Creating Value ...

Determination of the Bearing Resistance of Rock in West Virginia, 2012 Update

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... Delivering Solutions
The Problem
ASD Design

- $\sigma_v \text{ allowable}$ is a presumptive allowable bearing capacity
- Obtained from AASHTO Specs
- Based on a limiting settlement only (usually $\frac{1}{2}$ to 1”)
- Shear failure of foundation assumed to be not controlling

\[ \sigma_v \text{ max} < \sigma_v \text{ allowable} \]
- Presumptive (AASHTO 2006 Table 10.6.2.6-1 from NAVFAC DM-7)

<table>
<thead>
<tr>
<th>TYPE OF BEARING MATERIAL</th>
<th>CONSISTENCY IN PLACE</th>
<th>BEARING RESISTANCE (KSF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ordinary Range</td>
<td>Recommended Value of Use</td>
</tr>
<tr>
<td>Massive crystalline igneous and metamorphic rock: granite, diorite, basalt, gneiss, thoroughly cemented conglomerate (sound condition allows minor cracks)</td>
<td>Very hard, sound rock</td>
<td>120 to 200</td>
</tr>
<tr>
<td>Foliated metamorphic rock: slate, schist (sound condition allows minor cracks)</td>
<td>Hard sound rock</td>
<td>60 to 80</td>
</tr>
<tr>
<td>Sedimentary rock: hard cemented shales, siltstone, sandstone, limestone without cavities</td>
<td>Hard sound rock</td>
<td>30 to 50</td>
</tr>
<tr>
<td>Weathered or broken bedrock of any kind, except highly argillaceous rock (shale)</td>
<td>Medium hard rock</td>
<td>16 to 24</td>
</tr>
<tr>
<td>Compaction shale or other highly argillaceous rock in sound condition</td>
<td>Medium hard rock</td>
<td>16 to 24</td>
</tr>
<tr>
<td>Well-graded mixture of fine- and coarse-grained soil, glacial till, hardpan, boulder clay (GW-GG, GC, GC)</td>
<td>Very dense</td>
<td>16 to 24</td>
</tr>
<tr>
<td>Gravel, gravel-sand mixture, boulder-gravel mixtures (GW, GP, SW, SP)</td>
<td>Very dense</td>
<td>12 to 20</td>
</tr>
<tr>
<td></td>
<td>Medium dense to dense</td>
<td>8 to 14</td>
</tr>
<tr>
<td></td>
<td>Loose</td>
<td>4 to 12</td>
</tr>
<tr>
<td>Coarse to medium sand, and with little gravel (SW, SP)</td>
<td>Very dense</td>
<td>8 to 12</td>
</tr>
<tr>
<td></td>
<td>Medium dense to dense</td>
<td>4 to 8</td>
</tr>
<tr>
<td></td>
<td>Loose</td>
<td>2 to 6</td>
</tr>
<tr>
<td>Fine to medium sand, silty or clayey medium to coarse sand (SW, SM, SC)</td>
<td>Very dense</td>
<td>6 to 10</td>
</tr>
<tr>
<td></td>
<td>Medium dense to dense</td>
<td>4 to 8</td>
</tr>
<tr>
<td></td>
<td>Loose</td>
<td>2 to 4</td>
</tr>
<tr>
<td>Fine sand, silty or clayey medium to fine sand (SP, SM, SC)</td>
<td>Very dense</td>
<td>6 to 10</td>
</tr>
<tr>
<td></td>
<td>Medium dense to dense</td>
<td>4 to 8</td>
</tr>
<tr>
<td></td>
<td>Loose</td>
<td>2 to 4</td>
</tr>
<tr>
<td>Homogeneous inorganic clay, sandy or silty clay (CL, CH)</td>
<td>Very stiff to hard</td>
<td>8 to 12</td>
</tr>
<tr>
<td></td>
<td>Medium stiff to stiff</td>
<td>2 to 6</td>
</tr>
<tr>
<td></td>
<td>Soft</td>
<td>1 to 2</td>
</tr>
<tr>
<td>Inorganic silt, sandy or clayey silt, varved silt-clay-fine sand (ML, MH)</td>
<td>Very stiff to hard</td>
<td>4 to 8</td>
</tr>
<tr>
<td></td>
<td>Medium stiff to stiff</td>
<td>2 to 6</td>
</tr>
<tr>
<td></td>
<td>Soft</td>
<td>1 to 2</td>
</tr>
</tbody>
</table>
LRFD Design

Service Limit State
- Compute displacements and compare to tolerable displacement

Strength Limit State
- Check sliding failure
- Check overturning (e)
- Check bearing failure

Controlled for soft, fractured rocks
Current LRFD Methodology

1. 10.6.3.5 allows flexibility in the method used
2. Many engineers use equation 10.8.3.5.4c-2
3. This is equivalent to the $N_{ms}$ method that was presented in the old ASD specifications

$$q_n = \left[ \sqrt{s} + \sqrt{\left(m\sqrt{s} + s\right)} \right] q_u$$

$$q_{ult} = N_{ms} C_o$$

$$\phi q_n > \gamma \frac{V}{B} \left(1 + \frac{6e}{B}\right)$$
Research
(50 lbs of geotech reports)

- Estimate of RMR based on logs and descriptions
- Recommended allowable bearing capacity (presumptive)
- Estimate of GSI and other rock mass strength parameters
Distribution of Data

- Spread Footings
- Drilled Shafts
RMR = 50

Presumptive Bearing Resistance (KSF)

Nominal Bearing Resistance (KSF)

WV data using m & s method (AASHTO 2006)

Presumptive Bearing Resistance

N_{ms}
Design Recommendations

• Needed to be as objective as possible
• Needed to be easily implemented in the field
• Needed to provide results consistent with previous successful practice
Design Recommendations

• RMR as published in AASHTO selected as a reasonable basis for bearing resistance determination

• Different methods for RMR < 50 and RMR > 50
Design Recommendation for RMR < 50

- Empirical correlation of RMR to C and $\phi_f$ (Serafim and Pereira, 1983; Bieniawski, 1989)

\[
\text{Cohesion} = C = 104 \times RMR \quad \text{(in PSF)}
\]

\[
\text{Friction} = \phi_f = 5 + \frac{RMR}{2}
\]
Design Recommendation for RMR < 50

- General bearing resistance equation

\[ q_n = c \, N_{cm} + \gamma D_f N_{qm} \, C_{wq} + 0.5 \, \gamma B \, N_{\gamma m} \, C_{w\gamma} \]

\[ \phi \, q_n > \frac{\gamma \, V}{B - 2e_b} \]
## Design Recommendation for RMR > 50

- **m & s (AASHTO 2006 10.4.6.4-4)** Hoek and Brown

### Table 10.4.6.4-4 Approximate relationship between rock-mass quality and material constants used in defining nonlinear strength (Hoek and Brown, 1988)

<table>
<thead>
<tr>
<th>Rock Quality</th>
<th>Constants</th>
<th>Rock Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>Carbonate rocks with well developed crystal cleavage—dolomite, limestone and marble</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Lithified argillaceous rocks—mudstone, siltstone, shale and slate (normal to cleavage)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Arenaceous rocks with strong crystals and poorly developed crystal cleavage—sandstone and quartzite</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>Fine grained polymetallic igneous crystalline rocks—andesite, dolerite, diabase and rhyolite</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>Coarse grained polymetallic igneous &amp; metamorphic crystalline rocks—amphibolite, gabbro, granite, norite, quartzo-feldspar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTACT ROCK SAMPLES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laboratory size specimen free from discontinuities</td>
<td>m</td>
<td>7.00</td>
<td>10.00</td>
<td>15.00</td>
<td>17.00</td>
</tr>
<tr>
<td>CSIR rating: RMR = 100</td>
<td>s</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>VERY GOOD QUALITY ROCK MASS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tightly interlocking undisturbed rock with unweathered joints at 3-10 ft.</td>
<td>m</td>
<td>2.40</td>
<td>3.43</td>
<td>5.14</td>
<td>5.82</td>
</tr>
<tr>
<td>CSIR rating: RMR = 85</td>
<td>s</td>
<td>0.082</td>
<td>0.082</td>
<td>0.082</td>
<td>0.082</td>
</tr>
<tr>
<td>GOOD QUALITY ROCK MASS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fresh to slightly weathered rock, slightly disturbed with joints at 3-10 ft.</td>
<td>m</td>
<td>0.575</td>
<td>0.821</td>
<td>1.231</td>
<td>1.395</td>
</tr>
<tr>
<td>CSIR rating: RMR = 65</td>
<td>s</td>
<td>0.00293</td>
<td>0.00293</td>
<td>0.00293</td>
<td>0.00293</td>
</tr>
<tr>
<td>FAIR QUALITY ROCK MASS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Several sets of moderately weathered joints spaced at 1-3 ft.</td>
<td>m</td>
<td>0.128</td>
<td>0.183</td>
<td>0.275</td>
<td>0.311</td>
</tr>
<tr>
<td>CSIR rating: RMR = 44</td>
<td>s</td>
<td>0.00009</td>
<td>0.00009</td>
<td>0.00009</td>
<td>0.00009</td>
</tr>
<tr>
<td>POOR QUALITY ROCK MASS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numerous weathered joints at 2 to 12 in.; some gouge. Clean compacted waste rock.</td>
<td>m</td>
<td>0.029</td>
<td>0.041</td>
<td>0.061</td>
<td>0.069</td>
</tr>
<tr>
<td>CSIR rating: RMR = 23</td>
<td>s</td>
<td>3 x 10^-6</td>
<td>3 x 10^-6</td>
<td>3 x 10^-6</td>
<td>3 x 10^-6</td>
</tr>
<tr>
<td>VERY POOR QUALITY ROCK MASS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numerous heavily weathered joints spaced &lt; 2 in. with gouge. Waste rock with fines.</td>
<td>m</td>
<td>0.007</td>
<td>0.010</td>
<td>0.015</td>
<td>0.017</td>
</tr>
<tr>
<td>CSIR rating: RMR = 3</td>
<td>s</td>
<td>1 x 10^-7</td>
<td>1 x 10^-7</td>
<td>1 x 10^-7</td>
<td>1 x 10^-7</td>
</tr>
</tbody>
</table>
Design Recommendation for RMR > 50

- Lower bound equation (AASHTO 2006 10.8.3.5.4c-2)

\[ q_n = \left[ \sqrt{s} + \sqrt{m\sqrt{s} + s} \right] q_u \]

\( \phi q_n > \frac{\gamma V}{B} \left( 1 + \frac{6e_b}{B} \right) \)
Spread Footings

RMR 83, C & $\phi_f$, Gen. Eq. $B' = 15'$

WV data using m & s method (AASHTO 2006)

Approx. Upper Limit for Soil

Design as Soil

Presumptive Bearing Resistance

$q_u = 1728$ ksf
$q_u = 864$ ksf

Nominal Bearing Resistance (KSF)

RMR

RMR 83, m & s, AASHTO 2006

Spread Footings
Drilled Shafts

- RMR 83, C & $\phi_f$, Gen. Eq.
- D = 5'

- Approx. Upper Limit for Soil
- Design as Soil

- WV data using m & s method (AASHTO 2006)
- Presumptive Bearing Resistance
- Load Test Data

Nominal Bearing Resistance (ksf)

RMR 1983
Implementation of RMR

Contract Documents

Inspector Handbook

Being Updated

Being Updated
Implementation of RMR

7-3-10-20-4 (44)
3.12 FOUNDATIONS

3.12.1 General

Unless directed otherwise by the Director of Engineering Division, all substructures are to be founded upon bedrock, whether by spread footings, piles or drilled caissons. Only end bearing piles, either driven or predrilled and driven, are acceptable. Friction or combination friction and bearing piles shall not be used.

The Geotechnical Report will list design assumptions and recommend appropriate foundations. The Design Engineer will determine if the structure will accommodate the design assumptions (i.e., settlement tolerance).

3.12.1.1 General

The geotechnical investigation will include field testing and laboratory testing of the soils and rock to determine the suitability of materials for construction of drilled shafts, piles, cut-offs, and other substructure elements. The soil and rock testing and analysis shall be in accordance with AASHTO M149, M123, and M148.

3.12.1.1.1 General

Due consideration shall be given to testing and analysis in planning and performing a subsurface investigation. As a minimum, the potential for mining and mine subsidence, karst, and landslides shall be assessed. The following sections provide guidance on assessing the potential for these geologic hazards at the project site.

3.12.1.1.1 Mining and Mine Subsidence

If the project is in an area shown in figure 3.12.1.1.1-1, investigate the potential for mine subsidence related problems. Mining and mine subsidence can impact bridge structures due to loss of support for substructure elements, excessive differential settlement of substructures, and degradation of structural materials from acid surface and ground water.

For more detailed information on the potential for mining related hazards, refer to H.M. King and D.S. Kistler, "1087, Mineral Resources of West Virginia: 1500,006, 63° x 34°, Full Color. Shows visible coal extent, oil and gas fields, rock salt extent, major limestone cutrop, potential areas for limestone deep mining, Ohio River sand and gravel areas, transportation system (major highways, railroads, and navigable streams)."
Performance of implemented solution

Distribution of Data

- Spread Footings
- Drilled Shafts
- Recent
Factored Bearing Resistance vs. RMR

- >50
- <50
- Linear (>50)
- Linear (<50)
Performance of implemented solution

NO FAILURES!
Nominal Bearing Resistance (ksf)

RMR 83, m & s, AASHTO 2006
\( q_u = 1728 \text{ ksf} \)

RMR 83, Bieniawski C & \( \phi_f \), General Equation
\( B' = 15' \)

Original Data
Presumptive

Recent Data RMR > 50
Recent Data RMR < 50
Issues

• Discontinuity at RMR=50
• Resistance factor
• Confusion about design methodology
• Presentation of recommended bearing resistance for RMR < 50
Discontinuity at RMR=50
Factored Bearing Resistance

\[ y = 3.2325e^{0.066x} \]
Resistance Factor

Factored Bearing Resistance

$\phi = 0.45$

$\phi = 0.5$
Resistance Factor

Calibration to ASD:

\[
FS = \frac{\gamma}{\phi}
\]

Average load factor \(\gamma = 1.4\)

For \(\phi = 0.5\); \(FS = 2.8\)

For \(\phi = 0.45\); \(FS = 3.1\)

\(\phi = 0.45\) will be recommended in BDM
Confusion about Design Procedures

Currently Being Updated to Include these Design Recommendations
Presentation of Bearing Resistance

- Nominal Bearing Resistance (ksf)
- Effective Footing Width (B') - (ft)
Conclusions

• RMR = 50 is appropriate split between methods
Conclusions

• Not an LRFD statistical approach but a calibration to past successful practice retaining as much of AASHTO as possible
Conclusions

• Many fewer complaints about “unreasonable” bearing resistance
Questions?

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