Site Selection, Safety Review, Safety Confirmation, and Monitoring

7. Foundation and Slope Stability
(SER 2.5.4 & 2.5.5)

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Korea Institute of Nuclear Safety
Structural Systems and Site Evaluation Department

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Contents

Basic Information
Design considerations of Foundation Engineering properties of rocks
Foundation stability evaluation
Slope stability evaluation
Basic Information

Design considerations of Foundation Engineering properties of rocks Foundation stability evaluation Slope stability evaluation
**Basic Information**

**Basic considerations**

- Foundation stability evaluation methods, investigation or test methods are dependent on the site condition (rock site or soil site)
- Full understanding of geological characteristics is necessary before selecting the evaluation and test methods
- The range of application and restrictions of test methods are considered

**Understanding of representative value**

- Not one method of test results are utilized for the determination of the property value
- Results from more than two test methods are utilized
- Special attention be given the No. of test(samples) and its standard deviation
Rock and rock mass discrimination

- Rock (material)
  - Intact rock with no joint
  - Used for Rock classification and characterization

- Rock mass
  - Whole rock with joint, it represents the real condition of foundation materials
  - Large-scale rock mass behavior must be considered in all real rock engineering problem
  - Lab. Test on the specimen is only one step for understanding of in-situ rock performance
Basic Information
Design considerations of Foundation
Engineering properties of rocks
Foundation stability evaluation
Slope stability evaluation
Design considerations of foundation

Stable condition of foundation

- Stable geologic condition with homogeneous subsurface materials
- Suitable bearing capacity with limited (differential) settlement

Major evaluation items

- Bearing capacity
- Settlement or differential settlement
- Liquefaction potential
- Seismic wave propagation characteristics
- Slope stability
- Possibility of improvement of weak foundation materials
Design considerations of foundation

Basic data necessary to evaluate the foundation stability

- Geological characteristics and geological structure
- Static engineering properties
  - Unit weight, poisson’s ratio, compressive strength, young’s modulus, deformation modulus, etc.
- Dynamic engineering properties
  - Poisson’s ratio, young’s modulus, compressional/shear wave velocity, seismic wave velocity profile
- Ground water condition
  - Groundwater level, water quality, existence of artesian condition, etc
- Layout of the facilities and the nature of the structural foundation
- Characteristics of permanent or temporal cut slope
Contents

Basic Information
Design considerations of Foundation Engineering properties of rocks
Foundation stability evaluation
Slope stability evaluation
Representative geotechnical investigations and tests

- Surface geologic investigation
- Boring (borehole logging)
- Trenches
- Geophysical exploration (seismic wave velocity and velocity structure)
- Groundwater exploration
- In-situ test (rock mass deformation test, Point Load Test, Standard Penetration Test, etc.)
- Laboratory test (index test, compressive strength, sonic velocity, etc.)
**Engineering properties of rocks**

- **Uniaxial compressive strength** (Qu)
  - Using for the determination of **bearing capacity** of foundation material
  - Triaxial/Uniaxial compressive strength test
  - **Uniaxial compressive strength test**
    - \( \text{Qu} = \frac{P}{A} = \frac{4P}{\pi D^2} \) \( D \): Diameter of core, \( P \): stress acting parallel to axis of core, \( A \): cross section of the core
  - **Point load test** (PLT): in-situ test for obtaining point load index
    - \( I_s = \frac{P}{d^2} \), \( \text{Qu} = 24 I_{s(50)} \) \( P \): failure pressure, \( I_{s(50)} \): **point load index**
    - Correction: test results are corrected at \( D=50\text{mm} \)
    - \( I_{s(50)} = F \cdot I_s \) \( F \): correction factor, \( (D/50)^{0.45} \), \( I_s \): Point index by direct measurement
    - In general, \( \text{Qu} = 24 * I_{s(50)} \) (about 20-25 times) is applied
Example of uniaxial compressive strength (Qu) determination using point load index
Selection of representative value (R.V.)

- **Direct** measurement: in-situ test (rock mass deformation test, joint characteristics, groundwater level, etc.)
- **Indirect** measurement: correlation with related parameters (Rock Mass Rating, Rock Quality Designation, velocity index, etc.)
- Selection of R.V.: Consideration of test reliability and site condition

Rock mass deformation modulus, \((Ed)\)

- Used for evaluation of deformation characteristics and **settlement** for foundation materials
- Direct measurement – using the stress-strain relationship
- Indirect measurement – correlation with related parameters
Rock mass deformation modulus, (Ed)

- **Direct measurement**
  - Jack test, elastometer test, etc

- **Indirect measurement**
  - Correlation with RMR (Rock mass rating), RQD (Rock Quality Designation) and **Velocity index**
  - RMR method: Rating according to compressive strength, RQD, Spacing of joint, nature of joint (surface roughness, fillings, and aperture), joint orientation, and groundwater condition
    - Correction according to joint geometry
    - Determination of rock mass deformation modulus using the relationship of the modulus and RMR (Bieniawski, 1978)
### Definition of core recovery and RQD

<table>
<thead>
<tr>
<th>Run = 1600 mm</th>
<th>Core (all)</th>
<th>Modif. core (100 + mm)</th>
<th>% Recovery</th>
<th>RQD</th>
<th>Rock quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>132</td>
<td>132</td>
<td>% Recovery</td>
<td>RQD</td>
<td>Rock quality</td>
</tr>
<tr>
<td>139</td>
<td>135</td>
<td>135</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>120</td>
<td>120</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>116</td>
<td>116</td>
<td>116</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>232</td>
<td>232</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>222</td>
<td>222</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>112</td>
<td>112</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RQD = \(\frac{1208}{1600}\) x 100 = 75.5%

Rock quality = "fair"

\[\text{% Recovery} = \frac{1384}{1600}\times 100 = 86.5\%\]

- % recovery is the ratio of recovered core length to total length drilled, expressed as percentage
- RQD is the sum of the length of rock core pieces longer than 10cm. It is expressed as a percentage of a given total length drilled

<table>
<thead>
<tr>
<th>Compressive strength (MPa)</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 250</td>
<td>15</td>
</tr>
<tr>
<td>100-250</td>
<td>12</td>
</tr>
<tr>
<td>50-100</td>
<td>7</td>
</tr>
<tr>
<td>25-50</td>
<td>4</td>
</tr>
<tr>
<td>10-25</td>
<td>2</td>
</tr>
<tr>
<td>2-10</td>
<td>1</td>
</tr>
<tr>
<td>1-2</td>
<td>0</td>
</tr>
</tbody>
</table>

\[\text{RQD} = \frac{1208}{1600}\times 100 = 75.5\%\]

\[\text{Rock quality} = \text{"fair"}\]

\[\text{% Recovery} = \frac{1384}{1600}\times 100 = 86.5\%\]

\[\text{Rock quality}^{a} = \text{RQD, }\%\]

- Very poor: 0 – 25
- Poor: 25 – 50
- Fair: 50 – 75
- Good: 75 – 90
- Excellent: 90 –

\[^{a}\text{From Deere (1968)}\]
## Engineering properties of rocks

### RMR Score and Rock Quality by RQD

<table>
<thead>
<tr>
<th>RQD (%)</th>
<th>Score</th>
<th>Rock Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 ~ 100</td>
<td>20</td>
<td>Excellent</td>
</tr>
<tr>
<td>75 ~ 90</td>
<td>17</td>
<td>Good</td>
</tr>
<tr>
<td>50 ~ 75</td>
<td>13</td>
<td>Fair</td>
</tr>
<tr>
<td>20 ~ 50</td>
<td>8</td>
<td>Poor</td>
</tr>
<tr>
<td>&lt;25</td>
<td>3</td>
<td>Very Poor</td>
</tr>
</tbody>
</table>

### RMR Score by Joint Spacing

<table>
<thead>
<tr>
<th>Joint Spacing (m)</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;2.0</td>
<td>20</td>
</tr>
<tr>
<td>0.6 ~ 2.0</td>
<td>15</td>
</tr>
<tr>
<td>0.2 ~ 0.6</td>
<td>10</td>
</tr>
<tr>
<td>0.06 ~ 0.2</td>
<td>8</td>
</tr>
<tr>
<td>&lt;0.06</td>
<td>5</td>
</tr>
</tbody>
</table>

### RMR Score by Joint Condition

<table>
<thead>
<tr>
<th>Joint Condition</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very rough surface within a limited range; hard rock</td>
<td>30</td>
</tr>
<tr>
<td>Slightly rough surface; less than 1 millimeter in joint width; hard rock</td>
<td>25</td>
</tr>
<tr>
<td>Slightly rough surface; less than 1 millimeter in joint width; soft rock</td>
<td>20</td>
</tr>
<tr>
<td>Smooth surface; gouge-filling substances with the thickness of 1-5 millimeters;</td>
<td>10</td>
</tr>
<tr>
<td>joint extended for over several meters</td>
<td></td>
</tr>
<tr>
<td>Open joint filled with gouge of over 5 millimeters in thickness</td>
<td>0</td>
</tr>
<tr>
<td>Open by over 5 millimeters; joint extended for over several meters</td>
<td>0</td>
</tr>
</tbody>
</table>
## Engineering properties of rocks

### RMR Score by Groundwater Condition

<table>
<thead>
<tr>
<th>Water Inflow per Tunnel Length of 10 Meters (L/min)</th>
<th>Water Pressure within Joint/ Principal Stress</th>
<th>Ordinary Condition</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not applicable</td>
<td>0</td>
<td>Completely dry</td>
<td>15</td>
</tr>
<tr>
<td>&lt; 10</td>
<td>0.0 ~ 0.1</td>
<td>Humid</td>
<td>10</td>
</tr>
<tr>
<td>10 ~ 25</td>
<td>0.1 ~ 0.2</td>
<td>Wet</td>
<td>7</td>
</tr>
<tr>
<td>25 ~ 125</td>
<td>0.2 ~ 0.5</td>
<td>Water drops dripping</td>
<td>4</td>
</tr>
<tr>
<td>&gt; 125</td>
<td>&gt; 0.5</td>
<td>Fluid</td>
<td>0</td>
</tr>
</tbody>
</table>

### Grades of Rock Quality by RMR

<table>
<thead>
<tr>
<th>Grade</th>
<th>Rock Quality</th>
<th>RMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Very good rock</td>
<td>81 ~ 100</td>
</tr>
<tr>
<td>II</td>
<td>Good rock</td>
<td>61 ~ 80</td>
</tr>
<tr>
<td>III</td>
<td>Fair rock</td>
<td>41 ~ 60</td>
</tr>
<tr>
<td>IV</td>
<td>Poor rock</td>
<td>21 ~ 40</td>
</tr>
<tr>
<td>V</td>
<td>Very Poor rock</td>
<td>0 ~ 20</td>
</tr>
</tbody>
</table>
Engineering properties of rocks

Rock mass deformation modulus determination using RQD and uniaxial compressive strength (Plate jacking Test at Dworshak Dam, Deer, 1967)

Rock mass deformation modulus determination using velocity index \((V_F/V_L)^2\) and modulus ratio \((E_d/E_{50})\) (Coon and Merritt, 1970)
### Engineering properties of rocks

Example of rock mass deformation modulus determination

<table>
<thead>
<tr>
<th></th>
<th>XX Plant unit 1</th>
<th></th>
<th>XX Plant unit 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seismic Class I</td>
<td>Non-seismic Class I</td>
<td>Seismic Class I</td>
<td>Non-seismic Class I</td>
</tr>
<tr>
<td>RQD(%)</td>
<td>2.41</td>
<td>2.17</td>
<td>2.07</td>
<td>1.65</td>
</tr>
<tr>
<td>RMR</td>
<td>3.80</td>
<td>2.20</td>
<td>2.60</td>
<td>2.00</td>
</tr>
<tr>
<td>In-situ Test</td>
<td>2.37</td>
<td>2.30</td>
<td>2.87</td>
<td>3.20</td>
</tr>
<tr>
<td>Velocity Index</td>
<td></td>
<td></td>
<td>2.08</td>
<td>2.01</td>
</tr>
<tr>
<td>Index value(mean)</td>
<td>2.40</td>
<td></td>
<td>2.30</td>
<td></td>
</tr>
</tbody>
</table>
• Procedural example of unconfined compressive strength determination

Unconfined compressive test (#66)  
Point load test  first(#73), Second(#147)

Relationship bet. UCS and Point load index  
Qu = 34.27*Is\(_{(50)}\)(first), Qu = 18.5*Is\(_{(50)}\)(second)

Compressive strength determination as the mean value  
Compressive strength determination using the relationship of point load index and unconfined compressive strength

Average value of two test value

Unconfined compressive strength determination  
Unit 1: 1,011 kg/cm\(^2\), unit 2: 1,167 kg/cm\(^2\)
Engineering properties of rocks

- Procedural example of rock mass deformation determination

Young's Modulus \( (E_{50}) \) determination using unconfined compression test

E\(_{50}\) Determination using correlation with point load strength

\( E_{50} \) is the average of two test values
\( \times 10^5 \text{kg/cm}^2 \) unit 1: 3.91, unit 2: 4.44

RQD

Er determination using the relationship of \( Er/E_{50} \)

Velocity index

Er determination using the relationship of \( Er/E_{50} \)

RMR

Er determination using the relation with Er

Average of 4 test values

Rock mass deformation

Unit 1: \( 2.40 \times 10^5 \text{kg/cm}^2 \),
unit 2: \( 2.30 \times 10^5 \text{kg/cm}^2 \)

Er determination with jack test
Basic Information
Design considerations of Foundation Engineering properties of rocks
Foundation stability evaluation
Slope stability evaluation
Foundation stability evaluation

- Procedure for foundation stability analysis
Velocity structure model

- Development of the seismic response characteristics of foundation materials: site-specific response spectrum
- If the s-wave velocity is equal or more than specified value, then the foundation assumed to be a **fixed base**
- If the s-wave velocity is less than specified value, then the soil structure interaction (SSI) analysis should be conducted
  - The material with s-wave velocity less than specified value does not mean unsuitable for foundation materials
Bearing capacity (Qa) evaluation (CGS)

For rock site

- Qa = Ksp × Qu-core

Qa: allowable bearing pressure,

Qu-core: average unconfined compressive strength of rock cores (ASTM D2938),

Ksp: an empirical coefficient, which include safety factor of 3 and ranges from 0.1 to 0.4

<table>
<thead>
<tr>
<th>Spacing of discontinuities</th>
<th>Ksp</th>
<th>Spacing width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderately close</td>
<td>0.1</td>
<td>0.3 - 1</td>
</tr>
<tr>
<td>Wide</td>
<td>0.25</td>
<td>1 - 3</td>
</tr>
<tr>
<td>Very Wide</td>
<td>0.4</td>
<td>&gt; 3</td>
</tr>
</tbody>
</table>
Foundation stability evaluation

Settlement evaluation for rock site

\[ \rho = \frac{P(1-\nu_m^2)}{\beta_z E_m A^{0.5}} \]

\[ \rho = \frac{0.9P}{E_m A^{0.5}} = \frac{0.9P}{\alpha E_r A^{0.5}} \]

\[ \alpha_E = \frac{E_i}{E_r} \]

- P: load, \( \nu_m \): poisson’s ratio of rock, \( E_m \): young’s modulus of rock,
- \( A \): foundation area, \( \beta_z \): foundation shape coefficient
- For rock site, the settlement may negligible
- Computer simulation, 1.0 inch is accepted as allowable criteria
- In case of differential settlement, the safety of pipes between Structures should be considered

Liquefactions potential evaluation

- When the site is composed of rock materials, then this analysis is not needed
Foundation Stability Evaluation

Geological and geotechnical map of foundation material
Foundation Stability Evaluation

Development of discontinuities in foundation rock

Rose diagram of fault in the foundation rock

Rose diagram for dykes in the foundation rock
Foundation stability evaluation

Improvement of unsuitable foundation and slope materials
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**Slope stability evaluation**

Evaluation of slope stability

- Slopes are divided into rock slope and soil slope type
- Different evaluation methods are applied according to the slope type
- Static and dynamic analysis shall be conducted
- Special attention should be paid to the temporal slope such as cut slope during construction

Basic information (Data requirements)

- Dimensions and the type of slope
- Geologic characteristics especially information about discontinuities
- Grounder water condition
- Geophysical exploration results
- Borehole logging and borehole 3-D images
Analysis of slope stability

- For soil slope the factor of safety has minimum value of 1.5 in static analysis and of 1.2 in dynamic analysis
- For rock site numerical analysis and stereo net-based graphic analysis is possible

Treatment of unstable slope

- Lowering the slope angle, drainage, anchoring, rock bolting, grouting, shotcrete, etc.

Monitoring of long-term slope stability

- Monitoring of groundwater condition, slope angle, etc.
Slope stability evaluation

Example of surface geological map for slope stability analysis

Example showing plan and wedge failure analysis results
Slope stability evaluation

Detailed on-site slope investigation
Slope stability evaluation
Slope stability evaluation

On-site inspection for the treatment of slope
Thank you for your attention!