Seismic Hazard and Performance for Operating NPPs in Taiwan

Yuan-Chieh Wu

September 24, 2013

ENSREG Review Meeting

Outline

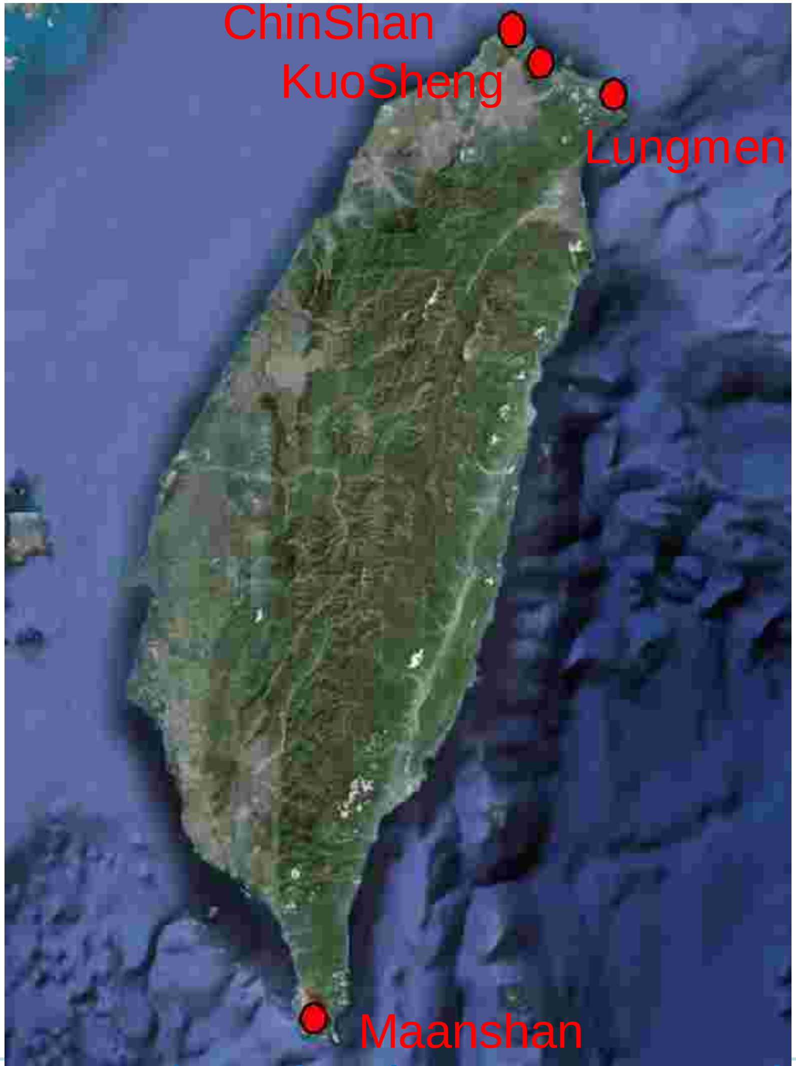
- **Seismicity, Geologic Characteristic and Tectonic Framework**
- **Geo-Science Data Updated and Source Characterization for Seismic Hazard Analysis**
- **Preliminary Probabilistic Seismic Hazard Analysis Result**
- **Seismic Performance and Strategy for Reducing Risk**
- **Conclusion**

Nuclear Power Plants in Taiwan

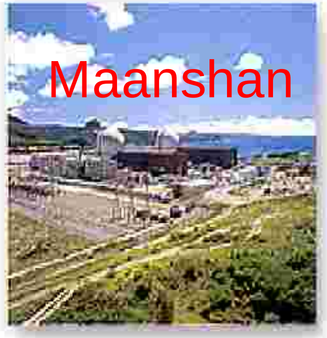
Chinshan

Reactor: BWR-4
Capacity: 636MW › 2
Commercial start
Unit 1: Dec. 1978
Unit 2: July 1979

Reactor: BWR-6
Capacity: 985MW › 2
Commercial start
Unit 1: Dec. 1981
Unit 2: Mar. 1983



Reactor: ABWR
Capacity: 1350MW › 2



Reactor: PWR
Capacity: 951MW › 2
Commercial start
Unit 1: July 1984
Unit 2: May 1985

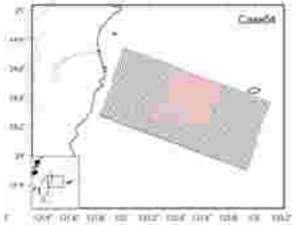
Nuclear Seismic Hazard Technique Development in Taiwan

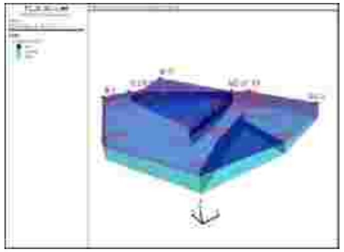
- To achieve worldwide new nuclear standard, INER upgrade domestic seismic abilities on geological investigation and Seismic Hazard Analysis in TaiPower's project and National Science Foundation's Project in recent years.

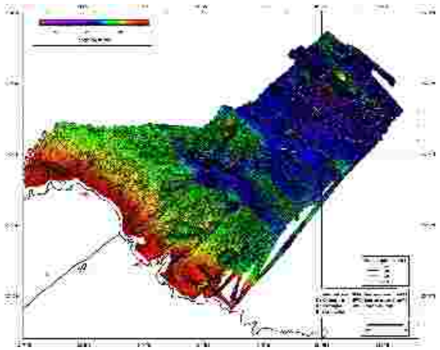
Spectral Attenuation Update → Probabilistic Seismic Hazard Analysis (PSHA)

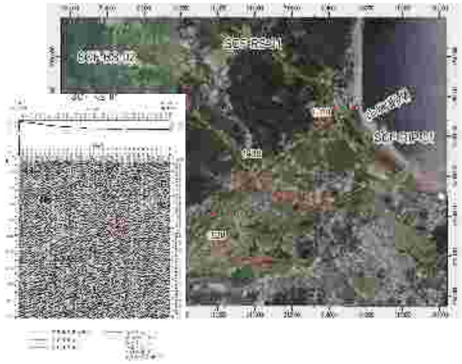
Geological Investigation → Seismic Source Characterization → Probabilistic Seismic Hazard Analysis (PSHA)

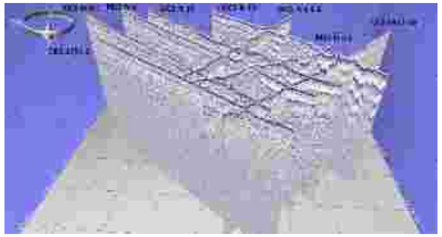
Probabilistic Seismic Hazard Analysis (PSHA) → Hazard Deaggregation → Site Response


Hybrid ground motion simulation


3D site response considering dipping bedrock


Offshore topography

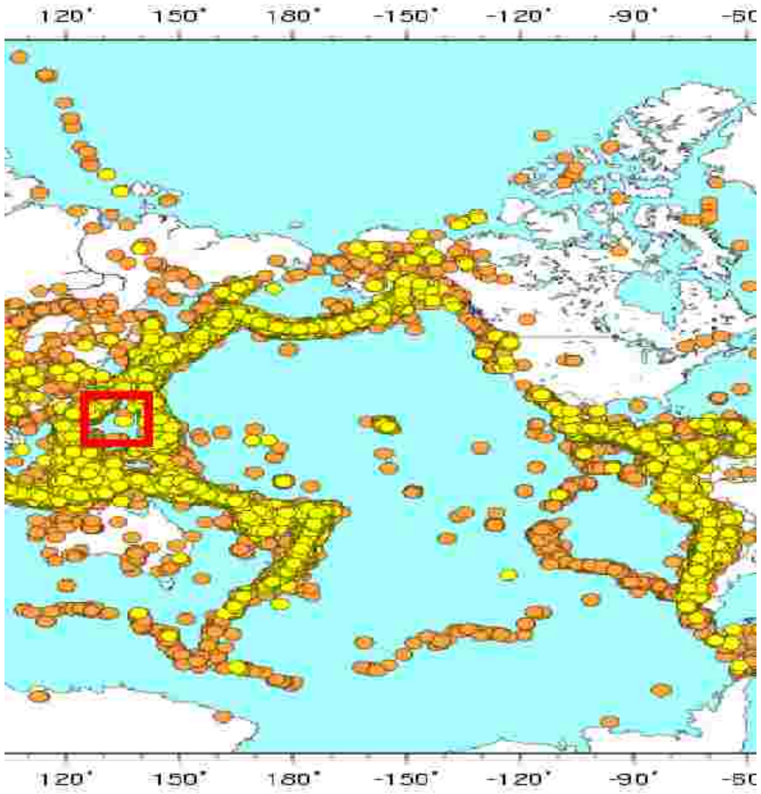

Onshore Seismic Reflection


Offshore Seismic Reflection

2010	2011	2012	2013	2014

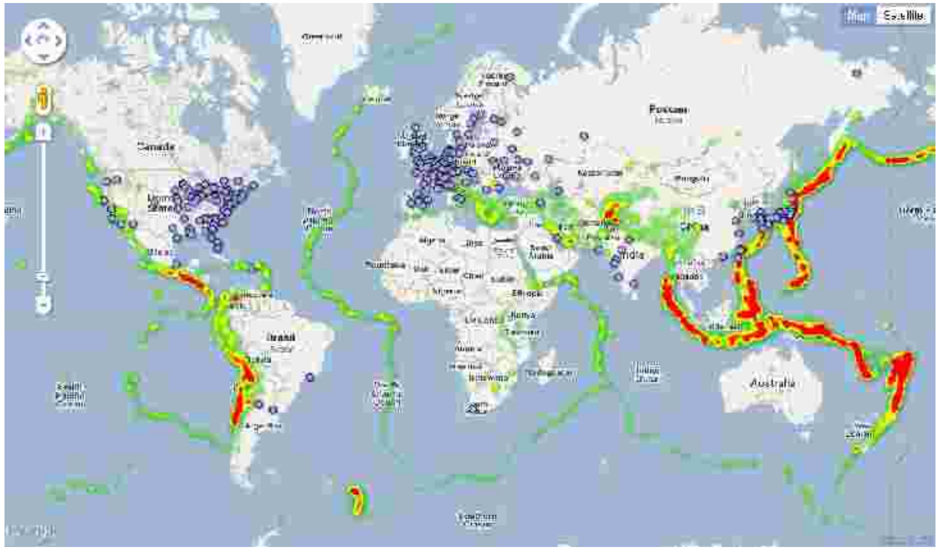
Planning | Geological Investigation | Level 2 PSHA | Extended Investigation, Level 2 PSHA Update | Level 3 PSHA (Proposed)

Global Seismicity and NPP Location



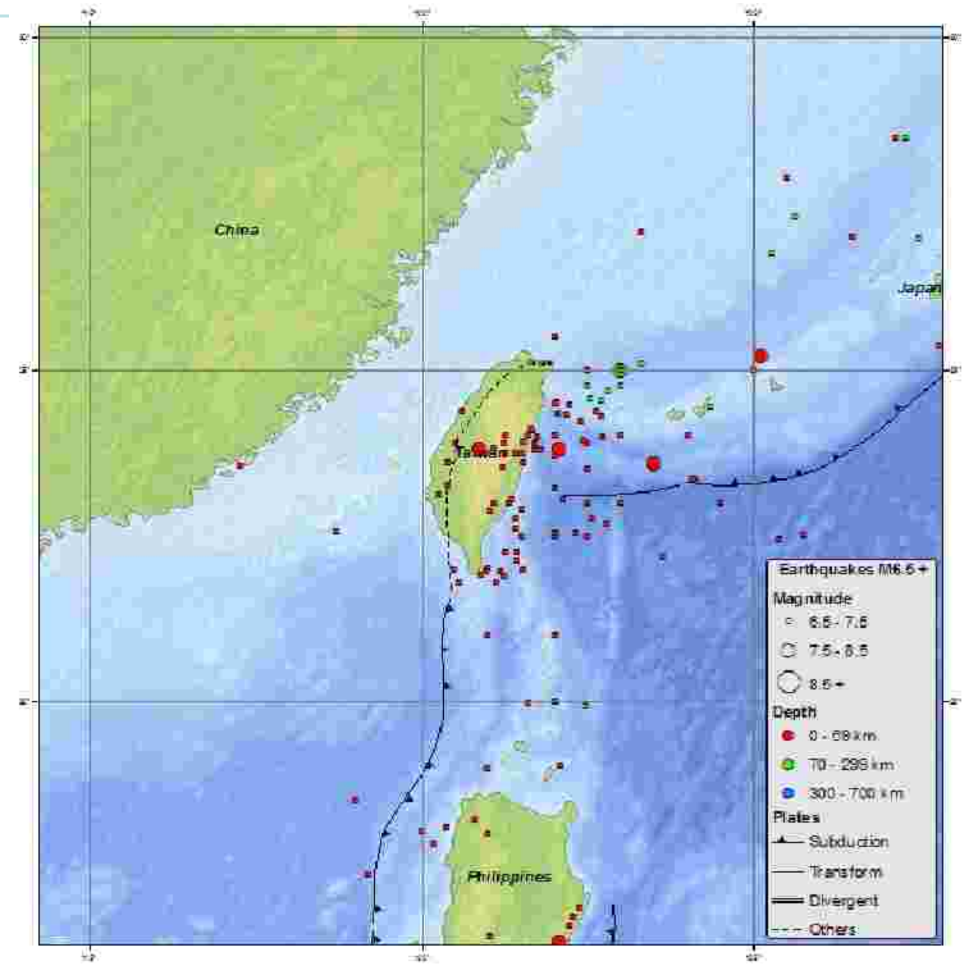
Source: USGS

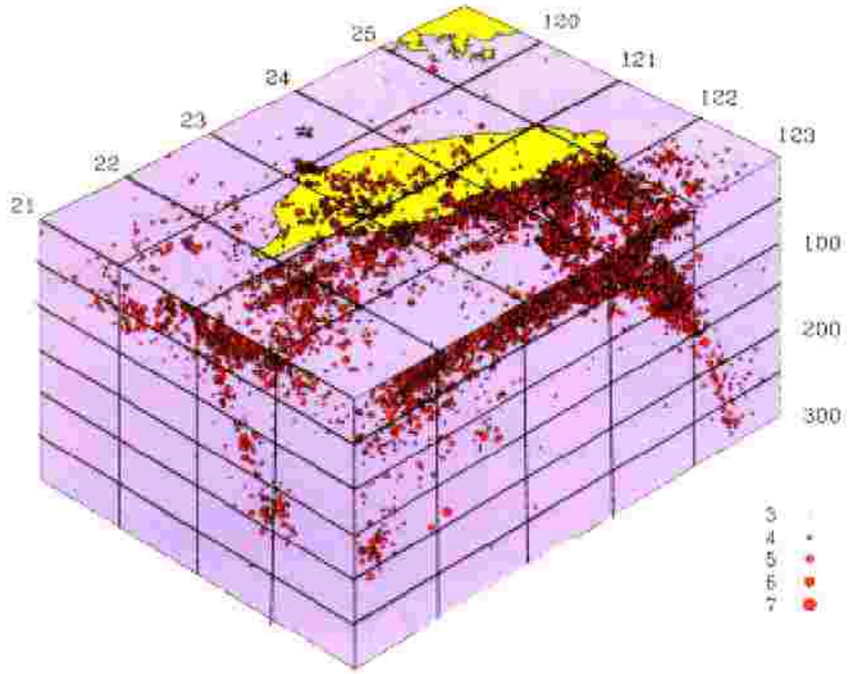
Each yellow (35-70 km deep) and orange (less than 35 km deep) dot represents an earthquake



•Worldwide map of nuclear power plants and earthquake
•4.5+ magnitude earthquake since to 1973 – around 174,000 in total
•The location of 248 NPPs
Source: mapdt.com

Three Dimensional Earthquake Data



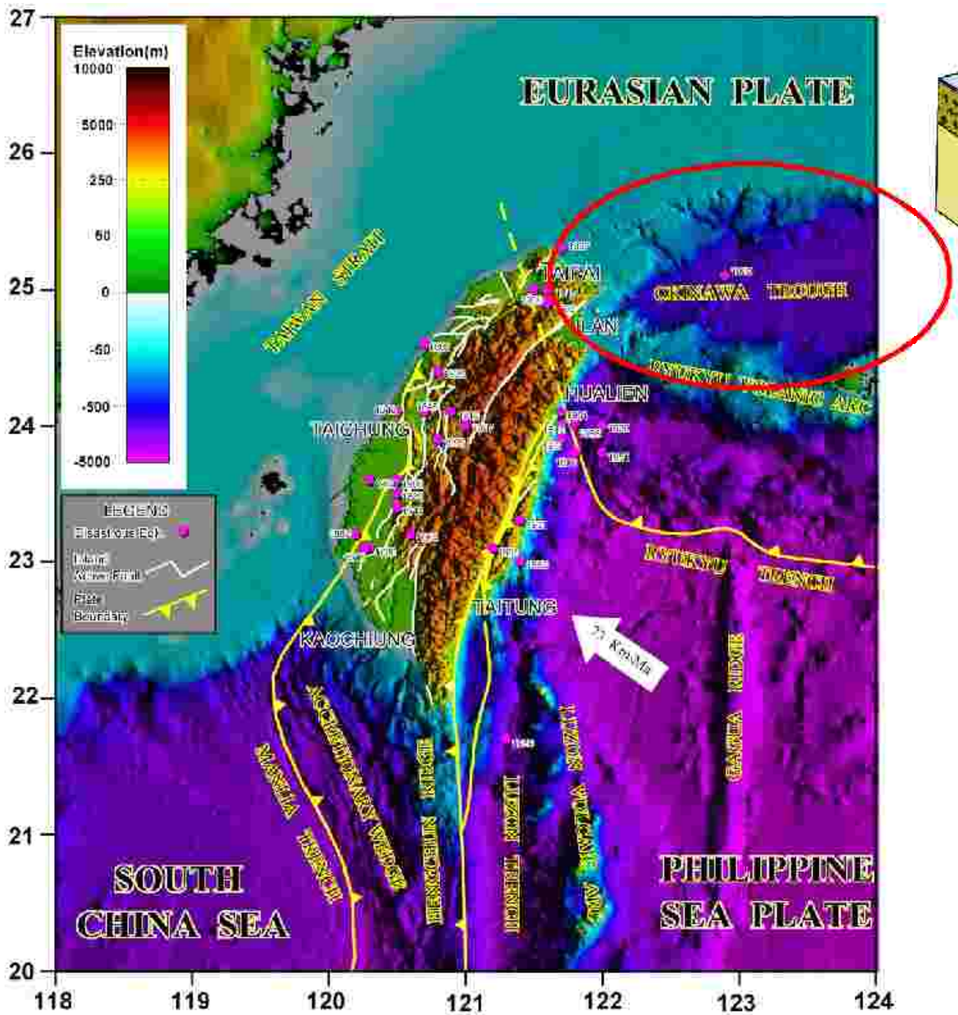


Source: cwb.gov.tw

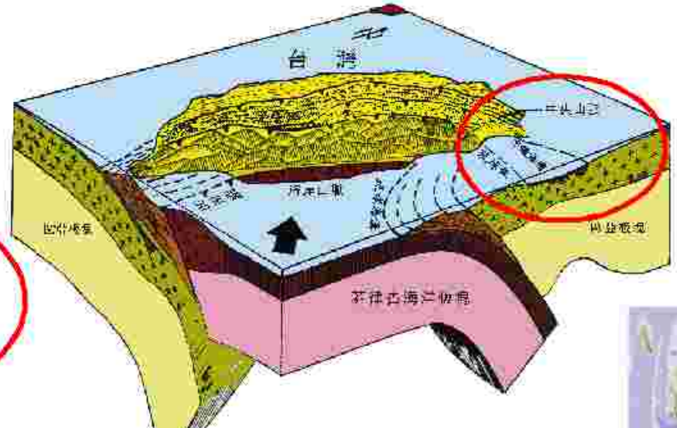
USGS Seismicity Map from 1900 to present

Misunderstanding come from ignoring three dimension source geometry

Tectonic Framework around Taiwan



Cheng (2010)



Back Arc

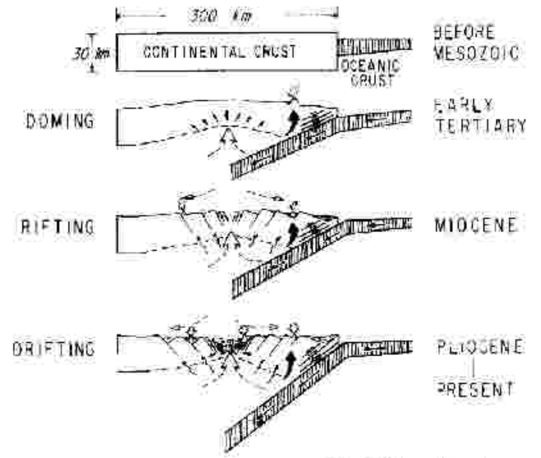
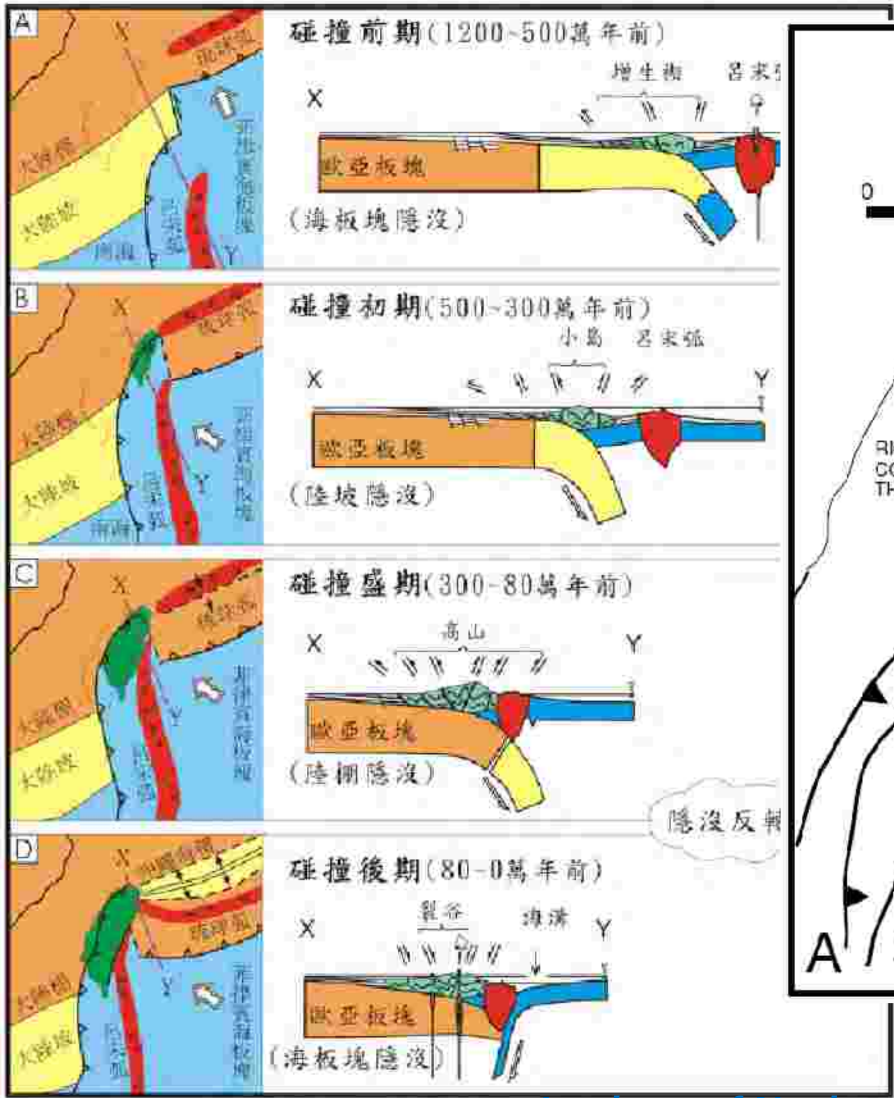


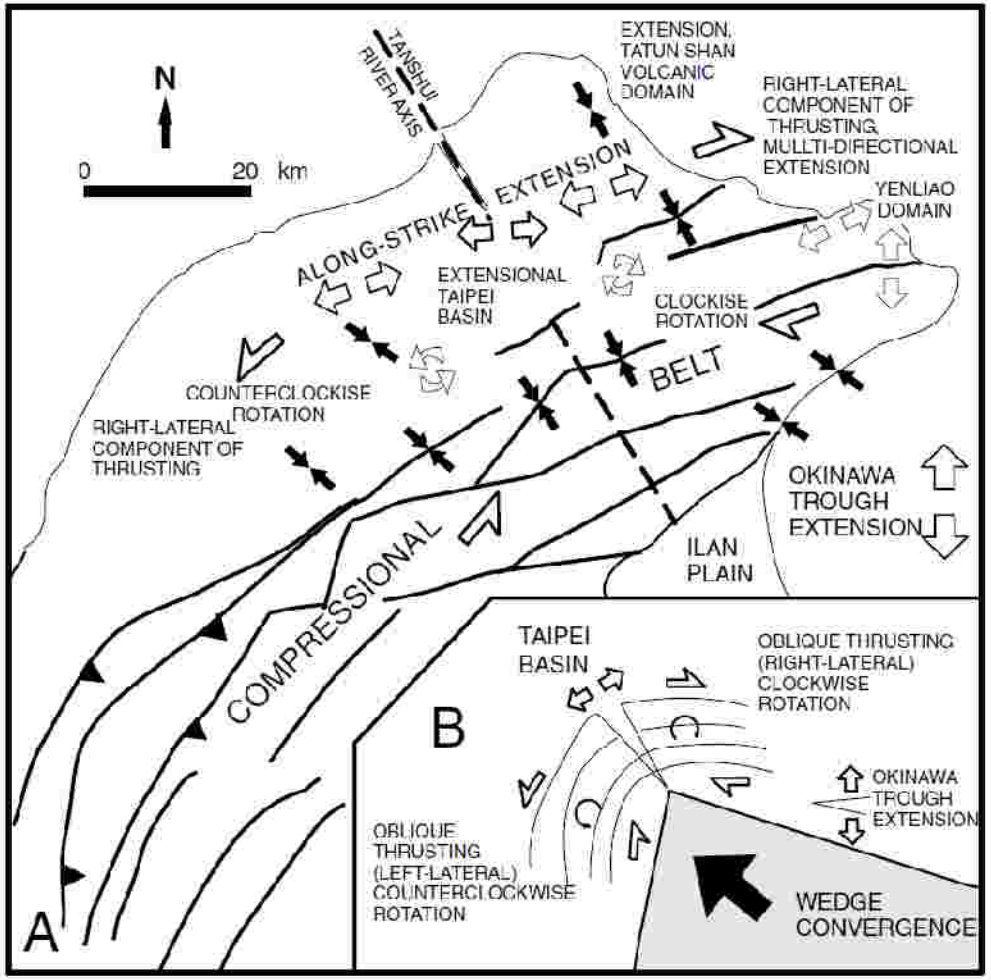
Fig.12. Cartoon of evolutionary stages of the Okinawa Trough.

Chao-Shing Lee, et al, (1980)

Seno (1977); Jean Letouzey, Masaaki Kimura (1985);

Extension Environment for Northern Taiwan

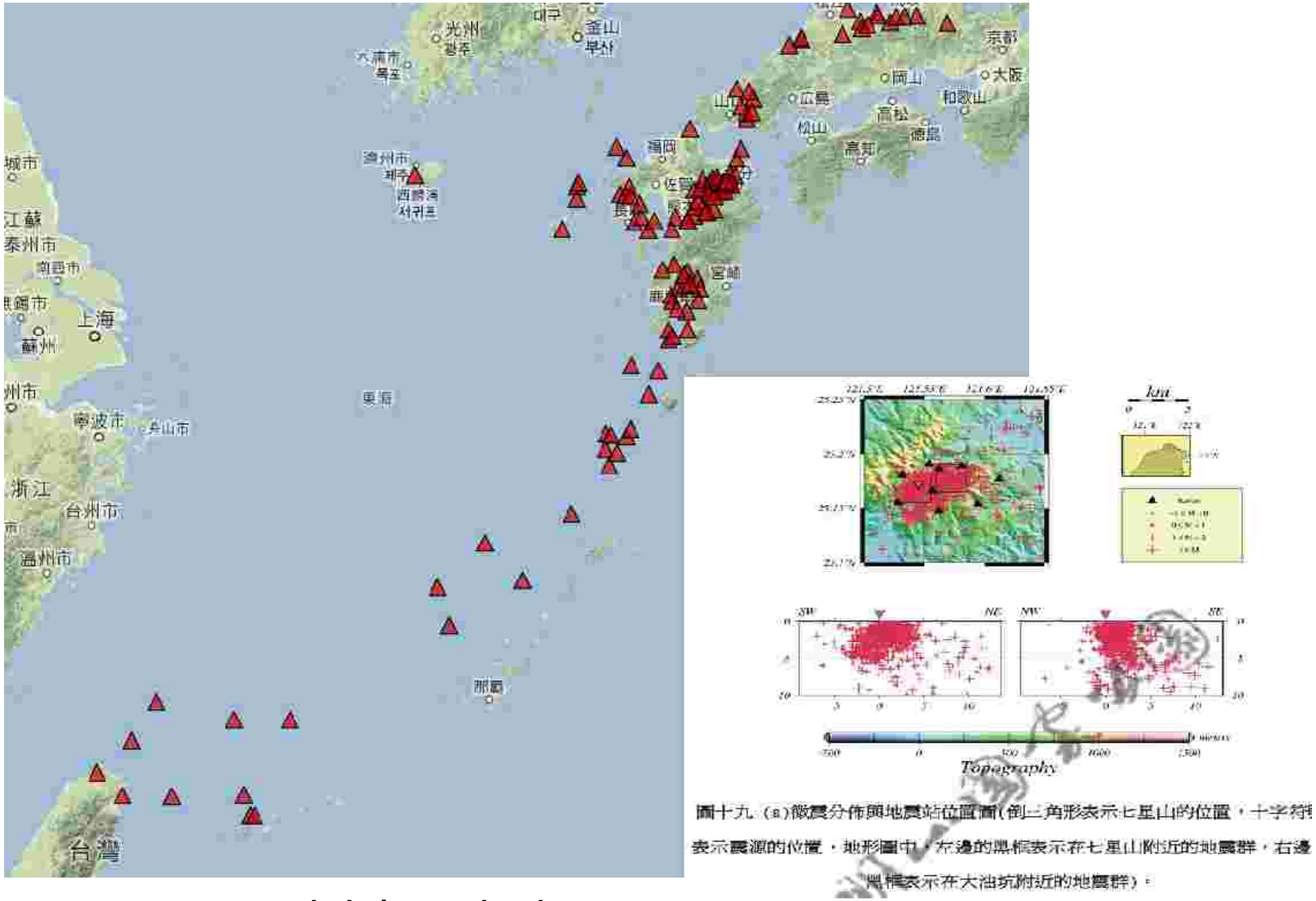




Teng, 2007

Jyr-Ching Hu, et al, 2002

Volcano Map

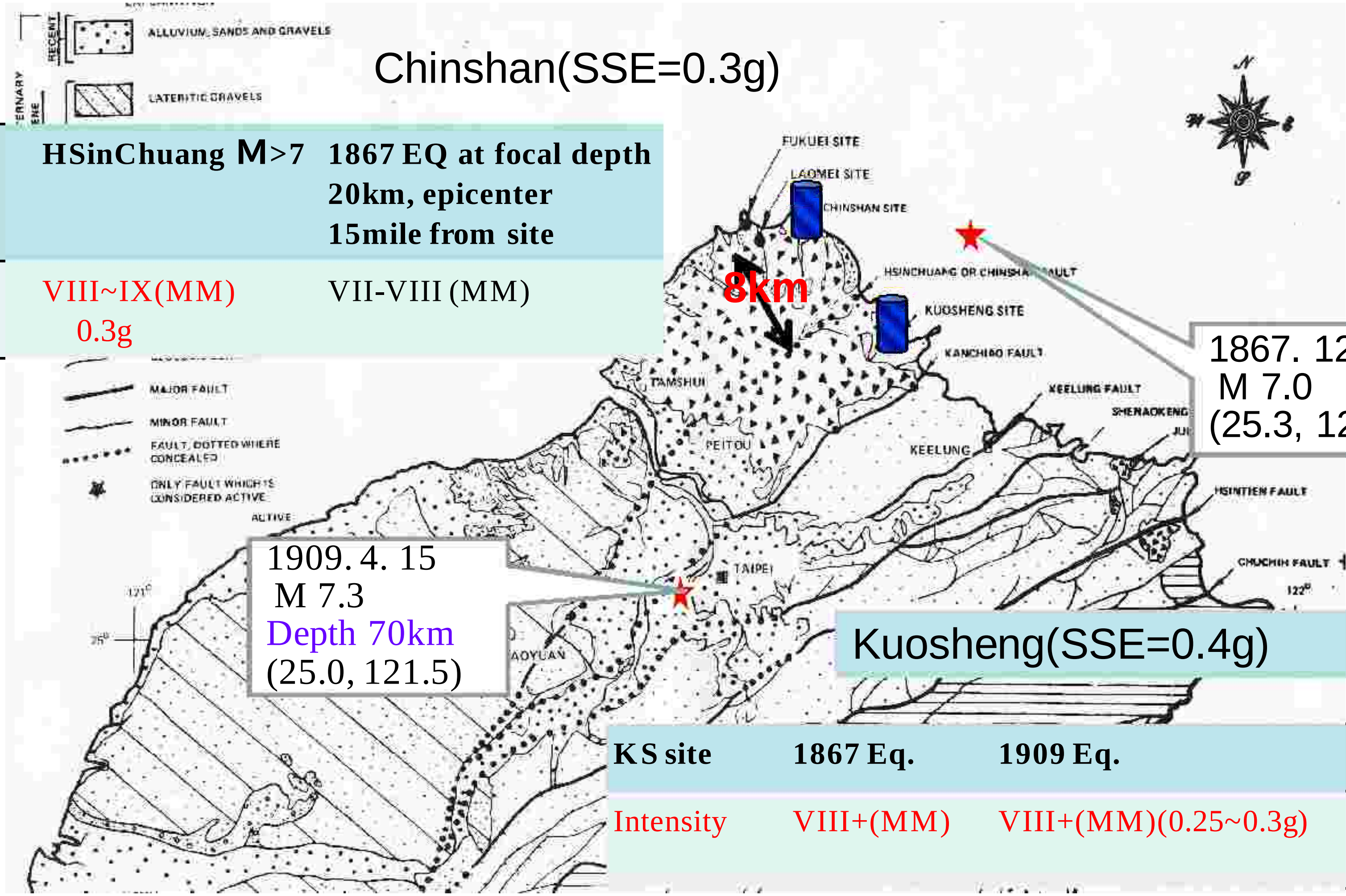


G-EVER (trial version)

Maximum Earthquake Potential Considered in NPP1 & NPP2 SSE

Chinshan(SSE=0.3g)

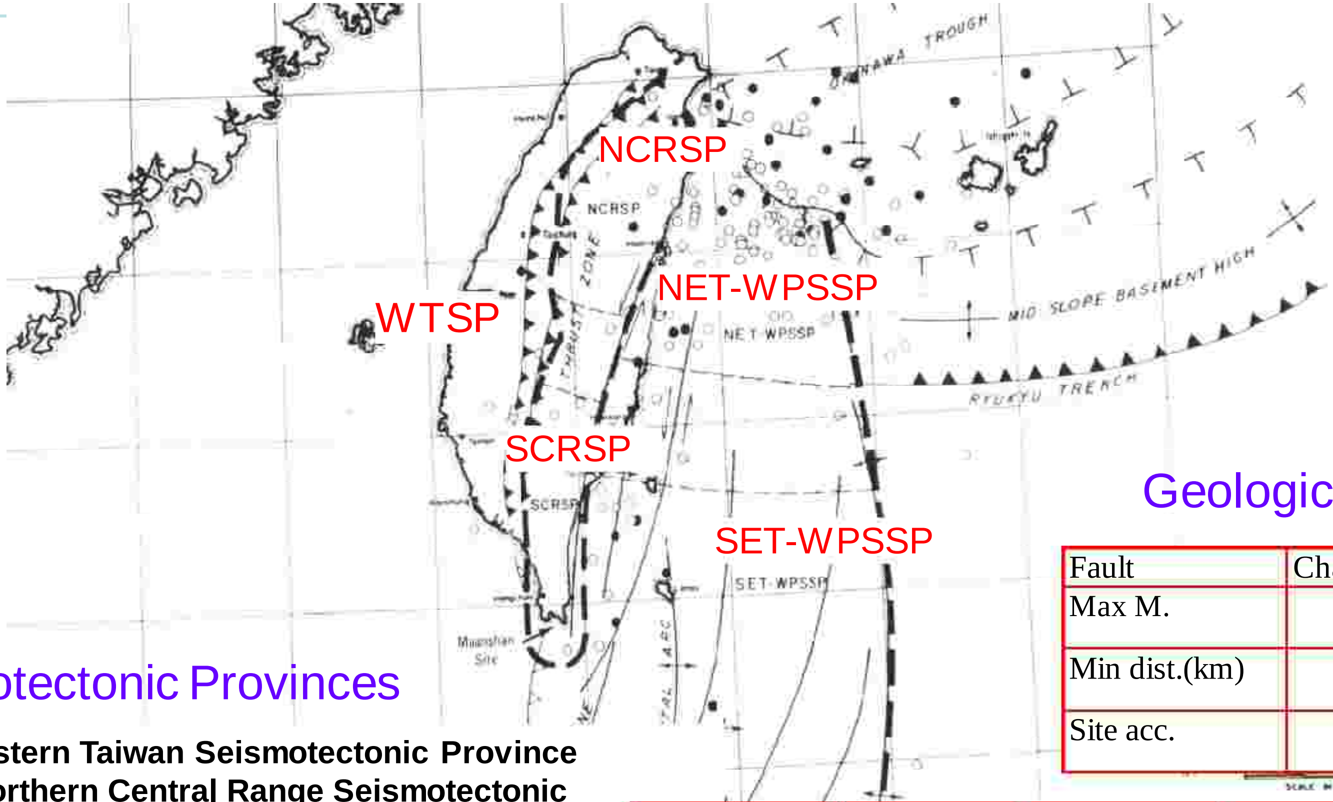
EQ.	HSinChuang M>7	1867 EQ at focal depth 20km, epicenter 15mile from site
Acc.	VIII~IX(MM) 0.3g	VII-VIII (MM)



Kuosheng(SSE=0.4g)

KS site	1867 Eq.	1909 Eq.
Intensity	VIII+(MM)	VIII+(MM)(0.25~0.3g)

Maximum Earthquake Potential Considered in NPP3 SSE



Geologic Structures

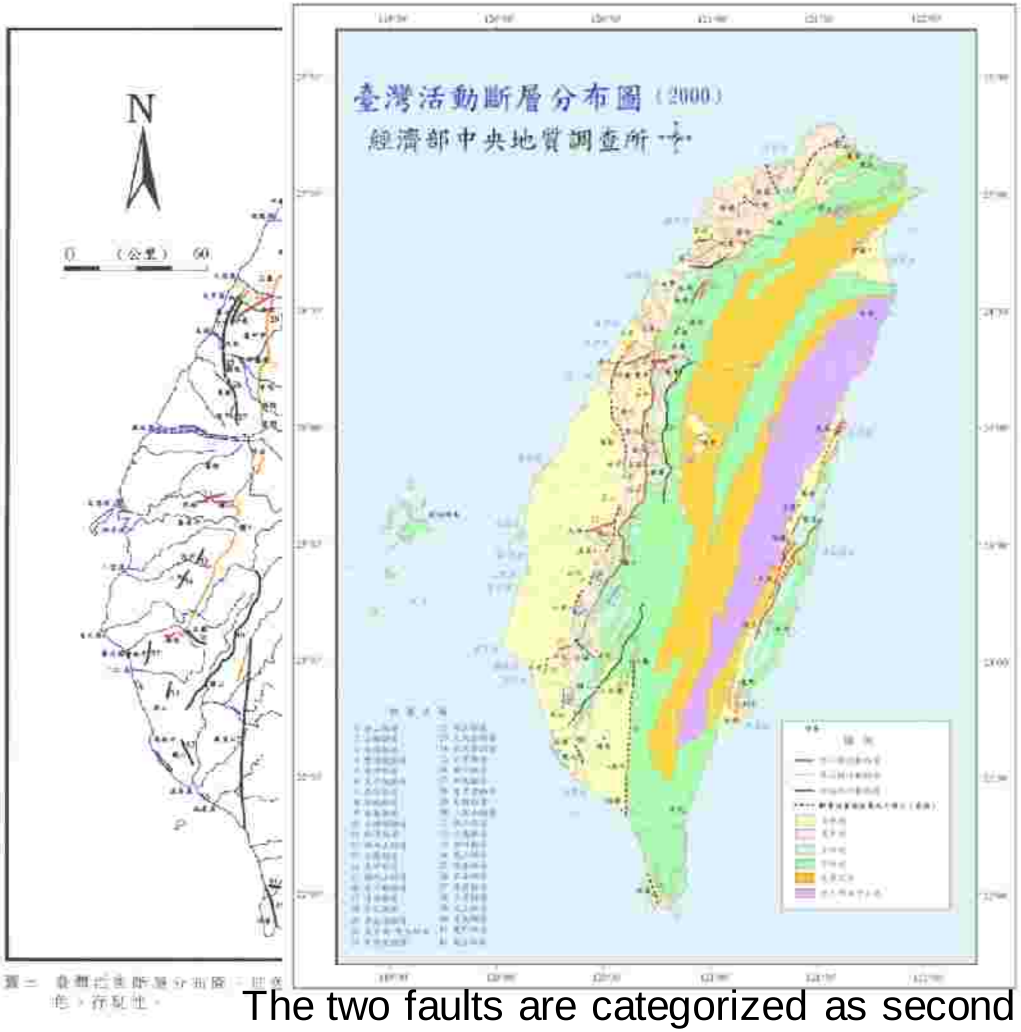
Fault	Chaochou	L.V fault
Max M.	7.1	7.3
Min dist.(km)	20	35
Site acc.	0.32g	0.39g

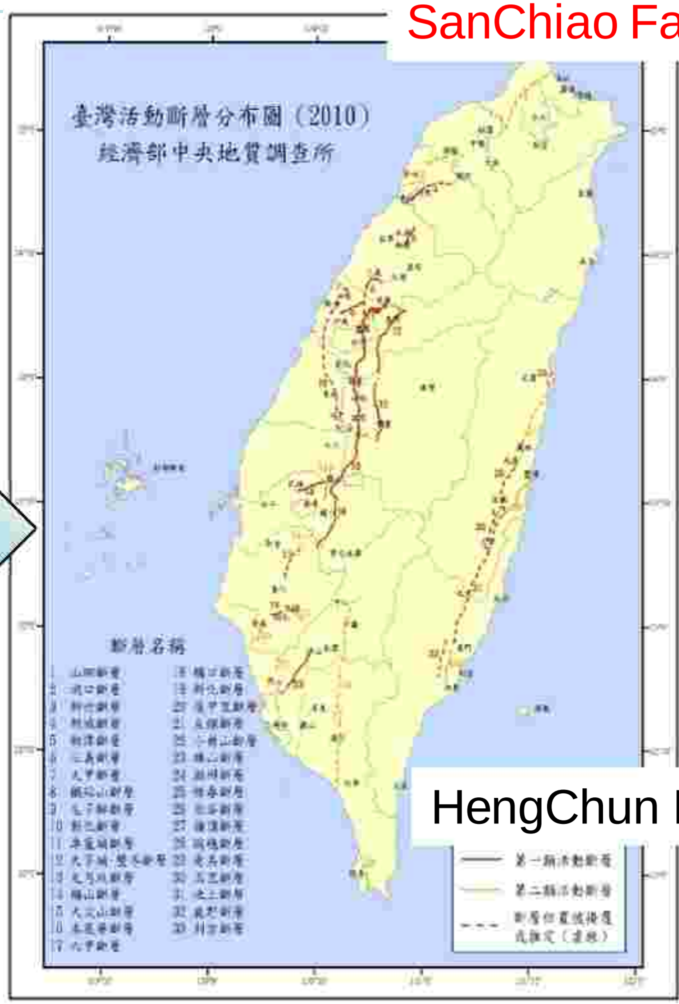
Seismotectonic Provinces

WTSP: Western Taiwan Seismotectonic Province
NCRSP: Northern Central Range Seismotectonic Province
SCRSP: Southern Central Range Seismotectonic Province
NET-WPSSP: Northern Eastern Taiwan-Western Philippine Sea Seismotectonic Province
SET-WPSSP: Southern Eastern Taiwan-Western Philippine Sea Seismotectonic Province

Province	SCRSP	WTSP	SET-WPSSP	1920 Haulien offshore
Max M.	5.4 (1972.11.7)	7.1 (MeiShan,1906)	7.5 (1959.8.15)	8.3
Min dist.(km)	site	20	20	90
Site acc.	0.1g	0.32g	0.39g	0.1g

Active Fault Map Updated by CGS

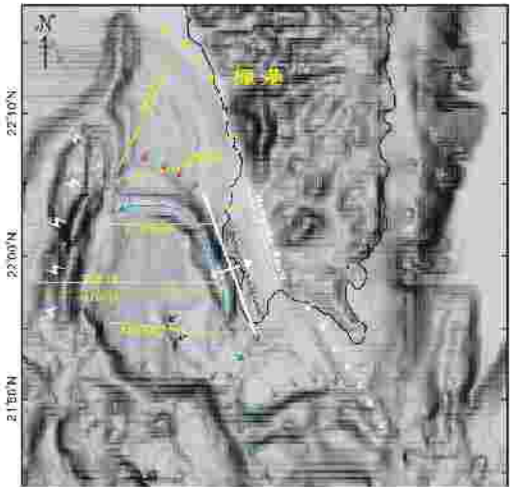


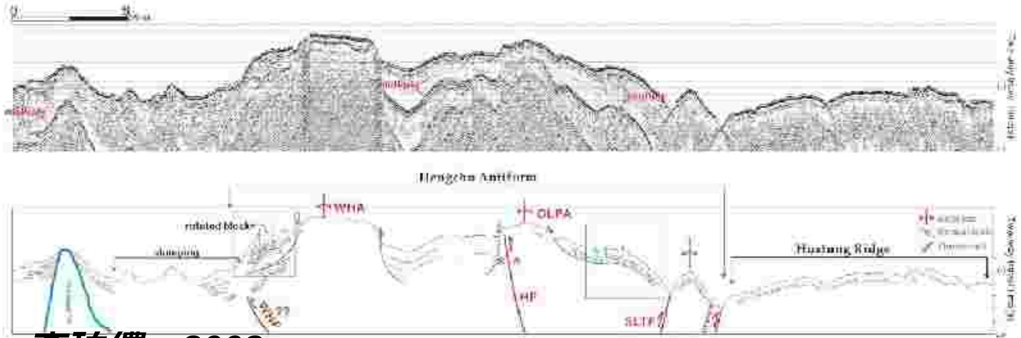


The two faults are categorized as second class fault whose latest movement occurred from 10,000 to 120,000 years ago.

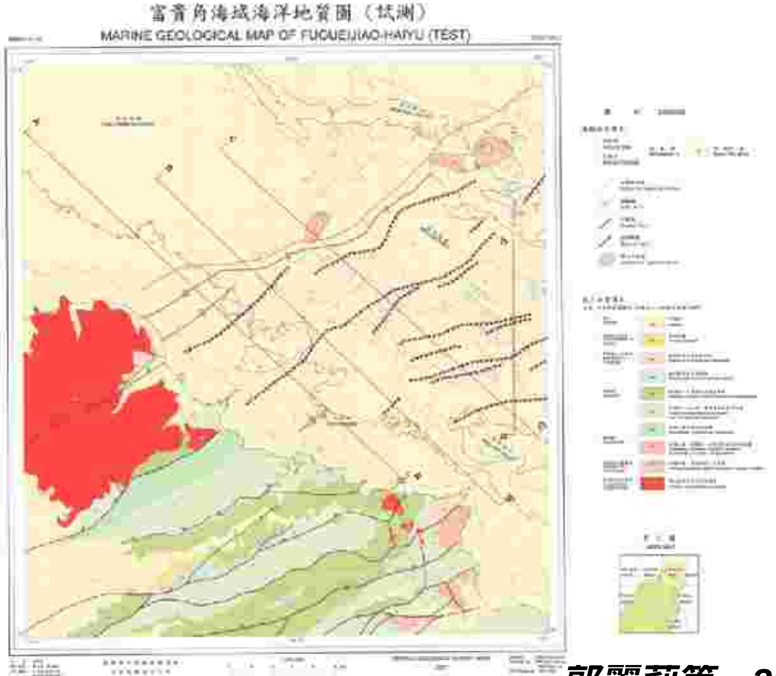
Recent Offshore Geology Study

About 5 years ago, marine geology investigation conducted by Central Geologic Survey shows offshore faults distributed near NPP

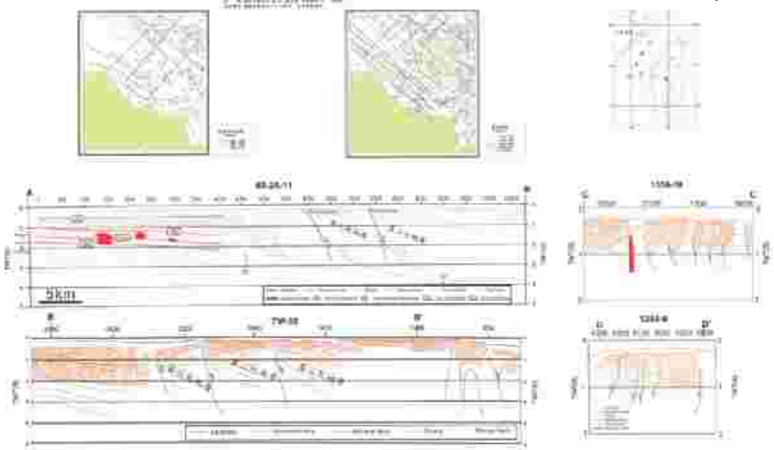




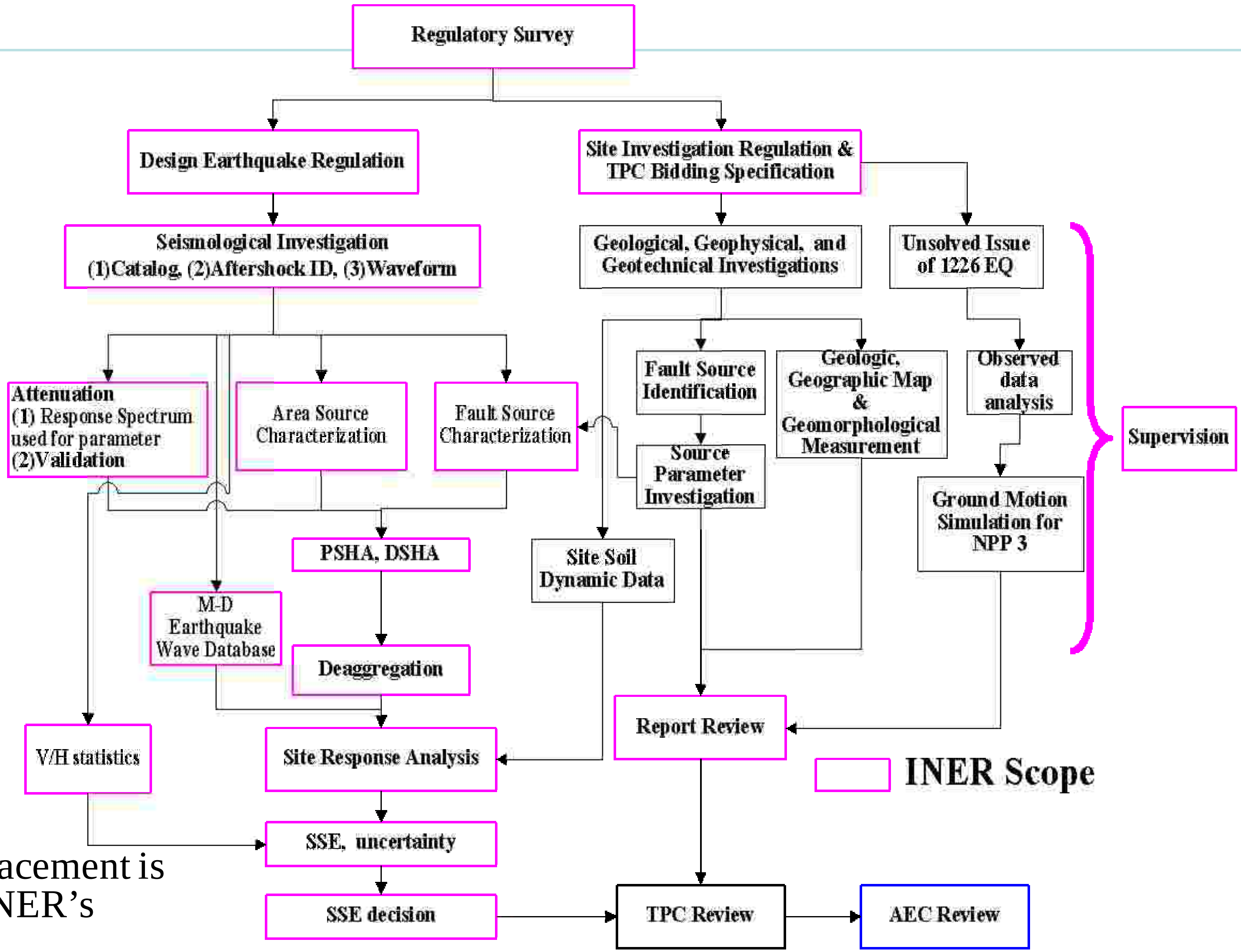
李珀儒，2008



郭麗莉等，2010



Updating Geo-data and SHA Plan



Note: Fault displacement is not included in INER's Scope

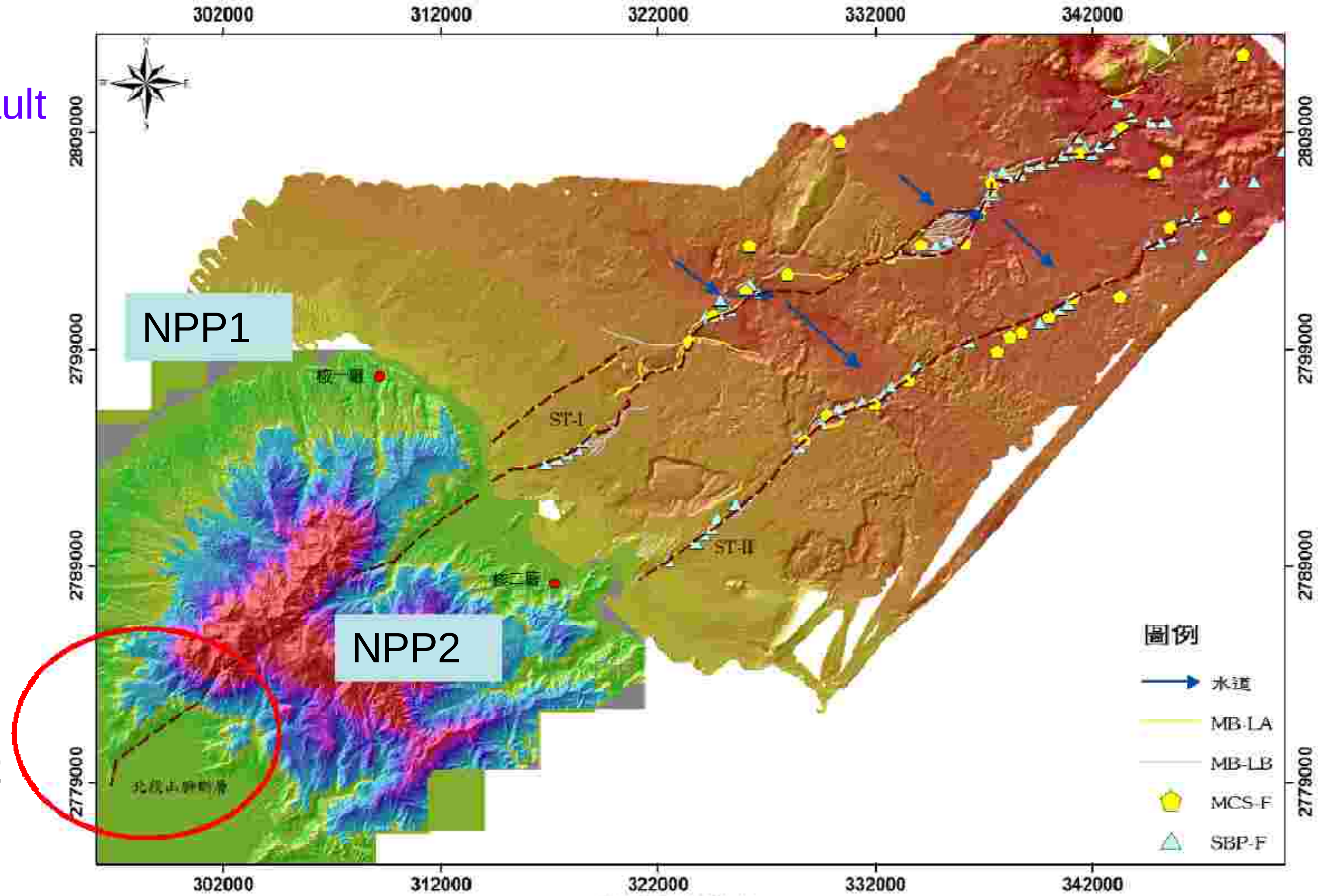
Contributor in Updating PSHA

Provider	Source	GMPE	Site Condition
SinoTech company **(Geologic Contractor)** **(中興顧問)**	SanChiao Fault HengChun Fault ST-II, HT-II and others		Vs30 Soil/Rock Profile
INER Integrating Existing source model of CGS, ..	Other faults (CGS, Interface)	Po-Shen Lin (2008) Po-Shen Lin(2011) TNGA	
INER (Integrating NCREE)		NCREE2011	
INER (Evaluator)	Logic Tree	NGA2008 **(AS, BA, CB, CY, IS)**	Site Response Analysis and Amplification Function

Seismic Hazard Curve, Ground Motion Response Spectra and Time History

New Geological Investigation Result for Northern NPPs

Normal Fault identified

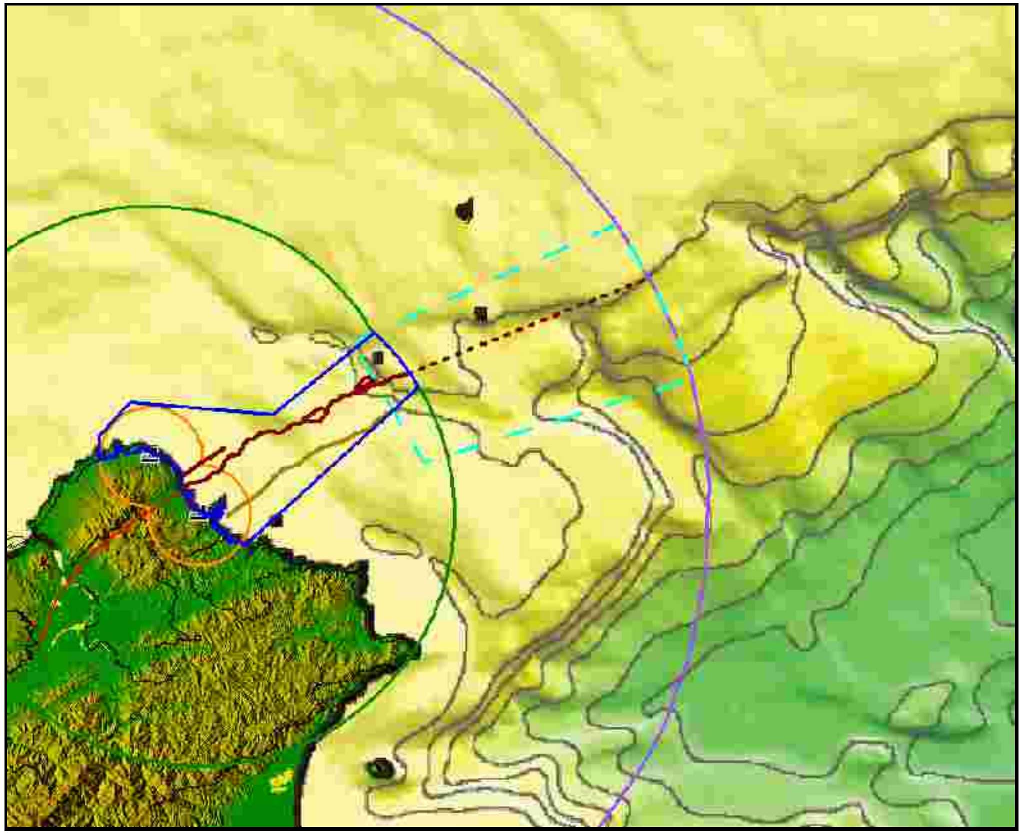


South Segment

(藍色箭頭為水道流向)

圖 4.8.7-2 山腳斷層北段與海域推估之斷層跡

Second Phase Investigation for SanChiao Fault

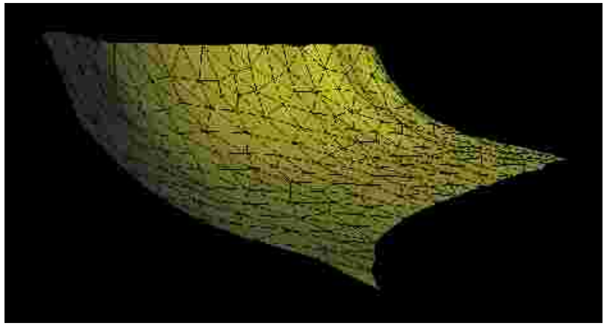


Current SanChiao Fault Parameters (1)

Parameter	Description	
Segmentation	Total	North Segment
		South Segment
Length (km)	Total 74	North Segment 61 (Sea Region: 40km)
		South Segment 13
Depth (km)	15	
Area (km²)	Total 1980	North Segment 1632
		South Segment 348
Dip Angle (degree)	0~1 km：82 degree 1~3 km ：75 degree 3~6 km ：60 degree 6~9 km ：45 degree 9~12 km ：30 degree 12~15 km ：15 degree	
Mechanism	Normal Fault (Caused by the continue movement of Okinawa Trough)	

Minimum distance to NPP1: 6.95km
Minimum distance to NPP2: 4.35km

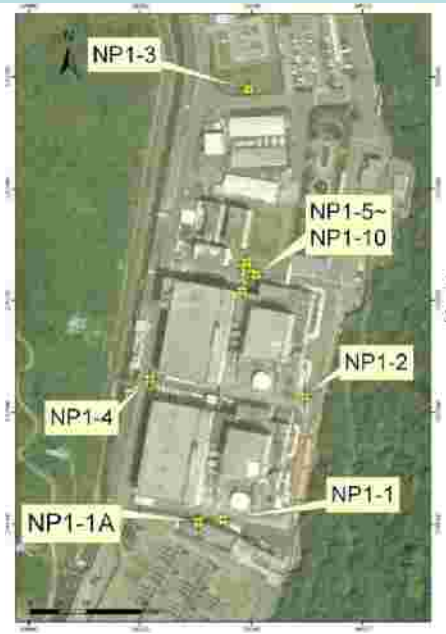
Additional 40 km or more is estimated and under surveyed in **current geological investigation**

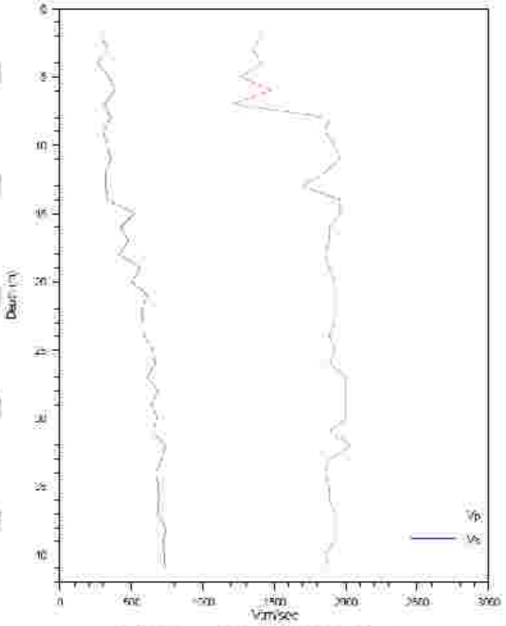


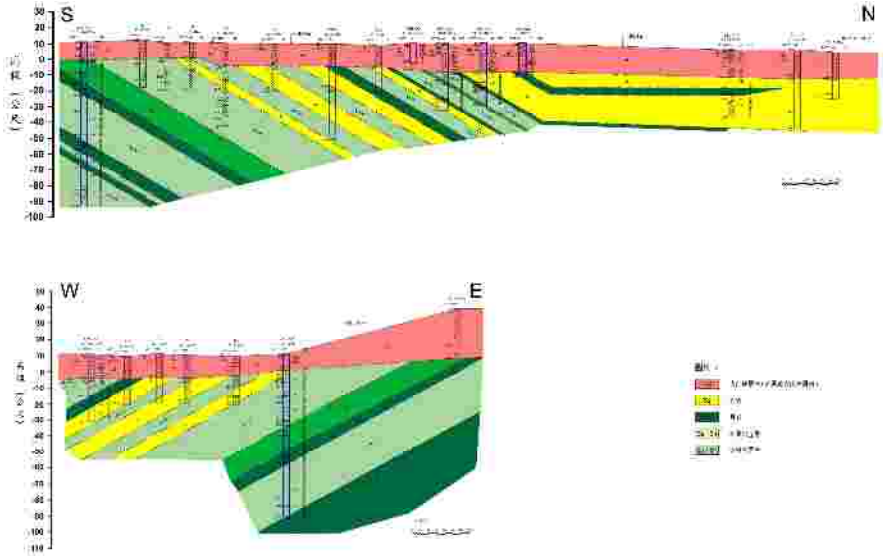
SanChiao Fault Parameters (2)

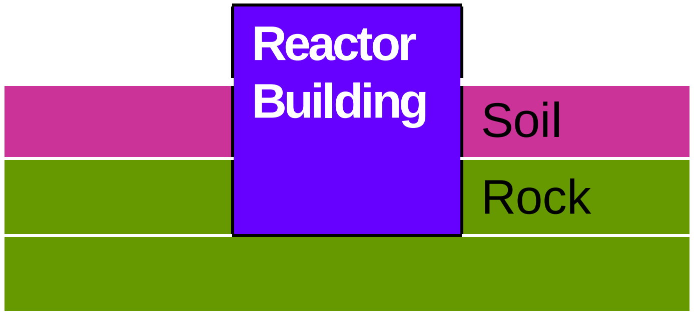
Parameter	Description		Note
Long-term slip rate (mm/yr)	North Segment	0.13 **(This Study)**	Logging and dating.
	South Segment	0.69~1.80 (Vertical Direction) **(Huang et.al, 2007)**	
		1.2~1.5(Vertical Direction) **(Chen et.al., 2008)**	Logging and dating in Taipei Basin
		2.3~3.3(Vertical Direction) **(Chen et.al., 2010)**	Logging and dating in Taipei Basin
Maximum magnitude (MW)	Total 7.3	North Segment 7.2	MW = 4.86 + 1.32 log L, s =0.34 (Wells and Coppersmith, 1994)
		South Segment 6.3	
	Total 7.3	North Segment 7.2	MW= (1.32 ±0.122) log (L) +(4.817 ±0.132) (Wu， 2000)
		South Segment 6.3	
	Total 7.2	North Segment 7.1	log Le = (1/2) log M0 - 8.08 Mw = (2/3) log M0 - 10.7 (Yen and Ma, 2011；Kanamori, 1977)
		South Segment 6.2	
Latest movement	1694 (felt only in Taipei Basin)		康熙台北湖Historic Earthquake

NPP1 Soil/Rock Profile





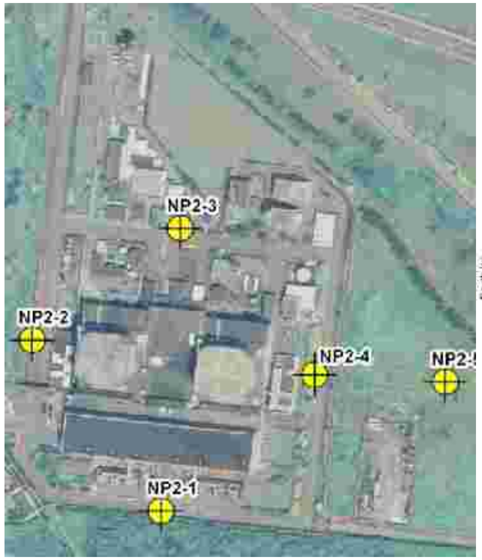




← Foundation level: 48.16ft (14.68m)

Vs30=609 m/s

NPP2 Soil/Rock Profile



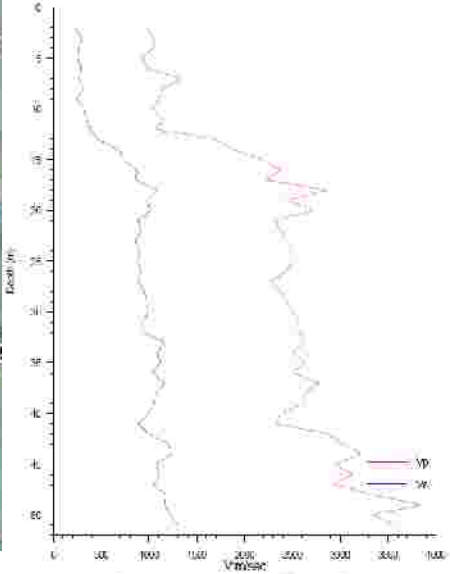
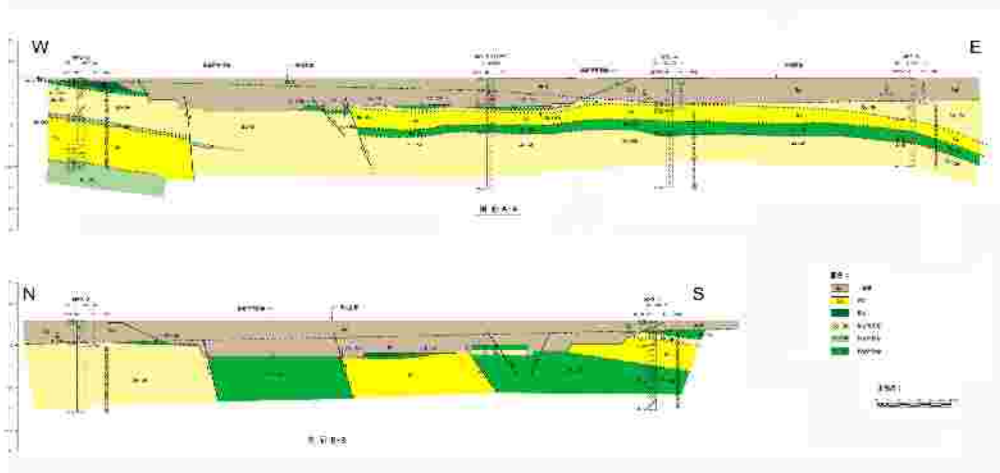
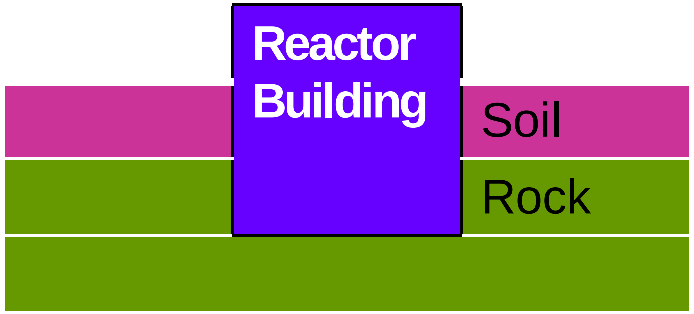


圖 3.2.3-1 鑽孔 NP2-1 速度剖面圖



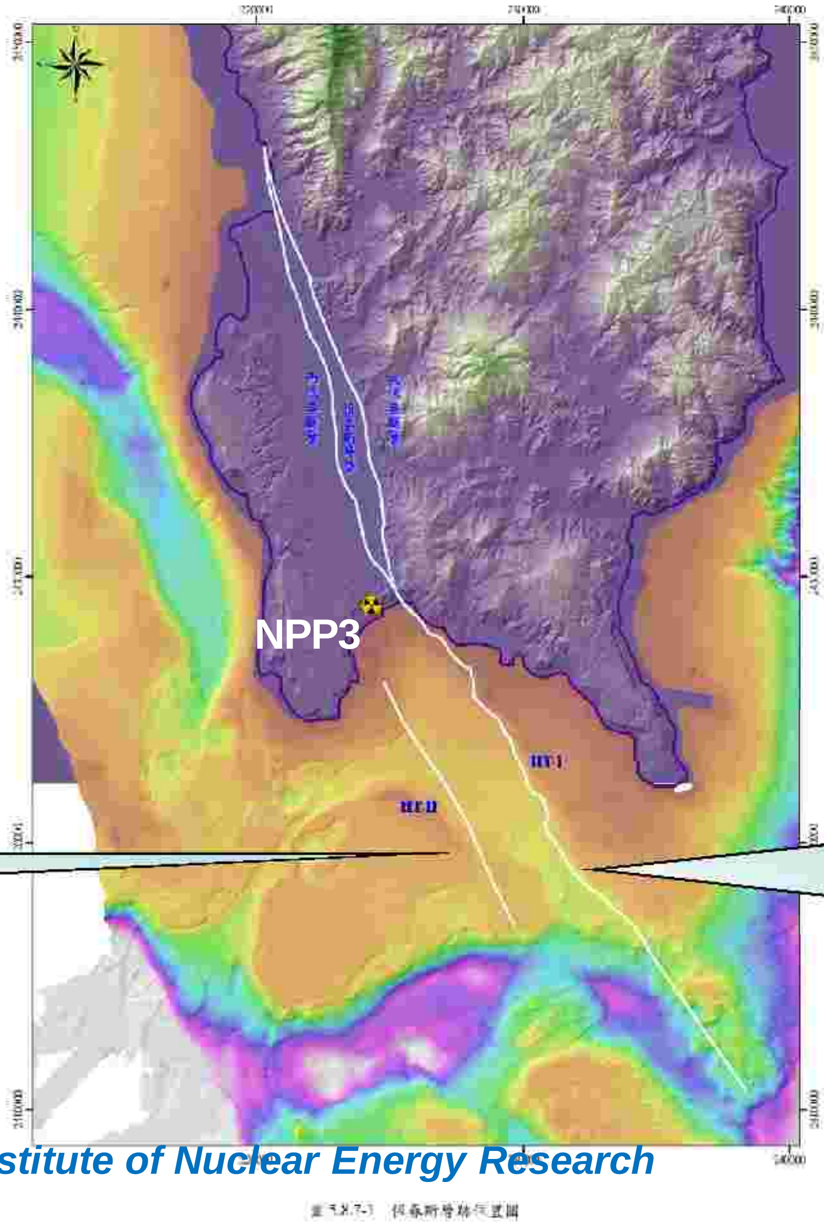


Foundation level: 50’9” (15.46m)

Vs30=1027 m/s

Investigation Result for NPP3

Minimum distance from HengChun Fault to NPP3: 1.1km



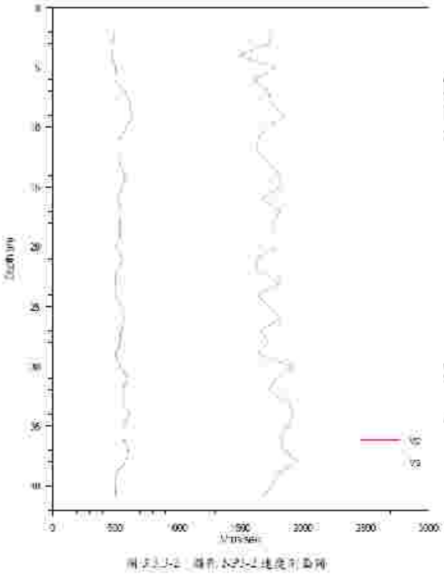
HengChun Fault Parameter

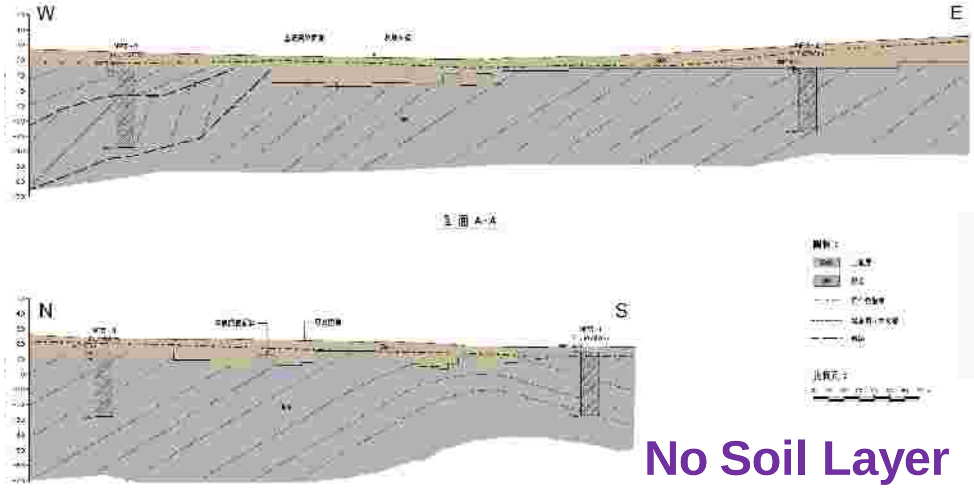
Parameter	Description
Segmentation	No
Length (km)	41(Sea Region: 21 km)
Width (km)	15.96
	21.21
Depth (km)	15
Area (km^2)	654.5
	869.7
Dip Angle (degree)	70/East （East HengChun）
	45/East （ West HengChun ）
Mechanism	Reverse

Parameter	Description
Long-term slip rate (mm/yr)	4.2±0.2 (Vertical Direction)**(Chen, 2010)**
	7.5±0.14 (Vertical Direction)**(Chen, 2006)**
	(Vertical Direction) **(This Study)** 0.7 mm/yr (West HengChun); 1.5-4.9 mm/yr (East HengChun) Long-term slip rate: 1.0 mm/yr (West HengChun); 1.6-5.2 mm/yr(East HengChun)
Maximum Magnitude (Mw)	7.0 MW = 4.86 + 1.32 log L (Wells and Coppersmith, 1994)
	7.0 MW= (1.32 ±0.122) log (L) +(4.817 ± 0.132) (Wu， 2000)
	6.9 log Le = (1/2) log M0 - 8.08 Mw = (2/3) log M0 - 10.7 (Yen and Ma, 2011; Kanamori, 1977)

- **Currently, slip rate is under review and many conflicts happen between dating data and energy release rate.**

NPP3 Soil/Rock Profile

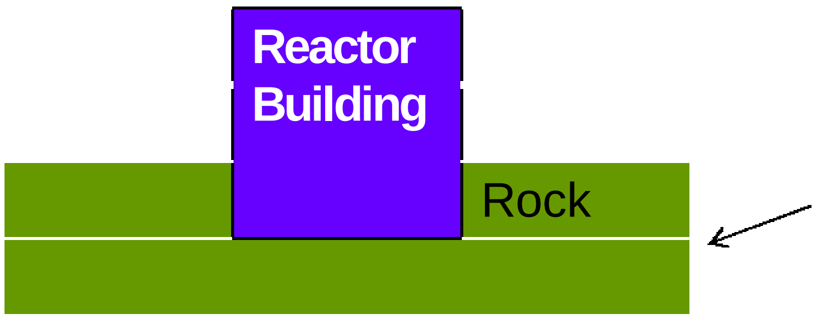




No Soil Layer

表 3.4.3-1 核三廠基礎地層地物特性

項次	地層 (材料)	Vp (m/sec)	Vs (m/sec)	柏松比 Poisson's Ratio μd	剪力模數 Shear Modulus Gd (kg/cm²)	楊氏模數 Young's Modulus Ed (kg/cm²)	體積彈性模數 Bulk Modulus Kd (kg/cm²)	備註
1	mudstone	1,200 (4,000~5,000 ft/sec)	555 (1,850 ft/sec)	0.3~0.4	-	3.0×10^5	-	核三廠終期安全分析報告 (FSAR)
2	岩層	1,299~2,083	592~637	0.420~0.474	3,201~8,486	9,283~24,321	30,841~82,952	本工作超度井測例套成果

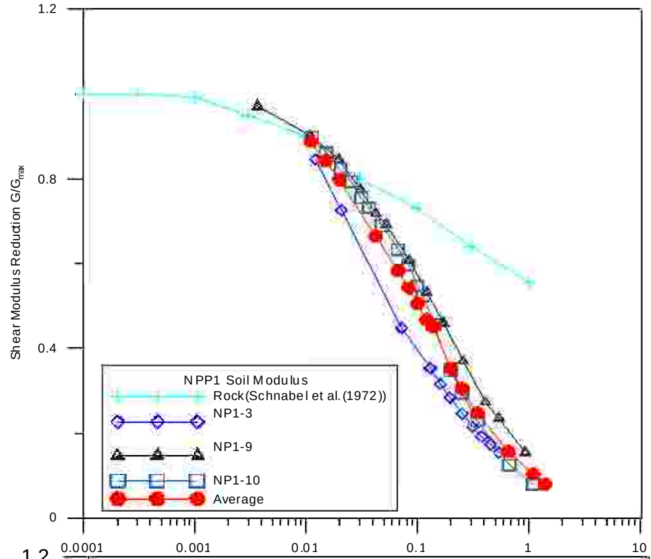


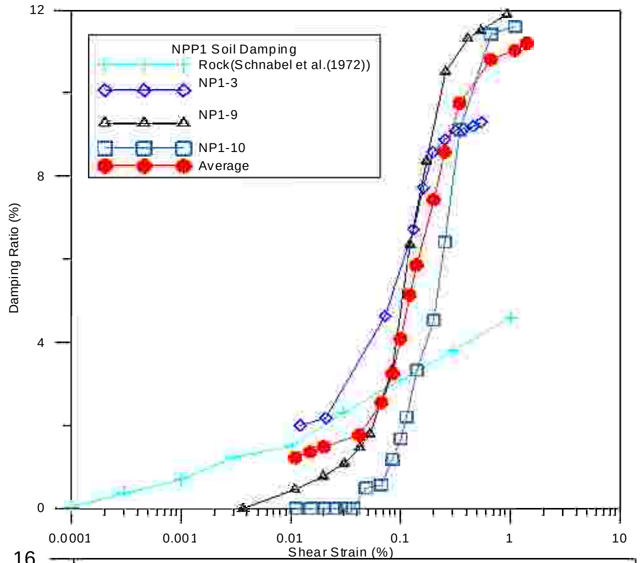
Foundation level: 23'(7m)

Vs30=521 m/s

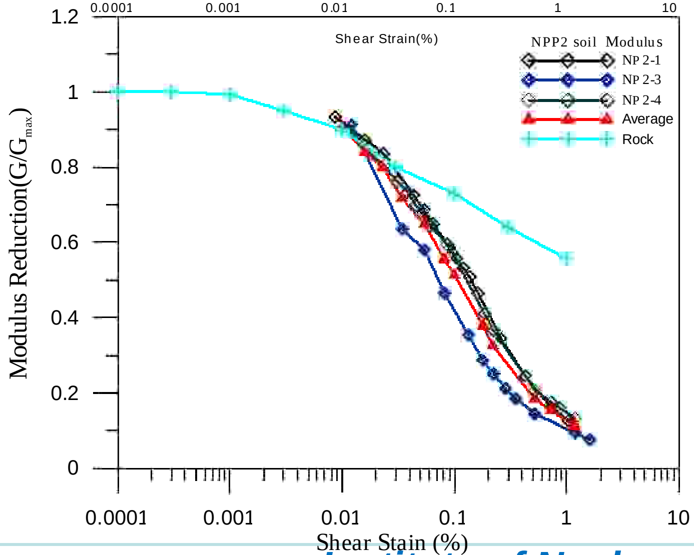
Soil Dynamic Properties

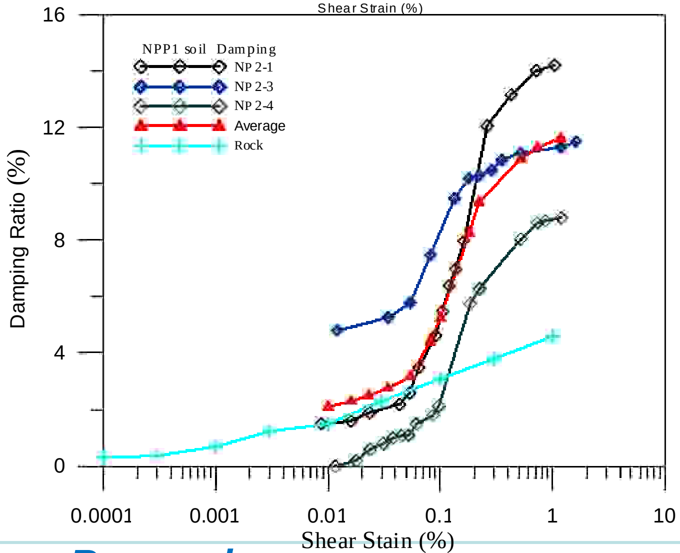
NPP1



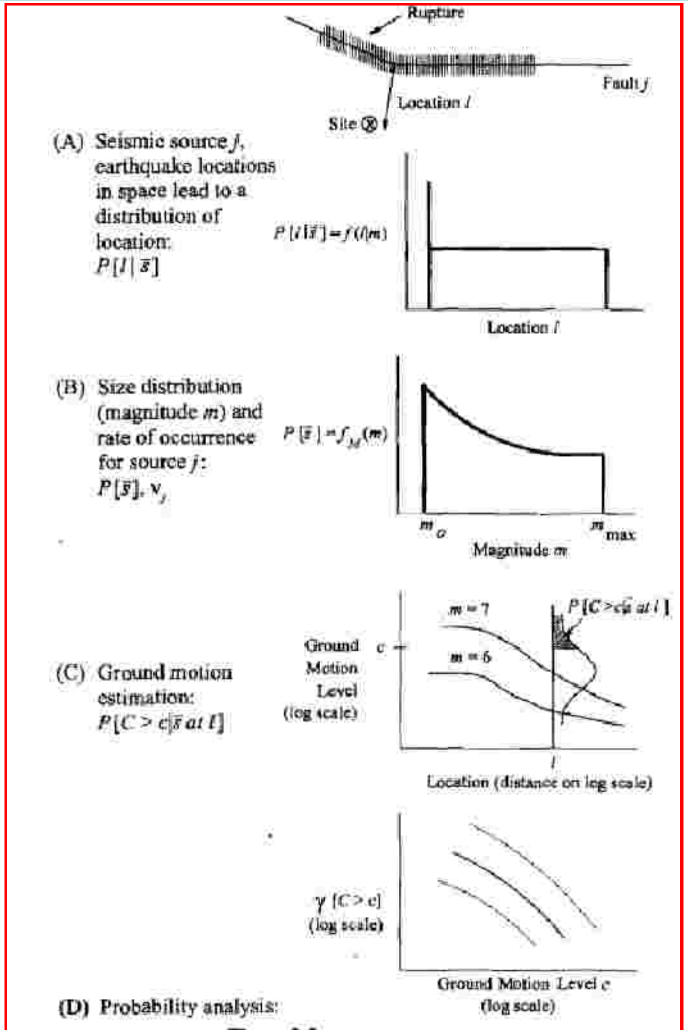


NPP2





Steps on Seismic Hazard Analysis



$$\gamma\ [C > c] = \sum_j \nu_j \int\int P_j[C > c|\bar{s}\ at\ l]\ P[\bar{s}\ at\ l]\ d\bar{s}dl$$

Robin McGuire (2004)

Ground Motion Prediction Equation

- Abrahamson, N., Silva, W., "Summary of the Abrahamson & Silva NGA Ground-Motion Relations", Earthquake Spectra, Volume 24, No. 1, pages 67–97, February 2008.
- Boore, D. M., Atkinson, G. M., "Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGA, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s", Earthquake Spectra, Volume 24, No. 1, pages 99–138, February 2008.
- Campbell, K. W., Bozorgnia, Y., "NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGA, PGD and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10s", Earthquake Spectra, Volume 24, No. 1, pages 139–171, February 2008.
- Chiou, B. J., Youngs, R. R., "An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra", Earthquake Spectra, Volume 24, No. 1, pages 173–215, February 2008.Idriss,
- I. M., "An NGA Empirical Model for Estimating the Horizontal Spectral Values Generated By Shallow Crustal Earthquakes", Earthquake Volume 24, No. 1, pages 217–242, February 2008.
- Lin, P. S., and C. T. Lee, " Ground-motion attenuation relationships for subduction-zone earthquakes in northeastern Taiwan", Bull. Seism. Soc. Am. 98, 220-240, 2008.
- Lin, P. S., Lee, C. T., Cheng, C. T. and Sung, C. H., "Response spectral attenuation relations for shallow crustal earthquakes in Taiwan", Geology, 121 150–164, 2011.
- 中興顧問社，「反應譜衰減律建置報告」，行政院原子能委員會核能研究所委託核電廠地質調查與地震危害度參數研究報告，2012。(TNGA Prediction Equation)
- 國家地震工程中心，「面震源與衰減律參數研究及核電廠地盤反應量測」，行政院原子能委員會核能研究所委託研究報告, 2011。(NCREE2011 Prediction Equation)

GMPE Development

- **At current status, some local GMPEs still have larger sigma and have some insufficiency, particularly in normal fault prediction due to lack of data**
- **INER recently sponsored the local developer to build up GMPE for the normal fault related to Okinawa Trough**
- **In the future, if possible in next phase, Kappa or Single Site Sigma would be considered in GMPE to reduce the aleatory uncertainties**

Performance-Based Ground Motion

- For long-term consideration on plant operation and safety analysis, NRC RG 1.208 is adopted to become the candidate for reviewed ground motion
- Risk and plant fragility embedded in performance-based ground motion response spectra (GMRS) through more than 15 years NRC's research

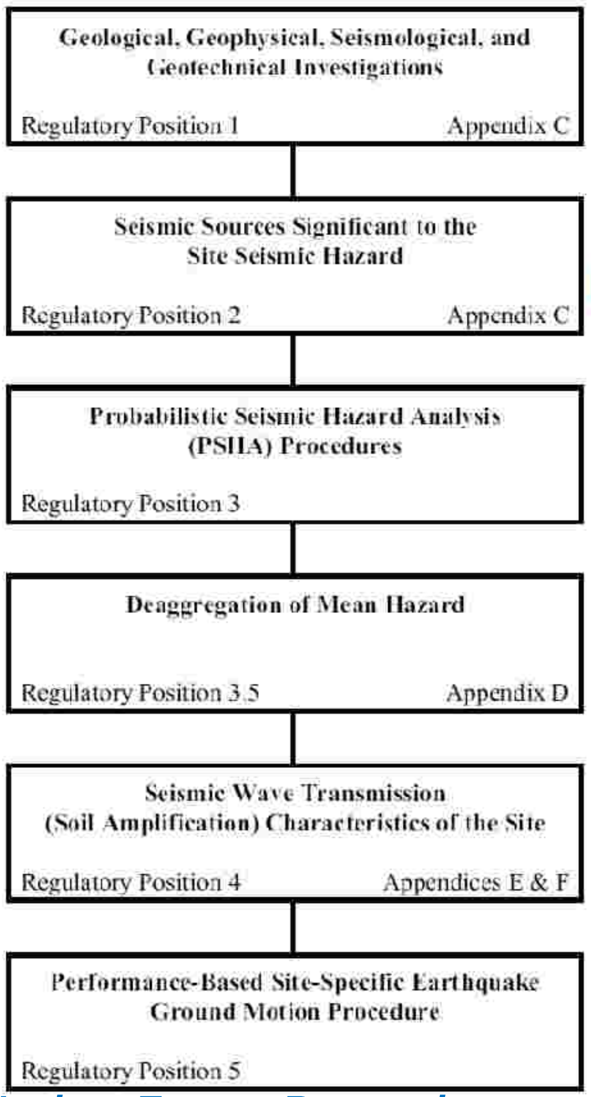


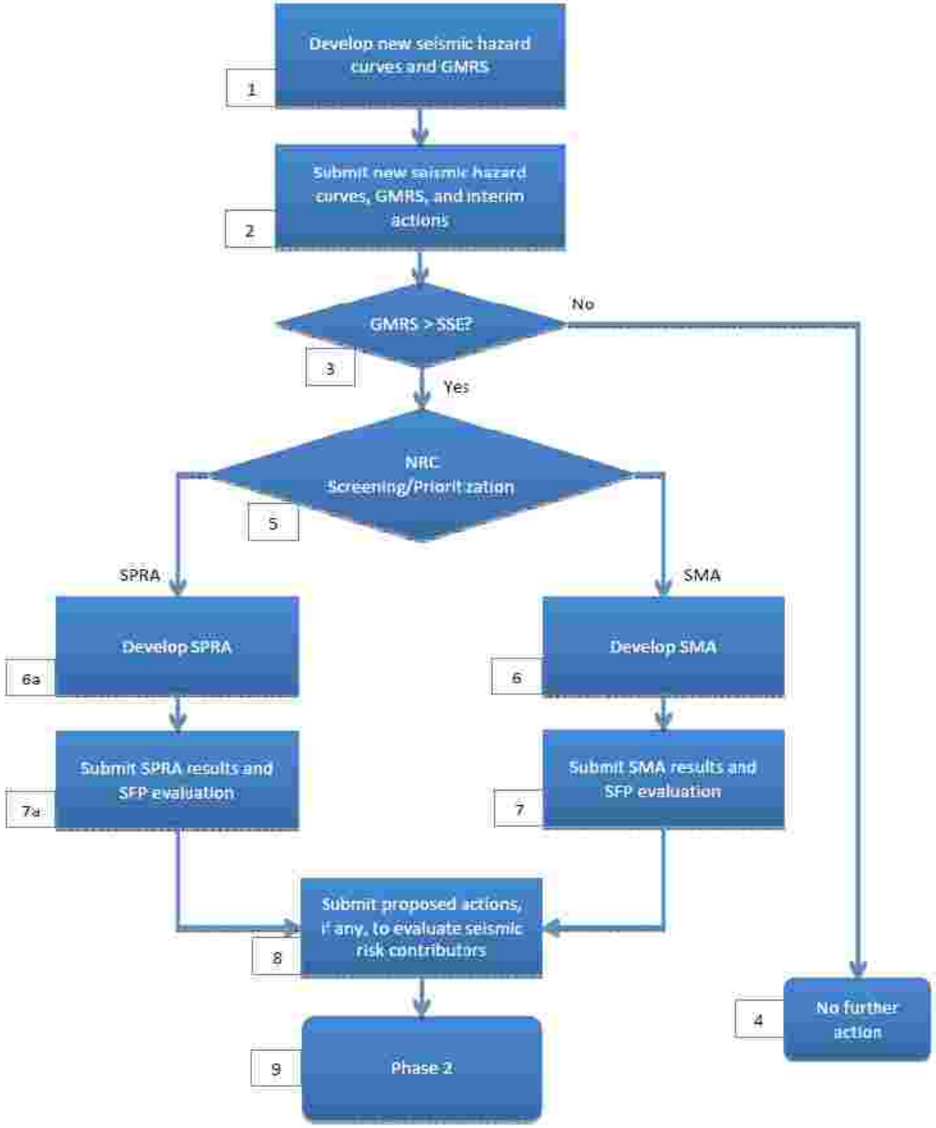
Figure 1. Flow Diagram

Determined by DSHA

- **GMRS = UHRS x DF**
- **DF = max { 1.0, 0.6(A_R)$^{0.8}$ }**
- **A_R = mean 1 E-05 UHRS ÷ mean 1 E-04 UHRS**

Risk Assessment

- **GMRS meet the requested Information for seismic risk assessment by NRC after Fukushima event**



Significant Seismic Source Identification

- **DSHA performed to identify significant source**

NPP1

Source Name	Mmax (Mw)	Min. Dist.(Km)	PGA (g)
SanChiao Fault	7.6	6.9	**0.370**
ST-II	6.9	15.0	0.177
Subduction Interface	8.2	138.7	0.068
Subduction Intraslab	7.6	72.6	0.115

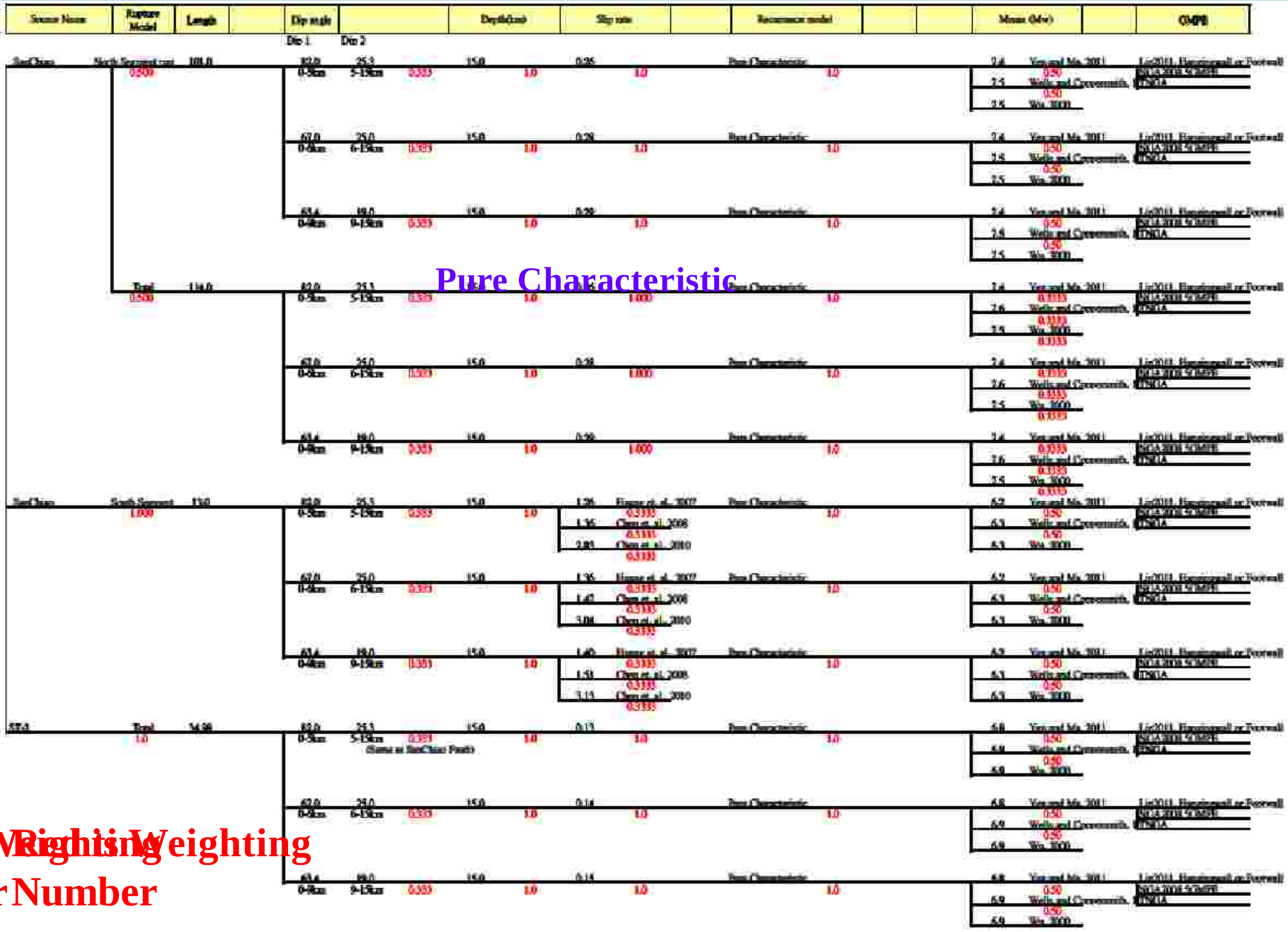
NPP2

Source Name	Mmax (Mw)	Min. Dist.(Km)	PGA (g)
SanChiao Fault	7.6	4.8	**0.470**
ST-II	6.9	4.4	0.321
Subduction Interface	8.2	127.0	0.074
Subduction Intraslab	7.6	60.5	0.123

NPP3

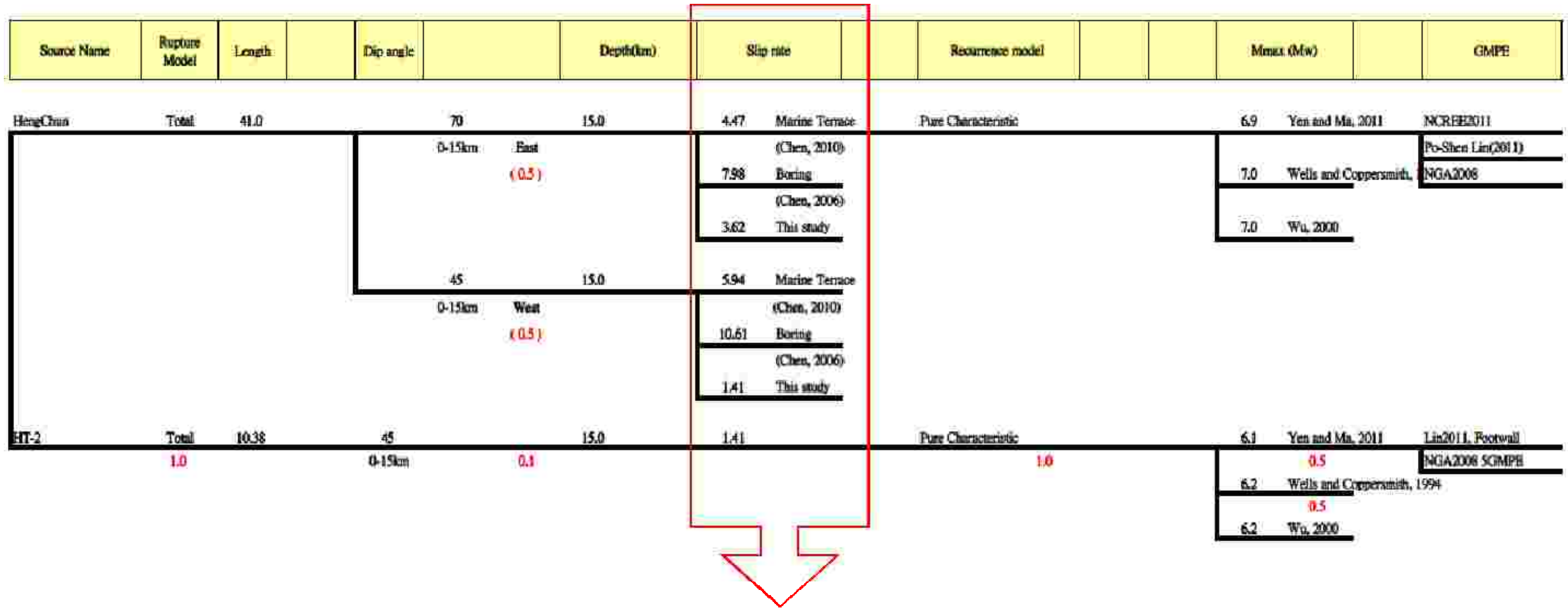
Source Name	Mmax (Mw)	Min. Dist.(Km)	PGA (g)
HengChun Fault	7.3	1.11	**0.597**
HT-II	6.2	2.92	0.454
Subduction Interface	7.9	15.0	0.218
Subduction Intraslab	7.6	35.5	0.168

Logic Tree for NPP1 and NPP2



Red is Weighting Number

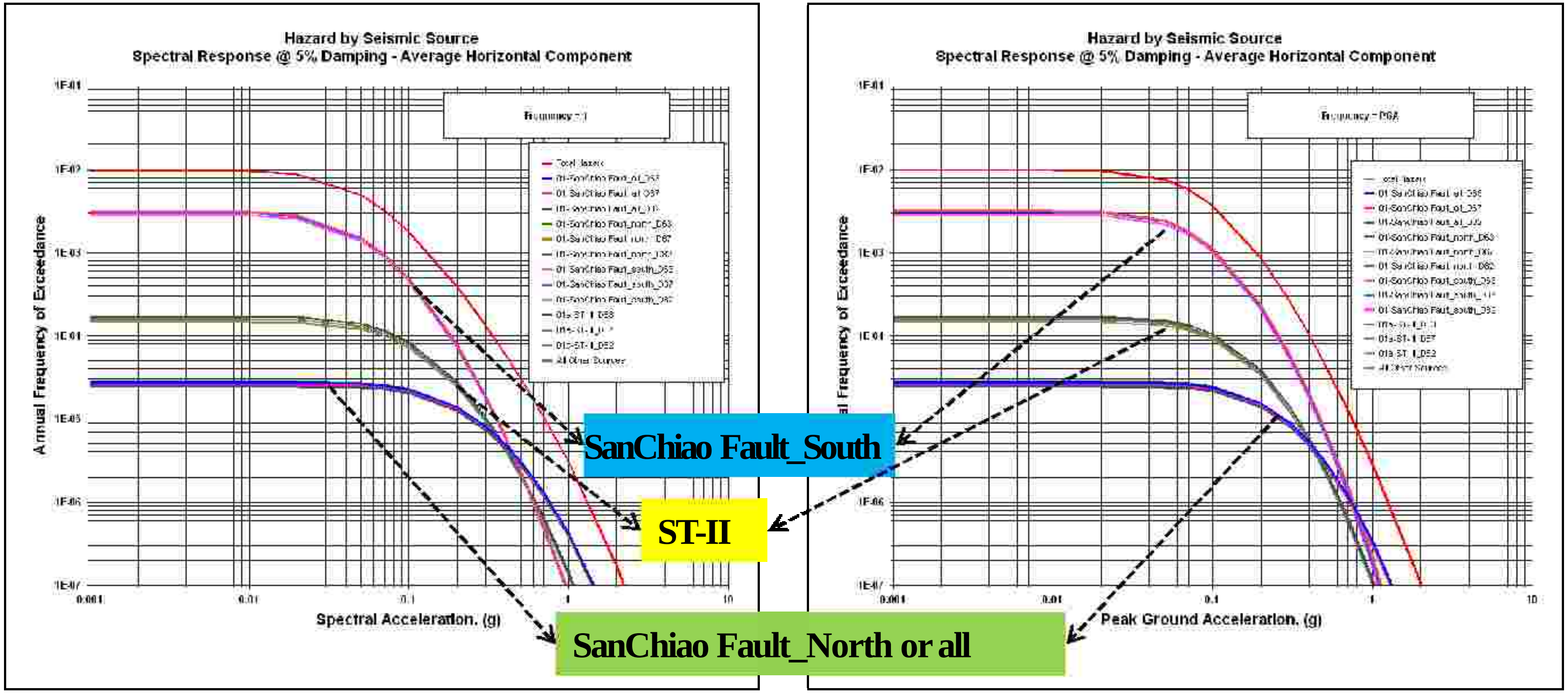
Logic Tree for NPP3



From announcement of Central Geologic Survey, the latest movement of HengChun Faut is more than 10,000 years ago, and it is categorized as second class active fault. However, Energy release from slip rate is too fast and not consistent with historic earthquake data.

Seismic Hazard Curves for NPP1

Preliminary Result based on sensitivity study

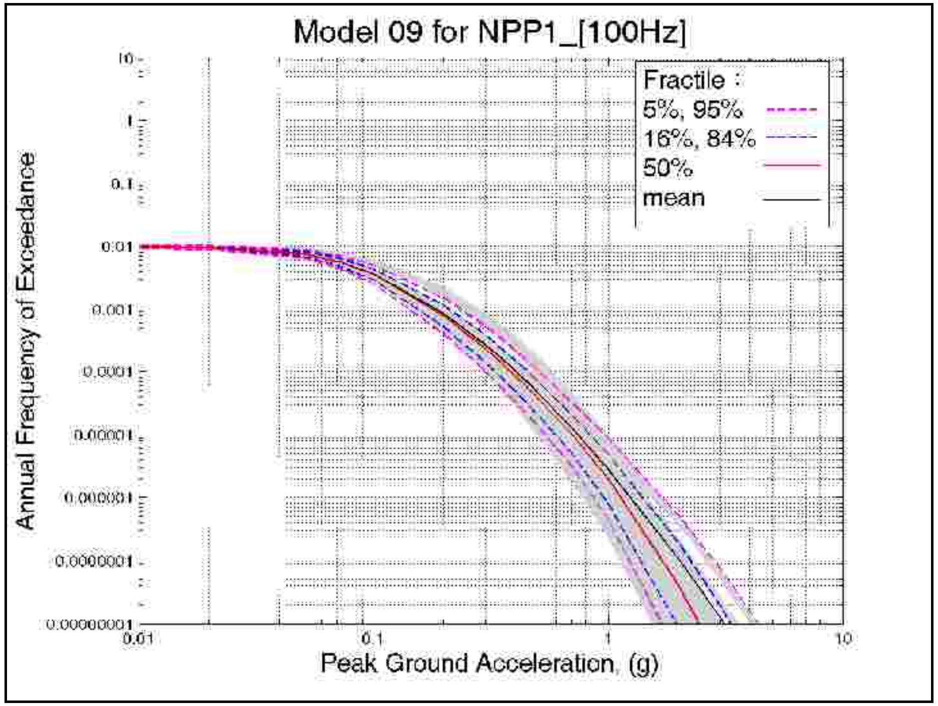


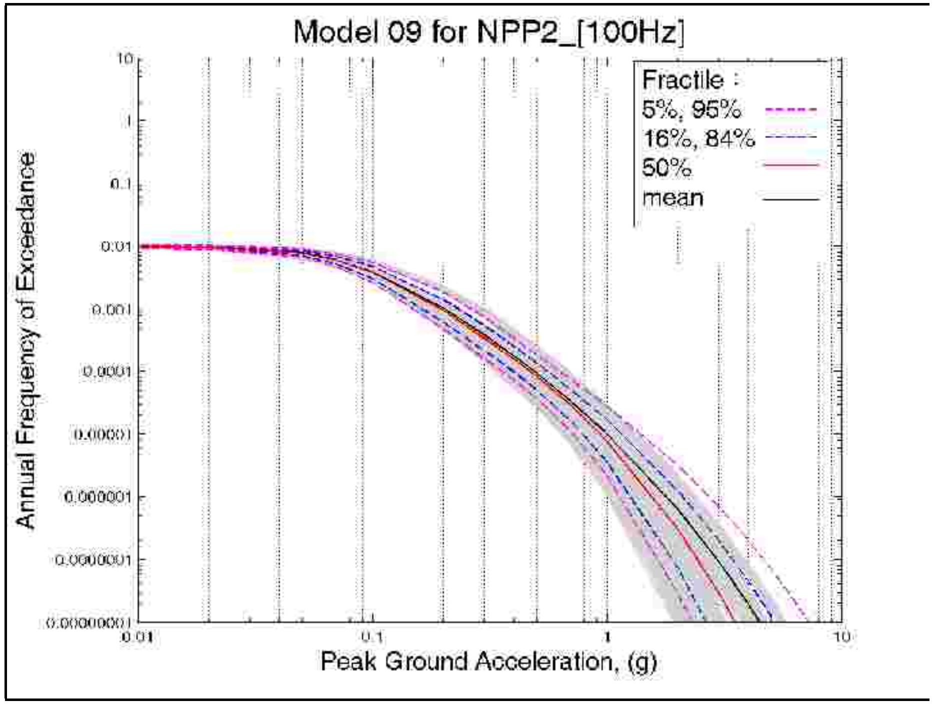
Frequency = 1Hz **Frequency = PGA**

Fractile Hazard Curve for NPP1

Preliminary Result based on sensitivity study

Fractile(5%、16%、50%、84%、95% & mean)





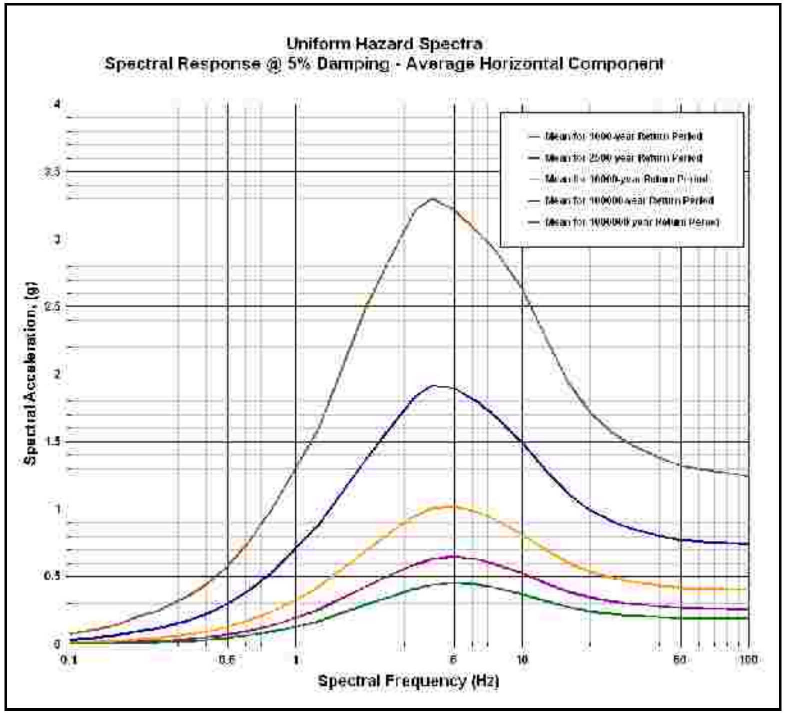
Frequency = PGA

UHRS at Foundation Level for NPP1

Preliminary Result based on sensitivity study

Frequency (Hz)	1E-4	1E-5
0.1	0.010	0.030
0.13	0.015	0.047
0.16	0.022	0.066
0.2	0.034	0.095
0.25	0.045	0.119
0.333333	0.070	0.175
0.4	0.092	0.223
0.5	0.128	0.301
0.63	0.181	0.409
0.79	0.244	0.538
1	0.331	0.711
1.25	0.422	0.876
2	0.682	1.351
2.5	0.803	1.566
3.33333	0.949	1.833
4	1.007	1.919
5	1.019	1.894
6.3	0.982	1.797
7.5	0.927	1.696
10	0.811	1.495
12.5	0.706	1.299
16	0.600	1.109
20	0.533	0.989
25	0.490	0.907
30	0.463	0.858
40	0.435	0.806
50	0.418	0.772
63	0.413	0.761
80	0.408	0.751
PGA	0.404	0.742

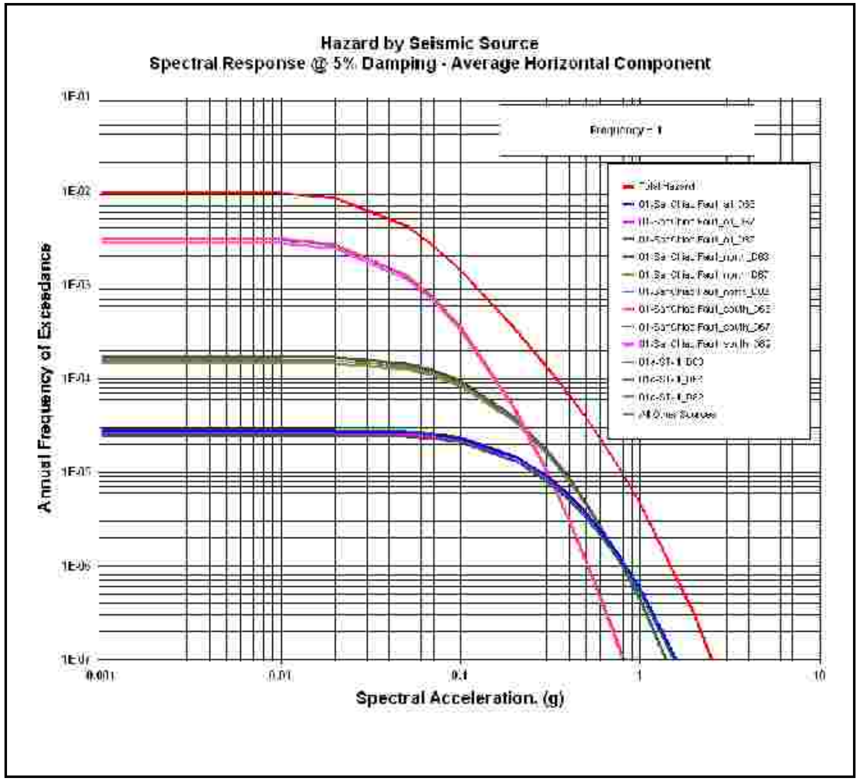
UHRS



Seismic Hazard Curves for NPP2

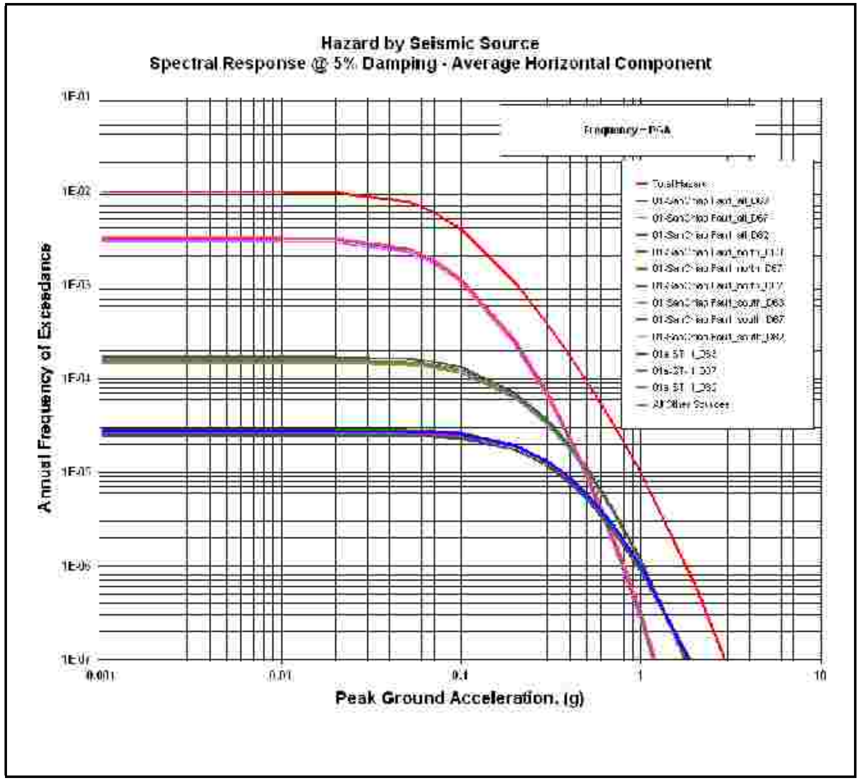
Preliminary Result based on sensitivity study

Hazard Curve



Frequency = 1Hz

Hazard Curve



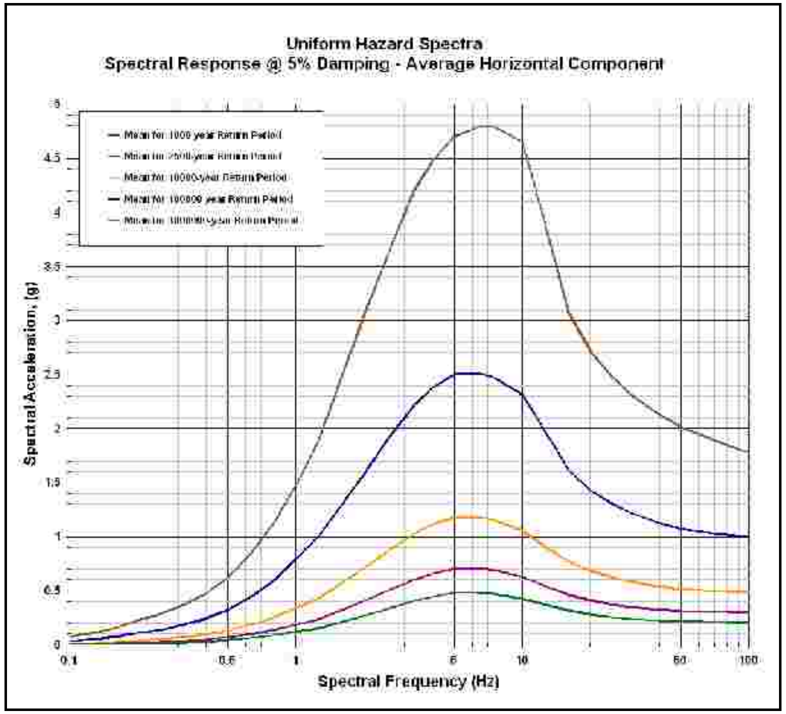
Frequency = PGA

UHRS at Foundation Level for NPP2

Frequency (Hz)	1E-4	1E-5
0.1	0.011	0.032
0.13	0.017	0.053
0.16	0.024	0.074
0.2	0.036	0.107
0.25	0.049	0.132
0.333333	0.074	0.194
0.4	0.096	0.242
0.5	0.131	0.323
0.63	0.185	0.444
0.79	0.250	0.590
1	0.339	0.791
1.25	0.427	0.994
2	0.709	1.575
2.5	0.856	1.879
3.33333	1.028	2.223
4	1.111	2.378
5	1.176	2.501
6.3	1.181	2.516
7.5	1.152	2.476
10	1.055	2.311
12.5	0.912	1.983
16	0.769	1.611
20	0.682	1.423
25	0.620	1.300
30	0.581	1.219
40	0.538	1.126
50	0.513	1.072
63	0.504	1.045
80	0.495	1.019
PGA	0.486	0.997

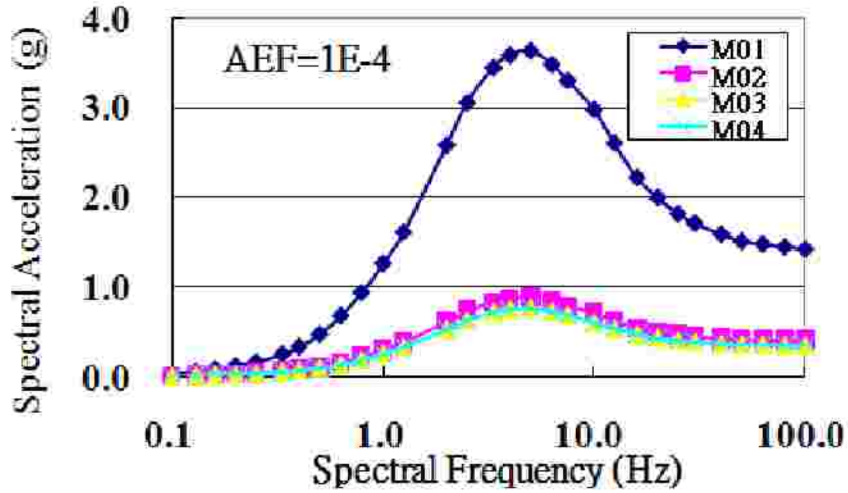
Preliminary Result based on sensitivity study

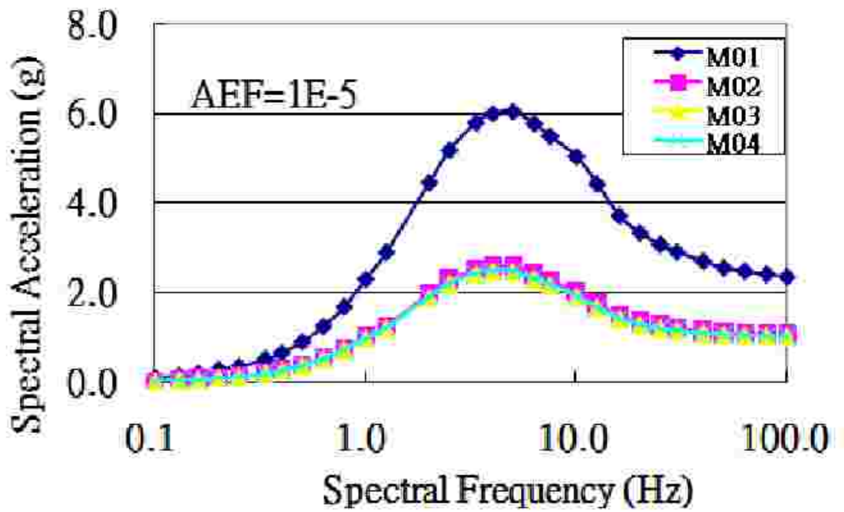
UHRS



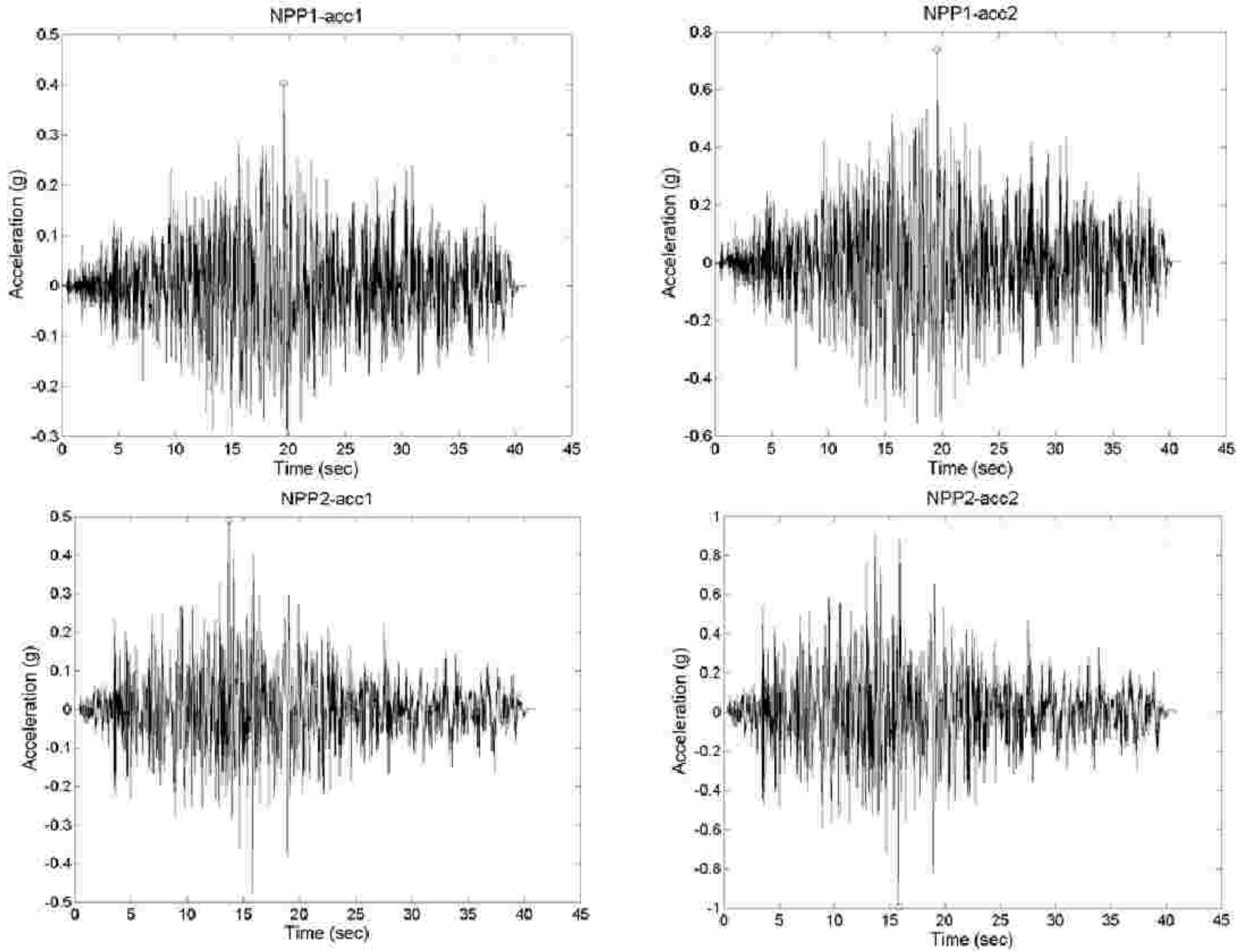
UHRS for NPP3

Data	Scenario	AEF=1E-4 PGA(g)	AEF=1E-5 PGA(g)
Slip rate listed in Geological Investigation Report	M1	1.428	2.345
Latest movement occurred from 10,000 to 40,000 years ago	M2	0.398	1.058
	M3	0.347	1.031
Latest movement occurred 10,000 years ago	M4	0.433	1.084

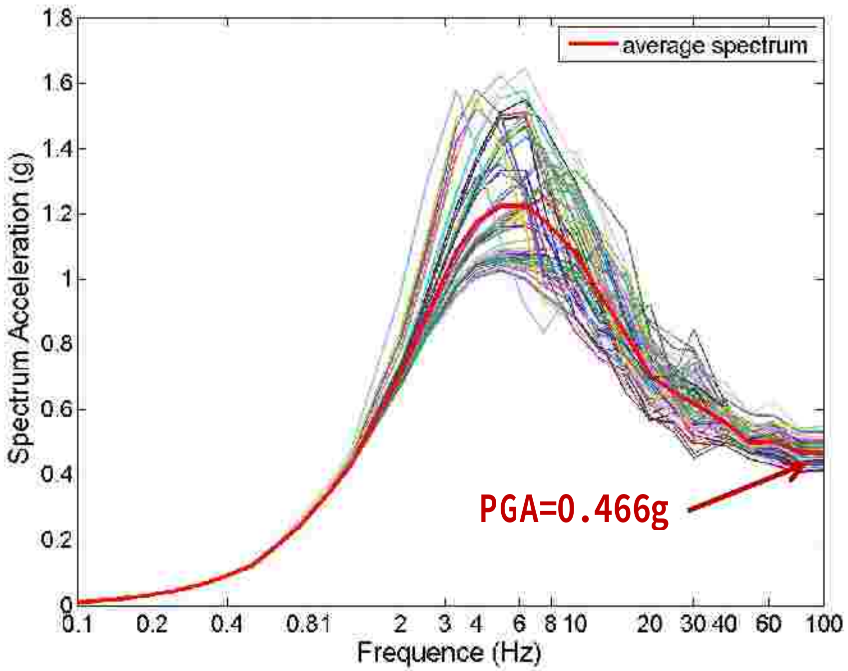




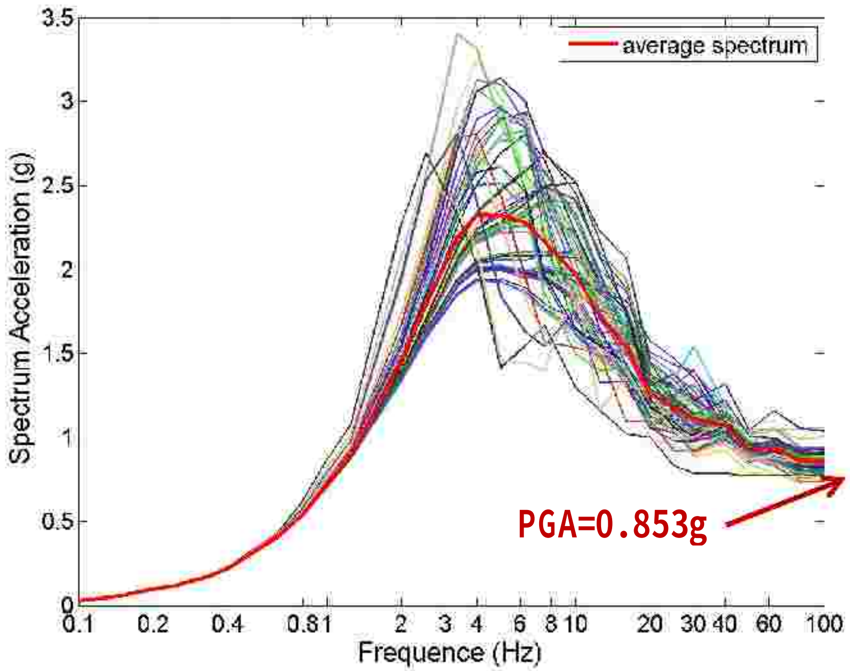
Input Motion for Site Response Analysis



Free-Field Ground Surface UHRS for NPP1

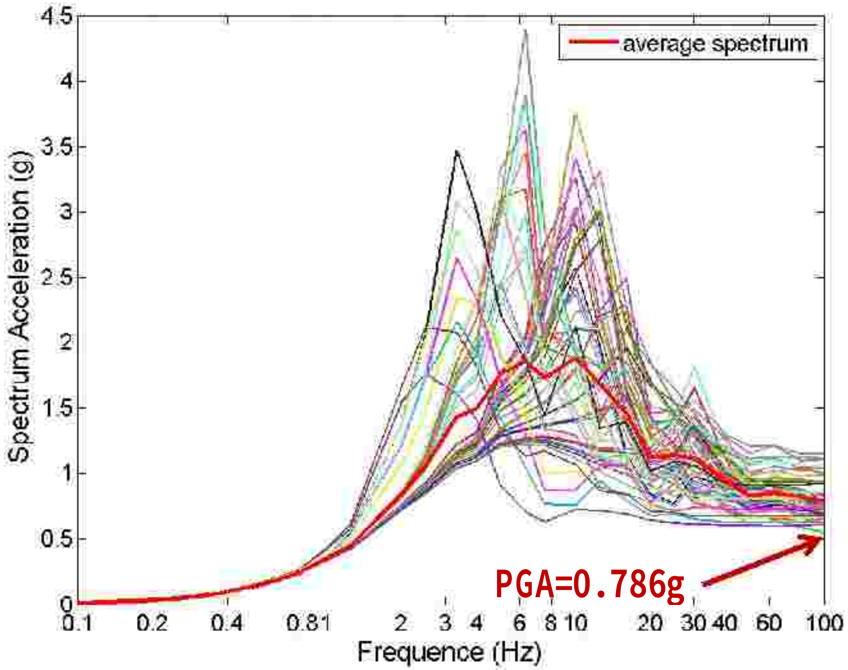


1E-4 Mean UHRS

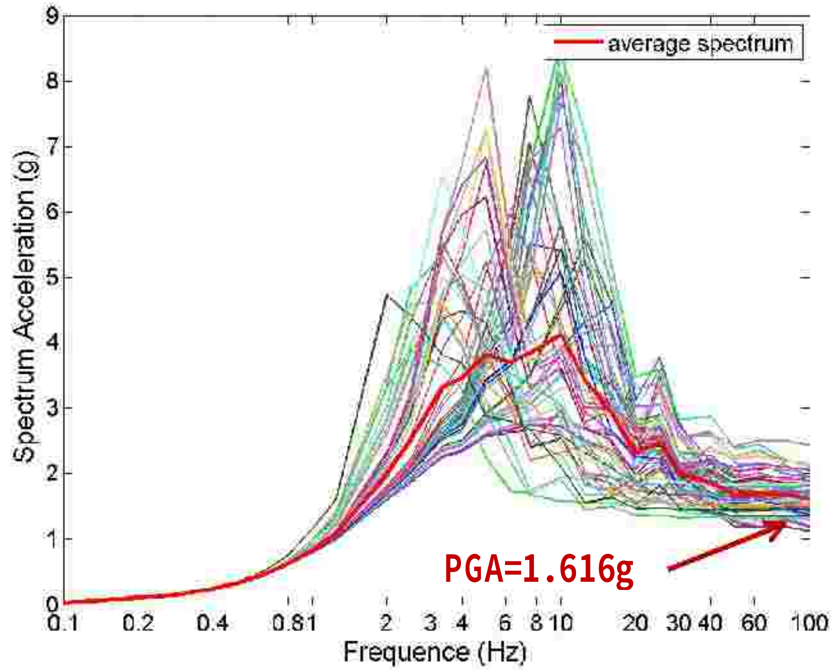


1E-5 Mean UHRS

Free-Field Ground Surface UHRS for NPP2

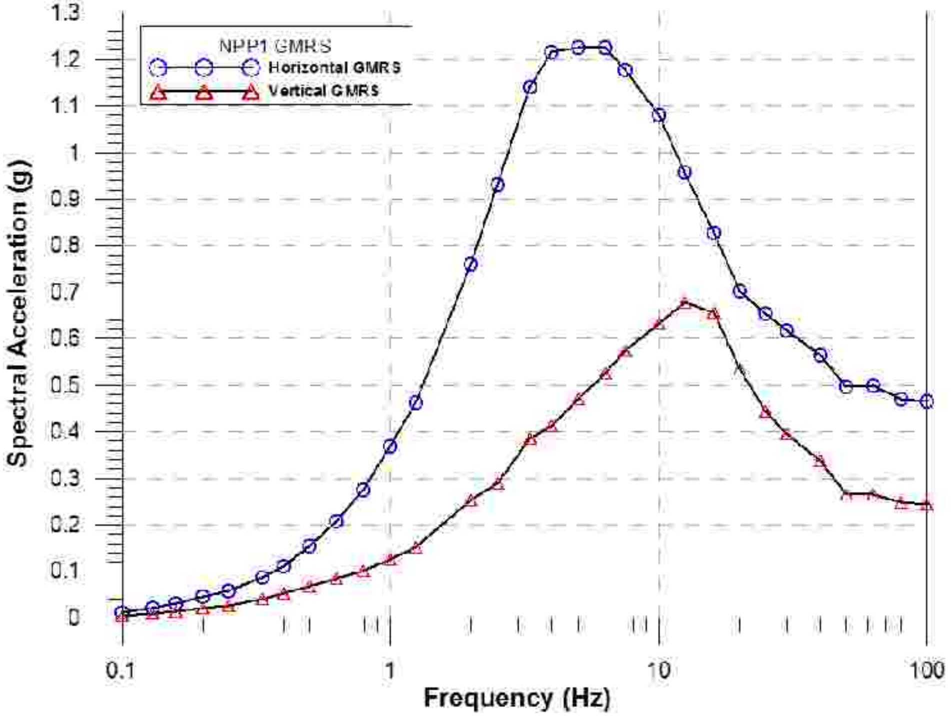


1E-4 Mean UHRS

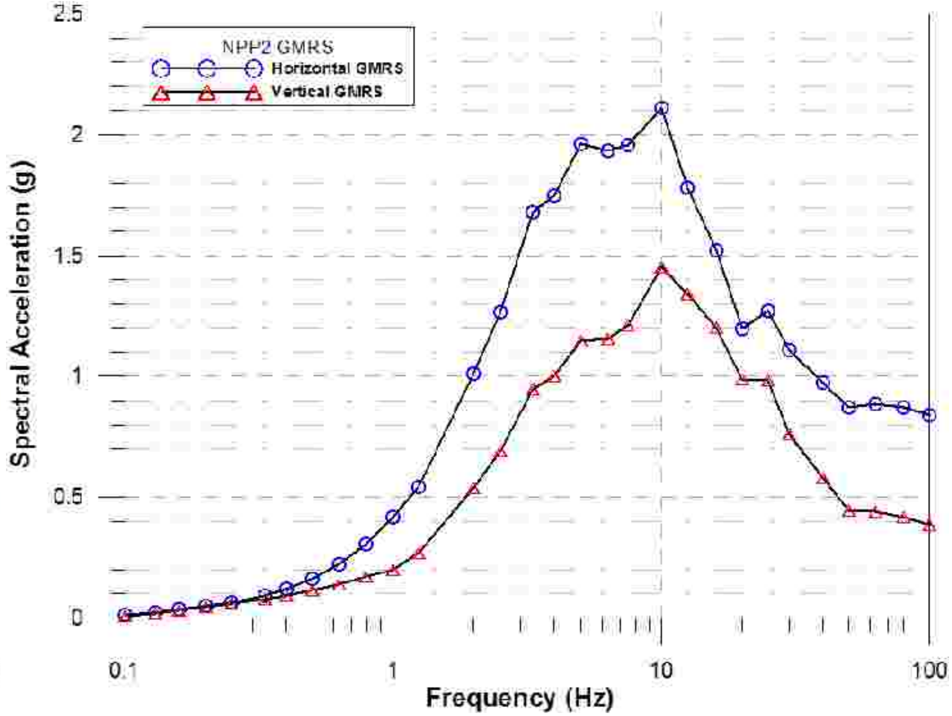


1E-5 Mean UHRS

GMRS



NPP1



NPP2

Seismic Performance using GMRS

- Based on NRC's research, GMRS can let plant have the following performance :

(1) less than about a 1% probability of unacceptable performance for the site-specific response spectrum ground motion

(2) less than about a 10% probability of unacceptable performance for a ground motion equal to 150% of the site-specific response spectrum ground motion

ü Target Performance Goal, P_F ： Target annual probability of exceeding the 1 E-05 frequency of onset of significant inelastic deformation (FOSID) limit state.

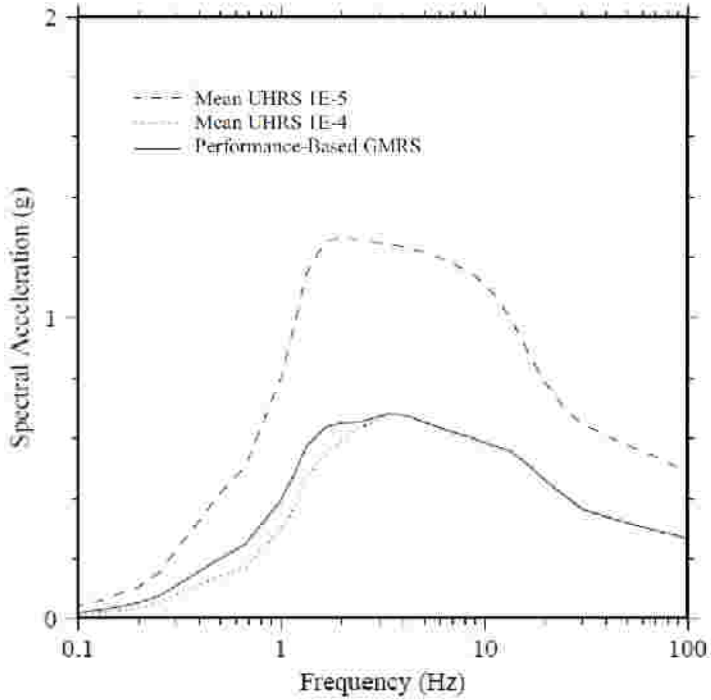


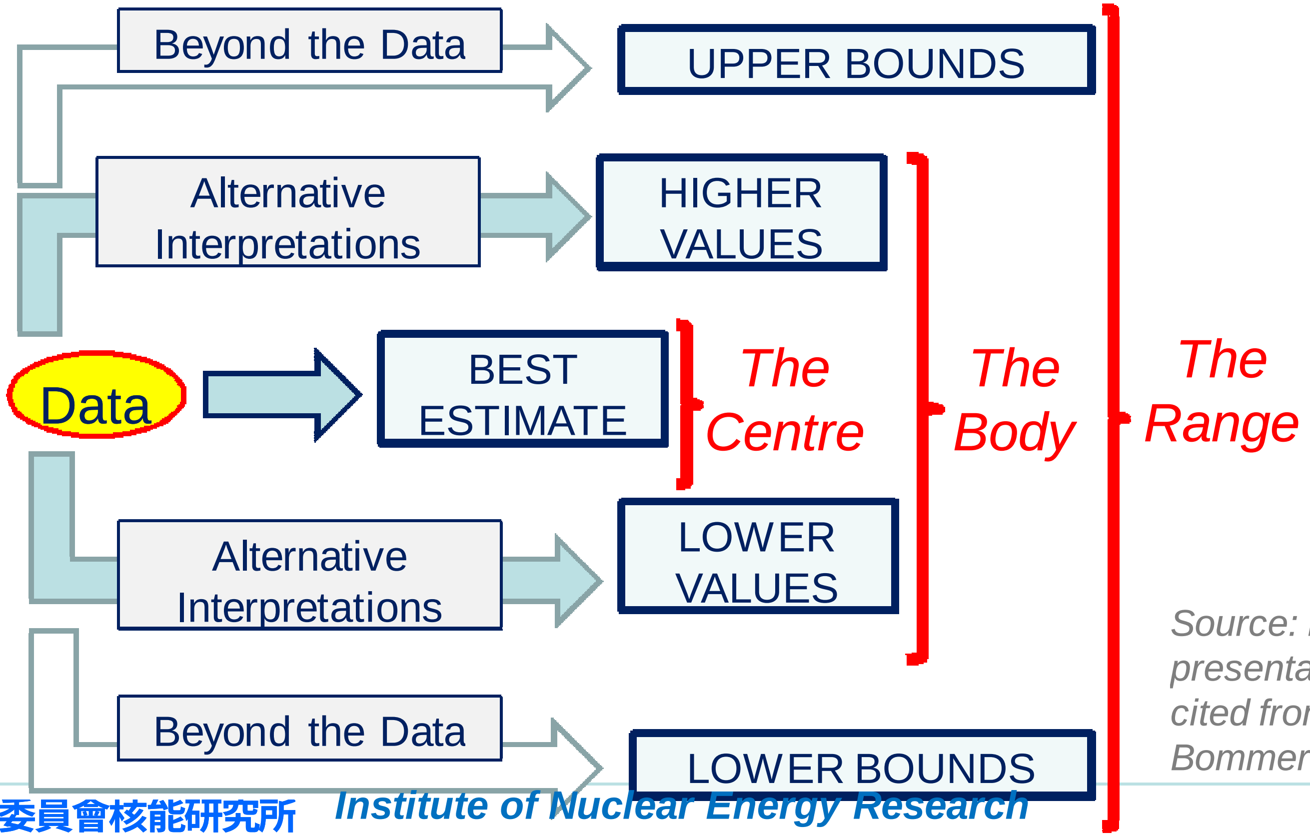
Figure 2. Comparison of the Mean 1 E-04 and 1 E-05 Uniform Hazard Response Spectra and the Performance-Based Ground Motion Response Spectrum (GMRS)

Strategy for Reducing Seismic Risk

- **TPC are performing SMA and SPRA, and seismic upgrade of structure, system, and components are on-going currently**
- **From ground motion aspect, soil improvement approach may be suitable for NPP2 and pile foundation retrofit is good for surface-found structures to reduce seismic risk**

SSHAC Level 3

- To enhance uncertainty integration in PSHA, SSHAC Level 3 provides the successful example for technically defensible interpretation on hazard calculation result, and INER strongly recommend to do
- TPC are willing to support Level 3 activities, particularly for solving the issue of HengChun Fault



Source: LCI presentation, cited from Bommer

Summary

- **Current seismic hazard analysis meets international standard to identify and characterize seismic source and ground motion model.**
- **Using RG 1.208, TPC can obtain better risk level from GMRS based on NRC's research, and the margin and risk assessment can be performed.**
- **The advanced integration and evaluation approach, SSHAC Level 3, has been introduced into Taiwan by INER, and local experts welcome it and are willing to cooperate with foreign senior experts to conduct it when the enforcement of NTTF is requested.**

Thank you for your attention