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First Kashiwazaki International Symposium on Seismic Safety of Nuclear Installations

– Mission for Technology Innovation toward Next Generation –

November 24-26, 2010 at Niigata Institute of Technology, Kashiwazaki-city, Niigata, JAPAN

"Session A: Earthquake and Ground Motion" and "
Workshop 1: Seismic Observation in Deep Boreholes and its Applications"

Further Advancement of Strong Motion Prediction

-Expectation for deep boreholes seismic observation and geophysical exploration from viewpoint of ground motion evaluation-

K. Irikura (*Univ. Aichi Inst. Tech.)*

The 1995 Kobe Earthquake urged to revise the Regulatory Guide for seismic safety of Nuclear Power Plants

The 2007 Chuetsu-oki Earthquake made further impacts and anxiety to people in Japan concerning seismic safety of Nuclear Power Plants.

Today’s Topics

1. Developments of strong motion evaluation after the 1995 Kobe erthquakes

2. Revised Regulatory Guide (2006) for Reviewing Seismic Design of Nuclear Power Reactor Facilities

3. Methodology of estimating ground motions from earthquakes

4. Seismic reevaluation (back-checks) of the existing Nuclear Power Plants based on the Regulatory Guide

5. Expectation for deep boreholes seismic observation and geophysical exploration from viewpoint of ground motion evaluation

6. Summary and future direction

1. Developments of strong motion evaluation after the 1995 Kobe earthquakes

Programs defining the Seismic Hazard in Japan

Long-term Evaluation:
Evaluate probabilities of the next occurrence of large earthquakes for major active faults and subduction-zones along troughs.

Strong Ground Motion Evaluation

Construct seismic hazard maps, probabilistic and deterministic.

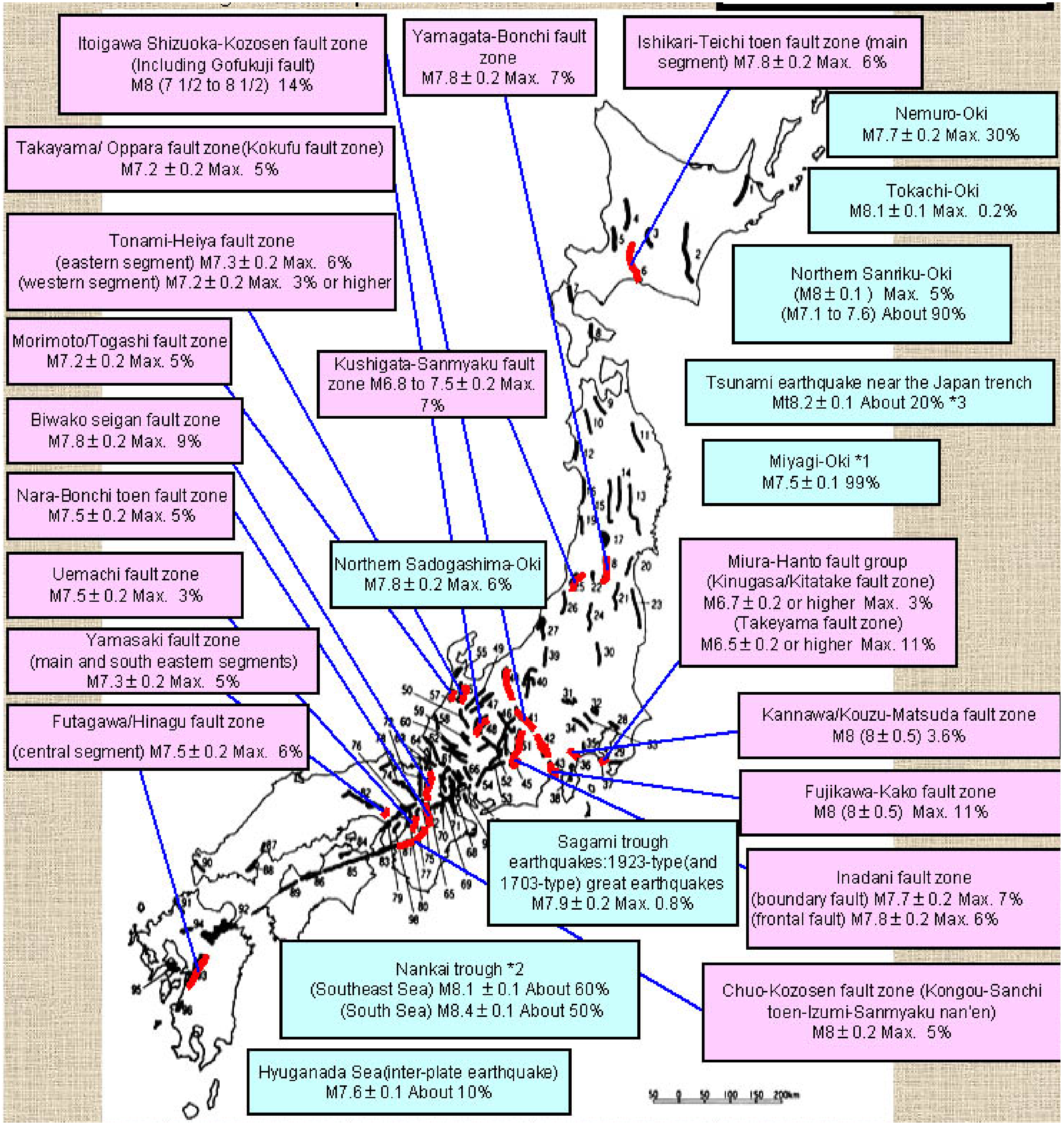
Probabilistic hazard map: predicted likelihood of ground motion level occurring in a given area within a set period of time.

Shaking map for scenario earthquakes: strong ground motion from hypothetical source models for specified active faults

Long-term Evaluations of Active Faults and Subduction-zone Earthquakes

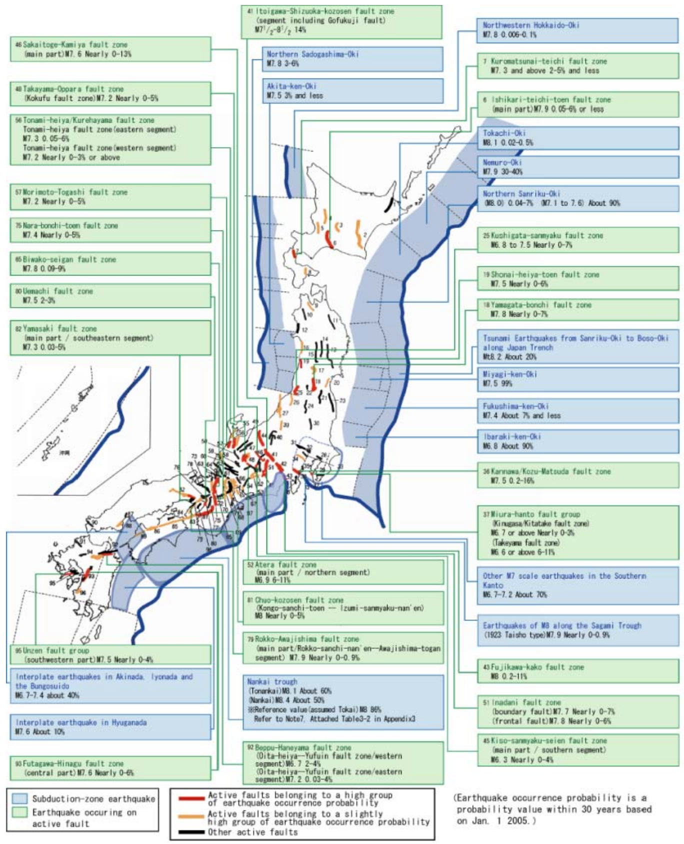
(Predicted magnitude and probability of occurrence within 30 years)

(Earthquake Research Committee, 2004)



Long-term Forecast (continued)

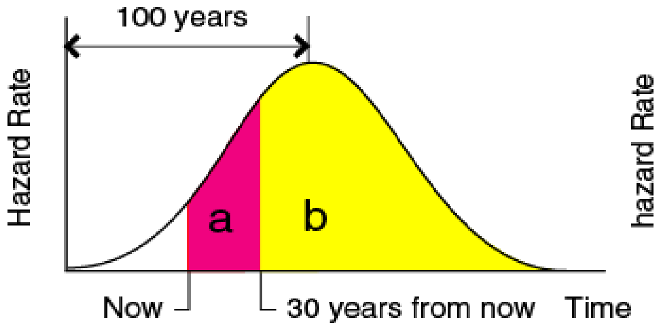
Next 30 years
- Subduction earthquakes
  - Miyagi-oki 99 %
  - Nankai Trough 50-60 %
- Inland Crustal earthquake
  - ISTL (inland fault) 14%
  - most active faults < 5%
  - Kobe eq. in 1995 0.02-8 %

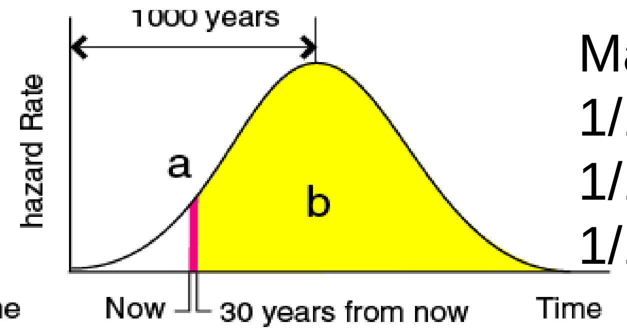


Subduction earthquake

Inland crustal earthquake

Probability = a/ (a+b)





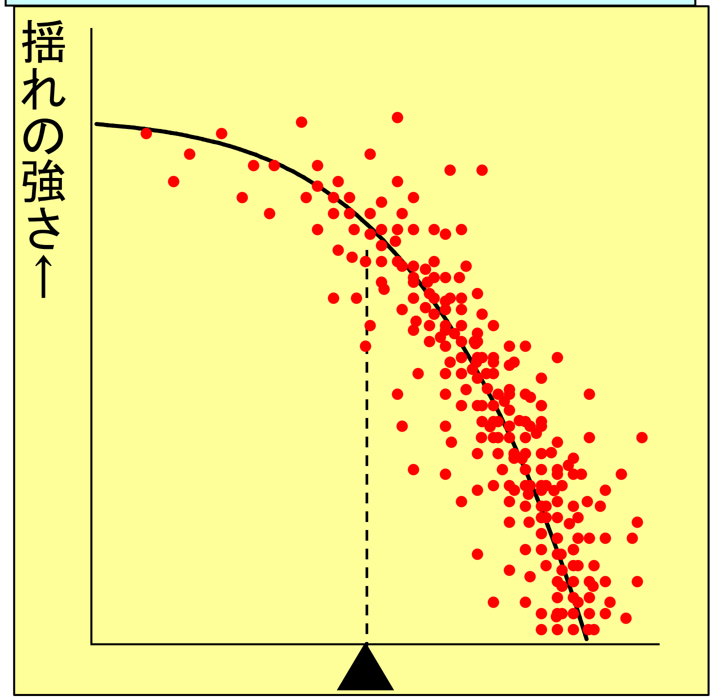
Max probability for 30 yrs
1/100 yr event ~ 90 %
1/1000 yr event ~ 20 %
1/10000 yr event ~ 2 %

Probabilistic Seismic Hazard Map

Long-term Forecast

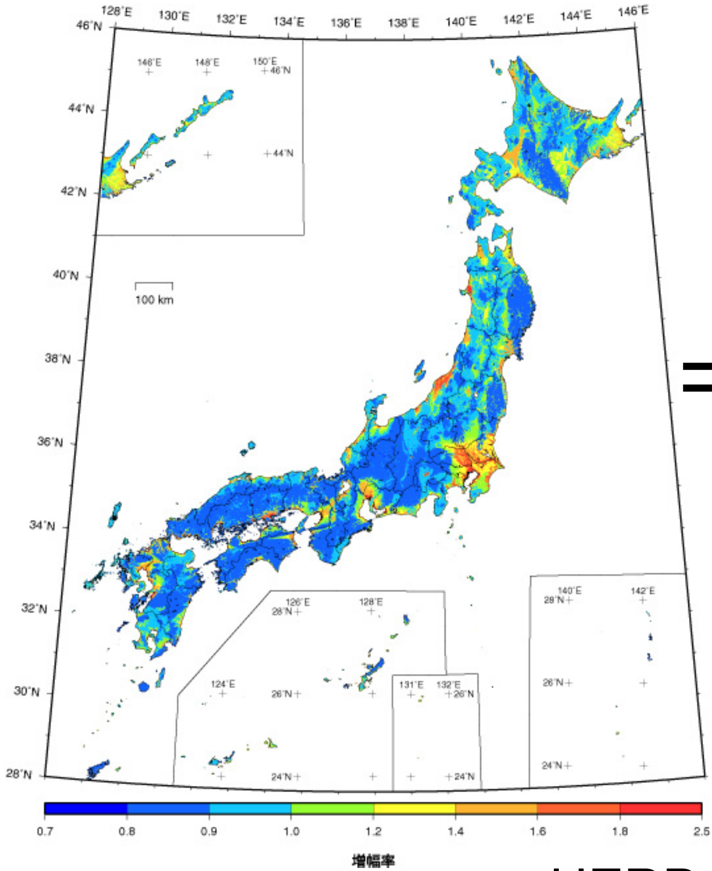
×

Ground motion – Distance Attenuation Relation



Distance from Source Fault

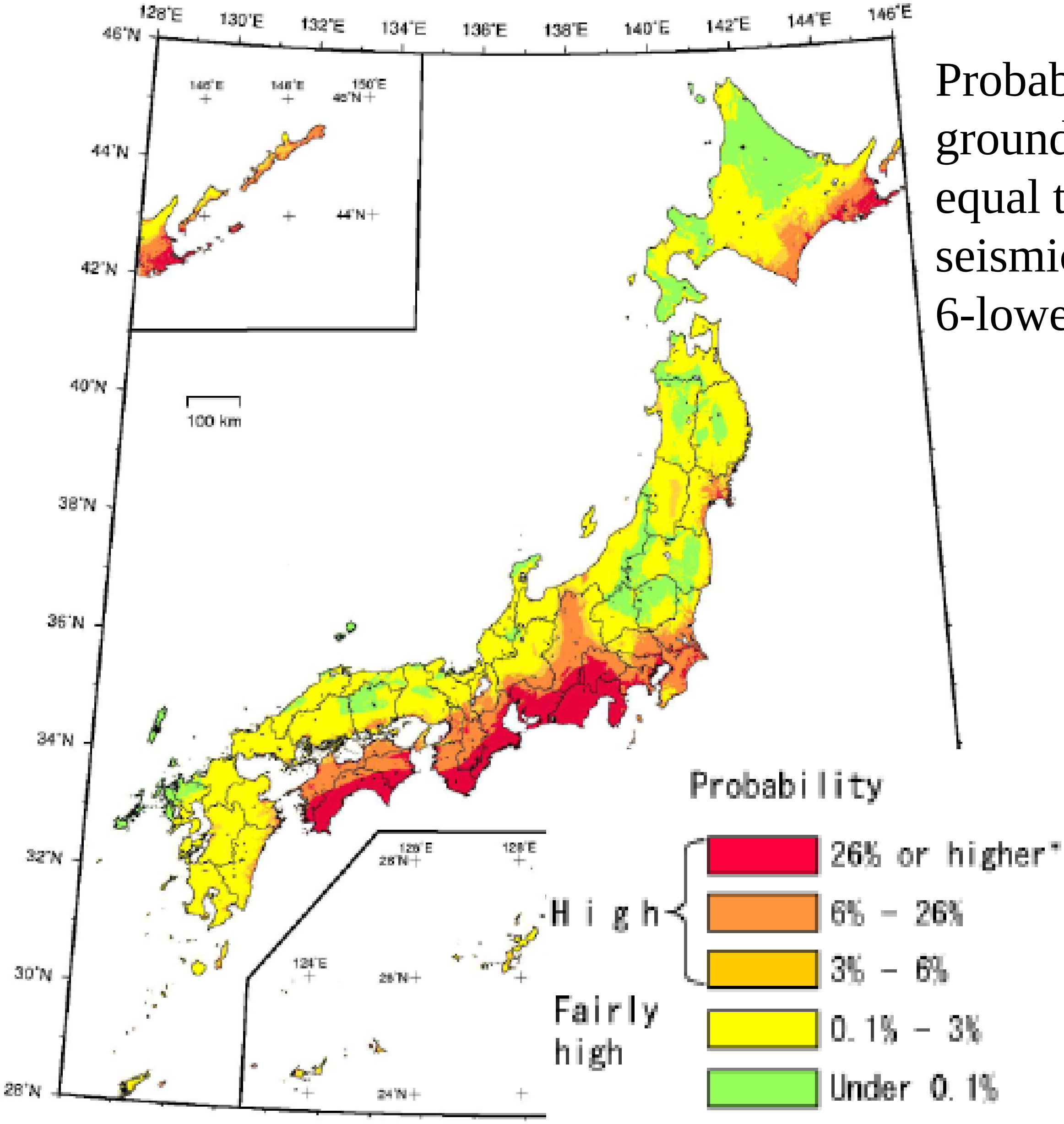
Surface Amplification



HERP

× ＝ PSHM

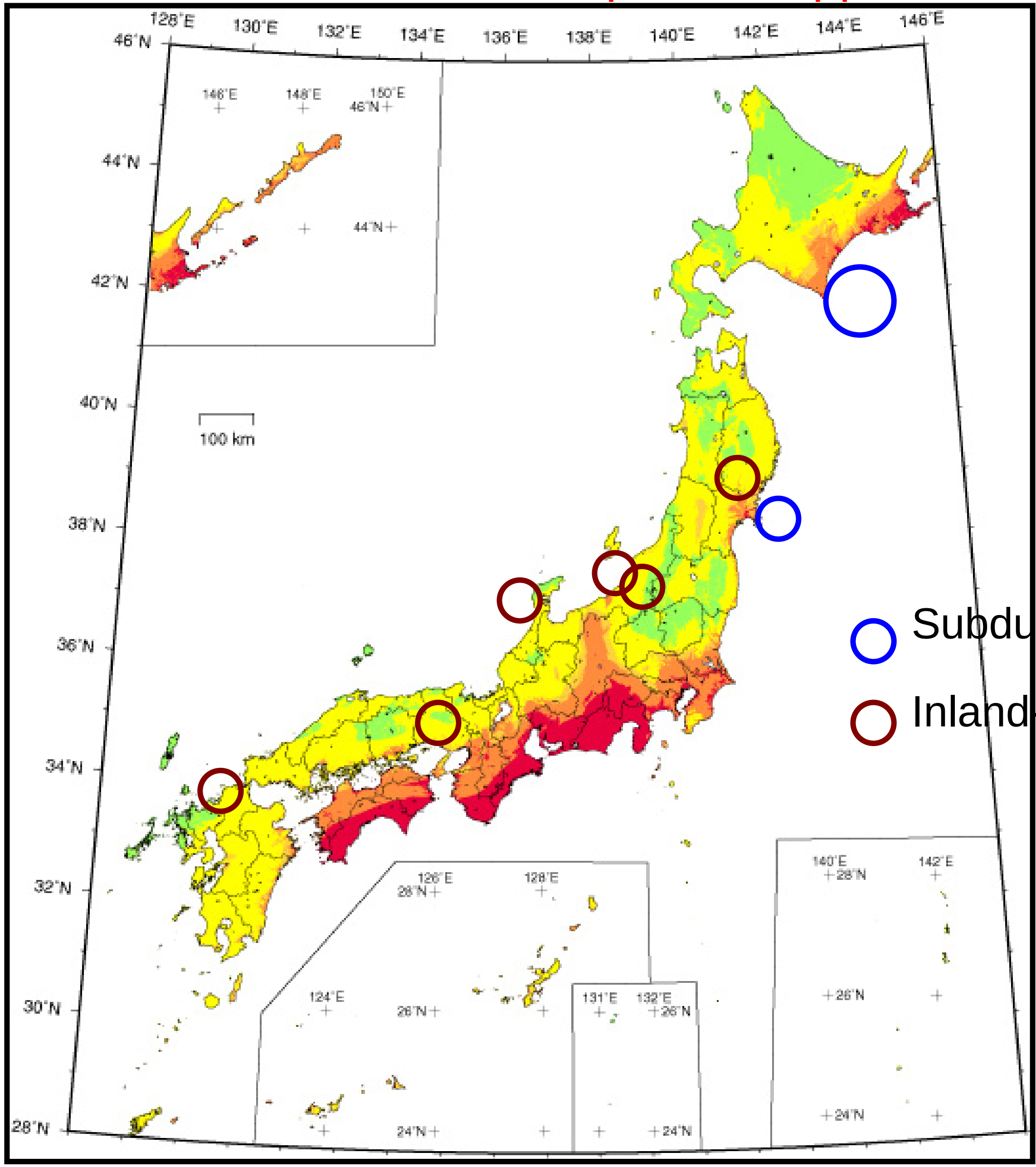
Probabilistic Seismic Hazard Map (2005)



Probability of
ground motions
equal to or larger than
seismic intensity (JMA)
6-lower within 30years.

Probabilistic Seismic Hazard Map (2005)

- Where have recent disastrous earthquakes happened near Japan ? -

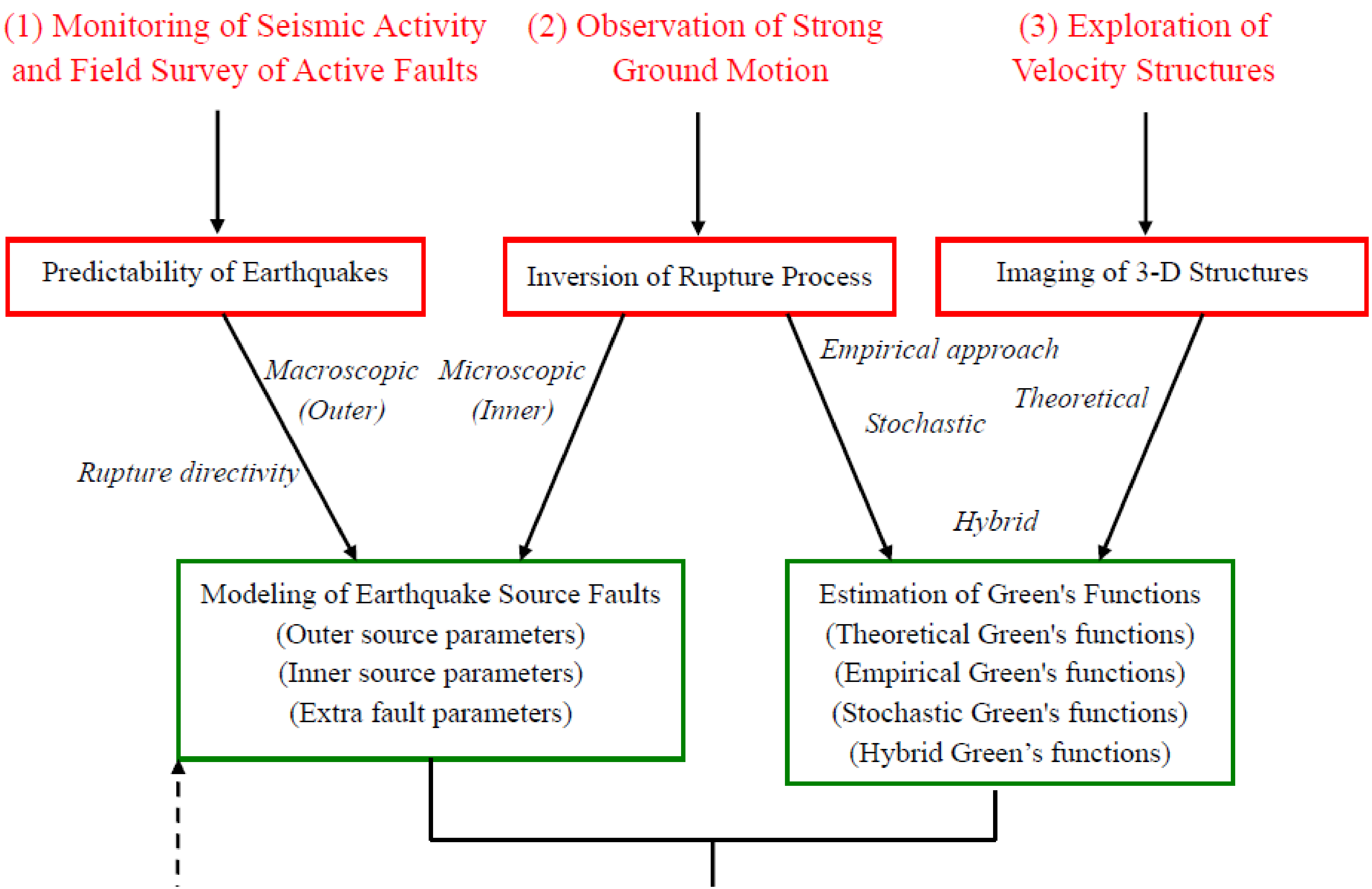


Subduction earthquake

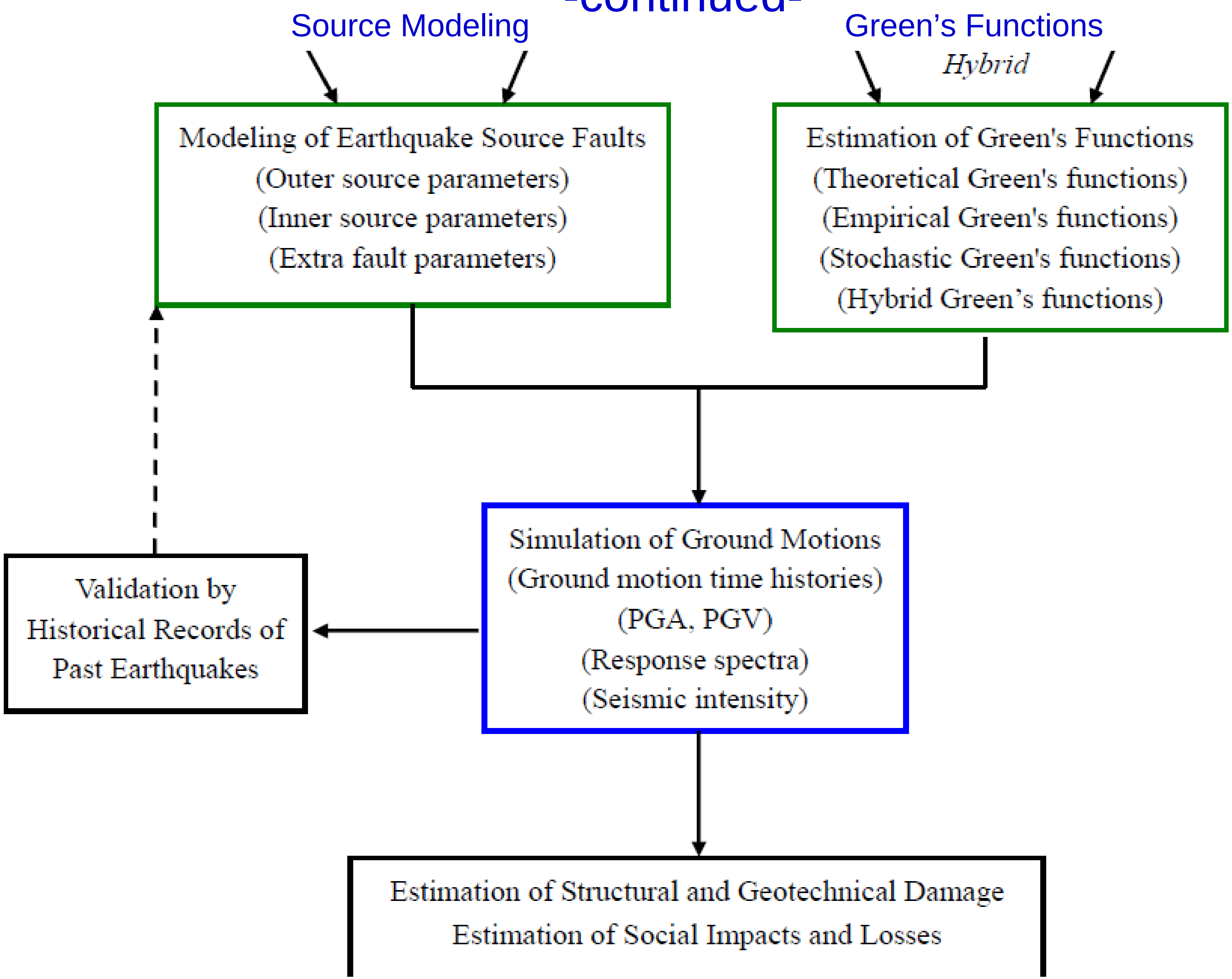
Inland-crust earthquakes

HERP

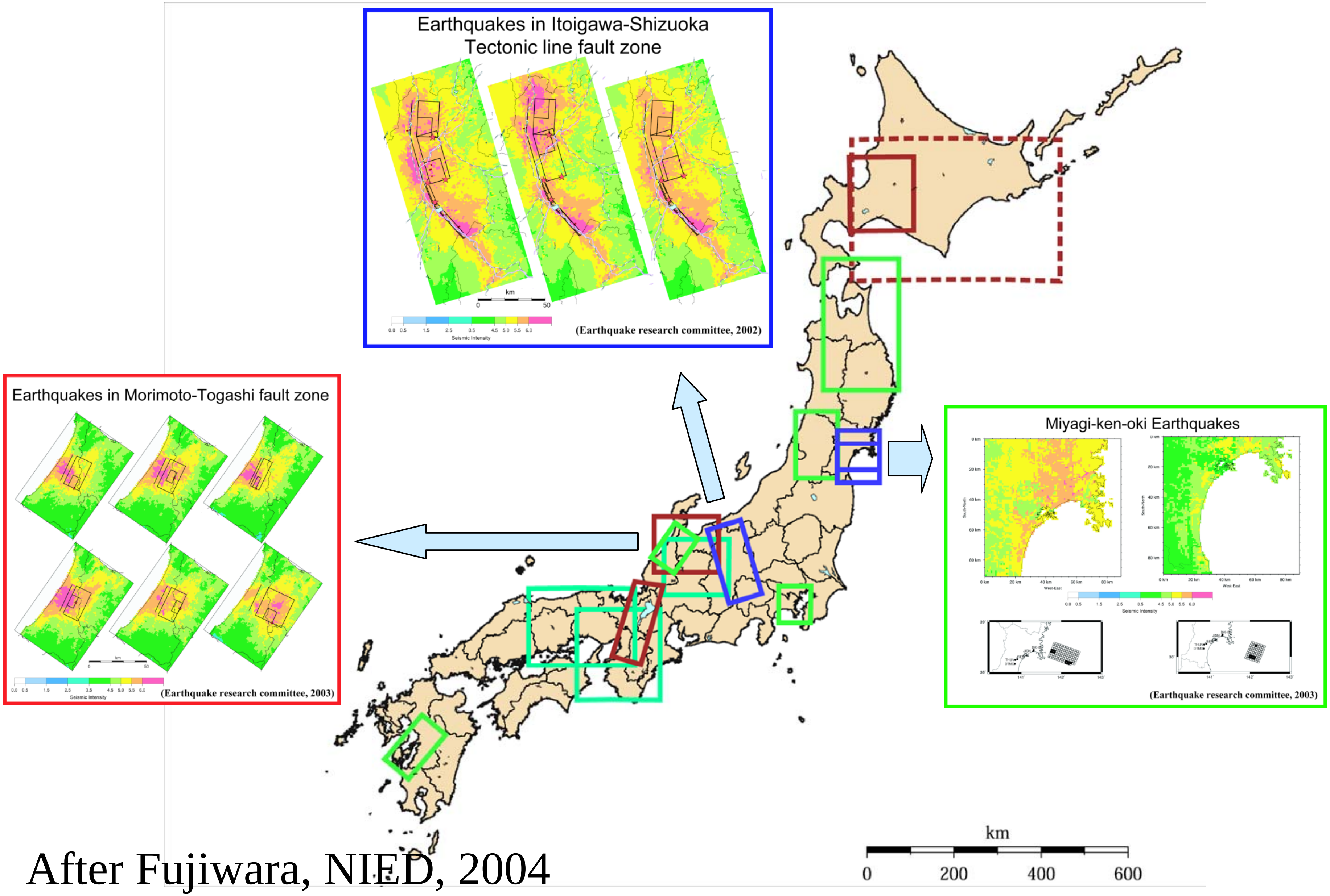
Framework of predicting strong ground motions for crustal earthquake scenarios (Deterministic Approach)



Framework of predicting strong ground motions -continued-



Deterministic Seismic Hazard Map



After Fujiwara, NIED, 2004

2. Revised Regulatory Guide (2006) for Reviewing Seismic Safety of Nuclear Power Reactor Facilities

Why did “Regulatory Guide” have to be revised ?

- Background

The previous “Regulatory Guide was made based on the most advanced knowledge (active fault survey, ground motion simulation based on response spectra, static seismic-force, and so on) for that day in 1981.

A lot of new findings and knowledge on seismology and earthquake engineering were accumulated for 25 years since 1981.

Seismic design technology for “Nuclear Power Reactor Facilities” was also rapidly developed for the last 25 years.

The impacts and lessons from the 1995 Kobe earthquake:

Studies about active faults, seismic source mechanisms, wave propagation , earthquake-resistant structures have been remarkably proceeded.

In particular, methodology for predicting strong ground motions from specific sources have been developed.

Introduction of “PSA (probabilistic safety assessment)” for seismic design of “Nuclear Power Reactor Facilities” in foreign countries, especially USA.

Basic Policy for Seismic Design -1

Important Facilities from the seismic design points shall be designed to bear seismic force exerted from earthquake ground motion and to maintain their safety function, which could be postulated appropriately to occur very scarcely in the operational period of Facilities from the seismological and earthquake engineering standpoints in the vicinity of the proposed site.

Moreover, any Facilities shall be designed to bear the design seismic force sufficiently which is assumed appropriately for every classification in the seismic design from the standpoint of radiological effects to the environment which could be caused by earthquake.

Basic Policy for Seismic Design -2

(Commentary)

The Design Basis Earthquake Ground Motion "Ss" shall be estimated deterministically from the ground motions caused by sufficiently strong earthquakes.

The existence of "Residual Risk" shall be realized and minimized as low as practically possible.

(Residual Risk is defined as a risk caused by the effects of the ground motions that exceed the Design Basis Ground Motion.)

Evaluation of Design Basis Ground Motion 1

1. Evaluate ground motions for the basis of seismic safety design of facilities as following two types,

   (1) “Ground motions for specified sources” at the proposed sites, that is, site-specific ground motions whose source to be identified with the proposed sites.

   (2) “Ground motions for unspecified sources”, that is, ground motions whose source not to be identified.

2. Select plural number of earthquakes which are feared making severe impact to the proposed site, active faults and subduction earthquakes.

   - Active faults considered in the seismic design shall be identified as the one of which activities since the late Pleistocene epoch can not be denied.

Evaluation of Design Basis Ground Motion 1

3. Evaluate ground motion by both methods
   (1) empirical response spectra and (2) fault models.

   (Commentary)
   Evaluation using the fault model method should be preferred in the case of earthquake whose source is near the proposed site.

4. Consider uncertainty concerned with the evaluation process of ground motions.

Deterministic Method and Residual Risk -1

- 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.

Deterministic Method and Residual Risk -2

- Exceeding probabilities of the design basis ground motions for the residual risk is estimated by probabilistic methods considering all scenarios concerning earthquakes and ground motions from earthquakes.

- Variability of the ground motions is estimated with standard deviations of observed data.

- Epistemic and aleatory uncertainties need to be separately estimated.

- The epistemic uncertainties are reduced by constraints on propagation-path effects (velocity and Q structure) and local site effects (rock and soil properties).

Deep boreholes seismic observation and geophysical exploration contribute to reduction of the epistemic uncertainties.

Points of New Regulatory Guide -1

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.

Points of New Regulatory Guide -2

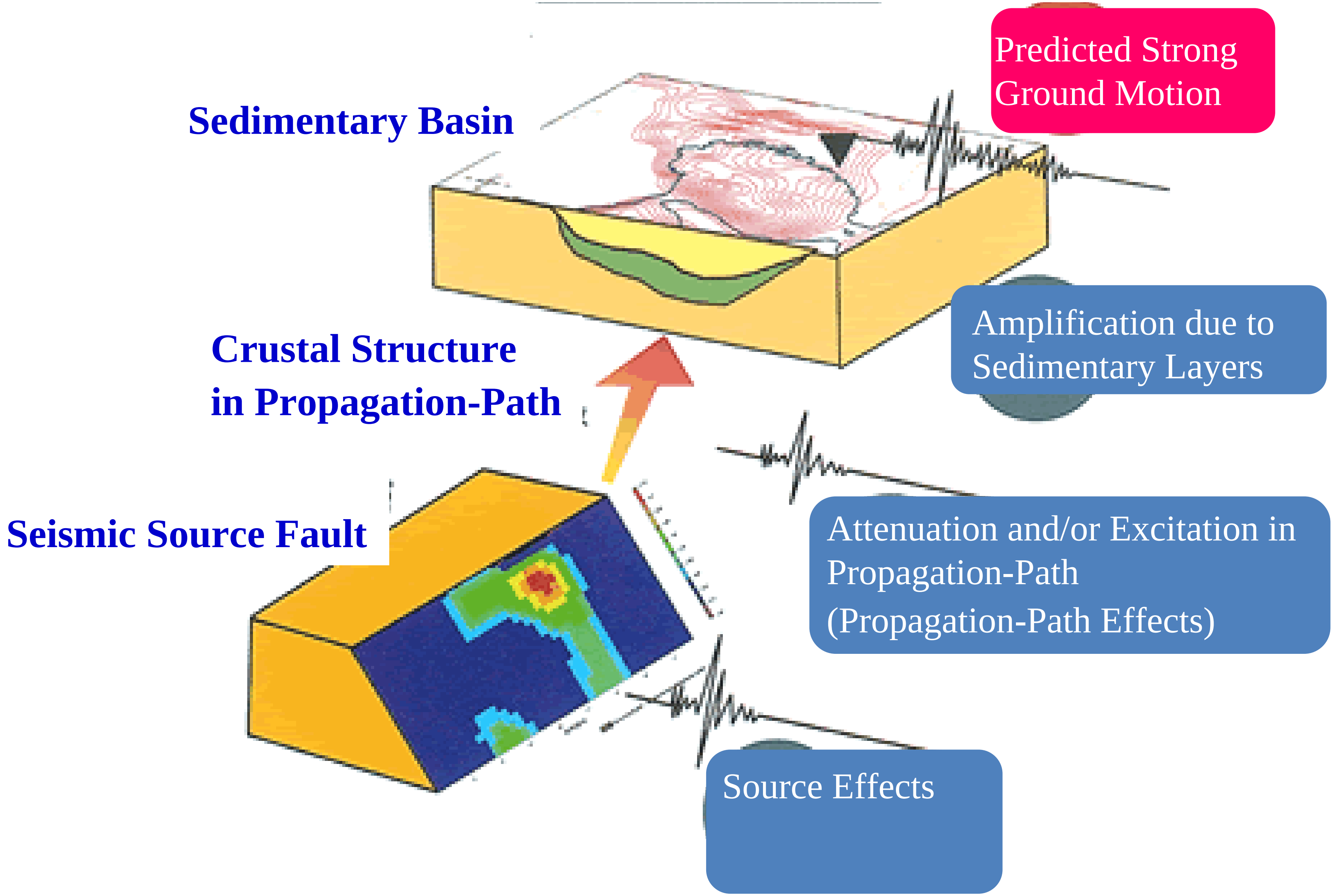
4. PSA is not directly introduced in the guide.
   Reasons: (1) No common understanding exists among experts concerning the maturity of the probabilistic safety assessment approach for risk assessment. (2) A number of issues still remain to be delivered because of lack of basic data and moreover the safety goal has not been determined in the NSC at that time.

5. The risk that may cause serious damage to the nuclear facilities due to the ground motions exceeding Ss is defined as “residual risk”. The efforts to minimize the “residual risk” as low as possible should be made. The safety review process refers to the exceeding probabilities of Ss’s.

6. The next regulatory guide should be revised to introduce probabilistic approaches in near future.

3. Estimation of ground motions from earthquakes based on the "Recipe"

Estimation of Strong Ground Motions



(Predicted Ground Motions) = (Source Effects)$*$(Path Effects)$*$(Surface Geology Effects)

Recipe for Strong Motion Prediction

Outer Fault Parameters

- **Rupture area S** is given.
- **Seismic moment Mo** from the empirical relation of **Mo-S**.
- **Average static stress-drop** $\Delta\sigma_c$ from appropriate physical model (e.g., circular crack model, tectonic loading model, etc.)

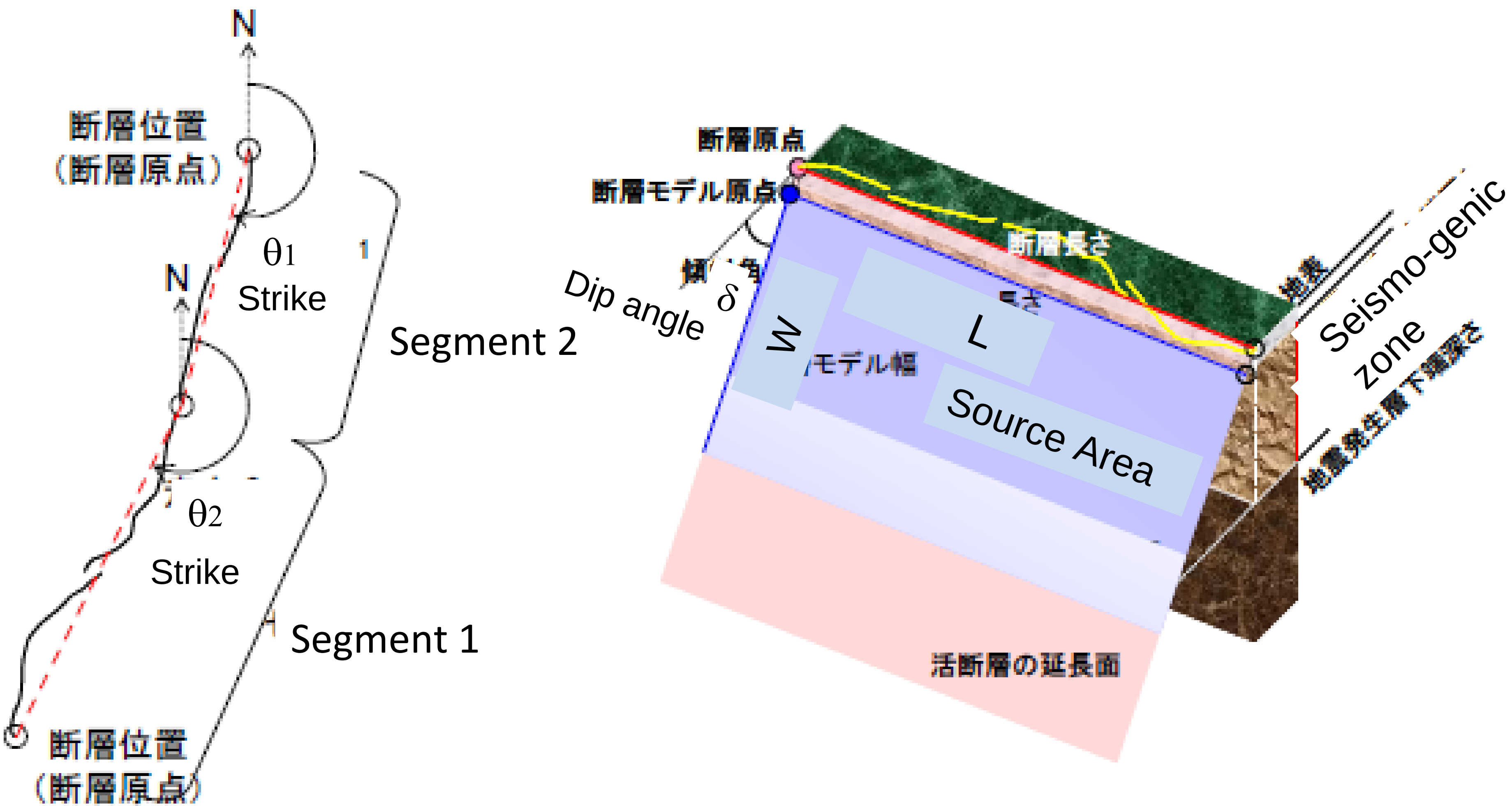
Inner Fault Parameters

- **Combined area of asperities Sa** from the empirical relations of **S-Sa** or **Mo-Ao**.
- **Stress drop** on asperities $\Delta\sigma_a$ based on the multiple asperity model.
- **Number** of asperities from fault segments.
- **Average slip** of asperities **Da** from **dynamic simulations**.
- **Effective stress** for asperities σ_a and background area σ_b are given.
- **Slip velocity time function** given as Kostrov-like function.

Extra Fault Parameters

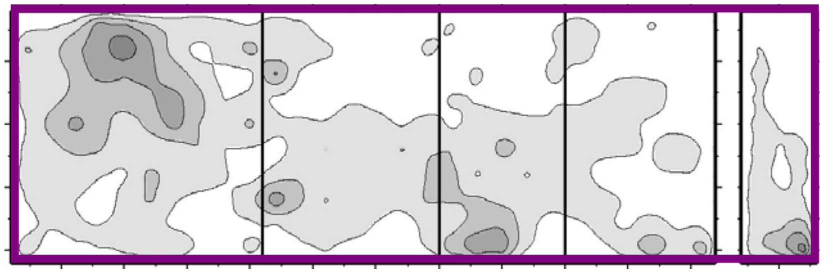
- Rupture nucleation and termination are related to **fault geometry**.

Outer Fault Parameters

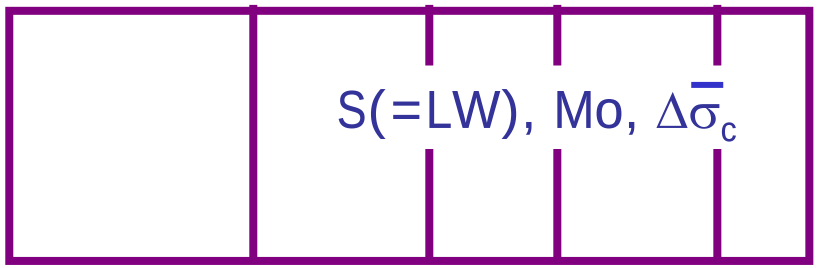


Source Characterization

Based on heterogeneous slip by waveform inversion...

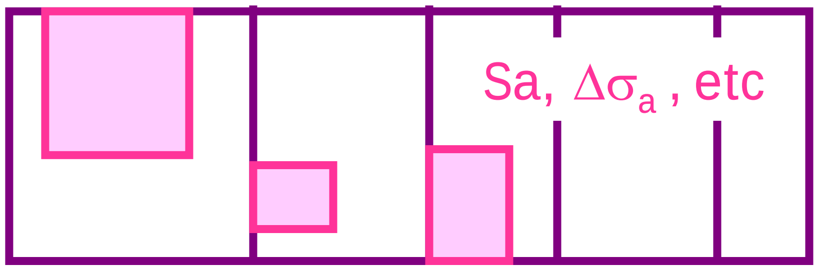


Outer Fault Parameters



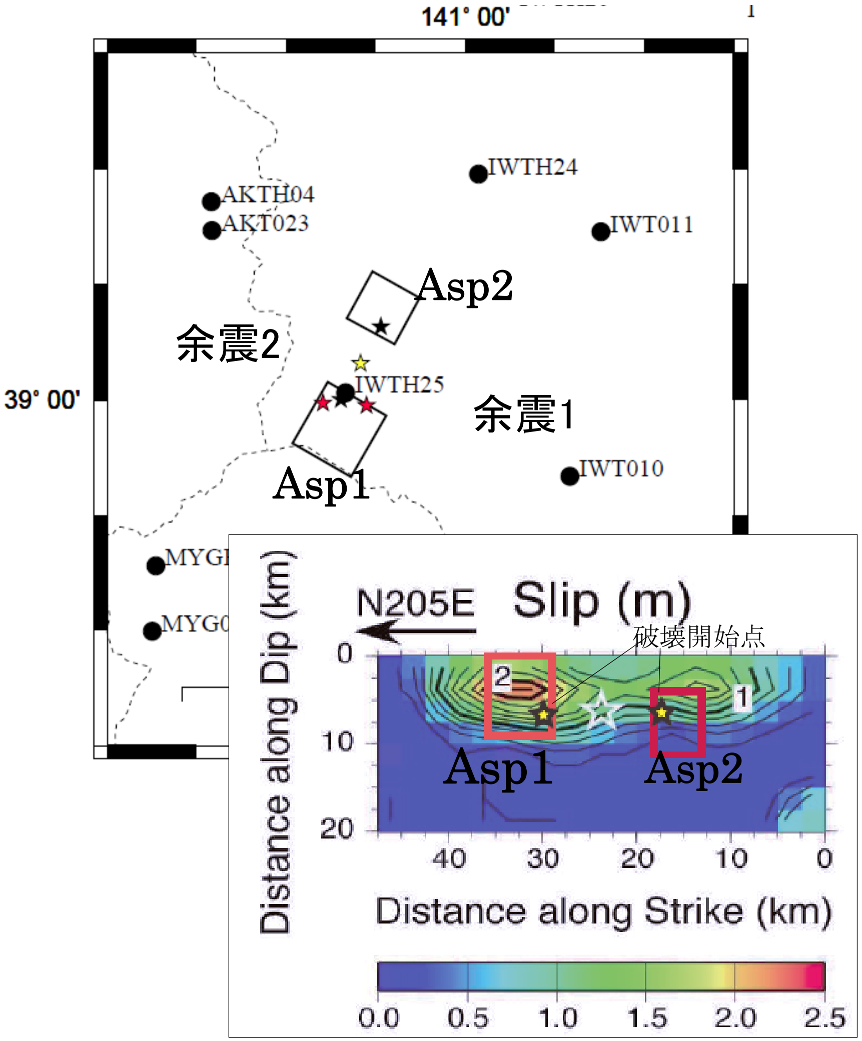
Inner Fault Parameters:

size and stress drop of asperities

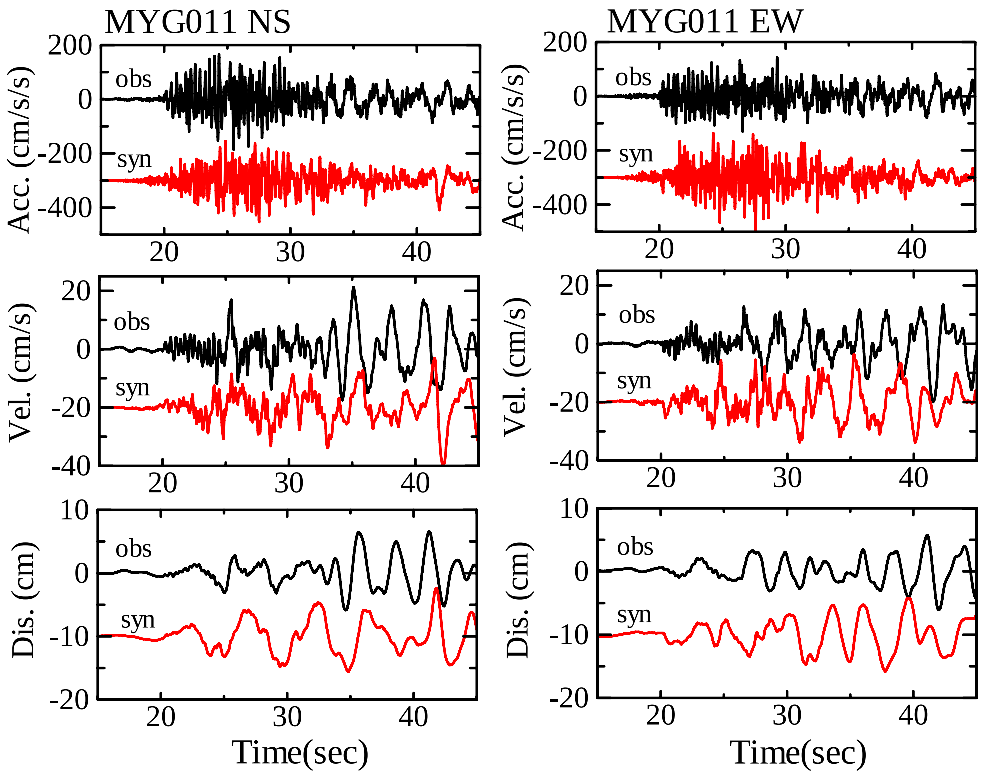


2008 Iwate-Miyagi Nairiku Earthquake (Mw 6.8)

Characterized Source Model



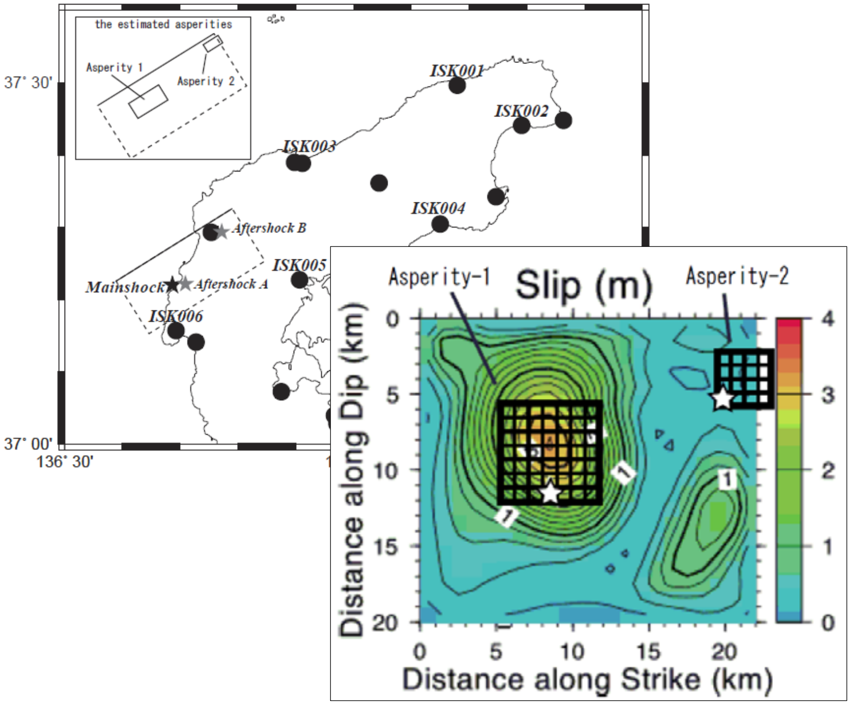
Comparison between Observed and Synthetic Motions



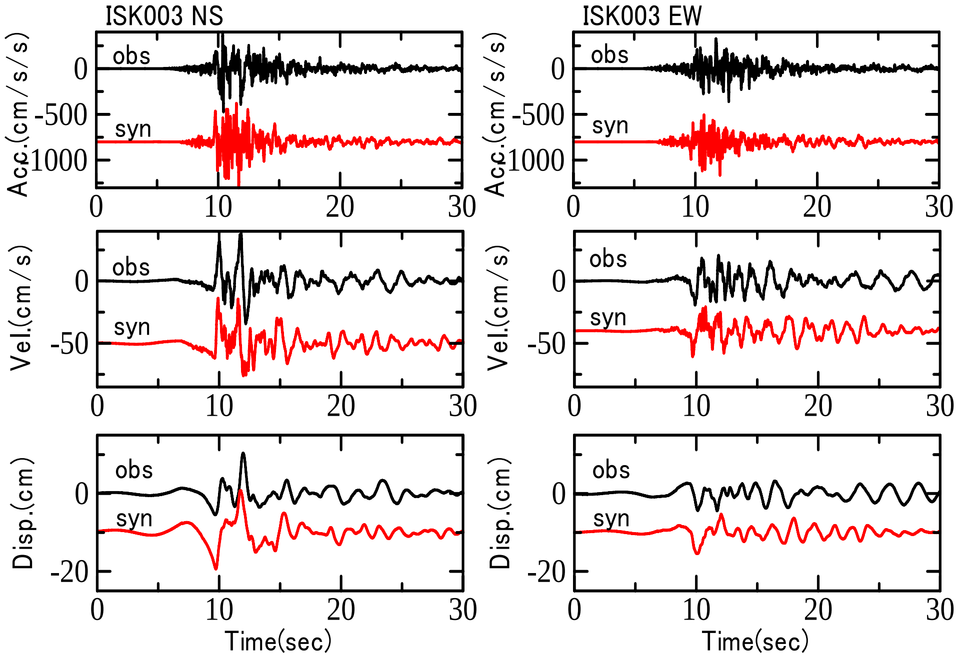
Black: Observed
Red : Synthetic

2007 Noto-Hanto Earthquake (Mw 6.7)

Characterized Source Model



Comparison between Observed and Synthetic Motions



Black: Observed
Red : Synthetic

4. Seismic Reevaluation (Back-checks) of the existing Nuclear Power Plants based on the Regulatory Guide

Re-evaluation of Seismic Safety Design of Nuclear Facilities, so-called "Back-checks"

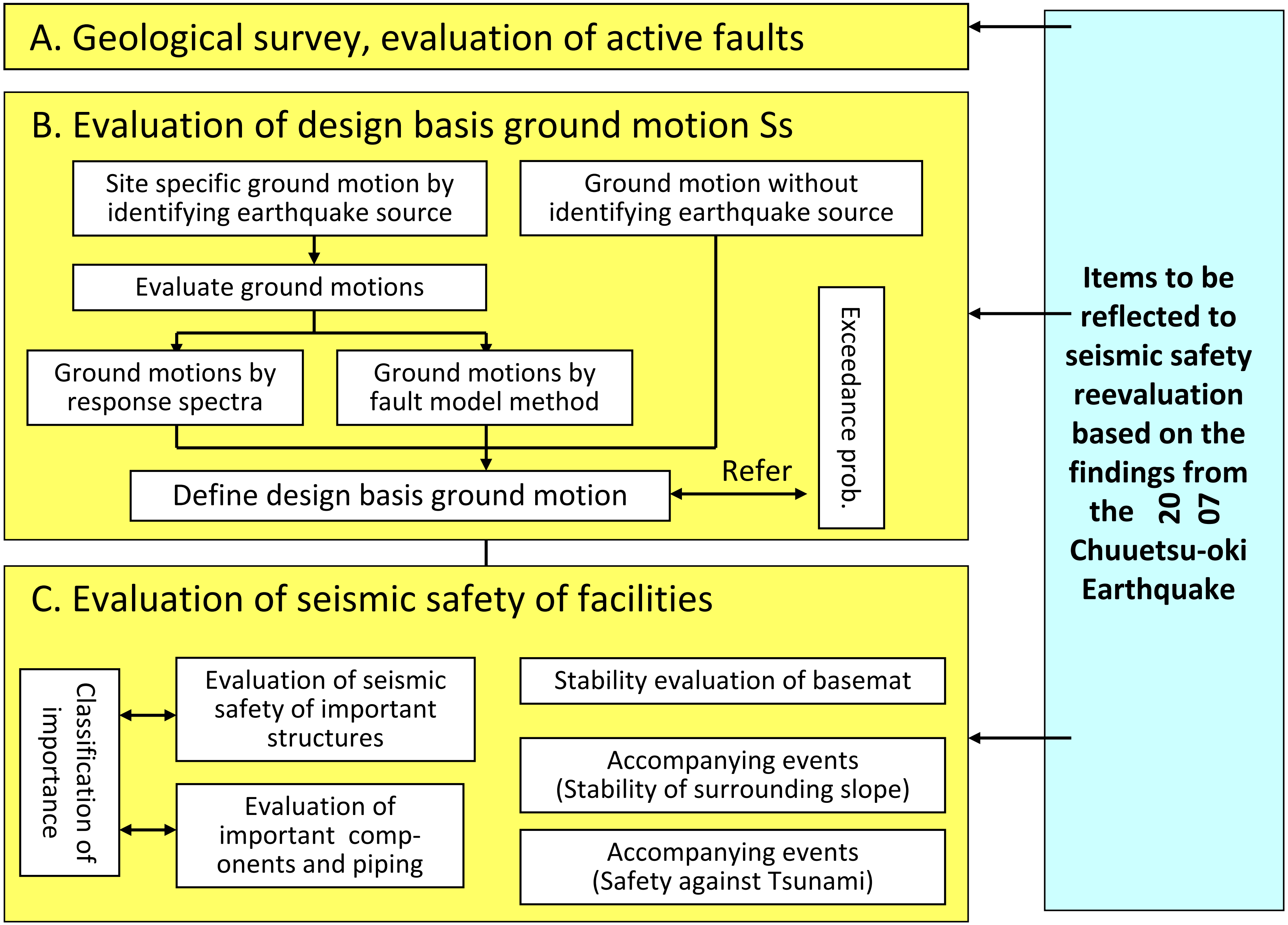
- NSC(Nuclear Safety Commission of Japan) asked governmental intendances to re-evaluate seismic safety design of all of existing nuclear power plants (NPP) for confirming their integrity on September, 2006, just after "the New Guide" was in effect.

- NISA(Nuclear and Industrial Safety Agency, METI), promptly required electric companies to re-evaluate seismic design of existing NPP's according to "the New Guide"

- 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.

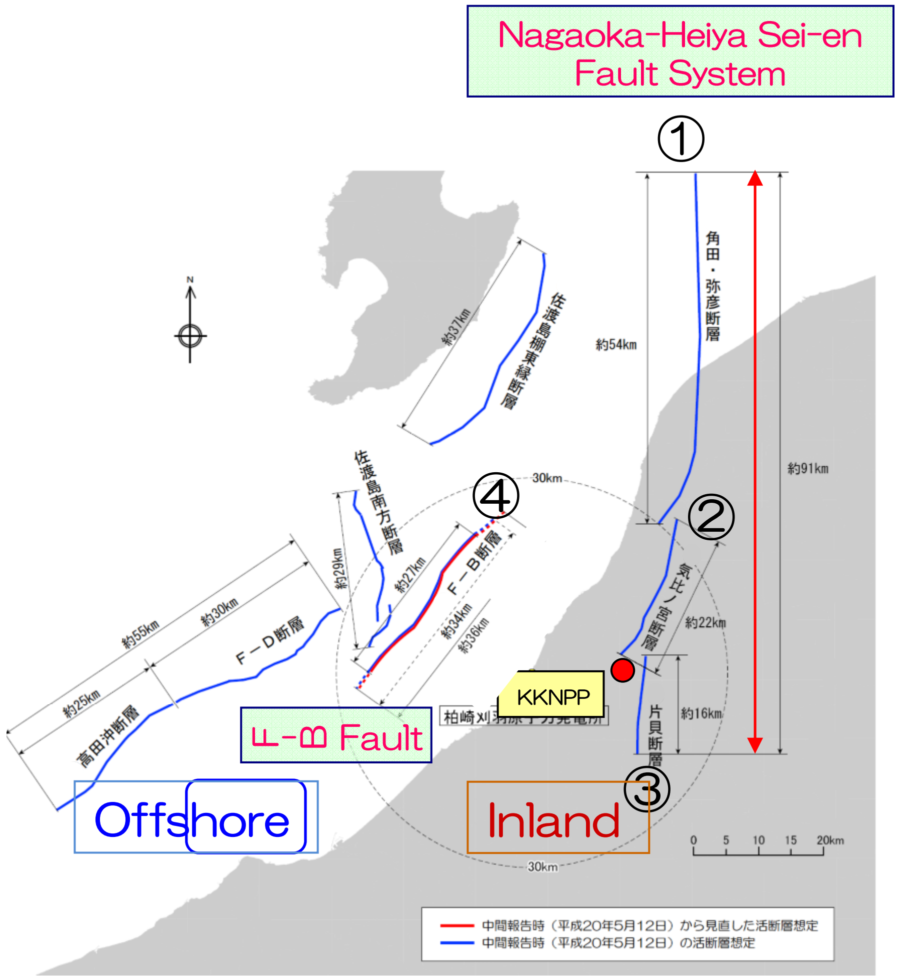
Flow of Seismic Reevaluation According to New Seismic Regulatory Guide



Example of Seismic Reevaluation

-The Kashiwazaki-Kariwa Nuclear Power Plant-

Selected Active Faults and Folds Inland and Offshore



Active Faults selected for D.B.S.M.

	Faults	Fault Length	Length of Source Fault.
Inland	①Kakuta-Yahiko	54km	Nagaoka-Heiya Sei-en Fault: Total length of ９１ｋｍ
	②Kihinomiya	22km	
	③ Katagai	16km	
Offshore	④F－B	36km	36km

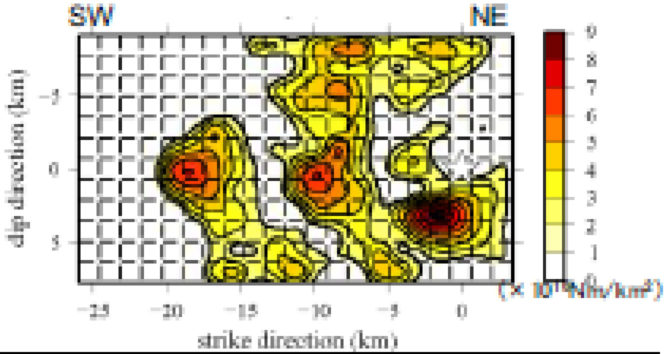
Evaluated Desin Basis Ground Motions for the Nagaoka Heiya Seien Danso評価

Maximum Acceleration (Unit:gal)

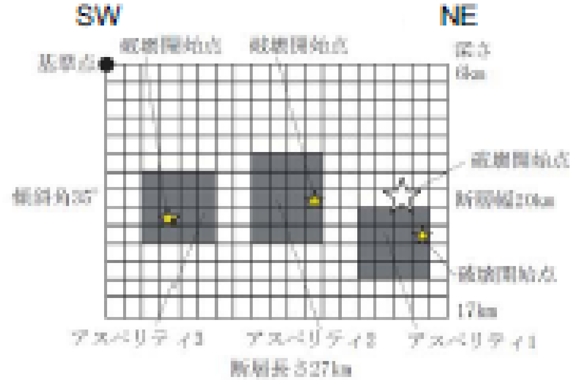
	Unit:1～4	Unit:5～7
Design Basis G.M. Ss	2300	1209
Old Regulatory Guide S2	450	

Source Model of F-B Fault

1. Asperity model was formulated based on the recipe for strong motion prediction by Headquarters for Earthquake Research Promotion (2008)
   (Fault length: 27km x width: 20km)

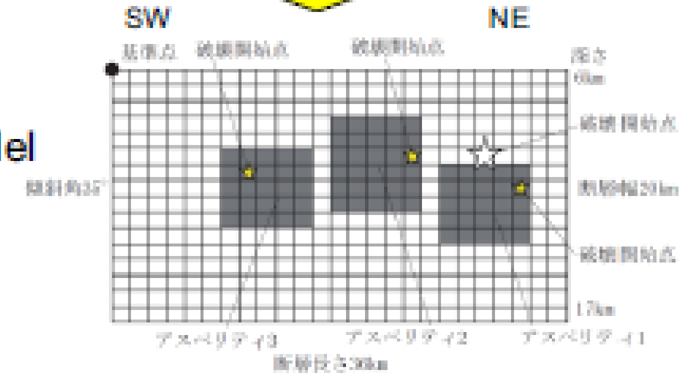


Seismic inversion of NCO EQ (M6.8)



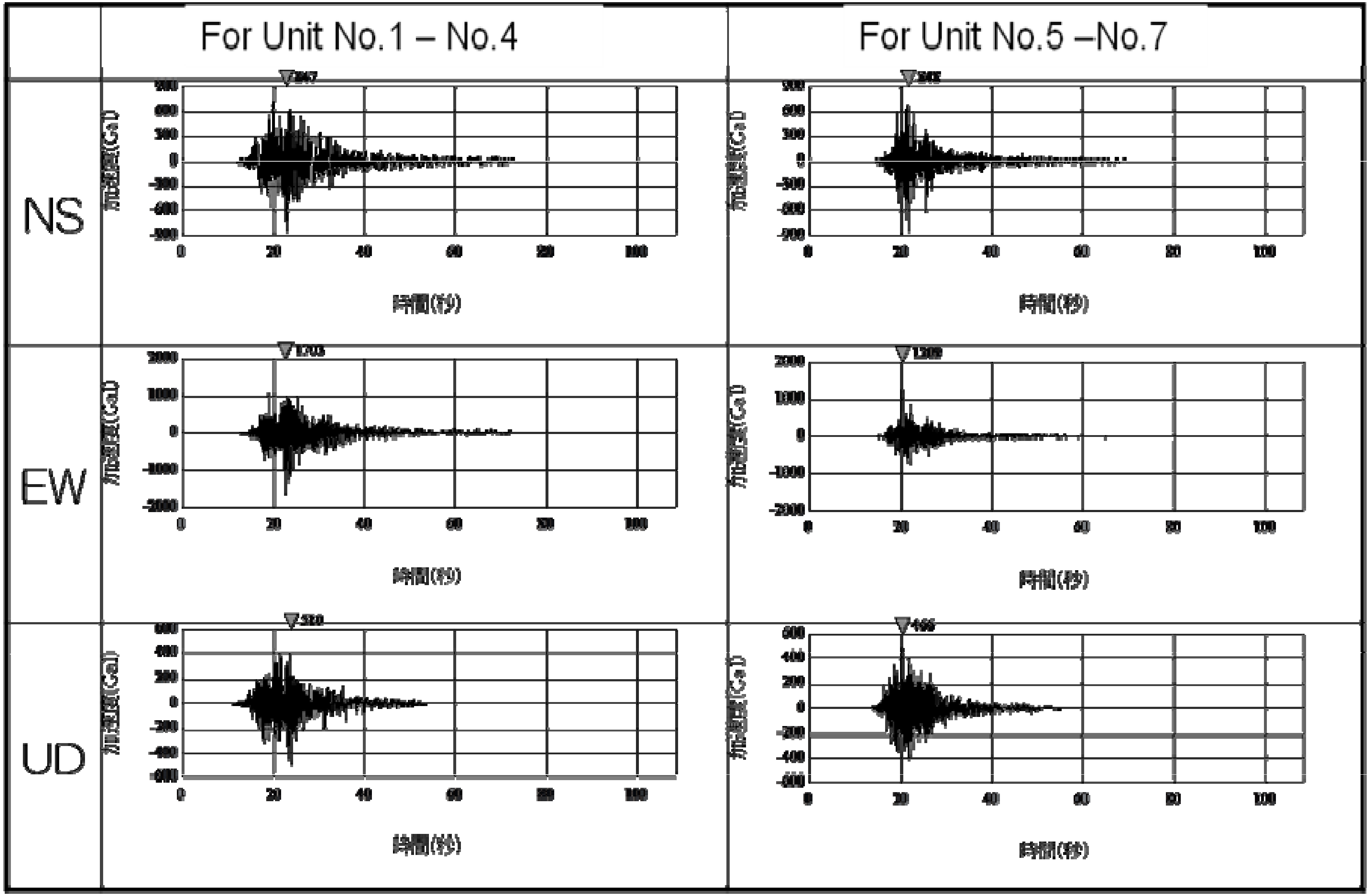
1. Asperity model for NCO EQ (M6.8)

2. Source fault model was formulated by extending fault length of the asperity model formulated at 1., into 36km (M7.0) which is based on the geological survey result



2. Source fault model of F-B fault (M7.0)

Acceleration Time Histories from the F-B Fault Earthquake

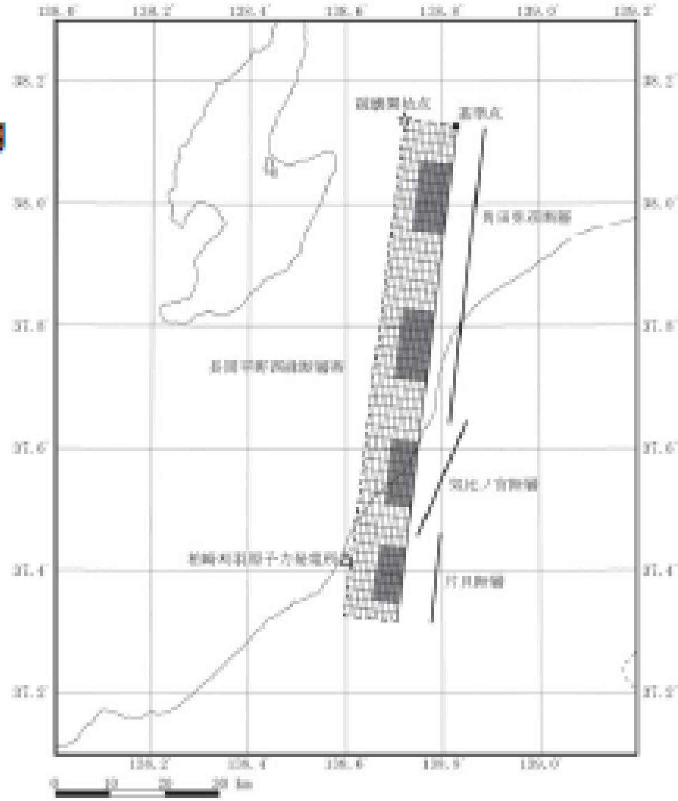


Source Model of Naoka Heiya Sei-en Fault

Three Faults (Katagai, Kihinomiya, and Kakuta-Yahiko) are connected.

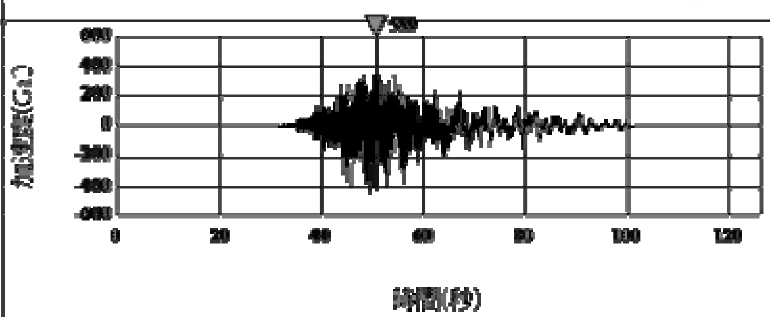
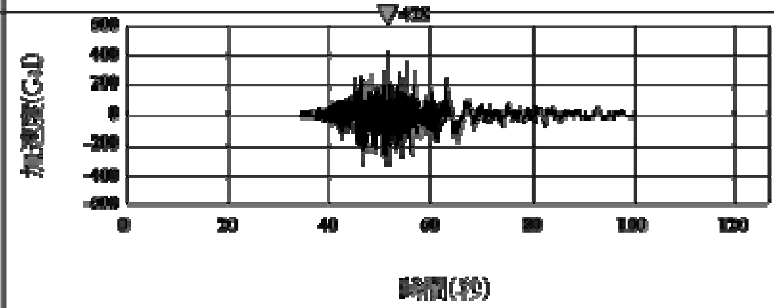
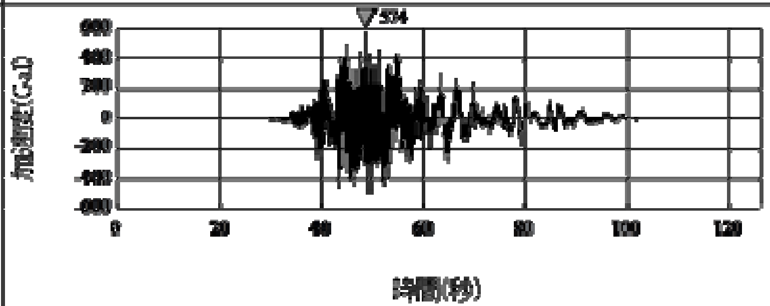
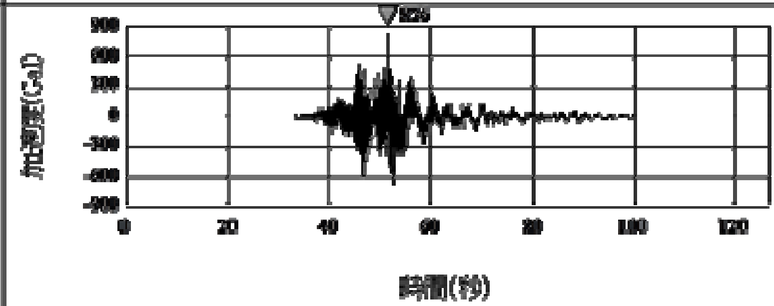
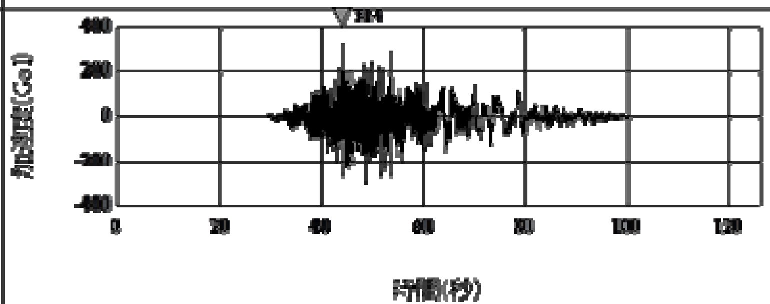
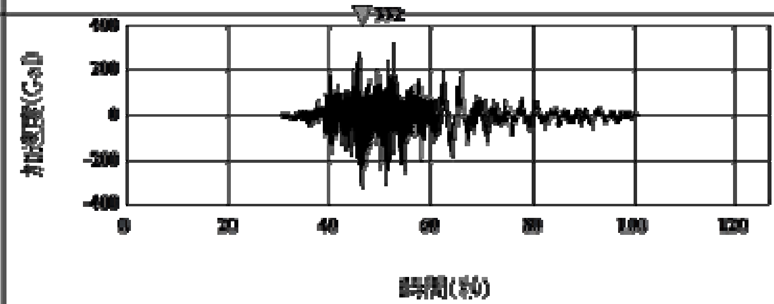
Parameters to be considered with uncertainty

- **Fault length**
  Activity of Katakai fault is standard case, and consider fault interlocking with its surrounding faults (Kihinomiya fault, Kakuda-Yahiko fault)
- **Fault dipping angle**
  50 deg. Is the standard case according to the evaluation of HERP, and 35 deg. is also taken into account as an uncertainty.
- **The number & location of asperity**
  Upper-center position of the fault plain is the standard case, and lower-center is also considered.
- **The amount of stress drop & avg. slip**
  1.5 times larger than recipe is considered.

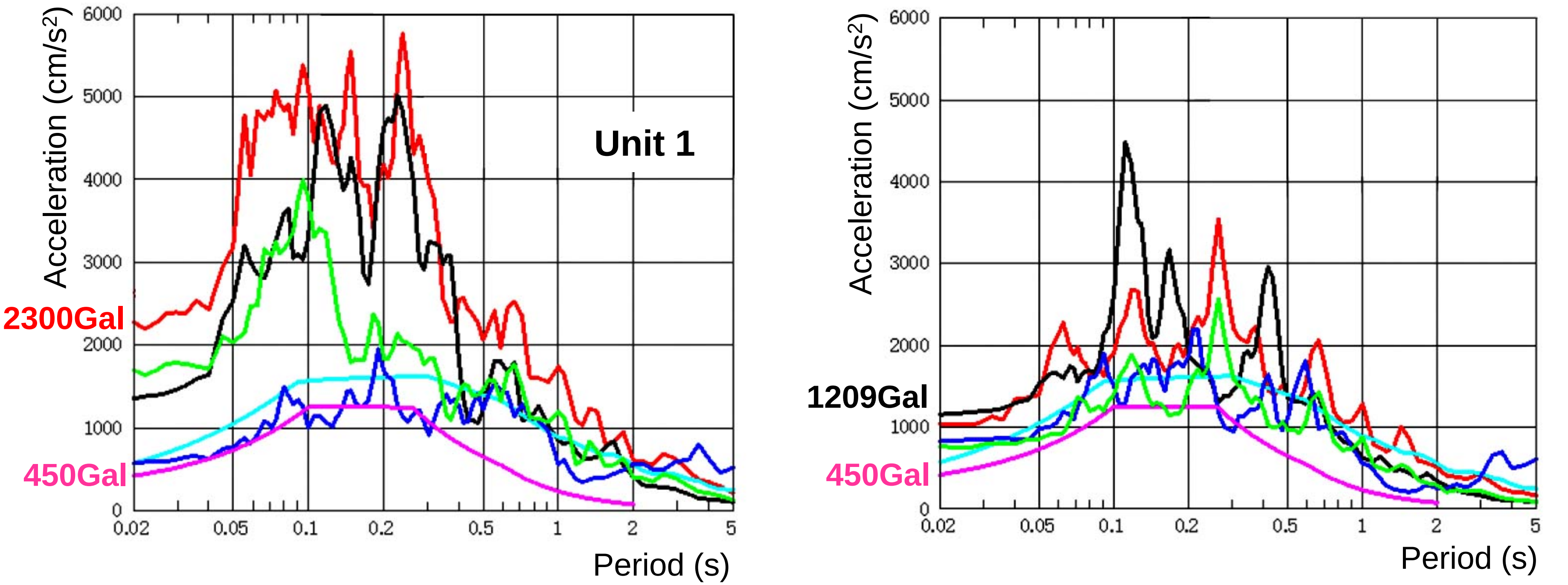


- **Rupture starting point**
  Place which rupture proceed toward the site is the standard case, and boundary of asperity is also considered as an uncertainty

Acceleration Time Histories from the Nagaoka-Heiya Sei-en Fault

	For Unit No.1 – No. 4	For Unit No. 5 – No.7
NS		
EW		
UD		

Response Spectra for the Design-basis Ground Motion
（Free surface of base stratum ）



- Ss-1H (F-B fault, response spectra)
- Ss-2EW (F-B fault, fault model method)
- Ss-3H (Nagaoka Plain Western Rim Fault Zone, response spectra)
- Ss-4EW (Nagaoka Plain Western Rim Fault Zone, fault model method)
- S2
- Estimated ground motion on the free surface of base stratum at the time of the Niigata-Chuetsu-Oki Earthquake

5. Expectation for deep boreholes seismic observation and geophysical exploration from viewpoint of ground motion evaluation

Expectation for deep boreholes seismic observation and geophysical exploration-1

- New technology has been developed for seismic observation in deep boreholes:
  High-precision and broad-band velocity sensors with super high heat-resistance available for 3000 m deep.
  Multiply-connected sensors in a deep borehole.

- Progress of advanced technology is expected for not only measuring seismic signals but also sampling, monitoring, and recording other geophysical data.

Expectation for deep boreholes seismic observation and geophysical exploration-2

- Detailed 3-D velocity structure models with damping factor of each layer, combining vertical array and horizontal array observation

- Epistemic uncertainties are reduced in estimating propagation-path and local-site effects based on the detailed velocity models, and then ground motion variability becomes smaller.

  Examples from seismic reevaluation:
  Influence of irregular structures on ground motions near the Kashiwazaki-Kariwa Nuclear Power Plant and near Hamaoka Nuclear Power Plant

Case of the Kasiwazaki-Kariwa Nuclear Power Plant -1

Overview of seismic observation points at the KKNPP site

Reactor buildings

On the foundation basemat and mezzanine floor

Turbine Buildings

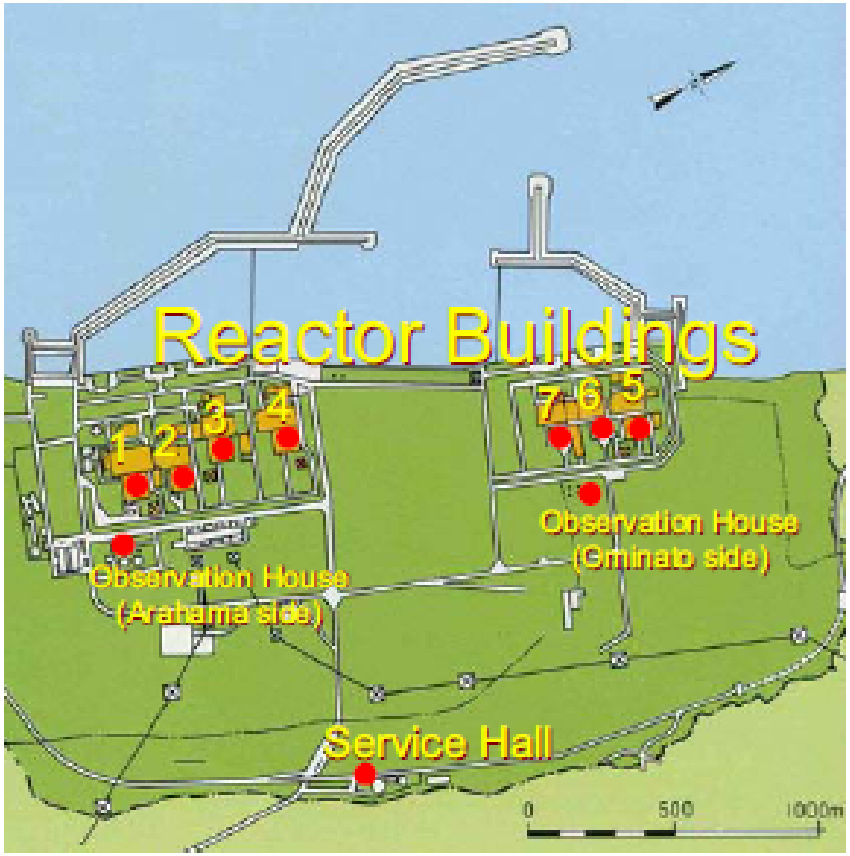
On the foundation basemat and mezzanine floor

Observation house

Near Unit 1 and Unit 5

Service Hall

Borehole array (4 depths in total)

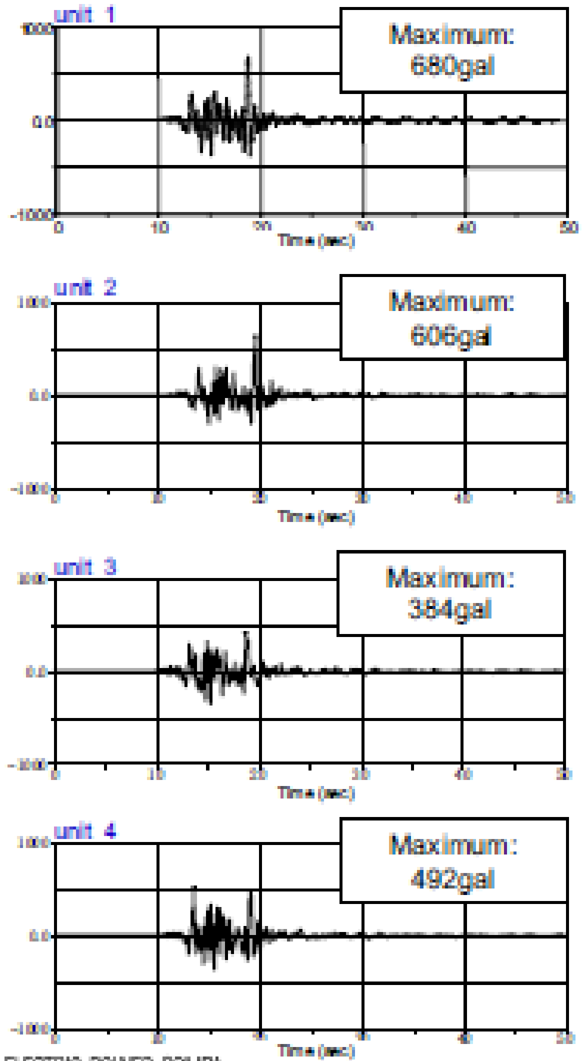


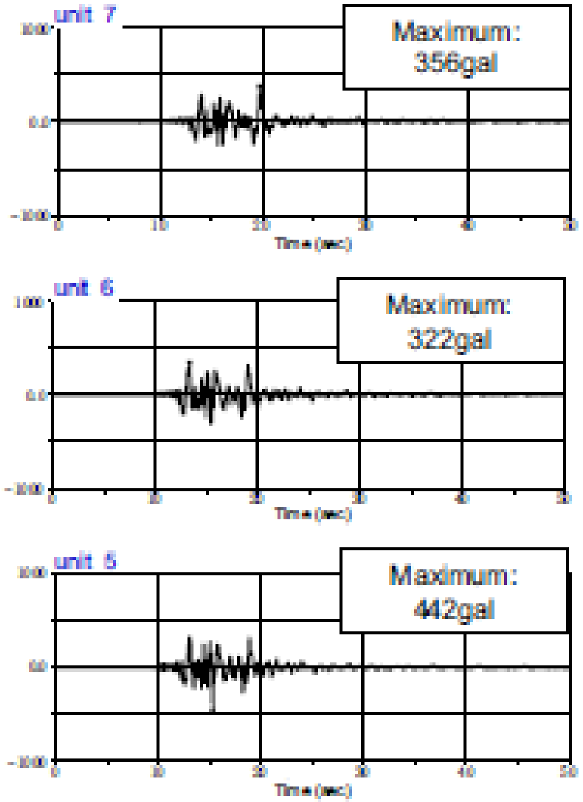
Observation points in KKNPP site

Case of the Kasiwazaki-Kariwa Nuclear Power Plant -2

Overview of the event (2)

(Comparison of the ground motions between each units)





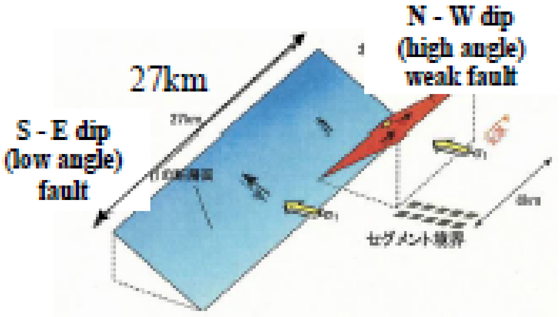
Time history waveform of acceleration observed on the foundation of the R/Bs (EW direction)

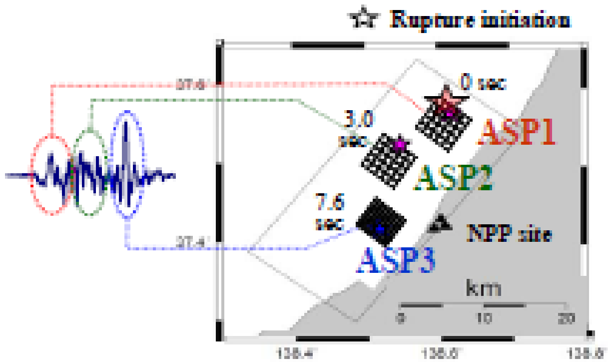
The difference in maximum acceleration between Units 1 – 4 and Units 5 – 7 is determined by the amplitude of a spike in the latter part of the event.

Case of the Kasiwazaki-Kariwa Nuclear Power Plant -3

Modelling of Source Fault and Ground Structure

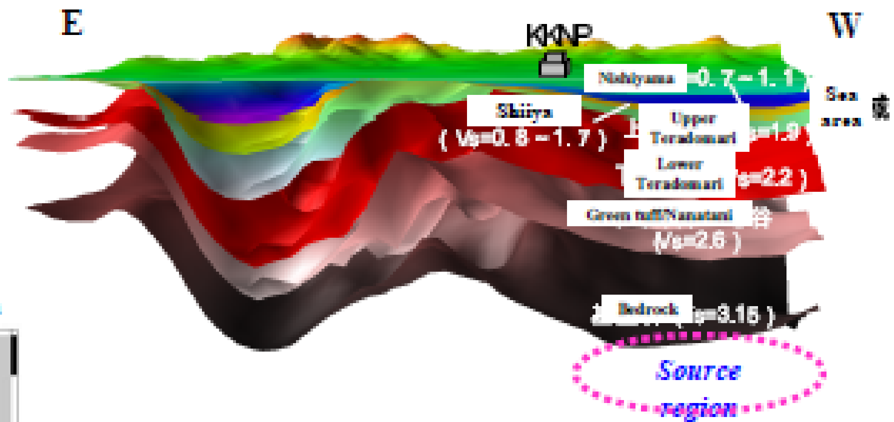
Source fault model





Strong seismic waves were generated by rupture of 3 asperities.

Cross section of geological layers

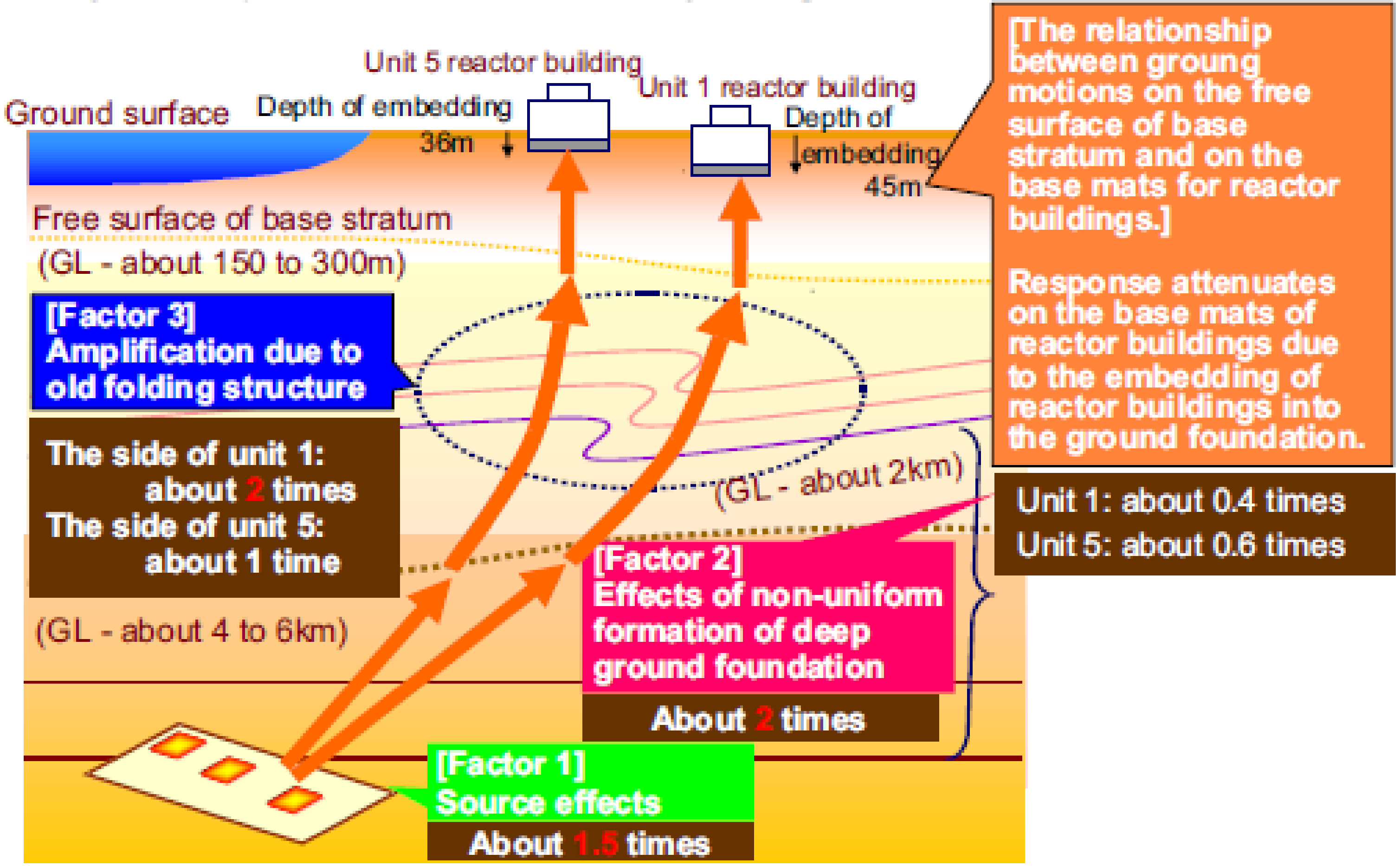


- The deep underground structure has irregularity, such as sharp dip zone beneath the site and anticline structure in north-east of the site.
- Earthquake bedrock near the site is deep as about 5~8 km, and sedimentary rock thickly cumulates on it.

Case of the Kasiwazaki-Kariwa Nuclear Power Plant -4

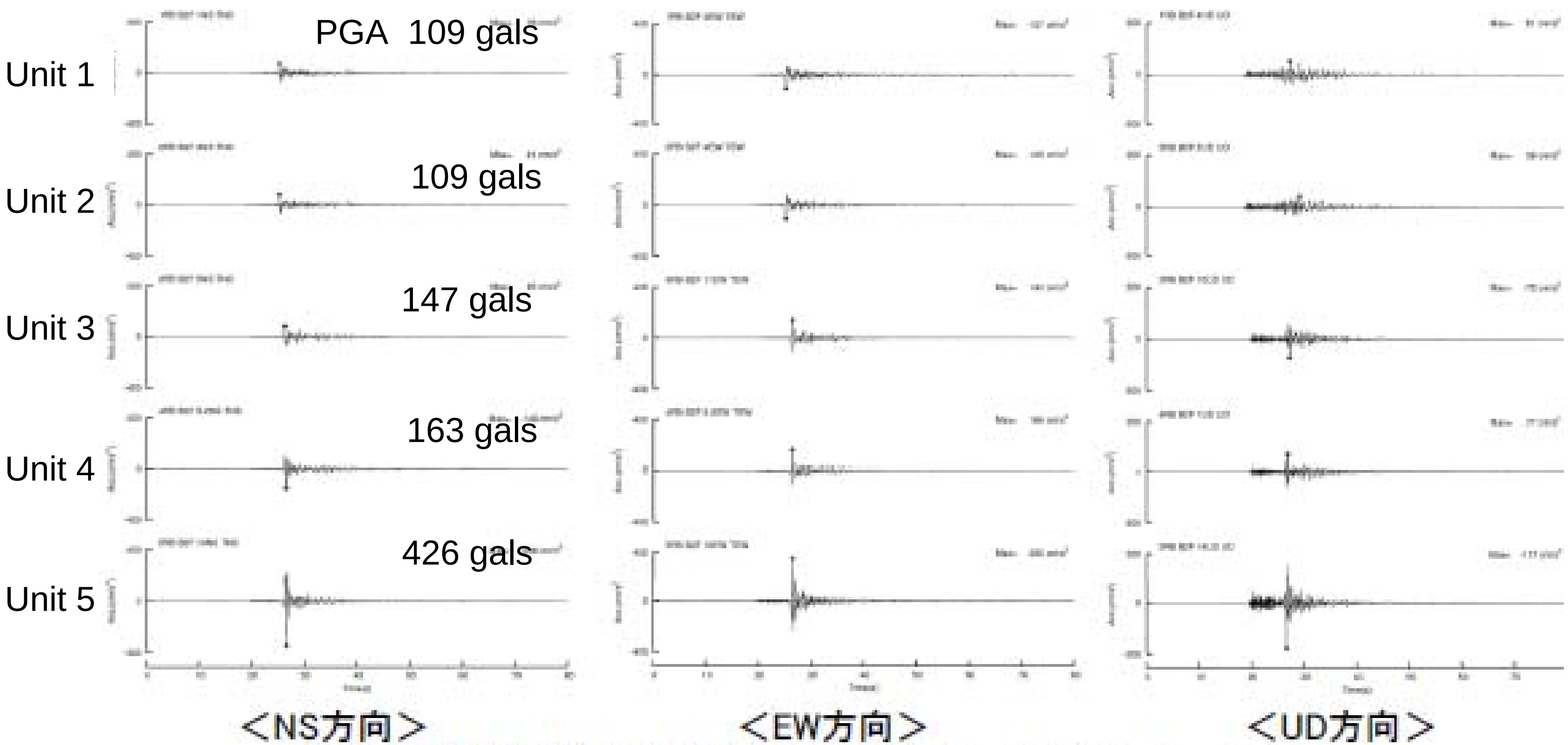
2.3 Reevaluation of Seismic Safety of KK NPS

- Analysis of Amplification of Ground Motions by Underground Structure



Case of the Hamaoka Nuclear Power Plant -1

Accelerations at Base Mats from 2009 Suruga Bay Earthquake

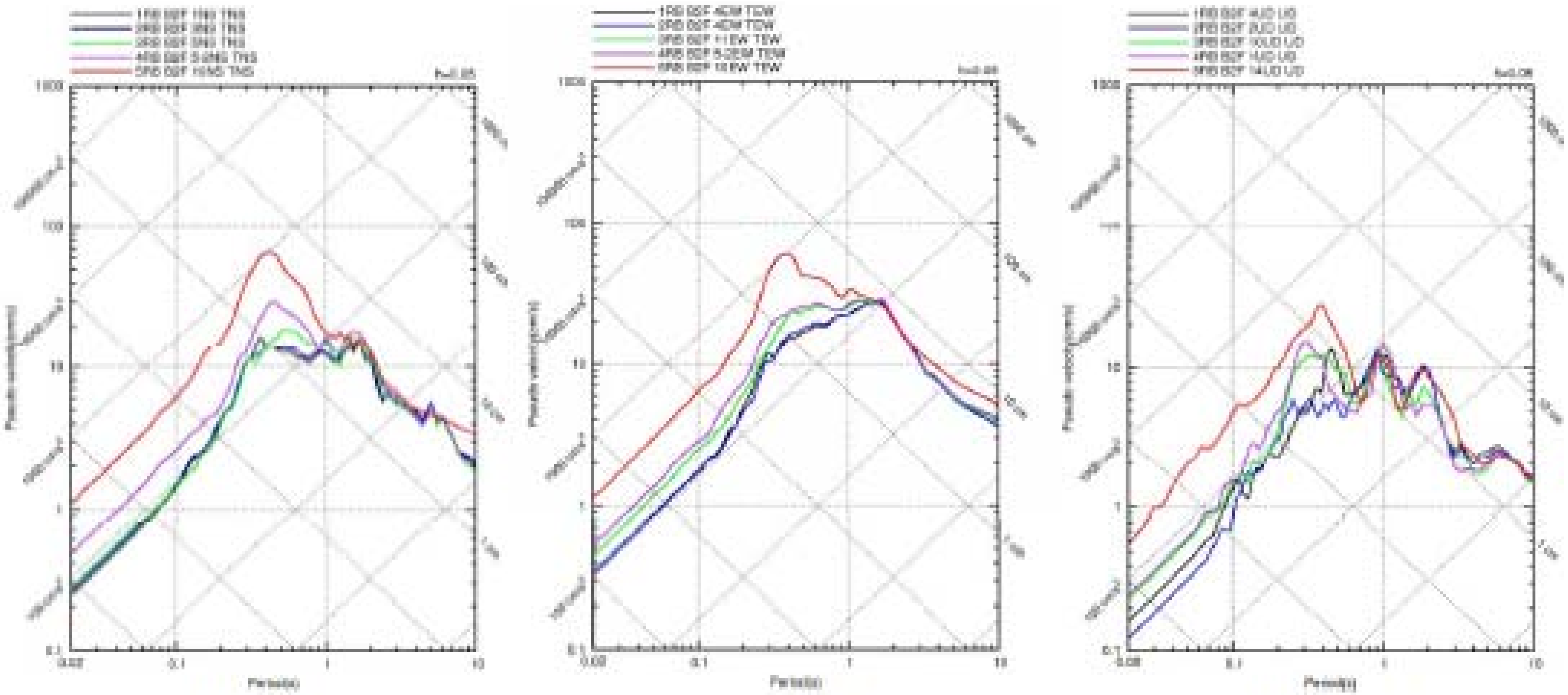


基礎上の加速度

※原子炉建屋基礎上（地下2階）の地震
を示した地震計の加速度記録を真北

Case of the Hamaoka Nuclear Power Plant -2

Acceleration Response Spectra at Base Mats from 2009 Suruga Bay Earthquake (Mw 6.2)



＜NS方向＞　　＜EW方向＞　　＜UD方向＞

基礎上の応答スペクトル（1u、2u、3u、4u、5u）

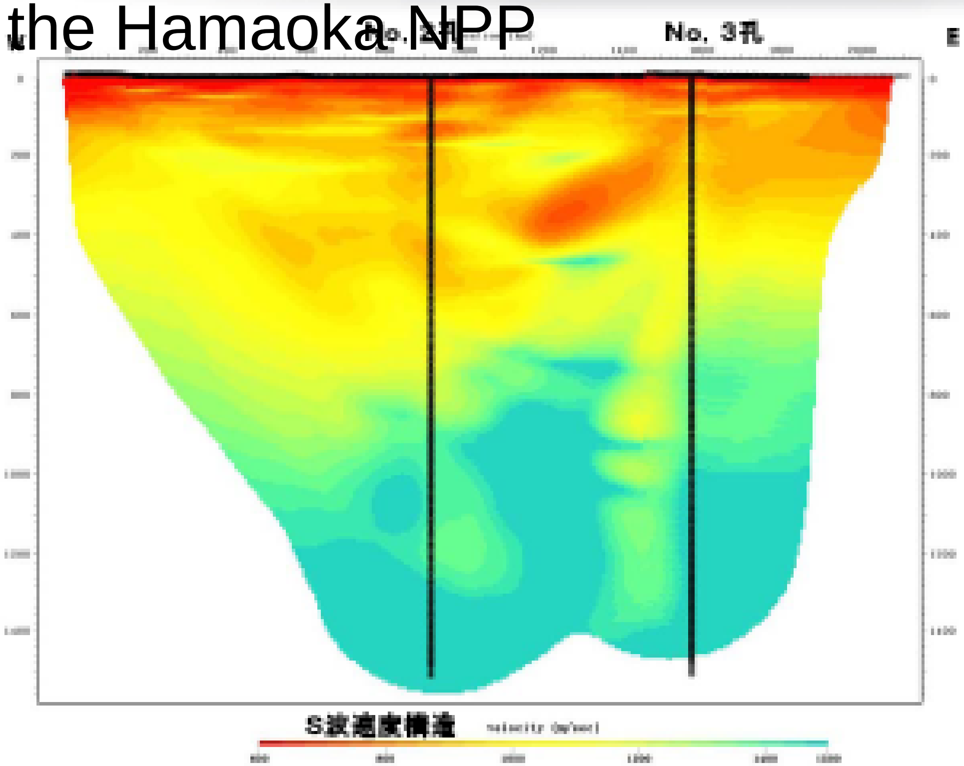
※原子炉建屋基礎上（地下2階）の地震計で観測された加速度記録のうち、最大値を示した地震計の加速度記録を真北基準に方位変換して評価

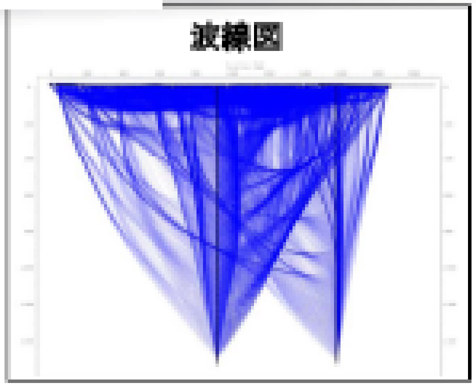
【減衰定数5%、真北基準】

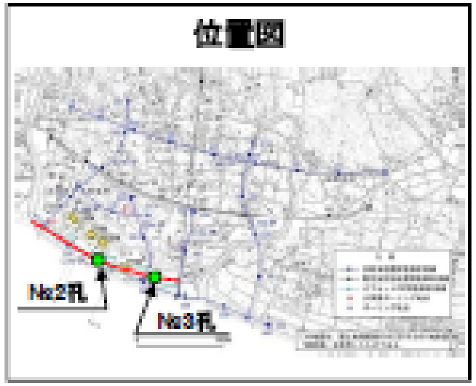
Case of the Hamaoka Nuclear Power Plant -3

S wave Velocity Profiling using Offset VSP in the Hamaoka NPP

既往報告
（合同W46-1）





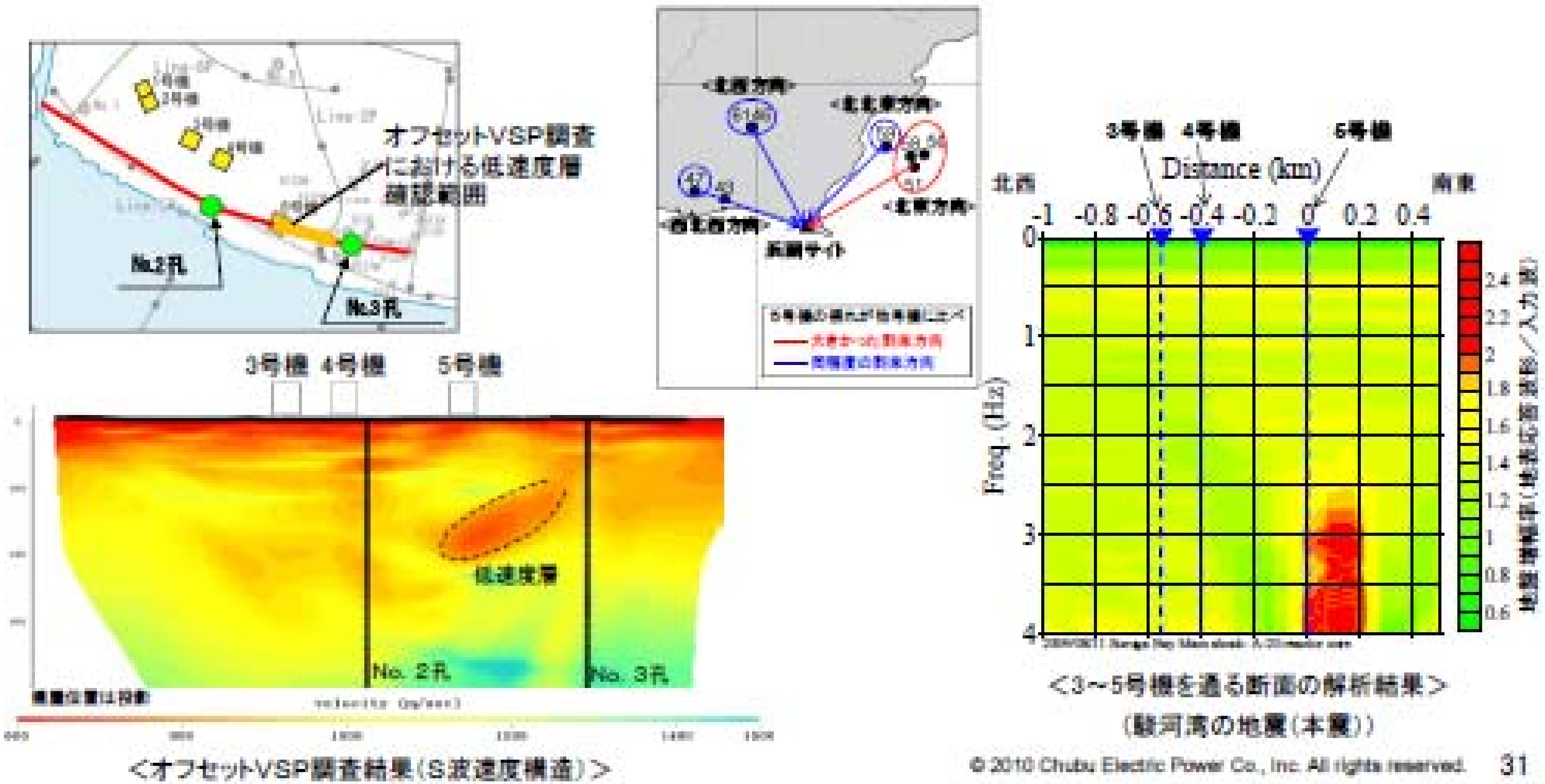


大深度ボーリングNo．2孔及びNo．3孔を利用したオフセットVSP調査結果によると、S波速度は深度200m程度までは概して深度方向に漸増する傾向があり、深度200m程度でVs=900m／s程度である。
深度200m程度以深では、No．2孔及びNo．3孔の間に、S波速度が700～800m／s程度と周囲の岩盤に比べ最大3割程度減少している低速度層が深度400m程度まで認められるが、それ以外では、S波速度は概して深度方向に漸増する傾向があり、深度800m程度でVs＝1300m／s程度である。

NISA JW46-1 (March 31, 2010)

Case of the Hamaoka Nuclear Power Plant -4

Map showing Location of Nuclear Power Reactor Units and
S wave Velocity Profiling using Offset VSP

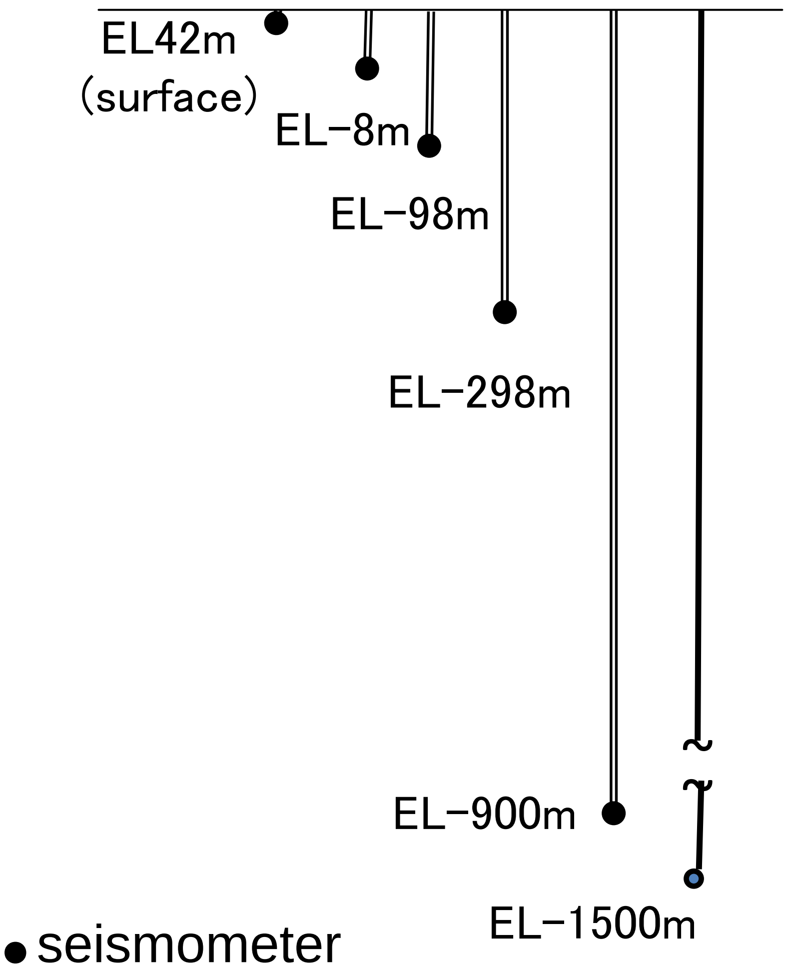


NISA JW47-2 (April 27, 2010)

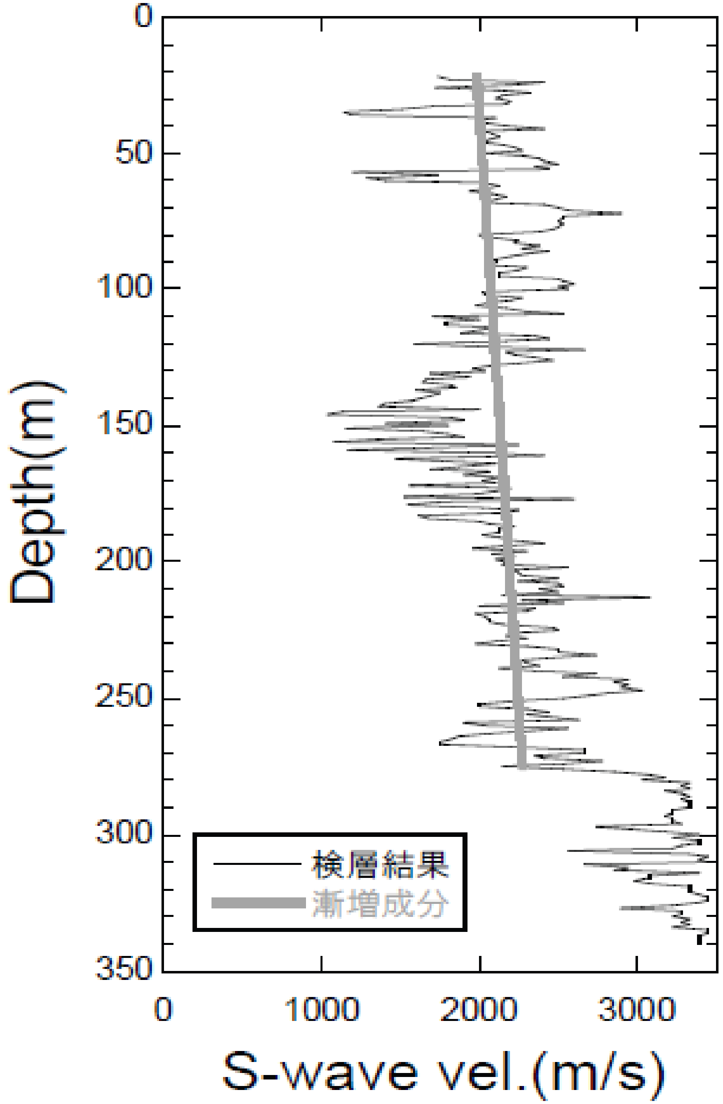
Deep Boreholes Seismic Observation and Geophysical Exploration

After NISA (2010)

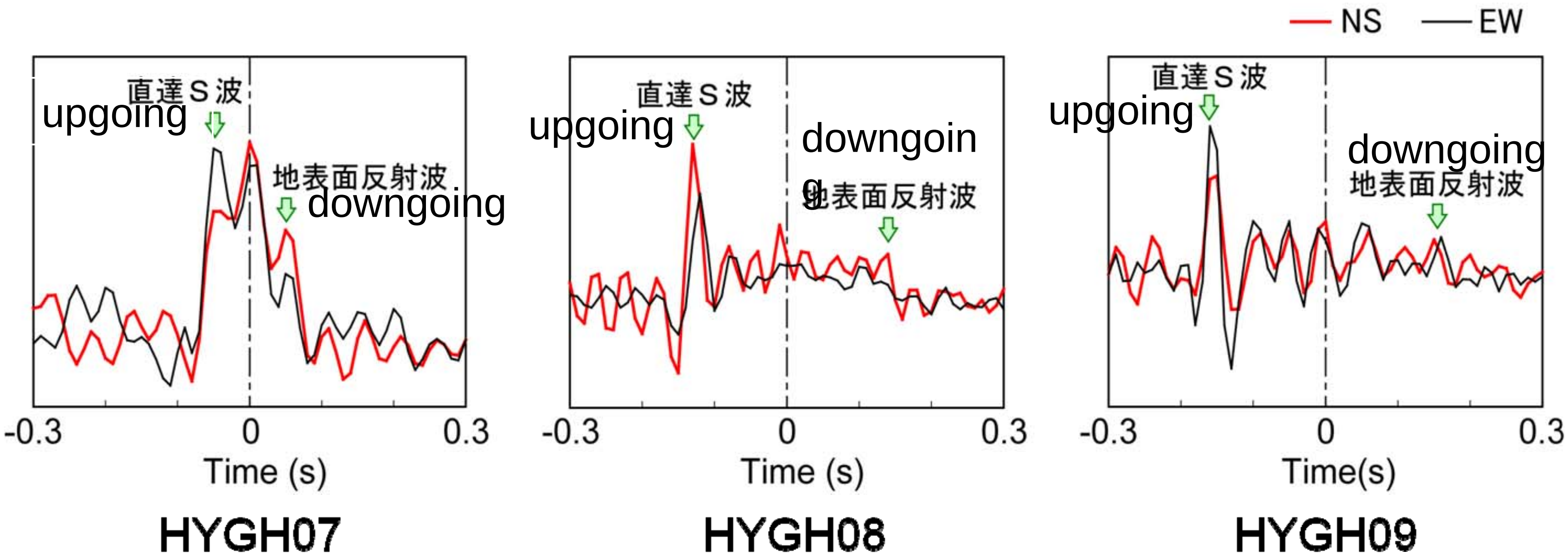
Vertical-Array Observation
Strong Ground Motions



S wave profile
by S-wave logging



Separation of Up-going and Down-going Waves in Boreholes Using Deconvolution Technique



We can estimate the velocity and Q factor of seismic waves propagating in borehole separating upgoing and downgoing waves using vertical array data.

Laboratory Measurements of P- and S-Wave Velocities and Damping Factors on Rock Core Samples

After NISA (2010)

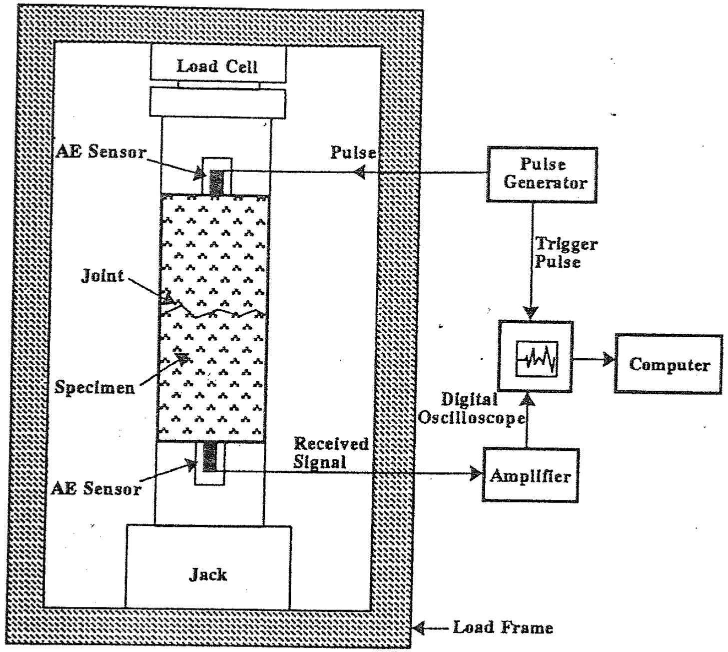


Fig.2 Schematic illustration of experimental set up for seismic measurements

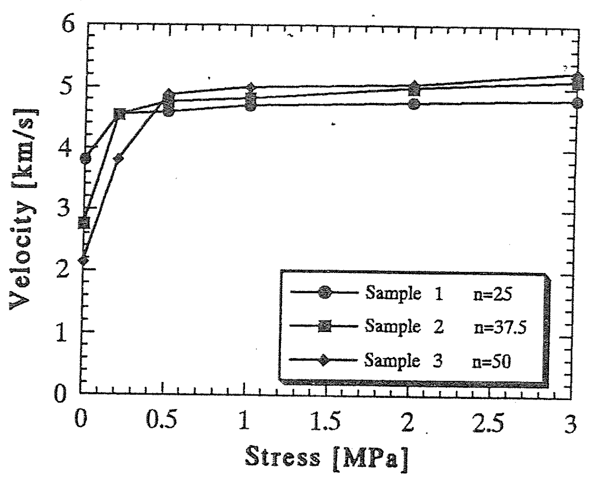


Fig.12 Velocity on joint frequency under normal stress (n = 25, 37.5, and 50 [1/m])

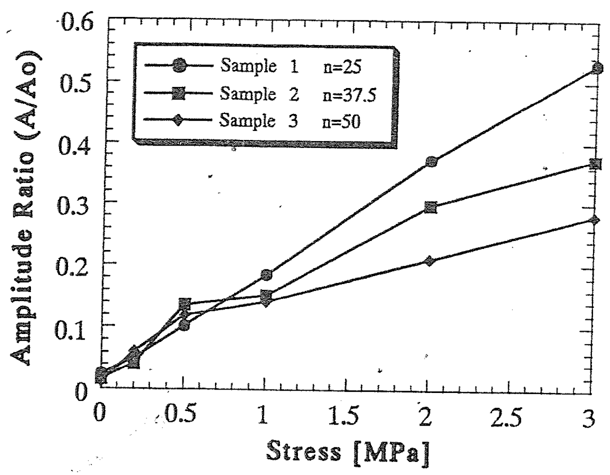


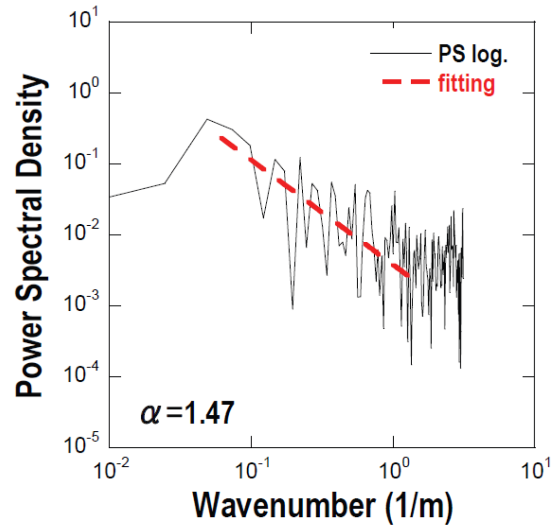
Fig.13 Amplitude ratio on joint frequency under normal stress (n = 25, 37.5, and 50 [1/m])

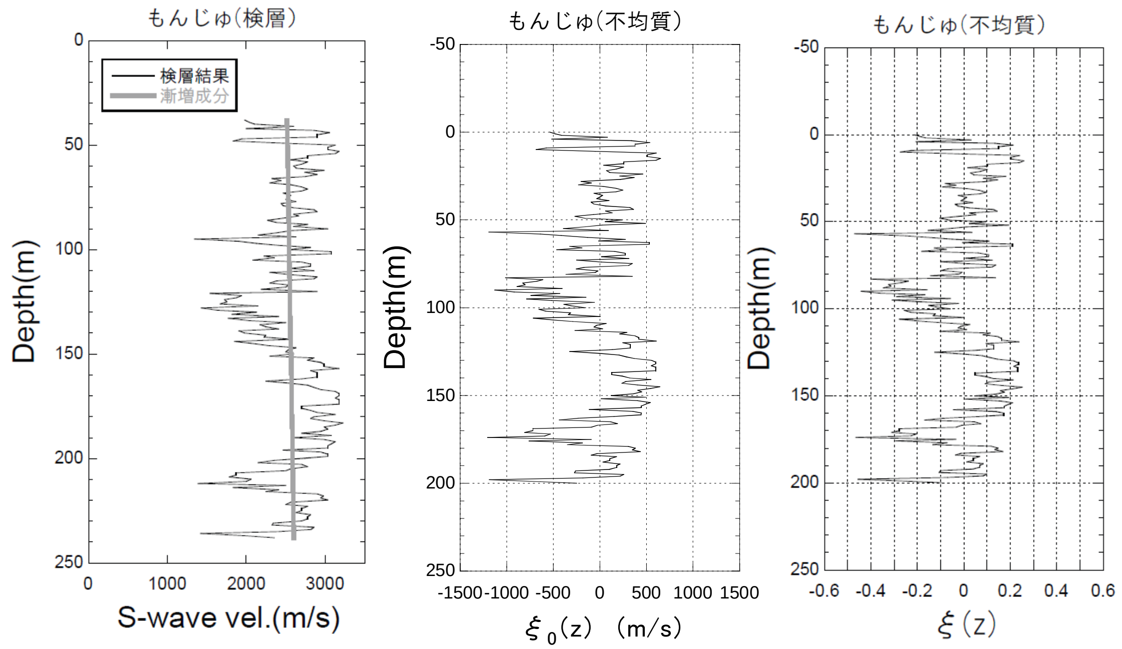
Figures are quoted from Tanimoto (1995)

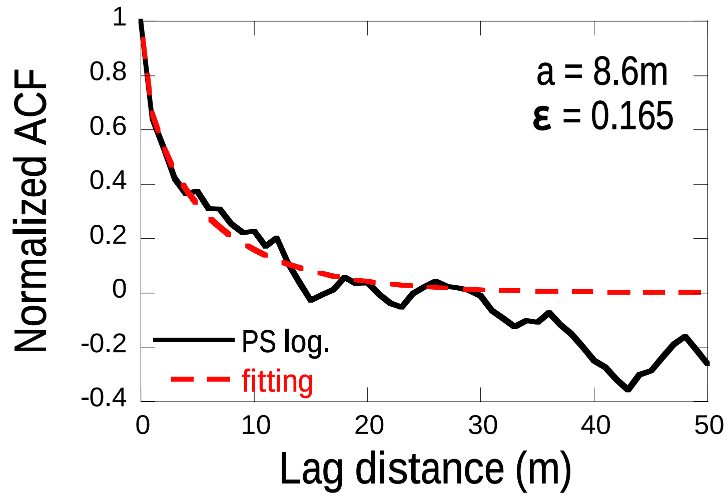
■Strength pf Random Velocity Fluctuation

Based on PS logging at Monju site

Depth Range (m)	AverageS wave Velocity (km/s)	Gradient of Increment (1/s)	Correlation Length a (m)	Hurst Index ν	Standard Deviation ε
GL−38 ～−238	2.56	0.43	8.6	0.24	0.165







Heterogeneities of S-Wave Velocities (left),
ξ_0(z) (middle)、ξ (z) (right)

Correlation Length and Standard Deviation
Of Velocity Heterogeneities

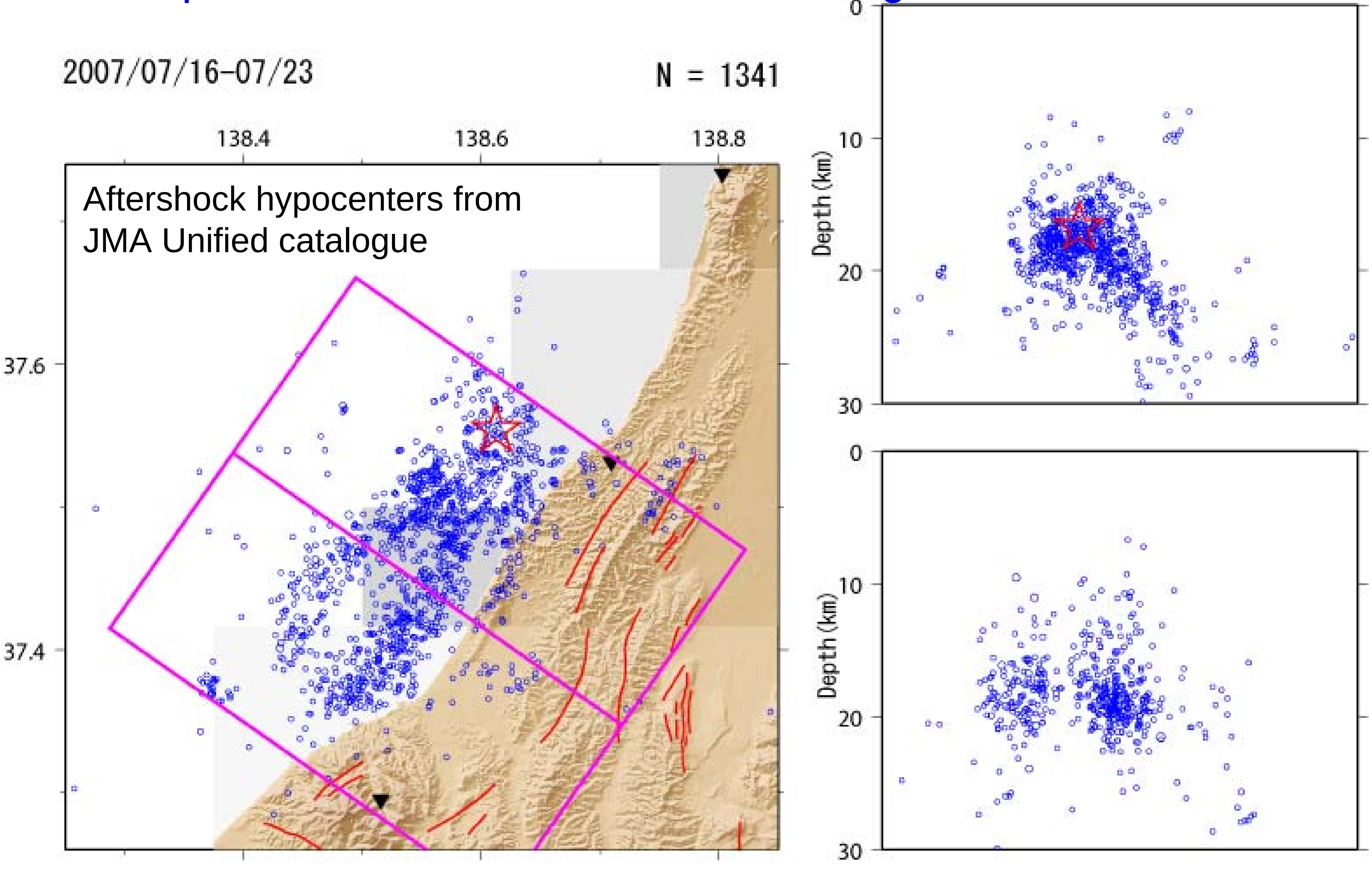
Expectation for deep boreholes seismic observation and geophysical exploration - 3

Improvement of detectability and hypocenter determination of earthquakes

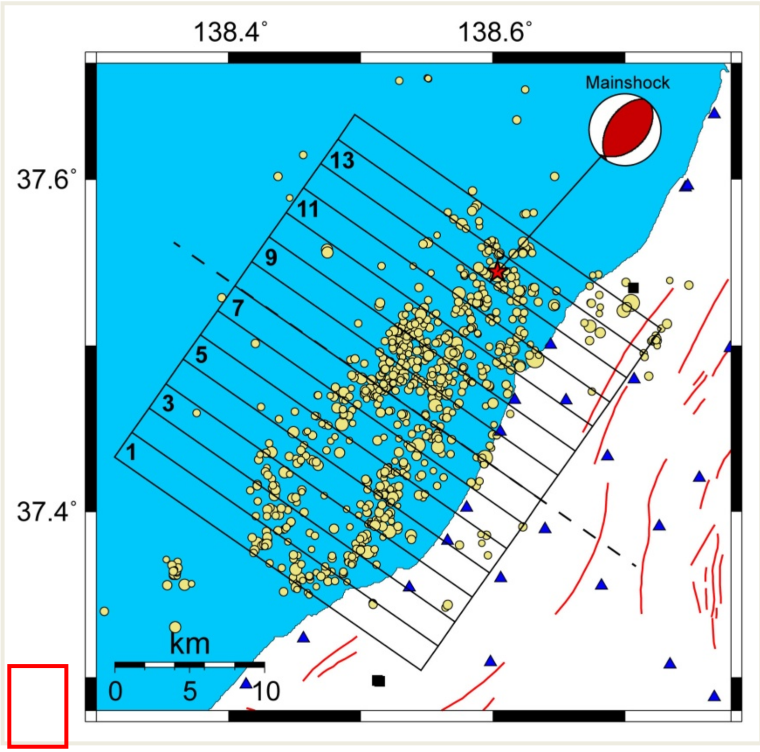
→Upgrading of active fault investigation and source model studies

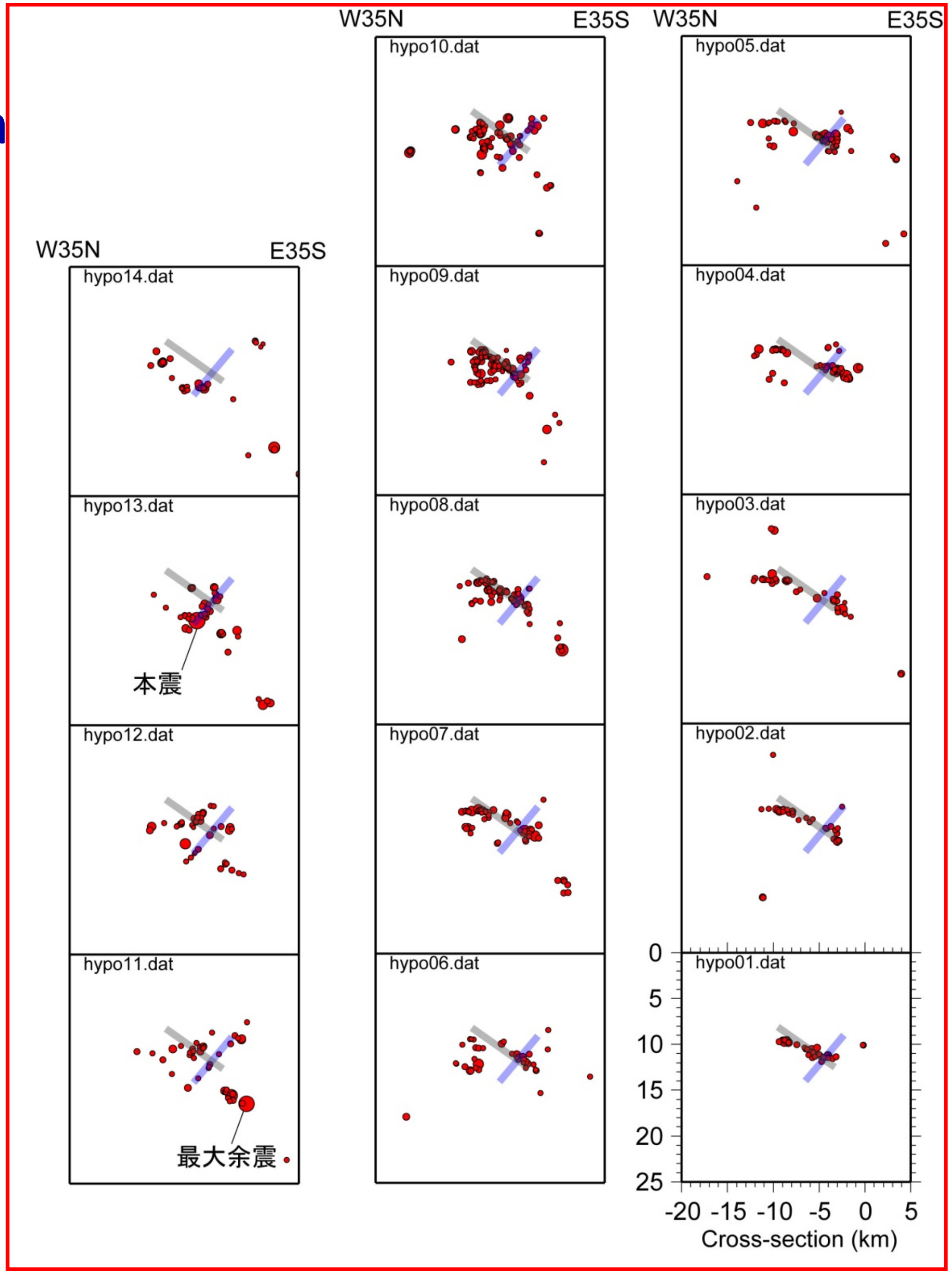
Example:
Ground motions from specified and unspecified sources

Aftershock Distribution of the 2007 Niigata-ken Chuetsu-oki earthquake from the JMA Unified Catalogue



Aftershock distribution by on-land and ocean-bottom seismometers





Bins with 2km wide

ERI, Univ. of Tokyo (2008)

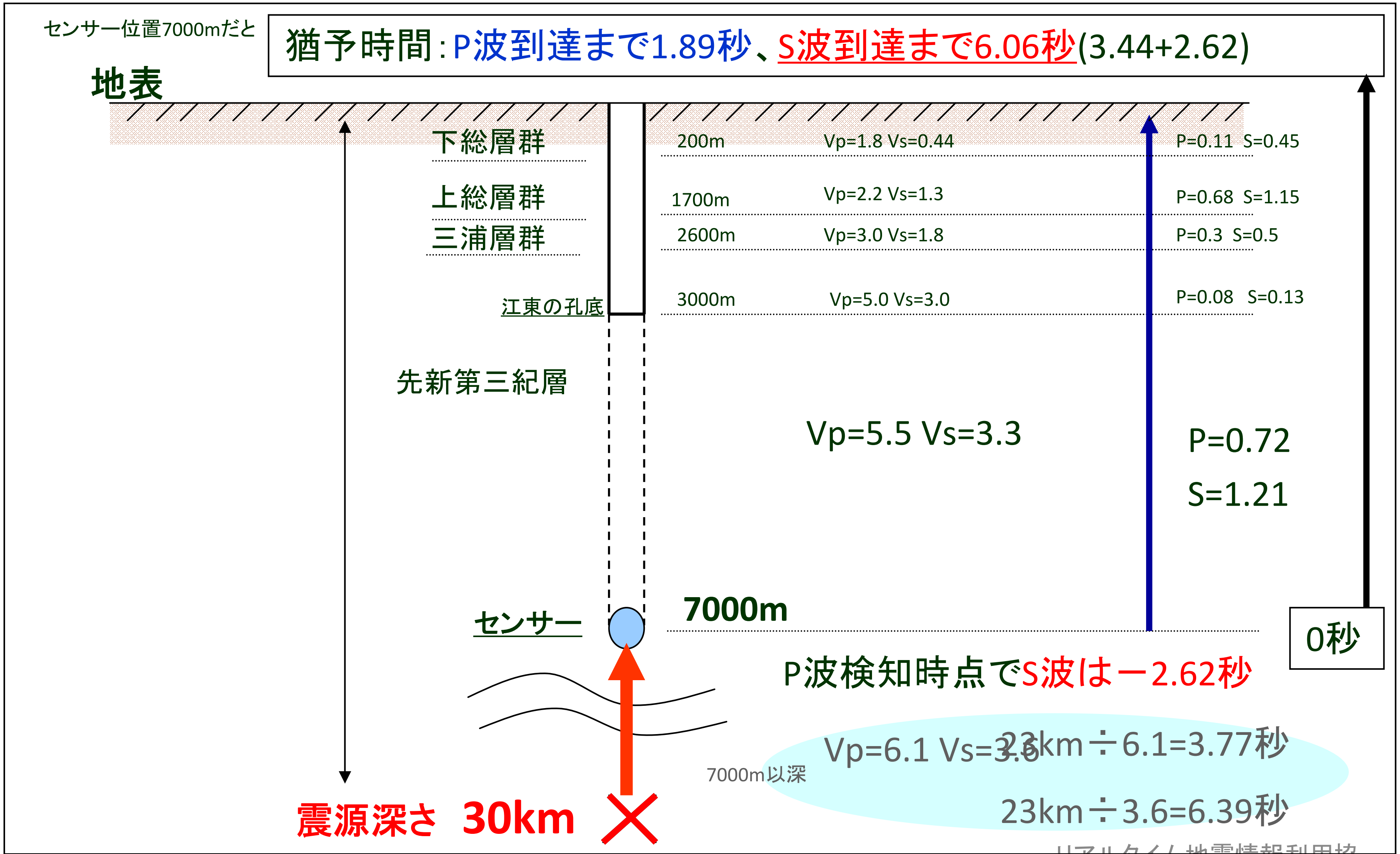
Expectation for deep boreholes seismic observation and geophysical exploration - 4

Introduction of earthquake early warning to shut-down systems of reactors

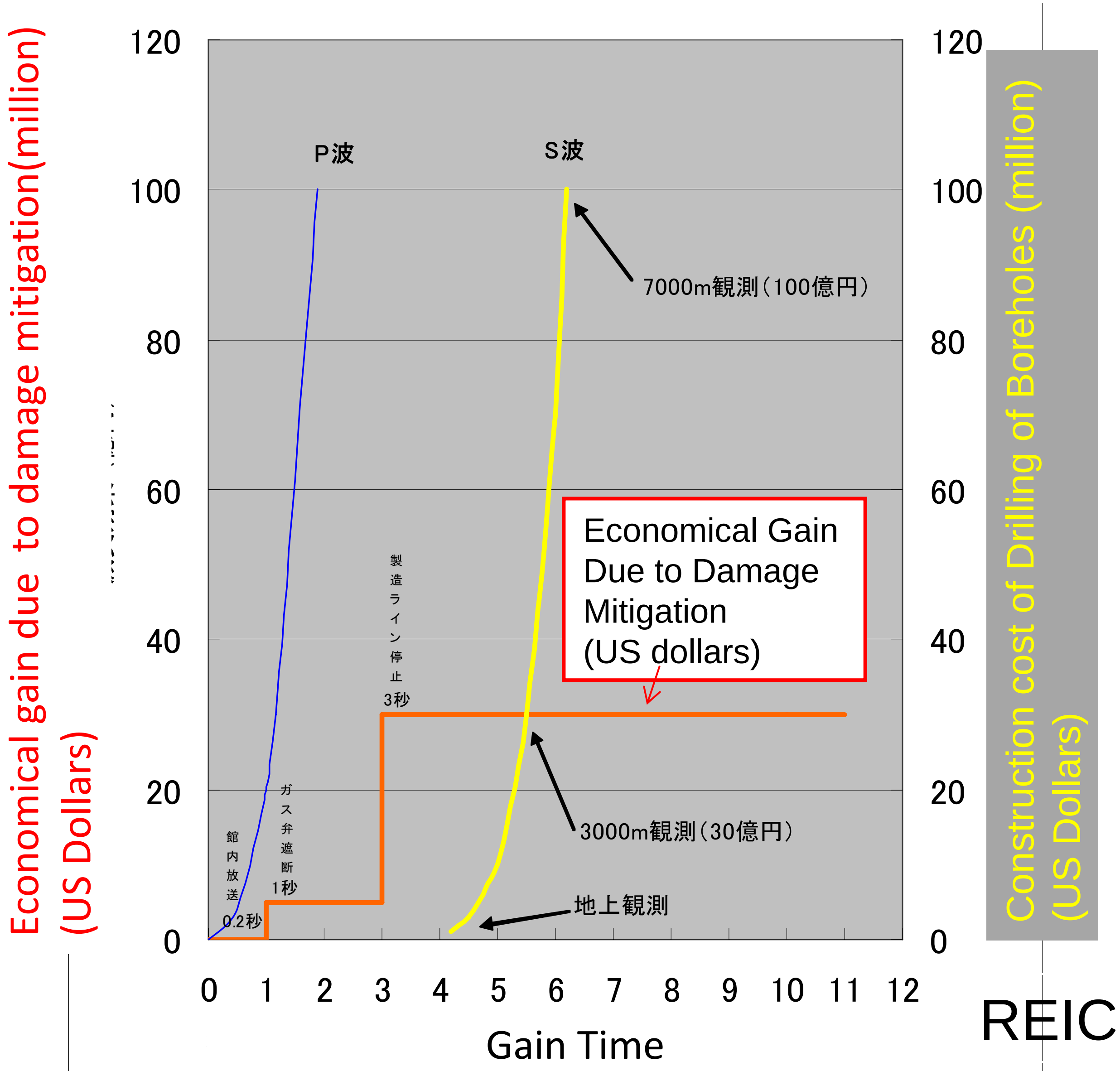
→ Gain time of more than 2 seconds putting borehole sensors of 3 km deep.

Example:
For an earthquake with hypocentral distance of 10 km, P wave travel time is about 1.4 seconds (10 km/6 km/s + 3 km/4 km/s) and S wave arrival time is about 4.8 seconds (10 km/3km/s + 3 km/2 km/s), then S-P time is about 1.4 seconds.

深層ボーリング江東（掘削深度3000m）のPS到達時間「震源深さ30km」



Economical Gain due to Damage Mitigation versus Gain Time by EEW System: Example of Semiconductor Factory



REIC (2010)

6. Summary and Future Directions -1

1. National Seismic Hazard Maps in Japan have been made by probabilistic and deterministic approaches, integrating advanced knowledge about Earth sciences, engineering, and social sciences related to earthquakes and seismic disasters since 1995 Kobe earthquake.
2. Ground motions from earthquakes caused to specified source faults are evaluated using the "recipe" proposed by the scaling relations of the outer and inner fault parameters.
3. *Ground motions from the Niigata-ken Chuetsu-oki (NCO) earthquake are well simulated with the characterized source models as long as the source fault are specified by geo-morphological and geological* surveys.
4. Design basis ground motions for seismic safety of nuclear facilities in Japan have been evaluated using deterministic approaches as long as fault modeling is appropriately made.

6. Summary and Future Directions -2

5. Deep boreholes seismic observation and geophysical exploration contribute upgrading of ground motion, reducing epistemic uncertainties by more constrains on propagation-path and local site effects.

6. Upgrading of numerical simulation methods of ground motions is inevitable to avoid the ergodic hypothesis and to reduce standard deviation of ground motion variabilities, in order to introduce probabilistic approaches in revision of the next regulatory guide.

Acknowledgements

- Strong motion data in Kik-net and K-NET was provided by the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan.

- Strong Motion Data at the Kashiwazaki-Kariwa Nuclear Power Plant from the Niigataken-Chuetsu-Oki (NCO) Earthquake of July 16, 2007, was provided by TEPCO.