

# HYDRAULIC TESTS IN A FRACTURED BEDROCK FORMATION

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**ABSTRACT** – 25 well fracture sets in a Fractured Bedrock Formation (FBF) were isolated with pneumatic straddle-packers. 100 Slug Tests (ST) were conducted and analyzed with the Hvorslev and Cooper methods, and the hydraulic parameters from these methods were compared with those from two Pumping Tests (PT) that utilized three Monitoring Wells (MW) for observation data; PT were analyzed by the Jacob method and a Finite-Difference method. Hydraulic Conductivity (K) estimates with the Hvorslev method, using an Effective Radius (ER) parameter of 200 times the effective radius of the well screen, as suggested in the literature, were half of the K values estimated with the Cooper Method. The ER had to be selected three orders of magnitude higher than the recommended value, in order to obtain K results equivalent to the Cooper method. PT K arithmetic average between Test Well (TW) and any MW were consistent with ST. Storage Coefficient (S) estimates by ST invariably were unrealistically low, suggesting that ST porous media models are inappropriate for S estimations in FBF. Equivalent K estimates were found between rising head and falling head ST, however K estimations decreased up to 30%, when the initial ST displacement ( $H_0$ ) was increased up to three times that of conventionally recommended values ( $H_0$  range of 0.5 to 3 ft). Large  $H_0$  values caused slight water level variations in all MW, which are located up to 200 ft away from the TW. This may indicate that high  $H_0$  ST could be useful in assessing well/fracture interconnectivity.

## 1. Introduction

Since 1999, the Bedrock Bioremediation Center (BBC) at the University of New Hampshire has been studying a fractured bedrock formation that exhibits contamination from chlorinated solvents. The BBC is funded by the US EPA on contract CR 827878-01-0. The primary project objective is to isolate distinct fractures and determine the nature of bioremediation processes in them. The site is located in Newington NH. The bedrock geology is characterized by fractured metasandstones and metashales of the Silurian or Ordovician Kittery Formation, underlying as much as 30 ft. of glacial till and glaciomarine clays (Bothner, 2002).

As part of the characterization of the site, each time a well is drilled, a continuous core is retrieved; heat pulse flow meter readings taken, and a complete suite of geophysical logs are made (acoustic televiewer, optical televiewer, gamma, resistivity, caliper, omnidirectional radar, and temperature). At selected isolated zones, after water sampling, hydraulic tests are run to estimate Hydraulic Conductivity (K) and Storage Coefficient (S). This paper describes the results of the hydraulic tests at one well: BBC3, figure 1.

Based on geophysical logs, such as that shown in figure 2, 25 well fracture sets were selected to be isolated with pneumatic straddle-packers and hydraulically tested. 100 Slug Tests (ST) were conducted in the well varying the following parameters: tested interval length, initial slug displacement ( $H_0$ ), and slug head direction (Rising/Falling, R/F). As an additional comparison of ST results (K and, S estimates, Pumping Tests (PT) with three Monitoring Wells (MW) were performed at two of the more conductive horizons, figure 3.

## 2. Experimental Procedure

Because of continuous coring, BBC3 has a very smooth 6-inch diameter. The straddle-packer has a 4.5-inch diameter, 3-ft long inflatable packer above and below a screened interval. The length of the screened interval is either three- or five ft. The screened interval is perforated, 2-inch ID brass pipe that connects to solid pipe at the packers, then goes through the upper and lower packers. Below the bottom packer, the pipe is capped. Above the top packer, the 2-inch pipe is connected to 2-inch ID threaded aluminum pipe that extends to above the top of casing, where it is capped and plugged to a vacuum pump

(falling head) or a nitrogen tank (rising head). Single-packer ST were conducted by removing the bottom packer, and using a single packer to isolate the lower well interval (the tested section) from the well above.

Three pressure transducers (accuracy 0.25% of full scale) were used to monitor pressure in the system during hydraulic tests: one below the bottom packer, one in the isolated interval, and the other above the top packer. The two extreme transducers were used to check the seal between the inflated packers and the well wall; the central recorded pressure in the isolated zone during hydraulic tests.

For (R/F) slug tests, the aluminum pipe was pressurized/depressurized with nitrogen gas/ vacuum pump, respectively. This step took a few minutes. When the readings from the central pressure transducer stabilized and the zones outside of the tested interval did not exhibit leakage, the pressure was released in a near-instantaneous fashion. Pressure was recorded at a rate of eight data points per second during the first minute, and it was decreased to a rate of one data point each five seconds until stabilization. For PT, water was pumped from BBC3 using a submersible pump. Flowrate was volumetrically measured every 15 minutes. Pressure was recorded every five seconds at BBC3, and each minute at MW.

Ten test intervals of 5-ft. length were investigated with ST. Eleven 3-ft. interval lengths were run with ST at the more conductive zones; at two of the more productive zones had PT performed on them. Finally, single-packer ST were conducted, with interval length varying from the lowest 3.7-ft. of the well, to the total open well length (55 ft).

### 3. Results and Discussion

ST were analyzed with the Cooper method (Cooper et.al. 1967). The field data fit the type curves at unrealistically low  $S$  values ( $S \sim 10^{-11}$ ). Data also were analyzed with the Hvorslev method (Hvorslev, 1951); by selecting an Effective Radius (ER) equal to 200 times the effective radius of the well screen, as suggested by Butler (1998). The Hvorslev  $K$  values were half of those obtained with the Cooper method. It was necessary to set ER three orders or magnitude higher than that suggested in the literature, in order to obtain equivalent  $K$  estimates to the Cooper model.

$K$  estimates for 5-ft intervals, 3-ft intervals, and single-packer ST are shown in tables 1, 2, and 3, respectively. As long as  $H_o$  was less than 3-ft, as suggested by Butler (1998),  $K$  estimates at each interval were essentially the same, regardless the head direction (R/F). Underlined values represent ST  $K$  estimates with  $H_o$  larger than suggested values. They were found significantly different from  $K$  mean estimates obtained with conventional  $H_o$  values (95% confidence, tables 1, 2, and 3).  $K$  was found to continually decrease with increasing  $H_o$ .  $K$  values were up to 30% lower than those obtained with conventional short  $H_o$  ST, figure 4. ST at BBC3 with  $H_o$  larger than 13-ft. caused small pressure variations in MW located up to 208-ft away, indicating well/fracture interconnectivity, figure 5.

PT responses in the MW were analyzed with the Jacob model (Cooper and Jacob, 1946); in addition, BBC3 (PW) data was analyzed by the Jacob method and by a finite-difference method, which takes into account well bore storage (Pulido and Ballesterro, 2002).  $S$  estimates ( $S \sim 10^{-4}$ ), indicate confined conditions consistent with the geology of the site.  $K$  estimates changed up to almost two orders of magnitude, depending if analyzing pumping well (PW) or MW data, table 4. Nevertheless, the  $K$  arithmetic average between PW and any MW was equivalent to the corresponding ST  $K$  estimate.

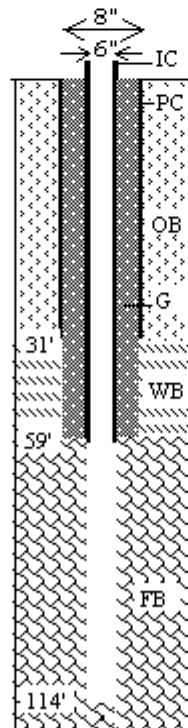
$K$  profiles show a low conductive upper zone ( $K < 5$  ft/day), followed by a one order of magnitude higher conductive zone below 95 ft, with a peak in the interval 110-114 ft ( $K > 90$  ft/day). As expected, transmissivity ( $T$ ) obtained by adding the discrete  $T$  values from each 5 ft intervals was basically the same as  $T$  value for the tests on the entire open borehole, figure 6.

### 4. References

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- J. Butler, Jr. 1998. *The design, performance, and analysis of Slug Tests*. Lewis Publishers, Boca Raton, FL.
- Cooper, H.H., Jr., and C.E. Jacob. 1946. A generalized graphic method for evaluating formation constants and summarizing well-field history. Transactions, American Geophysical Union, Vol 27, No.4, pp. 526-534.
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- Hvorslev, M.J., 1951. *Time lag and soil permeability in groundwater observations*. US Army Corps of Engineers, Waterways Experiment Station Bulletin 36. Vicksburg, MS.
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Depth [ft]	Type	Ho	K	Depth [ft]	Type	Ho	K		
Initial	Final	(F/R)	[ft]	[ft/day]	Initial	Final	(F/R)	[ft]	[ft/day]
58	63	R1	4.7	4	87	92	R2	5.00	4
<b>K[ft/day]:</b>									
<b>3.8+/-0.8</b>									
<b>(95% C.I.)</b>									
		F1	1.58	4			R3	2.78	4
		F2	2.32	3	<b>4.5+/-0.9</b>				
		F3	2.85	4			F1	1.97	5
66	71	R1	0.99	6	90	95	R1	<u>2</u>	<u>3</u>
<b>6.3+/-0.7</b>							R2	1.36	4
		R2	3.55	6			R3	2.25	4
		F1	2.68	6			F1	2.13	4
		F2	1.91	7			F2	2.77	5
72	77	R1	4.05	3	<b>4.2+/-0.6</b>				
		R2	1.03	4			F2	3.7	5
<b>3.5+/-0.7</b>							F3	3.11	4
		F1	2.61	3	95	100	R1	<u>7.1</u>	<u>21</u>
		F2	2.96	3.8			R2	2.86	30
77	82	R2	4.54	1.0	<b>30.5+/-6.4</b>				
		R3	3.47	1.0	100	105	R1	<u>6.8</u>	<u>34</u>
<b>1.4+/-0.5</b>							R2	0.66	40
		F2	3.00	1.4			R3	3.7	38
		F3	1.10	1.9	<b>39.3+/-2.8</b>				
81	86	R1	1.31	4			R4	1.92	40
		R3	1.27	4			R5	<u>13</u>	<u>30</u>
		F1	2.74	4	105	110	R1	<u>7.1</u>	<u>35</u>
<b>1.4+/-0.0</b>							R2	0.79	40
		F2	2.32	4			R3	3.1	39
		F3	2.04	4	<b>39.7+/-1.4</b>				
							R4	2.32	40
							R5	<u>14</u>	<u>31</u>

Depth [ft]	Type	Ho	K	
Initial	Final	(F/R)	[ft]	[ft/day]
59	62	F1	1.56	3.4
68	71	F1	2.21	2.8
72	75	R1	1.35	2.7
86	89	F1	2.85	4
89	92	F1	2.66	3
92	95	R1	0.49	1
<b>1.0+/-0.0</b>				
		F1	3.29	1
95	98	R1	0.76	1
<b>1.0+/-0.0</b>				
		F1	2.89	1
97.2	100	R1	<u>11</u>	<u>30</u>
		R2	3	44
<b>45.0+/-12.7</b>				
		R3	1.71	46
100	103	R1	1.51	41
<b>42.0+/-12.7</b>				
		F1	3	43
103	106	R1	1.52	46
		R2	<u>10</u>	<u>40</u>
		R3	<u>8.9</u>	<u>40</u>
		R4	<u>9.1</u>	<u>40</u>
<b>K[ft/day]:</b>				
<b>47+/-12.7</b>				
<b>(95% C.I.)</b>				
		F1	2.66	48
106	109	F1	1.6	12
<b>12.0+/-0.0</b>				
		F2	2.15	12



Initial Depth [ft]	Thickness [ft]	Type (F/R)	Ho [ft]	K [ft/day]
59	55	R1	1.42	13
		R2	2.63	12
<b>K[ft/day]:</b>				
<b>12.2+/-0.6</b>				
<b>(95% C.I.)*</b>				
		F1	2.2	12
		F2	<u>5.09</u>	<u>11</u>
		F3	2.02	12
78.3	35.7	R1	4.06	16
		R2	1.01	19
		R3	0.28	22
		F1	4.95	16
<b>18.0+/-2.4</b>				
		F2	2.96	17
		F3	2.01	18
99.8	14.2	R1	2.2	42
		R2	3.94	37
		R3	7.27	35
		R4	1.07	44
		R5	<u>12.4</u>	<u>30</u>
		F1	3.06	42
		F2	<u>6.74</u>	<u>37</u>
<b>40.4+/-3.1</b>				
		F3	2.24	40
		F4	1.72	43
110.3	3.7	R1	4.14	123
		R2	1.32	152
		R3	2.79	133
		F1	2.02	138
<b>135.2+/-13.5</b>				
		F2	3.04	130

(\* C.I. = Confidence Interval)

Well	BBC3	MW1	MW2	MW3
Distance [ft]	0	77	124	208
Metho	F.Diff.	Jacob	Jacob	Jacob
Depth [ft]	100 - 103			
Flowrate [ft <sup>3</sup> /hour]=5. Duration [Hours]=10.5				
K [ft/d:	2	0.5	65	57
S [ ]	1E-04	7E-04	1E-04	1E-04
Depth [ft]	103 - 106			
Flowrate [ft <sup>3</sup> /hour]=6. Duration [Hours]=2.7				
K [ft/d:	5	1	94	95
S [ ]	5E-05	7E-04	9E-05	2E-04

IC=Inner Casing PC=Protective Casing  
 OB=Overburden WB=Weathered Bedrock  
 FB=Fractured Bedrock G=Grout

**Figure 1. BBC3 well design (not to scale)**

Figure 2. BBC3 Acoustic Televiewer log

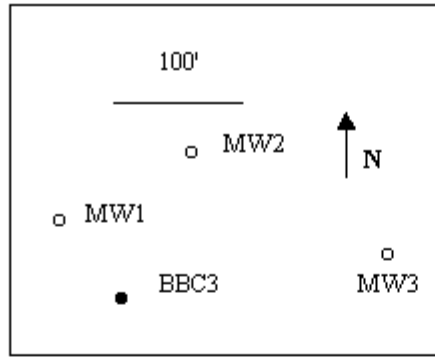
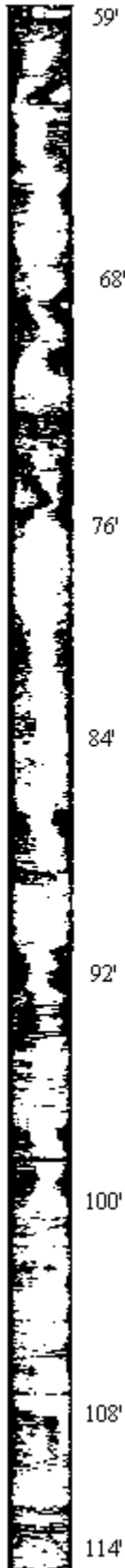


Figure 3. Ubication Map

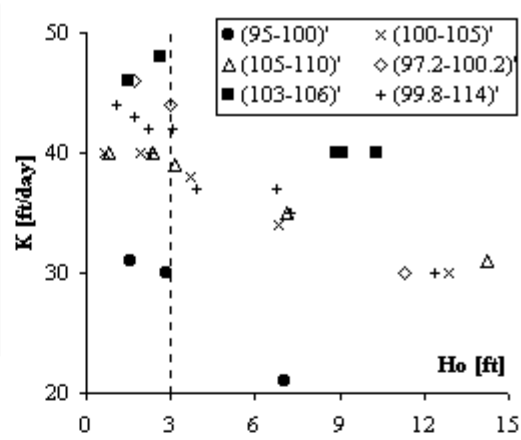


Figure 4. K dependence with Ho

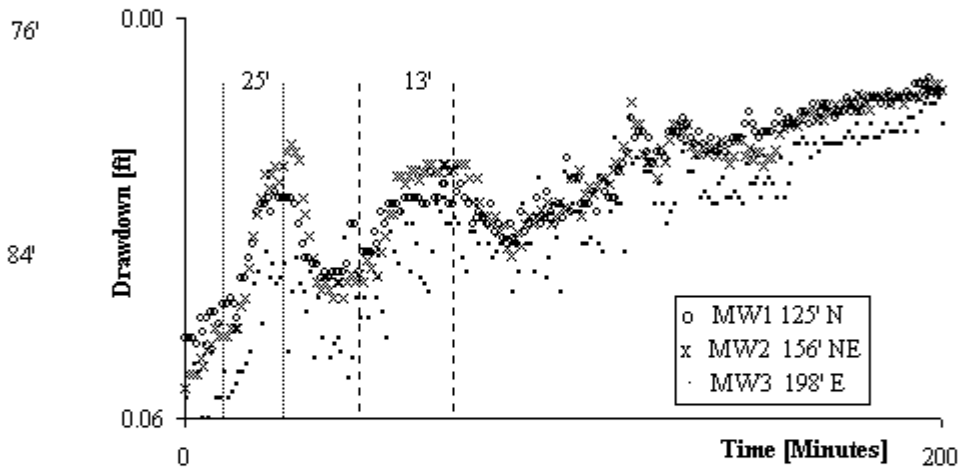


Figure 5. MW response to Large Ho ST

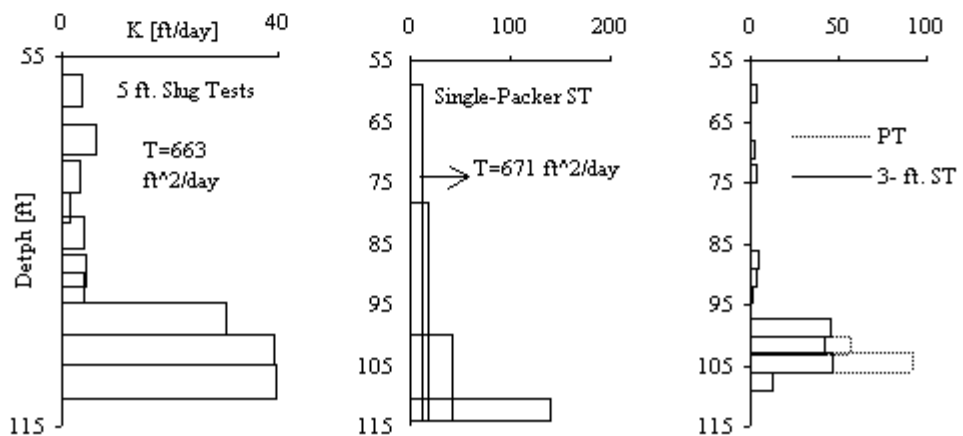


Figure 6. BBC3 Hydraulic Conductivity Profiles