Technical Workshop on the Accident of TEPCO's Fukushima Dai-ichi NPS

Earthquake Ground Motion Observed at the NPS and the Ground Motion Simulation

July 24, 2012

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TOKYO ELECTRIC POWER COMPANY

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2. Ground motion simulation at the sites
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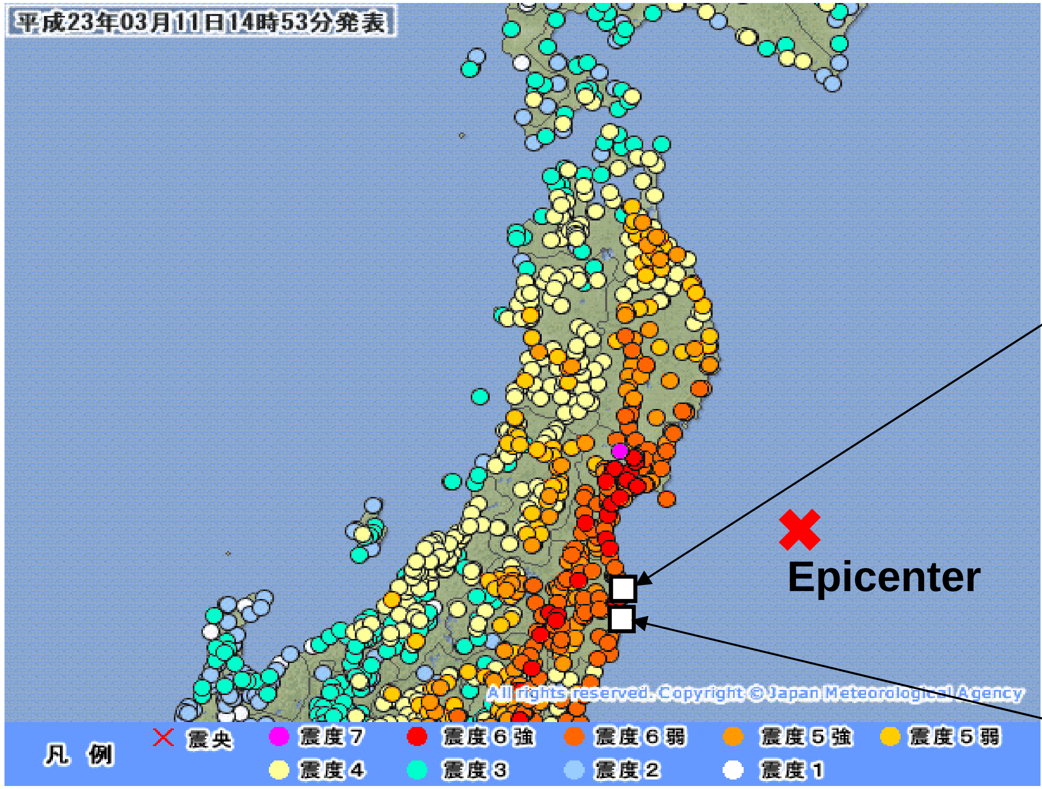
1. Seismic observation and strong motion observed at the NPS sites

- Outline of the seismic observation at the sites and strong motion observed at the downhole arrays

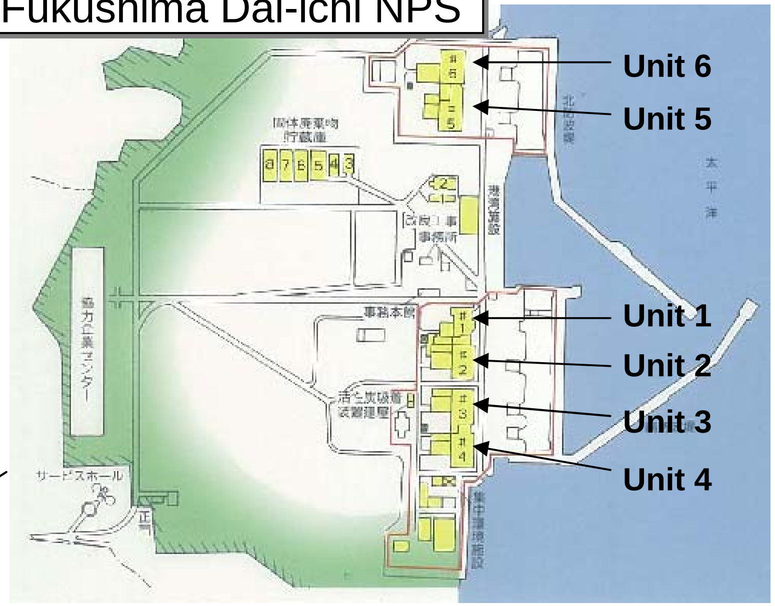
Location of Fukushima Dai-ichi NPS and Fukushima Dai-ni NPS

Distance from the epicenter: about 180km

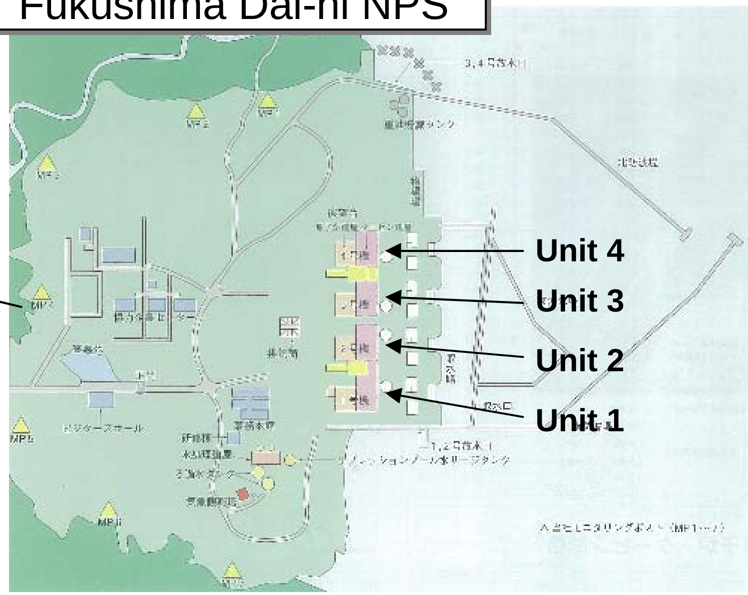


Seismic Intensity distribution map by JMA

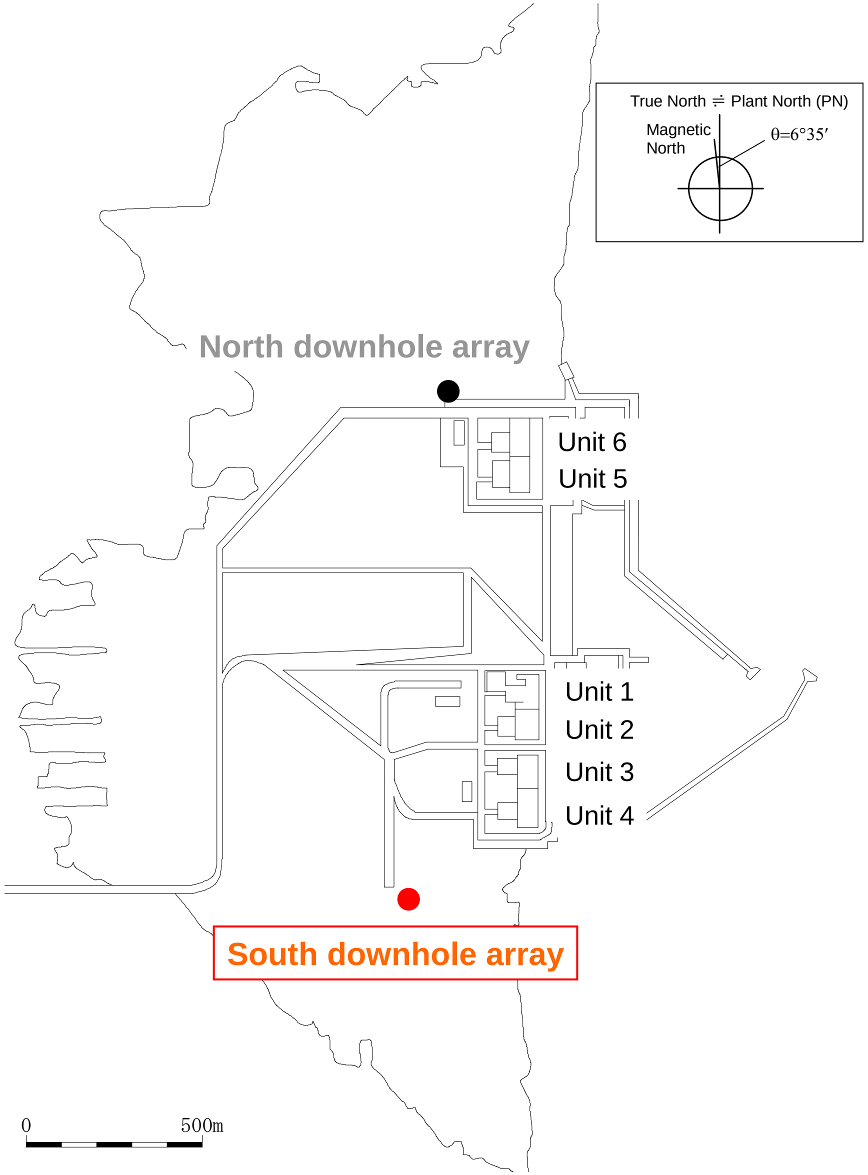
Fukushima Dai-ichi NPS



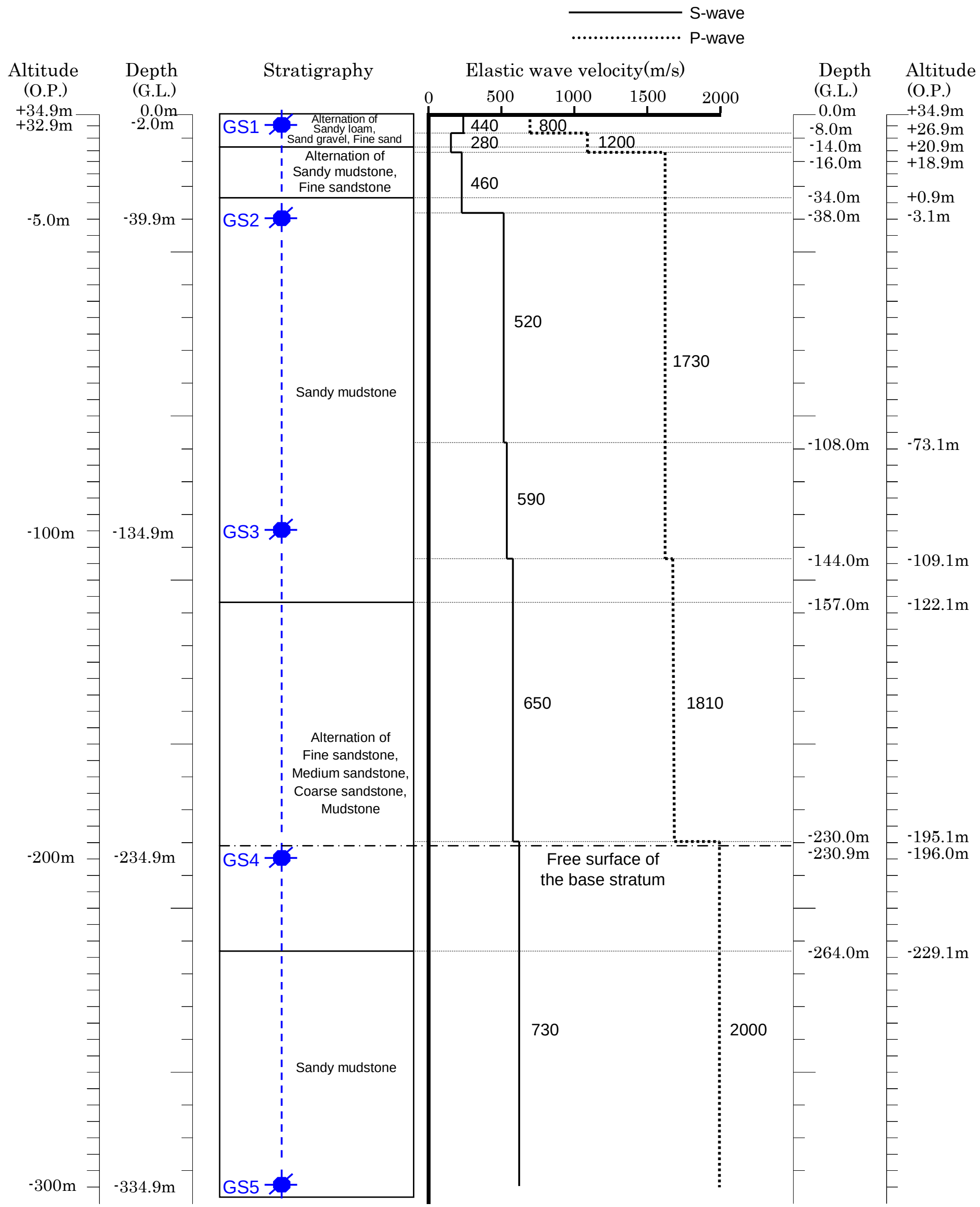
Fukushima Dai-ni NPS



Fukushima Dai-ichi NPS – South downhole array



Schematic location map of the south downhole array



Geological and geophysical logs at the south downhole array

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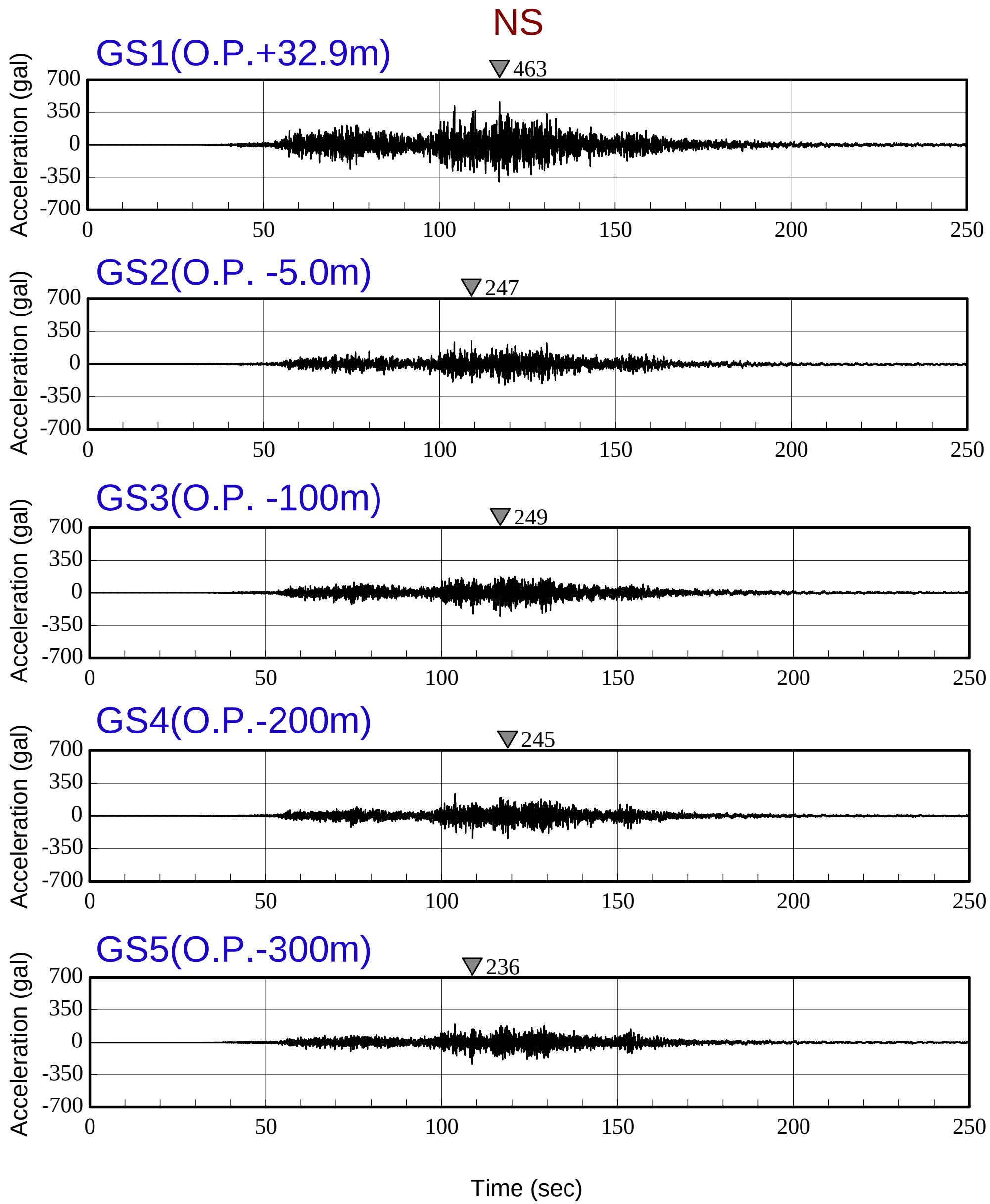
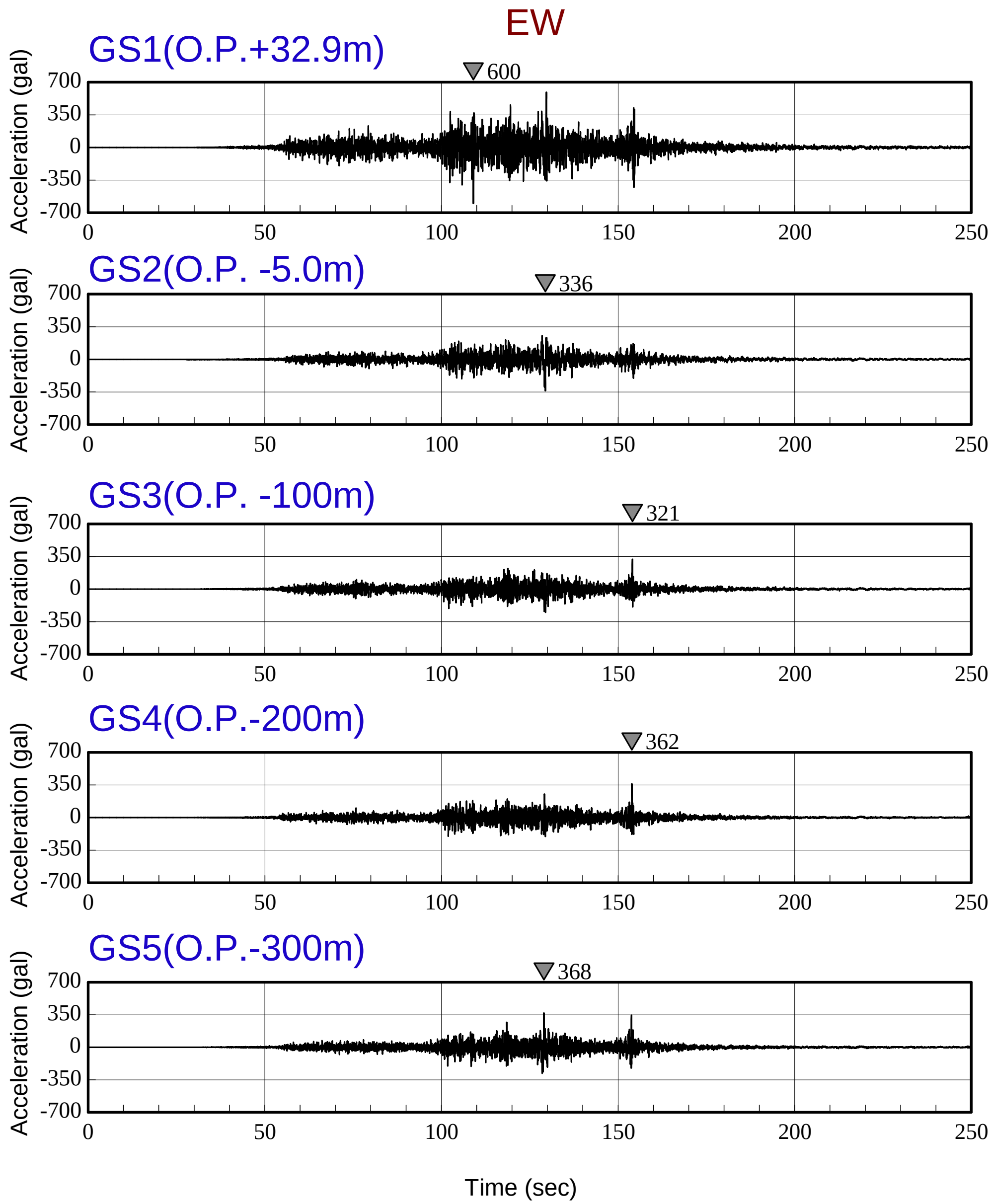
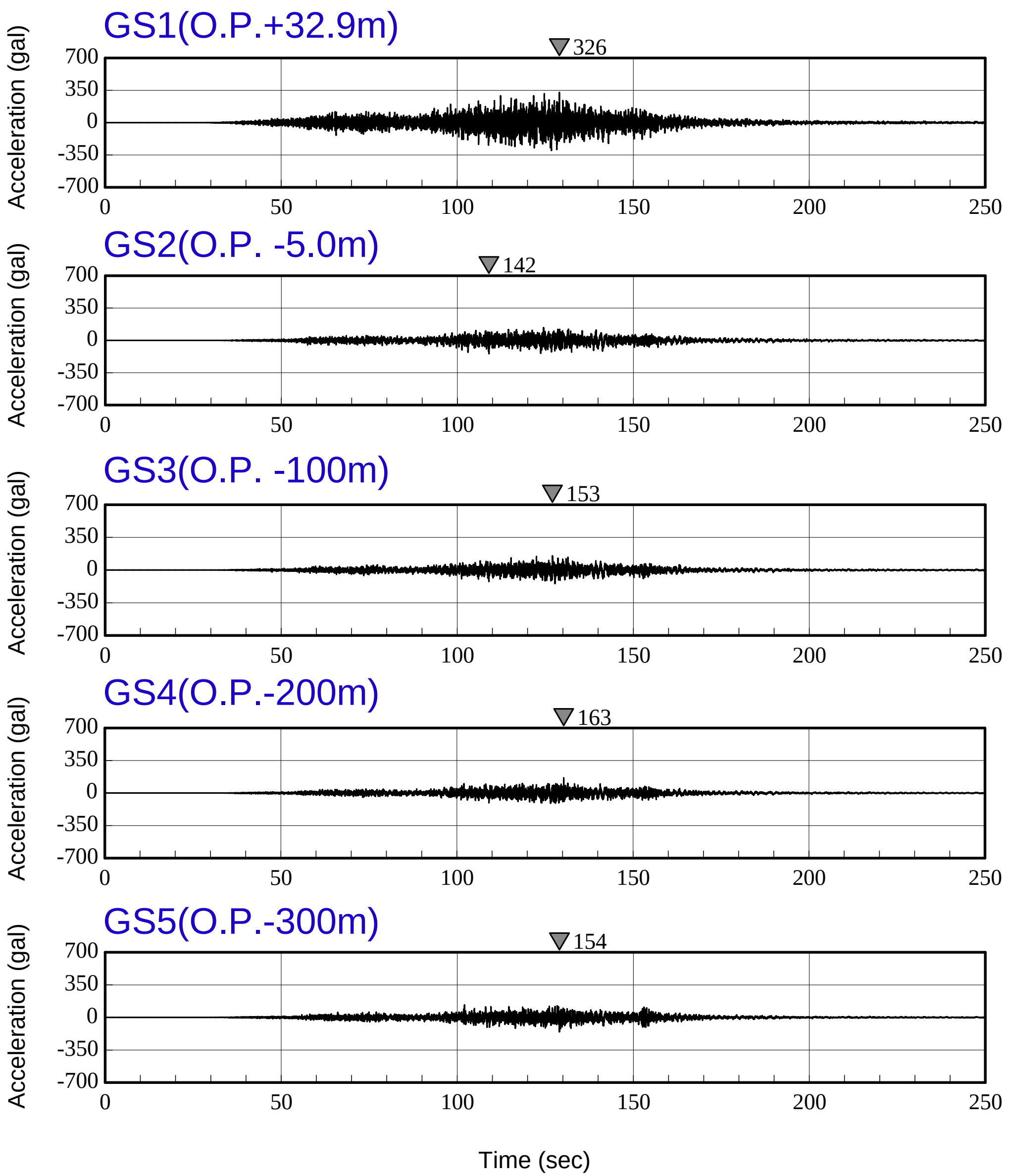
Acceleration time histories : South downhole array – NS and EW





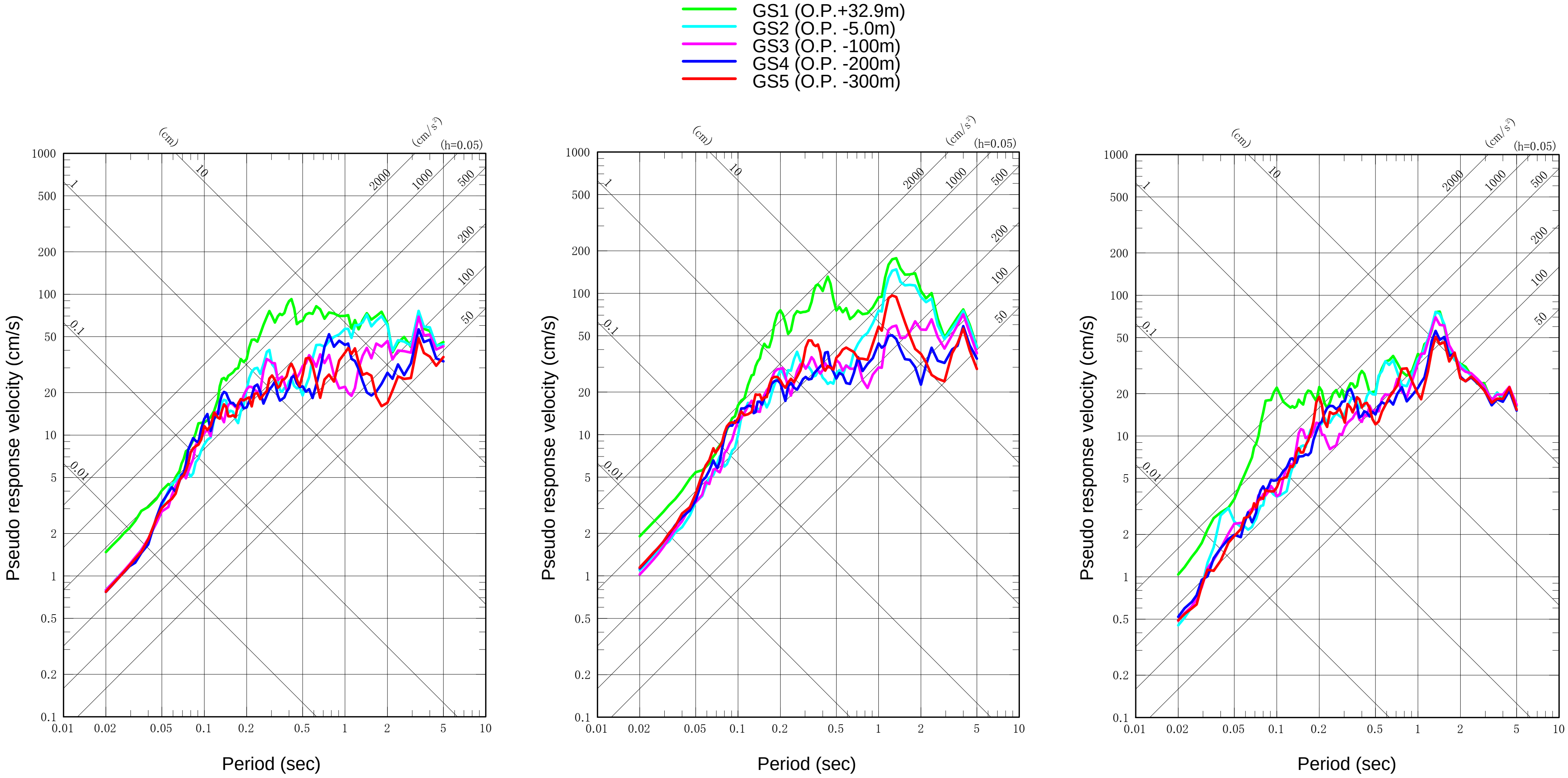
*correction of baseline shift and orientation error are applied

Acceleration time histories : South downhole array - UD



*correction of baseline shift and orientation error are applied

Response spectra: South downhole array

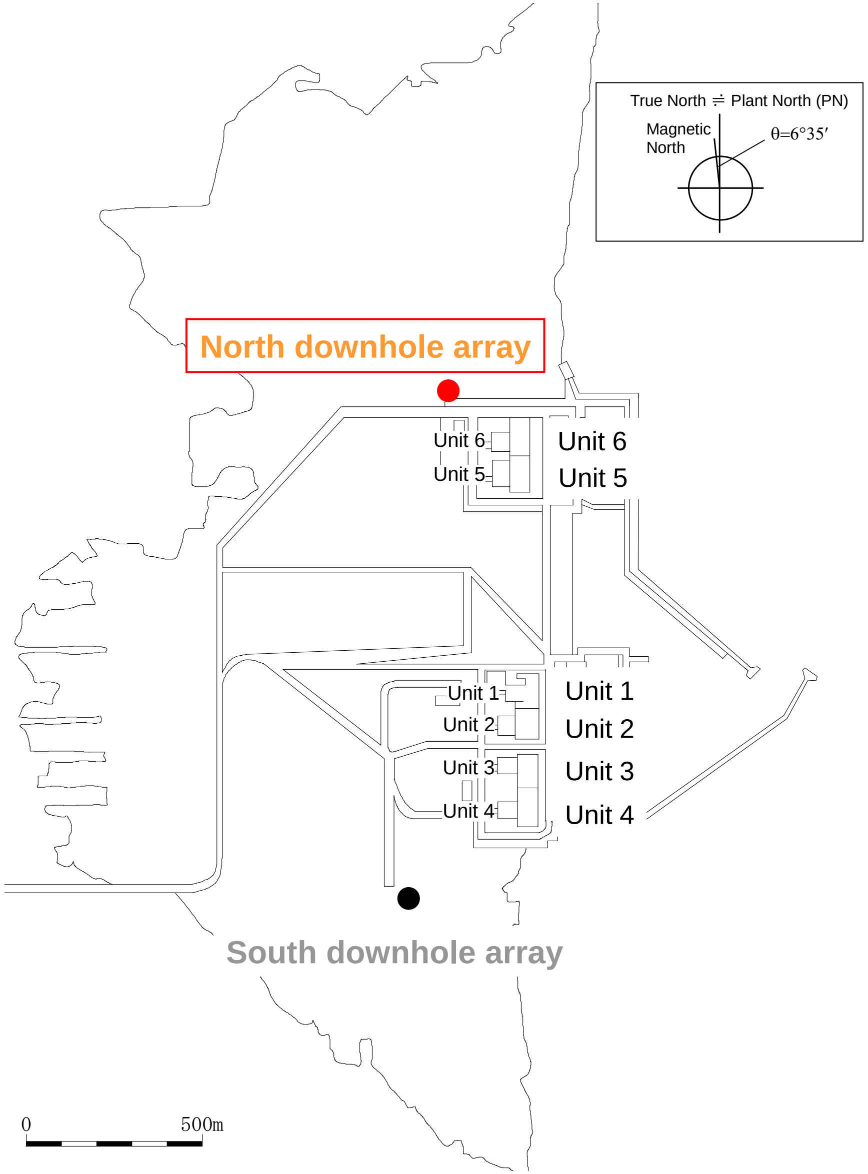


NS

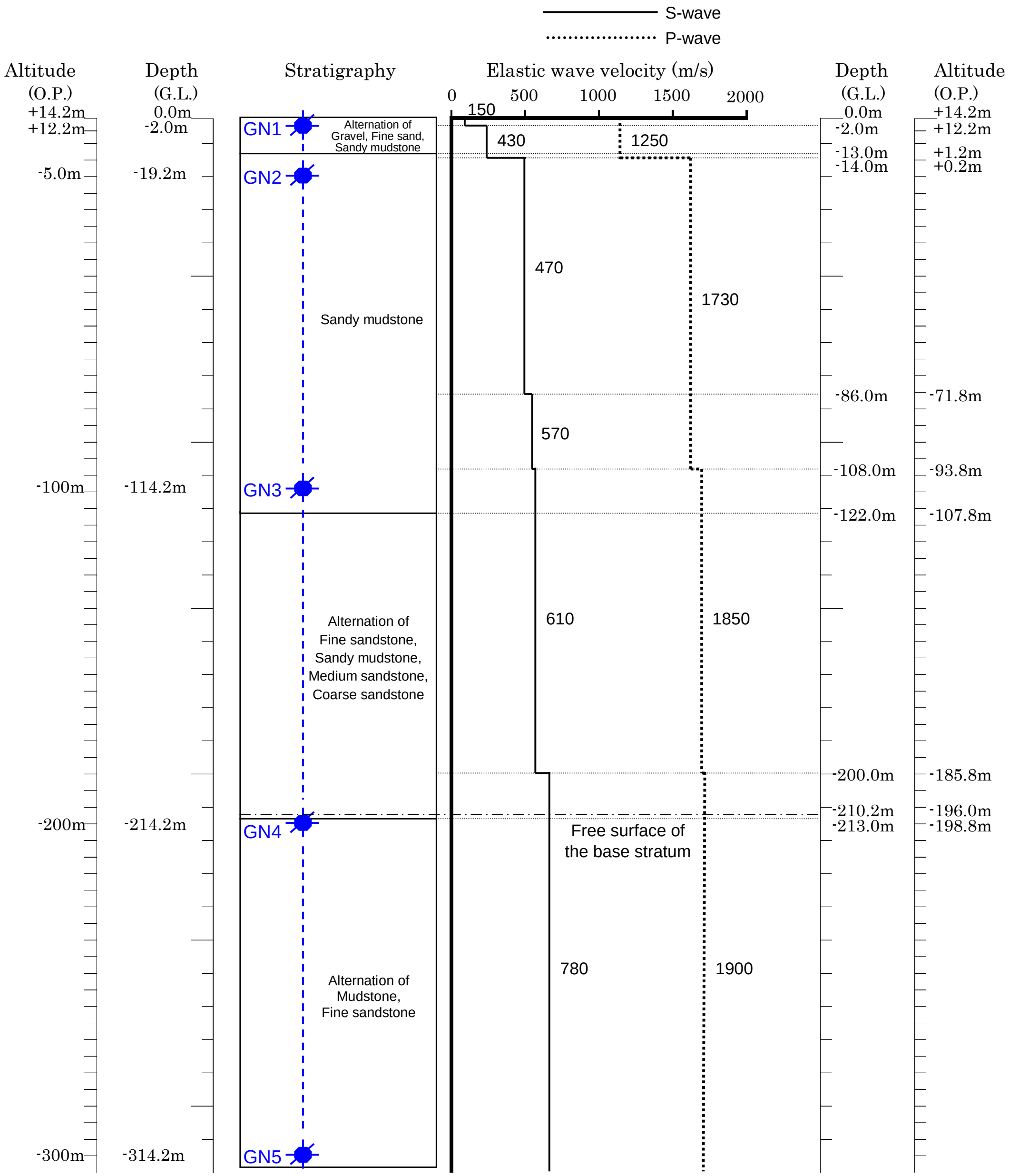
EW

UD

Fukushima Dai-ichi NPS – North downhole array

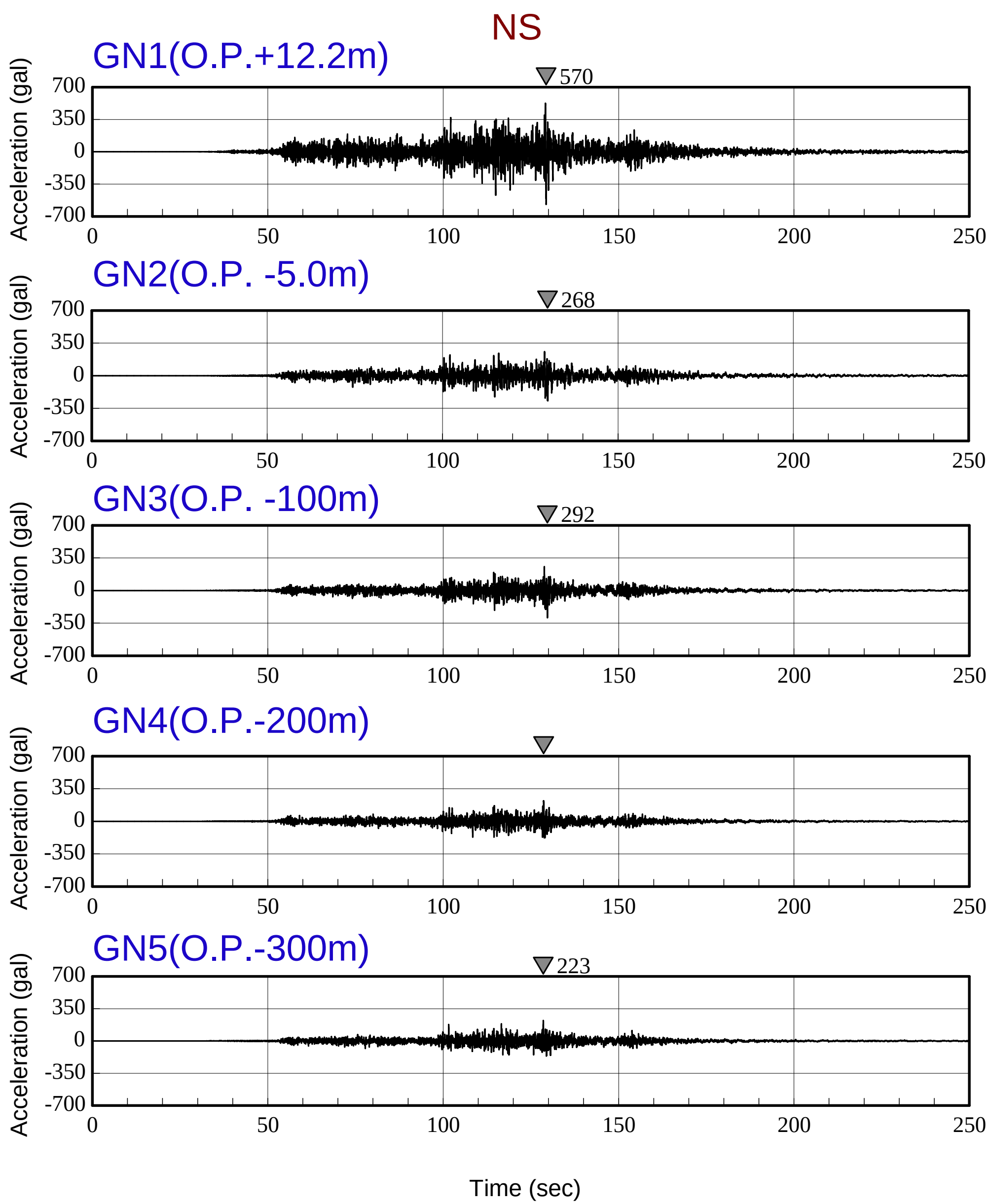


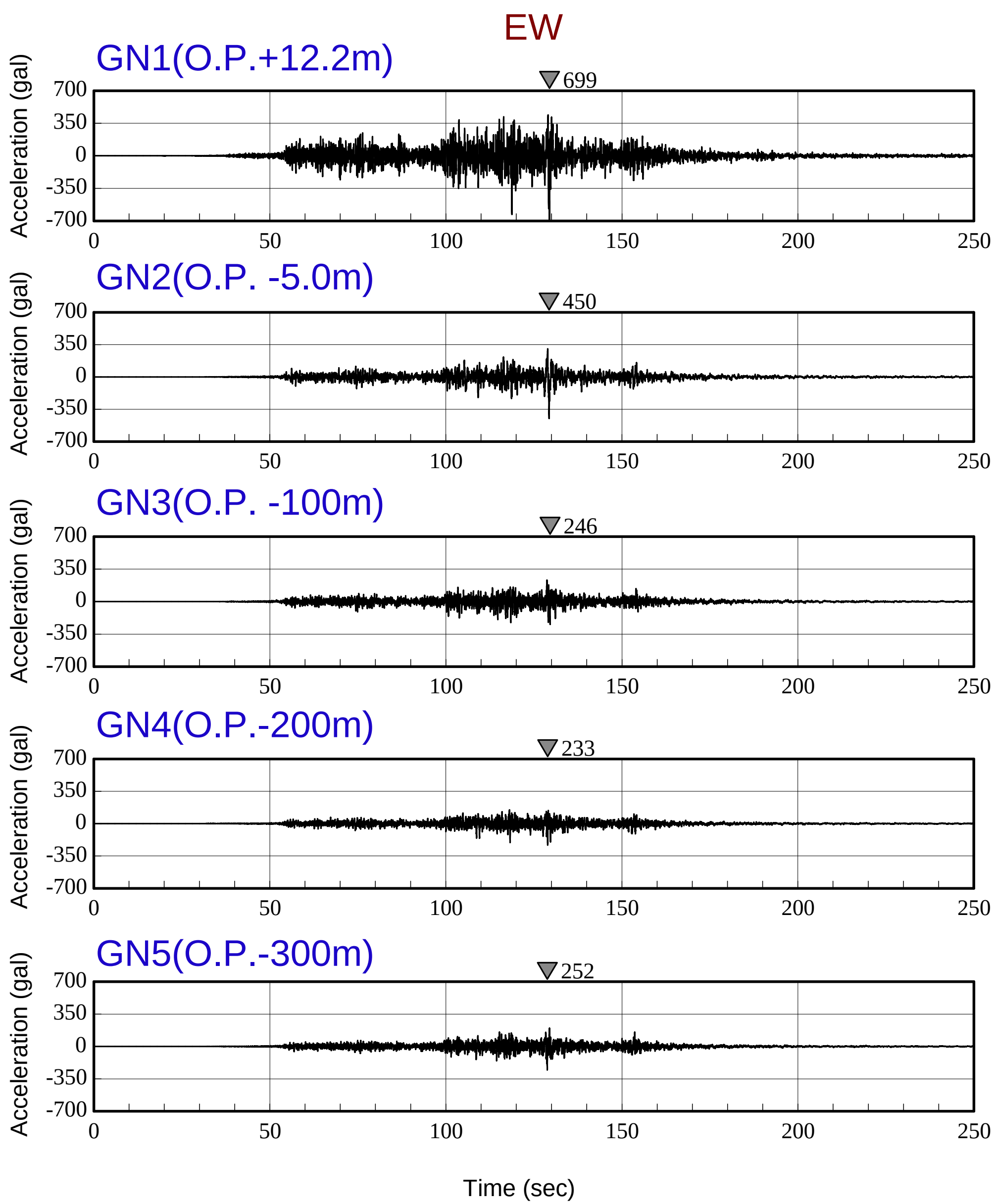
Schematic location map of the north downhole array



Geological and geophysical logs at the north downhole array

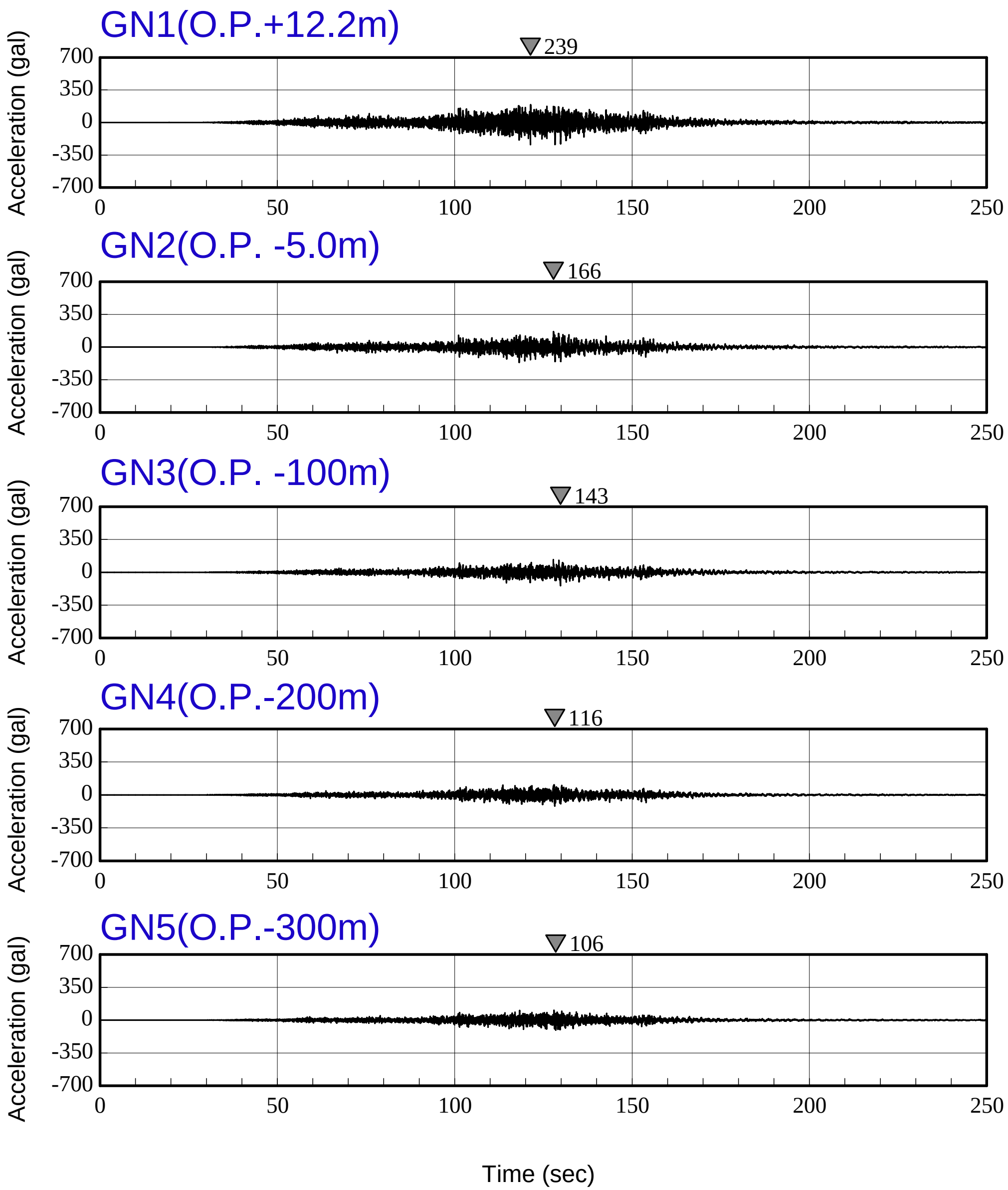
Acceleration time histories : North downhole array – NS and EW





*correction of baseline shift and orientation error are applied

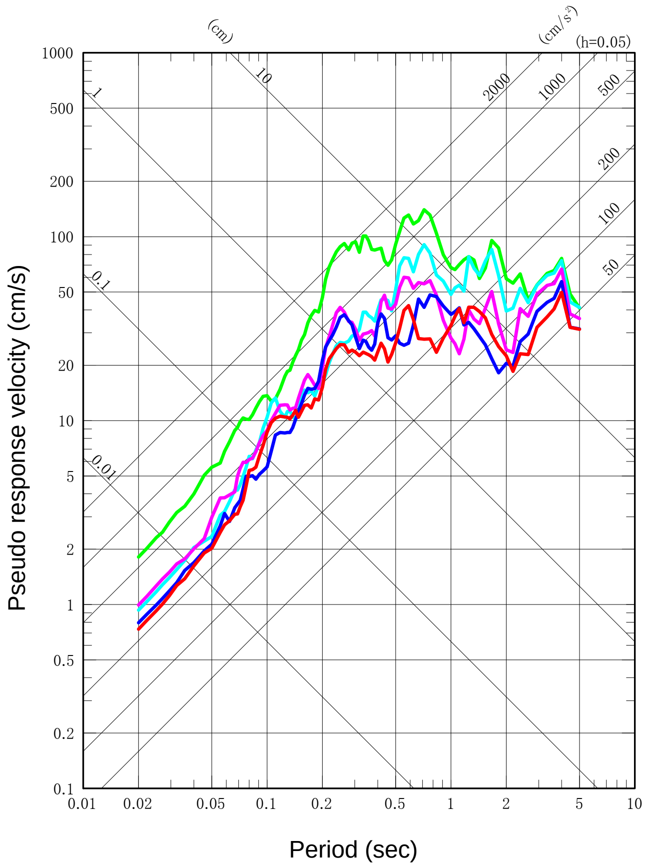
Acceleration time histories : North downhole array - UD



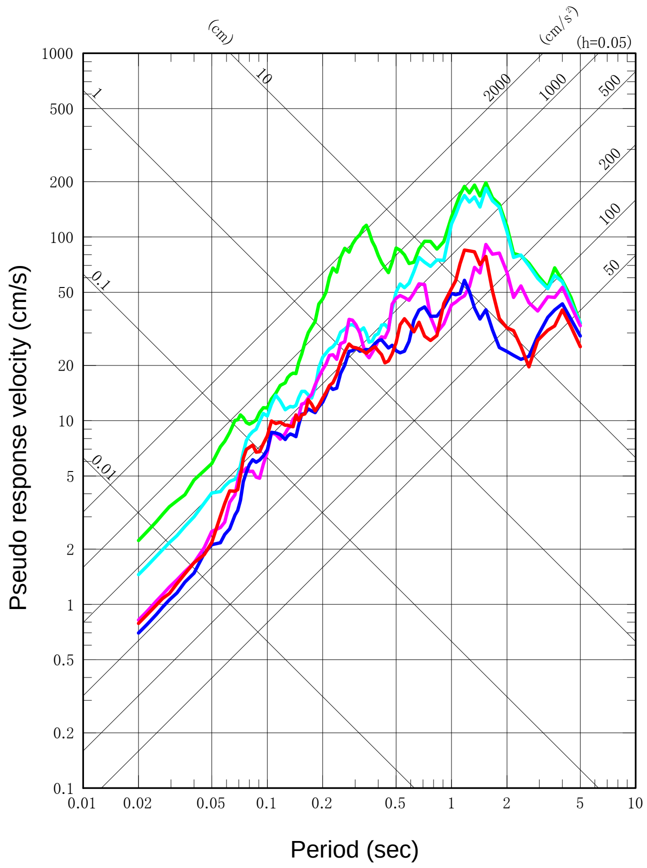
*correction of baseline shift and orientation error are applied

Response spectra: North downhole array

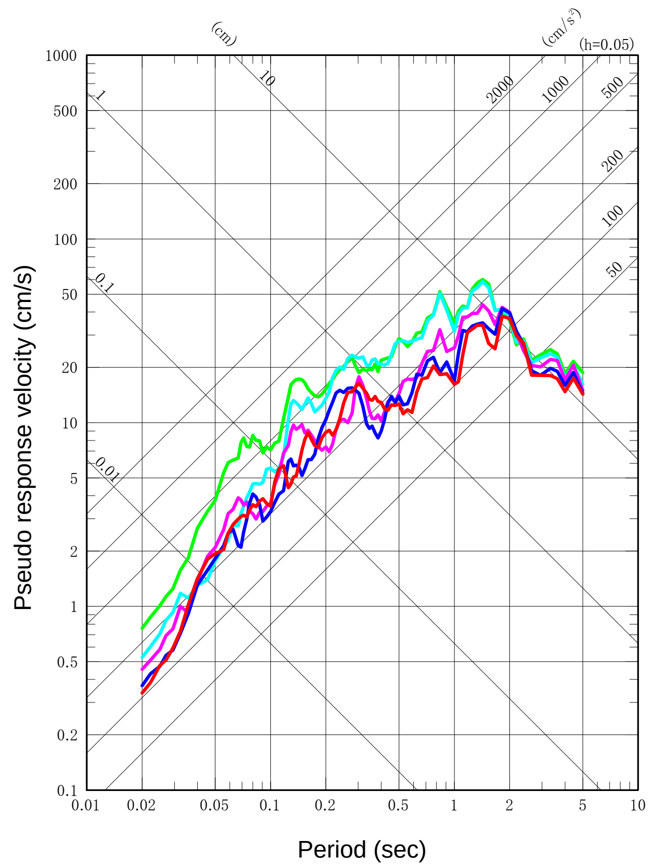
GN1 (O.P.+12.2m)
GN2 (O.P. -5.0m)
GN3 (O.P. -100m)
GN4 (O.P. -200m)
GN5 (O.P. -300m)



NS



EW



UD

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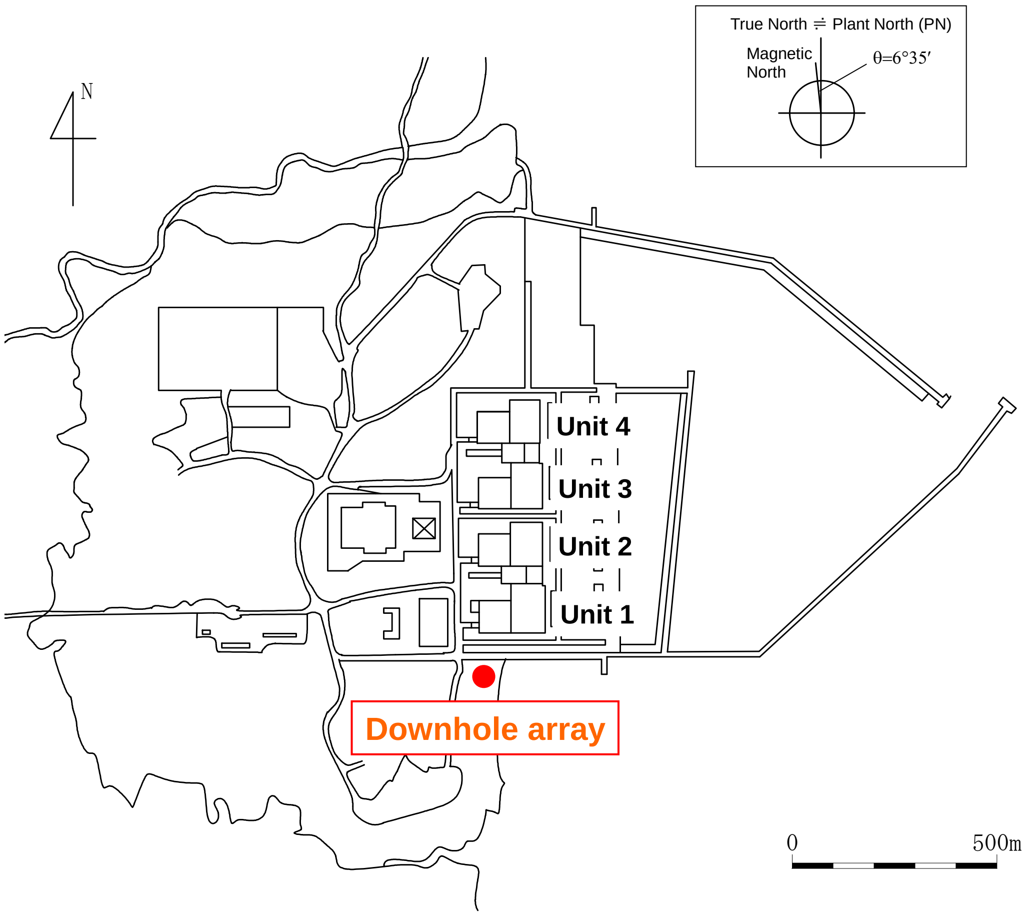
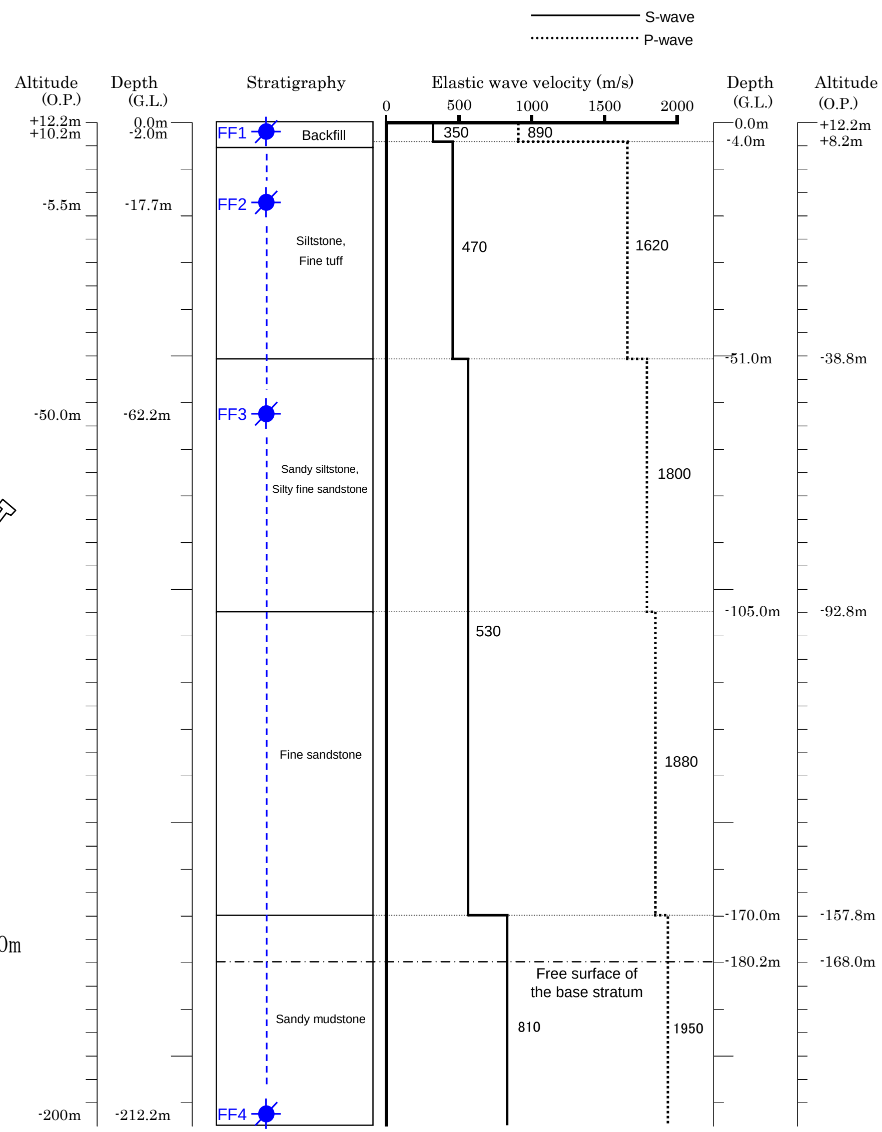
Fukushima Dai-ni NPS – Downhole array



Schematic location map of the downhole array

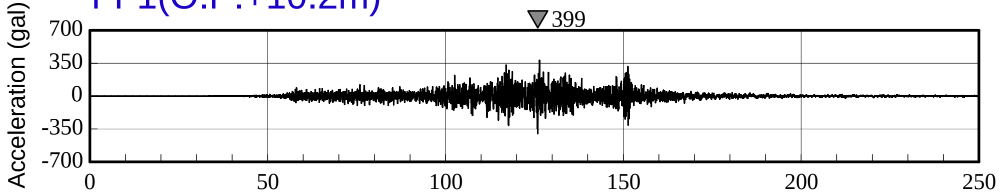


Geological and geophysical logs at the downhole array

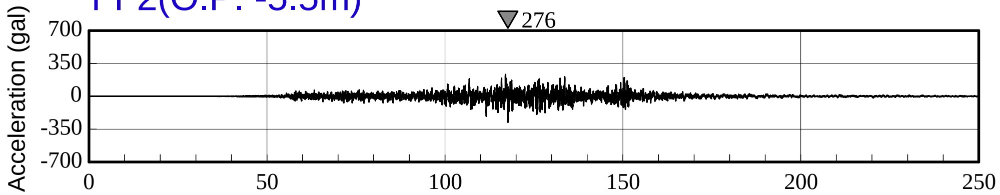
Acceleration time histories : Downhole array – NS and EW

NS

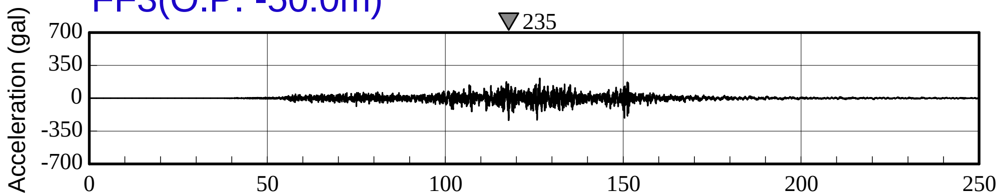
FF1(O.P.+10.2m)



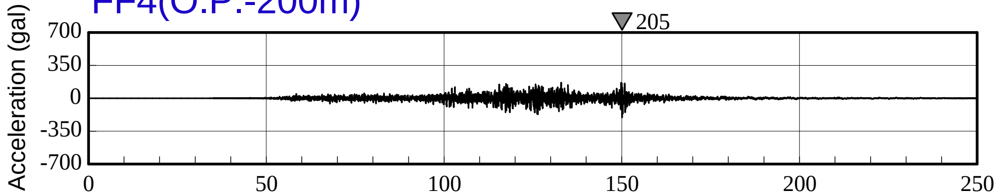
FF2(O.P. -5.5m)



FF3(O.P. -50.0m)



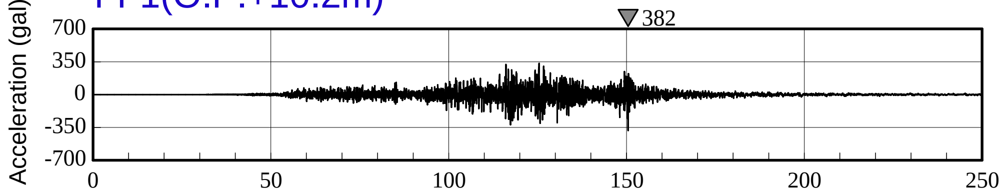
FF4(O.P.-200m)



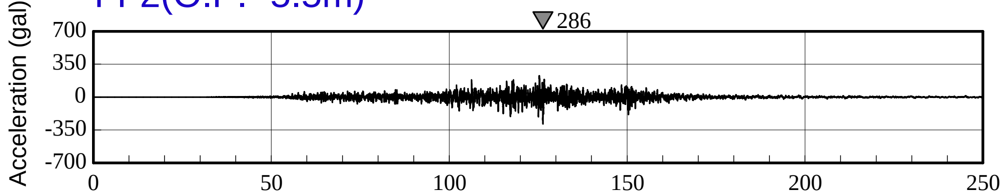
Time (sec)

EW

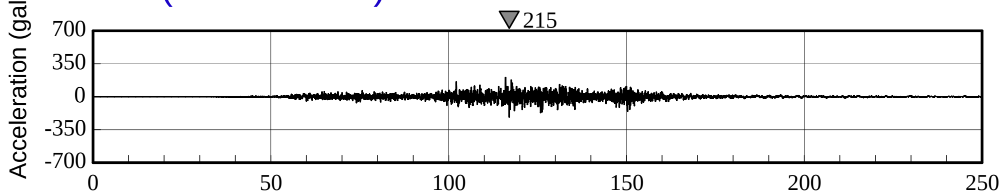
FF1(O.P.+10.2m)



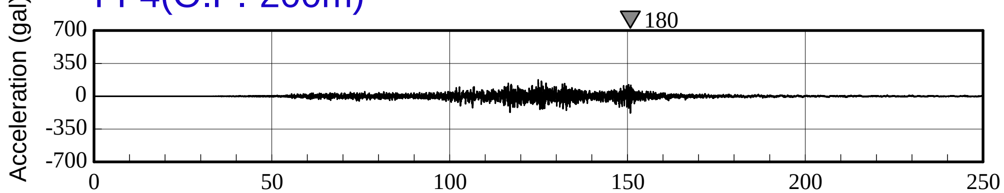
FF2(O.P. -5.5m)



FF3(O.P. -50.0m)



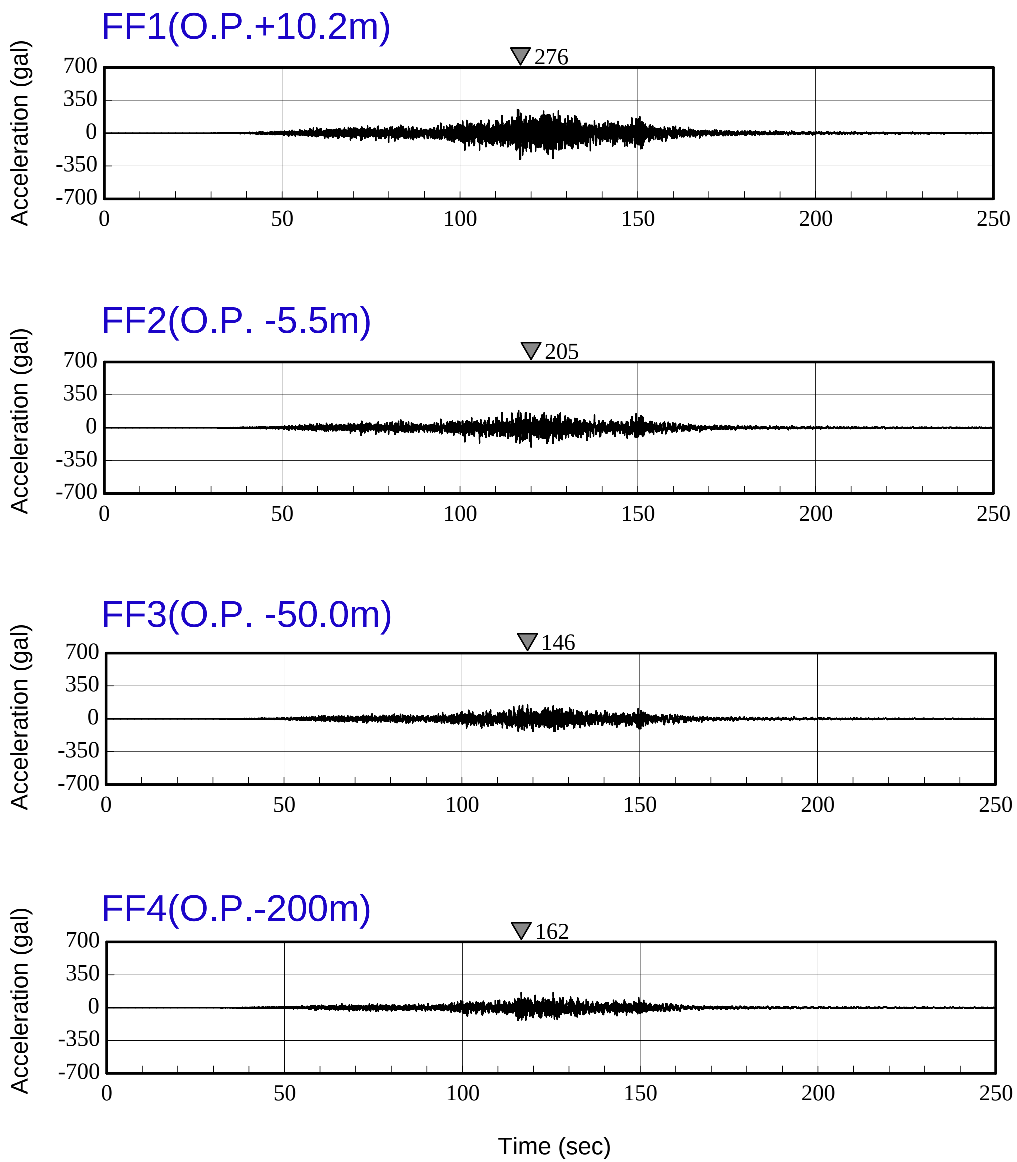
FF4(O.P.-200m)



Time (sec)

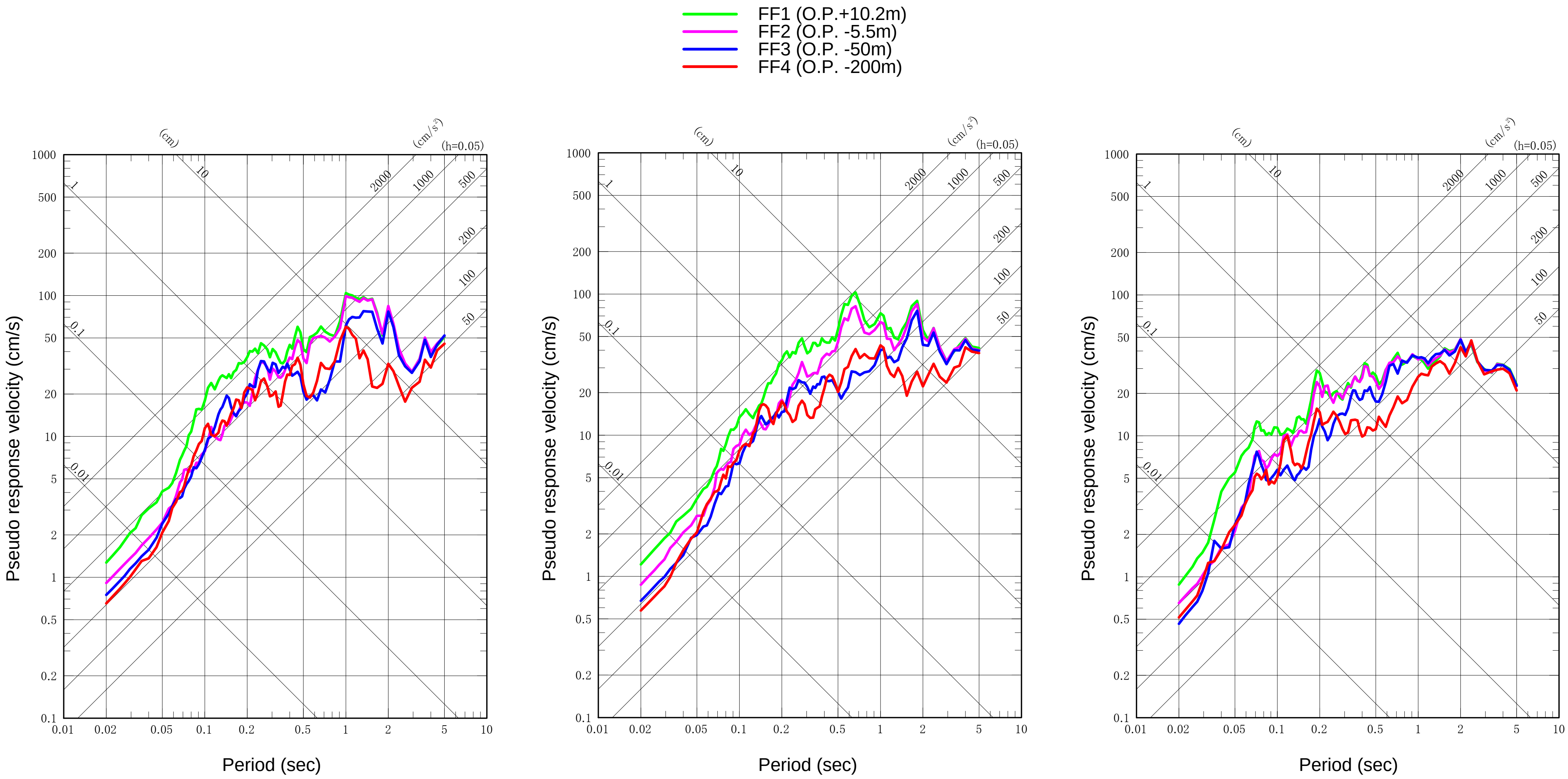
*correction of baseline shift and orientation error are applied

Acceleration time histories : Downhole array - UD



*correction of baseline shift and orientation error are applied

Response spectra: Downhole array

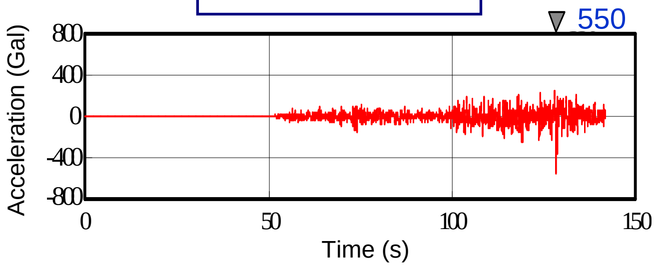


NS EW UD

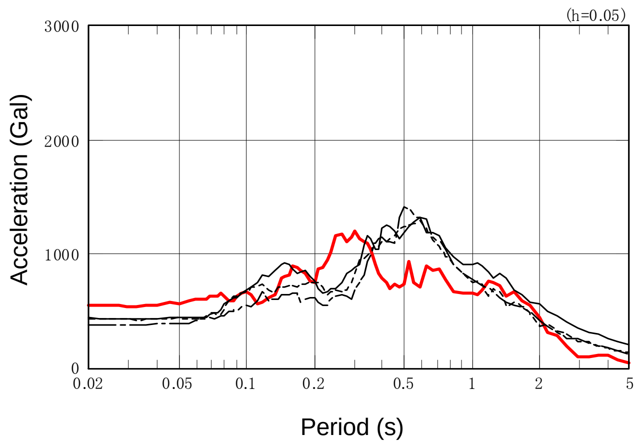
Comparison of 2011 Great East Japan Earthquake and 2007 NCO Earthquake

2011 Great East Japan Earthquake

Fukushima dai-ichi

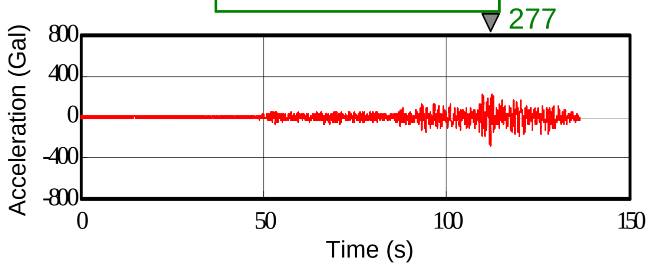


Observation records
Design-basis seismic ground motion Ss-1H
Design-basis seismic ground motion Ss-2H
Design-basis seismic ground motion Ss-3H

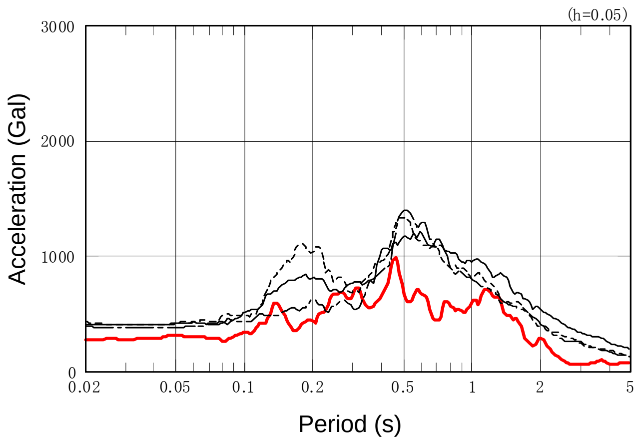


Unit 2 EW

Fukushima dai-ni



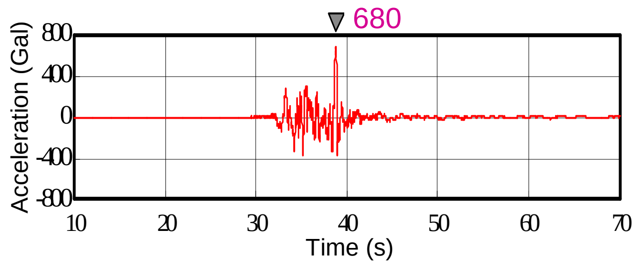
Observation records
Design-basis seismic ground motion Ss-1H
Design-basis seismic ground motion Ss-2H
Design-basis seismic ground motion Ss-3H



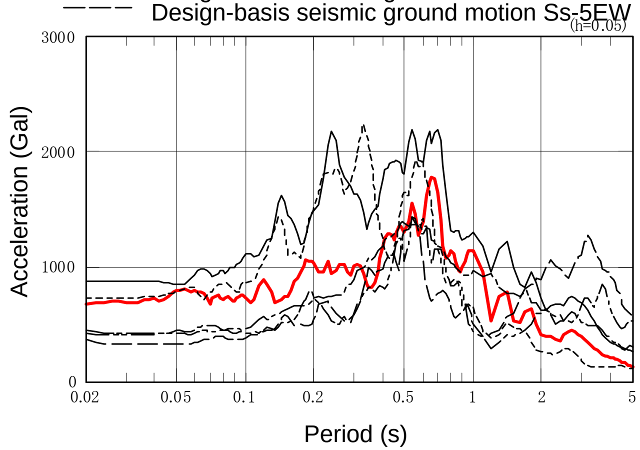
Unit 3 NS

2007 NCO Earthquake

Kashiwazaki-Kariwa



Observation records (2007 NCO Earthquake)
Design-basis seismic ground motion Ss-1H
Design-basis seismic ground motion Ss-2EW
Design-basis seismic ground motion Ss-3H
Design-basis seismic ground motion Ss-4EW
Design-basis seismic ground motion Ss-5EW



Unit 1 EW

2. Ground motion simulation at the sites

- Ground motion simulation at the NPS sites using source models by Kamae and Kawabe (2011) and Irikura and Kurahashi (2011)

Objective

- As for the Great East Japan earthquake, several source models are proposed using GPS data, tsunami records, strong motion records or teleseismic records.
- Source models proposed by Kamae and Kawabe (2011) and Irikura and Kurahashi (2011) are ones which can be used for the simulation of strong motion including high frequency range crucial for the seismic safety evaluation of nuclear facilities.
- Ground motion simulations at Fukushima Dai-ichi NPS and Fukushima Dai-ni NPS site are conducted using source models by Kamae and Kawabe (2011) and Irikura and Kurahashi (2011), in order to evaluate source characteristics of the main shock and effect on the sites.

Outline of the source model by Kamae and Kawabe (2011)

•A source model is proposed based on forward modeling by Empirical Green's Function method using records (0.1-10Hz) observed at KiK-net stations along the Pacific coast, which has 5 asperities in the region of Miyagi-oki, Southern Iwate-oki, Fukushima-oki, Ibaraki-oki etc.

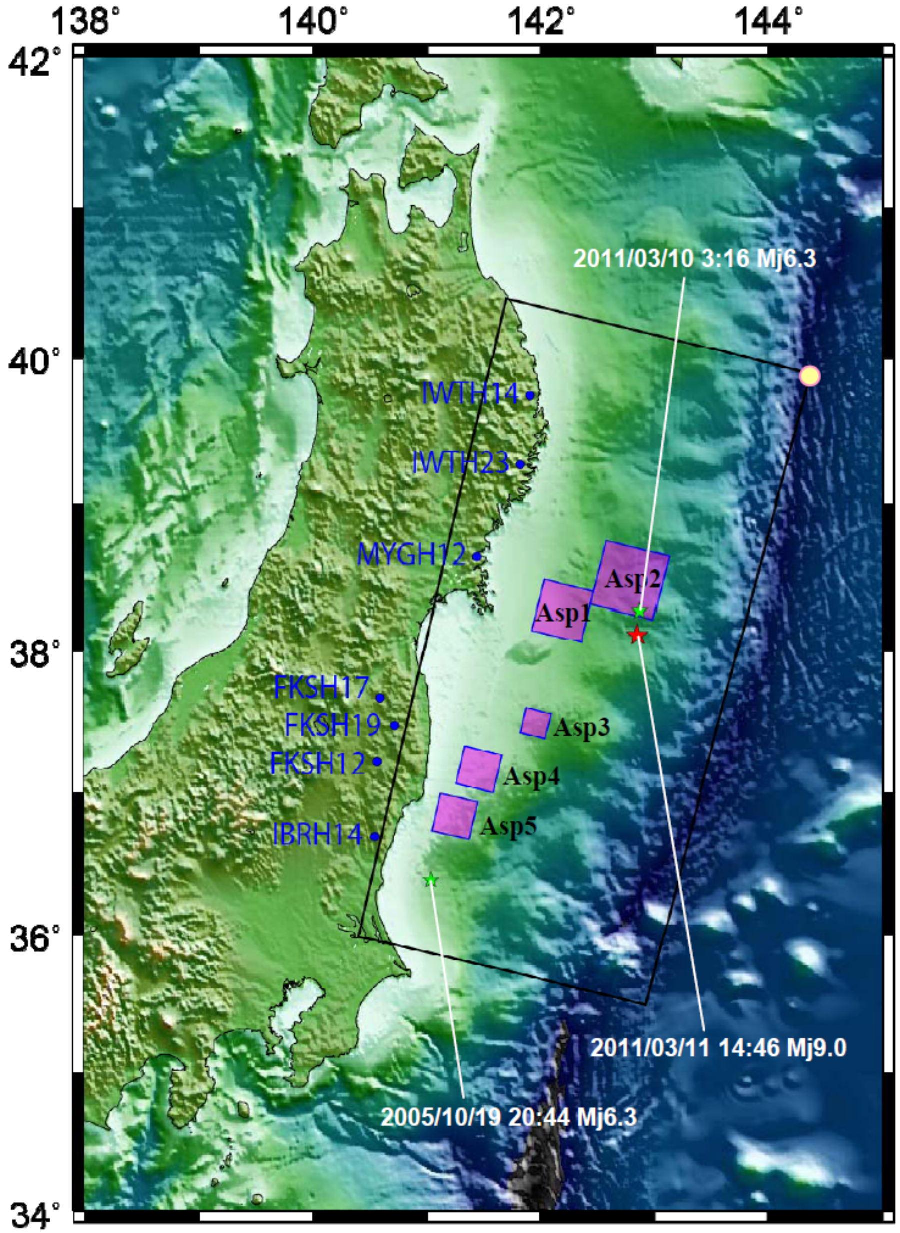
•Proposed model well reproduce significant waveforms observed at Kik-net stations located along the Pacific coast from Iwate pref. through Ibaraki pref.

Source parameters for the small events used as EGF

Origin Time (JST)*	2005/10/19 20:44	2011/3/10 3:16
Latitude (deg.)*	36.382	38.271
Longitude (deg.)*	141.043	142.879
Depth (km)*	48.3	28.9
Mj*	6.3	6.4
Mo (Nm)**	3.18×10^{18}	1.10×10^{18}
Strike/dip/rake** (deg.)	25/68/88 209/22/94	22/71/90 201/19/89

*JMA, **F-net

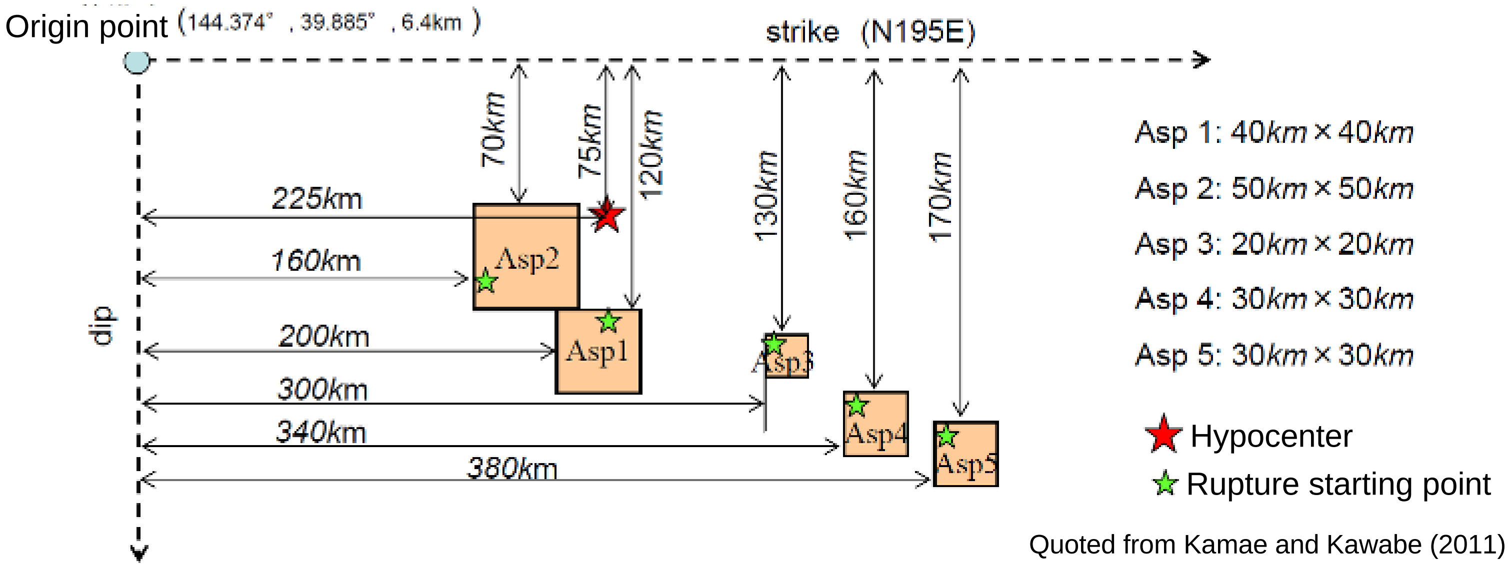
Quoted from Kamae and Kawabe (2011)



The source model and the location of asperities

Quoted from Kamae and Kawabe (2011)

Outline of the source model by Kamae and Kawabe (2011)



Quoted from Kamae and Kawabe (2011)

Source model consisting of 5 asperities

Source parameters for the main shock

	Asp1	Asp2	Asp3	Asp4	Asp5
S (km^2)	40 × 40	50 × 50	20 × 20	30 × 30	30 × 30
M_0 (N·m)	4.93×10^{20}	1.10×10^{21}	8.8×10^{19}	1.19×10^{20}	2.58×10^{20}
$\Delta\sigma$ (MPa)	18.9	21.6	27.0	10.8	23.1
Rise time (s)	3.6	4.5	1.8	2.7	2.7
Rupture starting time (s)	0.0	35.0	57.0	87.0	102.0
EGF	2011/03/10 3:16 M6.4	2011/03/10 3:16 M6.4	2011/03/10 3:16 M6.4	2011/03/10 3:16 M6.4	2005/10/19 20:44 M6.3

Quoted from Kamae and Kawabe (2011)

Ground motion simulation using the source model by Kamae and Kawabe (2011)

- Empirical Green's Function (EGF) method is applied to the simulation since observation records of the small events at the site are available, which are also used as EGFs by Kamae and Kawabe (2011).

Source parameters for the small events used as EGF

Origin Time (JST)*	2005/10/19 20:44	2011/3/10 3:16
Latitude (deg.)*	36.382	38.271
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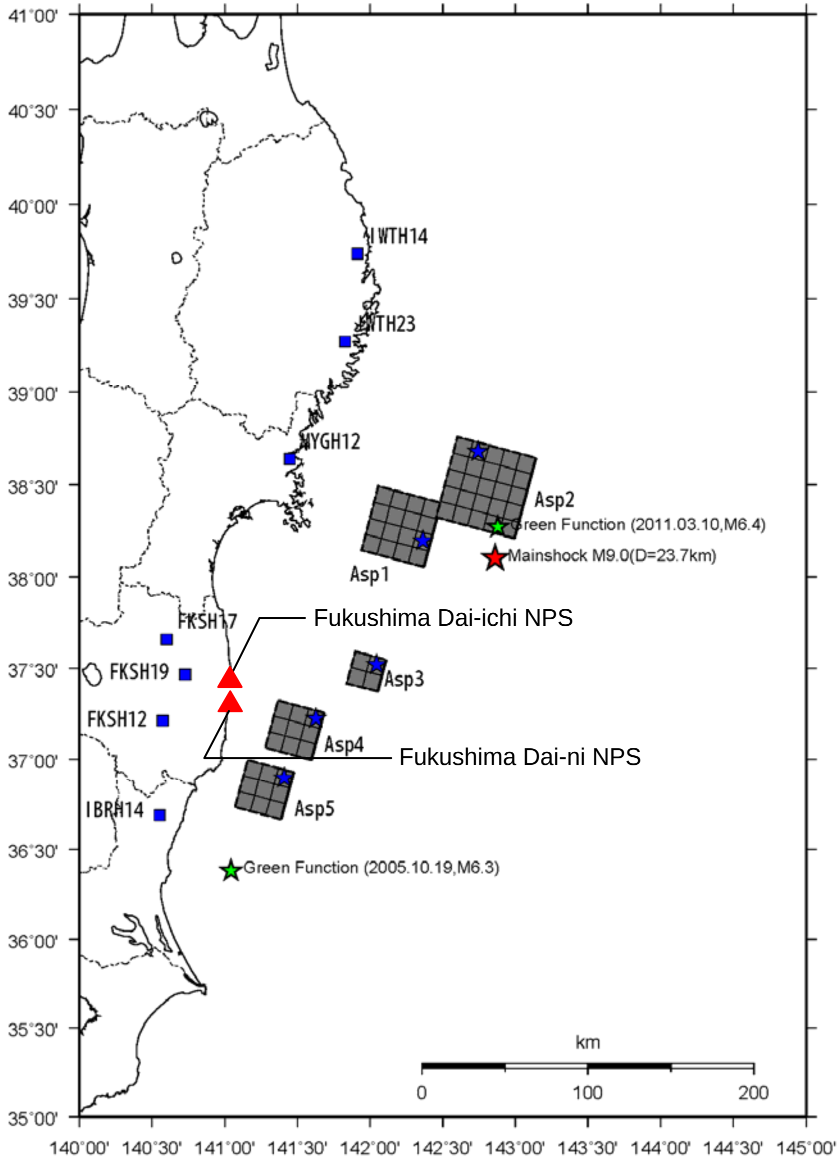
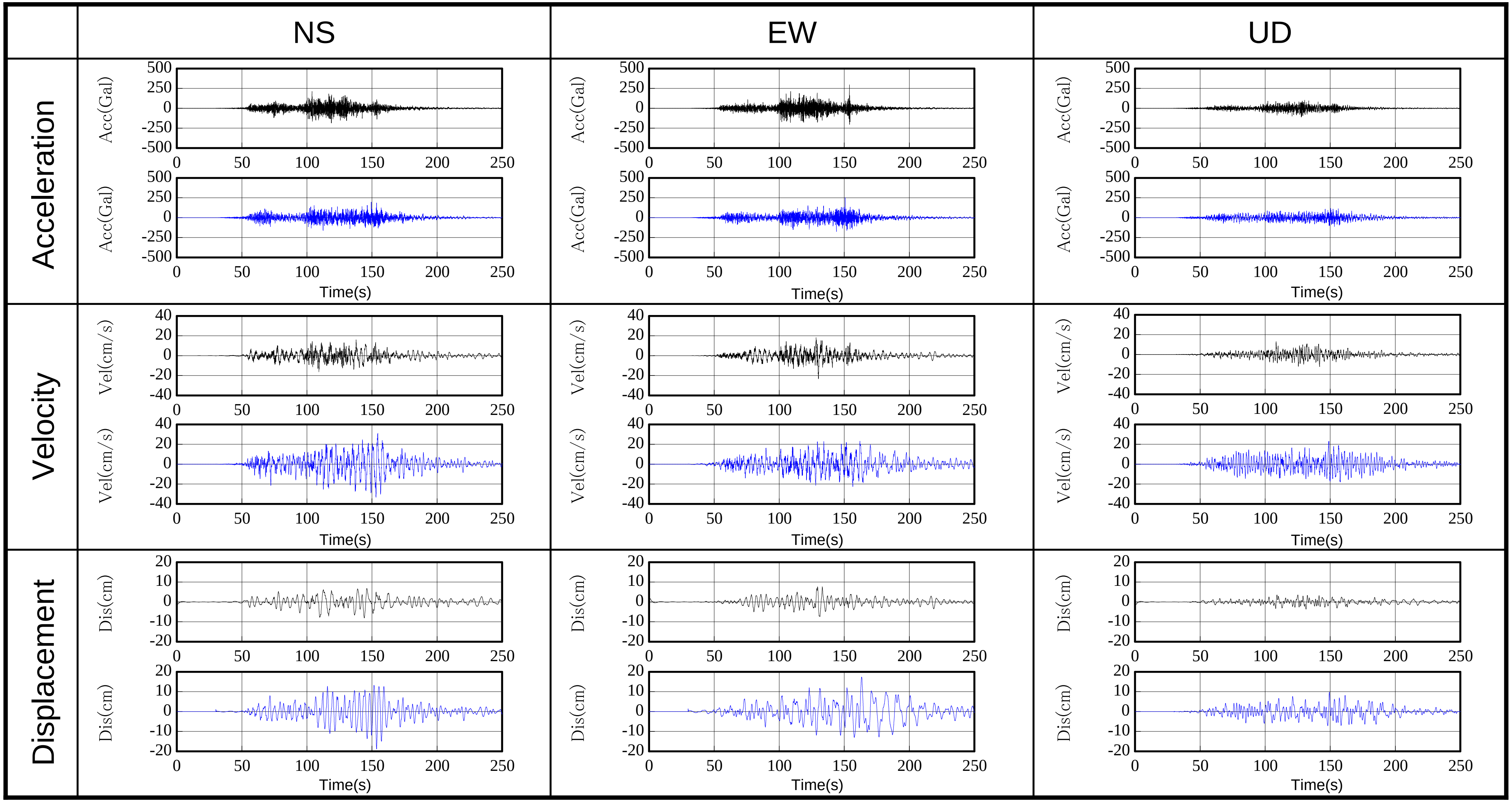


The source model and the location of SMGAs

Quoted from Kamae and Kawabe (2011)

Simulation result using the source model by Kamae and Kawabe (2011)

Fukushima Dai-ichi NPS: South downhole array



Comparisons of waveforms at GS4 (O.P.-200m)
Observed (black) vs Simulated (blue)

※O.P.:Onahama Peil (0.727m below Tokyo Peil)

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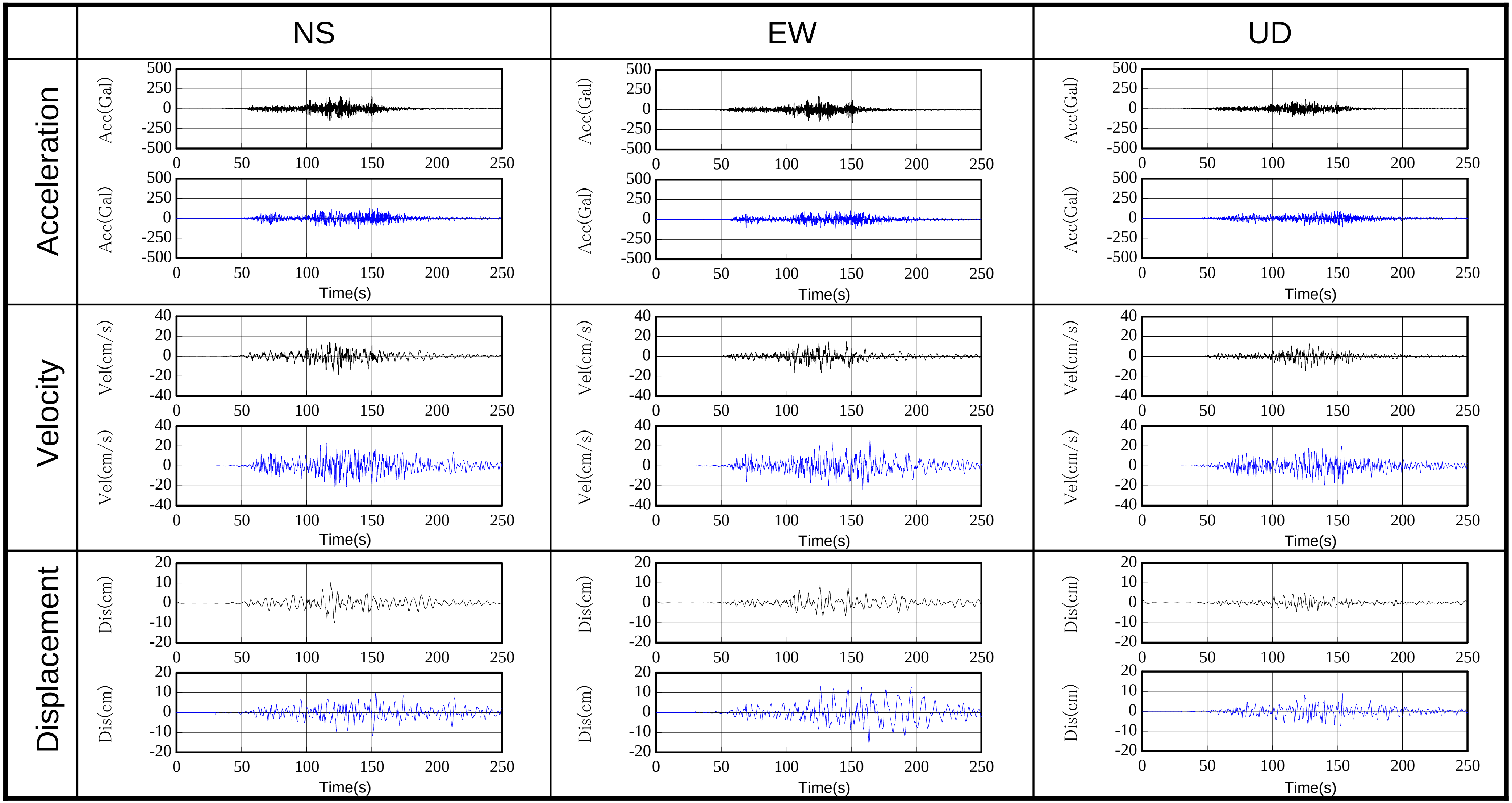
Simulation result using the source model by Kamae and Kawabe (2011)

Fukushima Dai-ni NPS: Downhole array

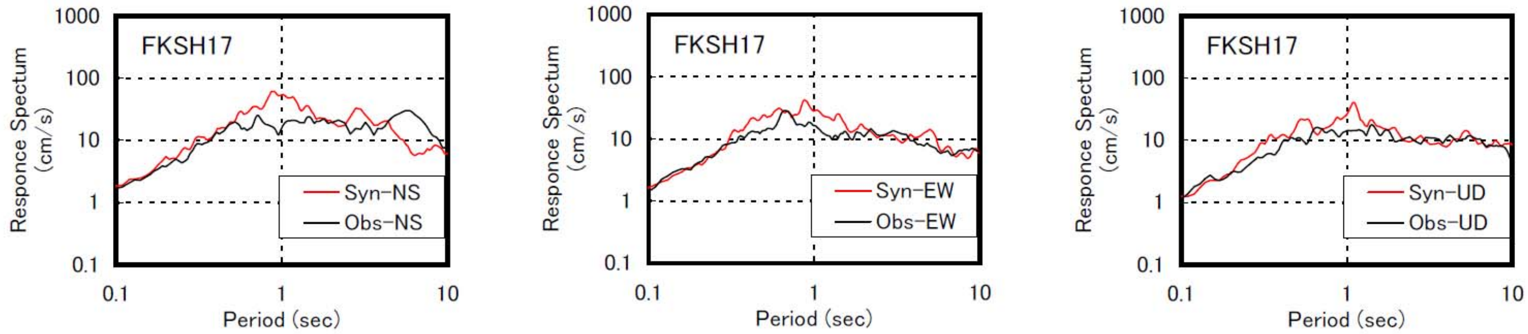


Comparisons of waveforms at FF4 (O.P.-200m)
Observed (black) vs Simulated (blue)

Simulation result using the source model by Kamae and Kawabe (2011)

Response spectra at the KiK-net station near the site (h=5%): quoted from Kamae and Kawabe (2011)

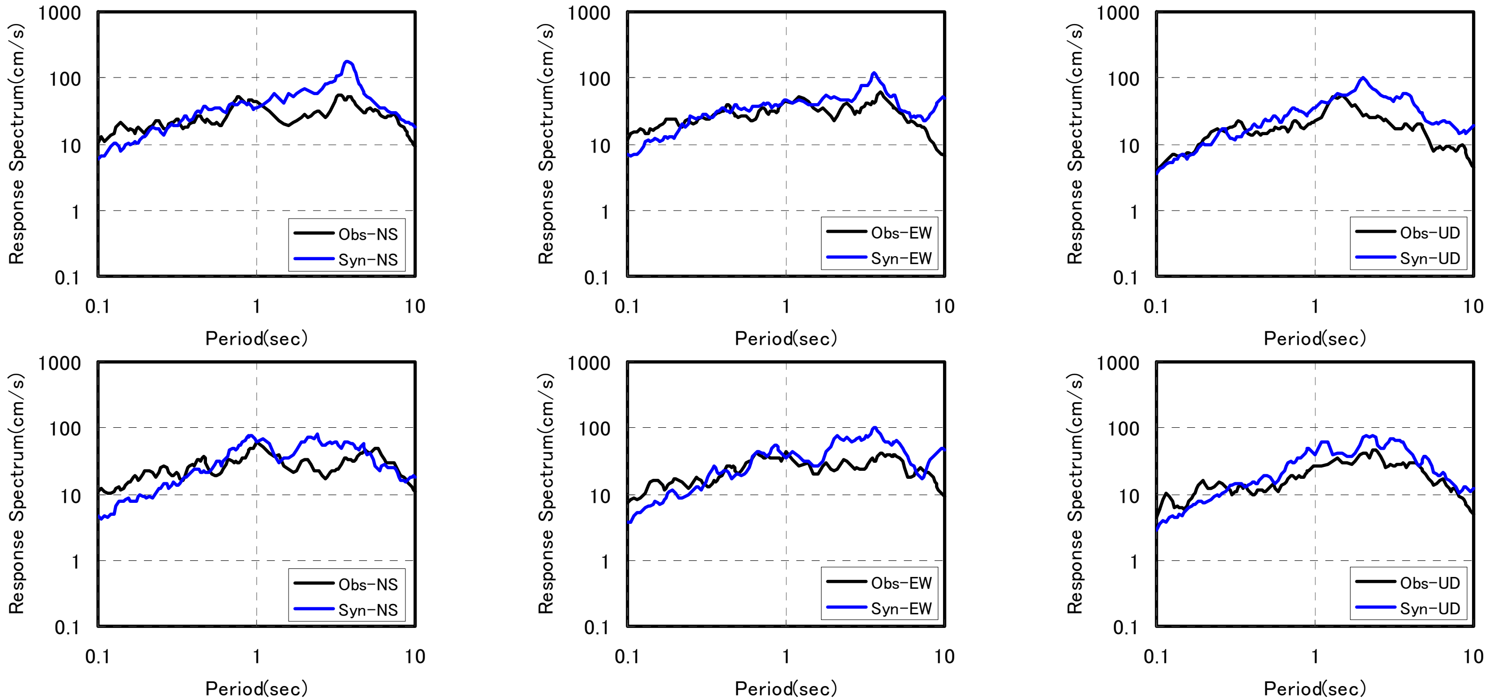
KiK-net
FKSH17
(Kawamata)



Response spectra at Fukushima Dai-ichi NPS and Dai-ni NPS site (h=5%)

Fukushima Dai-ichi
South downhole array
GS4
(O.P.-200m)

Fukushima Dai-ni
Downhole array
FF4
(O.P.-200m)

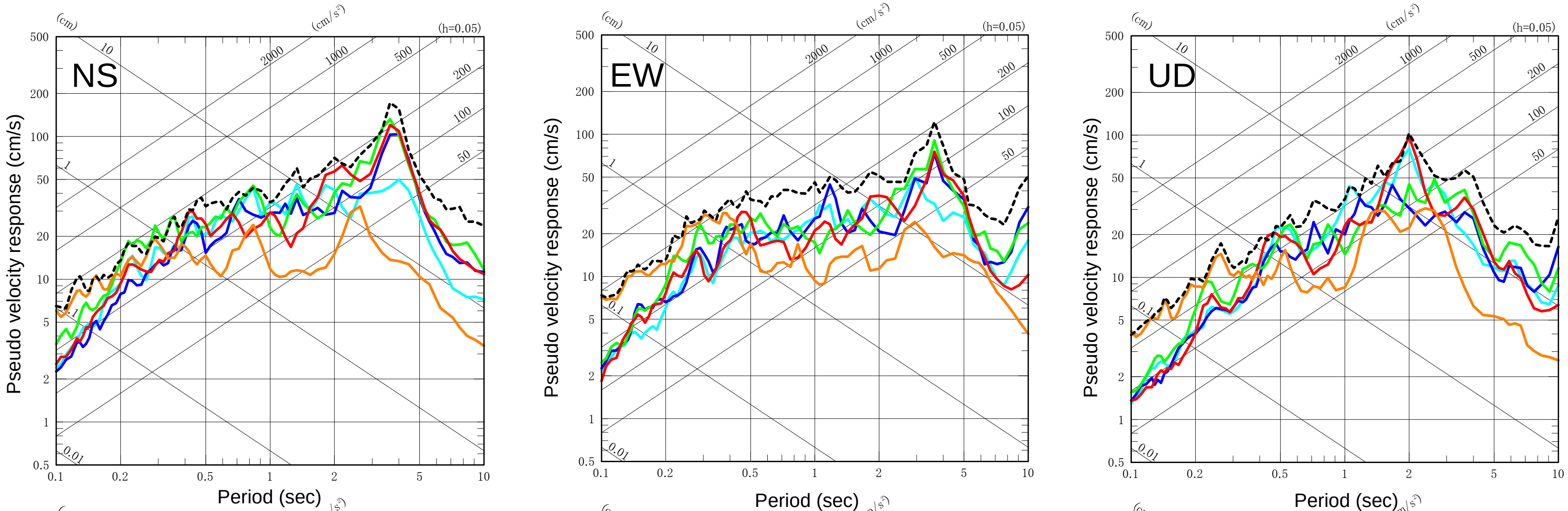


Simulation well reproduce response spectra of the observation records at Fukushima Dai-ichi NPS, Fukushima Dai-ni NPS and KiK-net station near the sites.

Simulation result using the source model by Kamae and Kawabe (2011)

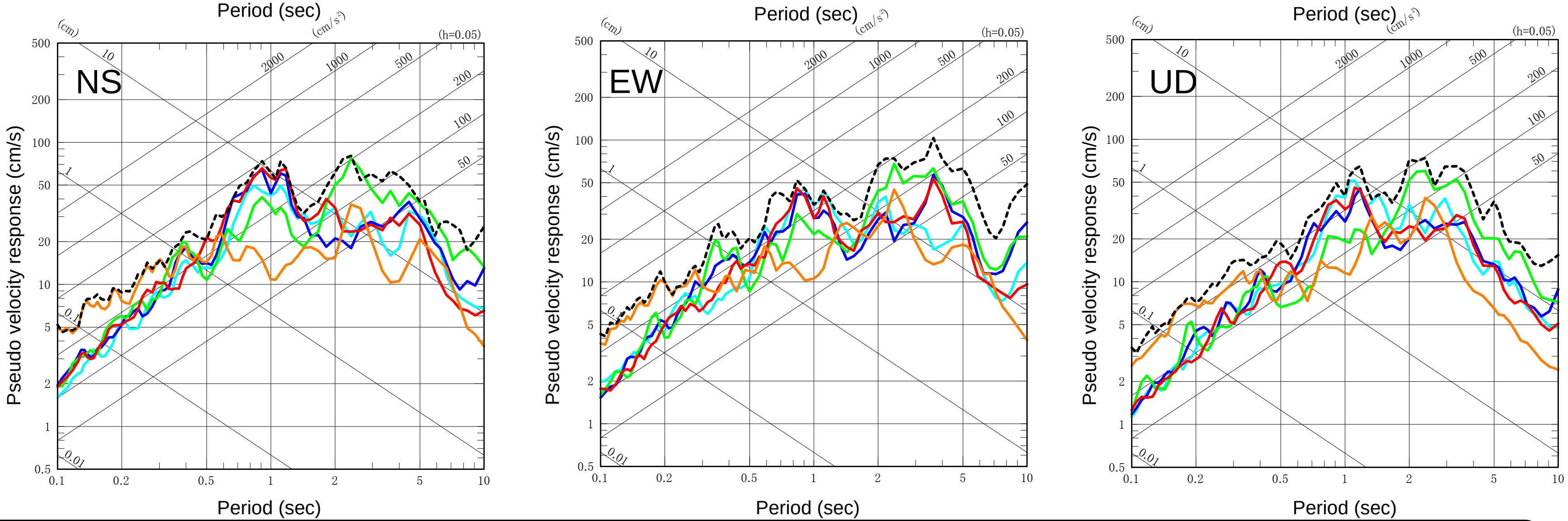
Response spectra produced by each asperities (h=5%)

Fukushima Dai-ichi
South downhole array
GS4
（O.P.-200m）



Whole area
ASP1
ASP2
ASP3
ASP4
ASP5

Fukushima Dai-ni
Downhole array
FF4
（O.P.-200m）



Ground motion produced by ASP5 is dominant in short period range (0.2 – 0.3 sec), and in longer period range the other asperities are also influential.

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Outline of the source model by Irikura and Kurahashi (2011)

•A source model is proposed based on forward modeling by Empirical Green's Function method using records (0.1-8sec) observed at K-net and KiK-net stations which has 5 Strong Motion Generation Areas (SMGAs).

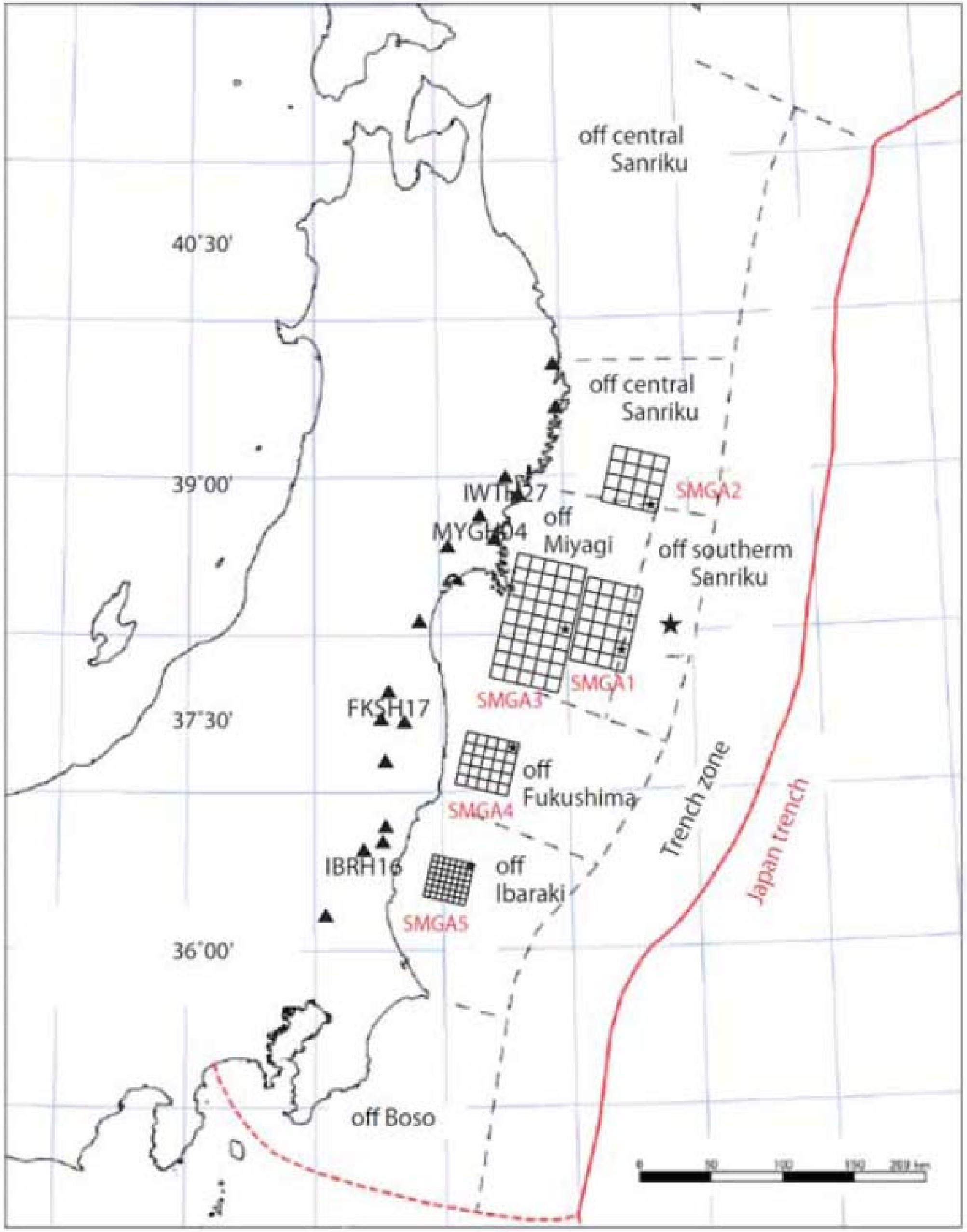
•Location of each SMGA corresponds to the source region for long-term forecast by Headquaters for Earthquake Research Promotion (HERP).

•Observed waveforms are well simulated using the proposed model.

Source parameters for the main shock

	L (km)	W (km)	Mo(Nm)	Stress Drop (Mpa)	Delay time from Origin time (sec)
SMGA 1	62.40	41.60	2.31E+21	41.3	15.64
SMGA 2	41.60	41.60	7.05E+20	23.6	66.42
SMGA 3	93.60	52.00	4.34E+21	29.5	68.41
SMGA 4	38.50	38.50	3.83E+20	16.4	109.71
SMGA 5	33.60	33.60	3.99E+20	26.0	118.17

Quoted from Kamae and Kawabe (2011)



Source model consisting of 5 SMGAs

Ground motion simulation using the source model by Irikura and Kurahashi (2011)

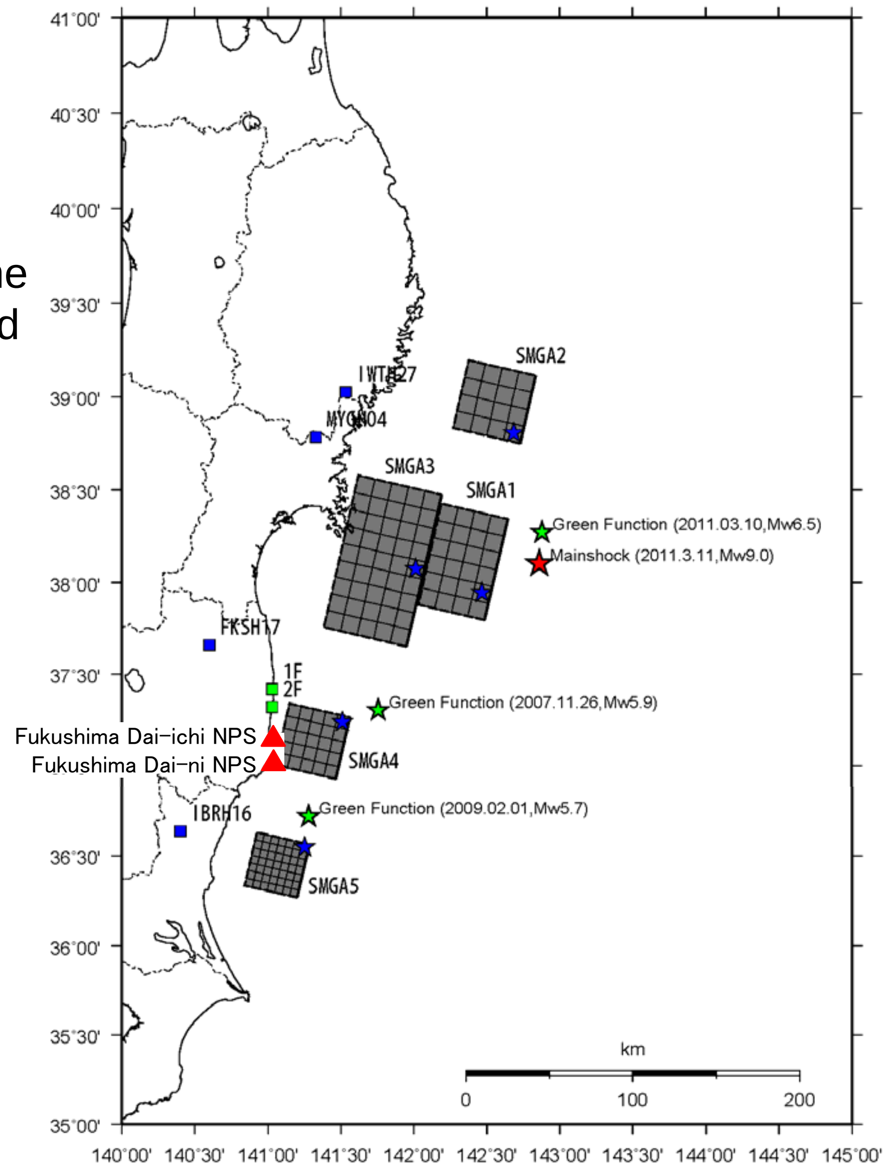
•Empirical Green's Function (EGF) method is applied to the simulation since observation records of the small events at the site are available, which are also used as EGFs by Irikura and Kurahashi (2011).

Source parameters for the small events used as EGF

	Event A	Event B	Event C
Origin time※1	2011/03/10 06:24	2007/11/26 22:51	2009/02/01 06:51
EGF	SMGA 1-3	SMGA 4	SMGA 5
Latitude (deg) ※1	38.172	37.304	36.717
Longitude (deg) ※1	143.045	141.757	141.279
Depth (km) ※1	9.3	44.1	47.0
M_{JMA} ※1	6.8	6.0	5.8
M_0 ※2	5.51×10^{18}	7.66×10^{17}	4.65×10^{17}

*1JMA, *2F-net

Quoted from Irikura and Kurahashi (2011)



The source model and the location of SMGAs

Quoted from Irikura and Kurahashi (2011)

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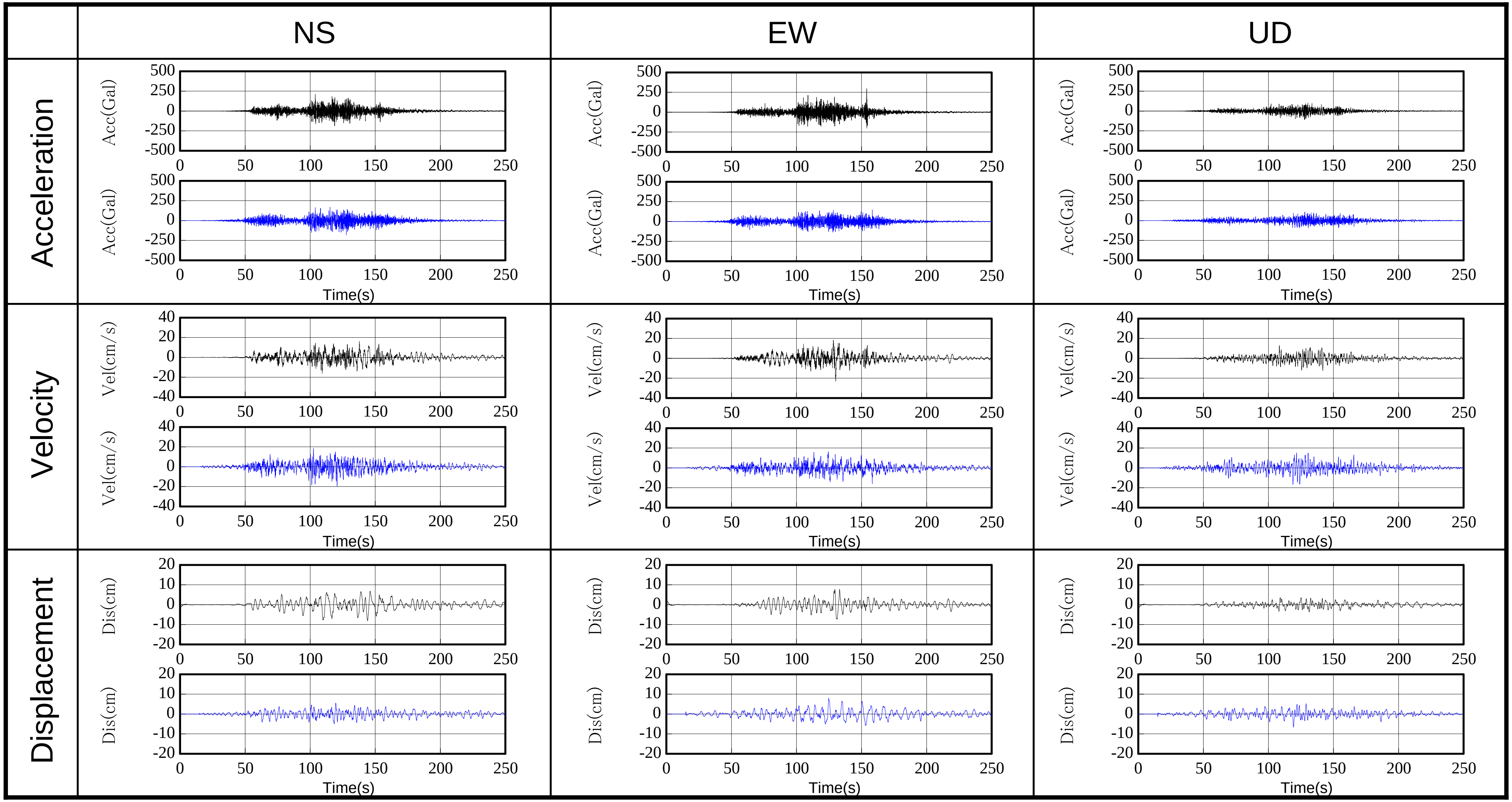
Simulation result using the source model by Irikura and Kurahashi (2011)

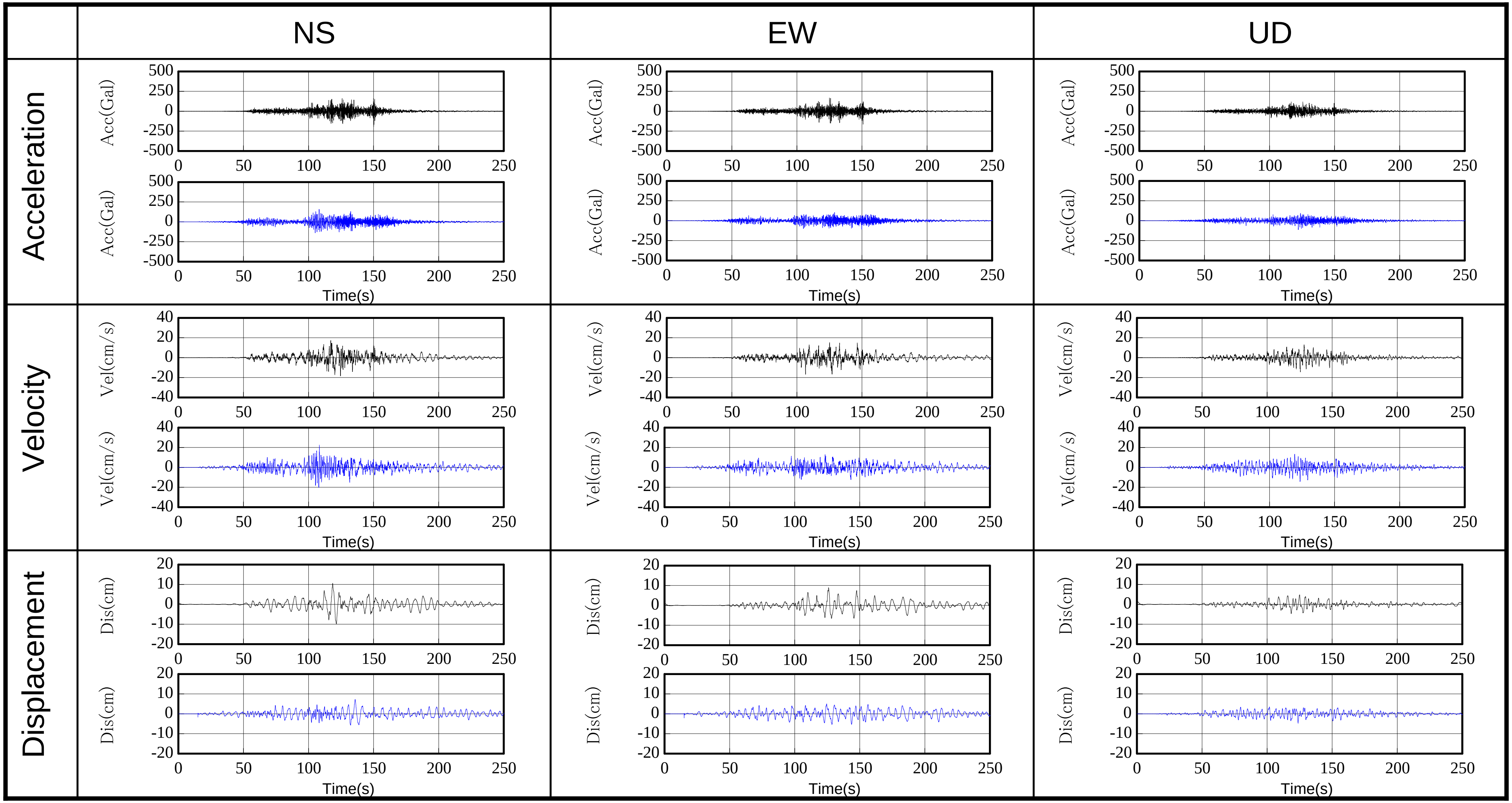
Fukushima Dai-ichi NPS: South downhole array



Comparisons of waveforms at GS4 (O.P.-200m)
Observed (black) vs Simulated (blue)

Simulation result using the source model by Irikura and Kurahashi (2011)

Fukushima Dai-ni NPS: Downhole array

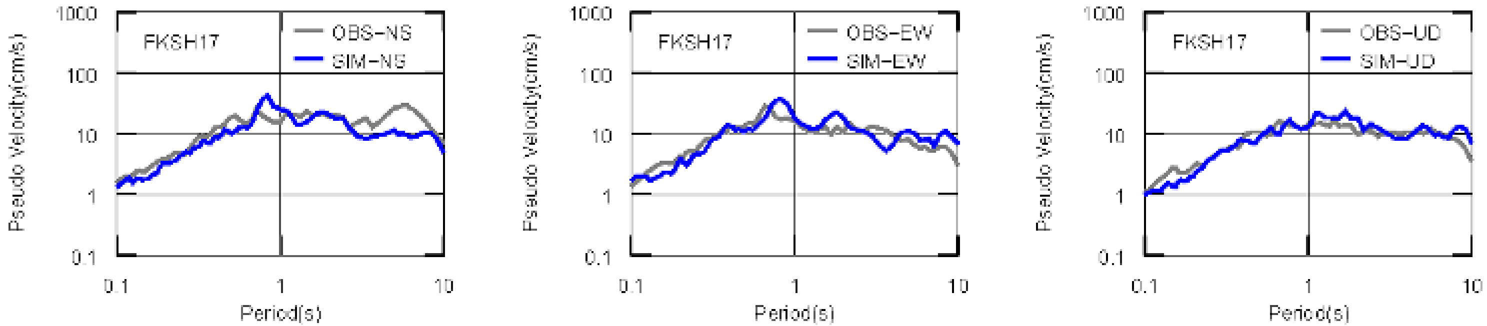


Comparisons of waveforms at FF4 (O.P.-200m)
Observed (black) vs Simulated (blue)

Simulation result using the source model by Irikura and Kurahashi (2011)

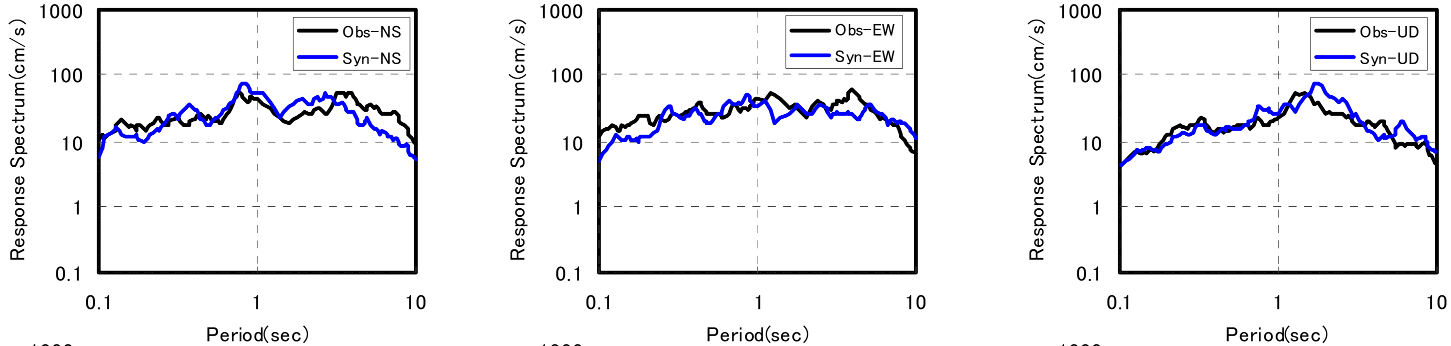
Response spectra at the KiK-net station near the site (h=5%)

KiK-net
FKSH17
(Kawamata)

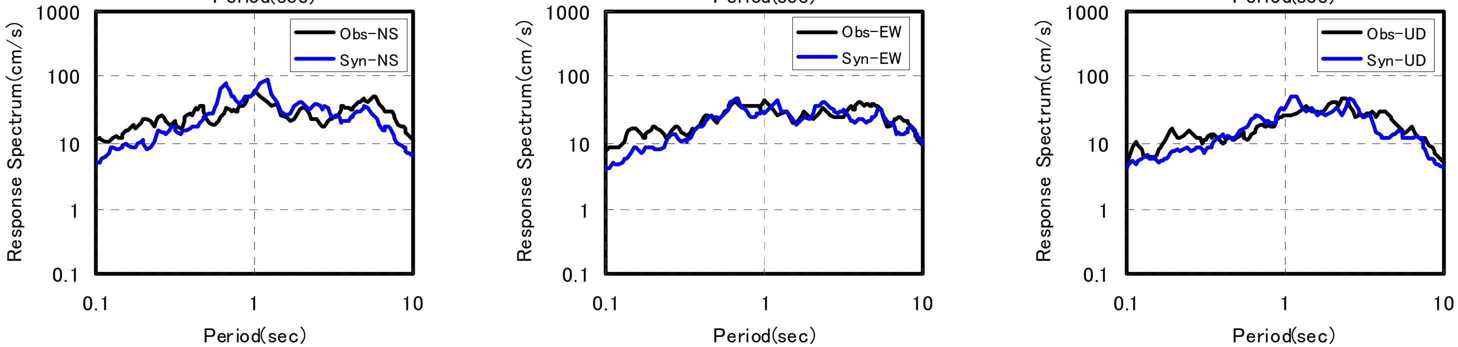


Response spectra at Fukushima Dai-ichi NPS and Dai-ni NPS site (h=5%)

Fukushima Dai-ichi
South downhole array
GS4
（O.P.-200m）



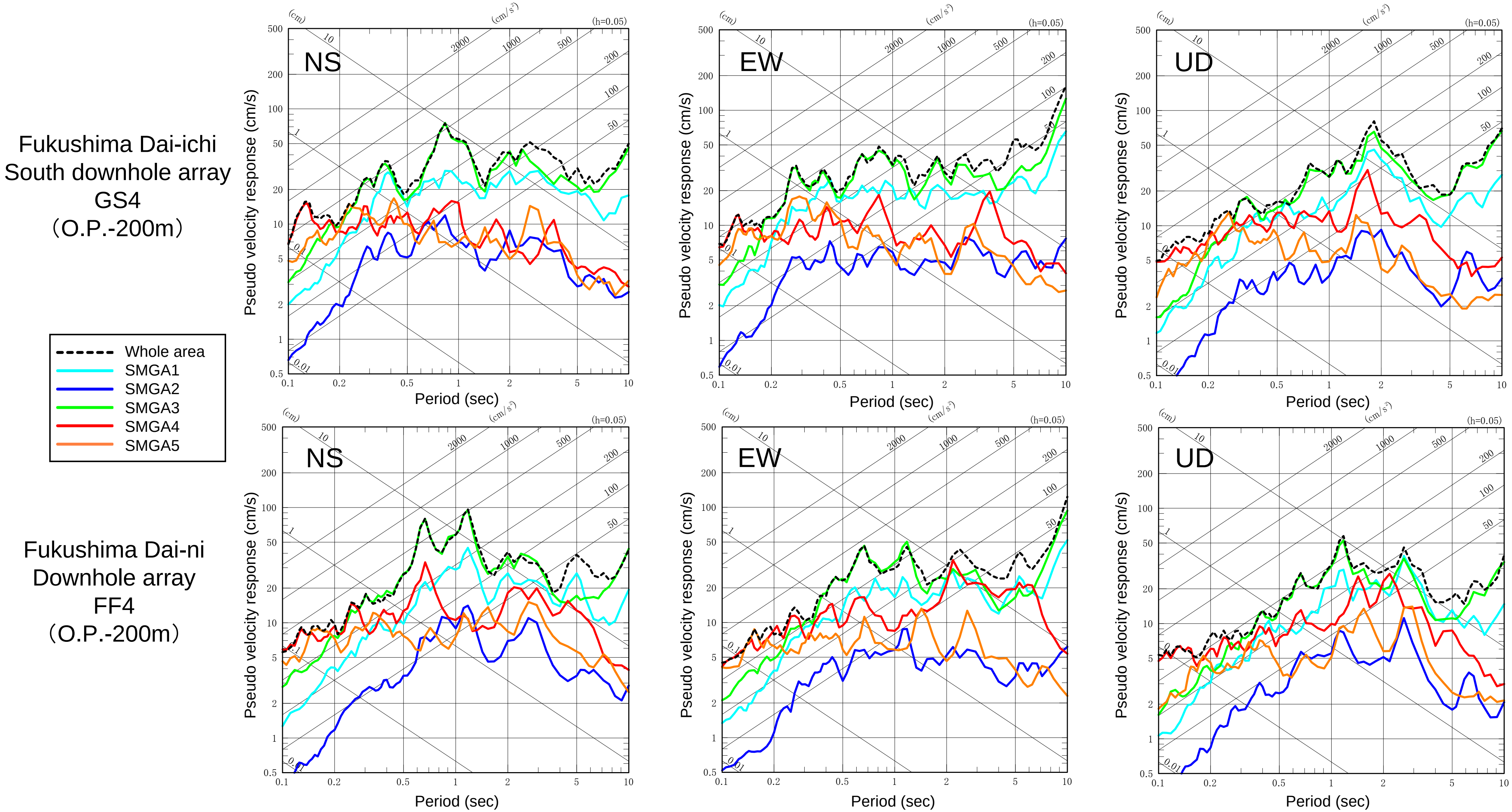
Fukushima Dai-nii
Downhole array
FF4
（O.P.-200m）



Simulation well reproduce response spectra of the observation records at Fukushima Dai-ichi NPS, Fukushima Dai-ni NPS and KiK-net station near the sites.

Simulation result using the source model by Irikura and Kurahashi (2011)

Response spectra produced by each SMGAs(h=5%)



Ground motion produced by SMGA4 & 5 are dominant in short period range (0.2 – 0.3 sec), and in longer period range the other SMGAs are also influential.

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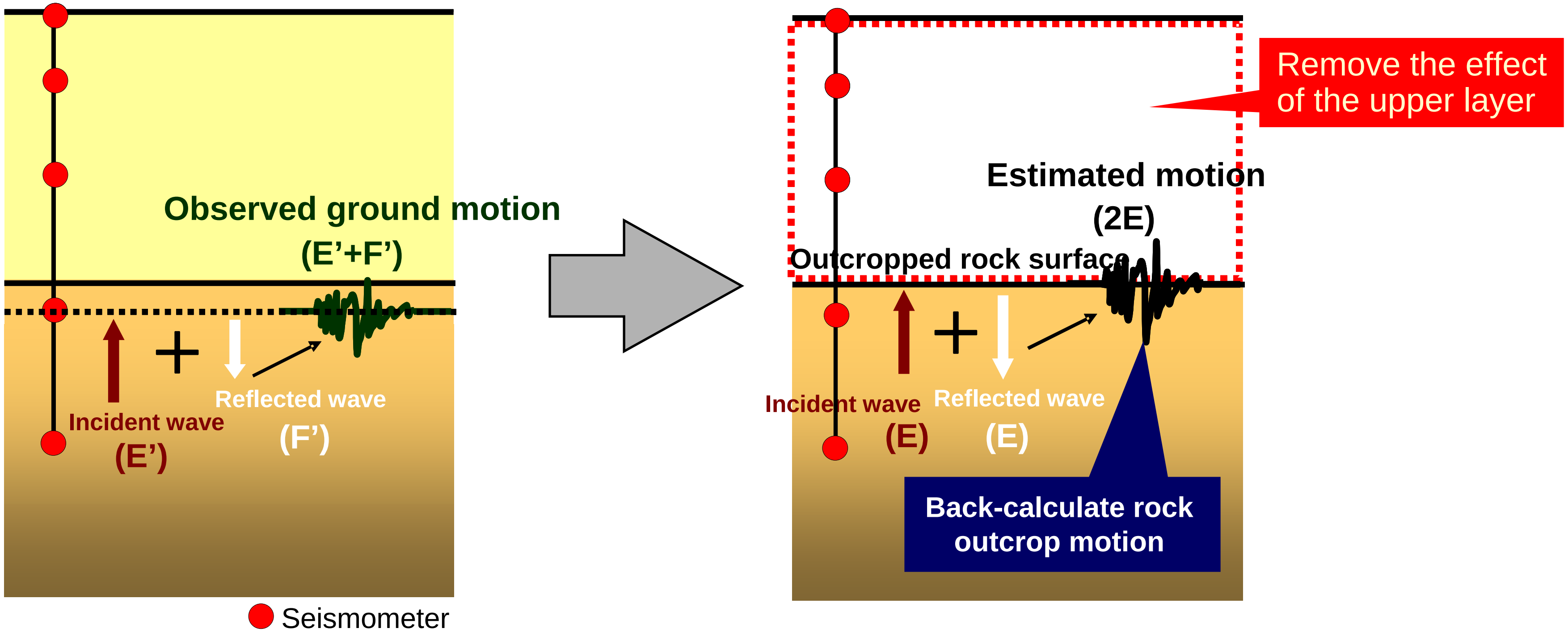
3. Rock outcrop motion estimation

- Back-calculation of rock outcrop motion using downhole array records observed at the NPS sites

The objective of rock outcrop motion back-calculation

•Rock outcrop motion is estimated using downhole array records and removing the effect of the upper layer.
•Rock outcrop motion can be directly compared with the Design Basis Ground Motions Ss (DBGM Ss), while they are defined on the imaginary outcropped rock surface below the site.



Concept of the rock outcrop motion

Procedures of the Simulation

1) Inversion analysis

·Finding a best fit soil model through the inversion analysis based on the transfer function evaluated from observation records of the main shock.

-Transfer functions are calculated using whole duration of the records.

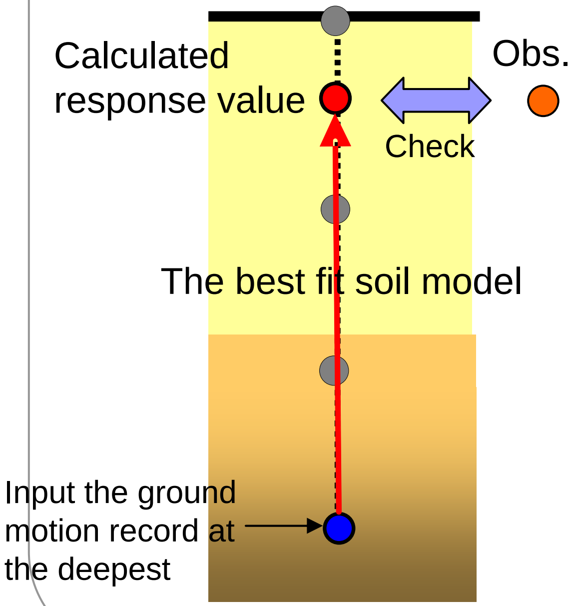
-Genetic Algorithm is adopted.

-Target parameters:
  Horizontal: Vs, h(f)
  Vertical: Vp, h(f)

-Thickness and density of the layers are fixed referring PS logging data

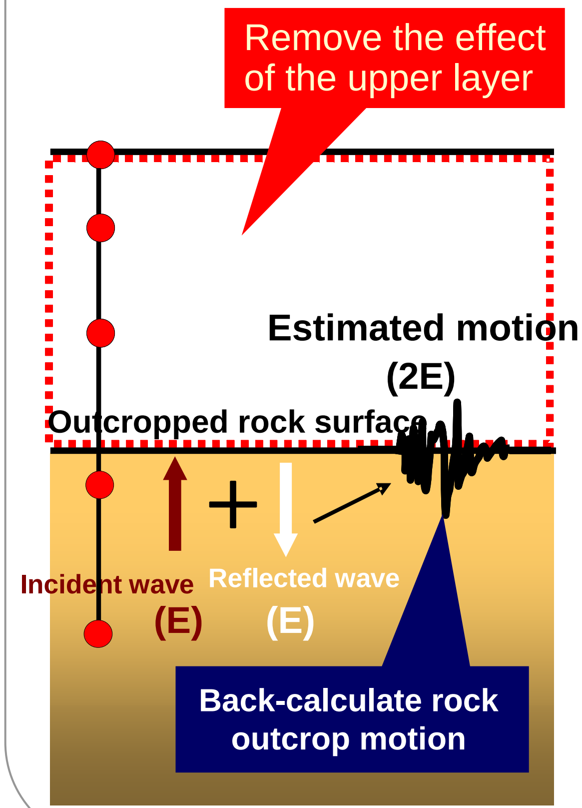
2) Fitness check

·Check the fitness of the soil model through the simulation using the observation records at the deepest point as an input



3) Rock outcrop motion estimation

·Ground motion simulation on the outcropped rock surface



South downhole array – back-calculation of soil model（horizontal）

•One dimensional equivalent linear response analysis is conducted in order to find the best fit soil model.

•Transfer functions are calculated as an average of NS & EW component, confirming little difference between them.

•Target parameters are Vs, h(f) (thickness and density of layers are fixed on the values by PS logging).

•Parameter search range:

(S-wave velocity)

O.P.+34.9m-O.P.+26.9m:

0.25 - 1.2times of the initial value

The others: 0.8 - 1.2times of the initial value

(Damping value)

$h(f)=h_0 \times f^{-\alpha}$　$0 \leqq h(f) \leqq 1$　･･･①

$0 \leqq h_0, \alpha \leqq 1$

•A total of 10 trials are made using Genetic Algorithm (GA). The soil layer having the best fitness is to be chosen.

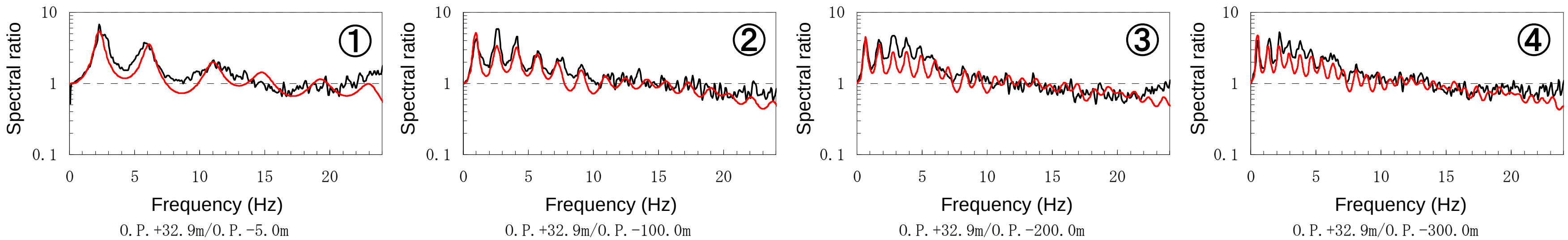
The best fit soil model (horizontal)

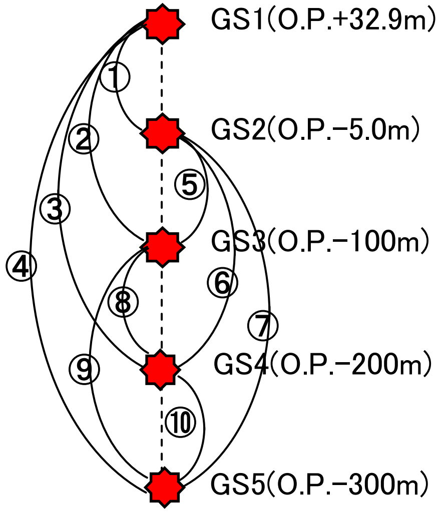
Fixed parameters			Initial value	Estimated value		
O.P. (m)	Layer thickness (m)	Density (g/cm^3)	S-wave velocity (m/s)	S-wave velocity (m/s)	Damping $h(f)=h_0 \times f^{-\alpha}$ h_0	α
+34.9	2.0	2.10	440	285	0.291	0.25
+32.9	6.0	2.10				
+26.9	8.0	2.00	280	252	0.274	1.00
+18.9	22.0	1.73	460	400		
-3.1	1.9	1.73	520	486	0.107	0.67
-5.0	44.1	1.73				
-49.1	24.0	1.80				
-73.1	24.0	1.80	590	592		
-97.1	2.9	1.77				
-100.0	9.1	1.77				
-109.1	46.0	1.77	650	659	0.063	1.00
-155.1	40.0	1.76				
-195.1	0.9	1.76	730	740		
-196.0	4.0	1.76				
-200.0	10.1	1.76				
-210.1	89.9	1.81				
-300.0	—	1.81				

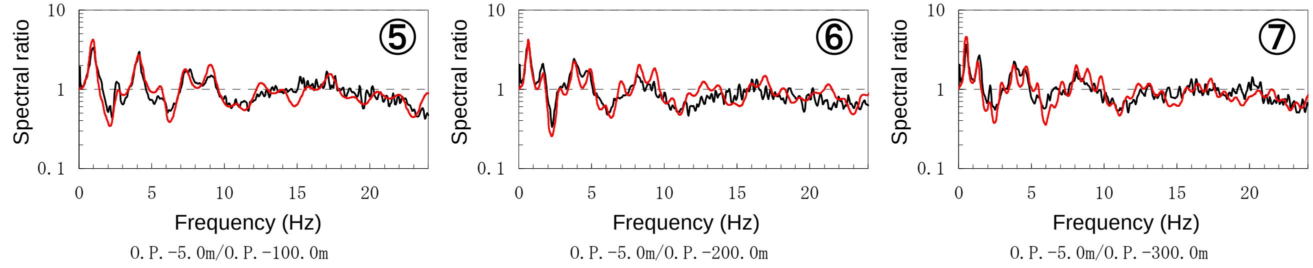
●:Seismometers

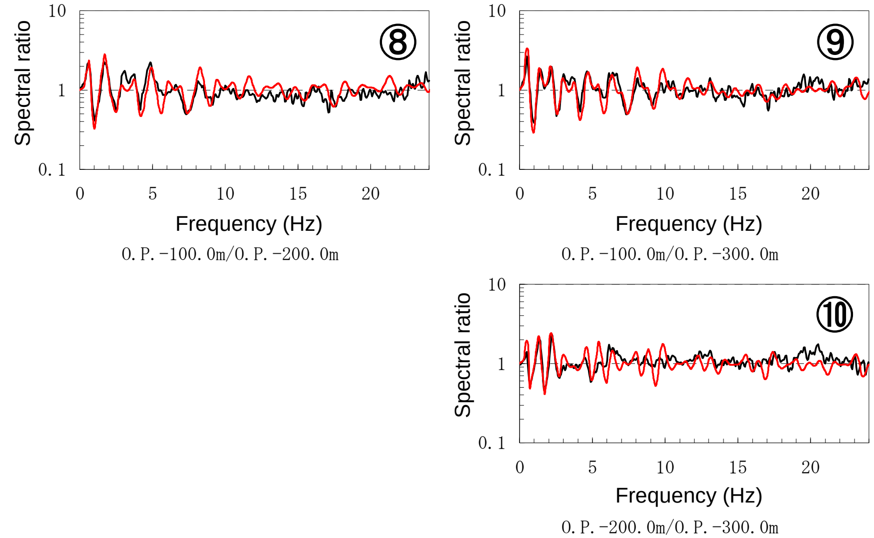
*Fixed and initial parameters are determined by PS logging.

South downhole array: Back-calculation of the soil model (horizontal)









Transfer functions are evaluated as:
-correction of baseline shift and orientation error are applied
-whole waveform are used（duration: 250sec）
-average of NS and EW are used

Comparisons transfer function between theoretical back−calculated from the best fit soil model (red) and that calculated for observed ground motion (black)

South downhole array – back-calculation of soil model (vertical)

•One dimensional equivalent linear response analysis is conducted in order to find the best fit soil model.

•Target parameters are Vp, h(f) (thickness and density of layers are fixed on the values by PS logging).

•Parameter search range:

(P-wave velocity)

O.P.+34.9m-O.P.+26.9m: 0.25 - 1.2times of the initial value

O.P.+26.9m-O.P.-3.1m: 0.7 - 1.3times of the initial value

The others: 0.8 - 1.2times of the initial value

(Damping value)

$h(f) = h_0 \times f^{-\alpha}$ $0 \leqq h(f) \leqq 1$ ･･･①

$0 \leqq h_0, \alpha \leqq 1$

•A total of 10 trials are made using Genetic Algorithm (GA). The soil layer having the best fitness is to be chosen.

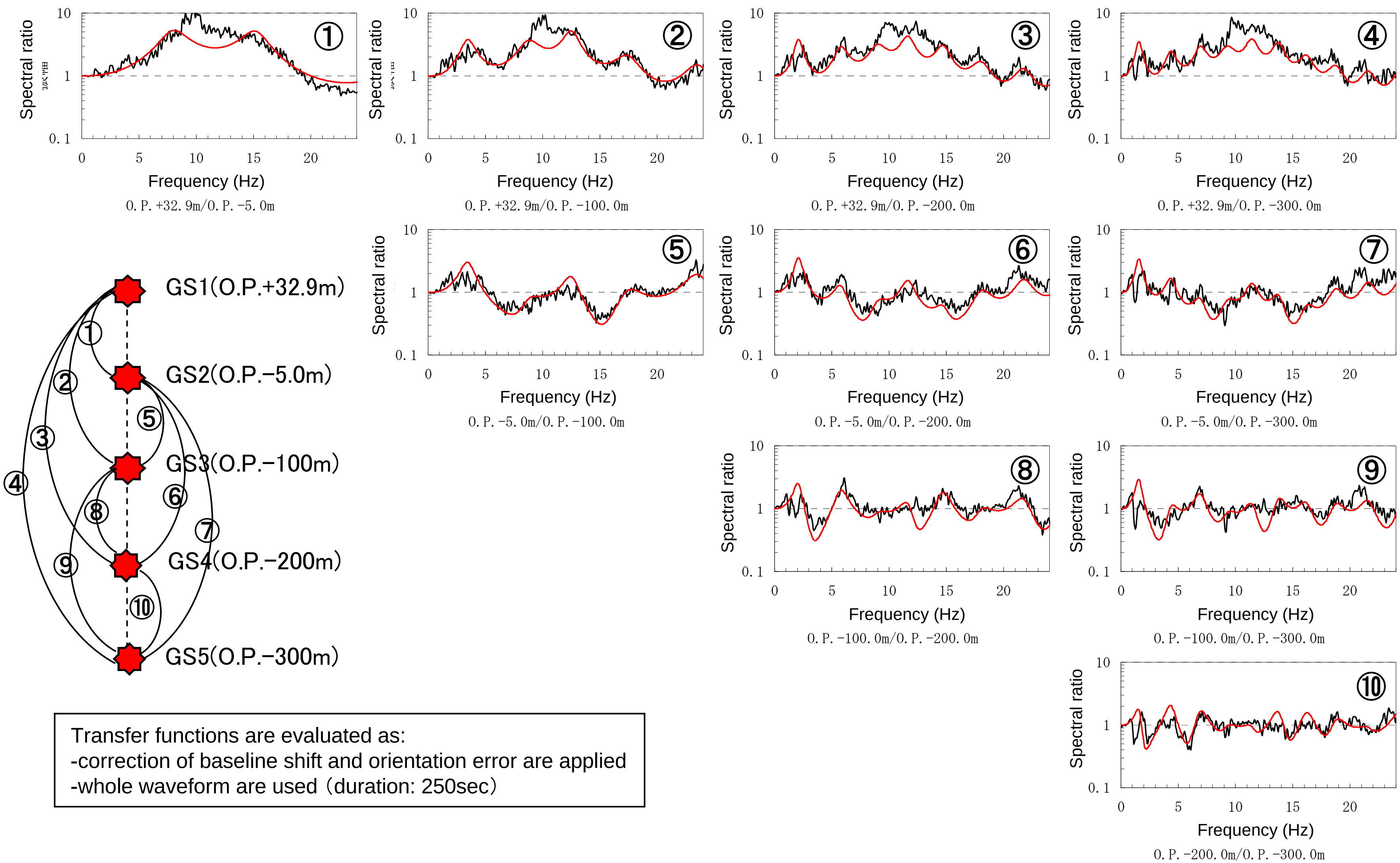
The best fit soil model (vertical)

Fixed parameters			Initial value	Estimated value		
O.P. (m)	Layer thickness (m)	Density (g/cm^3)	P-wave velocity (m/s)	P-wave velocity (m/s)	Damping $h(f)=h_0 \times f^{-\alpha}$: h_0	α
+34.9	2.0	2.10	800	366	0.139	0.55
+32.9	6.0	2.10				
+26.9	8.0	2.00	1200	1042	1.000	0.71
+18.9	22.0	1.73	1730	1502		
-3.1	1.9	1.73		1823	0.627	1.00
-5.0	44.1	1.73				
-49.1	24.0	1.80				
-73.1	24.0	1.80				
-97.1	2.9	1.77				
-100.0	9.1	1.77				
-109.1	46.0	1.77	1810	1907	0.252	1.00
-155.1	40.0	1.76				
-195.1	0.9	1.76	2000	2108		
-196.0	4.0	1.76				
-200.0	10.1	1.76				
-210.1	89.9	1.81				
-300.0	—	1.81				

●:Seismometers

*Fixed and initial parameters are determined by PS logging.

South downhole array: Back-calculation of the soil model (vertical)

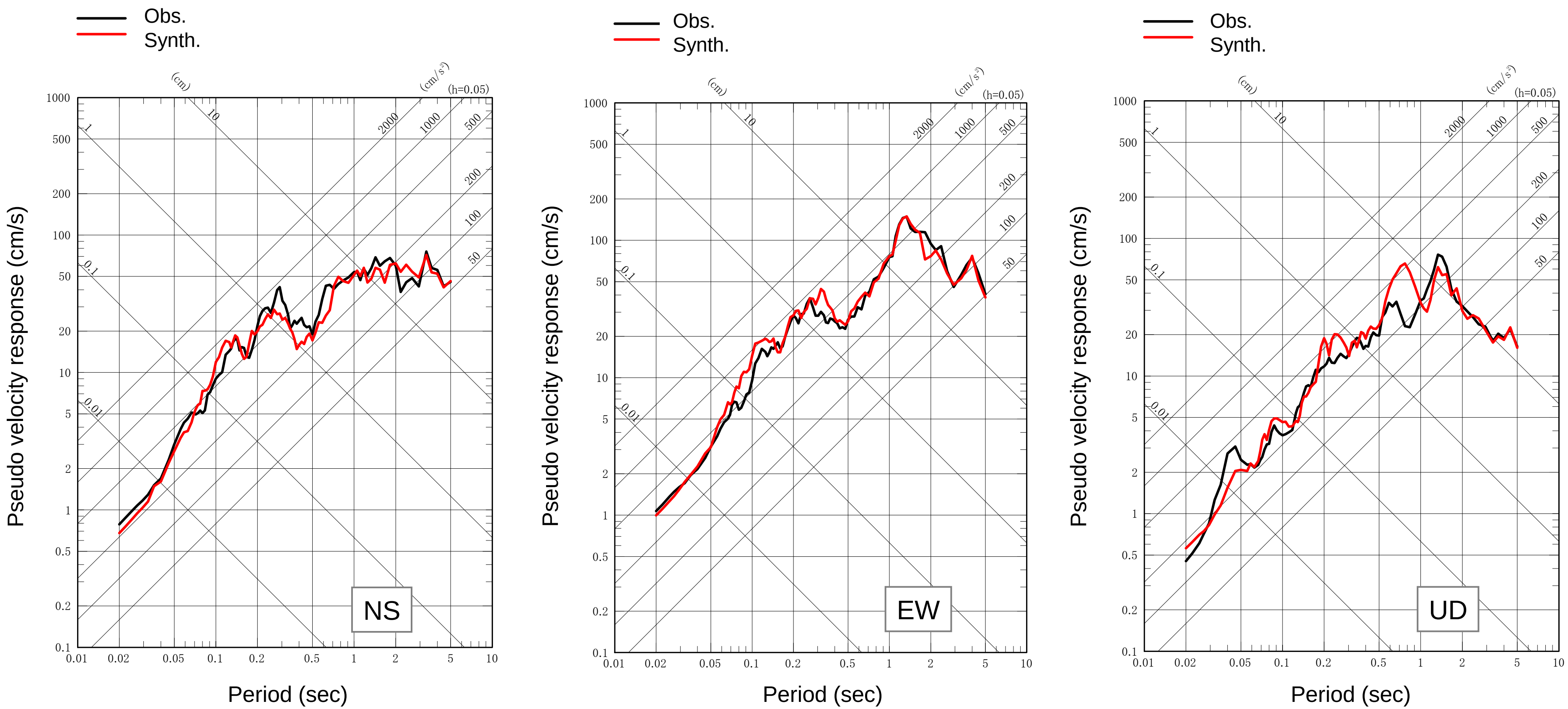


Transfer functions are evaluated as:
-correction of baseline shift and orientation error are applied
-whole waveform are used（duration: 250sec）

Comparisons of transfer functions between theoretical ones using the best fit model (red) and observed ones calculated from the records (black)

South downhole array: Fitness check of the back-calculated soil model

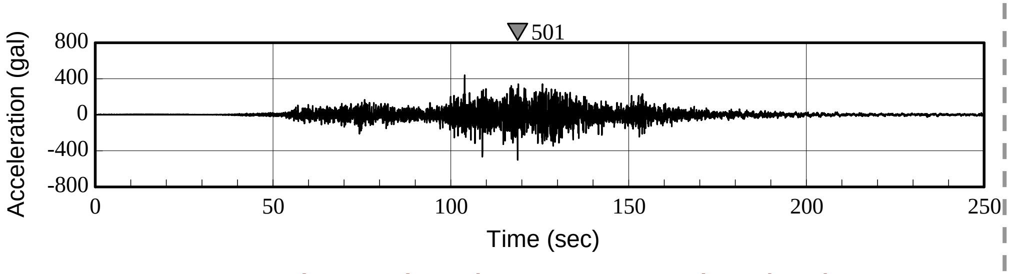
•Response analysis is conducted using the estimated soil model and observation records at O.P.-300m as an input, to compare the computed ground motion at O.P.-5.0m with observation records there.



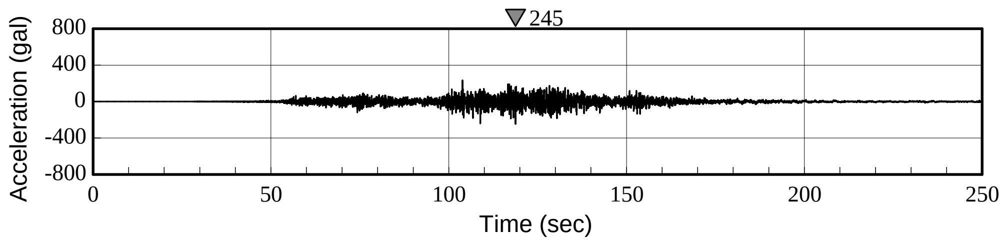
Result of the response analysis using the best fit soil model

Estimated rock outcrop motion: Fukushima dai-ichi south downhole

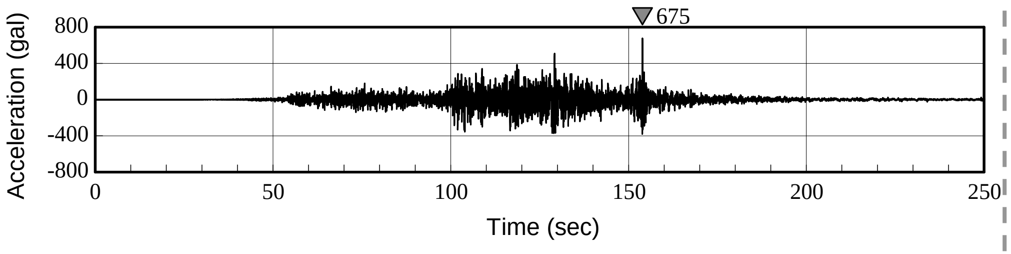
• Rock outcrop motions are back-calculated using the best fit soil model and observation records* at O.P.-200m (GS4), the nearest point from imaginary rock surface (O.P.-196m) where DBGM Ss are defined.



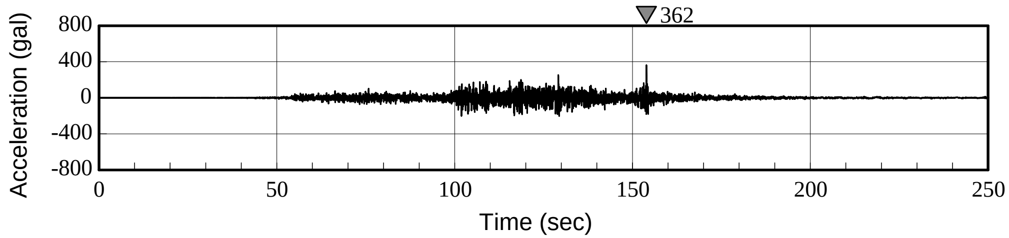
Estimated rock outcrop motion (NS)



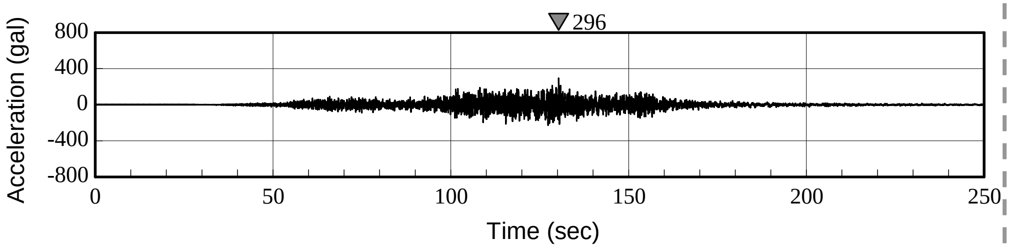
Observed at O.P.-200m (GS4: NS)



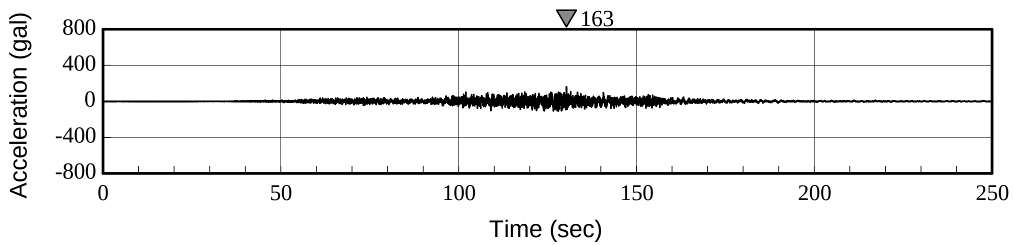
Estimated rock outcrop motion (EW)



Observed at O.P.-200m (GS4: EW)



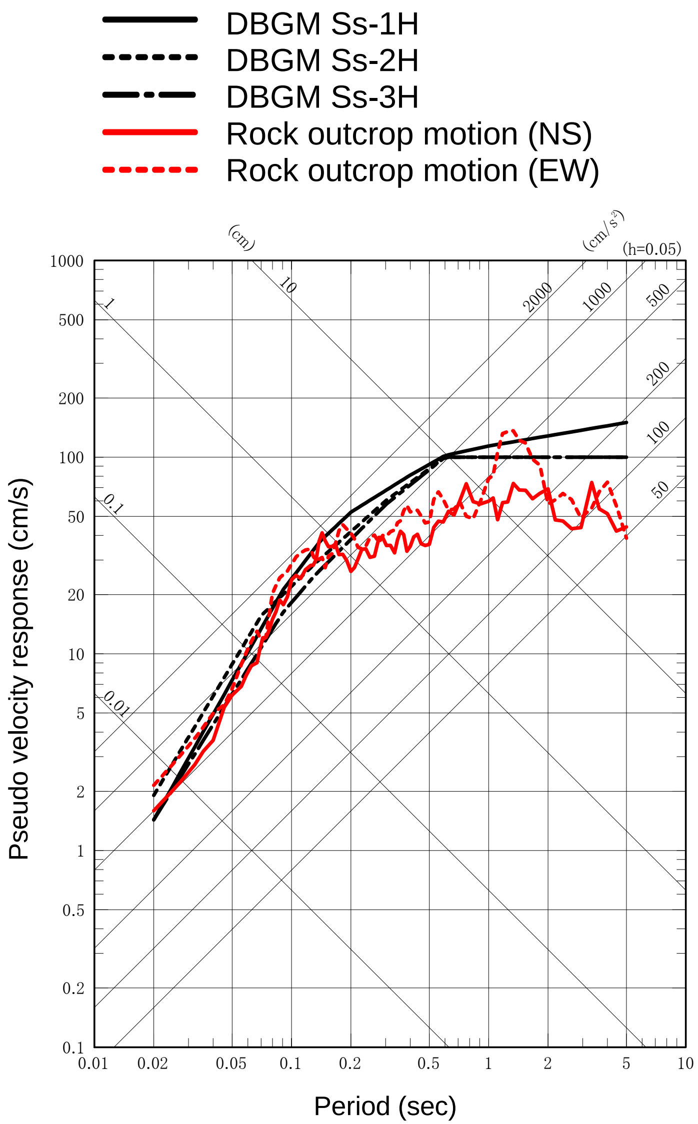
Estimated rock outcrop motion (UD)



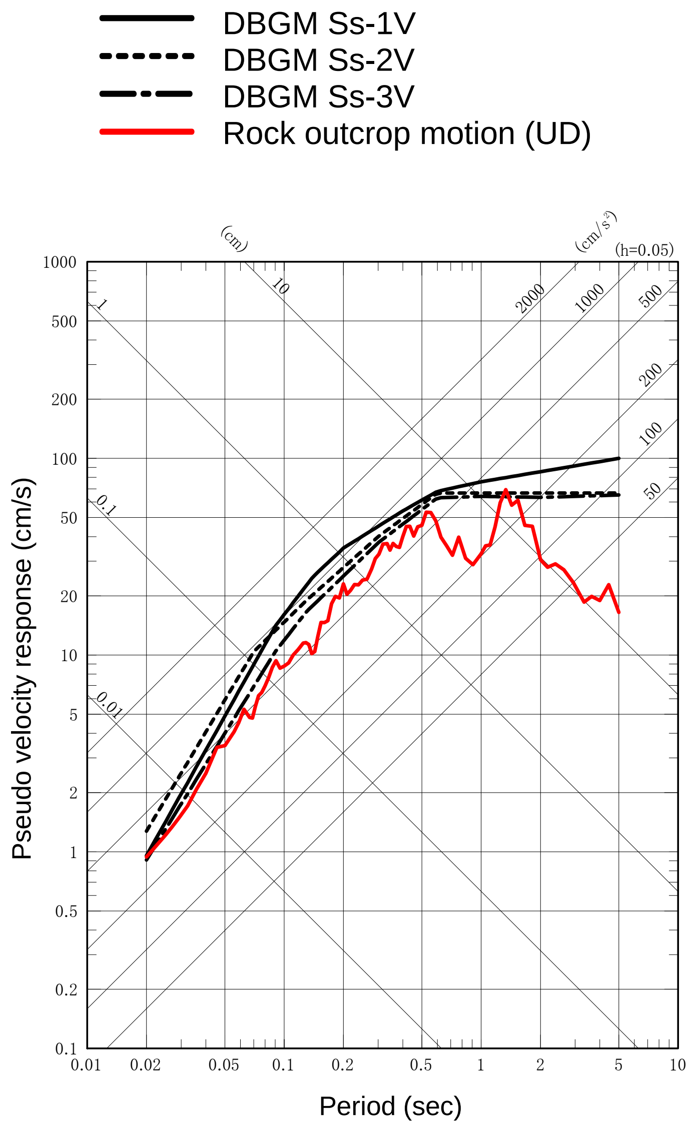
Observed at O.P.-200m (GS4: UD)

*correction of baseline shift and orientation error, and high-cut filter (24Hz) are applied

Estimated rock outcrop motion: Fukushima dai-ichi south downhole



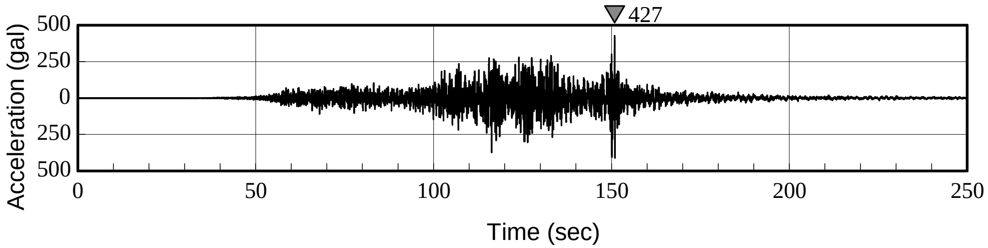
Response spectra of DBGMs and rock outcrop motion (NS&EW)



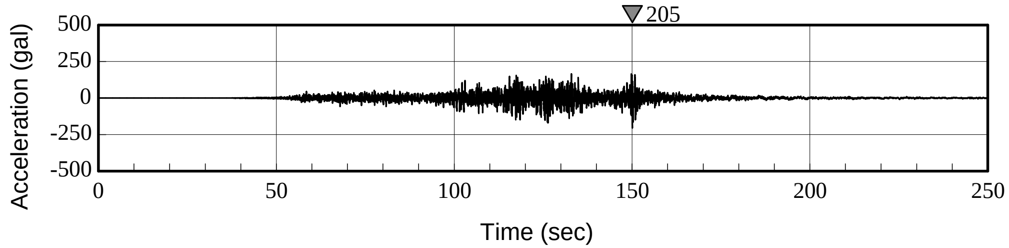
Response spectra of DBGMs and rock outcrop motion (UD)

Estimated rock outcrop motion: Fukushima dai-ni downhole

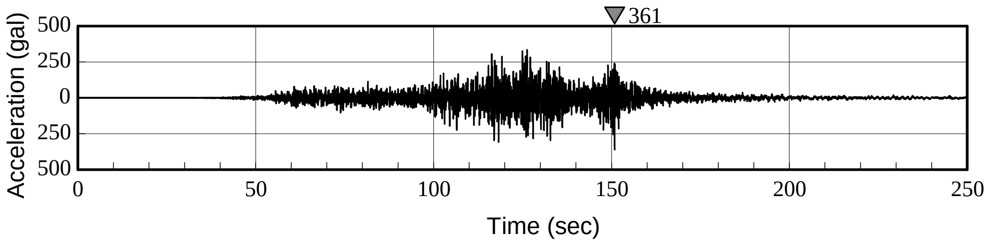
•Rock outcrop motions are back-calculated using the best fit soil model and observation records* at O.P.-200m (FF4), the nearest point from imaginary rock surface (O.P.-168m) where DBGM Ss are defined.



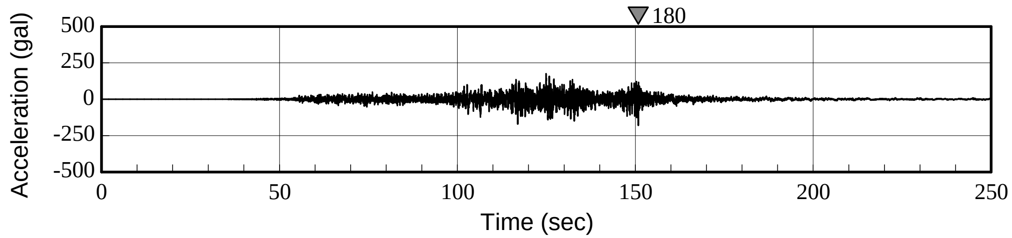
Estimated rock outcrop motion (NS)



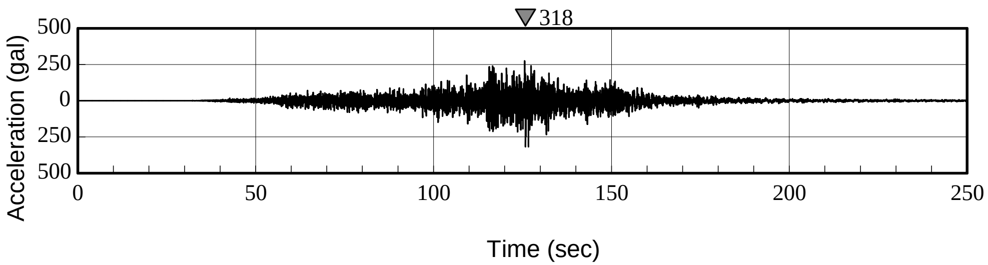
Observed at O.P.-200m (FF4: NS)



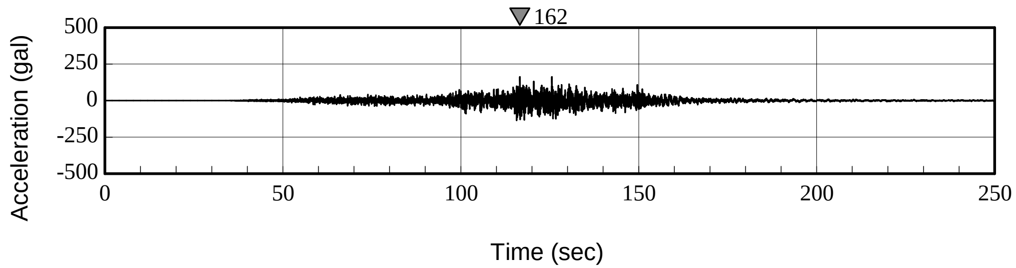
Estimated rock outcrop motion (EW)



Observed at O.P.-200m (FF4: EW)



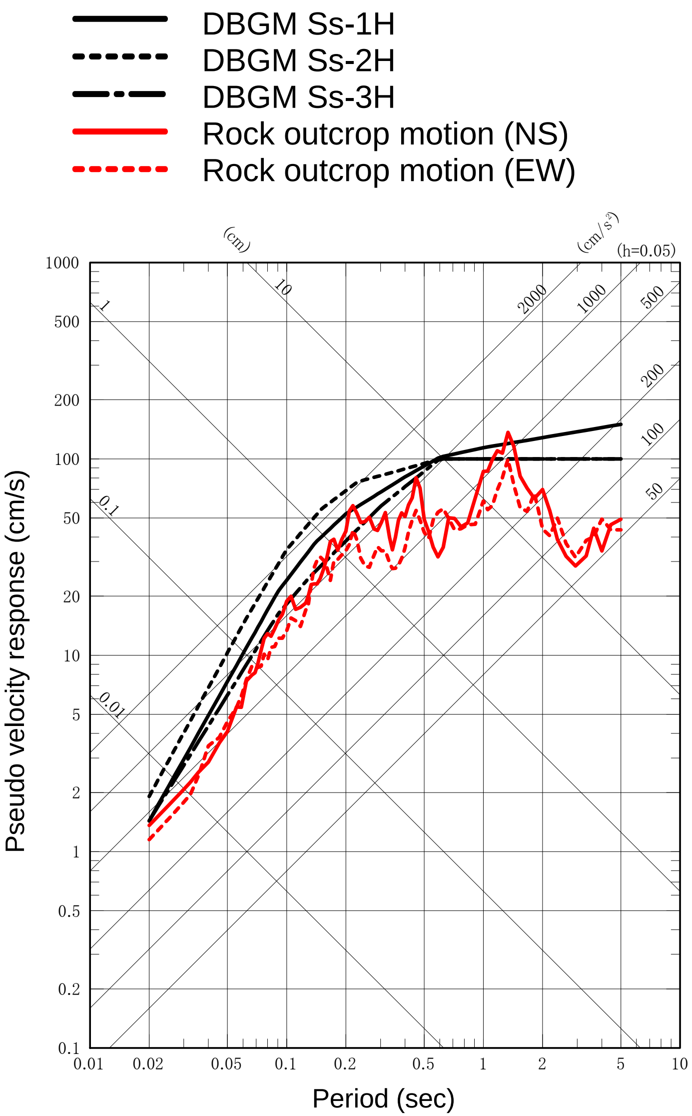
Estimated rock outcrop motion (UD)



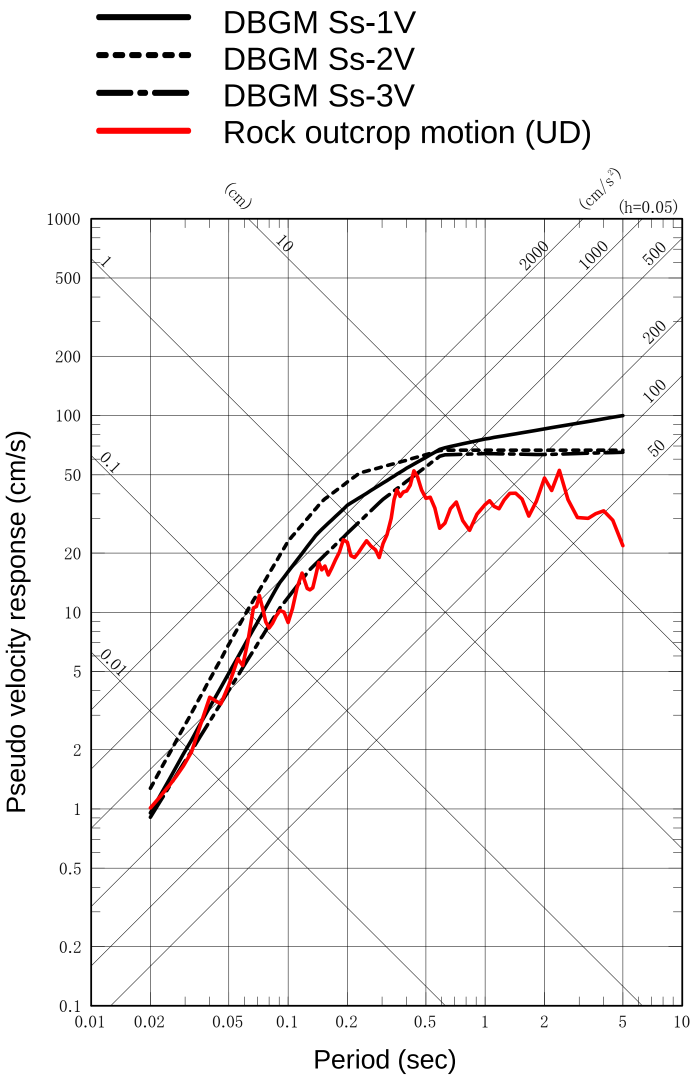
Observed at O.P.-200m (FF4: UD)

*correction of baseline shift and orientation error, and high-cut filter (24Hz) are applied

Estimated rock outcrop motion: Fukushima dai-ni downhole



Response spectra of DBGMs and rock outcrop motion (NS&EW)



Response spectra of DBGMs and rock outcrop motion (UD)

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Conclusion

Strong motion simulations at Fukushima Dai-ichi and Dai-ni NPS sites are carried out applying two models as a source fault model of the Great East Japan earthquake.
Also rock outcrop strong motions are calculated for each site using downhole strong motion records, in order to evaluate the ground motion at these NPS sites' compound.
The following conclusions are made tentatively.

1) The source models proposed by Kamae and Kawabe (2011) and Irikura and Kurahashi (2011) well reproduce the strong motion observed at Fukushima Dai-ichi NPS and Fukushima Dai-ni NPS site.
Ground motions generated by asperities (or SMGAs) near the sites are dominant in the short-period range, and the other asperities (or SMGAs) have influences on the ground motion level in relatively longer-period range at each NPS site.

2) The peak accelerations of the back-calculated rock outcrop motion at a depth of 200m are 675 Gal and 427 Gal at Fukushima Dai-ichi and Dai-ni NPS site respectively.
Estimated rock outcrop motions are almost the same level as the design basis ground motion Ss at Fukushima Dai-ichi NPS site although peak acceleration value slightly exceeded that of Ss.
At Fukushima Dai-ni NPS, estimated rock outcrop motions are below the level of Ss.

Thank you for your attention.