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STRONG MOTION RECORDS OF THE GREAT EAST JAPAN EARTHQUAKE OBSERVED AT FUKUSHIMA DAI-ICHI NUCLEAR POWER PLANT AND FUKUSIHIMA DAI-NI NUCLEAR POWER PLANT

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ABSTRACT: Strong motion simulations for Fukushima Dai-ichi and Dai-ni are carried out applying two models as a source fault model of the main shock. The result of these simulations well reproduce response spectra of the observation records at each site, and suggest that the asperity, or strong motion generation area, near the sites for each model have the largest impact in the higher frequency range of strong motion.

Key Words: Great East Japan earthquake, downhole array strong motion records, rock outcrop strong motion, empirical Green's function method, strong motion generation area

INTRODUCTION

On March 11th, strong motions caused by the Great East Japan earthquake were observed at Fukushima Dai-ichi Nuclear Power Plant and Fukushima Dai-ni Nuclear Power Plant. There were 53 seismometers installed at Fukushima Dai-ichi NPP and 43 at Fukushima Dai-ni NPP, both in the buildings and free field borehole arrays. At Fukushima Dai-ichi NPP, peak acceleration of 550Gal was observed on the foundation slab of the reactor building of Unit 2, and 305Gal at Fukushima Dai-ni Unit 1. Observation records in the Fukushima Dai-ichi reactor buildings are almost the same level as the response simulation result using the design basis ground motion Ss although some of the peak acceleration values slightly exceeded those of the simulation results.

Here strong motion simulations for Fukushima Dai-ichi and Dai-ni are carried out applying two models as a source fault model of the main shock. Also rock outcrop motions are estimated for each site using strong motion records at the downhole arrays, in order to evaluate the ground motion during the main shock at these NPP sites' compound.

STRONG MOTION OBSERVED AT FUKUSHIMA DAI-ICHI AND DAI-NI NPP

At Fukushima Dai-ichi Nuclear Power Plant and Fukushima Dai-ni Nuclear Power Plant, seismic observations have been made by seismometers installed in the site foundation, reactor building of each unit, and seismic observation house. At Fukushima Dai-ichi Nuclear Power Plant, total of 53 seismometers are installed for seismic observation. As for the Fukushima Dai-ni Nuclear Power Station, 43 seismometers are installed. Figure 1 - 4 show the overview of seismic observation points at Fukushima Dai-ichi Nuclear Power Plant and Fukushima Dai-ni Nuclear Power Plant, and observed strong motion records during the earthquake in the downhole arrays at each NPP site.

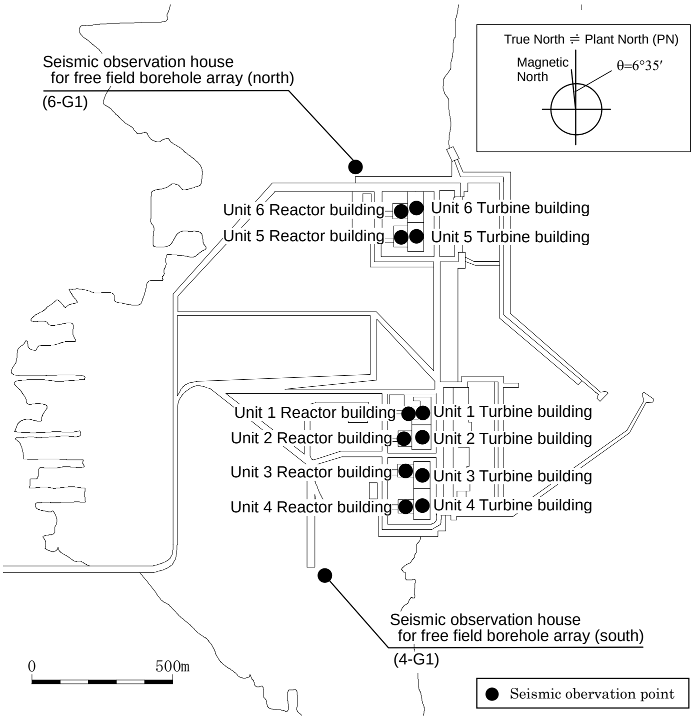


Fig. 1 Schematic location of the downhole seismic arrays installed at Fukushima Dai-ichi NPP

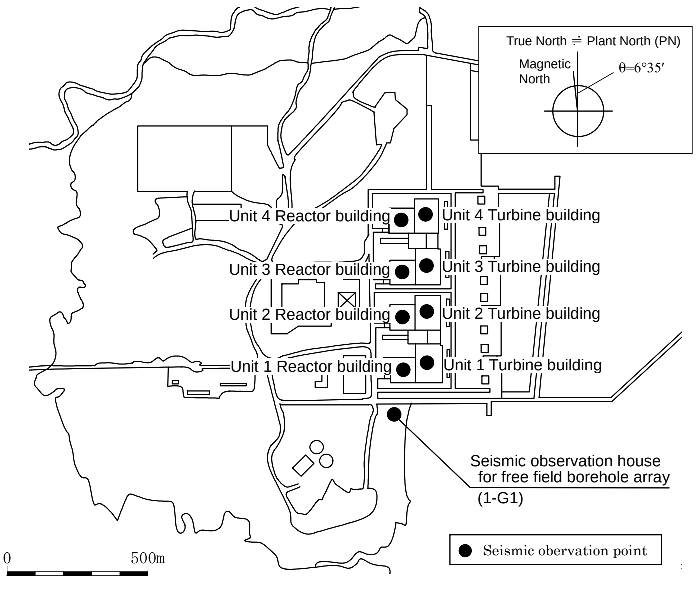


Fig. 2 Schematci location of the downhole seismic array installed at Fukushima Dai-ichi NPP

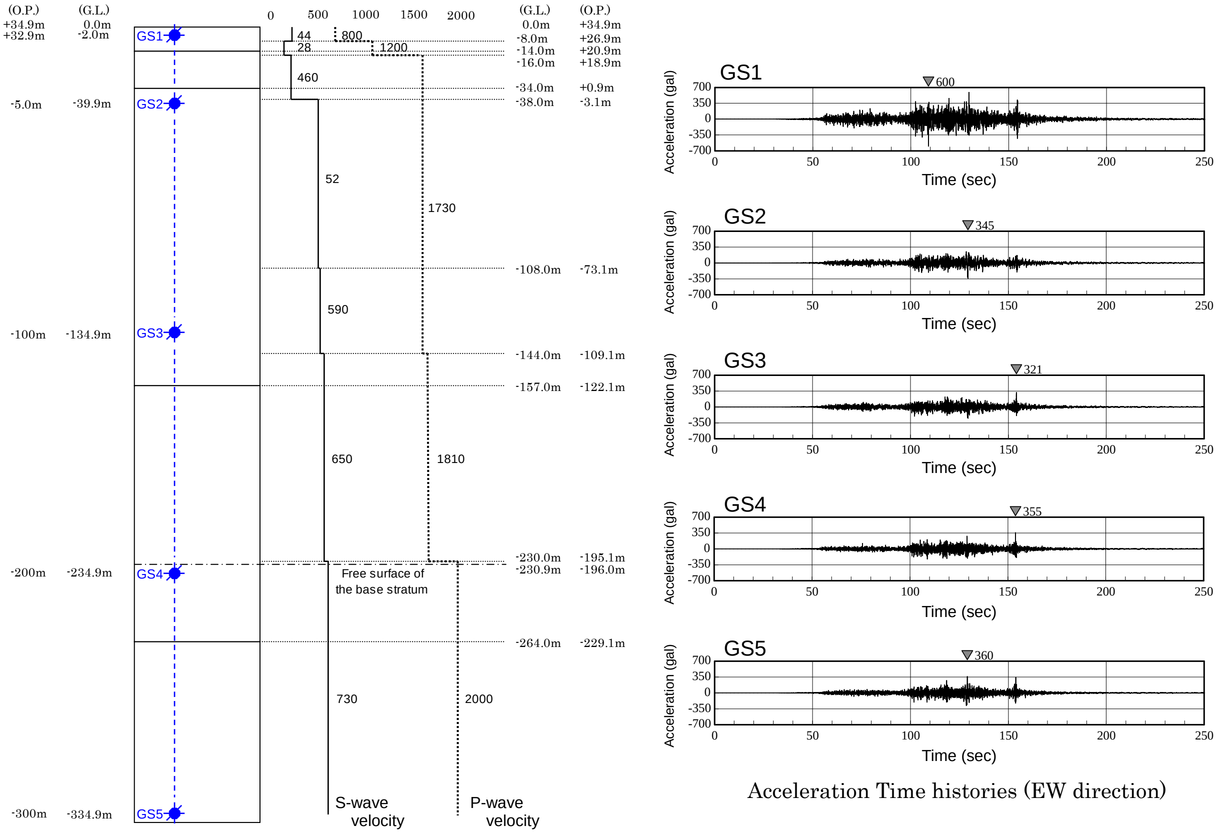


Fig. 3 Soil profile with seismometer locations and observed acceleration time history in the south free field bore hole array at Fukushima Dai-ichi NPP

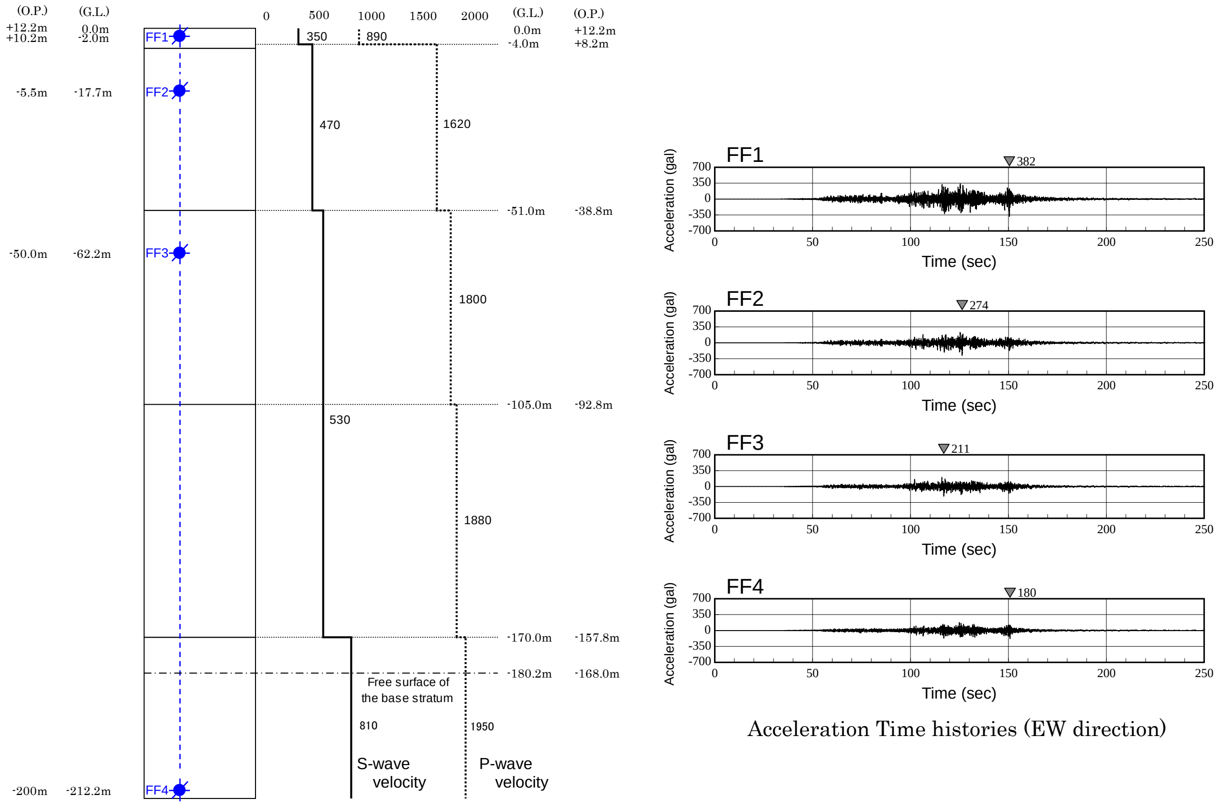


Fig. 4 Soil profile with seismometer locations and observed acceleration time history in the free field bore hole array at Fukushima Dai-ni NPP

GROUND MOTION SIMULATION AT FUKUSHIMA DAI-ICHI AND DAI-NI NPP SITES

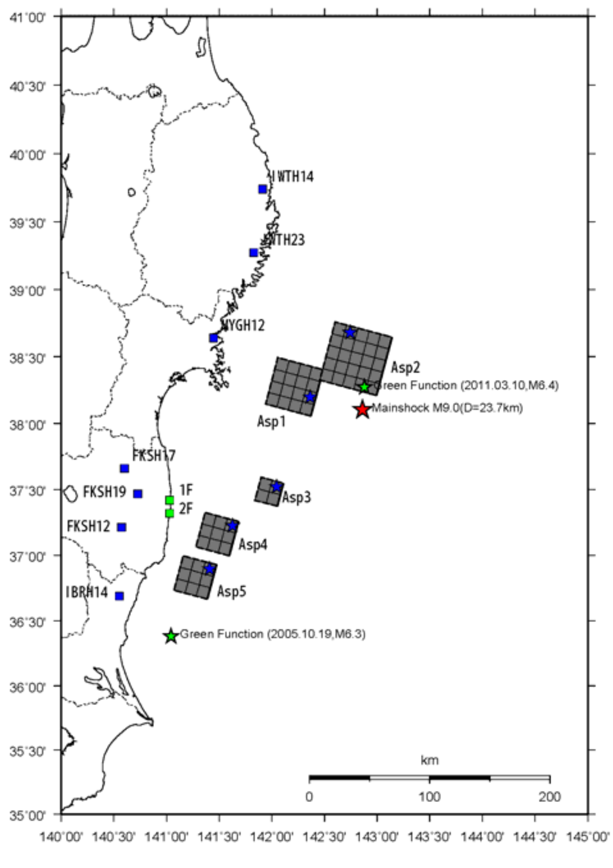
As for the Great East Japan Earthquake, several source models are proposed using GPS data, tsunami records, strong motion records or teleseismic records. Source models proposed by Kamae and Kawabe (2011) and Irikura and Kurahashi (2011) are ones which can be used for the estimation of strong motion including high frequency range, crucial for the seismic safety evaluation of nuclear facilities. Here ground motion simulations at Fukushima Dai-ichi and Dai-ni NPP 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.

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

First, ground motion simulation using the source model by Kamae and Kawabe (2011) is carried out. Fig. 5 shows the characterized source model consisting of five asperities proposed for the main shock, its source parameters and the source parameters of the two small events observation records of which are used as Empirical Green's Functions (EGFs) in order to synthesize ground motion of the main shock.

Fig. 6 shows the computed acceleration time histories and response spectra at a depth of 200m (GS4 and FF4), compared with the observation records at the same location. Not only the waveforms but also response spectra are consistent with the observed ones.

Fig. 6 also shows calculated response spectra for the ground motion produced by each asperity compared with the one produced by the whole source area. These comparisons suggest that strong motions in the high frequency range at each NPP site are mainly generated by the asperities near the sites (Asp 3 – 5).



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

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

Fig. 5 The source modlel and source parameters (quoted from Kamae and Kawabe (2011))

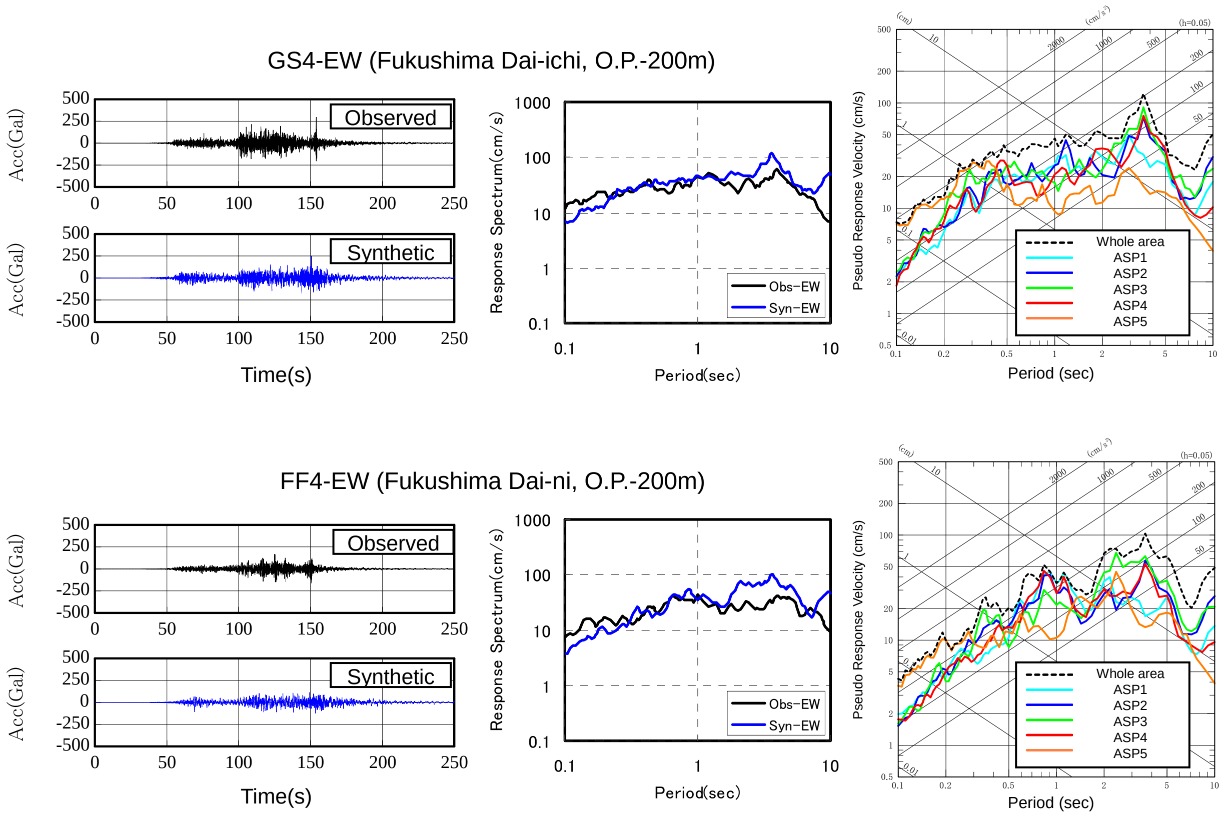


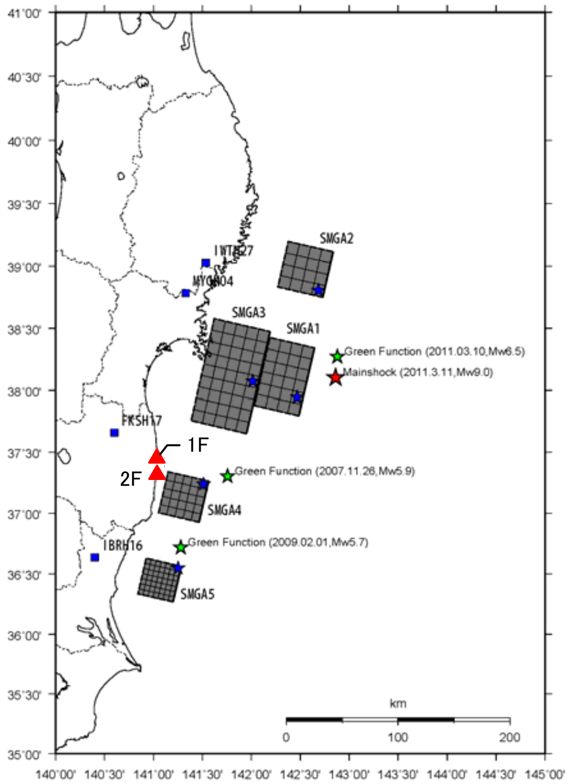
Fig. 6 Calculated acceleration time histories and response spectra using the source model by Kamae and Kawabe (2011)

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

Secondly, ground motion simulation using the source model by Irikura and Kurahashi (2011) is carried out. Fig. 7 shows the characterized source model consisting of five strong motion generation areas (SMGAs) with large slip velocity or high stress drop like asperities defined by Kamae and Kawabe (2011), with its source parameters and the source parameters of the three small events which are used as Empirical Green's Functions (EGFs) for the ground motion simulation of the main shock.

Fig. 8 shows the computed acceleration time histories and response spectra at a depth of 200m (GS4 and FF4), compared with the observation records at the same location. Both synthesized waveforms and response spectra are consistent with the observed ones.

Calculated response spectra for the ground motion produced by each SMGA are also shown in Fig.8, compared with the spectra produced by the whole source area. In the high frequency range ground motions generated by SMGA4 and SMGA5 mainly control the level of the strong motion, and the other SMGAs have influences on the ground motion level in relatively lower frequency range at each NPP site.



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

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

Fig. 7 The source modlel and source parameters (quoted from Irikura and Kurahashi (2011))

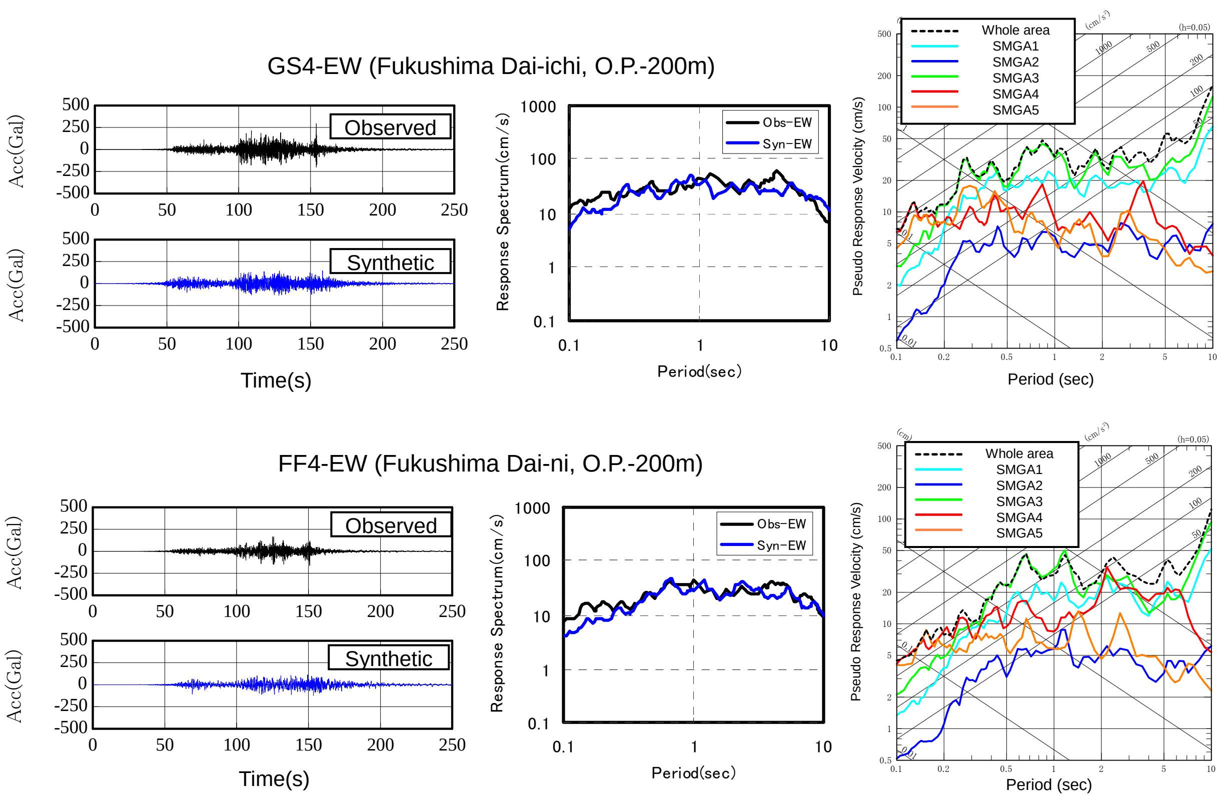


Fig. 8 Calculated acceleration time histories and response spectra using the source model by Irikura and Kurahashi (2011)

Now rock outcrop motions are back-calculated using strong motion downhole array records during the main shock at each NPP sites, based on the inversion analysis using the genetic algorithm combined with one dimensional linear response analysis. Fig. 9 shows back-calculated soil layer model that minimizes the misfit of observed and computed transfer functions between any of the two depth in the south downhole array at Fukushima Dai-ichi NPP site, and Fig. 10 shows estimated rock outcrop motions at each NPP site, compared with design basis ground motion Ss which are also defined as rock outcrop motions at every NPP sites.

Fixed parameters			Initial value	Estimated value		
O.P. (m)	Thickness (m)	Density (g/cm³)	S-wave velocity (m/s)	S-wave velocity (m/s)	Dumping $h(f)=h_0 \times f^{-\alpha}$ 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 parameters are determined by PS logging.

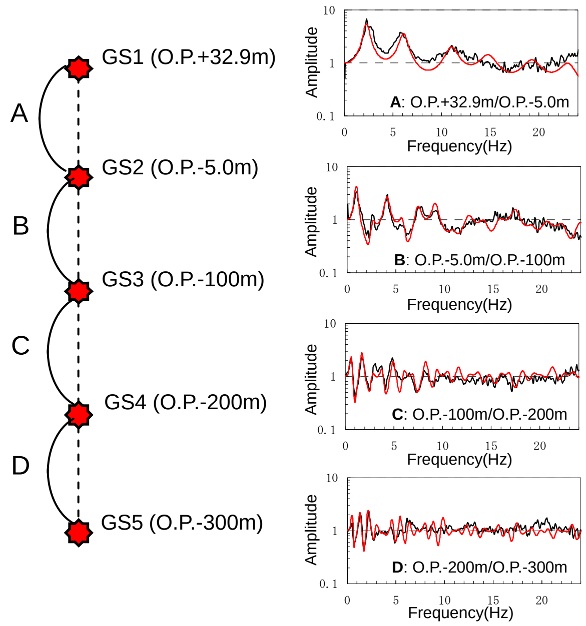


Fig. 9 Back-calculated soil model and transfer functions of the south downhole array at Dai-ichi NPP site

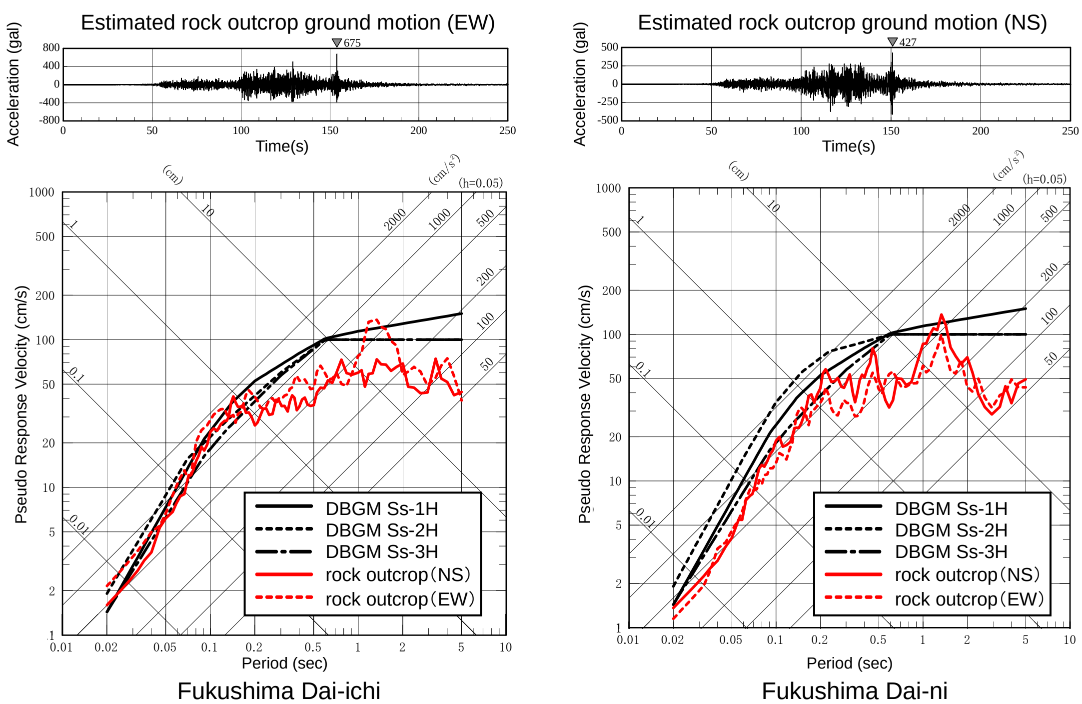


Fig. 10 Estimated acceleration time histories and response spectra of the rock outcrop motions

CONCLUSIONS

Strong motion simulations at Fukushima Dai-ichi and Dai-ni NPP 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 NPP sites' compound. The followings 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 NPP and Fukushima Dai-ni NPP site. Ground motions generated by asperities (or SMGAs) near site mainly control the level of the strong motion in the high frequency range, and the other asperities (or SMGAs) have influences on the ground motion level in relatively lower frequency range at each NPP 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 NPP site respectively. Estimated rock outcrop motions are almost the same level as the design basis ground motion Ss at Fukushima Dai-ichi NPP site although peak acceleration value slightly exceeded that of Ss. At Fukushima Dai-ni NPP, estimated rock outcrop motions are below the level of Ss.

REFERENCES

Dan, K., Watanabe, M., Sato, T. and Ishii, T.(2001). "Short-period source spectra inferred from variable-slip rupture models and modeling of earthquake faults for strong motion prediction by semi-empirical method." Journal of Structural and Construction Engineering (Transactions of AIJ), 545, 51-62

Headquarters for Earthquake Research Promotion(2009). Report: "National Seismic Hazard Maps for Japan (2009)." http://www.jishin.go.jp/main/index-e.html

Irikura, K. and Kurahashi, S.(2011). "Source Model for Generating Strong Ground Motions during the 11 March 2011 off Tohoku, Japan Earthquake." Japan Geoscience Union Meeting 2011, MIS036-P41

Irikura, K. and Kurahashi, S.(2011). "Source Model for Generating Strong Ground Motions during the 11 March 2011 off Tohoku,Japan Earthquake (Revised on August 17, 2011)." http://www.kojiro-irikura.jp/english.html

Kamae, K. and Kawabe, H.(2011). "Source Modeling of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake (Mw9.0)." http://www.rri.kyoto-u.ac.jp/jishin/

Kobayashi, K., Kyuke, H., Uetake, T., Mashimo, M., and Kobayashi, H.(1999). "Estimation of Q value for soil layers by simultaneous inversion of transfer functions at many sites Part 3." Summaries of Technical Papers of Annual meeting, Architectural institute of Japan, B-2, 255-256

Kawabe, H., Kamae, K. and Uebayashi, H.(2011). "Source Modeling of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake (Mw9.0)." Japan Geoscience Union Meeting 2011, MIS036-P35

Kurahashi, S. and Irikura, K.(2011). "Source model for generating strong ground motions during the 2011 off the Pacific coast of Tohoku Earthquake." Earth Planets Space, 63