Seismic Analysis of Concrete Dams

• Selection of analysis
• Selection of Materials Properties
  • Properties affected by “state of the art” for materials, mix designs, and construction methodology
• Typical mass concrete properties
• Static vs. dynamic properties
• Effects of aging
  • Alkali aggregate reaction
  • Freezing and thawing deterioration
  • Sulfate attack
  • Corrosion
• Know your structure’s history and know aging mechanisms

Seismic Analysis of Concrete Dams
Workshop
2017 USSD Annual Conference
April 6-7, 2017
Timeline for Aging Concrete

<table>
<thead>
<tr>
<th>Year</th>
<th>Event/Condition</th>
<th>Description</th>
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<tbody>
<tr>
<td>1902</td>
<td>Poor/Variable Quality</td>
<td>Hoover Dam – Improved Construction Practices - Process Quality Control</td>
</tr>
<tr>
<td>1920</td>
<td>Low-Strength</td>
<td>Low Water-Cement Ratio increases quality</td>
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<tr>
<td>1940</td>
<td>Alkali-Aggregate Expansion Swelling - Cracking</td>
<td>Sulfate Resisting Cement - Pozzolans</td>
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<tr>
<td>1960</td>
<td>Sulfate Attack /Cracking</td>
<td>Air-Entrained Concrete</td>
</tr>
<tr>
<td>1980</td>
<td>Freezing-Thawing Disintegration</td>
<td>Concrete Repair Methods Polymers – Silica Fume</td>
</tr>
</tbody>
</table>

Pioneers--- Abrams--- Hoover---Post War------ “Modern Concrete”
Many Variables for Mass Concrete Core Programs - both sampling and testing (this may lead to “apples and oranges” comparisons)

- Mix designs used in construction
- Core diameter
- NMSA
- Core moisture conditioning history
- Type of test
- Static vs. dynamic
Coring and Testing

• Appropriate core size for mass concrete
• Documentation of lift joint bonding and how to model in analysis (monolith or stack of blocks)
• Compressive strength
• Splitting vs. direct tensile strength (and size effects)
• Shear properties
• Effects of moisture content
• “Good” low modulus of elasticity vs. “bad” low modulus of elasticity
• Effects of aging
Construction season placements affect sampling programs
Construction season placements affect sampling programs (and test results)

Location of four vertical contraction joints

Elevation of downstream face showing three major sequences for concrete placements
Figure 3 – Field test, coring programs, photogrammetry, freeze-thaw measurements

A – Seasonal temperatures in the dam (up to 70 cycles per year)

Freezing

B – Photogrammetry results showing current depth of deterioration along a vertical contraction joint
Lift line between Zones (1 and 2) and 3

A – Upstream face

B – Downstream face

C – V-notch deterioration at contraction joint about 18-inches deep
A – Finite element model

B – Displaced shape and sliding along contraction joints

C – Deteriorated elements removed

D – 2X deteriorated model

E – 8X deteriorated model
Estimation of Tensile Strength of Mass Concrete

- Test data from construction (compressive strength)
- Data from drilled core tests (static or dynamic)
  - Compressive strength
  - Direct tensile strength
  - Splitting tensile strength
- Often only static compressive strength or splitting tensile strength
Testing Mass Concrete for “Tensile” Strength

• Tensile test procedures
  • Direct (USBR 4914 – 1992)
  • Splitting (ASTM C 496 or BS)
  • Flexural (ASTM C single point or C 1/3 point)

• Mass vs. conventional concrete
  • Nominal maximum size aggregate (NMSA) 3-6 in vs ¾ to 1.5 in
  • Core diameter (D) vs. NMSA (4-18 in)
  • ASTM C 42 recommends minimum D of 3.7 in or minimum D/NMSA = 2
Direct Tensile Strength of Mass Concrete Dams

Lift Line Tests
- Average All Lift Line Tests: 173 lb
- Average Lift Line Failure: 153 lb

Direct Tensile Strength - lb/in²

Frequency

0 40 80 120 160 200 240 280 320 360 400 440

Direct Tensile Strength - lb/in²

All Lift Line Tests
Direct Tensile Strength of Parent Mass Concrete

Average Parent - 219 lb/in²
Frequency Distribution - Direct Tensile Strength
Parent Concrete and Lift Lines (1905-1993)

All lift lines average 170 psi
All parent concrete average 220 psi

Direct Tensile Strength - psi
Frequency - percent

DT All Lift Lines
DT All Parent

Seismic Analysis of Concrete Dams
Frequency Distribution - Direct Tensile Strength of Mass Concrete Lift Lines (1905-1993)

All lift lines - 1905 to 1930
average 0.77 Mpa (110 psi)

All lift lines - 1905 to 1993
average 1.19 Mpa (173 psi)

Ruskin Dam
average lift lines - 1.0 MPa

Direct Tensile Strength - MPa
Frequency - percent

0.0 0.5 1.0 1.5 2.0 2.5 3.0
0.0 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
## Effects of Aging on Mass Concrete

<table>
<thead>
<tr>
<th></th>
<th>No Aging</th>
<th>AAR / FT</th>
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</thead>
<tbody>
<tr>
<td>Compressive Strength (lb/in²)</td>
<td>4880</td>
<td>3925</td>
</tr>
<tr>
<td>Modulus of Elasticity (10⁶ lb/in²)</td>
<td>5.38</td>
<td>2.24</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.19</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Alkali Aggregate Reaction (< ~ 1942*)
Compressive Strength vs. Modulus of Elasticity

\[ y = 0.0005x + 3.3341 \]  
\[ R^2 = 0.2832 \]

\[ y = 0.0005x + 0.2886 \]  
\[ R^2 = 0.3728 \]
Tensile Strength (no AAR/Aging)

Splitting Tension

Age DT LL
Age DT Parent
Age ST Parent
Log. (Age ST Parent)
Log. (Age DT LL)
Log. (Age DT Parent)
Critics of Split Tensile Test

• Hannet, et al (1973)
  • *Half cylinder tests* ($ST = 0$)
  • *Biaxial compressive zone under bearing strip*
  • *$ST$ differs with width of bearing strip*
  • *NMSA affects stress distribution*

$ST \sim 300 \text{ psi}$!
Direct vs. Splitting Tensile Strength
Parent Concrete – No Aging

Seismic Analysis of Concrete Dams
Direct vs. Splitting Tensile Strength

Circled data points have data sets with most test specimens.

Cores - Vertical cast
Cast cylinders - vertical and horizontal cast

Specimen Size - NMSA Ratio

Seismic Analysis of Concrete Dams
A curious strength “decline”

• Two main mass concrete mixtures
• Two purposely re-designed mass concrete mixtures
• Cores drilled at 6 months and 0.5, 1, 5, 10, and 25 years
• Strength decreased between 10 and 25 years?

• 10 year test moisture content
A curious strength “decline”

Compressive Strength of Drilled Cores

Compressive Strength - psi
0 1000 2000 3000 4000 5000 6000 7000 8000
0 5 10 15 20 25 30 35
Test Age - years

Seismic Analysis of Concrete Dams
A curious strength “decline”
A curious strength “decline”

Compressive Strength of Drilled Cores

Test Age - years

Tested dry

Seismic Analysis of Concrete Dams
A tale of two aggregates

- Projects 150 miles apart
- Started with same (4) cement manufacturers
- Same contractor
- Same equipment
- Probably same workforce
- Unlucky choice of wrong cement manufacturer
- Vastly different results
- (different river source for aggregates)
Hoover (no AAR) vs. Parker (1st AAR) Dams

Compressive Strength Development of Mass Concrete Cores
Effect of Alkali Aggregate Reaction

Parker Dam - deep cores (LA Cement?)

Series "Age Comp No Aging" Point "3650"
(3650, 3010)

Seismic Analysis of Concrete Dams
Good Modulus vs. Bad Modulus (i.e. one of them has cracking)

Seismic Analysis of Concrete Dams
AAR Effects

- Compressive strength
- Tensile strength
- Elastic properties
- Lift line bonding
- Strength vs. age
- Hot dams vs. cold dams
- “Changing” properties in risk assessment
Materials properties may not be constant – effects on risk analysis and conclusions.

Compressive Strength Development in ASR Affected Concrete Cores - Parker and Seminole Dams

Seismic Analysis of Concrete Dams
Other things that keep a dam engineer awake
AAR Declining Tensile Strength

Winter cooling
(exterior tension
interior compression)

Summer warming
(exterior compression
interior tension)
AAR Declining Tensile Strength

Tensile strength

Thermal stress

Initiate internal cracking?
Slab (or arch) and Buttress dams….Effects of carbonation and steel corrosion (loss of passive resistance)

- Cover depth = 3-4 in (150-200 mm)
- Carbonation depth = ?
- Are we “millimeters away” from disaster?
Open Discussion and Conclusions