利用地表地形分析古地震

指導教授: 董家鈞、李錫堤老師
報告者: 劉正隆
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Introduction

As the topography steepens, erosion rates increase until they balance rock uplift.

\[ E = E_0 + \frac{KH}{1 - (\bar{H}/H_c)^2} \]

It’s almost impossible to prepare representative cores of rock masses including discontinuities patterns for laboratory studies.

Marinos and Hoek (2001)

Hoek and Brown (1997)
Introduction

• Rock mass classification

• Empirical equations:

\[ UCS_i : \text{uniaxial compressive strength of intact rock mass} \]

\[ UCS_{RM} : \text{uniaxial compressive strength of rock mass} \]
Introduction

Geological strength index (GSI)

Hoek – Brown failure criterion

\[
\frac{\sigma_1}{\sigma_{ci}} = \frac{\sigma_3}{\sigma_{ci}} + \left( m_b \cdot \frac{\sigma_3}{\sigma_{ci}} + s \right)^a
\]

\[
a = \frac{1}{2} + \frac{1}{6} \cdot \left( e^{-GSI/15} - e^{-20/3} \right)
\]

\[
m_b = m_i \cdot \exp \left( \frac{GSI - 100}{28 - 14D} \right)
\]

\[
s = \exp \left( \frac{GSI - 100}{9 - 3D} \right)
\]

Hoek et al. (1998)
Introduction

- Slope performance curve (Slope response curve)

Haines and Terbrugge (1991)

Duran and Douglas (1999)
Introduction

- Slope performance curve (Slope response curve)

Empirical approach

Calculational approach

Bigot-Cormier and Montgomery (2007)

Schultz (2002)
Introduction

- Slope performance curve (Slope response curve)

\[ FS = \frac{\text{resisting stresses}}{\text{driving stresses}} = 1.0 \]
Introduction

- Slope performance curve (Slope response curve)

\[ FS = 1.0 \]

Unit weight \((\gamma)\)

UCS \((\sigma_{ci})\)

GSI

mi

Unit weight \((\gamma)\)

FS = 1.0

1600m

? deg.
Introduction

- Groundwater & Seismic Load

![Graph showing the relationship between relief (m) and slope (degrees) for different conditions.](image)

- **Dry condition**
- **Saturated condition**
- **Horizontal seismic accelerations of 0.6g**

Schmidt and Montgomery (1995)
Introduction

Relief & Rock mass strength
Introduction

Relief & Seismic Load
Purpose

- Construct the relationship between the earthquake and rock mass strength with the relief (slope height & slope angle).
- Use the rock mass strength and relief for paleoseismic analysis (magnitude & distribution).
Methodology

- Modes of failure of rock slope:
  - Structural control
    - Plane slide, Wedge slide and Toppling

  - Non-structural control

  Shear Strength of Discontinuities

  Strength of Rock Mass
Methodology

• Slide 5.0

Hoek – Brown failure criterion

\[ \frac{u}{\sigma_v} = \frac{\gamma_w \times h_w}{\gamma_t \times H} \times \left( \frac{m_b \cdot \sigma_3}{\sigma_{ci}} + s \right)^a \]

- \( a = \frac{1}{2} + \frac{1}{6} \cdot (e^{-GSI/15} - e^{-20/3}) \)
- \( m_b = m_i \cdot \exp \left( \frac{GSI - 100}{28 - 14D} \right) \)
- \( s = \exp \left( \frac{GSI - 100}{9 - 3D} \right) \)

FS = ?
Methodology

- Pseudostatic analysis  
  Terzhagi (1950)

\[ k_h = \frac{a_{h\ max}}{g} \]

\[ k_v = \frac{a_{v\ max}}{g} \]

\[ k_v = \frac{1}{2} k_h \]  
USACE (1989)

Melo and Sharma (2004)
Methodology

Field investigation

Experiment

Topographic Maps

Seismic load

FS = 1.0

Slope angle

Slope height

Ru

GSI

mi

UCS (\(\sigma_{ci}\))

Unit weight (\(\gamma\))
Sensitivity analysis

Base value:
- $FS = 1.0$
- $k_h = 0.5$
- $k_v = 1/2 k_h$
- $m_i = 17$
- $Ru = 0.25$
- $GSI = 50$
- $UCS = 100 \text{MPa}$
- Unit weight = 26 kN/m$^3$
- Slope height = 200 m
- Slope angle = 42.1°

$\gamma = 26 \ kN/m^3$
$UCS = 100 \text{MPa}$
$GSI = 50$
$mi = 17$
$Ru = 0.25$
<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Class</th>
<th>Group</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coarse</td>
<td>Medium</td>
</tr>
<tr>
<td>Clastic</td>
<td>Sedimentary</td>
<td>Conglomerates*</td>
<td>Sandstones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Breccias*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-Sedimentary</td>
<td>Crystalline Limestone</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dolomites</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Evaporites</td>
<td>Gypsum</td>
<td>8 ± 2</td>
</tr>
<tr>
<td></td>
<td>Organic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-Foliated</td>
<td>Marble</td>
<td>9 ± 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Metasandstone</td>
<td>19 ± 3</td>
</tr>
<tr>
<td></td>
<td>Slightly foliated</td>
<td>Migmatite</td>
<td>29 ± 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gneiss</td>
<td>28 ± 5</td>
</tr>
<tr>
<td></td>
<td>Foliated **</td>
<td>Schists</td>
<td>12 ± 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slates</td>
<td>7 ± 4</td>
</tr>
<tr>
<td>Plutonic</td>
<td>Light</td>
<td>Granite</td>
<td>32 ± 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Granodiorite</td>
<td>29 ± 3</td>
</tr>
<tr>
<td></td>
<td>Dark</td>
<td>Gabbro</td>
<td>27 ± 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Norite</td>
<td>20 ± 5</td>
</tr>
<tr>
<td></td>
<td>Hypabysal</td>
<td>Porphries</td>
<td>20 ± 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Porphyrite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volcanic</td>
<td>Lava</td>
<td>25 ± 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dacite</td>
<td>25 ± 5</td>
</tr>
<tr>
<td></td>
<td>Pyroclastic</td>
<td>Agglomerate</td>
<td>19 ± 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19 ± 3</td>
</tr>
</tbody>
</table>

FS = 1.0
Ru = 0.25
GSI = 50
UCS = 100

Hoek (2003)
Sensitivity analysis

Base value:
- $FS = 1.0$
- $k_h = 0.5$
- $k_v = 1/2 k_h$
- $m_i = 17$
- $Ru = 0.25$
- $GSI = 50$
- $UCS = 100 \text{MPa}$
- Unit weight = $26 \text{kN/m}^3$
- Slope height = 200 m
- Slope angle = 42.1°

Values to consider:
- $\gamma = 26 \text{ kN/m}^3$
- $UCS = 100 \text{MPa}$
- $GSI = 50$
- $mi = 17$
- $Ru = 0.25$
- $FS = 1.0$
Sensitivity analysis

**Lower**

Base value:
- FS = 1.0
- $k_h = 0.5$
- $k_v = \frac{1}{2} k_h$
- $m_i = 17$
- Ru = 0.25
- GSI = 50
- UCS = 100 MPa
- Unit weight = 26 kN/m$^3$
- Slope height = 200 m
- Slope angle = 42.1 deg.

**Higher**

Base value:
- FS = 1.0
- $k_h = 0.5$
- $k_v = \frac{1}{2} k_h$
- $m_i = 17$
- Ru = 0.25
- GSI = 50
- UCS = 100 MPa
- Unit weight = 26 kN/m$^3$
- Slope height = 700 m
- Slope angle = 26 deg.
Field investigation

Geological strength index (GSI)

Hoek – Brown failure criterion

\[
\frac{\sigma_1}{\sigma_{ci}} = \frac{\sigma_3}{\sigma_{ci}} + \left( m_b \cdot \frac{\sigma_3}{\sigma_{ci}} + s \right)^a
\]

\[
a = \frac{1}{2} + \frac{1}{6} \cdot \left( e^{-GSI/15} - e^{-20/3} \right)
\]

\[
m_b = m_i \cdot \exp \left( \frac{GSI - 100}{28 - 14D} \right)
\]

\[
s = \exp \left( \frac{GSI - 100}{9 - 3D} \right)
\]

Hoek et al. (1998)
### Field investigation

- **$F_{GSI}$** = GSI
- **$F_{RMR}$** = $R_2 + R_3 + R_4$

**$R_2$** = Drill core quality (RQD) rating

**$R_3$** = Spacing of discontinuities rating

**$R_4$** = Condition of discontinuities rating

$$F_Q = \frac{RQD \cdot J_r}{J_n \cdot J_a}$$

- **$RQD$** = Drill core quality
- **$J_n$** = Joint set number rating
- **$J_r$** = Joint roughness rating
- **$J_a$** = Joint alteration rating

$$F_{RMi} = 0.2 \sqrt{j_c} \cdot V_b^D$$

- **$D$** = $0.37 j_c^{-0.2}$
- **$V_b$** = Block volume

**$j_c$** = Joint condition factor

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**Tzamos and Sofianos (2007)**
**Field investigation**

Marinos and Hoek (2002)

<table>
<thead>
<tr>
<th>COMPOSITION AND STRUCTURE</th>
<th>SURFACE CONDITIONS OF DISCONTINUITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Thick bedded, very blocky sandstone</td>
<td>VERY GOOD - Very rough, fresh unweathered surfaces</td>
</tr>
<tr>
<td>The effect of pelitic coatings on the bedding planes is minimized by the confinement of the rock mass. In shallow tunnels or slopes these bedding planes may cause structurally controlled instability.</td>
<td>GOOD - Rough, slightly weathered surfaces</td>
</tr>
<tr>
<td>B. Sandstone with thin interlayers of siltstone</td>
<td>FAIR - Smooth, moderately weathered and altered surfaces</td>
</tr>
<tr>
<td>C. Sandstone and siltstone in similar amounts</td>
<td>POOR - Very smooth, occasionally broken surfaces with soft clay coatings or fillings</td>
</tr>
<tr>
<td>D. Siltstone or silty shale with sandstone layers</td>
<td>VERY POOR - Very smooth, highly weathered surfaces with soft clay coatings or fillings</td>
</tr>
<tr>
<td>E. Weak siltstone or clayey shale with sandstone layers</td>
<td></td>
</tr>
<tr>
<td>C, D, E and G - may be more or less folded than illustrated but this does not change the strength. Tectonic deformation, faulting and loss of continuity moves these categories to F and H.</td>
<td></td>
</tr>
<tr>
<td>F. Tectonically deformed, intensively folded/faulted, sheared clayey shale or siltstone with broken and deformed sandstone layers forming an almost chaotic structure</td>
<td></td>
</tr>
<tr>
<td>G. Undisturbed silty or clayey shale with or without a few very thin sandstone layers</td>
<td></td>
</tr>
<tr>
<td>H. Tectonically deformed silty or clayey shale forming a chaotic structure with pockets of clay. Thin layers of sandstone are transformed into small rock pieces.</td>
<td></td>
</tr>
</tbody>
</table>

GSI FOR HETEROGENEOUS ROCK MASSES SUCH AS FLYSCH (Marinos. P and Hoek, E, 2000)

From a description of the lithology, structure and surface conditions (particularly of the bedding planes), choose a box in the chart. Locate the position in the box that corresponds to the condition of the discontinuities and estimate the average value of GSI from the contours. Do not attempt to be too precise. Quoting a range from 33 to 37 is more realistic than giving GSI = 35. Note that the Hoek-Brown criterion does not apply to structurally controlled failures. Where unfavourably oriented continuous weak planar discontinuities are present, these will dominate the behaviour of the rock mass. The strength of some rock masses is reduced by the presence of groundwater and this can be allowed for by a slight shift to the right in the columns for fair, poor and very poor conditions. Water pressure does not change the value of GSI and it is dealt with by using effective stress analysis.

: Means deformation after tectonic disturbance
Field investigation
Field investigation

- **$F_{GSI}$ 計算 GSI**: 65.6
- **$F_{RMR}$ 對應 GSI**: 65
- **$F_Q$ 對應 GSI**: 68
- **$F_{RMI}$ 對應 GSI**: 72
- **主觀判定 GSI**: 65
Field investigation

\[ H = 490 \text{m} \]
\[ S = 24^\circ \]
Field investigation

<table>
<thead>
<tr>
<th>調查點編號</th>
<th>試體編號</th>
<th>單位重(kN/m³)</th>
<th>單壓強度(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>23.85</td>
<td>69.02</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>23.97</td>
<td>58.06</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>24.01</td>
<td>62.73</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>23.50</td>
<td>56.01</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>24.43</td>
<td>55.28</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>25.11</td>
<td>92.66</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>25.02</td>
<td>73.47</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>24.85</td>
<td>93.79</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>24.89</td>
<td>110.76</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>25.32</td>
<td>141.45</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>24.76</td>
<td>96.95</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>24.84</td>
<td>102.10</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>24.84</td>
<td>79.19</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>25.29</td>
<td>116.35</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>21.49</td>
<td>52.15</td>
</tr>
<tr>
<td>平均值</td>
<td></td>
<td>24.41</td>
<td>84.00</td>
</tr>
<tr>
<td>標準差</td>
<td></td>
<td>0.98</td>
<td>26.50</td>
</tr>
</tbody>
</table>
Sensitivity analysis

FS = 1.0
k_h = 0
k_v = 1/2 k_h
m_I = 17
R_u = 0
UCS = 84 MPa
Unit weight = 24.4 kN/m^3
Back analysis

- $F_{GSI}$ 計算 GSI: 65.6
- $F_{RMR}$ 對應 GSI: 65
- $F_Q$ 對應 GSI: 68
- $F_{RMI}$ 對應 GSI: 72
- 主觀判定 GSI: 65
Conclusion

• We observed that the seismic load affects the relief of landscape.

• GSI is the most sensitive to back analysis the seismic load then Ru, UCS and mi.

• In the result of the UCS experiment, the sample’s variation comes acceptable influence on back analysis.
Future work

• Collect more information to make sure the influence of the **seismic load** on relief.

• Decide a reliable GSI from the field investigation.

• Try to know the uncertainty of estimates the GSI in situ.

• More field investigation
Thanks for your attention