Engineering Geology Challenges During Design and Construction of the Marmet Lock Project

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Ron Adams & Mike Nield
Main Topics of Discussion
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1. PROJECT OVERVIEW
   a. Site Plan
   b. Site Geology
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2. DEEP SEATED SLIDING
   a. Design Concerns
   b. Cofferdam Foundation Movement
   c. New Chamber Lockwall Monoliths
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   e. Foundation Drilling and Grouting
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   a. Site Plan
   b. Site Geology
One Corps, One Regiment, One Team

Marmet Lock Replacement – Project Overview

Site Plan
Marmet Lock Replacement Project

- Purpose is to alleviate traffic on the Kanawha River
Marmet Lock Replacement Project

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• Existing and smaller 56’ X 360’ lock chambers inhibit river traffic
Marmet Lock Replacement Project

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- Project adds one larger 110' X 800' lock chamber and approach walls, located landward of old locks
Marmet Lock Replacement Project

- Purpose is to alleviate traffic on the Kanawha River
- Existing and smaller 56’ X 360’ lock chambers inhibit river traffic
- Project adds one larger 110’ X 800’ lock chamber and approach walls, located landward of old locks
- Construction started in summer 2002 with a current contract cost of $232 Million
Marmet Lock Replacement – Project Overview

Existing Lock – Prior to Construction

Twin 56’ X 360’ Chambers
Completed in 1934
Marmet Lock Replacement – Project Overview

Twin 56’ X 360’ Chambers
Completed in 1934

New 110’ X 800’ Chamber
Under Construction

New Lock – Conceptual Drawing
Marmet Lock Replacement – Project Overview

New Lock Construction - Ariel View - May 2005

Existing Lock Chambers

New Lock Chamber Under Construction
Marmet Lock Replacement – Project Overview

New Lock Construction - Ariel View - May 2005

Sheet Pile Cell
Cofferdam

Existing Landwall
Portion of Cofferdam

Contractor Designed Anchored Retaining Wall
Marmet Lock Replacement – Project Overview

New Lock Construction - Ariel View - May 2005
Cofferdam Components – Typical Sections

LEGEND
- **Yellow**: Existing locks and dam
- **Red**: New lock and approach walls
- **White**: New lock culvert alignment
- **Blue**: Cofferdam dams

**Concrete**
- Select Fill (15.67' r.)
- Top of Rock
- Anchors
- Thrust Block

**Small Diameter Cells**
One Corps, One Regiment, One Team

Marmet Lock Replacement – Project Overview

EXISTING LOCKS AND DAM
NEW LOCK AND APPROACH WALLS
NEW LOCK CULVERT ALIGNMENT
COFFER DAMS

Large Diameter Cells
Stone Cap
Cell Fill
(31.34' r.)
Bedrock

Existing Landwall

Small Diameter Cells

Cofferdam Components – Typical Sections

LEGEND
EXISTING LOCKS AND DAM
NEW LOCK AND APPROACH WALLS
NEW LOCK CULVERT ALIGNMENT
COFFER DAMS
One Corps, One Regiment, One Team

Marmet Lock Replacement – Project Overview

New Lock Features – Plan View

LEGEND
- Yellow: Existing Locks and Dam
- Red: New Lock and Approach Walls
- White: New Lock Culvert Alignment
- Blue: Cofferdams
Marmet Lock Replacement – Project Overview

New Lock Features

LEGEND
- Yellow: Existing Locks and Dam
- Red: New Lock and Approach Walls
- White: New Lock Culvert Alignment
- Blue: Coffers Dams

Lower Approach Wall
Concrete Filled Cells
Founded ~1’ below TOR
Marmet Lock Replacement – Project Overview

New Lock Features

EXISTING LOCKS AND DAM
NEW LOCK AND APPROACH WALLS
NEW LOCK CULVERT ALIGNMENT
COFFER DAMS

Lock Chamber
Lower Approach Wall

CONCRETE FILLED CELLS
Founded ~1’ below TOR
Marmet Lock Replacement – Project Overview

**New Lock Features**

- **EXISTING LOCKS AND DAM**
- **NEW LOCK AND APPROACH WALLS**
- **NEW LOCK CULVERT ALIGNMENT**
- **COFFER DAMS**

**Upper Approach Walls**
- Drilled Shafts
- Socketed 15' into Bedrock

**Lock Chamber**

**Lower Approach Wall**
- Concrete Filled Cells
- Founded ~1' below TOR

**LEGEND**

- Yellow: EXISTING LOCKS AND DAM
- Red: NEW LOCK AND APPROACH WALLS
- Light Blue: NEW LOCK CULVERT ALIGNMENT
- Blue: COFFER DAMS
Site Geology

- Relatively flat top of rock surface
- Sedimentary rock of the Pennsylvanian-aged Kanawha Formation
- Nearly horizontal bedding. Discovered low angled (5 - 10°) dip to the Northwest during construction with localized stratigraphic dip
- Rock Units:
  - Sandstone member (23 to 43 feet thick)
  - Shale member (19 to 33 feet thick)
- Sandstone member is competent but interbedded with many thin seams and stringers of coal and shale. Discovered to be continuous in excavated sidewalls during construction.
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Marmet Lock Replacement – Project Overview

Site Geology

Anchored Existing Landwall

Anchored Retaining Wall

Geologic Cross Section – Upper Miter Gate

- SOIL
- SANDSTONE
- WEAK SEAMS
- SHALE
Site Geology

Geologic Cross Section – Chamber Monoliths
Site Geology

- Light gray
- Moderately hard to hard
- Medium to fine grained
- Average unconfined compressive strength 8,442 psi

Sandstone Member
Site Geology

- Gray to dark gray
- Moderately hard to soft
- Silty
- Average unconfined compressive strength 6,678 psi

Shale Member
Rock Mechanics Testing

- **Design Sliding Friction Strength:**
  phi angle = 30°, cohesion = 4psi

- **Cross Bed Shear Strength:**
  phi angle = 45°, cohesion = 73psi

*Typical Sandstone Member Bedding Plane*
Rock Mechanics Testing

Design Sliding Friction Strength:
\( \phi \) angle = 23°, cohesion = 0 psi

Thin Shale and Coal Seams within Sandstone
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Marmet Lock Replacement – Deep Seated Sliding

Design Concerns

22-foot deep excavation

13-foot spacing

Excavation Adjacent to Structures – 3D view
Marmet Lock Replacement – Deep Seated Sliding

Design Concerns

- Existing Landwall - Cofferdam
- New Riverwall
- Culvert
- New Landwall
- Weak Seams
- Sandstone Member

Deep Seated Sliding – Daylighted Weak Seams
Marmet Lock Replacement – Deep Seated Sliding

Design Concerns

Pre-Construction Condition

Dewatered Chamber

Direction of Forces

Soil

Weak Seams

Existing Landwall

Sandstone Member

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US Army Corps of Engineers
Huntington District
One Corps, One Regiment, One Team

Marmet Lock Replacement – Deep Seated Sliding

Design Concerns

Pre-Construction Condition

Construction Condition

Upper Pool

Daylighted Weak Seam

Rock Excavation for New Lock Walls and Chamber
Marmet Lock Replacement – Deep Seated Sliding

Design Concerns

Pre-Construction Condition

Construction Condition

Permanent Condition

New Lock Riverwall

Backfill

Rock Excavation for New Lock Culvert
Marmet Lock Replacement – Deep Seated Sliding

Design Concerns

EXISTING LOCK (USED AS COFFERDAM)

UPPER POOL

OVERBURDEN

TOP OF ROCK

ROCK ANCHORS

STAGED ANCHORING DURING OVERBURDEN EXCAVATION
Analyzed for coal/shale seam at foundation (phi=23°, c=0psi)
INSTALL INSTRUMENTATION
Design Concerns

EXISTING LOCK (USED AS COFFERDAM)

UPPER POOL

THRUST BLOCK

THRUST BLOCK ANCHORED PRIOR TO ROCK EXCAVATION
Analyzed for daylighted horizontal fault gouge (phi=13°, c=0psi)

SUBSURFACE EXPLORATION PERFORMED
Marmet Lock Replacement – Deep Seated Sliding

**Design Concerns**

- **EXISTING LOCK (USED AS COFFERDAM)**
- **UPPER POOL**
- **LINE DRILLED SURFACE**
- **COMPLETE EXCAVATION FOR CULVER/INSPECTION TRENCH**
- **EXISTING LOCK (USED AS COFFERDAM)**
- **LINE DRILLED SURFACE**
- **INSPECTION TRENCH**

**COMPLETE EXCAVATION FOR CULVER/INSPECTION TRENCH**

**ESTABLISH PRESENCE AND EXTENT OF WEAK SEAMS – NEW LOCK**

**DETERMINE CORRECTIVE FOUNDATION TREATMENT – NEW LOCK**
Manual Instruments

Manually Read Instruments

- Portable Inclinometers
- Settlement And Alignment Pins
- Joint Monitoring Pins
- Saw Cuts
Deep Seated Sliding Occurs

-initial downstream movement

- August 2004 movement occurred along two weak planes
  - EL 540 +/- where there is a series of thin seams of carbonaceous shale and coal within an otherwise generally competent sandstone formation
  - EL 520 +/- where there is a discontinuous thin seam of clayey material near the bottom of the sandstone unit and an underlying shale formation. This seam is slightly lower than any required excavation
Initial Movement – Cell 6D
August 2004
Portable Inclinometer Displacement

Cofferdam Movement Based on Portable Inclinometer Data 10-04 to 4-05
E.A.P. Response

Recommended Actions Of The PDT

- Increase Frequency Of Instrumentation Readings And Evaluation Of Data
- Reanalyze Additional Failure Planes Within The Rock Foundation
- Add Additional Upstream Anchors
- Add Additional Inclinometers Of Greater Depth And At Additional Locations
- Obtained Contingency Anchors
EAP Movement Action Levels

- **0.20 in. Displacement**
  - Mobilize Contractor to Install “Contingency” Anchors
  - Accelerate Placement of Concrete on Deep Excavation Monoliths
  - Partial Flood and/or Backfill Chamber Work Area
  - Limit Rock Excavation

- **0.25 in. Displacement**
  - All Non-remediation Work Stopped and Evacuated
  - Work Area Partially or Completely Flooded and/or Backfill

- **0.35 in. Displacement**
  - Failure Imminent
  - Evacuate Excavation
Cofferdam Foundation Movement - Section

- SHEET PILE CELL COFFERDAM
- THRUST BLOCK WITH ANCHORS
- NEW LOCK WALL FOUNDATION
- SANDSTONE MEMBER
- SHALE MEMBER
- FOUNDATION ANCHORS
- WEAK SEAM
- SELECT FILL
- CONCRETE
- DIRECTION OF FORCE

One Corps, One Regiment, One Team

Marmet Lock Replacement – Deep Seated Sliding
Marmet Lock Replacement – Deep Seated Sliding

Cofferdam Foundation Movement - Section

- DIRECTION OF FORCE
- SHEET PILE CELL COFFERDAM
- INCLINOMETER RESULTS INCREMENTAL GRAPH
- WEAK SEAM
- SANDSTONE MEMBER
- SHALE MEMBER
- FOUNDATION ANCHORS
- NEW LOCK WALL FOUNDATION

552

528
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Marmet Lock Replacement – Deep Seated Sliding

**WEAK SEAM**

**DIRECTION OF FORCE**

**SHEET PILE CELL COFFERDAM**

**INCLINOMETER RESULTS INCREMENTAL GRAPH**

**THIN, DAYLIGHTED CARBONACEOUS SEAM AT 545 +/-**

**SANDSTONE MEMBER**

**NEAR SANDSTONE/SHALE CONTACT AT 520 +/-**

**SHALE MEMBER**
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Marmet Lock Replacement – Deep Seated Sliding

Cofferdam Foundation Movement

Sheet Pile Cell Cofferdam -1D

Carbonaceous Seam with Slickensided Surfaces
\( \phi = 15^\circ, c = 0 \text{psi} \)

Suitable factor of safety

Sheet Pile Cell

Clay Coated Sandstone/Shale Contact
\( \phi = 20^\circ, c = 0 \text{psi} \)

Sandstone Member

Passive Wedge through Fractured Sandstone
\( \phi = 30^\circ, c = 4 \text{psi} \)

Accelerated Concrete Placement to Enhance Passive Wedge

Cofferdam Foundation Movement – Cell 1D
One Corps, One Regiment, One Team

Marmet Lock Replacement – Deep Seated Sliding

Cofferdam Foundation Movement

COFFERDAM: EXISTING LOCKWALL MONOLITH M-22

ADDITIONAL 12-STRAND ANCHORS REQUIRED (Bond Zone Founded Below Installed Anchors)

Passive Wedge through Fractured Sandstone phi=30°, c=4psi

Clay Seam at Sandstone/Shale Contact phi=15°, c=0psi

SANDSTONE MEMBER

SHALE MEMBER

Cofferdam Foundation Movement – M-22
Cofferdam Foundation Movement

- Some displacement is required to engage rock mass shear strength
- Establish how much movement is acceptable

![Graph showing shear stress vs. horizontal displacement]

- Peak Strength
- Failure

Scale effect or length of sheared block was taken into consideration:

0.35 inches established as approaching failure
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Marmet Lock Replacement – Deep Seated Sliding

COFFERDAM (EXISTING LOCKWALL) -> NEW LOCKWALL

CULVERT EXCAVATION & INSPECTION TRENCH

SANDSTONE MEMBER -> DAYLIGHTED WEAK SEAM

SHALE MEMBER

New Chamber Lockwall Monoliths
Inspection Trench Sidewall - Photo

MONOLITH R-15A

New Chamber Lockwall Monoliths
Inspection Trench Sidewall - Photo

MONOLITH R-15A

New Chamber Lockwall Monoliths
One Corps, One Regiment, One Team

Marmet Lock Replacement – Deep Seated Sliding

US Army Corps of Engineers
Huntington District

Inspection Trench Sidewall - Map

Zones of Carbonaceous Stringers & open bedding planes (\( \phi=30^\circ, c=0\)psi)

Potential Sliding Failure Plane through various materials

Thin Coal Seams (\( \phi=23^\circ, c=0\)psi)

Carbonaceous Shale w/ many slickensided fractures (\( \phi=17^\circ, c=0\)psi)

New Chamber Lockwall Monoliths
One Corps, One Regiment, One Team

Marmet Lock Replacement – Deep Seated Sliding

NEW LOCKWALL

CULVERT EXCAVATION & INSPECTION TRENCH

Daylighted Failure Plane (Weighted Average Phi Angle)

Sandstone/Shale Contact (phi=22°, c=0psi)

Cross Bed Shear (phi=30°, c=4psi)

SANDSTONE MEMBER

Backfill

SHALE MEMBER

New Chamber Lockwall Monoliths
One Corps, One Regiment, One Team

Marmet Lock Replacement – Deep Seated Sliding

NEW LOCKWALL

12- & 9-STRAND ANCHORS IN ALL NEW CHAMBER LOCKWALL MONOLITHS

CULVERT

SANDSTONE MEMBER

SHALE MEMBER

Rock Mass Engaged by Anchor

Anchor Bond Length

New Chamber Lockwall Monoliths
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Over 560 anchors required
Anchor Drilling
Anchor Alignment Specifications

◆ Initial Alignment
  ● Within 0.5° of Specified Azimuth
  ● Within 0.5° of Specified Inclination

◆ Drilling Alignment
  ● Within 0.5° Starting Azimuth
  ● Within 0.5° Specified Inclination
  ● Less than 1 in. Deviation per 10 ft. of Drilling
Anchor Alignment Testing

Tropari

Maxibor
Anchor Tensioning
# Anchor Tensioning Loads

<table>
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<th>GUTS</th>
<th>Design Load</th>
<th>Lock Off Load (70% GUTS)</th>
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<td>9 Strand</td>
<td>527 kips</td>
<td>316 kips</td>
<td>369 kips</td>
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<tr>
<td>12 Strand</td>
<td>703 kips</td>
<td>422 kips</td>
<td>492 kips</td>
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<td>15 Strand</td>
<td>879 kips</td>
<td>527 kips</td>
<td>615 kips</td>
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Specified Anchor Testing

- **Followed PTI**
- **Performance Tests**
  - One Anchor per Cofferdam Element
- **Proof Tests**
  - All Remaining Anchors in each Cofferdam Element
- **Extended Creep Tests**
  - Due to Shale in Bond Zone
  - Conducted on All Performance Tested Anchors
Performance Test Results

Movement vs Test Load

- Total
- \( \text{de}(\text{min.}) \)
- \( \text{de}(\text{max}) \)
- Elastic

<table>
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US Army Corps of Engineers
Huntington District

One Corps, One Regiment, One Team
Creep Test Results

Creep movement vs Log time

min.

in
Excavation Restrictions

- Pre-blast Survey of Community
- 50’ Maximum Blasting Dimension Along Axis
- Buffer Zone and Sill Excavation Methods
- 3 in/sec Peak Particle Velocity at Nearest Structure
- Line Drilled Perimeters
Evaluating Specified Vibration Equation

Slope Represents Specified Equation to Predict Blast Vibration

\[ V = 160 \left( \frac{R}{W} \right)^{0.5} \cdot 1 \]
Evaluating Specified Vibration Equation

Specified Equation is Suitable for Critical Blasts

Critical Seismograph Closest to Blast

Distant Seismograph (will not govern blast design)

\[ V = 160 \left( \frac{R}{W}^{0.5} \right)^{-1.6} \]
Line Drilled Perimeter

08/18/2004
Foundation Preparation Challenges

- Lenticular Shale Bedding
- Blast Damage
- Thin Bedded Carbonaceous Laminations and Tree Fossils
- Artesian Joints
Lenticular Beds
Lenticular Shale Bed Plan View
Blasting Damage Types

- Over Break Behind Line Drilled Faces
- Sub Drilling
Over Break Behind
Line Drilled Face
Over Break Behind
Line Drilled Face
Sub Drilled Shot Hole Damage

Shot Holes Sub-Drilled > 2 ft.

05/25/2005
Shot Hole Damage
Shot Damage Post
Foundation Prep.

06/02/2005
Artesian Joints
Pipes Placed

7/12/2005
Concrete Placed
Carbonaceous Laminations and Tree Fossils
Upstream Approach Walls

Thrust Block

10’ X 10’ Precast Beam
122’ & 105’ span

6’ Diameter Shaft
Drilled 15’ into Bedrock
Developed PY Curves

Utilized Borehole Jack Results

Utilized Passive Wedge Results
Drilled Shaft Drill Rig
Auger Drill Bits

Pilot Auger

Reaming Auger
Drilled Shaft Core Bit
Rebar and Concrete Placement
Drilled Shaft
CSL Test Results
Drilled Shaft Low Density Concrete
Foundation Drilling and Grouting

- Grout Curtain Extends to Elevation 510
- 10’ Spacing Between Primary and Secondary Holes
- Optional Tertiary and Higher Order Holes
- All Holes Pressure Testing
- Neat Cement Grout
QUESTIONS AND ANSWERS

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