Review of Site Characterization and Conceptual Dam Design

State Agency Briefing
December 12, 2016
Olympia, WA

- Summary of Site Characterization
- Seismic Hazards
- Landslides
- Dam Design
- Cost Estimates
- Future Site Characterization
- Schedule
Summary of Site Characterization
Site Characterization Activities

• Seismic Hazards
• Landslides
• Phase 1 Site Explorations
• Phase 2 Site Explorations
• Construction Materials
Site Investigation Overview

- Reservoir Landslide Seismic Lines 1-5
- Dam Site: 16 Borings, 7 Seismic Lines
- Quarry 3 (Rock Creek)
- Quarry-1
- Quarry-2
- Hand Samples
- Reservoir Landslide Seismic Lines 10
Phase 2 Site Characterization

- Characterization of the subsurface at the proposed outlet works, and along diversion tunnel alignment with angled borings, seismic lines and direct shear laboratory testing.

- Structural Geology: characterization of major joint set orientations.

- Preliminary evaluation of the quality and quantity of quarry rock available at three possible sites to be used as RCC aggregate through borings, seismic lines and laboratory testing.
Overview - Dam Site Investigation

Legend

- BH-1: DRILL HOLE LOCATION - PHASE 1
- DB-1: DRILL HOLE LOCATION - PHASE 2 & 3
- SEISMIC LINE - PHASE 1
- SEISMIC LINE - PHASE 2
- EXISTING ROAD
- NEW PHASE 2 ROAD

GEOLOGIC UNITS:
- Qa: ALLUVIUM
- Qls: LANDSLIDE DEPOSITS
- Qz: COLLUVIUM
- Qop: OLDER ALLUVIUM
- Qox: OVERBURDEN SOIL
  UNSPECIFIED (Cross Section Only)

Phase 1:
6 Borings
5 Seismic Lines

Phase 2:
16 Borings
7 Seismic Lines
Composite Boring Log Example
Hydraulic Conductivity
Phase 2 Site Characterization Updates

- Refined understanding of the **Crescent Formation** claystone/siltstone (Tcs)
  - units of unknown shape and lateral extents with no discernable regional orientation
  - depositional features with variable dip within the same layer ranging from horizontal to approximately 20 degrees, near horizontal top elevations between some borings that is not consistent with published and mapped regional orientation
  - variable elevations of Tcs between proximal borings suggesting discontinuous deposition and a varying depositional topography

- The excavation objective updated; slightly deeper in some locations. 3D model
Phase 2 Site Characterization

Updates

Valley Cross-section at Hydraulic Structures
Phase 2 Site Characterization Updates

- Characterization of the diversion tunnel alignment with 3 borings
- Characterization of stilling basin foundation from an additional seismic line
- Characterization of the saddle embankment foundation through 3 new borings and seismic line
Quarry Investigations

All 3 quarry locations show promising laboratory testing results:

<table>
<thead>
<tr>
<th>Quarry Site</th>
<th>No. of Samples</th>
<th>Compressive Strength (psi)</th>
<th>Absorption %</th>
<th>LA Abrasion Loss %</th>
<th>Alkali Silica Reactivity 16 Day Avg. Length Change %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarry 1</td>
<td>3</td>
<td>4,278</td>
<td>6.47</td>
<td>27.1</td>
<td>0.093</td>
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<tr>
<td>Quarry 2</td>
<td>2</td>
<td>11,433</td>
<td>3.88</td>
<td>24.45</td>
<td>0.035</td>
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<td>Rock Creek</td>
<td>1</td>
<td>NA</td>
<td>1.37</td>
<td>18.9</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Quarry 1 is the preferred quarry site (shortest haul distance <2 miles)  
Rock Creek (Quarry 3) provides a better haul road (Highway 6)
Seismic Hazards
Chehalis Dam Seismic Hazard

Structural Design Criteria

• Cascadia Subduction Zone (CSZ) earthquake loading controls design / cross-section requirements

• Three-tiered Risk-based Design Criteria
  o Elastic Response – minimum 500-year event
  o Non-linear response, limited damage – minimum 5,000-year event
  o Non-linear response, moderate damage, no post-earthquake dam failure – 10,000 and 50,000 year events
Chehalis Dam Seismic Hazard

• Response spectrum analysis for CSZ events (500; 2,500; 5,000; 10,000 year recurrence intervals)

• Ground Motions including Maximum Credible Earthquake MCE
Chehalis Dam Seismic Hazard
Landslides
Landslides
Landslides

Removed or stability improved during dam construction
Landslides – Excavation spoils used to improve stability

Stability improved during dam construction using spoils
Notes:
1. FS ranges above are for the 100-year inundation event for the Flood Retention Flow Augmentation (FRFA) retention facility.
2. Modified 100-year inundation curves were developed to evaluate the impact reducing the drawdown rates have on Factor of Safety (FS) against landslide instability.
3. The boxplot diagrams for each landslide in the chart above indicate, from top to bottom, the maximum FS, the third quartile FS, the median FS, the first quartile FS, and the minimum FS.
4. Landslides without a FS boxplot are in locations not affected by drawdown of the FRFA facility.
Landslides

Monitor Toe Erosion Protection

Improve Stability

Monitor
Dam Design

Foundation
Cross-section
Hydraulic Structures
Putting it all Together
Dam Foundation Design
Field Data

- Borehole and core sampling (SPT, recovery, RQD)
- Hydraulic Conductivity (Kh)
- Geophysical Surveys (Seismic Refraction Tomography, Vs, Vp)
- Optical/Acoustic Televiewer
- Sonic Suspension Logging
- Geological mapping
Laboratory Data

- Index tests (gradation, plasticity)
- Compressive strength (UCS)
- Point load test
- Elastic modulus
- Slake durability (potential to degrade when exposed in excavations)
- Petrographic examination of aggregates for concrete
Material Properties (1/5)

Unconfined Compressive Strength based on Point Load Tests

Table 4.4
Phase 2 Rock Laboratory Testing Results – Point Load (ASTM 5731)

<table>
<thead>
<tr>
<th>BOREHOLE</th>
<th>LITHOLOGY</th>
<th>DEPTH (FT)</th>
<th>UCS (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FROM</td>
<td>TO</td>
</tr>
<tr>
<td>OB-1</td>
<td>basalt</td>
<td>43.8</td>
<td>44.5</td>
</tr>
<tr>
<td>OB-2</td>
<td>basalt</td>
<td>48.3</td>
<td>48.7</td>
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<td>basalt</td>
<td>70.9</td>
<td>71.4</td>
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<td>43.3</td>
<td>43.6</td>
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<td>DB-7</td>
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<td>45.0</td>
<td>45.5</td>
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<td>77.9</td>
<td>78.6</td>
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<td>TB-2</td>
<td>basalt</td>
<td>105.4</td>
<td>105.7</td>
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<td>80.8</td>
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<td>TB-3</td>
<td>basalt</td>
<td>102.5</td>
<td>103.1</td>
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<tr>
<td>TB-5</td>
<td>claystone</td>
<td>72.8</td>
<td>73.2</td>
</tr>
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</table>

Note: All tests performed as diameter tests. PSI – pounds per square inch.
### Material Properties (2/5)

**Unconfined Compressive Strength from Compression Test**

#### Table 4.5

Phase 1 and 2 Rock Laboratory Testing Results - Bulk Density and Compressive Strength

<table>
<thead>
<tr>
<th>PHASE</th>
<th>BOREHOLE</th>
<th>DEPTH (FT) FROM</th>
<th>TO</th>
<th>LITHOLOGY</th>
<th>BULK DENSITY (POUNDS/CUBIC FEET)</th>
<th>COMPRRESSIVE STRENGTH (PSI)</th>
<th>ASTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BH-1</td>
<td>45.76, 46.2</td>
<td>76.22, 76.66</td>
<td>Basalt - Tcb</td>
<td>171</td>
<td>15,683</td>
<td>D7012 - Method C</td>
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<tr>
<td></td>
<td>BH-2</td>
<td>41.7, 42.14</td>
<td>62.15, 62.59</td>
<td>Basalt - Tcb</td>
<td>171</td>
<td>14,043</td>
<td>D7012 - Method C</td>
</tr>
<tr>
<td></td>
<td>BH-5</td>
<td>96.5, 96.94</td>
<td>123.5, 123.94</td>
<td>Basalt - Tcb</td>
<td>170</td>
<td>26,083</td>
<td>D7012 - Method C</td>
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<tr>
<td></td>
<td>BH-6</td>
<td>105.06, 105.5</td>
<td>213.86, 214.3</td>
<td>Basalt - Tcb</td>
<td>171</td>
<td>17,751</td>
<td>D7012 - Method C</td>
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<td>2</td>
<td>DB-1</td>
<td>40.1, 40.55</td>
<td>77.93, 78.38</td>
<td>Basalt - Tcb</td>
<td>171</td>
<td>13,883</td>
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<td>DB-5</td>
<td>75.04, 75.54</td>
<td>81.28, 81.73</td>
<td>Basalt - Tcb</td>
<td>171</td>
<td>13,883</td>
<td>D7012 - Method C</td>
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<td></td>
<td>DB-7</td>
<td>61.95, 62.55</td>
<td>168</td>
<td>Basalt - Tcb</td>
<td>168</td>
<td>8,271</td>
<td>D7012 - Method C</td>
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<tr>
<td></td>
<td>LSB-1</td>
<td>41.0, 41.6</td>
<td>168</td>
<td>Basalt - Tcb</td>
<td>168</td>
<td>14,175</td>
<td>D7012 - Method C</td>
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<tr>
<td></td>
<td>OB-1</td>
<td>42.2, 43.0</td>
<td>158</td>
<td>Basalt - Tcb</td>
<td>158</td>
<td>1,229</td>
<td>D7012 - Method C</td>
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<tr>
<td></td>
<td>OB-2</td>
<td>45.6, 46.8</td>
<td>170</td>
<td>Basalt - Tcb</td>
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<td>18,359</td>
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<td>OB-3</td>
<td>38.8, 39.6</td>
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<td>1,834</td>
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<td>QB-2</td>
<td>125.7, 126.7</td>
<td>163</td>
<td>Breccia - Tcb</td>
<td>163</td>
<td>5,237</td>
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<td>QB-3</td>
<td>6.0, 6.8</td>
<td>168</td>
<td>Basalt - Tcb</td>
<td>168</td>
<td>13,210</td>
<td>D7012 - Method C</td>
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<tr>
<td></td>
<td>TB-1</td>
<td>35.1, 35.55</td>
<td>167</td>
<td>Basalt - Tcb</td>
<td>167</td>
<td>8,271</td>
<td>D7012 - Method C</td>
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<td></td>
<td>TB-2</td>
<td>77.3, 77.75</td>
<td>167</td>
<td>Basalt - Tcb</td>
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<td>8,805</td>
<td>D7012 - Method C</td>
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<td>TB-3</td>
<td>92.6, 93.05</td>
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<td>Basalt - Tcb</td>
<td>166</td>
<td>15,282</td>
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<td>TB-4</td>
<td>36.0, 36.8</td>
<td>169</td>
<td>Basalt - Tcb</td>
<td>169</td>
<td>5,093</td>
<td>D7012 - Method C</td>
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</tbody>
</table>
## Material Properties (3/5)

### Young’s Modulus and Poisson’s Ratio

#### Table 4.6

Phase 1 Rock Laboratory Testing Results – Young’s Modulus and Poisson’s Ratio (ASTM D7012-Method D)

<table>
<thead>
<tr>
<th>BOREHOLE</th>
<th>DEPTH (FEET)</th>
<th>LITHOLOGY</th>
<th>STRESS RANGE (PSI)</th>
<th>YOUNG’S MODULUS (X10^6 PSI)</th>
<th>AVG. YOUNG’S MODULUS (X10^6 PSI)</th>
<th>POISSON’S RATIO</th>
<th>AVG. POISSON’S RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH-1</td>
<td>76.22</td>
<td>76.66</td>
<td>Basalt - Tcb</td>
<td>2100 7600</td>
<td>9.410</td>
<td>8.933</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>7600 13100</td>
<td>9.360</td>
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<td></td>
<td></td>
<td></td>
<td>13100 18600</td>
<td>8.030</td>
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<td>BH-2</td>
<td>62.15</td>
<td>62.59</td>
<td>Basalt - Tcb</td>
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<td>11.000</td>
<td>10.147</td>
<td>0.29</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>9600 16500</td>
<td>10.300</td>
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<td></td>
<td></td>
<td></td>
<td>16500 23500</td>
<td>9.140</td>
<td></td>
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<tr>
<td>BH-5</td>
<td>123.5</td>
<td>123.9</td>
<td>Basalt - Tcb</td>
<td>1500 5600</td>
<td>8.370</td>
<td>8.100</td>
<td>0.26</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5600 9700</td>
<td>8.120</td>
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<td></td>
<td></td>
<td></td>
<td>9700 13800</td>
<td>7.810</td>
<td></td>
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<tr>
<td>BH-6</td>
<td>105.0</td>
<td>105.5</td>
<td>Basalt - Tcb</td>
<td>1800 6500</td>
<td>8.340</td>
<td>7.600</td>
<td>0.29</td>
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<td></td>
<td>6</td>
<td></td>
<td></td>
<td>6500 11200</td>
<td>7.900</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>11200 15800</td>
<td>6.560</td>
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</table>

Note: psi = pounds per square inch
## Material Properties (4/5)

### Slake Durability

#### Table 4.8

Phase 1 and 2 Rock Laboratory Testing Results - Slake Durability (ASTM D4644)

<table>
<thead>
<tr>
<th>PHASE</th>
<th>BOREHOLE</th>
<th>DEPTH (FT)</th>
<th>LITHOLOGY</th>
<th>SLAKE DURABILITY %</th>
<th>WATER TEMP. AVG. °C</th>
<th>AS-RECEIVED WATER CONTENT %</th>
<th>DESCRIPTION OF FRAGMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BH-1</td>
<td>108.0 - 109.0</td>
<td>Siltstone - Tcs</td>
<td>84.7</td>
<td>22</td>
<td>11.8</td>
<td>Type II</td>
</tr>
<tr>
<td></td>
<td>BH-2</td>
<td>84.0 - 85.2</td>
<td>Siltstone - Tcs</td>
<td>38.4</td>
<td>23</td>
<td>13.5</td>
<td>Type II</td>
</tr>
<tr>
<td></td>
<td>BH-5</td>
<td>58.0 - 59.3</td>
<td>Siltstone - Tcs</td>
<td>56.0</td>
<td>22</td>
<td>11.2</td>
<td>Type III</td>
</tr>
<tr>
<td></td>
<td>BH-6</td>
<td>56.5 - 57.5</td>
<td>Siltstone - Tml</td>
<td>10.7</td>
<td>22.0</td>
<td>13.6</td>
<td>Type III</td>
</tr>
<tr>
<td>2</td>
<td>DB-1</td>
<td>87.1 - 87.9</td>
<td>Basalt - Tcb</td>
<td>98.0</td>
<td>21</td>
<td>6.8</td>
<td>Type II</td>
</tr>
<tr>
<td></td>
<td>DB-5</td>
<td>100.0 - 100.8</td>
<td>Claystone - Tcs</td>
<td>88.0</td>
<td>21</td>
<td>12.0</td>
<td>Type II</td>
</tr>
<tr>
<td></td>
<td>DB-6</td>
<td>67.4 - 68.8</td>
<td>Claystone - Tcs</td>
<td>8.9</td>
<td>21</td>
<td>16.6</td>
<td>Type II</td>
</tr>
<tr>
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<td>TB-1</td>
<td>26.2 - 26.9</td>
<td>Claystone - Tcs</td>
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<td>20</td>
<td>15.9</td>
<td>Type II</td>
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<td>TB-2</td>
<td>54.6 - 55.5</td>
<td>Claystone - Tcs</td>
<td>74.1</td>
<td>21</td>
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<td>Type II</td>
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<td></td>
<td>TB-4</td>
<td>53.1 - 53.7</td>
<td>Claystone - Tcs</td>
<td>37.8</td>
<td>21</td>
<td>11.9</td>
<td>Type III</td>
</tr>
<tr>
<td></td>
<td>TB-5</td>
<td>61.0 - 61.5</td>
<td>Claystone - Tcs</td>
<td>26.3</td>
<td>21</td>
<td>12.7</td>
<td>Type III</td>
</tr>
<tr>
<td></td>
<td>TB-5</td>
<td>71.4 - 72.0</td>
<td>Claystone - Tcs</td>
<td>5.0</td>
<td>21</td>
<td>13.2</td>
<td>Type III</td>
</tr>
</tbody>
</table>

Description of the appearance of the fragments retained in the drum:
- Type I - Retained pieces remain virtually unchanged
- Type II - Retained materials consist of large and small fragments
- Type III - Retained material is exclusively small fragments
## Material Properties (5/5)

### Direct Shear Test

<table>
<thead>
<tr>
<th>BOREHOLE</th>
<th>DEPTH (FT)</th>
<th>LITHOLOGY</th>
<th>CONFINING STRESS (PSI)</th>
<th>PEAK FRICTION ANGLE (DEG.)</th>
<th>PEAK COHESION (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FROM</td>
<td>TO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB-1</td>
<td>48.73</td>
<td>49.0</td>
<td>Basalt - Tcb</td>
<td>14</td>
<td>70</td>
</tr>
<tr>
<td>DB-5</td>
<td>51.07</td>
<td>51.36</td>
<td>Basalt - Tcb</td>
<td>7</td>
<td>48</td>
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<tr>
<td>OB-1</td>
<td>43.2</td>
<td>43.6</td>
<td>Basalt - Tcb</td>
<td>14</td>
<td>40</td>
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<tr>
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<td>41.8</td>
<td>42.2</td>
<td>Basalt - Tcb</td>
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<td>175</td>
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<td>175</td>
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<tr>
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<td>37.0</td>
<td>Basalt - Tcb</td>
<td>14</td>
<td>55</td>
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<td>TB-2</td>
<td>87.07</td>
<td>87.33</td>
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<td>107.07</td>
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<td>Basalt - Tcb</td>
<td>70</td>
<td>140</td>
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<td>37.0</td>
<td>37.4</td>
<td>Basalt - Tcb</td>
<td>14</td>
<td>40</td>
</tr>
</tbody>
</table>

**Table 4.9**

Phase 2 Rock Laboratory Testing Results – Direct Shear (ASTM D5607)

- Specimen cut to length using diamond tipped saw blade.
- Tested at as-received moisture content and density.
- 'Hydro-Stroke Super X' encapsulating compound used to mount specimen in test rings.
- Actual strength parameters may vary and should be determined by an engineer for site-specific conditions.
- Reverse peak based on return displacement. Due to directional change, values are negative.
**Dam Profile**

- Strength index (with rock hammer)
- Weathering index (discoloration, oxidation, deterioration)
- RMR
- Discontinuity data
- Water pressure test data
- Televiewer data
- Sonic suspension logging
- Modulus from RMR with empirical relations
- Joint sets
Foundation Excavation Objective and Grout Curtain Profile
Borehole Log OB-2

Excavation to 81 feet depth
**Dam Section (Boring OB-2)**

- **Station 0**: RQD 0-100%
  - Kh 2E-5 to 1.0E-7
  - Minor to major open joint/fracture
  - Vs = 9000 ft/s encountered around 50 to 85 ft depth based on SL-1 and DSL-2, respectively

- **Station 1**: RQD 80-100%
  - Kh 1.8E-5
  - Minor to major open joint/fracture
  - Vs > 9000 ft/s

- **Station 2**: RQD 35-100%
  - Kh 2E-5 to 1.0E-7
  - Minor to major open joint/fracture
  - Vs > 9000 ft/s

- **43’ basalt removed (dozer ripable)**
  - RMR 30-70
  - Weathering index 2 to 5.0
  - Not acceptable for dam foundation

- **14’ basalt left in place (blasting required for removal)**
  - RMR 55-70
  - Weathering index 2
  - Acceptable for dam foundation

- **Blasting required for removal**
  - RMR 50-85
  - Weathering index 1.5 to 5.0
  - Acceptable for dam foundation
Excavation to 40.5 feet depth
Dam Section (Boring BH-2)

- **RQD 20-60%**
  - Partially open to filled joint/fracture
  - Vs = 9000 ft/s encountered around 50 ft depth based on SL-1

- **RQD 90-100%**
  - Partially to minor open joint/fracture
  - Vs > 9000 ft/s

- **RQD 35-100%**
  - Partially to minor open and filled joint/fracture
  - Vs > 9000 ft/s

---

**10’ basalt removed (dozer ripable)**
- RMR 40-55
- Strength index 1 to 5
- Weathering index 1.5 to 5.0
- Not acceptable for dam foundation

**40’ basalt left in place (blasting required for removal)**
- RMR 55-70
- Strength index 4 to 4.5
- Weathering index 1 to 3
- Acceptable for dam foundation

**Blasting required for removal**
- RMR 40-60
- Strength index 1 to 5
- Weathering index 1.5 to 5.0
- Acceptable for dam foundation
Dam Design - Cross-section
Risk Informed Design

Three-tiered Risk-based Design Criteria

- Elastic Response – minimum 500-year event
- Non-linear response, limited damage – minimum 5,000-year event (cracking, < 1’ disp)
- Non-linear response, moderate damage, no post-earthquake dam failure – 10,000 and 50,000 year events (FOS > 1.0)
FRFA Dam Design – Plan View
Chehalis Dam Conceptual Design
## Structural Analyses

### Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>RCC/Lift Joints</th>
<th>Rock/Rock-Concrete Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit weight (pcf)</td>
<td>150</td>
<td>165 (Rock)</td>
</tr>
<tr>
<td>Compressive strength (psi)</td>
<td>3000</td>
<td>N/A*</td>
</tr>
<tr>
<td>Direct tensile strength (psi)</td>
<td>150 (intact RCC)</td>
<td>0</td>
</tr>
<tr>
<td>Apparent static tensile strength (psi)</td>
<td>270 (lift joint)</td>
<td>0</td>
</tr>
<tr>
<td>Actual dynamic tensile strength (psi)</td>
<td>300 (lift joint)</td>
<td>0</td>
</tr>
<tr>
<td>Apparent Dynamic tensile strength (psi)</td>
<td>400 (lift joint)</td>
<td>0</td>
</tr>
<tr>
<td>Dynamic Mod. Of Elasticity (psi)</td>
<td>$3.24 \times 10^6$</td>
<td>$2.61 \times 10^6$ (weighted average)</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.20</td>
<td>0.33</td>
</tr>
<tr>
<td>Hysteresis damping (percent)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Intact bonded friction angle (degrees)</td>
<td>65</td>
<td>55</td>
</tr>
<tr>
<td>Friction angle for cracked concrete, but no sliding has occurred (degrees)</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Residual friction angle of smoothed sliding planes (for sliding of more than two feet) (degrees)</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>Average friction angle of rock-concrete interface or RCC lift joints after for sliding of less than one foot (degrees)</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Average friction angle of rock-concrete interface or RCC lift joints after for sliding between one to two feet (degrees)</td>
<td>45</td>
<td>35 to 55</td>
</tr>
</tbody>
</table>

* Cracked but with no sliding (limited the force resultant location to the base but no sliding during earthquake.

**No cohesion was assumed along the lift joints, concrete to rock interface, of bedding planes in the foundation.
Chehalis Dam Structural Analysis

Normal Loading – Non-overflow section FRFA
Chehalis Dam Structural Analysis

Normal+ CMS Interface 5000-yr Loading
Structural Analyses
Model and Stresses

- Normal + CMS Interface 10,000yr loading; weighted average modulus

Maximum compression for rock around 1,700 psi
Chehalis Dam Structural Analysis

Normal Loading – Normal Loading FRFA
Chehalis Dam Structural Analysis

Normal+ CMS Interface 5000-yr Loading
Chehalis Dam Conceptual Design

Flexible/Rigid Foundation - 45 Degree Friction Angle - 5k Ground Motion

- Weighted Average (Siltstone and Basalt)
- Siltstone
- Basalt
- Rigid
Chehalis Dam Conceptual Design
**Structural Analyses**

Displacements

<table>
<thead>
<tr>
<th>Friction Angle</th>
<th>500-yr</th>
<th>5,000-yr</th>
<th>10,000-yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>0.08</td>
<td>2.73</td>
<td>4.91</td>
</tr>
<tr>
<td>45</td>
<td>0.00</td>
<td>1.07</td>
<td>2.20</td>
</tr>
<tr>
<td>55</td>
<td>0.00</td>
<td>0.34</td>
<td>0.86</td>
</tr>
</tbody>
</table>

1Rigid foundation, flexible foundation has less displacement

<table>
<thead>
<tr>
<th>Friction Angle</th>
<th>500-yr</th>
<th>5,000-yr</th>
<th>10,000-yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>0.00</td>
<td>1.12</td>
<td>2.73</td>
</tr>
<tr>
<td>45</td>
<td>0.00</td>
<td>0.08</td>
<td>0.53</td>
</tr>
<tr>
<td>55</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
</tr>
</tbody>
</table>

2Flexible foundation, weighted average of siltstone/basalt

Sliding Displacements for Varying Friction Angles and EQ Return Periods, Rigid Foundation Assumption

Sliding Displacements for Varying Friction Angles and EQ Return Periods, Flexible Foundation Assumption

Comparison of Maximum Sliding Displacements
### Structural Analyses

#### Sliding Stability

<table>
<thead>
<tr>
<th>Friction Angle</th>
<th>Normal Uplift</th>
<th>Full Uplift</th>
<th>Extreme Uplift</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>2.08</td>
<td>1.77</td>
<td>1.06</td>
</tr>
<tr>
<td>35</td>
<td>2.52</td>
<td>2.15</td>
<td>1.28</td>
</tr>
<tr>
<td>40</td>
<td>3.02</td>
<td>2.57</td>
<td>1.54</td>
</tr>
<tr>
<td>45</td>
<td>3.60</td>
<td>3.06</td>
<td>1.83</td>
</tr>
<tr>
<td>50</td>
<td>4.29</td>
<td>3.65</td>
<td>2.18</td>
</tr>
<tr>
<td>55</td>
<td>5.14</td>
<td>4.38</td>
<td>2.62</td>
</tr>
</tbody>
</table>

Post-Earthquake Factor of Safety for Varying Friction Angle Assumptions
Dam Design – Hydraulic Structures
Chehalis Dam Design

• Basic Hydraulic Design Criteria
  – PMF Discharge = 75,000 cfs
  – Spillway Design Flood = 75,000 cfs
  – Low Level Flood Regulation Outlet Works Capacity = 15,000 cfs

• FRO-Specific Hydraulic Design Criteria
  – Dam Crest Elevation 654.0 ft
  – Spillway Crest Elevation 628.0 ft
  – Maximum Flood Pool Elevation = 650.0 ft
  – Fish Passage Maximum Discharge = 2,000 cfs

• FRFA-Specific Hydraulic Design Criteria
  – Dam Crest Elevation 713.4 ft
  – Spillway Crest Elevation 687.0 ft
  – Maximum Flood Pool Elevation = 709.4 ft
  – Water Quality Outlet Maximum Discharge = 500 cfs
Putting It All Together
Conceptual Level Structural Analysis Results

- Confirmed Cross-section
- Input to future foundation property investigations
- Input to RCC aggregate and mix design requirements
- Proceed with hydraulic structure and foundation design
- Configure section details (galleries, etc.)
Putting It All Together
Cost Estimates
Construction Cost Estimate

• FRO
  – Weighted Cost (2016): $250,000,000
  – Lower Bound Cost: $209,000,000
  – Upper Bound Cost: $306,000,000
  – Escalated Weighted (+5.4 yrs @ 3.5%) $302,000,000
  – Annual Operation and Maintenance $650,000

• FRFA
  – Weighted Cost (2016): $371,000,000
  – Lower Bound Cost: $315,000,000
  – Upper Bound Cost: $450,000,000
  – Escalated Weighted (+6.3 yrs @ 3.5%) $460,000,000
  – Annual Operation and Maintenance $1,400,000

Note: estimates based on in-progress designs in Sept/October 2016. Estimates to be revised for the final Conceptual Design Report based on updated designs and any relevant comments.
# Construction Cost Estimate

<table>
<thead>
<tr>
<th>Column1</th>
<th>FRO</th>
<th>FRFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Weighted Project Cost$^{1}$</td>
<td>250,000,000</td>
<td>371,000,000</td>
</tr>
<tr>
<td>Low End Project Cost$^{1}$</td>
<td>209,000,000</td>
<td>315,000,000</td>
</tr>
<tr>
<td>High End Project Cost$^{1}$</td>
<td>306,000,000</td>
<td>450,000,000</td>
</tr>
<tr>
<td>Project Cost Range from Total Weighted</td>
<td>84% - 122%</td>
<td>85% - 121%</td>
</tr>
<tr>
<td>Escalation period from Oct-2016$^{2}$</td>
<td>5.4 yr</td>
<td>6.3 yr</td>
</tr>
<tr>
<td>Escalated Total Weighted Project Cost$^{3}$</td>
<td>302,000,000</td>
<td>460,000,000</td>
</tr>
<tr>
<td>RCC Unit Bid - Likely</td>
<td>$80.00</td>
<td>$83.00</td>
</tr>
<tr>
<td>RCC Unit Bid Range</td>
<td>$66.00 - $97.00</td>
<td>$69.00 - $100.00</td>
</tr>
<tr>
<td>RCC - as % of Contractor Bid</td>
<td>38%</td>
<td>47%</td>
</tr>
<tr>
<td>Main Dam (including outlet works) - as % of Contractor Bid</td>
<td>69%</td>
<td>74%</td>
</tr>
<tr>
<td>Phase 1 - Site Prep - Diversion - % of Contractor Bid</td>
<td>21%</td>
<td>17%</td>
</tr>
<tr>
<td>Diversion - as % of Contractor Bid</td>
<td>9%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Notes: 1 - prior to escalation, 2 - approximately 2 years allowed for design, to midpoint of construction, 3 - 3.5% annual
Future Site Characterization
Future Site Investigation Overview

- 11 Dam Site Borings
- 11 Landslide Borings
- 5 Quarry Borings
- 3 Landslide Seismic Lines
- 7 Quarry Seismic Lines 400 ft long, locations TBD
**Dam Site Boring Locations**

- 7 Borings along the alignment
- 4 Borings to establish cross sections

**Investigation Goals**
- Fill in data gaps in geologic model
- Refine Excavation and Grout Curtain Extents
- Evaluate Reservoir Landslides
Schedule
Approximate Project Schedule

- **Final design** (after completion of the preliminary design) including site characterization: up to 2 years
- **Bidding and Award** of Phase 1 construction: 4 to 6 months
- **Construction Schedule Phase 1**: 1 year
- **Bidding and Award** of Phase 2: 4 to 6 months, concurrent with Phase 1 construction
- **Construction Schedule Phase 2**: 2 to 3 years
- **Approximate total time for completion**: 6 to 7 years
Questions/Discussion

Photo courtesy of The Chronicle, Centralia, Washington
Phase 2 Site Characterization Work Plan

- Geologic sections and 3-D model update in progress
- Foundation material properties
- Dam cross section refinement based on 2-D finite element (FE) modeling
- Full excavation objective and grout curtain requirements
- Update of quantity estimates and unit prices for key items of work
- Landslide mitigation plan