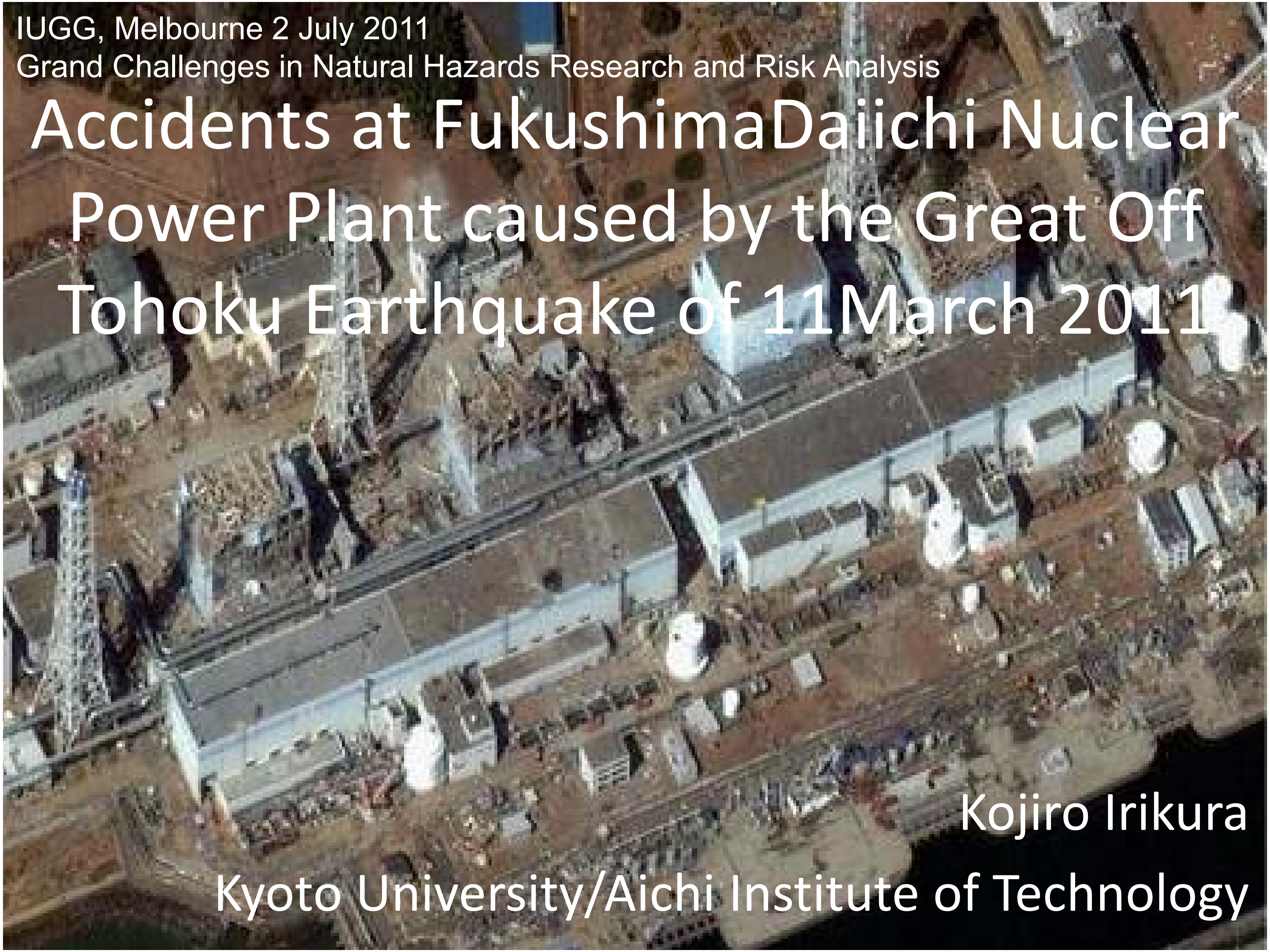


IUGG, Melbourne 2 July 2011
Grand Challenges in Natural Hazards Research and Risk Analysis

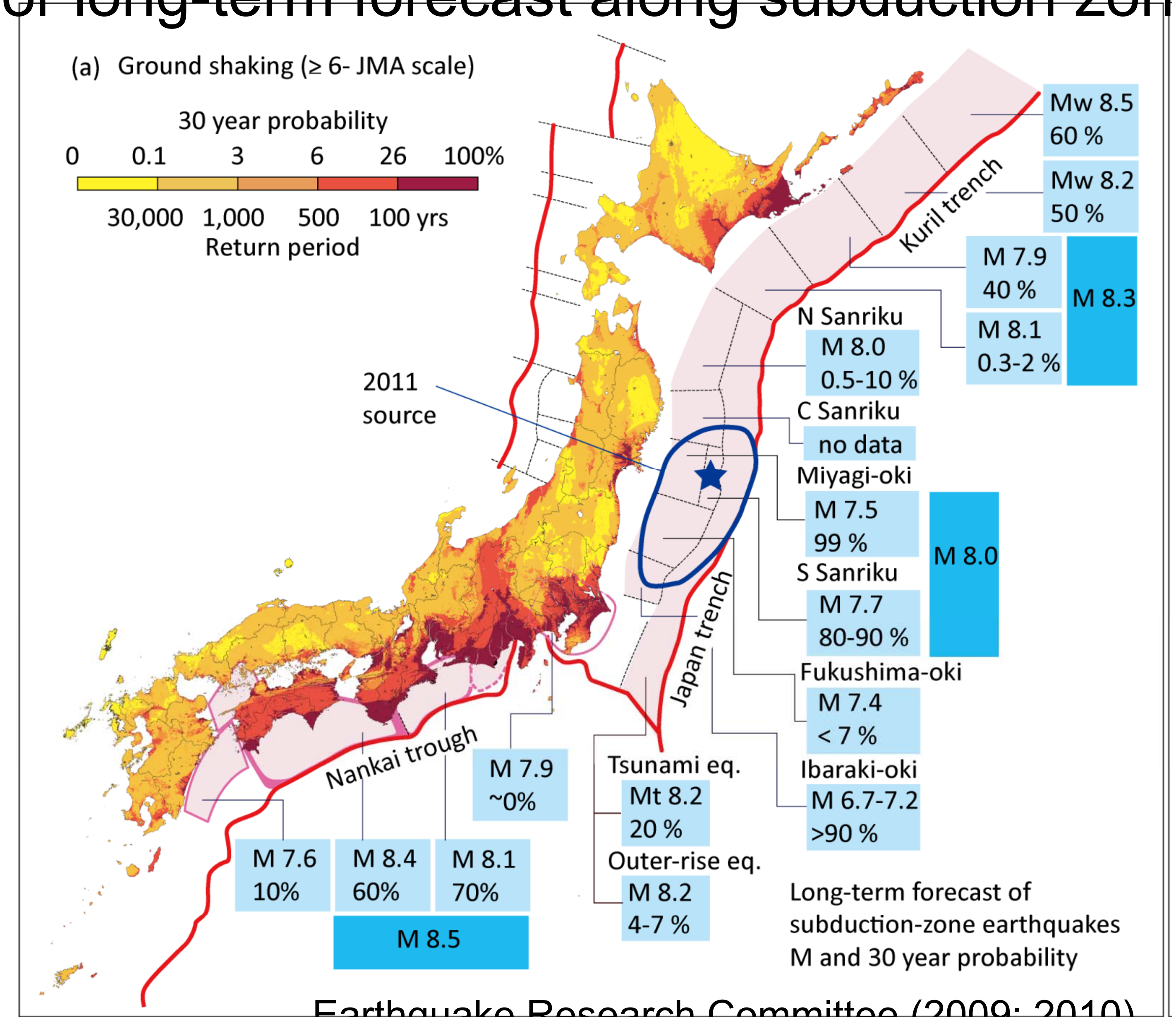
Accidents at FukushimaDaiichi Nuclear Power Plant caused by the Great Off Tohoku Earthquake of 11March 2011

Kojiro Irikura
Kyoto University/Aichi Institute of Technology

Topics

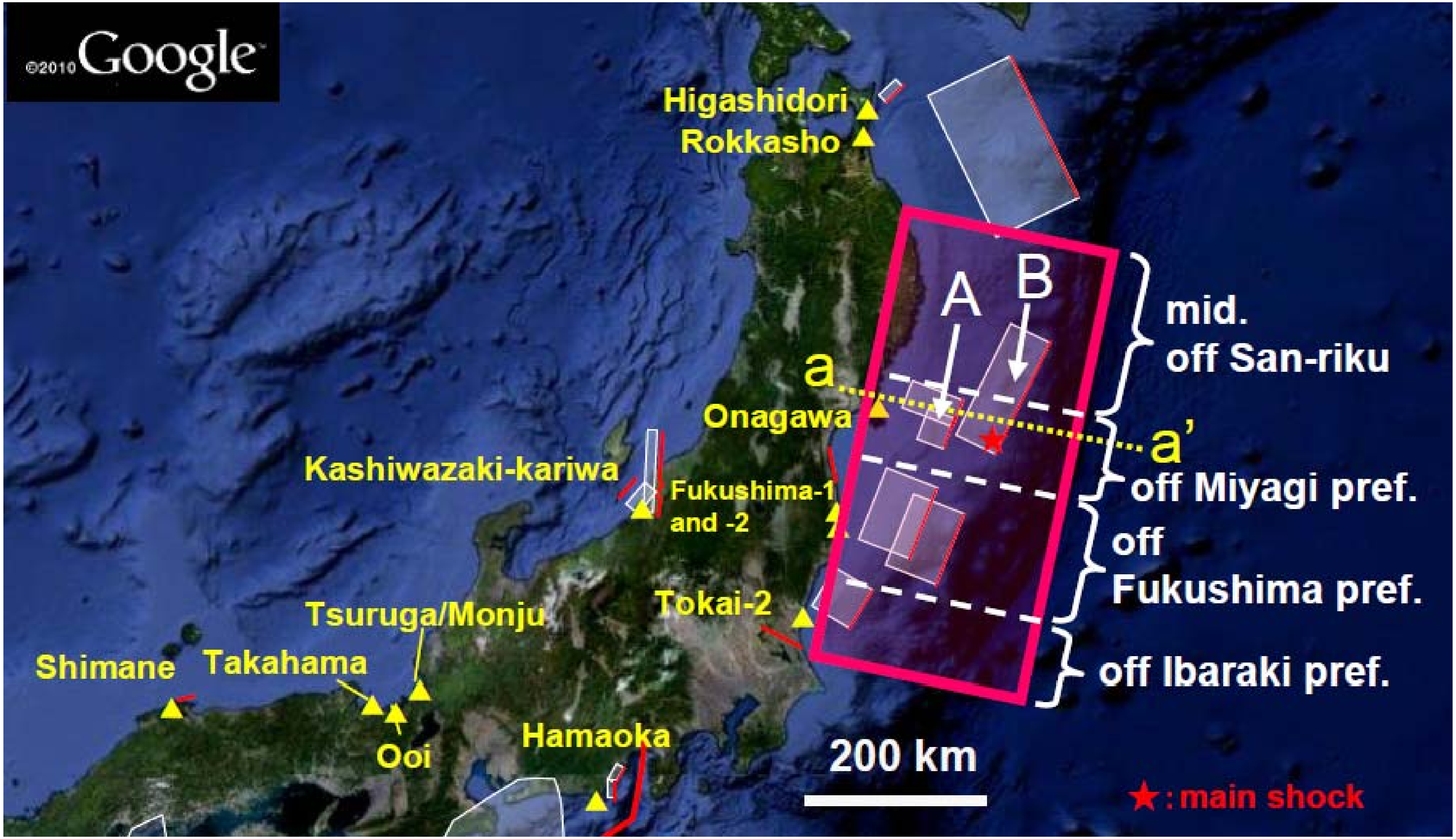
1. Outline of the Great Off Tohoku earthquake – Tsunami and Strong Ground Motions –
2. What happened at Nuclear Power Plants during the 2011 Tohoku earthquake ?
3. Revision of Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities and Reevaluation of Seismic Safety for Existing NPSs
4. Effects of Ground Motions and Tsunami Waves to Existing NPSs.
5. Main Chronology (Provisional) of Serious Accidents at Fukushima Daiichi NPS – Case of Unit 1 as an example –
6. Summary – What are problems to solve ? -

National seismic hazard map for Japan and regions for long-term forecast along subduction zone



Earthquake Research Committee (2009; 2010)

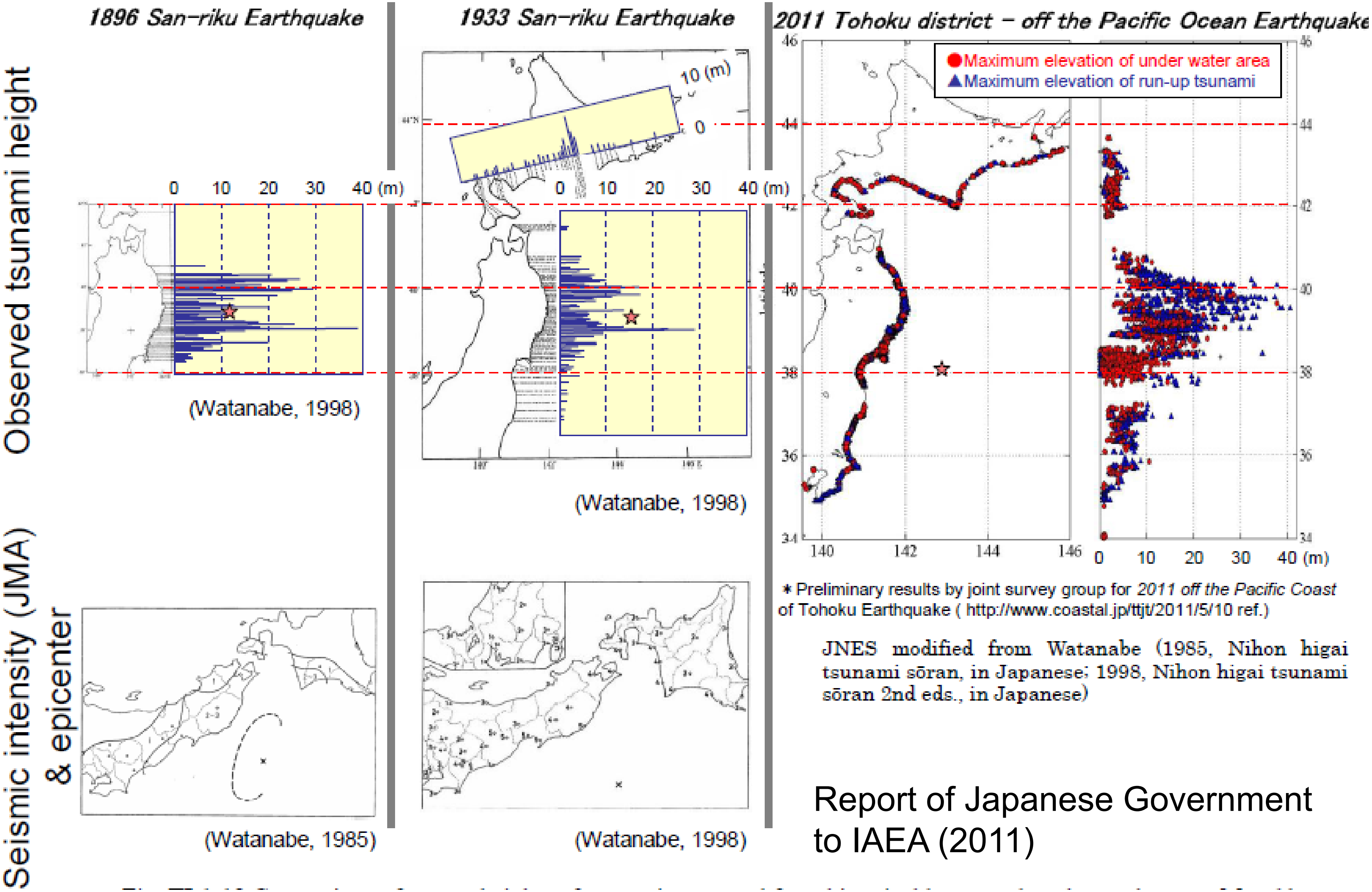
Source Area of the 2011 Off Tohoku Earthquake



JNES modified a part of the Google map

Report of the Japanese Government to the IAEA, 2011

Comparison the height of 3.11/2011 Tsunami with historical San-riku Tsunami

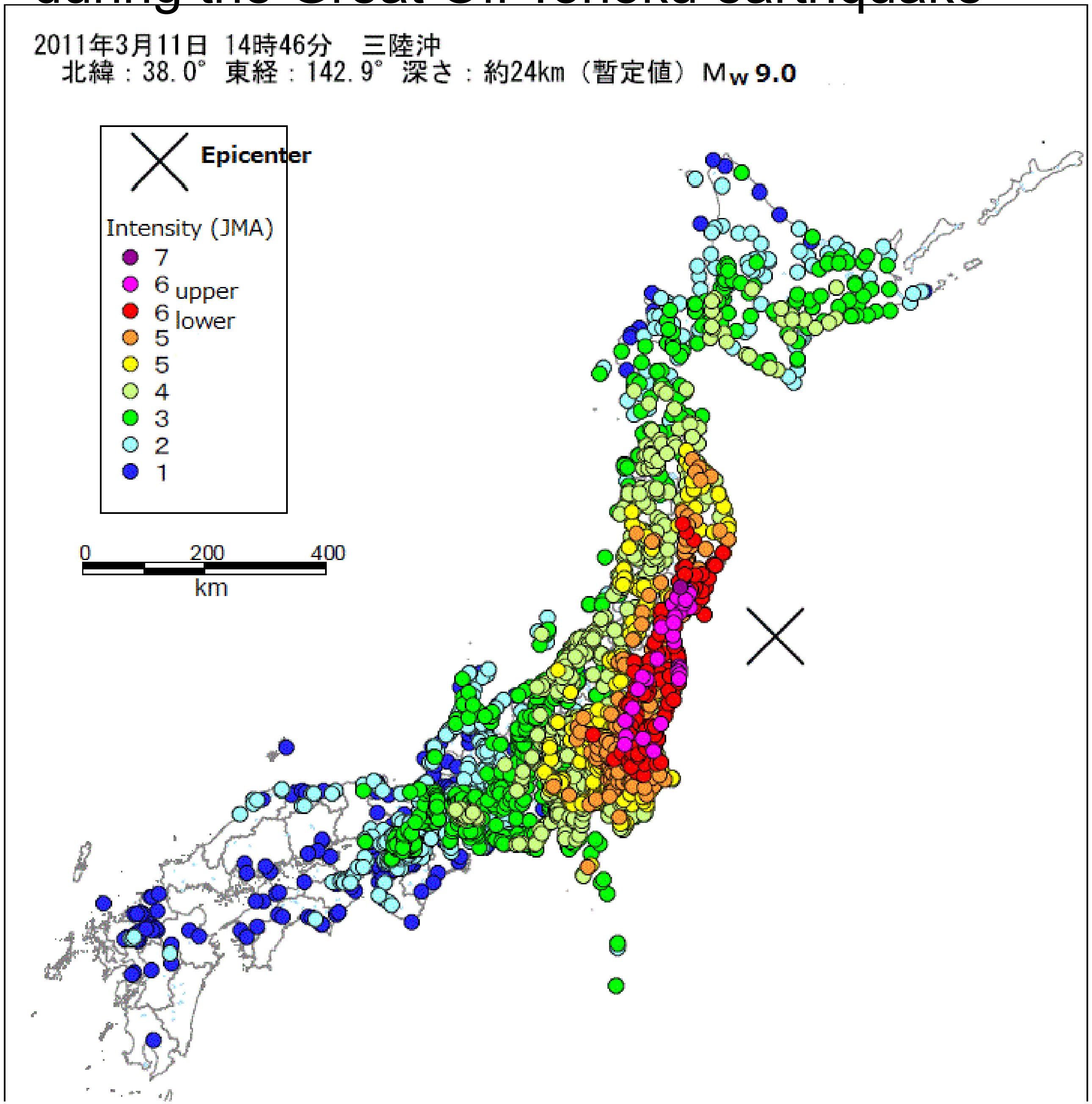


＊Preliminary results by joint survey group for *2011 off the Pacific Coast* of Tohoku Earthquake (http://www.coastal.jp/ttjt/2011/5/10 ref.)

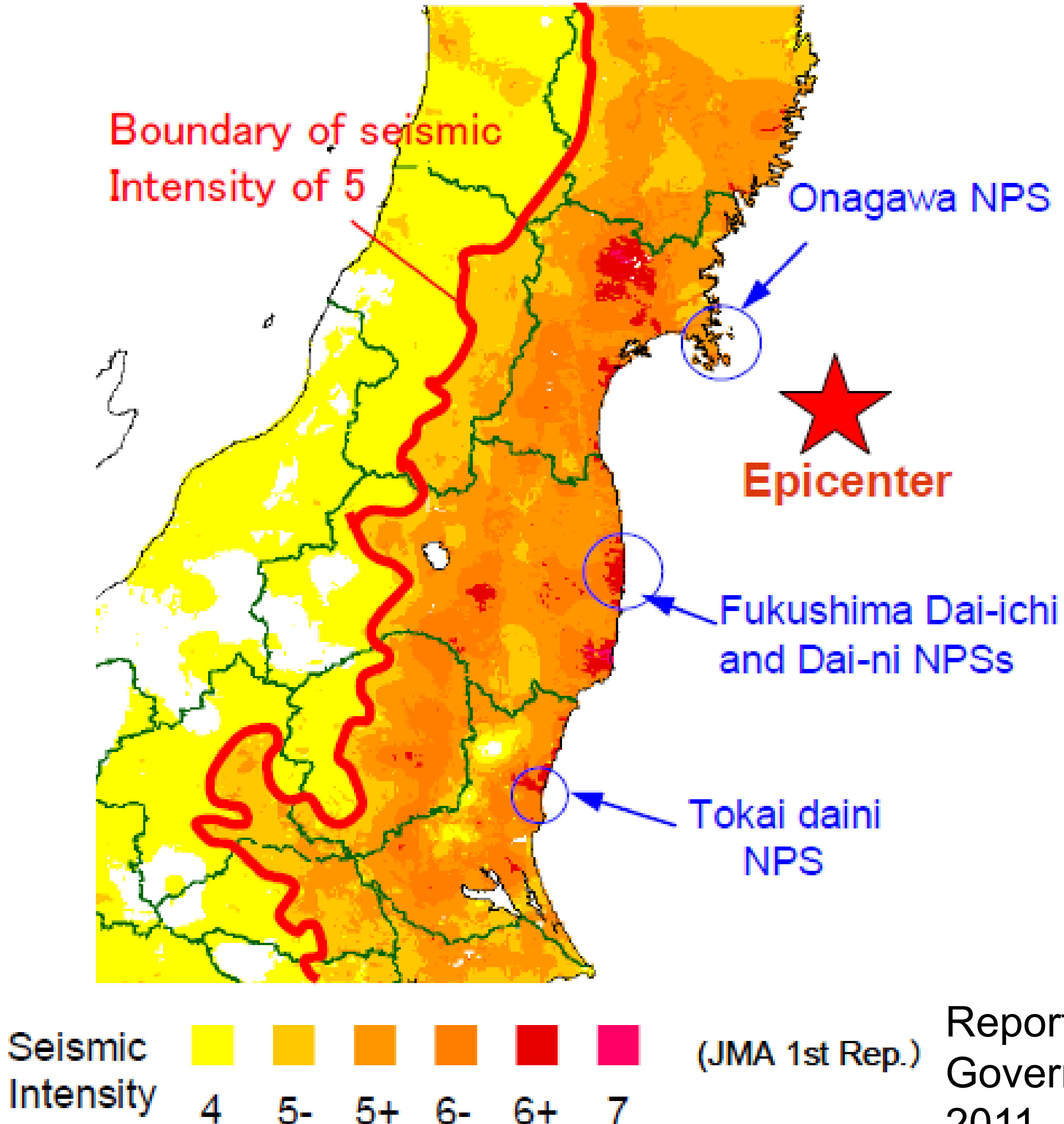
JNES modified from Watanabe (1985, Nihon higai tsunami sōran, in Japanese; 1998, Nihon higai tsunami sōran 2nd eds., in Japanese)

Report of Japanese Government to IAEA (2011)

Seismic Intensity Distribution during the Great Off Tohoku earthquake

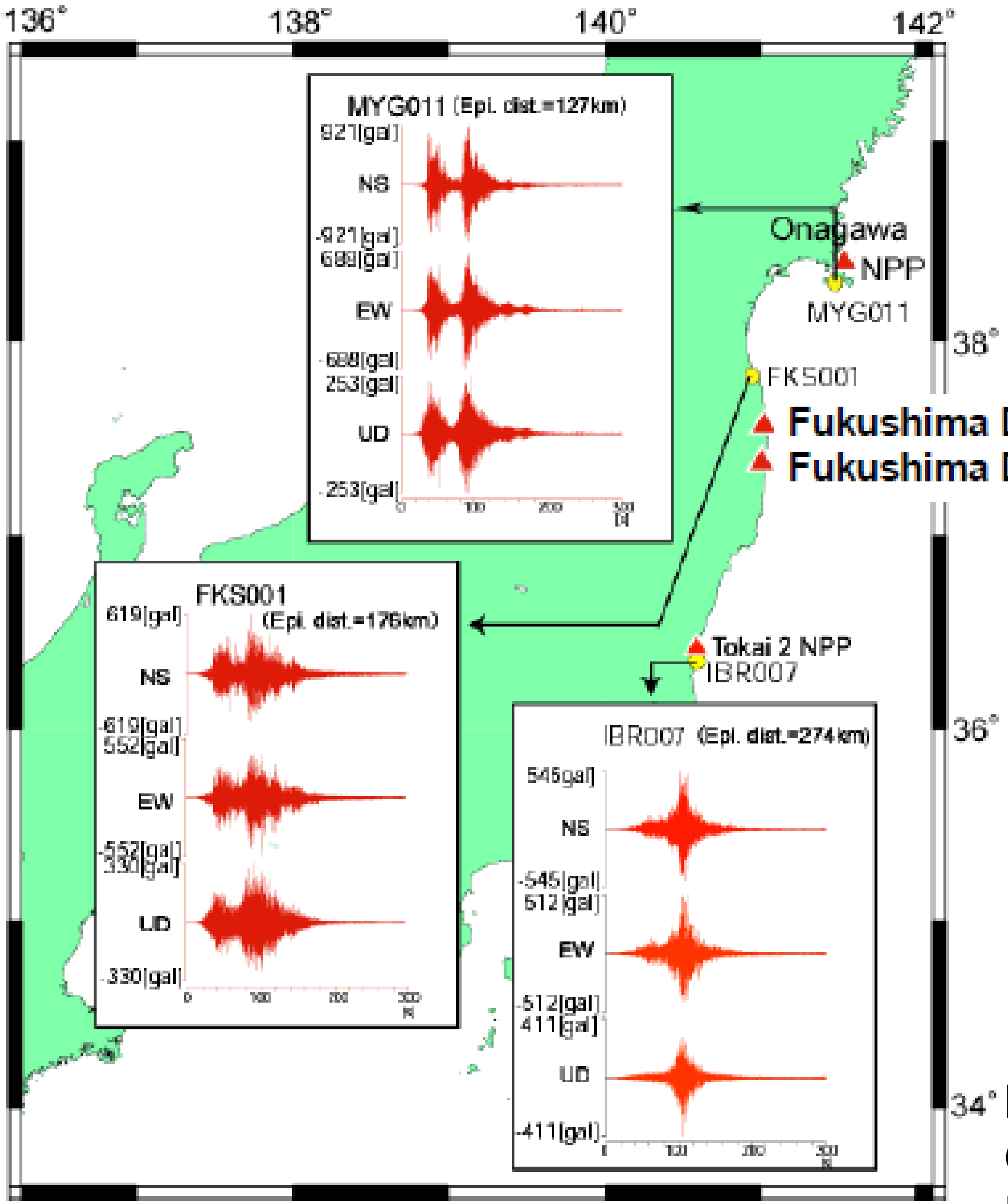


Seismic Intensities (JMA scale) near the Nuclear Power Stations

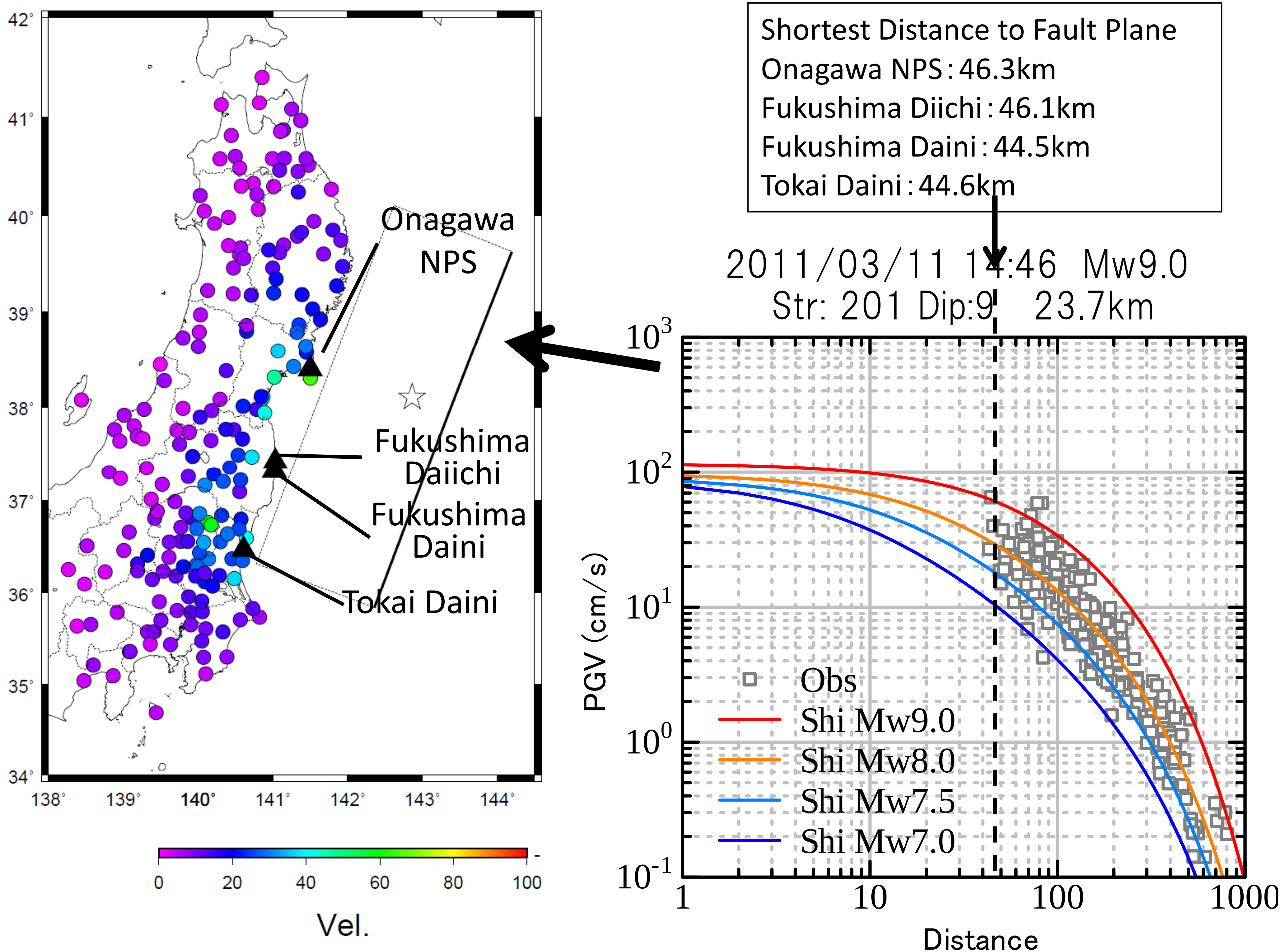


Report of the Japanese Government to the IAEA, 2011

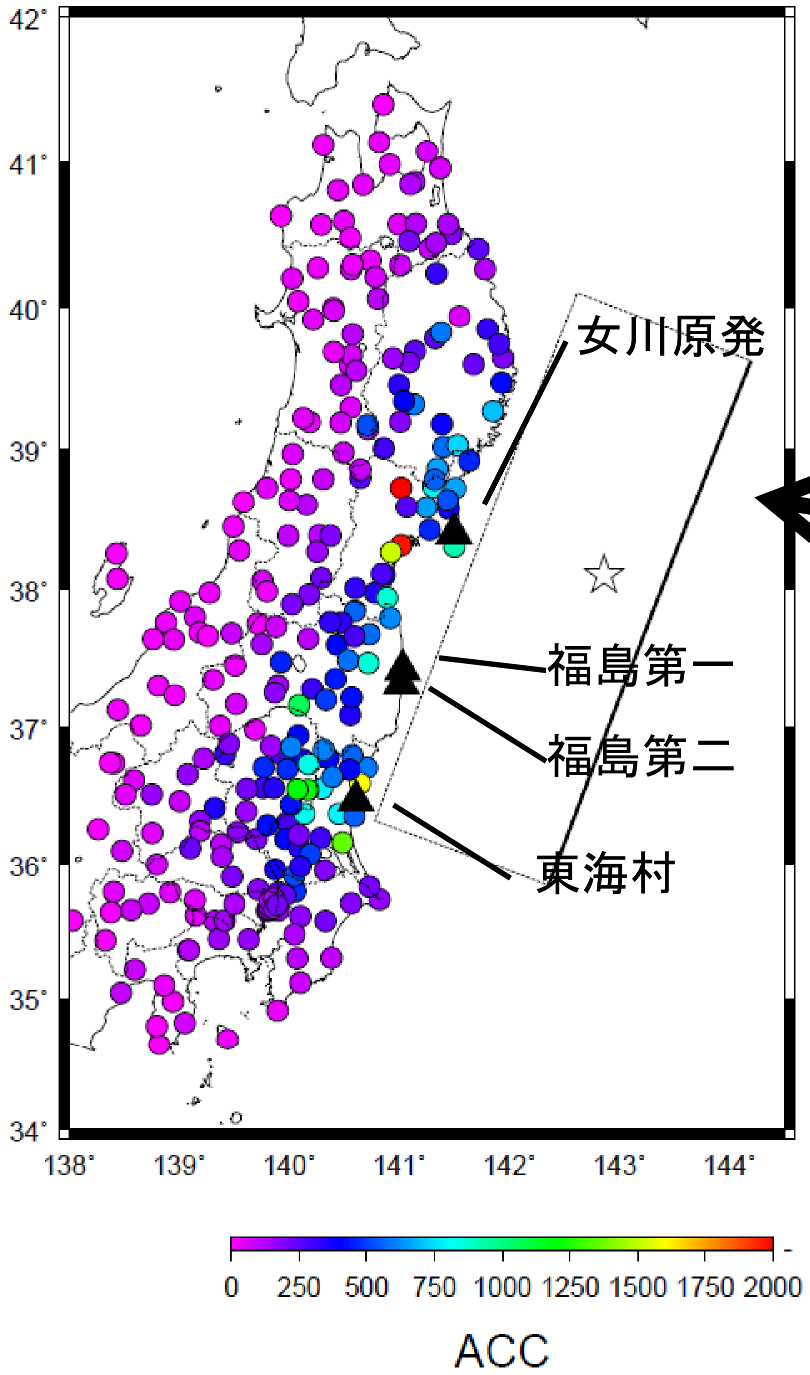
Acceleration Seismograms recorded around NPSs



Report of the Japanese Government to the IAEA, 2011

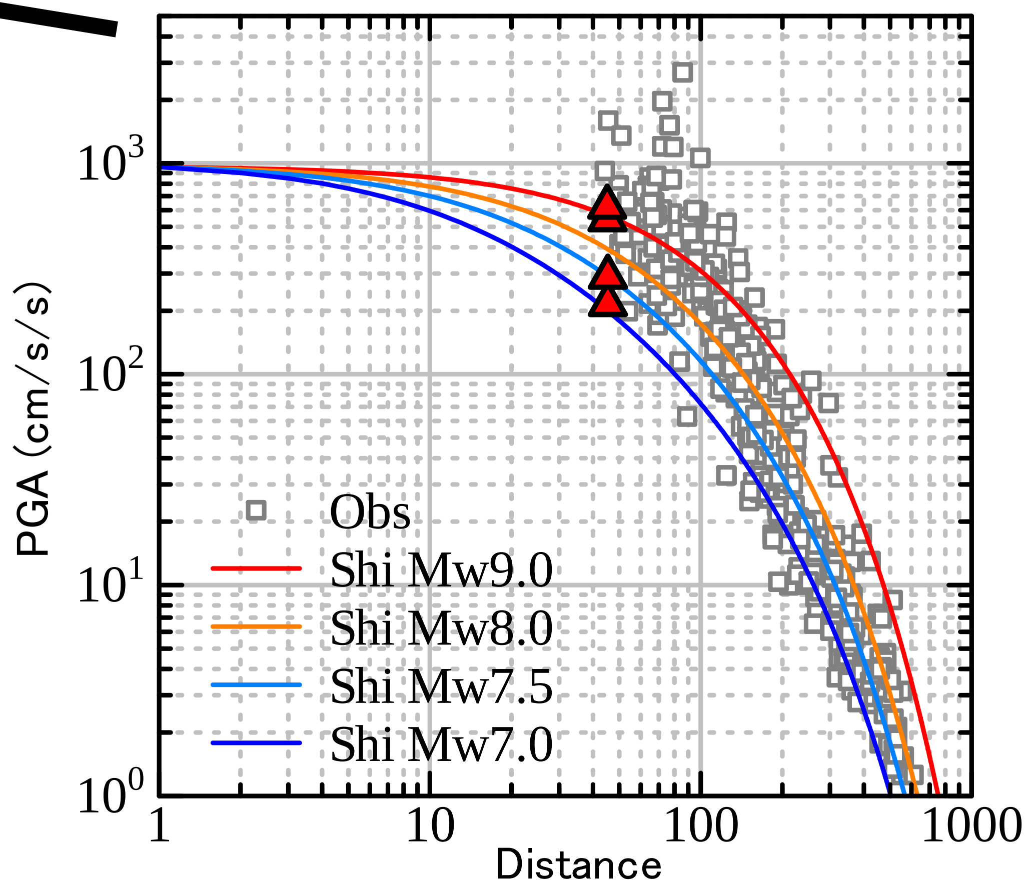


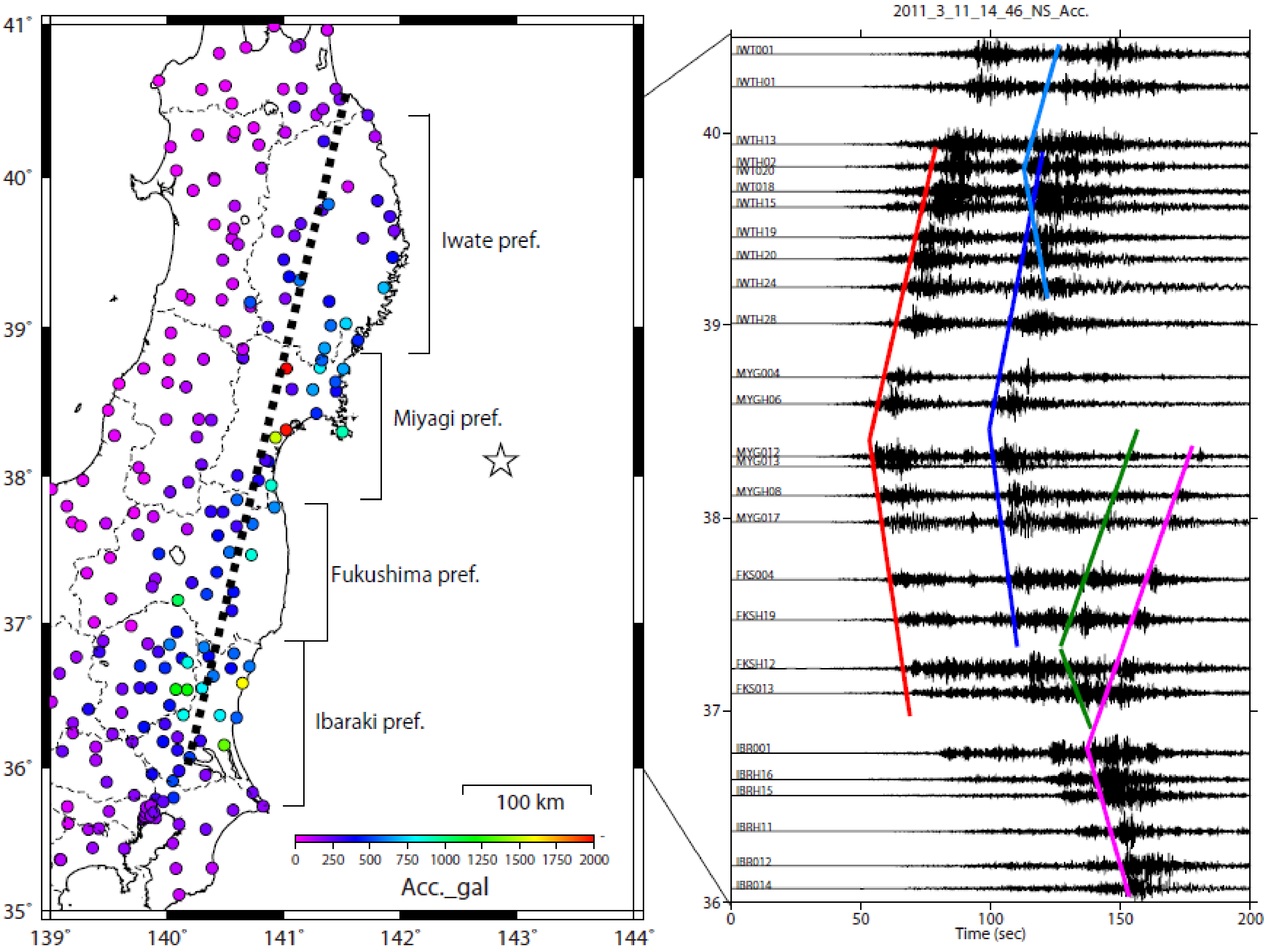
Shortest Distance to Fault Plane
Onagawa NPS : 46.3km
Fukushima Diichi : 46.1km
Fukushima Daini : 44.5km
Tokai Daini : 44.6km
2011/03/11 14:46 Mw9.0
Str: 201 Dip:9 23.7km
Onagawa NPS
Fukushima Daiichi
Fukushima Daini
Tokai Daini
Vel.
PGV (cm/s)
Distance
Obs
Shi Mw9.0
Shi Mw8.0
Shi Mw7.5
Shi Mw7.0



Shortest Distance to Fault Plane
Onagawa NPS : 46.3km :607gal
Fukushima Daiichi : 46.1km : 550gal
Fukushima Daini : 44.5km : 288gal
Tokai Daini : 44.6km :225.4gal

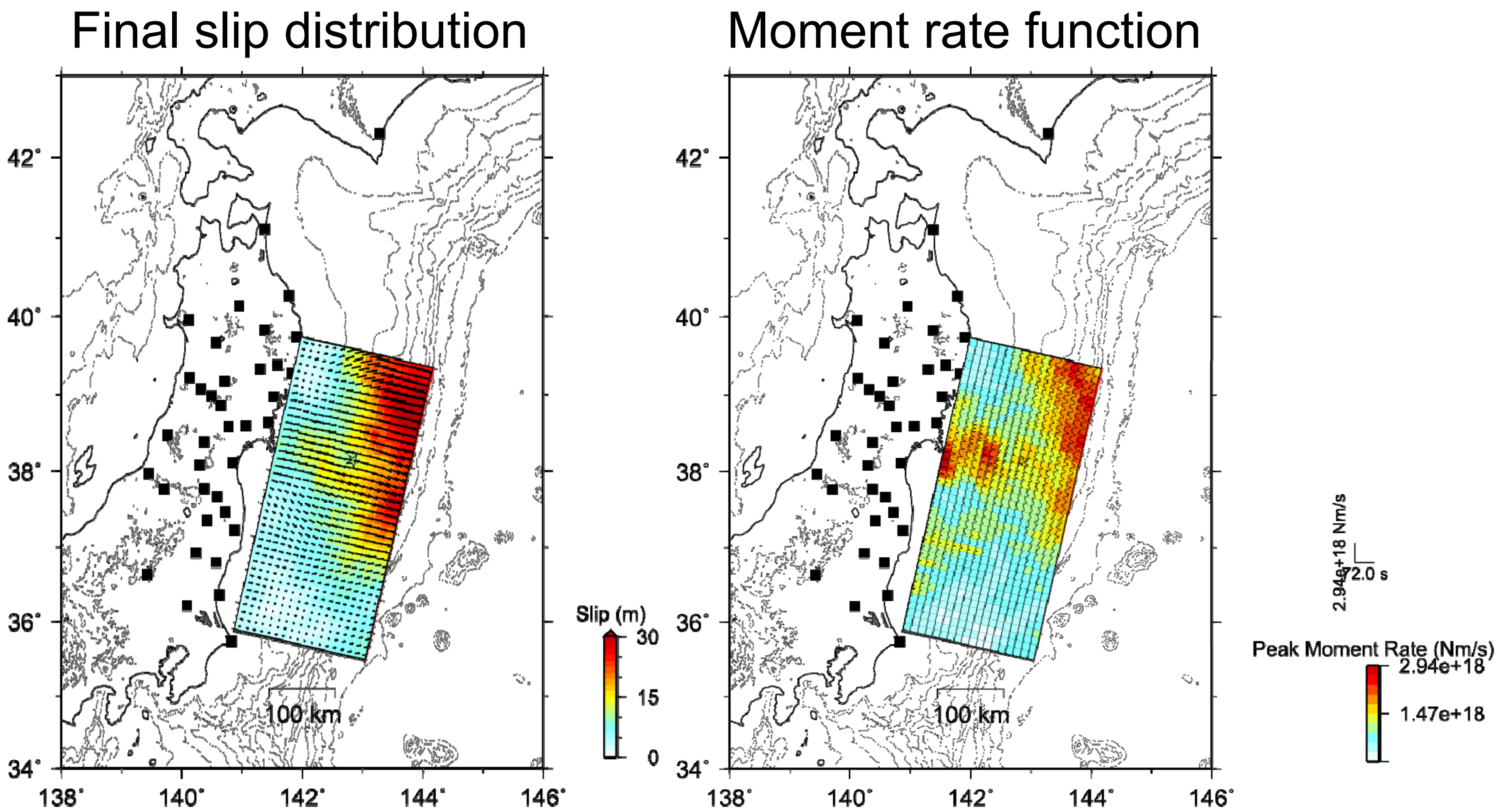
2011/03/11 14:46 Mw9.0
Str: 201 Dip:9 23.7km





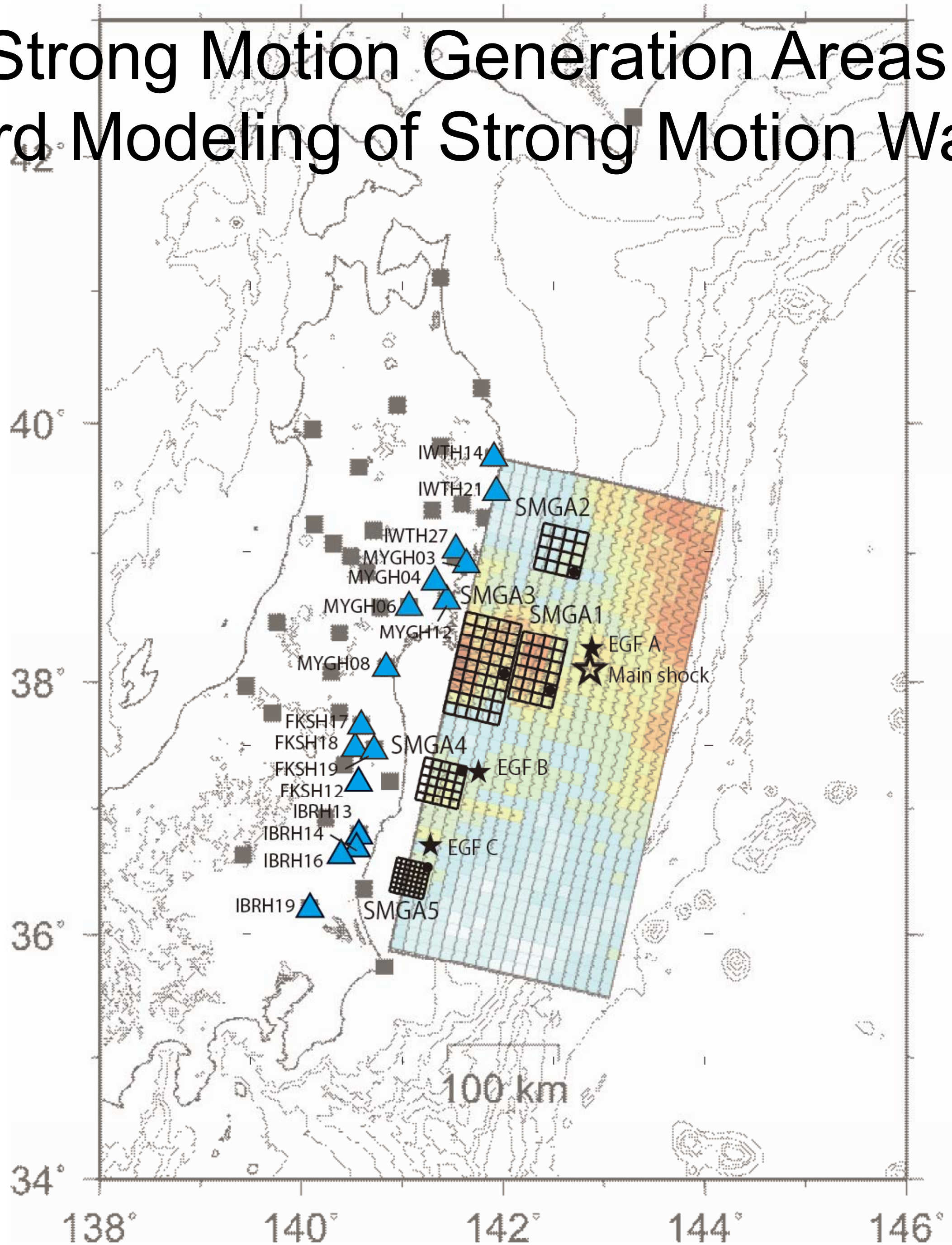
2011_3_11_14_46_NS_Acc.
Iwate pref.
Miyagi pref.
Fukushima pref.
Ibaraki pref.
100 km
Acc._gal
0 250 500 750 1000 1250 1500 1750 2000
139° 140° 141° 142° 143° 144°
35° 36° 37° 38° 39° 40° 41°
IWT001
IWTH01
IWTH13
IWTH02
IWT020
IWT018
IWTH15
IWTH19
IWTH20
IWTH24
IWTH28
MYG004
MYGH06
MYG012
MYG013
MYGH08
MYG017
FKS004
FKSH19
FKSH12
FKS013
IBR001
IBRH16
IBRH15
IBRH11
IBR012
IBR014
0 50 100 150 200
Time (sec)

Slip and Moment-Rate Distribution inverted from Long Period Ground Motions



Yoshida, Miyakoshi, Irikura and Petukhin (2011)

Strong Motion Generation Areas by Forward Modeling of Strong Motion Waveforms



What happened at Nuclear Power Plants during the 2011 Tohoku earthquake ? - 1 -

◆There are four nuclear power plants near the source area of the earthquake, the Onagawa, the Fukushima-Daiichi, the Fukushima-Daini, and the Tokai-Daini.

◆ When strong ground motions from the earthquake struck those plants, all of reactor-units at those four plants were automatically shut down and began to be cooled by cooling systems until they were attacked by big tsunami waves.

◆ All units at the Onagawa and the Tokai-No. 2 NPPs got out of troubles because the heights of tsunami waves were lower than the altitudes of the plant sites.

What happened at Nuclear Power Plants during the 2011 Tohoku earthquake ? - 2 -

◆However, the Fukushima-No.1 and the Fukushima-No.2 plants were damaged by big tsunami waves, because the tsunami heights were much higher the altitudes of the plant sites.

◆ At the Fukushima No.2 Plant, some of the independents power generation systems were not broken because they were put at a little high ground, then the cooling systems at the Fukushima No. 2 Plant were soon recovered.

◆ At the Fukushima No.1 plant, external electric powers were stopped, water-tanks were broken, and further all of the independents power generation systems were broken.

Revision of Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities was made on September, 2006.

Re-evaluation of Seismic Safety Design of Nuclear Facilities, so-called “Back-checks” for 54 Units in 17 Nuclear Power Stations has been done and still going on.

- The electric companies started geological survey and reevaluation of design ground motions for getting back-checks of the existing NPP’s.
- The Niigataken Chuetsu-oki earthquake on 16 July, 2007, occurred very close to the Kashiwazaki-Kariwa Nuclear Power Plants at that time.
- Design ground motions for four NPSs (Onagawa, Fukushima-Daiichi, Fukushima-Daini and Tokai-Daini) were reevaluated and their facilities were reevaluated at the time of the Great Off Tohoku earthquake.
- Tsunami assessments for those NPSs was planning at the next stages, therefor not reevaluated yet based on the new regulatory guide.

Points of New Regulatory Guide

1. Deterministic approaches are emphasized in evaluating design basis ground motions (DBGM) Ss's with engineering decision.

2. On the other hand, the idea of probabilistic approaches is taken in the guide.

   For example, they request consideration of "uncertainties" of source parameters and propagation-path and site effect parameters and calculation of exceeding probability of the Ss's, to provide comprehensive information about the conservatism in evaluating the Ss's.

3. The basic policy is to adhere the concept of "defense-in-depth" and to ensure the necessary safety margin.

Seismic Reevaluation (Back-checks) of the existing NPSs the Regulatory Guide

-Deterministic Method and Residual Risk -

- Design basis ground motions are evaluated from specified sources for given earthquake scenarios with source models and propagation-path and local site effects and from unspecified sources with past earthquake data.

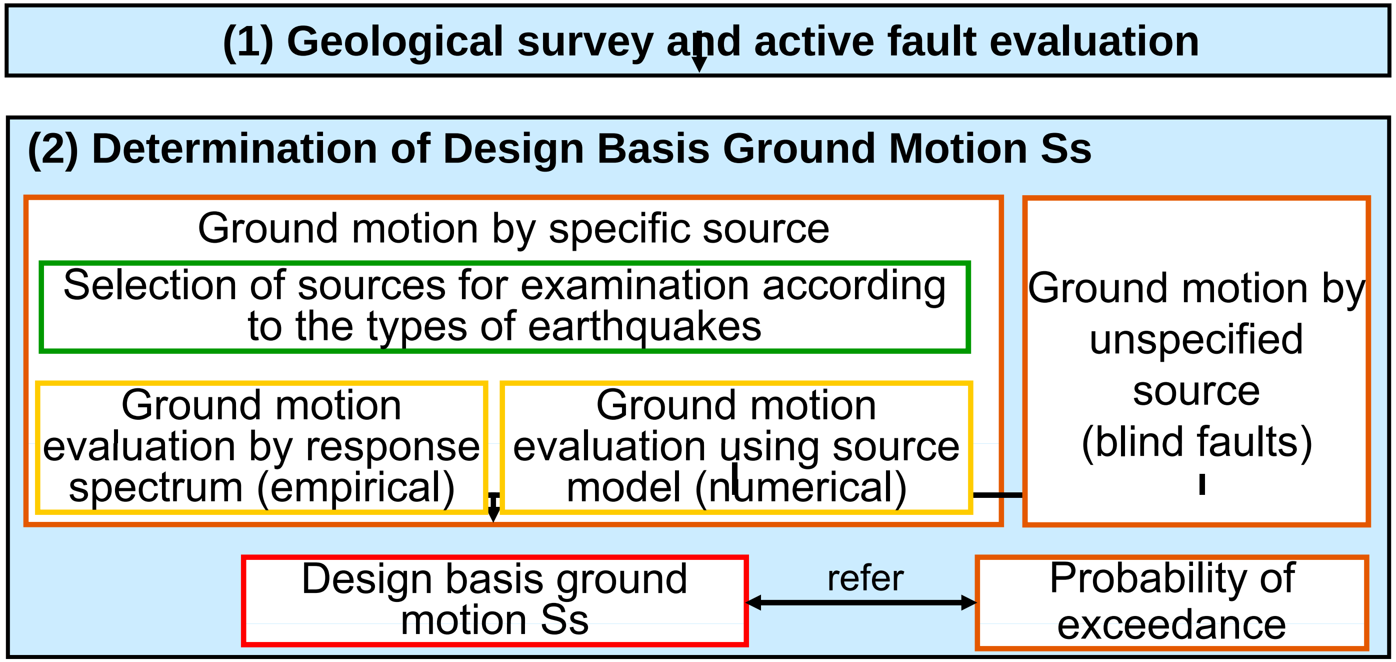
- Largest possible ground motions are estimated considering physical limits with uncertainties. They are not always worst-case ground motions.

→ Therefore, some residual risk remains.

→ Design basis ground motions are determined to lead to the residual risk that is acceptably small.

Seismic Safety Assessments based on the new Regulatory Guide (2006)

- Determination of design basis ground motion Ss for NPP defined based on the new Regulatory Guide (2006).
- Policy on determining design basis ground motion Ss



- Design basis ground motion Ss for the existing NPPs in Japan were determined and the facilities' seismic safety were reevaluated. The facilities' seismic safety was upgrading to improve their margin.

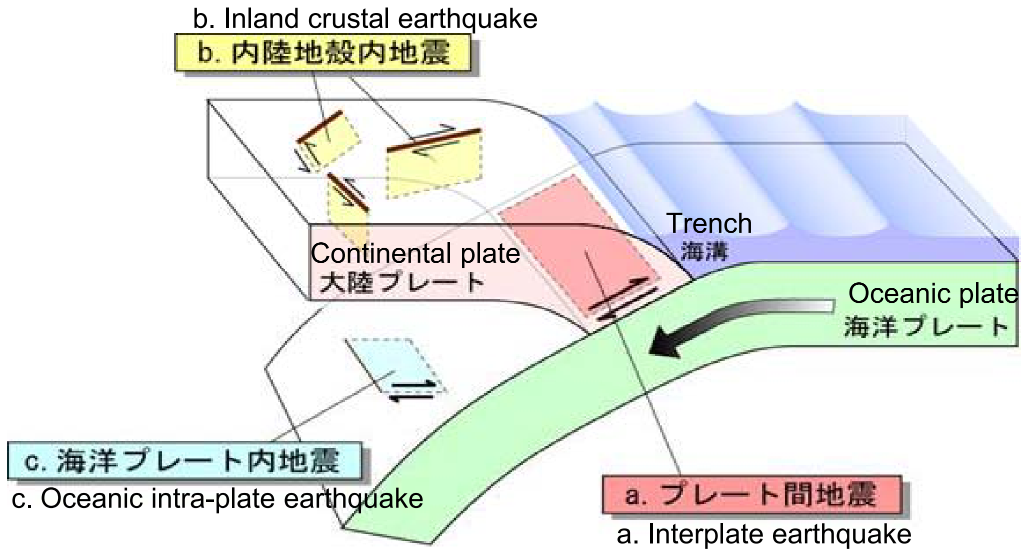
Ground Motion by Specific Source

■**For each types of earthquake, a comparison of the impact on the site is made to select earthquakes for analysis.**

a) Interplate earthquake

b) Inland crustal earthquake

c) Oceanic intra-plate earthquake



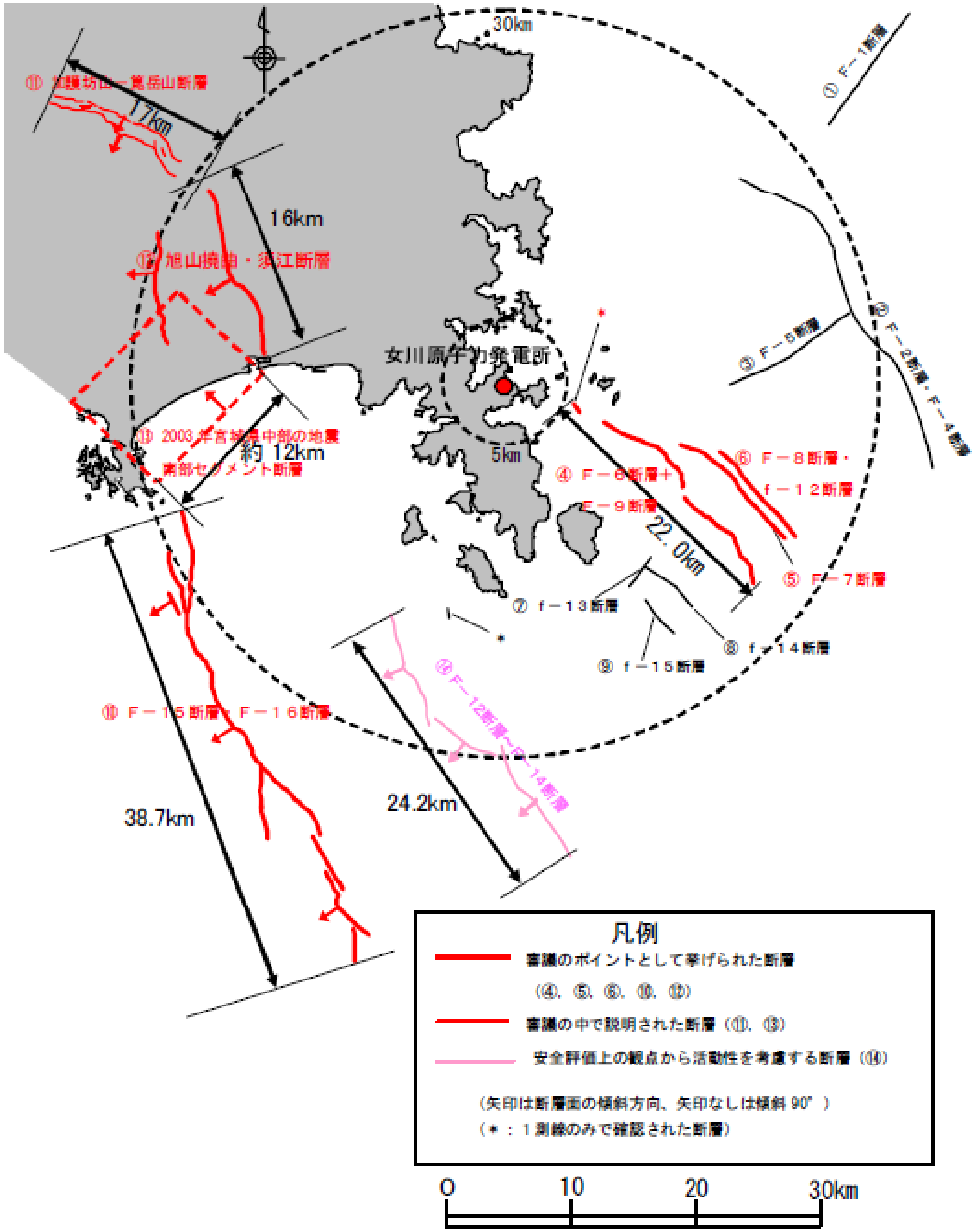
■**Source models pertaining to earthquakes for analysis**

- Basic source model
- Models accounting for uncertainty

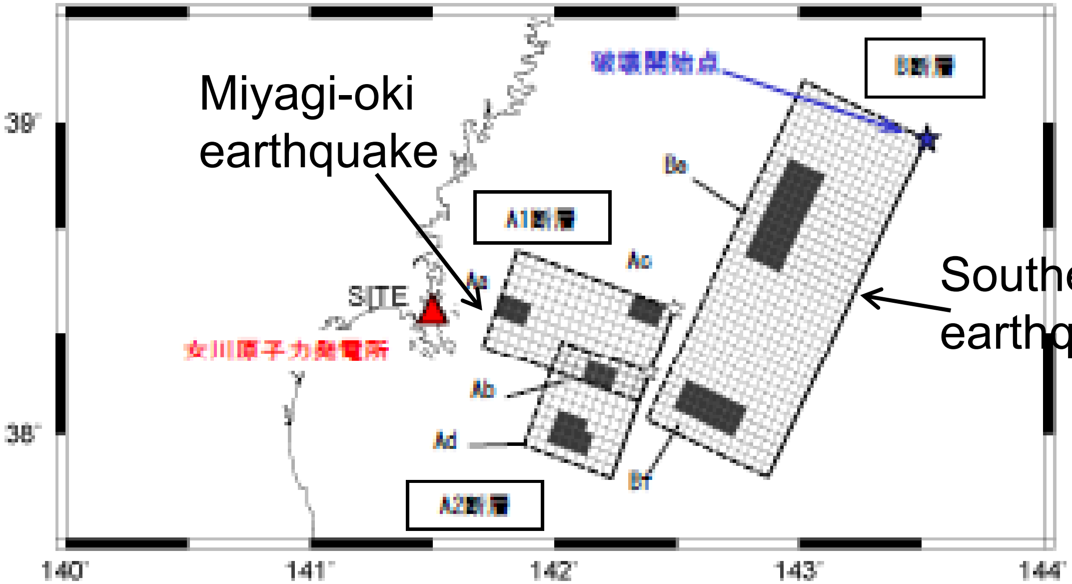
■**Seismic ground motion assessment**

- Ground motion evaluation by response spectrum (empirical)
- Ground motion evaluation using source model (numerical)

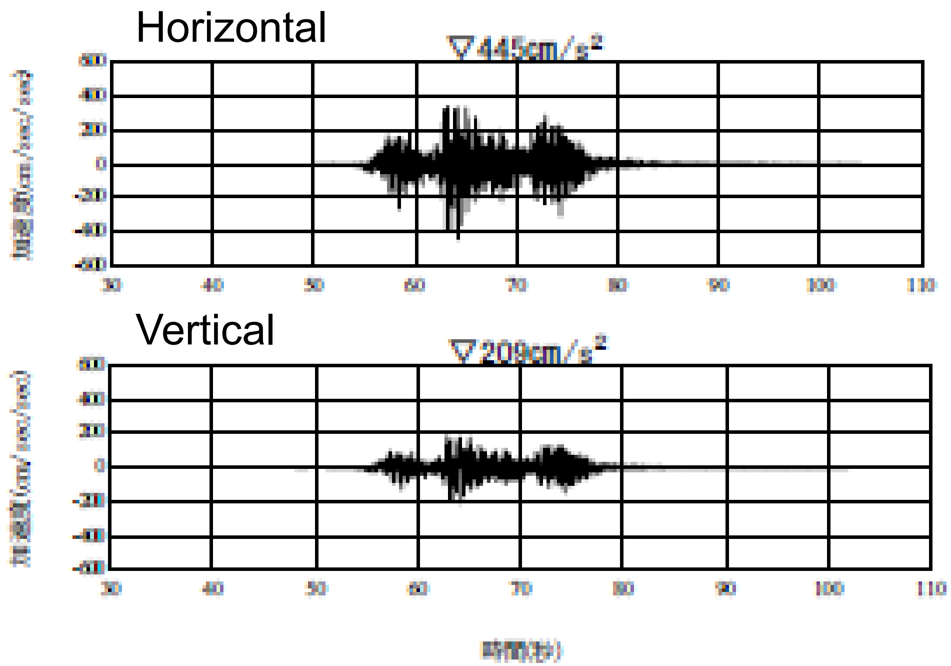
Active Faults near Onagawa NPS for evaluating Design Basis Ground Motions



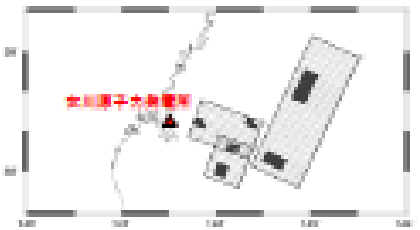
Subduction Earthquakes near Onagawa NPS for evaluating Design Basis Ground Motions



Acceleration motions



Response Spectra of Design Basis Ground Motions (DBGM) at Onagawa NPS



【基本ケース】 Mw8.2, Xeq＝100.1 (km)※
RSPL＝6.00 × 10^{17}※

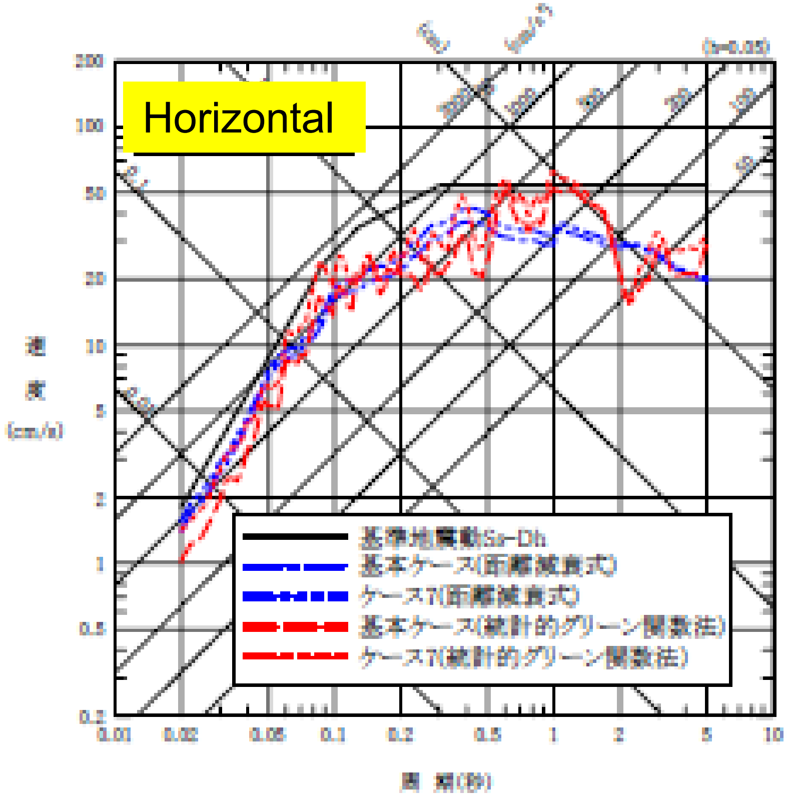
【ケース7】 Mw8.2, Xeq＝98.8 (km)※
RSPL＝6.95 × 10^{17}※

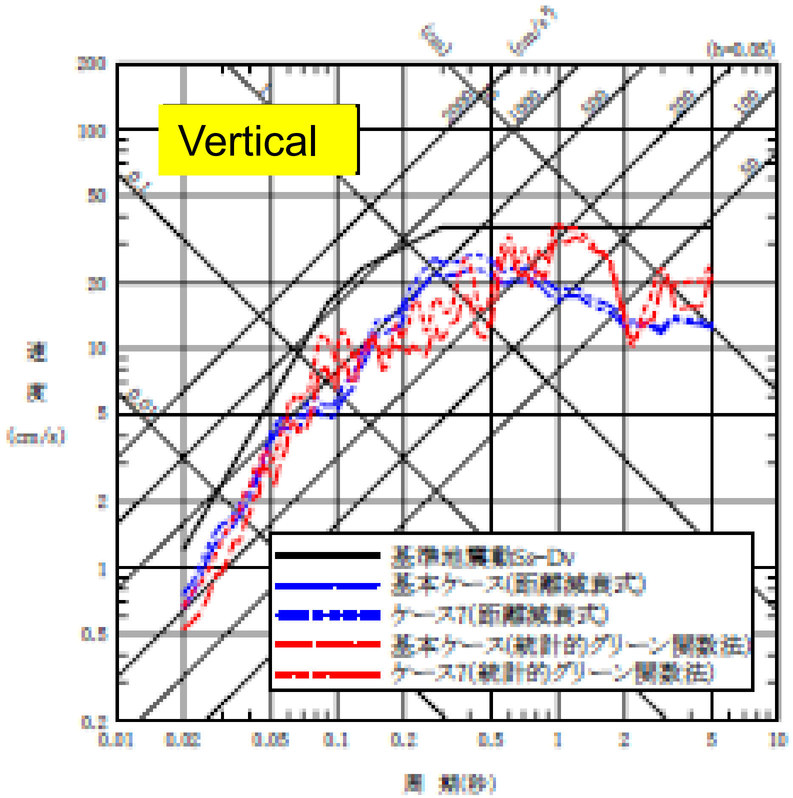
※：断層モデルから算定

上図：連動型想定宮城県沖地震の断層モデル

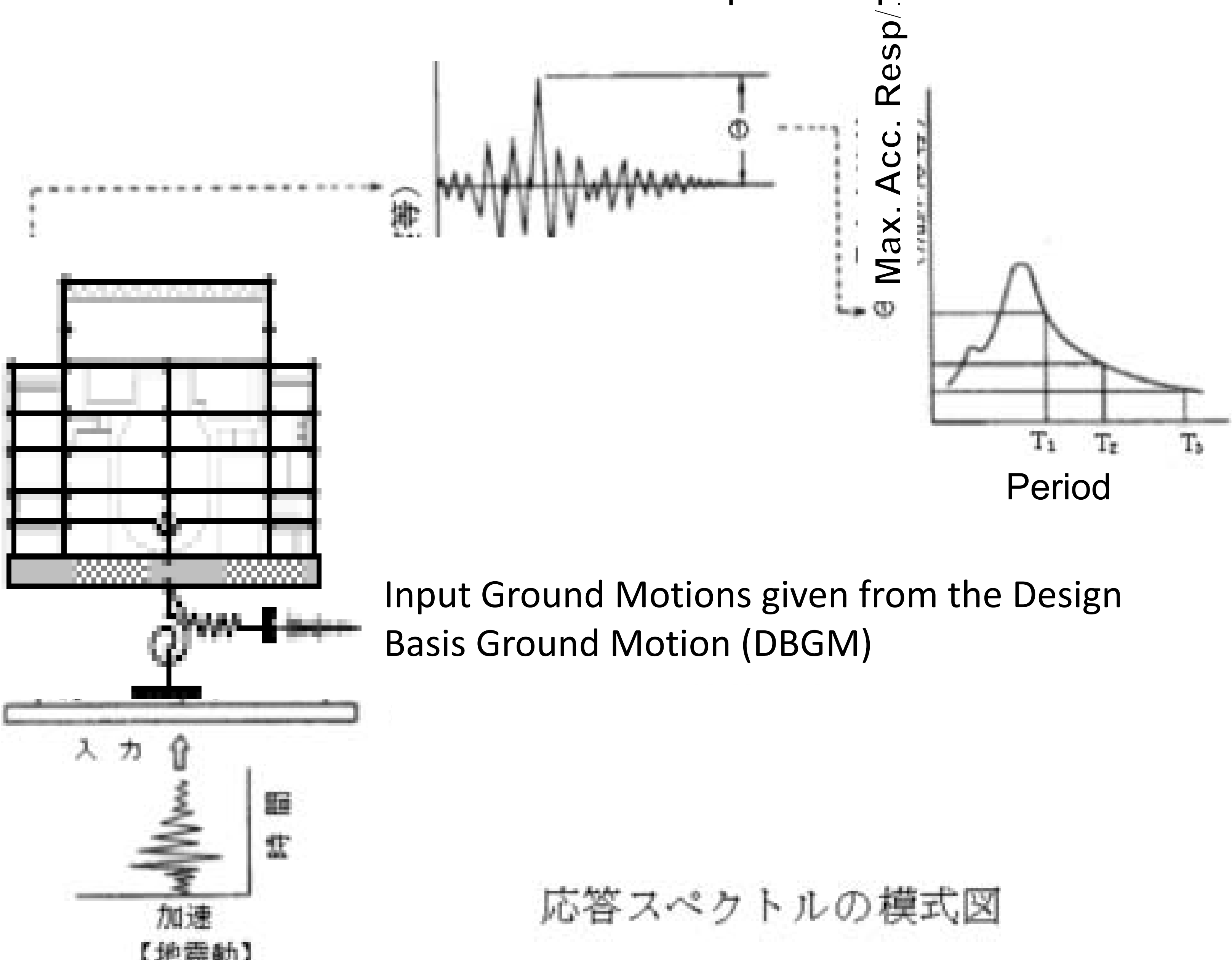
主な断層パラメータ

	Mw	M_0 (Nm)	応力降下量(MPa)						
			Aa	Ab	Ac	Ad	Ba	Bf	背景
基本ケース	8.17	2.24×10^{21}	29.0	72.6	63.6	55.1	35.4	35.4	3.43
ケース7	8.17	2.24×10^{21}	38.9	97.3	85.3	73.9	47.5	47.5	4.09





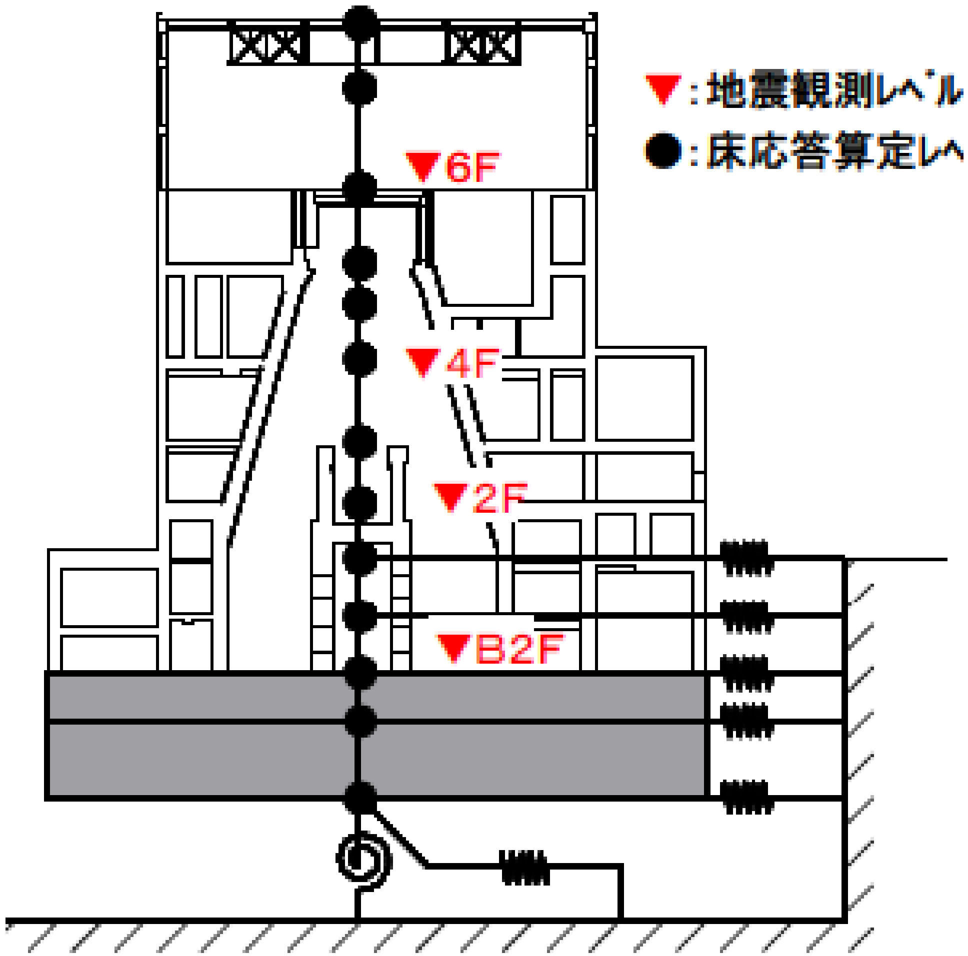
Analysis of Seismic Safety for Nuclear Power Plants
- Calculation of Acceleration Response Spectrum-



Input Ground Motions given from the Design Basis Ground Motion (DBGM)

応答スペクトルの模式図

Reactor Model for Seismic Design



What happened at Onagawa NPS during the Off Tohoku Earthquake

Comparison between recorded acceleration and design acceleration to the DBGM Ss on Base Mats at Units 1 – 3.

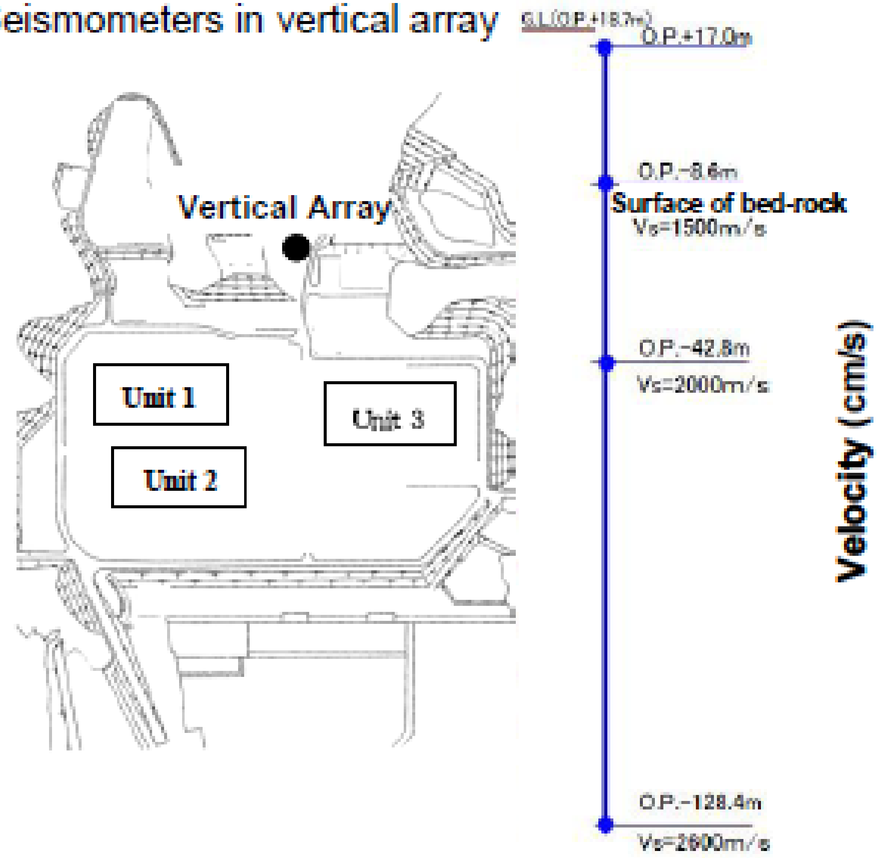
Loc. Of Seismometer (bottom floor of reactpr bld.)		Record Max. acc. (Gal)			Max. response acceleration to the DBGM Ss (Gal)		
		NS	EW	UD	NS	EW	UD
Onagawa	Unit 1	540	587	439	532	529	451
	Unit 2	607	461	389	594	572	490
	Unit 3	573	458	321	512	497	476

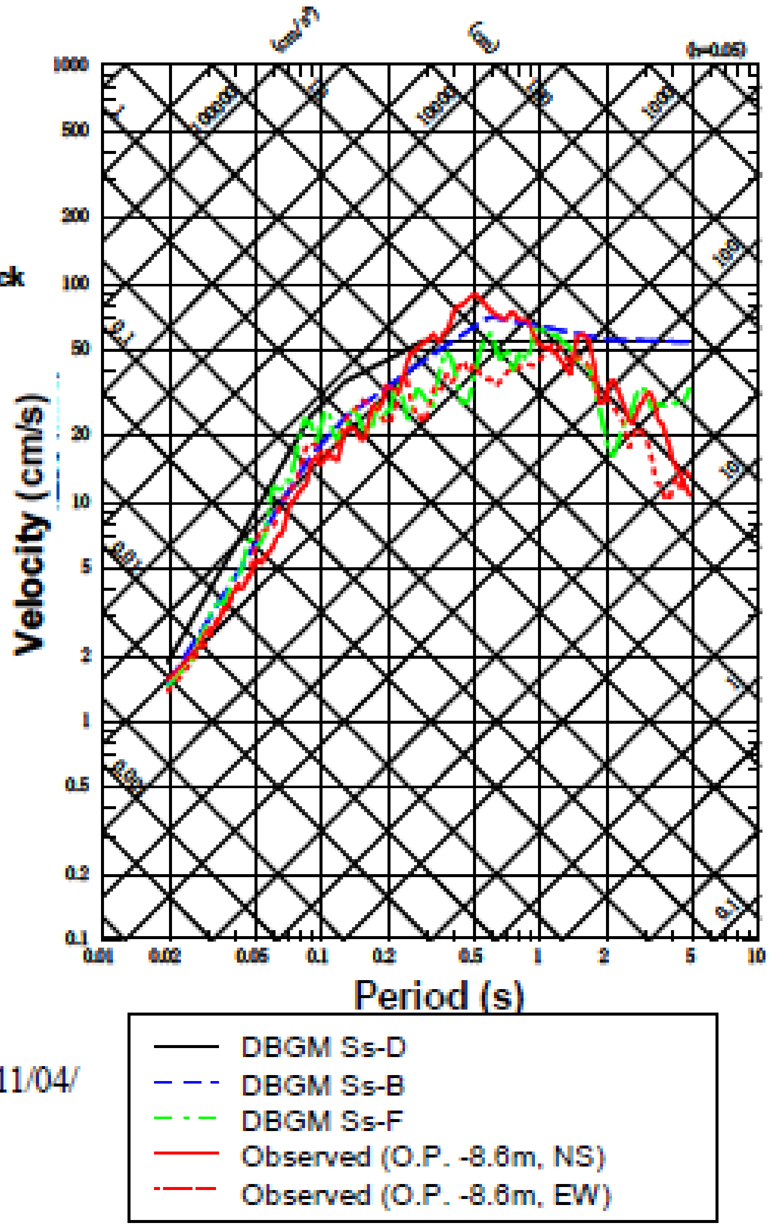
(red circle) Observed records were larger than design levels marked be (blue circle) .

Comparison between Observed Response Spectra and the DBGM

Partially modified by JNES.

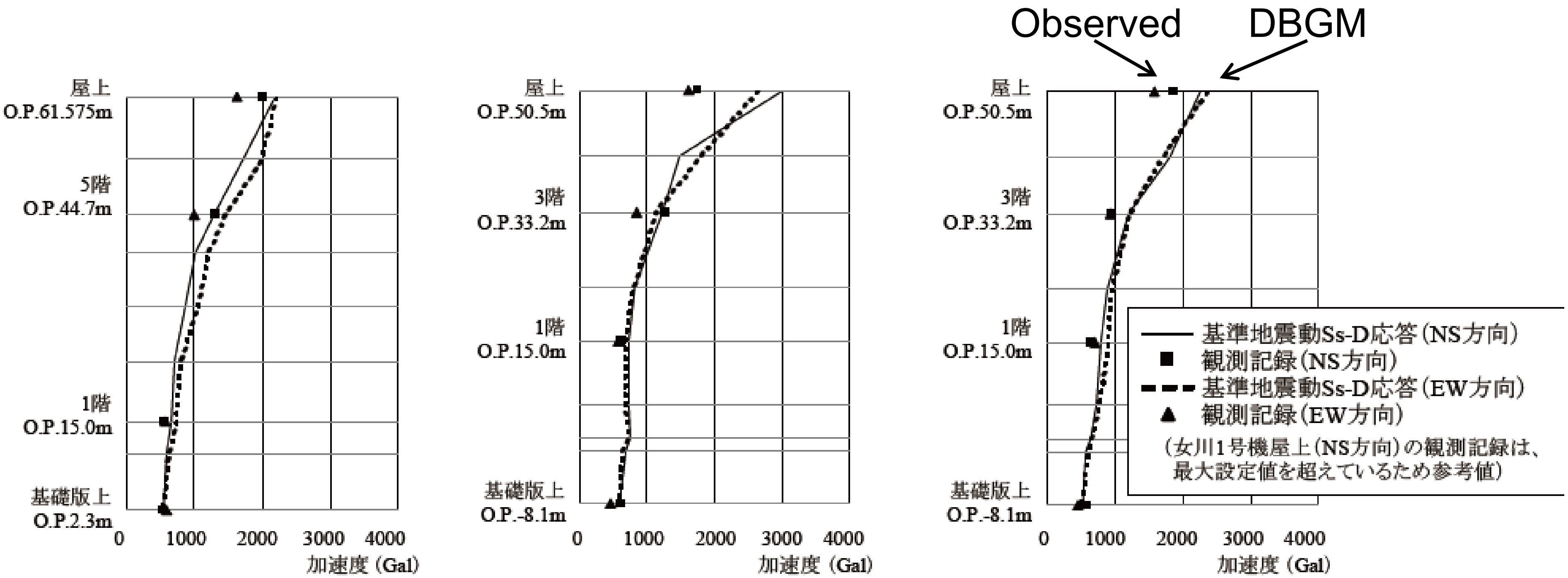
Seismometers in vertical array





Reference: Tohoku Electric Power Co., Inc
[Online] http://www.tohoku-epco.co.jp/ICSFiles/afieldfile/2011/04/25/110425np_s.pdf
Partially modified by JNES.

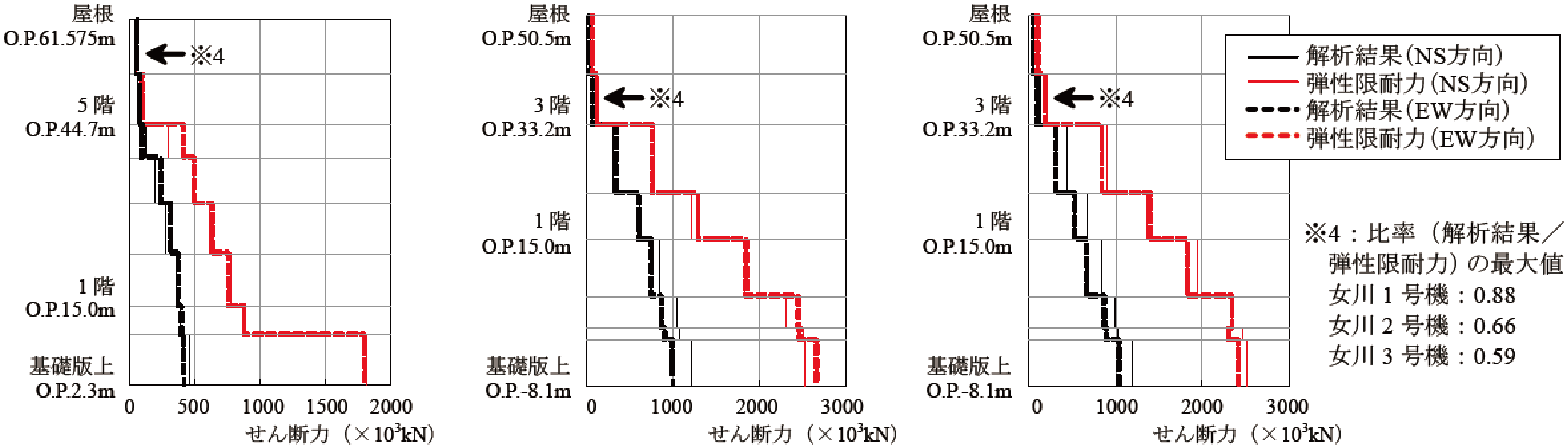
Comparison between PGAs observed from the earthquake and those given from the DBGM at the Onagawa NPP



Unit No.1 Unit No. 2 Unit No. 3

Report of NISA (2011)

Limit of shear stress acting on earthquake-resistant wall at each floor of the reactor building of the Onagawa NPP



Unit 1 Unit 2 Unit 3

Report of NISA (2011)

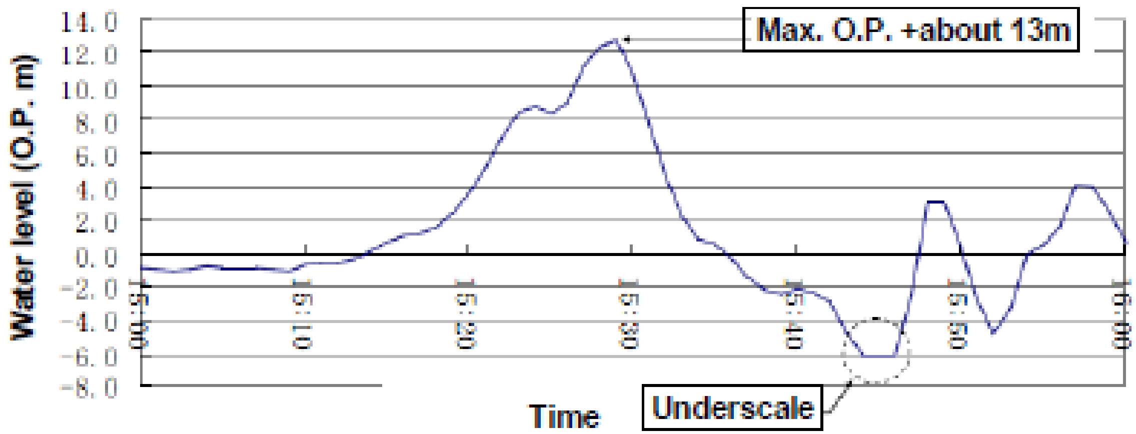
Comparison between analyzed values from observed records and reference levels for seismic safety with respect to the maximum shear strain responses at the Onagawa NPP

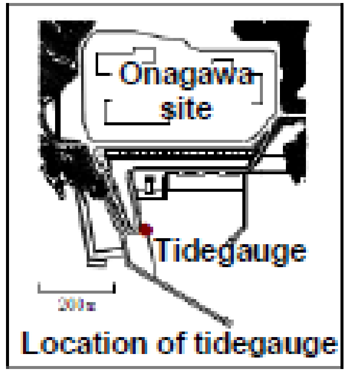
		解析結果	評価基準値※3	（参考）基準地震動 Ss
女川 1 号機	NS 方向	0.36×10^{-3}	2.0×10^{-3}	0.65×10^{-3}
	EW 方向	0.35×10^{-3}		0.56×10^{-3}
女川 2 号機	NS 方向	0.49×10^{-3}		1.15×10^{-3}
	EW 方向	0.28×10^{-3}		0.55×10^{-3}
女川 3 号機	NS 方向	0.81×10^{-3}		0.99×10^{-3}
	EW 方向	0.18×10^{-3}		0.41×10^{-3}

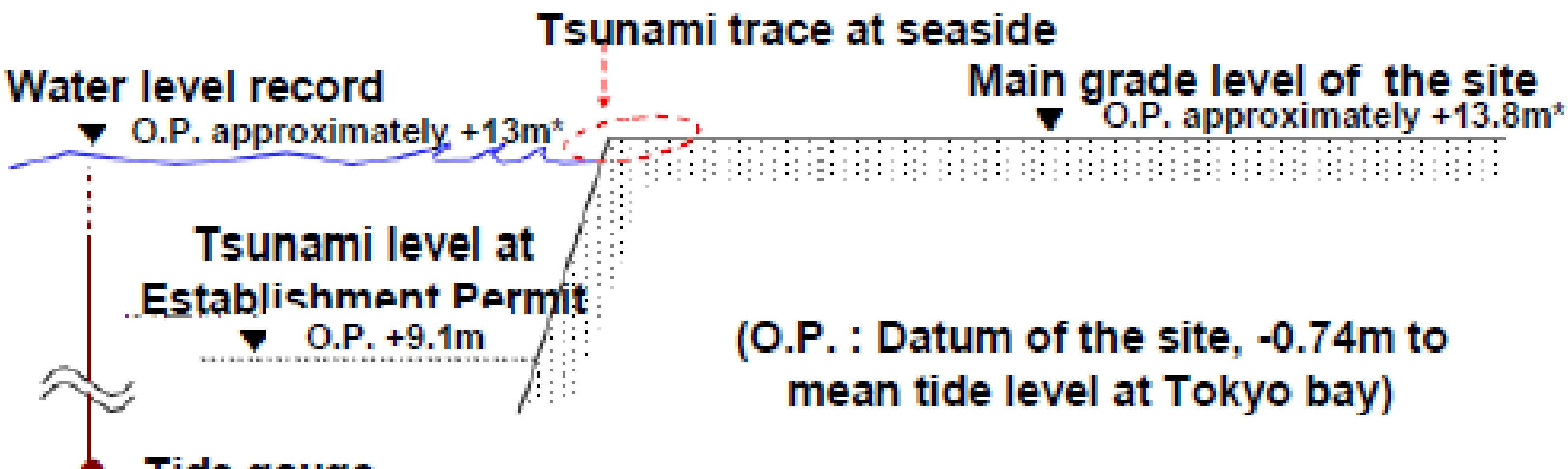
Report of NISA (2011)

Tsunami at Onagawa NPS

Time history of water level changes observed at Onagawa NPS



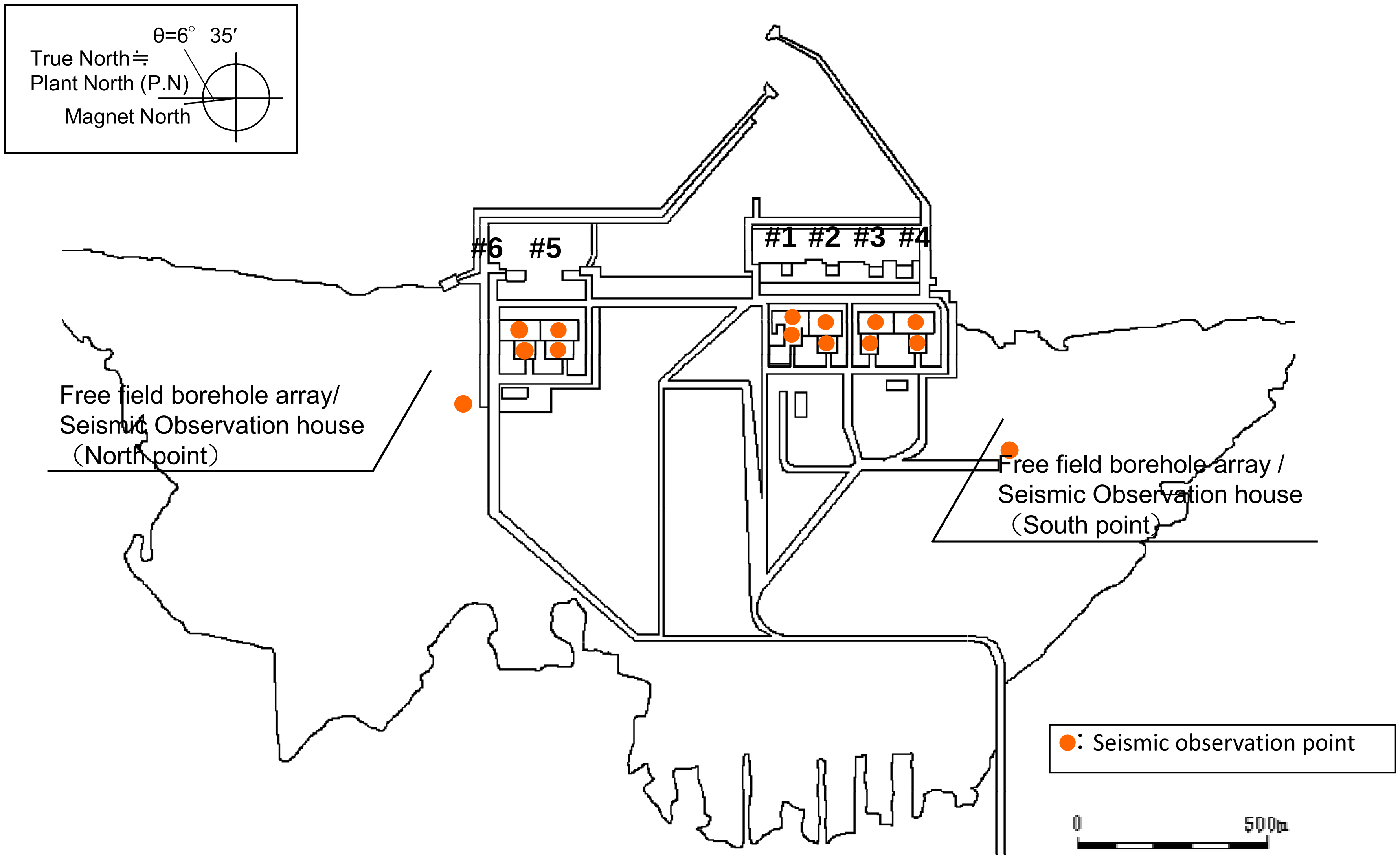




* Subsidence of 1m at Onagawa site is considered

What

Arrangement of Reactor Units at Fukushima Daiichi NPS



Comparison between recorded acceleration and design acceleration to the Design Basis Ground Motion Ss on Base Mats on Units 1 – 5 at Fukushima Dai-ichi NPS

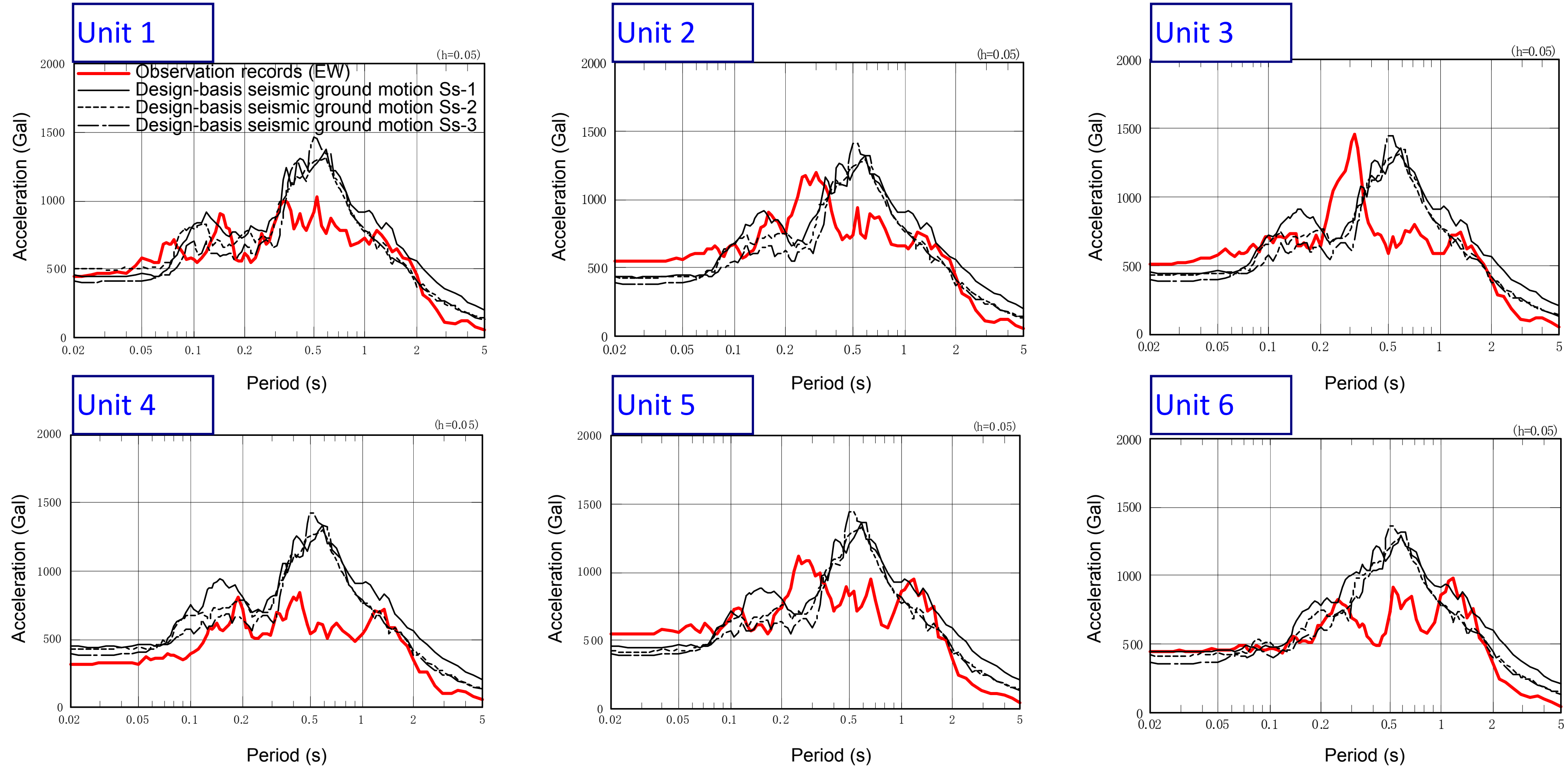
Loc. Of Seismometer (bottom floor of reactpr bld.)		Record Max. acc. (Gal)			Design Max. acceleration to the DBGM Ss (Gal)		
		NS	EW	UD	NS	EW	UD
Fukushima Dai-ichi	Unit 1	460	447	258	487	489	412
	Unit 2	348	550	302	441	438	420
	Unit 3	322	507	231	449	441	429
	Unit 4	281	319	200	447	445	422
	Unit 5	311	548	256	452	452	427
	Unit 6	298	444	244	445	448	415

Observed records were larger than design levels marked be .

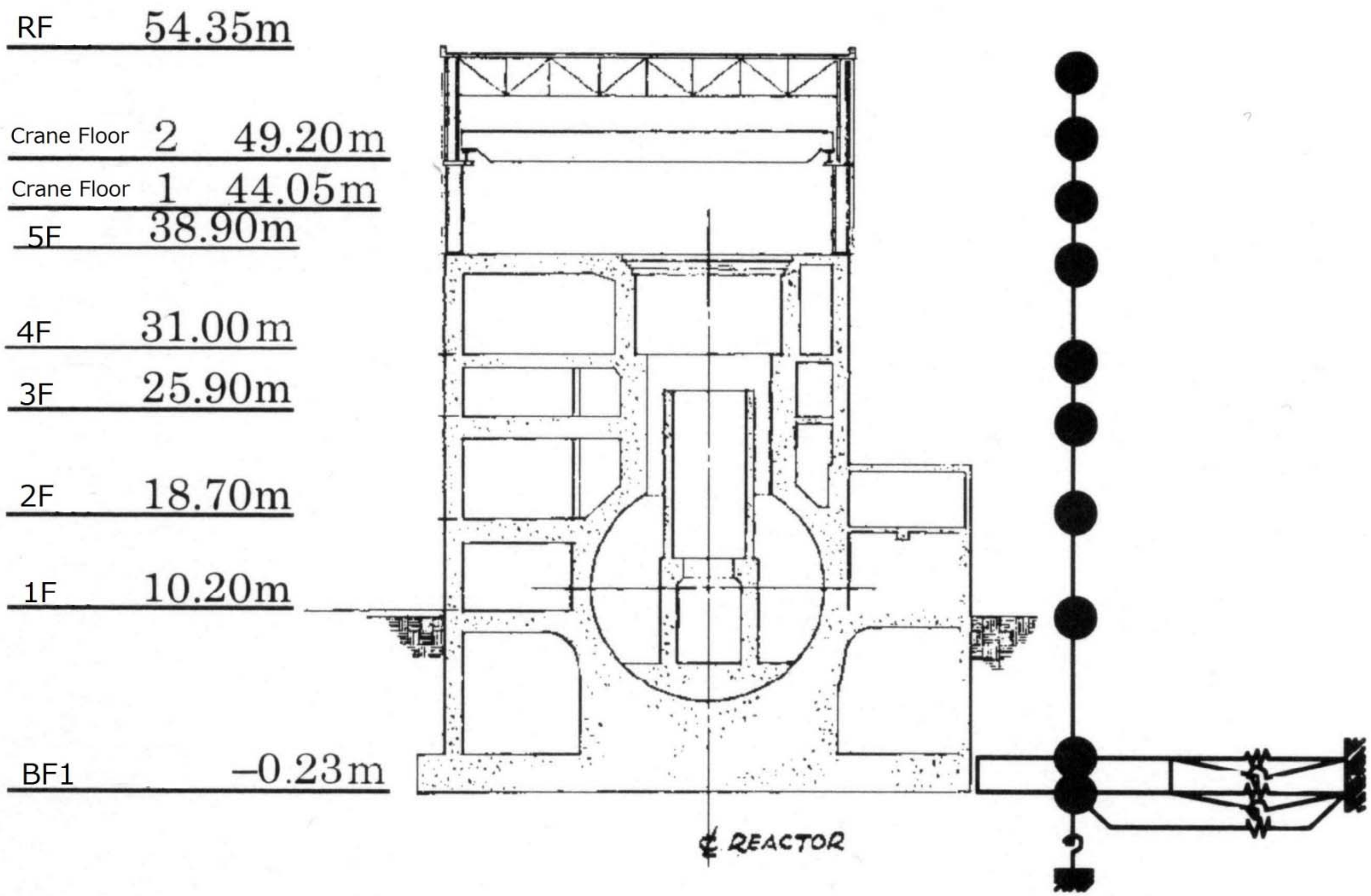
Records of Observations at Base Mat of Reactor Building at Fukushima Daiichi NPS

■Comparison of response spectra calculated by observation records and design-basis seismic ground motion Ss

The response spectra of observation records were mostly the same as those due to design-basis seismic ground motion Ss, though they exceeded in some periodic bands.



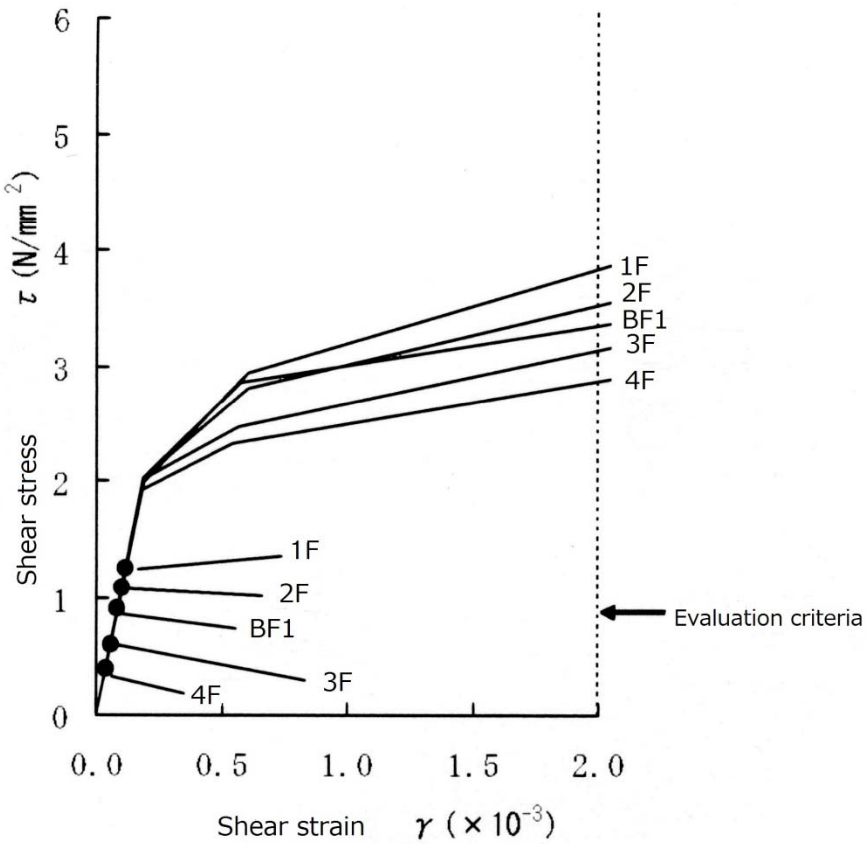
Model for Seismic Design of Reactor Building



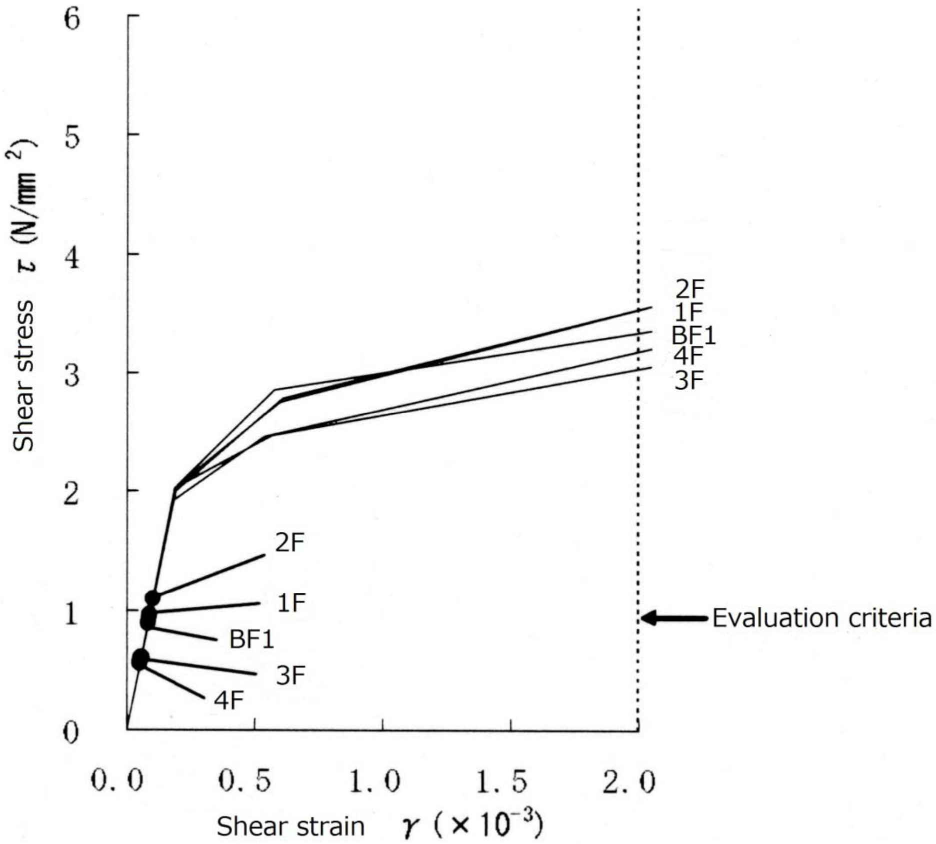
Seismic Safety Assessments for Reactor Building No. 1 at Fukushima Daiichi NPS against Design Basis Ground Motions Ss

Stress-Strain Relations for Earthquake-Resistant wall of Reactor Building

Horizontal NS



Horizontal EW



Seismic Safety Evaluation for Reactor Building No. 1 at Fukushima Daiichi NPS during the Great Off Tohoku Earthquake

Analyzed Model for Seismic Response of Reactor Building Unit No.1

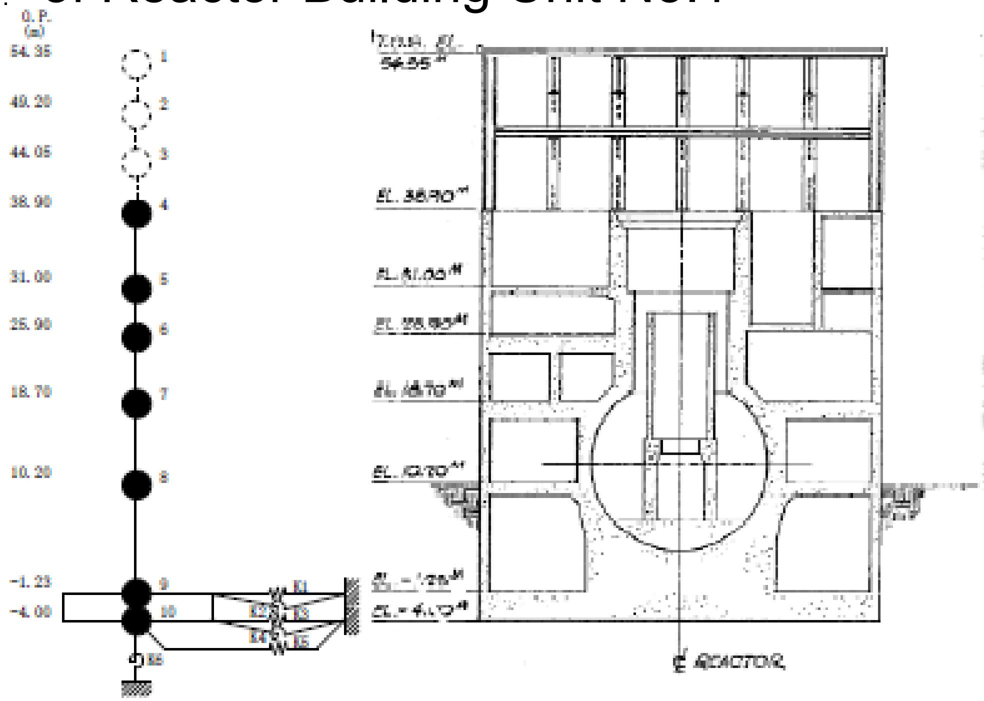


図１　１号機原子炉建屋　地震応答解析モデル
(NS 方向)

Stress-Strain Relations for Earthquake-Resistant Wall

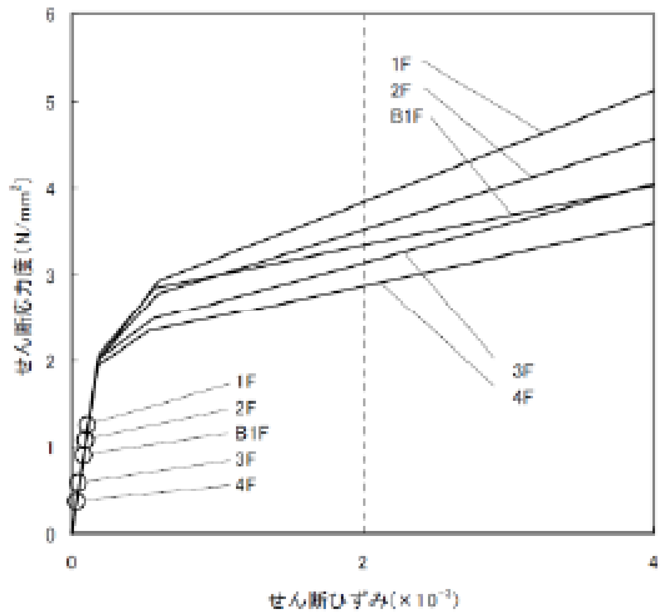


図２　せん断スケルトン曲線上の最大応答値
(１号機、Ss-1、NS 方向)

Seismic Safety Evaluation for Reactor Building No. 4 at Fukushima Daiichi NPS during the Great Off Tohoku Earthquake

Analyzed Model for Seismic Response of Reactor Building Unit No.4

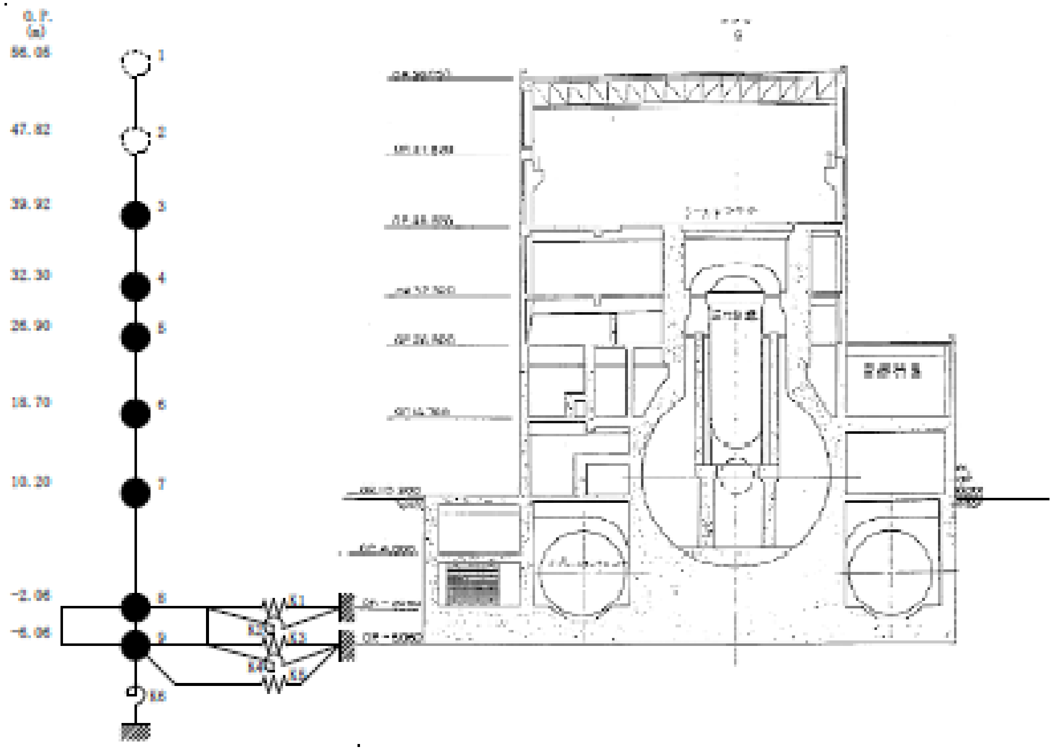


図３　４号機原子炉建屋　地震応答解析モデル
（EW 方向）

Stress-Strain Relations for Earthquake-Resistant Wall

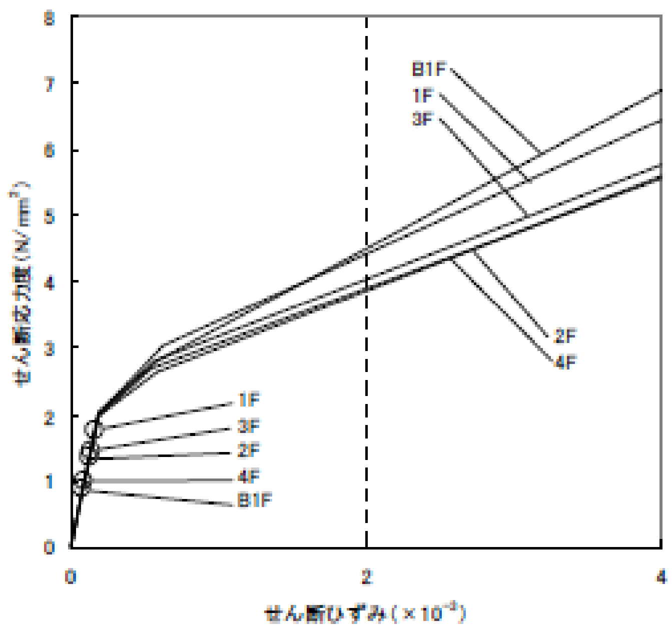
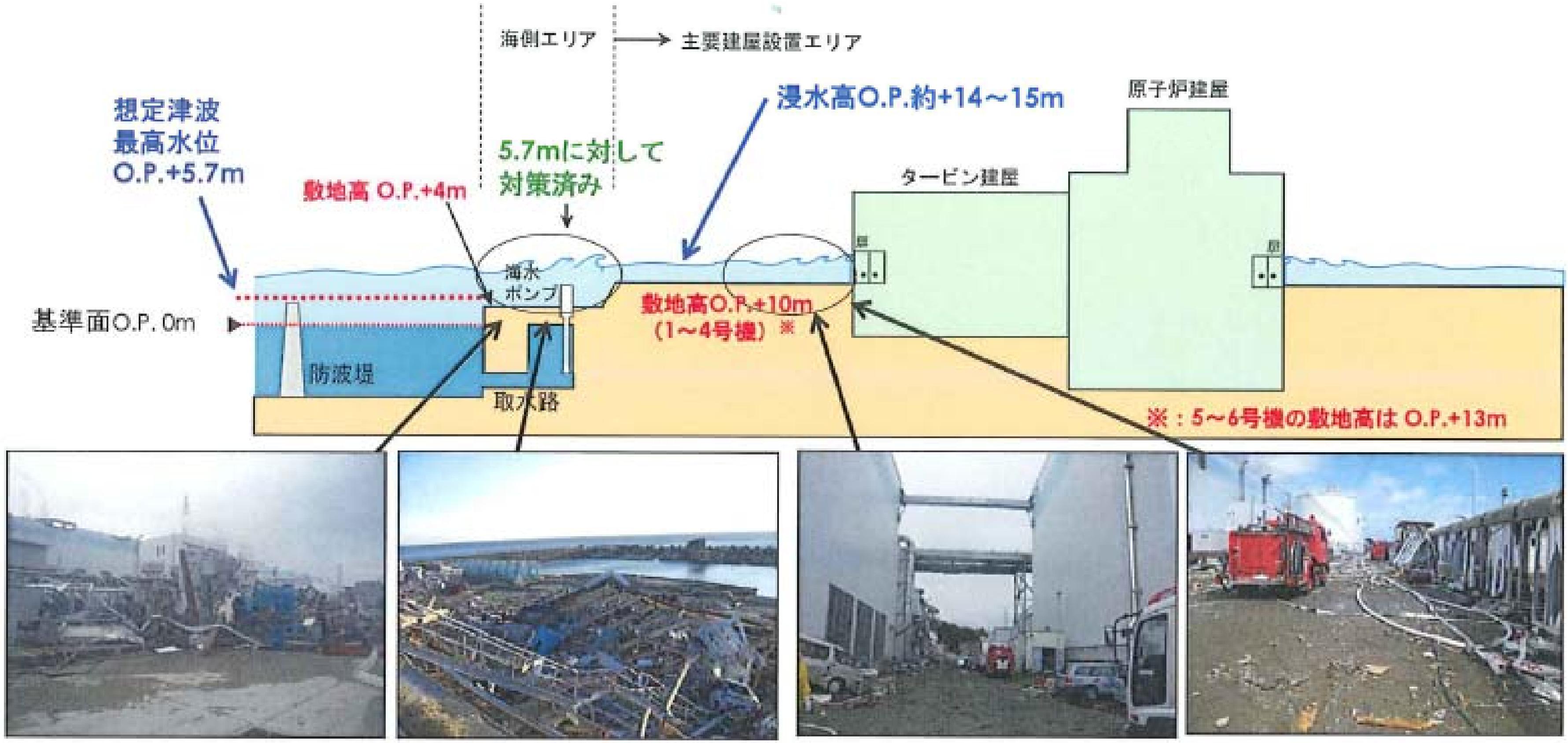
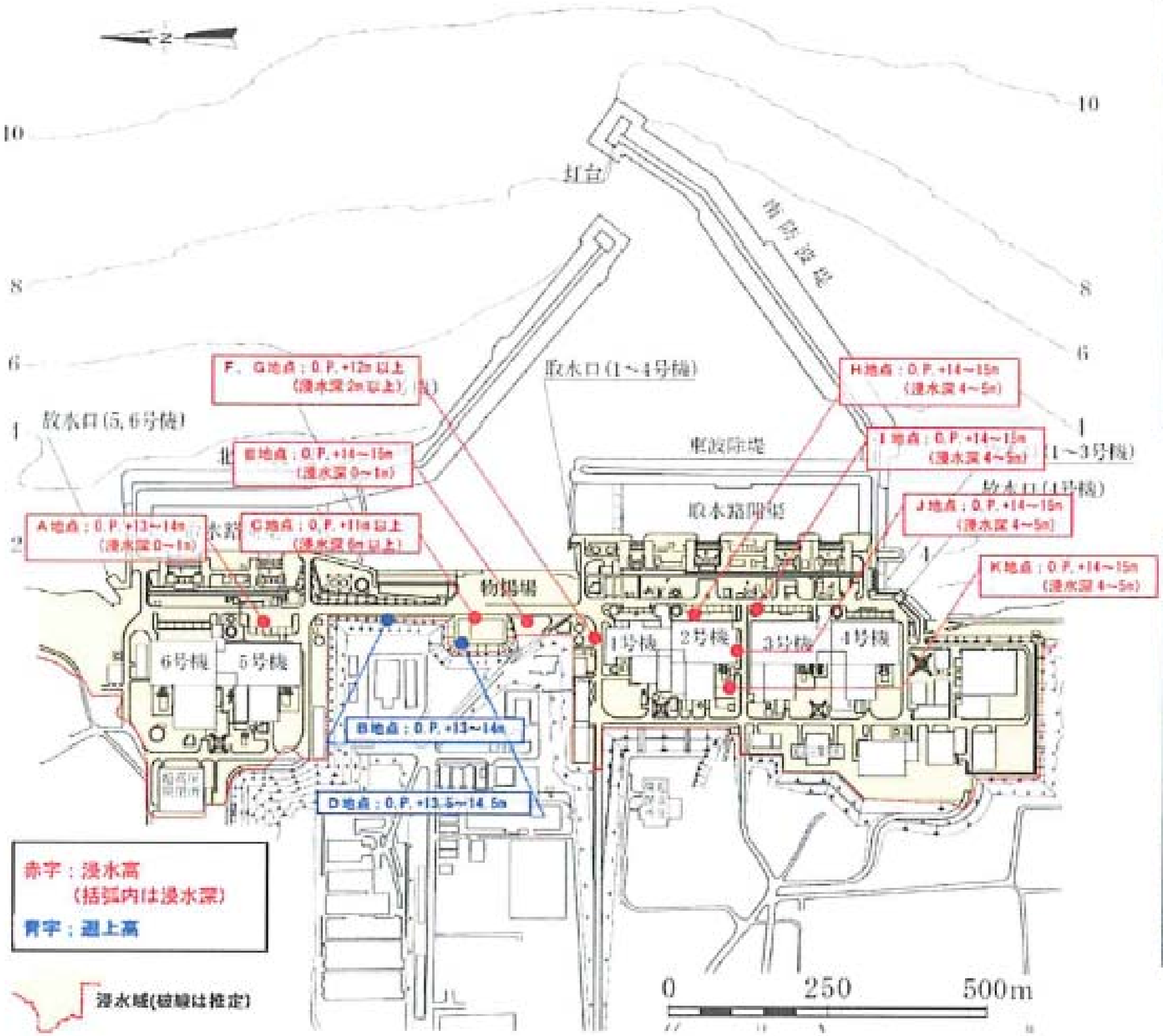


図４　せん断スケルトン曲線上の最大応答値
（４号機、Ss-1、EW 方向）

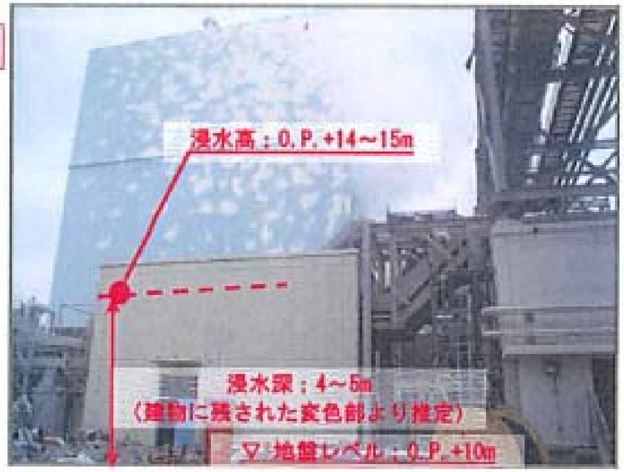
Damage of Fukushima Dai-ichi due to the Tsunami During the Great Off Tohoku earthquake



Inundation Height, Inundation Area, and Run-up Height At Fukushima Dai-ichi NPS during the Great Off Tohoku earthqujake



浸水高判読結果の一例（J地点）



浸水高判読結果の一例（K地点）

Damage of External Power Supply Systems of the Fukushima Dai-ichi and Dai-ni NPSs

Okuma line 1L (O-81)
Circuit Breaker damaged

Okuma line 2L (O-81)
Circuit Breaker damaged

Okuma line 3L, Ground wire (disconnected)

Okuma line 3L & 4L, Steel structure for lead-in (tilted)

Yorunomori line, Cable in substation (subsidence)

Landslide of slope

Overview of landslide

Collapsed tower

Main Chronology (Provisional) of Serious Accidents at Fukushima Daiichi NPS – Case of Unit 1 as an example –

a. From the earthquake to the invasion of the tsunami

The earthquake which occurred at 14:46 on March 11, 2011 brought all of the Fukushima Daiichi NPS Units 1 through 3, which were in operation, to an automatic shutdown due to the high earthquake acceleration.

The NPS was unable to receive electricity from offsite power transmission lines mainly because some of the steel towers for power transmission outside the NPS site collapsed due to the earthquake. For this reason, the emergency DGs for each Unit were automatically started up to maintain the function for cooling the reactors and the spent fuel pools.

b. Effects from the tsunami

At 15:37, the effects of the tsunami were felt, and the water, meaning that two emergency diesel generators stopped operation, and the emergency bus distribution panel was submerged, leading to all AC power being lost, affected both the seawater pump and the metal-clad switchgear of Unit 1.

c. Emergency measures

TEPCO started pumping alternative water injection (fresh water) through fire pumps at 5:46 on March 12. Therefore, since cooling using the IC had stopped due to the failure of all AC power at 15:37 on March 11, that meant that there was a 14-hour-and-9-minute period when cooling using pumped water had stopped.

c. Emergency measures (continued)

TEPCO worked to vent the PCV in order to lower its pressure. However, since radiation inside the reactor building was already at the high radiation environment level, the work proceeded with difficulty.

A temporary air pressurization machine was set up to drive the AO valve and the PCV vent was operated. TEPCO judged that the PCV vent had succeeded since the PCV pressure had been reduced by 14:30.

d. The building explosion and measures taken subsequently

At 15:36 on March 12, an explosion, thought to be a hydrogen explosion, occurred in the upper part of the reactor building. The roof, and the outer wall of the operation floor as well as the waste processing building roof, were destroyed. Radioactive materials were released into the environment during these processes, thereby increasing the radiation dose in the area surrounding the site.

Summary – What are problems to solve ? - I

1. The observed ground motions on the reactor base mats were almost the same level as the design input motions estimated the design basis ground motions. But some observed ones at the Fukushima Dai-ichi and Onagawa were at most 30 % larger than the design input motions.

2. The evaluation of tsunami waves at Fukushima Dai-ichi and Dai-ni was absolutely underestimated because such great large earthquakes have not been predicted. The revised Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities in 2006 specifies that "During the service period of the facilities, safety features in the facilities might not be significantly affected even by such a tsunami that could likely to occur on very rare occasions," and the guideline asks for proper design for such a possible tsunami. But, unfortunately, reevaluation of seismic safety for NPSs against tsunami waves has not been done yet after the revision of the Regulatory Guide.

3. More careful investigations for evaluating design basis ground motions and tsunami heights including source, path, and site effects as the lessons from the extremely severe accident of the Fukushima First Nuclear Power Plants.

Summary – What are problems to solve ? - 2

4. The structural soundness of important nuclear facilities at the NPP was examined for the design basis ground motions. The seismic safety capacities of those facilities to the input motions were evaluated. For example, the responses of the reactor buildings are confined about half to the elastic limits in the stress-strain relationships. Other facilities also have sufficient seismic safety capacity. Therefore, the seismic safety of the important facilities probably has been kept during the earthquake. The tsunami safety capacities of the nuclear facilities should be evaluated as one of the most important lessons learned from this earthquake disasters.

5. The Regulatory Guide for Evaluating Safety Assessment of Light Water Reactor Facilities takes loss of external power supply as an abnormal transient during operation and requires check of appropriateness of relevant safety equipment. On the contrary, the Regulatory Guide for Reviewing Safety Design does not take total AC power loss as a design basis event. This is because it requires emergency power supply systems to be designed with a high degree of reliability as AC power supplies. However, this guide clearly violates the concept of “defence in depth” in designing the safety systems of nuclear power plants.

Summary – What are problems to solve ? - 3

5. Guidelines for accident management
   Since the guidelines for accident management were established by the Nuclear Safety Commission in 1992, accident management was prepared at each nuclear power plant over ten years.
   Such accident management based on PSA and an analysis of scenarios involving internal events caused by equipment failure and human error conducted in 80's. This guideline was highlighted to emphasize the effectiveness of introducing accident management, and failed to focus on the environmental conditions so as to make accident management effective. The accident management guidelines by introducing new findings for effective operation should have constantly reviewed, taking into account the importance of the role that accident management has for achieving the safety goal,