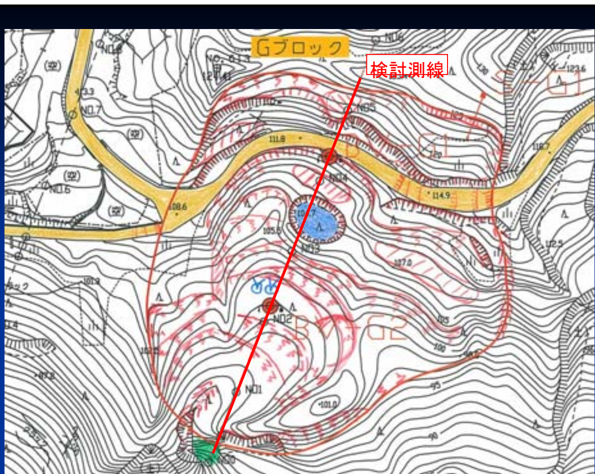
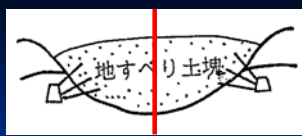
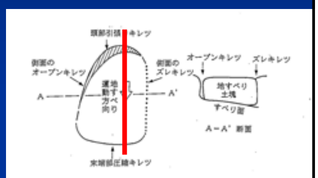
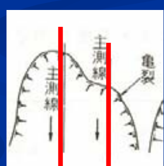
# Slope Stability Analysis



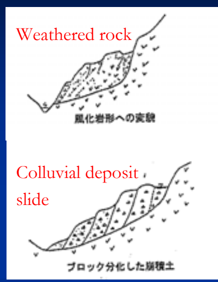






(after Watari and Kobashi, 1986)

- (Main) survey control line for slope stability analysis
  - Direction of landslide movement
  - Middle of landslide (max. depth)
  - Perpendicular to the scarp at crest
  - Parallel to the lateral scarp

# Factor of Safety




- Typical allowable decrease of FS
  - Colluvial deposit slide 3%
  - Weathered rock slide 5%
- Initial FS
  - Continuous movement without rainfall FS=0.95
  - Continuous movement with rainfall FS=0.98
  - No significant movement FS=1.00
- Designed (planned) FS
  - Temporary works FS=1.05
  - Permanent works FS=1.12 - 1.20

# Slope stability analysis

- ***Conventional method***
- *Probable rainfall approach*

Analysis method — Ordinary method of slice

Current (initial) FS — FS=0.95-1.00; Field investigation; Monitoring

Geometry — Geometry of slope, slip surface, groundwater; Topographic & field investigation; Monitoring

Unit weight — $\gamma$ = 18 kN/m³

Cohesion (C) — C (kN/m²) = Depth of slip surface (m)

Friction angle ( $\phi$ )

↓ Back-calculation

Planned FS

↓ FS=1.05-1.20

FS with control measures

↓ Earth removal, fill, gravity drains, drainage well etc

End force to satisfy Planned FS

| Max. depth of slip surface (m) | C (kN/m²) |
|---|---|
| 5 | 5.0 |
| 10 | 10.0 |
| 15 | 15.0 |
| 20 | 20.0 |
| or above | 25.0 |

$$Fs = \frac{\sum (N-U)\tan\phi + C\sum L}{\sum T}$$

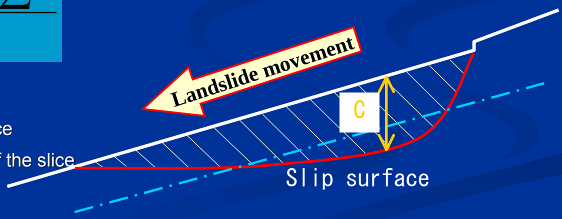
L: length of failure surface

N: normal force on the base of the slice

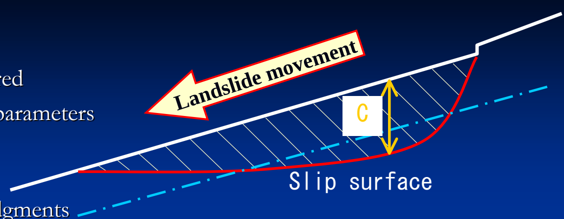
U: pore water pressure on the base of the slice

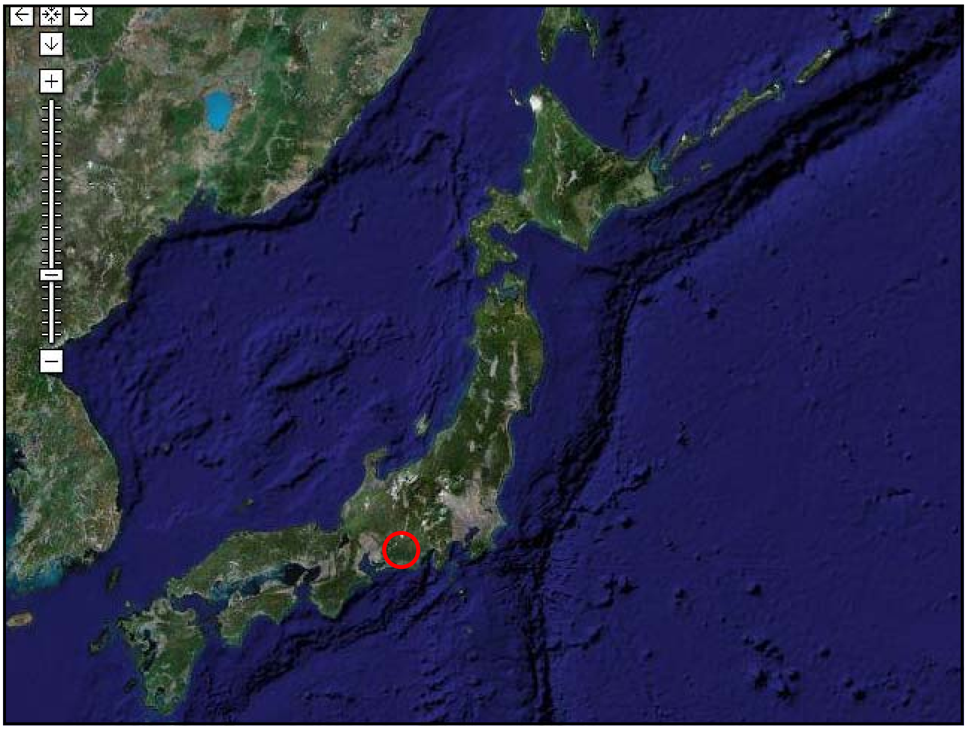
S: landslide resisting force

T: landslide force




- Advantages
  - No sample required
  - No laboratory test required
  - Easy to obtain strength parameters
- Limitations
  - Required engineering judgments
    - Initial factor of safety
    - Geometry (slope & slip surface geometries)
    - Groundwater is variable!

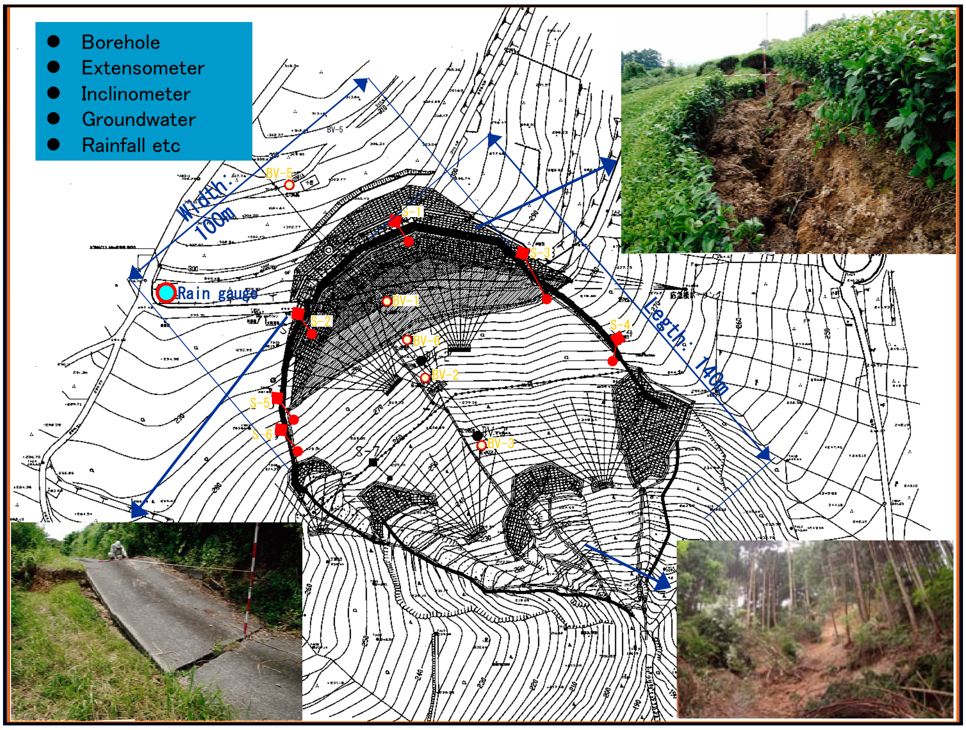


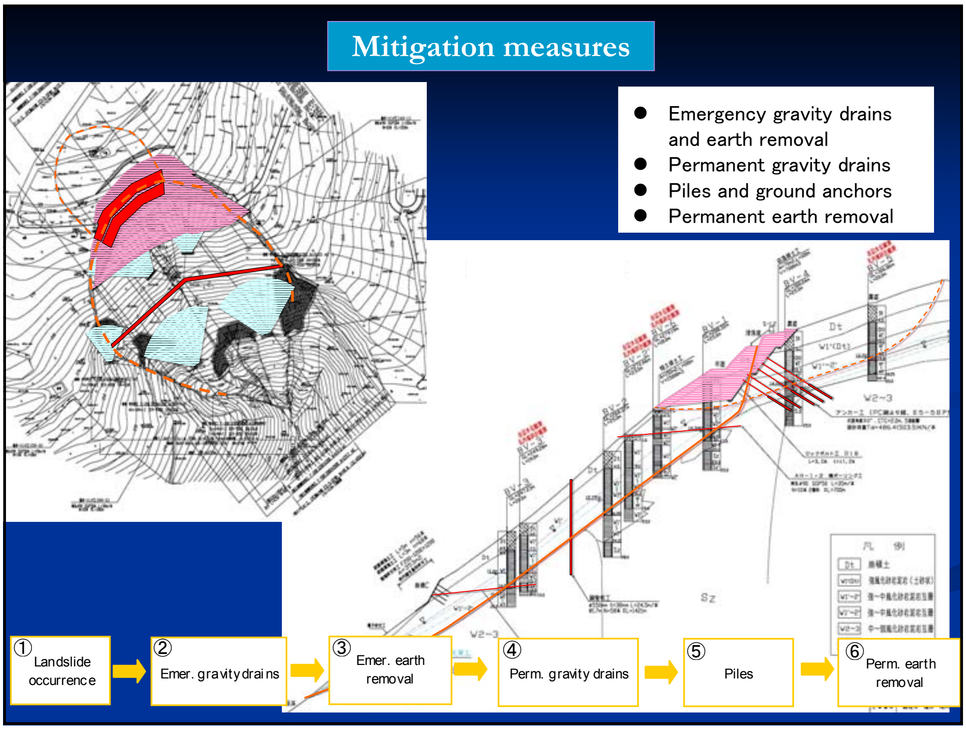
Width: 100m
Volume:
150,000m3
Length: 140m
Debris flow

Scarp near the crest
Left side lateral scarp
Right side lateral scarp


1
2
3
4
5
6



Borehole
Extensometer
Inclinometer
Groundwater
Rainfall etc
Width: 100m
Rain gauge
Length: 140m

Mitigation measures
Emergency gravity drains and earth removal
Permanent gravity drains
Piles and ground anchors
Permanent earth removal
① Landslide occurrence
② Emer. gravity drains
③ Emer. earth removal
④ Perm. gravity drains
⑤ Piles
⑥ Perm. earth removal

Analysis method — Ordinary method of slices

Current (initial) FS — FS = 0.95

Geometry — slope, slip surface, grounwater

Unit weight — 18 kN/m$^3$

Cohesion (C) — 17 kN/m$^2$

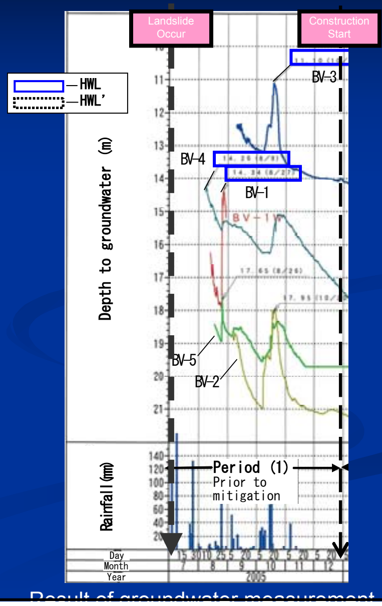
Friction angle ($\phi$) — 32.01 °

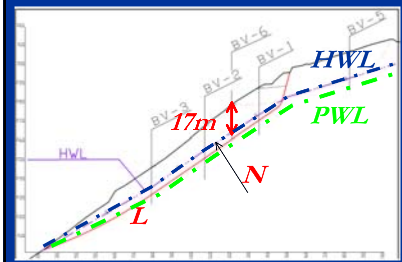
Planned FS — FS = 1.20

FS with control measures — Emer. & perm. earth removal and gravity drain

End force to satisfy Planned FS

$$Fs = \frac{\sum (N-U)\tan\phi + C\sum L}{\sum T}$$




Result of groundwater measurement

Analysis method — Ordinary method of slices

Current (initial) FS — FS = 0.95

Geometry — slope, slip surface, grounwater

Unit weight — 18 kN/m$^3$

Cohesion (C) — 17 kN/m$^2$

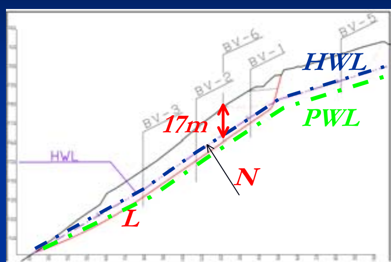
Friction angle ($\phi$) — 32.01 °

Planned FS — FS = 1.20

FS with control measures — Emer. & perm. earth removal and gravity drain

End force to satisfy Planned FS

$$Fs = \frac{\sum (N-U)\tan\phi + C\sum L}{\sum T}$$

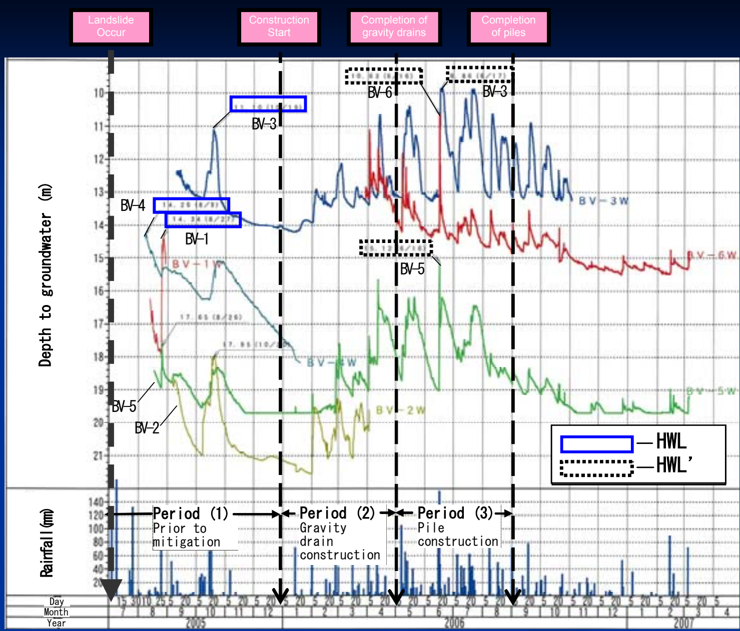



① Landslide occurrence Fs1 = 0.950 → +3% → ② Emer. gravity drains Fs = 0.980 → +2% → ③ Emer. earth removal Fs = 1.000 → +9.7 →

Fs (plan): ④ Perm. gravity drains Fs = 1.071 → +10.3 → ⑤ Piles Fs = 1.174 Pr = 1548.1kN/m → +2.6% → ⑥ Perm. earth removal Fs = 1.200

C=17.0kN/m²

φ=32.01°(tanφ=0.6251)




Result of groundwater measurement

# Conventional method

① Landslide occurrence Fs1 = 0.950 → (+3%) ② Emer. gravity drains Fs = 0.980 → (+2%) ③ Emer. earth removal Fs = 1.000 → (+9.7)

C=17.0kN/m²
φ=32.01°(tanφ=0.6251)

Fs (plan): ④ Perm. gravity drains Fs = 1.071 → (+10.3) ⑤ Piles Fs =1.174 Pr = 1548.1kN/m → (+2.6%) ⑥ Perm. earth removal Fs = 1.200

Fs (actual): ⑦ Perm. gravity drains Fs = 0.905 → ⑧ Piles Fs =0.999 Pr = 1548.1kN/m → ⑨ Perm. earth removal Fs = 1.019

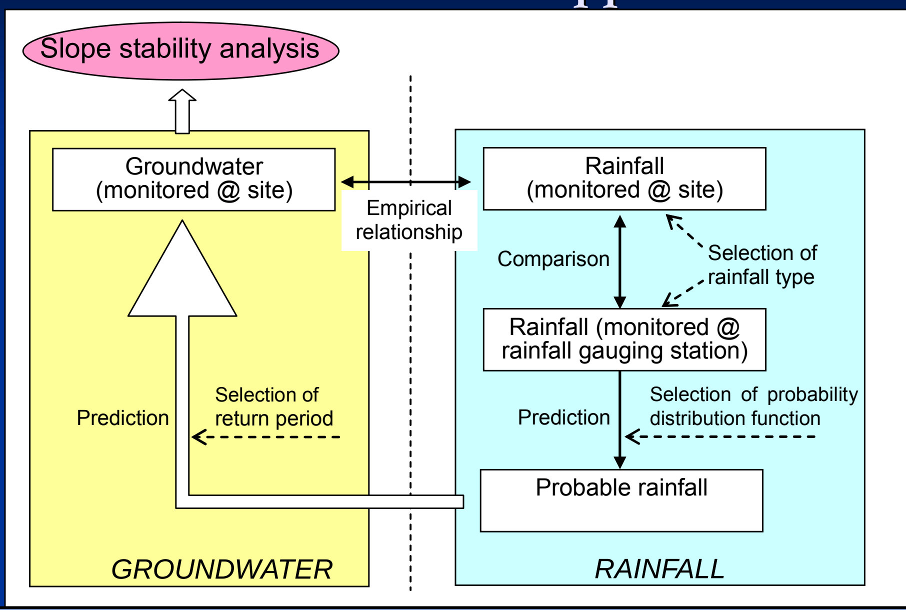
**Conventional method are very sensitive to the groundwater input!**

- Municipal landslide control projects
- Groundwater monitoring could be in the dry season
- Urgent landslide mitigation
- Bending of boreholes & casings

# Slope stability analysis

- Conventional method
- Probable rainfall approach

# Probable rainfall approach



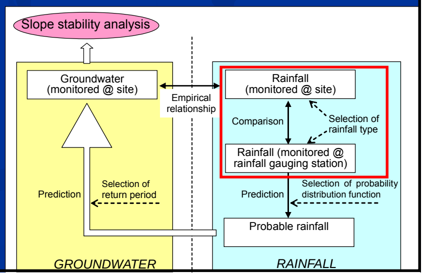
| | Monthly rainfall (mm) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1月 | 2月 | 3月 | 4月 | 5月 | 6月 | 7月 | 8月 | 9月 | 10月 | 1月 | 12月 | Sum |
| ①Landslide | 97. 0 | 222. 0 | 173. 5 | 342. 5 | 368. 0 | 379. 5 | 393. 0 | 243. 0 | 239. 0 | 143. 0 | 114. 5 | 98. 0 | 2813. 0 |
| ②Rainfall gauging station | 88. 0 | 204. 0 | 146. 0 | 315. 0 | 343. 0 | 354. 0 | 348. 0 | 271. 0 | 207. 0 | 136. 0 | 106. 0 | 92. 0 | 2610. 0 |
| (②/①) ×100% | 90. 7 | 91. 9 | 84. 1 | 92. 0 | 93. 2 | 93. 3 | 88. 5 | 111. 5 | 86. 6 | 95. 1 | 92. 6 | 93. 9 | 92. 8 |
| | Maximum daily rainfall (mm) | | | | | | | | | | | | Averag |
| ①Landslide | 72. 0 | 92. 0 | 57. 0 | 119. 5 | 105. 0 | 156. 0 | 62. 5 | 80. 0 | 77. 5 | 33. 0 | 27. 0 | 53. 5 | 77. 9 |
| ②Rainfall gauging station | 62. 0 | 88. 0 | 43. 0 | 107. 0 | 100. 0 | 135. 0 | 58. 0 | 84. 0 | 68. 0 | 28. 0 | 26. 0 | 65. 0 | 72. 0 |
| (②/①) ×100% | 86. 1 | 95. 7 | 75. 4 | 89. 5 | 95. 2 | 86. 5 | 92. 8 | 105. 0 | 87. 7 | 84. 8 | 96. 3 | 121. 5 | 93. 1 |
| | Maximum daily effective rainfall (n=30 days) (mm) | | | | | | | | | | | | Averag |
| ①Landslide | 72. 9 | 123. 4 | 136. 1 | 206. 8 | 189. 0 | 273. 4 | 193. 5 | 140. 2 | 124. 3 | 91. 8 | 58. 9 | 69. 7 | 140. 0 |
| ②Rainfall gauging station | 63. 5 | 116. 6 | 127. 7 | 192. 5 | 178. 2 | 255. 8 | 164. 6 | 137. 7 | 115. 2 | 84. 3 | 54. 5 | 72. 5 | 130. 3 |
| (②/①) ×100% | 87. 1 | 94. 5 | 93. 8 | 93. 1 | 94. 3 | 93. 6 | 85. 1 | 98. 2 | 92. 7 | 91. 8 | 92. 5 | 104. 0 | 93. 4 |

- Type of rainfall
  - Monthly rainfall
  - Max. daily rainfall
  - Max. daily effective rainfall

*Effective rainfall (Dn)*

$D_n = \alpha^{n-0} r_0 + \alpha^{n-1} r_1 + \dots\dots\dots\dots + \alpha^1 r_{n-1} + r^n$

$D_n$ : Effective rainfall after n days
$r_n$ : Daily rainfall after n days
$\alpha$ : Recession coefficient ($\alpha$ = 0.9)
n : Cumulated days




## *Effective rainfall (Dn)*

$D_n = \alpha^{n-0} r_0 + \alpha^{n-1} r_1 + \dots\dots\dots\dots + \alpha^1 r_{n-1} + r^n$

$D_n$ : Effective rainfall after n days
$r_n$ : Daily rainfall after n days
$\alpha$ : Recession coefficient
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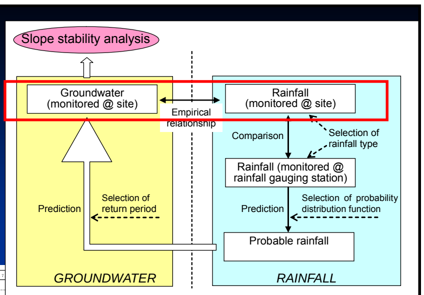
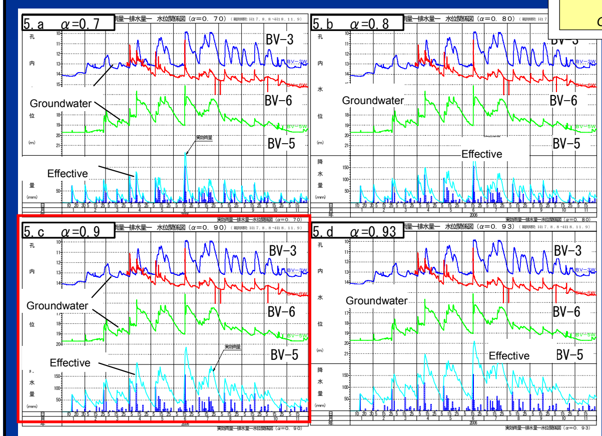
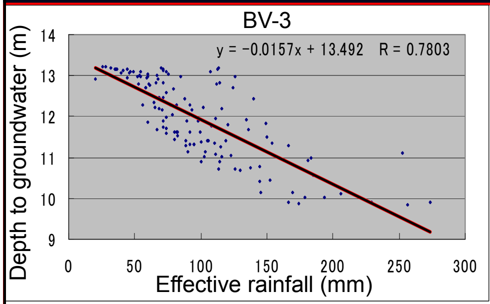


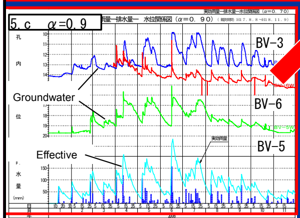

Effective rainfall with different recession coefficient α




Example of relationship between groundwater measurement and effective rainfall ($\alpha$ = 0.9)

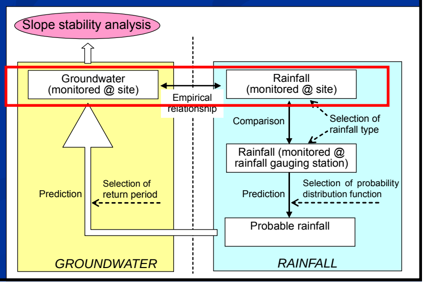
| Boring No. | Linear trend equation | R value |
|---|---|---|
| BV-1 | Y=-0.0366x+18.677 | R=0.9428 |
| BV-2 | Y=-0.0190x+20.932 | R=0.8635 |
| BV-3 | Y=-0.0157x+13.492 | R=0.7803 |
| BV-5 | Y=-0.0044x+19.133 | R=0.4390 |

Relationships between effective rainfall and groundwater levels ($\alpha$ = 0.9)




*Effective rainfall (Dn)*

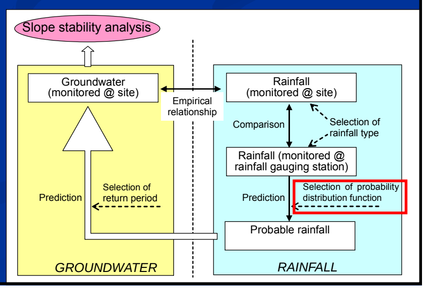
$$D_n = \alpha^{n-0} r_0 + \alpha^{n-1} r_1 + \dots\dots\dots\dots + \alpha^{1} r_{n-1} + r^n$$



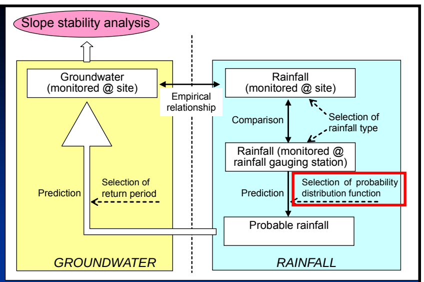

| Probability distribution function | |
|---|---|
| Normal distribution | Normal distribution |
| | Lognormal distribution (Iwai's Method) |
| Extreme value distribution | Gumbel distribution |
| | Log extreme value type A distribution |
| Gamma distribution | Exponential distribution |
| | Pearson type III distribution |
| | Log Pearson type III distribution |

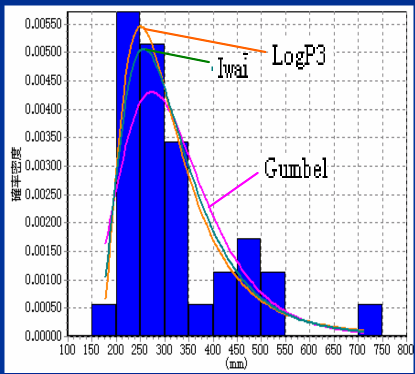
Commonly used hydrological distribution functions in Japan (after Japan River Association, 1997)

- Histogram
- Probability papers
- Standard least-square criterion (SLSC)



- **Histogram**
  - Shape of histogram – shape of probability density function

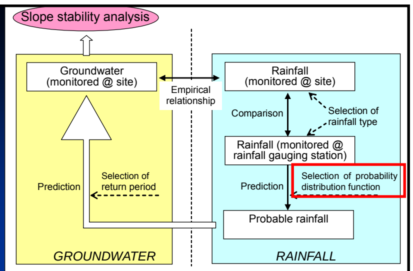


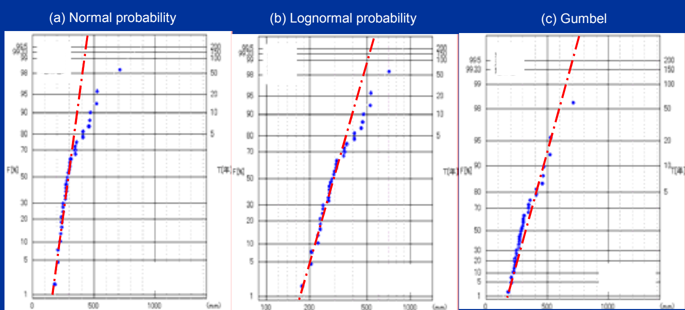




Relationship between histogram of effective rainfall and probability density functions

| Fitness | Histogram |
|---|---|
| good | ③Log Pearson type III distribution |
| ⇩ | ②Lognormal distribution (Iwai's Method) |
| bad | ①Gumbel distribution |

- **Probability papers**
  - The suitability of the probability paper is assessed by the linearity of data distribution on the paper.



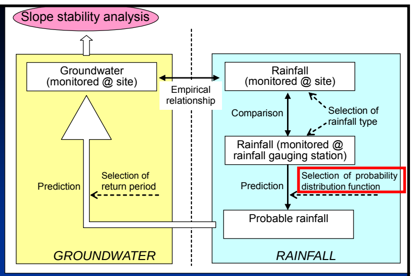

| Fitness | Probability paper |
|---|---|
| good | Gumbel paper ① |
| ⇩ | Lognormal probability paper ②,③ |
| bad | Normal probability paper |

Probability distribution functions plotted on normal probability paper, lognormal probability paper, and Gumbel paper

- Standard least-square criterion (SLSC)

$$SLSC = \frac{\sqrt{\xi^2_{min}}}{|S_{1-p} - S_p|}$$

  - Quantifies the fitness of the probability distribution function. Generally,
    - fairly good when SLSC ≈ 0.02 and
    - good when SLSC < 0.04



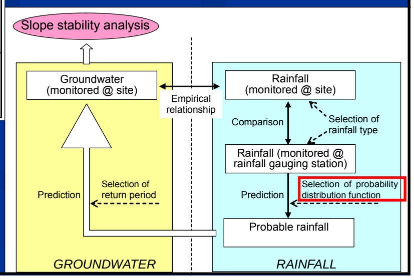

SLSC of daily and effective rainfall for Gumbel distribution, lognormal distribution (Iwai's method) and log Pearson type III distribution

| Type of rainfall | ①Gumbel distribution | ②Lognormal distribution (Iwai's method) | ③Log Pearson type III distribution |
|---|---|---|---|
| Effective rainfall | 0.045 | 0.030 | 0.026 |

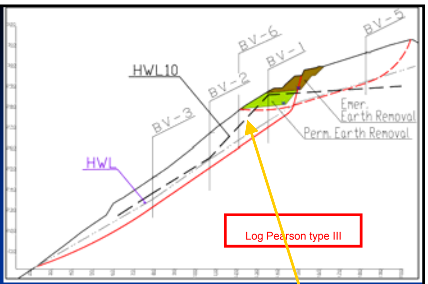
| Fitness | SLSC |
|---|---|
| good | ③Log Pearson type III distribution |
| ⇩ | ②Lognormal distribution (Iwai's Method) |
| bad | ①Gumbel distribution |

Summary of comparisons

| Fitness | Histogram | Probability paper | SLSC |
|---|---|---|---|
| good | ③Log Pearson type III distribution | Gumbel paper ① | ③Log Pearson type III distribution |
| ⇩ | ②Lognormal distribution (Iwai's Method) | Lognormal probability paper ②,③ | ②Lognormal distribution (Iwai's Method) |
| bad | ①Gumbel distribution | Normal probability paper | ①Gumbel distribution |

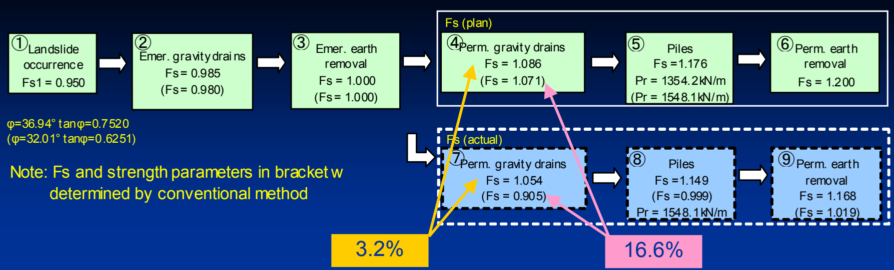


- Recommended return periods = 10 to 1000 years (Hong Kong; (GCO 1979))
- Return periods of 10 years and 1000 years are often used as key values (Endicott, 1982)
- The groundwater level of BV-1 located near the crest of landslide will be above the ground surface with rainfalls of more than 10 year return periods.

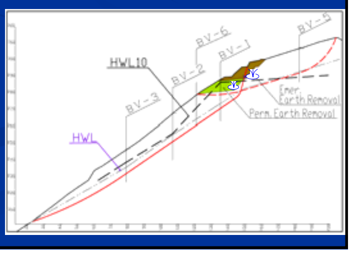



| Return period (Yr) | Probable rainfall (mm) (Y) | Pre-construction groundwater level (GL-m) (X) | | | |
|---|---|---|---|---|---|
| | | BV-1 | BV-2 | BV-3 | BV-5 |
| | | Y=-0.0365x+18.677 | Y=-0.0190x+20.932 | Y=-0.0157x+13.492 | Y=-0.0044x+19.133 |
| 200 | 884.8 | -13.707 | 4.121 | 3.267 | 15.240 |
| 100 | 769.5 | -9.487 | 6.312 | 4.593 | 15.747 |
| 50 | 666.4 | -5.713 | 8.270 | 5.778 | 16.201 |
| 30 | 597.3 | -3.184 | 9.583 | 6.573 | 16.505 |
| 20 | 546.0 | -1.307 | 10.558 | 7.163 | 16.731 |
| 10 | 464.7 | 1.669 | 12.103 | 8.098 | 17.088 |
| 5 | 389.7 | 4.414 | 13.528 | 8.960 | 17.418 |
| 2 | 293.7 | 7.928 | 15.352 | 10.064 | 17.841 |
| 1.5 | 260.6 | 9.139 | 15.981 | 10.445 | 17.986 |

HWL10

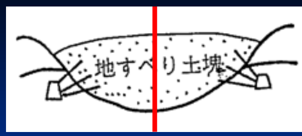


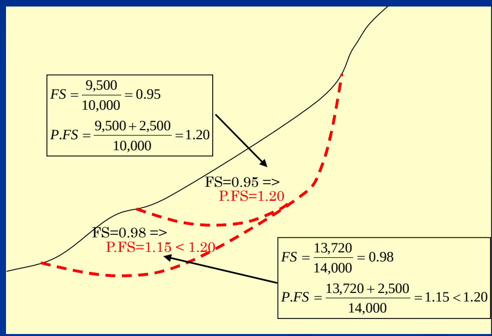

- Flow of factor of safety
- Pr = 1354.2 kN/m (approximately 12 % less than the conventional method)
- Probable rainfall approach has a possibility of yielding more appropriate results:
  - Friction angle
  - Groundwater
  - Difference between the planned Fs and the actual Fs
    - 16.6% with the conventional method
    - 3.2% with the probable rainfall approach
  - Effect of piles
    - Fs = 0.999 with conventional method
    - Fs = 1.149 with the probable rainfall approach
    - Effect of gravity drains evaluated as approximately 10 % increase in Fs

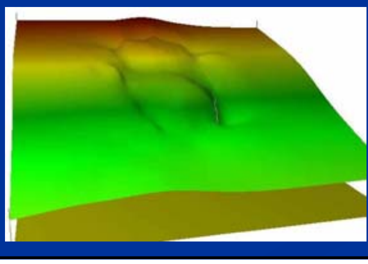


## Tips!

- Always analyze max. cross-sectional area
- Importance of data input
- Min. FS may not be equal to max. required force
- 2-D or 3-D analysis?
  - Require information
  - Time consuming
  - Engineering judgment
- Simplified 3-D analysis



(Godai Development Co. Ltd, 2006)

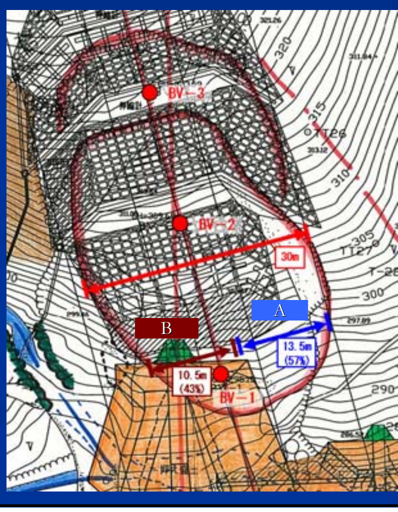
## Tips!

- Simplified 3-D analysis

$$Fs = \frac{ka\left[\tan\phi a(\Sigma Na - \Sigma Ua) + Ca \times \Sigma La\right] + kb\left[\tan\phi b(\Sigma Nb - \Sigma Ub) + Cb \times \Sigma Lb\right]}{ka\Sigma Ta + kb\Sigma Tb}$$

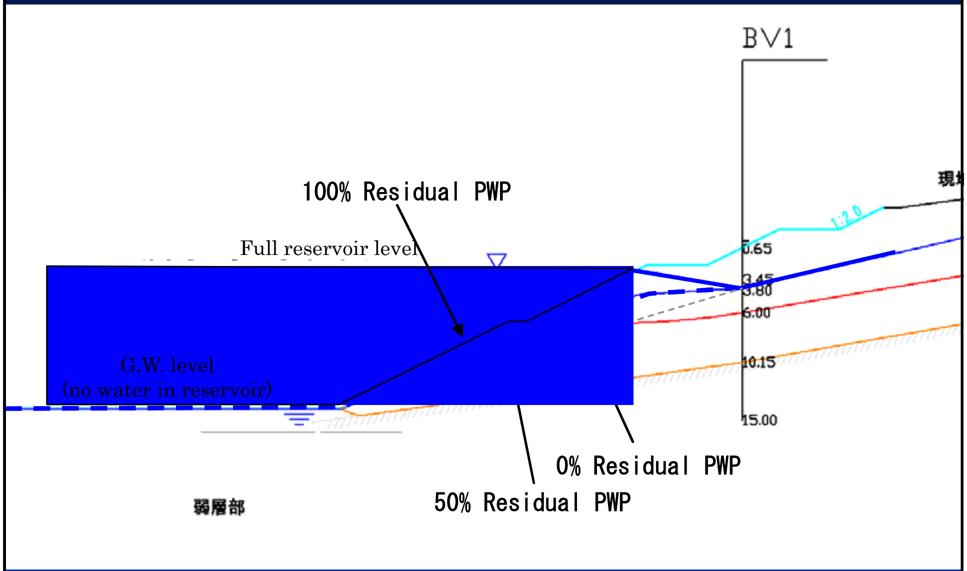
ki: volume ratio (=volume of i / volume of total mass)
L: length of failure surface
N: normal force on the base of the slice
U: pore water pressure on the base of the slice
S: landslide resisting force
T: landslide force

| | | |
|---|---|---|
| A | with structure（57% of landslide width）<br>FS=1.059<br>Pr=197.8 kN/m (P.Fs=1.150) | FS=1.099<br>Pr=114.36 kN/m (P.Fs=1.150) |
| B | without structure（43% of landslide width）<br>FS=1.149<br>Pr=1.4 kN/m (P.Fs=1.150) | |



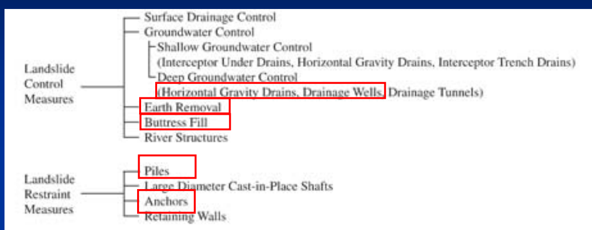
Tips!

- Stability analysis of slopes at reservoir

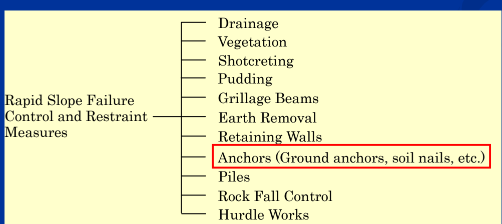


# *Landslide Mitigation Measures*

## Commonly Used Landslide Mitigation Measures in Japan



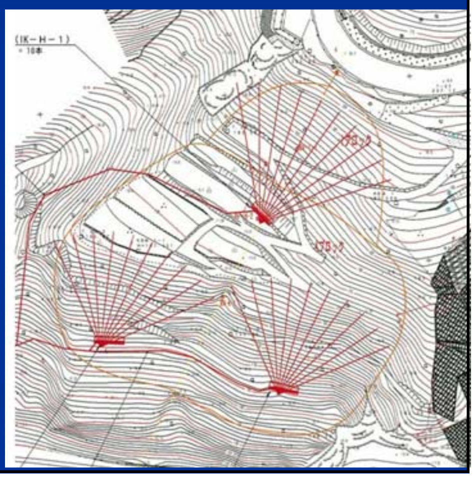

Landslide mitigation measures
(Japan River Association, 1997)



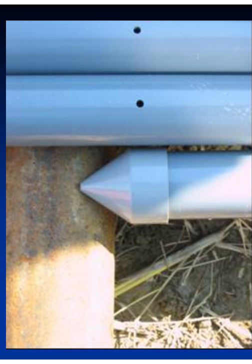

Mitigation measures for rapid slope failures
(after Japan River Association, 1997)

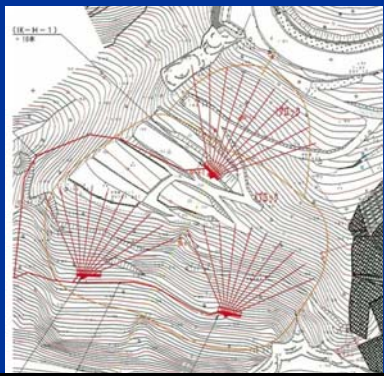
# Gravity Drains

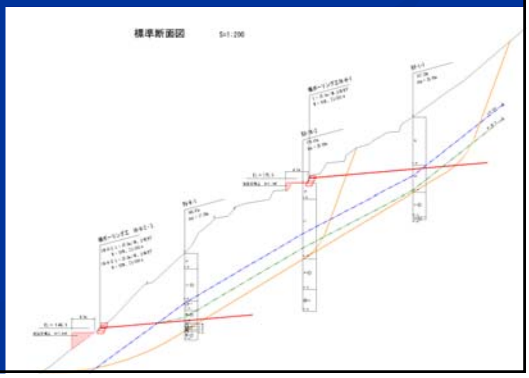
- Purposes
  - To remove groundwater from the landslide area
  - To prevent inflow of groundwater into the landslide area
- Characteristics
  - Applicable to gentle to steep slopes
  - Quick
  - Easy to construct
  - Flexible
  - Cheap (¥20K – 30K/m)
  - Temporary & permanent control measures



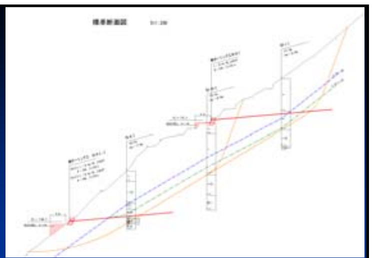
- Guidelines (Japan River Association, 1997)
  - Materials: perforated PVC or steel pipe
  - Max length: 50m
  - Inclination: 5 – 10 degree
  - 5 – 10 m in bedrock
  - 5 – 10m spacing @ tip
  - Layout of gravity drains
  - PWL = HWL – 3m

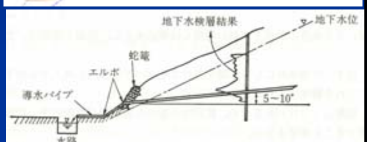






- Tips !
  - Install near the crest of landslide
  - Groundwater levels and movement
  - Less effective in clayey materials (PWL = HWL – 3m?)
  - Construct before restrain measures
  - Treatment of drained groundwater
  - Maintenance

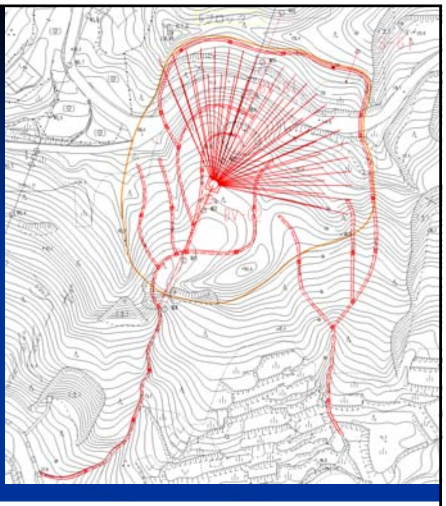


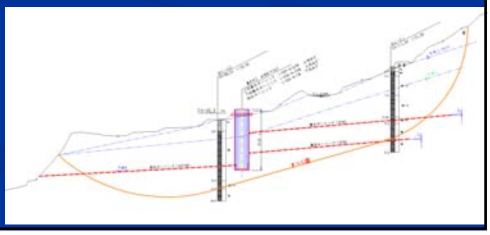


(Japan River Association, 1997)

## Drainage Wells

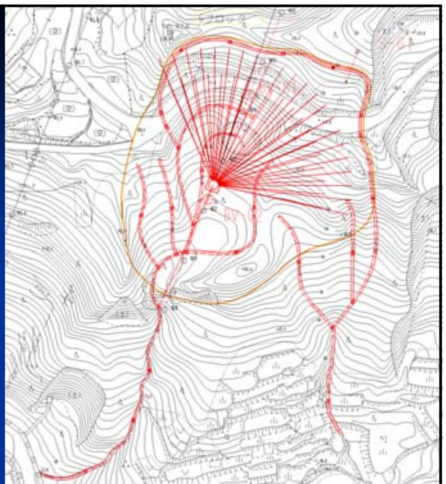
- Purposes
  - To remove groundwater from the landslide area
  - To prevent inflow of groundwater into the landslide area
- Characteristics
  - Well + gravity drain
  - Ø3.5 – 4.0m diameter well
  - ¥5,000K (Well) + ¥20K – 30K/m (gravity drains)
  - Time consuming
  - Drainage capacity
  - Permanent control measures
  - Applicable to gentle slope

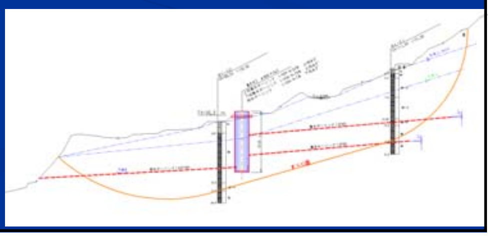




- Guidelines (Japan River Association, 1997)
  - Gravity drains
  - Drainage
    - Max drainage length: 80m
  - Well
    - 2 m > above slip surface (active landslide)
    - 2 – 3 m in bedrock

      (outside landslide area, non active landslide)

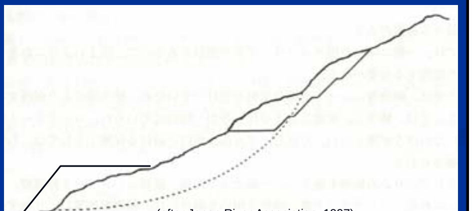




(after Sabo Technical Center, 2006)

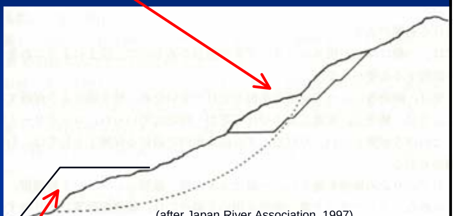
# Earth Removal and Counterweight Fill

- Purposes
  - To stabilize the slope by removing the head portion of the slide / adding the counterweight at the lower portion of the landslide mass


(after Japan River Association, 1997)

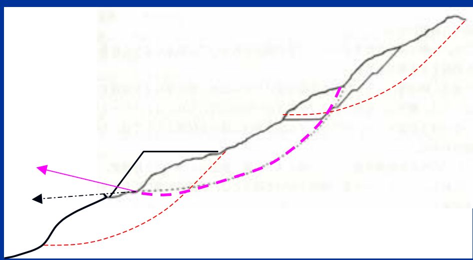
- Characteristics
  - Direct & Effective
  - Simple & Quick
  - Flexible
  - Cheap (¥2K – 3K/$m^3$)
  - Temporary & permanent control measures

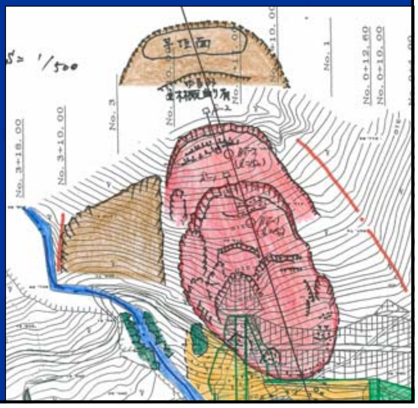
- Guidelines for Earth Removal (Japan River Association, 1997)
  - Weathered rocks
    - Slope angle: 1 : 0.5 – 1 : 1.2 (V : H)
    - Bench: every 7m in height
    - Bench width: 1.0 – 2.0 m
  - Sandy materials
    - Slope angle: 1 : 1.0 – 1 : 1.5 (V : H)
    - Bench: every 5m in height
    - Bench width: 1.0 – 2.0 m


(after Japan River Association, 1997)

- Guidelines for Counterweight Fill (Japan River Association, 1997)
  - Slope angle: 1 : 1.8 – 1 : 2.0 (V : H)
  - Bench: every 5m in height
  - Bench width: 1.0 – 2.0 m

- Tips !
  - Stable gradient (cut & fill slopes)
  - Crest could be the toe of upper slope
  - Toe could be the crest of lower slope
  - Placement of removed soil
  - Fill materials
  - Strength of landslide mass
    - Landslide overflows counterweight?
  - Shape of slip surface

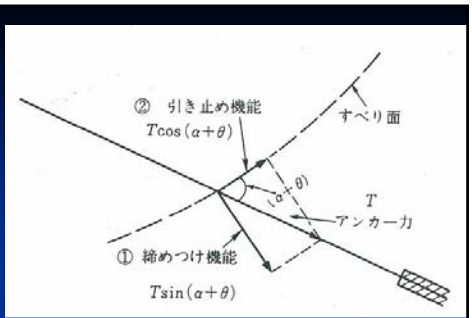


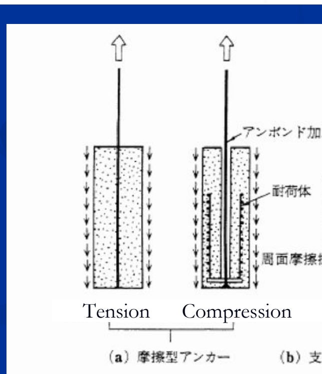


- Tips !
  - Surface drainage
  - Slope surface protection
    - Shotcrete, vegetation, etc

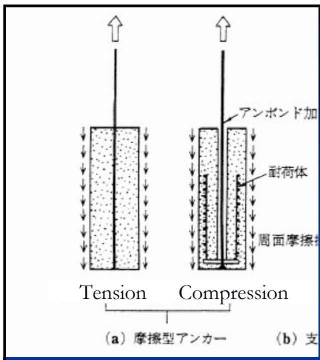
# Ground Anchors

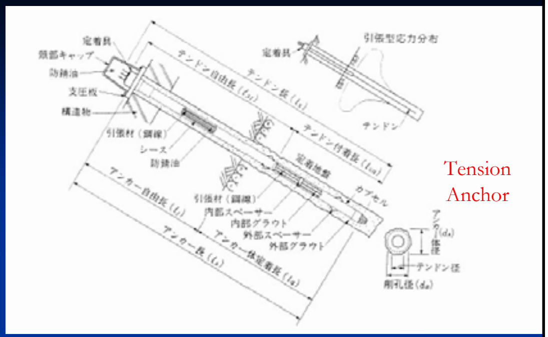
- Purposes
  - To stop the landslide movement by adding a resisting force
- Characteristics
  - Permanent control measures
  - Applicable to relatively steep slope
  - 2 anchor forces
    - Gentle slope T cos ( $\alpha + \theta$ )
    - Steep slope T sin ( $\alpha + \theta$ )
  - Anchor types
    - Tension
    - Compression

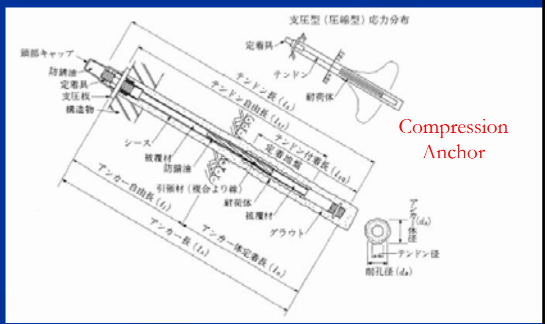



http://www.jisuberi-kyokai.or.jp/gijyoho/gijyutu/sekkei/ankako/model.html



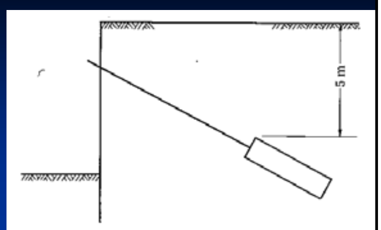



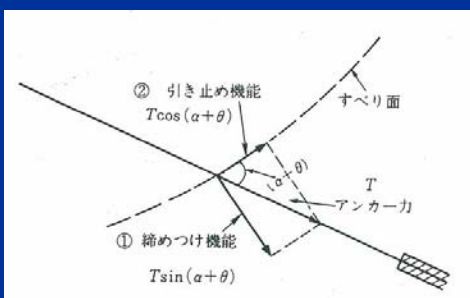

http://www.jisuberi-kyokai.or.jp/gijyoho/gijyutu/sekkei/ankako/model.html

- Tips !
  - Compression anchor may not be suitable to weak rocks (?)

- Guidelines (The Japanese Geotechnical Society, 2000)
  - Installation angle:
    Avoid - 5 – +5 degree from horizontal
  - Depth of anchor: > 5m
  - Free length: > 4m
  - Bond length: 3m – 10m
  - Pre-tension:
    - T cos ( $\alpha+\theta$ ) 20 – 30% of design load
    - T sin ( $\alpha+\theta$ ) 100% of design load
    - Both 40 – 80% of design load

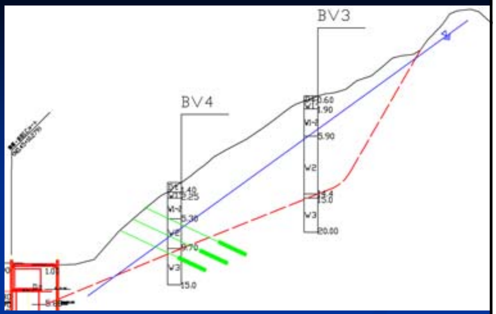


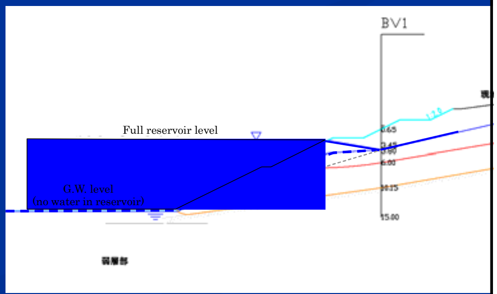

(The Japanese Geotechnical Society, 2000)



## Tips !

- Pullout test
- Installation of ground anchors after completion of landslide control measures
- Installation in compression zone
- Install anchors as soon as after cutting slope
- Avoid installation under water



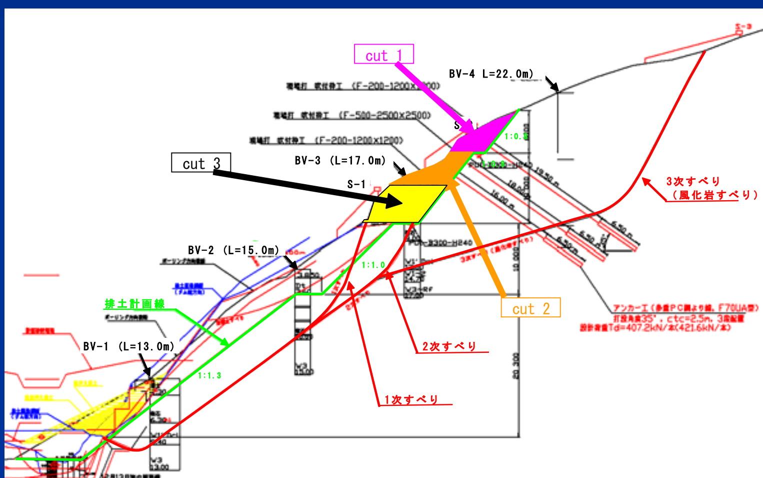




## Tips !

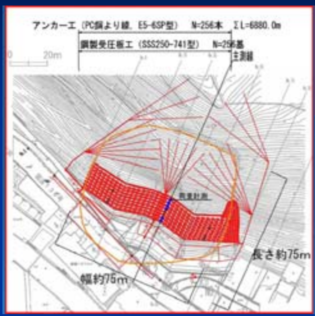
- Decrease of FS during cut & anchor
- Failure at lower slope

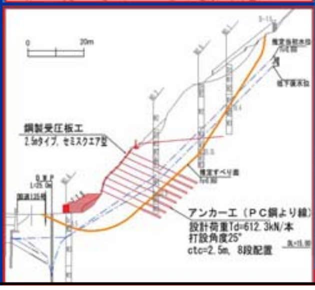
FS@ occurred FS=1.050 → cut 1: FS=1.045 → 1st Anchor: FS=1.075 → cut 2: FS=1.069 → 2nd Anchor: FS=1.101 → 3rd Anchor: FS=1.132 → cut 3: FS=1.050

C=19.5、φ=17.1298

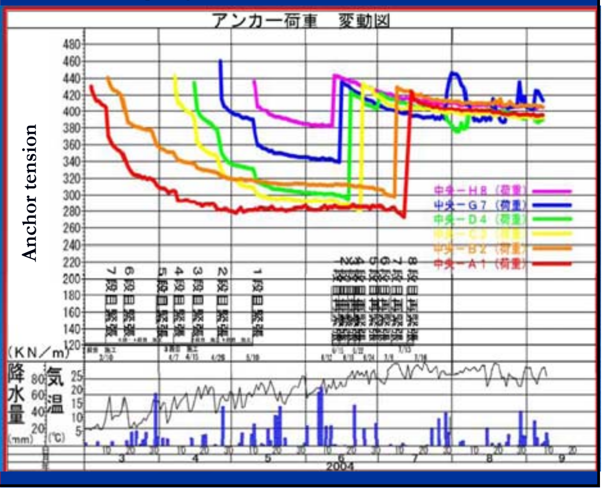


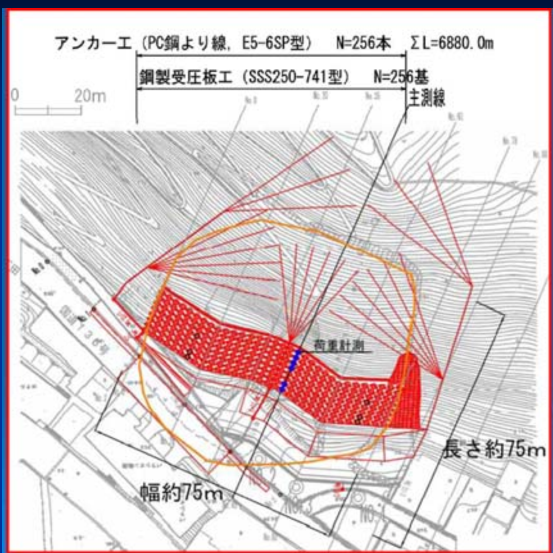
- Tips !
  - Decrease of tension during the installation & after installation (relaxation)

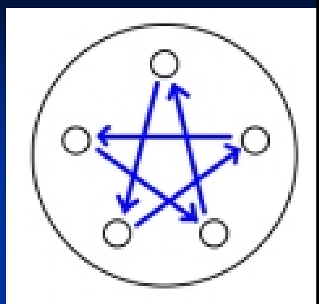


- 75m width × 75m length × 20m depth
- Ground anchors:
  - Tension: 612.3 kN
  - Declination : 25 degree
  - Spacing: 2.5m



- Tips !
  - Slope surface protection
  - Surface water and Groundwater treatment

# Soil Nailing

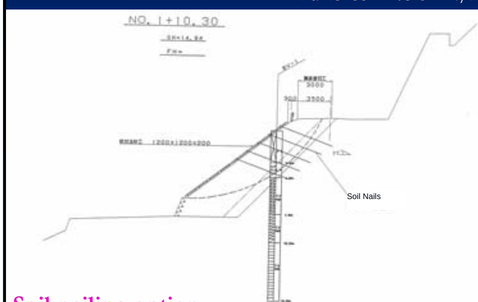
- Use of soil nails started in 1970's
- Approximately 50,000 nails / year

- General specifications
  - Factor of Safety
    - Permanent P.FS ≧ 1.20 (1.10 – 1.20)
    - Temporary P.FS ≧ 1.05, 1.10
  - Diameter 19 to 25 mm
  - Length 2.0 to 5.0 m
  - Hole diameter 65mm
  - Spacing 1.0 to 1.5 m
  - Installation angle
    perpendicular to the slope surface

Japan Highway Public Corporation (2004)

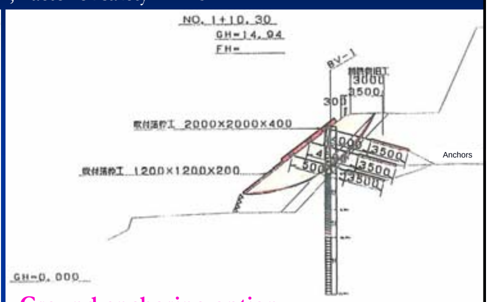

# Case Studies – Case A

End force = 48.6 kN/m, Factor of safety = 1.15




**Soil nailing option**

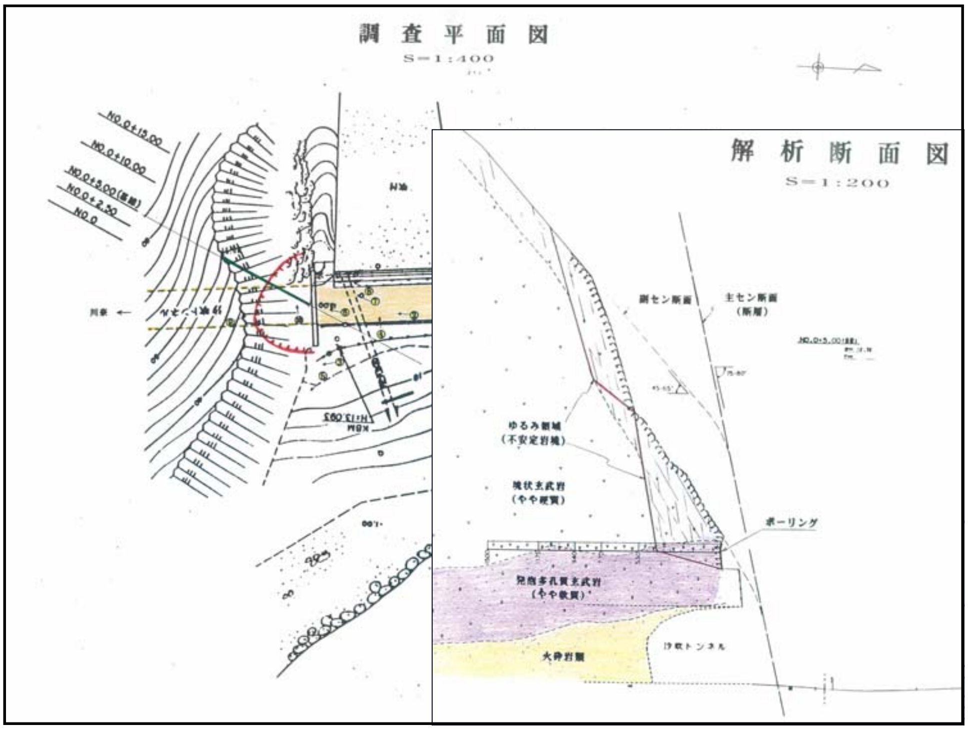
- Five rows
- Diameter 22 mm
- Length 5.4 m
- Hole diameter 65 mm
- Spacing 1.2x1.2 m
- Installation angle 25° from horizontal
- Pullout capacity 0.25 kN/m$^2$
- Cost 14 million yen




**Ground anchoring option**

- Three rows
- Length 7.5 – 8.5 m (Anchoring length = 3.5 m)
- Hole diameter 116 mm
- Spacing 2.0x2.0 m
- Installation angle 15° from horizontal
- Design capacity 80.2 kN
- Cost 18 million yen

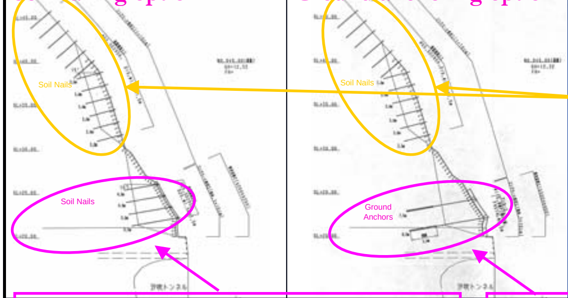

Case S


調 査 平 面 図
S=1:400
解 析 断 面 図
S=1:200
主セン断面
(断層)
ゆるみ領域
(不安定岩塊)
ボーリング
大井岩盤

# Case Studies – Case B

End force = 56.3 kN/m (upper part), 42.0 kN/m (lower part), Factor of safety = 1.15

Soil nailing option | Ground anchoring option




**Soil nailing (upper part)**

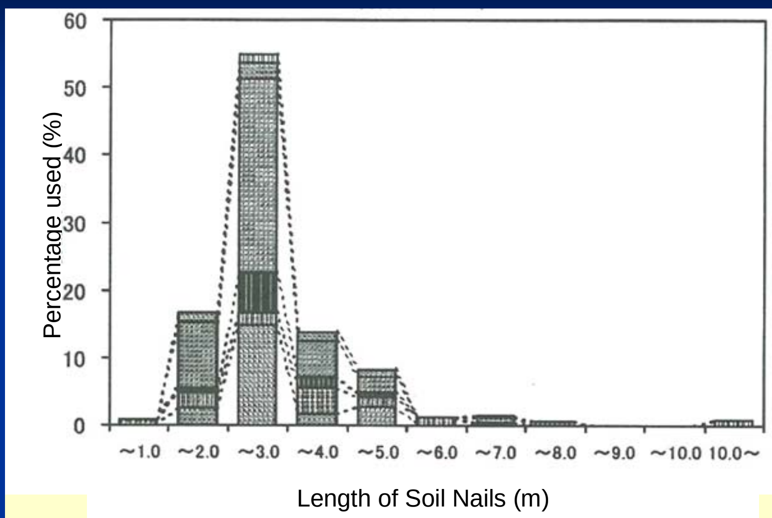
- Diameter 19 mm
- Length 3.0 m
- Hole diameter 65 mm
- Spacing 1.5x1.5 m
- Installation angle 25 - 40° from horizontal
- Pullout capacity 0.8 kN/m$^2$

**Soil nailing option (lower part)**

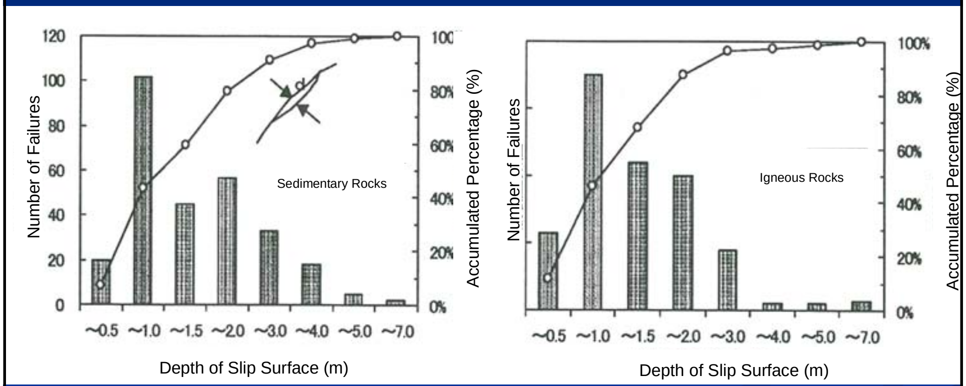
- Four rows
- Diameter 25 mm
- Length 4.0 – 5.5 m
- Hole diameter 65 mm
- Spacing 1.5x1.5 m
- Installation angle 10° from the horizontal
- Design capacity 0.8 kN/m$^2$
- Cost 22 million yen

**Ground anchoring option (lower part)**

- Three rows
- Diameter 22 mm
- Length 7.5 – 8.5 m (Anchoring length = 3.0 m)
- Hole diameter 115 mm
- Spacing 2.5x2.5 m
- Installation angle 10° from the horizontal
- Design capacity 179.3 kN
- Cost 21 million yen




Length of soil nails commonly used in slope stabilization works in Japan
(after Japan Highway Public Corporation, 2004)




Depth of slip surface in rapid slope failures in Japan
(after Japan Highway Public Corporation, 2004)

- The soil nailing technique usually becomes the first choice for stabilizing shallow slope failures in Japan.
- Soil nails used in the slope stabilization works are typically shorter than 5 m since majority of rapid slope failures have their slip surface shallower than 2m.
- Many engineers in Japan do not feel comfortable with using long soil nails.
- Using the long soil nails may not be resulted in the economical slope stabilization measure in Japan. When the length of soil nail excesses 5 m, the ground anchoring could be more economical than the soil nailing in Japan.