The Abdus Salam
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Advanced School on Direct and Inverse Problems of Seismology

27 September - 8 October, 2010

**Achievements of strong motion seismology
and its future directions**

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The Abdus Salam International Centre for Theoretical Physics (*ICTP*)
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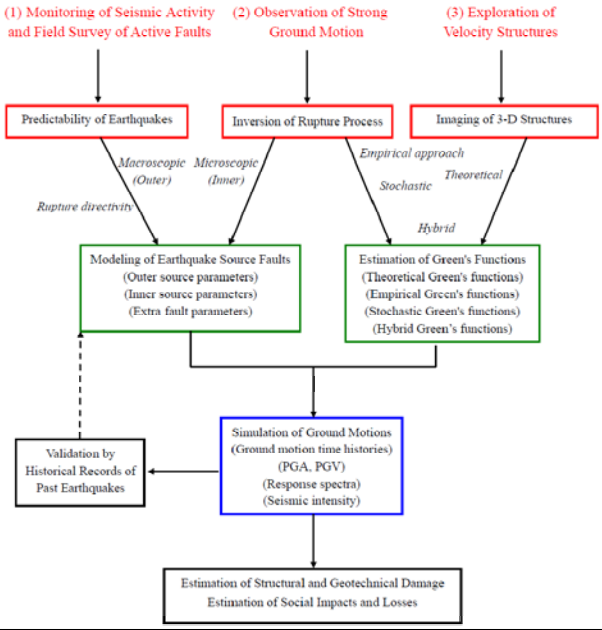
Achievements of strong motion seismology and its future directions -Chapter 3-

Scaling Relations of Fault Parameters for Inland Crustal Earthquakes

1. Framework of predicting strong ground motions for crustal earthquake scenarios.
2. Scaling relations of outer fault parameters
   M_0 vs. L, M_0 vs. S, L vs. W
   M_0 vs. D_{surf}, D_{surf} vs. D_{sub}, L_{surf} vs. D_{surf}, etc.
3. Scaling relations of inner fault parameters
   M_0 vs. S_a, M_0 vs. A_0, S vs. S_a, etc.

Framework of predicting strong ground motions for crustal earthquake scenarios

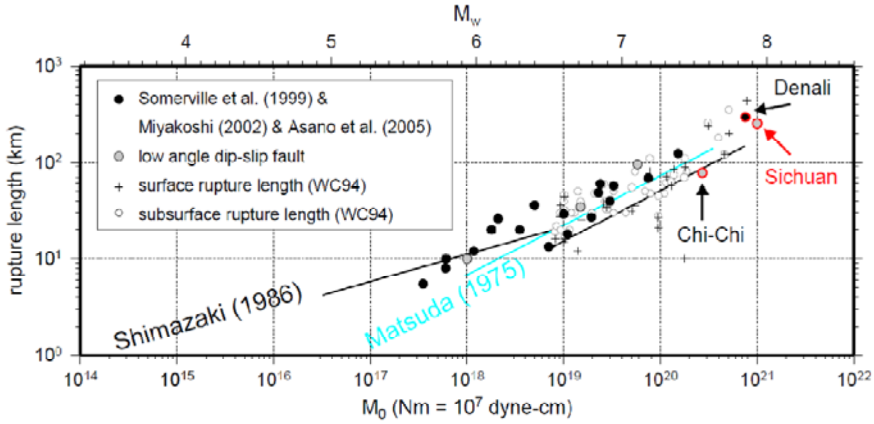


Scaling Relations of Fault Parameters for Inland Crustal Earthquakes

1. Outer Fault Parameters

   Empirical Scaling Relations between Seismic Moment, Rupture Area, Fault Length, Fault Width and Fault Displacement

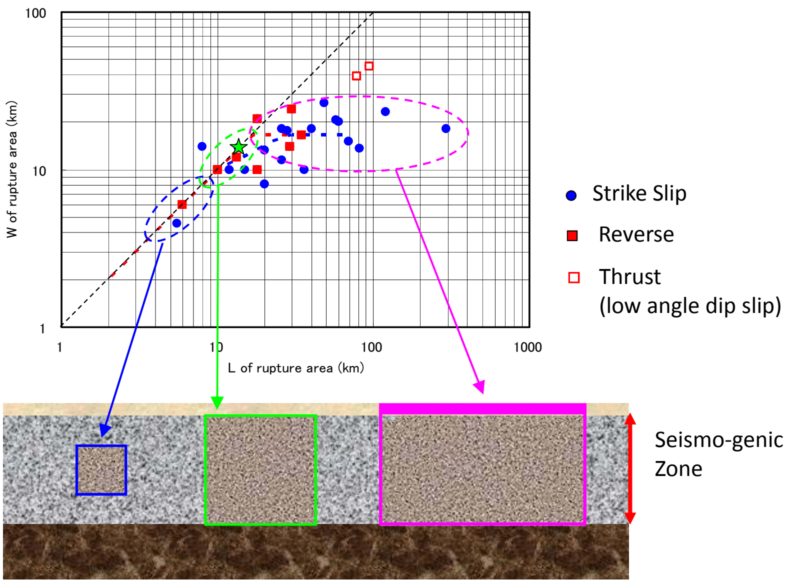
Relation between Seismic Moment and Fault Length



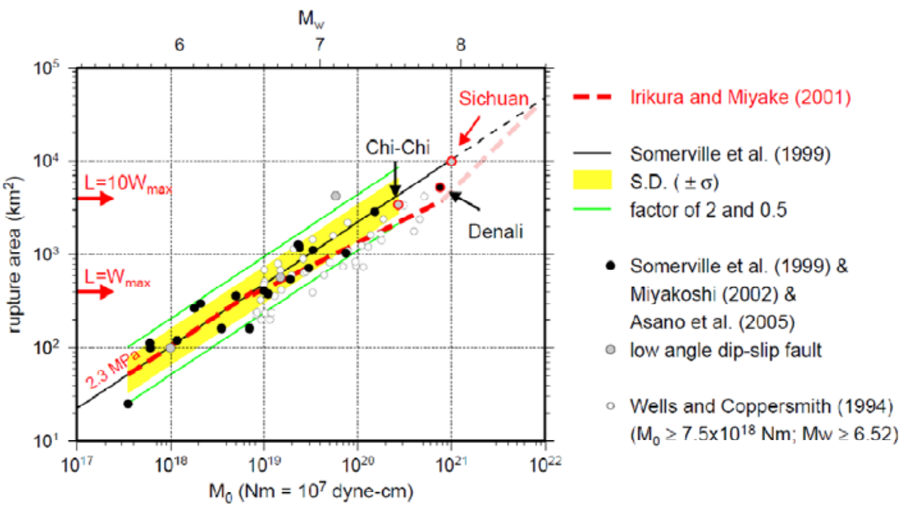
WC94: Wells and Coppersmith (1994), BSSA 84

Relation between Fault Length and Fault Width

from Slip Distribution by the Waveform Inversion Using Strong Motion Data



Relationship between Seismic Moment and Rupture Area



Mega-fault systems subjected for analysis in this study

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- Select earthquakes on mega-fault systems which,
  - Slip distribution on the seismic fault has been analyzed
  - Displacement on the surface rupture is surveyed
  - Earthquakes included in Stirling et al. (2002), but newly analyzed recently

    ⇒Total 10 earthquakes + 1891 Nobi (reference)

- Focus on the relation between parameters of the source fault and surface rupture
  - If there are several analysis or surveys, we took the average of the parameters

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Parameters obtained from surveys of the surface rupture

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Event	L (km)	D_{surf} (m)	Reference
Wenchuan, 2008	230	9.8	Lin(2008), Li et al.(2009), Liu-Zeng et al.(2009)
Kashmir, 2005	70	9.2	Kaneda et al.(2008)
Denali, 2002	341	8.8	Eberhart-Phillips et al.(2003), Haeussler et al.(2004)
Duzce, 1999	40	4.8	Akyuz et al. (2002)
Chi-Chi, 1999	78	8.9	Azuma et al.(2000), Dominguez et al.(2003)
Izmit, 1999	145	5.3	Barka et al.(2002), Langridge et al.(2002), Lettis et al.(2002)
Hyogo, 1995	11	2.5	Awata et al.(1996), Nakata and Okada(1999)
Landers, 1992	85	6.0	Sieh et al.(1993)
Tabas, 1978	85	3.0	Berberian(1979)
San Francisco, 1906	480	8.6	Thatcher et al.(1997)
Nobi, 1891	80	7.7	Matsuda(1974), JNES Research Report(2006)

Parameters obtained from source rupture process analysis

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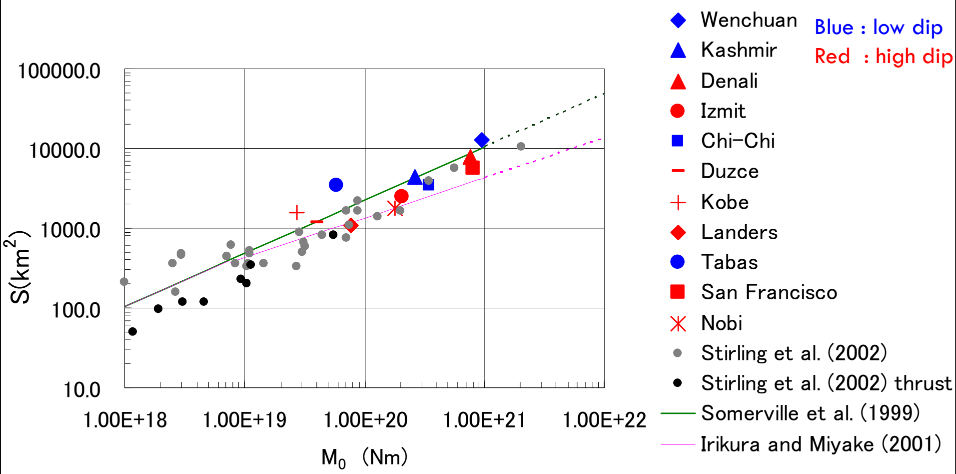
Event	L (km)	M_0 (Nm)	D_{sub_ave} (m)	D_{sub_max} (m)	S (km^2)	Reference
Wenchuan, 2008	279	9.5E+20	2.9	9.7	12,781	Koketsu et al.(2008) etc.
Kashmir, 2005	120	2.6E+20	2.7	5.9	4,320	Yagi (Personal letter)
Denali, 2002	320	7.7E+20	3.4	10.5	7,827	Oglesby et al.(2004) etc.
Duzce, 1999	31	4.0E+19	1.0	6.5	1,158	Delouis et al. (2002) etc.
Chi-Chi, 1999	89	3.5E+20	3.5	16.3	3,435	Chi et al.(2001) etc.
Izmit, 1999	126	2.0E+20	2.4	7.4	2,499	Yagi and Kikuchi(2000) etc.
Hyogo, 1995	57	2.7E+19	0.8	3.9	1603	Yoshida et al. (1996) etc.
Landers, 1992	74	7.7E+19	2.3	6.4	1,090	Cohee and Beroza(1994) etc.
Tabas, 1978	86	5.8E+19	0.4	1.4	3,463	Hartzell and Mendoza(1991)
San Francisco, 1906	460	8.2E+20	4.4	9.7	5,520	Song et al.(2008)
Nobi, 1891	122	1.8E+20	3.3	-	1,795	Fukuyama et al. (2007)

Seismic moment andArea of seismic fault



Data falls in between scaling relations of Somerville et al. (1999) and Irikura and Miyake (2001)

Max. surface disp. Dsurf and Ave. slip on source fault Dsub_ave

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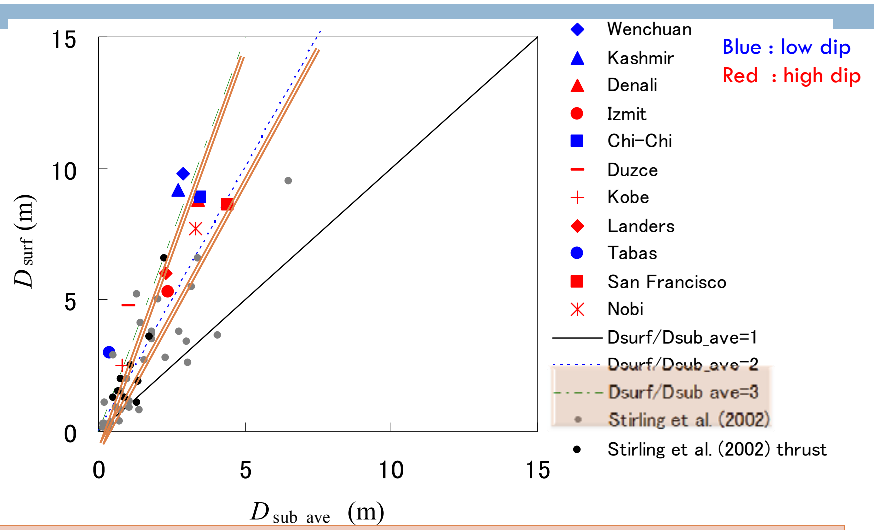

For mega-fault systems, $D_{surf}/D_{sub\_ave} = 2 \sim 3$

Surface fault length Lsurf and length of source fault Lsub

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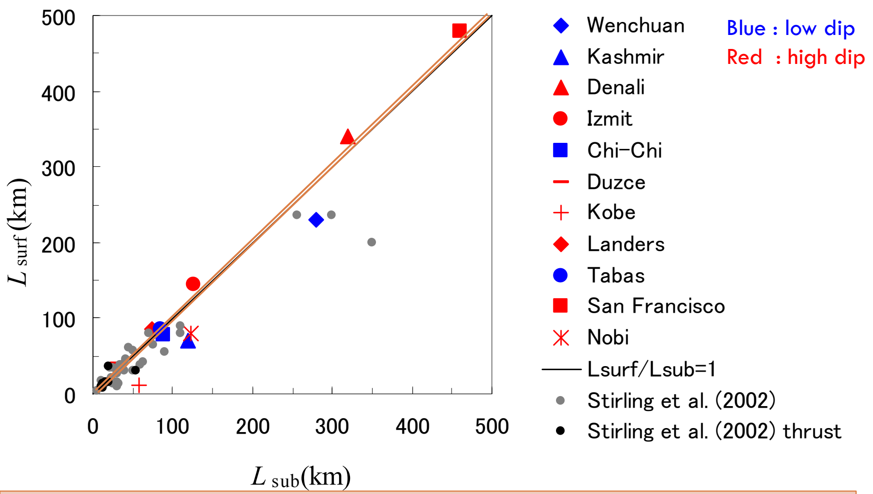

For mega-fault systems, $L_{surf}/L_{sub} \fallingdotseq 1$

Max. surface disp. Dsurf and Max. slip on source fault Dsub_max

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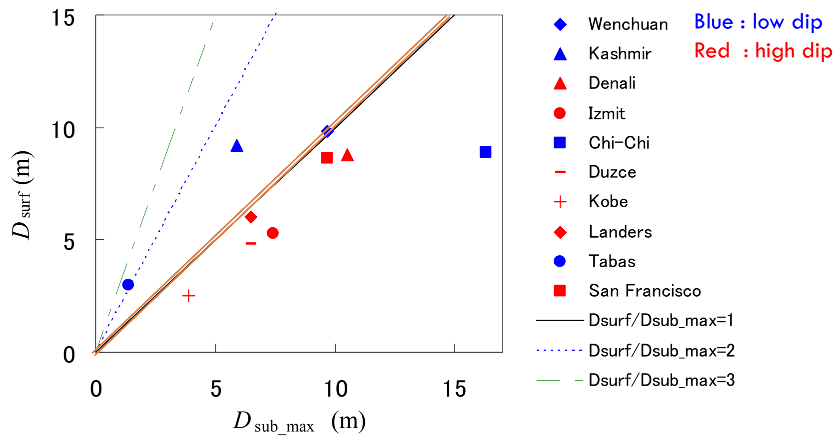

For mega-fault systems, $D_{surf}/D_{sub\_max} \leqq 1$

Max. surface disp. Lsurf and Length of source fault Lsub

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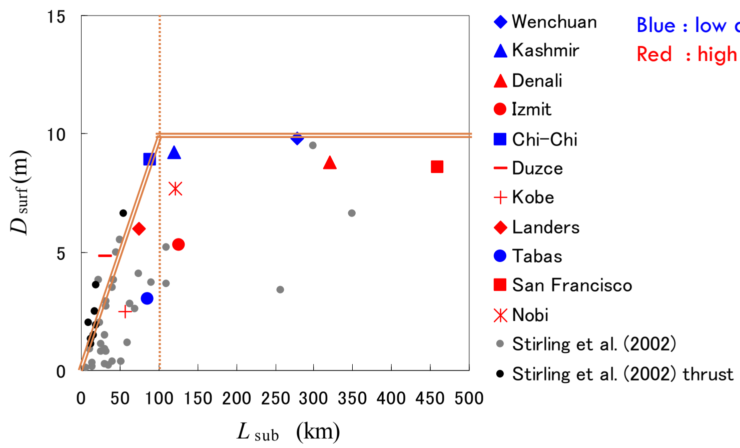

Max. surface disp. is proportional to length of source

...0m

Segmentation is not considered

New scaling relations (1)

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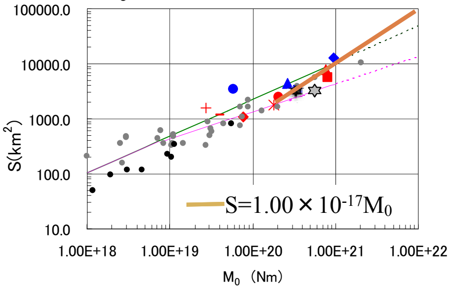
- Scaling relations for mega-fault systems
  - Slip saturates at D=10m when L=100km
    - Assuming W=18km
    - S=1800km^2, M_0=1.8×10^{20} [Nm]



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New scaling relations (2)

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- $S \propto M_0^{2/3}$ ($M_0 \leqq 7.5\text{x}10^{18}$Nm) ∝L, W, D
  - S = 2.23x10^{-15}x$M_0^{2/3}$ (Somerville et al., 1999)
- $S \propto M_0^{1/2}$ ($M_0 > 7.5\text{x}10^{18}$Nm) ∝L, D (W fixed)
  - S = 4.24x10^{-11}x$M_0^{1/2}$ (Irikura and Miyake, 2001)
- $S \propto M_0^{1/1}$ ($M_0 \leqq 1.8\text{x}10^{20}$Nm) ∝L (D&W fixed)
  - S = 1.00x10^{-17}x$M_0^{1/1}$ (This study)

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Estimation of Average Stress

- Asperity stress drop for circular crack model is given by Eshelby (1957) as

$$\Delta\sigma_c = \frac{7}{16}\frac{Mo}{R^3}$$

MO: seismic moment, *R*: radius of crack

$$\Delta\sigma_c = \frac{7\pi^{3/2}}{16}\frac{Mo}{(LW)^{3/2}}$$

L: fault length, *W*: fault width

- Asperity stress drop for a rectangular fault considering tectonic loading is given by Fijii and Matsuura (2000) as

$$\Delta\overline{\sigma}_c = \frac{\alpha L + \beta}{L^2 W} M_0$$

- Average stress drop for infinite-length strike-slip fault is estimated for strike-slip fault by Starr (1928) as

$$\Delta\sigma = \frac{2}{\pi}4(\lambda+\mu)\pi(\lambda+2\mu)\frac{M_0}{LW^2}$$

and for dip-slip fault by Knopofff (1958).

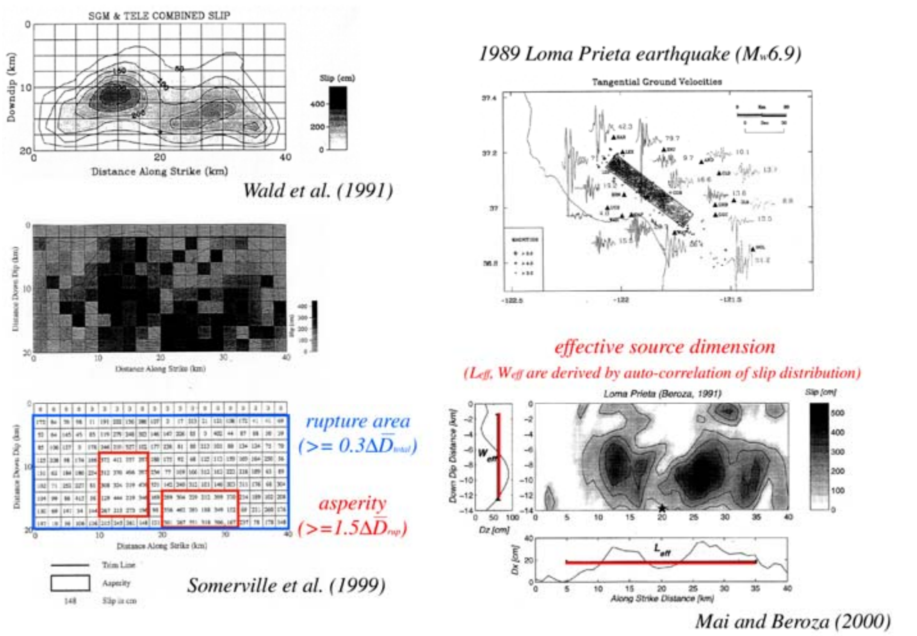
$$\Delta\sigma = \frac{2}{\pi}\frac{M_0}{LW^2}$$

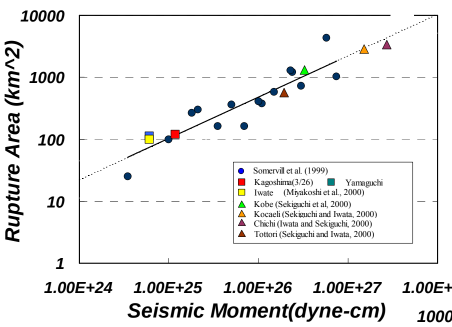
Scaling Relations of Fault Parameters for Inland Crustal Earthquakes

2. Inner Fault Parameters

Empirical Scaling Relations concerning Slip Heterogeneities inside Rupture Area.

Source Characterization for Simulating Strong Ground Motion



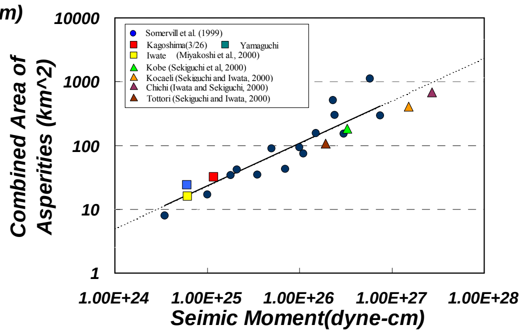


Relation between Rupture Area and Mo

→ **Outer Fault Parameters**

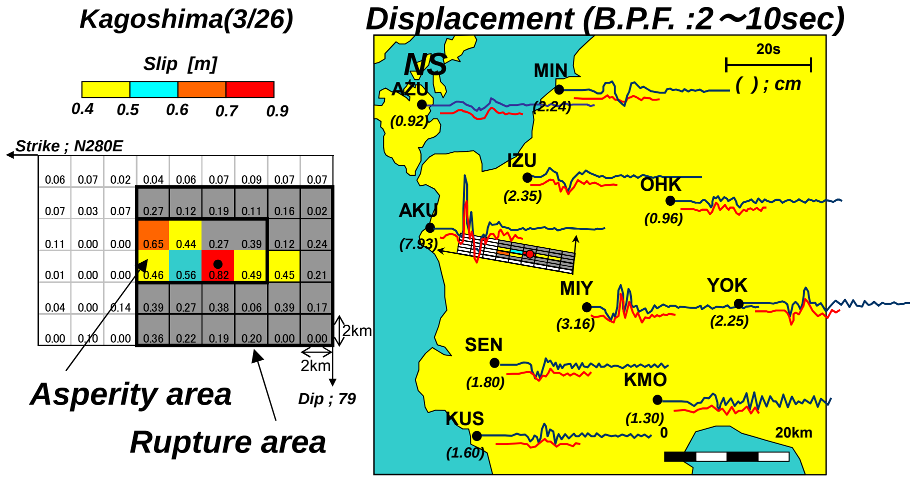
Relation between Combined Area of Asperities and Mo

→ **Inner Fault Parameters**



Somerville *et al*. (1999) and Miyakoshi *et al*. (2001)

Source Model by Inversion Method



Identification for Rupture and Asperity Area

(Somerville et al., 1999)

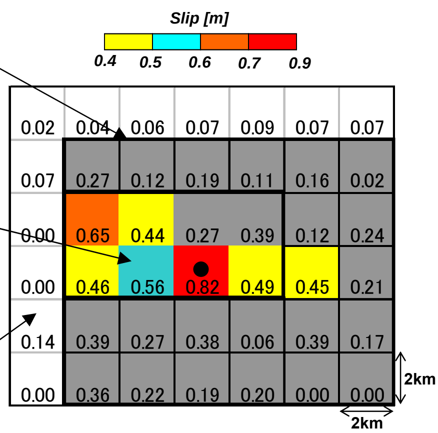
Rupture area

- *More than 0.3 times the average slip of the whole fault.*

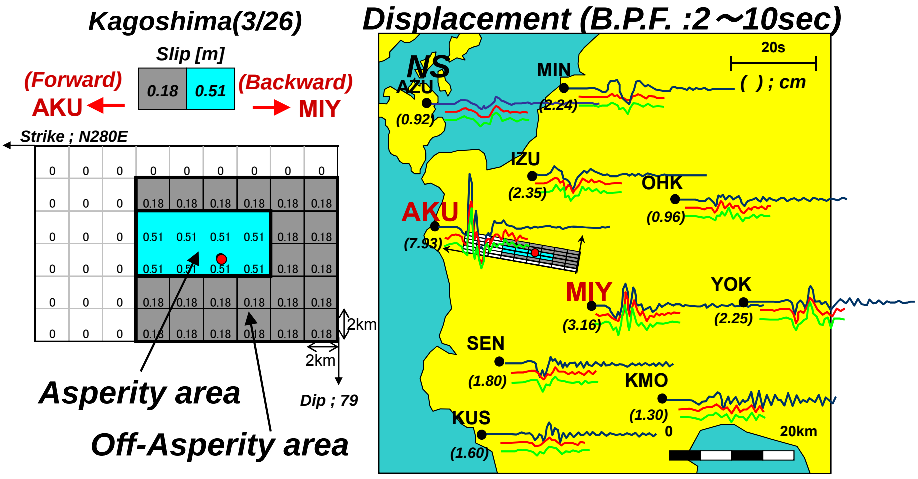
Asperity area

- *More than 1.5 times the average slip of the whole fault.*

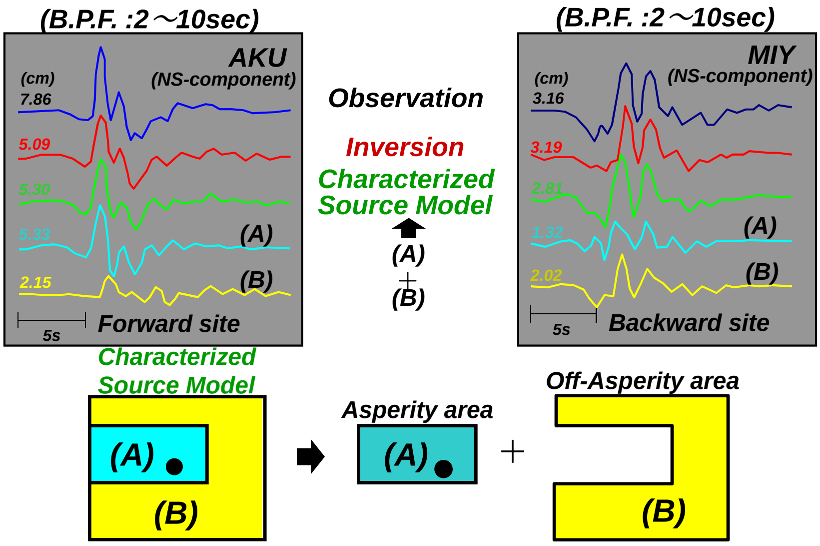
Removed area



Characterized Source Model

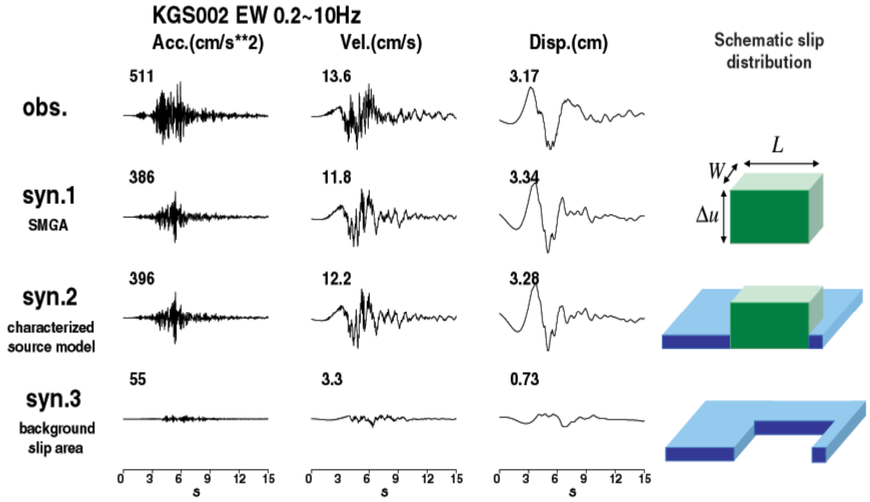


Asperity Area vs. Off-Asperity Area



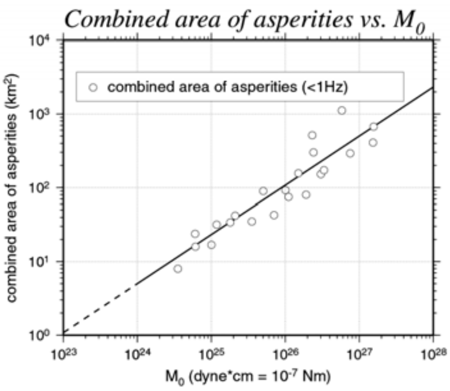
What is characterized source model ? (1)

- simulation of broadband ground motion for the 1997 Kagoshima-ken Hokuseibu earthquake -

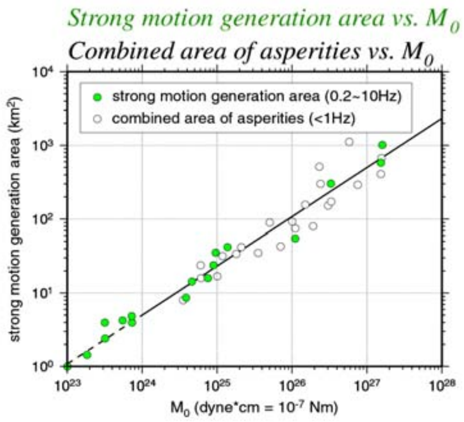


Miyake *et al*. (2000)

Strong motion generation area is coincident with the area of asperities characterized by the waveform inversion

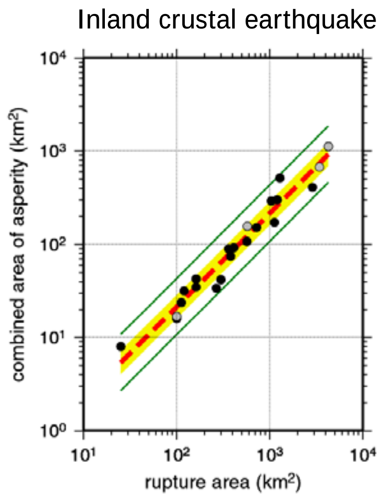


Somerville *et al*. (1999) and Miyakoshi *et al*. (2001)



Kamae and Irikura (1998, 2000), Kamae *et al*. (1999), and Miyake *et al*. (2001)

Relation between Combined Asperity Size (Sa) and Total Rupture Area (S)



入倉・三宅 (2001)

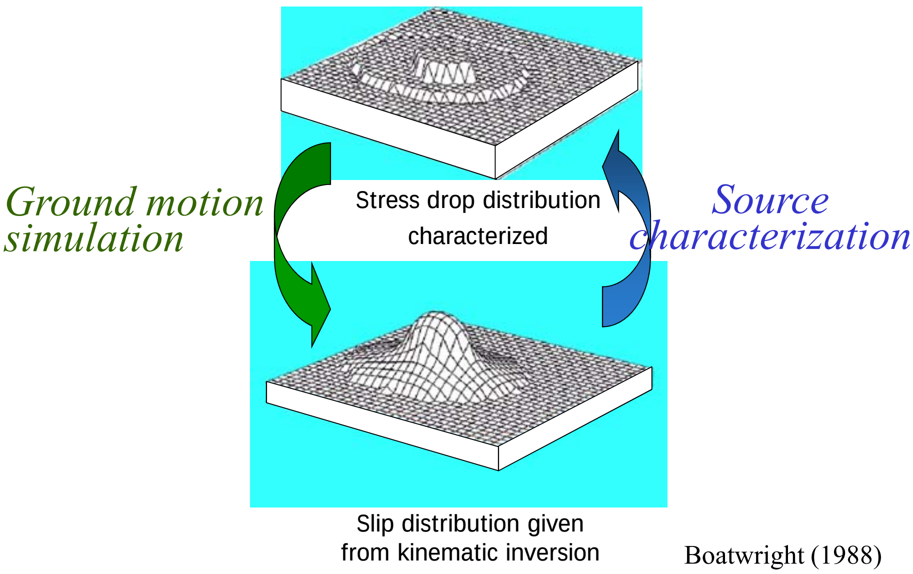
Sa: Combined Asperity Area
S: Total Fault Area
Sa/S = 0.215

Da: Average Slip on Asperities
D: Average Slip on Total Fault
Da/D = 2.0
(Somerville et al., 1999)

$\Delta\sigma_c$: Average stress drop
$\Delta\sigma_a$: Stress drop on asperity

$$\Delta\sigma_a = \Delta\overline{\sigma}_c \cdot \frac{S}{S_a}$$

Asperity Source Model for Simulating Strong Ground Motion



Boatwright (1988)

Asperity Source Model (Das and Kostrov, 1986)

Basic Equations

Seismic Moment
(Boatwright, 1986)

$$M_0 = \frac{16}{7}\Delta\sigma_a r^2 R$$

$$M_0 = \frac{16}{7\pi^{3/2}}\Delta\sigma_a S_a S^{1/2}$$

Stress Drop
(Boatwright, 1988)

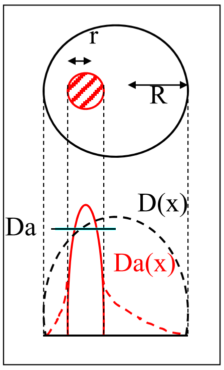
$$\Delta\sigma_a = \frac{7}{16}\frac{Mo}{r^2 R}$$

$$\Delta\sigma_a = \frac{7\pi^{3/2}}{16}\frac{Mo}{S_a S^{1/2}}$$

Acceleration Source- spectrum
(Madariaga, 1977)

$$A_0^a = 4\pi\beta v_R \Delta\sigma_a r$$

$$A_0^a = 4\pi^{1/2}\beta v_R \Delta\sigma_a S_a^{1/2}$$



r<<R

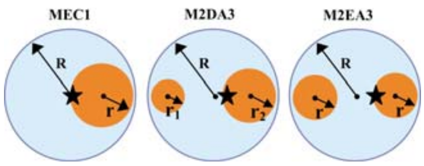
$\Delta\sigma_a \neq 0, \quad \Delta\sigma_b = 0$

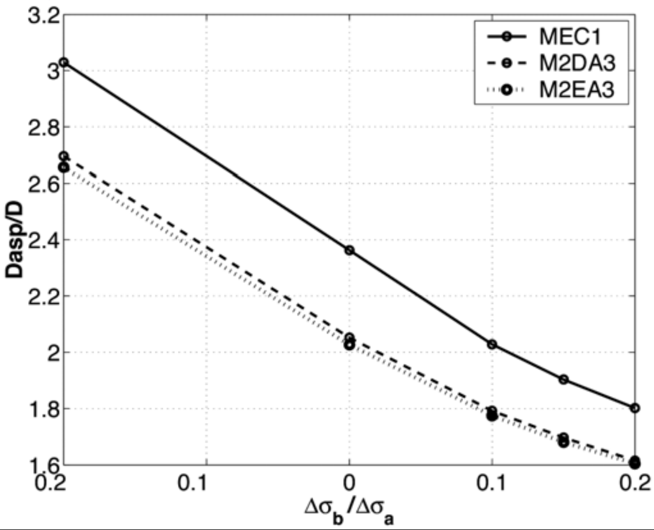
$S = \pi R^2, \quad S_a = \pi r^2$

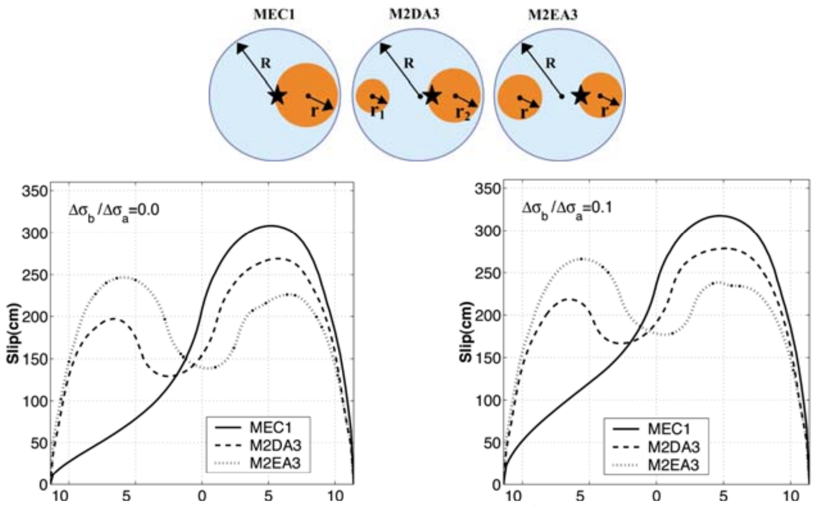
Slip Distribution for Single and Double Asperity

Dasp: Average slip on asperity

D : Average on total fault







$\Delta\sigma_b/\Delta\sigma_a = 0.0$			
	MEC1	M2DA3	M2EA3
Masp/Mo	0.530	0.458	0.450
Dasp/D	2.363	2.052	2.027
Dmax/D	2.921	2.638	2.476

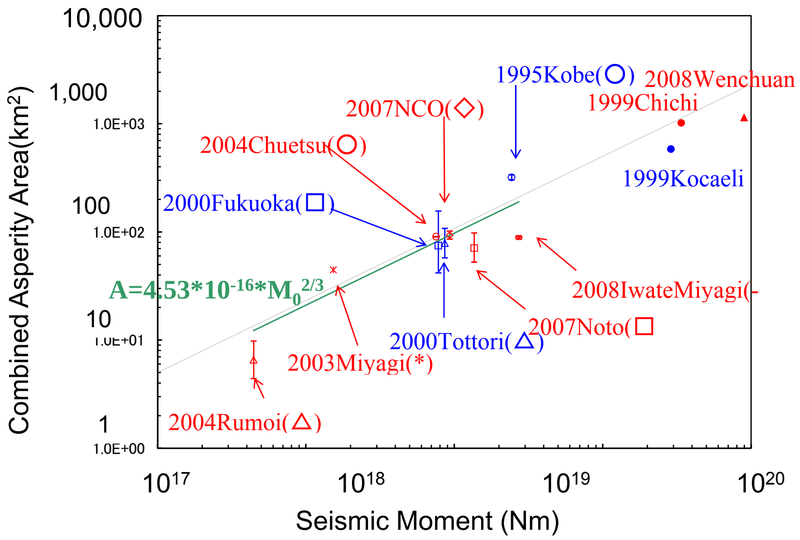
$\Delta\sigma_b/\Delta\sigma_a = 0.1$			
	MEC1	M2DA3	M2EA3
Masp/Mo	0.455	0.400	0.394
Dasp/D	2.028	1.792	1.775
Dmax/D	2.449	2.209	2.157

Inland Crustal-Earthquakes in Japan

#	Mw	Source Type	Year	Region	Damage	
1.	*6.9*	*Strike-slip*	1995	Hyogo-ken Nanbu (Kobe)	killled 6,437	injured 43,792
2.	*6.1*	*Strike-slip*	1997	Kagoshima-ken Kokubu	killed 0	injured 37
3.	*5.8*	*Strike-slip*	1997	Yamaguchi-ken Hokubu	killed 0	injured 2
4.	*6.7*	*Strike-slip*	2000	Tottori-ken Seibu	killed 0	injured 182
5.	*6.6*	*Strike-slip*	2005	Fukuoka-ken Seiho	killed 1	injured 1,037
6.	*5.9*	*Reverse*	1998	Iwate-ken Nairiku Hokubu	killed 0	injured 9
7.	*6.1*	*Reverse*	2003	Miyagi-ken Hokubu	killed 0	injured 677
8.	*6.6*	*Reverse*	2004	Niigataken Chubu	killed 67	injured 4,805
9.	*5.9*	*Reverse*	2004	Hokkaido Rumoi Nanbu	killed 0	injured 8
10.	*6.8*	*Reverse*	2007	Noto Hanto	killed 1	injured 356
11.	*6.6*	*Reverse*	2007	Niigata-ken Chuetsu Oki	killed 15	njured 2,346
12	*6.8*	*Reverse*	**2008**	Iwate-Miyagi Nairiku	killed 23	injured 426

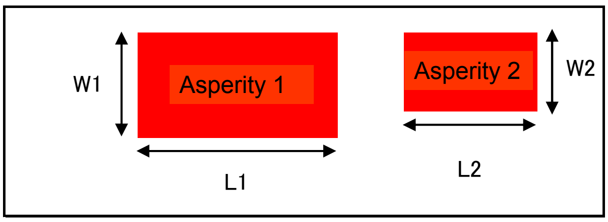
"killed" include death and missing toll.

Relation between Seismic Moment and Combined Asperity Area from the waveform inversion using strong motion data



Comparison of Observed Acceleration Source Spectral Levels with Estimated Ones from Characterized Source Model

Characterized Source Model

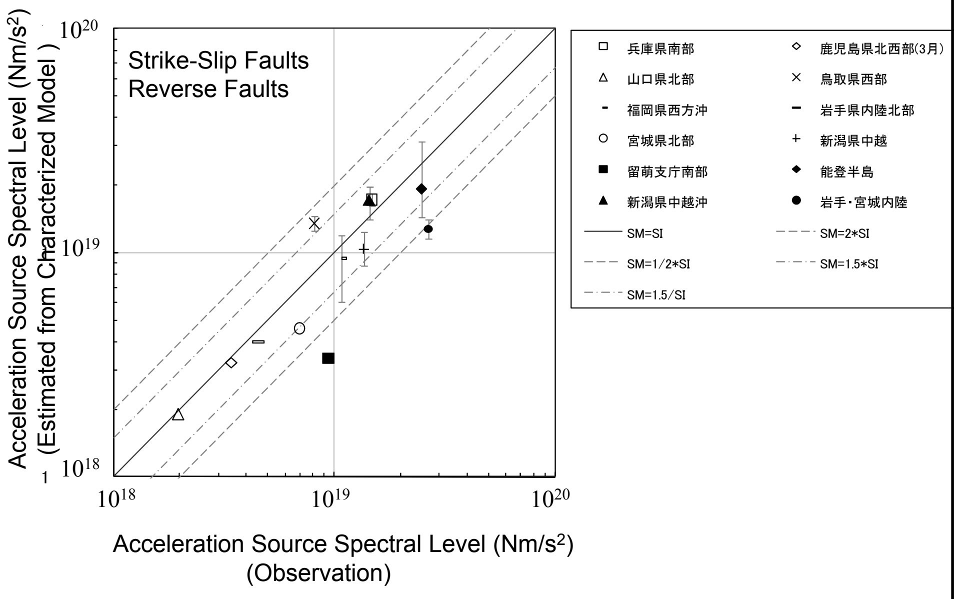


Acceleration Source Spectral Level *A*

$$A = 4\pi\beta^2\left[\sum_{i=1}^{N}\left(\Delta\sigma_i r_i\right)^2\right]^{1/2}$$

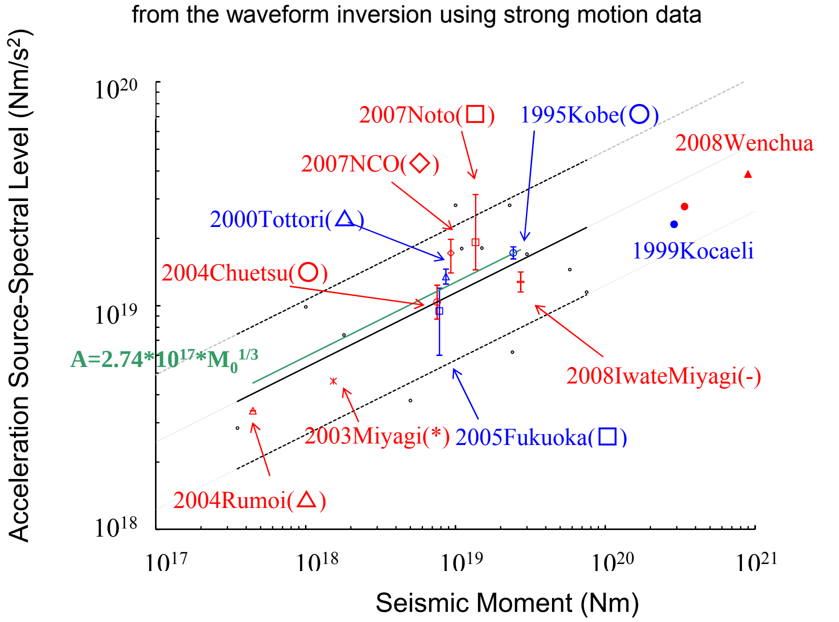
β: S wave velocity in source area
N: Number of asperities
$\Delta\sigma_i$: Stress drop of Asperity i
r_i: Equivelent radius of Asperity i
i.e. $\pi r^2 = L \times W$)

Comparison of Observed Acceleration Source Spectral Levels with Estimated Ones from Characterized Source Model



Relation between Seismic Moment and Combined Asperity Area

from the waveform inversion using strong motion data



Estimation of Asperity area (*Sa*) from Acceleration Source Spectral Level (*Ao*)

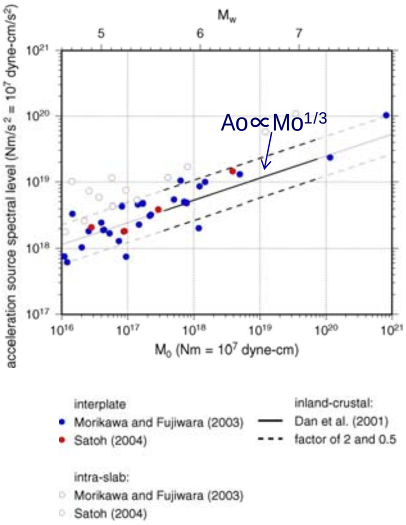
- Empirical relationship between seismic moment M_0 and acceleration source spectral level A_0 (Dan et al., 2001)

$$A_0 = 2.46 \times 10^{17} \times M_0^{1/3}$$

- Asperity area (Sa) is eastimated from theoretical representation of A_{0a}, M_0, and S, assuming $A_0 \sim A_{0a}$

$$\frac{A_0^b}{A_0^a} = \sqrt{\frac{S_b}{S_a}} \cdot \frac{\sigma_b}{\sigma_a} << 1 \quad \therefore \quad \frac{A_0^a}{A_0} = \frac{1}{\sqrt{1+\left(A_0^b / A_0^a\right)^2}} \approx 1$$

$$S_a = \left(\frac{7\pi^2}{4}\beta v_r\right)^2 \cdot \frac{(M_0)^2}{S(A_0^a)^2}$$



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27 September - 9 October , 2010

Achievements of strong motion seismology and its future directions -Chapter 4-

Recipe for Predicting Strong Ground Motions, Aiming to Earthquake Disaster Prevention

Recipe for Predicting Strong Ground Motions (Irikura and Miyake, 2001)

"Recipe" is to characterize source-fault models necessary for estimating strong ground motions from specified faults, when the faults are ruptured in future.

Everybody can get ground motions with almost the same characteristics by using the "recipe", just like a cooking book.

Empirical Relationships for the Recipe

(1) Scaling Relations of Outer Fault Parameters

Empirical Relationship between Seismic Moment (Mo) and Total Rupture Area (S)

⇒ Average Stress Drop on the Fault ($\Delta\bar{\sigma}_c$) is estimate

(2) Scaling Relations of Inner Fault Parameters

Empirical Relationship between Combined Asperity Area (Sa) and Total Rupture Area (S) or

Theoretical / Empirical Relationships between Seismic Moment (Mo) and Acceleration Source Spectral Level (Ao)

⇒ Combined Asperity Area (Sa) and Stress Drop on Asperities ($\Delta\sigma_a$) are estimate

(3) Constraint on Average Slip of Asperities (Da) from Dynamic Simulations

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.

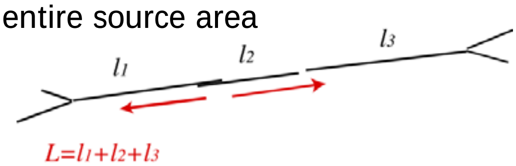
Extra Fault Parameters

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

Outer Fault Parameters

Parameters characterizing entire source area

Inland crustal earthquake

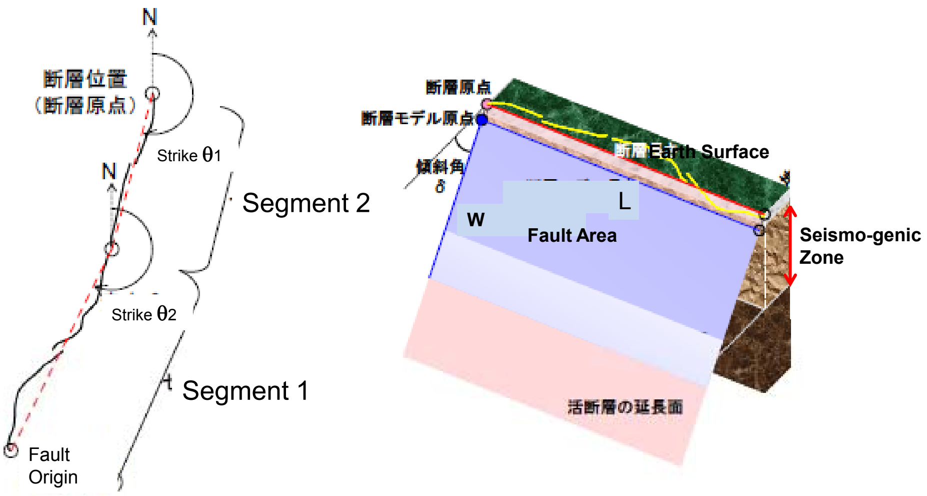


- Step 1: Give total rupture area ($S=LW$)
  - Fault length (L) is related to grouping of active faults from geological and geomophological survey.
  - Fault width (W) is related to thickness of seismogenic zones (Hs) and dip (θ), *i.e.* $W=Hs/\sin\theta$.

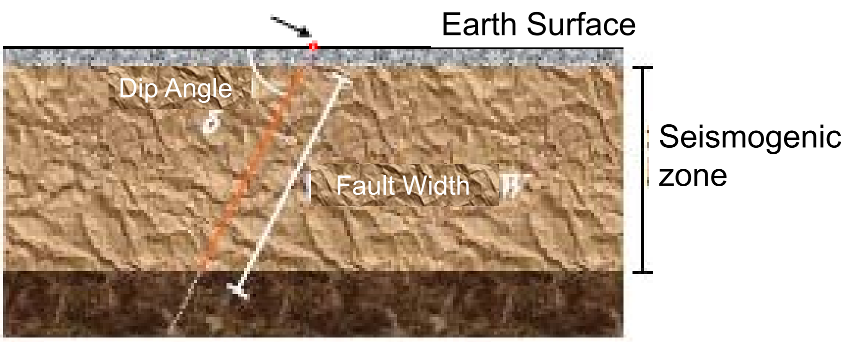
- Step 2: Estimate total seismic moment (Mo)
  empirical relationships

- Step 3: Estimate average static stress-drop ($\Delta\sigma_c$) on the fault
  a circular-crack model (Eshelby, 1957) for L/W less than 2
  or a loading model (Fujii and Matsu'ura, 2000) for L/W more than 2.

Outer Fault Parameters -continued 1-



Outer Fault Parameters -continued 2-



Inner Fault Parameters

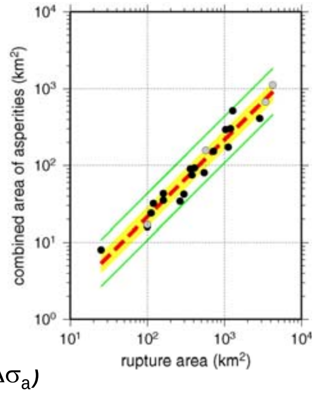
Slip heterogeneity or roughness of faulting

Inland crustal earthquake

- Step 4: Estimate combined area of asperities (Sa) from empirical relation Sa-S
  (Somerville et al., 1999; Irikura and Miyake, 2001 →)

  Sa/S = 0.22

  Sa: combined area of asperities (inner)
  S : total rupture area (outer)



– Step 5: Estimate Stress Drop on Asperities ($\Delta\sigma_a$) from multi-asperity model (Madariaga, 1979)

$$\Delta\sigma_a = \Delta\overline{\sigma}_c \cdot \frac{S}{S_a}$$

$\Delta\sigma_a$: stress drop on asperity (inner)
$\Delta\sigma_c$: average stress drop (outer)

Inner Fault Parameters –continued 1-

Slip heterogeneity or roughness of faulting

Inland crustal earthquake

Alternative

- Step 4: Evaluate acceleration source spectral level from entire fault (Ao) using the records of past earthquakes

  Reference: Empirical relationship of Mo-Ao →

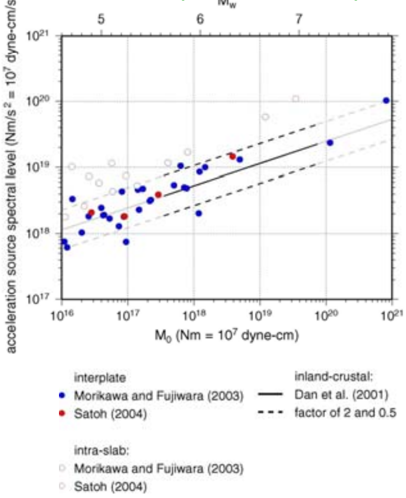
- Step 5: Assuming Ao∼Ao_a, estimate Asperity area (Sa) from theoretical representation of Ao_a, Mo, and S

$$\frac{A_0^b}{A_0^a} = \sqrt{\frac{S_b}{S_a}}\cdot\frac{\sigma_b}{\sigma_a} << 1 \quad \therefore \quad \frac{A_0^a}{A_0} = \frac{1}{\sqrt{1+\left(A_0^b/A_0^a\right)^2}} \approx 1$$

$$S_a = \left(\frac{7\pi^2}{4}\beta v_r\right)^2 \cdot \frac{(M_0)^2}{S(A_0^a)^2}$$

(Sa = 722.4 km²)

Empirical relationship shows Ao∝$Mo^{1/3}$(Dan et al., 2001)

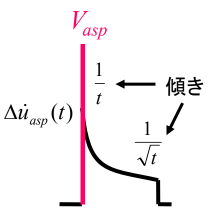


Inner Fault Parameters –continued 3-

Slip heterogeneity or roughness of faulting

- Step 9: parameterization of slip velocity time functions

最大すべり速度 V (目安)

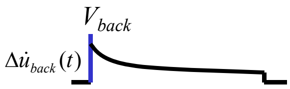


アスペリティ領域

低周波数側は Day (1982) に従い

$$V_{asp} = \sqrt{2 f_{lowpass} W_{asp} v_R} \frac{\sigma_a}{\mu}$$

高周波数側は $V_{asp} \propto \sigma_a$



背景領域 $V_{back} \propto \sigma_b$

剛性率 μ, アスペリティと背景領域の実効応力 σ_aとσ_b

source-controlled f_{max}: $f_{lowpass}$，領域の幅 W_{asp}，破壊伝播速度 v_R

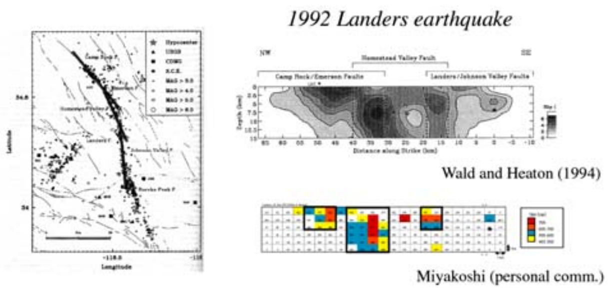
注意：すべり速度関数の傾きが $\frac{1}{\sqrt{t}}$ だけだと，マッチングフィルターの手前で振幅スペクトルの落ち込みが出来てしまうため，$\frac{1}{t}$ の要素が必要

Inner Fault Parameters –continued 4-

Slip heterogeneity or roughness of faulting

Inland crustal earthquake

- Step 6: Estimate number of asperities (N): The asperities in the entire fault rupture are related to the active-fault segments
  location ← from surface offsets measured along fault



- Step 7: Estimate average slip on asperities (Da) based on Step 6 and empirical relationships from dynamic simulations

(ex. N=1 → Da/D=2.3, N=2 → Da/D=2.0, N=3 → Da/D=1.8)
reference: average Da/D = 2.0 (Somerville et al., 1999)

Are asperities repetitious ?

Some proofs:

1. Repetition of asperities from source inversion results

the 1968 Tokachi-oki Earthquake and 1994 Sanriku-oki Earthquake

2. Coincidence of surface slip variation and locations of asperities

the 1994 Landers earthquake and the 1999 Chi-chi earthquake

How to find the asperities ?

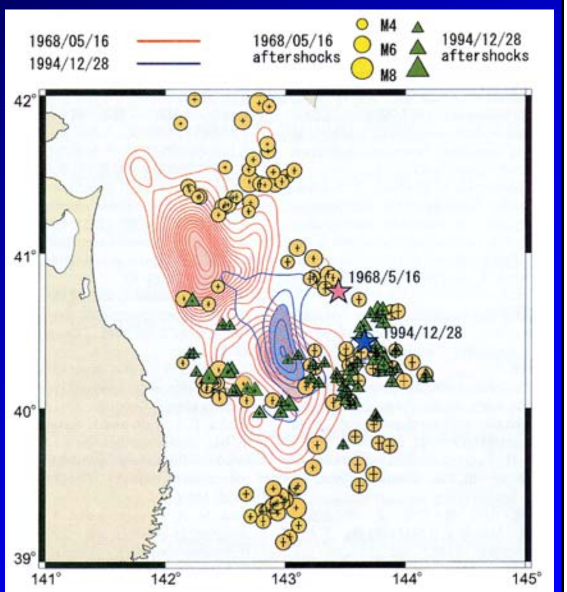
1. Surface slip distribution along active faults

2. Seismic activity: less active inside asperities and relatively more active surrounding the asperities

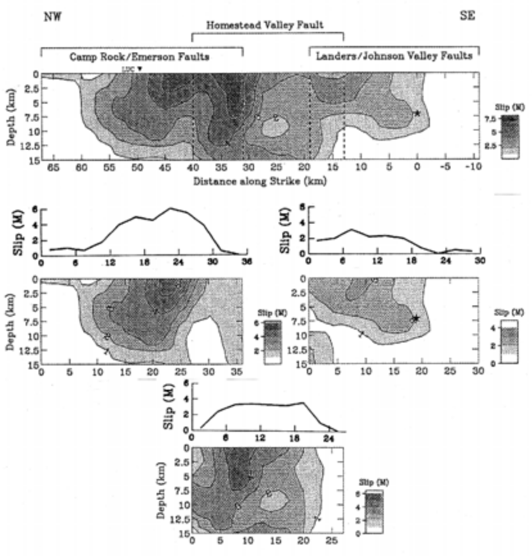
3. Reflected (scattered) waves: strong : less reflection (scattering) coefficients inside asperities and relatively high outside asperities.

Repetition of Asperities

Spatial Distribution of Moment Releases during 1968 Tokachi-oki Earthquake and 1994 Sanriku-oki Earthquake



(Nagai et al., 2001)



Correlation between surface offsets measured along fault traced and asperities on fault segments during the 1992 Landers earthquake (Wald and Heaton, 1994)

Extra Fault Parameters

Propagation pattern of rupture

- Rupture starting point
- Rupture propagation pattern
- Rupture velocity

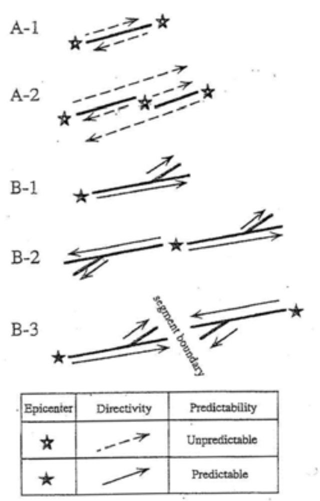
Inland crustal earthquakes

→ Rupture nucleation and termination are related to geomorphology of active faults

Subduction earthquakes

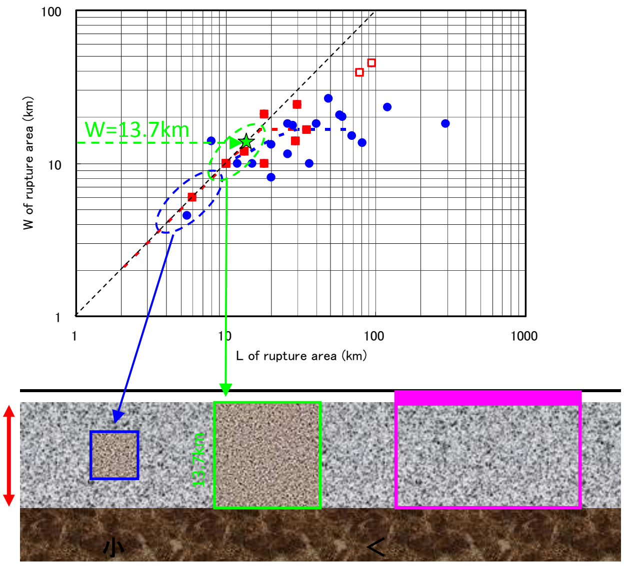
→ Information from past earthquakes

from off-sea to land (e.g., Tokachi-oki, Sanriku-oki)
from land to off-sea (e.g., Tonankai)

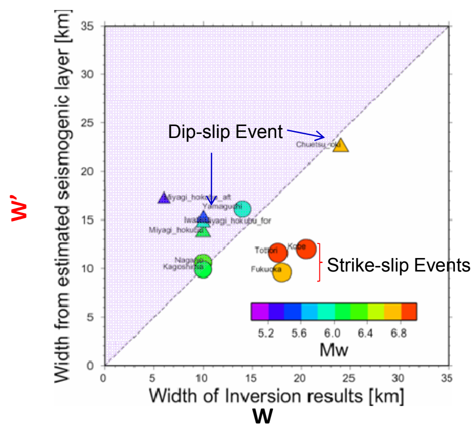


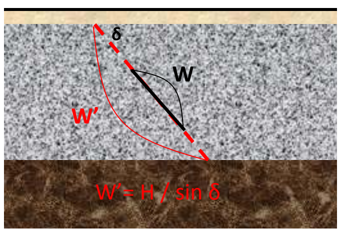
Nakata et al. (1998)

Relation between Fault Length and Fault Width



Fault Width W estimated from the Waveform Inversion versus Fault Width W' inferred from the Thickness of Seismogenic Zone



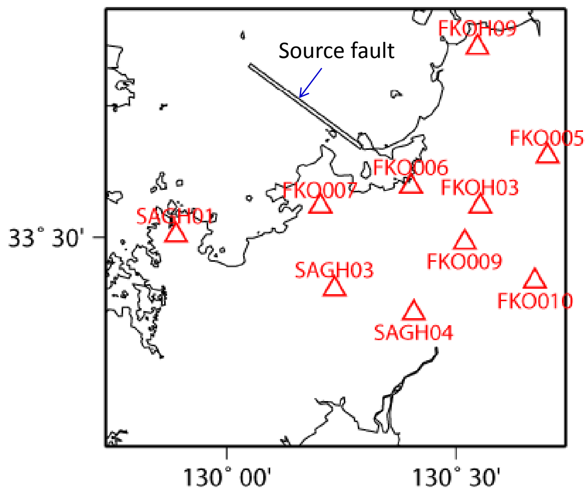


Validation of the Recipe for Recent Disastrous Earthquakes

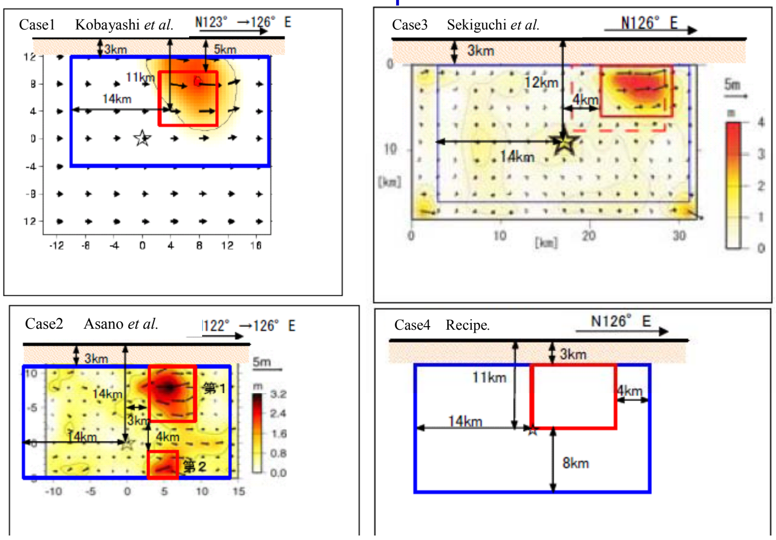
So far, the recipe have been examined comparing the observed records with simulated motions for recent desastrous earthquakes by the Strong Motion Evaluation Sub-committee under the Earthquake Research Committee of the Head Quarter of Earthquake Research Promotion, Japan.

Example:
2005 Fukuoka-ken Seiho Oki (Mw 6.6) in Japan

2005 Fukuoka Warthquake (Mw 6.6)

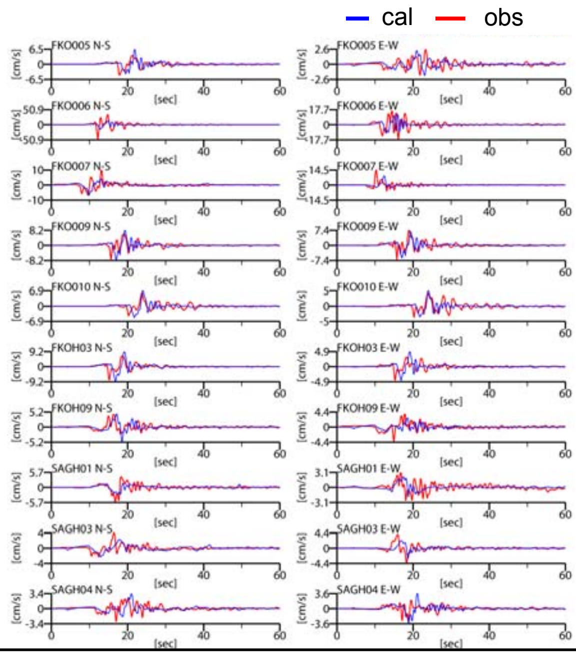


Four Characterized Source Models with Asperities inside the Rupture Area.

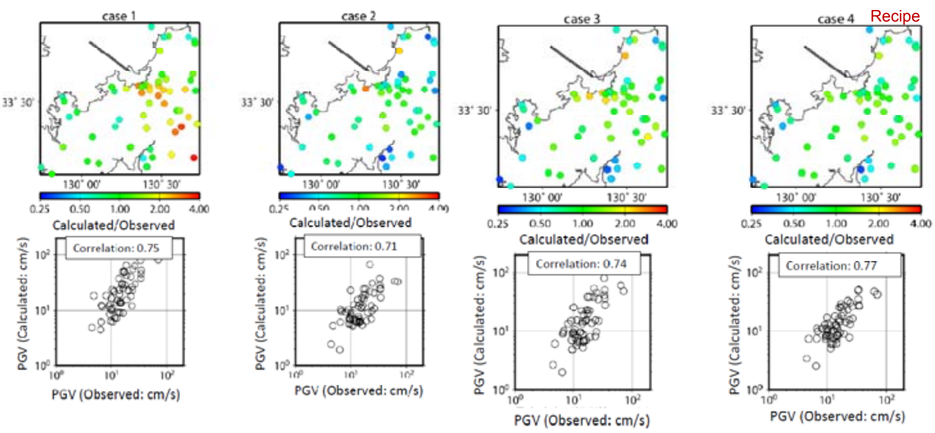


Cases 1, Case 2 and Case 3 are from waveform inversion results by Kobayashi *et al*. (2006), Asano *et al*. (2006), and Sekiguchi *et al*. (2006), respectively.
Case 4 is a source model based on the "recipe."

Comparison between Observed and Simulated Ground Velocities on Engineering Bedrock for Case 4 by the Hybrid Method.



Comparison of observed and calculated PGVs for the 2005 Fukuoka earthquake.



Upper: The ratios of calculated to observed PGVs .
Lower: Correlations between calculated and observed PGVs

Simulation of Strong Ground Motions from the 2008 *Wenchuan earthquake* (汶川大地震)

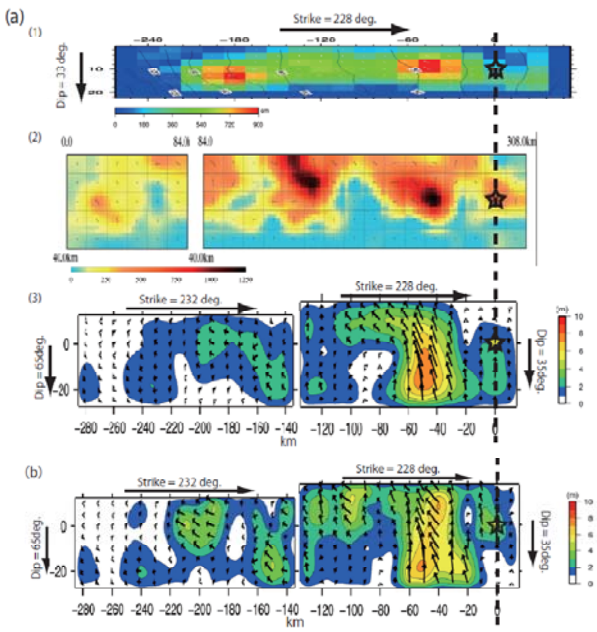
Summary of strong motion observation

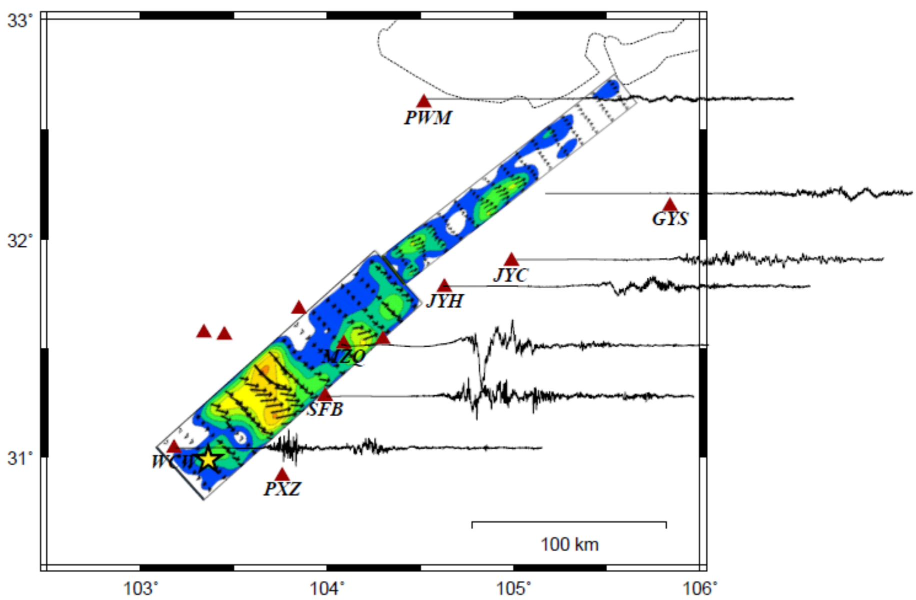
- 398 stations, 1191 records
- 19 stations within 100km from the epicenter, 34 stations within 200-300km from the epicenter
- 12 stations within 20km from the fault, 11 within 20-50km from the fault, 22 within 50-100km from the fault;
- 120 records with PGA over 100gal;
- Closest fault distance is 0.74km at Qingping Station, with a PGA of 824.1gal
- Closest epicenter distance is 22.2km at Wolong, with a PGA of 956.7gal and 1.09km fault distance.

2008-8-25

After Wang et al.(2008)

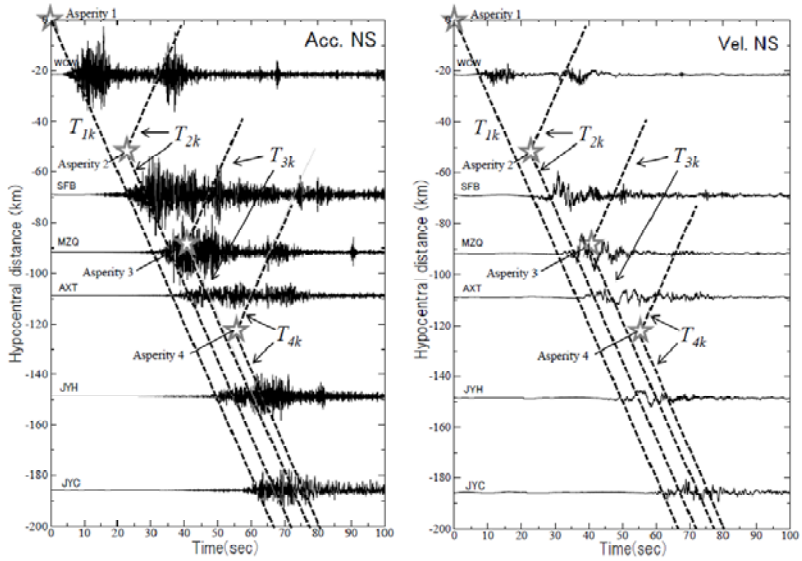
Slip distributions on source fault during the 2008 Wenchuan earthquake



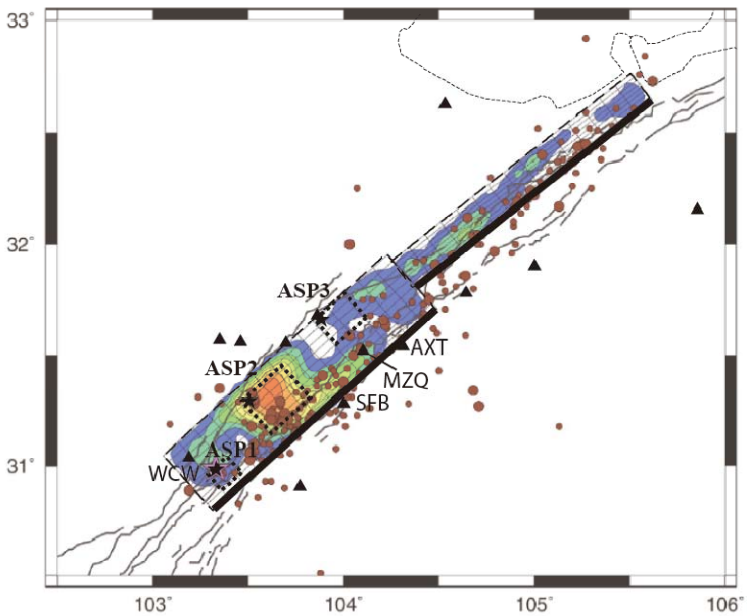


Kohkestu, et al., 2008

Observed Records at Near-Field Stations
(WCW, SFB, MZQ, AXT, JYH and JYC)



Characterized Source Model with Three Asperities for the Northern Segment of the 2008 Wenchuan Earthquake

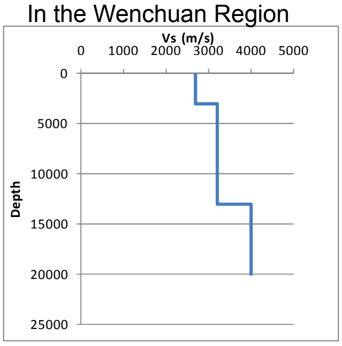


Simulation of Strong Ground Motions Using Hybrid Green's Function Method

Long Periods (> 1 sec):
Numerical Green's Functions by the Discrete Wavenumber Method by Bouchon (1981)

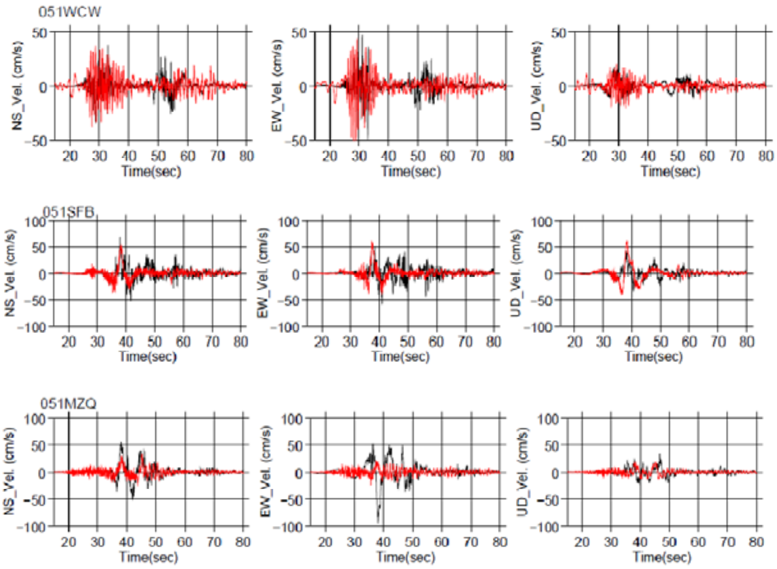
Short Periods (< 1sec):
Empirical Green's Finctions using Small Earthquake Records

Velocity Structure Model In the Wenchuan Region



Lou Hai et al. (2008)

Comparison between the observed (black) and synthesized (red) velocity motions at WCW, SFB, and MZQ near the source fault using the Hybrid method.



Summary

1. 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.
2. Ground motions from recent disastrous inland-earthquakes such as e.g. the 2005 Fukuoka-ken Seiho-oki earthquake (Mw 6.6), are well simulated with the characterized source models based on the recipe, as long as the source fault are specified by geo-morphological and geological surveys.
3. Prediction errors by the recipe are within 50 % at ground motion level.
4. Ground motions from the 2008 Great Wenchuan earthquake (Mw 7.9) are well simulated using the characterized source model with three asperities for the south-eastern segment of the earthquake fault.

Acknowledgements

- This study was partly based on discussions in the committee and sub-committees of the Strong Motion Evaluating Committee of the Headquarters for Earthquake Research Promotion in Japan.
- This study was also made in the seismic safety of nuclear power plants performed by Nuclear Safety Commission, Japan.
- Database of slip distribution of source processes obtained from waveform inversion complied by Dr. Mai (SRCMOD) was used for this study. Also some data were obtained via personal communication.
- Strong motion data was provided by the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan.

The Abdus Salam International Centre for Theoretical Physics (*ICTP*)
27 September - 9 October , 2010

Achievements of strong motion seismology and its future directions -Chapter 5-

Application to Design Basis Ground Motion for Seismic Safety of Nuclear Power Plant

- Lessons Learned from the 2007 Niigataken Chuetsu Oki Earthquake-

THE NIIGATAKEN-CHUETSU OKI EARTHQUAKE

MAIN SHOCK:

- **Magnitude: 6.8 M_{JMA} (6.6 Moment Magnitude)**
- **Epicentre: N37.5 , E138.6**
- **Time: 16 July 2007, 10:13(JST), i.e. 10:13 in the morning**
  National Holiday in Japan, 120 staff in plant (1000).
- **Depth: 17 km**
- **Distance to KK NPP:**
  - **Epicentre: 16 km**
  - **Hypocentre: 23 km**

IAEA

Effects on the region

IAEA

KK NPP - Main Data

Total output

8,212 MW

Biggest NPP in the world

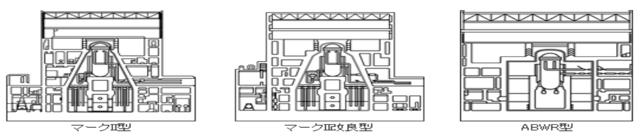
BWR : 5 units

ABWR : 2 units

設備の概要 | 沿　革 | アクセス | 資料画像

柏崎刈羽原子力発電所　設備の概要

			1号機	2号機	3号機	4号機	5号機	6号機	7号機
プラント主要諸元	電気出力(万kW)		110.0	110.0	110.0	110.0	110.0	135.6	135.6
	建設着工		1978/12	1983/10	1987/7	1988/2	1983/10	1991/9	1992/2
	営業運転開始		1985/9	1990/9	1993/8	1994/8	1990/4	1996/11	1997/7
	原子炉形式		沸騰水型軽水炉(BWR)						
	格納容器形式		マークII	マークII改良				鉄筋コンクリート製(ABWR)	
	国産化率(%)		99					89	
	主契約者		東芝			日立		東芝 日立 GE	日立 東芝 GE
原子炉	熱出力(万kW)		329.3					392.6	
	燃料集合体数(体)		764					872	
	燃料集合体全長(m)		約4.47						
	制御棒本数(本)		185					205	
	圧力容器	内径(m)	6.4					7.1	
		全高(m)	23					21	
		全重量(t)	750					910	
	格納容器	全高(m)	約48					約36	
		直径(m)	26	29					
		圧力抑制室プール水量(t)	3,300	4,000				3,600	
タービン	回転数(rpm)		1,500						
	入口蒸気温度(℃)		282					284	
	蒸気圧力(kg/cm2g)		66.8					68.2	
燃料	種類		二酸化ウラン						
	ウラン装荷量(t)		132					150	
	燃料集合体(本)		764					872	



※各型のイラストの大きさの比率は一致していません。

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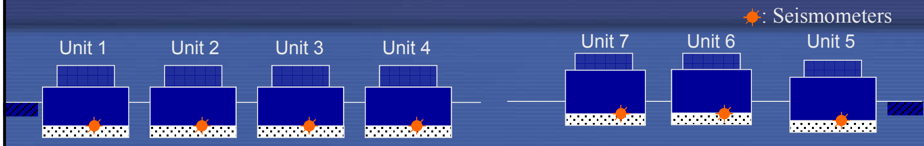
Observation Records on R/B base mat



Gal:cm/s/s

Observation point				Observed Maximun Acc.			Design value	
				NS	EW	UD	NS	EW
Unit1	R/B	1-R2	B5F(Base Mat)	311	680	408	274	273
Unit2	R/B	2-R2	B5F(Base Mat)	304	606	282	167	167
Unit3	R/B	3-R2	B5F(Base Mat)	308	384	311	192	193
Unit4	R/B	4-R2	B5F(Base Mat)	310	492	337	193	194
Unit5	R/B	5-R2	B5F(Base Mat)	277	442	205	249	254
Unit6	R/B	6-R2	B5F(Base Mat)	271	322	488	263	263
Unit7	R/B	7-R2	B5F(Base Mat)	267	356	355	263	263

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3.2.5 Main damage and restoration state in Unit1 to 6

Example of No or Minor Damage in the Building

■No Damage in Safety Related Facilities

Inside view of unit 6's equipment
(around steam piping)

Inside view of unit 6's equipment
(around main steam isolation valves)

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3.2.6 Main damage in the yard

■Road Damages

Road damage near water discharge

Road damage near switch yard

■Other Damages

Crane rail near water discharge

Inside of low level radioactive waste storage

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3.2.6 Main damage in the yard

■Office Damages

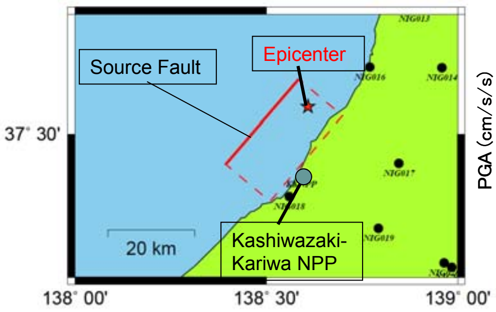
Inside of the office

Emergency response center
(at that time)

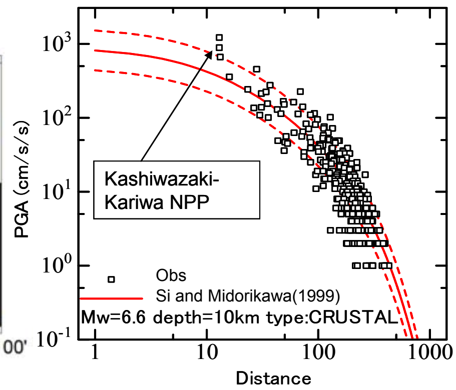
TOKYO ELECTRIC POWER COMPANY

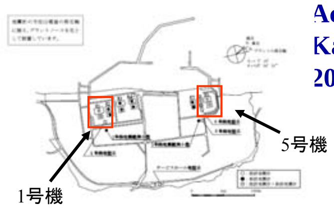
Strong ground motions from the 2007 Chuetsu-oki earthquake

Source Model for Calculation
(Horikawa, 2007)



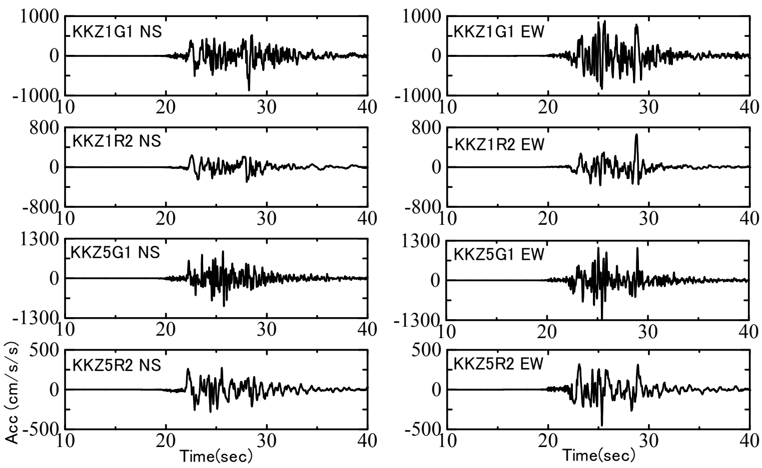
Attenuation Distance Relation of PGA





Acceleration Ground Motions recorded at the Kashiwazaki-Kariwa Nuclear Power Station from the 2007 Chuetsu-oki Earthquake

KKZ1G1 : Surface Obs. P. of Unit 1 KKZ1R2 : Base Mat Obs. P. of Unit 1
KKZ5G1 : Surface Obs. P. of Unit 5 KKZ5R2 : : Base Mat Obs. P. of Unit 5

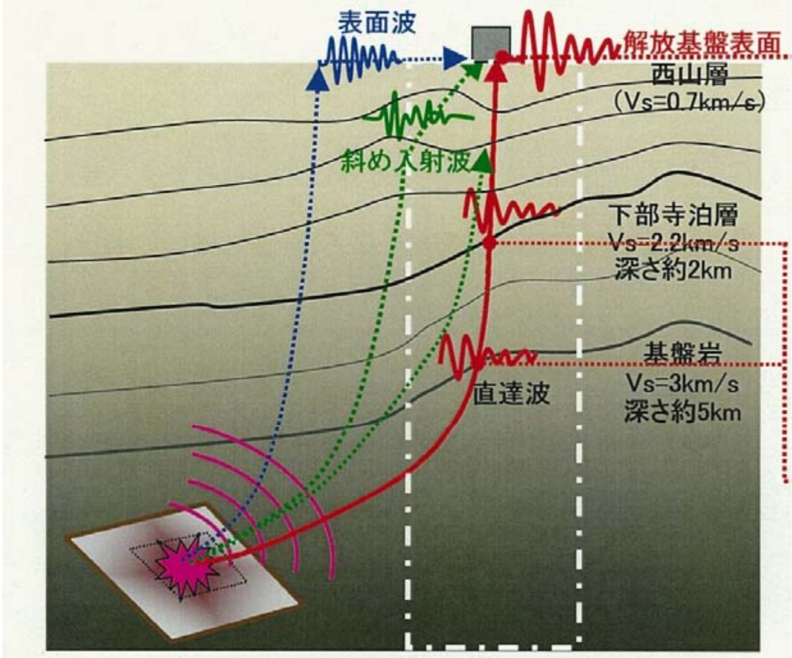


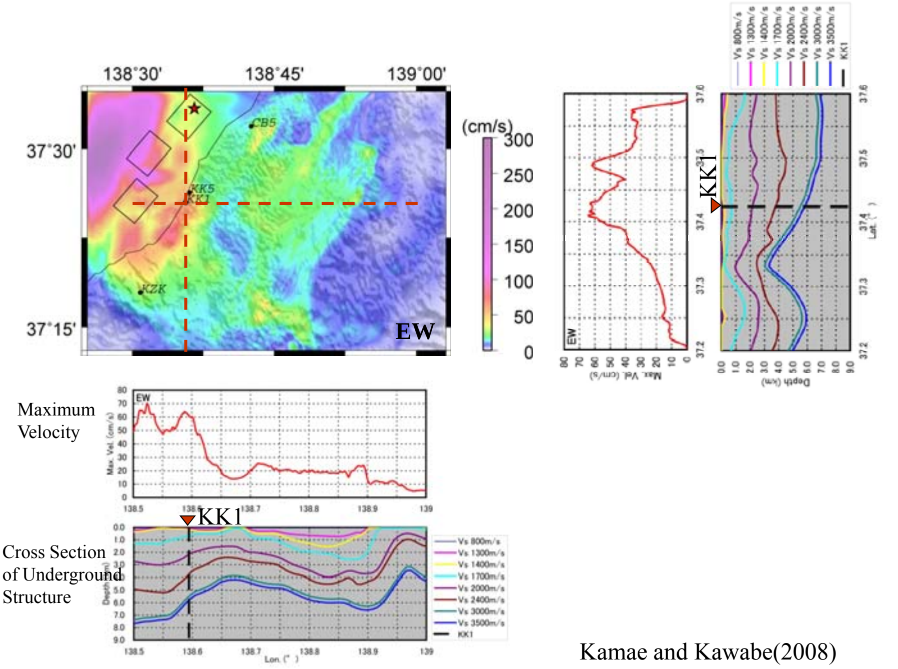
Why were so large ground motions recordedat the Kashiwazaki-Kariwa station, especially at Unit 1 base mat ?

Possible causes

1. Source characteristics such as radiation pattern and directivity effects.
2. Propagation-path effects such as focusing, basin-induced surface waves and so on.
3. Amplification by soft layers near surface.

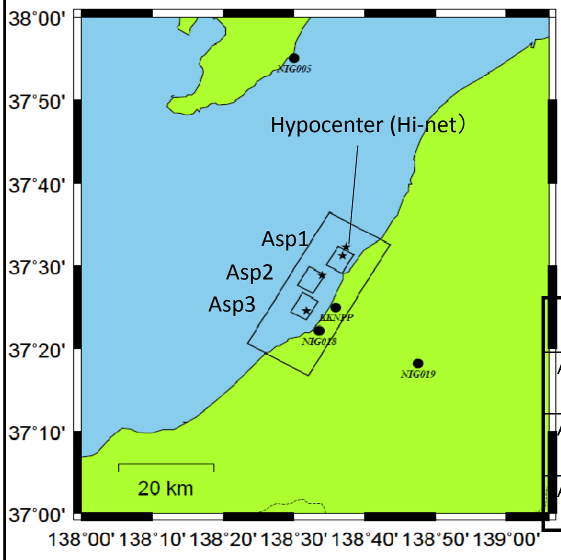
柏崎刈羽原発周辺地域で大きくなった一因(フォーカッシング効果）





Kamae and Kawabe(2008)

SOURCE MODEL OF THE 2007 CHUETSU-OKI EARTHQUAKE



Best-fit source model with three asperities (ASP1, ASP2 AND ASP3) is estimated from comparison between observed and simulated motions using the Empirical Green's Function Method.

	L (km) × W (km)	⊿σ (MPa)	Mo (Nm)
ASP 1	5.5 × 5.5	23.7	1.69×10^{18}
ASP 2	5.5 × 5.5	23.7	1.69×10^{18}
ASP 3	5.04 × 5.04	19.8	1.02×10^{18}

- Strike：30°，Dip Angle：40°

Star mark on each asperity shows rupture starting point in the asperity.

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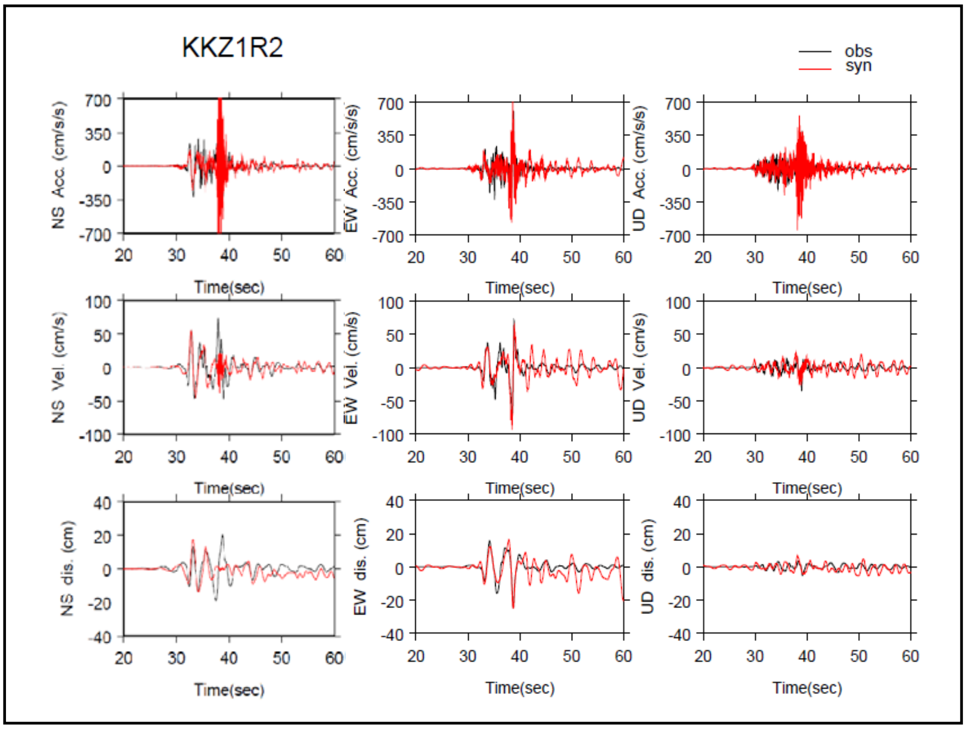
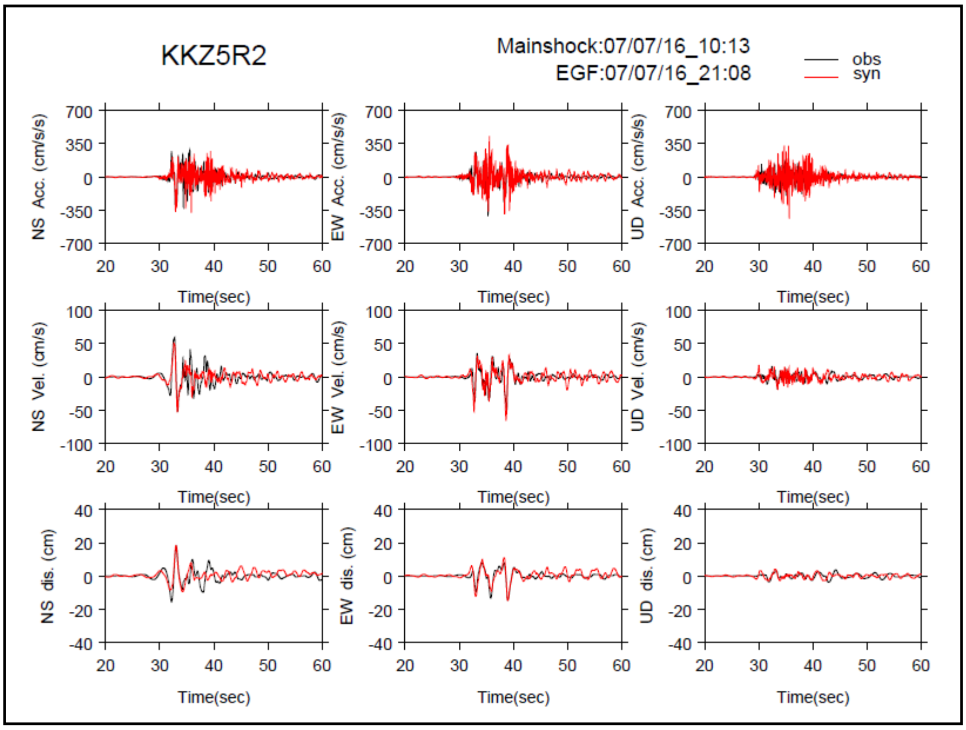
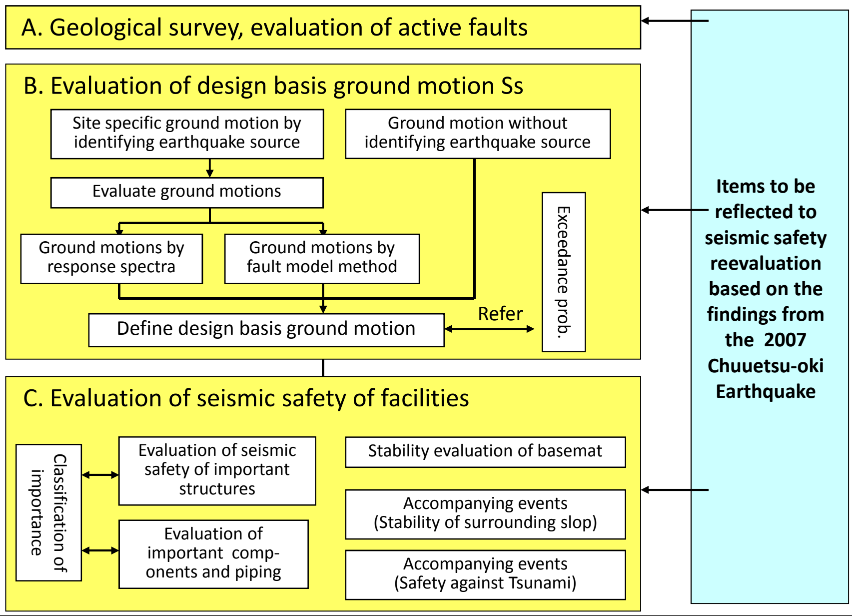

KKZ1R2
obs
syn
NS Acc. (cm/s/s)
EW Acc. (cm/s/s)
UD Acc. (cm/s/s)
NS Vel. (cm/s)
EW Vel. (cm/s)
UD Vel. (cm/s)
NS dis. (cm)
EW dis. (cm)
UD dis. (cm)
Time(sec)


KKZ5R2
Mainshock:07/07/16_10:13
EGF:07/07/16_21:08
obs
syn
NS Acc. (cm/s/s)
EW Acc. (cm/s/s)
UD Acc. (cm/s/s)
NS Vel. (cm/s)
EW Vel. (cm/s)
UD Vel. (cm/s)
NS dis. (cm)
EW dis. (cm)
UD dis. (cm)
Time(sec)

Flow of Seismic Reevaluation According to New Seismic Regulatory Guide



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New Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities (September, 2006)

“Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities in Japan was first made in 1981 by Nuclear Energy Commission in Japan.

The “Regulatory Guide” was revised their on 19 September in 2006 by Nuclear Safety Commission in Japan,

to reflect progresses of seismology, earthquake engineering, and related fields of science and technology after the 1995 Kobe earthquake.

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.

Points of New Regulatory Guide

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 nor be identified.

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

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

5. Request to minimize the residual risk.

ACTIVE FAULTS AND FOLDS

4. Sado-shima-eastern-boundary Flexure • • approx. 37km

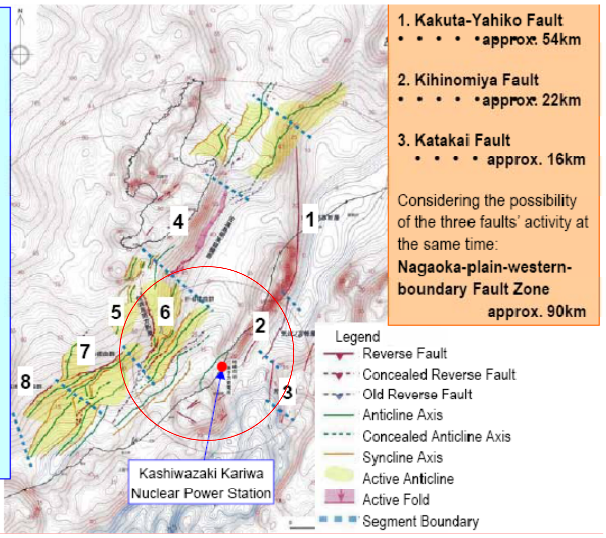
5. Sado-shima-southern Fault • • • • • • approx. 29km

6. F-B Folds Band approx. 34km

7. F-D Folds Band approx. 30km

8. Takada-oki Fold Band • • • • • • approx. 25km

Considering the possibility of the these faults' activity at the same time:
Takada-oki & F-D Folds Bands • • • • • approx. 55km• •



1. Kakuta-Yahiko Fault • • • • •approx. 54km

2. Kihinomiya Fault • • • • •approx. 22km

3. Katakai Fault • • • • approx. 16km

Considering the possibility of the three faults' activity at the same time:
Nagaoka-plain-western-boundary Fault Zone approx. 90km

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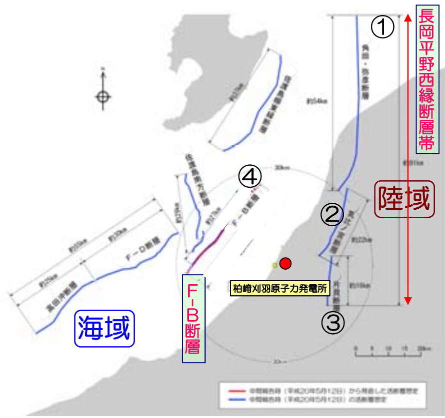
Selected Active Faults and Folds Inland and Offshore



検討用地震として選定した活断層

	断層名	断層長さ	考慮すべき断層長さ
陸域	①角田・弥彦断層	54km	3つの断層の連動を想定した、長岡平野西縁断層帯　９１ｋｍ
	②気比ノ宮断層	22km	
	③片貝断層	16km	

	断層名	断層長さ	考慮すべき断層長さ
海域	④F－B断層	36km	36km

長岡平野西縁断層帯、F－B断層をもとに基準地震動を評価

基準地震動の最大加速度　（単位：ガル）

	1～4号機	5～7号機
基準地震動Ss	2300	1209
旧指針に基づく基準地震動S2	450	

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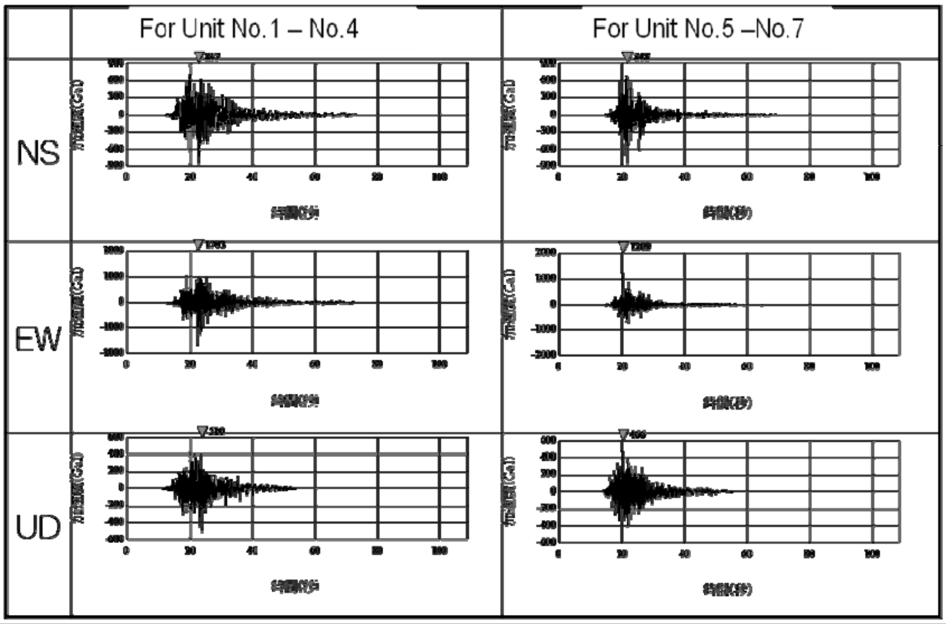
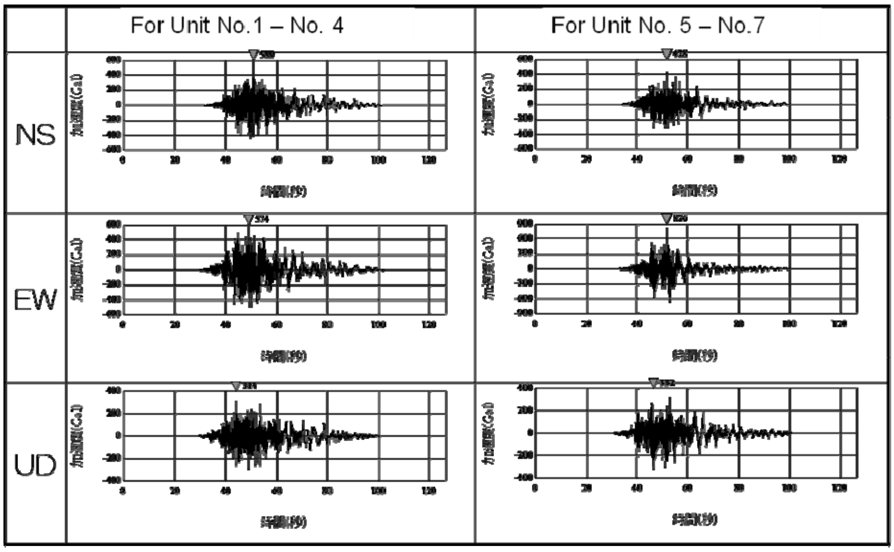
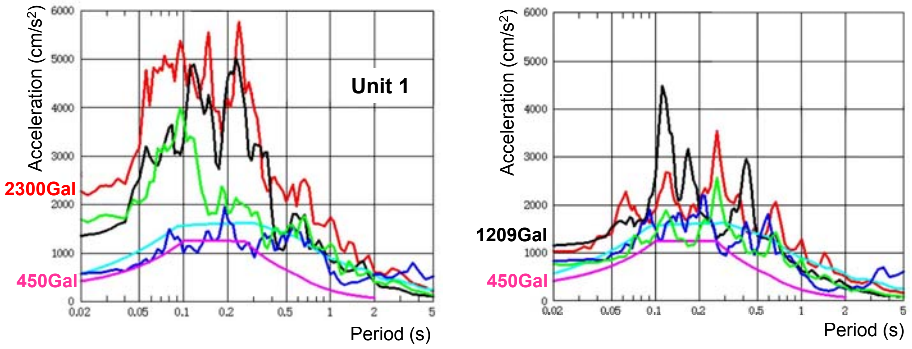
Acceleration Time Histories from the F-B Folds Band Earthquake



Acceleration Time Histories from the Nagaoka-Plane-Western- Rim Fault Zone Earthquake



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

Revised New Seismic Hazard at the K-K NPP Site

- The following faults were taken into consideration upon determining the design-basis seismic motion.

Active fault		Length of fault	Scale of earthquake [*1]		Angle of inclination [*2]	Notes
F-B fault		About 34km[*3] (About 27km)	34km	M7.0	Southeastern inclination 35•	As a conservative approach, the total length of the fault was identified as about 34km.
Nagaoka Plain Western Boundary Fault Zone	Kakuda-Yahiko fault	About 54km	91km	M8.1	Western inclination 50•	As a conservative approach, these faults were assumed to move together.
	Kihinomiya fault	About 22km				
	Katagai fault	About 16km				
F-D fault • •		About 30km	55km	M7.7	Southeastern inclination 35•	As a conservative approach, these faults were assumed to move together.
Takada-oki fault		About 25km				

Note 1: With regard to the F-B fault, the scale of magnitude was determined by the scale of the assumed fault surface
• between the magnitude and the size of the fault surface at the hypocenter of the Niigata-Chuetsu-Oki earthquake.
• • • magnitude was determined by the length of ground surface faults using the formula of Matsuda (1975).
Note 2: Angle of inclination: the inclination of fault surface against the horizontal surface.
Note 3: The length of the fault, according to our survey, is 27km, but taking a conservative approach, it is assumed to

This assessment was slightly revised later

Seismic motion	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7
Niigataken Chuetsu-oki Earthquake (observed on the foundation of reactor building)	680	606	384	492	442	322	356
Response to the design basis seismic motion Ss (on the foundation of reactor building)	829	739	663	699	543	656	642
The peak value of the design basis seismic motion Ss (on the free surface of base stratum)	2,280				1,156		

The value represents the larger value among horizontal ones (south-north and east-west). (Unit: Gal)

Summary and Future Directions

1. 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.

2. Design ground motions for seismic safety are possibly evaluated as long as fault modeling is appropriately made.

3. Methodology for estimating design ground motions without specifying earthquake sources should be further improved as one of the lessons learned from the NCO earthquake.

Acknowledgements

- 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.
- Strong motion data in Kik-net and K-NET was provided by the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan.
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- The pictures of damaged and non-damaged facilities during the NCO earthquake were kindly provided by Dr. Atsushi Taniguchi, TEPCO.