Land subsidence and Landslide
- Natural/Man-made Disaster -

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Hazard in a river basin under “Climate Change”

◆ Natural Hazard
◆ Man-Made Hazard

[Diagram showing various hazards related to climate change, including land subsidence, landslide, mud flow, flood, coastal erosion, and saltwater intrusion.]

Sources: WCR team based on World Bank, Kathoming et al., Bates and others 2000.
Natural Disaster/Man-Made Disaster
Comparison of problems between in Japan & in Thailand

Problems inside Mega-City
Land subsidence caused by "Excessive Groundwater Extraction"

Disorderly Expansion of urban area toward outskirts

Problems Associated with Linkage between Mega-City and Rural Areas
Landslide/Slope failure under "Climate Change"

Inside Megacities:
Land subsidence in Asian countries
Damage/Loss Caused by Excessive Groundwater Extraction
Mitigation of Natural/Man-Made Disaster

Required Policy Responses

1. Regulatory Measures

2. Economic Measures

Which measures are effective?

Land Subsidence Caused by Groundwater Extraction in Osaka

Regulatory Measures was effective

(a) Contour of land subsidence (1935-1968)  (b) Amount of groundwater extraction & observed land subsidence
Groundwater Extraction in Bangkok

Regulatory Measures was not effective

<table>
<thead>
<tr>
<th>Public supply</th>
<th>Private pumpage</th>
<th>Total pumpage</th>
</tr>
</thead>
</table>

Who controls amount of groundwater extraction?

Economic Measures in BMR

- Implementation of groundwater use charges

- Implementation of preservation charges
  2003: Levied for all GW users in the critical zone
  (1.00THB/m³, Sep 04 → 8.50THB/m³, Sep 06)
  Expected total GW charge:
  9.50THB/m³, 2004 → 12.50THB/m³, 2005 → 17.00THB/m³ by July 2006

- Levying surcharges and penalizing violators of regulations

Groundwater abstraction volume and charges for use in Bangkok (IGES, 2006)
Two examples related to Excessive GW extraction and infrastructure development

1. Osaka (Japan)
   - Imposition of “regulatory measures”
   - Land subsidence → GWL recovery
     - 1960’s
     - Infrastructure development

2. Bangkok (Thailand)
   - Imposition of “economic measure”
   - Land subsidence → GWL recovery
     - 2000’s
     - Infrastructure development

Losses due to Excessive GW Extraction (1) in BMR

1) Damages on Housing/Building
2) Damages on elevated highway

- Land subsidence
- GWL Drawdown
- GWL Recovery
- Infrastructure development
Losses due to Excessive GW Extraction (2) in BMR

1) GWL Drawdown
2) GWL Recovery
3) Increase of flooding risk

Land subsidence

Losses due to Excessive GW Extraction (3) in BMR

1) GWL Drawdown
2) GWL Recovery

1) Uplift acting UG structures
2) Damages on Infrastructure foundation

Uplift

Underground structures

Elevated highway

Highway bridge

Piles
### Classification of Losses Caused by Excessive GW Extraction

<table>
<thead>
<tr>
<th>Type of Damages</th>
<th>Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWL Drawdown</td>
<td></td>
</tr>
<tr>
<td>damages on</td>
<td>Individual</td>
</tr>
<tr>
<td>housing/building</td>
<td></td>
</tr>
<tr>
<td>damages on elevated highway</td>
<td>Society</td>
</tr>
<tr>
<td>increase of flooding risk</td>
<td></td>
</tr>
<tr>
<td>coastal erosion</td>
<td></td>
</tr>
<tr>
<td>salt water intrusion</td>
<td></td>
</tr>
<tr>
<td>GWL Recovery</td>
<td></td>
</tr>
<tr>
<td>uplift acting UG structures</td>
<td></td>
</tr>
<tr>
<td>damages on infrastructure foundation</td>
<td></td>
</tr>
</tbody>
</table>

### Focal Area to Investigate the Effect of GWL Recovery

**Thailand**

Bangkok Metropolitan Region, BMR

- Ayutthaya
- Chao Phraya River
- Pathum Thani
- Nonthaburi
- Bangkok
- Nakhon Pathom
- Samut Sakhon
- Samut Prakan
Modeling of Bangkok Aquifer System

3D-FDM Numerical Code (MODFLOW)

(Bangkok Aquifer System)

Distribution of Wells

Record in 2006

2. Phra Pradaeng Aquifer
3. Nakhon Luang Aquifer
4. Nonthaburi Aquifer

IGES “Stakeholder Meeting on Sustainable Groundwater Management in Bangkok, Thailand” (2006)
Initial Piezo-metric Head Distribution

Observed data (2006)
- PD layer (2nd Aquifer)
- NL layer (3rd Aquifer)
- NB layer (4th Aquifer)

Simulation (2006)
- PD layer (2nd Aquifer)
- NL layer (3rd Aquifer)
- NB layer (4th Aquifer)

Numerical results on Change of Groundwater Level Distribution in Aquifers

Typical recovery of groundwater level in Samut Prakan and Pathum Thani, where currently amount of groundwater extraction is relatively large, compared with other provinces.

Change of Groundwater level in BK Aquifer (2006-2030)
Change of Groundwater level in NL Aquifer (2006-2030)
Prediction of Vertical Movement in 4 Aquifers in 2030

- Vertical movement in aquifers is relatively small.
- Considering secondary consolidation at Bangkok clay, the effect of vertical movement at ground surface will be offset.

Evaluation of the effect of GWL Recovery on Underground Infrastructures
Evaluation of the effect of uplift on Bangkok Subway Stations

Uplift acting on station and FS

Decrease of Pile Bearing Capacity due to GWL Recovery

Reduction rate of pile bearing capacity
Classification of Losses Caused by Excessive GW Extraction

<table>
<thead>
<tr>
<th>Type of Damages</th>
<th>Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWL Drawdown</td>
<td></td>
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<tr>
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<td></td>
</tr>
<tr>
<td>Increase of flooding risk</td>
<td>Society</td>
</tr>
<tr>
<td>Coastal erosion</td>
<td></td>
</tr>
<tr>
<td>Salt water intrusion</td>
<td></td>
</tr>
<tr>
<td>GWL Recovery</td>
<td></td>
</tr>
<tr>
<td>Uplift acting UG structures</td>
<td></td>
</tr>
<tr>
<td>Damages on Infrastructure foundation</td>
<td></td>
</tr>
</tbody>
</table>

Flooding Site Investigation from November 16-19
Chao Phraya Basin

cause of Flooding (1)

Chao Phraya Basin is low-lying area from 0-3 m MSL
Cause of Flooding (2)

Land subsidence due to excessive groundwater extraction

Low-lying area from 0-3 m MSL Canal network

Long-term inundation without pumpage

Delay of recovery/restoration

Coastal erosion due to land subsidence

High tide

Summary on Problems Associated with Bangkok Groundwater Usage

<table>
<thead>
<tr>
<th>Timing</th>
<th>Type of Damages</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWL Drawdown</td>
<td>Present Damages on Housing/Building</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Present Damages on elevated highway</td>
<td>Required</td>
</tr>
<tr>
<td></td>
<td>present Increase of flooding risk</td>
<td>Required</td>
</tr>
<tr>
<td></td>
<td>Present-Future Coastal erosion</td>
<td>Required under climate change (sea level rise)</td>
</tr>
<tr>
<td></td>
<td>Present Salt water intrusion</td>
<td>-</td>
</tr>
<tr>
<td>GWL Recovery</td>
<td>Future Uplift acting UG structures</td>
<td>OK?</td>
</tr>
<tr>
<td></td>
<td>Future Damages on Infrastructure foundation</td>
<td>Required</td>
</tr>
</tbody>
</table>

It is required to establish new training program on geotechnical asset management.
Three examples related to Excessive GW Extraction and infrastructure development

1. Osaka (Japan)
   - Imposition of "regulatory measures"
   - Land subsidence
   - Water level recovery
   - Infrastructure development
   - t (time)

2. Bangkok (Thailand)
   - Imposition of "economic measure"
   - Land subsidence
   - Water level recovery
   - Infrastructure development
   - t (time)

3. Hanoi (Vietnam)
   - What will happen?
   - Land subsidence?
   - Infrastructure development
   - t (time)

It is required to establish new training program on geotechnical infrastructure management considering project life.

Problem associated with Linkage with rural area:
Landslide/slope failure

Subsoil profile of weathered rock

- VI
  - Soil/Residual soil
- V
  - Completely Weathered
- IV
  - Highly Weathered
- III
  - Moderately Weathered
    - Rock 50% to 90%
- II
  - Slightly Weathered
- I
  - Fresh Rock

Natural slope
Cut slope
(SORALUMP, 2010)
Increase of landslide events all over the world

Frequency of landslide events occurred between 1970 to 2009

Damage worth of lives and properties due to landslide

<table>
<thead>
<tr>
<th>Year</th>
<th>Losses of Life (Person)</th>
<th>Damage Worth of Property (Million Baht)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968 - 1977</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>1978 - 1987</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>1988 - 1997</td>
<td>230</td>
<td>1,000.00</td>
</tr>
<tr>
<td>1998 - 2009</td>
<td>312</td>
<td>3,595.60</td>
</tr>
</tbody>
</table>

Landslide in Thailand

- Climate change?
- Man-made hazard?
  Construction of highways/residential areas

Basic concept of risk evaluation
Def. in the discipline of Engineering

Expected losses

\[ R = \sum_{i=1}^{J} P_i \times C_i \]

\( R \): Expected loss (Risk)

\( P_i \): The probability of event \( i \) occurring

\( C_i \): The loss incurred when the event \( i \) occurs

Damage scenario due to road slope failure

Classification of damage pattern

Pattern 1: Collapsed debris stops besides road
Pattern 2: Collapsed debris moves to road
Pattern 3: Collapsed debris move to residential area
Establishment of damage scenario using ET(Event Tree)

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>No.</th>
<th>Damage scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope failure</td>
<td>Failure pattern</td>
<td>Damage to Road users</td>
<td>Damage to housing</td>
<td>1</td>
</tr>
<tr>
<td>No</td>
<td>Pattern 1</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Yes</td>
<td>Pattern 2</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>No</td>
<td>6</td>
<td>Pattern 3 Damage to housing</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>Yes</td>
<td>7</td>
<td>Pattern 3 Damage to Road users No Damage to housing</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>No</td>
<td>8</td>
<td>Pattern 3 Damage to Road users Damage to housing</td>
</tr>
</tbody>
</table>

Risk analysis Using ET

\[ R = p \times C \]

Slope failure probability against rainfall intensity \( \alpha \)

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>No.</th>
<th>Damage scenario</th>
<th>Probability ( p_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope failure</td>
<td>Failure pattern</td>
<td>Damage to Road users</td>
<td>Damage to housing</td>
<td>1</td>
<td>Nothing</td>
</tr>
<tr>
<td>No</td>
<td>Pattern 1</td>
<td>0.90</td>
<td>0.60</td>
<td>2</td>
<td>Pattern 1</td>
</tr>
<tr>
<td>Yes</td>
<td>Pattern 2</td>
<td>0.10</td>
<td>0.60</td>
<td>3</td>
<td>Pattern 2 No Damage to Road users</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.30</td>
<td>0.80</td>
<td>4</td>
<td>Pattern 2 Damage to Road users</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pattern 3</td>
<td>0.10</td>
<td>0.80</td>
<td>5</td>
<td>Pattern 3 No Damage to housing</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.80</td>
<td>Yes</td>
<td>6</td>
<td>Pattern 3 Damage to housing</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.90</td>
<td>Yes</td>
<td>7</td>
<td>Pattern 3 Damage to Road users No Damage to housing</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>Yes</td>
<td>8</td>
<td>Pattern 3 Damage to Road users Damage to housing</td>
<td>( p_8 )</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Sigma )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.0000</td>
</tr>
</tbody>
</table>
Consequence (Losses caused by slope failure)

1. Direct Loss
   - Loss due to slope restoration cost, $L_R$
   - Loss due to compensation for damages to vehicles, passengers and private properties, $L_C$

2. Indirect Loss
   - Traveling energy loss, $L_{d_e}^e$
   - Traveling time loss, $L_{D_t}^t$

Mathematic Background of Probability of Slope Failure
Performance Function

\[ Q = -1 + \left( \frac{1}{\gamma H} \cdot \frac{1}{\sin \alpha \cos \alpha} \right) c + \left( 1 - \frac{\gamma_w H_w}{\gamma H} \right) \cdot \frac{1}{\tan \alpha} \tan \phi \]

- \( \gamma \): Unit weight of soil
- \( \phi \): Internal friction angle
- \( c \): Cohesion
- \( \alpha \): Inclination angle of slope
- \( H \): Width of failure plane
- \( H_w \): Depth of groundwater level

**Linear Performance Function**

\[ Q > 0 \quad \text{Stable} \]
\[ Q = 0 \quad \text{Limit-state} \]
\[ Q < 0 \quad \text{Instable} \]

PDF of Normal Distribution

\[ f(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2 \right] \]

- \( \mu \): Mean
- \( \sigma \): Standard deviation

(a) random variable \( X \) (cohesion \( c \))
(b) random variable \( Y \) (\( \tan \phi \); frictional angle \( \phi \))
Performance Function

\[ Q = \left(1 - \frac{\gamma_w H_w}{\gamma H}\right) \cdot \tan \phi + \frac{c}{\gamma H} \cdot \frac{1}{\sin \alpha \cos \alpha} - 1 \]

Assuming \( X = c \) & \( Y = \tan \phi \)

\[ Q = a_0 + a_1 X + a_2 Y \]

In which, \( a_0 = -1 \)

\[ a_1 = \frac{1}{\gamma H} \cdot \left(1 - \frac{\gamma_w H_w}{\gamma H}\right) \cdot \frac{1}{\tan \alpha} \]

Formulation of PDF

\[ Z = aX_1 + bX_2 + c \]

\[ \mu_z = E[aX_1 + bX_2 + C] = aE[X_1] + bE[X_2] + c \]

\[ \sigma_z^2 = VAR[aX_1 + bX_2 + C] = a^2VAR[X_1] + b^2VAR[X_2] + 2abCOV[X_1, X_2] \]

Performance Function \( Q \)

\[ Q = \left(1 - \frac{\gamma_w H_w}{\gamma H}\right) \cdot \tan \phi + \frac{c}{\gamma H} \cdot \frac{1}{\sin \alpha \cos \alpha} - 1 \]

Random Variables: \( c, \phi \)

\[ \mu_Q, \sigma_Q \]
\[
p_f(\alpha) = \int_{-\infty}^{0} \frac{1}{\sigma_Q(\alpha) \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{X - \mu_Q(\alpha)}{\sigma_Q(\alpha)} \right)^2 \right] dX
\]

\[
s = \frac{X - \mu_Q(\alpha)}{\sigma_Q(\alpha)}
\]

\[
dX = \sigma_Q(\alpha) ds\quad s: \left[ -\infty, \left( \frac{\mu_Q(\alpha)}{\sigma_Q(\alpha)} \right) \right]
\]

\[
p_f(\alpha) = \Phi \left( -\frac{\mu_Q(\alpha)}{\sigma_Q(\alpha)} \right) = \int_{-\infty}^{-\frac{\mu_Q(\alpha)}{\sigma_Q(\alpha)}} \frac{1}{\sqrt{2\pi}} \exp \left[ -\frac{1}{2} s^2 \right] ds
\]

**Performance Function:**

\[
Q = a_0 + \sum_{i} a_i X_i
\]

If variable \(X_i\)s are independent

\[
\mu_Q = a_0 + \sum_{i} a_i \mu_{X_i}
\]

Reliability Index:

\[
\beta = \frac{a_0 + \sum_{i} a_i \mu_{X_i}}{\sqrt{\sum_{i} (a_i \sigma_{X_i})^2}}
\]

\[
\sigma_Q = \sqrt{\sum_{i} (a_i \sigma_{X_i})^2}
\]

\[
p_f(\alpha) = \Phi(-\beta) = \int_{-\infty}^{-\beta} \frac{1}{\sqrt{2\pi}} \exp \left[ -\frac{1}{2} s^2 \right] ds
\]
Evaluation Sheet (Probability of slope failure)

<table>
<thead>
<tr>
<th>parameter</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric condition</td>
<td></td>
</tr>
<tr>
<td>inclination angle (α)</td>
<td>degree</td>
</tr>
<tr>
<td>Height of slope (H)</td>
<td>m</td>
</tr>
<tr>
<td>Soil property</td>
<td></td>
</tr>
<tr>
<td>unit weight of soil (γ)</td>
<td>kN/m³</td>
</tr>
<tr>
<td>frictional angle (ϕ)</td>
<td>degree</td>
</tr>
<tr>
<td>cohesion (c)</td>
<td>kN/m²</td>
</tr>
<tr>
<td>unit weight of water (γw)</td>
<td>kN/m³</td>
</tr>
<tr>
<td>groundwater level (Hw)</td>
<td>m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>random variable</th>
<th>mean (μ)</th>
<th>coefficient of variation (cov)</th>
<th>standard deviation (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cohesion (c)</td>
<td>5.00</td>
<td>0.40</td>
<td>2.00</td>
</tr>
<tr>
<td>frictional angle (ϕ)</td>
<td>30.00</td>
<td>0.40</td>
<td>12.00</td>
</tr>
<tr>
<td>tan ϕ</td>
<td>0.5774</td>
<td>0.40</td>
<td>0.2309</td>
</tr>
</tbody>
</table>

performance function

FOSM method

<table>
<thead>
<tr>
<th>reliability index (β)</th>
<th>-0.00789</th>
</tr>
</thead>
<tbody>
<tr>
<td>probability of failure (pf)</td>
<td>5.03E-01</td>
</tr>
</tbody>
</table>

Evaluation of Conditional Probability of Failure
Physical Meaning of Performance Function $Q$

| $Q > 0$ | Stable |
| $Q = 0$ | Limit-state |
| $Q < 0$ | Instable |

Probability of Failure: $p_f(H_{wi})$

\[ p_f(H_{wi}) = \text{Prob}[Q(H_{wi}) < 0] \]

\[ p(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi} \sigma} \exp \left[ -\frac{1}{2} \left( \frac{X - \mu}{\sigma} \right)^2 \right] dX \]

How shall we associate water level $H_w$ with rainfall intensity $\alpha$?

Methodology
- Regression Curve
- Seepage Analysis
- Tank Model
Equation of Continuity: \[ Q_R = Q_E + Q_I + Q_S \]

- \( Q_R \): amount of rainfall
- \( Q_E \): amount of evaporation
- \( Q_I \): amount of infiltration into subsoil
- \( Q_S \): amount of flow along slope surface, Horton’s flow (run-off), which does not infiltrate into subsoil.

Observed Surface Flow (Run-off)

Landslide vs. Flooding
Evaluation of Annual Probability of Failure and Annual Expected Risk

Performance function $Q$ as a function of rainfall intensity $\alpha$.

Conditional probability of failure $p_f(\alpha)$.

Fragility Curve.
**Exercise-II: Calculation of Conditional Probability of Failure**

- Unit weight of water: $\gamma = 10\text{kN/m}^3$
- Unit weight of soil: $\gamma_w = 20\text{kN/m}^3$
- Height of slope: $H = 5\text{m}$
- Slope angle: $i = 25\text{ degree}$
- Frictional angle of soil: $\phi = 30\text{ degree}$

**Variation of Groundwater Level:**
Assume simplified correlation between rainfall intensity $\alpha$ and groundwater table level $H_w$ as follow:

$$H_w = 0.015\alpha$$

**Performance Function**

$$Q = a_0 + a_1X$$

In which,

$$a_0 = -1 + \left(1 - \frac{\gamma_w H_w}{\gamma H}\right) \cdot \tan \phi \div \tan \alpha$$

$$a_1 = \frac{1}{\gamma H} \times \frac{1}{\sin \alpha \cos \alpha}$$

$$\mu_Q = a_0 + a_1 \mu_c$$

**Cohesion (Random variable)**

<table>
<thead>
<tr>
<th>Cohesion (Expectation)</th>
<th>Coefficient of variation, cov</th>
</tr>
</thead>
<tbody>
<tr>
<td>20kN/m²</td>
<td>0.4</td>
</tr>
<tr>
<td>15kN/m²</td>
<td></td>
</tr>
<tr>
<td>10kN/m²</td>
<td></td>
</tr>
</tbody>
</table>
Solution (Exercise-II)

Fragility curve against rainfall intensity

Rainfall Hazard Model

- The statistics of extreme value is applied to model the occurrence of rainfall hazard following a Poisson process.
- Gumbel distribution is an appropriated model to predict the exceedance property ($\Psi$) at a certain rainfall intensity ($\alpha$) as below:

**Gumbel Distribution**

$$\Psi(\alpha) = 1 - \exp\left\{ -e^{a(\alpha - b)} \right\}$$

$1 / \Psi(\alpha)$ : Return period of hazard
Gumbel Distribution  
\[ \psi(\alpha) = 1 - \exp\left\{ - e^{-\alpha - b} \right\} \]

Parameter \( a \) and \( b \) involved in the above equation are associated with mean \( \mu \) and standard of deviation \( \sigma \) of historical rainfall data as shown in Table 4.1 as follows:

\[ \mu = b + 0.45\sigma \]
\[ \sigma = 1.283 / a \]

\[ b = \mu - 0.45\sigma = 318.65 - 0.45 \times 103.669 = 271.999 \]
\[ a = 1.283 / \sigma = 1.283 / 103.669 = 0.012376 \]

\[ \Psi(\alpha) = 1 - \exp\left\{ - \exp\left\{ - 0.012376(\alpha - 271.999) \right\} \right\} \]

\[ \mu = 318.65(\text{mm}) \quad \sigma = 103.669(\text{mm}) \]

<table>
<thead>
<tr>
<th>Rank</th>
<th>Daily rainfall (mm)</th>
<th>( b )</th>
<th>( a )</th>
<th>Rank</th>
<th>Annual Exceedance probability ( \psi(\alpha) )</th>
<th>( P(\alpha) )</th>
<th>( 1 - P(\alpha) )</th>
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</tr>
<tr>
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<tr>
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<tr>
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<td>3</td>
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<tr>
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<td>1</td>
<td>0.05</td>
<td>0.9929</td>
<td>0.0071</td>
</tr>
</tbody>
</table>

![Graph showing annual exceedance probability vs. daily rainfall](graph.png)
Example of change of Rainfall Hazard (in Wakayama, Japan)

Hazard curve In 1997
Hazard curve In 2007
Shift

Evaluation of Loss

Indirect losses
Socio-Economic View Point

Social

Direct losses
Financial View Point

Individual
1. Direct Loss
   1) Loss due to slope restoration cost, $L_R$
   \[ L_R = (C_{v0} \times V + C_{A0} \times A) \times (1 + a) + C_{M0} \times n \]
   - $C_{v0}$: cost of debris removal per unit volume
   - $V$: volume of collapsed debris
   - $C_{A0}$: cost of slope restoration per unit area
   - $A$: area of slope to be restored
   - $a$: miscellaneous expense ratio
   - $C_{M0}$: cost of management and labor wage per day
   - $n$: the number of day during road interruption

   2) Loss due to compensation for damages to vehicles, passengers and private properties, $L_C$
   \[ L_C = n_V \times (C_V + n_P \times C_P) + C_D \]
   - $n_V$: estimated number of damaged vehicles
   - $C_V$: average loss of one vehicle
   - $n_P$: average number of passengers per car
   - $C_P$: monetary loss of one human life
   - $C_D$: estimated damage to surrounding private properties
2. Indirect Loss

- Traveling energy loss, $L_D^e$
- Traveling time loss, $L_D^t$

**Traveling velocity**
- 60km/h
- 40km/h
- 30km/h

**Diversion route, DBC**
- Location A
- Location B
- Location C
- Location D
- Location E
- Location F

**Diversion route, DDE1**
- Location D
- Location E
- Location F

**Diversion route, DDE2**
- Location E
- Location F

### Required information
1) Unit value of traveling energy cost corresponding to vehicle type $m$ along diversion route, $B_m^d$ (JPY/count/minute)
2) Unit value of traveling energy cost losses corresponding to vehicle type $m$ along original route, $B_m^o$ (JPY/count/minute)
3) Traveling distance of diversion route, $L_d^d$ (km)
4) Traveling distance of original route, $L_o$ (km)
5) Daily traffic count corresponding to vehicle type $m$, $N_m$ (count)
6) Days of interruption of road service after occurrence of road slope failure, $n$ (days)

**Unit value of traveling energy cost**

**Corresponding to vehicle type $m$, $B_m$**

<table>
<thead>
<tr>
<th>Normal road (Urban area)</th>
<th>Car</th>
<th>Bus</th>
<th>Light truck</th>
<th>Medium truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (km/h)</td>
<td>10</td>
<td>27</td>
<td>81</td>
<td>42</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>20</td>
<td>71</td>
<td>35</td>
</tr>
<tr>
<td>30</td>
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<td>66</td>
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</tr>
<tr>
<td>60</td>
<td>17</td>
<td>66</td>
<td>33</td>
<td>39</td>
</tr>
</tbody>
</table>

(20km) (40km) (100km) (10km)
2. Indirect Loss

2) Traveling time loss, \( L_D^t \)
\[
L_D^t = n \sum_m \left( A_m \times N_m \times \Delta T \right)
\]
\[
\Delta T = \frac{L_d}{v_d} - \frac{L_o}{v_o}
\]

**Required information**

1) Unit value of traveling time corresponding to vehicle type \( m, A_m \) (JPY/count/minute)
2) Daily traffic count corresponding to vehicle type \( m, N_m \) (count)
3) Traveling distance along diversion route, \( v_d \) (min)
4) Traveling distance along original route, \( v_o \) (min)
5) Traveling velocity of diversion route, \( L_d \) (km/minute)
6) Traveling velocity of original route, \( L_o \) (km/minute)
7) Days of interruption of road service after occurrence of road slope failure, \( n \) (days)

**Unit value of traveling time corresponding to vehicle type \( m, A_m \)**

<table>
<thead>
<tr>
<th>Type of vehicle</th>
<th>Weekday</th>
<th>Weekend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>56</td>
<td>84</td>
</tr>
<tr>
<td>Bus</td>
<td>496</td>
<td>744</td>
</tr>
<tr>
<td>Light truck</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Medium truck</td>
<td>101</td>
<td>101</td>
</tr>
</tbody>
</table>

(JPY/count/minute)

**(Example 5.1)**

(i) Traveling energy loss, \( L_D^e \)
\[
L_D^e = n \sum_m N_m \left( B_m^d \times L_d - B_m^o \times L_o \right)
\]

<table>
<thead>
<tr>
<th>Type of vehicle</th>
<th>Diversion route</th>
<th>Original route</th>
<th>Daily traffic count ( N_m ) (count/day)</th>
<th>Days of interruption ( n ) (days)</th>
<th>Loss (x1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>10 19.3</td>
<td>8 15.6</td>
<td>2,274</td>
<td>180</td>
<td>27,916</td>
</tr>
<tr>
<td>Bus</td>
<td>41 19.3</td>
<td>31 15.6</td>
<td>74</td>
<td>180</td>
<td>4,099</td>
</tr>
<tr>
<td>Light truck</td>
<td>19 19.3</td>
<td>14 15.6</td>
<td>983</td>
<td>180</td>
<td>26,240</td>
</tr>
<tr>
<td>Medium truck</td>
<td>24 19.3</td>
<td>19 15.6</td>
<td>1263</td>
<td>180</td>
<td>37,920</td>
</tr>
<tr>
<td>Remarks</td>
<td>60km/h road</td>
<td>90km/h Highway</td>
<td></td>
<td>( \Sigma )</td>
<td>96,175</td>
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</table>

Travel time loss \( \Delta T \):
\[
\Delta T = \frac{L_d}{v_d} - \frac{L_o}{v_o} = \left( \frac{19.3}{60} - \frac{15.6}{90} \right) \times 60 = 8.9
\]
(Example 5.1)

(ii) Traveling time loss, $L_D^t$

\[ L_D^t = n \sum m (A_m \times N_m \times \Delta T) \]

\[ \Delta T = \frac{L_d}{v_d} - \frac{L_o}{v_o} \]

<table>
<thead>
<tr>
<th></th>
<th>Unit value $A_m$ (count/minute)</th>
<th>Daily traffic count $N_m$ (count/day)</th>
<th>Travel time loss $\Delta T$ (minute)</th>
<th>Days of interruption $n$ (days)</th>
<th>Loss (x1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>56</td>
<td>2,274</td>
<td>8.9</td>
<td>2,355,864</td>
<td>180</td>
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<tr>
<td>Bus</td>
<td>497</td>
<td>74</td>
<td>8.9</td>
<td>680,393</td>
<td>180</td>
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<tr>
<td>Light truck</td>
<td>90</td>
<td>983</td>
<td>8.9</td>
<td>1,636,695</td>
<td>180</td>
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<tr>
<td>Medium truck</td>
<td>101</td>
<td>1263</td>
<td>8.9</td>
<td>2,359,916</td>
<td>180</td>
</tr>
<tr>
<td>Remarks</td>
<td>weekday traffic count</td>
<td></td>
<td></td>
<td></td>
<td>$\Sigma$</td>
</tr>
</tbody>
</table>

Travel time loss $\Delta T$:

\[ \Delta T = \frac{L_d}{v_d} - \frac{L_o}{v_o} = \left( \frac{19.3}{60} - \frac{15.6}{90} \right) \times 60 = 8.9 \]

(a) Fragility curve

(b) Rainfall hazard curve:

\[ \Psi(\alpha) = 1 - \exp\left(-e^{-a(\alpha-b)}\right) \]
1. Rainfall hazard curve

\[ \Psi(\alpha) = 1 - \exp\left[-e^{-(\alpha-b)}\right] \]

\(a=0.0287 \text{ and } b=81.87\)

2. Hazard probabilistic density

\[ p_\alpha = \int_0^\infty p_f(\alpha) \varphi(\alpha) d\alpha = -\int_0^\infty p_f(\alpha) \frac{\partial \Psi(\alpha)}{\partial \alpha} d\alpha \]

\[ p_\alpha = -\int_0^\infty p_f(\alpha) \frac{\partial \Psi(\alpha)}{\partial \alpha} d\alpha = \sum_{j=1}^{\infty} p_i(\alpha_j) [\psi(\alpha_{j+1}) - \psi(\alpha_j)] \]
Stability Analysis and Risk Evaluation

Reliability-Based Slope Stability Analysis (based on FOSM)

- Reliability index: \[ \beta = \frac{\mu_x}{\sigma_x} = \frac{-\sum_i x_i^c \left( \frac{\partial g}{\partial X_i} \right)_{x_i}}{\sqrt{\sum_i \left( \sigma_i^2 \frac{\partial g}{\partial X_i} \right)^2}} \]

- Prob. of failure: \[ P_f = 1 - \Phi(\beta) \]

Risk Evaluation Related to Arrival of Hazard

- Annual prob. of failure: (considering exceedance prob. of hazard) \[ P_a = -P_f \left( \alpha \right) \left( \frac{\partial \psi(\alpha)}{\partial \alpha} \right) d\alpha \]

- Annual risk: (considering socio-economic losses due to slope fail) \[ R_s(x) = P_a \times L \]
Example

Evaluation of Risk (Expected Loss) Caused by Slope Failure Adjacent to National Road

Consequence: $C$

$C = C_1 + C_2$

- $C_1$: Direct Loss
- $C_2$: Indirect Loss due to Diversion

(Result of Consequence)
Priority of Slope to be Reinforced Based on Evaluated Risk

\[ R_{ai} = \int_{0}^{\infty} R_i(\alpha) \varphi(\alpha) d\alpha = -\int_{0}^{\infty} R_i(\alpha) \frac{\partial \psi(\alpha)}{\partial \alpha} d\alpha \]

\[ R_i(\alpha) = C \cdot p_i(\alpha) \]

**Human Security Engineering**

- Young Vietnamese people generally are **not interesting in Engineering**.
- Even if Some Young Vietnamese people are interested in Engineering fields, their concerns are **usually IT and advanced technology**.
- Young Vietnamese people are **fancied more with business/financial management** than “Engineering”.

Engineering requires to combine **engineering principles** with interdisciplinary knowledge such as **sound business practices and socio-economic theory**, which are relating to logical approach to decision-making.

The above features may attract concerns of Young Vietnamese people.
Thank you for your attention

Xin cảm ơn