Demonstration and Validation of the Fractured Rock Passive Flux Meter

ESTCP Project ER0831

Kirk Hatfield
University of Florida

November 9, 2010
Project Team

University of Florida:
  Michael Annable, Harald Klammler, Mark Newman and Jaehyun Cho

University of Guelph:
  Beth Parker, John Cherry, and Ryan Kroeker

RAS Incorporated:
  William Pedler
Technical Objectives

The objective of this project is to demonstrate and validate the fractured rock passive flux meter (FRPFM) as an innovative closed-hole technology. Specific project objectives are:

1. Demonstrate and validate an innovative technology for the direct in situ measurement of cumulative water and contaminant fluxes in fractured media

2. Formulate and demonstrate methodologies for interpreting contaminant discharge from point-wise measurements of cumulative contaminant flux in fractured rock
Technology Description

Unfractured Bedrock

Ground Surface

Water Table

Fracture planes and flow directions

FRPFM packer or inflating fluid

FRPFM impermeable flexible liner and attached sorbent layer

Flow through matrix blocks

FRPFM Packer Design

Unfractured Bedrock

Flow through matrix blocks

Packer minimizes vertical cross-flow between fractures
Technology Description

- The FRPFM is essentially an inflatable packer or impermeable flexible liner that holds a reactive permeable fabric against the wall of the borehole and to any water-filled fractures intersected by the borehole.

- Reactive fabrics capture target contaminants and release non-toxic resident tracers (e.g., visible dyes and branch alcohols).

- Tracer loss is proportional to ambient fracture flow.

- Leached visible tracers reveal location and orientation of active fractures and flow direction.

- Contaminant mass captured is proportional to ambient contaminant flux.
Inflatable Packers

Air line to packers

Inflatable Core with mesh 5 mm

Sorbent (AC Felt 2.5 mm) \( K = 0.2 \text{ cm/s} \)

Sock with visual tracer

FRPFM Shield Air line to core

Inflatable Shield-Packer

Air line to shield-packer

FRPFM Prototype with Shield

Dimensions

Borehole ID = 3.8 in (9.652 cm)
Nominal 4 in borehole

Un-Inflated Dimensions
Shield packer OD = 3.5 in
Shield OD = 3.5 in
Packer OD = 3.3 in
Core OD = 3.2 in
(with sorbent and sock)

Note: When inflated all dimensions match borehole ID

Nominal 4-inch Diameter Borehole

Accelerometer
Selection of Sorbents and Resident Tracers
Suite of Non-toxic Branched Alcohols

Batch Tracer Sorption Isotherms on Felt 1300
Resident Tracer Results

- Water Flux Measurements can be interpreted from resident tracer losses.
- Tracer retardation factors and elution functions are sensitive to the nonlinear sorption isotherms.
- Consistent use of tracers and sorbents is critical!

*Elution curves for varying thickness of sorbent material (Klammler, 2004).*
Fracture Dimensions:
• Horizontal
• Aperture = 500 μm
• Width = 26 cm
• Length = 53 cm
• Conductivity ~0.7 cm/s

Borehole:
• Diameter 10.16 cm

Flow Convergence:
• Maximum = 1.76
FRPFM Performance in the Laboratory

Visual Tracer Reveals Fracture Location and Orientation and Flow Direction

- Front Up Gradient
- Left
- Right
- Back Down Gradient

4 mm

Visual indication of flowing fracture

- 0.5 mm fracture aperture
- \( Q = 1.5 \text{ ml/min}, \ q = 2500 \text{ cm/day} \)
- Duration 1 day
- Visual fracture zone (max) aperture 4 mm
- Visual fracture zone length along circumference 147 mm

Flow
Large Aquifer Box (High contrast flow zones)

Box Dimensions
(length x width x height)
2.0 x 0.5 x 1.3 m

Screened Wells (4-inch diameter PVC)
Alternating Sand and Gravel Layers
Visual Indication of Flow
FRPFM Results in Aquifer Box

- **Sand Surface**
- **Well 1**
- **Well 2**
- **Darcy Velocity (cm/day)**

Layers:
- Sand Layer 1
- Gravel Layer 1
- Sand Layer 2
- Gravel Layer 2
- Sand Layer 3
- Gravel Layer 3
- Sand Layer 4

Distance from bottom of well (cm):
- BHD

Note:
- 

Graphical representation of FRPFM results in an aquifer box, showing various layers and their respective distances from the bottom of the wells.
Two Field Sites

Guelph Tool Site, Ontario, Canada

Former Naval Air Warfare Center (NAWC), West Trenton, NJ
Site Description

Guelph Tool Site, Ontario, Canada

- Guelph Tool Inc. facility
- Site is well characterized
- Fractured Dolostone
- High bulk conductivity
- Medium to large apertures
- TCE
- Natural gradient conditions
- Excellent infrastructure
- Leverage the FRFRF
Test Design
Guelph Tool Site, Ontario, Canada

Project will:

1. Validate FRPFM performance in one or two fractured rock holes or sections of holes located in a chlorinated solvent plume

2. Combine existing site data with new data generated from this study to explore potential cost-savings derived from using the FRPFM in conjunction with other borehole technologies

<table>
<thead>
<tr>
<th>Zone</th>
<th>Top Depth (mbTOC)</th>
<th>Bot Depth (mbTOC)</th>
<th>T (m²/s)</th>
<th>Number of ATV Fractures in Test Interval</th>
<th>ATV Fractures Equivalent 2b (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.5</td>
<td>43.04</td>
<td>1.59E-05</td>
<td>4</td>
<td>185</td>
</tr>
<tr>
<td>2</td>
<td>39</td>
<td>40.5</td>
<td>1.78E-06</td>
<td>5</td>
<td>82</td>
</tr>
<tr>
<td>3</td>
<td>37.5</td>
<td>39</td>
<td>7.81E-06</td>
<td>4</td>
<td>151</td>
</tr>
<tr>
<td>3</td>
<td>37.5</td>
<td>39</td>
<td>7.81E-06</td>
<td>4</td>
<td>151</td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>37.5</td>
<td>1.29E-06</td>
<td>4</td>
<td>79</td>
</tr>
<tr>
<td>5</td>
<td>34.5</td>
<td>36</td>
<td>4.47E-07</td>
<td>4</td>
<td>58</td>
</tr>
<tr>
<td>6</td>
<td>33</td>
<td>34.5</td>
<td>1.97E-06</td>
<td>5</td>
<td>89</td>
</tr>
<tr>
<td>7</td>
<td>31.5</td>
<td>33</td>
<td>1.58E-06</td>
<td>6</td>
<td>78</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>31.5</td>
<td>2.98E-06</td>
<td>5</td>
<td>102</td>
</tr>
<tr>
<td>9</td>
<td>28.5</td>
<td>30</td>
<td>2.62E-06</td>
<td>1</td>
<td>159</td>
</tr>
</tbody>
</table>
## Test Design

<table>
<thead>
<tr>
<th>Performance Tests</th>
<th>FRP FM Technology</th>
<th>Competing Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Measurement</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Flux</td>
<td>Resident Tracers</td>
<td>Borehole Dilution</td>
</tr>
<tr>
<td>Contaminant Flux</td>
<td>Contaminant Sorption</td>
<td>Modified Borehole Dilution</td>
</tr>
<tr>
<td>Detection of Flowing Fractures</td>
<td>Visual Tracer</td>
<td>Hydrophysical Logging (open hole) ,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature Logging (closed hole)</td>
</tr>
<tr>
<td>Flow Direction</td>
<td>Visual Tracer</td>
<td>Scanning Colloidal Borescope</td>
</tr>
<tr>
<td>Fracture Orientation</td>
<td>Visual Tracer</td>
<td>Optical and Acoustic Televiewer</td>
</tr>
</tbody>
</table>
Field-Scale Prototype Test: Deployment

Well MW-26: Nominal 4-inch open borehole.
Selected zone for location of FRPFM based upon ATV, Tadpoles, HPL, HRTP, and Caliper data

FRPFM Measured Water Fluxes:
• 9.6 cm/d average specific discharge
• 36-180 m/d fracture flow
Visual indication of discrete flow intercepting FRPFM (MW-26 at 13.87 m below TOC) Sample zone 88-98 cm

Visible light

UV light

Black marks provide frame of reference.

Specific Discharge (cm/day)

0 2 4 6 8 10 12 14 16

0 2 4 6 8 10 12 14 16

39

60

62

64

91

92

93

108
Selected zone for location of FRPFM. Based upon ATV, Tadpoles, HPL, HRTP, and Caliper data.
Visual indication of tracer washout (under UV light) from high permeability zone in upper portion of MW-26
Visual indication of discrete flow intercepting FRPFM MW-25 at 26ft bgs (under UV light)
Physical Setup: Transect, Borehole(s), Traces, Intersections

Problems:

1) Estimate discharge $Q$ through traces in transect from measured fluxes $q_i$ at borehole-trace intersections

2) Quantify estimation uncertainty
Parameters Involved

- **Intersections**: number $N_i$, orientations $\theta_i$
- **Fluxes** $q_i^*$ (at each intersection perpendicular to transect): flow per unit trace length = velocity times aperture
  \[ \rightarrow \text{As } q_i^* \text{ are measured directly, fracture aperture, roughness and gradients are not required.} \]
- **Transect**: width $W$, height $H$, number of wells
- **Traces**: number $N_t$ (in transect) or areal fracture density $\lambda_A$, lengths $l_t$, mean flux $q_t$, orientations $\theta_t$

**True discharge** (in $L^3/T$):

\[ Q = \sum_{t=1}^{N_t} l_t q_t \]
Discharge Estimation at Transects

- Total number of fractures $N_t$, Areal fracture density $\lambda_A$ and fracture length $l$ are not easily determined from borehole data.
- However fracture frequency $\lambda_L$ (# of fractures intersected per unit length of borehole) is directly measured at each borehole.
- Fracture frequency is a measure of the product of fracture density and length (Robertson, 1970; Baecher et al., 1977):

$$\frac{\lambda_L}{\cos \theta} = \lambda_A \bar{l}$$
Ground Water Discharge Estimation

- For each borehole:

\[
Q = \left( \sum q \frac{\lambda_L}{\cos \theta} \right) \text{(transect area)}
\]

Q : groundwater discharge estimated at the borehole [L³/T]
q : FRPFM groundwater flux measurement [L²/T]
    ( q = Darcy velocity*aperture )
\( \lambda_L /\cos \theta \) : measured fracture frequency corrected for orientation bias
\( \theta \) : orientation angle between joint normal and borehole
Contaminant Discharge Estimation

- At each borehole:

\[ M_Q = \left( \sum \left( J_c \frac{\lambda_L}{\cos \theta} \right) \right) \text{(transect area)} \]

- \( M_Q \): contaminant mass discharge estimated at the borehole [M/T]
- \( J_c \): FRPFM mass flux measurement [M/LT]
  \( J_c = \text{contaminant mass flux } \times \text{aperture} \)
- \( \lambda_L / \cos \theta \): measured fracture frequency corrected for orientation bias
- \( \theta \): orientation angle between joint normal and borehole
Project Status

- FRPFM was validated in the laboratory.
- FRPFM is being demonstrated and validated in the field.
- Stochastic methods for estimating contaminant discharge look promising.
Questions?