Debris Flow
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Landslide Hazard
Seismic Hazard
中興社防災科技研究中心
Reservoir
Infrastructure
Urban Disaster
Risk Analysis

Ground-Motion Prediction Equation (GMPE) for Taiwan

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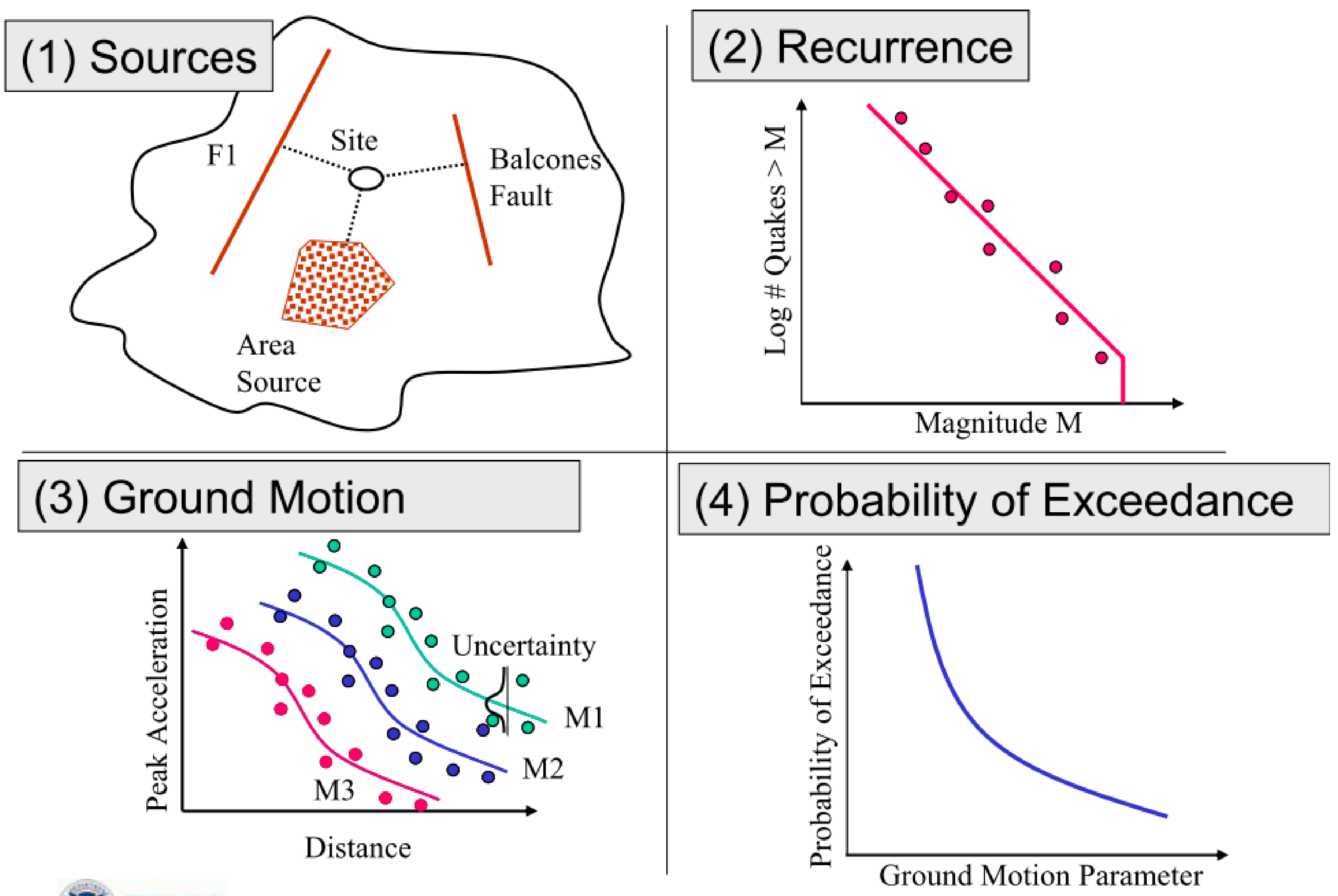
Outline

- Introduction of GMPE
  - Important component of PSHA
  - From attenuation equation to GMPE
  - Steps for building GMPE
- Taiwan’s GMPE – Past 、 Present 、 Future
- Conclusion
- Future work

Steps in Probabilistic Seismic Hazard Analysis



What is GMPE

- “Was”
  - Attenuation relations
  - Attenuation relationships
  - Attenuation equations
- It is an equation that can be used to predict the possible ground-motion value during a future earthquake.
- Most of then are “empirical”, and was developed from a set of ground-motion data with proper physical meaning

Why Call them "Ground-Motion Prediction Equations"

- "Attenuation Equations" is a poor term
  - They describe the INCREASE of amplitude with magnitude at a given distance
  - They describe the CHANGE of amplitude with distance for a given magnitude (usually, but not necessarily, a DECREASE of amplitude with increasing distance).

Art McGarr, 2006

Ground Motion Prediction Equations

- Empirical regressions of recorded data
- Estimate ground shaking parameter (peak ground acceleration, peak velocity, spectral acceleration or velocity response) as a function of

  (1) magnitude

  (2) distance

  (3) site
- May consider fault type (strike-slip, normal, reverse)

Art McGarr, 2006

Steps for building GMPE

- Establish database
- Select form of predictive equation
- Perform regression analyses
- Evaluate uncertainty

Combination of horizontal measurements

- Arithmetic mean (算數平均數)
- Both
- Geometric mean (幾何平均數)
- Largest component
- Random
- Resultant (a=a1*cosθ+a2*sinθ)
- Vectorial addition ($a_v = \sqrt{a_1(t)^2 + a_2(t)^2}$)
- GMRotI50

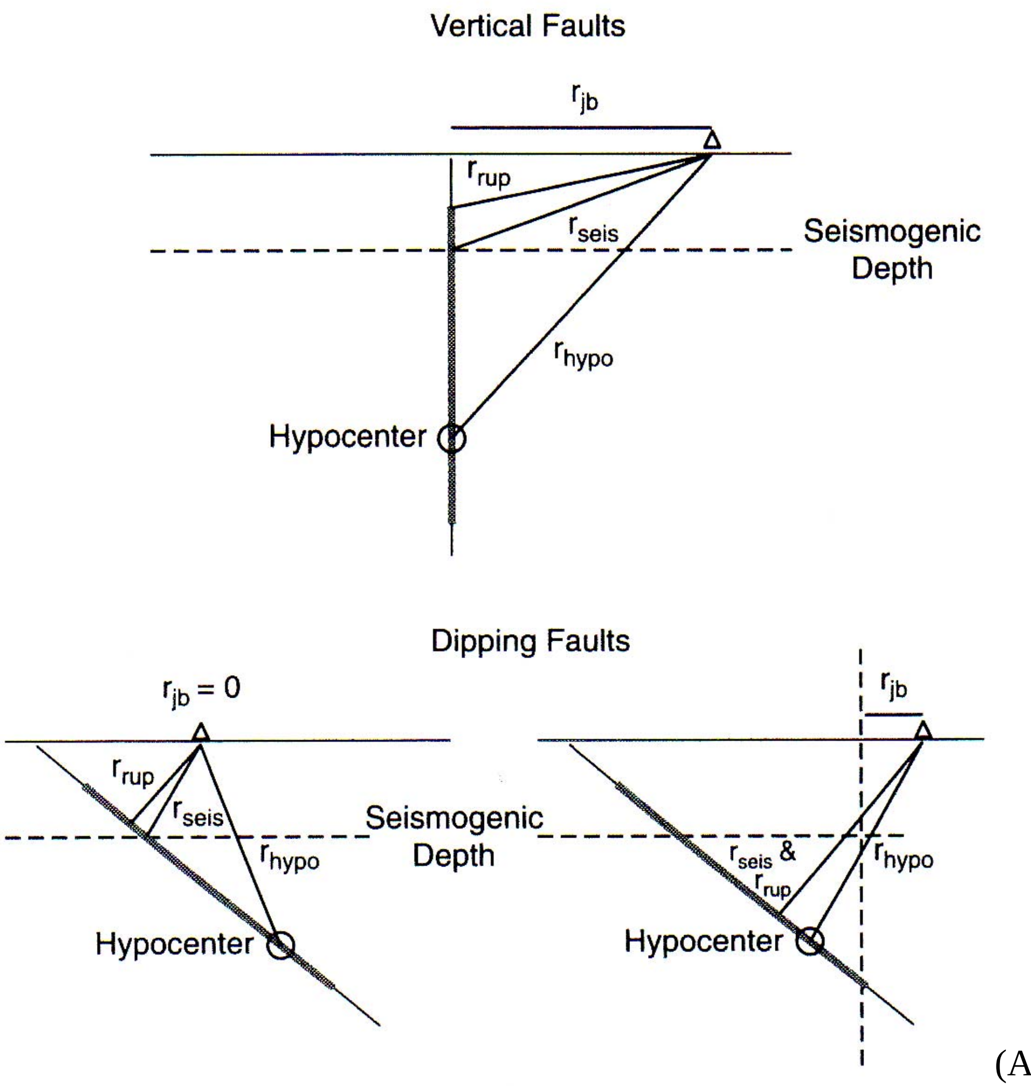
Characterisation of source

- Earthquake magnitude, *M*
  - M_L
  - M_S
  - m_b
  - M_W
- Source mechanism
  - Strike slip、normal faulting、reverse
- Tectonic setting
  - Crustal、subduction

Characterisation of path

- Definitions of source-to-site distance
  - Epicentral distance、hypocentral distance、rupture centroid distance、centre-of-energy-release distance、surface projection distance (R_{jb})、surface projection distance with focal depth、rupture distance (R_{rup})、seismogenic distance、average site to rupture end distance、equivalent hypocentral distance (EHD)

source-to-site distance



(Abrahamson and Shedlock, 1997)

Characterisation of site

- From data selection
- Multiplicative factor
- Shear-wave velocity (Vs30)

Form of the predictive equation

$$Y=f(M,R,P_i)$$

Y: Ground motion parameter of interest

– *M*: The magnitude of the earthquake
– *R*: Distance from the source to the particular site
– P_i: Other parameters (earthquake source, local site conditions, wave propagation path…)

Analysis techniques

- The majority of ground motion estimation studies use the ***ordinary least squares method***
- Two-stage method
- Non-linear regression
- Maximum-likelihood method (mixed effects method)

Author	Equation	Parameter	Region	Data	Events	Records
茅聲燾 (1978)	$Y = 0.3725e^{0.876M}D^{-1.836}$，$D=(R^2+400)^{1/2}$ (g)	*R*為震源距離	台灣地區	CWB震度	5	
Tsai & Bolt (1983)	$PGA = 17.5e^{0.869M}(R+0.0606e^{0700M})^{-1.09}$ (gal)	*R*為震源距離，M為芮氏規模(M_L)	台灣東北部	SMART-1	6	
倪與邱 (1991)	$\ln(PGA) = 6.09 + 0.26M - 0.87\ln(R+6.9)$ (gal)	*R*為震央距離，M為芮氏規模(M_L)	台灣地區(岩盤)	SMA-1	49	
Chiu and Ni (1993)	$\ln(PGA) = 4.15 + 1.41M_L - 2.37\ln(R+13.7)$ (gal)	*R*為震央距離，M為芮氏規模(M_L)	花蓮地區	SMART-2		
黃正耀 (1995)	$Y = 0.0253e^{1.5873M}(R+0.3155e^{0.6165M})^{-2.3027}$ (g)	*R*為測站至斷層破裂面之最短距離，M為芮氏規模(M_L)	台灣地區	TSMIP (7個地震)	7	526
劉坤松 (1996)	$Y = 0.0308e^{1.20M}(R+0.1413e^{0.6892M})^{-1.741}$ (g)	*R*為震源距離，M為芮氏規模(M_L)	台灣東北部地區	TSMIP		
羅俊雄 (1996)	$Y = 0.0267e^{1.354M}(R+0.2138e^{0.7499M})^{-1.0329}$ (g)	*R*為震源距離，M為芮氏規模(M_L)	台灣地區(岩盤)	SMA-1		
羅俊雄 (1996)	$Y = 0.0273e^{0.1058M}(R+0.141e^{0.656M})^{-1.6472}$ (g)	*R*為測站至斷層破裂面之最短距離，M為芮氏規模(M_L)	台灣地區	TSMIP		
辛在勤 (1998)	$PGA = 12.44e^{1.31M_L}r^{-1.487}$ (gal)	*r*為震源距離，M_L為芮氏規模(M_L)	台灣地區	TSMIP	22	
劉坤松 (1999)	$\ln(PHA)=-1.339\ln(r+2.12)-0.0071r+1.167M+2.192+G(1.475\ln(r)-6.792)$ $\ln(PVA)=-1.681\ln(r+2.45)-0.0036r+1.250M+2.210+G(1.009\ln(r)-4.464)$ $\ln(PHV)=-1.377\ln(r+1.67)-0.0023r+1.581M-3.070+G(1.066\ln(r)-4.909)$ $\ln(PVV)=-1.415\ln(r+1.58)-0.0012r+1.666M-$	r 為震源距，M 為地震矩規模	台灣地區	TSMIP	35	2187

Most used GMPE for the Engineer

Campbell's form

$$a = b_1\ e^{b_2 M} (R + b_4\ e^{b_5 M})^{-b_3}$$

Joyner and Boore's form

$$\log_{10}(a) = b_1 + b_2 M + b_3 \log_{10}\left[(R^2 + b_5^2)^{b_4}\right]$$

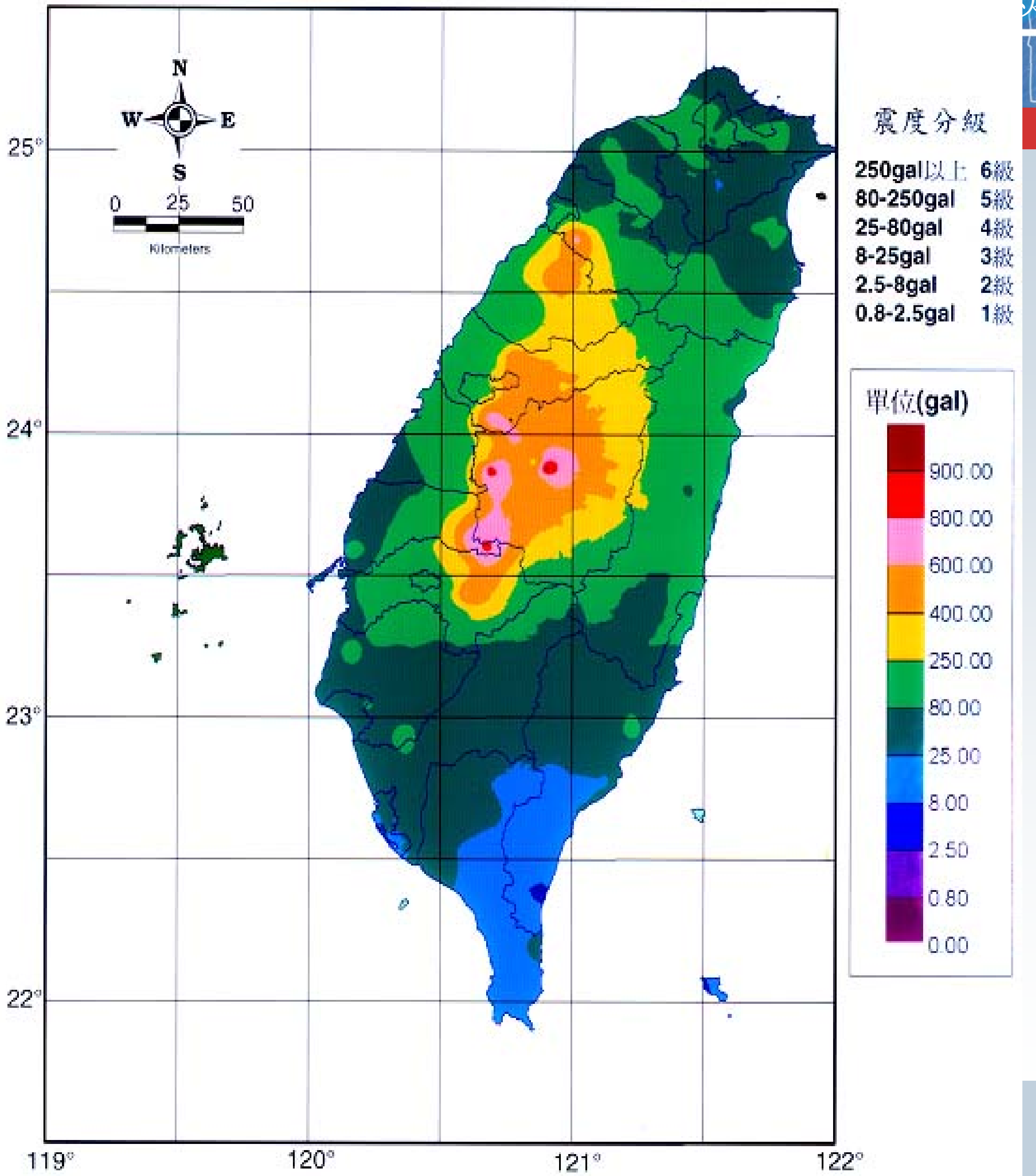
Kanai's form

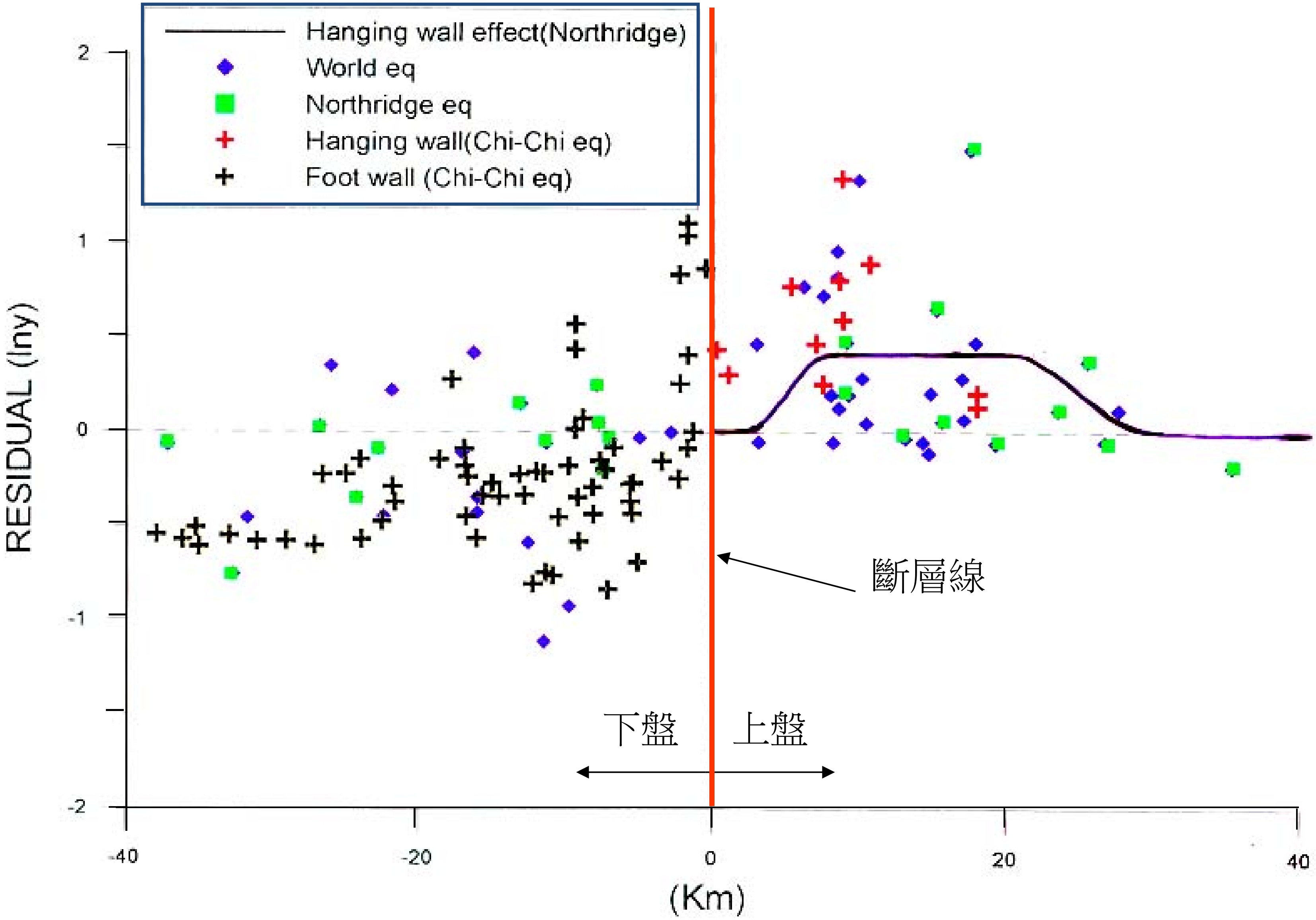
$$a = b_1\ e^{b_2 M}\ (R + b_4)^{-b_3}$$

Japan Rock Site's form

$$\log_{10}(0.981a) = \left(\frac{R + b_4}{b_5}\right) \cdot (-b_1 + b_2 M - b_3 M^2)$$

921集集地震台灣地區震度圖



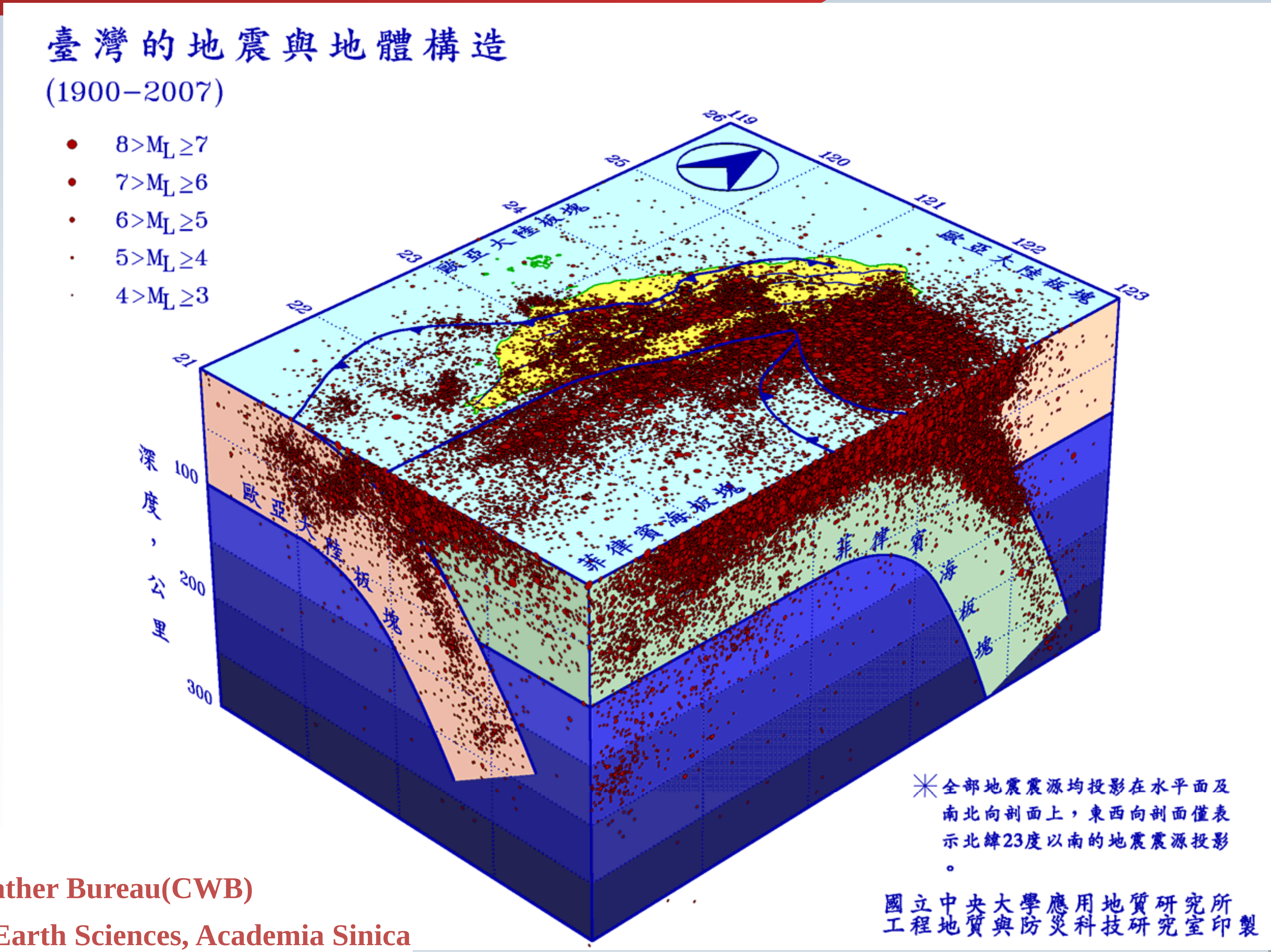


集集大地震與 Northridge 地震及世界其他大地震比較上盤效應

李錫堤等 (1999)			台灣地區美濃水庫	TSMIP		
Loh et al. (2000)	$Y = 0.02968e^{1.2\,M}(R+0.1464e^{0.698M})^{-1.7348}$ (g)	R為測站至斷層破裂面之最短距離，M為(M_W)?	台灣地區	TSMIP		
羅俊雄與溫國樑，2000	Spectral Acceleration at 80 periods (0.029~10 sec)		台灣地區	TSMIP		
Chang et al. (2001)	$\ln A = 2.8096 + 0.8993M – 0.4381 \ln D_p – (1.0954–0.0079 D_p) \ln D_e$ $\ln A=4.7151 + 0.8468M–0.1745 \ln D_p –1.2972 \ln D_h$	D_e、D_h、D_p分別為震央距、震源距與震源深度(km)	台灣地區	TSMIP	45 19	
趙曉玲 (2001)			台灣地區	TSMIP	9	3104
Wu et al. (2001)	$\log10(PGA)=0.00215+0.581M-\log10(r_{rup}+0.00871\times100.5M)-0.00414r_{rup}$ $\log10(PGV)=-2.49+0.810M-\log10(r_{rup}+0.00871\times100.5M)-0.00268r_{rup}$	M為地震矩規模M_W，r_{rup}為距斷層破裂面距離(km)	台灣地區	TSMIP	60	1941

Jean(2001)	$Y = 0.00369e^{1.75377M}(R+0.12220e^{0.78315M})^{-2.05644}$	震央距以及距斷層面最短距離	台灣地區	TSMIP		
Liu and Tsai (2005)			台灣地區	TSMIP	51	7900
Jean et al. (2006)	$PGA = 0.0028e^{1.7331M}(R+0.0999e^{0.7719M})^{-2.0639}$ $Sa03 = 0.0079e^{1.7253M}(R+0.1199e^{0.7850M})^{-2.0489}$ $Sa10 = 0.0027e^{1.7731M}(R+0.1154e^{0.7714M})^{-2.0419}$	堅硬地盤, M_L ,震央距以及距斷層面最短距離	台灣地區	TSMIP		
吳芳儒 (2008)	$\ln Y_{ij} = C_1+C_2M_i+C_3(R_{ij}+C_5 10^{C_6M_i})+C_4\ln(R_{ij}+C_5 10^{C_6M_i})$ $\begin{cases}BC\\DE\end{cases}$ $\ln Y_{ij} = C_1+C_2M_i+C_3(R_{ij}+C_5 10^{C_6M_i})+C_4\ln(R_{ij}+C_5 10^{C_6M_i})+C_7\ln(V_{S30j})$ $\ln Y_{ij} = C_1+C_2M_i+C_3(R_{ij}+C_5 10^{C_6M_i})+C_4\ln(R_{ij}+C_5 10^{C_6M_i})+C_7\ln(A_j)$	地震矩規模（Mw）震央距	台灣地區 (2006屏東地震)	TSMIP	3 (186)	921 (5852)
Lin and Lee (2008)	Subduction zone earthquake	地震矩規模Mw 距斷層面最短距離 (R_{rup})	台灣地區 (隱沒帶)	TSMIP	54	4823
Lin et al.(2011)	Crustal earthquake (hanging-wall, footwall)	地震矩規模Mw 距斷層面最短距離 (R_{rup})	台灣地區 (地殼地震)	TSMIP	52	5268
Lee et al. (2012)	Arias Intensity	地震矩規模Mw 距斷層面最短距離 (R_{rup})	台灣地區	TSMIP	62	6570

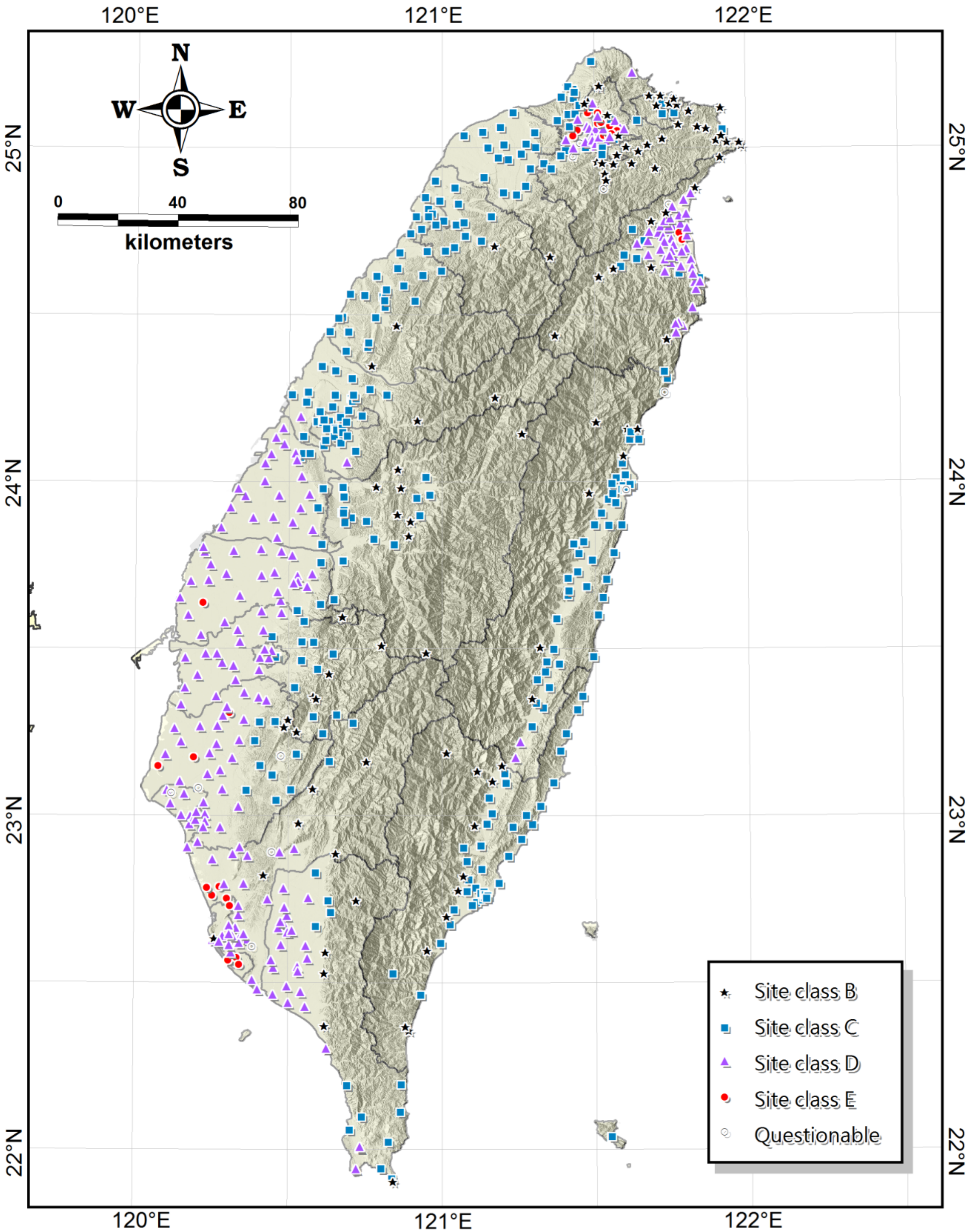
Seismotectonic framework of Taiwan



Data source:

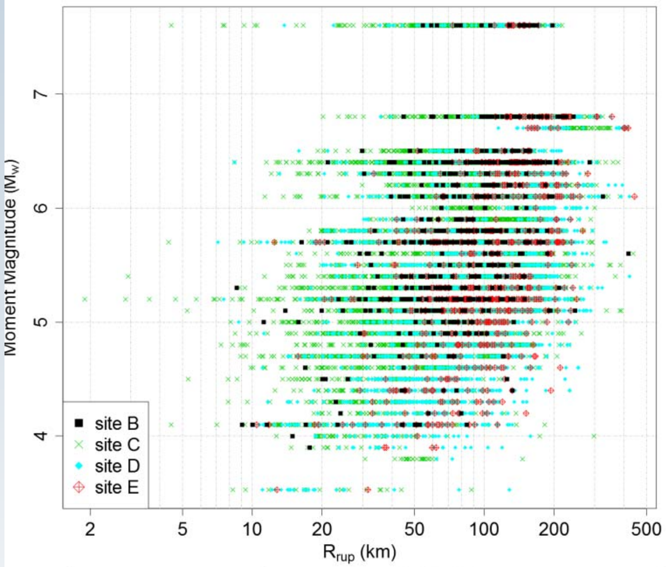
1.Central Weather Bureau(CWB)

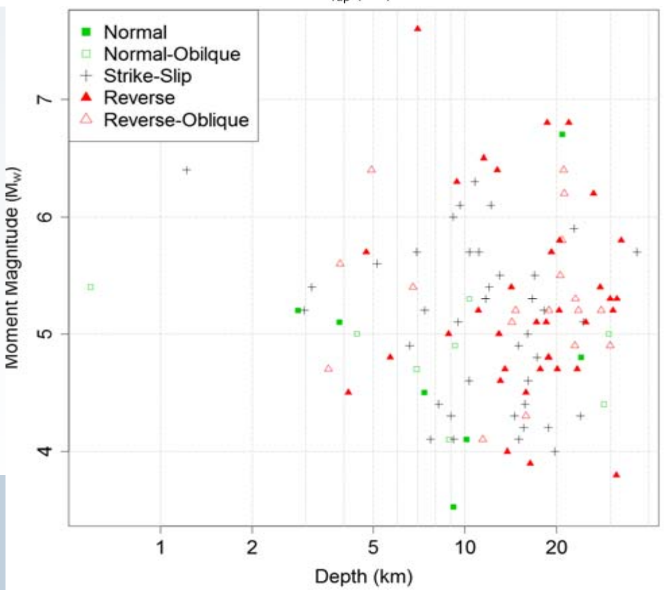
2.Institute of Earth Sciences, Academia Sinica

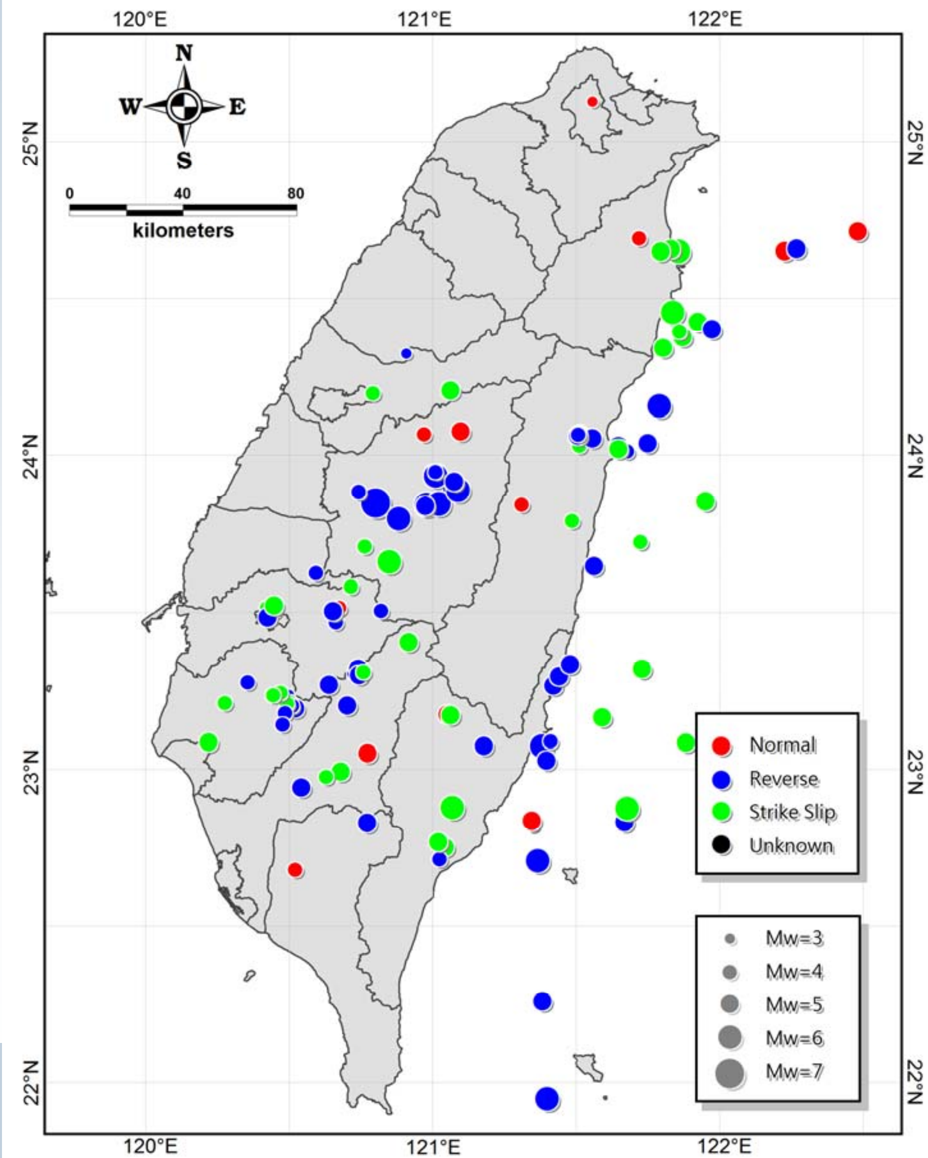


120°E
121°E
122°E
25°N
24°N
23°N
22°N
N
W
E
S
0
40
80
kilometers
Site class B
Site class C
Site class D
Site class E
Questionable

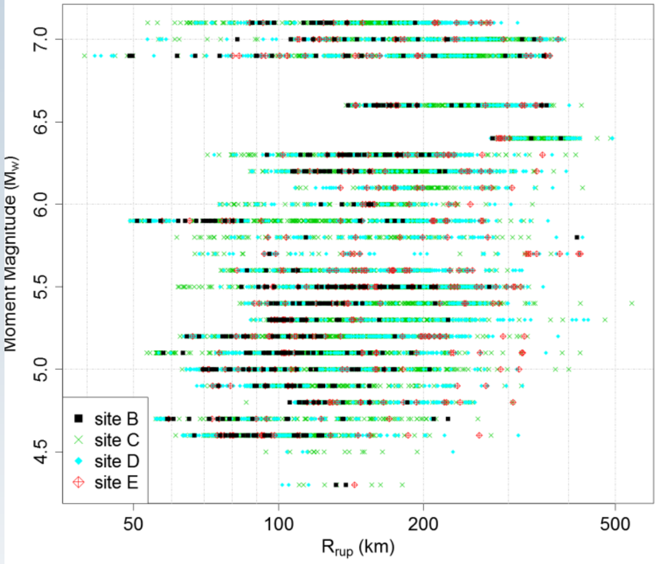
Strong-motion data for GMPE – Crustal

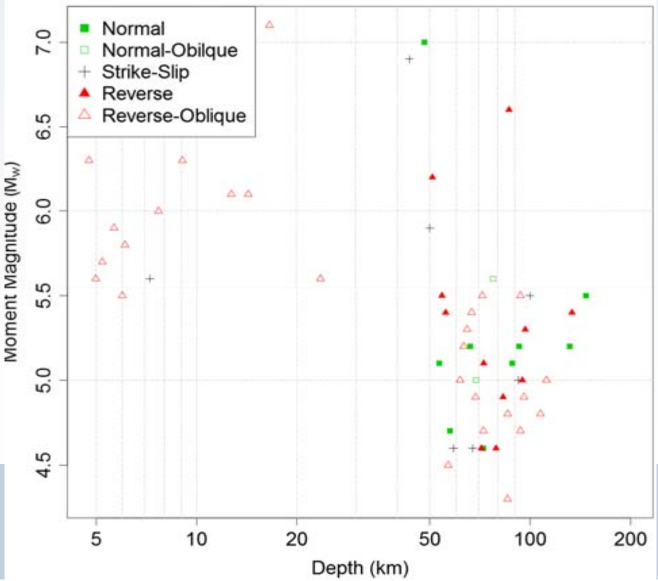


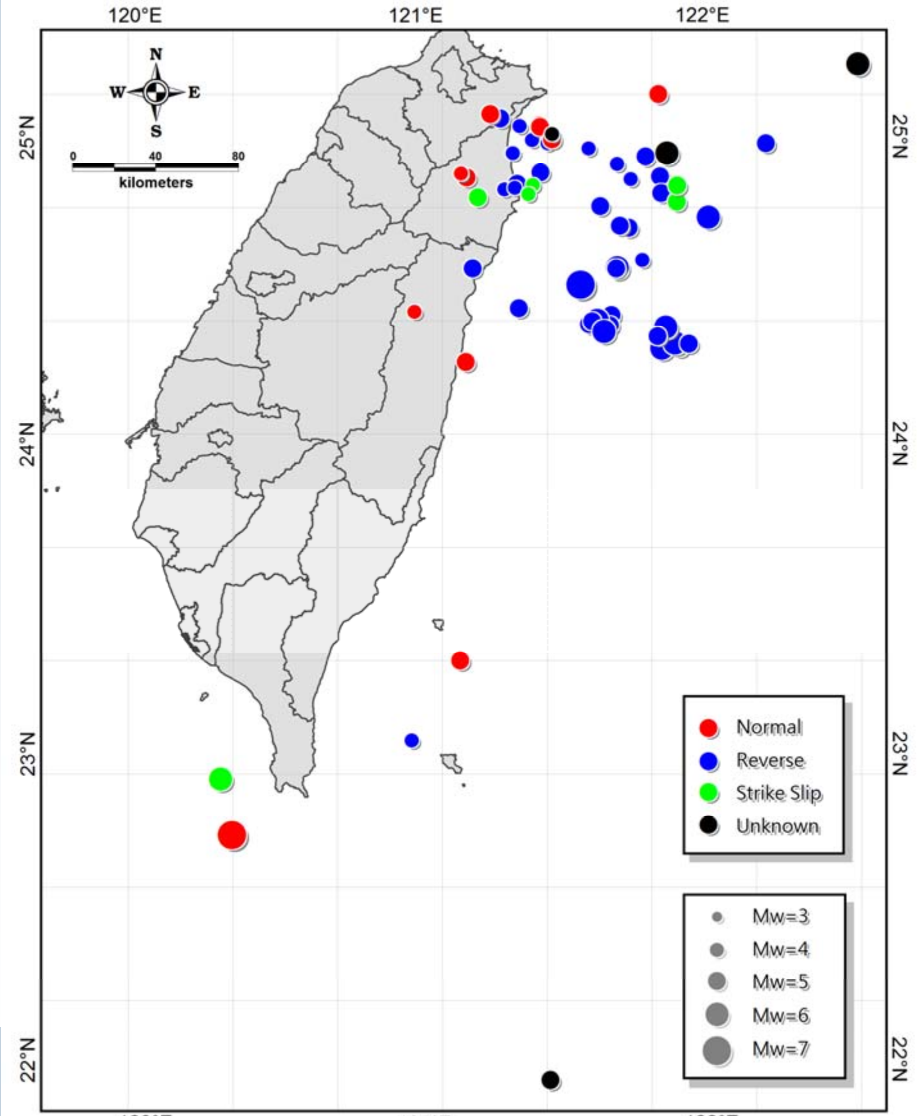




Strong-motion data for GMPE – Subduction





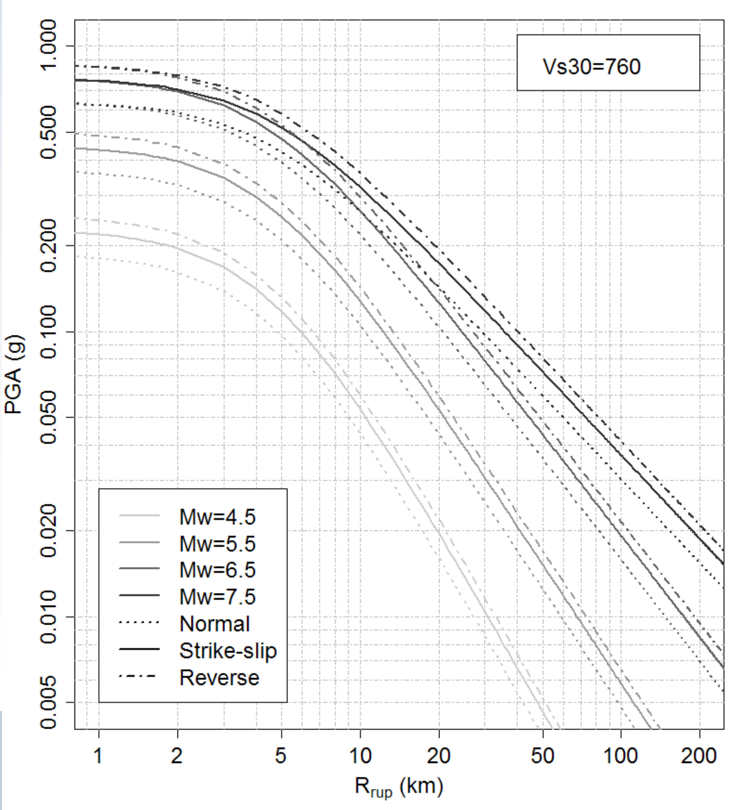


Ground-motion prediction equation

For Crustal Earthquake

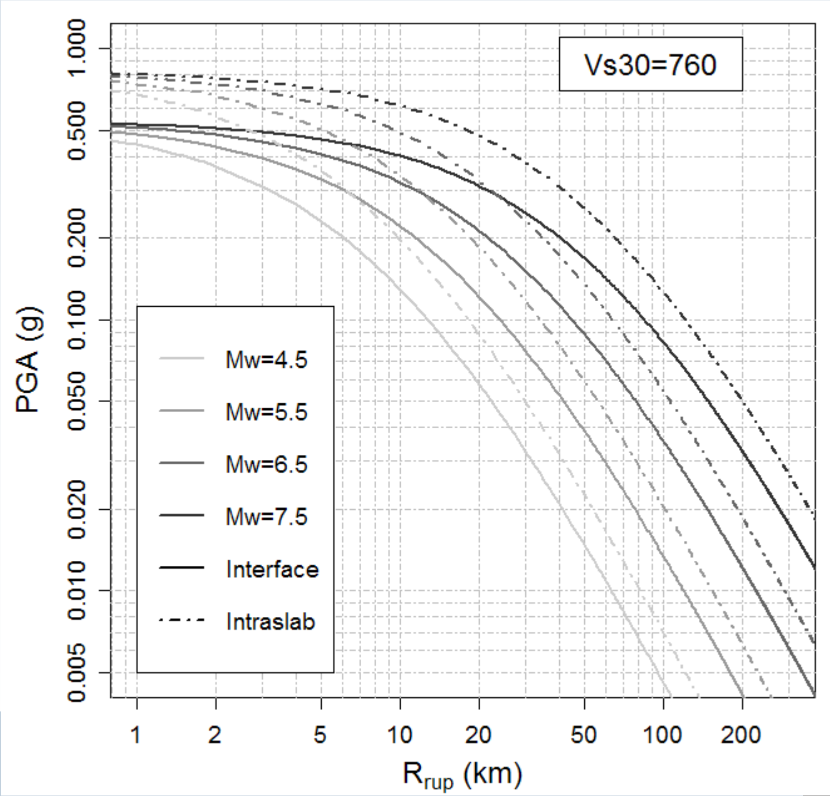
$$\ln y = C_1 + F_1 + C_3(8.5 - M_W)^2 + (C_4 + C_5(M_W - 6.3))\ln(\sqrt{(R^2 + \exp(H)^2)}) + C_6 F_{NM} + C_7 F_{RV} + C_8 \ln(VS_{30}/1130)$$

$$\begin{cases} F_1 = C_2(M_W - 6.3) & \text{Where} \quad M_W \le 6.3 \\ F_1 = (-H \cdot C_5)(M_W - 6.3) & \text{Where} \quad M_W > 6.3 \end{cases}$$

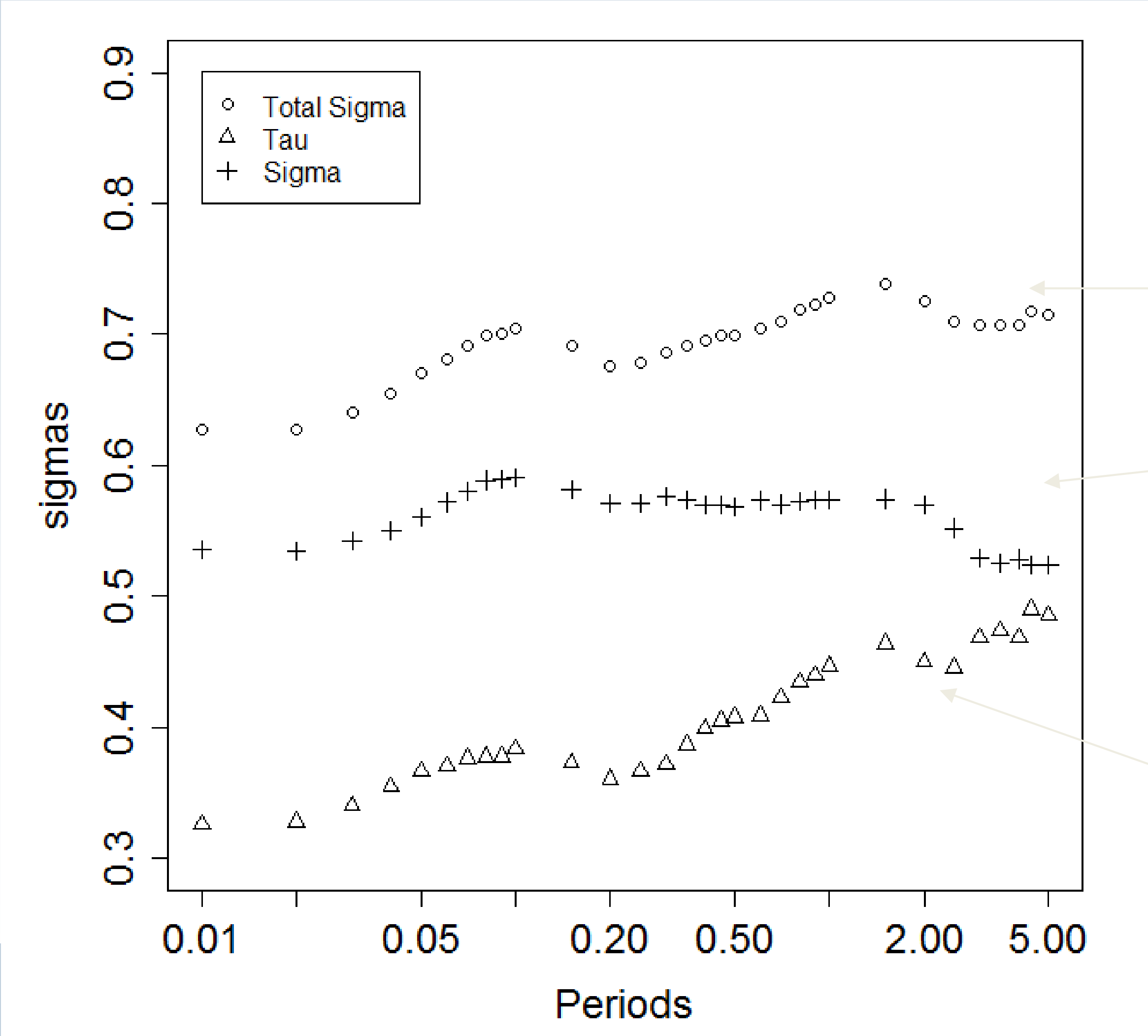


For Subduction zone earthquake

$$\ln y = C_1 + C_2 M + C_3 \ln\left(R + C_4 e^{C_5 M}\right) + C_6 H + C_7 Z_t + C_8 \ln(Vs_{30}/1130)$$



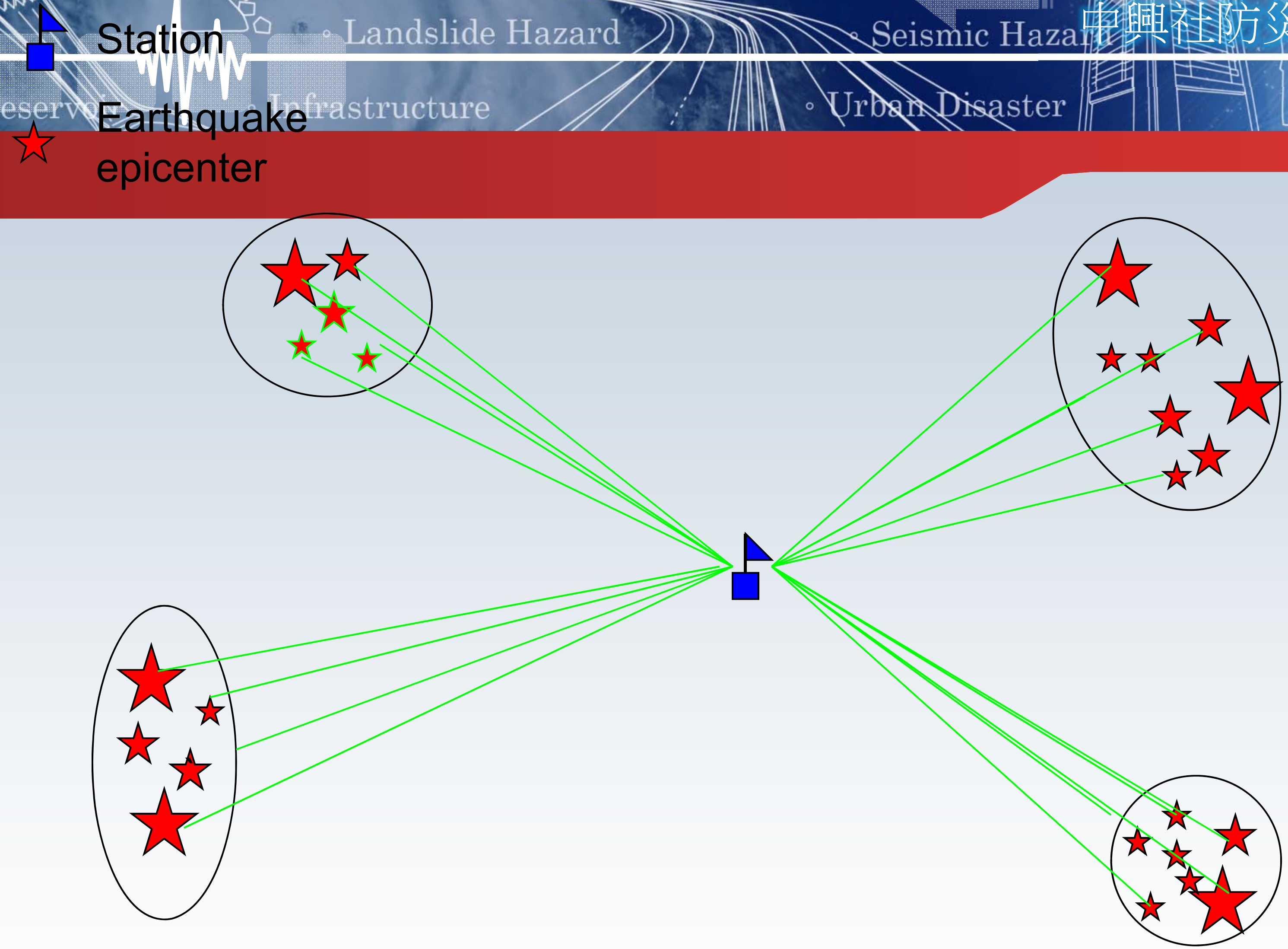
Variation of the standard deviation in the SA equation with periods from 0.01-5.0 sec

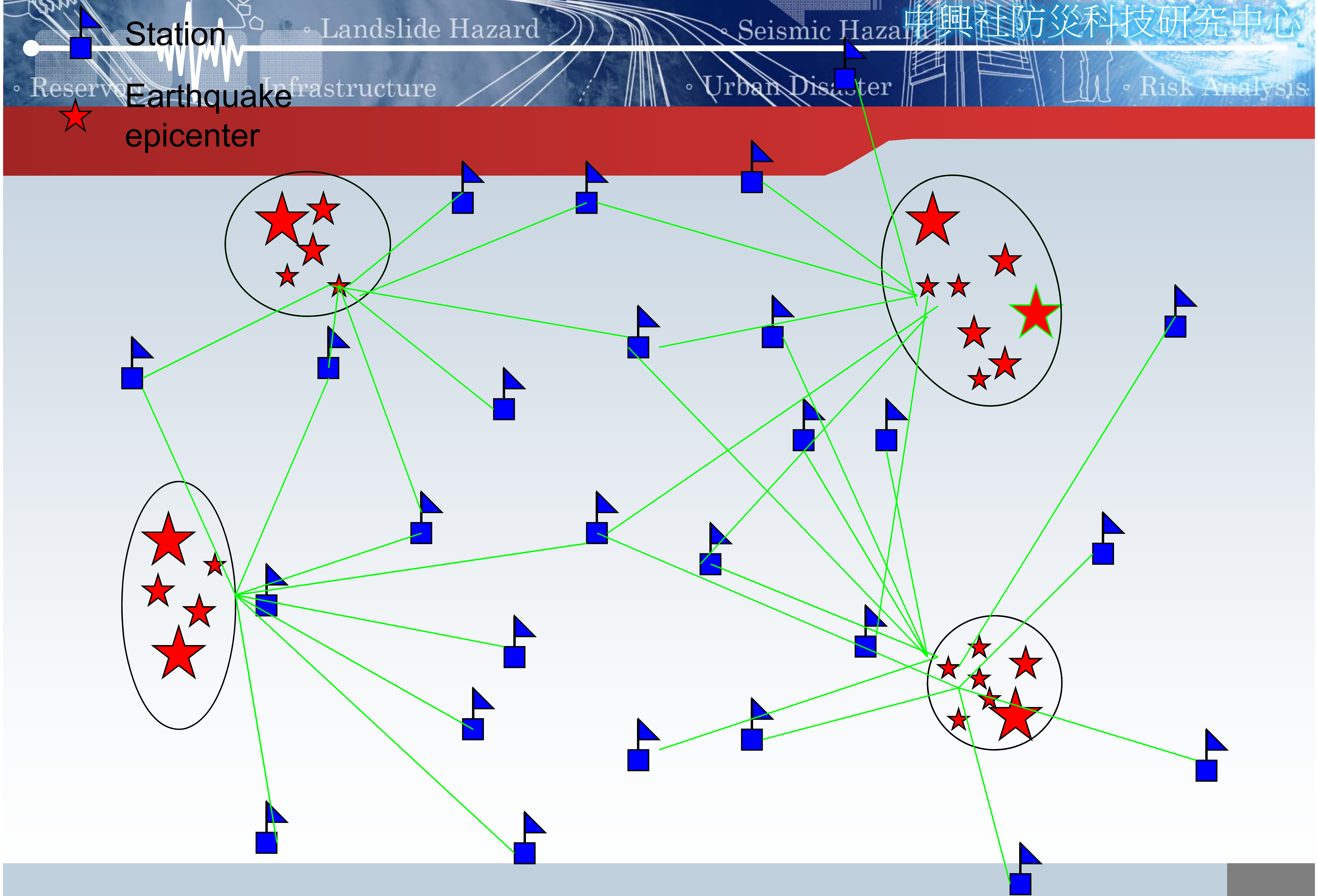


Total sigma

Intra-event sigma (σ)

Inter-event sigma (τ)


Station
Earthquake epicenter


Station
Earthquake epicenter

The notations

- i → event
- k → station
- l → region
- Residuals
  - Intra-event, ξ_{ik} inter-event η_i
  - Inter-station, ξ_{sk} intra-station ξ_{rik}
  - Inter-path, ξ_{pkl} intra-path ξ_{0ik}
  - Inter-region, η_{SR_l} intra-region η_{0_i}
- Standard deviations
  - Intra-event, σ inter-event τ
  - Inter-station, σ_s intra-station σ_r
  - Inter-path, σ_p intra-path σ_0
  - Inter-region, τ_{SR} intra-region τ_0

Following the notation of Walling (2009)

Decomposition of the variability of empirical ground motion prediction equation - conclusion

$$\sigma_T = \sqrt{\tau^2 + \sigma^2}$$

$$\sigma_T = \sqrt{\tau_{SR}^2 + \tau_0^2 + \sigma_s^2 + \sigma_p^2 + \sigma_0^2}$$

Inter-event

$$\tau^2 = \tau_{SR}^2 + \tau_0^2$$

small source region

unexplained inter-event variability

Intra-event

$$\sigma^2 = \sigma_s^2 + \sigma_r^2$$

Inter-site (site-term)

record-to-record

$$\sigma_r^2 = \sigma_p^2 + \sigma_0^2$$

unexplained intra-event variability

path-to-path

$$\sigma^2 = \sigma_s^2 + \sigma_p^2 + \sigma_0^2$$

Single-path sigma $\sigma_{sp} = \sqrt{\tau_0^2 + \sigma_0^2}$

Single-site sigma (single-station sigma) $\sigma_{ss} = \sqrt{\tau^2 + \sigma_r^2}$

Reduction of the inter-event, intra-event, and total standard deviation from the TSMIP data, if the ergodic assumption is removed

	Single Site		Single Path		
	Total	Intra-event	Total	Inter-Event	Intra-Event
	σ_{SS}	σ_r	σ_{SP}	τ_0	σ_0
PGA	$0.91\sigma_T$	0.86σ	$0.54\sigma_T$	0.69τ	0.43σ
T=0.1	$0.88\sigma_T$	0.81σ	$0.53\sigma_T$	0.69τ	0.42σ
T=0.3	$0.90\sigma_T$	0.86σ	$0.60\sigma_T$	0.69τ	0.55σ
T=0.5	$0.89\sigma_T$	0.83σ	$0.61\sigma_T$	0.69τ	0.57σ
T=1.0	$0.86\sigma_T$	0.75σ	$0.59\sigma_T$	0.69τ	0.51σ
T=3.0	$0.86\sigma_T$	0.69σ	$0.60\sigma_T$	0.69τ	0.51σ

Correlation of notation differences for components of variability from previous studies with the current study

Standard Deviation	This Study	Chen & Tsai (2002)	Atkinson (2006)	Morikawa et al (2008)
Total	σ_T		σ_{reg}	δ
Inter-event	τ	σ_E		τ (no correction)
Intra-event	σ			σ (no correction)
Inter-site	σ_S	σ_S		
Single site, record-to-record	σ_r	σ_r		
Inter-path	σ_P			
Intra-event, Single Path	σ_0			σ (applied correction)
Inter-source region	τ_{SR}			
Inter-event, Single Region	τ_0			τ (applied correction)
Single Site (total)	σ_{SS}		σ_i	
Single Path (total)	σ_{SP}		σ_{ie}	(applied correction)

Comparison of single-path standard deviations (σ_{SP}) as a fraction of σ_T

	This Study	Atkinson (2006)	Morikawa et al. (2008)
PGA	$0.54\sigma_T$	$0.67\sigma_T$	$0.46\sigma_T$
T=0.1	$0.53\sigma_T$		$0.38\sigma_T$
T=0.3	$0.60\sigma_T$	$0.68\sigma_T$	$0.44\sigma_T$
T=0.5	$0.61\sigma_T$		$0.45\sigma_T$
T=1.0	$0.59\sigma_T$	$0.67\sigma_T$	$0.47\sigma_T$
T=3.0	$0.60\sigma_T$		$0.47\sigma_T$

Conclusion

- More and more strong-motion data
- Strong ground motion parameters
  - PGA, PGV, PGD, Ia and Sa
- Including crustal earthquake and subduction zone earthquake
- Source-to-site distance
  - From epicenter distance to the closest distance to fault rupture plane
- Site parameters
  - From rock/soil to Vs30
- Hanging-wall and footwall

Future work

- For GMPE
  - More predictor variables for source, path and site
  - Directivity
  - Nonlinear site effect
  - Strong-motion difference due to various stress drop
- For Ground-motion prediction
  - Empirical approach
  - Seismological approach
    - Empirical Green's functions (EGFs)
    - Stochastic Green's functions (SGFs)
    - Hybrid Green's functions (HGFs)

Thank you for your attention.