發展台灣地震動模型
以及其於地震動境況模擬之應用

Development of Taiwan Ground Motion Model and Its Application to the Ground Motion Simulation for a Scenario Earthquake

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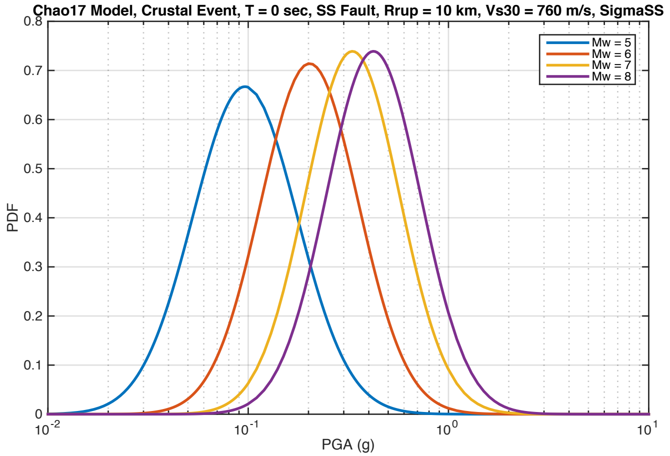
Ground Motion Model

- **A statistical model developed from empirical (measured) ground motion data which can be used to predict/evaluate the PDF of ground motion intensity for different ground motion scenarios**
- **From the observation of the ground motion residual distribution, the PDF of ground motion intensity is approximate to log-normal PDF which can be described by median and sigma**
  - $\ln S_a = f(M, R, \dots) + \delta_e + \delta_s + \delta_r$
    - $\ln S_a$: predicted GM intensity PDF
    - $f(\dots)$: predicted median GM intensity
    - δ_e: event-specific zero mean normal r.v.
    - δ_s: station-specific zero mean normal r.v.
    - δ_r: record-specific zero mean normal r.v.



Objectives

- **Develop a new Taiwan ground motion model**
  - To estimate **horizontal** GM intensity for structural periods from **0.01 sec to 5 sec**
  - For different source types
    - **Crustal** earthquake up-to Mw 8.0
    - **Subduction** earthquake up-to Mw 9.0
  - To describe important ground motion characteristics
    - Depth Scaling
    - Style-of-faulting effect
    - Aftershock effect
    - Rrup-based attenuation
    - Linear site effect and nonlinear site effect
  - Evaluate data truncation effect
  - Decompose sigma to represent event-to-event, site-to-site and record to record variability of ground motion

國家地震工程研究中心
NATIONAL CENTER FOR RESEARCH ON EARTHQUAKE ENGINEERING

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發展適用於台灣地區地殼地震與隱沒帶地震的水平向地震動模型

Development of Horizontal Taiwan Ground Motion Model for Crustal Earthquake and Subduction Earthquake

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Matlab code and excel file can be provided to use by email to: shchao@ncree.narl.org.tw

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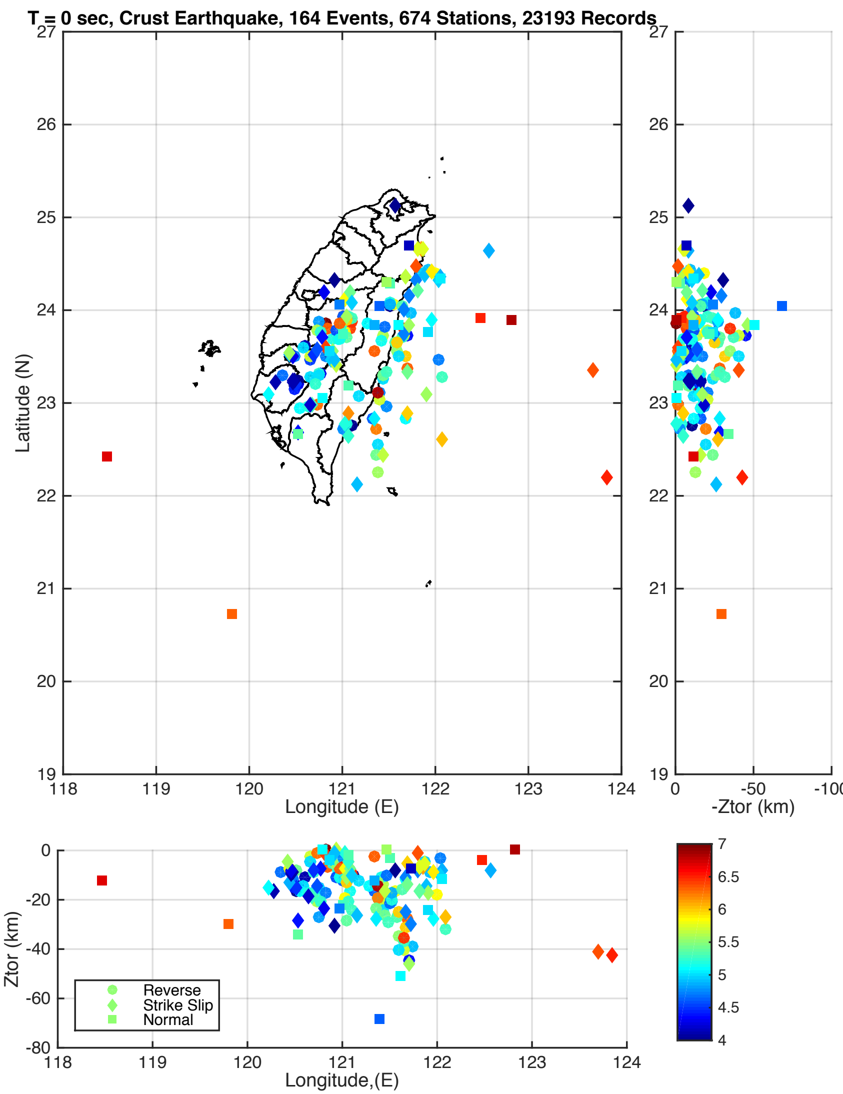
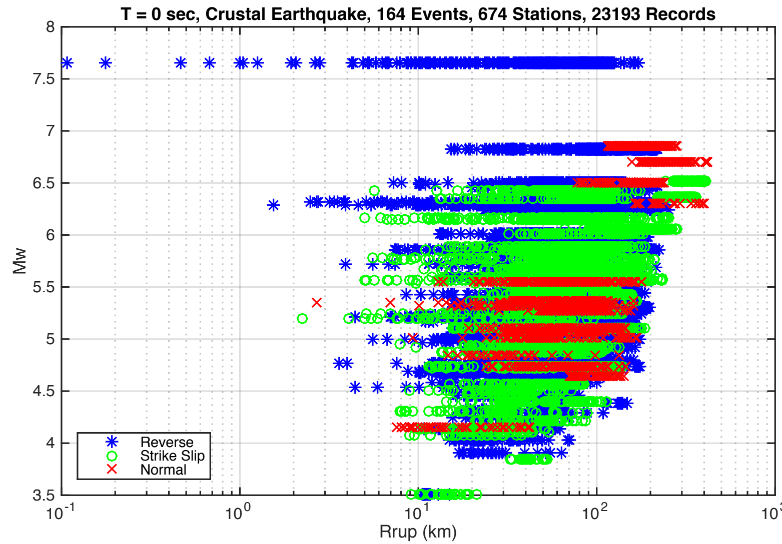
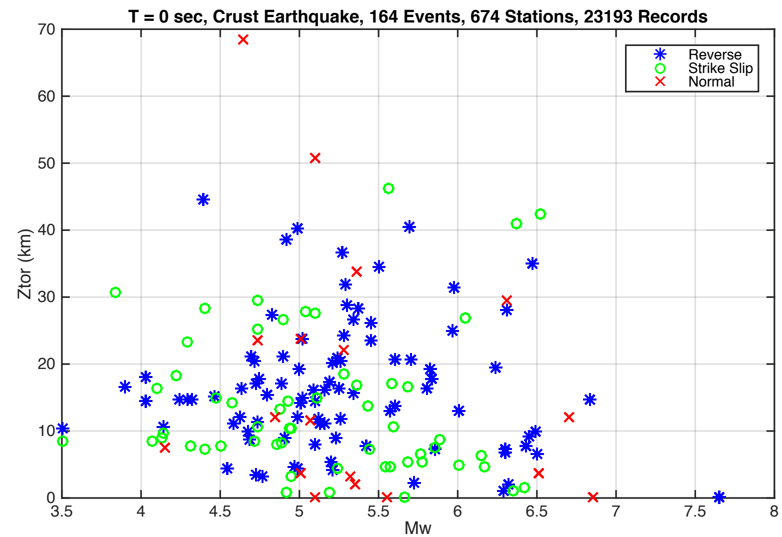
Selection Criteria of Ground Motion Data

- **The ground motion database of Taiwan SSHAC Level 3 project (http://sshac.ncree.org.tw) is used in this study (273 events, 768 stations, 37371 records)**
- **Selection Criteria**
  - PGAraw,max > 4 gal
  - Exclude four crustal events and one subduction event
    - The estimated event terms of them show significant bias from other events
  - Exclude records from RTD stations with lower resolutions
  - Exclude record with T > Tmax
  - Exclude records from
    - events with less than 10 records
    - stations with less than 10 records

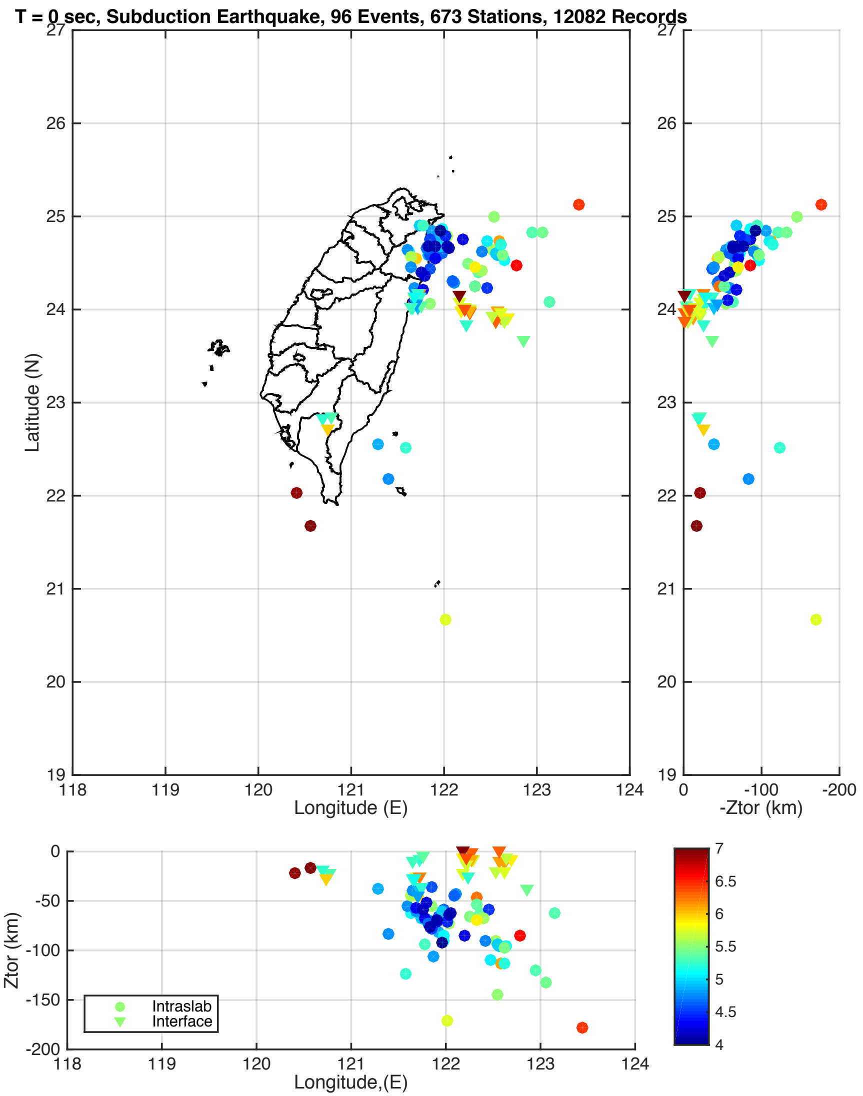
Selected Ground Motion Data for Crustal Source

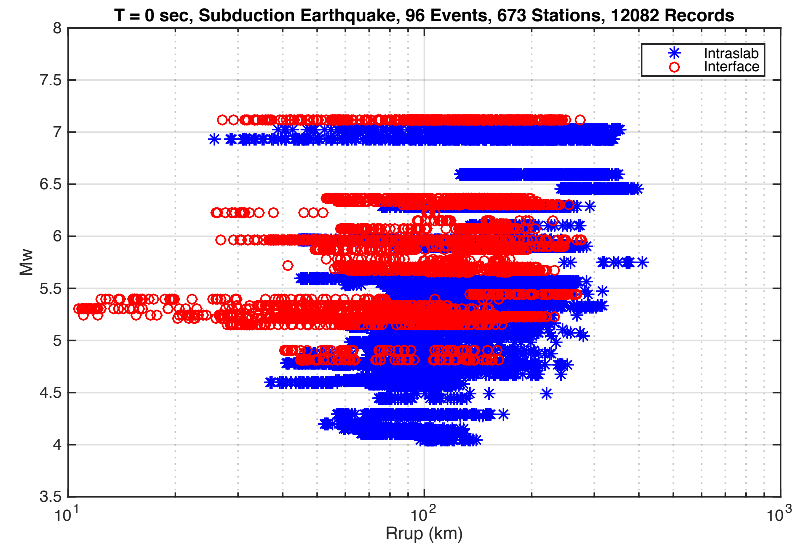


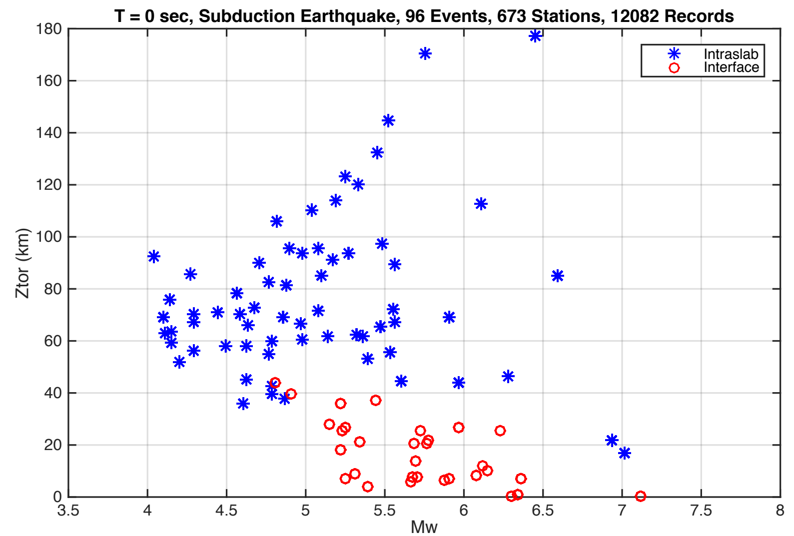




Selected Ground Motion Data for Subduction Source

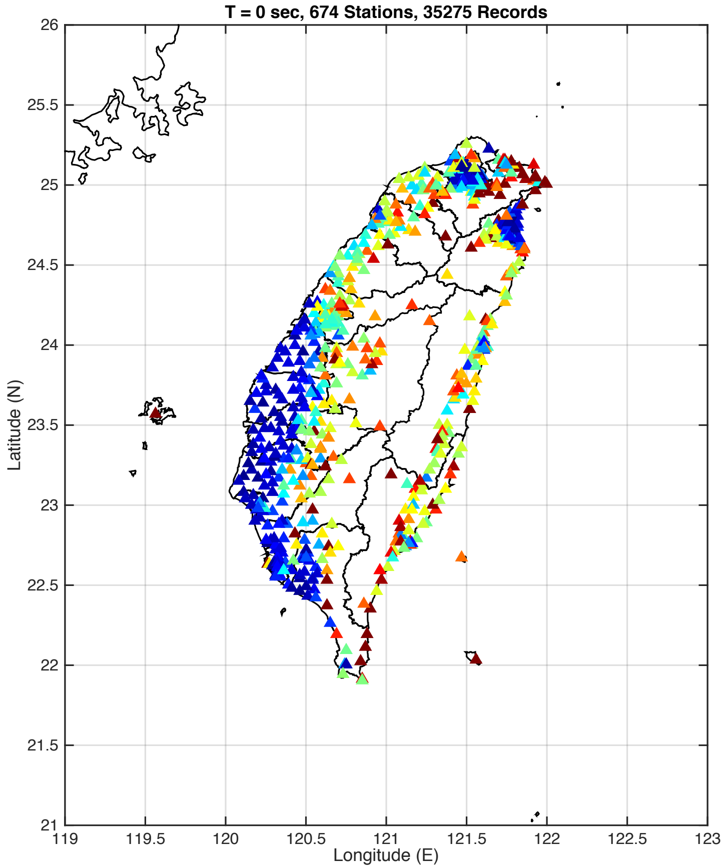


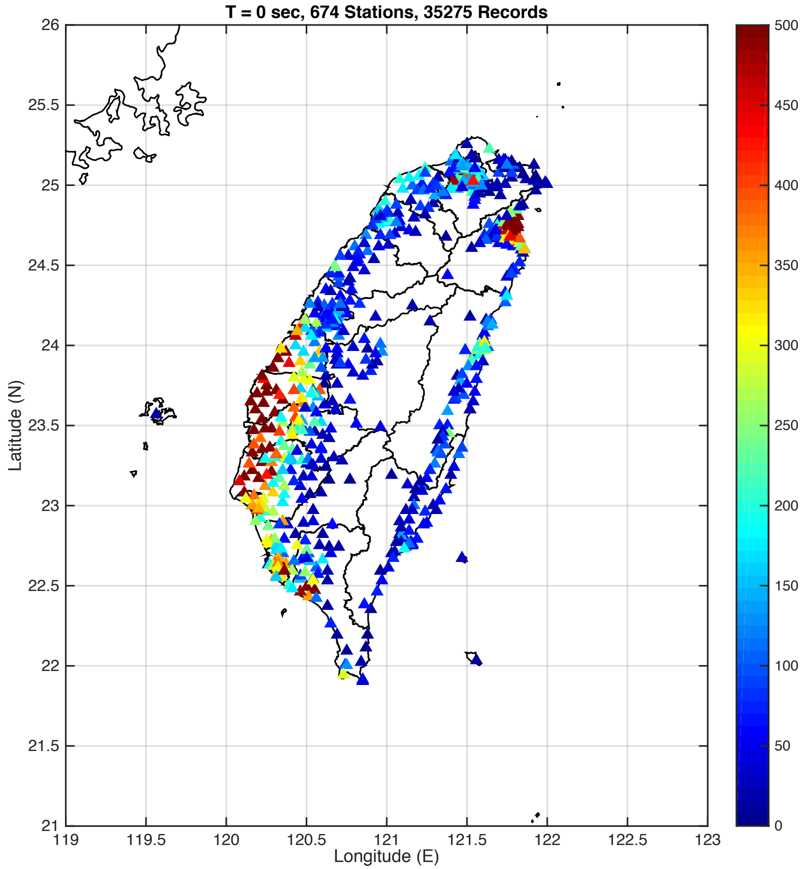




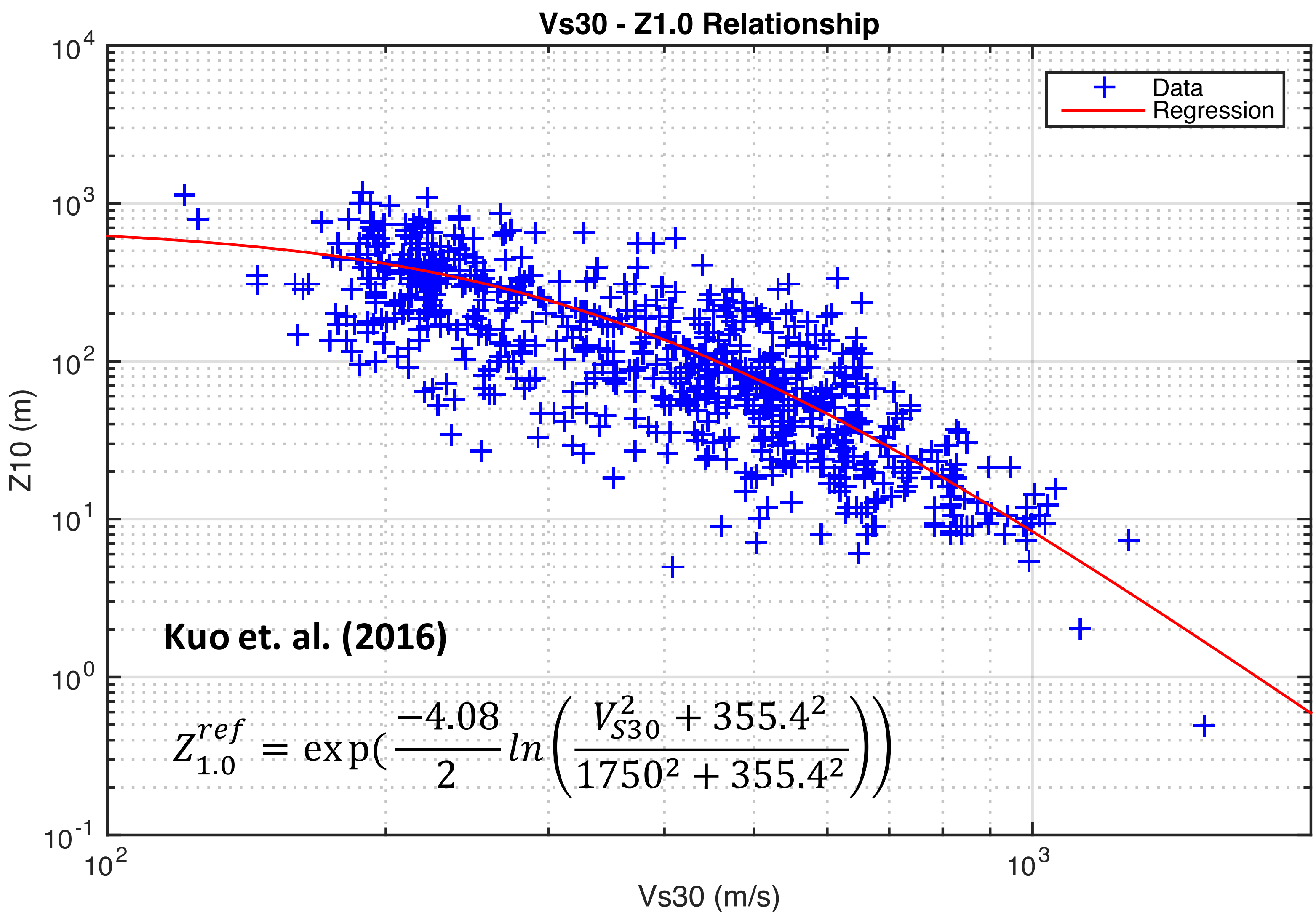
Vs30 and Z1.0 of Stations

- **Vs30 (m/s): The average shear-wave velocity of soil between 0 and 30-meters depth**
- **Z1.0 (m): The depth (m) to where shear-wave velocity of soil achieves 1.0 km/sec (the first occurrence if more than one depth exists)**



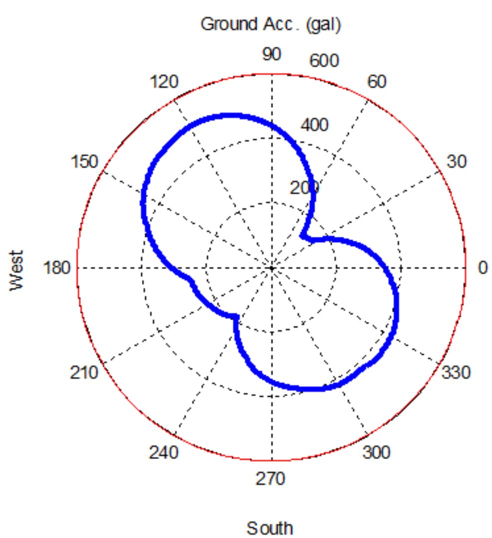


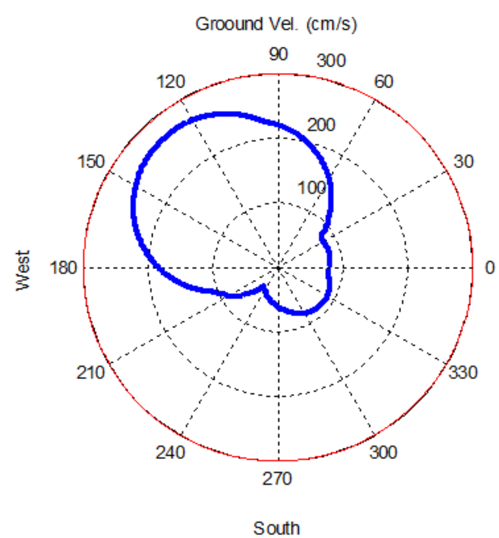
Vs30 vs. Z1.0 Relationship in Taiwan

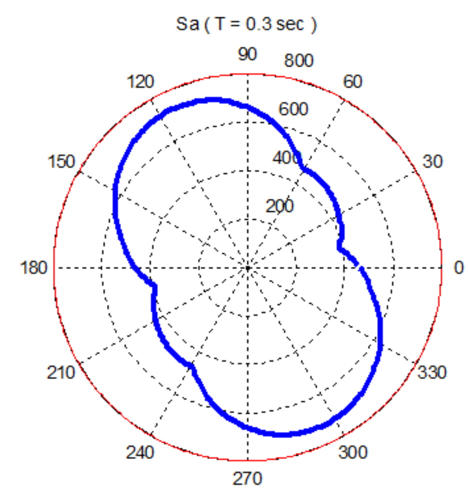


Directionality and IM Selection

- **IM Selection for Horizontal Component**
  - Maximum or Geometric Mean of Two Components (ex. EW and NS)
  - Maximum or Minimum Components of All Direction
  - **Median of Components in All Direction (RotD50)**
  - Components in one Direction for All Periods which is most approximate to RotD50 (RotI50)





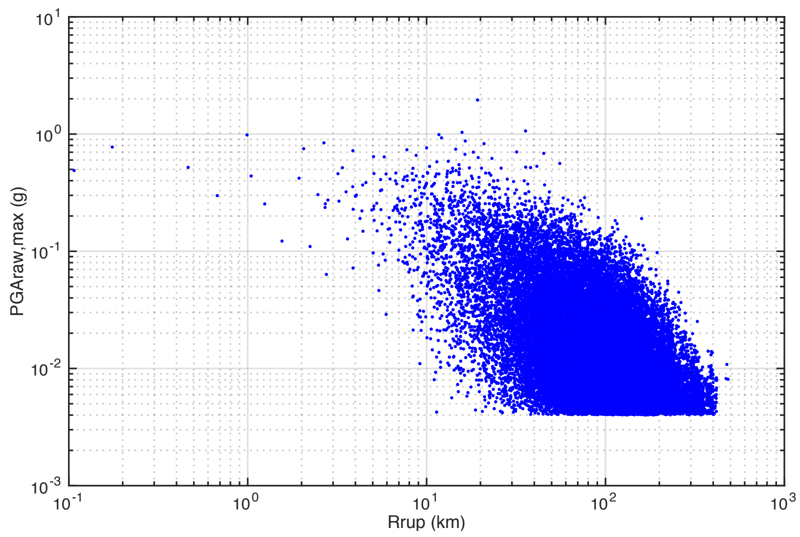


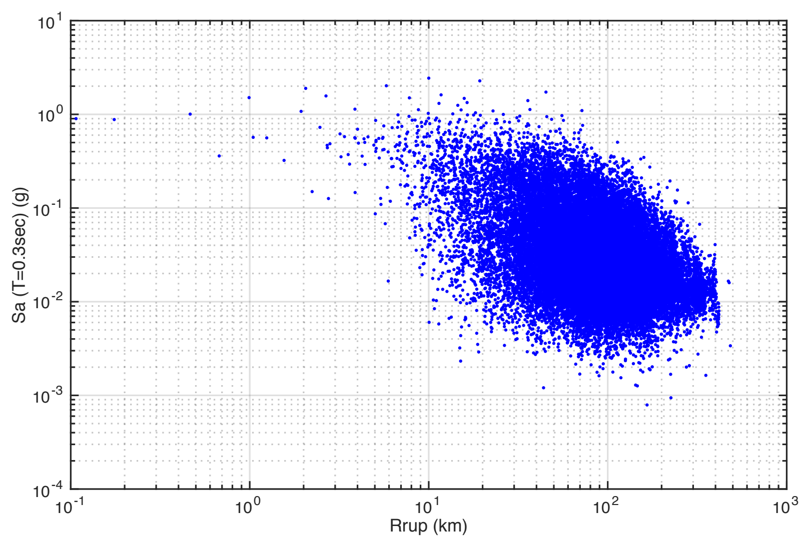
Trigger Level and Truncation Level

- **While the maximum PGA values from 3-axis accelerometers (PGAraw,max) exceeds the trigger level, instrument will record the GM time histories**
- **Generally the trigger level CWB strong motion network is set equal to 0.2% full scale range**
- **Two types of full scale range (± 1 or ± 2g) for all instruments**
  - Trigger level is about 4 gal for ± 2g instrument
  - Trigger level is about 2 gal for ± 1g instrument
- **We only select GM records with PGAraw,max > 4 gal**
  - We can assume that the truncation level of PGAraw,max is 4 gal

Random Truncation Level

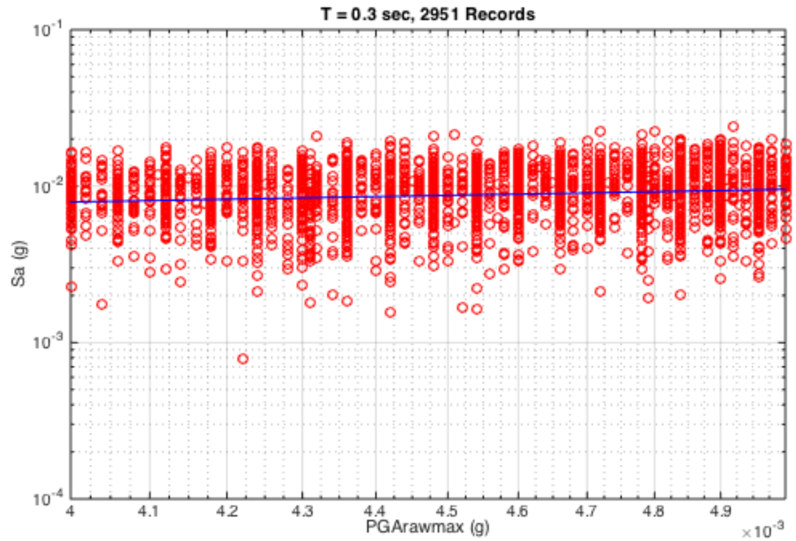
- **We use RotD50 as intensity measure, as a result the truncation level of each period is a random variable**
  - Transformation from PGA of raw data to PGA of processed data
  - Transformation from one direction component to RotD50 components
  - Transformation from PGA to spectral acceleration
- **The standard deviation of the truncation level is larger for long period intensity measure**

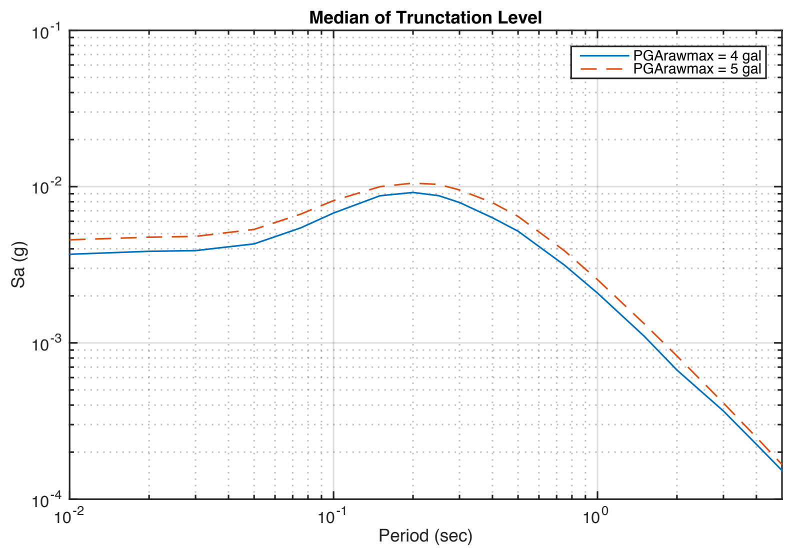


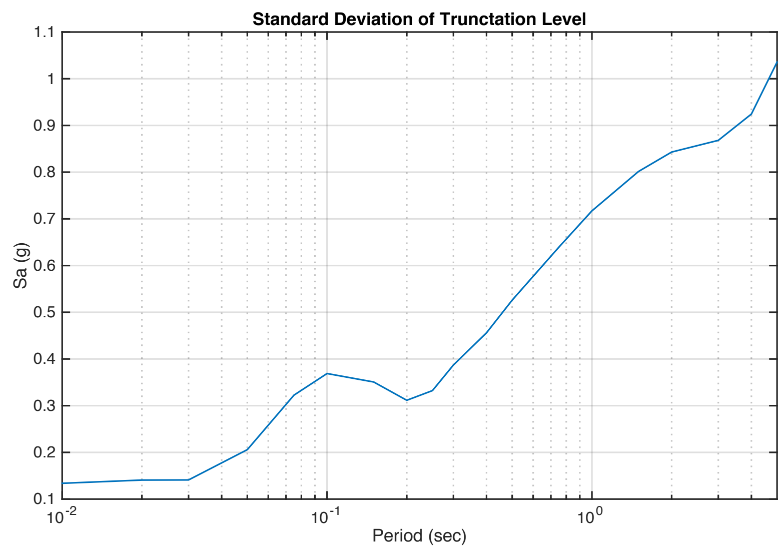


Evaluation of Random Truncation Level

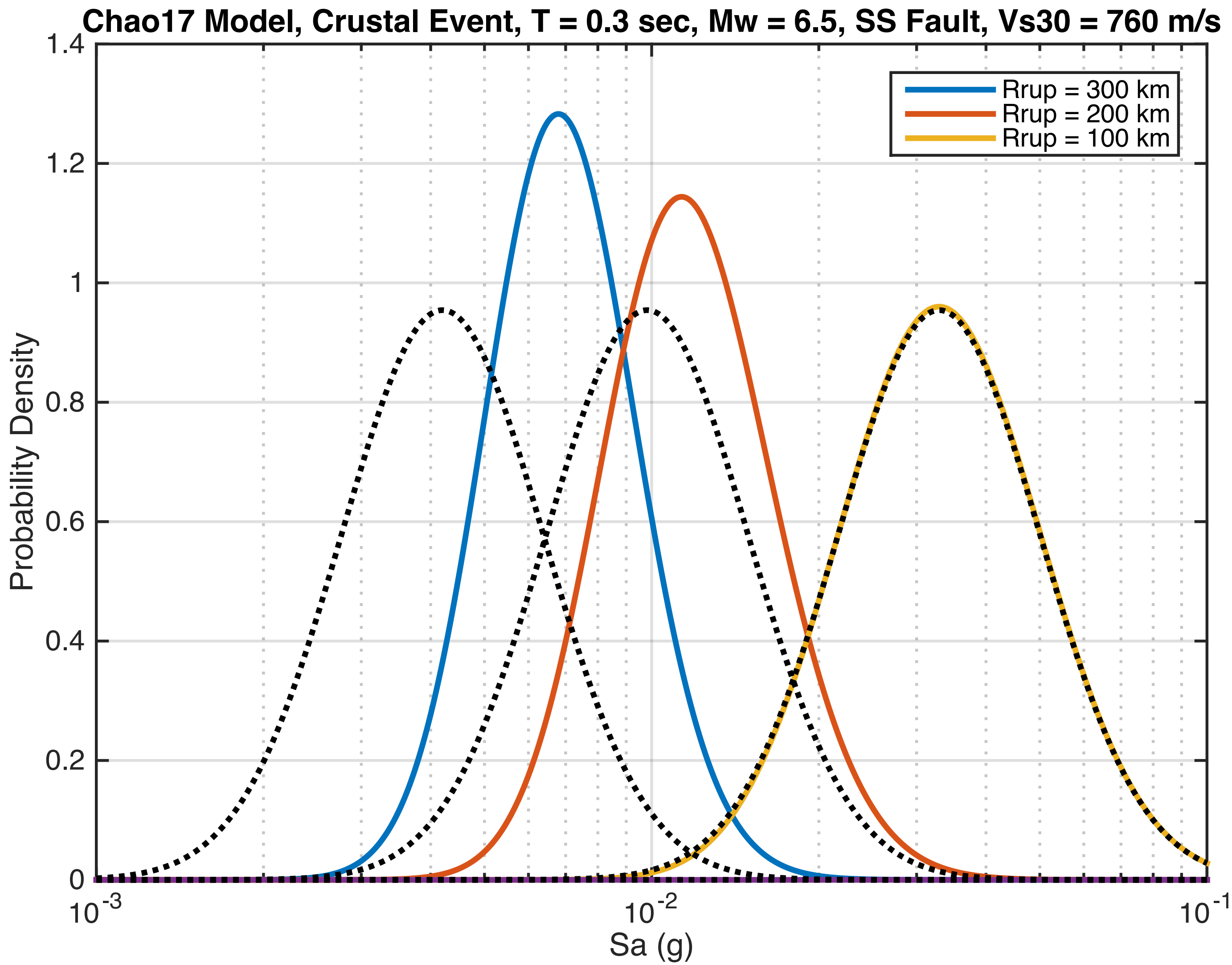
- **Evaluate the relationship between $PGA_{raw,max}$ and RotD50 and determine median and sigma of truncation level for each period**







Random Truncation Effect on Observed GM Distribution



Regression Approaches for Random Truncation Effect

- **Two approaches to address random truncation effect during regression analysis**
  - Rmax approach with normal PDF residuals (Chiou et. al 2014)
    - Only use records with Rrup < Rmax
      - Rmax is depended on event
    - It is easier to implement general regression approach
    - Many records need to be drop out
  - **MLE approaches with random truncated PDF residuals**
    - **New approach proposed in this study**
    - Use all records including Rrup > Rmax
    - Analysis is more time consuming
    - More information can be derived
      - Ground motion characteristics of deep event

Function Form of Proposed Taiwan GMM

- **Function From**

$$\boldsymbol{ln\,S_a = lnS_a^{ref} + S_{source} + S_{path} + S_{site,lin} + S_{site,non} + \delta_e + \delta_s + \delta_r}$$

  - S_a: predicted spectral acceleration
  - S_a^{ref} : predicted spectral acceleration **for reference condition**
  - S_{source} : source scaling (ground motion ratio)
  - S_{path}: path scaling
  - $S_{site,lin}$: linear site scaling
  - $S_{site,non}$: nonlinear site scaling
  - δ_e: event-specific residual
  - δ_s: site-specific residual
  - δ_r: record-specific residual

Two Steps MLE Regressions

- **Equation of Step 1 Regression**

$$ln\, S_a = S_{path} + S_{site,non} + E_e + S_s + \delta_r$$

E_e: Event term of each event

S_s: Station term of each station

- **Equation of Step 2 Regression**

$$E_e = E^{ref} + S_{source} + \delta_e$$

$$S_s = S^{ref} + S_{site,lin} + \delta_s$$

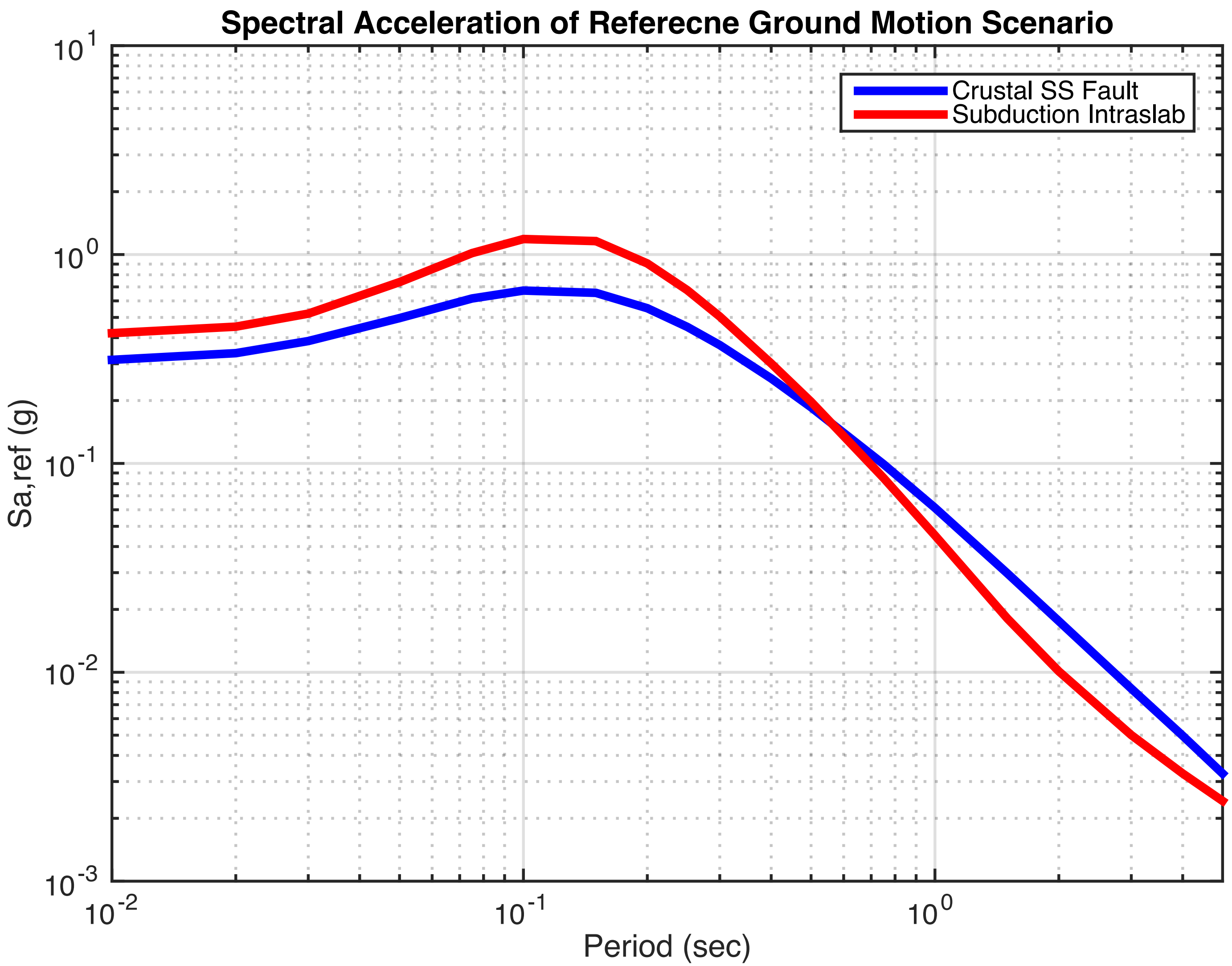
- **Equation of Reference Spectrum**

$$lnS_a^{ref} = E^{ref} + S^{ref}$$

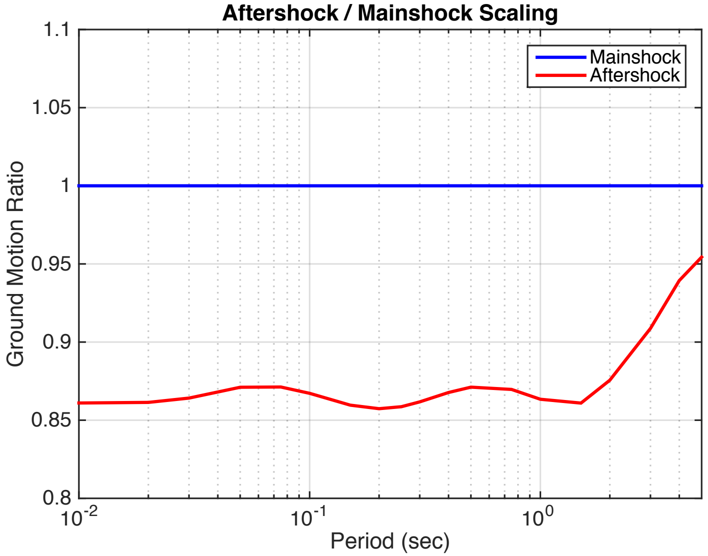
Reference Condition

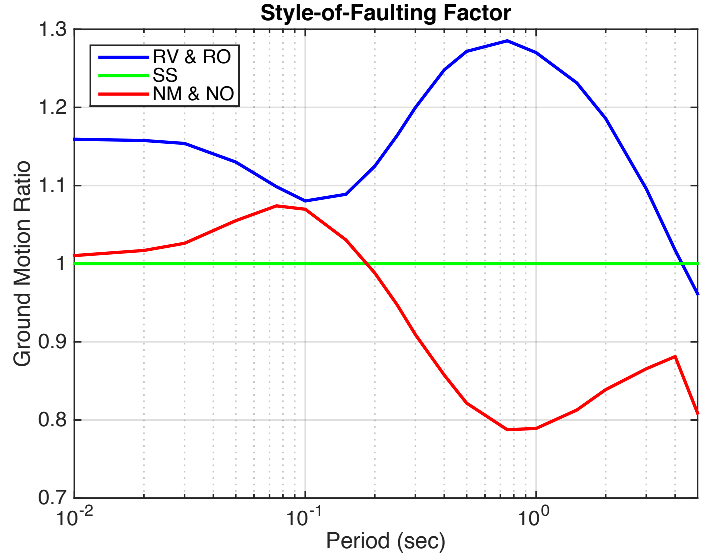
- **Reference Condition of Reference Spectrum**
  - Reference Magnitude Mw 5.5
    - It is selected based on data rich region
  - Reference Ztor
    - It is selected based on the data rich region
      - 15 km for crustal source
      - 50 km for subduction source
  - Reference Rrup 0 km
    - It is selected because it will be easy to constrain the magnitude scaling
  - Reference Vs30 760 m/s
  - Reference Z1.0 is calculated by Vs30-Z1.0 relationship proposed by Kuo. et. al. 2016 with Vs30 760 m/s

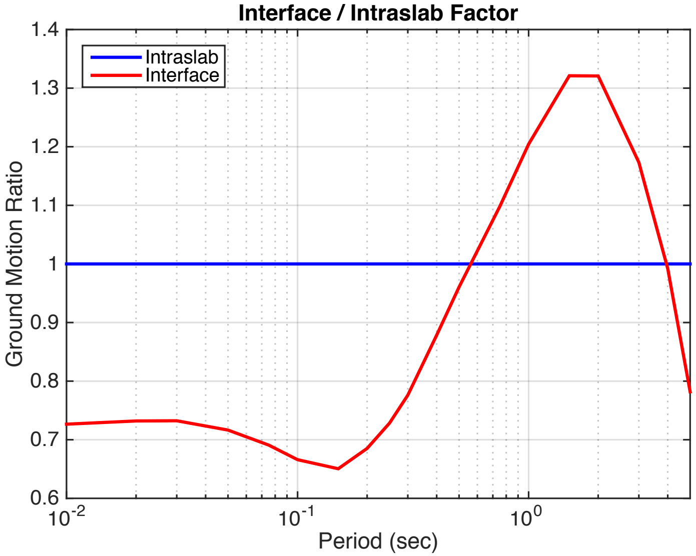
Reference Spectrum

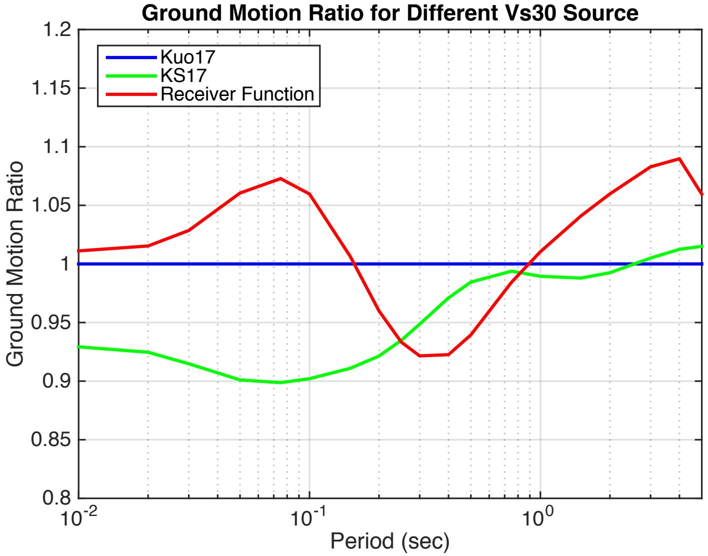


Other Scalings on Reference Spectrum







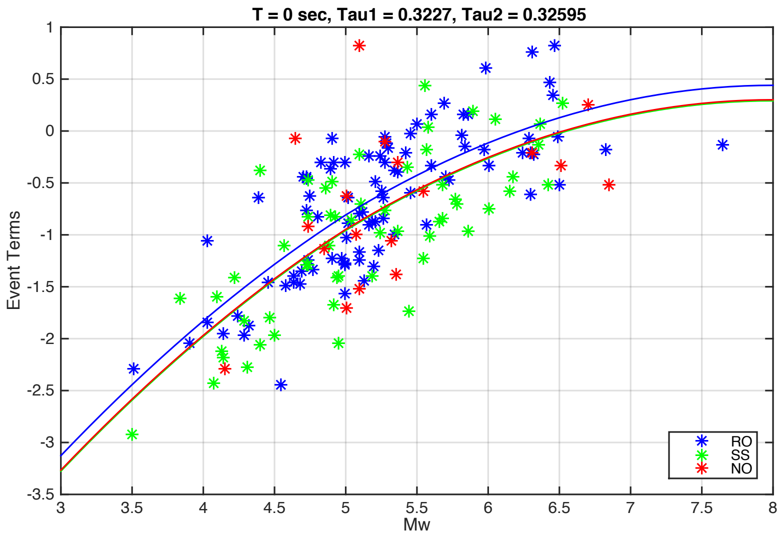


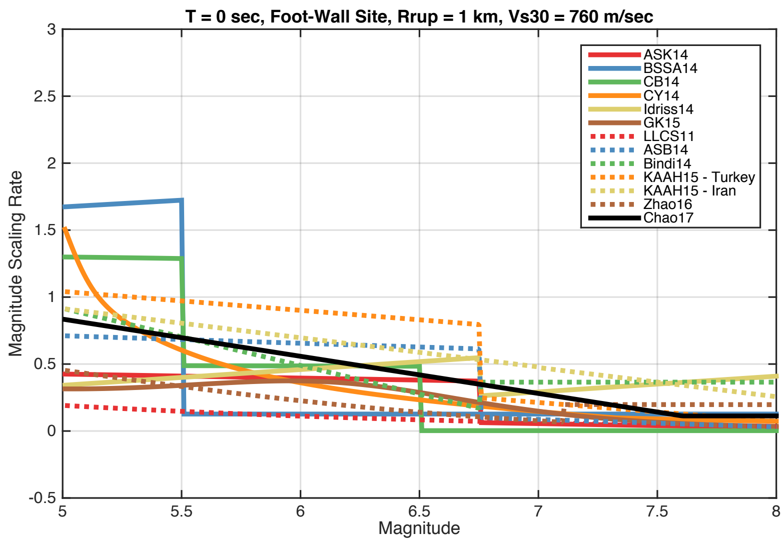
Source Scaling – Magnitude Scaling

- **Two approaches to derive large magnitude scaling**
  - 1. Use foreign ground motion date of large magnitude
    - Ex. 5 NGA-West 2 models
    - Challenge
      - Consistency of different database
      - Regional difference
  - **2. Use scaling of foreign ground motion models**
    - Ex. Adjusted foreign models (Taiwan SSHAC Level 3 Project)
      - Use model coefficients controlling large magnitude scaling and adjust other model coefficients by using Taiwan GM data
    - Challenge
      - Epistemic uncertainty

Magnitude Scaling for Crustal Source

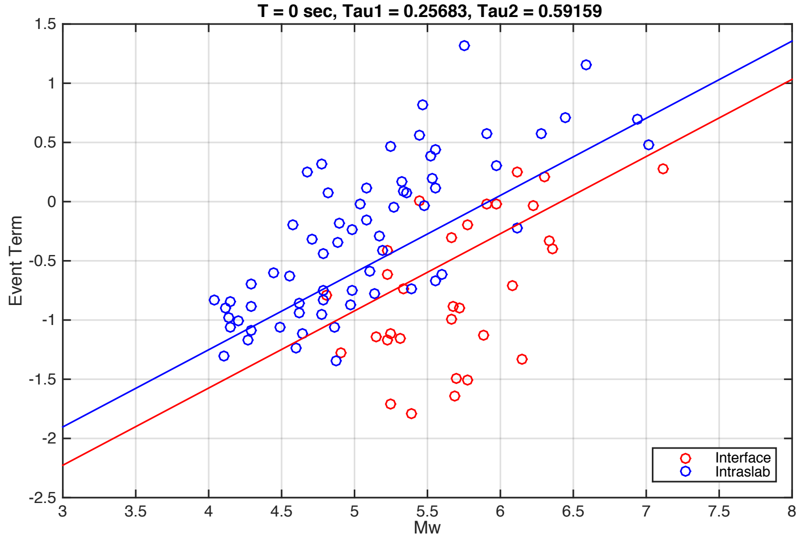
- **For Mw < 7.0 is constrained by:**
  - Empirical GM data
- **For 7.0 < Mw < 7.6 is constrained by:**
  - Ground motion data of Chi-Chi earthquake
  - The magnitude scaling rate should be larger than zero for the crustal event with Mw < 8.0
- **For 7.6 < Mw < 8.0 is constrained by:**
  - Magnitude scaling of global models

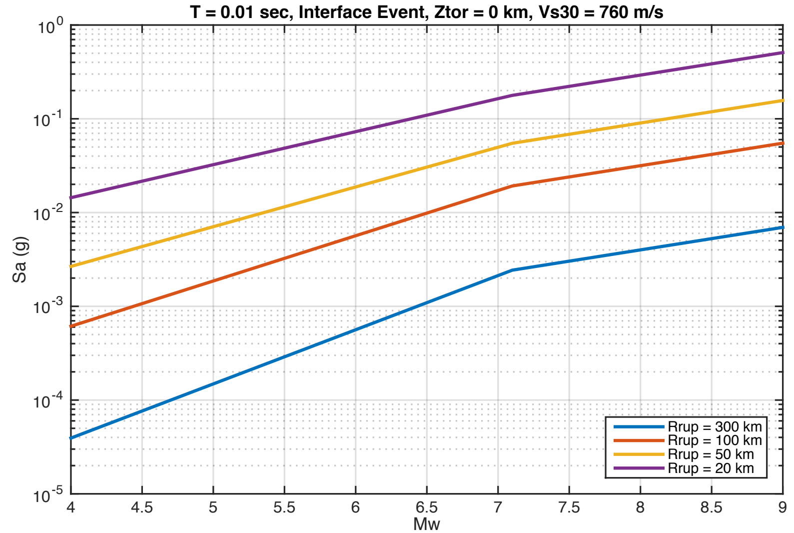




Magnitude Scaling for Subduction Source

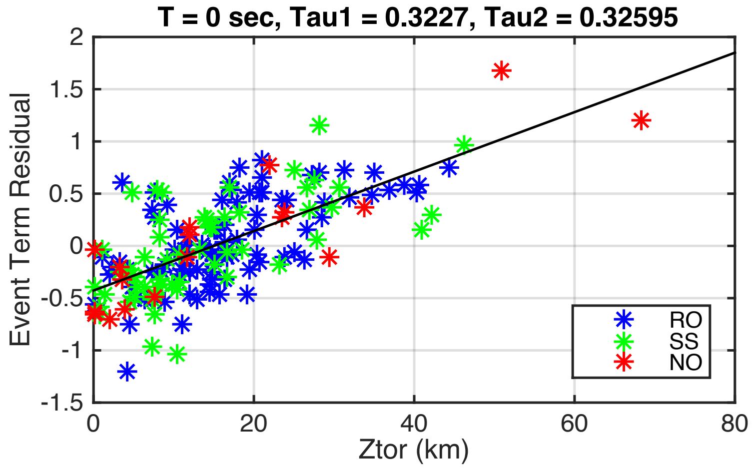
- **For Mw < 7.1 is constrained by:**
  - Empirical GM data
- **For Mw > 7.1**
  - We use the magnitude scaling of interface and intraslab events (Mw > 7.1) proposed by **Zhao et. al. 2016** developed by Japan GM data including Tohoku event
  - It is Rrup-independent for Mw > 7.1 based on the reason that for a very large event, only a part of the fault contribute to the ground motion

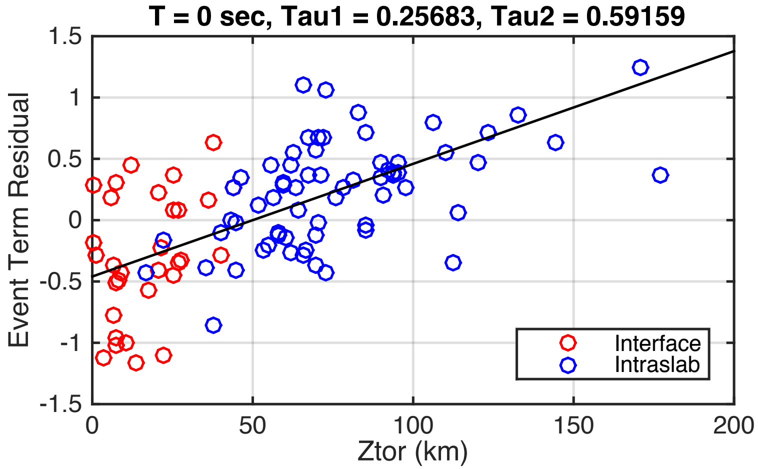




Source Scaling – Depth Scaling

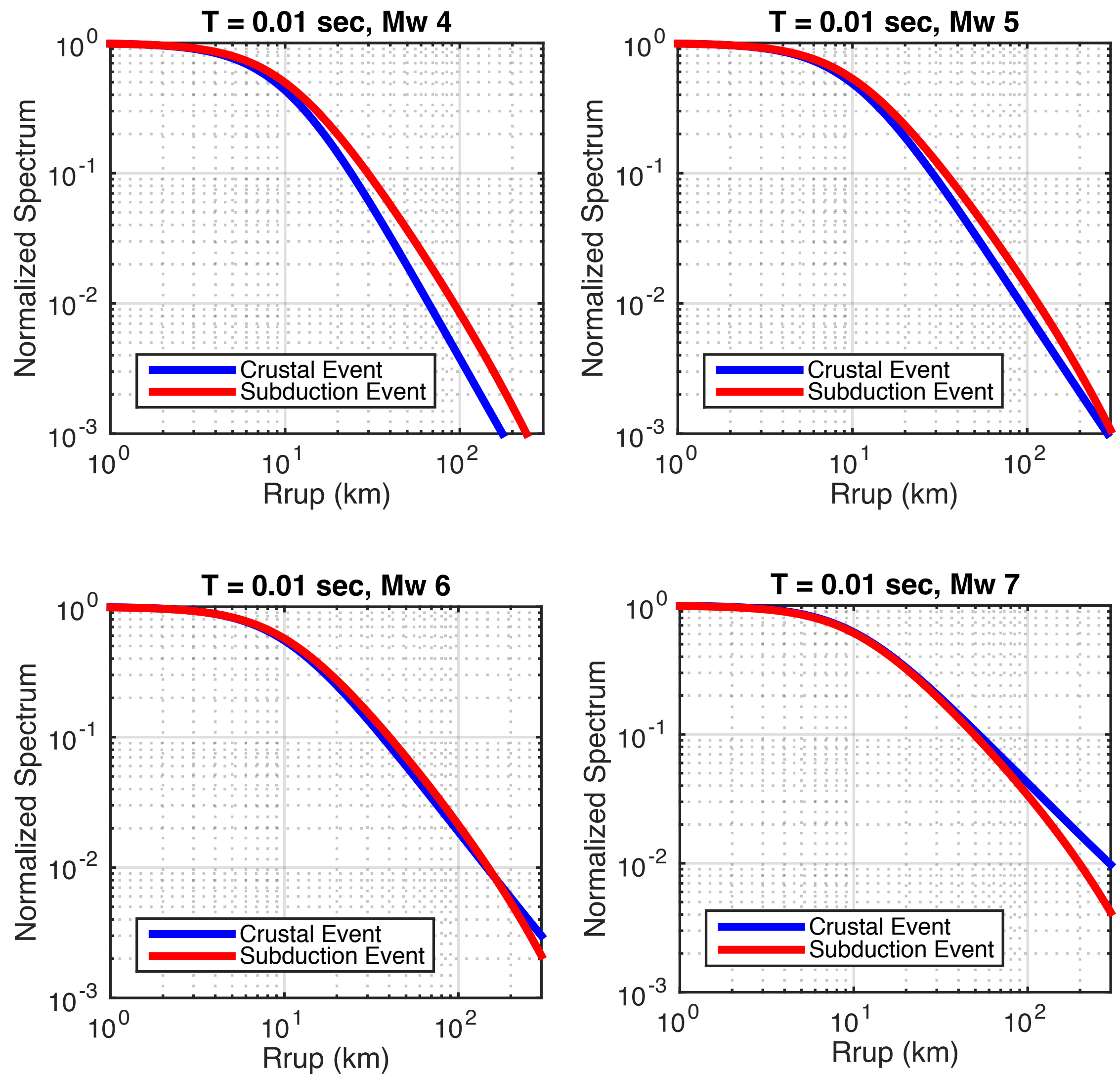
- **Crustal earthquake**
  - Linear scaling up to Ztor 60 km
- **Subduction earthquake**
  - Linear scaling up to Ztor 180 km
- **Magnitude scaling is stronger for crustal source**
- **Under the same Mw, Rrup and site condition, deeper earthquake potentially produce higher PGA**





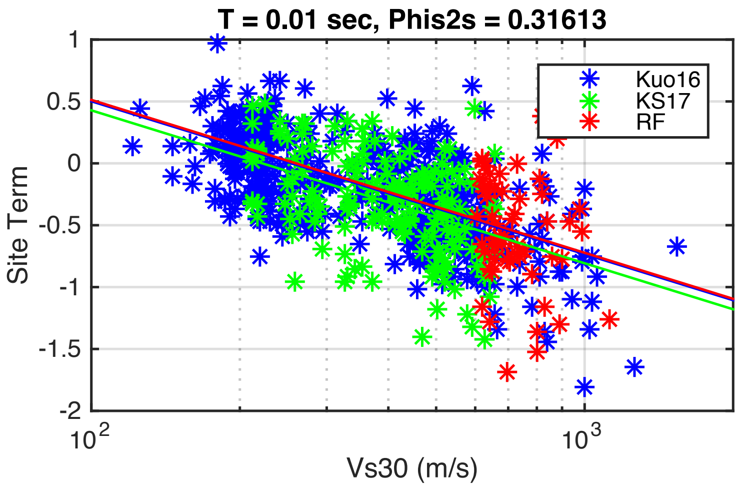
Distance Scalings for Different Magnitude

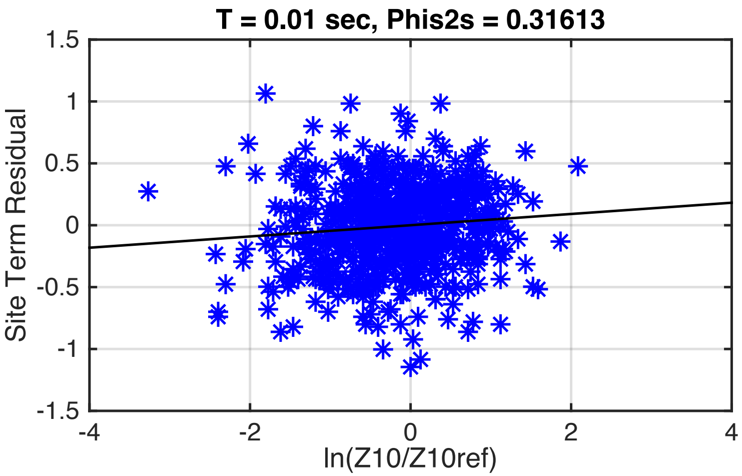
- **Attenuation rate of crustal event is more dependent on magnitude**
- **Attenuation rate of crustal event is higher than subduction for small magnitude but smaller for higher magnitude**



Linear Site Scaling

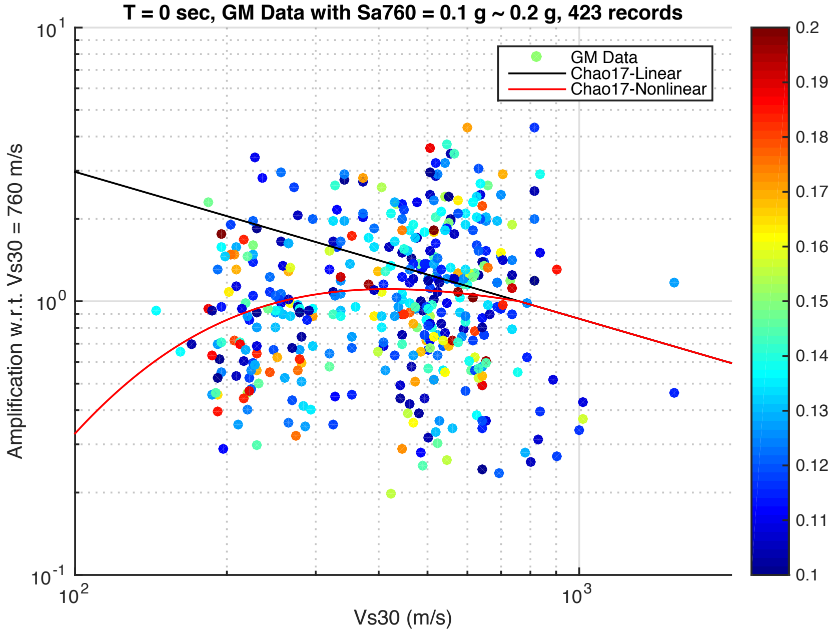
- **For weak input rock motion, the material nonlinearity of soil layer is not significant**
- **The ground motion amplification of free surface soil site w.r.t. input rock motion is linear proportional to ln(Vs30) and ln(Z1.0)**

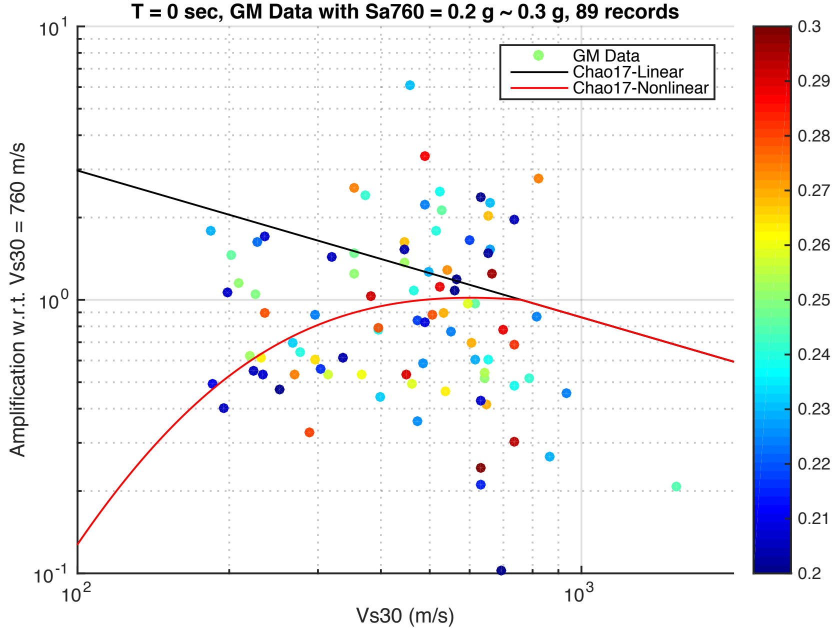




Nonlinear Site Scaling

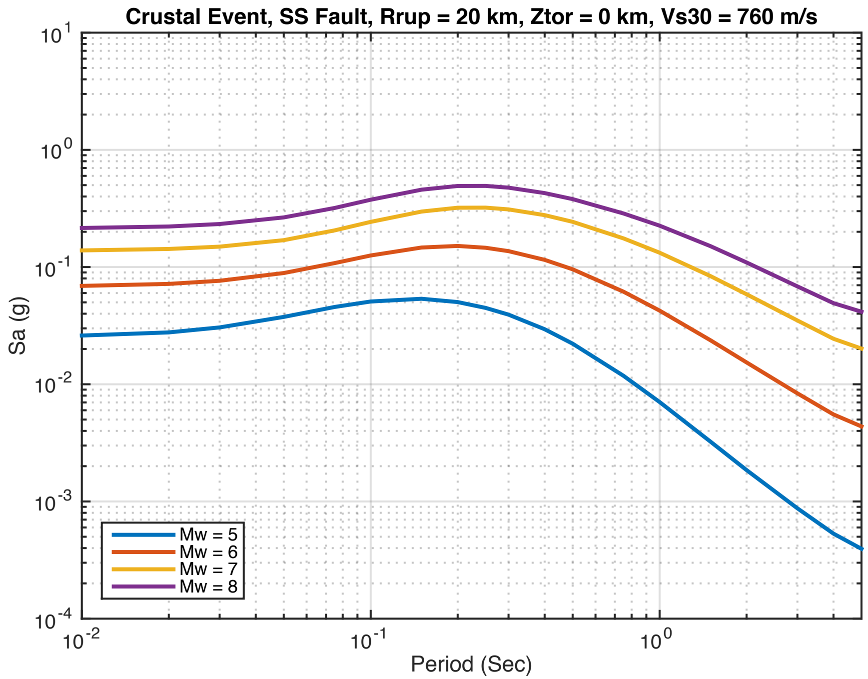
- For strong input rock motion, the material nonlinearity of soil layer is significant
- The ground motion of free surface soil w.r.t. input rock motion may be deamplified

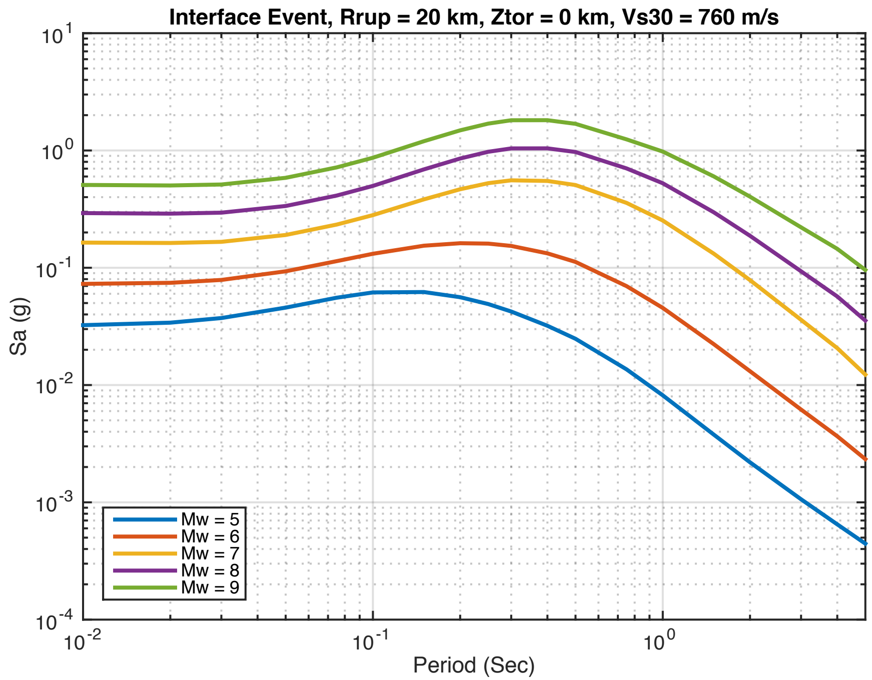




Chao17 Model Prediction – Response Spectrum

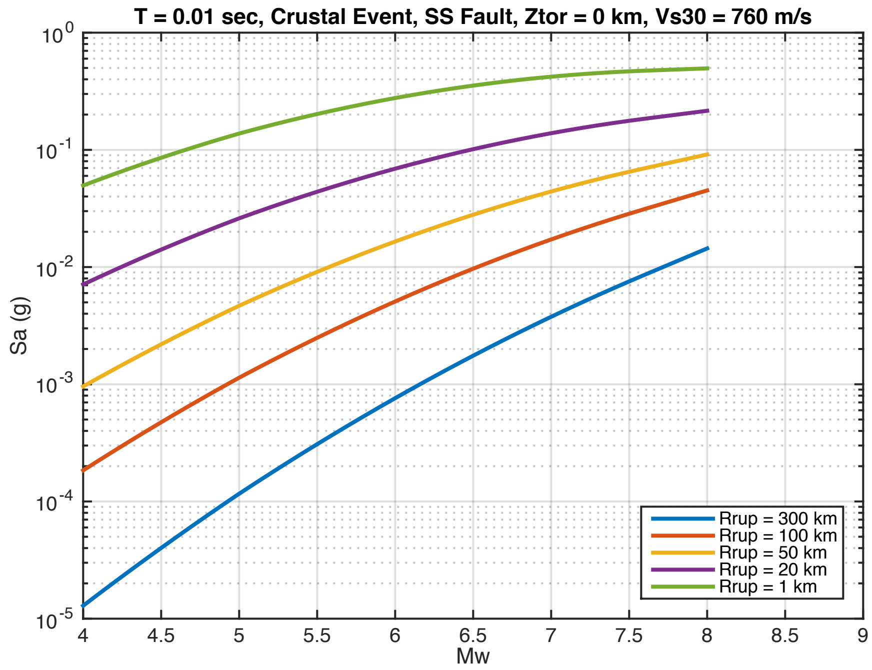
- **Ground motion scenarios**
  - Crustal strike-slip fault / subduction interface, Ztor 0 km
  - Rrup 20 km
  - Vs30 760 m/s, Z1.0ref

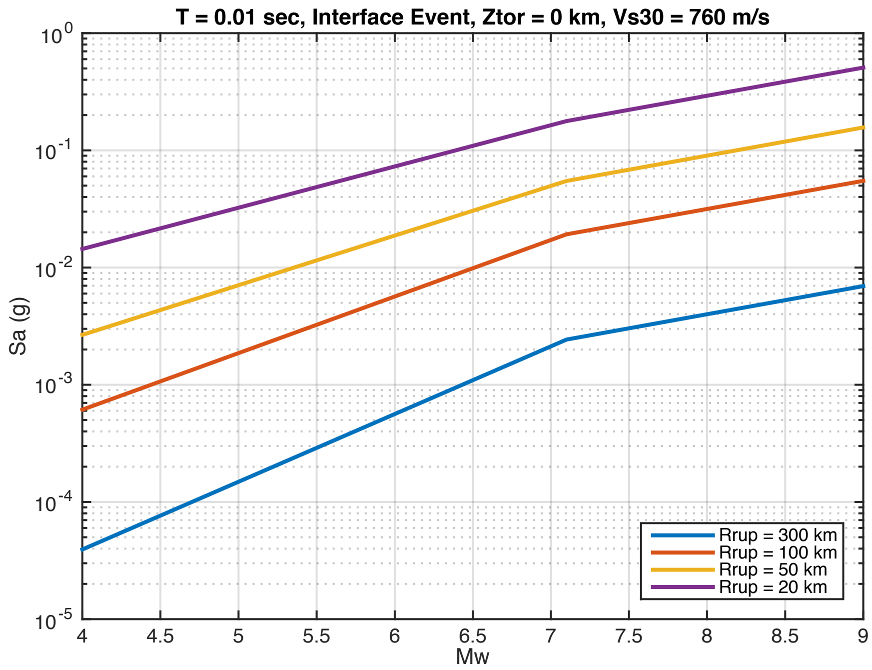




Chao17 Model Prediction
– Magnitude Scalings for Different Distances

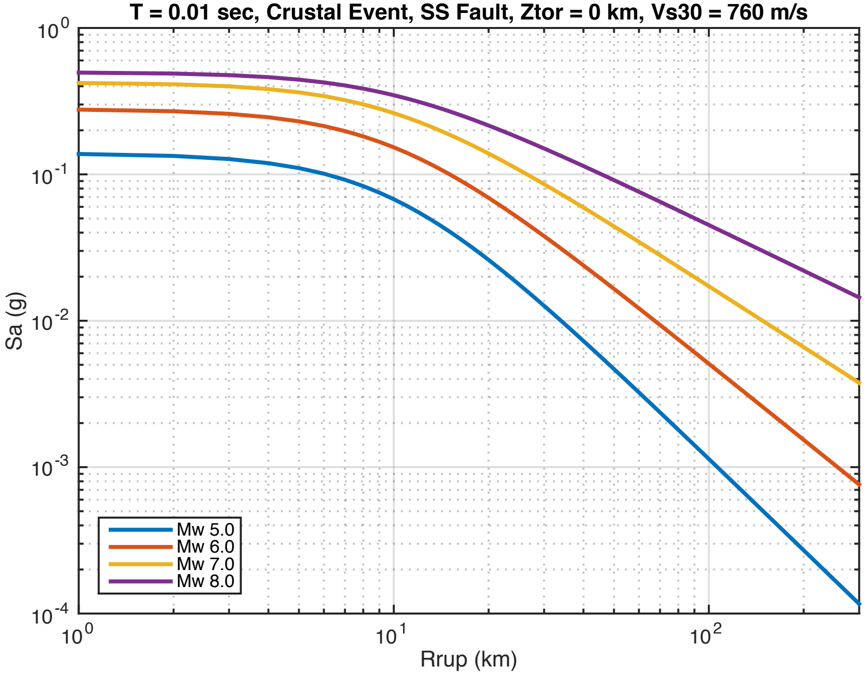
- **Ground motion scenarios**
  - T 0.01 sec
  - Crustal strike-slip fault / subduction interface, Ztor 0 km
  - Vs30 760 m/s, Z1.0ref

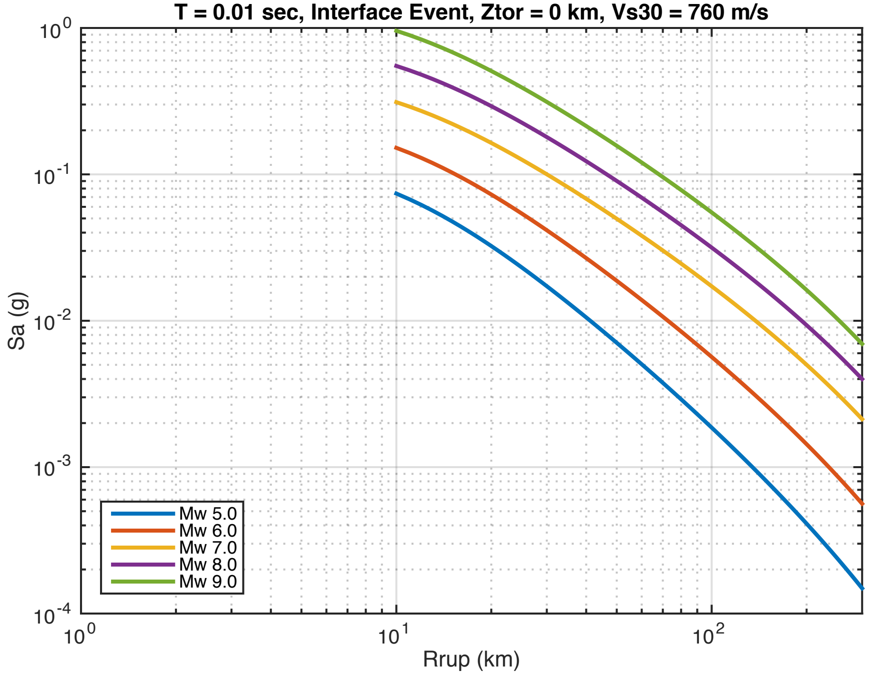




Chao17 Model Prediction
– Distance Scalings for Different Magnitudes

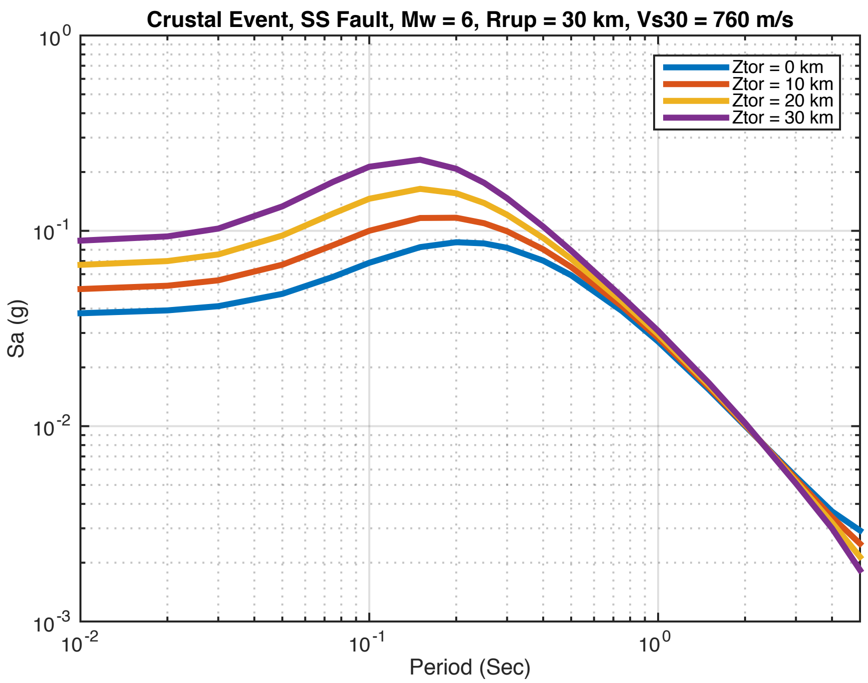
- **Ground motion scenarios**
  - T 0.01 sec
  - Crustal strike-slip fault / subduction Interface, Ztor 0 km
  - Vs30 760 m/s, Z1.0ref

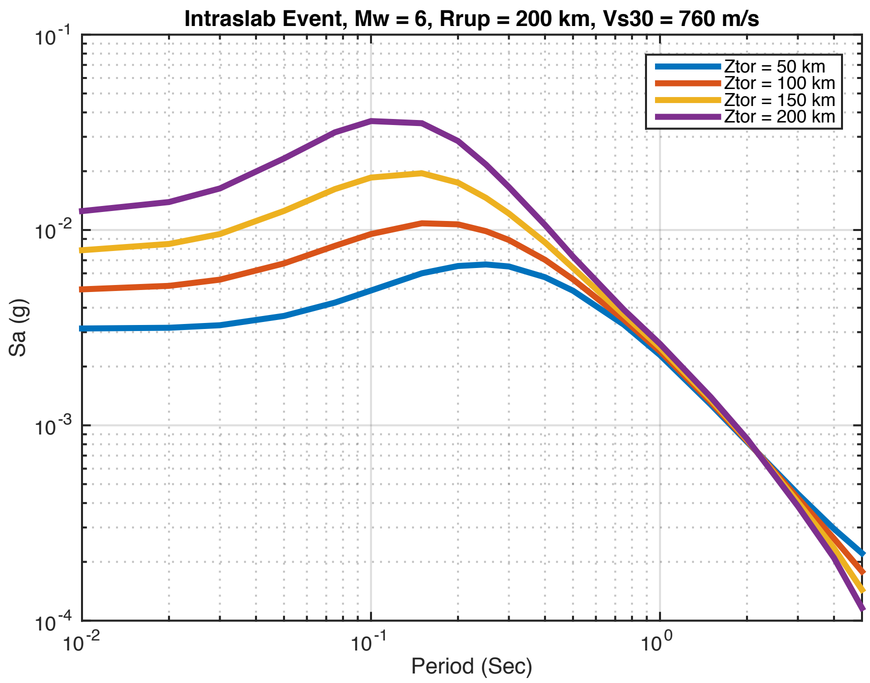




Chao17 Model Prediction
– Different Depth

- **Ground motion scenarios**
  - Crustal strike-slip fault and subduction intraslab, Mw 6.0
  - Rrup 30 km for crustal source and Rrup 200 km for subduction source
  - Vs30 760 m/s, Z1.0ref

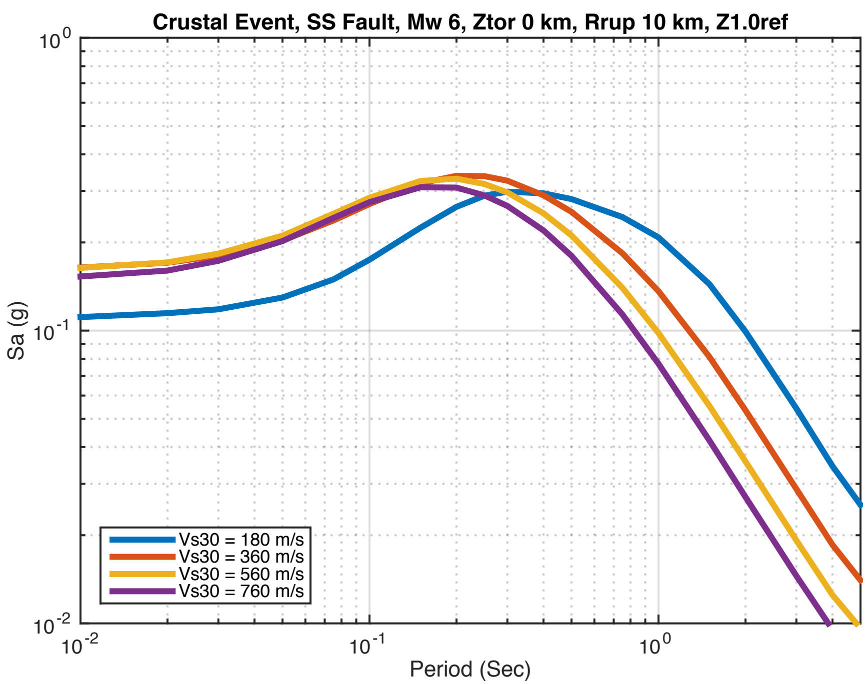


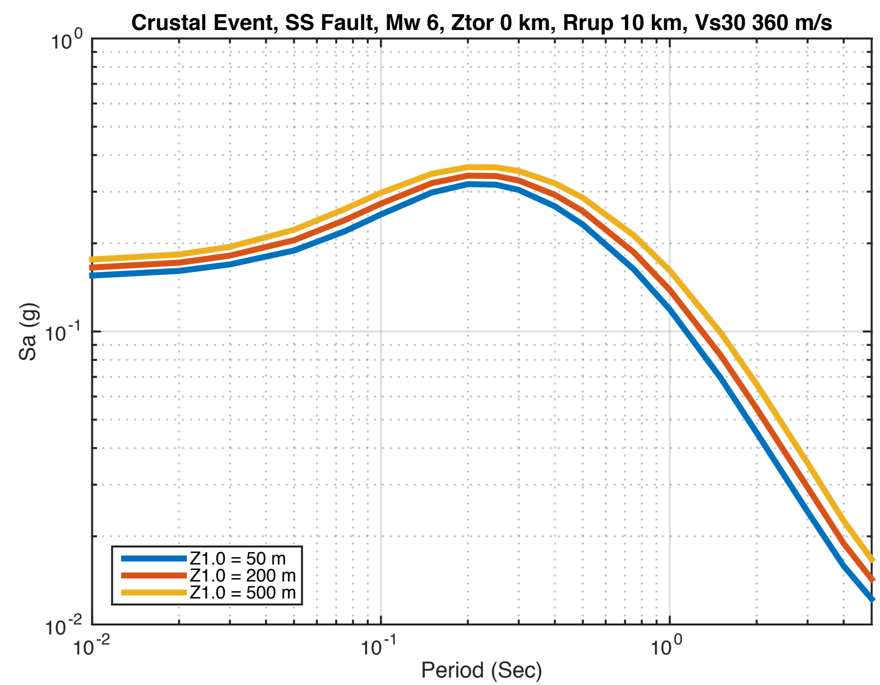


Chao17 Model Prediction – Different Site Condition

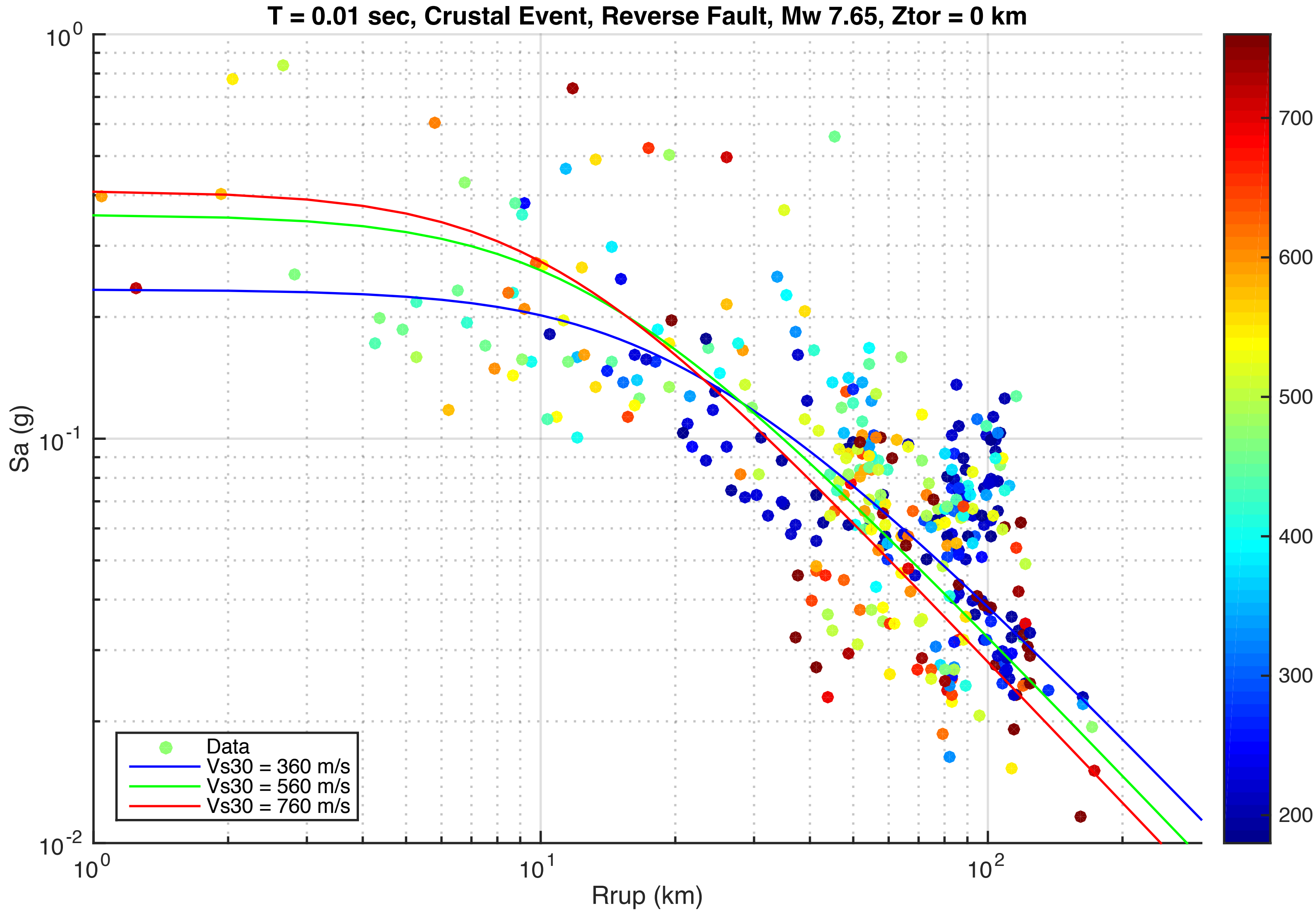
Ground motion scenarios

- Crustal strike-slip fault, Mw 6.0, Ztor 0 km, Rrup 10 km
- Case 1: Vs30 180, 360, 560, 760 m/s with different Z1.0ref
- Case 2: Vs30 360 m/s with Z1.0 50 m, 200 m and 500 m



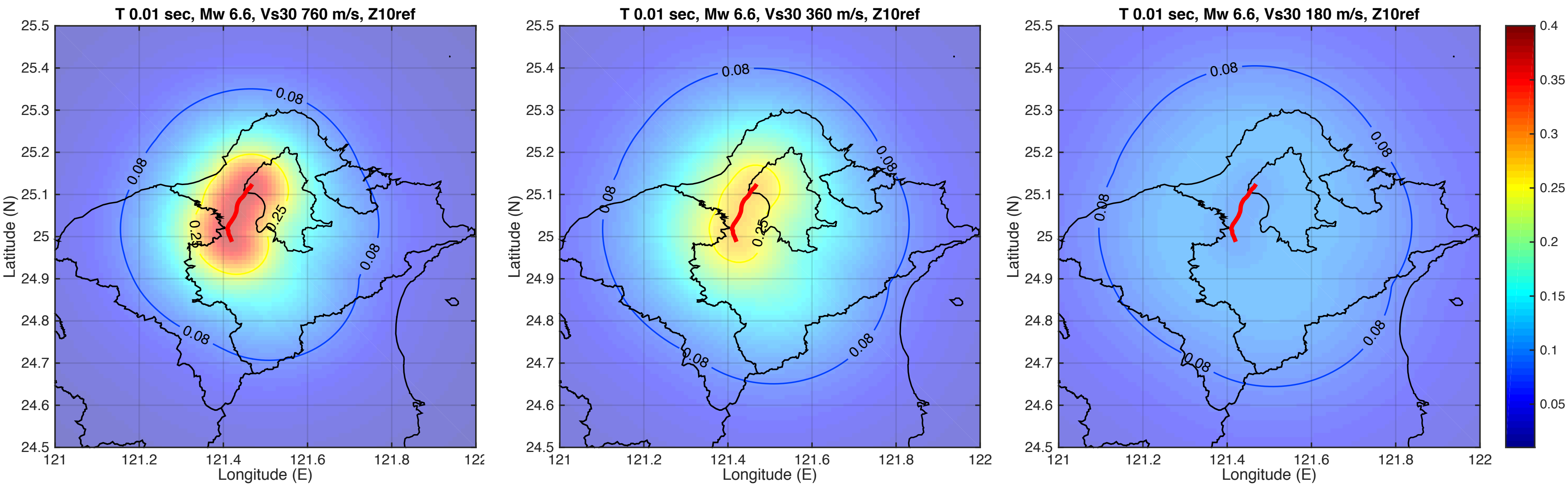


Chao17 Model Prediction – Chi-Chi Earthquake



Chao17 Model Prediction – Scenario Earthquake

- **Scenario earthquake**
  - ShanChiao Fault south part (Shyu et. al. 2016)
  - Normal fault, Mw 6.6, Lr 16 km
  - Vs30 760, 360 180 m/s, different Z1.0ref
  - T 0.01 sec

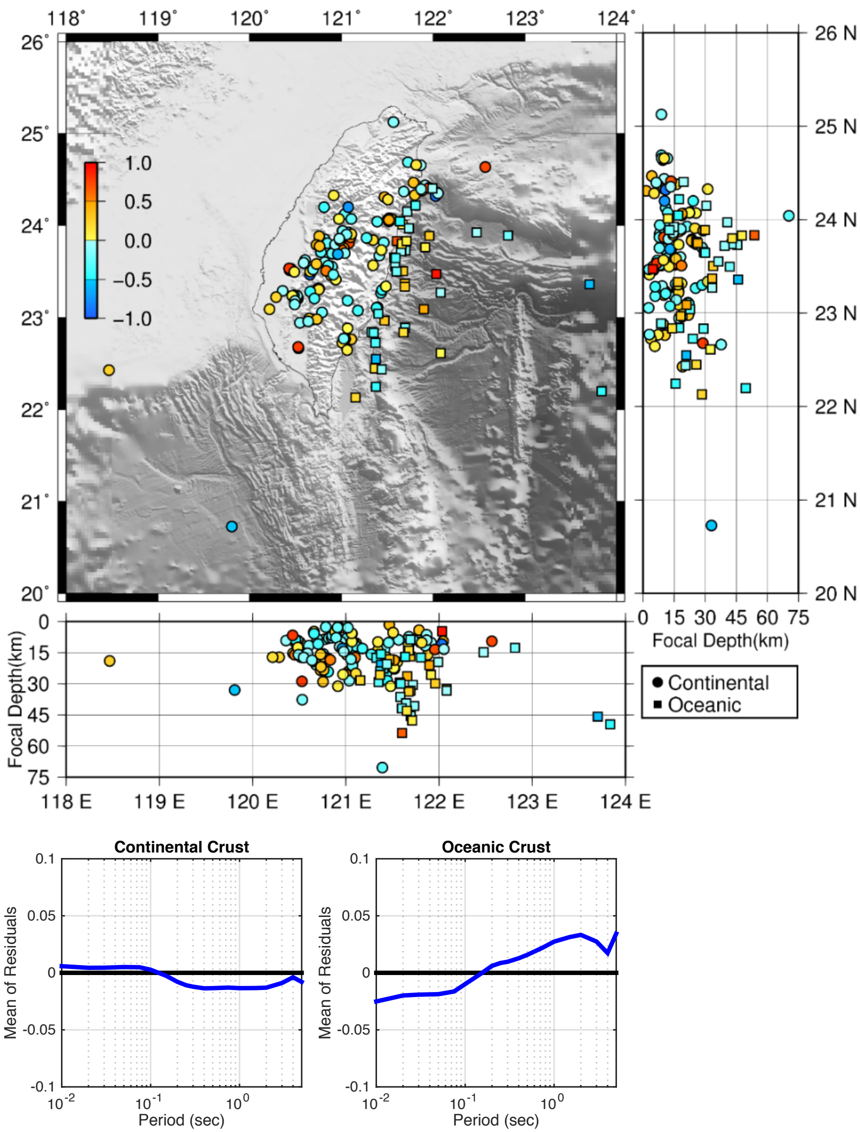


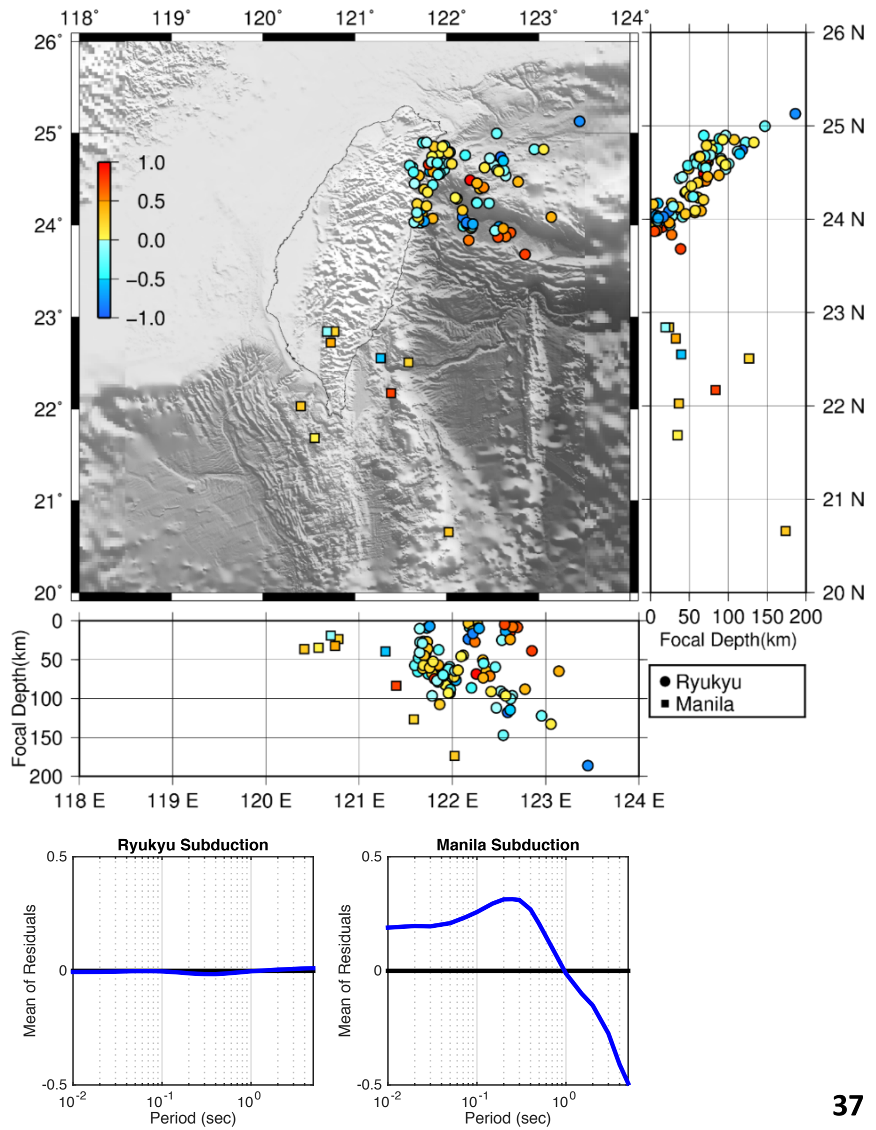
Ground Motion Simulation for Scenario Earthquake

- **Advantages of using ground motion model for scenario earthquake**
  - Easy and fast to derive intensity map
  - Time history can also be developed by spectrum compatible technique to adjust real ground motion time history

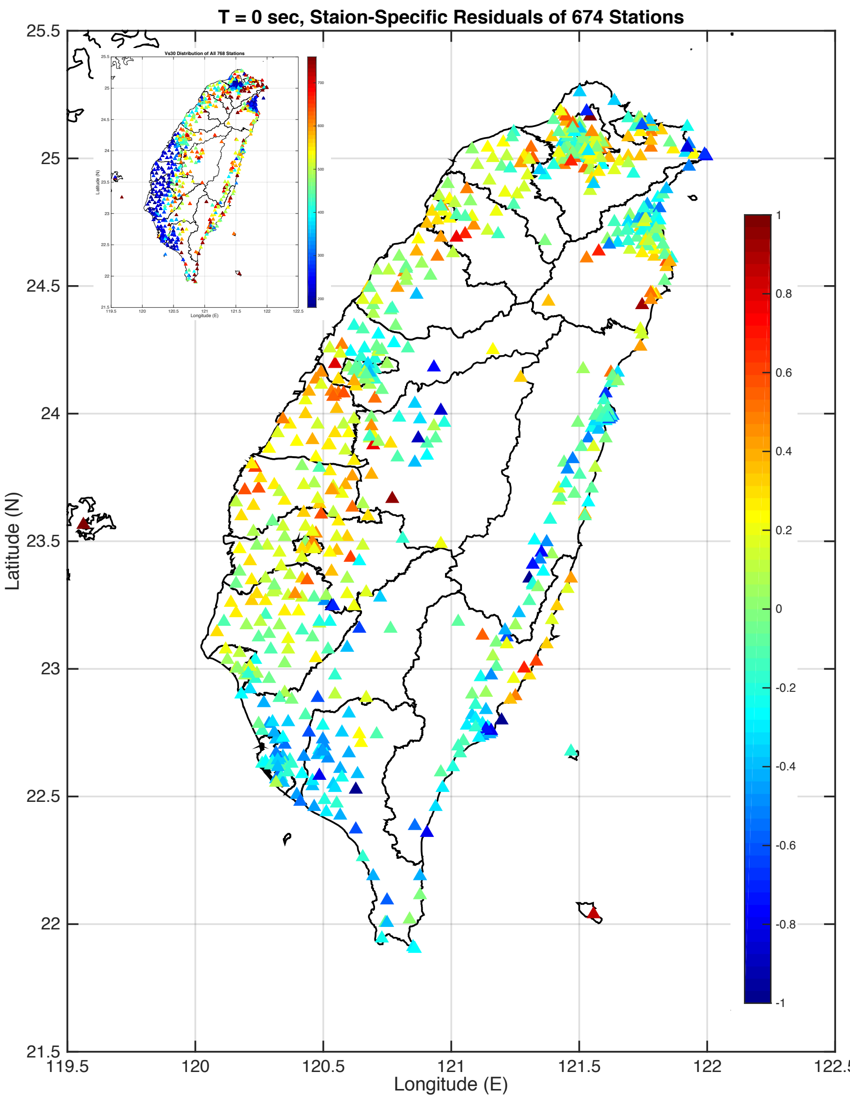
- **Limitations of using ground motion model for scenario earthquake**
  - Ergodic assumption of the ground motion model
    - This can be improved by developing partially non-ergodic (regionalized) ground motion model

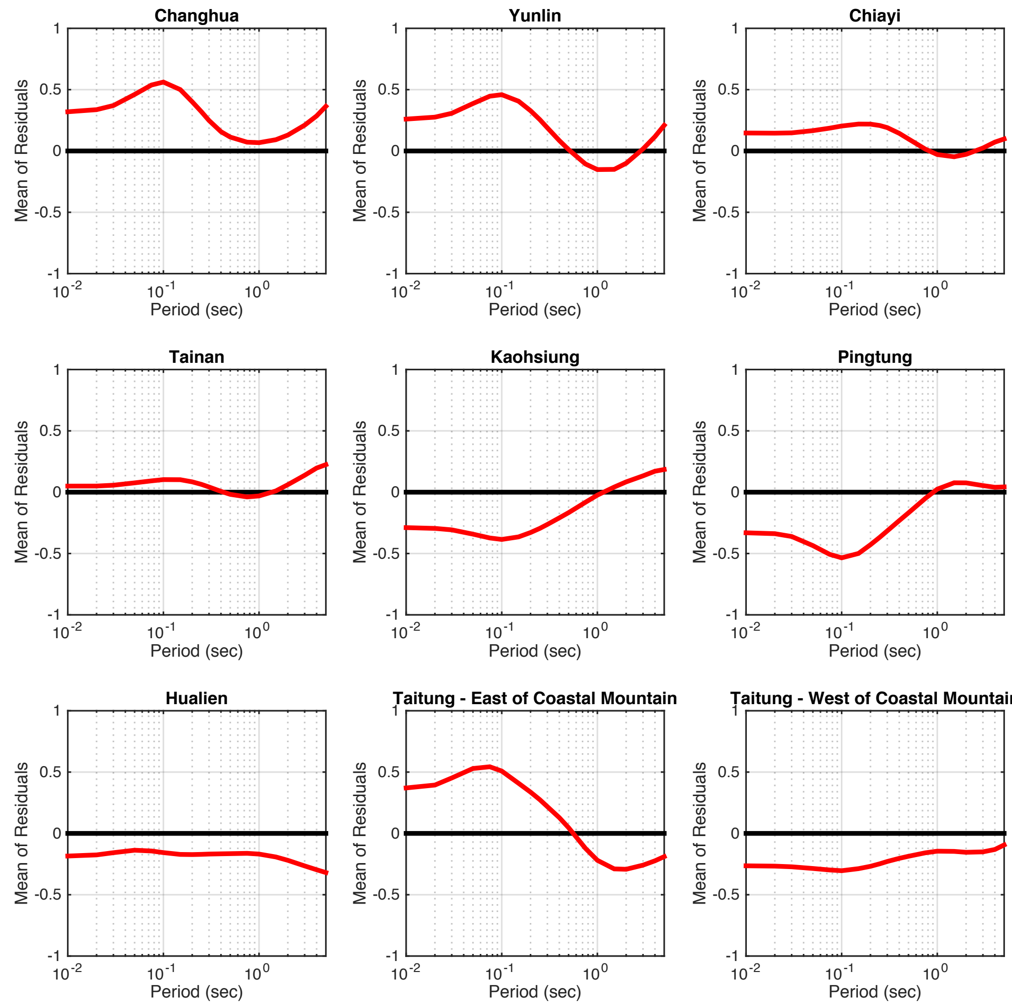
Spatial Distribution of Event-Specific Residual



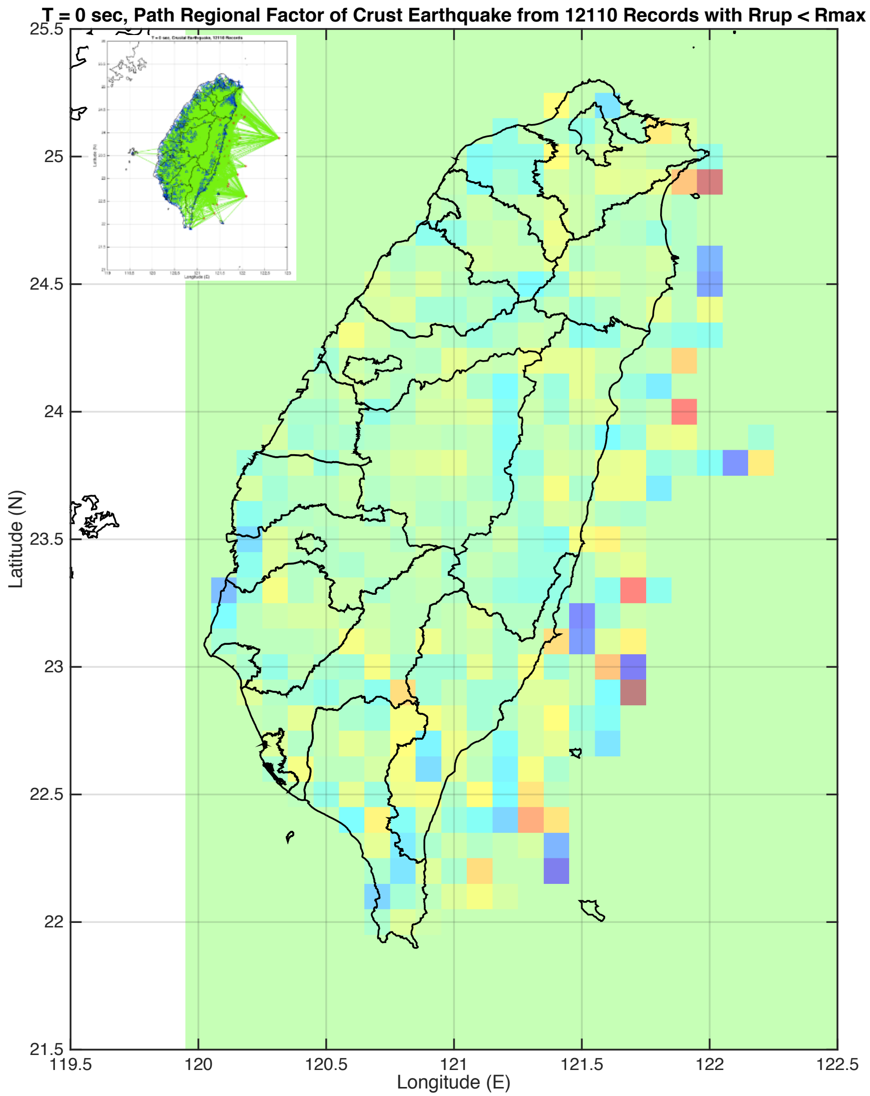


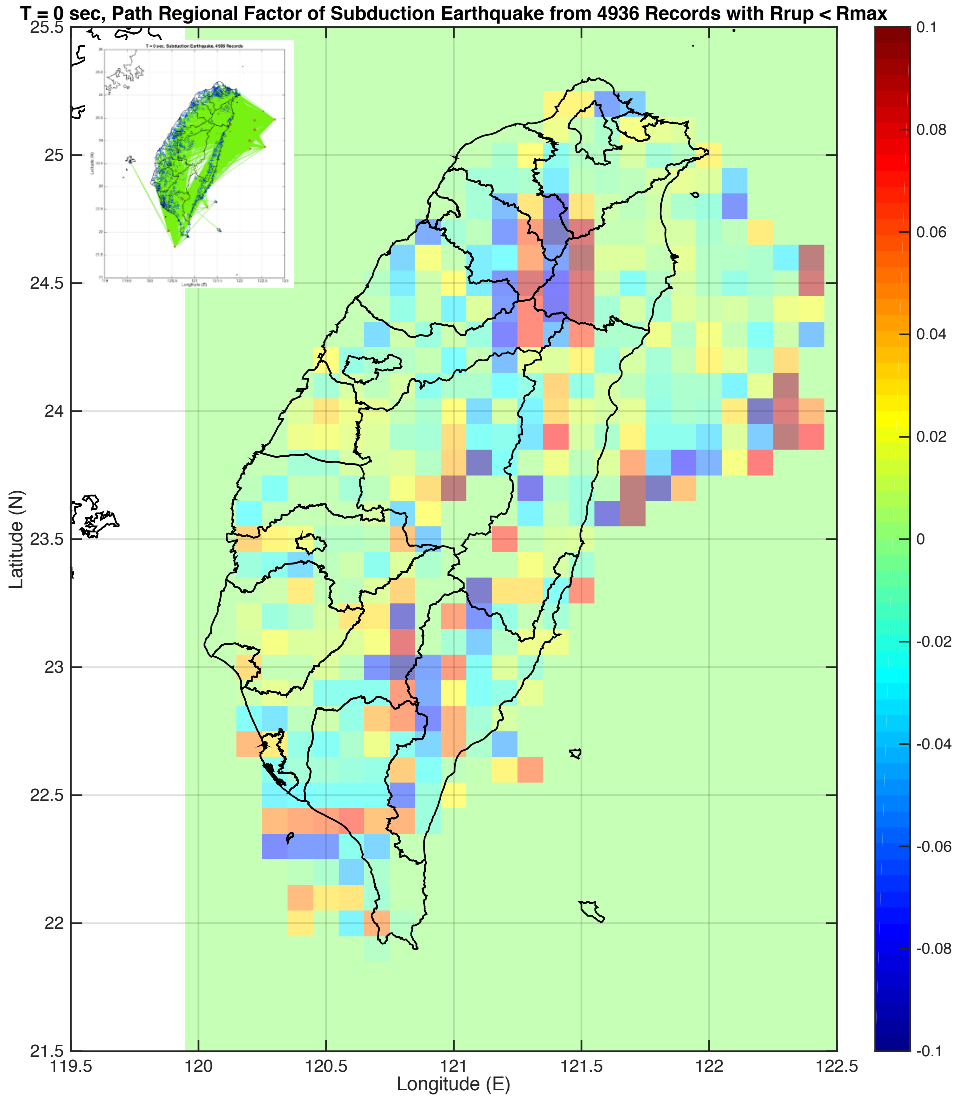
Spatial Distribution of Station-Specific Residual





Spatial Distribution of Record-Specific Residual





Summary

- **We have developed a new Taiwan ground motion model for engineering application which can represent important ground motion characteristics**
  - Source type effect
  - Style-of-faulting effect
  - Aftershock effect
  - Rrup-based attenuation
  - Linear site effect and nonlinear site effect
- **Features of the proposed ground motion model**
  - It is developed by **random truncated regression approach**
  - It is constructed by the **reference spectrum** at reference ground motion scenario plus **different scalings**
  - One equation with same site scaling term but different reference spectrum, source scaling terms, path scaling terms but for both **crustal** and **subduction** source

Future Works

- **Collect additional GM data of normal fault crustal event to derive better normal fault factor**
- **Develop vertical ground motion model and V/H ratio model**
- **Develop regionalized Taiwan ground motion model**
- **Conduct ground motion simulation to derive better characteristics of large magnitude scaling and short distance scaling <u>especially for subduction events</u>**
- **Conduct site response analysis to derive better characteristics of horizontal and vertical non-linear site effects**

Thank You for Your Attention !!

Questions ?

Source Scaling – I

- **Source Scaling**
  - $S_{source} = S_{mag} + S_{Ztor}$
- **Magnitude Scaling**
  - $S_{mag} = S_{mag,cr}F_{cr} + S_{mag,sb}F_{sb}$
    - $S_{mag,cr} = c_8\left(M_w - M_w^{ref}\right) + c_{10}\left(M_w - M_w^{ref}\right)^2$
      $-c_{10}(M_w - 7.6)^2 u(M_w - 7.6) + c_{11}(5 - M_w)u(5 - M_w)$
    - $S_{mag,sb} = c_9\left(M_w - M_w^{ref}\right) + c_{26}F_{inter}(M_w - M_c)u(M_w - M_c)$
      $+c_{27}F_{intra}(M_w - M_c)u(M_w - M_c)$
- **Depth Scaling**
  - $S_{Ztor} = c_{12}\left(Z_{tor} - Z_{tor,cr}^{ref}\right)F_{cr} + c_{13}\left(Z_{tor} - Z_{tor,sb}^{ref}\right)F_{sb}$

Path Scaling

- **Path Scaling**
  - $S_{path} = S_{geom} + S_{anel}$
- **Geometric Attenuation**
  - $S_{geom} = S_{geom,cr}F_{cr} + S_{geom,sb}F_{sb}$
    - $S_{geom,cr} = \left[c_{14} + c_{16}\left(min\{M_w, M_{max}\} - M_w^{ref}\right)\right] ln\left(\frac{\sqrt{R_{rup}^2 + h^2}}{\sqrt{(R_{rup}^{ref})^2 + h^2}}\right)$
    - $S_{geom,sb} = \left[c_{15} + c_{17}\left(min\{M_w, M_c\} - M_w^{ref}\right)\right] ln\left(\frac{\sqrt{R_{rup}^2 + h^2}}{\sqrt{(R_{rup}^{ref})^2 + h^2}}\right)$
- **Anelastic Attenuation**
  - $S_{anel} = c_{18}\left(R_{rup} - R_{rup}^{ref}\right)F_{cr} + c_{19}\left(R_{rup} - R_{rup}^{ref}\right)F_{sb}$

Site Scaling

- **Nonlinear Site Scaling**
  - $S_{site,non} = c_{20} u\left(V_{s30}^{ref} - V_{s30}\right)$

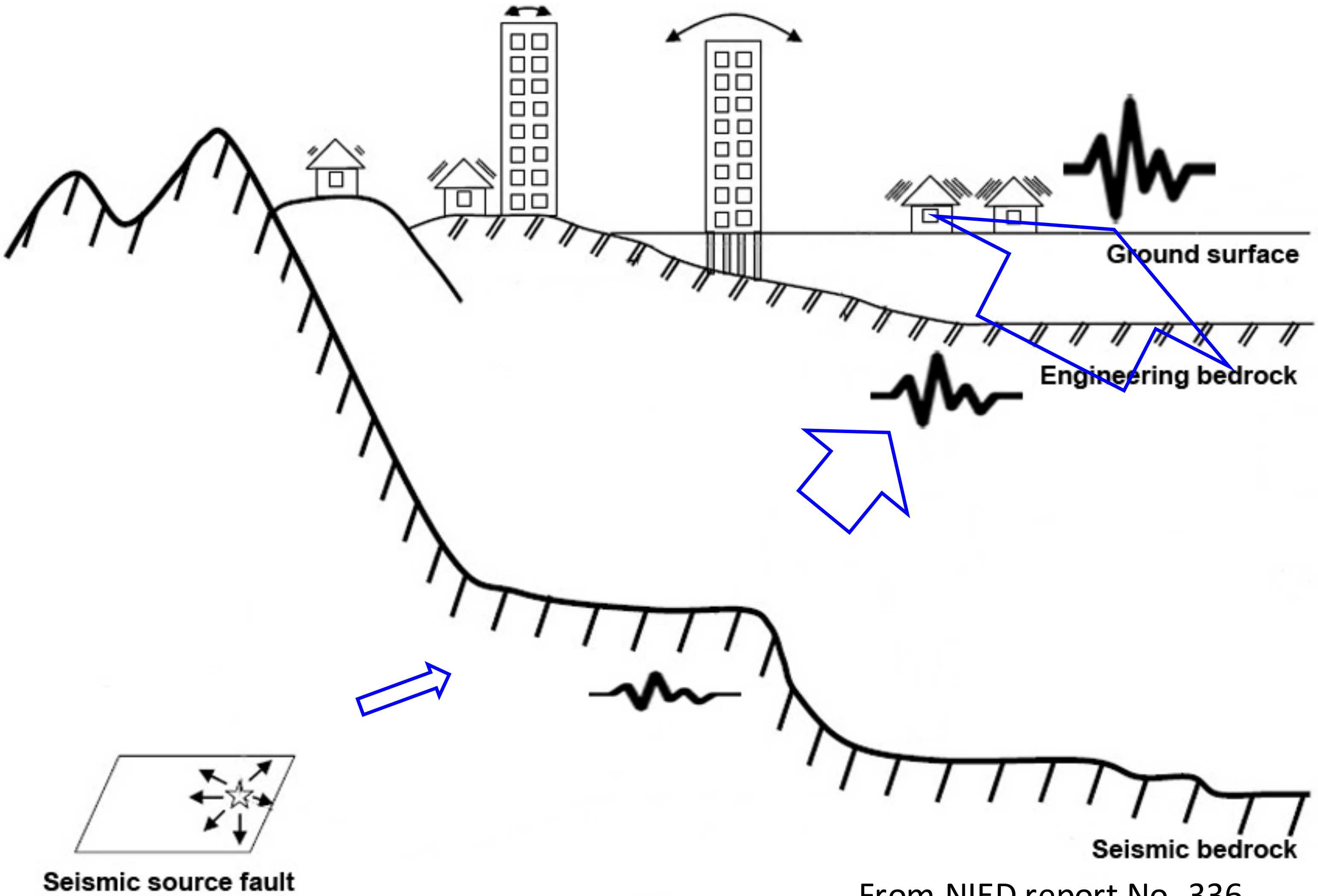
$$\left\{-1.5 ln\left(\frac{V_{s30}}{V_{s30}^{ref}}\right) - ln\left(\hat{S}_{a1100} + 2.4\right) + ln\left(\hat{S}_{a1100} + 2.4\left(\frac{V_{s30}}{V_{s30}^{ref}}\right)^{1.5}\right)\right\}$$

- **Linear Site Scaling**
  - $S_{site,lin} = c_{21}\, ln\left(\frac{V_{s30}}{V_{s30}^{ref}}\right) + c_{22}\, ln\left(\frac{Z_{1.0}}{Z_{1.0}^{ref}}\right)$
    - $Z_{1.0}^{ref} = \exp\left(\frac{-4.08}{2} ln\left(\frac{V_{S30}^2 + 355.4^2}{1750^2 + 355.4^2}\right)\right)$ **Kuo et. al. (2016)**

Contents

- **Introduction**
  - What is the ground motion model ?
  - Why we develop new ground motion model ?
  - What are the characteristics of ground motion ?
  - Objectives of this study
- **Model Development Approach**
- **Application to the Ground Motion Simulation for a Scenario Earthquake**
  - Advantages and limitations
- **Summary and Future Work**

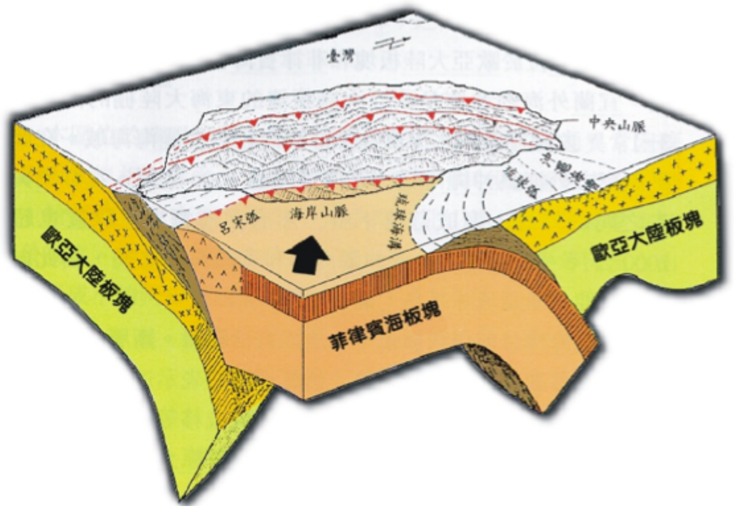
Seismic Source and Ground Motion



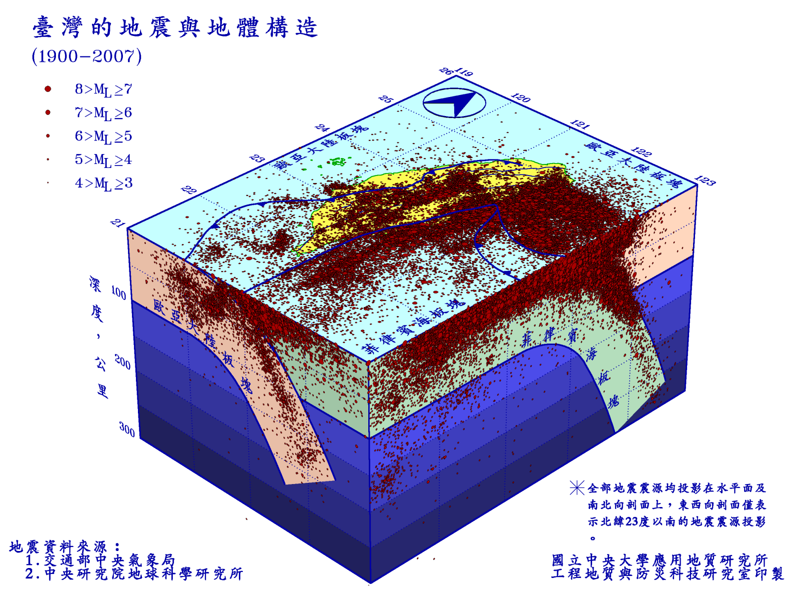
From NIED report No. 336

Seismic Source Classification

- **Crustal Earthquake**
  - Chi-Chi Earthquake (Mw 7.6)
  - MeiNong Earthquake (Mw 6.4)
  - Mmax ~ Mw 8.0

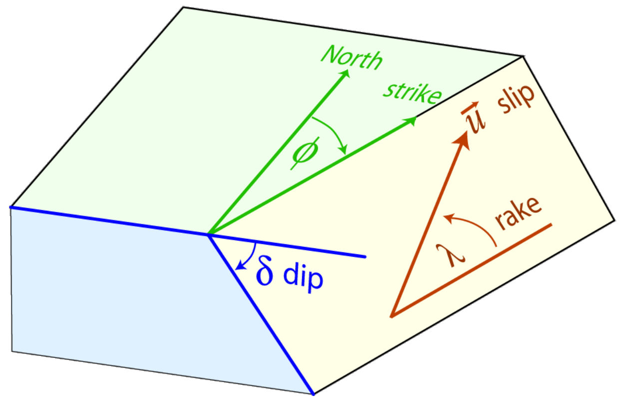


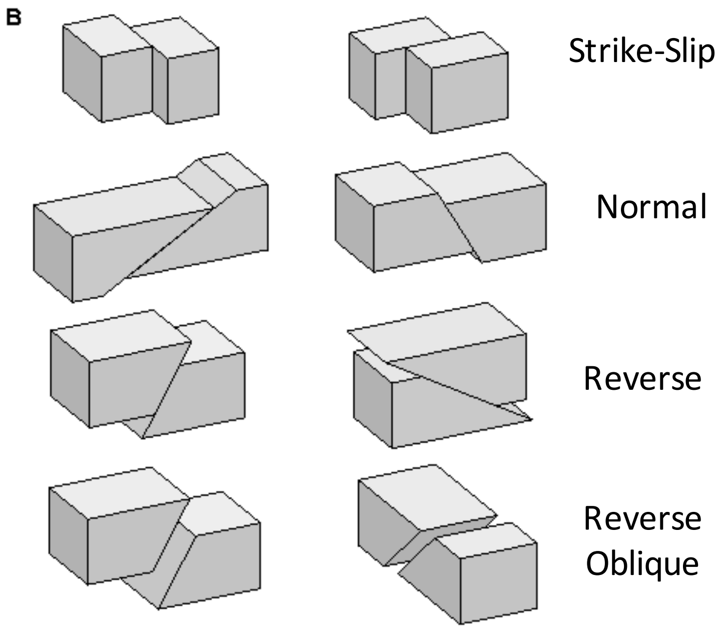
- **Subduction Earthquake**
  - Interface Earthquake
    - 331 Earthquake (Mw 7.1)
    - Tohoku Earthquake (Mw 9.0)
    - Mmax ~ Mw 9.0
  - Intraslab Earthquake
    - HengChun Earthquake (Mw 7.1)
    - Mmax ~ Mw 8.0



Seismic Source Parameters

- **Magnitude**
- **Hypocenter**
  - Longitude and Latitude
  - Depth
- **Focal Mechanism**
  - Strike, Dip, Rake
- **Style of Faulting**
  - Strike-Slip
  - Normal/Normal Oblique
  - Reverse/Reverse Oblique
- **Rupture Plane**
  - Rupture Length
  - Rupture Width
  - Ztor: depth to top of rupture plane
- **Mainshock or Aftershok**

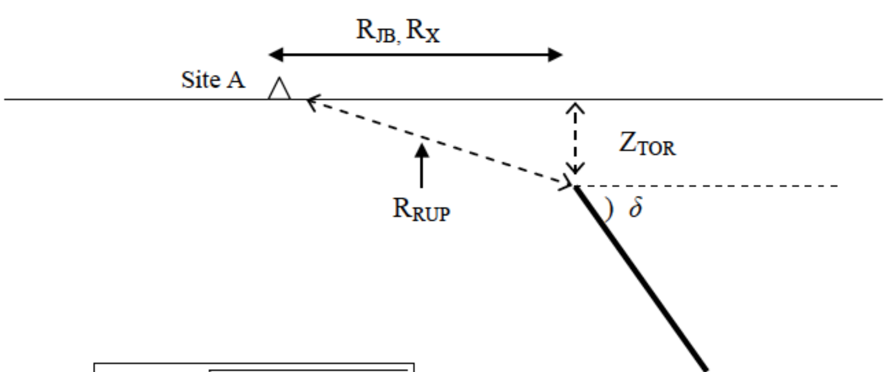




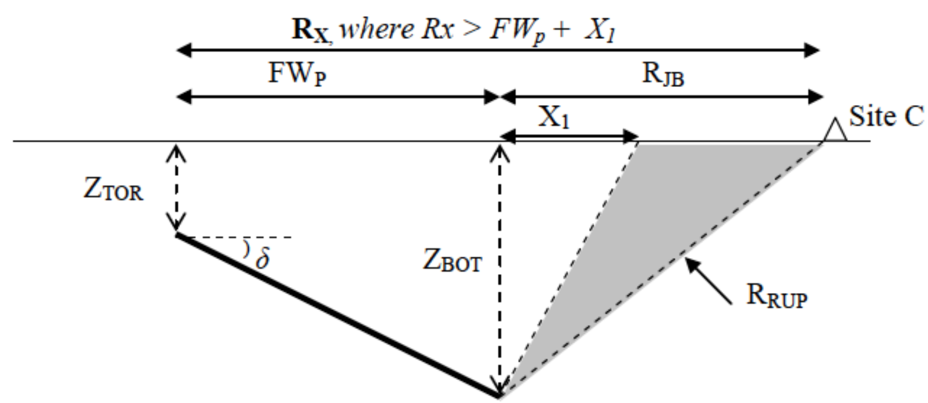
USGS, 1996

Different Types of Distance from Seismic Source to Site

- **Rrup**
  - Closest distance from the recording site to the ruptured fault area
- **Rjb**
  - Shortest horizontal distance from the recording site to the vertical projection of the rupture on the surface
- **Rx**
  - Horizontal distance (km) from top edge of rupture. Measured perpendicular to the fault strike.

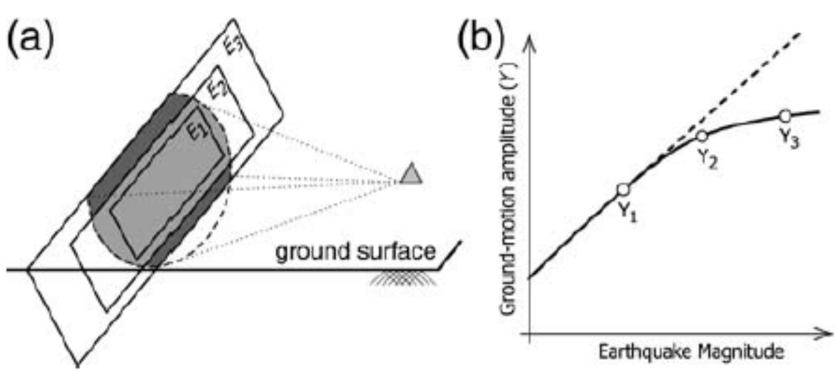


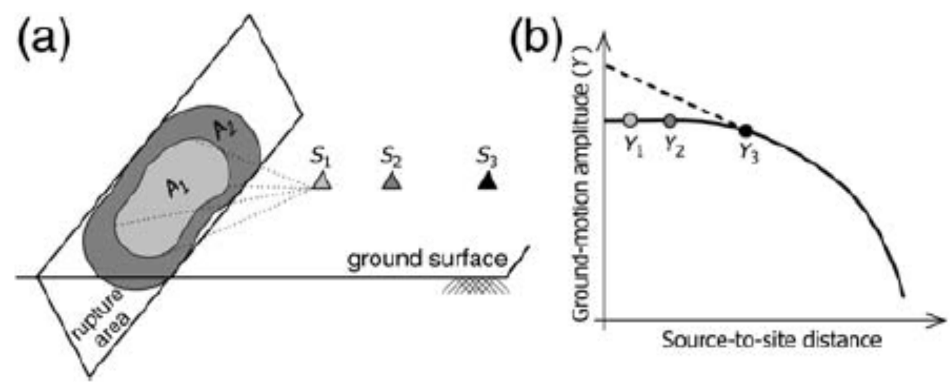
$$R_{RUP} = \sqrt{(Z_{TOR})^2 + (R_X)^2}$$



Ground Motion Saturation

- **Origins**
  - The commonly accepted origin of ground-motion saturation effects relates to the fact that the closest portions of the rupture dominate the motions from large earthquakes close to the fault.
- **Two Types of Ground Motion Saturation**
  - The ground motion saturated with magnitude at close distance
  - The ground motion saturated with distance for large magnitude event

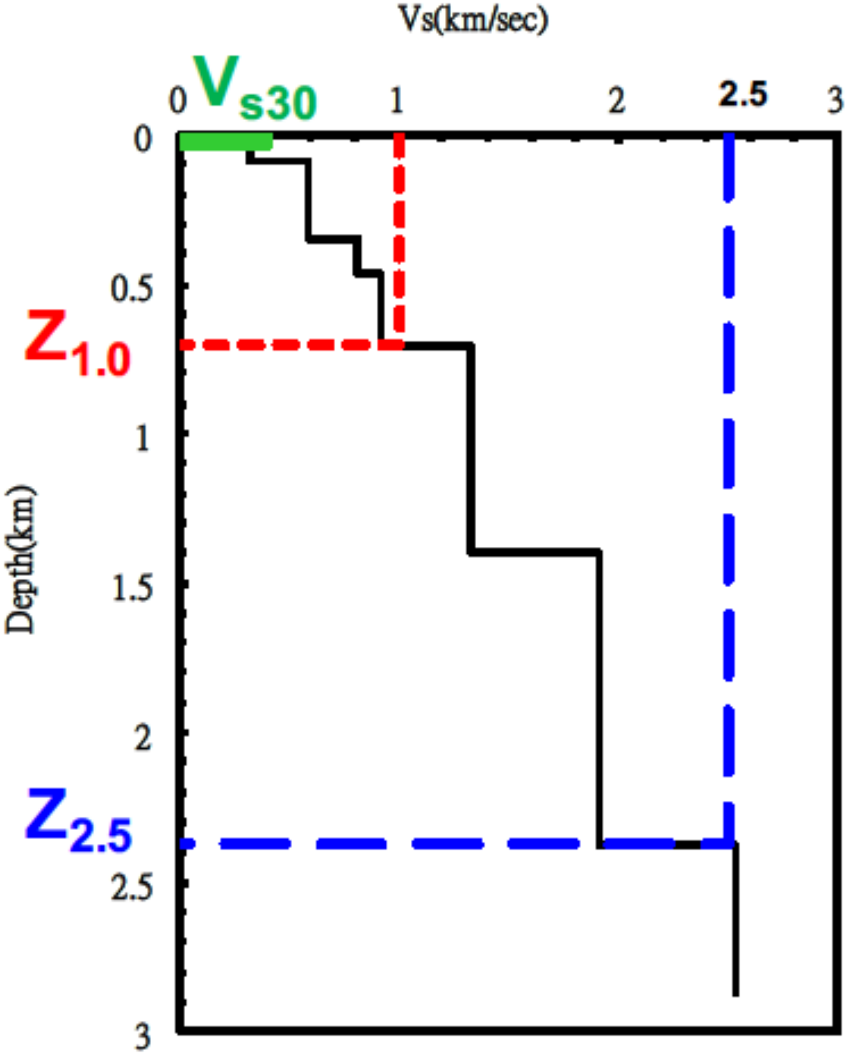




Bulletin of the Seismological Society of America, Vol. 104, No. 3, pp. 1458–1478, June 2014, doi: 10.1785/0120130147

Site Condition and Site Parameters

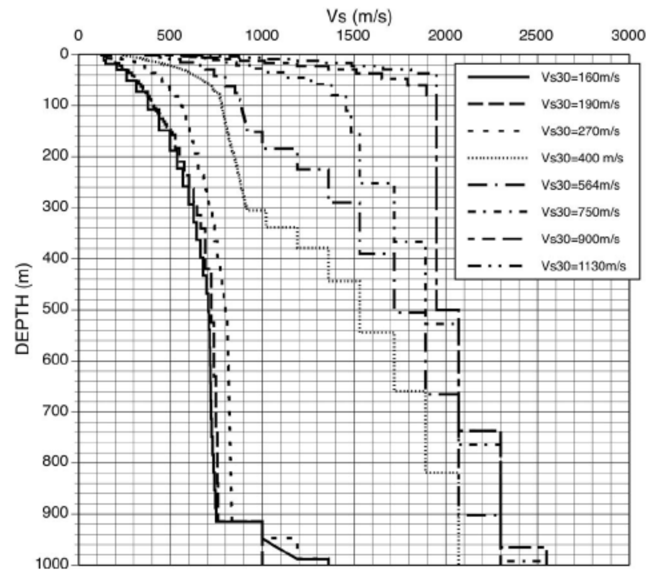
- **Vs30 (m/s)**
  - The average shear-wave velocity of soil between 0 and 30-meters depth
- **Z1.0 (m)**
  - The depth (m) to where shear-wave velocity of soil achieves 1.0 km/sec (the first occurrence if more than one depth exists)

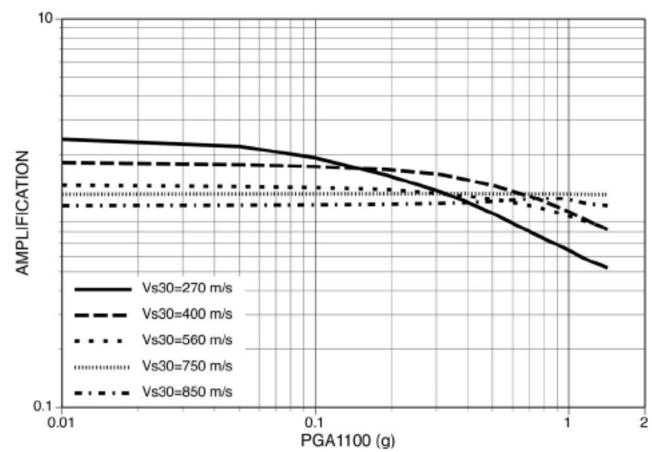


From Taiwan SSHAC Level 3 Project

Site Effect on Ground Motion

- **Linear Site Effect**
  - For weak input rock motion, the material nonlinearity of soil layer is not significant
  - The ground motion amplification of free surface soil site w.r.t. input rock motion is linear proportional to ln(Vs30) and ln(Z1.0)
- **Nonlinear Site Effect**
  - For strong input rock motion, the material nonlinearity of soil layer is significant
  - The ground motion of free surface soil w.r.t. input rock motion may be deamplified

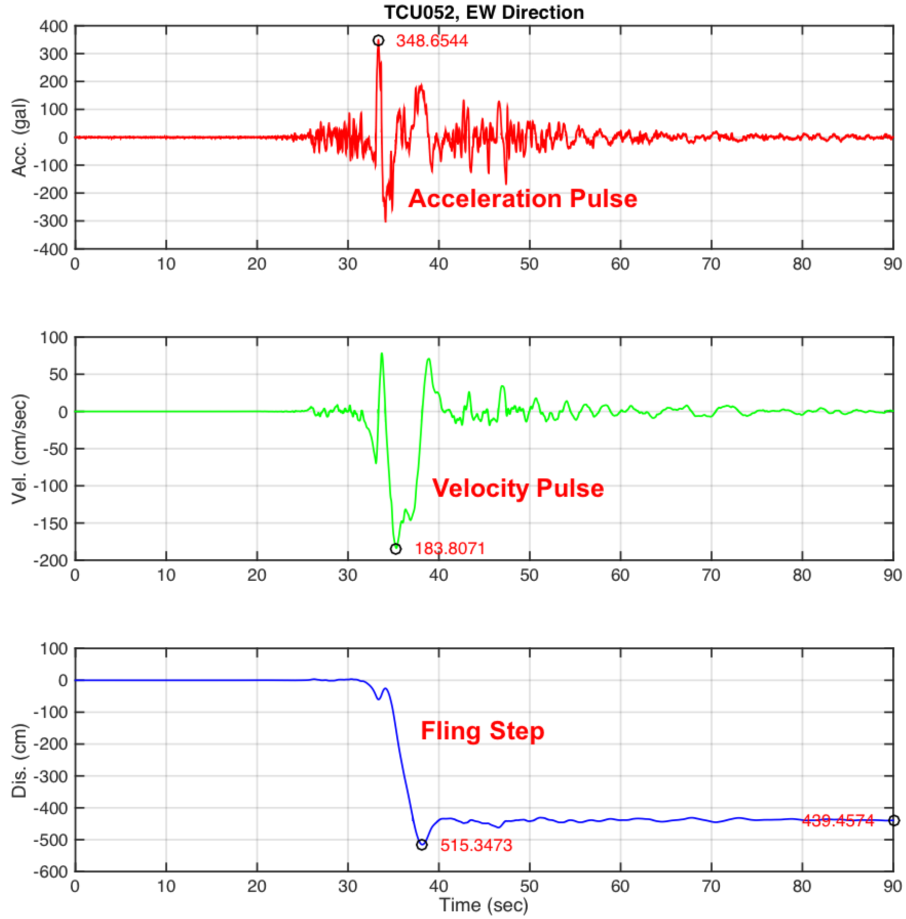




Earthquake Spectra, Volume 24, No. 1, pages 243–255, February 2008; © 2008, Earthquake Engineering Research Institute

Ground Motion Intensity Measurement (IM)

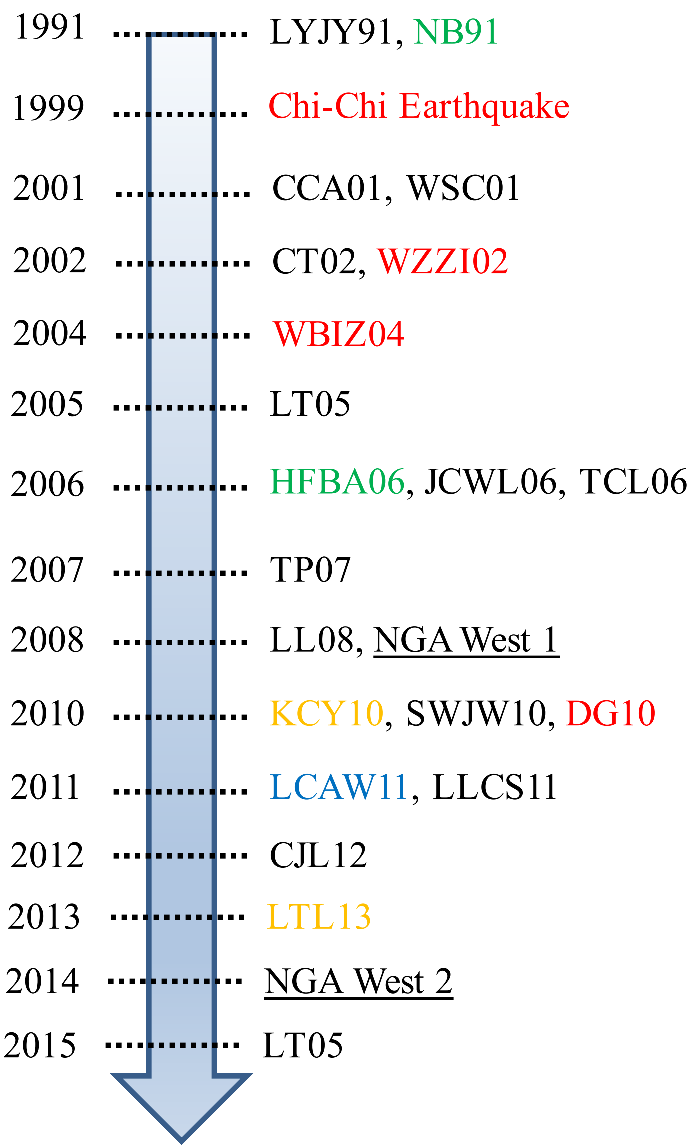
- **Intensity**
  - Peak ground acceleration (PGA)
  - Peak ground velocity (PGV)
  - Peak ground displacement (PGD)
  - Residual ground displacement (RD)
  - Response Spectrum
    - Spectral acceleration (Sa)
    - Spectral velocity (Sv)
    - Spectral displacement (Sd)
    - Function of damping ratio and period
- **Component**
  - Horizontal
  - Vertical



Regression Approaches – Basics

- **Two types of statistical models**
  - Fixed-effected model: residuals are uncorrelated
  - Mixed-effected model: residuals are correlated
- **Two types of solution schemes**
  - Least Square-Error Estimation (LSE)
    - Able to get accurate solution of
      - fixed effect model with normal distributed residual
    - Unable to get accurate solution of
      - fixed effect model with other distributed residual
      - mixed effect model
  - Maximum Likelihood Estimation (MLE)
    - Able to get accurate solution of
      - fixed effect model with other distributed residual
      - mixed effect model with normal distributed residual
    - No available algorithm for
      - mixed effect model with other distributed residual

List of Taiwan Ground Motion Models



No.	Year	Authors	Abbreviation
1	1991	C.H. Loh, Y.T. Yeh, W.Y. Jean, Y.H. Yeh	LYJY91
2	1991	M. Niazi, Y. Bozorgnia	NB91
3	2001	T.Y. Chang, F. Cotton, J. Angelier	CCA01
4	2001	Y.M. Wu, T.C. Shin, C.H. Chang	WSC01
5	2002	Y.H. Chen, C.C. Tsai	CT02
6	2002	G.Q. Wang, X.Y. Zhou, P.Z. Zhang, H. Igel	WZZI02
7	2004	G.Q. Wang, D.M. Boore, H. Igel, X.Y. Zhou	WBIZ04
8	2005	K.S. Liu, Y.B. Tsai	LT05
9	2006	B. Hernandez, Y. Fukushima, R. Bossu, J. Albaric	*HFBA06
10	2006	W.Y. Jean, Y.W. Chang, K.L. Wen, C.H. Loh	JCWL06
11	2006	C.C. Tsai, Y.H. Chen, C.H. Liu	TCL06
12	2007	B. Tavakoli, S. Pezeshk1	TP07
13	2008	P.S. Lin, C.T. Lee	LL08
14	2010	C.Y. Kuo, J.K. Chung, Y.T. Yeh	KCY10
15	2010	V. Sokolov, F. Wenzel, W.Y. Jean, K.L. Wen	SWJW10
16	2010	S. Das, V.K. Gupta	DG10
17	2011	P.S. Lin, B. Chiou, N. Abrahamson, M. Walling, C.T. Lee, C.T. Cheng	LCAW11
18	2011	P.S. Lin, C.T. Lee, C.T. Cheng, C.H. Sung	LLCS11
19	2012	Y.W. Chang et, W.Y. Jean, C.H. Loh	*CJL12
20	2013	K.S. Liu., Y.B. Tsai, P.S. Lin	LTL13
21	2015	K.S. Liu., Y.B. Tsai	LT15

Limitations of Available Taiwan GM Models

- **Limited applicable period range**
  - most of them are only for PGA
- **Some important ground motion characteristics have not been considered**
  - Source effect: source classification, depth scaling, style-of-faulting effect, aftershock effect
  - Path effect: Rrup-based geometric attenuation
  - Site effect: linear site effect and nonlinear site effect
- **Ground motion data truncation effect have not been addressed**
  - It may derive biased ground motion model

Random Truncation Effect – I

- **Consider y is a random variable with PDF f(y) and CDF F(y) for observation without truncation and y_T is a random variable with PDF $f_T(y)$ for the observation with truncation**
- **The truncated level is a random variable with PDF g(y) and CDF G(y).**
- **The $f_T(y)$ for the observation can be expressed as (Bragato, 2004)**

$$f_T(y) = \frac{f(y)G(y)}{\int_{-\infty}^{\infty} f(y)G(y)\,dy}$$

Iterations for Nonlinear Site Effect

- **Step A: Solve model coefficients without considering nonlinear site effect and derive initial rock motion prediction Sa1100 (Sa for Vs30 = 1100 m/s) of each record**

- **Step B: Solve model coefficients considering nonlinear site effect with initial Sa1100 prediction and derive updated Sa1100 prediction of each record**

- **Step C: Repeat Step B until Sa1100 prediction of each record are converges ($MSE < 10^{-5}$)**