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Some features of strong ground motions and structural damage during the 2011 Mw 9.0 Off the Pacific Coast of Tohoku Earthquake

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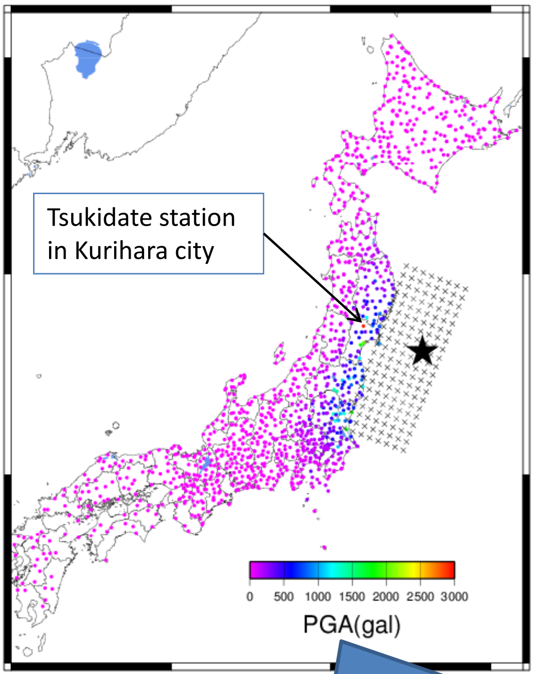
Today's Topics

1. Some features of structural damage during the 11 March 2011 Mw 9.0 Tohoku earthquake
2. Short-period source model estimated from strong motion data
3. Period-dependence of rupture processes
4. Recipe of predicting strong ground motions for subduction megathrust earthquakes
5. Estimation of strong ground motions at damaged sites during 2013 Tohoku earthquake for fragility curves of buildings

Outline of the 2011 Tohoku Earthquake

2011/03/11, 14:46. Depth=24km, Interplate

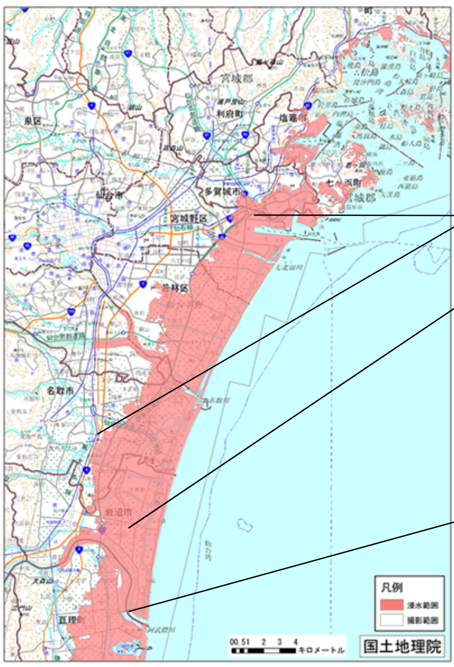


Peak **G**round **A**cceleration

- Mw=9.0 (the largest earthquake recorded in Japan)
- JMA seismic intensity=7. Largest PGA approached 2933 gal (Tsukidate, Kurihara city of Miyagi Prefecture)
- Focal region was very large (450km X 200km)
- Damage area was wide (20 prefectures, Tokyo, Osaka)
- Over 1200 strong ground motion records were observed all over Japan.

Buildings damage data (FDMA, 2012)

Total collapse | Partial collapse | Partial damage



Geospacial Information Authority

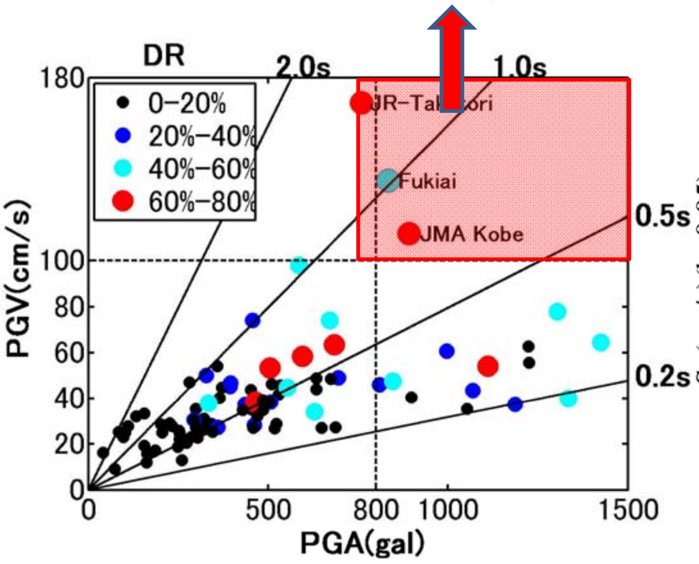
平 成 2 4 年
消 防 庁

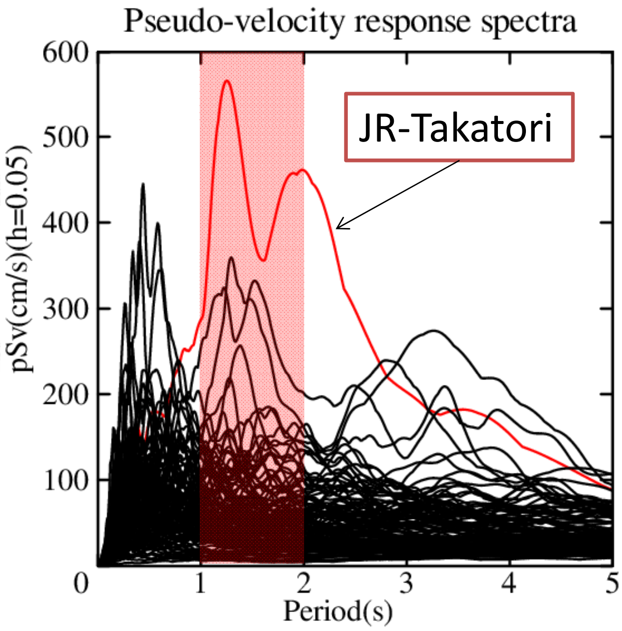
March 11, 2012

都道府県名	市町村	住家被害 全壊	住家被害 半壊	住家被害 一部破損	住家被害 床上浸水	住家被害 床下浸水	非住家被害 公共建物	非住家被害 その他	火災
		棟	棟	棟	棟	棟	棟	棟	件
宮城県	名取市	2,801	1,129	10,061	3,403	1,179	2,805		12
	角田市	13	158	996			15		
	多賀城市	1,730	3,605	5,804	不明	不明	不明		15
	岩沼市	688	1,477	2,734	1,540	114	3,126		1
	登米市	198	1,612	3,292		3	761		5
	栗原市	57	368	4,554		3	2	46	
	東松島市	5,470	5,542	3,522	不明	不明	989		1
	大崎市	584	2,376	8,937			71	257	3
	蔵王町	16	142	1,095			681		
	七ヶ宿町			9					
	大河原町	10	142	1,298			111		
	村田町	9	114	636			252		1
	柴田町	13	188	1,623			不明		
	川崎町		14	425			3		
	丸森町	1	36	512			22		1
	亘理町	2,298	1,055	2,251	797	275	468		3
	山元町	2,333	1,095	1,142	不明	不明	339		
	松島町	220	1,580	1,526	191	90	97		2
	七ヶ浜町	673	635	2,537	不明	不明	824		
	利府町	57	906	3,501	45	14	不明		
	大和町	41	262	2,709			不明		
	大郷町	50	274	749			203		
	富谷町	16	523	5,185			不明		1

Period characteristics of ground motions

Kobe Earthquake, 1995

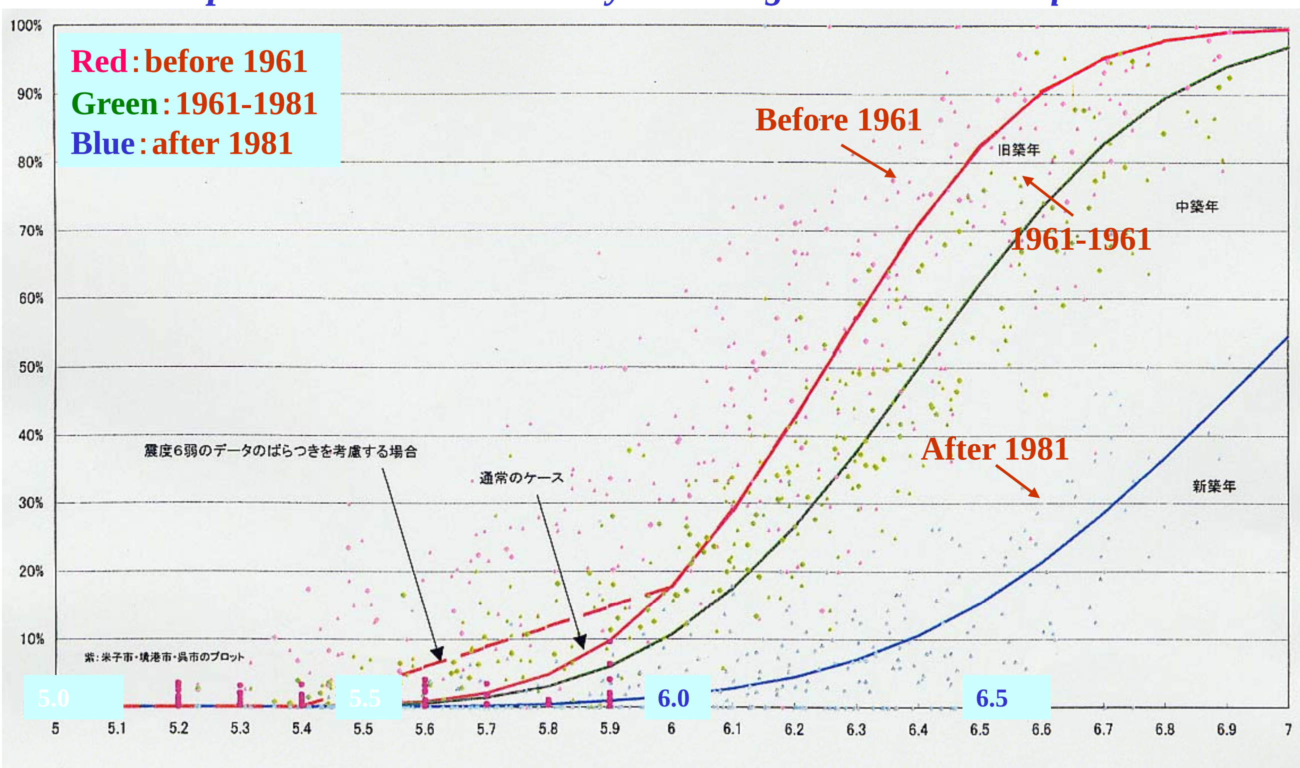




$T_{eq}=2\pi PGV/PGA$

Relationship between Total-Collapse Ratio and Seismic Intensity

Dependence on construction year during 1995 Kobe earthquake



After investigation in Nishinomiya during 1995 Kobe earthquake (CDMC,2004)

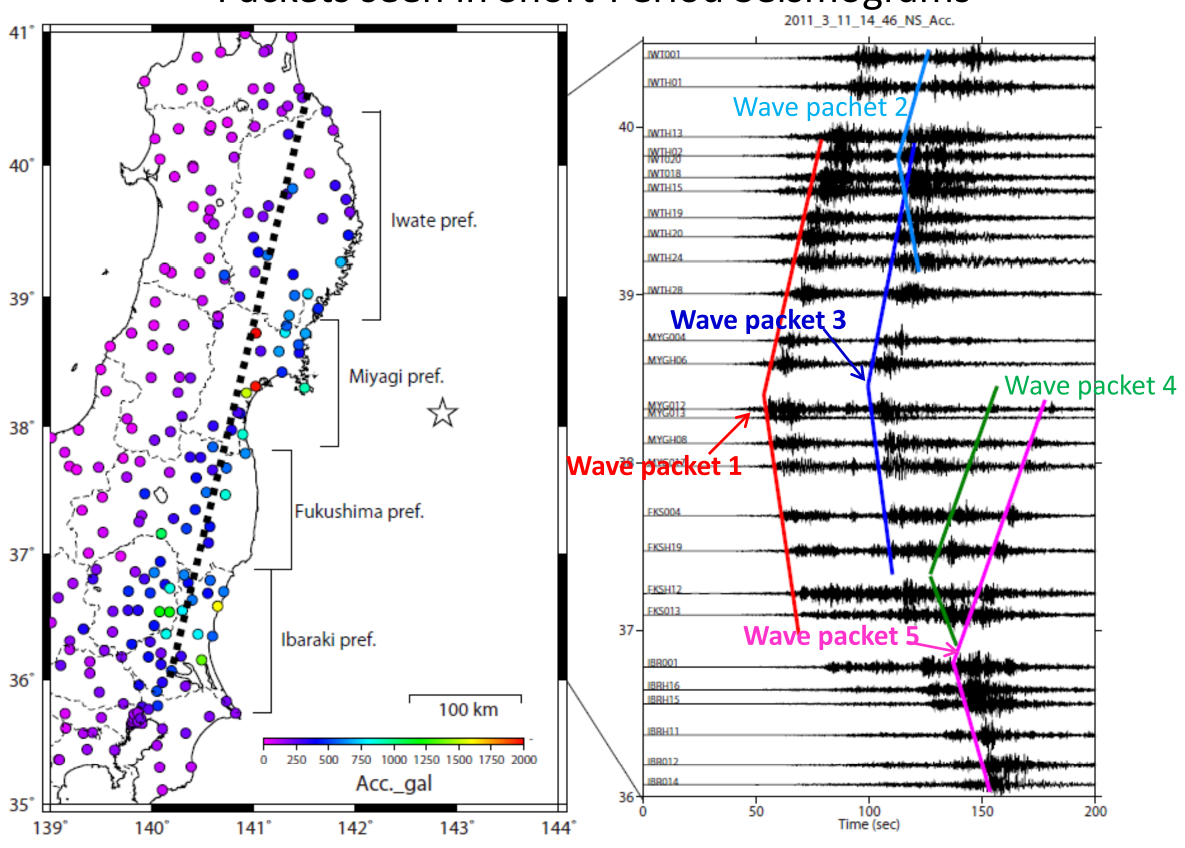
2. Short-period source model estimated from strong motion data

■ Five distinctive wavapackets were detected on strong motion sesimograms at stations near the source fault.

■ The arrival azimuths of those wavepackets were estimated using the semblance analysis in several small arrays.

■The locations of strong motion generation areas (SMGAs) are coincident with the origins of those wavepackets.

Re-estimation of Locations of SMGAs from Semblance Analysis of Wave-Packets seen in Short-Period Seismograms



After Irikura and Kurahashi (2011)

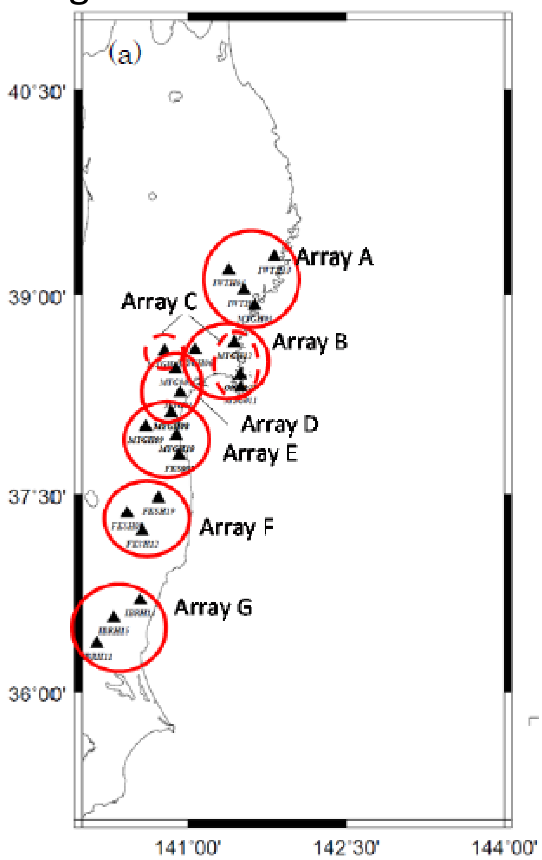
Simulation of Strong Ground Motions during the 2011 Tohoku Earthquake Using the Empirical Green's Function Method

■ Strong Motion Generation Areas are relocated using the semblance analysis of the wave-packets in small arrays.

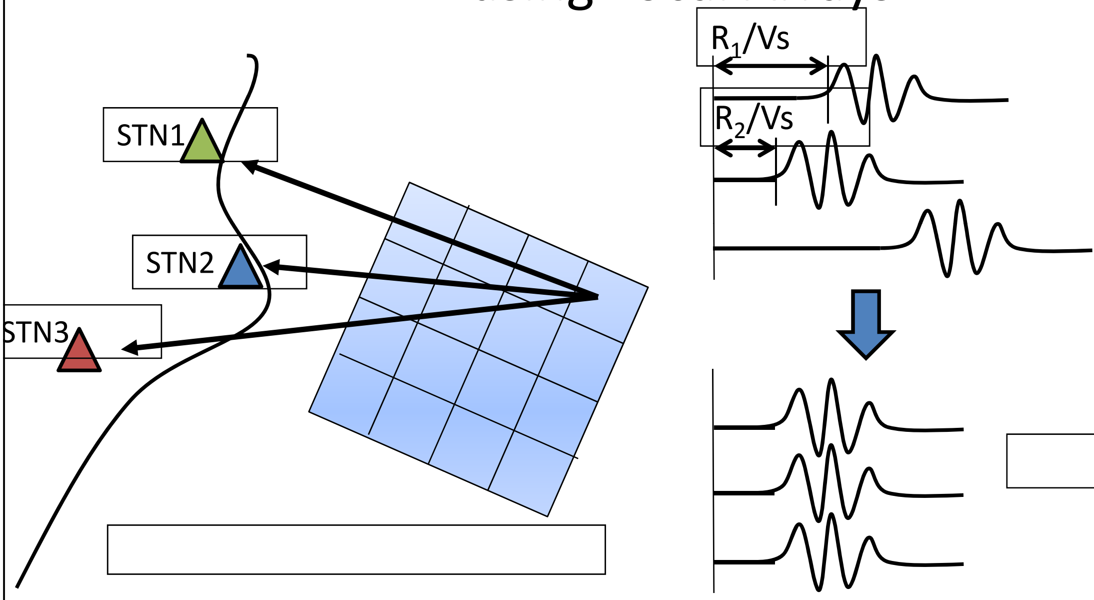
■ The observed data from medium-sized earthquakes occurring near each strong motion generation area are adopted as the empirical Green's functions.

■ Strong motion records of the 2005 Miyagi-Oki earthquake (Mw 7.2) are used as the empirical Green's functions for SMGA1 (WP1) and SPGA3 (WP2).

Mini-arrays (A, B, C, D, E, F, and G)
for estimating arrival azimuths of wave-packets

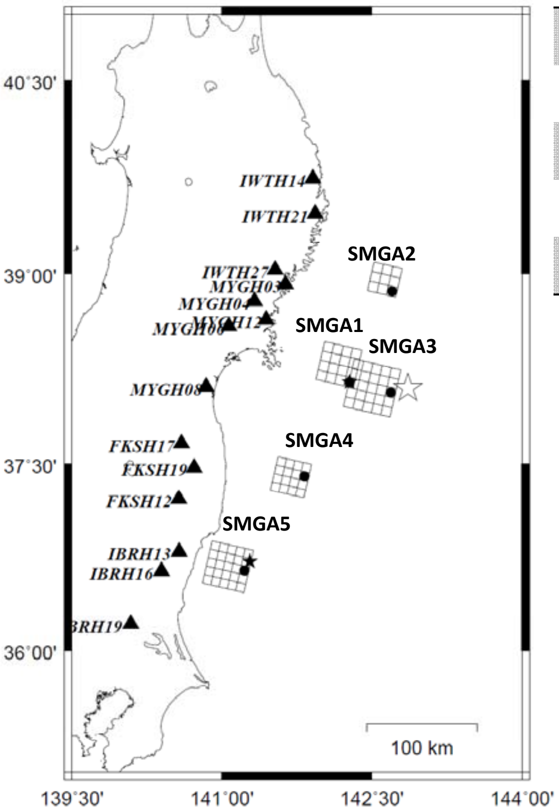


Semblance Analysis for Wave Packets using Local Arrays

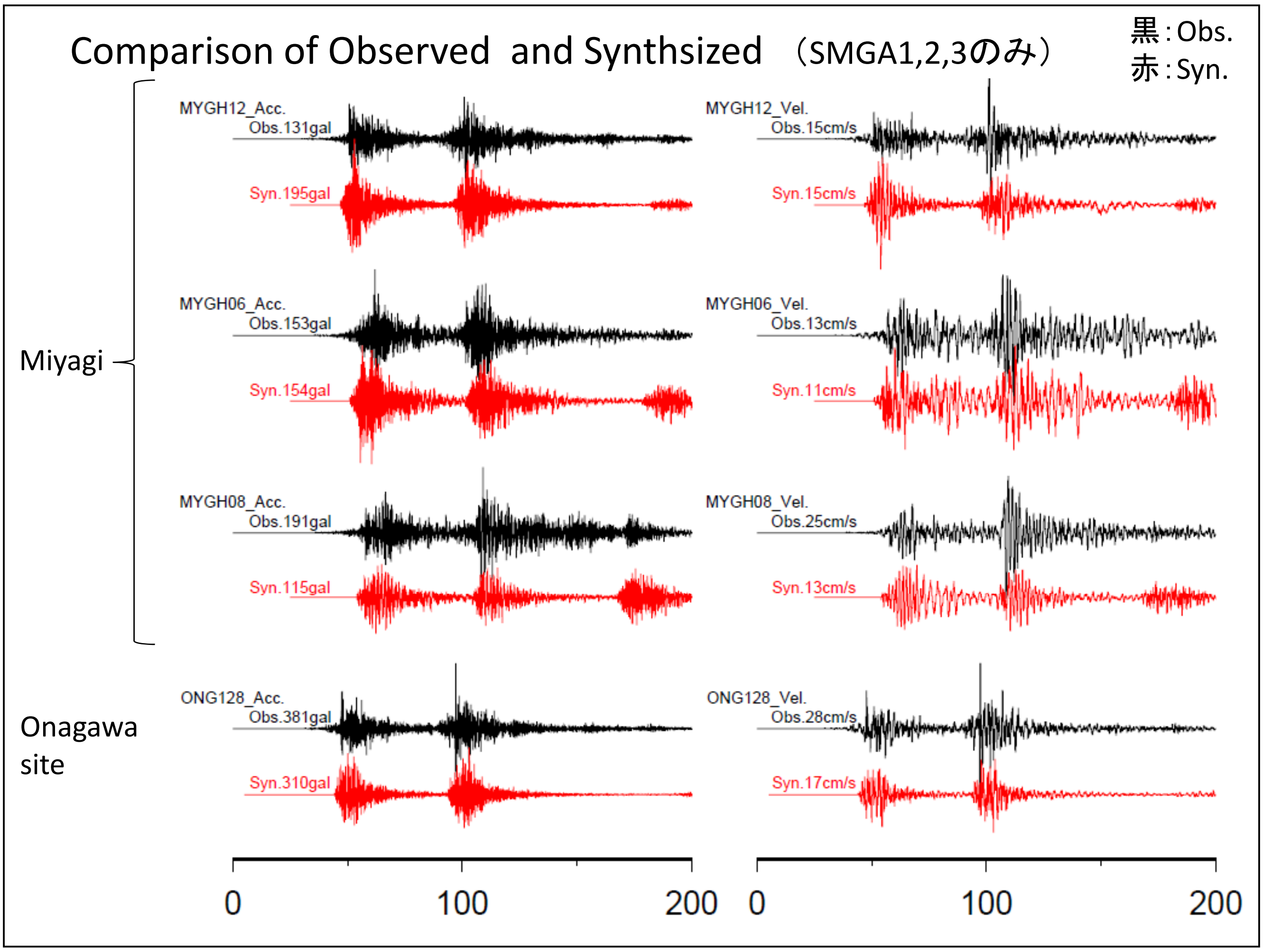


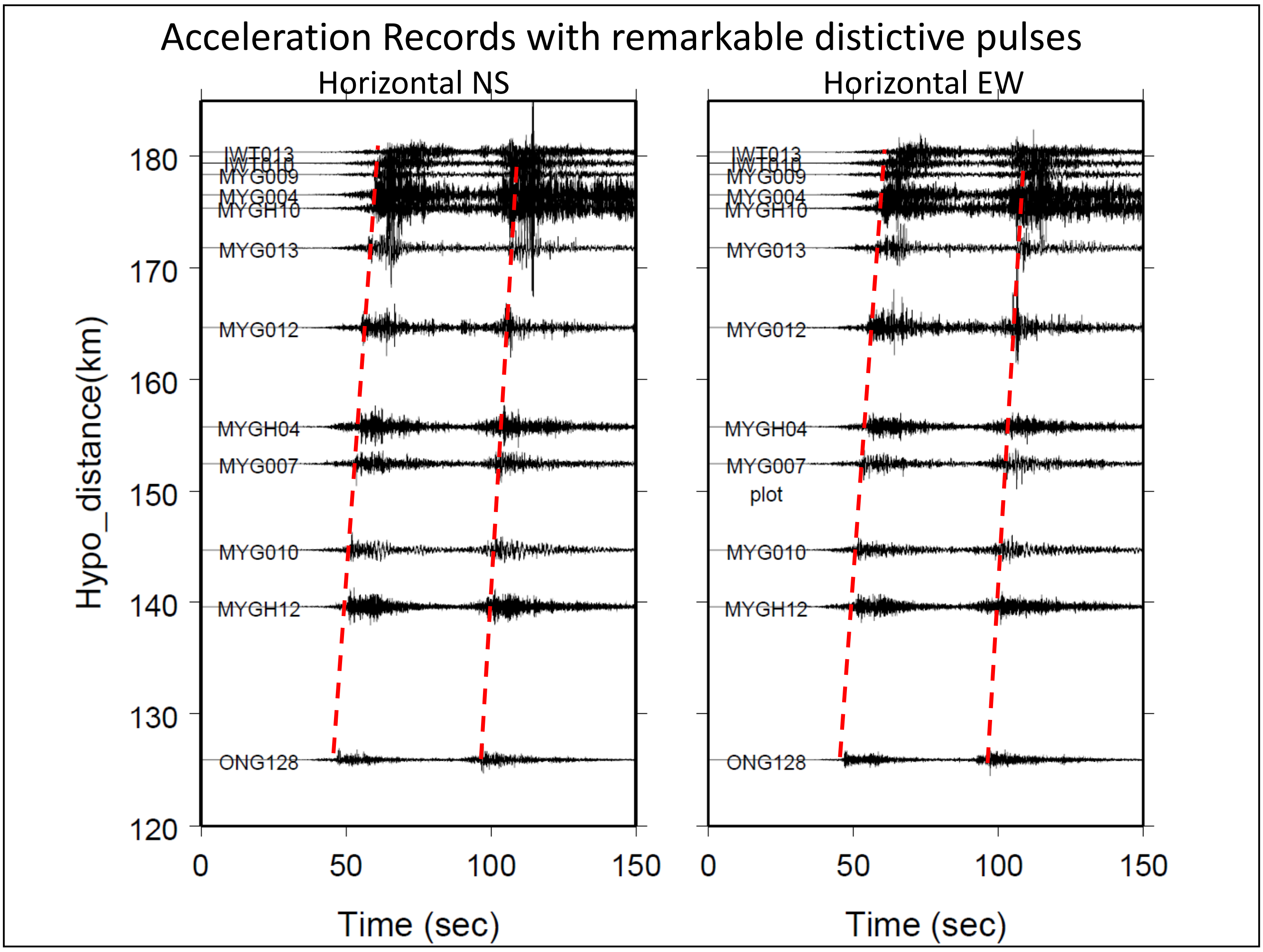
$$S_e(s) = \frac{1}{N} \frac{\sum_{k=1}^{M} \left[\sum_{i=1}^{N} u(x_i, t_k + s \cdot x_i) \right]^2}{\sum_{k=1}^{M} \sum_{i=1}^{N} u(x_i, t_k)^2}$$

Revised Model

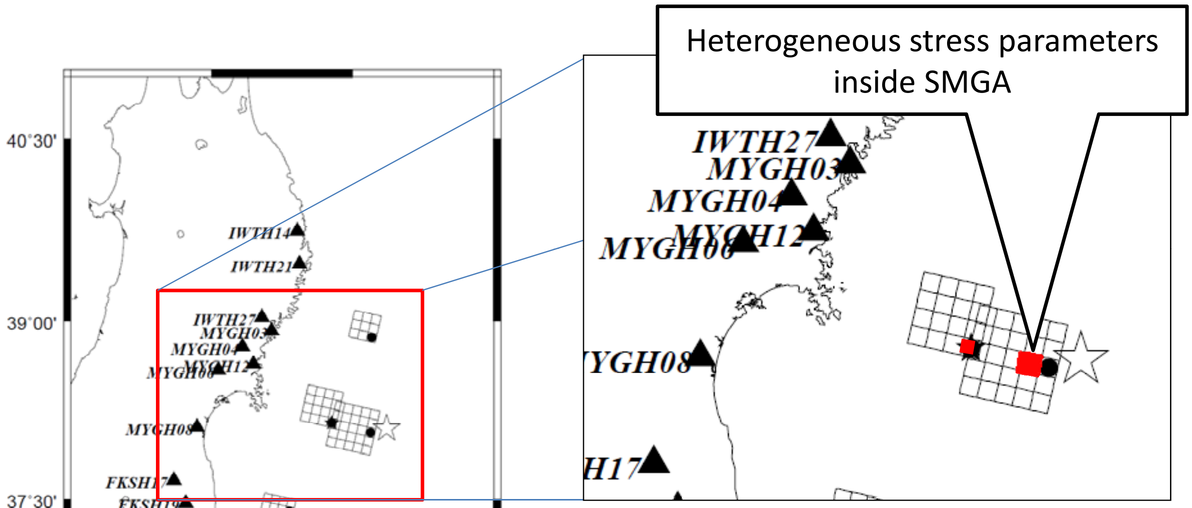


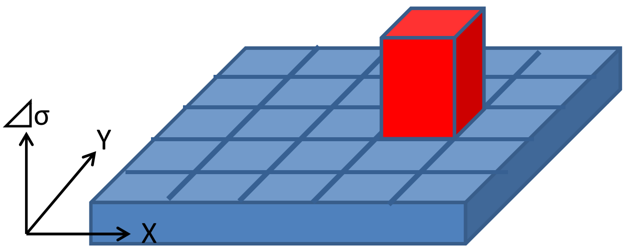
	L,W	Mo	Stress drop
SMGA1	34 × 34	2.68E+20	16
SMGA2	23.1 × 23.1	1.41E+20	20
SMGA3	42.5 × 42.5	6.54E+20	20
SMGA4	25.5 × 25.5	1.24E+20	25.2
SMGA5	38.5 × 38.5	5.75E+20	25.2


Comparison of Observed and Synthsized （SMGA1,2,3のみ）
黒:Obs.
赤:Syn.
Miyagi
Onagawa site
MYGH12_Acc.
Obs.131gal
Syn.195gal
MYGH12_Vel.
Obs.15cm/s
Syn.15cm/s
MYGH06_Acc.
Obs.153gal
Syn.154gal
MYGH06_Vel.
Obs.13cm/s
Syn.11cm/s
MYGH08_Acc.
Obs.191gal
Syn.115gal
MYGH08_Vel.
Obs.25cm/s
Syn.13cm/s
ONG128_Acc.
Obs.381gal
Syn.310gal
ONG128_Vel.
Obs.28cm/s
Syn.17cm/s
0
100
200


Acceleration Records with remarkable distictive pulses
Horizontal NS
Horizontal EW
Hypo_distance(km)
IWT013
MYG009
MYG004
MYGH10
MYG013
MYG012
MYGH04
MYG007
plot
MYG010
MYGH12
ONG128
Time (sec)

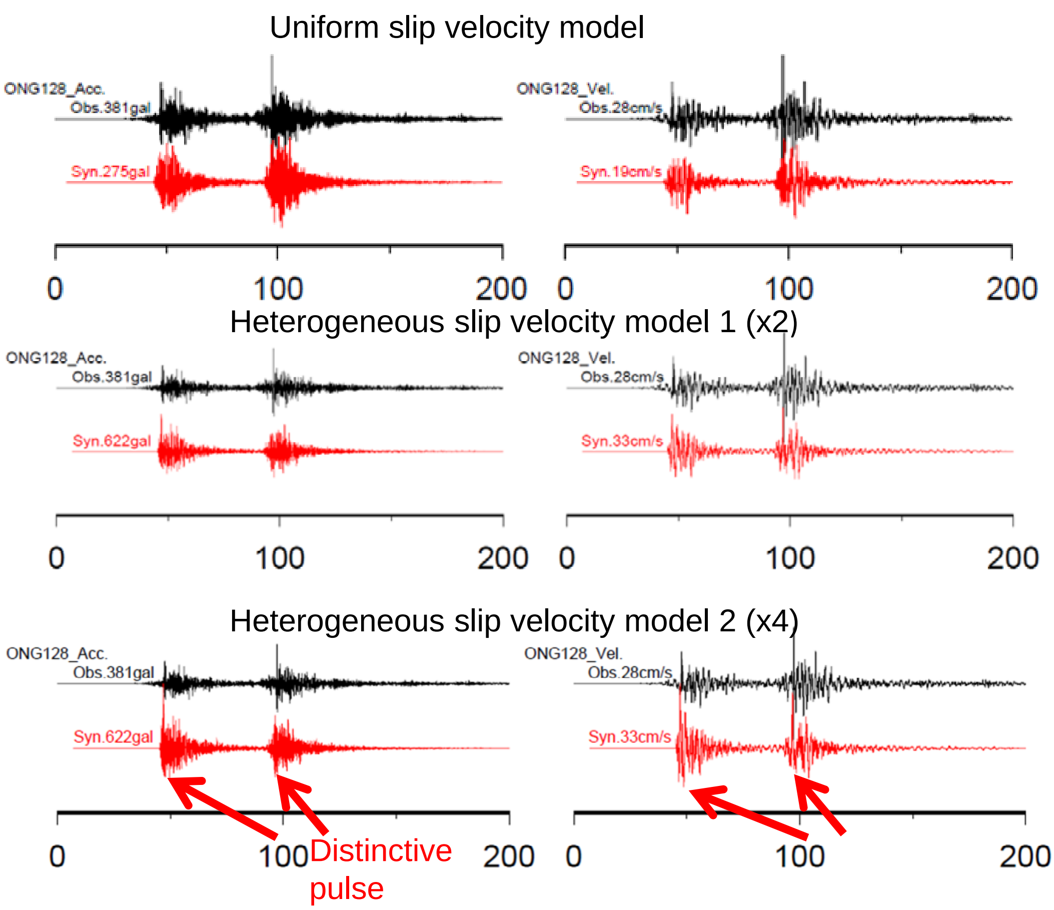
Heterogeneity of stress parameters inside SMGA





Matsushima and Kawase (2006)

Uniform slip velocity model



Period range of ground motions generated from the SMGAs

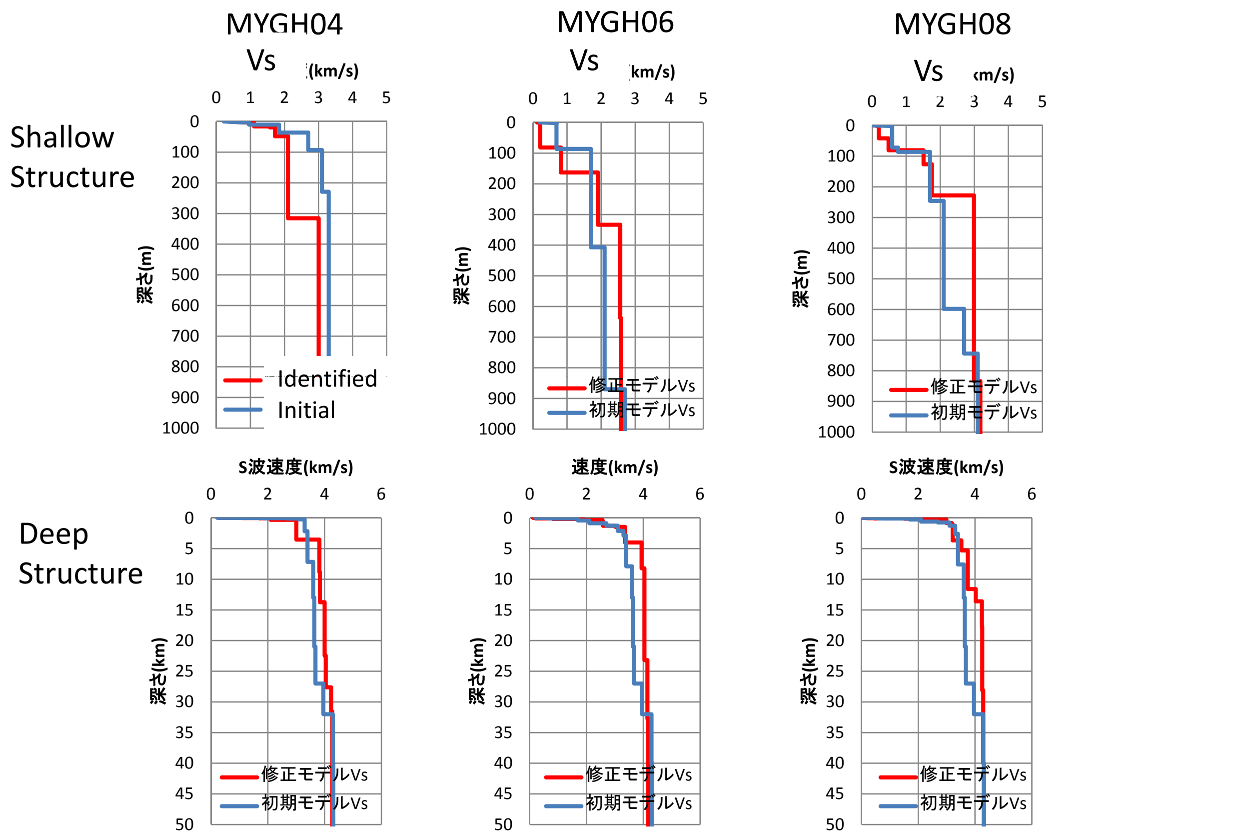
- Longer-period motions from the Strong Motion Generation Areas (SMGAs) are estimated using numerical Green’s functions: the Discrete Wavenumber method (Bouchon, 1981) and the Reflection/Transmission coefficient matrix method (Kennet, 1983) using a stratified medium.

- Effective period range of ground motions generated from the SMGAs are confirmed by comparing simulated motions with observed motions.

- Verification of the fault parameters are made, mainly inner fault parameters of Strong Motion Generation Areas (SMGAs) estimated using the empirical Green’s function method

Velocity Structure Models (Vs)

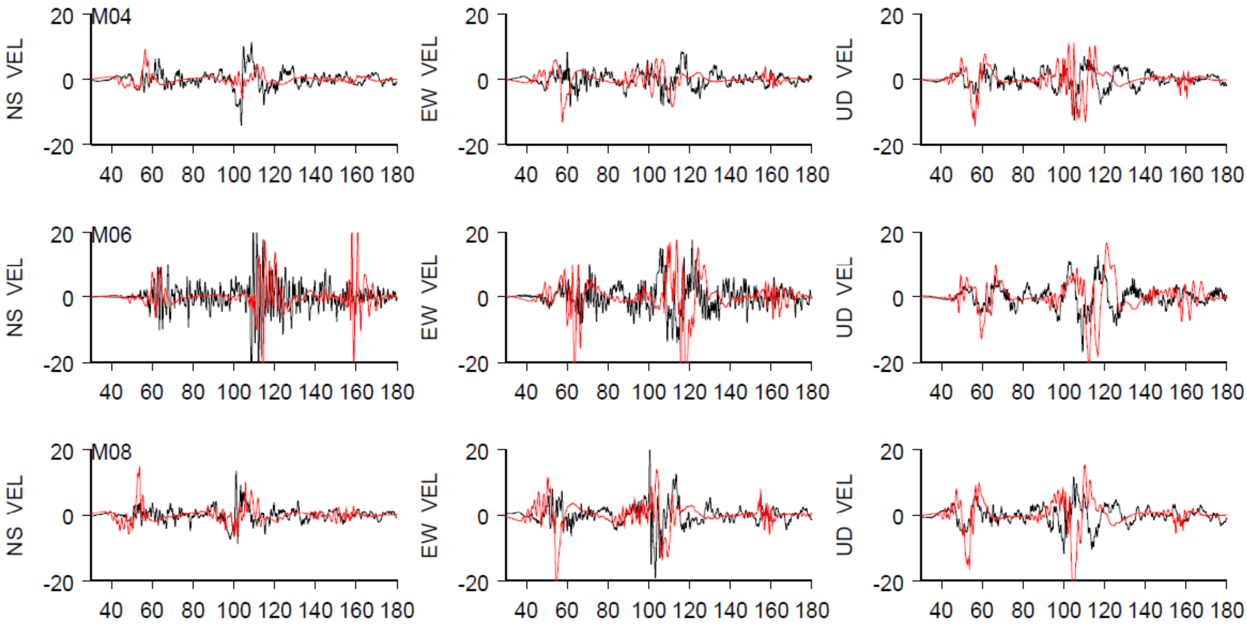
1-D velocity structures from stations to source are modeled comparing synthetic motions with observed ones from small events.



Comparison between Observed and Synthetic Motions in Miyagi Prefecture

Frequency Range
0.05 – 1.0 Hz

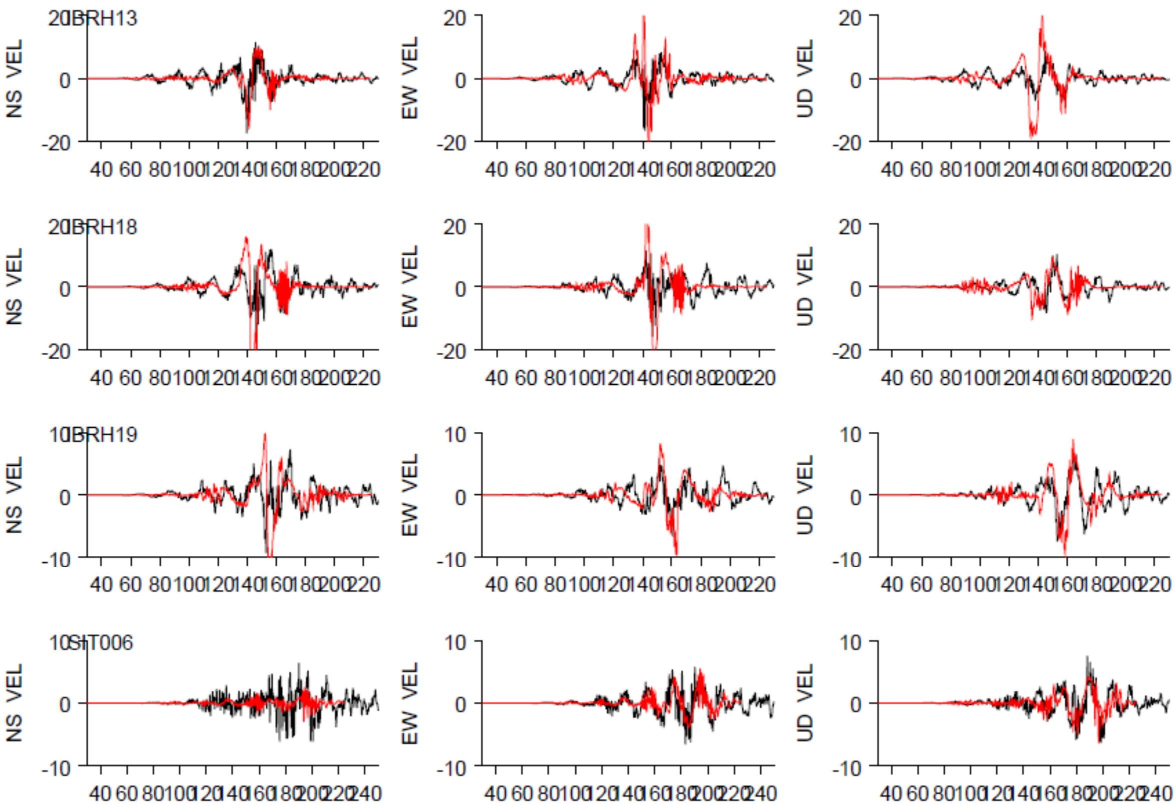
Observed
Synthetic



Comparison between Observed and Synthetic Motions in Kanto Region

Frequency Range
0.05 - 1Hz

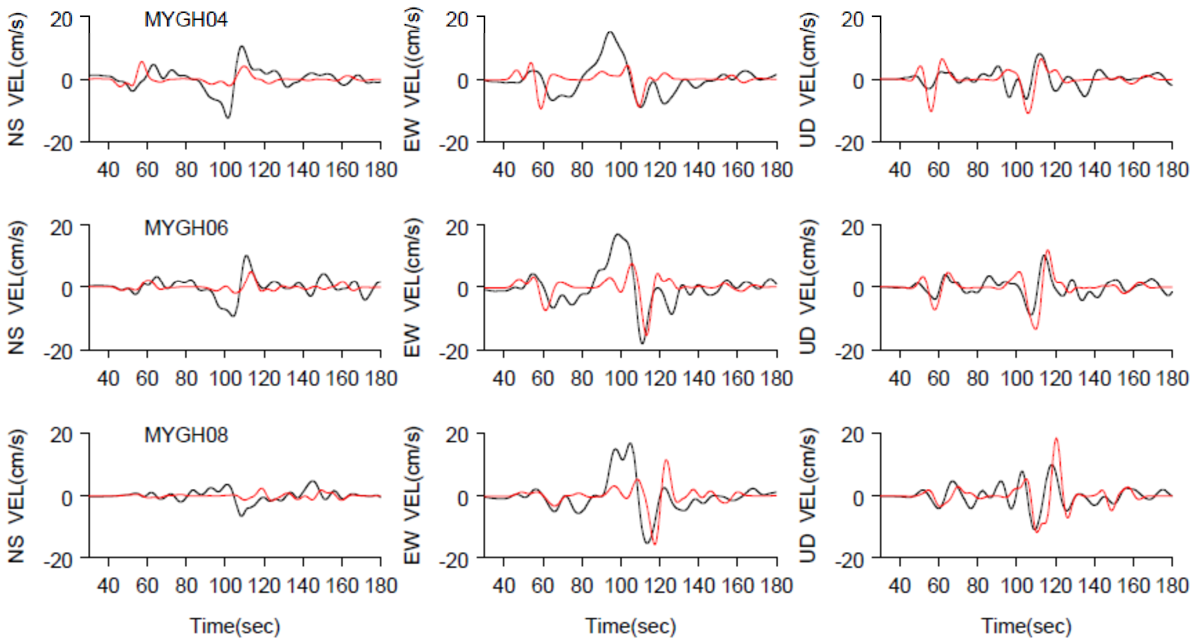
Observed
Calculated



Comparison between Observed and Synthetic Motions in Miyagi Prefecture

Frequency Range
0.01 - 0.1Hz

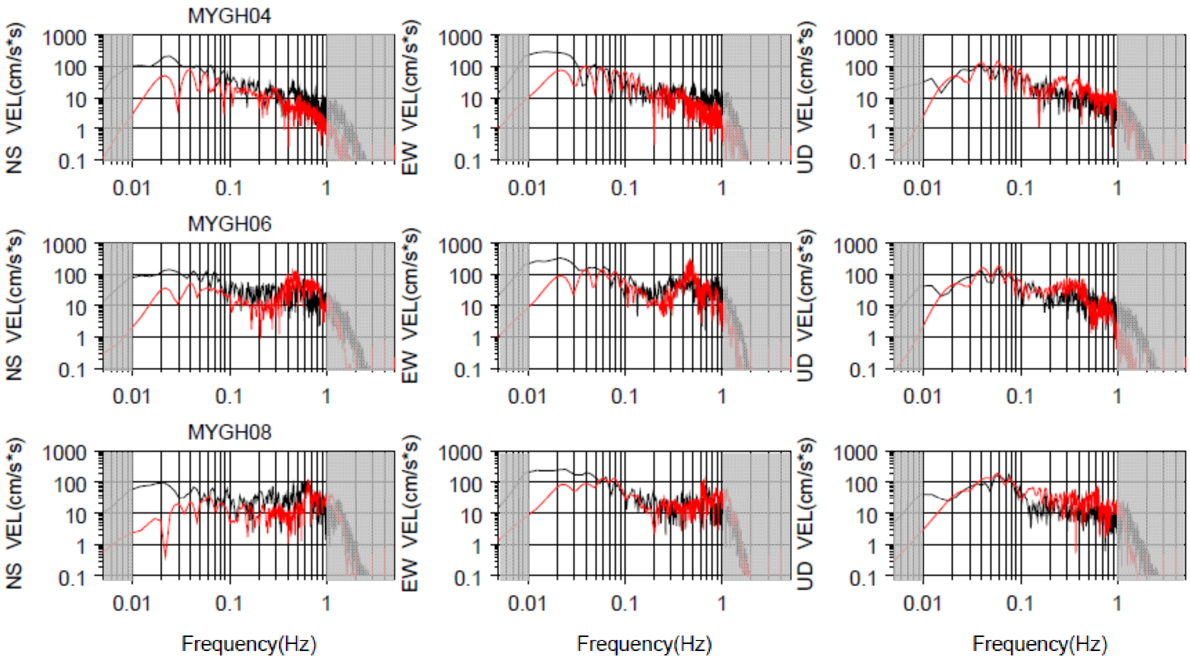
Observed
Calculated



Comparison between Observed and Synthetic Motions in Miyagi Prefecture

Frequency Range
0.01-1Hz

Observed
Synthetic



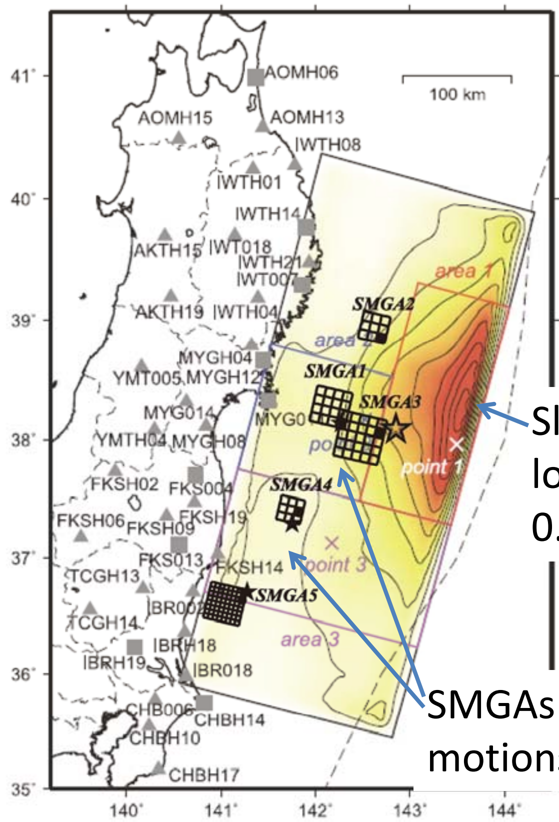
3. Period-dependence of rupture processes

– Comparison of short-period source model and long-period source models inverted long-period strong motion data, tsunami waveforms, geodetic data -

■ Short-period source models using backprojection of teleseismic short-period P-waves (e.g. Ishii, 2011; Honda et al., 2011)

■ Long-period source models inverted from tsunami data (Fujii et al., 2012) , geodetic data (Iinuma et al., 2012) and joint data (Yokota et al.)

Comparison between slip distribution using long-period motions (Suzuki et al, 2011) and SMGAs in this study

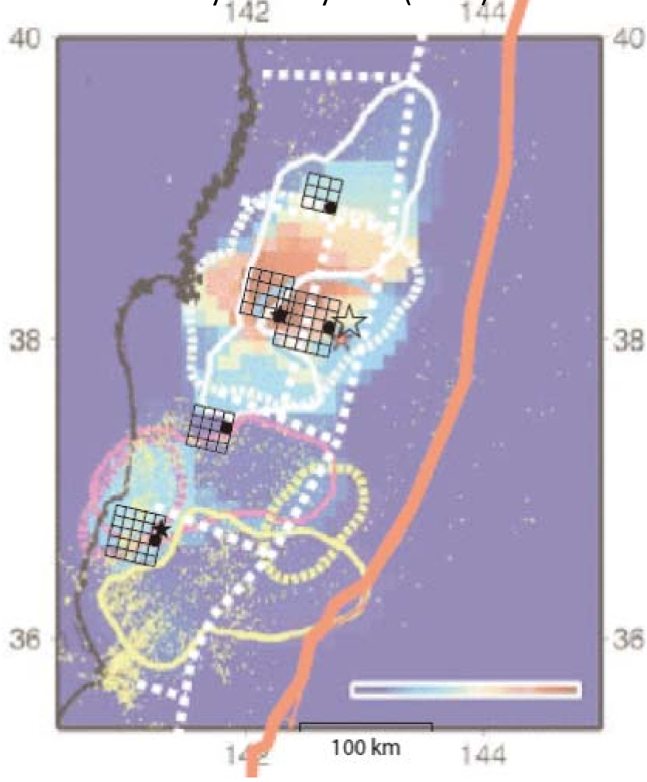


Slip distribution inverted from long-period motions filtered 0.01-125Hz (100 – 8 s)

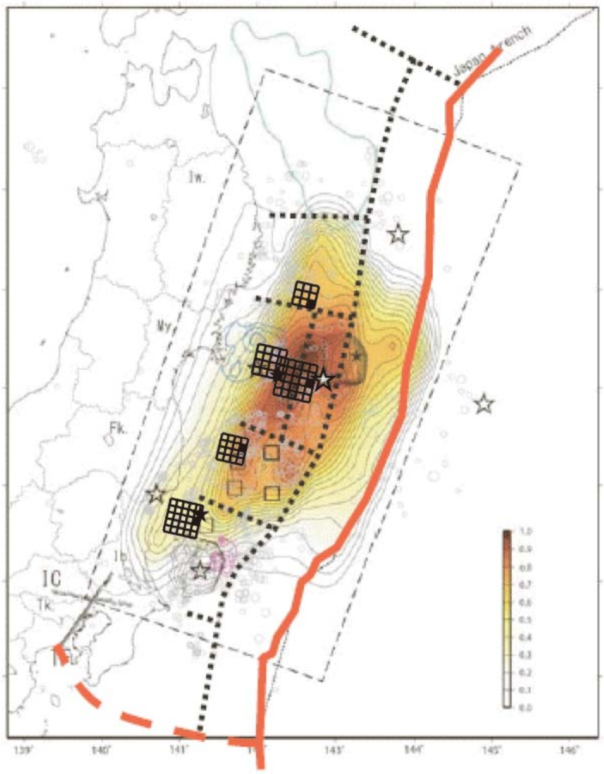
SMGAs estimated from short-period motions filtered 0.15-10Hz (6.6 – 0.1 s)

Comparison of Short-Period Source Model in This Study with Short-Period Released Energy by the back-projevtion method

US Array Data by Ishii (2011)

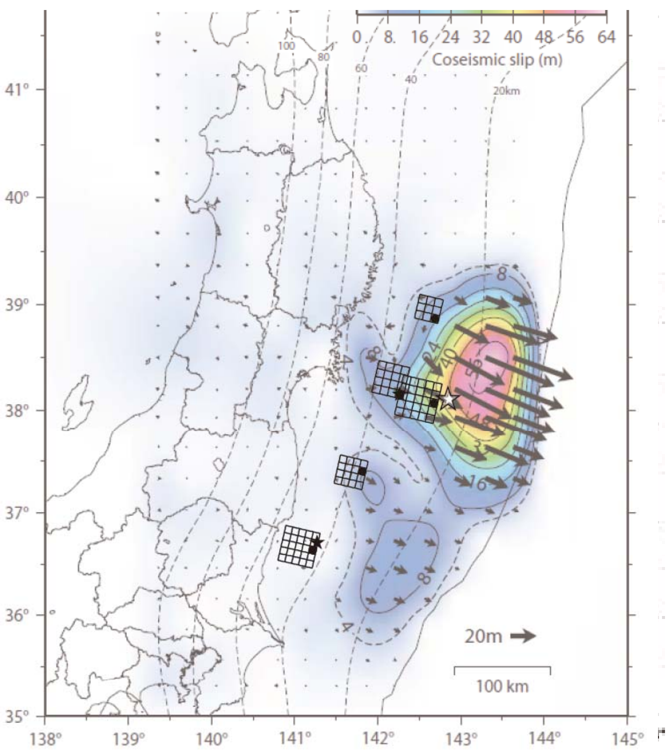


Kanto Array Data by Hoda et al, (2011)



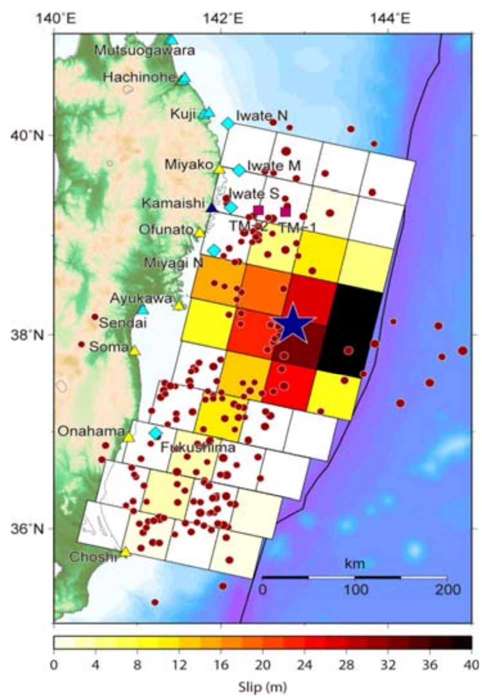
Slip Distribution of the 2011 Tohoku Earthquake

DPS data including inland and off-shore observation



Geographical Institute (2011)

Tsunami Waveform Data



Fujii and Satake (2011)

4. Recipe of predicting strong ground motions for subduction-zone megathrust earthquakes

■ Rupture process of subduction-zone megathrust earthquakes show period-dependence.

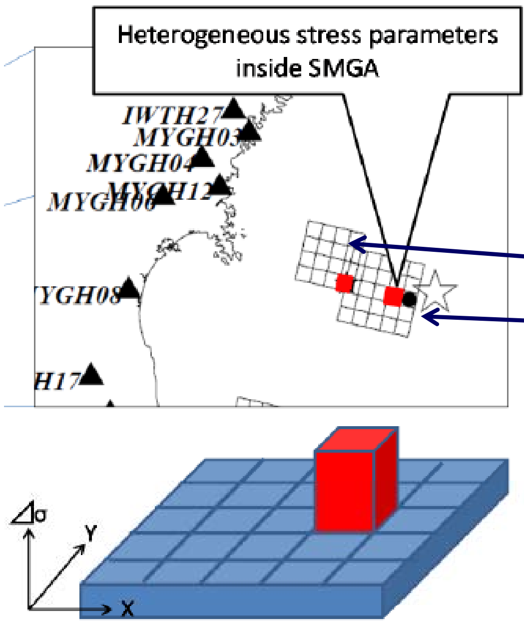
■ New source image for period-dependent source process is expressed as multi-step heterogeneous-source-model.

■ Strong ground motions of engineering interest in the period-range from 0.1 to 10 sec are estimated using the basic characteristic source model with outer-fault parameters and inner fault parameters, that is, just one step heterogeneity source model.

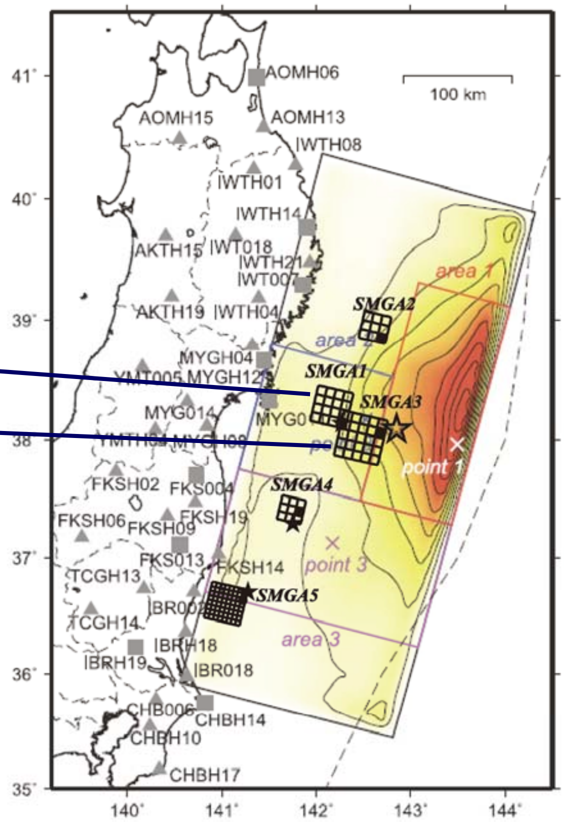
Multi-Step Heterogeneous Source Model - 1

Second step: Heterogeneity model for very short-periods 0.05 – 0.2 s

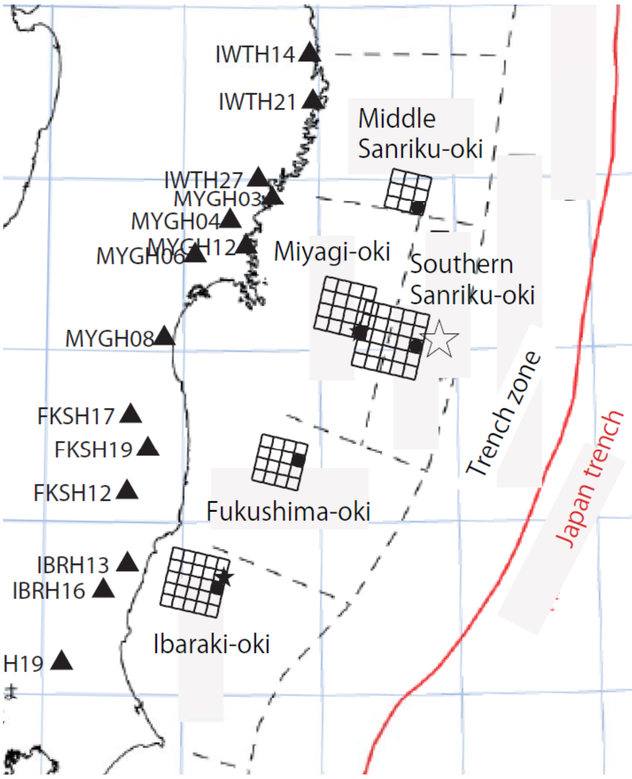
First step: Heterogeneity model for short periods 0.1 – 20 s

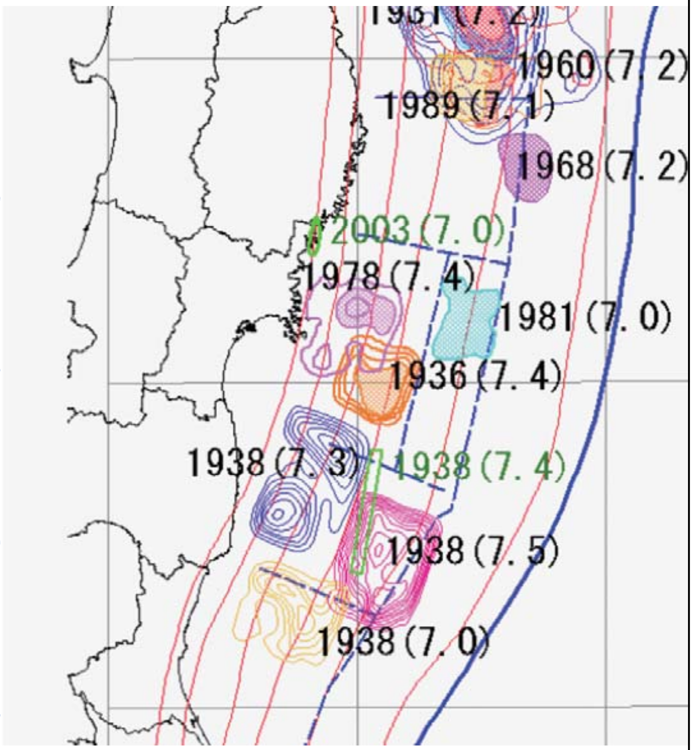


Matsushima and Kawase (2006)



Comparison between SMGAs in this study and source locations of past earthquakes off the Pacific coast of Tohoku



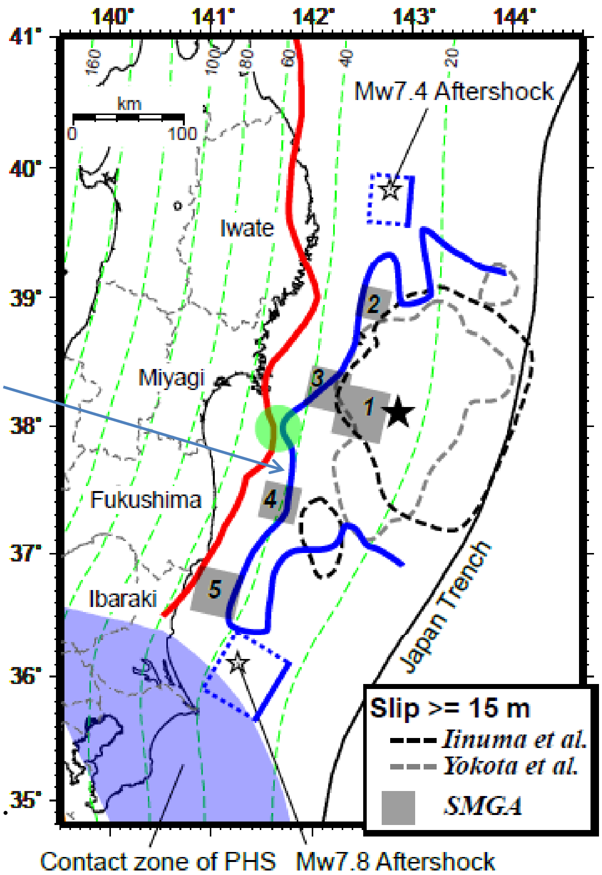


Heterogeneous Model for Broad-band Motions from 0.1 to 10 s

The SMGAs are located along outer edge of the large slip delineated based on the seismicity rate (Kato and Igarashi, 2012)

Brue solid line is the outer edge of the large-slip zone of the mainshock, ~35 km.

Stress parameter (σ_a) on strong motion generation areas is given as ~ 26 MPa from the empirical relations for mega-thrust earthquakes.



5. Estimation of strong ground motions at damaged sites during 2013 Tohoku earthquake

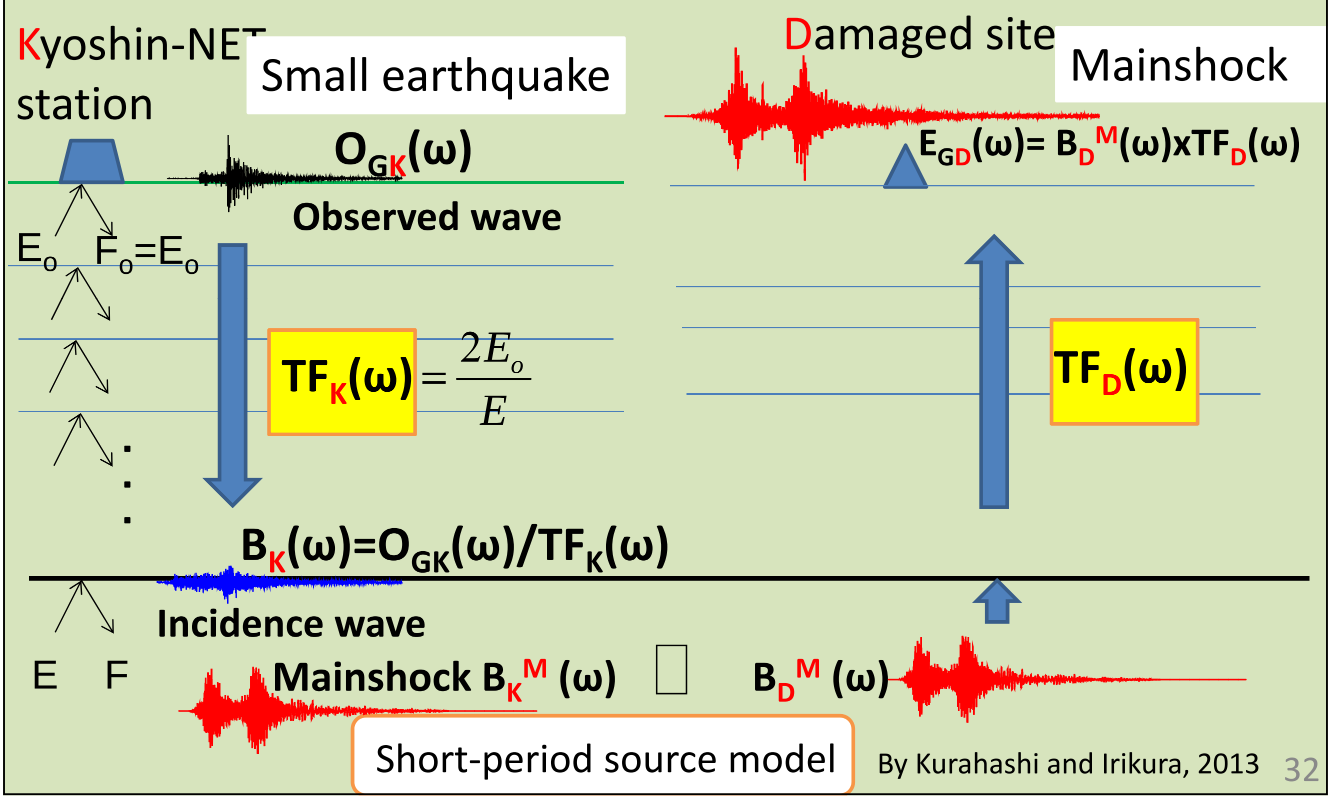
■ Velocity structures beneath strong motion stations are identified by use of earthquake H/V spectral ratios (Kawase et al., 2011).

■ Empirical Green’s functions at bedrock beneath the strong motion station are calculated with observed ground motions on the surface from small events and transfer functions between surface and bedrock.

■ The transfer functions at damaged sites are calculated from velocity structures beneath the sites using microtremor H/V (Arai and Tokimatsu, 2000; Sanchez-Sesma, et al, 2011).

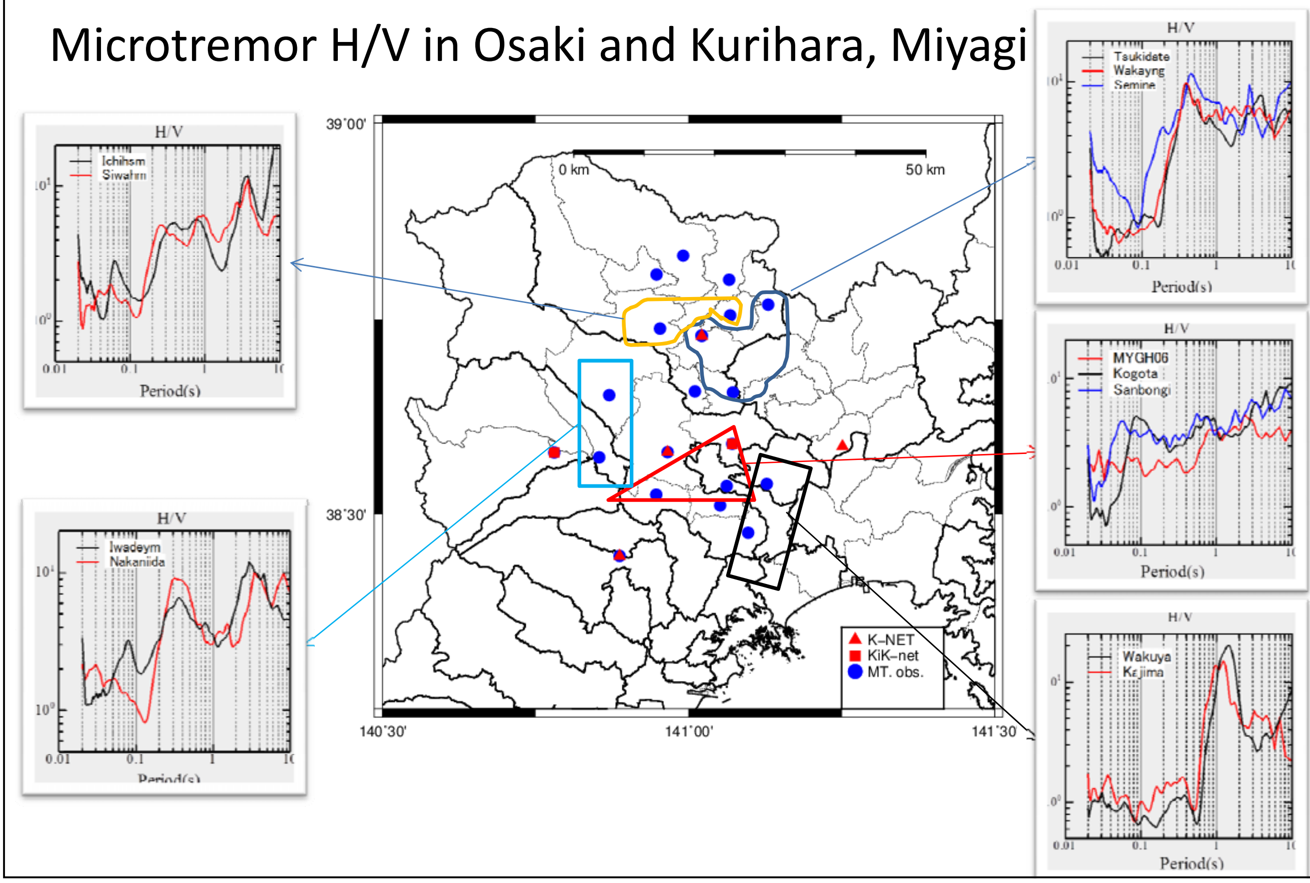
■ Ground motions at damaged sites during the mainshock are calculated the transfer functions, the empirical Green’s functions and the short-period source model of the mainshock.

3.1 Methodology of estimating ground motions at damaged sites during the mainshock



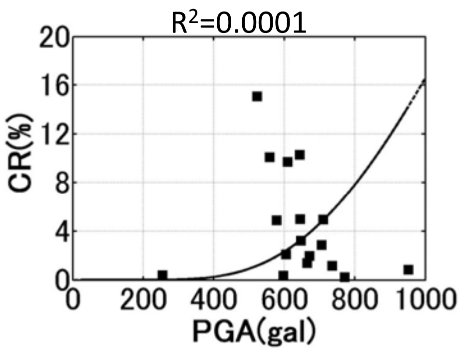
Microtremor measurement

Microtremor H/V in Osaki and Kurihara, Miyagi

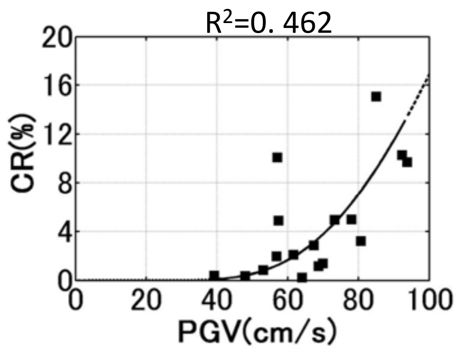


4.3 Fragility curves in subdistricts

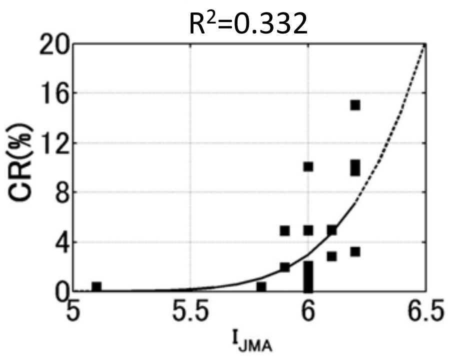
CR: Collapse ratio



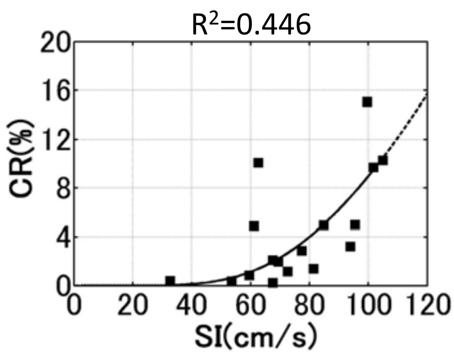
Peak **G**round **A**cceleration



Peak **G**round **V**elocity



JMA Seismic **I**ntensity



Spectral **I**ntensity

Summary

1. The 2011Tohoku earthquake (Mw 9.0) produced devastating tsunami waves, causing 16,500 fatalities (including missing) and serious damage to nearby Fukushima nuclear power plants. Extremely strong and long-duration ground motions were also generated, but damage due to strong ground motions were relatively less.

2. Short-period source model of the 2011 Tohoku earthquake (Mw 9.0) have five distinctive strong –motion-generation areas (SMGAs) fitting observed acceleration and velocity records to synthetic motions. The SMGAs are located west of the hypocenter and along the down-dip edge of the source fault. Synthetic motions from the SMGAs match well with observed motions in the period-range from 0.1 to 10 sec.

3. Period-dependence of rupture process was found, that is large slips in shallow zones of the source fault near the trench west of the hypocenter and short-period generation in deeper zones west of the hypocenter.

4. Strong ground motions of engineering interest in the period-range from 0.1 to 10 sec are estimated using the characteristic source model with outer-fault parameters and inner fault parameters as the recipe of predicting strong ground motions for subduction earthquakes.

Basic Characterized Source Model

Step 1: Heterogeneous Model for Broad-band Motions from 0.1 to 10 sec

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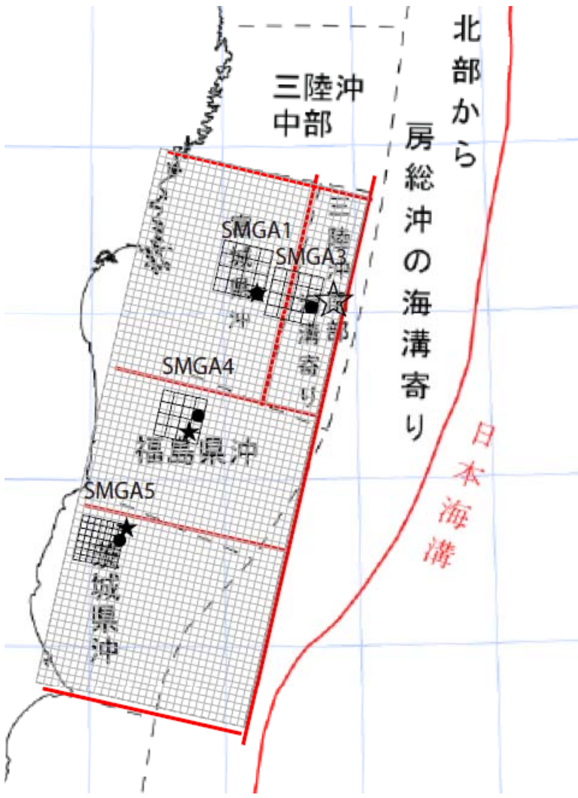
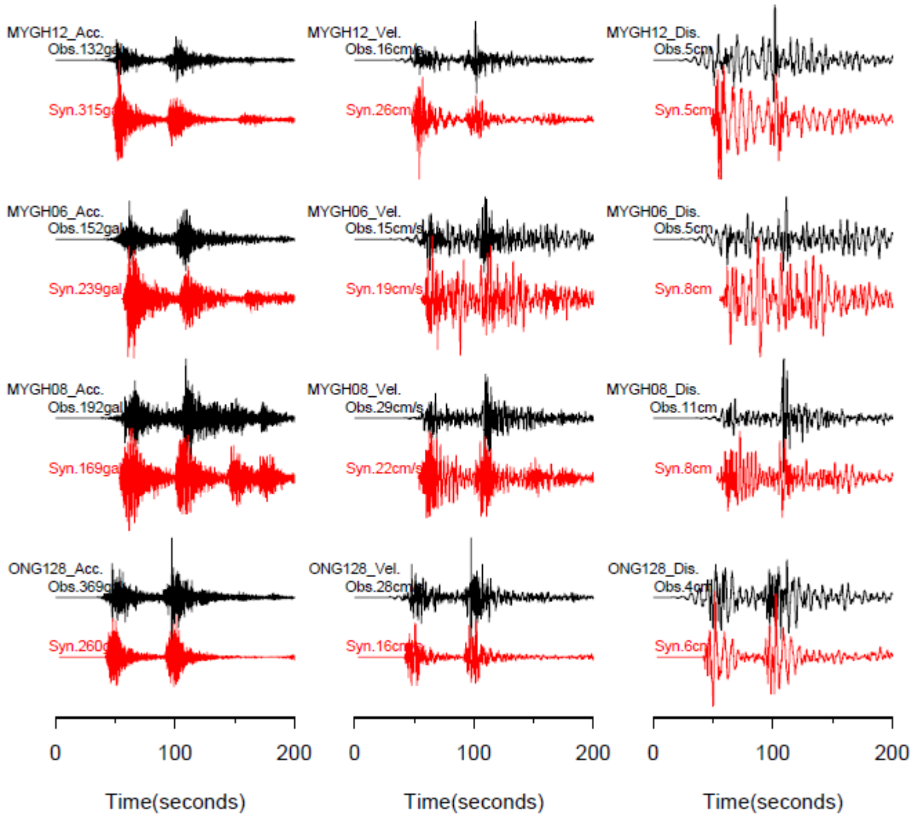


Comparison between observed and synthetic waveforms in the region near the source fault (Miyagi and Onagawa)



Comparison of Seismic Intensity between Observed and Synthetics