GMC Roadmap and Current Logic Tree

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Taiwan SSHAC Level 3 PSHA Study
Taipei, Taiwan
GMC Roadmap

- **Hazard Sensitivity Analysis**
  - Significant and Non-Significant Issues

- **Development of Ground Motion Database**
  - Empirical Ground Motion Database (Taiwan, NPPs, Foreign)
    - Source, Path, Site Parameters
  - Simulated Ground Motion Database (Taiwan, Foreign)

- **Selection of Ground Motion Models**
  - Empirical Ground Motion Models (Median, Sigma)
  - Stochastic Ground Motion Models (Crustal Profiles, Q, Kappa etc.)
  - Other Features (Listric Fault + Edge Effect)

- **Current GMC Logical Tree and Weights**
# GMC Sensitivity Results – Crustal – PGA

<table>
<thead>
<tr>
<th>Node</th>
<th>GMPEs used in Sensitivity</th>
<th>GM Ratio greater than 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NPP1</td>
</tr>
<tr>
<td>1</td>
<td>GMPE for Median</td>
<td>✔</td>
</tr>
<tr>
<td>2</td>
<td>Additional Epistemic Uncertainty for Median</td>
<td>✔</td>
</tr>
<tr>
<td>3</td>
<td>SigmaSS</td>
<td>✔</td>
</tr>
<tr>
<td>4</td>
<td>Form of Distribution of ln(SA)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Splay fault (only for NPP3)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Deep events</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Dip implementation for listric fault (only for NPP2)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Directivity model (only for period larger than 0.5 sec)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Style of Faulting</td>
<td>✔</td>
</tr>
<tr>
<td>10</td>
<td>Hanging-wall Effect</td>
<td>✔</td>
</tr>
</tbody>
</table>
# GMC Sensitivity Results – Crustal – 2 sec

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## GMC Sensitivity Results – Subduction – PGA

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<td>Form of Distribution of ln(SA)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Depth scaling for intraslab</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Large Mag scaling for intraslab</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Edge Effect for interface (only for NPP1, NPP2 and NPP4)</td>
<td></td>
</tr>
</tbody>
</table>
## GMC Sensitivity Results – Subduction – 2 sec

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<td>Edge Effect for interface (only for NPP1, NPP2 and NPP4)</td>
<td></td>
</tr>
</tbody>
</table>
GMC GM Database of Taiwan SSHAC Level 3 Project

- **Taiwan GM Database**
  - 367 events
  - 41,547 records

- **Foreign GM Database**
  - NGA-West2 (exclude Taiwan events)
    - 589 events with 19,526 records
  - NGA-Sub (Japan, South America)
    - Japan
      - 120 events (78 interface, 42 intraslab) with 26,818 records
    - South America
      - 25 events (23 interface, 2 intraslab) with 589 records
  - RESORCE
    - 1713 events with 5,367 records
### Earthquake Number with Different Style of Faulting - Taiwan

<table>
<thead>
<tr>
<th>Earthquake type</th>
<th>Style of faulting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NM</td>
</tr>
<tr>
<td>deep crustal</td>
<td>6</td>
</tr>
<tr>
<td>shallow crustal</td>
<td>24</td>
</tr>
<tr>
<td>subduction interface</td>
<td>0</td>
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<tr>
<td>subduction intraslab</td>
<td>11</td>
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# Earthquake Number with Different Style of Faulting - Foreign

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Style of faulting</th>
<th>NM</th>
<th>NO</th>
<th>RO</th>
<th>RV</th>
<th>SS</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGA-West2</td>
<td></td>
<td>84</td>
<td>27</td>
<td>37</td>
<td>102</td>
<td>326</td>
<td>13</td>
</tr>
<tr>
<td>NGA-Sub (Japan)</td>
<td>interface</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>66</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>NGA-Sub (Japan)</td>
<td>intraslab</td>
<td>7</td>
<td>8</td>
<td>3</td>
<td>14</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>NGA-Sub (S. Am.)</td>
<td>interface</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>11</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NGA-Sub (S. Am.)</td>
<td>intraslab</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RESORCE</td>
<td></td>
<td>381</td>
<td>39</td>
<td>154</td>
<td>491</td>
<td>648</td>
<td></td>
</tr>
</tbody>
</table>
Studies on Vs30 in Taiwan

- **Wald and Allen (2007); Allen and Wald (2009)**
  - Vs30 are correlated against topographic slope to develop two sets of coefficients for deriving Vs30. One for active tectonic regions and the other for stable continental regions.

- **Lee and Tsai (2008)**
  - They adopted Geo-statistical method to estimate Vs30 of free-field TSMIP stations using 257 velocity profiles from EGDT (2000 to 2005) and 4885 boreholes from Geo2005 of CGS.

- **Kuo et al. (2012)**
  - Site classification and Vs30 calculation at 451 drilled stations were achieved according to the Vs30 criteria of NEHRP.

- **Kuo et al. (2016a; 2016b)**
  - 2016a: Modifications for several investigated strong motion stations with Vs profiles less than 30 m and new measured Vs30 recently particularly at NPP sites.
  - 2016b: Result of microtremor array measurement in CHY region.

- **Kwok and Stewart (2017, preparing)**
  - They used a Hybrid Proxy Method to estimate Vs30 of TSMIP sites. A averaged Vs30 of Geology/slope/elevation based Vs30 and terrain based Vs30 are used.

- **Lin et al. (2017, preparing)**
  - They used high-frequency Receiver Function method for Vs profile inversion at TSMIP stations.
Residuals for Vs30 Models

Better models!!
RF is the most accurate Vs30 model for high Vs30 sites
New Vs30 Components

SSHAC Vs30 816

Measured Vs30 556
- EGDT 460
- Microtremor Array 3

Receiver Function 93

Estimated Vs30 260
- KS17 260

For Vs30 > 600 m/s and offshore island if available
Z1.0 of TSMIP Stations

- Multiple methods have been used to provide the Z1.0 values of the TSMIP stations. Now, there are 746 stations having the measured Z1.0 values.
  - Downhole P-S logging data of Engineering Geological Database for TSMIP (EGDT)
  - Microtremor array measurement (ARRAY)
  - Receiver Function analysis of strong-motion data (RF)
  - Microtremor H/V spectral ratio modeling (HVSR)

- According to the measured Z1.0, an empirical relationship between Z1.0 and Vs30 for Taiwan was regressed to infer the Z1.0 values of the stations without it.

<table>
<thead>
<tr>
<th></th>
<th>EGDT</th>
<th>ARRAY</th>
<th>RF</th>
<th>HVSR</th>
<th>Inferred by Vs30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1.0 Amount</td>
<td>36</td>
<td>42</td>
<td>738</td>
<td>108</td>
<td>70</td>
</tr>
<tr>
<td>Usage Amount in Database</td>
<td>36</td>
<td>42</td>
<td>665</td>
<td>3</td>
<td>70</td>
</tr>
</tbody>
</table>
Z1.0 of TSMIP Stations
Studies on kappa ($\kappa_0$) in Taiwan

- **Chen et al. (2013)**
  - They studied the $\kappa_0$ at strong motion stations in Southwestern Taiwan using earthquakes with $M_L > 3$.

- **Lai et al. (2016)**
  - They used the recently installed surface-downhole stations to calculate the $\kappa_0$.

- **Huang et al. (2017)**
  - They studied the $\kappa_0$ inside and around the Taipei Basin.

  - They studied the $\kappa_0$ at the TSMIP stations through Taiwan. The relationships between $\kappa_0$ and $Vs30$ and $Z1.0$ were evaluated.
$\kappa_0$ Model of Cea17
Relationship of Vs30 and Z1.0

Number of data sets:
- EGDT: 38
- Array: 53
- RF: 379
- HVSR: 2
- **472** in total

The Equations are:

**Kea16:**
\[
\ln(Z_{1.0}) = -\frac{3.8}{2} \ln \left( \frac{V_{S30}^2 + 266^2}{1750^2 + 266^2} \right)
\]

**KL16:**
\[
\ln(Z_{1.0}) = -\frac{4.15}{2} \ln \left( \frac{V_{S30}^2 + 358^2}{1750^2 + 358^2} \right)
\]

**KL17:**
\[
\ln(Z_{1.0}) = -\frac{4.08}{2} \ln \left( \frac{V_{S30}^2 + 355.4^2}{1750^2 + 355.4^2} \right)
\]
Current Z1.0 Map
Current $\kappa_0$ Map

![Map of Current $\kappa_0$](image1.png)

![Stations Map](image2.png)

![Histogram](image3.png)
On-site Ground-motion Data of NPP Sites

- Collect the on-site GM data recorded by the NPP free-field stations and CWB TSMIP stations inside NPPs
- Data quality, data processing, usable bandwidth, and triggering level of on-site data were checked
- Some significant events will be included by GM database

<table>
<thead>
<tr>
<th>NPP1 (TAP123)</th>
<th>Period</th>
<th>Event</th>
<th>$M_L$</th>
<th>Depth(km)</th>
<th>Hypo-Dist. (km)</th>
<th>PGA (gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1999~2016FEB</td>
<td>20</td>
<td>2.6~7.3</td>
<td>3.4~269</td>
<td>7.5~288.1</td>
<td>2.3~31.5</td>
</tr>
<tr>
<td>NPP2 (TAP114)</td>
<td>2001~2016FEB</td>
<td>59</td>
<td>2.5~7.1</td>
<td>1.4~92</td>
<td>6.0~383.1</td>
<td>1.2~33.4</td>
</tr>
<tr>
<td>NPP3 (KAU098)</td>
<td>1995~2016FEB</td>
<td>51</td>
<td>3.7~7.1</td>
<td>8.6~178</td>
<td>29.6~436.8</td>
<td>1.3~170.4</td>
</tr>
<tr>
<td>NPP4 (TAP105)</td>
<td>2000~2016FEB</td>
<td>45</td>
<td>3.4~7.1</td>
<td>4.9~91</td>
<td>18.1~174.6</td>
<td>2.9~27.7</td>
</tr>
</tbody>
</table>
Available GM data recorded by TSMIP/MTN rock stations within 5/10km of NPP sites are also collected and compared with the on-site data.
Site Conditions of NPP Sites

- Downhole PS-logging velocity profiles and geotechnical engineering parameters of NPP sites were all collected.
- More drillings exactly locate beside the on-site stations were conducted in 2016.

<table>
<thead>
<tr>
<th></th>
<th>NPP1</th>
<th>NPP2</th>
<th>NPP3</th>
<th>NPP4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. depth (m)</td>
<td>350</td>
<td>47</td>
<td>237</td>
<td>33</td>
</tr>
<tr>
<td>Vp (m/sec)</td>
<td>870~2326</td>
<td>926~3871</td>
<td>1299~2150</td>
<td>2555~3734</td>
</tr>
<tr>
<td>Vs (m/sec)</td>
<td>246~840</td>
<td>209~1408</td>
<td>311~707</td>
<td>1006~1827</td>
</tr>
<tr>
<td>Vs30</td>
<td>415~838</td>
<td>469~778</td>
<td>422~535</td>
<td>1267</td>
</tr>
<tr>
<td>Vs30 (2016)</td>
<td>440~654</td>
<td>722~739</td>
<td>372~491</td>
<td>1465</td>
</tr>
<tr>
<td>Site Classification</td>
<td>C (~B)</td>
<td>C (~B)</td>
<td>C</td>
<td>B</td>
</tr>
</tbody>
</table>
Simulated Ground Motion Database - I

- The SWUS GMC Project for Diablo Canyon Nuclear Power Plant
- The NGA-East GMC Project
- The BC Hydro Project
- Forward simulations for specific-crustal faults
- Forward simulations for subduction zone earthquakes with large magnitude
<table>
<thead>
<tr>
<th>Target source</th>
<th>Subset</th>
<th>Output</th>
<th>Use of dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse fault</td>
<td>$M_w : 6.5, 7.0, 7.5$&lt;br&gt;$\text{Dip(°)} : 40, 60, 75$</td>
<td>Ground motion time history &amp; Response spectrum</td>
<td>In order to compensate the lack of observed data in specific faulting mechanisms and magnitude ranges for ground motion model</td>
</tr>
<tr>
<td>Normal fault</td>
<td>$M_w : 6.0, 6.5, 7.0, 7.5$&lt;br&gt;$\text{Dip(°)} : 60, 70, 80$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shanchiao Fault</td>
<td>$M_w : 6.5, 6.6, 6.9, 7.1, 7.5$&lt;br&gt;$\text{Dip(°)} : 25$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hengchun Fault</td>
<td>$M_w : 7.2$&lt;br&gt;$\text{Dip(°)} : 60$</td>
<td></td>
<td>Ground motion simulation for the specific fault-rupture scenario</td>
</tr>
<tr>
<td>Ryukyu Trench</td>
<td>$M_w : 8.2, 8.3, 8.6, 8.8$&lt;br&gt;$\text{Dip(°)} : 22.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manila Trench</td>
<td>$M_w : 8.2, 8.3, 8.6, 8.8$&lt;br&gt;$\text{Dip(°)} : (10.0, 22.5)$</td>
<td></td>
<td></td>
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1. Ground Motion Models for Sensitivity Analysis
   - These models are determined by PTI and GMC TI Team according to their experience for running the hazard sensitivity analysis to capture the uncertainty range of each parameter and define the key issues of this project.
   - These models are also dynamically adjusted according to the GMC TI Team’s requirements.

2. Available Ground Motion Models
   - The ground motion models which may be applicable to this project will be classified as the available ground motion models.
   - These models are compiled by GMC TI and GMC TI staff and some models are from the feedback of Resource Experts during Workshop #1 and Workshop #2.
Definition for Different Types of GMM Models - II

3. Candidate Ground Motion Models
   - Candidate ground motion models are derived after the screening of the available ground motion models.
   - The screening criteria is defined by PTI and GMC TI Team.
   - These models are further evaluated or adjusted to derive the ground motion model with TDI for this project.

4. Ground Motion Models with TDI
   - Ground motion models with TDI are determined after GMC TI Team’s evaluation process for capturing the CBR.

5. Ground Motion Models for GMC Logical Tree
   - These models are integrated from GMMs with TDIs to construct the GMC Logical Tree.
Selection Criteria of the GMMs with TDIs - I

- The ground motion models should involve appropriate magnitude scaling and distance scaling to well fit ground motion data in the available magnitude range of the Taiwan ground motion database
  - Shallow crustal earthquakes with Mw 4.0 – 6.5
  - Subduction earthquakes with Mw 4.0 – 7.1

- The ground motion models should extrapolate well outside the magnitude range of the Taiwan ground motion database
  - Shallow crustal earthquakes with Mw 6.5 – 8.0
  - Interface earthquakes with Mw 7.1 – 9.0
  - Intraslab earthquake with Mw 7.1 – 8.0
Summary of GMMs with TDIs – Crustal Source

**Crustal Source**

- Seven adjusted foreign models
  - Five global models from NGA West 2 Project
    - ASK14adj, BSSA14adj, CB14adj, CY14,adj Idriss14adj
  - Two models from Europe
    - ASB14adj, Bindi14adj
  - Two Taiwan models
    - Phung et. al. 2017 (Phung17)
    - Chao et. al. 2017 (Chao17)

**These models will be integrated to develop GMC Logic Tree for Crustal Source**
Summary of GMMs with TDIs – Subduction Source

- Subduction Source
  - One adjusted foreign models
    - AGA16adj model from BC-Hydro Project
  - Three Taiwan models
    - Lin and Lee 2008 (LL08)
    - Phung et. al. 2017 (Phung17)
    - Chao et. al. 2017 (Chao17)

- These models will be integrated to develop GMC Logic Tree
Validation of GMM Codes - I

Sources of GMM Codes and Usage

- Matlab
  - Development of Taiwan Models
    - Chao et al. 2017 and Phung et al. 2017
  - Running Sammon’s map approach
  - Comparison of GMMs with TDIs
  - Integration of SOF factors, Tau and PhiSS models
- Fortran
  - Running hazard calculation
- R-Code
  - Adjustment of foreign models for Taiwan
Validation of GMM Codes - II

- A total of 3476 Ground Motion Scenario Used to Validate GMM Codes for Crustal Source
  - Crustal Earthquake
  - Mw: 3.5 : 0.5 : 8.0
  - Ztor: 0 – 20 km
  - Dip: 40, 45, 90 Degree
  - SOF: NM, SS, RV
  - Rjb: 0 – 200 km
  - Hanging wall site
  - Vs30: 180, 360, 760, 1500 m/s
  - Z1.0: 0.0038 – 0.3529 km

- Spectral Acceleration of 20 periods from 0.01 sec – 3 sec are calculated and compared
## Progress of Validation – Crustal GMMs

<table>
<thead>
<tr>
<th>Sources of GMM Codes and GMMs with TDIs</th>
<th>Matlab</th>
<th>Fortran</th>
<th>R-Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASB14adj</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>ASK14adj</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>BSSA14adj</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Bindi14adj</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>CB14adj</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>CY14adj</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>I14adj</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Chao17</td>
<td>O</td>
<td>O</td>
<td>-</td>
</tr>
<tr>
<td>Phung17</td>
<td>(on-going)</td>
<td>(on-going)</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: O means that the maximum error is smaller than 0.1%
## Progress of Validation – Subduction GMMs

<table>
<thead>
<tr>
<th>Sources of GMM Codes and GMMs with TDIs</th>
<th>Matlab</th>
<th>Fortran</th>
<th>R-Code</th>
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<tbody>
<tr>
<td>LL08</td>
<td>(on-going)</td>
<td>(on-going)</td>
<td>-</td>
</tr>
<tr>
<td>AGA16adj</td>
<td>(on-going)</td>
<td>(on-going)</td>
<td>(on-going)</td>
</tr>
<tr>
<td>Chao17</td>
<td>(on-going)</td>
<td>(on-going)</td>
<td>-</td>
</tr>
<tr>
<td>Phung17</td>
<td>(on-going)</td>
<td>(on-going)</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: O means that the maximum error is smaller than 0.1%
A Vs profile for generic rock site (NEHRP B/C, $Vs30 = 760 \text{ m/s}$) in Taiwan is required for GMRS.

We defined the generic rock condition as $Vs30 = 760 \text{ m/s}$ in Taiwan.

In practice, we used the Vs profiles with $Vs30$ between 600 ~ 900 m/s to create a Generic Vs Model with a depth to the source.

Vs Models of four depth scales were used.

- Very shallow (0~54m): logging data
- Shallow (54~1200m): microtremor array and receiver function
- Medium (1.2~4.6km): surface wave and ambient noise
- Deep (4.6~16km): tomography
Stations have Vs30 between 600~900 m/s are considered as the generic rock site.
Vs Profiles of Generic Rock Sites

Shallow Vs model for the generic rock site (Vs30=760 m/s) in Taiwan shows significant difference from that in California and Japan. Higher Vs at very shallow part and lower Vs at deeper part.

Data of California and Japan are from R. Kamai et al. (2016)
Generic Rock Vs Profile in Taiwan (v3.0)

- Very shallow (0~54m): 60 Vs profiles
  - EGDT (Kuo et al. 2012)
  - NPP sites (Sinotech)
- Shallow (54~1200m): 36 Vs profiles
  - Microtremor array (Kuo et al., 2016)
  - Receiver function (Dr. C.M. Lin)
- Medium (1.2~4.6km): 4 Vs profiles
  - Surface wave (Chung and Yeh, 1997)
  - Ambient noise (Lai et al., 2014)
- Deep (4.6km~10km): 242 Vs profiles
  - Tomography
    - Chen and Shin (1998)
    - Kim et al. (2005)
    - Wu et al. (2009)
    - Kuo-Chen et al. (2012)
    - Huang et al. (2014)
- Still need smooth
Compare with Vs Profile in Other Countries

The generic rock Vs profile in Taiwan is obviously **LOW**ER than 1D Vs profiles in other regions.

Depth: 0~1km

Depth: 0~8km

Depth: 0~16km

Courtesy of Dr. Y. T. Yen
Stochastic Ground Motion Simulation Models for Foreign and Taiwan Region - I

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Source spectrum model</td>
<td>Single corner frequency $\omega^2$</td>
<td>Single corner frequency $\omega^2$</td>
<td>Single corner frequency $\omega^2$</td>
</tr>
</tbody>
</table>
| Stress parameter, $\Delta\sigma$ (bars) | $\log_{10}\Delta\sigma = f(M) + \delta k + \varepsilon$  
$f(M) = a + b\log_{10}(M_0/M_0^{ref})$  
$\varepsilon = 1.5$; $a = 0.159$; $b = 0.404$  
$\delta k = 0.254$, $H < 6$ km;  
$0.031$, $6 \leq H < 10$ km;  
$-0.285$, $H \geq 10$ km  
$M_0^{ref} \approx M_w = 3.75$ | 150    | 300 |
| Shear-wave velocity, $\beta_s$ (km/s) | 3.7    | 3.7    | 3.7 |
| Density, $\rho_s$ (gm/cm$^3$) | 2.8    | 2.8    | 2.8 |
| Geometric spreading, $1/R^b : b=$ | $1/R^b : b=$ | 1.0    | $1.3(R \leq 50$ km), $0.5(R > 50$ km) |
| Quality factor, $Q$ | $290f^{0.16}$ | $\max(40, 135f^{0.76})$ | $\max(100, 170f^{0.45})$ |
| Site amplification, $A(f)$ | H/V ratio for each site | $V_s = 760$ m/s | $V_s = 760$ m/s |
| Kappa, $\kappa_0$ (sec) | 0.012 | Niigata: 0.04, Tottori: 0.02 | 0.02 |
| Duration | - | - | $1/f_0 + 0.05 R_{hypo}$ |
# Stochastic Ground Motion Simulation Models for Foreign and Taiwan Region - II

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Deep eq. for subduction zone, Taiwan Sokolov et al. (2009)</th>
<th>Crustal large eq., Taiwan D’amico et al. (2012)</th>
<th>Crustal eq., Taiwan Huang et al. (2017)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source spectrum model</td>
<td>Single corner frequency $\omega^2$</td>
<td>Single corner frequency $\omega^2$</td>
<td>Single corner frequency $\omega^2$</td>
</tr>
<tr>
<td>Stress parameter, $\Delta\sigma$ (bars)</td>
<td>Zone DT: 300</td>
<td>$M_w=5.5$, 60 ; $M_w=6.5$, 80 ; $M_w=7.6$, 90</td>
<td>$M_w&lt;5.5$, 60 ; 5.5≤$M_w&lt;6.5$, 80 ; $M_w\geq6.5$, 90</td>
</tr>
<tr>
<td>Shear-wave velocity, $\beta_s$ (km/s)</td>
<td>3.6</td>
<td>3.2</td>
<td>3.6</td>
</tr>
<tr>
<td>Density, $\rho_s$ (gm/cm$^3$)</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Geometric spreading, $1/R^b$ : $b=$</td>
<td>1.0 (1-50km), 0.0 (50-170km), 0.5 (&gt;170km)</td>
<td>1.2 (1-10km), 0.7 (10-40km), 1.0 (40-80km), 0.5 (&gt;80km)</td>
<td>1.0 (1-50km), 0.0 (50-170km), 0.5 (&gt;170km)</td>
</tr>
<tr>
<td>Quality factor, $Q$</td>
<td>Zone DT: 60$f^{1.0}$</td>
<td>350$f^{0.32}$</td>
<td>Zone ST: 80$f^{0.9}$; Zone SO: 120$f^{0.8}$; Zone DT: 60$f^{1.0}$</td>
</tr>
<tr>
<td>Site amplification, $A(f)$</td>
<td>-</td>
<td>Boore &amp; Joyner (1997)</td>
<td>ENA-A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Generic Rock(Vs30=520m/s)</td>
<td>Empirical Transfer Function</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Generic Soil(Vs30=270m/s)</td>
<td></td>
</tr>
<tr>
<td>Kappa, $\kappa_0$ (sec)</td>
<td>0.01</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>Duration</td>
<td>-</td>
<td>-</td>
<td>Lee et al. (2015). Combined duration source, duration path and duration site in one equation</td>
</tr>
</tbody>
</table>
Survey of well-proved stochastic-based ground motion models for possible used foreign and Taiwan region have been done at WS#2.

Preliminary host-target adjustment factor for FAS between California and Taiwan have been discussed at WS#2.
Based on suggestion of WS#2, GMC support team try to inverted stochastic-based GM model of Taiwan from Levenberg-Marquardt algorithm based on GMC rock database (FAS).

Reasonable range of each parameter which were all together but not individually selected from different studies have been done, including stress drop, Q and kappa of rock response in Taiwan.

Ongoing validation of inverted stochastic-based GM model in Taiwan was continued.
Other Features: Listric Fault - 1

- **Completion of simulation for listric fault**
  - Adopt the fault geometry and parameters setting from SSC
  - Ground motion character of the listric fault
  - Preliminary simulation result for listric fault of shallow crust earthquake

- **Evaluate the applicability of GMPEs**
  - Application of the Candidate GMMs to Listric Fault
  - Additional cases to evaluate model of WS#2
Other Features: Listric Fault - II

Modified model provided after WS#2

- WS#2 – Simulation results revealed a rule for the applicability of GMPEs
- A model have to complete for the hazard calculation in sensitivity analysis

\[ M_{\text{upper}} - M_{\text{lower}} > 0.3 \quad M_{\text{upper}} - M_{\text{lower}} \leq 0.3 \quad \& \quad h = 9 \text{ km} \]
\[ M_{\text{lower}} > M_{\text{upper}} \quad \& \quad h = 9 \text{ km} \]
\[ M_{\text{upper}} - M_{\text{lower}} \leq 0.3 \quad \& \quad h = 6 \text{ km} \]
\[ M_{\text{lower}} > M_{\text{upper}} \quad \& \quad h = 6 \text{ km} \]

Applying Dip_1

Applying avg. dip of Dip_1 & Dip_2

Applying Dip_2
Other Features: Listric Fault - III

Final suggestion model

- Additional cases to evaluate modified model of WS#2
- Adjusted the model for hazard calculation

![Diagram with turning depth (h) and dips Dip1 and Dip2.](image)

- $M_{\text{upper}} - M_{\text{lower}} > 0.5$
- $0 < M_{\text{upper}} - M_{\text{lower}} \leq 0.5$
- $M_{\text{upper}} - M_{\text{lower}} \leq 0$

- Applying Dip1
- Applying avg. dip of Dip1 & Dip2
- Applying Dip2
Other Features: Listric Fault - IV

Final suggestion model

A model is governed by the dip and magnitude of upper and lower segment.
Adjusting subduction GMPE – GM off end of rupture

– Seismic stations in Taiwan are distributed off the end of Ryukyu Trench subduction zone. It is important to determine the ground motions for NPP sites off the end of rupture of the subduction zone relative to sites located in along the rupture.

– Due to the lack of records for sites located in along Ryukyu Trench, the task was carried out by ground motion simulation technique.
Other Features: Edge Effect - II

Source-station Framework for Ground Motion Simulation

Fault trace

Decollement

Sea floor

8 km (top)

30 km (bottom)

Megathrust

Segment of Megathrust
Length: 190 km
Width: 56 km
M_W: 8.0
Hypocenter: 3 locations
Simulation: 90 realizations

Fault trace of Ryukyu Trench

R_Y0

NPP sites

Rx

Fictitious stations

Source-station - Framework for Ground Motion Simulation

Other Features:

- Edge Effect
Other Features: Edge Effect - III

Remark
Ground motions de-amplified for all samples of period (ranging from 0.86 to 0.97, and a mean of 0.90)

\[
SpectralRatio_j(T_i) = \frac{RSP_{NPPsite}^{mean}(T_i)}{RSP_{j^{th\, station}}^{mean}(T_i)}
\]
Other Features: Edge Effect - IV

- Simulated response spectra of the fictitious stations show higher ground motions with respect to all NPP sites. A maximum reduction of $\sim 14\%$ and a mean reduction of $\sim 10\%$ can be found for NPP sites which are located off the end of subduction zone.

- **Rule**: applying a tapered-cosine function of $R_{Y0}$ for GM from edge effect

\[ SR = \begin{cases} 
  h + (1 - h) \times 0.5 \times \left(1 + \cos \left(\pi \times \frac{R_{Y0}}{35}\right)\right), & 0 \leq R_{Y0} \leq 35\text{km} \\
  h, & R_{Y0} > 35\text{km} 
\end{cases} \]

**SR**: spectral ratio

- $h$: reduced spectral ratio (i.e. 0.86 or 0.90)
- $R_{Y0} = 0$ km for the top edge of fault plane
- $R_{Y0} = 35$ km for the nearest site NPP4
Current GMC Logic Tree

- Median for Crustal Source
- Median for Subduction Source
- SigmaSS for Crustal Source
- SigmaSS for Subduction Source
General Approach

- Capturing the center, body, range of the epistemic uncertainty involving **model-to-model variability** and **within model variability** form the ground motion models with technical defensive interpretations (GMMs with TDIs) for each node in GMC logic tree.

- Three points approximation (lower, center and upper values with weighs 0.2, 0.6, 0.2) are used to capture the full distribution of probability density function

- The weights for some branches and nodes will be further discussed in Workshop #3.
GMC Logic Tree Nodes
– Median for Shallow Crustal Event

Logic Tree of the Median for Crustal Source

Median for Vertical Dip SS Faults

- Model 1
- ... Model 2
- ... Model ...
- Model 17
- ...

SOF Factors - I
- Mag. Dep.
- ...

SOF Factors - II
- Mag. Indep.
- ...

HW Factor
- Model 1
- Model 2
- Model ...
- Model 17
- ...

Listric Fault Factor
- Model 1
- 1.0

Factors - I
- Lower: 0.2
- Center: 0.6
- Upper: 0.2

Factors - II
- Lower: 0.2
- Center: 0.6
- Upper: 0.2

Mag. Dep.
- 0.2
- 0.6
- 0.2

Mag. Indep.
- 0.2
- 0.6
- 0.2
GMC Logic Tree Nodes – Median for Subduction Event

Logic Tree of the Median for Subduction Source

Median

Model 1

... Model 2

... Model ...

... Model 17

... Model 1

1.0

Edge Effect for Interface
GMC Logic Tree Nodes
– Sigma for Shallow Crustal Event

Logic Tree for the SigmaSS for Crustal Sources

Tau Model-I  |  Tau Model-II  |  Tau Model-III  |  PhiSS Model-I  |  PhiSS Model-II  |  PhiSS Model-III  |  In(Sa) Distribution

Global  |  Mag. Dep.  |  Lower 0.2  |  Center 0.6  |  Upper 0.2  |  Mag. Dep.  |  Lower 0.2  |  Center 0.6  |  Upper 0.2  |  Taiwan 1.0  |  Mag. Dep.  |  Lower 0.2  |  Center 0.6  |  Upper 0.2  |  Model 1 1.0

Taiwan  |  Mag. Indep.  |  Lower 0.2  |  Center 0.6  |  Upper 0.2  |  Mag. Indep.  |  Lower 0.2  |  Center 0.6  |  Upper 0.2

...
GMC Logic Tree Nodes
– Sigma for Subduction Events

Logic Tree for the SigmaSS for Subduction Sources

Tau Model-I      Tau Model-II      Tau Model-III      PhiSS Model-I      PhiSS Model-II      PhiSS Model-III      In(Sa) Distribution

Global
...  Mag. Indep.  1.0  Center  0.6

Taiwan
...  Mag. Dep.  ...  Lower  0.2  Center  0.6  Upper  0.2
...  Mag. Indep.  ...  Lower  0.2  Center  0.6  Upper  0.2

Taiwan
1.0

Model 1  1.0
Focused Topics for Workshop #3

- Feedback of Hazard Analysis and Sensitivity
- GMMs with TDIs
  - Adjusted foreign median and sigma models for Taiwan
  - Taiwan median and sigma model
- GMC Logic Tree for Median
  - Sammon’s Map Approach
  - SOF Factors
- GMC Logic Tree for Sigma
  - Tau and PhiSS Models
Thank You for Your Attention !!

Questions ?
Available Ground Motion Models

- **Taiwan**
  - From 1991 to 2015 a total of 23 ground motion models are available as shown in Workshop #1 presentation and feedbacks from REs in Workshop #1 and Workshop #2
  - New models developed in on-Going Project (ex. TGMM project)

- **Global and Foreign**
  - Refer to the candidate ground motion models of foreign SSHAC project including:
    - SWUS GMC Project
    - BC-Hydro Project
    - Hanford PSHA Project
  - Feedbacks from REs in Workshop #1 and Workshop #2
  - New models developed in on-Going Project (ex. NGA-Sub project)
Screening Criteria for Candidate GMMs - I

- **General**
  - Models that have not been peer reviewed or vetted by the larger scientific community were not selected.
  - More recent published GMPEs by the same development team were selected over older GMPEs on the basis that the newer models would have benefited from more data and refinements to the approach.
  - Models developed as research tools were not selected.

- **Database**
  - Models that do not clearly separate shallow crustal earthquake from those occurring as a part of subduction were not selected.
  - Models that do not distinguish between interface and intraslab earthquakes were not selected.
  - Models developed for a relatively small specific region different from the ones of interest were not selected.
## Screening Criteria for Candidate GMMs - II

### Function Form

- The GMPEs that do not cover the frequency range of interest for the project (0.5Hz–100 Hz) were not selected.
- The GMPEs that do not extrapolate reasonably over the required magnitude-distance range for which they will need to be applied in the hazard were not selected.
- The GMPEs that were derived by adjustment (referenced or hybrid) to another region were not selected.
- The GMPEs functional form that do not have an assigned Vs30 value or site condition were not selected.

### Others

- BC-Hydro SSHAC level 3 concluded that subduction GMPEs available up to 2007 all had significant limitations for scaling up to M9 for interface earthquakes.
Evaluation Items for Candidate GMMs

- **Ground motion database**
  - Horizontal component
  - Data range of magnitude, depth and distance
  - Large magnitude event

- **Median**
  - Prediction for hazard significant M-R bins
  - Magnitude scaling
  - Depth scaling
  - Distance scaling
  - SOF factors
  - HW factors
  - Residual analysis of Chi-Chi earthquake

- **Sigma**
  - Tau and Phi_ss
  - Magnitude dependence

- **Others**
  - Regression approach
The ground motion models should involve appropriate depth scaling to well fit Taiwan data in the available depth range of the Taiwan ground motion database:

- Crustal earthquakes with Ztor 0 – 70 km
- Interface earthquakes with Ztor 0 – 35 km
- Intraslab earthquake with Ztor 20 – 180 km

The ground motion models should involve appropriate linear site effect term to derive the ground motion prediction for reference rock (Vs30 = 760 m/s).

The ground motion models should involve appropriate nonlinear site effect term to avoid underestimate the ground motion of reference rock for large magnitude and short distance scenario.
Selection Criteria of the GMMs with TDIs - III

- The ground motion models should be developed with the consideration of mixed effect model and data truncation issue.

- The ground motion components should be GM or RotD50 to derive consistent ground motion prediction.