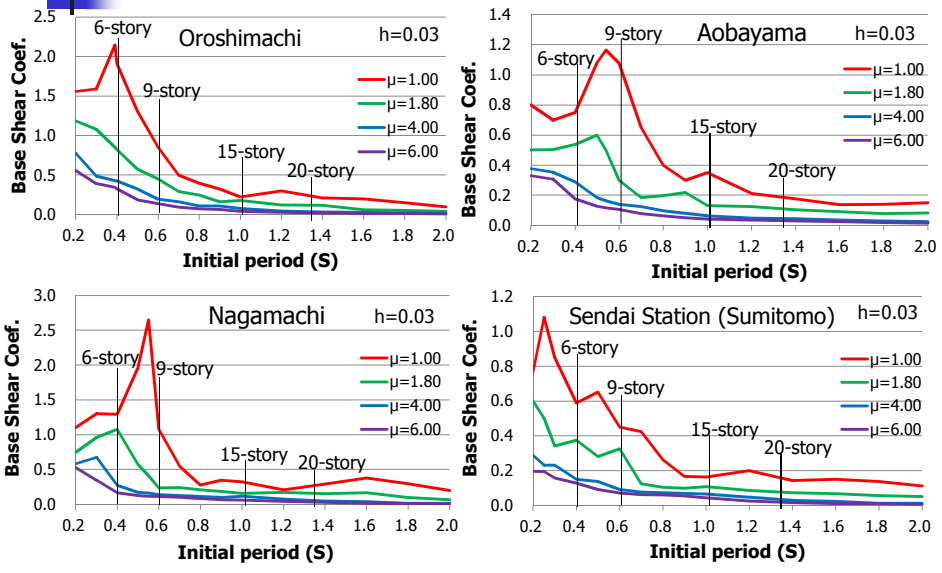
Num. Story	1st period(s)
6	0.41
9	0.61
15	1.02
20	1.36

Pseudo Velocity (NS-component)



At around 1s period content, Nagamachi site is amplified by 4 times compared to Sendai station (Sumitomo), Aobayama site is 2 times, and Oroshimachi site is 1.8 times.

Strength Demand Spectra



Necessary base-shear demand at Nagamachi, Aobayama, and Oroshimachi compared to Sendai Station (Engineering bedrock)

μ =1.0	Sendai Station	Nagamachi	Aobayama	Oroshi-machi
6-story	1.0	2.1	1.3	3.0
9-story	1.0	2.4	2.4	1.6
15-story	1.0	1.8	2.0	1.4
20-story	1.0	2.0	1.1	1.6

μ =4.0	Sendai Station	Nagamachi	Aobayama	Oroshi-machi
6-story	1.0	1.7	1.9	2.9
9-story	1.0	1.6	1.6	2.3
15-story	1.0	1.4	1.0	1.3
20-story	1.0	1.5	1.3	1.0

μ =1.8	Sendai Station	Nagamachi	Aobayama	Oroshi-machi
6-story	1.0	3.0	1.5	2.3
9-story	1.0	0.8	0.9	1.4
15-story	1.0	1.4	1.2	1.5
20-story	1.0	2.9	1.5	1.8

μ =6.0	Sendai Station	Nagamachi	Aobayama	Oroshi-machi
6-story	1.0	1.3	1.4	2.6
9-story	1.0	1.6	1.5	2.0
15-story	1.0	1.5	1.0	1.0
20-story	1.0	1.7	1.4	1.2

About 3 times differences for 6 to 9-story buildings and
About 2 times differences for 15 to 20-story buildings

Concluding Remarks

- Due to progress of Seismic Building Code and seismic retrofit promotion, amount of structural damage of building structures was decreased
- Remarkable damage difference due to soil conditions
  * Retrofit building on the hill was severely damaged
  * Necessity of appropriate seismic microzoning
- Relation of observed high-acceleration records and structural damage
  * appropriate ground motion index for structural damage
- Effect of number of displacement cycles due to ground motions of main shock with long-duration and many after shocks

Concluding Remarks (continued)

- Effect of non-stationary ground motion comprising multi-phases on non-linear structural response
  * Moving resonance
- Appropriate remaining seismic resistant capacity of the damaged building due to past earthquake
  * Necessity of damage inspection for pile- foundation building
- Effectiveness of reinforced part but the surrounding remaining part
- Well balanced seismic design
  * foundation and super-structure
  * Structural element and non-structural elements, equipments

Necessity of holistic and well-balanced earthquake counter measures

✓ Necessity of holistic earthquake counter measures in recent too much sectionalized society !

✓ Collaboration beyond each academic field
・・・Synergic combination

✓ Local governments' collaboration, international collaboration・・・'cooperation and collaboration'

Dr. Torahiko Terada
(1878-1935)

'Father of disaster prevention'
'Contemporary Leonardo da Vinci'

Essay 'Tensai to Kokubou (Natural disaster and national defense) '(1934)
- ✓ Evolution of human society=differentiation
- ✓ Destruction of one small portion may cause the whole destruction
- ✓ Lower animals have ability to regenerate!