# Development of the Prediction Equation for Horizontal PGD in Taiwan

**Chih-Hsuan Sung** | Civil and Environmental Engineering, University of California, Berkeley
**Norman A. Abrahamson** | Civil and Environmental Engineering, University of California, Berkeley
**Jyun-Yan Huang** | National Center for Research on Earthquake Engineering (NCREE), Taiwan

## Abstract

We develop a conditional ground-motion model (GMM) for peak ground displacement (PGD) for Taiwan. The conditional GMM includes the observed pseudo-spectral acceleration (PSA(T)) as an input parameter in addition to magnitude and distance. Furthermore, the conditional PGD model can be combined with the traditional GMMs for PSA values to develop a GMM for PGD without the dependence on PSA. The main advantages of the conditional model approach are that it can be quickly developed; it is easily understandable; it can fully capture the magnitude, distance, and site scaling of the secondary parameters that are compatible with the design response spectral values; and lastly, it has much smaller aleatory variability than traditional GMMs. In this study, we use part of the database of the Taiwan SSHAC Level 3 project (13691 strong-motion records from 158 crustal events which occurred between 1992 and 2018 with 4.5 ≤ Mw ≤ 7.65) to develop a new conditional GMM for horizontal PGDs with PSA(T), rupture distance, and moment magnitude as predictor variables. We combine this conditional GMM with two Taiwan-specific GMM models and four NGA-West2 GMMs for PSA(T) to derive new non-conditional GMMs for the median and standard deviation of the PGD. The resulting PGD GMMs include more the complex ground-motion scaling in the PSA GMMs, such as hanging-wall effects, sediment-depth effects, soil nonlinearity effects, and regionalization effects.

## Data Set

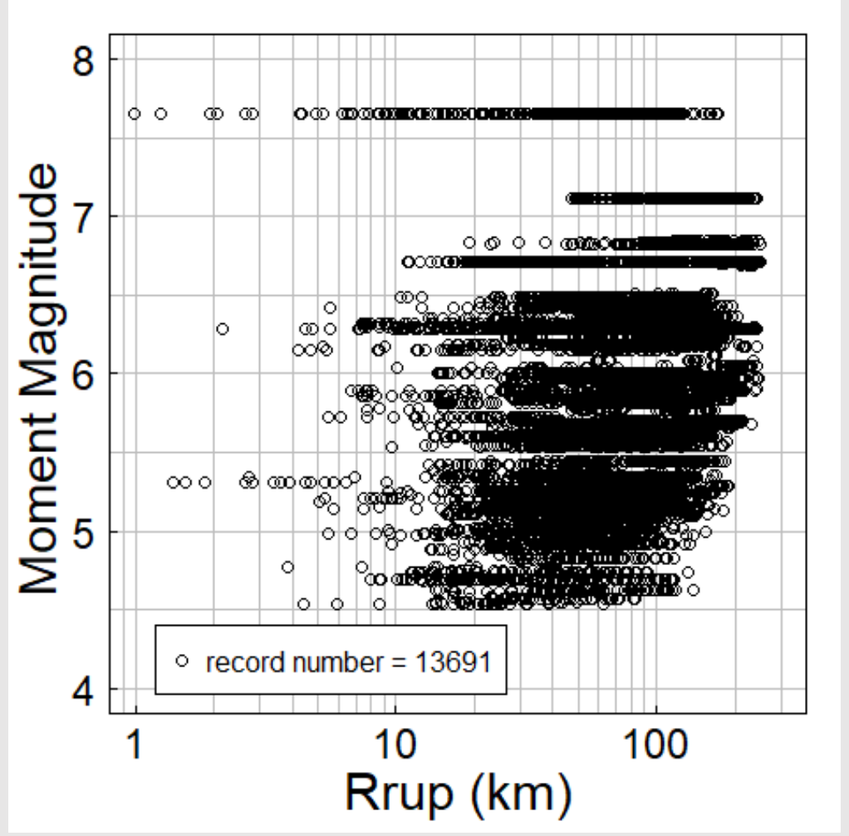


**Figure 1.** Magnitude-distance distribution of the SSHAC Level 3 dataset for crustal earthquakes.

The Taiwan, the SSHAC Level 3 PSHA Project (NCREE, 2018) developed a ground-motion database that includes the records from the TSMIP with available three-axis components. In this study, we selected a subset of this database with moment magnitudes (Mw) greater than 4.5 and rupture distances less than 200 km. In addition, only earthquakes recorded at a minimum of 10 stations and station with a minimum of 10 recordings are used to avoid poorly sampled events or sites. The resulting subset has 13,691 recordings from 158 crustal events that occurred between 1992 and 2018. An issue with the PGD data is that the data processing often uses record-specific corner frequencies of the filters which can affect the PGD values. To develop a PGD data set that has PGD values for a fixed bandwidth, we calculate the PGD using a high-pass filter with a fixed corner frequency of 0.1 Hz. As a result, the GMM developed in this study represents the PGD for frequencies greater than 0.1 Hz.

## Previous Conditional Models for secondary ground-motion parameters (PGV and IA)

**Newmark and Hall (1982)**:

$$\ln(PGV) = 4.55 - \ln(T) + 1.0\ln(PSA(T))$$

**Bommer and Alarcon (2005)**: $\ln(PGV) = 3.89 + 1.0\ln(PSA(T = 0.5))$

**Watson-Lamprey and Abrahamson (2006)**:

$$\ln(I_a) = c_1 + c_2\ln(Vs30) + c_3M + c_4\ln(PGA) + c_5\ln\big(SA(T)\big) + c_6\ln(R_{RUP}) + c_7\ln(R_{RUP})^2$$

**Huang and Whittaker (2015)**: $\ln(PGV) = 3.75 + 1.0\ln\big(PSA(T = 1)\big) + 0.13M$

**Abrahamson et al. (2016)**:

$$\ln(I_a) = c_1 + c_2\ln(Vs30) + c_3M + c_4\ln(PGA) + \ln\big(SA(T)\big) + c_8HW$$

**Abrahamson and Bhasin (2019):**

$$\ln(PGV) = c_1 + c_2(M-6) + c_3(8.5-M)^2$$
$$+c_4 ln(R_{rup} + c_5 exp(c_6(M-6)) + f_1(M)\,ln\big(PSA(T_{PGV})\big)$$

where M is the moment magnitude, Rrup is the rupture distance in km, and the PSA is the 5% damped spectral acceleration in g. f1 is related to the differences in the aleatory standard deviations for ln(PGV) and ln(PSA(TPGV ))).

## Conditional Ground-Motion Models

### Conditional Ground-Motion Models for PGD

$T_{PGD}$ crosses the source corner frequency

$$ln(PGD) = c_1 + c_2(M-6) + \boxed{c_3(8.5-M)^2} + \boxed{c_4 ln(R_{rup} + c_5 exp(c_6(M-6))} + \boxed{f(M)\,ln\big(PSA(T_{PGD})\big)}$$

the saturation of PGD at short distances

where ***M*** is the moment magnitude, ***R****rup* is the rupture distance (km), ***PSA*** is the 5% damped spectral acceleration (g).

f(M) is the differences in the standard deviations for ln(PGD) and ln(PSA($T_{PGV}$ )) with magnitude dependent:

$$f(M) = \begin{cases} a_1 & for\ M \le 5.0 \\ a_1 + \dfrac{(a_2-a_1)}{2.5} & for\ 0.5 < M \le 7.5 \\ a_2 & for\ M > 7.5 \end{cases}$$

**Table 1**. Conditional PGD Model Coefficients for Crustal Earthquakes.

| Coeff | | Coeff | |
|---|---|---|---|
| $c_1$ | 5.273 | $a_1$ | 0.843 |
| $c_2$ | 0.485 | $a_2$ | 0.878 |
| $c_3$ | -0.043 | | |
| $c_4$ | -0.188 | $\varphi$ | **0.213** |
| $c_5$ | 2.984 | $\tau$ | **0.091** |
| $c_6$ | 1.762 | $\sigma$ | **0.231** |

### the magnitude dependence of the ($T_{PGD}$ )

set up the linear relation for the magnitude dependence of the $T_{PGV}$:

$$ln(T_{PGD}) = b_1 + b_2M_w$$

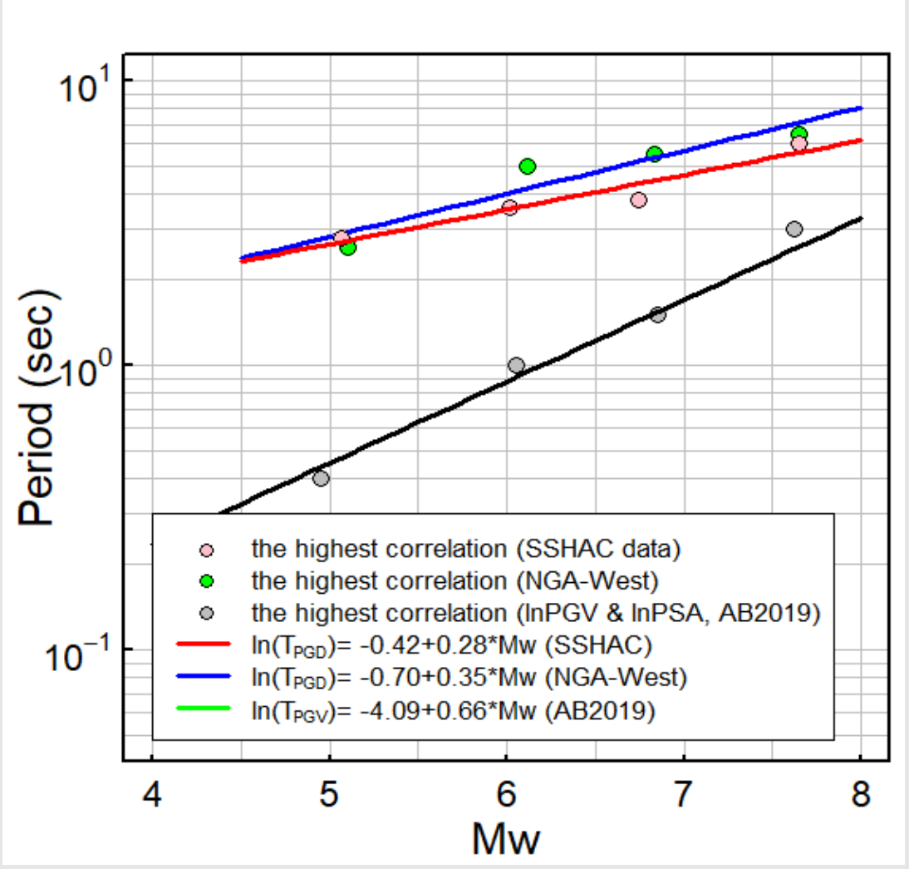


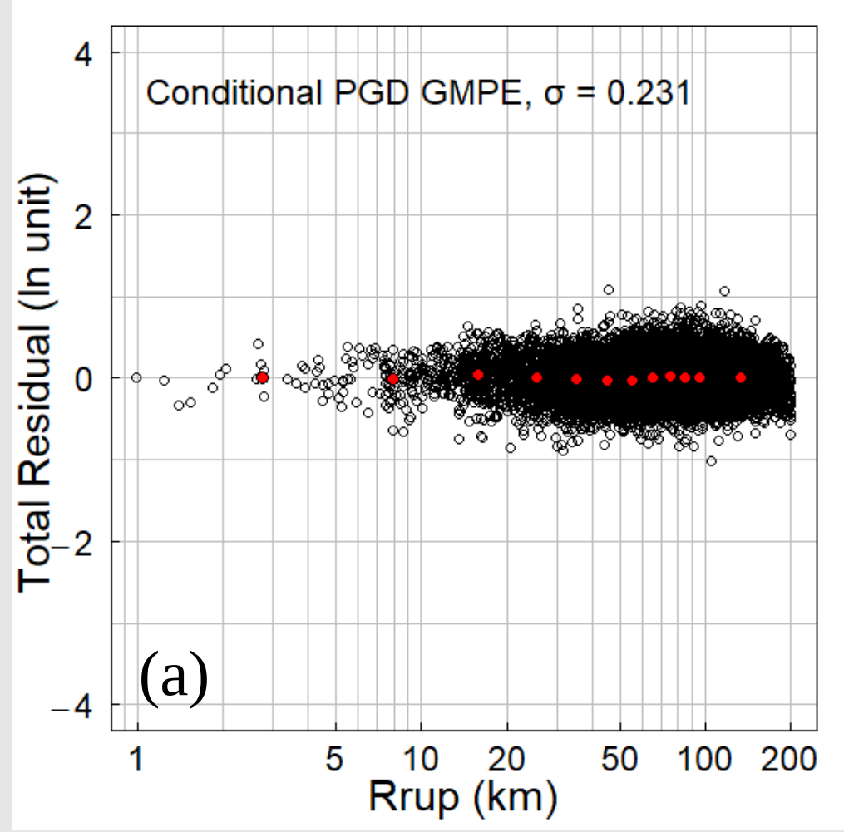
**Figure 2.** Magnitude dependence of the period with highest correlation between ln(PGV) and ln(PSA).

**Table 2.** the spectral period ($T_{PGD}$) with the highest correlation between ln(PSA(T)) and ln(PGV) for each magnitude bin.

| Mw Range | Mean Mw | $T_{PGD}$ (sec) |
|---|---|---|
| Mw4.5 – Mw5.5 | 5.10 | 2.6 |
| Mw5.5 – Mw6.5 | 6.11 | 5.0 |
| Mw6.5 – Mw7.5 | 6.83 | 5.5 |
| Mw7.5 – Mw8.5 | 7.65 | 6.5 |

## Result 1: Residuals

[ Total residuals versus Rrup ]



[ Between-event residuals versus Mw ]

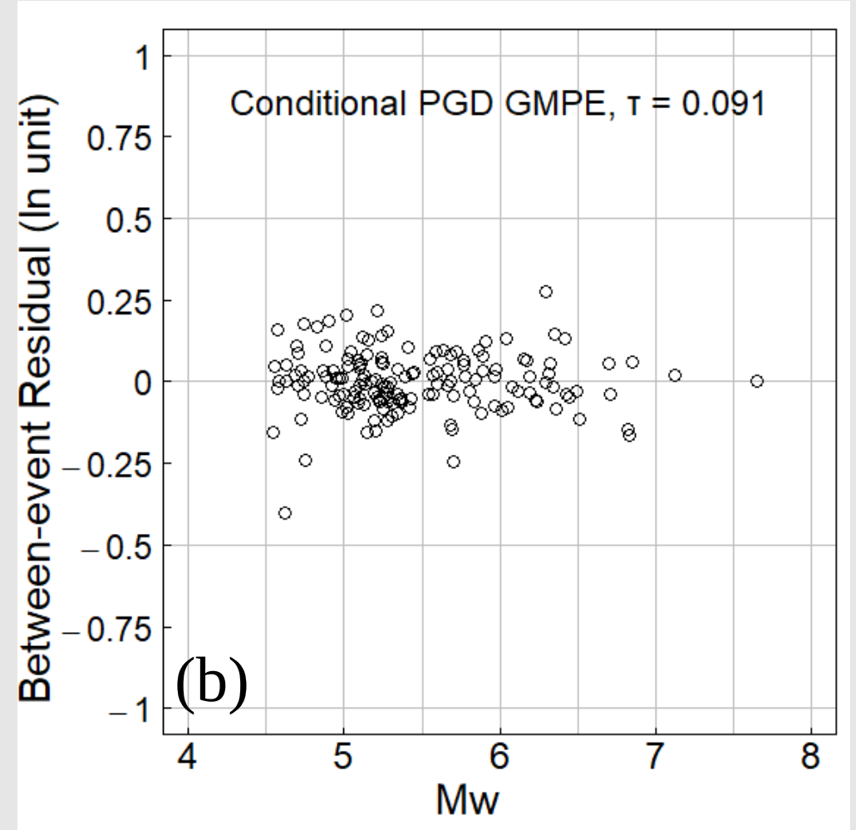


**Figure 3** (a) Distance dependence of the total residuals, and (b) Mw dependence of the between-event residual for the conditional PGD model.

[ Within event residuals versus PSA(T) ]

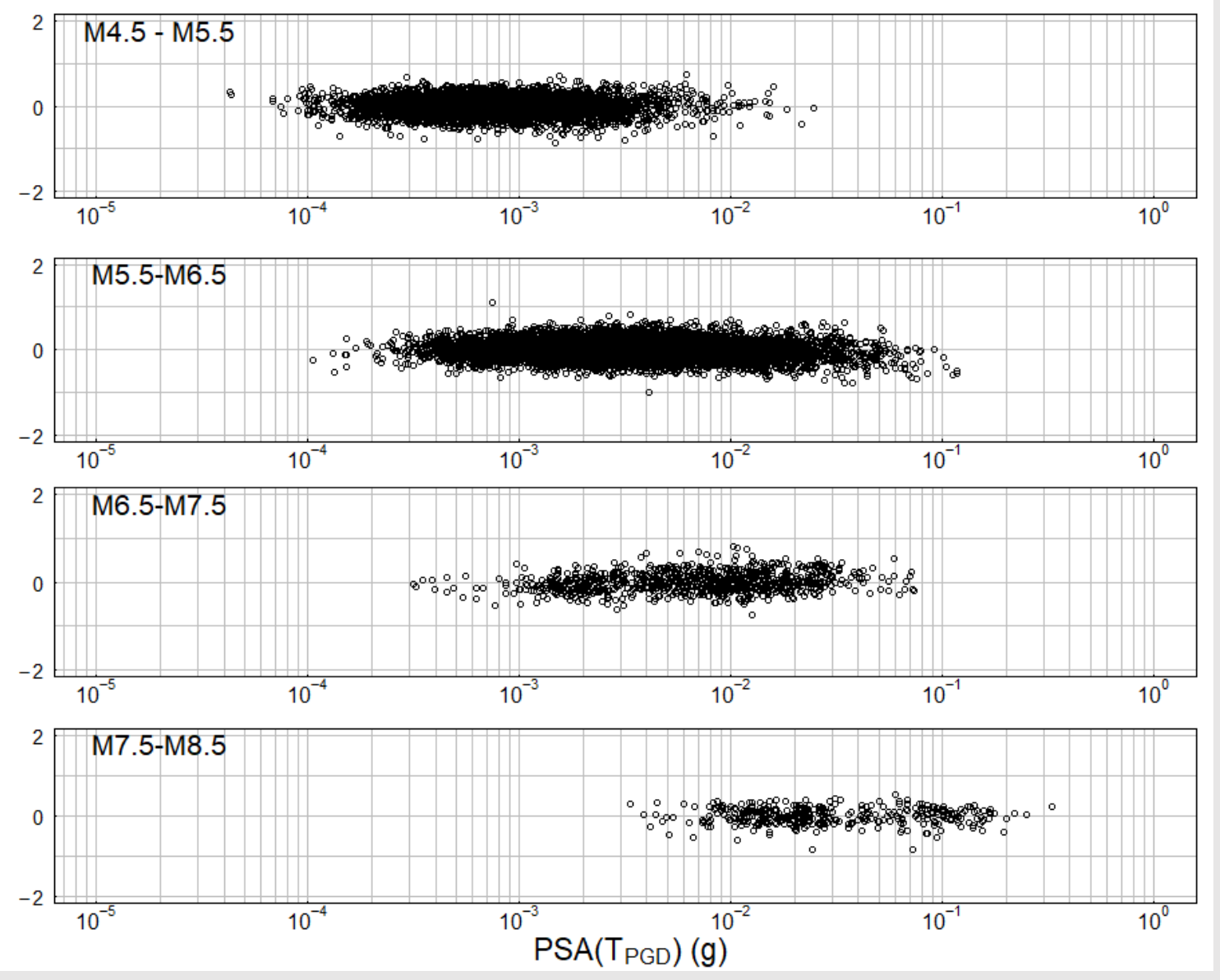


**Figure 4**. PSA dependence of the within-event residuals for the conditional PGD model.

[ Within event residuals versus Rrup ]

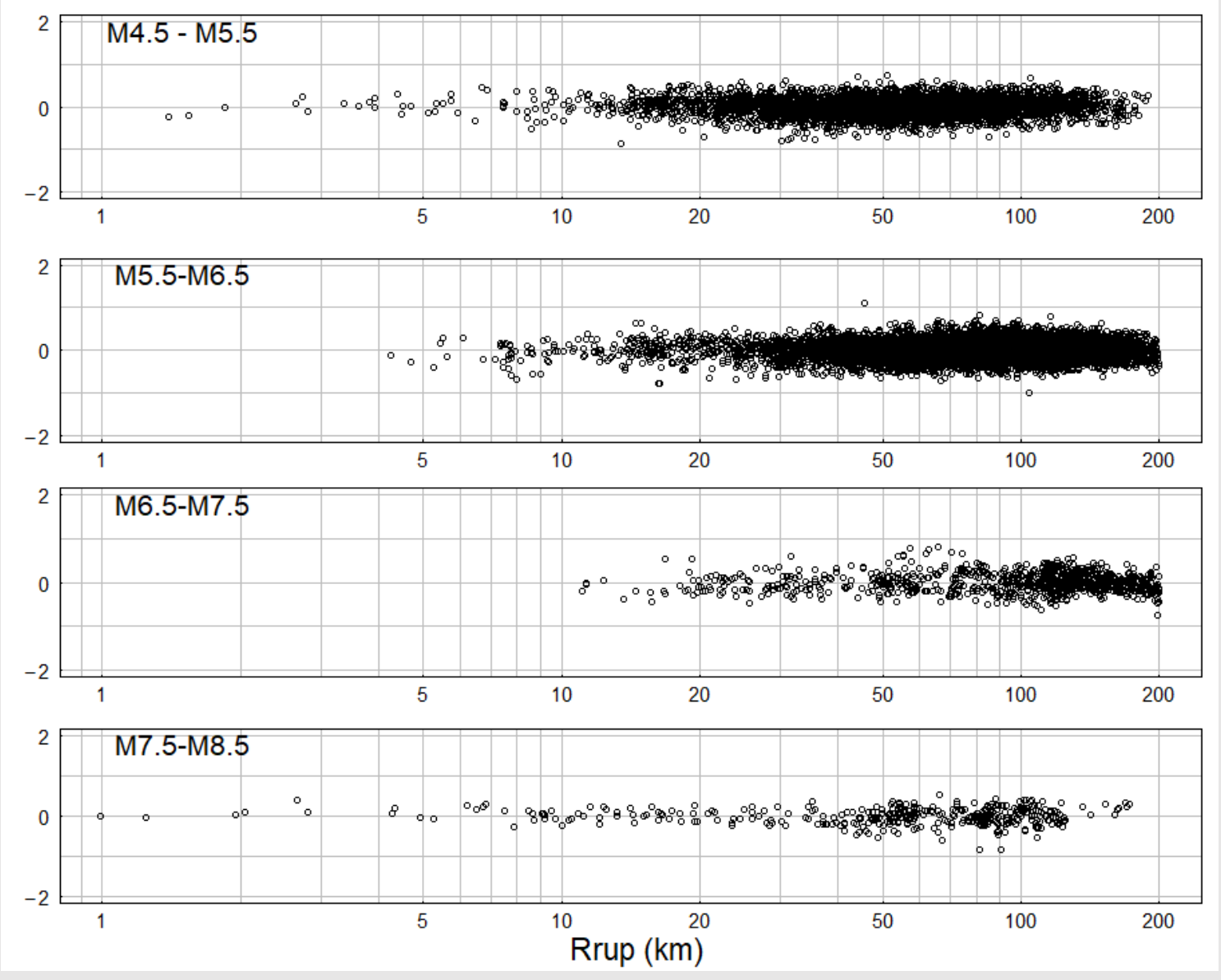


**Figure 5**. Distance dependence of the within-event residuals for the conditional PGD model.

**Table 3**. Standard deviation of the conditional PGD residuals by magnitude bin

| Mw | Number (Earthquake) | Number (Recording) | $\varphi$ | $\tau$ | $\sigma$ |
|---|---|---|---|---|---|
| 4.5 – 5.5 | 96 | 4006 | 0.214 | 0.094 | 0.236 |
| 5.5 – 6.5 | 54 | 7764 | 0.213 | 0.085 | 0.228 |
| 6.5 – 7.5 | 7 | 876 | 0.221 | 0.095 | 0.233 |
| 7.5 – 8.5 | 1 | 378 | 0.200 | - | 0.200 |

## Result 2: Conditional PGD model with GMMs for the PSA

We can convert the conditional GMM to a traditional scenario-based (non-conditional) PGD model by combining it with a GMM for the PSA(T). We use two Taiwan GMMs (Chao *et al.*, 2019 (Chao19), Phung *et al.*, 2019 (Phung19)) and four four NGA-West 2 GMMs (Abrahamson *et al.*, 2014 (ASK14), Boore *et al.*, 2014 (BSSA14), Campbell and Bozorgnia, 2014 (CB14), Chiou and Youngs, 2014 (CY14)) to generate six PGD GMMs for Taiwan. The magnitude scaling of the resulting median PGD for strike-slip earthquakes with a rupture distance of 25 km and Vs30 = 350 m/s are shown in **Figure 6**.

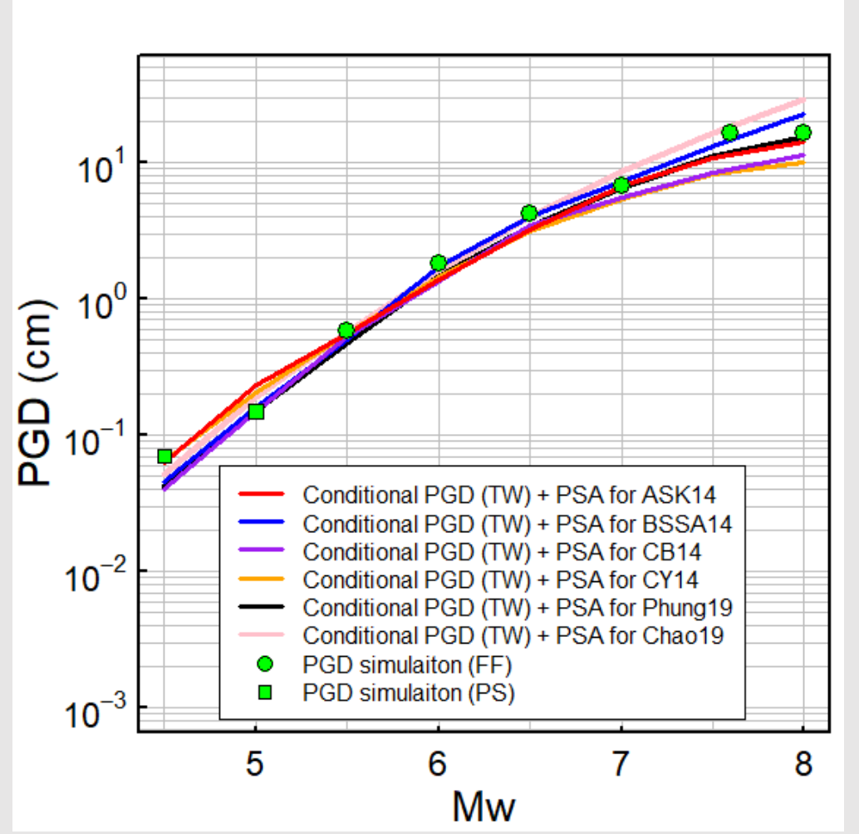
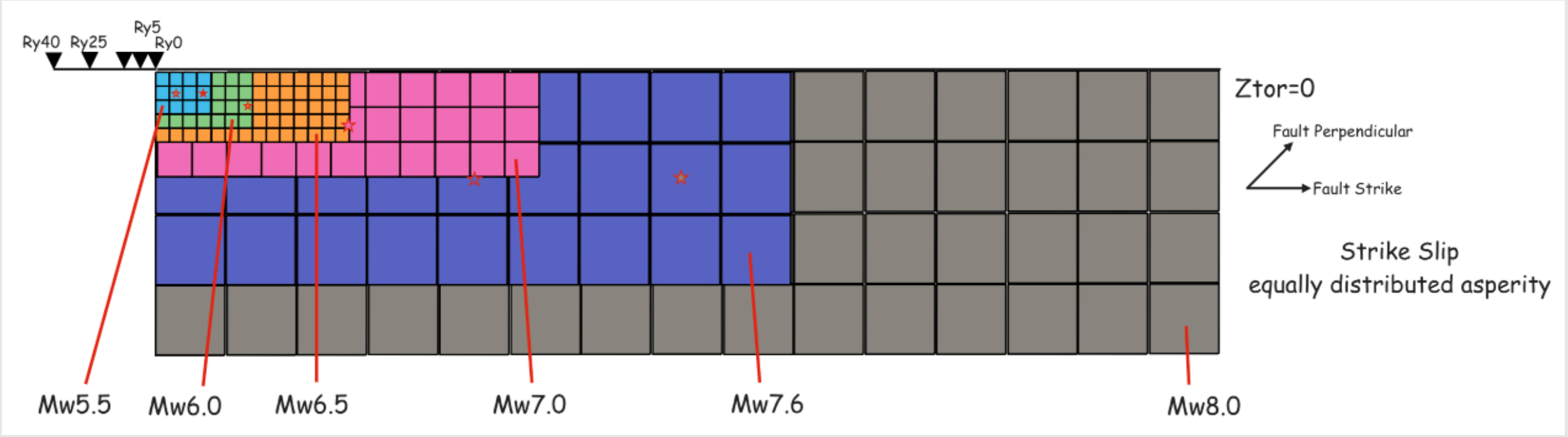


**Figure 6**. Comparison of the magnitude scaling for the PGD using six different GMMs (ASK14, BSSA14, CB14, CY14, Phung19, Cha019) to compute the PSA(T) values for the median spectrum.

For the purpose of constraining source scaling relations for conditional predicted PGD, a finite-fault stochastic simulation technique (Boore, 1983; Boore, 2003; Beresnev and Atkinson, 1998; Motezedian and Atkinson, 2005) is used to understand the magnitude scaling behavior, especially for large magnitudes. The Sub-fault sizes of finite-fault simulations for synthetic motions from Mw 5.5 to 8.0 are shown in **Figure 7**, and the detail of the setting is listed in Table 4. The simulations show a similar trend in the magnitude scaling with the PGD model for the moderate magnitudes range where we have data (green points in **Figure 6**)

**Figure 7** Finite fault images for synthetic motions from Mw 5.5 to 8.0. Pseudo stations located from the top edge of rupture fault and all the simulations were rupture to the surface.



## Result 3: Standard deviation of the scenario-based PGD model

$$\sigma^2_{\ln PGD} = \left(\frac{\partial \ln(PGD)}{\partial \ln(PSA(T))}\right)^2 \sigma^2_{\ln PSA(T)} + \sigma^2_{\ln PGD|PSA(T)}$$

in which $\sigma_{lnPGD}$ is the standard deviation of the residuals from a scenario-based PGD model, $\sigma_{lnPSA(T)}$ is the standard deviation of the residuals from the PSA(T) of traditional GMMs, and $\sigma_{lnPGD|PSA(T)}$ is the total standard deviation of the conditional PGD model. The partial derivative $\partial ln(PGD)/\partial ln(PSA(T))$ is equal to *f*(*M*) in Equation (2).

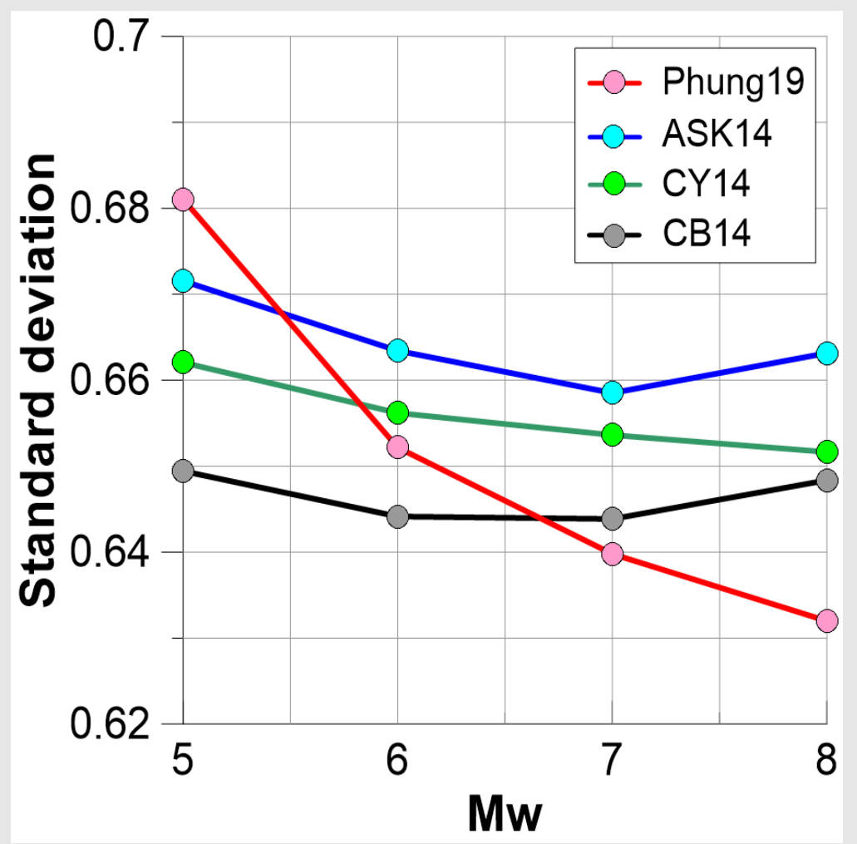


**Figure 8.** the standard deviation of four scenario-based PGD models (ASK14, CY14, CB14, Phung19)

**Table 4.** Fault sizes of finite-fault simulation for synthetic motions from Mw 5.5 to 8.0.

| Mw | Fault Length(L) (km) | Fault Width(W) (km) | Fault Area(A) (km²) | Subfault size (km²) |
|---|---|---|---|---|
| 5.5 | 8 | 6 | | 2*2 |
| 6.0 | 14 | 8 | | 2*2 |
| 6.5 | 30 | 10 | | 2*2 |
| 7.0 | 60 | 15 | | 5*5 |
| 7.6 | 90 | 30 | 2630 | 10*10 |
| 8.0 | 150 | 40 | 6026 | 10*10 |