Fine Coal Refuse – 25 Years of Field and Laboratory Testing Data and Correlations

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Blaise E. Genes
Gonzalo Castro, Ph.D., P.E.
Thomas O. Keller, P. E.
Fatma Ciloglu, Ph.D., P. E.
1. Introduction

2. Upstream-Constructed Coal Refuse Impoundments and Key Design Aspects

3. Fine Coal Refuse (FCR) In-Situ Field and Laboratory Testing

4. FCR Field and Laboratory Data Application Summary

5. FCR Data Correlations

6. FCR Undrained Strength Analyses Examples
Introduction

- Evaluated FCR tailings at numerous WV, KY and IL impoundment sites since 1991 – 10 WV, 2 KY, 3 IL.

- Amassed a database of field and laboratory data from 15 large, high-hazard upstream-constructed impoundments.

- CPT-based evaluations and undrained strength analyses performed to evaluate:
  - Material characteristics;
  - Liquefaction triggering;
  - Post-earthquake stability; and
  - Construction loading rate.
Upstream-Constructed Coal Refuse Impoundments

- Some of the tallest earth structures in the world;
- Unique characteristics;
- FCR hydraulically-deposited and used as foundation for subsequent embankment construction;
- FCR requires sufficient time to settle and excess pore pressure to dissipate;
- Undrained conditions control upstream pushout and seismic loading;

**Figure 6.8** Upstream construction following initial development.
Key design aspects:

- Developing and implementing risk-appropriate in-situ field and laboratory testing;
- Evaluating FCR material characteristics, i.e., does FCR behave more sand-like or clay-like;
- Estimating undrained shear strength and $S_u/\sigma'_v$ ratio;
- Evaluating if strength loss is triggered due to undrained loading event;
- Evaluating post-earthquake stability with appropriate $S_u$ and corresponding safety factor; and,
- Evaluating incremental $S_u$ required vs. $S_u$ gained due to excess pore pressure and consolidation.
In-Situ Field Testing Methods:

- Cone Penetration Testing (CPT);
- Shear wave velocity measurements;
- Pore-pressure dissipation and vane shear testing;
- Fixed-piston undisturbed sampling; and,
- In-situ/in-tube void ratio.
PS-CPT Field Testing Data

GAI Consultants

Job No: 16-53085
Date: 08/29/16 14:12
Site: SCPT16-J01
Cone: 468-T1500F15U500

El. 1246.6'  ct (tsf)  fs (tsf)  Rf (%)  u (ft)  SBT
El. 1225.6'  CCR
El. 1211.6'  Mix
El. 1110.6'  FCR
El. 1046.6'  CCR

Max Depth: 61,000 m / 200.13 ft
Depth Inc: 0.050 m / 0.164 ft
Avg Int: Every Point

Hydrostatic Line  Ueq  Assumed Ueq  PPD, Ueq achieved  PPD, Ueq not achieved

The reported coordinates were acquired from consumer-grade GPS equipment and are only approximate locations. The coordinates should not be used for design purposes.

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Laboratory Testing:

- Grain-size, Atterberg limits, moisture content, specific gravity;
- CU triaxial shear strength:
  - Peak, $S_{up}$ and steady-state, $S_{us}$ undrained shear strength;
  - Peak shear strain, $\varepsilon$; and,
  - $S_{up}/\sigma'_v$ and $S_{us}/\sigma'_v$ strength-to-effective stress ratios.
Material characterization depends on laboratory data (% passing #200, plasticity, peak strain), which influence behavior.

Key Differences – Sand-like or Clay-like Behavior:
- Strain at peak undrained shear strength
- Abruptness of the drop-off in shearing resistance
Characterizing FCR From CPT

Soil Behavior Type Index, $I_c$ | Zone
--- | ---
$I_c < 1.31$ | 7
$1.31 < I_c < 2.05$ | 6
$2.05 < I_c < 2.60$ | 5
$2.60 < I_c < 2.95$ | 4
$2.95 < I_c < 3.60$ | 3
$I_c > 3.60$ | 2

Zone | Soil Behavior Type
--- | ---
7 | Gravelly sand to dense sand
6 | Sands: clean sand to silty sand
5 | Sand mixtures: silty sand to sandy silt
4 | Silt mixtures: clayey silt to silty clay
3 | Clays: silty clay to clay
2 | Organic soils: peats

After MSHA. 2009

Characterizing FCR From CPT

Zone A: Loose sand-like; Liquefaction Possible – Depends on EQ M and duration.

Zone B: Clay-like; Liquefaction Unlikely – Check other criteria, i.e., cyclic stress/strain.

Zone C: Sensitive Clay-like; Liquefaction Possible – Depends on plasticity and EQ M.

Soils with $I_c > 2.6$ and $F > 1.0\%$ are Likely Non-liquefiable.


Normalized Tip Resistance ($Q$) and Friction ($F$) Ratio for FCR Materials/Sites

After MSHA. 2009
Summary of Shear Strain Range for Laboratory Tested FCR Samples
Laboratory-Derived Undrained Strength

- High quality undisturbed samples used to measure $S_{us}$ and $S_{up}$.

- $S_{us}$ measured in the laboratory will be higher than in-situ.

- Disturbance accounted for by correcting laboratory $S_{us}$ back to the in-situ $S_{us}$, which requires:
  1. Careful measurement of void ratio during sampling and handling; and,
  2. Estimating slope of the Steady-State Line ($\Delta e/\Delta \log S_{us}$).
Laboratory-Field Undrained Strength

Correction of $S_{us}$ from Laboratory to In-Situ Void Ratio

FIGURE 7.12  INTERPRETATION OF LABORATORY $S_{us}$ TESTING

MSHA. 2009
Laboratory-Derived SSL

Undrained Steady State Shear Strength vs Void Ratio During Shear

Undrained Steady State Shear Strength, $S_{us}$, ksc

Steady-State Line – WV, KY and IL Sites
Applications for Testing Data

- CPT data and $S_{up}/\sigma_v'$ or $S_{us}/\sigma_v'$ used in engineering analyses to evaluate:
  - Liquefaction…will the undrained loading trigger a strength loss in FCR?
    - Yes…Use $S_{us}/\sigma_v'$
    - No…Use $S_{up}/\sigma_v'$
  - Post-earthquake stability factors of safety; and,
  - Pushout strength required for 1.3 safety factor in construction stability.
Post-Earthquake Stability Analyses

Upstream Stability

Downstream Stability

FINE COAL REFUSE

$S_{up}/\sigma^3_v$ or $S_{us}/\sigma^3_v$

FOUNDATION SOILS
Laboratory-Derived FCR $S_{us}$

Undrained Steady State Shear Strength In-Situ vs Estimated Vertical Effective Stress

Undrained Steady State Shear Strength In-Situ, $S_{us}$, ksc

Estimated Vertical Effective Stress, $\sigma_v$

- $S_{us} = 0.16 \sigma_v$
- $S_{us, min} = 0.03 \sigma_v$
- $S_{us, max} = 0.27 \sigma_v$

Undrained Steady-State Shear Strength to Effective Stress Strength Ratio
### $S_{us}/\sigma'_v$ Correlations - References

#### Table 7.3: Correlations of $S_{us}/\sigma'_v$ Versus SPT and CPT Data Back-Calculated from Case Histories

<table>
<thead>
<tr>
<th>Reference</th>
<th>Reported $S_{us}/\sigma'_v$</th>
<th>Types of Data and Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baziar and Dobry (1995)</td>
<td>0.04 to 0.20</td>
<td>Back-calculated values from failure case histories for 9 sites with silty sand or sandy silt material (more than 10 percent fines). One of the 9 sites was identified as a tailings dam.</td>
</tr>
<tr>
<td>Yoshimine, Robertson and Wride (1999)</td>
<td>0.03 to 0.19</td>
<td>Back-calculated values from case histories involving multiple submarine slides at 3 sites. Materials were natural clean sand, silty sand, and sandy silt.</td>
</tr>
<tr>
<td>Olson and Stark (2002)</td>
<td>0.05 to 0.12 (proposed limits of ratios)</td>
<td>Back-calculated values from 33 failure case histories, including re-evaluation of the Baziar and Dobry sites. Four of the 33 sites were identified as tailings dams as compared to dams or slopes consisting of natural soils. Four of the 33 sites, including one of the tailings dam sites, had ratios of 0.02 to 0.04, outside their proposed boundary.</td>
</tr>
<tr>
<td>Idriss and Boulanger (2007)</td>
<td>0.05 to 0.22</td>
<td>Back-calculated values based on select case histories published by Seed (1987), Seed and Harder (1990), and Olson and Stark (2002) with adequate amount of in-situ measurements and reasonably complete geometric details (7 of the 35 case histories reviewed).</td>
</tr>
</tbody>
</table>

MSHA. 2009

#### Literature Correlations of $S_{us}/\sigma'_v$ from Failure Cases
Laboratory-Derived FCR $S_{up}$

Peak Undrained Shear Strength In-Situ vs Estimated Vertical Effective Stress

Peak Undrained Shear Strength In-Situ, $S_{up}$ ksc

- $S_{up} = 0.24 \sigma'_v$
- $S_{up \text{ min}} = 0.19 \sigma'_v$
- $S_{up \text{ max}} = 0.35 \sigma'_v$
Fines Data Correlations – $S_{us}$

**$S_{us}$ vs. $I_c$**

- Equation: $y = 0.589x - 1.0939$
- $R^2 = 0.0995$

**$S_{us}$ vs. $I_c$**

- Equation: $y = 0.0111x$
- $R^2 = -0.328$

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*S*us vs. Soil Behavior Index, *Ic*  
*S*us vs. Laboratory Fines Content
**N_{1,60} Data Correlations – \( S_{us} \) and \( S_{up} \)**

**\( S_{us} \) vs. \( N_{1,60} \)**

- \( y = 0.2715e^{0.1003x} \)
- \( R^2 = 0.2872 \)

**\( S_{up} \) vs. \( N_{1,60} \)**

- \( y = 0.6601e^{0.0697x} \)
- \( R^2 = 0.4033 \)
**Undrained Steady-State Shear Strength vs Shear Wave Velocity**

- **Equation**: $y = 0.0044x$
- **Correlation Coefficient**: $R^2 = -0.049$

**Legend**:
- Site 3
- Site 4
- Site 6
- Site 7
- Site 8
- Site 9
- Site 10
- Site 12

**Notes**:
- The graph shows the relationship between undrained steady-state shear strength ($S_{us}$) and shear wave velocity ($V_s$).
- The linear equation $y = 0.0044x$ represents the trend, with a negative correlation coefficient $R^2 = -0.049$.
### Literature Correlations of $S_{us}$ with SPT and CPT Data

#### TABLE 7.2 REFERENCES FOR CORRELATIONS OF $S_{US}$ WITH SPT AND CPT DATA

<table>
<thead>
<tr>
<th>Reference</th>
<th>Correlated Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed (1987)</td>
<td>$S_{us}$ vs. $N_{1,60}$</td>
</tr>
<tr>
<td>Davis, Castro and Poulos (1988)</td>
<td>$S_{us}$ vs. $N_{1,60}$</td>
</tr>
<tr>
<td>Seed and Harder (1990)</td>
<td>$S_{us}$ vs. $N_{1,60}$</td>
</tr>
<tr>
<td>Baziar and Dobry (1995)</td>
<td>$S_{us}$ and $S_{us}/\sigma'<em>v$ vs. $N</em>{1,60}$</td>
</tr>
<tr>
<td>Castro (1995)</td>
<td>$S_{us}$ vs. $N_{1,60}$</td>
</tr>
<tr>
<td>Wride, McRoberts and Robertson (1999)</td>
<td>$S_{us}$ and $S_{us}/\sigma'<em>v$ vs. $N</em>{1,60}$</td>
</tr>
<tr>
<td>Yoshimine, Robertson and Wride (1999)</td>
<td>$S_{us}/\sigma'<em>v$ vs. $q</em>{c1N(CS)}$</td>
</tr>
<tr>
<td>Olson and Stark (2002)</td>
<td>$S_{us}/\sigma'<em>v$ vs. $N</em>{1,60}$ and $q_{lt1}$</td>
</tr>
<tr>
<td>Idriss and Boulanger (2007)</td>
<td>$S_{us}$ and $S_{us}/\sigma'<em>v$ vs. $N</em>{1,60}$ and $q_{c1N(CS)}$</td>
</tr>
</tbody>
</table>

**Note:**
- $S_{us}$ = Undrained steady state (residual) strength.
- $N_{1,60}$ = Standard Penetration Test (SPT) N-value, normalized to an effective overburden stress of one atmosphere (typically 1 tsf) and normalized to a hammer efficiency of 60 percent.
- $S_{us}/\sigma'_v$ = Undrained steady state strength normalized to vertical effective stress.
- $q_{c1N(CS)}$ = Cone Penetration Test (CPT) tip resistance normalized to a reference pressure of one atmosphere and corrected to an equivalent value for clean sand.
- $q_{lt1}$ = CPT tip resistance normalized to an effective overburden stress of one atmosphere.

MSHA. 2009
Staged Construction Stability Analysis

$S_u$ required for stability $FS=1.3$

Updated 10 ft Stage J Push-Out

Name: Coarse Coal Refuse (CCR)  Unit Weight: 122 pcf  Unit Wt. Above Water Table: 111.2 pcf  Cohesion: 0 psf  Phi: 36 °
Name: Pondered FCR  Unit Weight: 90 pcf  Unit Wt. Above Water Table: 85 pcf  Tau/Sigma Ratio: 0.32
Name: Mixed  Unit Weight: 122 pcf  Unit Wt. Above Water Table: 111.2 pcf  Cohesion: 0 psf  Phi: 29 °
Name: Consolidating FCR  Unit Weight: 90 pcf  Unit Wt. Above Water Table: 85 pcf  C-Datum: 220 psf  C-Rate of Change: 8.8 psf/ft  Elevation: 1210 ft
Name: Fresh FCR  Unit Weight: 90 pcf  Unit Wt. Above Water Table: 85 pcf  Tau/Sigma Ratio: 0.22

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**Staged Construction Stability Analysis**

**S_u** required for stability FS=1.3

*Updated 20 ft Stage J Push-Out*

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit Weight</th>
<th>Unit Wt. Above Water Table</th>
<th>Cohesion</th>
<th>Phi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Coal Refuse (CCR)</td>
<td>122 pcf</td>
<td>111.2 pcf</td>
<td>0 psf</td>
<td>36°</td>
</tr>
<tr>
<td>Ponded FCR</td>
<td>90 pcf</td>
<td>85 pcf</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>Mixed</td>
<td>122 pcf</td>
<td>111.2 pcf</td>
<td>0 psf</td>
<td>29°</td>
</tr>
<tr>
<td>Consolidating FCR</td>
<td>90 pcf</td>
<td>85 pcf</td>
<td>310 psf</td>
<td>8.8</td>
</tr>
<tr>
<td>Fresh FCR</td>
<td>90 pcf</td>
<td>85 pcf</td>
<td>0.22</td>
<td></td>
</tr>
</tbody>
</table>
Staged Construction Stability Analysis

$S_u$ required for stability $FS=1.3$

Updated 30 ft Stage J Push-Out

Name: Coarse Coal Refuse (CCR)  Unit Weight: 122 pcf  Unit Wt. Above Water Table: 111.2 pcf  Cohesion: 0 psf  Phi: 36°
Name: Ponded FCR  Unit Weight: 90 pcf  Unit Wt. Above Water Table: 85 pcf  Tau/Sigma Ratio: 0.32
Name: Mixed  Unit Weight: 122 pcf  Unit Wt. Above Water Table: 111.2 pcf  Cohesion: 0 psf  Phi: 29°
Name: Consolidating FCR  Unit Weight: 90 pcf  Unit Wt. Above Water Table: 65 pcf  C-Datum: 400 psf  C-Rate of Change: 8.8 psf/ft  Elevation: 1210 ft
Name: Fresh FCR  Unit Weight: 90 pcf  Unit Wt. Above Water Table: 85 pcf  Tau/Sigma Ratio: 0.22
Staged Construction Stability Analysis

$S_u$ required for stability $FS=1.3$

Updated 40 ft Stage J Push-Out

- Coarse Coal Refuse (CCR): Unit Weight 122pcf, Unit Wt. Above Water Table 111.2pcf, Cohesion 0 psf, Phi 36°
- Ponded FCR: Unit Weight 90pcf, Unit Wt. Above Water Table 85pcf, Tau/Sigma Ratio 0.32
- Mixed: Unit Weight 122pcf, Unit Wt. Above Water Table 111.2pcf, Cohesion 0 psf, Phi 29°
- Consolidating FCR: Unit Weight 90pcf, Unit Wt. Above Water Table 85pcf, C-Datum 500 psf, C-Rate of Change 8.8 psf/ft, Elevation 1210 ft
- Fresh FCR: Unit Weight 90pcf, Unit Wt. Above Water Table 85pcf, Tau/Sigma Ratio 0.22
Staged Construction Stability Analysis

$S_u$ required for stability $FS=1.3$

Updated 50 ft Stage J Push-Out

Name: Coarse Coal Refuse (CCR)  Unit Weight: 122 pcf  Unit Wt. Above Water Table: 111.2 pcf  Cohesion: 0 psf  Phi: 36°
Name: Ponded FCR  Unit Weight: 90 pcf  Unit Wt. Above Water Table: 85 pcf  Tau/Sigma Ratio: 0.32
Name: Mixed  Unit Weight: 122 pcf  Unit Wt. Above Water Table: 111.2 pcf  Cohesion: 0 psf  Phi: 29°
Name: Consolidating FCR  Unit Weight: 90 pcf  Unit Wt. Above Water Table: 85 pcf  C-Datum: 580 psf  C-Rate of Change: 8.8 psf/ft  Elevation: 1210 ft
Name: Fresh FCR  Unit Weight: 90 pcf  Unit Wt. Above Water Table: 85 pcf  Tau/Sigma Ratio: 0.22
Conclusions

- Upstream-constructed impoundments must endure high level of scrutiny particularly for seismic and push-out construction undrained loading conditions.

- 25+ years of consistent field and laboratory testing of FCR yielded a significant volume of high quality data.

- FCR data and correlations present ranges to evaluate peak and steady-state undrained shear strength in absence of, or for data comparison.

- Risk-appropriate site-specific testing should be performed to estimate undrained shear strengths.

- Site-specific FCR strength ultimately control undrained strength analyses.
Questions??

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