Ground-Motion Prediction Equation (GMPE) for Taiwan

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Outline

• Introduction of GMPE
  – Important component of PSHA
  – From attenuation equation to GMPE
  – Steps for building GMPE
• Taiwan’s GMPE – Past 、 Present 、 Future
• Conclusion
• Future work
Steps in Probabilistic Seismic Hazard Analysis

(1) Sources

(2) Recurrence

(3) Ground Motion

(4) Probability of Exceedance
What is GMPE

• “Was”
  – Attenuation relations
  – Attenuation relationships
  – Attenuation equations

• It is an equation that can be used to predict the possible ground-motion value during a future earthquake.

• Most of then are “empirical”, and was developed from a set of ground-motion data with proper physical meaning
Why Call them “Ground-Motion Prediction Equations”

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

Art McGarr, 2006
Ground Motion Prediction Equations

- Empirical regressions of recorded data
- Estimate ground shaking parameter (peak ground acceleration, peak velocity, spectral acceleration or velocity response) as a function of
  1. magnitude
  2. distance
  3. site
- May consider fault type (strike-slip, normal, reverse)

Art McGarr, 2006
Steps for building GMPE

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

- Arithmetic mean (算數平均數)
- Both
- Geometric mean (幾何平均數)
- Largest component
- Random
- Resultant ($a = a_1 \cos \theta + a_2 \sin \theta$)
- Vectorial addition ($a_v = \sqrt{a_1(t)^2 + a_2(t)^2}$)
- GMRotI50
Characterisation of source

- Earthquake magnitude, $M$
  - $M_L$
  - $M_S$
  - $m_b$
  - $M_W$

- Source mechanism
  - Strike slip, normal faulting, reverse

- Tectonic setting
  - Crustal, subduction
Characterisation of path

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

(Abrahamson and Shedlock, 1997)
Characterisation of site

- From data selection
- Multiplicative factor
- Shear-wave velocity (Vs30)
**Form of the predictive equation**

\[ Y = f(M, R, P_i) \]

- **Y**: Ground motion parameter of interest
- **M**: The magnitude of the earthquake
- **R**: Distance from the source to the particular site
- **P_i**: Other parameters (earthquake source, local site conditions, wave propagation path...)

Analysis techniques

• The majority of ground motion estimation studies use the *ordinary least squares method*
• Two-stage method
• Non-linear regression
• Maximum-likelihood method (mixed effects method)
<table>
<thead>
<tr>
<th>Author</th>
<th>Equation</th>
<th>Parameter</th>
<th>Region</th>
<th>Data</th>
<th>Events</th>
<th>Records</th>
</tr>
</thead>
<tbody>
<tr>
<td>茅聲燾 (1978)</td>
<td>( Y = 0.3725e^{0.378D}D^{1.836}, \quad D=(R^2+400)^{1/2} ) (g)</td>
<td>( R )為震源距離</td>
<td>台灣地區</td>
<td>CWB震度</td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>
| Tsai & Bolt (1983) | \( PGA = 17.5e^{0.869(R+0.0606e^{0.0700M})-0.09} \) (gal)          | \( R \)為震源距離，
M為芮氏規模(M) | 台灣東北部    | SMART-1    |        | 6       |
| 倪與邱 (1991)   | \( \ln(PGA) = 6.09 + 0.26M - 0.87\ln(R+6.9) \) (gal)      | \( R \)為震央距離，
M為芮氏規模(M) | 台灣地區(岩盤) | SVA-1     |        | 49      |
| Chiu and Ni (1993)  | \( \ln(PGA) = 4.15 + 1.41ML-2.37\ln(R+13.7) \) (gal)    | \( R \)為震央距離，
M為芮氏規模(M) | 花蓮地區     | SMART-2    |        |         |
| 黃正耀 (1995)   | \( Y = 0.0253e^{1.5873M}(R+0.3155e^{0.6165M})^{2.3027} \) (g) | \( R \)為測站至斷層破裂面之最短距離，
M為芮氏規模(M) | 台灣地區     | TSMIP (7個地震) | 7     | 526     |
| 劉坤松 (1996)   | \( Y = 0.0308e^{1.20M}(R+0.1413e^{0.6892M})^{1.741} \) (g) | \( R \)為震源距離，
M為芮氏規模(M) | 台灣東北部地区 | TSMIP    |        |         |
| 劉坤松 (1996)   | \( Y = 0.0267e^{1.354M}(R+0.2138e^{0.7499M})^{1.0329} \) (g) | \( R \)為震源距離，
M為芮氏規模(M) | 台灣地區(岩盤) | SVA-1     |        |         |
| 劉坤松 (1996)   | \( Y = 0.0273e^{0.1058M}(R+0.141e^{0.656M})^{1.6472} \) (g) | \( R \)為測站至斷層破裂面之最短距離，
M為芮氏規模(M) | 台灣地區     | TSMIP    |        |         |
| 辛在勤 (1998)   | \( \ln(PHA)=-1.339\ln(r+2.12)+0.0071r+1.167M+2.192+G(1.475\ln(r)-6.792) \) | \( r \)為震源距離，
M為地震矩規模 | 台灣地區     | TSMIP    | 35     | 2187    |
| 劉坤松 (1999)   | \( \ln(PVA)=1.681\ln(r+2.45)-0.0036r+1.250M+2.210+G(1.009\ln(r)-4.464) \) | \( r \)為震源距離，
M為地震矩規模 | 台灣地區     | TSMIP    |        |         |
|                | \( \ln(PHV)=-1.377\ln(r+1.67)-0.0023r+1.581M+3.070+G(1.066\ln(r)-4.909) \) | |              |          |        |         |
|                | \( \ln(PVV)=-1.415\ln(r+1.58)-0.0012r+1.666M- \) | |              |          |        |         |
Most used GMPE for the Engineer

Campbell's form

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

Joyner and Boore's form

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

Kanai's form

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

Japan Rock Site's form

\[ \log_{10}(0.981a) = \left( \frac{R+b_4}{b_5} \right) \cdot (-b_1 + b_2 M - b_3 M^2) \]
921 集集地震台灣地區震度圖

震度分級

250gal以上 6級
80-250gal 5級
25-80gal 4級
8-25gal 3級
2.5-8gal 2級
0.8-2.5gal 1級

單位(gal)

900.00
800.00
600.00
400.00
250.00
25.00
20.00
15.00
10.00
5.00
0.00
中興社防災科技研究中心

斷層線

下盤 上盤

集集大地震與 Northridge 地震及世界其他大地震比較上盤效應
<table>
<thead>
<tr>
<th>作者</th>
<th>年份</th>
<th>等式或公式</th>
<th>备注</th>
</tr>
</thead>
<tbody>
<tr>
<td>李錫堤等</td>
<td>1999</td>
<td>( Y = 0.0296e^{1.2M} )</td>
<td>台灣地區美濃水庫</td>
</tr>
<tr>
<td>Loh et al.</td>
<td>2000</td>
<td>( g )</td>
<td>TSMIP</td>
</tr>
<tr>
<td>羅俊雄與溫國樑</td>
<td>2000</td>
<td>Spectral Acceleration at 80 periods (0.029~10 sec)</td>
<td>TSMIP</td>
</tr>
<tr>
<td>Chang et al.</td>
<td>2001</td>
<td>( \ln A = 2.8096 + 0.8993M - 0.4381 \ln D_p - (1.0954 - 0.0079 D_p) \ln D_s )</td>
<td>台灣地區</td>
</tr>
<tr>
<td>地震學家</td>
<td>2001</td>
<td>( \ln A = 2.8096 + 0.8993M - 0.4381 \ln D_p - (1.0954 - 0.0079 D_p) \ln D_s )</td>
<td>TSMIP 45</td>
</tr>
<tr>
<td>趙曉玲</td>
<td>2001</td>
<td>( \log(PGA) = 0.00215 + 0.581M \log r_{rup} + 0.00871 \times 100.5M - 0.00414 r_{rup} )</td>
<td>台灣地區</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>2001</td>
<td>( \log(PGV) = -2.49 + 0.810M \log r_{rup} + 0.00871 \times 100.5M - 0.00268 r_{rup} )</td>
<td>TSMIP 60</td>
</tr>
</tbody>
</table>

\( R \) 為測站至斷層破裂面之最短距離，
\( M \) 為 \( (M_W) \)？

\( D_s, D_p, D_h \) 分別為震央距、震源距與震源深度 (km)

\( r_{rup} \) 為距斷層破裂面距離 (km)
<table>
<thead>
<tr>
<th>Author(s) (Year)</th>
<th>Equation or Description</th>
<th>Type of Event</th>
<th>Location</th>
<th>Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jean (2001)</td>
<td>$Y = 0.00369e^{1.75377M} (R+0.12220e^{0.78315M})^{-2.05644}$</td>
<td>Earthquake Magnitude</td>
<td>Taiwan Region</td>
<td>TSMIP</td>
</tr>
<tr>
<td>Liu and Tsai (2005)</td>
<td></td>
<td></td>
<td>Taiwan Region</td>
<td>TSMIP</td>
</tr>
<tr>
<td>Jean et al. (2006)</td>
<td>$PGA = 0.0028e^{1.7331M} (R+0.0999e^{0.7719M})^{-2.0639}$, $SA03 = 0.0079e^{1.7253M} (R+0.1199e^{0.7850M})^{-2.0489}$, $SA10 = 0.0027e^{1.7731M} (R+0.1154e^{0.7714M})^{-2.0419}$</td>
<td>Earthquake Magnitude</td>
<td>Taiwan Region</td>
<td>TSMIP</td>
</tr>
<tr>
<td>Wu (2008)</td>
<td>$ln Y_i = C_1 + C_2M + C_3(R_i+C_110^{2.03M}) + C_4(ln R_i+C_110^{2.03M})$</td>
<td>Earthquake Magnitude</td>
<td>Taiwan Region (2006 Easter Earthquake)</td>
<td>TSMIP</td>
</tr>
<tr>
<td>Lin and Lee (2008)</td>
<td>Subduction zone earthquake</td>
<td>Earthquake Magnitude</td>
<td>Taiwan Region (2009 Earthquake)</td>
<td>TSMIP</td>
</tr>
<tr>
<td>Lin et al. (2011)</td>
<td>Crustal earthquake (hanging-wall, footwall)</td>
<td>Earthquake Magnitude</td>
<td>Taiwan Region (2011 Earthquake)</td>
<td>TSMIP</td>
</tr>
<tr>
<td>Lee et al. (2012)</td>
<td>Arias Intensity</td>
<td>Earthquake Magnitude</td>
<td>Taiwan Region</td>
<td>TSMIP</td>
</tr>
</tbody>
</table>
Seismotectonic framework of Taiwan

![Image of a 3D seismic activity model showing the seismic activity and tectonic features of Taiwan.](image.png)

Data source:
1. Central Weather Bureau (CWB)
2. Institute of Earth Sciences, Academia Sinica
Strong-motion data for GMPE – Crustal
Ground-motion prediction equation

For Crustal Earthquake

\[ \ln y = C_1 + F_1 + C_2(8.5 - M_w)^2 + (C_4 + C_5(M_w - 6.3))\ln(\sqrt{R^2 + \exp(H)^2}) \]
\[ + C_6F_{NM} + C_7F_{RV} + C_8\ln(Vs_{30}/1130) \]

\[ F_1 = C_2(M_w - 6.3) \quad \text{Where} \quad M_w \leq 6.3 \]
\[ F_2 = (-H \cdot C_5)(M_w - 6.3) \quad \text{Where} \quad M_w > 6.3 \]

For Subduction zone earthquake

\[ \ln y = C_1 + C_2M + C_3\ln(R + C_4e^{C_5M}) + C_6H + C_7Z_t + C_8\ln(Vs_{30}/1130) \]
Variation of the standard deviation in the SA equation with periods from 0.01-5.0 sec
The notations

- $i \rightarrow$ event
- $k \rightarrow$ station
- $l \rightarrow$ region
- Residuals
  - Intra-event, $\xi_{ik}$ inter-event $\eta_i$
  - Inter-station, $\xi_{sk}$ intra-station $\xi_{rik}$
  - Inter-path, $\xi_{pkl}$ intra-path $\xi_{0ik}$
  - Inter-region, $\eta_{SRl}$ intra-region $\eta_{0i}$
- Standard deviations
  - Intra-event, $\sigma \rightarrow$ inter-event $\tau$
  - Inter-station, $\sigma_s \rightarrow$ intra-station $\sigma_r$
  - Inter-path, $\sigma_p \rightarrow$ intra-path $\sigma_0$
  - Inter-region, $\tau_{SR} \rightarrow$ intra-region $\tau_0$

Following the notation of Walling (2009)
Decomposition of the variability of empirical ground motion prediction equation - conclusion

\[
\sigma_T = \sqrt{\tau^2 + \sigma^2}
\]

Inter-event

\[
\tau^2 = \tau_{SR}^2 + \tau_0^2
\]

small source region

unexplained inter-event variability

Intra-event

\[
\sigma^2 = \sigma_s^2 + \sigma_r^2
\]

Inter-site (site-term)

record-to-record

unexplained intra-event variability

\[
\sigma_r^2 = \sigma_p^2 + \sigma_0^2
\]

path-to-path

\[
\sigma^2 = \sigma_s^2 + \sigma_p^2 + \sigma_0^2
\]

Single-path sigma

\[
\sigma_{sp} = \sqrt{\tau_0^2 + \sigma_0^2}
\]

Single-site sigma (single-station sigma)

\[
\sigma_{ss} = \sqrt{\tau^2 + \sigma_r^2}
\]
Reduction of the inter-event, intra-event, and total standard deviation from the TSMIP data, if the ergodic assumption is removed

<table>
<thead>
<tr>
<th></th>
<th>Single Site</th>
<th>Single Path</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Intra-event</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{SS}$</td>
<td>$\sigma_r$</td>
</tr>
<tr>
<td>PGA</td>
<td>0.91$\sigma_T$</td>
<td>0.86$\sigma$</td>
</tr>
<tr>
<td>T=0.1</td>
<td>0.88$\sigma_T$</td>
<td>0.81$\sigma$</td>
</tr>
<tr>
<td>T=0.3</td>
<td>0.90$\sigma_T$</td>
<td>0.86$\sigma$</td>
</tr>
<tr>
<td>T=0.5</td>
<td>0.89$\sigma_T$</td>
<td>0.83$\sigma$</td>
</tr>
<tr>
<td>T=1.0</td>
<td>0.86$\sigma_T$</td>
<td>0.75$\sigma$</td>
</tr>
<tr>
<td>T=3.0</td>
<td>0.86$\sigma_T$</td>
<td>0.69$\sigma$</td>
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</table>
Correlation of notation differences for components of variability from previous studies with the current study

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>$\sigma_T$</td>
<td></td>
<td>$\sigma_{\text{reg}}$</td>
<td>$\delta$</td>
</tr>
<tr>
<td>Inter-event</td>
<td>$\tau$</td>
<td>$\sigma_E$</td>
<td></td>
<td>$\tau$ (no correction)</td>
</tr>
<tr>
<td>Intra-event</td>
<td>$\sigma$</td>
<td></td>
<td></td>
<td>$\sigma$ (no correction)</td>
</tr>
<tr>
<td>Inter-site</td>
<td>$\sigma_S$</td>
<td>$\sigma_S$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single site, record-to-record</td>
<td>$\sigma_r$</td>
<td>$\sigma_r$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-path</td>
<td>$\sigma_P$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intra-event, Single Path</td>
<td>$\sigma_0$</td>
<td></td>
<td></td>
<td>$\sigma$ (applied correction)</td>
</tr>
<tr>
<td>Inter-source region</td>
<td>$\tau_{SR}$</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Inter-event, Single Region</td>
<td>$\tau_0$</td>
<td></td>
<td></td>
<td>$\tau$ (applied correction)</td>
</tr>
<tr>
<td>Single Site (total)</td>
<td>$\sigma_{SS}$</td>
<td></td>
<td>$\sigma_i$</td>
<td></td>
</tr>
<tr>
<td>Single Path (total)</td>
<td>$\sigma_{SP}$</td>
<td></td>
<td>$\sigma_{ie}$</td>
<td>(applied correction)</td>
</tr>
</tbody>
</table>
Comparison of single-path standard deviations ($\sigma_{sp}$) as a fraction of $\sigma_T$

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
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<tbody>
<tr>
<td>PGA</td>
<td>$0.54\sigma_T$</td>
<td>$0.67\sigma_T$</td>
<td>$0.46\sigma_T$</td>
</tr>
<tr>
<td>$T=0.1$</td>
<td>$0.53\sigma_T$</td>
<td></td>
<td>$0.38\sigma_T$</td>
</tr>
<tr>
<td>$T=0.3$</td>
<td>$0.60\sigma_T$</td>
<td>$0.68\sigma_T$</td>
<td>$0.44\sigma_T$</td>
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<tr>
<td>$T=0.5$</td>
<td>$0.61\sigma_T$</td>
<td></td>
<td>$0.45\sigma_T$</td>
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<tr>
<td>$T=1.0$</td>
<td>$0.59\sigma_T$</td>
<td>$0.67\sigma_T$</td>
<td>$0.47\sigma_T$</td>
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<tr>
<td>$T=3.0$</td>
<td>$0.60\sigma_T$</td>
<td></td>
<td>$0.47\sigma_T$</td>
</tr>
</tbody>
</table>
Conclusion

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

• For GMPE
  – More predictor variables for source, path and site
  – Directivity
  – Nonlinear site effect
  – Strong-motion difference due to various stress drop

• For Ground-motion prediction
  – Empirical approach
  – Seismological approach
    • Empirical Green’s functions (EGFs)
    • Stochastic Green's functions (SGFs)
    • Hybrid Green’s functions (HGFs)
Thank you for your attention.