NARLabs
National Applied Research Laboratories
National Center for Research on Earthquake Engineering

臺灣地區隨機式地動模擬技術之工程應用開發

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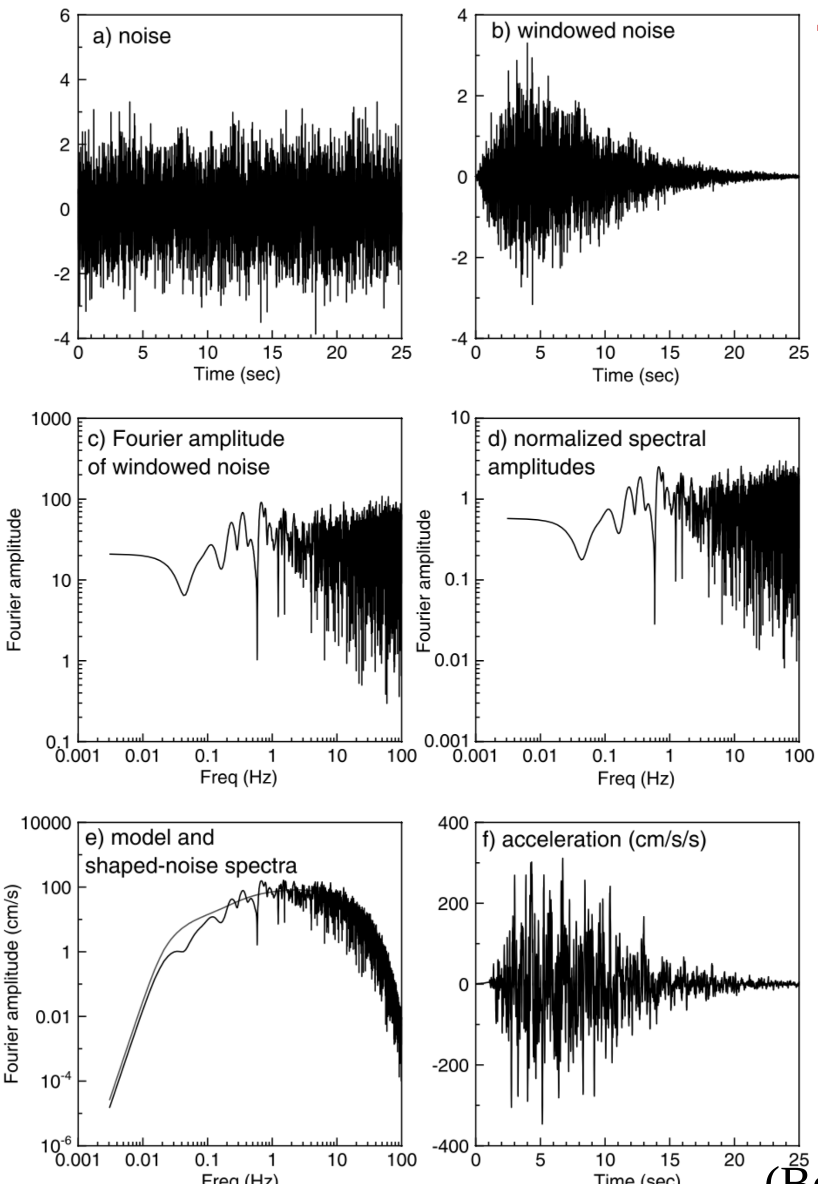
2018.08.28

Outlines

- Introductions.
- Site Correction from ETF.
- Applications.

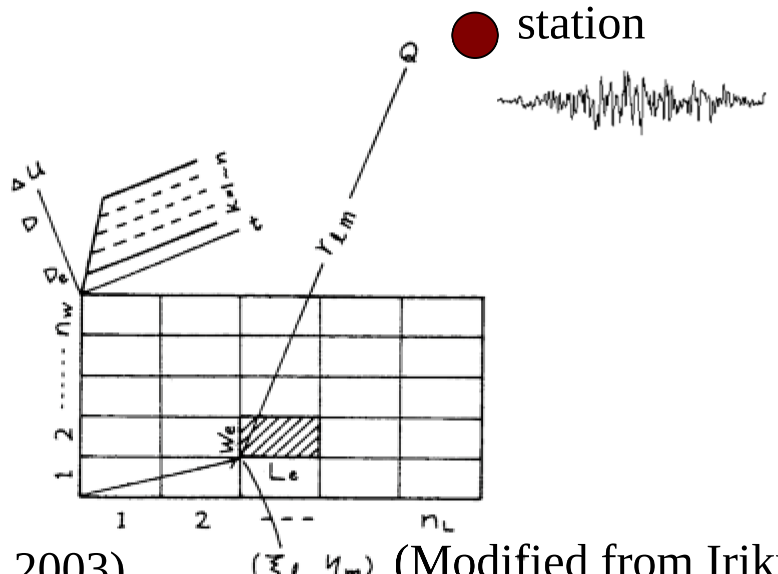
NARLabs

Introductions



(Boore, 2003)

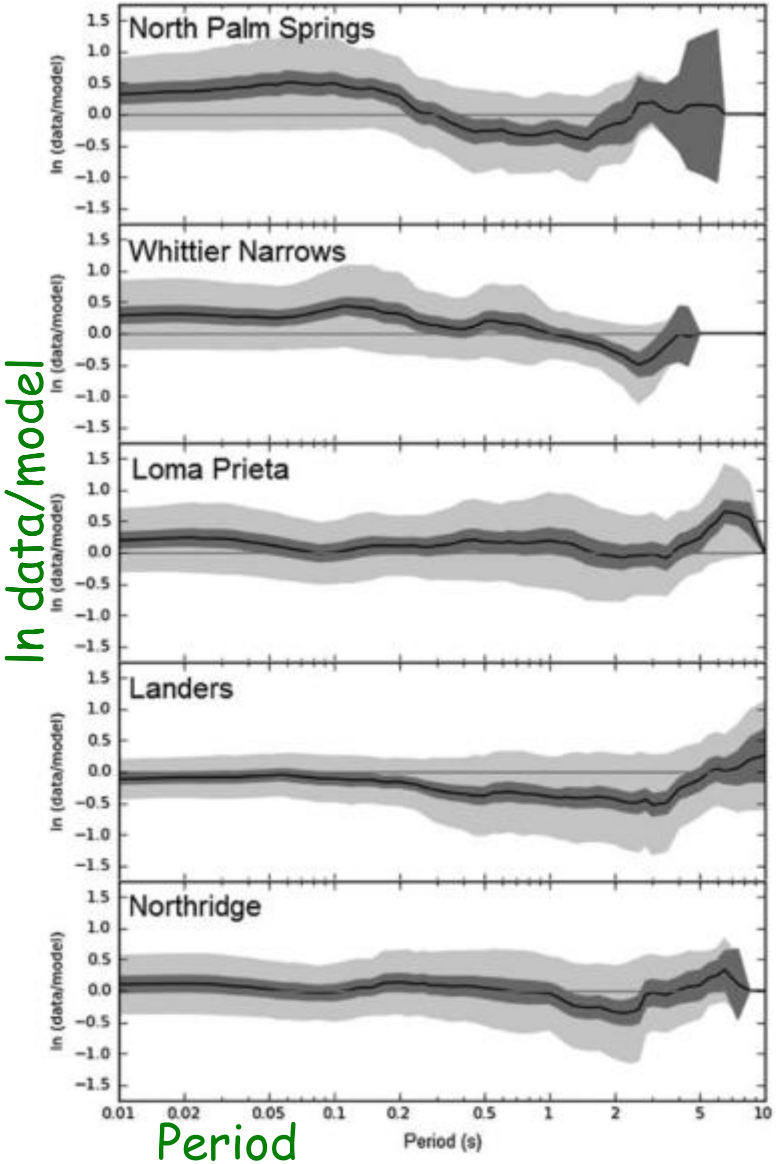
- SMSIM (Boore, 1983; Boore, 2003; Boore, 2009)：點震源。
- EXSIM (Motazedian and Atkinson 2005; Assatourians and Atkinson 2007; Boore 2009): 有限斷層。

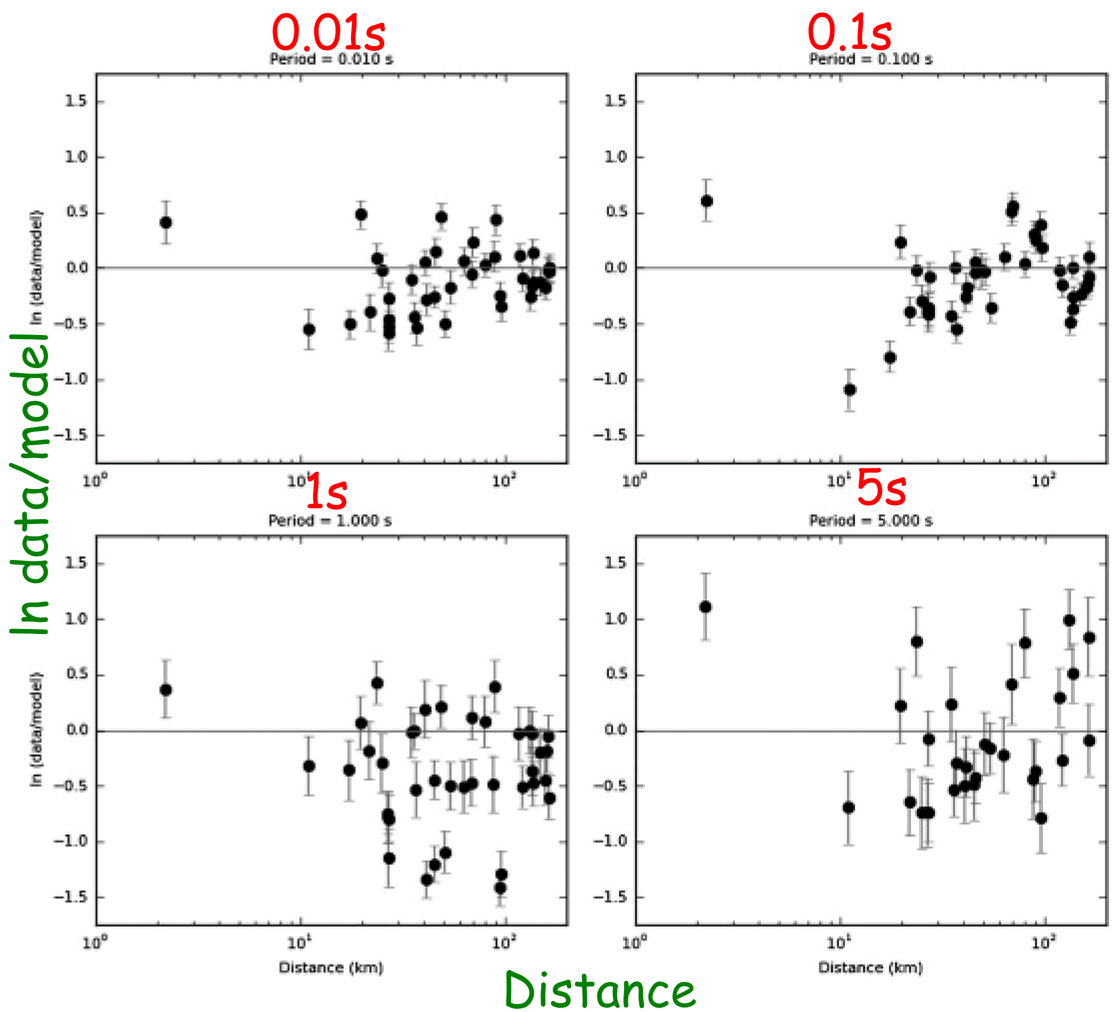


(Modified from Irikura, 1983)

NARLabs

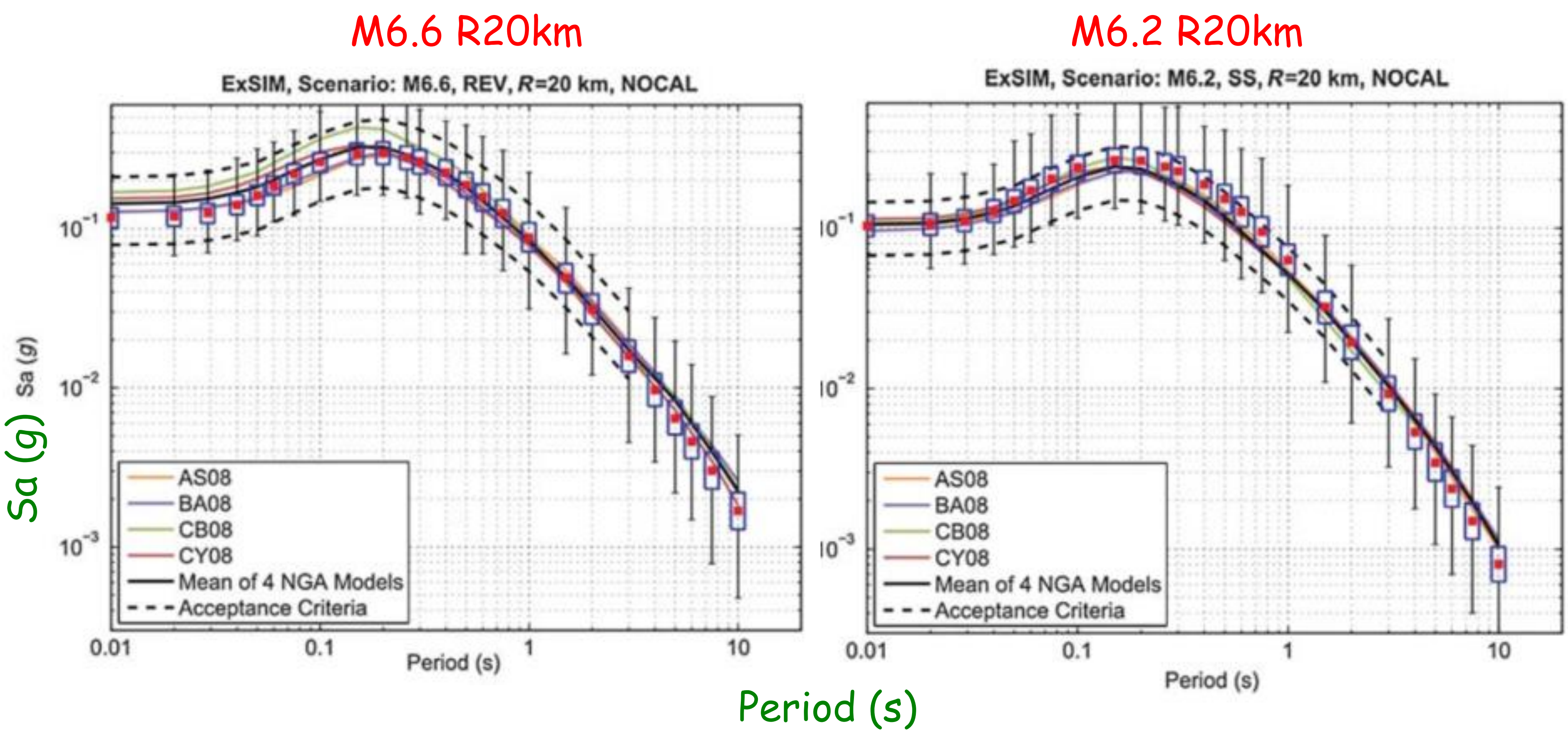
Introductions





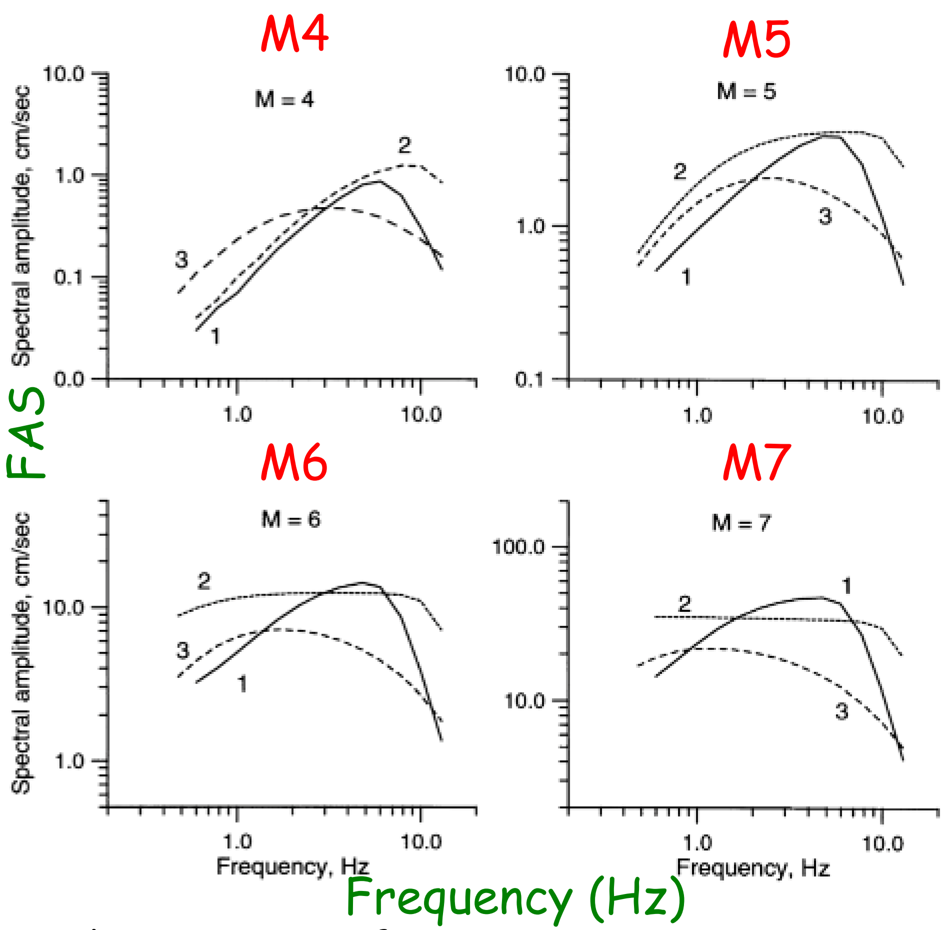
(Atkinson and Assatourians, 2015 for SCEC BBP)

Introductions



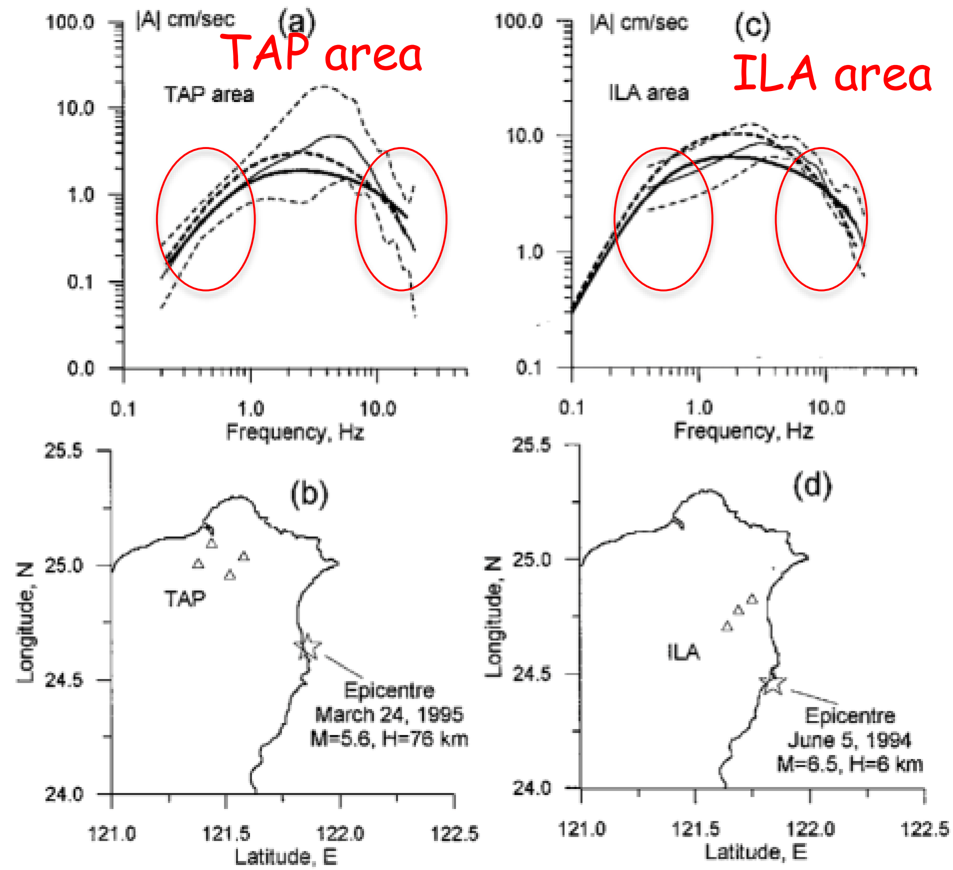
(Atkinson and Assatourians, 2015 for SCAC BBP)

Introductions



Rock response of
1 Ratchi (高加索地區)
2 Spitak (亞美尼亞地區)
3 Taiwan

(Sokolov, 2000)

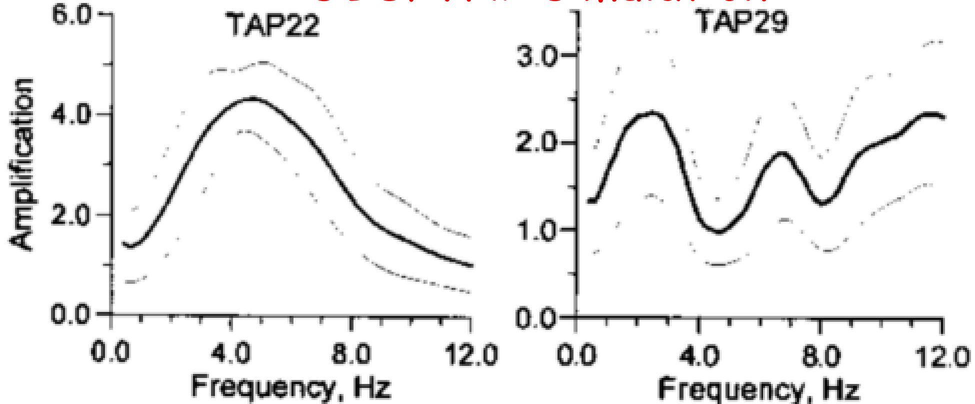


Theoretical VHR FAS (Taiwan)
(ENA BJ97)
Average observation FAS

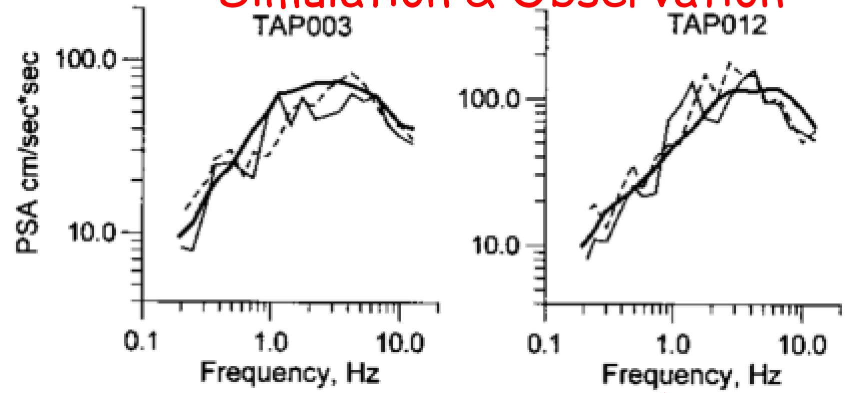
(Sokolov et al., 2000)

Introductions

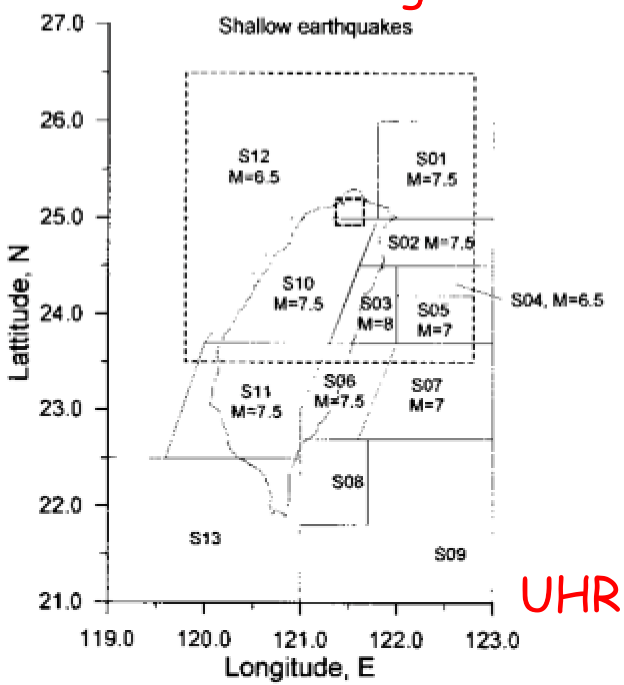
OBS/VHR simulation

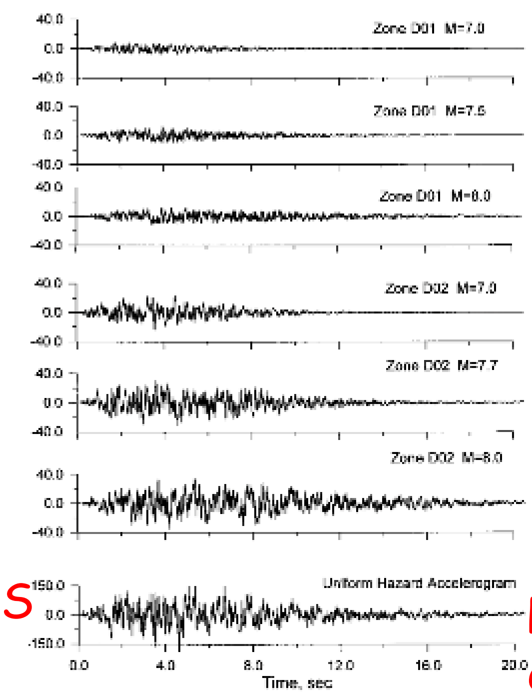


Simulation & Observation



Hazard Zoning

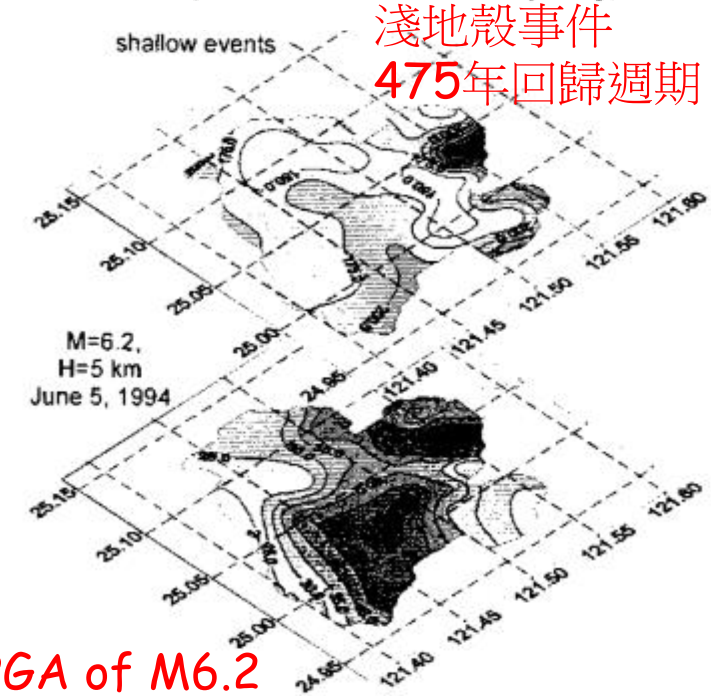




UHRS

淺地殼事件

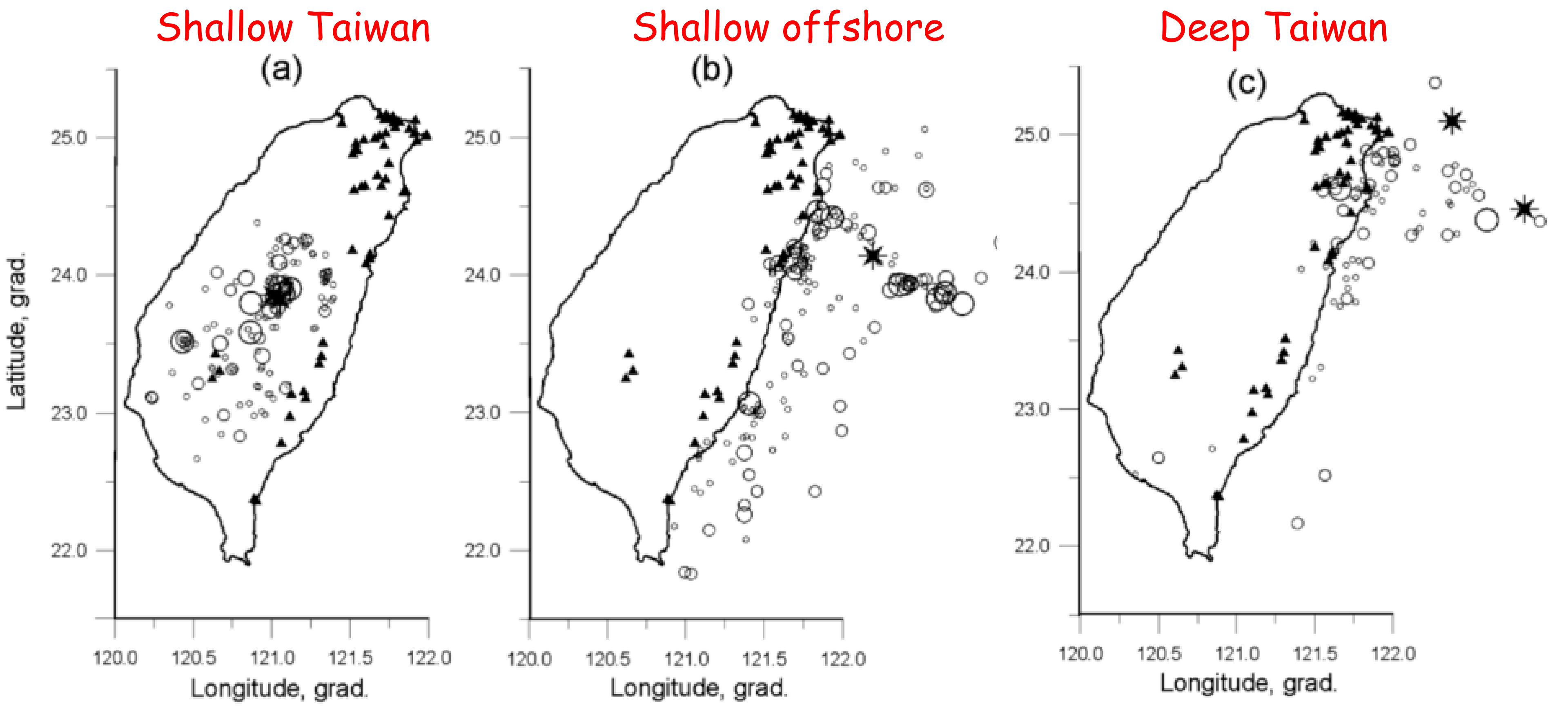
475年回歸週期



PGA of M6.2 earthquake

(Sokolov et al., 2001)

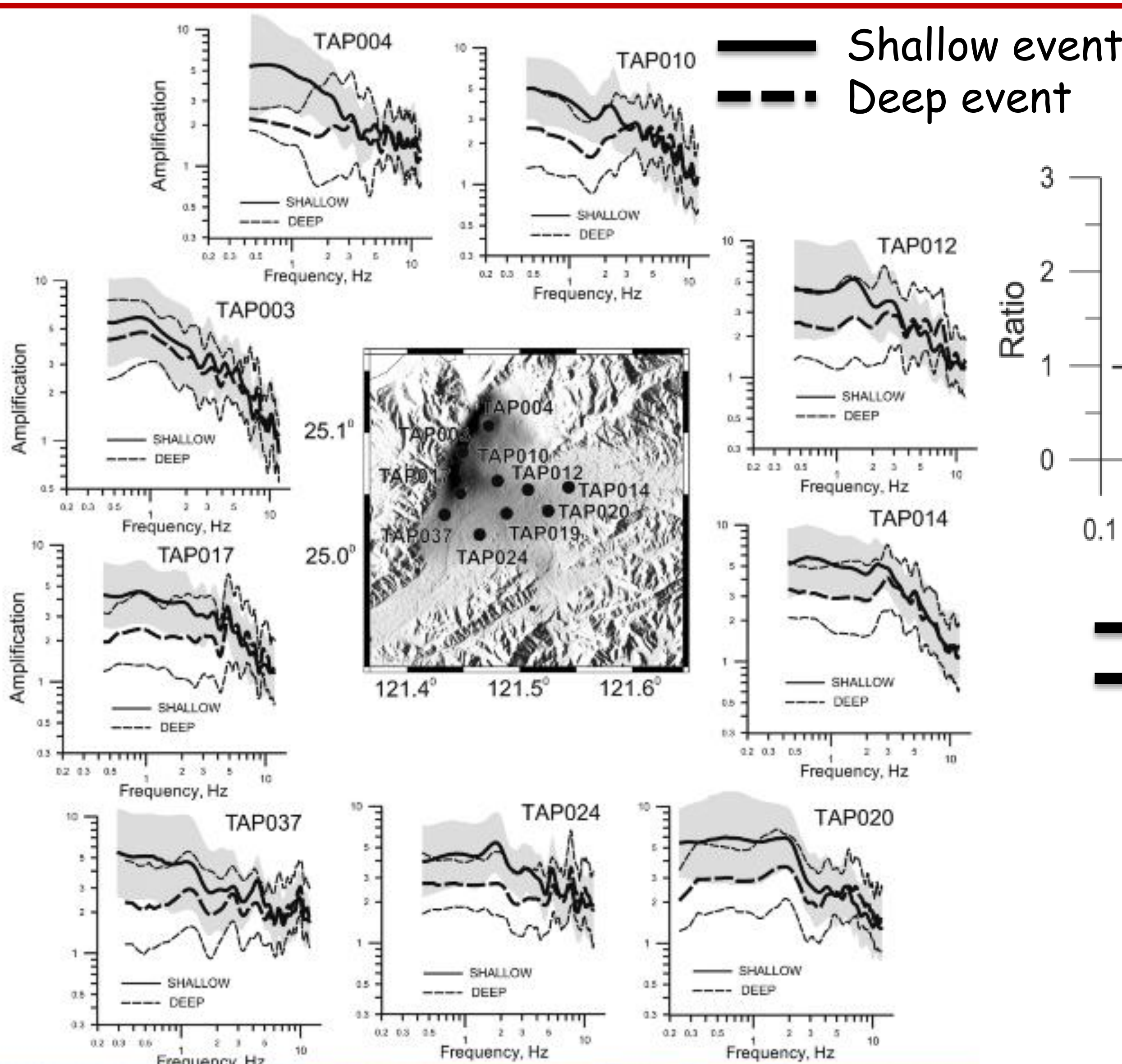
Introductions

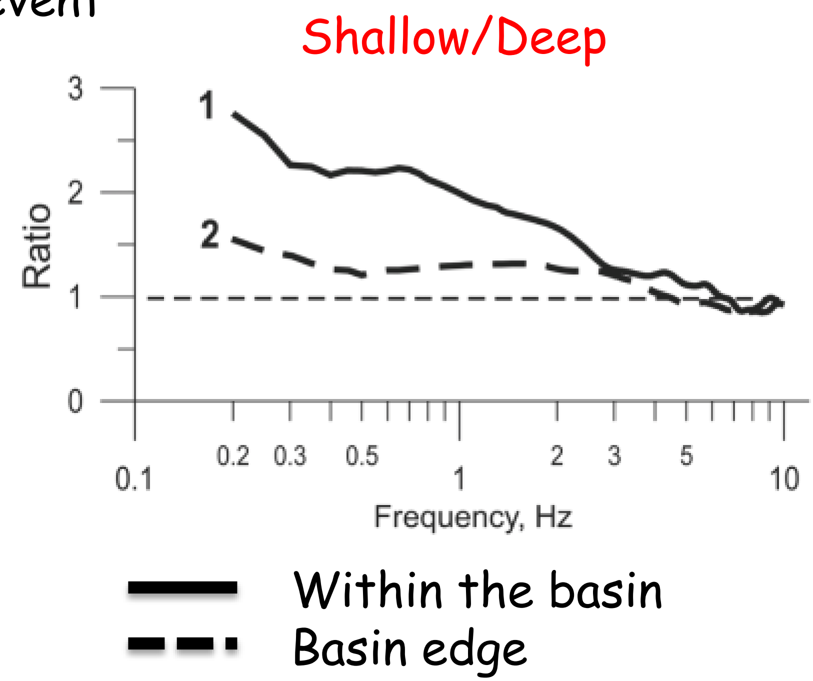


Solve source scaling from different regions with three attenuation models.

(Sokolov et al., 2006)

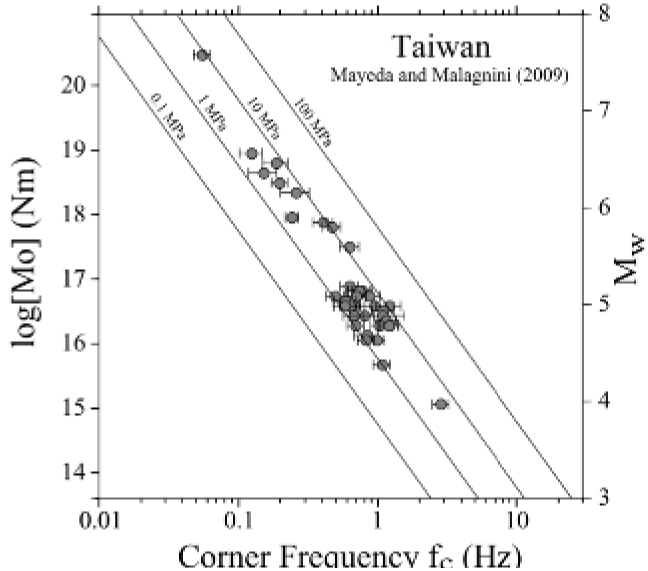
Introductions

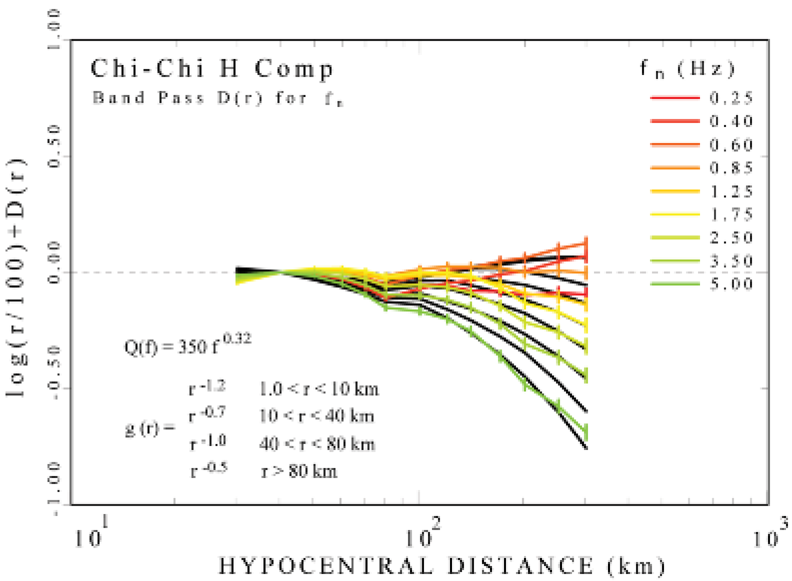


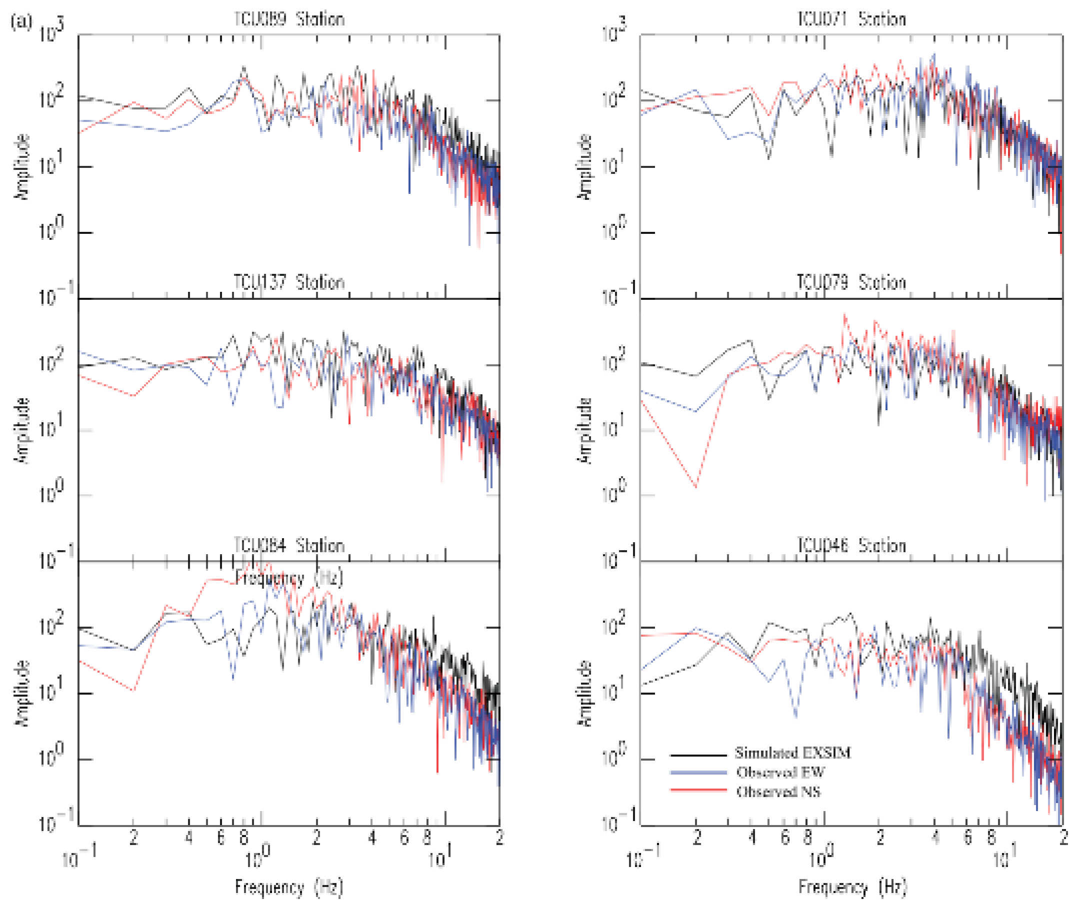


(Sokolov et al., 2009)

Introductions







(Damico et al., 2012)

NARLabs

Site Correction from ETF

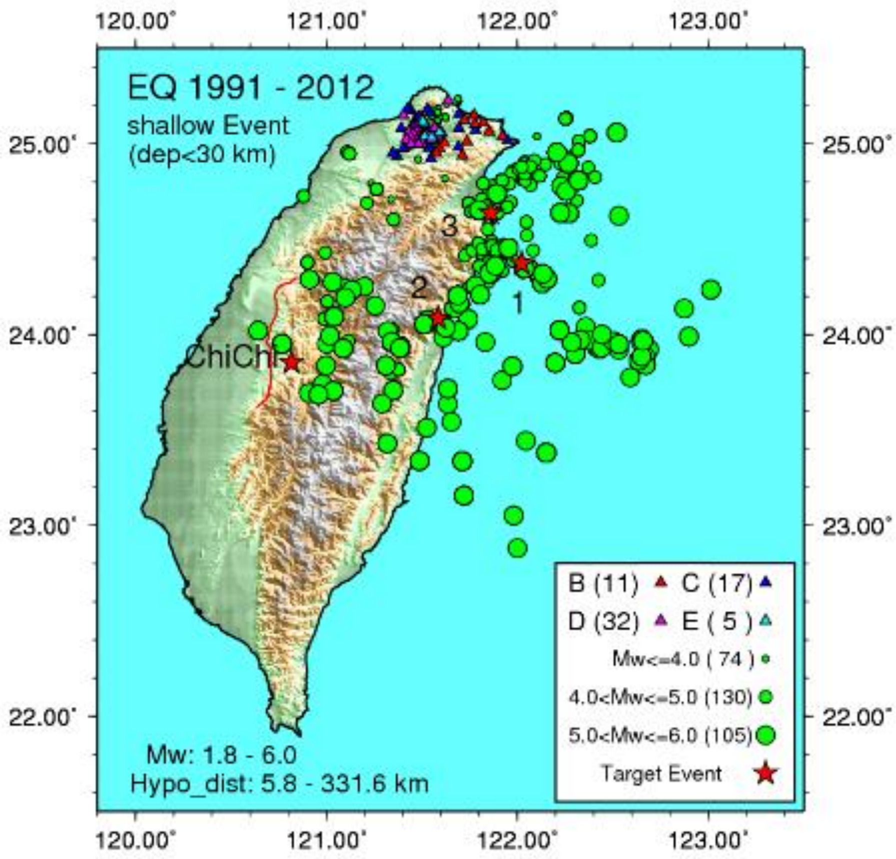
- Review the FAS/PSA based methods for Taiwan.

Parameters	Sokolov et al. (2009)	D'amico et al. (2012)	Huang et al. (2017)
Source spectrum model	Single corner frequency ω^{-2}	Single corner frequency ω^{-2}	Single corner frequency ω^{-2}
Stress parameter, $\Delta\sigma$ (bars)	Zone ST: increase from 100 for M=5.0 to 300 for M=7.0 Zone SO: 100 Zone DT: 300	Mw =5.5, 60 Mw =6.5, 80 Mw =7.6, 90	Mw <5.5, 60 5.5<Mw <6.5, 80 Mw >6.5, 90
Shear-wave velocity, β_S (km/s)	3.6	3.2	3.6
Density, ρ_S (gm/cc)	2.8	2.8	2.8
Geometric spreading, $\frac{1}{R^b}$: b=	1.0 (1-50km) 0.0 (50-170km) 0.5 (>170km)	1.2 (1-10km) 0.7 (10-40km) 1.0 (40-80km) 0.5 (>80km)	1.0 (1-50km) 0.0 (50-170km) 0.5 (>170km)
Quality factor, Q	Zone ST: $80f^{0.9}$ Zone SO: $120f^{0.8}$ Zone DT: $60f^{1.0}$	$350f^{0.32}$	Zone ST: $80f^{0.9}$ Zone SO: $120f^{0.8}$ Zone DT: $60f^{1.0}$

Parameters	Sokolov et al. (2009)	D'Amico et al. (2012)	Huang et al. (2017)
Site amplification, $A(f)$	-	Boore & Joyner (1997) Generic Rock (Vs30=520m/s) Generic Soil (Vs30=270m/s)	ENA-A Empirical Transfer Function (ETF)
Kappa, κ_0 (sec)	0.01	0.05	0.01
Duration	-	-	Lee et al. (2015) Combined duration source, duration path and duration site in one equation
Generated model for validation	FAS	PGA, FAS, PSA for Chi-Chi earthquake data	PGA, FAS for shallow earthquake including Chi-Chi data
Purpose	Construct a VHR response and compared site response for shallow and deep earthquakes	Construct stochastic simulation model based on small earthquake database, validation with Chi-Chi earthquake data	Construct ETF as site corrected method for stochastic simulation

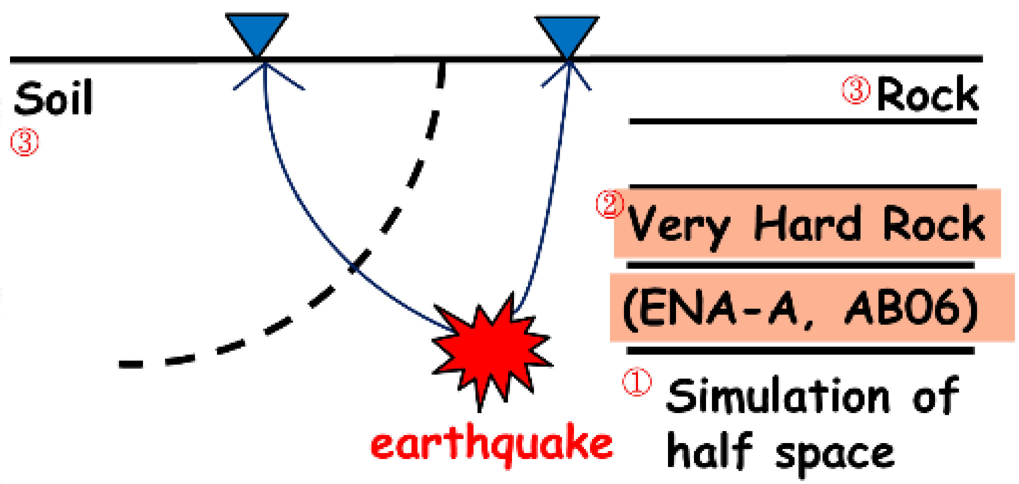
Site Correction from ETF

Empirical Transfer Function (ETF) based site correction of stochastic simulation (Huang et al., 2017).



① $S_{SIM\_HS} \times S_{ENA\_A} = S_{SIM\_VHR}$ ②

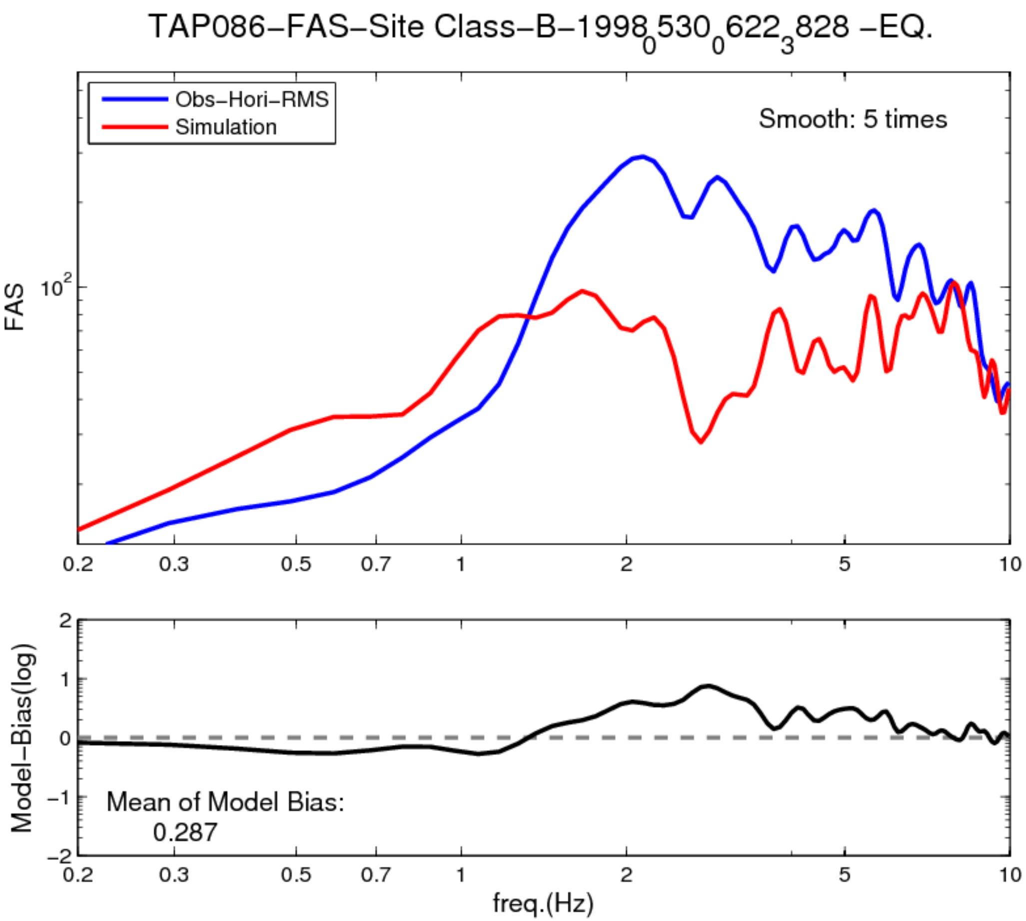
$\frac{S_{OBS\_S}}{S_{SIM\_VHR}} = ETF$ ③

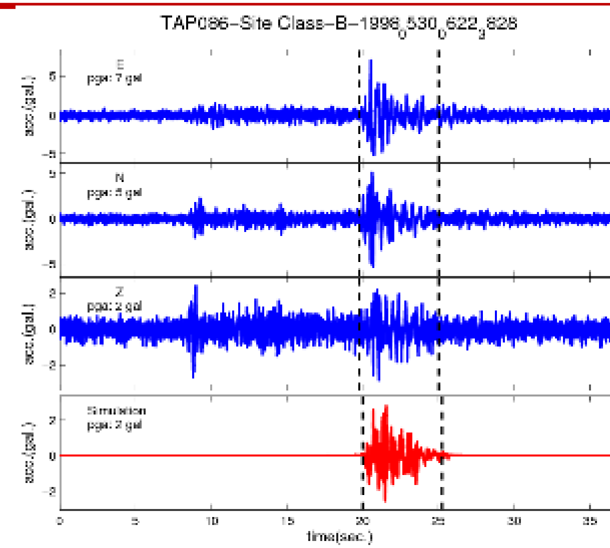


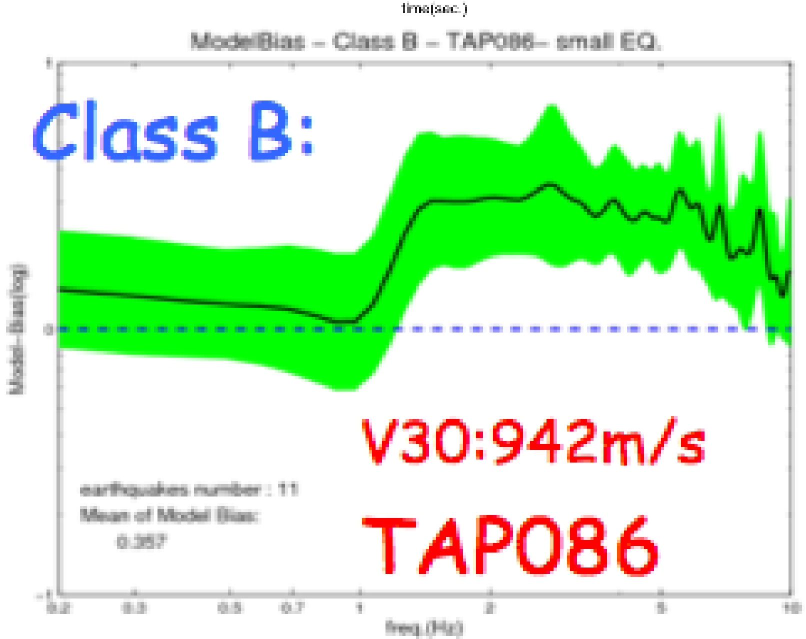
Constructing shallow ETF based on Very Hard Rock response.

Site Correction from ETF

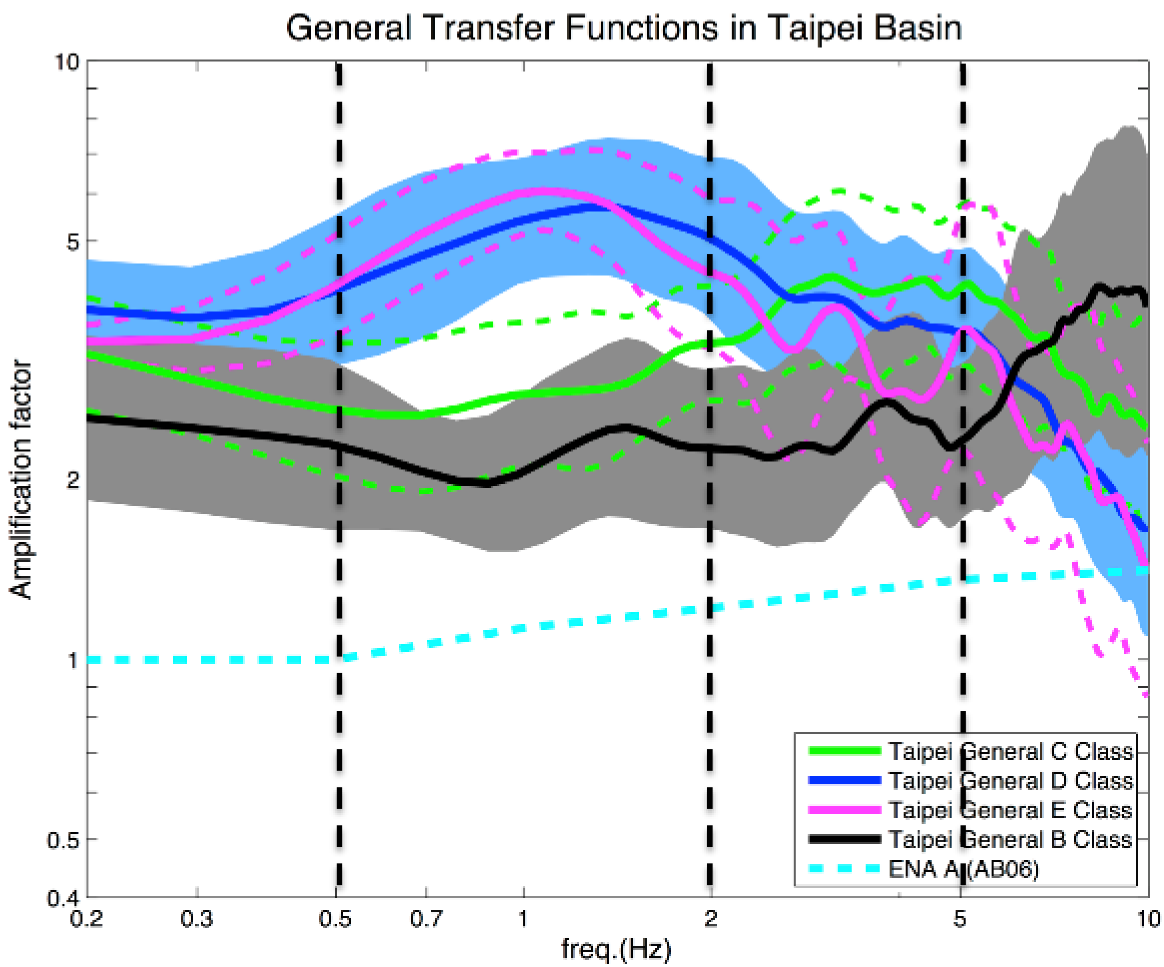
Empirical Transfer Function (ETF) based site correction of stochastic simulation (Huang et al., 2017).



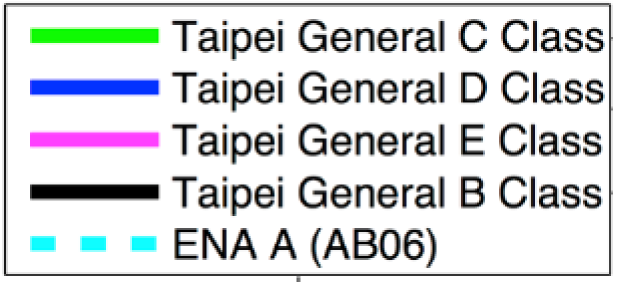




Site Correction from ETF



General ETF of Taipei Basin for site class B to E

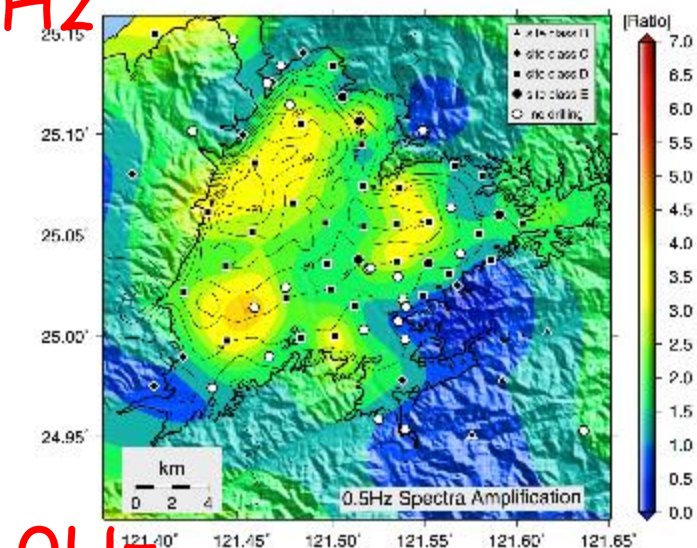


(Huang et al., 2017)

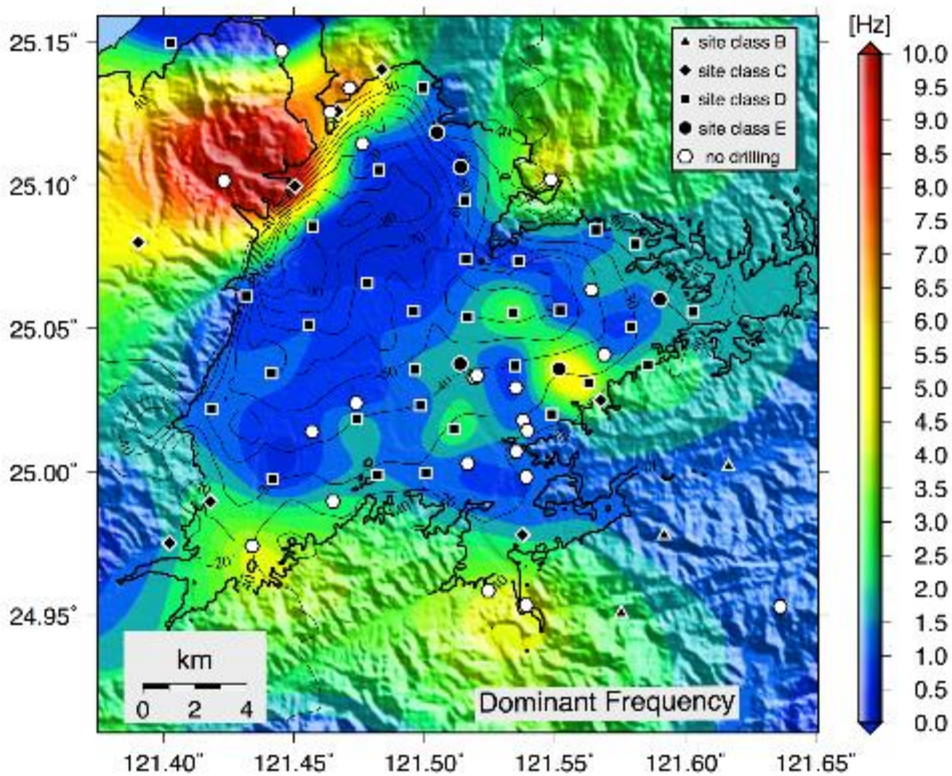
Site Correction from ETF

Empirical Transfer Function (ETF) based site correction of stochastic simulation (Huang et al., 2017).

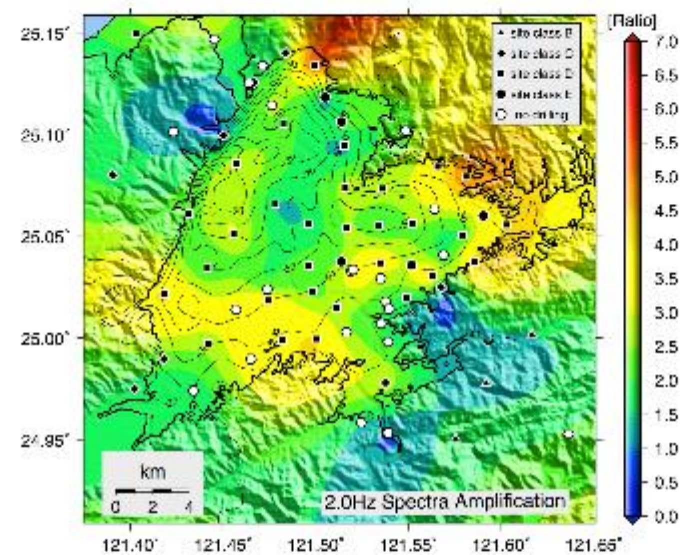
AMP_0.5Hz



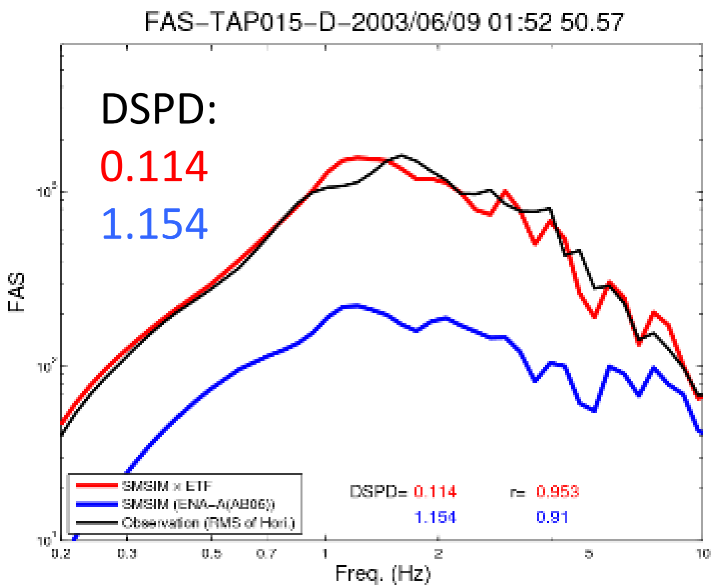
Dominant Frequency

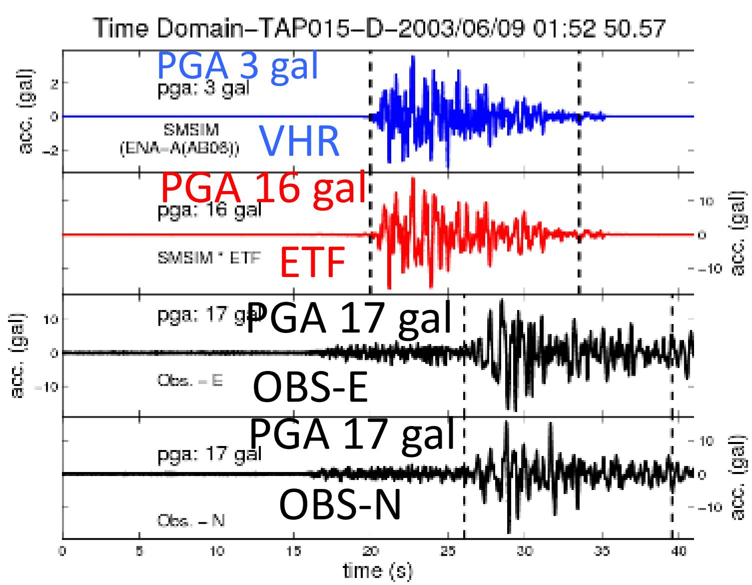


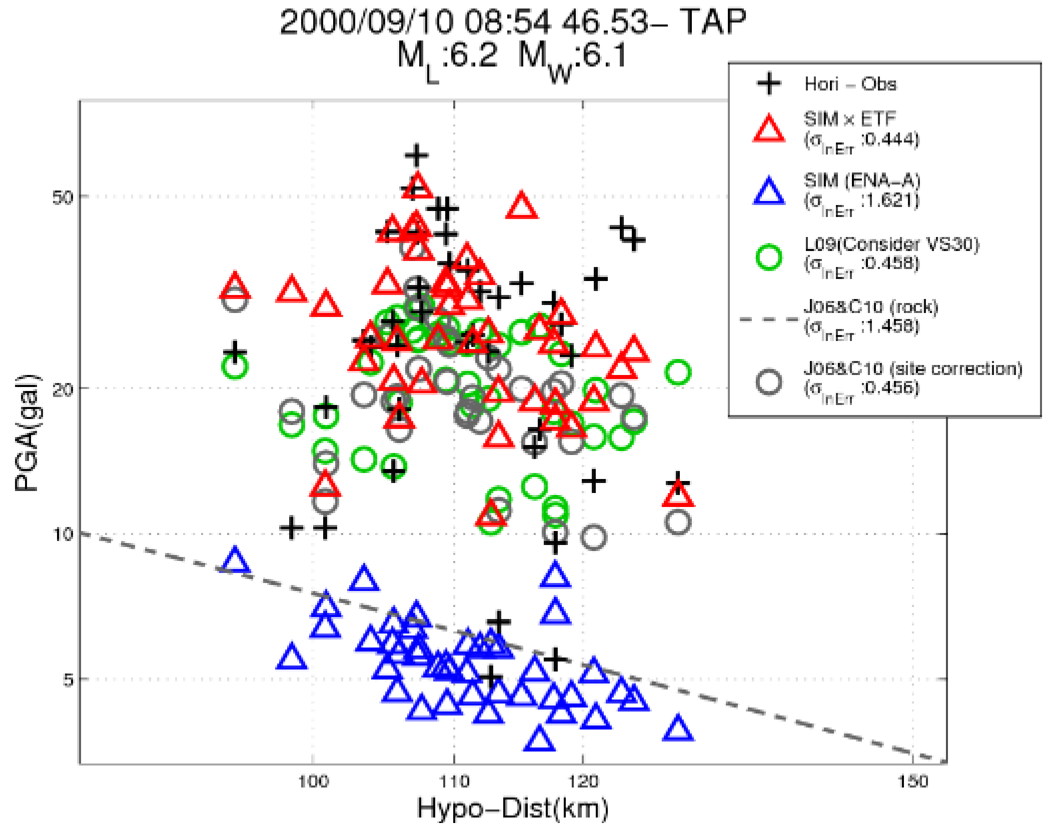
AMP_2.0Hz



Site Correction from ETF





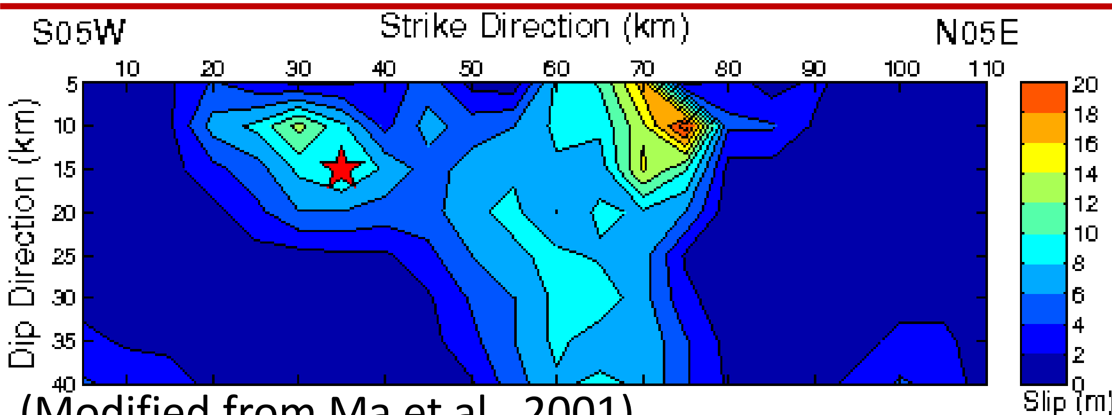


Observation
VHR Simulation
ETF Correction
GMPE(L09)
GMPE(J06&C10)

Empirical Transfer Function (ETF) based site correction of stochastic simulation

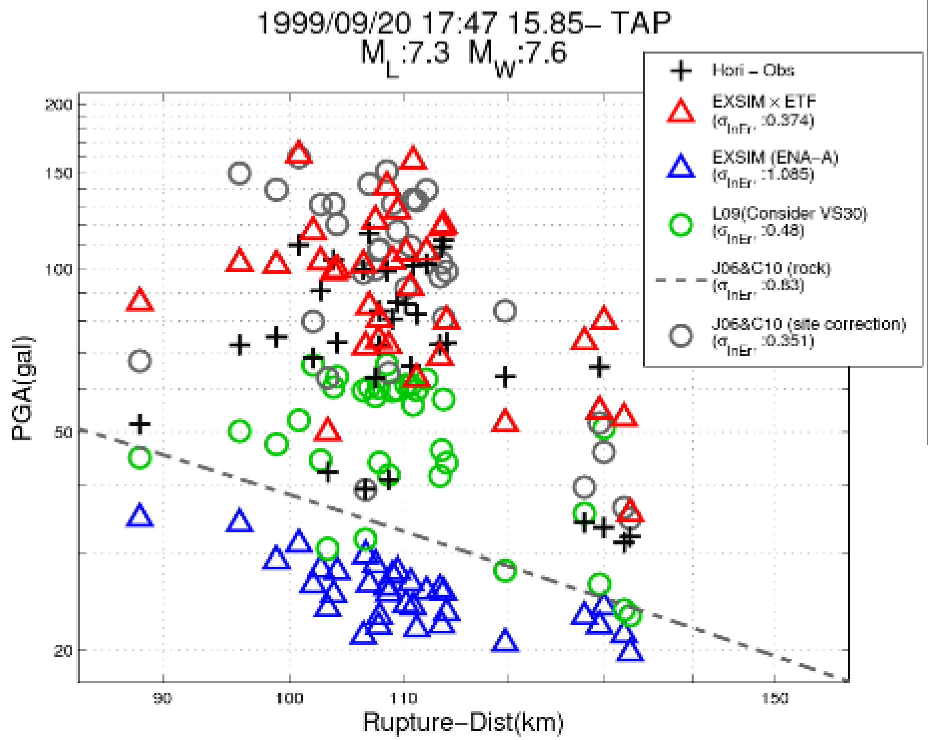
(Huang et al., 2017)

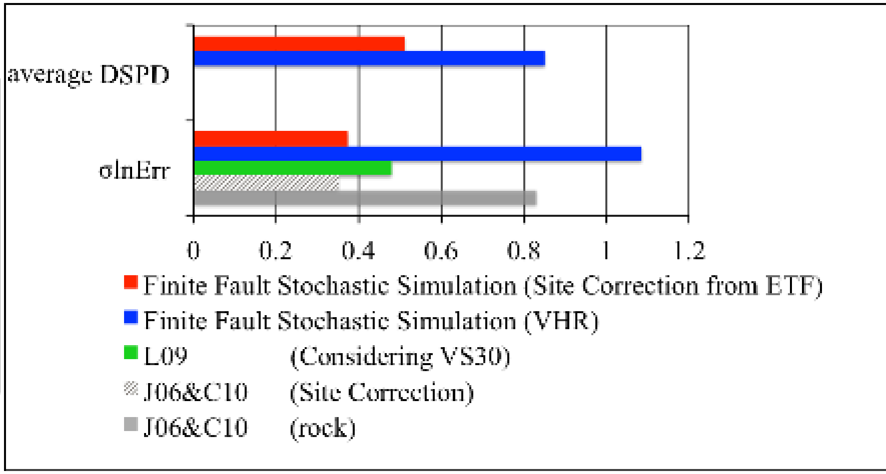
Site Correction from ETF



(Modified from Ma et al., 2001)

ETF based site correction could also applied to finite fault simulation.





(Huang et al., 2017)

Site Correction from ETF

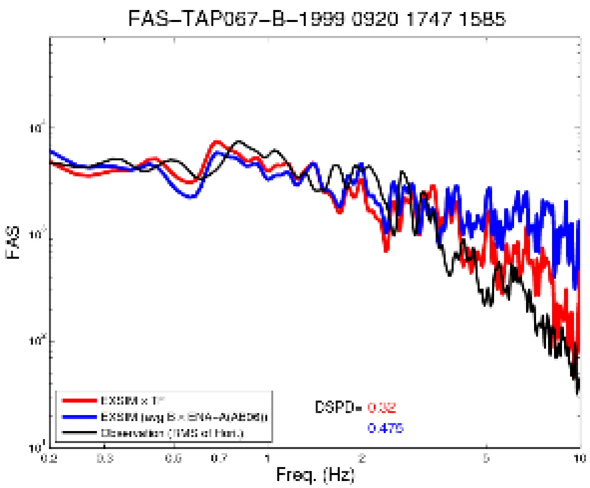
Class B:

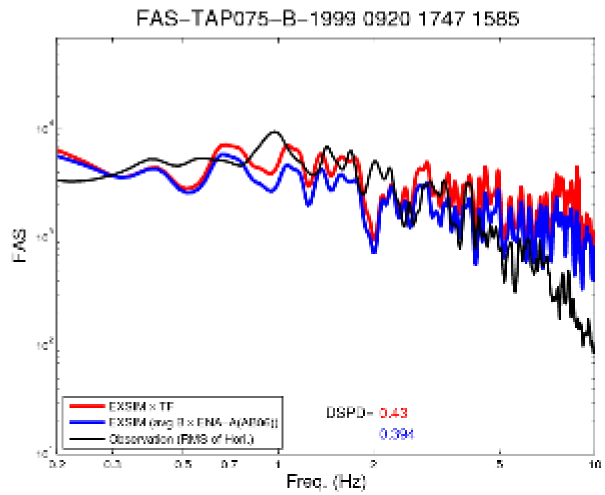
1999_0921 Mw7.6 depth 8km

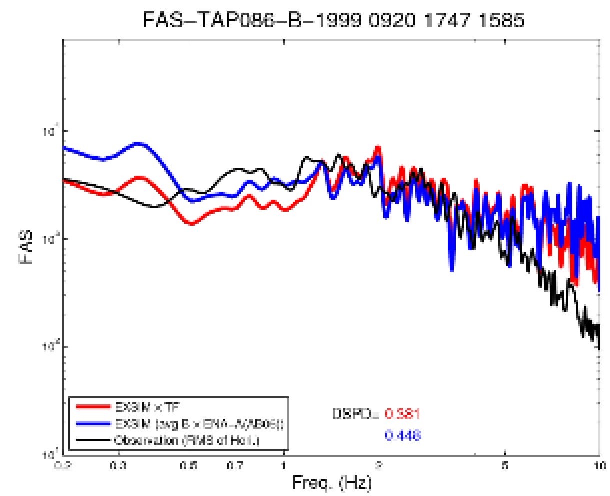
TAP067

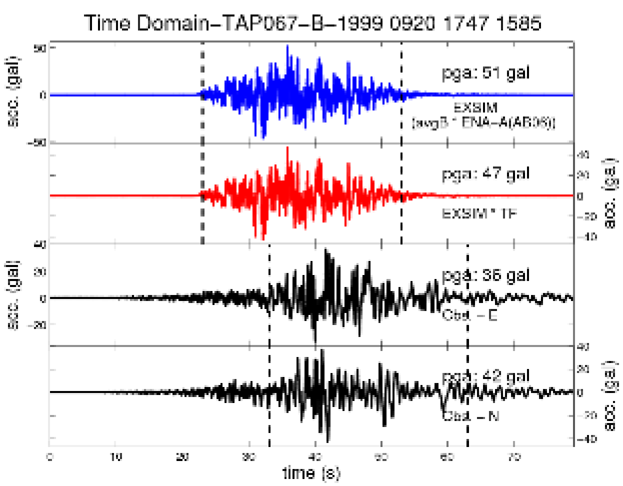
TAP075

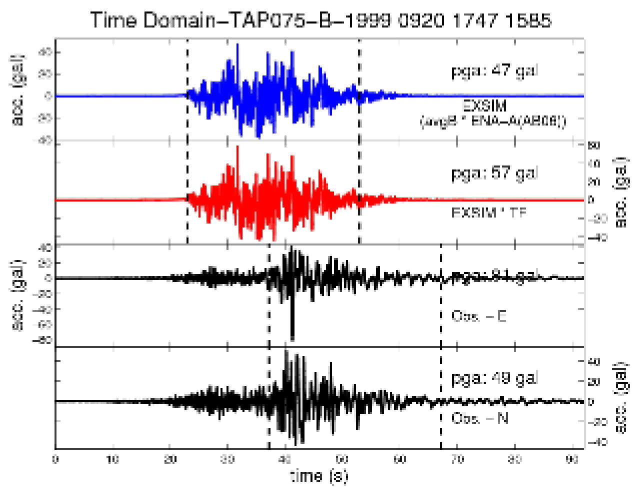
TAP086

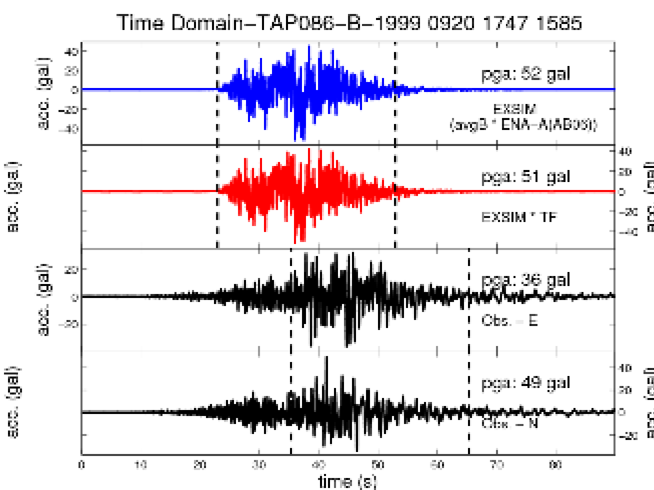












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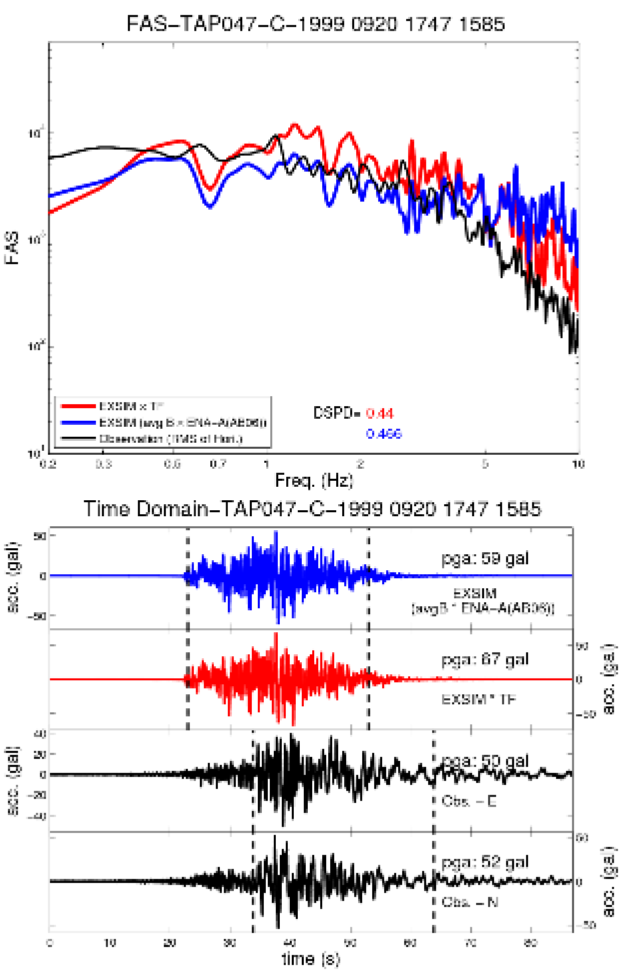
Site Correction from ETF

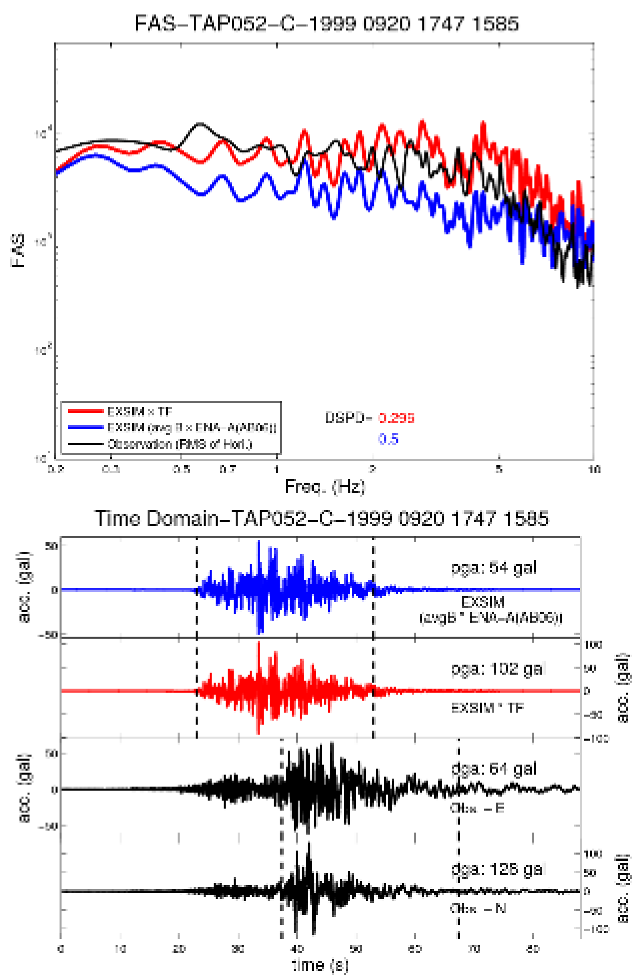
1999_0921 Mw7.6 depth 8km

Class C:

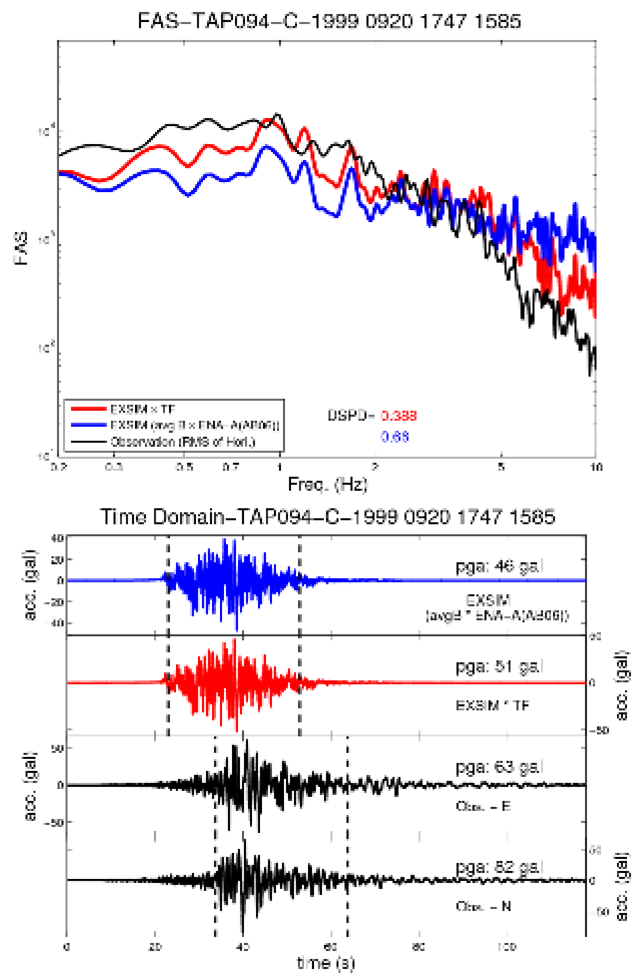
TAP047



TAP052



TAP094

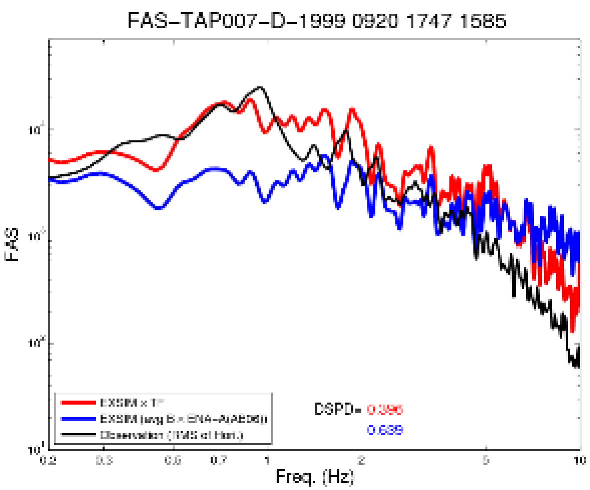


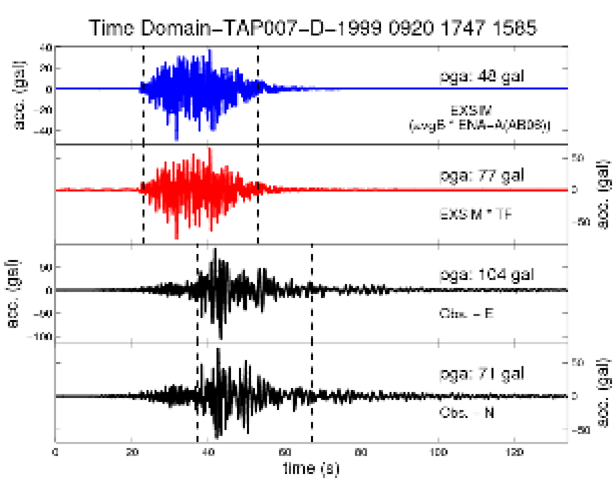
Site Correction from ETF

1999_0921 Mw7.6 depth 8km

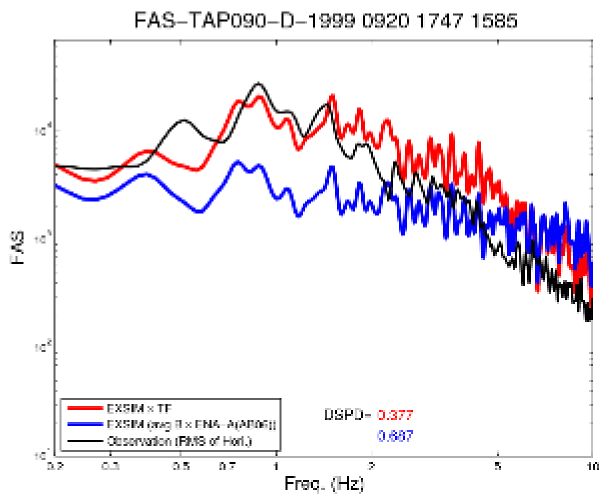
Class D:

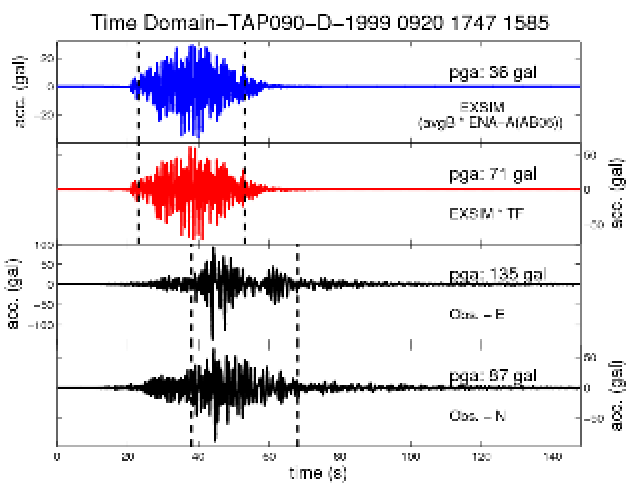
TAP007





TAP090





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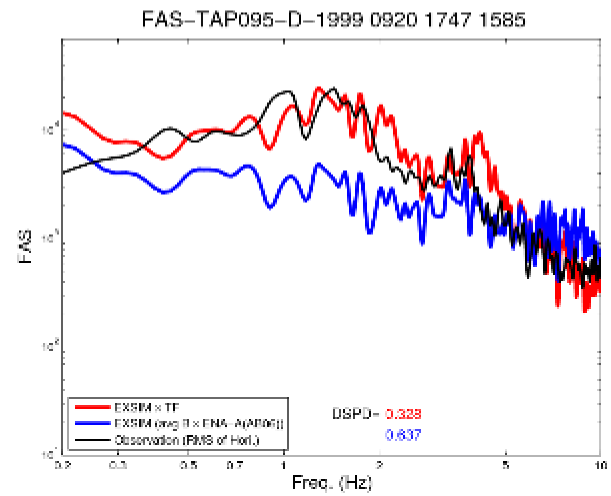
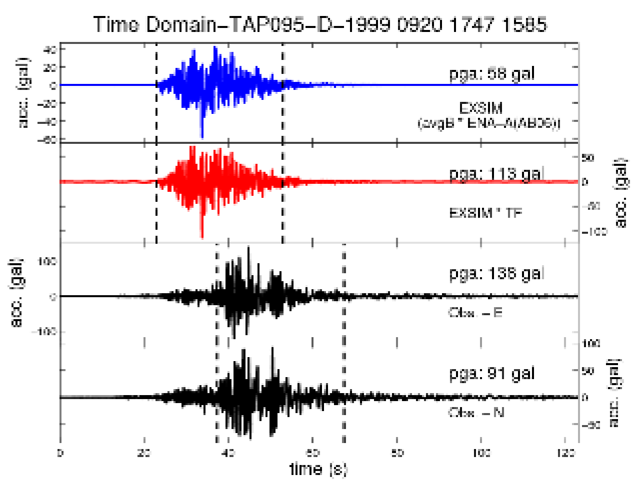
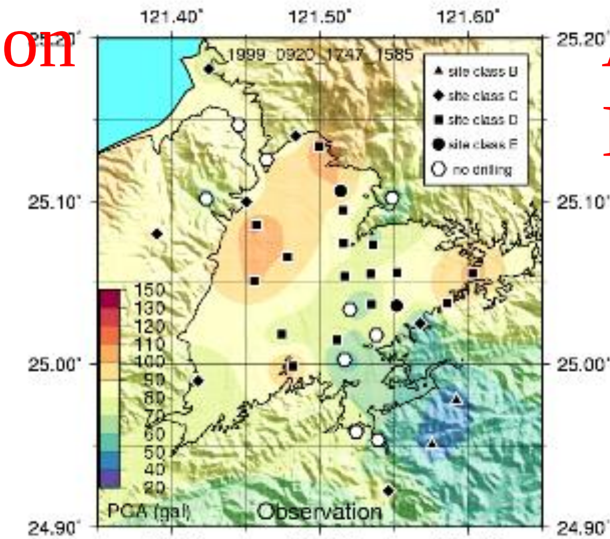


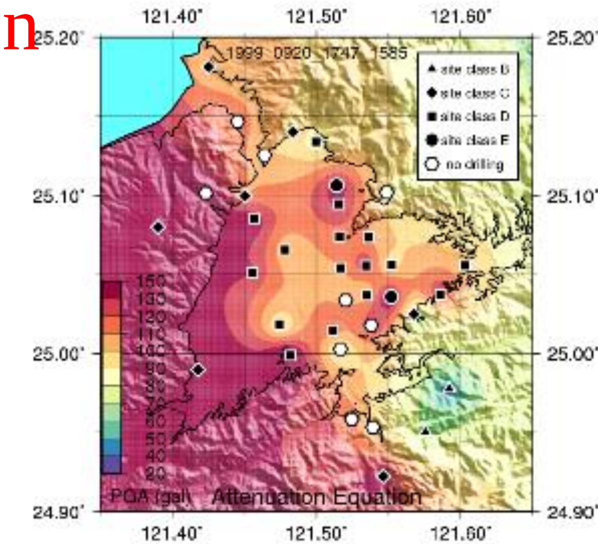


Site Correction from ETF

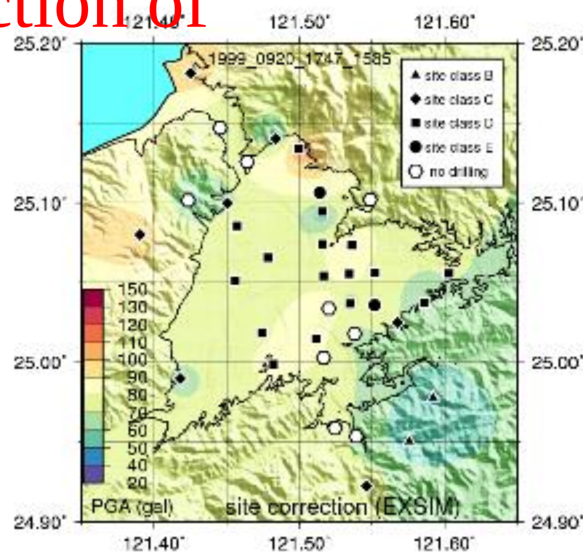
Observation



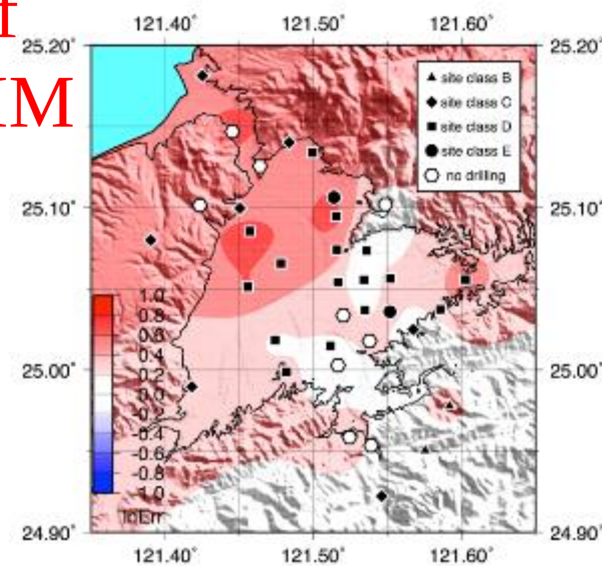
Attenuation Equation



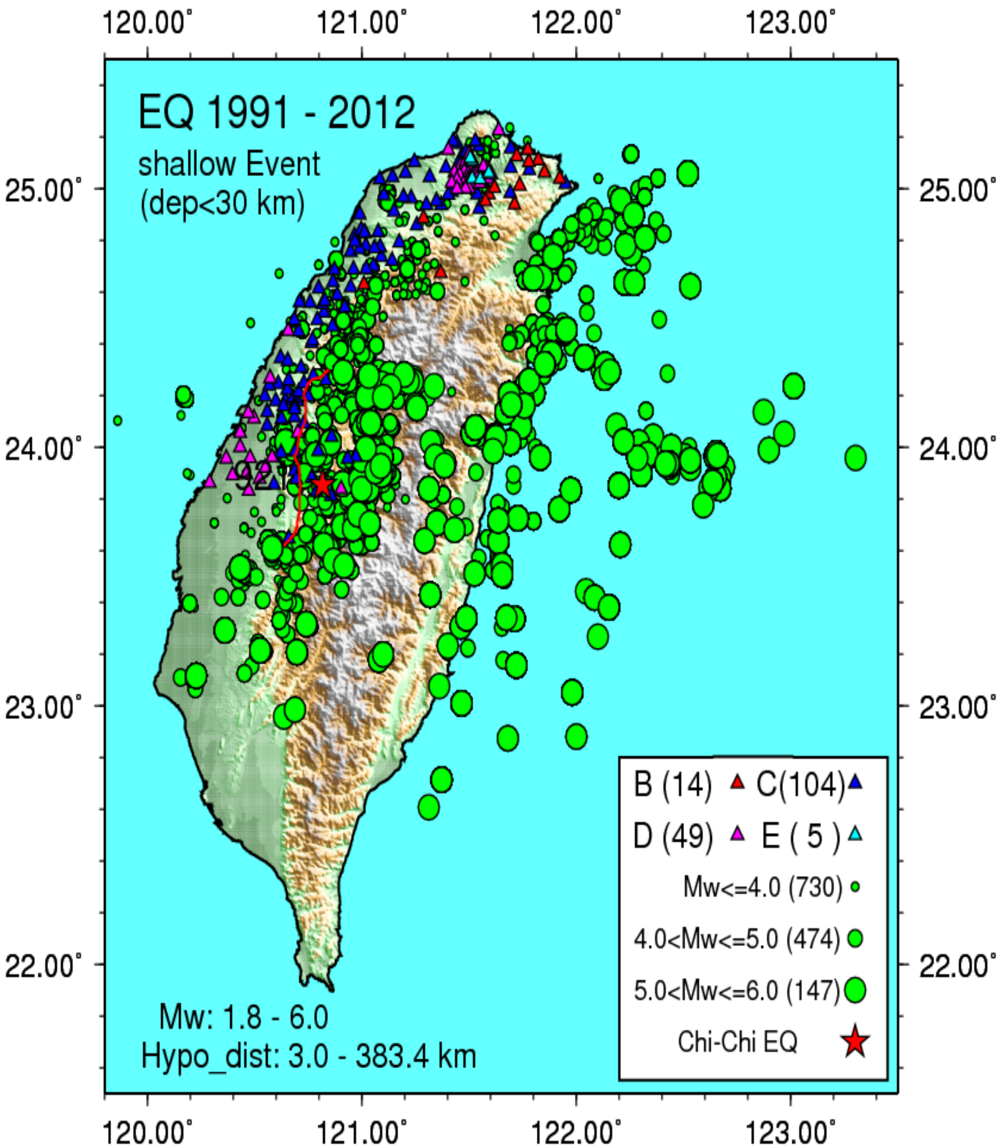
Site correction of EXSIM



Residual of OBS/EXSIM



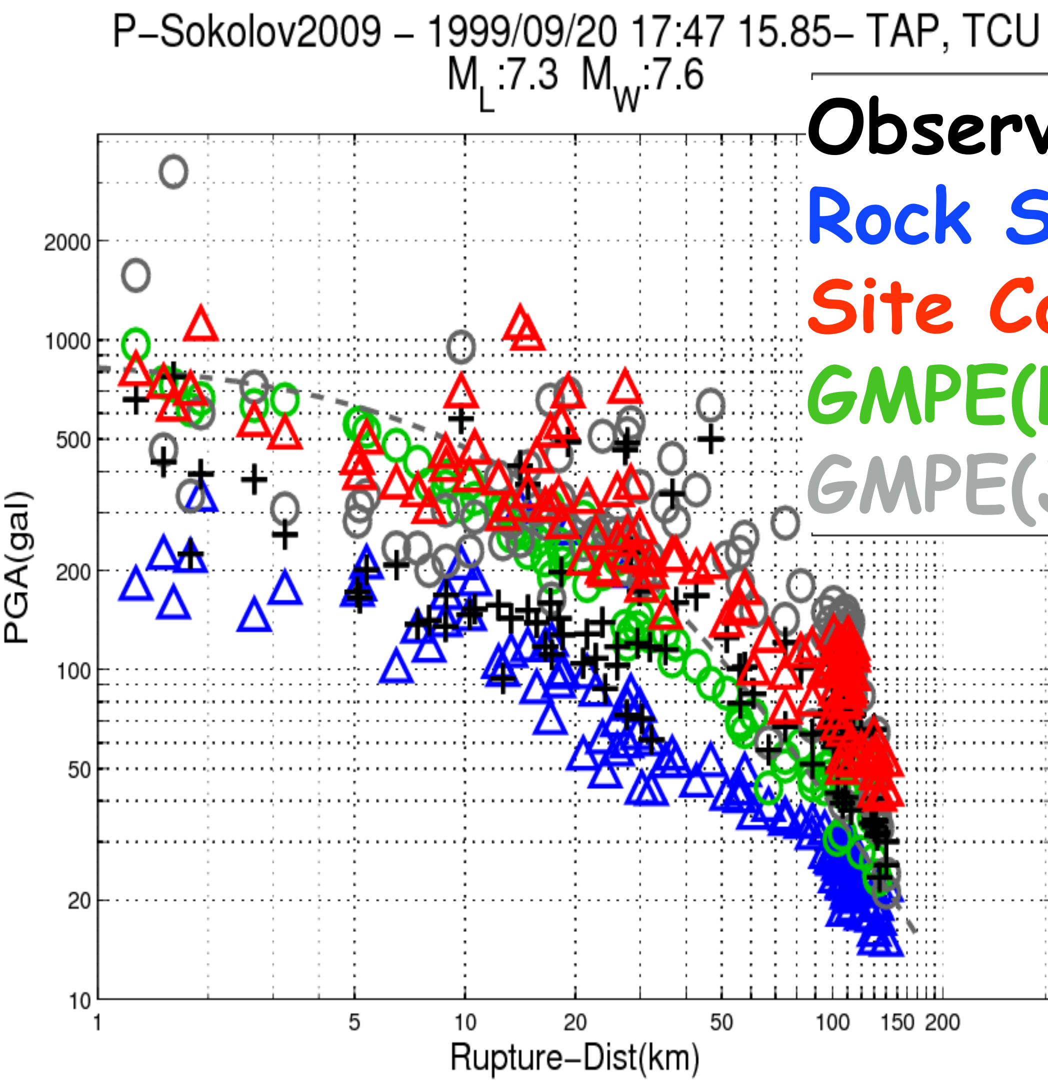
Site Correction from ETF

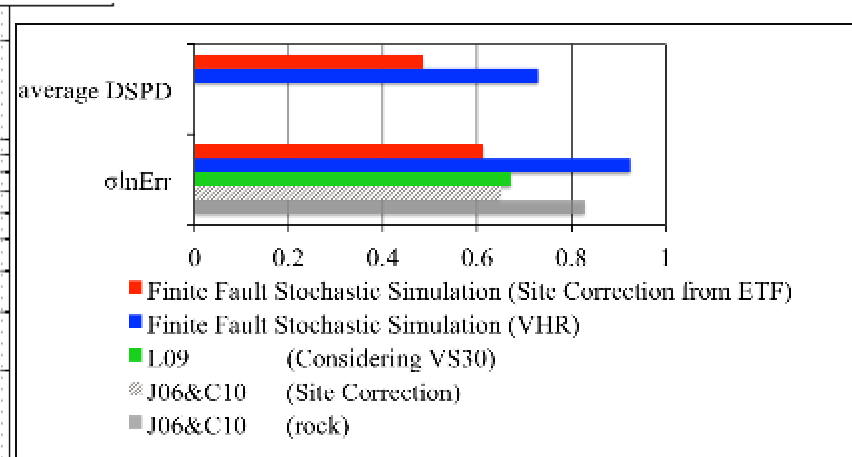


Database of Small earthquake: 1991 ~ 2012

Mw < 6.0
Focal Depth< 30 km
1351 Events

Site Correction from ETF





Applications- identify possible ground motion range from random asperity model

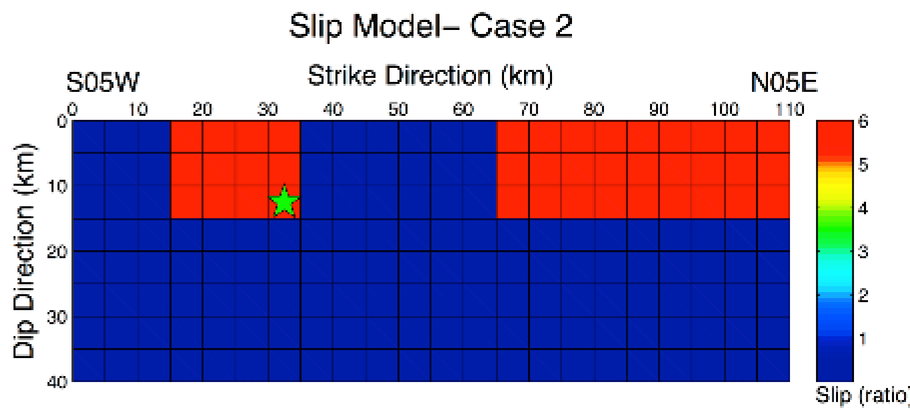
A_a= 22% * S_a= 968 km^2

= 39 Subfaults.

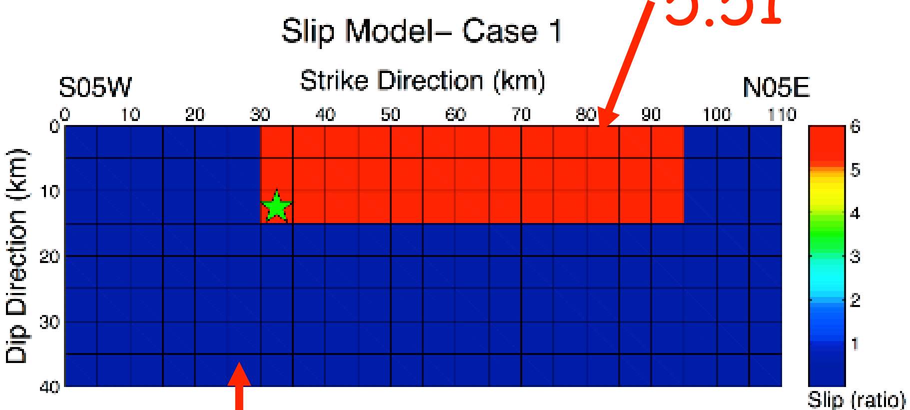
Aa: Area of Asperity.

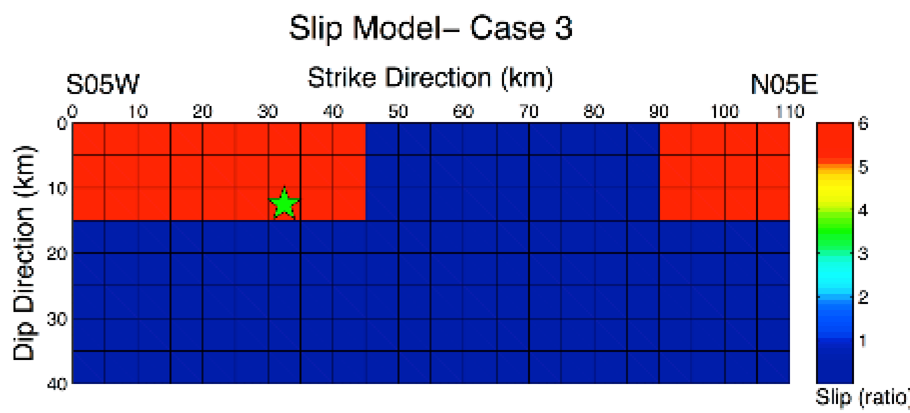
Sa: Total Area of Fault.

(follow Japan's Recipe:
Irikura et al., 2004; NIED, 2009; Irikura and Miyake, 2011)



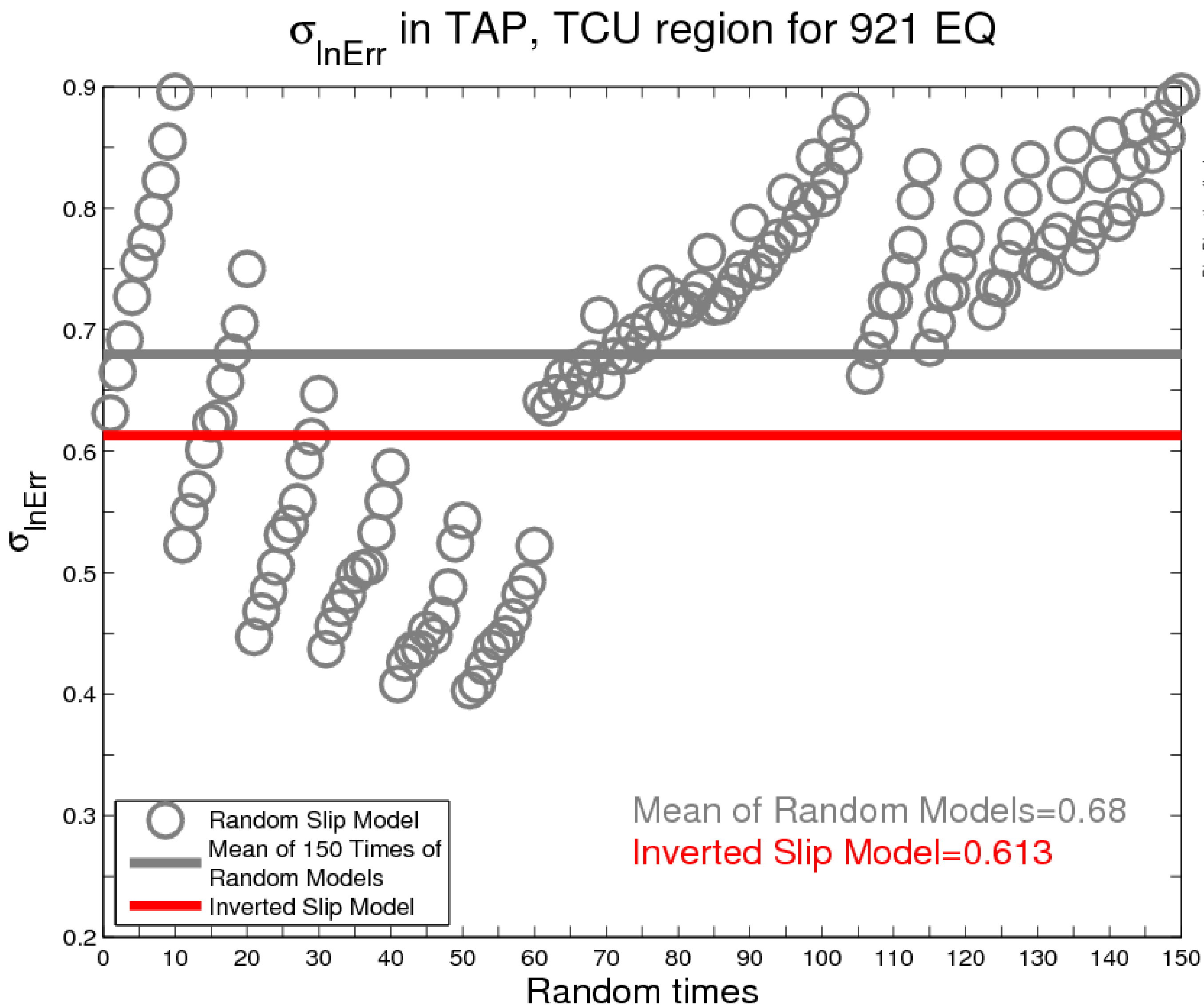
5.51

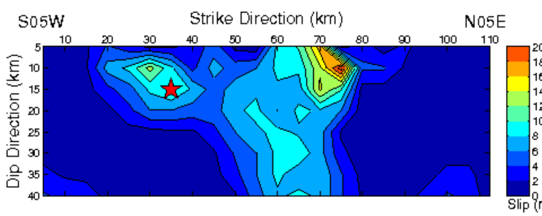




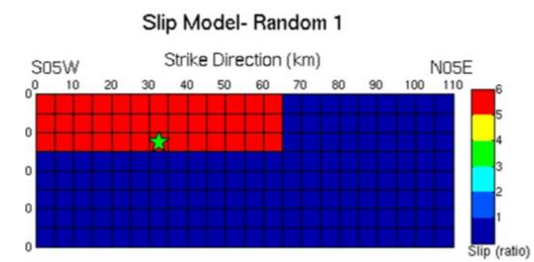
Slip Ratio for each subfaults
= 1

Applications- identify possible ground motion range from random asperity model



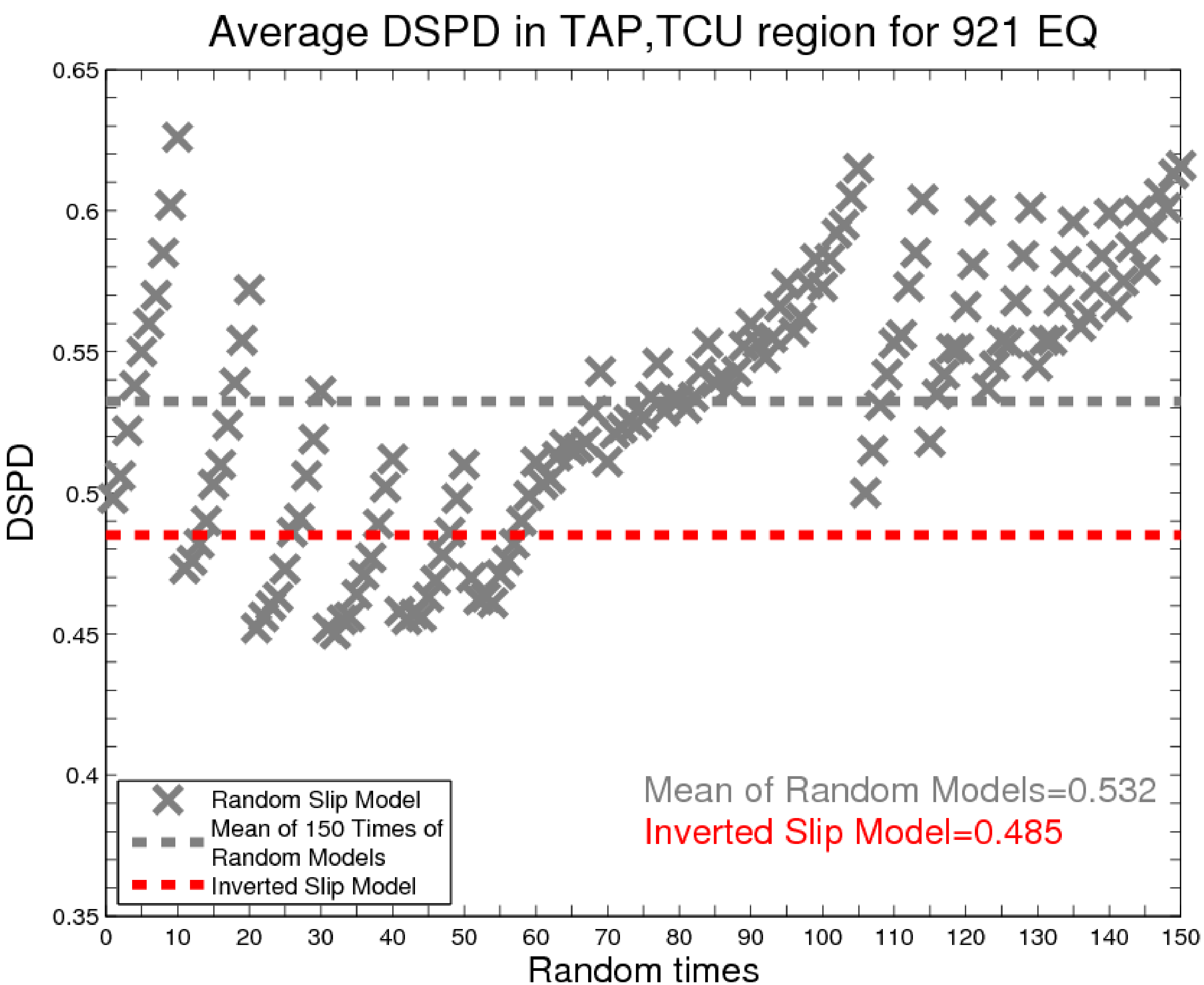


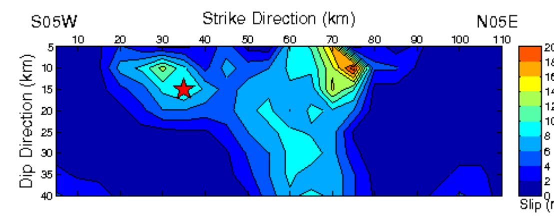
(Modified from Ma et al., 2001)



Applications- identify possible ground motion range from random asperity model

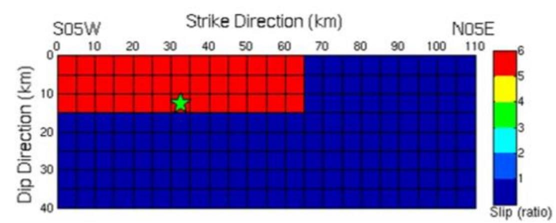
NARLabs



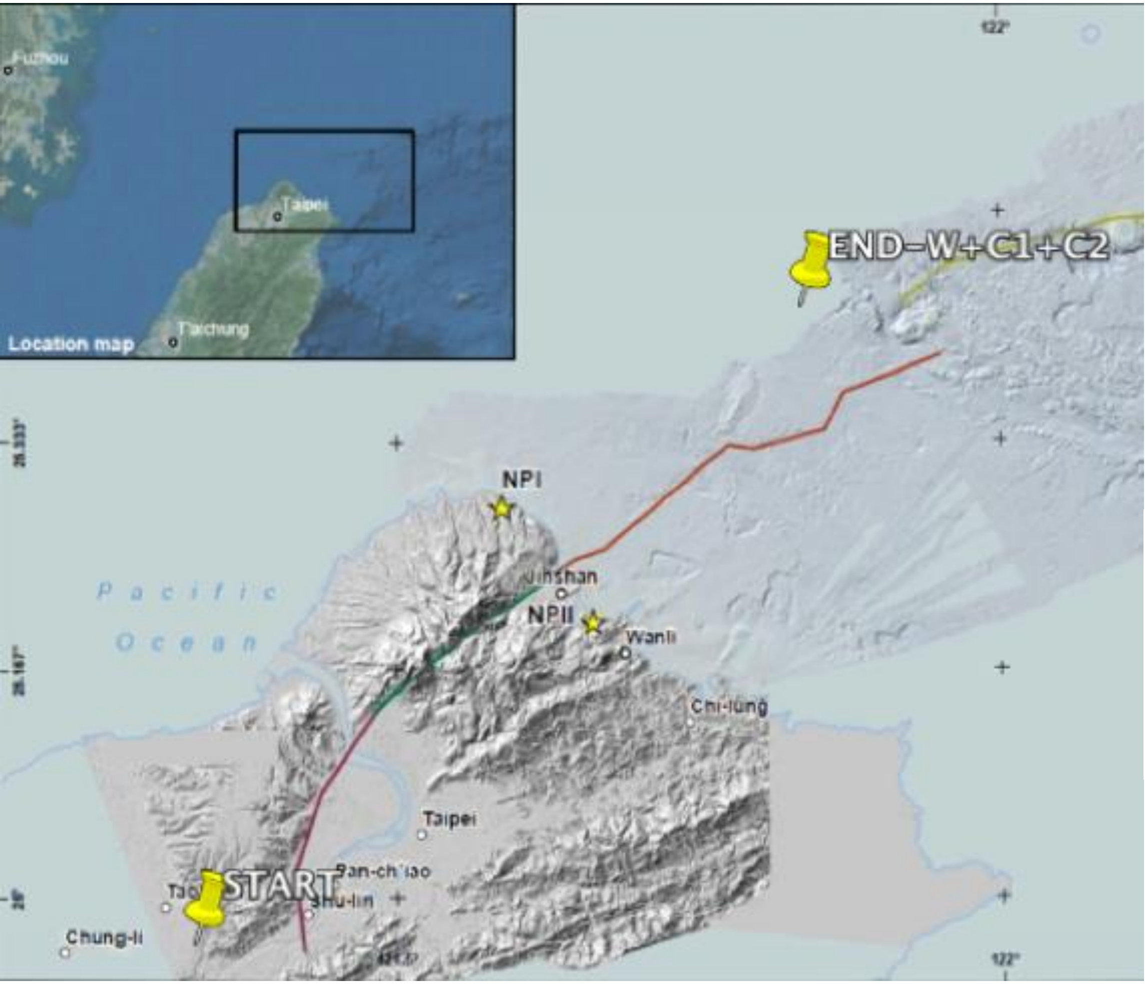


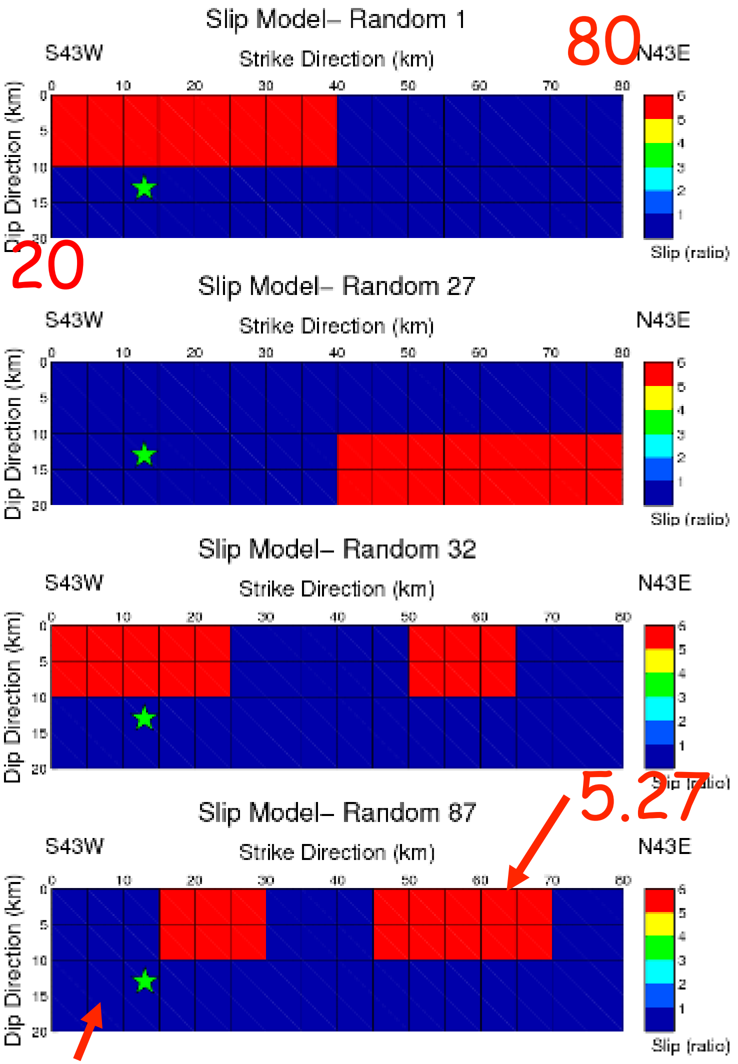
(Modified from Ma et al., 2001)

Slip Model- Random 1



Applications- identify possible ground motion range from random asperity model

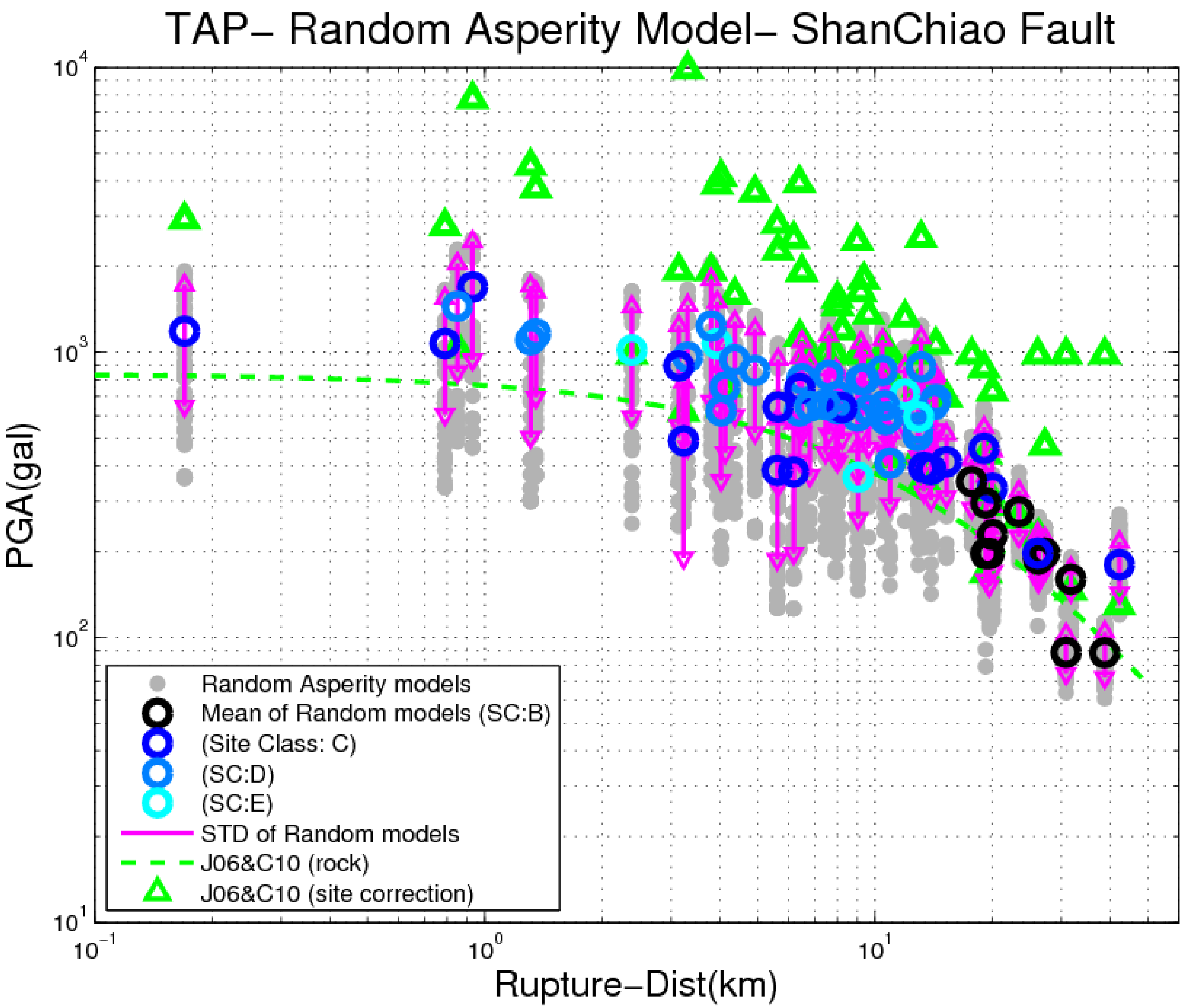




Mw=7.15

Slip Ratio for each subfaults= 1

Applications- identify possible ground motion range from random asperity model



Applications- applied to EEW in SANTA from grid search point source simulation

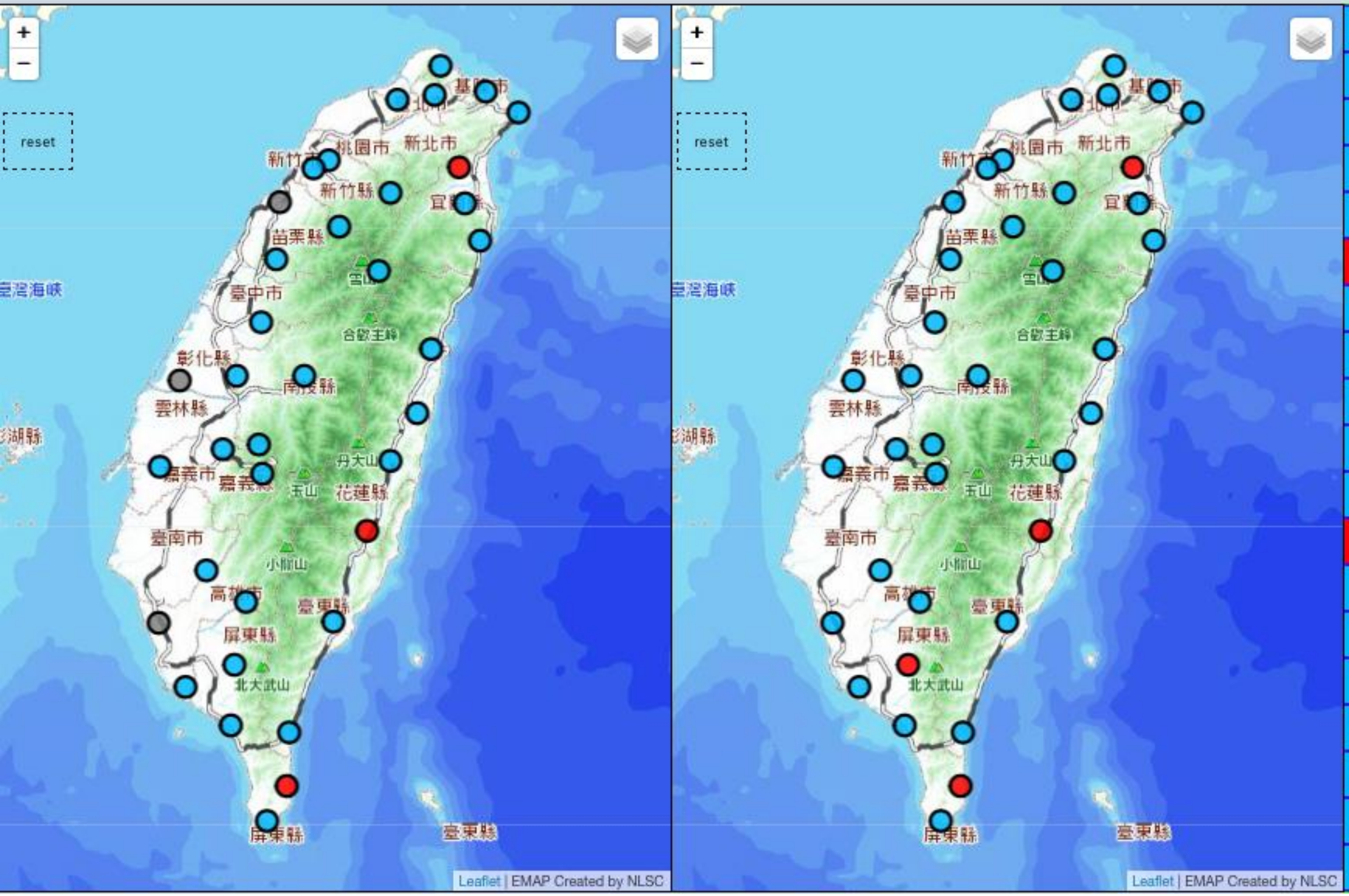
Seismic Array of NCREE in TAiwan
(SANTA)

Load Time : Tue Nov 14 03:07:47 2017

Strong Motion (SM)

Broadband (BB)

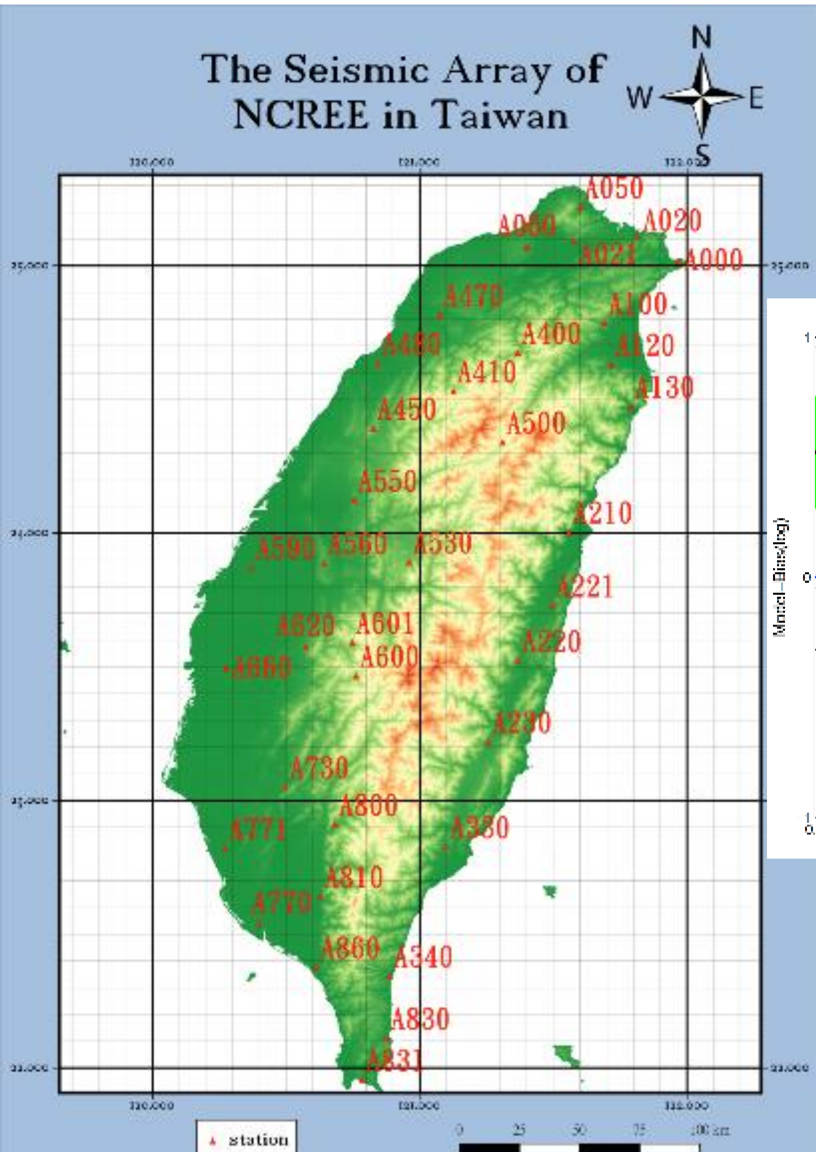
CWB data link



A000	A480	B000	
A020	A500	B020	B500
A021	A530	B021	B530
A050	A550	B050	B550
A060	A560	B060	B560
A100	A590	B100	
A120	A600	B120	B600
A130	A601	B130	B601
A210	A620	B210	B620
A220	A660	B220	B660
A221	A730	B221	B730
A230	A770	B230	B770
A330	A771	B330	
A340	A800	B340	B800
A400	A810	B400	B810
A410	A830	B410	B830
A450	A831	B450	B831
A470	A860	B470	B860
A471		B471	

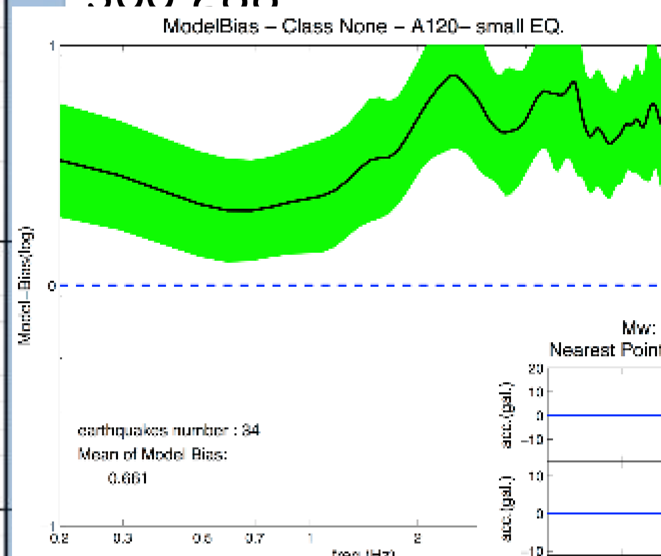
santa.ncree.org

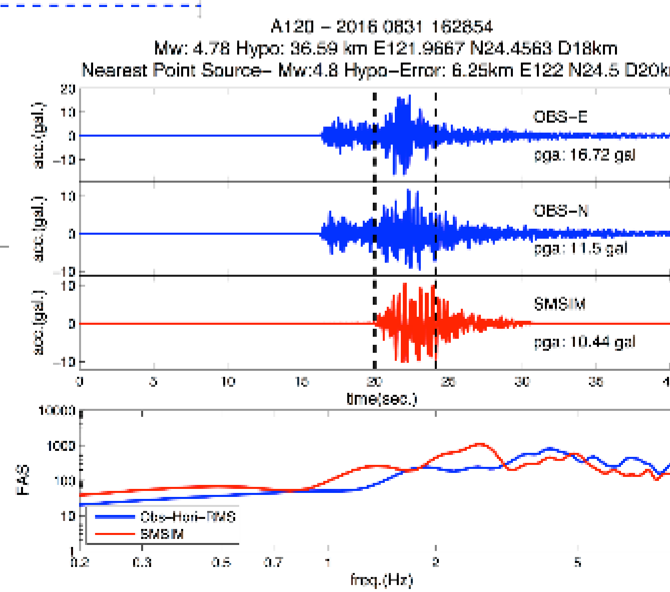
Applications- applied to EEW in SANTA from grid search point source simulation



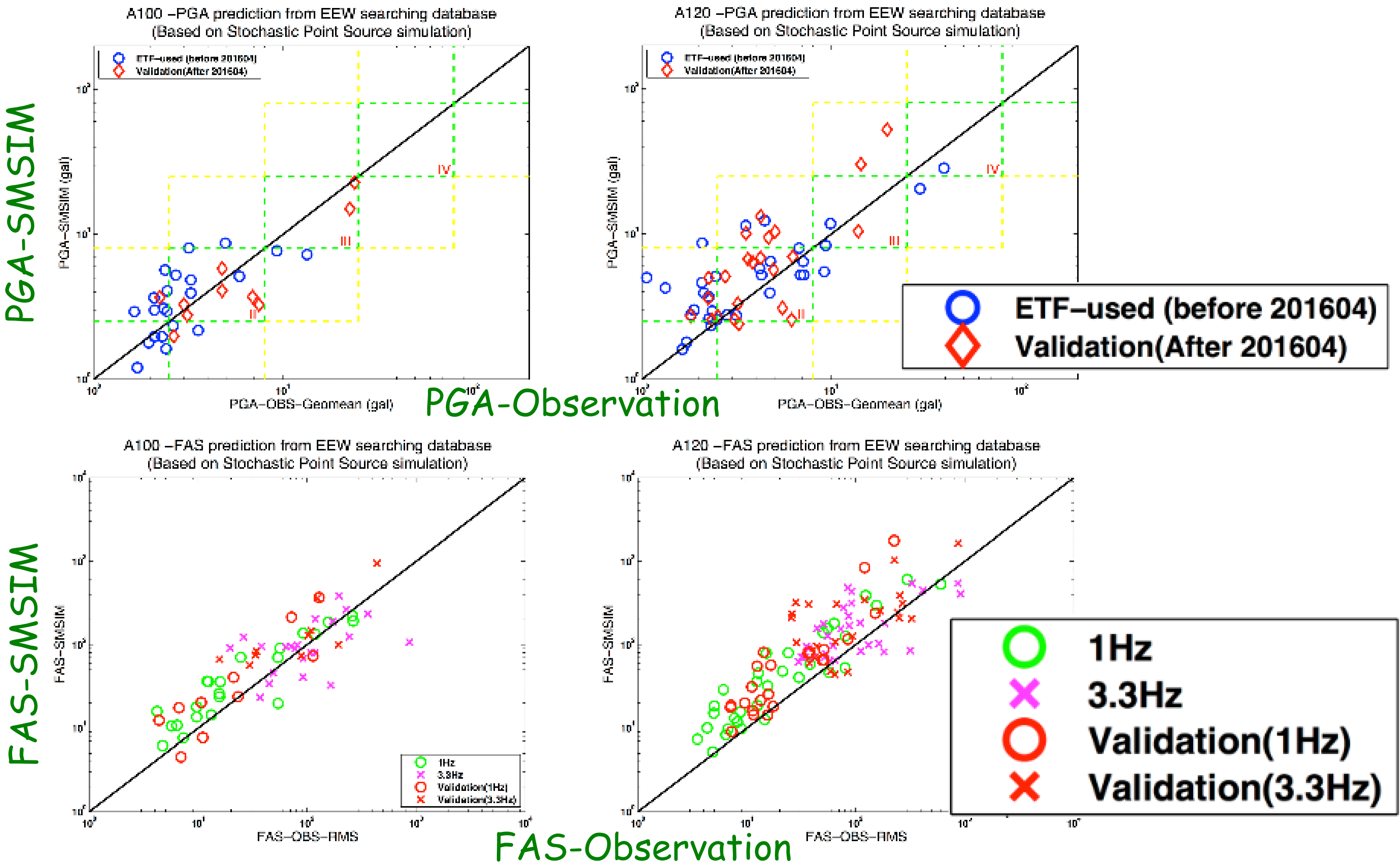
Grid Scheme:
Size- 10km*10km*5km (Depth to 60km)
Mw- 4.0-7.0 (0.2 interval)
Source numbers for one station:

300 288



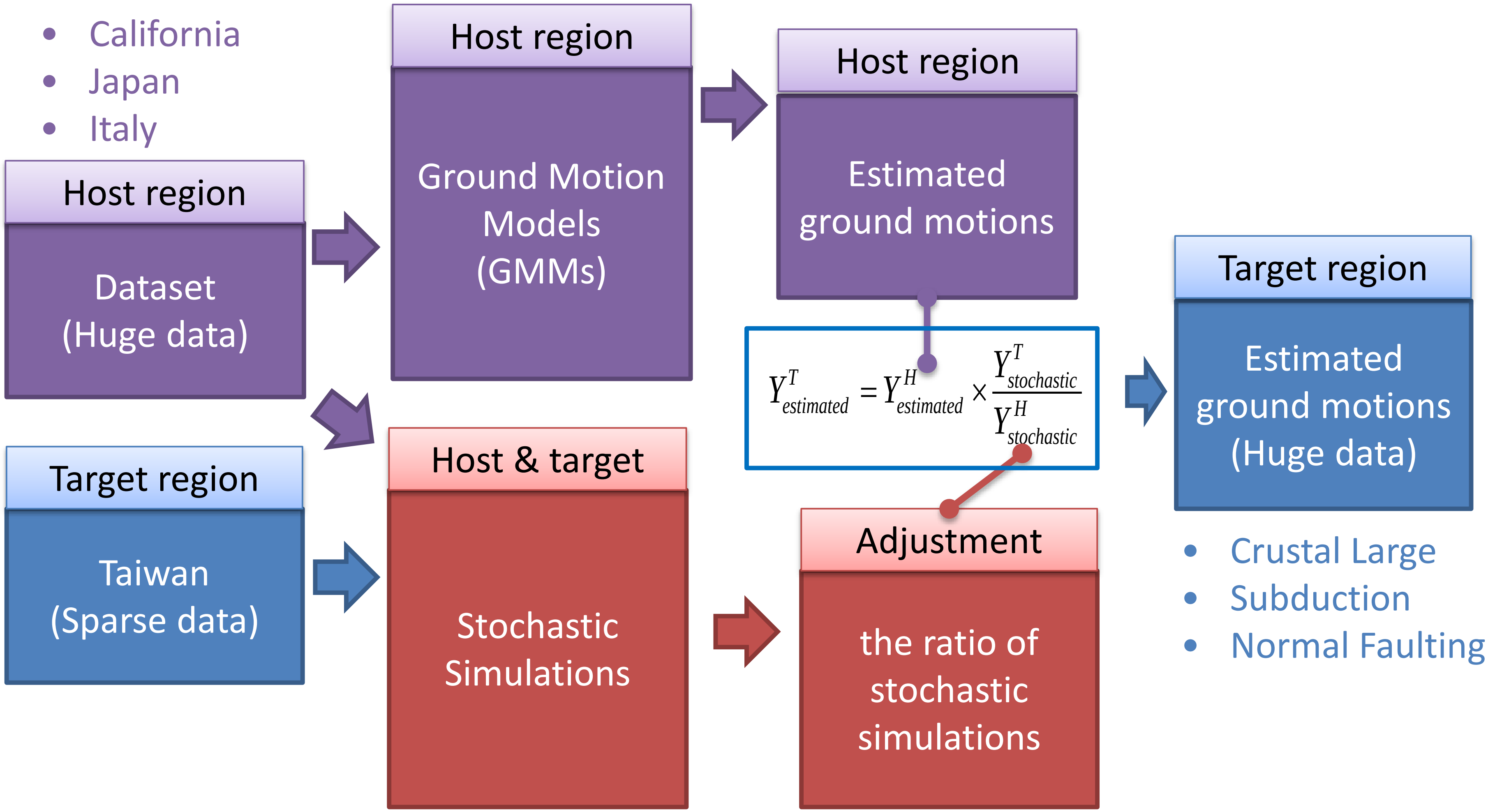


Applications- applied to EEW in SANTA from grid search point source simulation



Applications- host to target adjustment factor for GMPE

Hybrid Empirical Method (HEM)



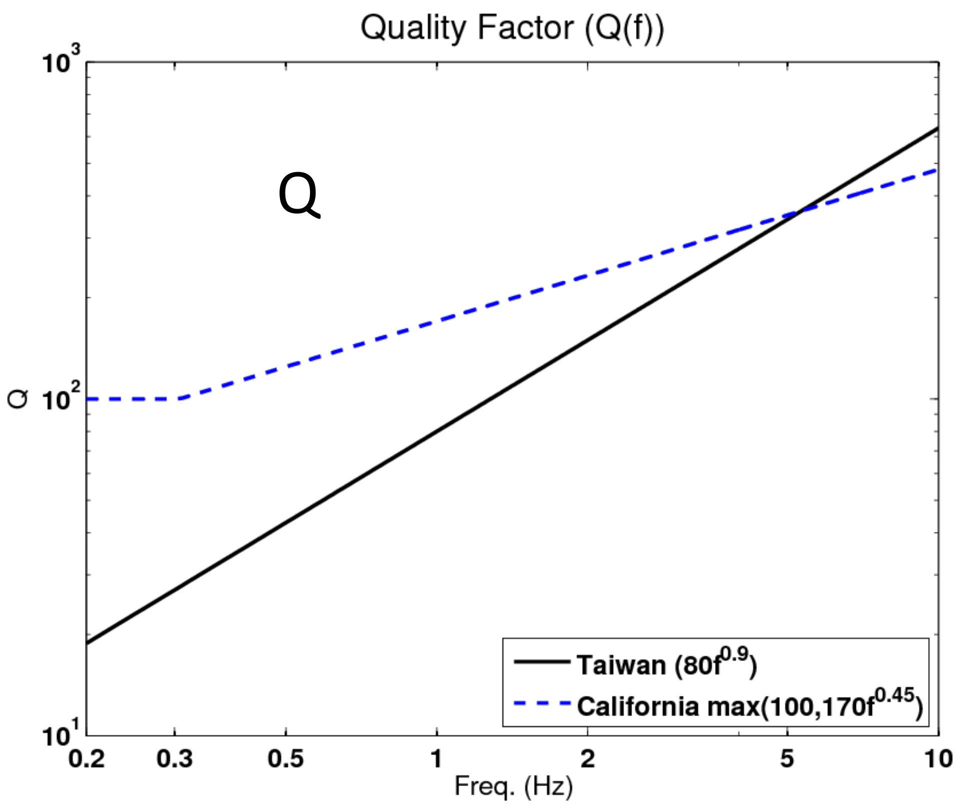
- Calibration of stochastic model for Target region
- Search the well proofed stochastic models for Host region

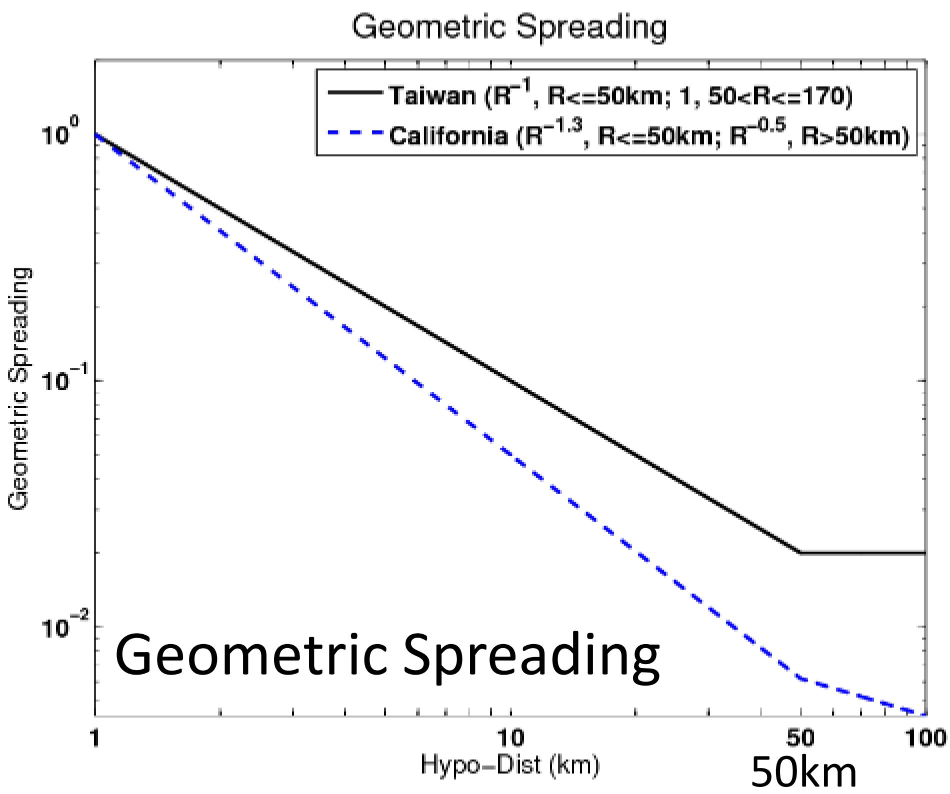
Applications- host to target adjustment factor for GMPE

NARLabs

*From Stochastic Simulation models

Case study for shallow earthquake of California & Taiwan





Faster attenuation from California against Taiwan

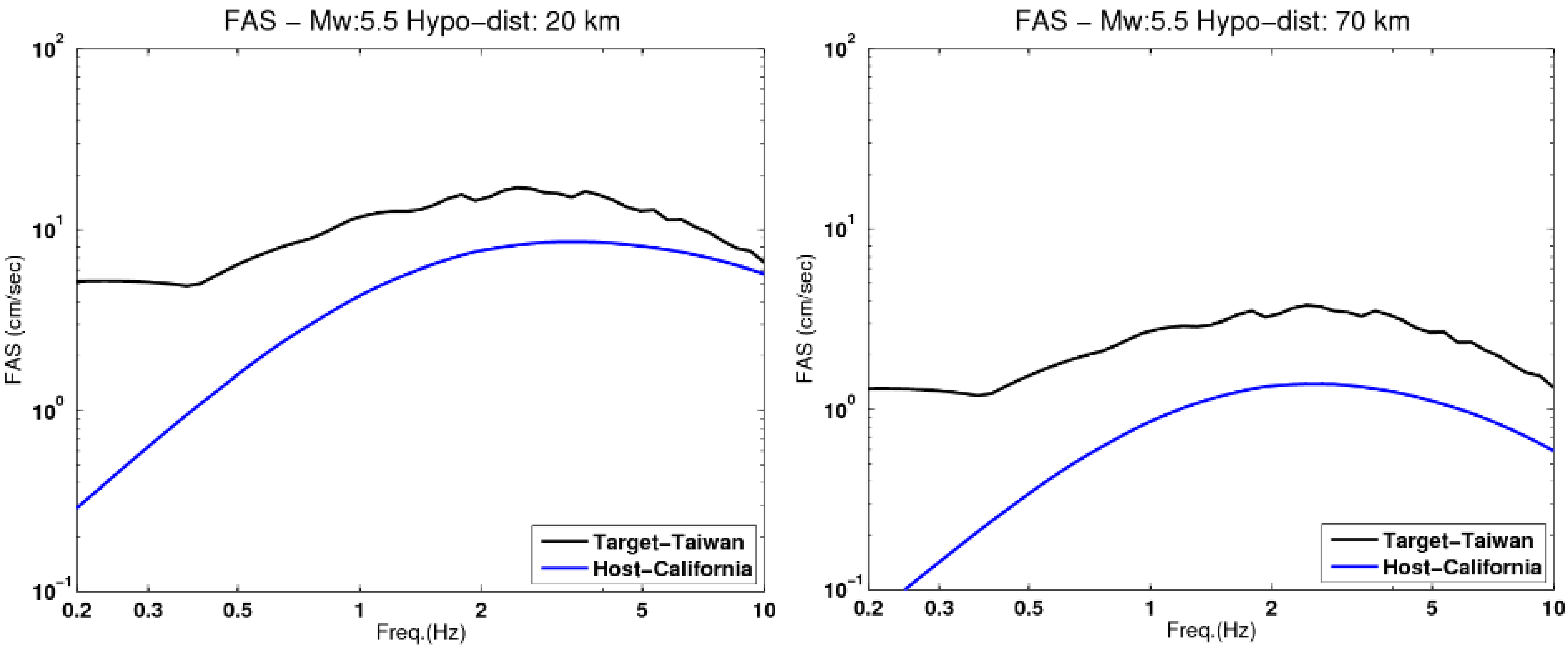
Applications- host to target adjustment factor for GMPE

*From Stochastic Simulation models

Case study for shallow earthquake of California & Taiwan

Mw 5.5 Hypo-Dist: 20km

Mw 5.5 Hypo-Dist: 70km

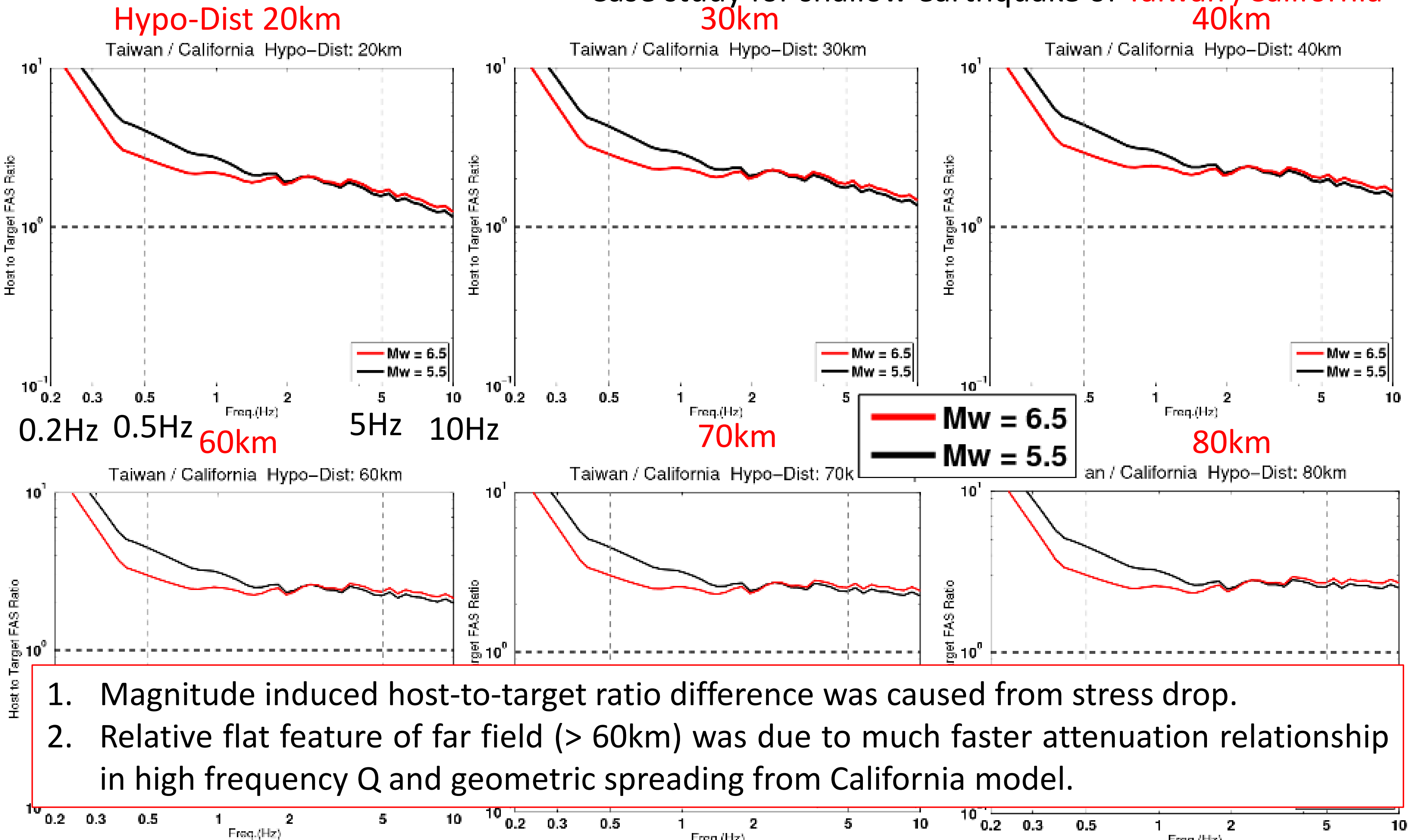


FAS of Ground motion simulation were larger in Taiwan than in California in 0.2-10 Hz.

Applications- host to target adjustment factor for GMPE

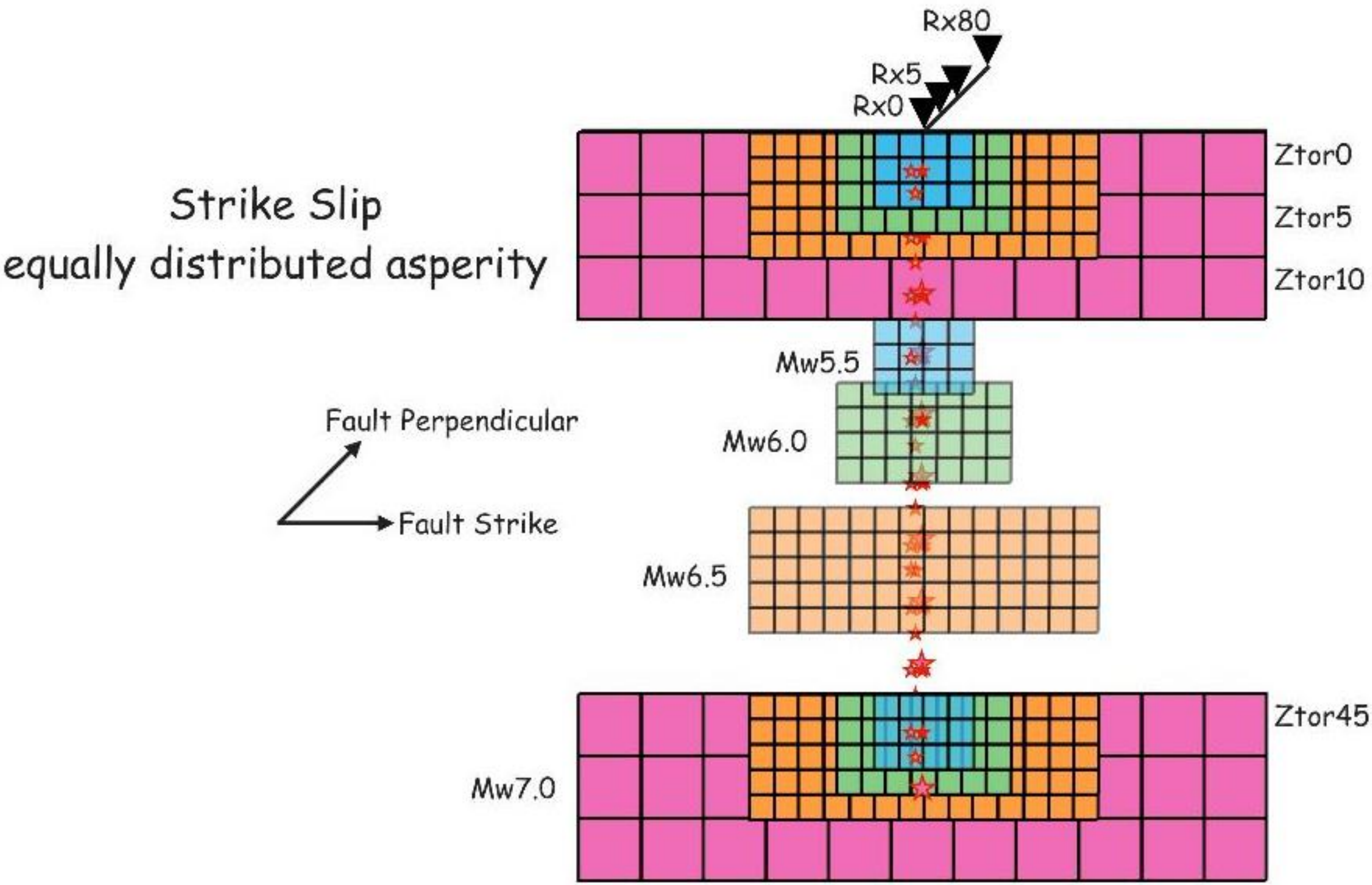
NARLabs

*From Stochastic Simulation models Case study for shallow earthquake of Taiwan /California



1. Magnitude induced host-to-target ratio difference was caused from stress drop.
2. Relative flat feature of far field (> 60km) was due to much faster attenuation relationship in high frequency Q and geometric spreading from California model.

Applications- simulating depth scaling relation for GMPE

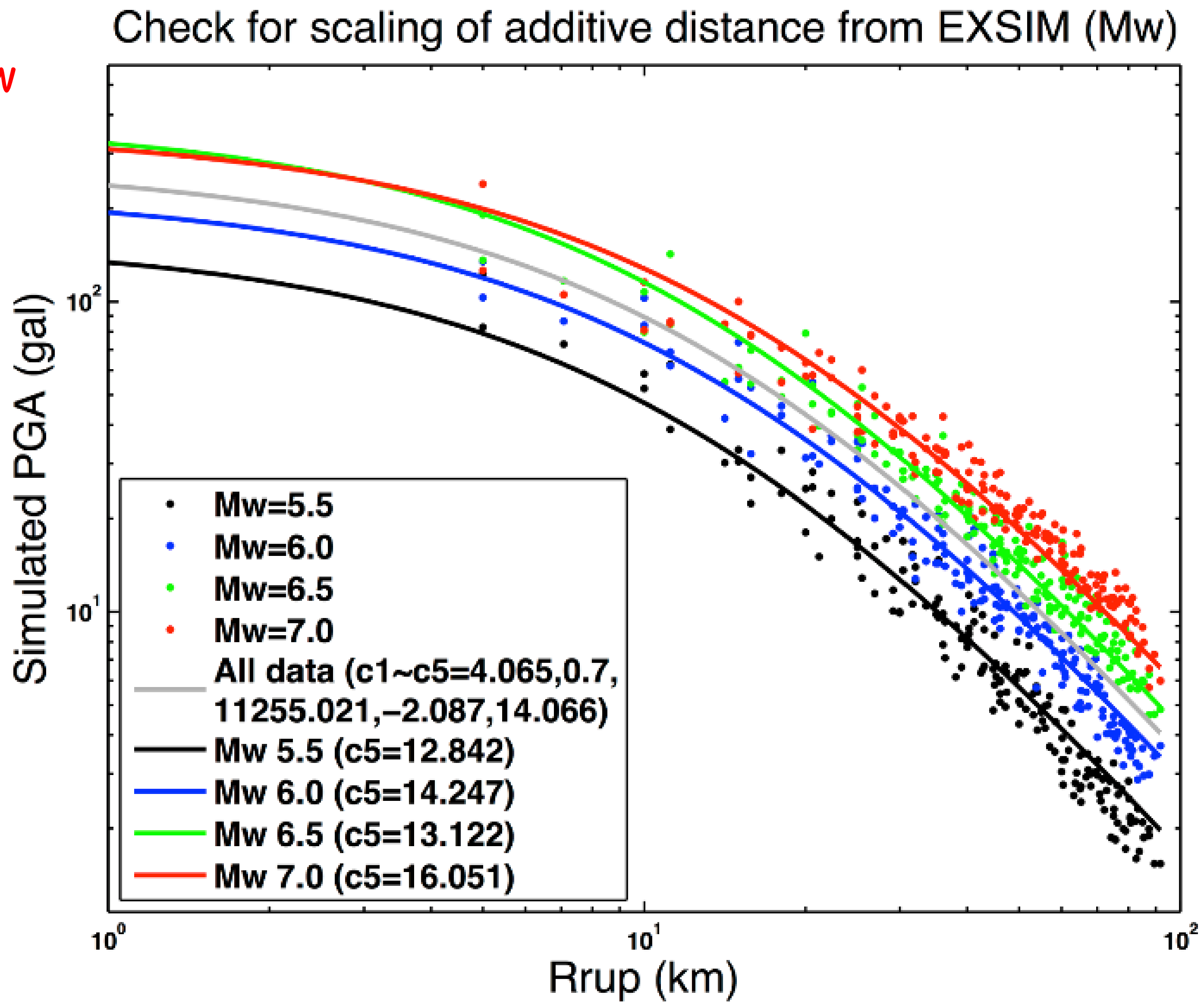


Applications- simulating depth scaling relation for GMPE

NARLabs

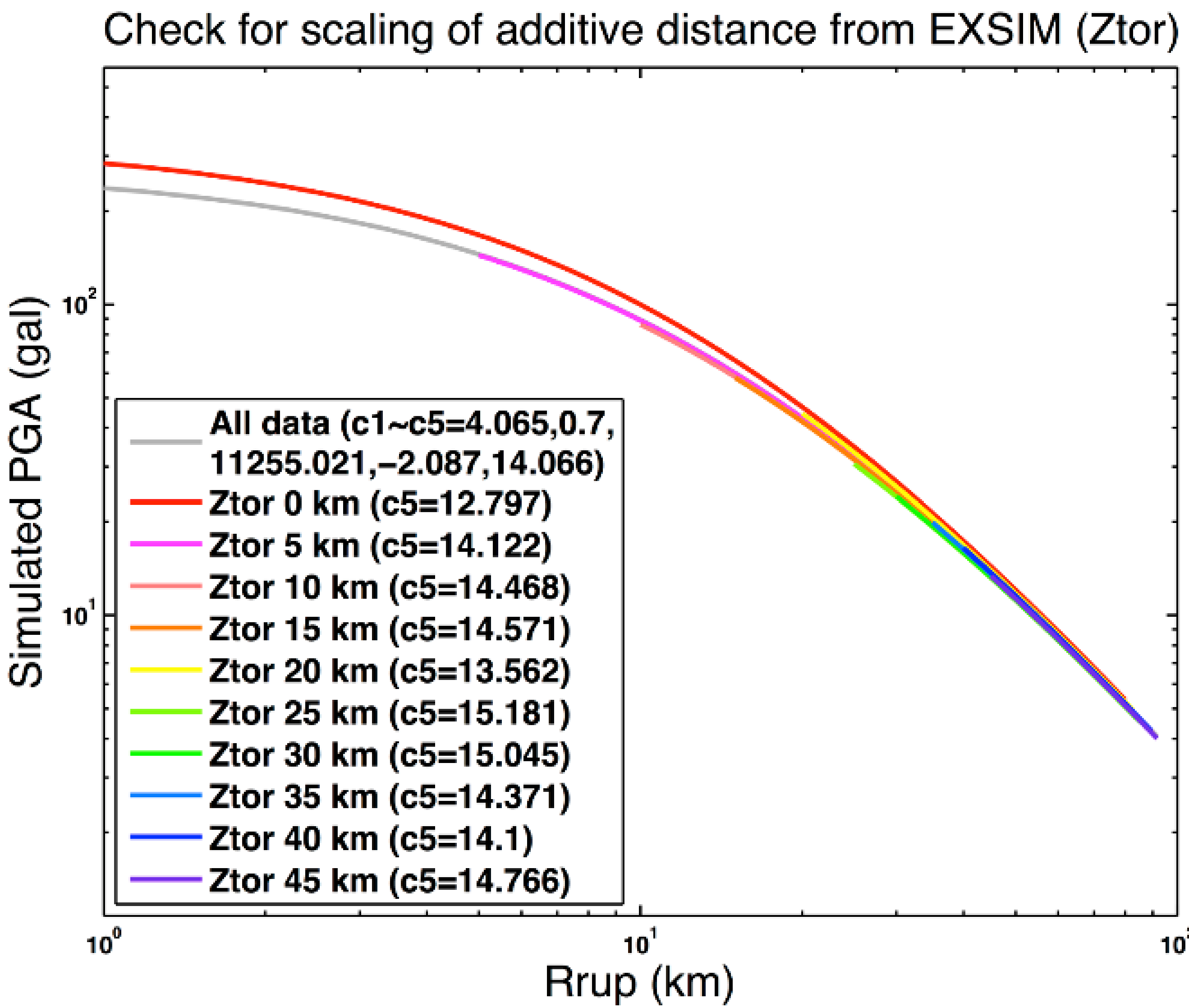
Relation with Mw (PGA)

1. c1~c5 are fitted from all data first.
2. Fix c1~c4, regress c5 for different dataset



Applications- simulating depth scaling relation for GMPE

Relation with Ztor (PGA)



Applications- simulating depth scaling relation for GMPE

NARLabs

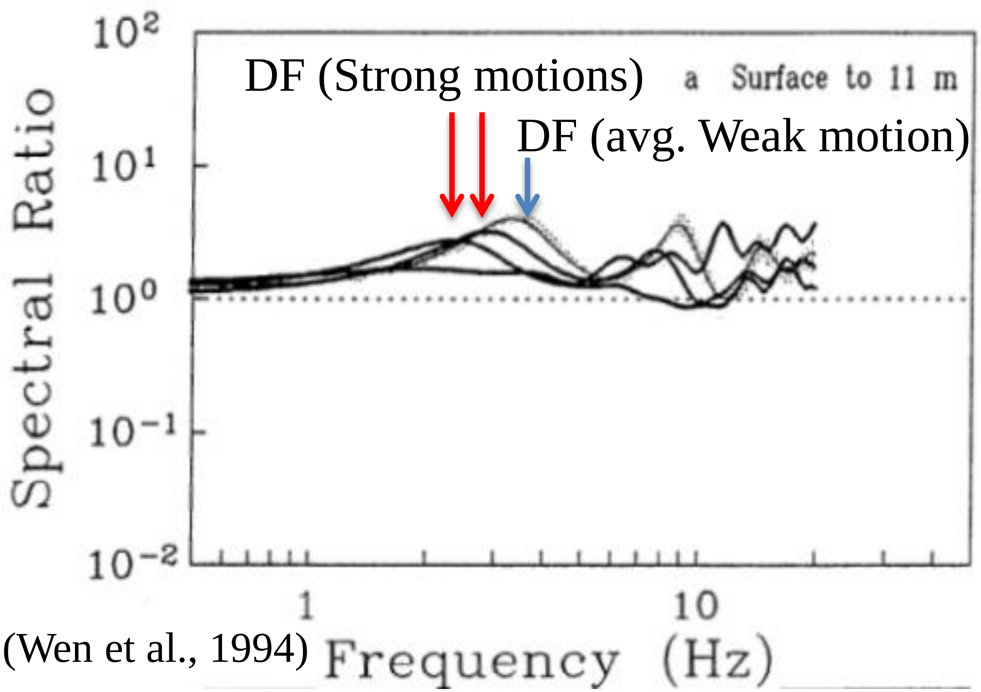
Range of case Ry	Greater than average	Lower than average

c5 value	All data	Mw 5.5	Mw 6.0	Mw 6.5	Mw 7.0	Range of case Ry
PGA	14.1	12.8	14.2	13.1	16.1	14.9-17.1
PSA 0.2 sec	16.2	15.2	16.3	15.6	17.8	18.2-20.1
PSA 2 sec	13.5	12.4	13.6	12.9	14.9	15.8-17.6

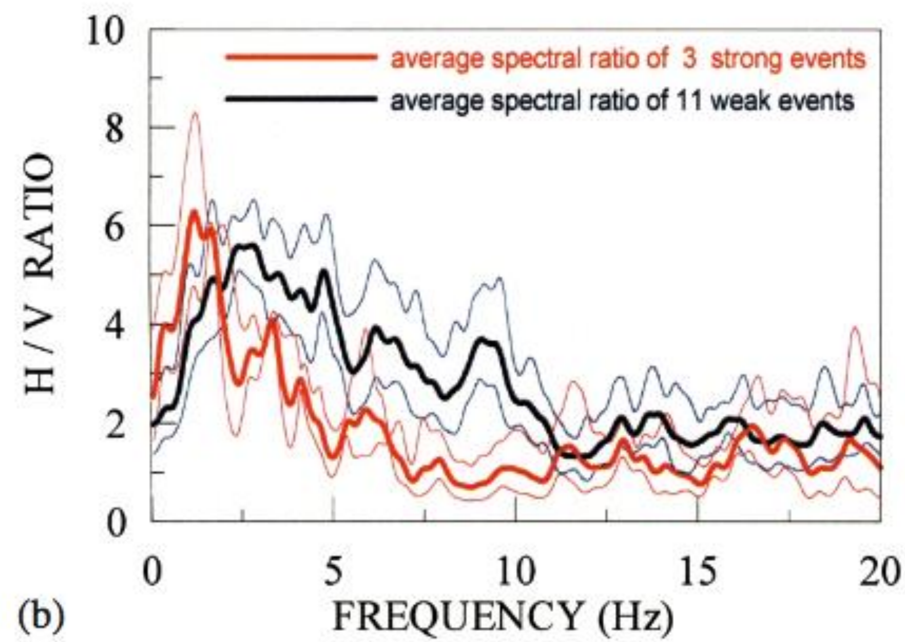
c5 value	Ztor 0	Ztor 5	Ztor 10	Ztor 15	Ztor 20	Range of case Ry
PGA	12.8	14.1	14.5	14.5	13.6	14.7-17
PSA 0.2 sec	14.7	16.1	16.6	16.6	16.7	17.8-19.7
PSA 2 sec	12.0	13.5	13.8	13.8	14.0	15.4-17.4

c5 value	Ztor 25	Ztor 30	Ztor 35	Ztor 40	Ztor 45
PGA	15.2	15.0	14.4	14.1	14.8
PSA 0.2 sec	16.7	16.7	16.8	17.1	17.3
PSA 2 sec	13.7	13.9	14.1	14.3	14.7

Applications-High Frequency Ground Motion Simulation (with nonlinearity)



(Wen et al., 1994)



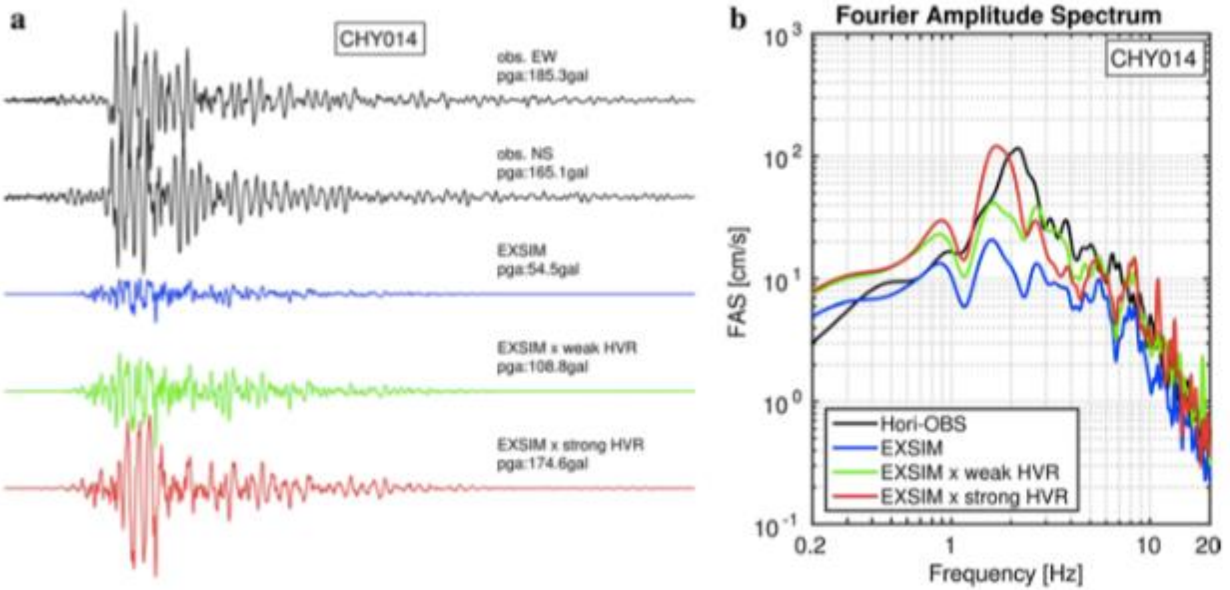
(Wen et al., 2006)

Dominant frequency (DF) drop from LSST array in Taiwan using spectral ratio method (Soil to Rock).

DF drop & de-amplification of high frequency from LSST array in Taiwan using HVSR.

Applications-High Frequency Ground Motion Simulation (with nonlinearity)

NARLabs

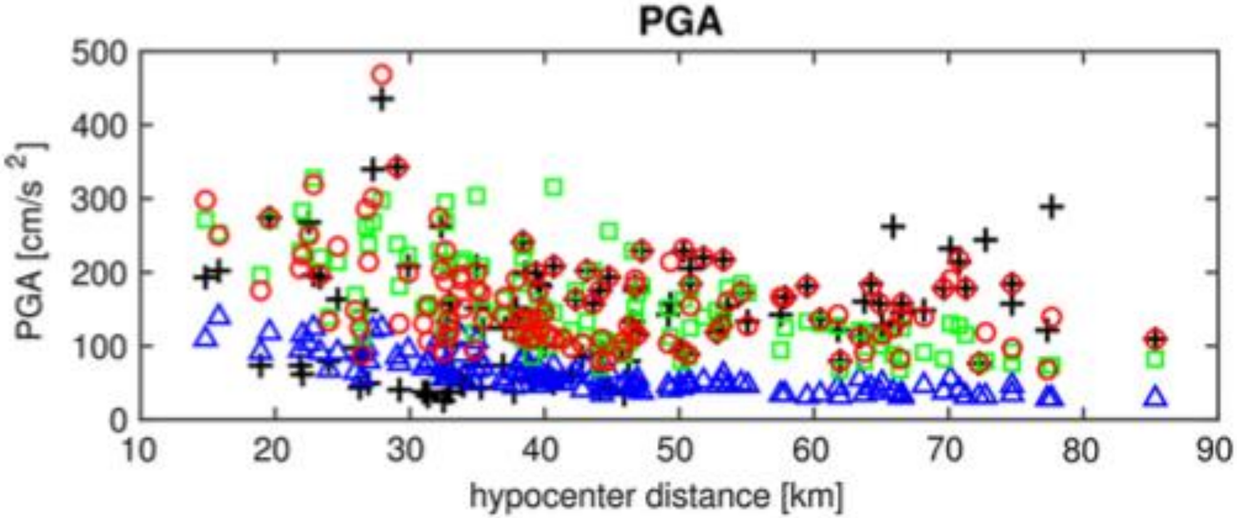


Observation

VHR Simulation

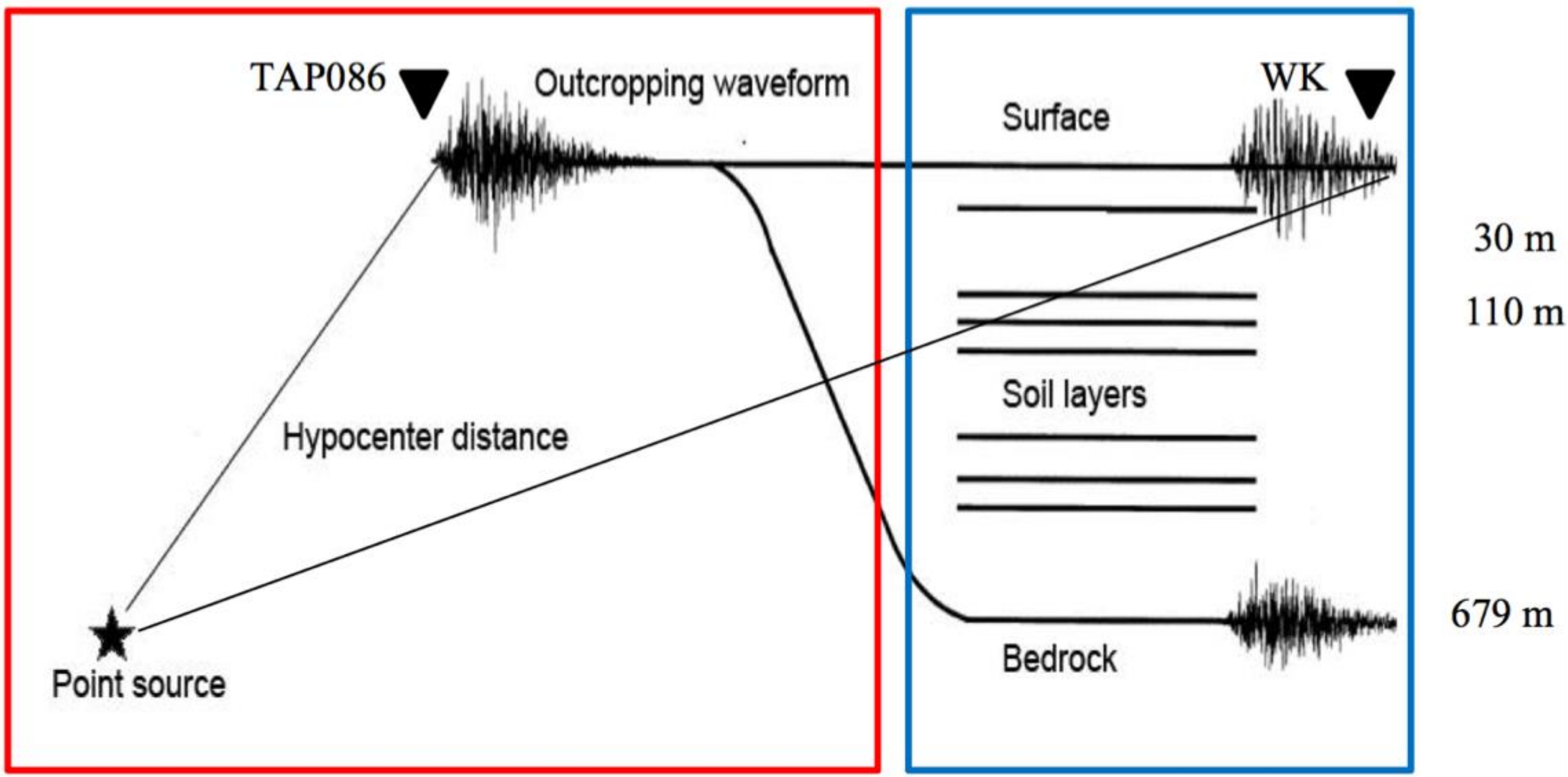
Site **Correction with HVSR of weak motions**

Site Correction with HVSR of main shock



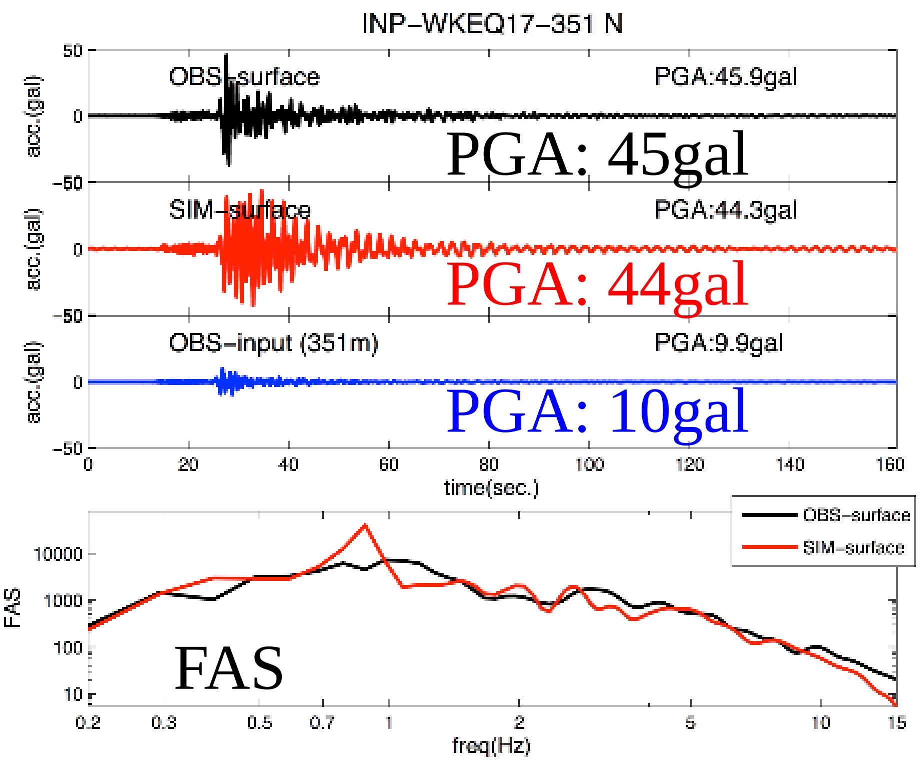
(Chen et al., 2017)

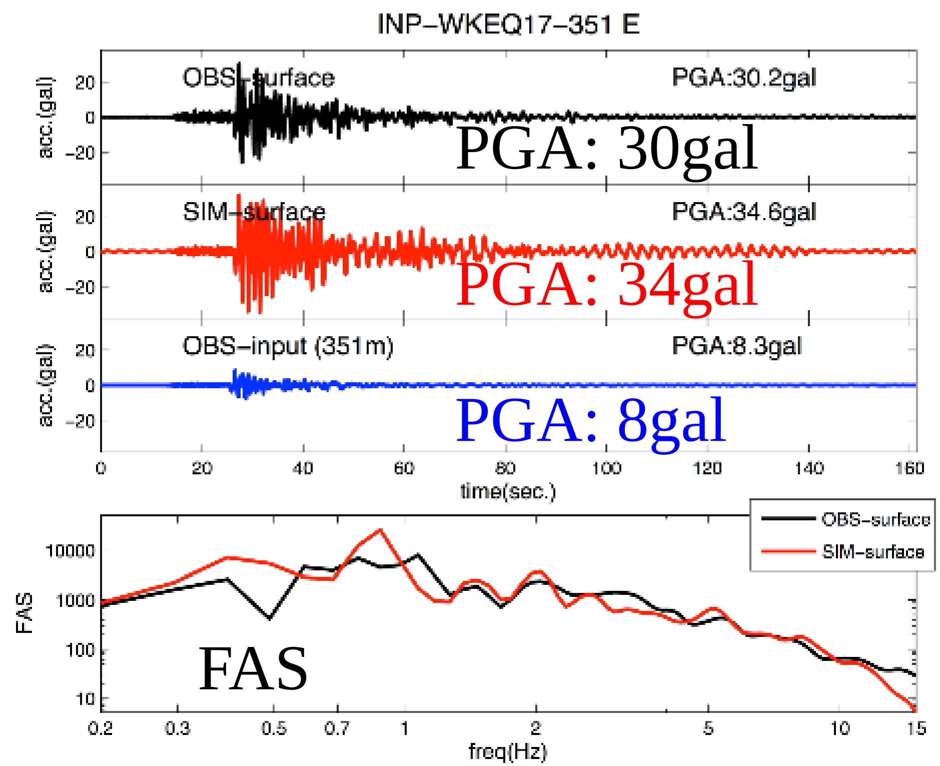
Applications-High Frequency Ground Motion Simulation (with nonlinearity)



Applications-High Frequency Ground Motion Simulation (with nonlinearity)

Validation of structures of WK downhole from equivalent linear method



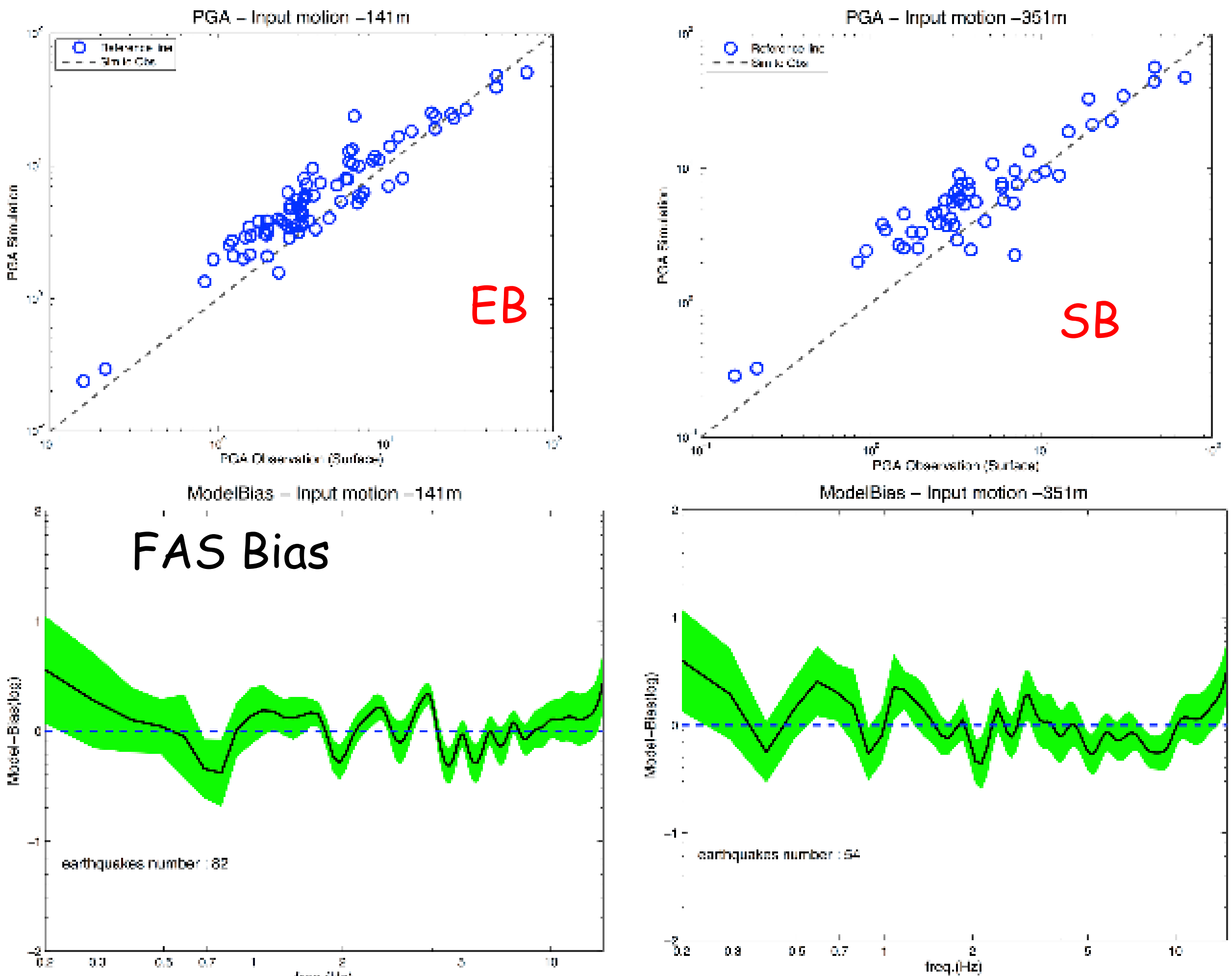


Observation (free field)
Simulation (to free field)
Input Motion (Observation, SB)

Applications-High Frequency Ground Motion Simulation (with nonlinearity)

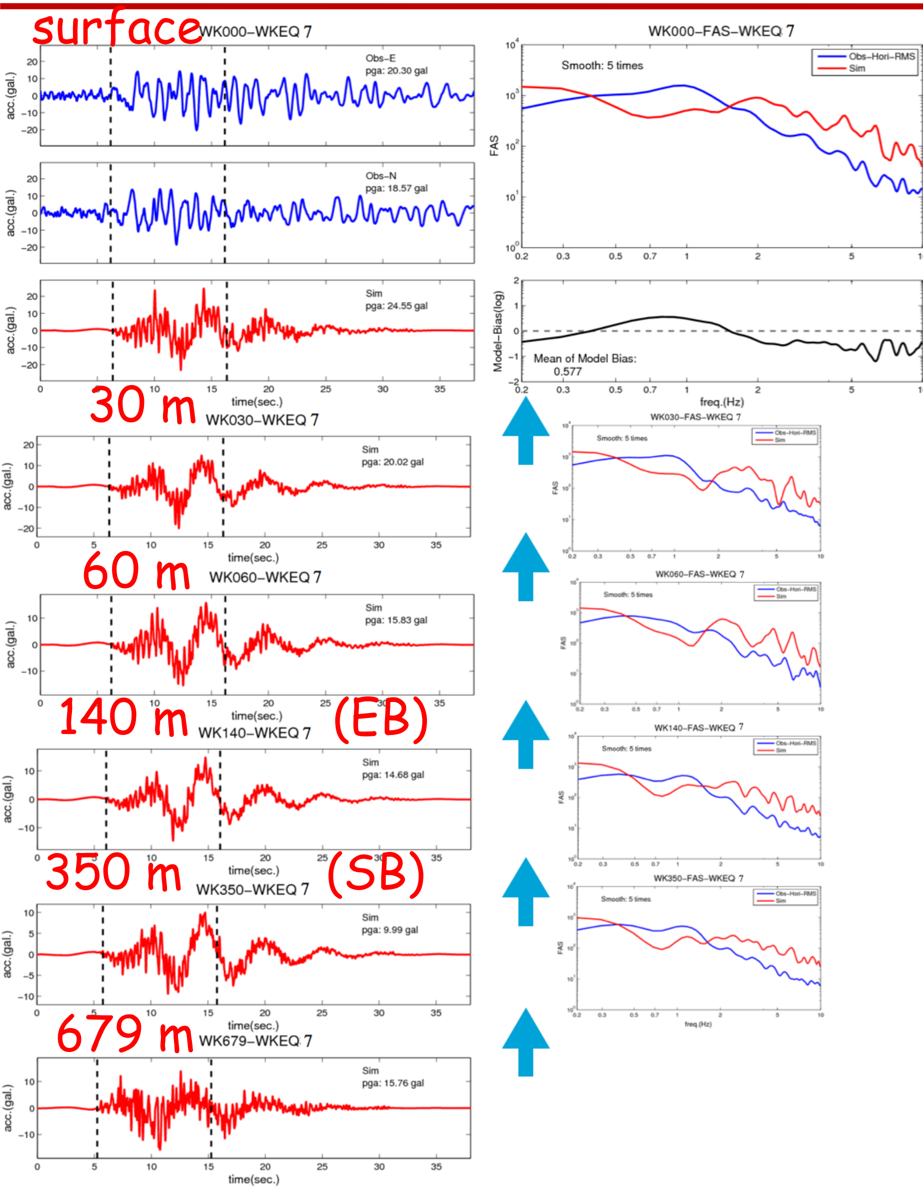
NARLabs

Input motion from observation in SB-351m and EB-141m

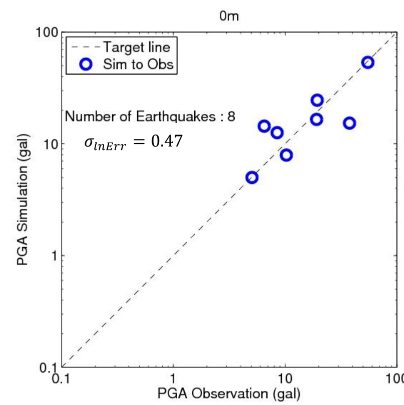


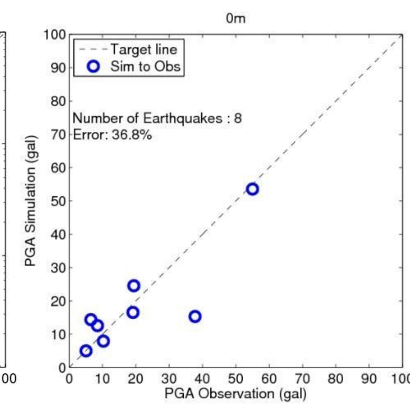
Velocity and geological structure were suitable for WK borehole to predict ground motion from both EB and SB

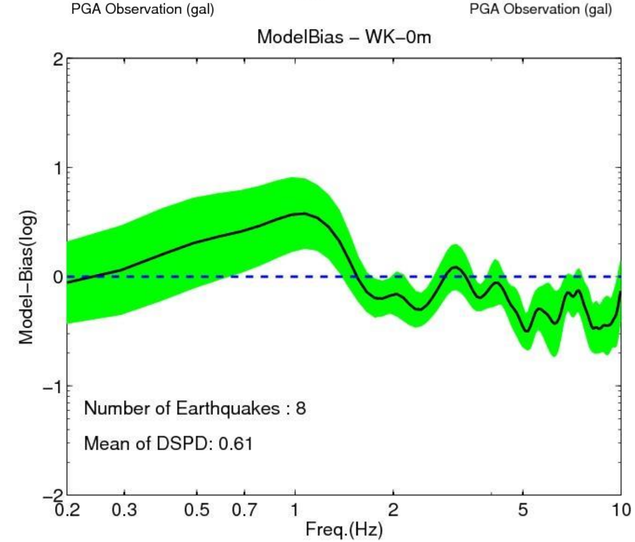
Applications-High Frequency Ground Motion Simulation (with nonlinearity)



Example of simulations, input motion from SMSIM on geological bedrock (679m)

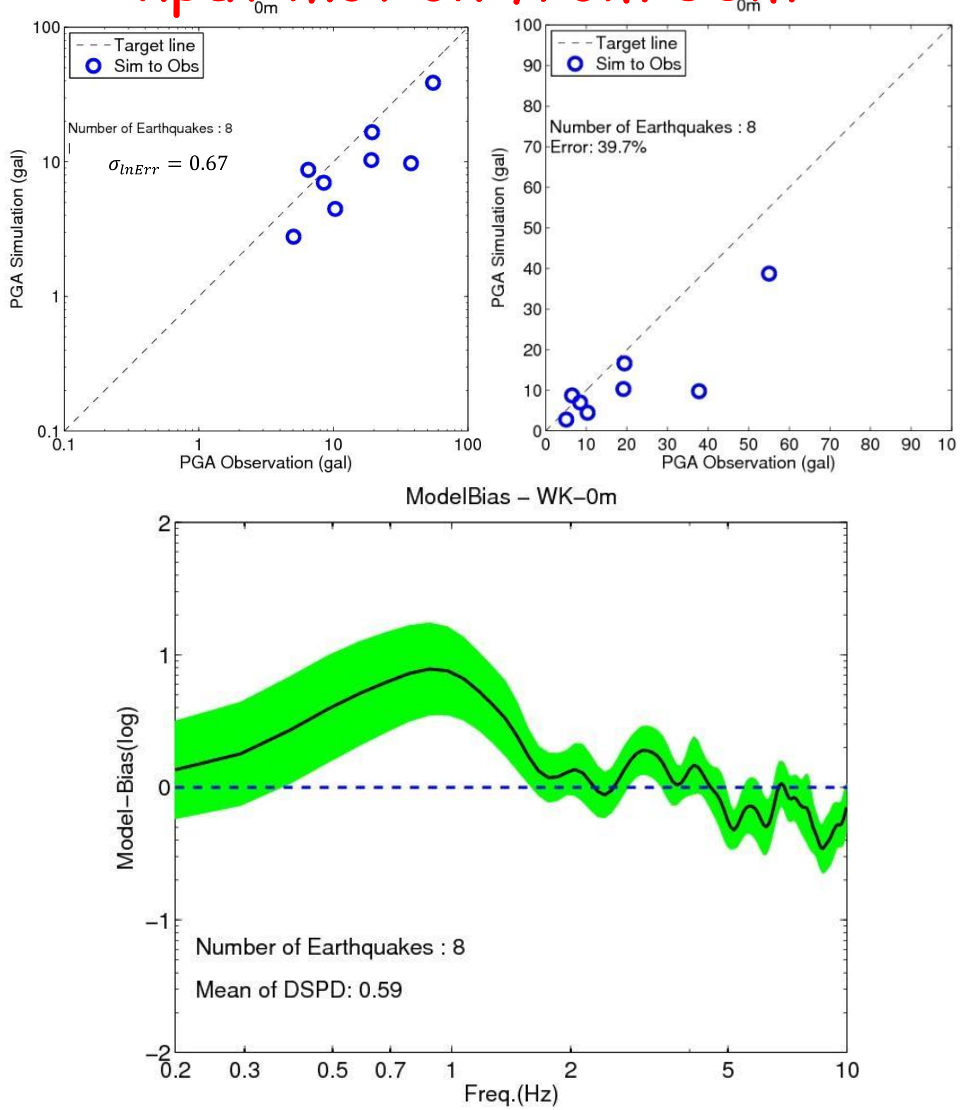




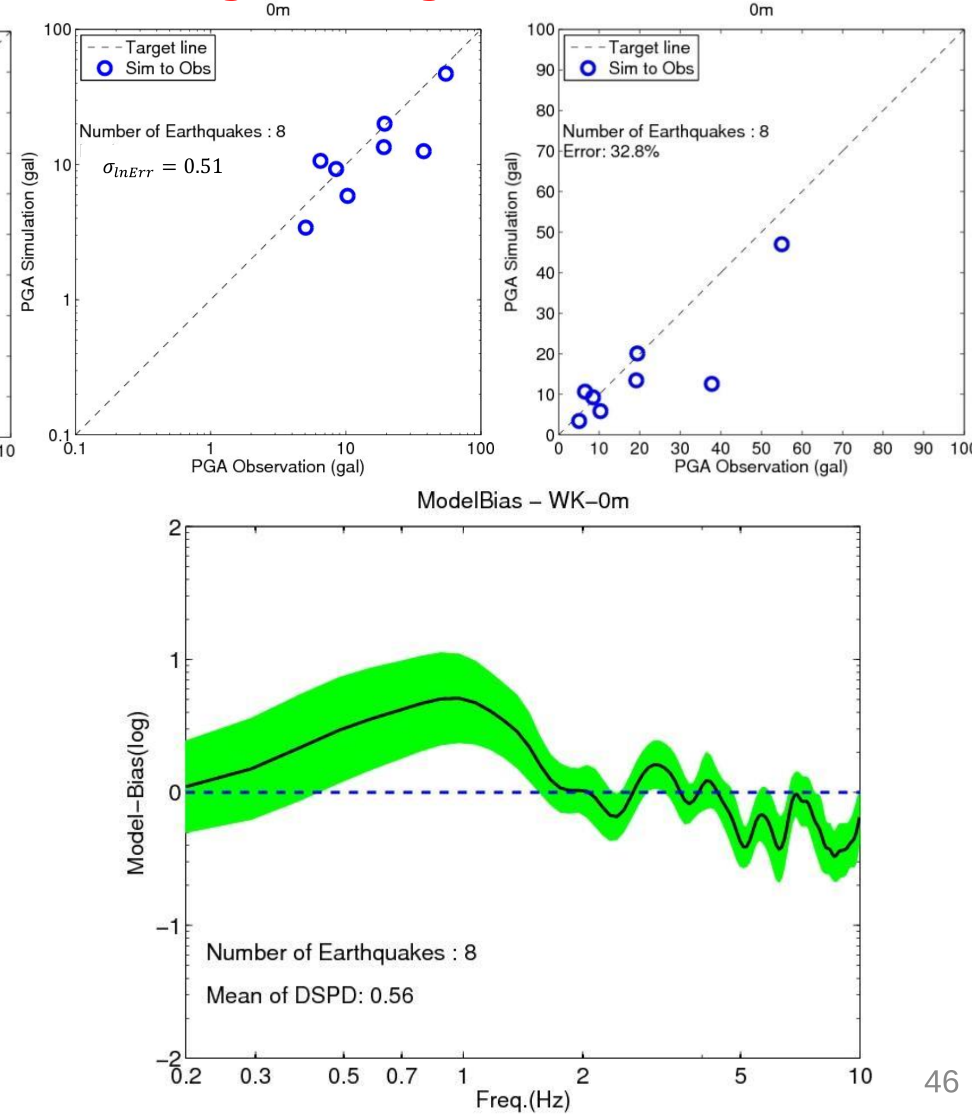


Applications-High Frequency Ground Motion Simulation (with nonlinearity)

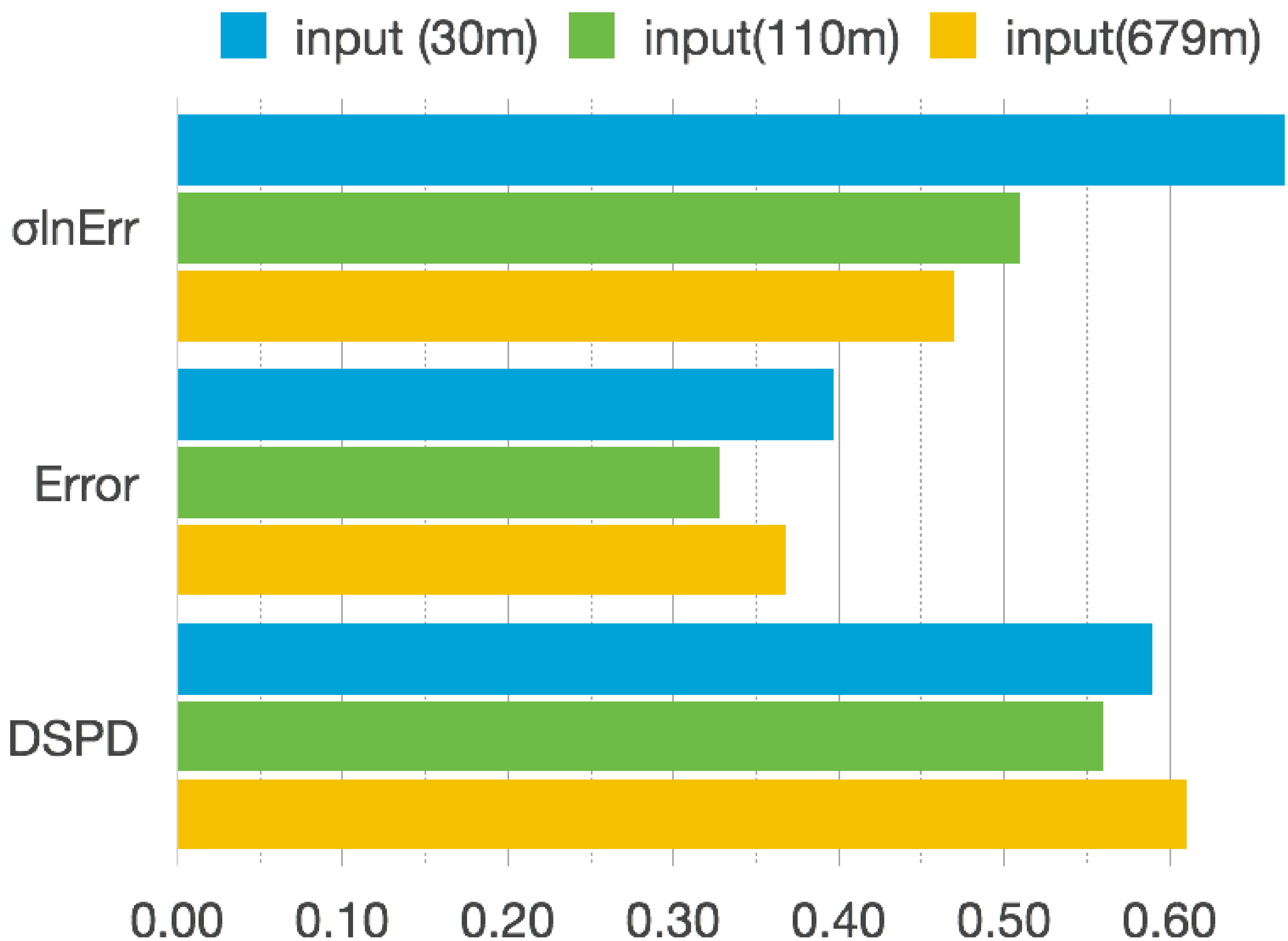
input motion from 30m



from Engineering bedrock (EB) (110m)



Applications-High Frequency Ground Motion Simulation (with nonlinearity)



Thanks for your attention

Applications- host to target adjustment factor for GMPE

Acceleration spectrum

$$Y(M_0, R, f) = E(M_0, f)P(R, f)G(f)$$

$$E(M_0, f) = Const \cdot M_0 S(M_0, f)$$

Source term

$$S(M_0, f) = \frac{4\pi^2 f^2}{R_1(1 + (f/f_0)^2)}$$

$$f_0 = 4.9\times10^6 \beta(\Delta\sigma/M_0)^{1/3}$$

$$\log_{10} M_0 = 1.5M_w + 16.1$$

$$Const = \frac{R_{\theta\phi}\cdot V\cdot F}{4\pi\rho\beta^3} = \frac{0.777818e^{-20}}{4\pi\rho\beta^3}$$

$$P(R, f) = exp[-\pi f R/Q(f)\beta]$$

Path term

$$G(f) = Amp(f)Damp(f)$$

Site term

$$Amp(f) = Af^3 + Bf^2 + Cf + D$$

$$Damp(f) = e^{-\pi\kappa_0 f}$$

Applications- host to target adjustment factor for GMPE

Acceleration spectrum (nature log)

*Levenberg-Marquardt algorithm

Constant — Source term — Site term

$$\ln Y = \ln\left(\frac{0.777818e^{-20}}{4\pi\rho\beta^3}\cdot\frac{4\pi^2 f^2}{R_1(1+(f/f_0)^2)}\cdot(Af^3+Bf^2+Cf+D)\right)$$

Geometrical Spreading(R_1)

$$+\,2.3\cdot(1.5M_w+16.1)-\frac{\pi f R}{Q(f)\beta}-\pi\kappa_0 f$$

ln(M_0) — Path term — Site term

Select inverted parameters (optionally)

Hessian matrix

Partial differential for each parameters

(Q, eta, β, ρ, R_0, M_w, f_0, gamma, κ_0, R)

$$\begin{bmatrix}
\frac{\partial^2 \ln y}{\partial Q^2} & \frac{\partial^2 \ln y}{\partial Q\partial eta} & \frac{\partial^2 \ln y}{\partial Q\partial f_0} & . & . & \frac{\partial^2 \ln y}{\partial Q\partial \kappa_0} \\
\frac{\partial^2 \ln y}{\partial Q\partial eta} & \frac{\partial^2 \ln y}{\partial eta^2} & \frac{\partial^2 \ln y}{\partial Q\partial eta} & . & . & \frac{\partial^2 \ln y}{\partial eta\partial \kappa_0} \\
\frac{\partial^2 \ln y}{\partial Q\partial f_0} & . & \frac{\partial^2 \ln y}{\partial {f_0}^2} & . & . & \frac{\partial^2 \ln y}{\partial f_0\partial \kappa_0} \\
. & . & . & . & . & . \\
. & . & . & . & . & . \\
\frac{\partial^2 \ln y}{\partial Q\partial \kappa_0} & . & . & . & . & \frac{\partial^2 \ln y}{\partial {\kappa_0}^2}
\end{bmatrix}$$

Applications- host to target adjustment factor for GMPE

NARLabs

*Levenberg-Marquardt algorithm

Hessian matrix * $\begin{bmatrix} 1+\lambda & 1 & 1 & 1 & 1 & 1 \\ 1 & 1+\lambda & 1 & 1 & 1 & 1 \\ 1 & 1 & 1+\lambda & 1 & 1 & 1 \\ 1 & 1 & 1 & 1+\lambda & 1 & 1 \\ 1 & 1 & 1 & 1 & 1+\lambda & 1 \\ 1 & 1 & 1 & 1 & 1 & 1+\lambda \end{bmatrix}$ $\Rightarrow Covar$

New matrix for next iteration

Still Hessian form

Manually setting $\lambda = 0.001$

→ $\mathrm{p_{j+1}} = \mathrm{p_j} + \beta_{LM}(\mathrm{p_j})$

$\beta_{\mathrm{LM}}(\mathrm{p}) = (\ln Y_{OBS} - \ln Y) \cdot \frac{\partial y}{\partial \mathrm{p}}$

P = Inverted Parameters

j = Iterations

CHISQ

$$\chi^2 = \sum \left(\frac{(\ln Y_{OBS} - \ln Y)^2}{SIGMA^2} \right) \; ; \; \mathrm{SIGMA} = 1$$

→ Use Gauss-Jorden method to solve Covar

→ Calculate $\ln(Y)_{j+1}$ using p_{j+1}

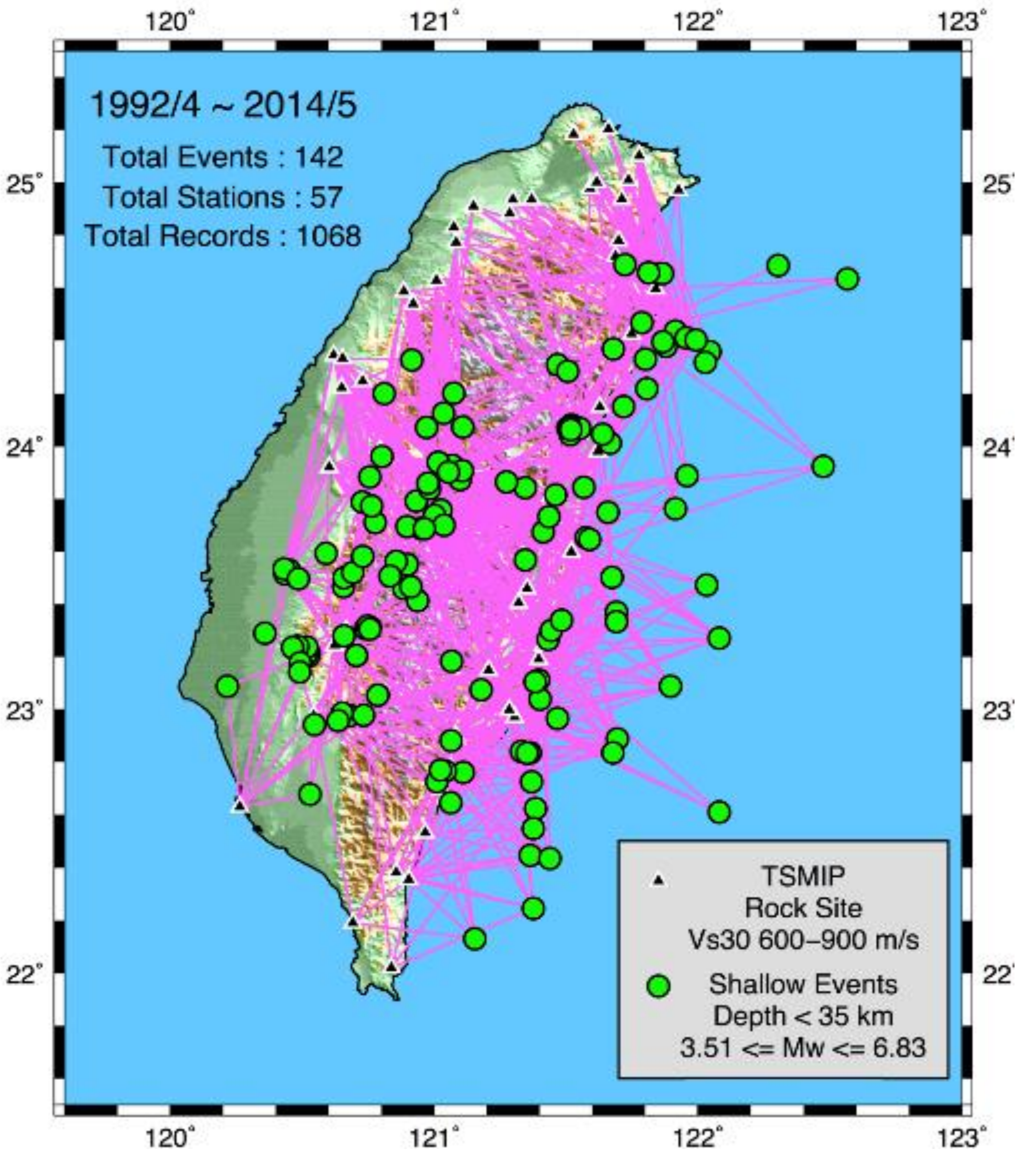
→ $\lambda_{j+1} = 0.1\lambda_j \; ; \; when\ {\chi^2}_{j+1} < {\chi^2}_j \quad \lambda_{j+1} = 10\lambda_j \; ; \; when\ {\chi^2}_{j+1} \geq {\chi^2}_j$

→ Do while $\left|{\chi^2}_j - {\chi^2}_{j-1}\right| < tol \; \& \; \left|{\chi^2}_{j-1} - {\chi^2}_{j-2}\right| < tol$

Manually setting

Applications- host to target adjustment factor for GMPE

NARLabs



- TSMIP 1992-2014
- Mw>3.5
- Rrup <100km
- Rock Site

(600<=Vs30<=900m/s)

- 142 Events
- 57 Stations
- 1068 FAS records

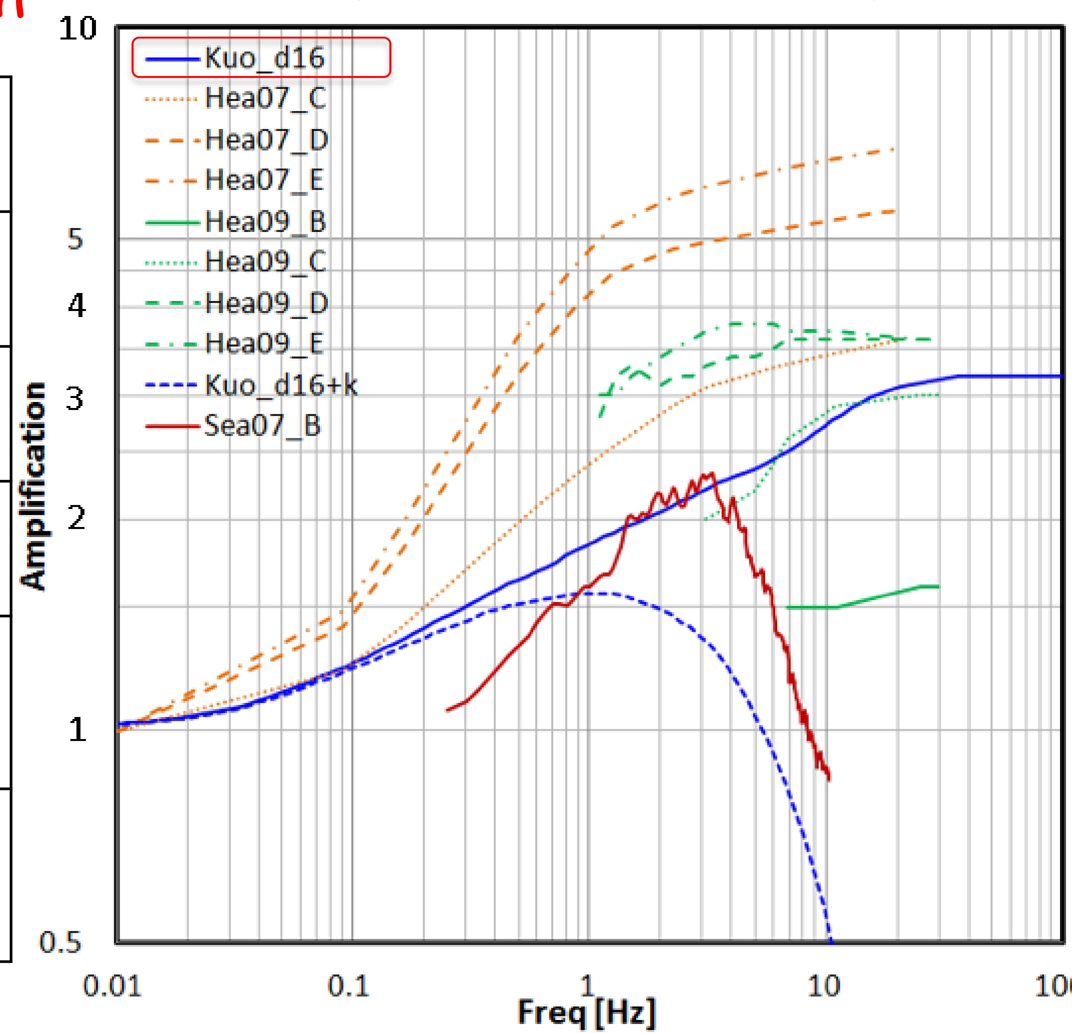
Applications- host to target adjustment factor for GMPE

NARLabs

Initial Model for inversion

Vs (β)	3.6 km/s
Density (ρ)	2.8 gm/cc
Q	$80f^{0.7}$
Kappa (κ)	0.0518
Stress drop (Δσ)	100 bar
Geometric spreading	1/R

Crustal Amplification Function (depth 16km)



(Kuo et al., 2016, Taiwan SSHAC L3, WM#2)

Applications- host to target adjustment factor for GMPE

NARLabs

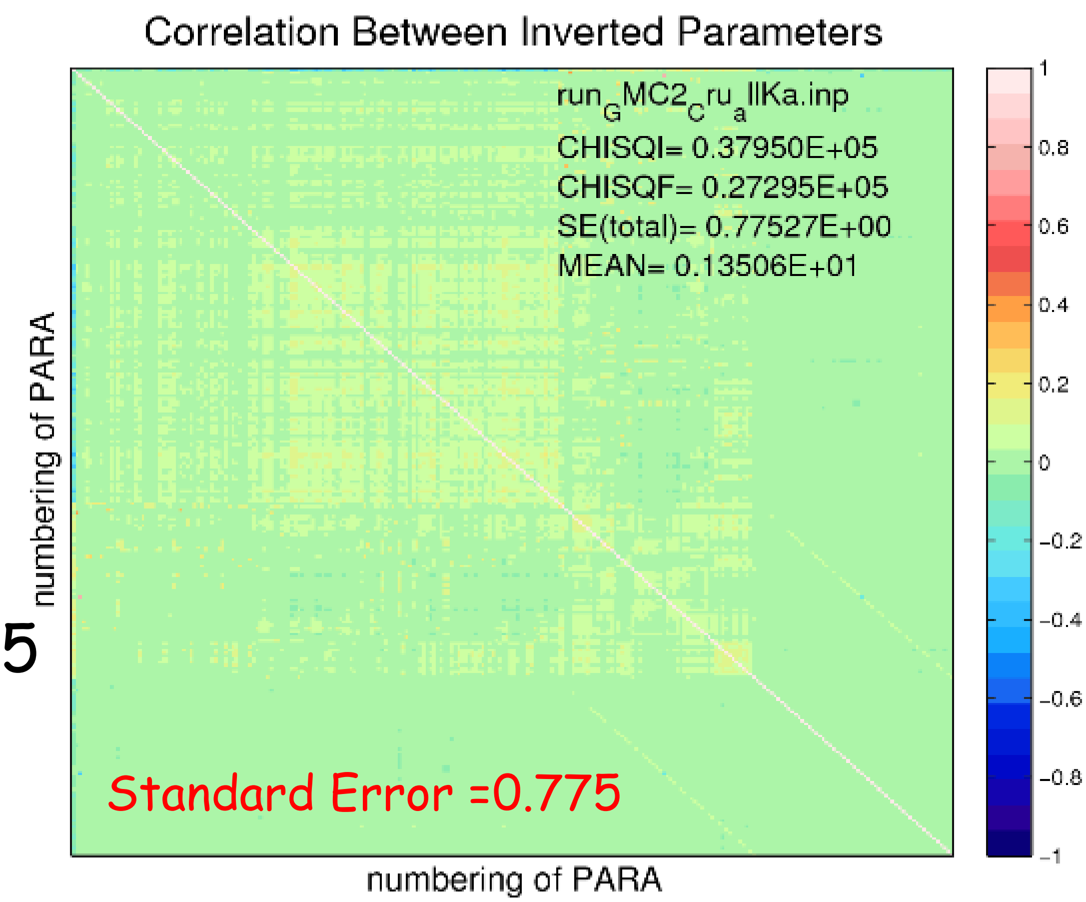
Inverted parameters:

- Q, Fc, Kappa, Amplification function

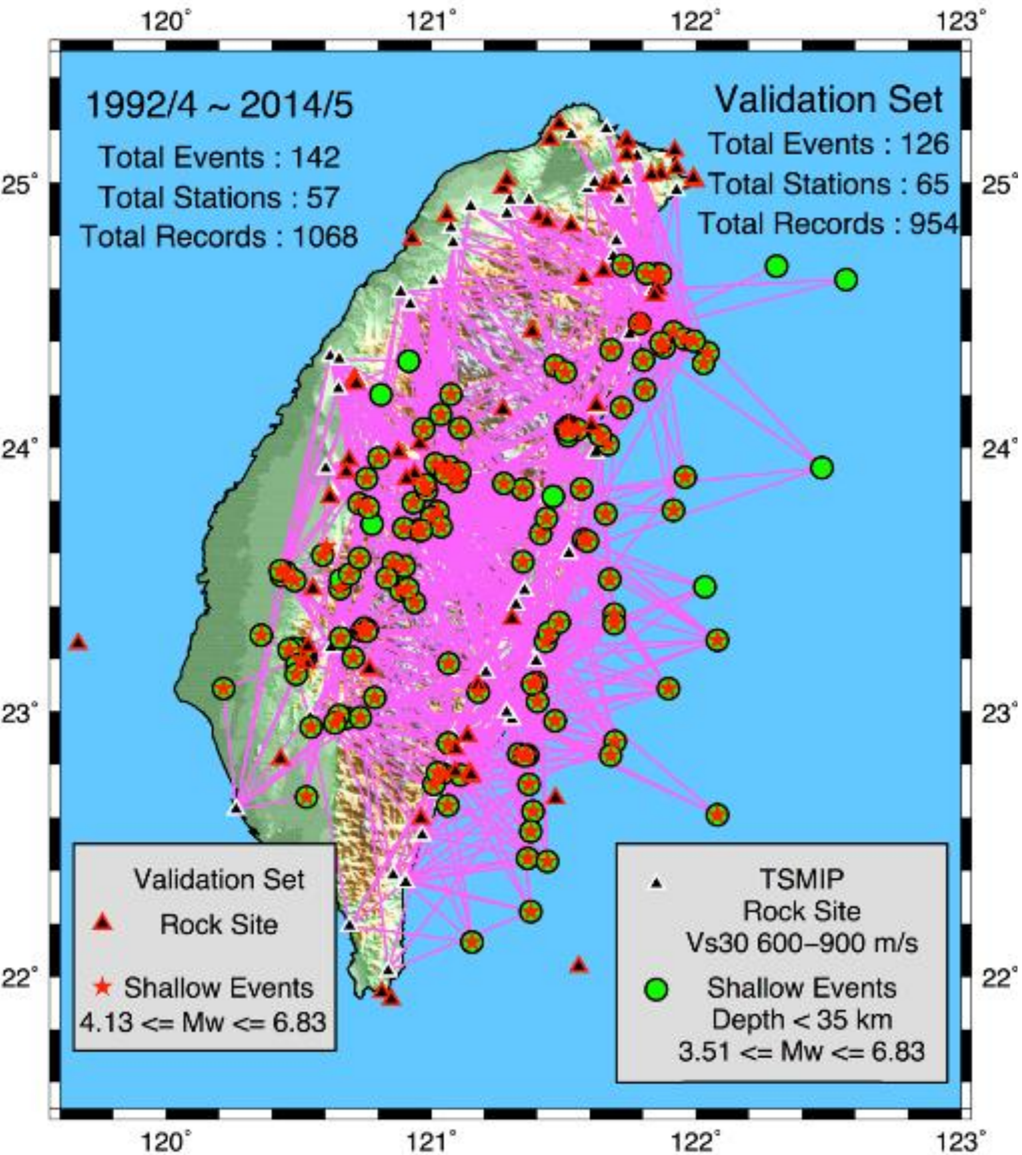
Solution:

- Q= $205f^{0.7}$
- Kappa = 0.0398
- Amplification (D) = 0.65

Covariance Matrix



Applications- host to target adjustment factor for GMPE

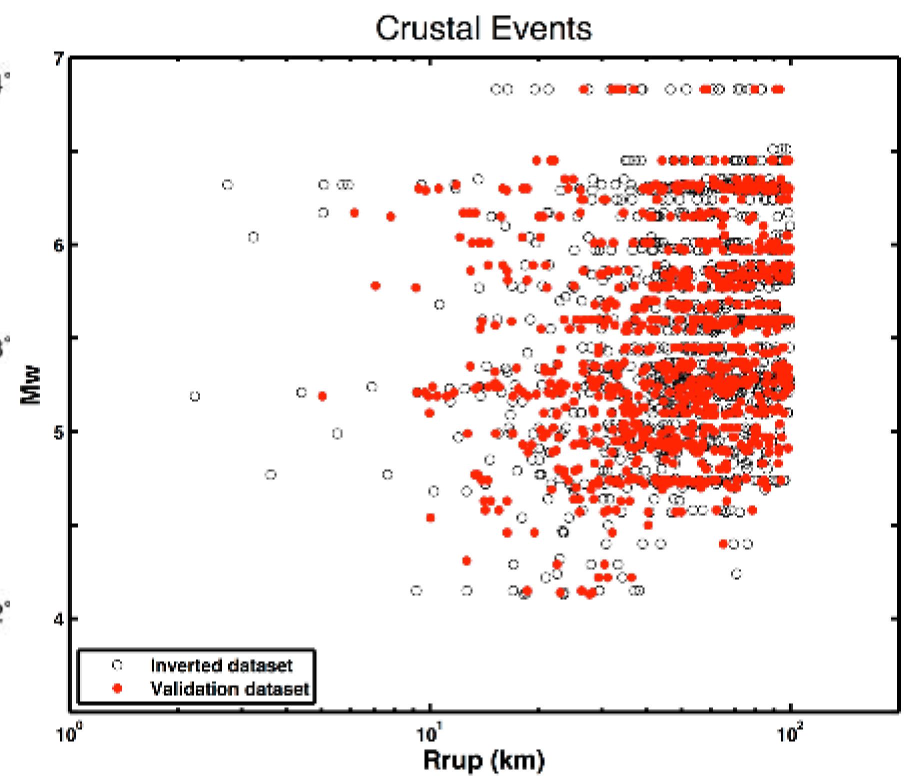


Validation Set

Rock Site

Shallow Events

4.13 <= Mw <= 6.83



Applications- host to target adjustment factor for GMPE

Residual plots