# Scour Vulnerability Evaluation of Pile Foundations During Floods for National Highway Bridges

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2012. 8. 29

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# Introduction

## Bridge failure due to scour

- After disasters caused by big typhoons Rusa (2002) and Maemi (2003), the failures of even large bridges attracted more concerns on scour problem in Korea.

**Gam-cheon railroad bridge failure(2002)**
**Typhoon 'Rusa'**

**Gu-po bridge failure(2003)**
**Typhoon 'Maemi'**

# Research Purposes

## Prioritization Based on Vulnerability

- Prior researches : analysis, inspection, and countermeasure
- For the reasonable plan of action, vulnerability evaluation and prioritization is needed
- Bridge Scour Management System (BSMS) (2005) based on (1) GIS DB and (2) Prioritization
- Scour vulnerability evaluation and prioritization → real twelve highway bridges with pile foundations located in central part of Korean peninsula

# Scour Vulnerability Evaluation

## Concept of foundation vulnerability to scour

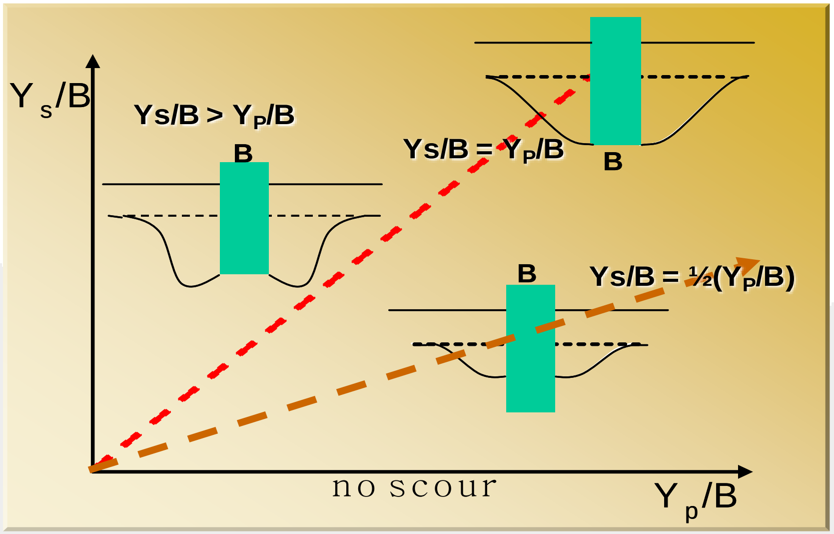
- Determination of scour vulnerability
  - hydraulic instability
  - structural instability
  - geotechnical instability

- Geotechnical factors in the analysis of scour vulnerability has recently been acknowledged.
- Studies in the past was generally focused on geometrical and physical conditions in analysis.

- During scour
  - displacements and rotations of piers could be induced (serviceability)
  - bearing capacity reduces (ultimate)

- The <u>failure</u> of bridge is mainly related to the <u>ultimate limit states (bearing capacity problem</u>) of the foundation.

# Vulnerability Evaluation


- Simple method using scour depth($Y_s$), foundation embedded depth($Y_p$), foundation width (B) (De Falco et al., 1997) – geometrical concept
- Geotechnical factors brought in the analysis of the vulnerability to scour of shallow foundation (Federico et al., 2003)

## Scour vulnerability prioritization : totally 5 Grades

- Expanded method applicable to both of shallow foundation and pile foundation
- For the maintenance, expected scour depth ≥ foundation embedded depth ( $Y_s \geq Y_P$ ):
  → Grade 1
- Expected scour depth < foundation embedded depth ( $Y_s < Y_P$ ):
  - 3 areas : $S.F._{(scour)} < 1.0$ $\xi \geq 3.0$ → Grade 2
  - $1.0 \leq S.F._{(scour)} < 2.0$ , $1.5 \leq \xi < 3.0$ → Grade 3
  - $S.F._{(scour)} \geq 2.0$ , $1.0 \leq \xi < 1.5$ → Grade 4

5 Grades

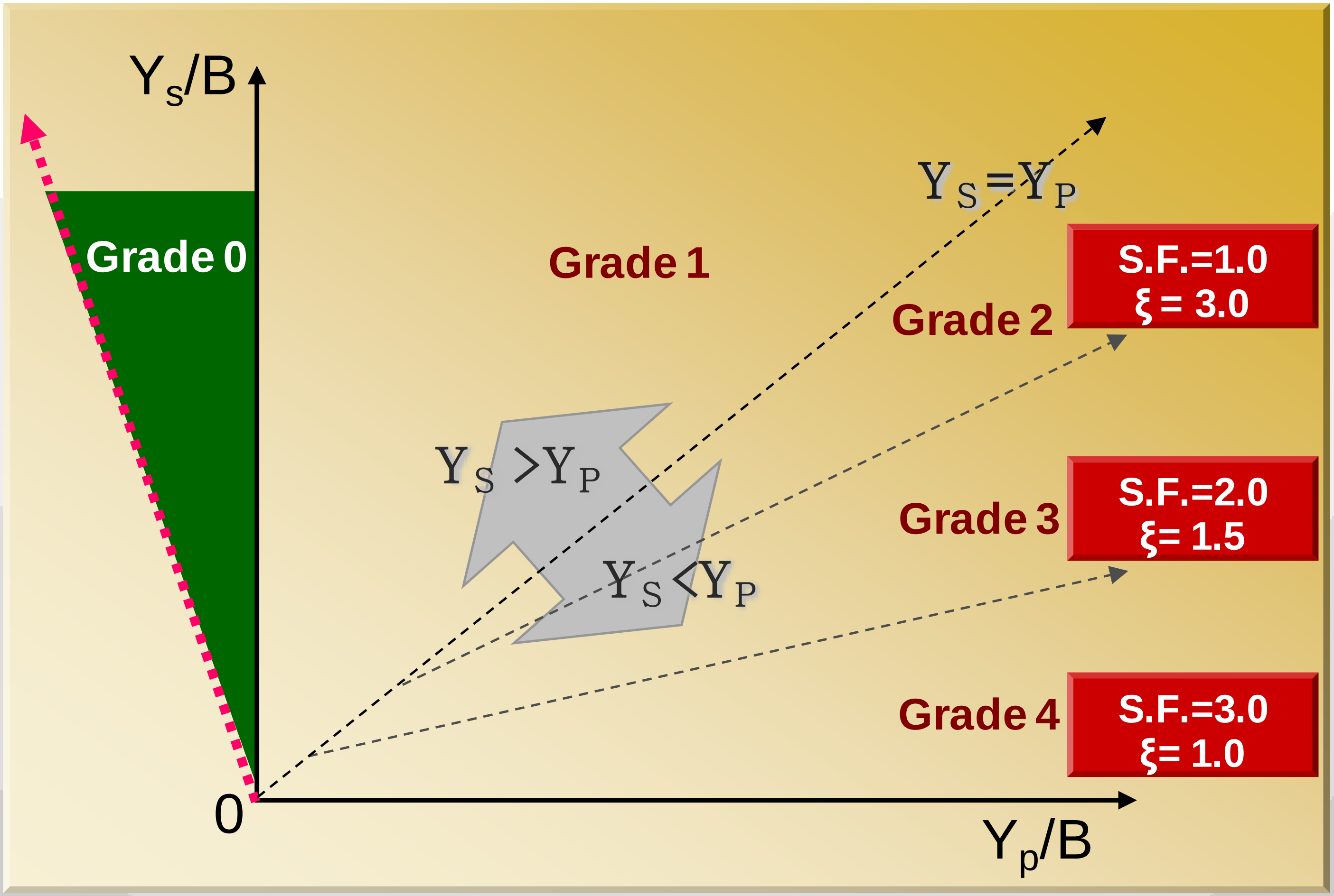
- **Vulnerability ratio(ξ)** : bearing capacity ratio between before and after scouring

$$\xi = \frac{Q_u^{normal}}{Q_u^{scour}} = \frac{Q_a \times (S.F.)_{normal}}{Q_a \times (S.F.)_{scour}} = \frac{S.F._{normal}}{S.F._{scour}}$$

Qu = Ultimate Bearing Capacity
Qa= allowable Bearing Capacity
S.F. = Safety Factor

- Adjust grade according to present field condition (with engineering judgment)
  - bridge in need of urgent measure → Grade 0
  - bridge in worse condition - upgrade the calculated level
  - bridge in sound condition - fix the calculated level

## Scour Vulnerability Prioritization : totally 5 Grades



# Case Study of Piles

# Scour Analysis

- **Hydraulic, geotech., structural information on bridge foundation.**
- **Scour analysis is performed in worst condition of 100yr design flood.**

- **All 12 cases have non-cohesive material -> scour depth calculation :**
  - **- CSU, Froehlich, Laursen, Neill**
  - **- The equations incorporate different variables**
    **→ inherently different scour depths calculated**
  - **- Representative scour depth : avg. value of scour depths accepted**

- **Considering geological stratum in subsurface from boring test.**
  - **- soft and hard rocks are not erodible in this study**

# Scour Analysis

## CSU

$$y_s = 2.0\,K_1\,K_2\,K_3\,K_4\,a^{0.65}\,y_1^{0.35}\,Fr_1^{0.43}$$

Where: $y_s$ = Depth of scour in feet (m)
$K_1$ = Correction factor for pier nose shape
$K_2$ = Correction factor for angle of attack of flow
$K_3$ = Correction factor for bed condition
$K_4$ = Correction factor for armoring of bed material
a = Pier width in feet (m)
$y_1$ = Flow depth directly upstream of the pier in feet (m). This is taken from the flow distribution output for the cross section just upstream from the bridge.
$Fr_1$ = Froude Number directly upstream of the pier. This is taken from the flow distribution output for the cross section just upstream from the bridge.

## Neill

Ys/b = 1.5 (y/b)0.3

## Froehlich

$$y_s = 0.32\,\phi\,(a')^{0.62}\,y_1^{0.47}\,Fr_1^{0.22}\,D_{50}^{-0.09} + a$$

where: $\phi$ = Correction factor for pier nose shape: $\phi = 1.3$ for square nose piers; $\phi = 1.0$ for rounded nose piers; and $\phi = 0.7$ for sharp nose (triangular) piers.
$a'$ = Projected pier width with respect to the direction of the flow, feet (m)

## Laursen

$$\frac{y_c}{y_a} = \left(\frac{Q_c}{Q_a}\right)^{6/7}\left(\frac{W_a}{W_c}\right)^{A}\left(\frac{n_c}{n_a}\right)^{B}$$

and

$$y_s = y_c - y_a$$

where
$y_s$ = scour depth (ft)
$y_a$ = average depth in the main reach (ft)
$y_c$ = average depth in the contracted section (ft)
$W_a$ = width of the main reach (ft)
$W_c$ = width of the contracted section (ft)
$Q_a$ = flow in the main reach (cfs)
$Q_c$ = flow in the contracted section (cfs)
$n_a$ = Manning n for main reach ($s/ft^{1/3}$)
$n_c$ = Manning n for contracted section ($s/ft^{1/3}$)

# Scour Depth Calculation

## Basin information of bridges, piles, and streams

| No. | Bridge code | Bridge length (m) | Maximum span length (m) | Pile embed depth (m) | Stream bed slope | 100-year Design flood ($m^3$/sec) | 100-year Design water depth (m) | 100-year Design water velocity (m/s) |
|---|---|---|---|---|---|---|---|---|
| 1 | GC | 65 | 25.0 | 11.7 | 0.007 | 530 | 2.77 | 3.87 |
| 2 | HS | 75 | 16.3 | 17.9 | 0.001 | 577 | 3.50 | 2.24 |
| 3 | NC | 90 | 30.0 | 9.2 | 0.007 | 361 | 2.45 | 1.96 |
| 4 | DM | 124 | 31.0 | 18.3 | 0.006 | 1,286 | 4.02 | 3.81 |
| 5 | IW1 | 44 | 16.0 | 13.0 | 0.004 | 250 | 3.12 | 2.59 |
| 6 | JA | 108 | 27.0 | 24.9 | 0.001 | 480, | 3.14 | 1.66 |
| 7 | JS | 205 | 53.0 | 14.1 | 0.004 | 1,125 | 2.63 | 4.10 |
| 8 | NP | 65 | 14.0 | 23.6 | 0.002 | 487 | 4.58 | 2.42 |
| 9 | NC1 | 85 | 42.5 | 17.5 | 0.011 | 500 | 3.80 | 3.48 |
| 10 | YA1 | 62 | 17.0 | 7.9 | 0.021 | 145 | 3.00 | 1.38 |
| 11 | CH | 91 | 30.2 | 6.7 | 0.001 | 590 | 6.15 | 2.00 |
| 12 | GE | 100 | 20.0 | 7.9 | 0.006 | 650 | 7.03 | 1.67 |

- **12 pile foundation bridges selected for the analysis**
- **Bridge length : 44~205m , Pile embedded depth : 6.7m ~ 24.9m**
- **streambed slope : 0.001 ~ 0.011 , 100yr water depth : 2.45 ~ 7.03m**
- **100yr water velocity : 1.66 ~ 4.10 m/s**

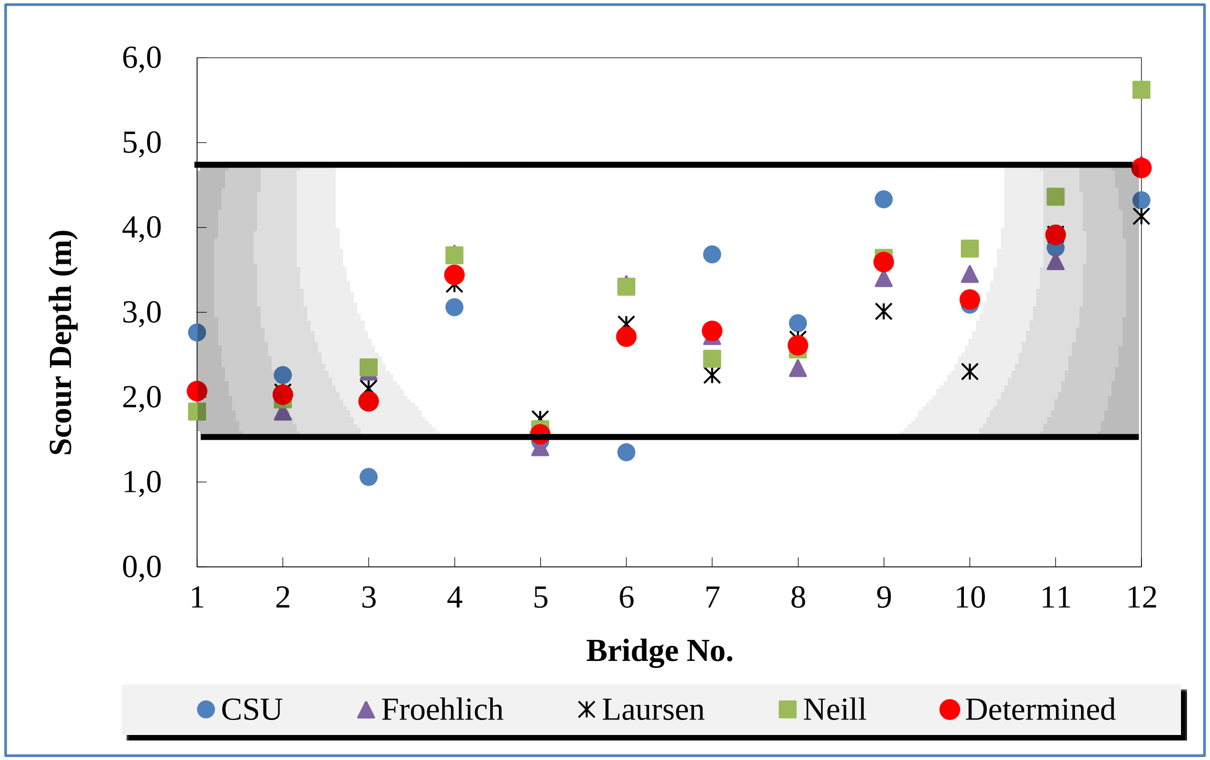
# Scour Depth Calculation

## Scour depth calculation results

| No. | Bridge code | Streambed particle size (mm) | | | | Rock depth (m) | Pier width (m) | Pier length (m) | Calculated scour depth(m) | | | | Determined (Average) scour depth (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $D_{10}$ | $D_{50}$ | $D_{60}$ | $D_{95}$ | | | | CSU | Froehlich | Laursen | Neill | |
| 1 | GC | 0.09 | 1.00 | 1.57 | 15.0 | 13.2 | 1.0 | 1.0 | 2.76 | 1.84 | 1.83 | 1.83 | **2.1** |
| 2 | HS | 0.37 | 0.81 | 0.96 | 1.70 | 21.5 | 3.6 | 16.0 | 2.26 | 1.83 | 2.06 | 1.97 | **2.0** |
| 3 | NC | 0.08 | 4.00 | 6.98 | 30.00 | 7.5 | 4.8 | 22.3 | 1.06 | 2.30 | 2.10 | 2.35 | **2.0** |
| 4 | DM | 0.21 | 6.00 | 8.83 | 30.00 | 5.9 | 6.5 | 8.5 | 3.06 | 3.69 | 3.33 | 3.67 | **3.4** |
| 5 | IW1 | 0.21 | 6.00 | 11.75 | 34.00 | 12.4 | 3.6 | 12.0 | 1.48 | 1.41 | 1.74 | 1.62 | **1.6** |
| 6 | JA | 0.42 | 2.20 | 2.69 | 6.50 | N/A | 4.0 | 20.8 | 1.35 | 3.33 | 2.86 | 3.30 | **2.7** |
| 7 | JS | 0.12 | 0.25 | 0.28 | 1.00 | N/A | 5.0 | 8.0 | 3.68 | 2.72 | 2.26 | 2.45 | **2.8** |
| 8 | NP | 0.12 | 1.50 | 3.89 | 33.0 | N/A | 4.0 | 11.5 | 2.87 | 2.34 | 2.68 | 2.56 | **2.6** |
| 9 | NC1 | 0.35 | 1.11 | 1.51 | 12.91 | N/A | 2.0 | 2.0 | 4.33 | 3.40 | 3.01 | 3.64 | **3.6** |
| 10 | YA1 | 0.31 | 1.62 | 2.33 | 11.17 | N/A | 1.2 | 1.2 | 3.09 | 3.45 | 2.30 | 3.75 | **3.2** |
| 11 | CH | 0.46 | 1.61 | 1.94 | 4.39 | N/A | 1.8 | 1.8 | 3.76 | 3.60 | 3.92 | 4.36 | **3.9** |
| 12 | GE | 0.45 | 1.09 | 1.39 | 5.41 | N/A | 2.0 | 2.0 | 4.32 | 4.74 | 4.13 | 5.62 | **4.7** |

# Scour Depth Calculation

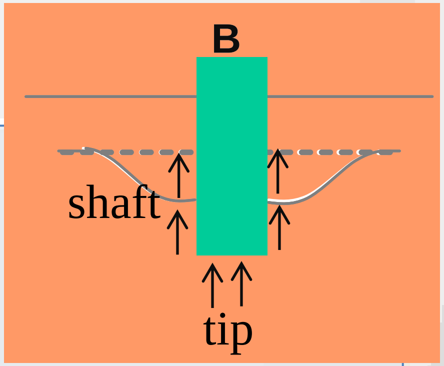
## Scour depth calculation results




- **Expected scour depth : 1.6 – 4.7m**
- **CSU : smaller scour depth in case large size particle exists due to armoring effect (3,4,6,12)**
- **Froehlich : larger scour depth than Laursen and Neill due to considering inflow angle of water**

# Scour Vulnerability

## Bearing capacity calculation




- **Bearing capacity of pile = tip resistance +shaft resistance**

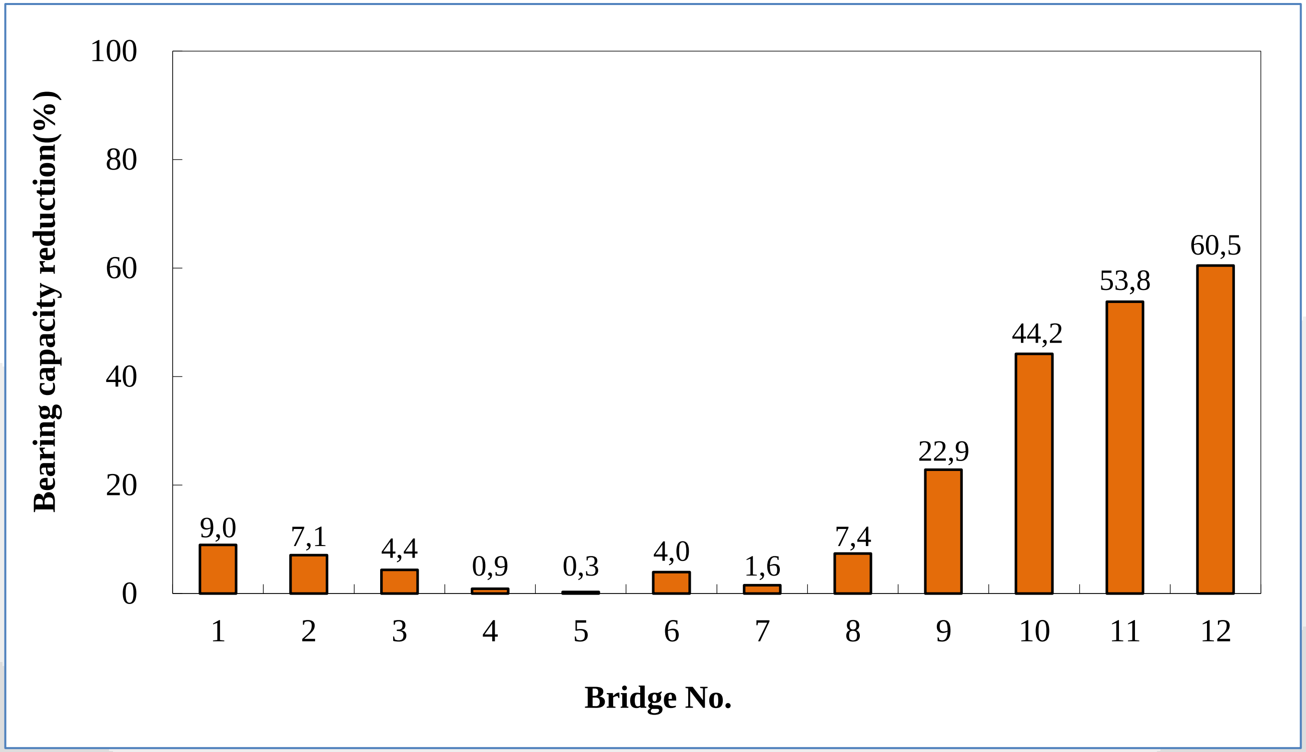
$$(\sigma'_v N_q + cN_c)A_p \qquad \sum f_s A_s$$

- **Bearing capacity reduction due to scour :**
  - **tip : overburden pressure ($\sigma_v$') reduction**
  - **shaft : resistance reduction of exposed area to the flow due to scour**

| No. | Bridge code | Pile embedded length (m) | Scour depth (m) | Bearing capacity(tonf) | | Bearing capacity reduction (%) | Scour vulnerability (ξ) | S.F. after scour | Scour vulnerability prioritization |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Before scour | After scour | | | | |
| 1 | GC | 11.7 | 2.1 | 66.8 | 60.8 | 9.0 | 1.01 | 2.96 | 4 |
| 2 | HS | 17.9 | 2.0 | 59.2 | 55.0 | 7.1 | 1.01 | 2.98 | 4 |
| 3 | NC | 9.2 | 2.0 | 115.7 | 110.6 | 4.4 | 1.00 | 3.00 | 4 |
| 4 | DM | 18.3 | 3.4 | 1195.3 | 1184.6 | 0.9 | 1.00 | 3.00 | 4 |
| 5 | IW1 | 13.0 | 1.6 | 59.6 | 59.4 | 0.3 | 1.00 | 3.00 | 4 |
| 6 | JA | 24.9 | 2.7 | 108.8 | 104.5 | 4.0 | 1.02 | 2.95 | 4 |
| 7 | JS | 14.1 | 2.8 | 76.9 | 75.7 | 1.6 | 1.00 | 3.00 | 4 |
| 8 | NP | 23.6 | 2.6 | 73.0 | 67.6 | 7.4 | 1.02 | 2.94 | 4 |
| 9 | NC1 | 17.5 | 3.6 | 359.4 | 277.2 | 22.9 | 1.30 | 2.31 | 4 |
| 10 | YA1 | 7.9 | 3.2 | 171.1 | 95.5 | **44.2** | **1.79** | **1.67** | **3** |
| 11 | CH | 6.7 | 3.9 | 20.8 | 9.6 | **53.8** | **2.16** | **1.38** | **3** |
| 12 | GE | 7.9 | 4.7 | 145.0 | 57.3 | **60.5** | **2.53** | **1.19** | **3** |

# Scour Vulnerability

## Bearing capacity calculation




- **reduction (%) = 1-(bearing capacity after scour / bearing capacity before scour)**
- **Piles has large embedded depth so that they are more stable to scour than spread footings.**
- **Three (10, 11, 12), however, exhibit considerable reduction in resistance after scour in the range of 44% ~ 60% → significant negative effects such as lateral displacement as well as axial resistance problem**

# Conclusions

# Conclusions

**Introduction**

-**Bridge scour vulnerability prioritization** is introduced with multidisciplinary concept using the correlation between bridge scour and bearing capacity of foundation.

**Scour depth calculation**

-Scour depths were estimated using: (1) the CSU equation; (2) the Froehlich's equation; (3) the Laursen's equation; and (4)the Neill's equation. → 1.6~4.7m

**-Different scour depths due to different variables considered in equations**

**Scour vulnerability analysis**

-Scour vulnerability evaluation results show that three of 12 pile foundation have potential risk of failure due to scour. It is noted that **pile foundations may have considerable decrease in their bearing capacity due to scour.**

**-Ongoing research has started to apply this to offshore structures**

Korea Institute of Construction Technology

Toward High Performance Organization..

**Thanks for attention !**

## Conditions related to scour in Korea

**Geographical**

- mountainous area
  - 70 of the territory
- high avg. streambed slope
- non-cohesive materials

**Climatic**

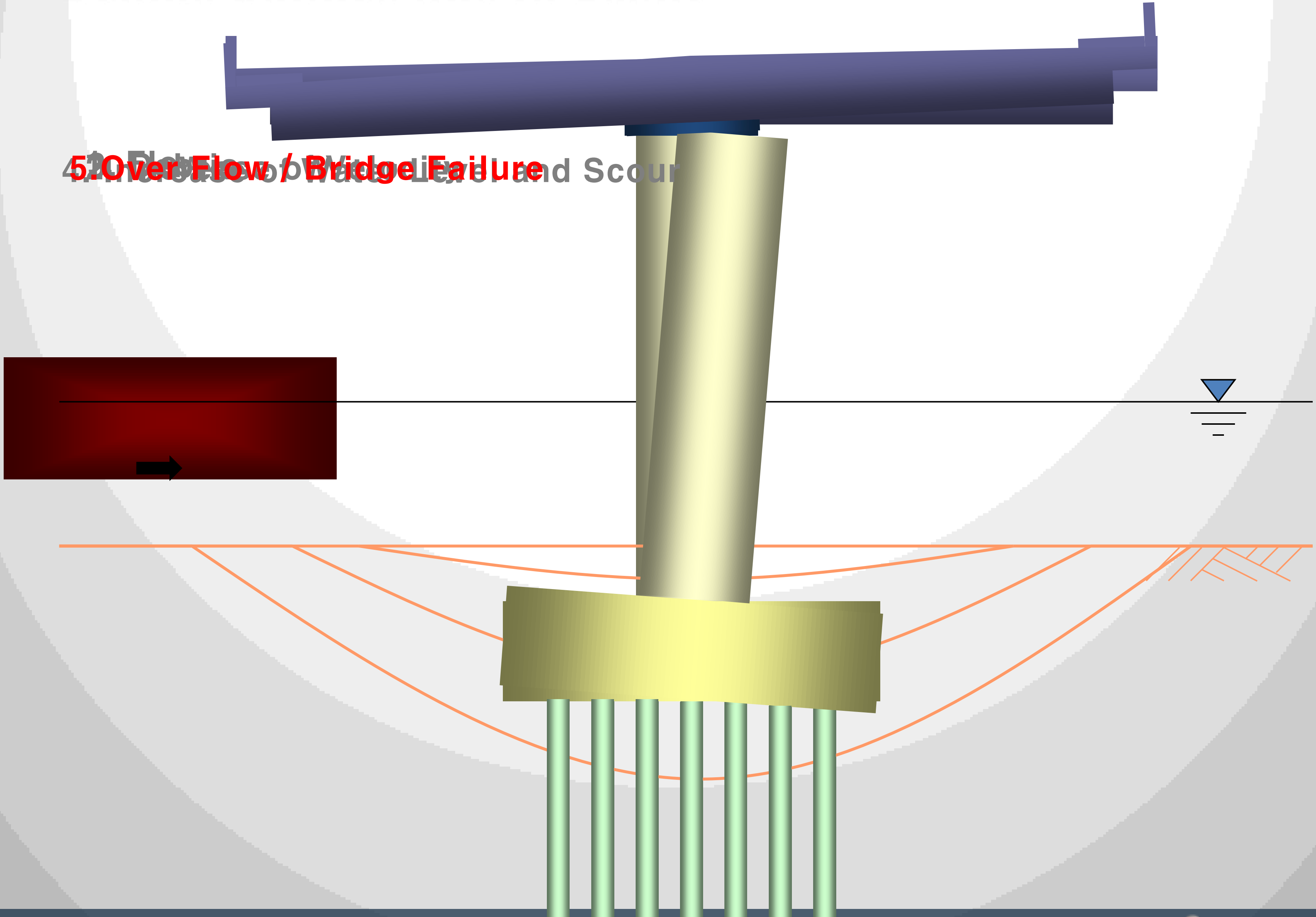
- uneven seasonal rainfall distribution
  - 2/3 annual precipitation
  - several typhoons
- extremely variable annual precipitation

**Lots of bridge foundations annually damaged due to scour**

# Bridge Failure due to Scour

**5. Over Flow / Bridge Failure**

4. Increase of Water Level and Scour



## Concept of foundation vulnerability to scour

- **Significant factors governing soil scour and bearing capacity of foundation**
  - shape and size of foundation
  - hydraulic characteristics of the flow
  - physical and mechanical properties of ground
  - estimated scour depth and present field condition

- **Scour analysis**
  - appropriate scour model with geotechnical characteristics
  - accurate design floods with hydraulic characteristics

- **Bearing capacity of bridge foundation : bed material , foundation type**
  - spread footing (Federico et al., 2003)
  - pile foundation