Bedrock Dewatering for Construction of Marmet and Soo Lock Projects

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1. Marmet Lock Replacement Project (construction)
   - Project Description
   - Site Geology
   - Permeability and Groundwater Inflow
   - Dewatering Provisions

2. Soo Lock Replacement Project (design)
   - Project Description
   - Site Geology
   - Permeability and Predicted Groundwater Inflow
   - Impact to Design
Located on Kanawha River, near Charleston, West Virginia.

Permits economic river transportation of coal, aggregate and chemicals.

Construction of the new replacement lock was completed in 2009.
Twin 56’ X 360’ Chambers
Completed in 1934

“Busiest Lock in USA” Prior to New Lock

Aerial View – Original Locks
New 110’ X 800’ Lock Chamber

Original Locks

New Guard Wall

New Guide Walls

Aerial View – New Replacement Lock
Subsurface Exploration – Boring Location Plan

- 157 TOTAL BORINGS
- 10,200’ TOTAL DRILLING
- 3,700’ ROCK CORE
- 294 PRESSURE TESTS
General Geology

- Soil thickness 40 to 60 feet
- Relatively flat top of rock surface at elev. 552 ± 3’
- Sedimentary rock of the Pennsylvanian-aged Kanawha Formation
  Sandstone member (23 to 43 feet thick)
  Shale member (19 to 33 feet thick)
- Low angled bedding with 0°-10° dip to the Northwest
- Slightly fractured with occasional high angled joints (70°-90°)
**Bedrock Units - Sandstone Member**

- Light gray
- Moderately hard to hard
- Medium to fine grained
- Average unconfined compressive strength 8,442 psi
- Foundation for lock walls
- Occasional thin coal seam or zone of carbonaceous stringers
Bedrock Units - Shale Member

- Gray to dark gray
- Moderately hard to soft
- Silty
- Average unconfined compressive strength 6,678 psi
Geologic Cross Section - During Construction

Geologic Cross Section – Chamber Monoliths

Anchored Existing Landwall

Anchored Retaining Wall

SOIL
SANDSTONE
WEAK SEAMS
SHALE
Pressure Testing

WATER LINE
BORE HOLE
BLADDER
OPEN DISCONTINUITIES
5'
WATER METER
PRESSURE GAUGE
VALVE
BEDROCK
**Pressure Testing**

- Measure water flow while maintaining predetermined pressure, typically recorded in gal/min, CFM.
- Values are often converted to Lugeons
Hydraulic Conductivity

- 294 individual pressure tests in 36 holes located within cofferdam.

- Convert pressure testing results to Hydraulic Conductivity value $K$ using equation from USBR:
  $$K = \frac{Q}{2\pi LH} \log_e(L/r)$$
  ($Q$=flow, $L$=length tested, $H$=pressure, $r$=hole radius)

- Convert pressure test data to Lugeon then convert to Hydraulic Conductivity $K$:
  $$K = Lu \times 10^{-7}$$
  (1 Lugeon equals one liter per minute per meter hole at a pressure of 10 bars)
**Hydraulic Conductivity – Groundwater Inflow**

- **Average** permeability or **Hydraulic Conductivity** (K) value from pressure testing results at Marmet is $1.69 \times 10^{-6}$ m/s ($5.54 \times 10^{-6}$ ft/s), which is **typical for sandstone**.

- **Average Hydraulic Conductivity values in bedrock increased when overlying soil was removed** during construction at both Marmet and Winfield projects.

- Hydraulic Conductivity, along with known hydraulic gradient and excavated surface area can be utilized to **help develop preliminary estimate of groundwater inflow** during construction (using Darcy’s law).

- **Calculated inflow** from average K value is **520 gal/min** and upper bound inflow value is 7,000 gal/min.
Permeability Comparison – Logarithmic Scale

<table>
<thead>
<tr>
<th>Hydraulic Conductivity K (m/s)</th>
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<tbody>
<tr>
<td>10^{-9}</td>
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<tr>
<td>MARMET DODSON-STILSON</td>
</tr>
<tr>
<td>MARMET PRESSURE TESTS</td>
</tr>
<tr>
<td>WINFIELD PRESSURE TESTS</td>
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<tr>
<td>SANDSTONE TYPICAL (Brassington, 1988)</td>
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SOIL DEWATERING DESIGN VALUE

MAXIMUM TEST VALUE

MEAN TEST VALUE

CALCULATED RANGE

PUBLISHED RANGE
Accurately portray bedrock conditions in contract documents, alerting the contractor to potential dewatering concerns and work effort.
- Graphic Logs of Borings
- Geologic Sections
- Geologic Mapping
- Geotechnical Baseline Report

Address in the specifications groundwater concerns during construction and provide appropriate bid items for compensation.
- Dewatering
- Grout Curtains
- Concrete Placement
- Anchor Installation
Graphic Logs of Borings – Indicators of Permeability

- Quantify descriptive terms in legend
- Include down-hole camera images if available

Drill Water Loss
Pressure Test Data
RQD

Top of Rock and Depth of Weathering
Bedding Plane Spacing
Fractures
Iron Staining
Seams

Elevation (Meters) WSL
Symbol
Description of Materials
Remarks or Test Results

- Sand (SP), brownish grey, non-plastic, qtd to f.g., sand, f.g., gravel, coal, silt
- Silty gravelly sand (SM), greyish brown, non-plastic, qtd to f.g., sand, silt
- Sandy gravel (SP), greyish brown, non-plastic, qtd to f.g., gravel
- Weathered sandstone, brownish grey to light brown
- Roller bit impression at 168.21
- Numerous micaceous bedding planes from 166.07-166.51, 167.34-167.71
- Mechanical decrease in core diameter from 167.92-167.39
- High angle (50°) fracture with smooth and planar surface from 167.03-166.97
- High angle (60°) incipient fracture from 167.03-166.44
- Many thin, discontinuous, carbonate stringers with occasional ferruginous staining from 164.84-164.20, 160.56-160.57
- High angle (60°) fracture, smooth and planar surface from 164.84-164.75
- Thin 1.01 m Coal seam: Black, mod. hard at 164.26
- Numerous thin, discontinuous, shaly stringers from 163.93-164.06, 162.64-162.25, 162.31-162.26
- Slightly broken from 163.92-163.83
- 0.03 m Shale seams: Grey, soft from 163.86-163.83
- Calcarenite cemented from 162.10-161.54
Existing Foundation Maps – Indicators of Permeability

- Fracture orientation, spacing, length and aperture
- Foundation grout takes
- Records of groundwater seepage and control methods

Original Lock Chamber and Lock Wall
Existing Foundation Maps – Indicators of Permeability

- Fracture orientation, spacing, length and aperture
- Foundation grout takes
- Records of groundwater seepage and control methods

![Diagram of Existing Foundation Maps with various fracture widths and orientations]

Original Lock Chamber and Lock Wall
Groundwater Flow Through Fractures

Fractures are the primary mechanism for bedrock groundwater inflow into an excavation.

Groundwater flow can be estimated through individual bedrock fractures utilizing the following equation (maximum value – does not take into consideration joint roughness, shape, infilling, laminar flow etc.):

\[ q = \frac{\gamma_w}{12\mu_w} e^3 i \]

\( q = \) flow, \( \gamma_w = \) unit weight of water, \( \mu_w = \) dynamic viscosity of water, \( e = \) fracture aperture, \( i = \) hydraulic gradient
Cofferdam – Construction of New Lock – Aerial View

- Cofferdam (sheet pile cells and original lock)
- Slurry Wall and Relief Wells
- Soil Retaining Wall
- New Lock Chamber
Cofferdam – Construction of New Lock – Rock Excavation

Original Lock
Sheet Pile Cells
Soil Retaining Wall
Cofferdam – Hydraulic Gradient & Uplift

Hydraulic gradient ranges from 0.13 to 1.2

Uplift pressures measured using piezometers during construction – found to be as anticipated or less.
Specifications – Dewatering Bedrock Groundwater

- “The Dewatering Systems shall be designed and operated so as to allow construction of the lock chamber to be accomplished essentially in the dry, as well as to facilitate construction of all other project features.”
- “The Contractor's Dewatering System shall be designed in order to control groundwater, surface water, and incidental water, including seepage through the rock foundation…
- “…and then sumping the remaining groundwater and any other seepage into the bottom of the excavation.”
- “…dewatering facilities and supplemental dewatering facilities that may be required to control any seepage from excavated slopes or into the bottom of the excavation…”
- “Supplemental measures may include the installation of wellpoints, inverted filters, french drains, relief wells drilled into either soil or rock, and appropriate pumps, piping, and appurtenances as necessary…”
“Rock surfaces upon which concrete is to be placed shall be clean and free from oil, standing or running water, ice, mud, drummy rock, coatings, debris, and loose, semi-detached, overhanging, or unsound fragments.”
Control Groundwater Seepage – Foundation Treatment

Profile – Prior to Concrete Lift Placement
Control Groundwater Seepage – Foundation Treatment

Profile – After Concrete Lift Placement

ONCE THE HEIGHT OF THE CONCRETE PLACEMENT HAS OVERCOME THE HYDROSTATIC HEAD OF THE GROUNDWATER, THEN THE STAND PIPE AND HORIZONTAL DRAINS SHALL BE TREMIE FILLED WITH A CEMENTITOUS GROUT.

WATER BEARING FEATURE WITHIN BEDROCK
Control Groundwater Seepage - Foundation
Isolate Groundwater Seepage from Mass Concrete Placement
Dewater and Control Groundwater Seepage

Primary Discharge Pump

Sand Bags & Sump Pump

Control of Seepage - Sidewalls
Provisions in Specifications Concerning Artesian Pressure

Control Artesian Pressures:
- Grouting for Foundation Anchor Installation
- Foundation Drilling and Grouting
Grout Curtain Inhibits Groundwater Flow Into Lock Chamber
Grout Curtain Extends to Elevation 510
10’ Spacing Between Primary Secondary Holes
Optional Tertiary and Higher Order Holes
Know Location of Top of Rock Surface:

- Sheet Pile Driven to Rock – Cofferdam & Retaining Wall
- Seepage Cutoff Wall Through Soil – Key into Rock
BEDROCK DEWATERING FOR CONSTRUCTION

OUTLINE

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SOO LOCKS – PROJECT DESCRIPTION


- All shipping in/out of Lake Superior travels through Soo Locks.

- New lock is in plans and specifications phase. Partial cofferdam has been constructed and approach channel deepened.
Aerial View of Project - Taken From Upstream
Aerial View of Locks

- Sabin 80’x1350’ 1919
- Davis 80’x1350’ 1914
- Poe 110’x1200’ 1968
- MacArthur 80’x800’ 1943
Aerial View of Locks – Proposed New Lock

New Lock 110’x1200’

Poe 110’x1200’ 1968

MacArthur 80’x800’ 1943
- 76 Borings
- 6,036 Total Feet of Exploratory Drilling
- 4,139 Feet of Coring
- 24 Piezometers

Subsurface Exploration – Boring Location Plan
Subsurface Exploration – Down Hole Testing

496 Pressure Tests

21 Borehole Jack Tests

1,000’ of Down-the-Hole Camera Images

BUILDING STRONG®
General Geology

- Soil and rock fill – 0 to 35 feet thick
- Natural top of rock dips downstream (1%) – altered by past excavations
- Jacobsville Sandstone Formation (Cambrian Age) - interbedded sandstones
  - Hard Sandstone Member
  - Moderately Hard Sandstone Member
  - Shaly & Weathered Sandstone Members
- Thin, continuous seams of clay, claystone and shale within sandstone.
- Bedding plane dip in a westerly direction at a 3 percent slope.
Bedrock Units – Hard Sandstone

HARD SANDSTONE MEMBER is typically light gray, light red or light purple with few light gray reduction spots, hard to very hard, fine to medium grained, occasionally cross bedded and medium to thick bedded.

12,400 psi Average Unconfined Compressive Strength

Increased number of high-angled joints
Bedrock Units – Moderately Hard Sandstone

MODERATELY HARD SANDSTONE MEMBER is typically red with few to numerous light gray reduction spots, moderately hard, fine to medium grained and thin to medium bedded.

9,900 psi Average Unconfined Compressive Strength

The predominant member sampled.
**WEATHERED SANDSTONE MEMBER** is typically red with numerous light gray reduction spots, moderately hard, fine to medium grained, moderately weathered and thin bedded.

**SHALY SANDSTONE MEMBER** is typically red to dark red with light gray reduction spots, soft to moderately hard, fine grained and thin bedded

Increased number of weak / clay seams within these two members.
**WEAK / CLAY SEAMS** are typically thin (ranging from 0.4-foot to 0.02-foot thick), laterally continuous and have a scattered vertical distribution (1-foot to 7-foot vertical spacing). These weak seams consist of:

- Clay Seams
- Clay Coated Bedding Planes
- Zones of Severely Broken Rock
- Claystone or claystone interlaminated with clay seams
The predominant joint set orientation has been measured to have a dominant direction of N 70° E, and a secondary direction of N 30° E.

Joints are typically high-angled (70° to vertical) with a smooth and planar surface, occasionally displaying some discoloration of the bedrock, and aperture ranging from tight to open with occasional clay coating or filling.

Few faults were noted during construction of Poe Lock. These were high angled with limited vertical extent.
Geologic Cross Section – Existing Lock Chambers

- Soil and Rock Fill
- Moderately Hard Sandstone Member
- Hard Sandstone Member
- Weathered and Shaly Sandstone Members
- Continuous Weak/Clay Seams
Geologic Cross Section – New Lock Chamber

- Soil and Rock Fill
- Moderately Hard Sandstone Member
- Hard Sandstone Member
- Weathered and Shaly Sandstone Members
- Continuous Weak/Clay Seams

NEW LOCK
NEW CONCRETE
ROCK ANCHORS
Cross Section – Pressure Testing – Downstream Cofferdam
Cross Section – Pressure Testing – Upstream Cofferdam
Hydraulic Conductivity – Groundwater Inflow

- Hydraulic Conductivity or Permeability of the bedrock is determined from pressure test results.

- **Average bedrock permeability** at the Soo Lock Replacement Project located between top of rock surface and the excavated chamber elevation (533.6) is **5.4 x10^{-3}** ft/min.

- **Magnitude greater than Marmet L&D** (3.3x10^{-4} ft/min) or Winfield L&D (6.9 x10^{-4} ft/min).

- **Individual pressure tests** resulted in localized permeability of 1.3x10^{-1} ft/min (comparable to clean sand) and flow rates up to **9.3 cfm (70 gal/min)** within a 5-foot increment.

- **Estimated** groundwater inflow through bedrock ranged from **1,480 to 2,625 gpm**.
Seepage Through Bedrock During Dewatering
Groundwater Inflow During Construction

- Study performed in 2010 by Dr. Frank Schwartz, Ohio State University.
- Preliminary study with limited scope.
- Developed groundwater model using FTWORK, a finite-difference modeling package.

<table>
<thead>
<tr>
<th>Trial #</th>
<th>$K_B$ (ft/s)</th>
<th>Davis Lock</th>
<th>Replacement Lock</th>
<th>Total: DL+RL</th>
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<tr>
<td>1</td>
<td>$6 \times 10^{-5}$</td>
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<tr>
<td>5</td>
<td>$9 \times 10^{-5}$</td>
<td>735</td>
<td>1890</td>
<td>2625</td>
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$K_B$: Hydraulic Conductivity Background
DL + RL: Davis Lock plus Replacement Lock

Summary: Trial 1 dewater new lock excavation only, Trial 2 dewatered new lock and Davis Locks. Trial 3: same as 2 with conservative grout curtain, Trails 4&5: same as 3 with varying $K$ values.
Groundwater Model

Map of Model Grid in Relation to the Lock Structure

- Simulation domain
- Inactive cells
- Constant head
- General head
Groundwater Model

Distribution of Hydraulic Head
SOO LOCKS – IMPACTS TO DESIGN

Grout Curtain for Dewatering Purposes - Upstream

Plan View – Upstream Monoliths
Grout Curtain and Slurry Trench for Dewatering Purposes

Plan View – Downstream Monoliths
Grout Curtain Details
Groundwater Flow Into Excavation – Lock Chamber

- **EXISTING NORTH DAVIS LOCKWALL**
- **SOIL**
- **NEW SOUTH WALL**
- **SKIRT WALL**
- **EXCAVATED LOCK CHAMBER**
- **NEW CULVERT**
- **BEDROCK**
- **HYDROSTATIC PRESSURE**
Groundwater Flow Into Excavation – Drainage Sheets

- EXISTING NORTH DAVIS LOCKWALL
- SOIL
- DRAINAGE SHEETS (Required to reduce hydrostatic pressure against Skirt Wall)
- SKIRT WALL
- BEDROCK
- HYDROSTATIC PRESSURE

BUILDING STRONG®
Groundwater Flow Into Excavation – Drainage Sheet Details
Questions & Discussion