Attenuation Relationship of Arias Intensity for Taiwan

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• Motivation
• Background
• Procedure
• Strong motion dataset
• Methodology
• Preliminary Result
• Future Work
• Ground motion attenuation relationship is the important parameter of Seismic Hazard Analysis
  ◦ Ground-motion prediction
  ◦ Site specific ground motion characteristic
  ◦ Estimating geohazard induced by ground motion
  ◦ Seismic-Resistant Construction

• Arias intensity is better than PGA (peak ground acceleration) for responding the geohazard induced by earthquakes (Jibson, 1993)

• Develop a Attenuation Relationship of Arias Intensity for Taiwan to engineer for estimating landslide and liquefaction hazard triggered by high level ground motion.

Motivation
Background

- Arias Intensity
- Literature review
• Arias intensity \((I_a)\), as defined by Arias (1970), is the total energy per unit weight stored by a set of undamped simple oscillators at the end of the ground motion. The Arias intensity for ground motion in the \(x\) direction \((I_{aX})\), is calculated as follows:

\[
I_{aX} = \frac{\pi}{2g} \int_{0}^{T_d} (a_X(t))^2 \, dt
\]

• where \(a_X(t)\) is the acceleration time history in the \(x\) direction, and \(T_d\) is the total duration of ground motion. \(I_{aX}\) is a measure of energy, which is scalar in nature, and \(I_a\) in the present investigation is considered as the median of the average horizontal components (east–west and north–south), calculated as follows: \(I_a = (I_{aX} + I_{aY})/2\)
The performance-based design of earthquake engineering structures requires the identification of critical indices of damage. Parameters related solely to the amplitude of the ground motion, such as peak ground acceleration (PGA), are often poor indicators of damage. Conversely, parameters that incorporate the amplitude, frequency content, and duration of the ground motion are likely to be more reliable predictors of its damage potential.

In several research, they found that $I_a$ correlates well with several commonly used demand measures of structural performance, liquefaction, and seismic slope stability.

- $I_a$ correlates well with distributions of earthquake-induced landslides (Wilson and Keefer, 1985; Harp and Wilson, 1987; 1995)
- An approach to assess liquefaction potential of soil deposits during earthquakes based on Arias Intensity (Kayen and Mitchell, 1997; Mitchell and Kramer, 2005)
- Electric Power Research Institute (EPRI, 1988) found that the best correlation between the onset of damage and ground motion occurred when $CAV$ and $I_a$ measures are used, another application is the development of early warning systems.

Why Using $I_a$ for Engineering?
Keefer and Wilson (1989) developed the attenuation relationship by the earthquakes in California, found the high correlation between $I_a$ and landslides triggered by earthquakes:

\[ \log I_a = -4.1 + M - 2 \log r + 0.44 P \]

They defined the intensity thresholds of the different types of landslide triggered by earthquakes:

- 0.11 m/sec for falls, disrupted slides, avalanches;
- 0.32 m/sec for slumps, block slides, earth flows;
- 0.54 m/sec for lateral spreads and flows

Harp and Wilson (1995) used two earthquakes in South California in 1987 (Superstition Hills and Whittier Narrows) to validate the correction of these thresholds.
Sabetta, F., and A. Pugliese (1996), build the attenuation by 190 horizontal components and 95 vertical components of strong motions recorded from 17 Italian earthquakes.

\[
\log_{10} I_a = -4.066 + 0.911M - 1.818\log_{10} \left( R^2 + 5.3^2 \right)^{1/2} + 0.244S_1 + 0.139S_2 \pm 0.397
\]

M corresponds to the surface-wave magnitude \( (M_s) \) when both local magnitude \( (M_L) \) and \( M_s \) are greater than or equal to 5.5 and corresponds to \( M_L \) when magnitude is lower than this value.

R defined as the shortest distance between the recording station and the surface projection of the fault rupture \( (R_{jb}) \) (Joyner and Boore, 1981).

\( S_1 \) and \( S_2 \) classified according to geological and geotechnical information:
- \( (0,0) \) for stiff rocks
- \( (1,0) \) for shallow soils
- \( (0,1) \) for deep soil

Review--Arias Intensity
Kayen and Mitchell (1997) developed the attenuation relationship by the earthquakes in California, found the high correlation between $I_a$ and liquefaction potential.

\[
\text{Rock sites: } \log I_a = M - 4.0 - 2 \log r^* + 0.63P \quad (10)
\]

\[
\text{Alluvium sites: } \log I_a = M - 3.8 - 2 \log r^* + 0.61P \quad (11)
\]

Soft soil sites (insufficient number of samples to determine $P$):

\[
\log I_a = M - 3.4 - 2 \log r^* \quad (12)
\]

\[
\log(I_h) = M - 2 \log(R) - 3.990 + 0.365P \quad (8)
\]

The probit, $P$, is the exceedance probability of Arias intensity in terms of standard deviation about the mean ($P = \pm 1$ for $\pm 1\sigma$), and $R$ is the source distance in kilometers.
Paciello et al. (2000) developed the attenuation relationship by the earthquakes in Italia and Greece.

Review--Arias Intensity
Travasarou et al. (2003) developed an empirical relationship based on 75 earthquakes in global active plate-margins, derived from the theoretical model:

\[
\ln(I_a) = c_1 + c_2(M - 6) + c_3 \ln(M / 6) + c_4 \ln(\sqrt{R^2 + h^2}) \\
+ (s_{11} + s_{12}(M - 6))S_C + (s_{21} + s_{22}(M - 6))S_D \\
+ f_1 F_N + f_2 F_R
\]

- \(R\), closest distance to the rupture place (km)
- \(h\), fictitious hypocentral depth determined by the regression (km)
- Site B, \(S_C=S_D=0\); site C, \(S_C=1,S_D=0\); site D, \(S_C=01,S_D=1\)
- strike-slip, \(F_N=F_R=0\); normal, \(F_N=1,F_R=0\); reverse, \(F_N=0,F_R=1\)

| Table III. Coefficients of empirical equation for Arias intensity. |
|------------------|------------------|------------------|------------------|------------------|
| \(c_1\)         | 2.800            | \(c_2\)         | -1.981           | \(c_3\)         | 20.72            |
| \(c_4\)         | -1.703           | \(h\)           | 8.78             |
| \(s_{11}\)      | 0.454            | \(s_{12}\)      | 0.101            | \(s_{21}\)      | 0.479            |
| \(s_{22}\)      | 0.334            | \(f_1\)         | -0.166           | \(f_2\)         | 0.512            |

Review--Arias Intensity
• Hwang et al. (2004) develop a attenuation for four types of site, regression by the Chi-chi earthquake mainshock and three aftershocks data

\[
\ln I_h = aM_w + b \ln r + c + \varepsilon
\]

• Lin and Lee (2004) developed a relationship based on 44 crustal earthquakes in Taiwan, derived from the Cambell form (Campbell, 1981)

\[
\ln(I_a) = C_1 + C_2 M + C_3 \ln(r_{rup} + C_4 e^{C_5 M}) + C_6 S
\]

<table>
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<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
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Review—Arias Intensity
Laurentiu Danciu and G-Aakis Tselentis (2007) developed a attenuation relationship based on 151 earthquakes, 335 ground motion data in Greece, employing mixed effects regression analysis.

\[
\log_{10}(Y_{ij}) = a + bM_i + c \log_{10}(R_{ij}) + d + eS_0 + fF_0 + \varepsilon_{ij}
\]

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Review--Arias Intensity
• Refer to Travasarou et al. (2003) to develop a Attenuation Relationship of Arias Intensity for Taiwan based on theoretical model

• Improve the site term to continual $V_{s30}$

• Coefficients determined by employing mixed effects model nonlinear regression analysis

• reduce the sigma of the regression result
Procedure

1. Literature and structure
2. Geotectonic
   - Focal mechanism
   - Site classification
3. Earthquake catalog
   - Earthquake parameters
4. SGM data processing
   - Arias intensity database
5. Attenuation form
6. Mixed effect regression
7. Arias intensity attenuation for Taiwan
• Taiwan’s Next Generation Attenuation of Ground Motions Project, TNGA
  - NGA (The Pacific Earthquake Engineering Research Center, PEER)
- [1] "EQ.ID" "STA.ID." "LAT" "LON"
- [5] "Depth" "MW.SUG" "Distance" "Hypo.Dis"
- [9] "R.rup" "R.jb" "R.SUGG" "STA.Lat"
- [13] "STA.Lon" "Vs30.Mapped" "PGA" "FN"
- [17] "T.SEC" "Ia.NS." "Ia.EW." "Ia.Z."
- [21] "Ia..V.q" "Ia.GeoMean" "Ia.AriMean." "Vs30.Lab"
- [25] "Site.Class" "FaultType" "GEO" "PGAZ"
- [29] "PGANS" "PGAEW" "PGVZ" "PGVNS"
- [33] "PGVEW" "PGDZ" "PGDNS" "PGDEW"
- [37] "PGA.g" "PGV.cm.sec" "PGD.cm" "residual"
- [41] "GEO.Factor1" "GEO.Factor2" "SOF1" "SOF2"
- [45] "residual.b" "residual.b.ls" "GEO.Factor3" "SOF3"
- [49] "residual.vs30" "predict.ia" "In.predict.ia" "In.Ia.AriMean."
- [53] "Distance.2" "Hypo.Dist.2" "R.rup.2" "R.jb.2"
- [57] "R.SUGG.2" "Depth.2"
The five Chi-chi aftershock (1392 recordings)

Data selection

before:
τ = 0.58, σ = 0.91

after:
τ = 0.52, σ = 0.89
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<td>R</td>
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</table>

62 earthquakes (crustal)  
Mw: 3.53~7.62  
6173 SGM data

N: Normal  
SS: Strike-slip  
R: Reverse  
RO: Reverse-Oblique  
S1: Unknown
- Empirical
- Theoretical (numerical)
- Theoretical + Empirical
  - Travasarou et al. (2003) theoretical form
  - Continual $V_{s30}$
  - Mixed effects nonlinear regression analysis
Mixed effects = Fixed effects + Random effects

\[ \ln (y_{ij}) = C_1^* + C_2 m_i + C_3^* \ln [\text{term}] + C_5^* m_i] + C_6 Z_i^R + \eta_i + \epsilon_{ij} \]

- Attenuation equation
- Intra-error term, fixed
- Inter-error term, random

Figure 4. Schematic illustration of the error terms \( \eta_i \) and \( \epsilon_{ij} \) for two events with the same magnitude.
1. Estimate the model parameter values, $\theta$, using a fixed effects (equation 1) regression procedure.

2. Given $\theta$, estimate $\sigma^2$ and $\tau^2$ by maximizing the likelihood given in equation (7).

3. Given $\theta$, $\sigma^2$ and $\tau^2$, estimate $\eta_i$ by equation (10).

4. Given $\eta_i$, estimate new $\theta$ using a fixed effects (equation 1) regression procedure for $(\ln y_{ij} - \eta_i)$.

5. Repeat steps 2, 3, and 4 until the likelihood in step 2 is maximized.

\[
\ln y_{ij} = f(M_i, r_{ij}; \theta) + \epsilon_{ij},
\]

\[
\ln L = -\frac{1}{2} N \ln(2\pi) - \frac{1}{2} (N - M) \ln(\sigma^2) - \frac{1}{2} \sum_{i=1}^{M} \ln(\sigma^2 + n_i \tau^2) + \frac{1}{2} \sum_{i=1}^{M} \frac{n_i (\bar{y}_i - \bar{\mu}_i)^2}{\sigma^2 + n_i \tau^2},
\]

\[
\eta_i = \frac{\tau^2 \sum_{j=1}^{n_i} y_{ij} - \mu_{ij}}{n_i \tau^2 + \sigma^2}.
\]
• Travasarou’s study & this study
• Residual v.s Distance
• Inter-event Residual v.s Magnitude
• Intra-event Residual v.s Distance
• Intra-event Residual v.s Magnitude
• Intra-event Residual v.s $V_{s30}$

Preliminary Result
\[
\ln(I_a) = c_1 + c_2 (M - 6) + c_3 \ln(M/6) + c_4 \ln(\sqrt{R^2 + h^2}) \\
+ (s_{11} + s_{12} (M - 6)) S_C + (s_{21} + s_{22} (M - 6)) S_D \\
+ f_1 F_N + f_2 F_R
\]

Travasasarou’s study
\[
\ln(I_a) = c_1 + c_2(M - 6) + c_3 \ln(M/6) + c_4 \ln(\sqrt{R^2 + 3^2}) \\
+ \phi \ln(V_{s30}/1130) + f_1 F_N + f_2 F_R
\]
Residuals
Residual Distribution
Residual vs Distance

Standard deviation: 1.03
Inter-event residual vs Mw

Standard deviation: 0.52
Intra-event residual

Standard deviation: 0.89
New data

Intra-event residual
Intra-event residual vs $M_w$
Intra-event residual vs $V_{s30}$
New data: $V_{s30}$ (Tsai, 2007)

Comparison with foreign relationship

Validation with seismic-induced landslides

Comparison between crustal and subduction

Future work
Thanks for your attention 😊